

UC Santa Cruz

UC Santa Cruz Electronic Theses and Dissertations

Title

Multiwavelength Modeling of the Blazar 1ES 0647+250 and the Impact of Cosmic Voids on the High-Energy Detection of Active Galactic Nuclei

Permalink

<https://escholarship.org/uc/item/6wh9b9vk>

ISBN

9798190917666

Author

Splettstoesser, Megan

Publication Date

2026-08-28

Copyright Information

This work is made available under the terms of a Creative Commons Attribution License, available at <https://creativecommons.org/licenses/by/4.0/>

Peer reviewed|Thesis/dissertation

UNIVERSITY OF CALIFORNIA
SANTA CRUZ

**MULTIWAVELENGTH MODELING OF THE BLAZAR
1ES 0647+250 AND THE IMPACT OF COSMIC VOIDS ON THE
HIGH-ENERGY DETECTION OF ACTIVE GALACTIC NUCLEI**

A dissertation submitted in partial satisfaction of the
requirements for the degree of

DOCTOR OF PHILOSOPHY

in

PHYSICS

by

Megan Splettstoesser

August 2026

The Dissertation of Megan Splettstoesser
is approved:

Professor Amy Furniss, Chair

Professor David Williams

Professor David Smith

Professor Jason X. Prochaska

Donald Smith
Interim Vice Provost and Dean of Graduate Studies

Copyright © by

Megan Splettstoesser

2026

Contents

Abstract	xvi
Acknowledgments	xviii
Nomenclature	xx
I Multiwavelength Modeling of the Blazar 1ES 0647+250	1
1 Observations of Very High-Energy Photons	2
1.1 Active Galactic Nuclei: Blazars	2
1.2 Imaging Atmospheric Cherenkov Telescopes (IACTs)	7
1.2.1 Cherenkov Radiation (CR)	10
1.2.2 Extensive Air Showers (EAS)	15
2 Multiwavelength Analysis	20
2.1 Selection of States	20
2.1.1 State A (2012)	21

2.1.2	State B (2020)	22
2.1.3	State C (2024)	23
2.2	VERITAS Analysis with VEGAS	24
2.2.1	VEGAS vaStage1	26
2.2.2	VEGAS vaStage2	29
2.2.3	VEGAS vaStage4	32
2.2.4	VEGAS vaStage5	38
2.2.5	VEGAS vaStage6	39
2.2.6	1ES 0647+250 (VER J0650+250)	51
2.3	<i>Fermi</i> -LAT	56
2.4	<i>Swift</i> -XRT	62
2.4.1	Intrinsic SEDs via <code>nHDeabsorb</code>	67
2.4.2	Representative SEDs	68
2.4.3	Fastest observed variability	71
2.5	<i>Swift</i> -UVOT	73
2.6	FLWO	75
2.7	Keck ESI	77
2.8	OVRO	79
2.9	TELAMON	80
3	Multiwavelength Modeling with <code>Bjet_MCMC</code>	83
3.1	Overview of States	84
3.2	<code>Bjet_MCMC</code> Configuration	86

3.3	SSC Model with All Parameters Freed	87
3.4	Parameter Filtering	98
4	Results and Discussion	106
4.1	Overview of Relevant Parameters	107
4.2	SSC Model and Implications	110
4.3	Conclusion	124
II	Simulations of High-Energy and Very High-Energy Photon Propagation	125
5	Cosmic Voids and Active Galactic Nuclei	126
6	CRPropa Simulations	138
6.1	Cosmology	138
6.2	Particle Interactions and Propagation	139
6.2.1	Propagation	139
6.2.2	Interactions	143
6.3	Sources	154
6.4	Observer	155
6.5	Break Conditions	157
6.6	Magnetic Fields and their Evolution and Evaluation	161
7	Analysis of CRPropa Simulations	169
7.1	“Detection” of Events on the Large Observer Sphere	170

7.2	Energy Flux Per Decade	177
7.3	Injected Spectrum	180
8	Results and Discussion	181
8.1	Overview of Dominant Interactions and Relevant Distances	184
8.1.1	Impact of Magnetic Field	184
8.1.2	Impact of Redshift	185
8.1.3	Impact of Distance Traveled	189
8.2	(Detected) Primary Photons	191
8.3	Detected Cascade Photons	195
8.3.1	Sources at $z = 0.1$	195
8.3.2	Sources at $z = 0.4$ and $z = 0.7$	197
8.3.3	Sources in $B = 0$	200
8.3.4	Impact of the Cone Half-Opening Angle ψ	202
8.4	Detected Total Photons and Implications for F25 and J26	205
8.5	Conclusion	217
A	Appendix for Part I	220
A.1	Significance of Multiple Datasets	220
A.2	<i>Swift</i> -XRT Analysis	226
A.2.1	Galactic Absorption	226
A.2.2	<i>Swift</i> -XRT SEDs	226
A.2.3	<i>Swift</i> -XRT Lightcurves	232
A.3	<i>Swift</i> -UVOT Analysis	241

A.3.1	<i>Swift</i> -UVOT Rocking	241
A.3.2	<i>Swift</i> -UVOT Lightcurves	242
A.3.3	<i>Swift</i> -UVOT SEDs	242

List of Figures

1.1	The VERITAS array.	8
1.2	Photomultiplier tube schematic.	9
1.3	Polarized atoms in a medium due to a charge traveling at fixed $ \vec{v}_q $, in the case of $v_q < c/n$ and $v_q > c/n$	11
1.4	Cherenkov cone annotated with the directions of $\vec{E}$, $\vec{H}$, and prop- agation of light.	13
1.5	Radiation wavefronts in the case of $v_q < c/n$ and $v_q > c/n$	13
1.6	Spectrum of Cherenkov radiation in the atmosphere.	15
1.7	Electromagnetic air shower and hadronic air shower.	16
1.8	Interaction lengths relevant to electromagnetic air showers in the atmosphere.	18
1.9	Cherenkov light in an extensive air shower, as seen in the atmo- sphere and the camera.	19
2.1	Cleaned VERITAS camera image of a candidate gamma-ray event.	30
2.2	Raw VERITAS camera image of a candidate gamma-ray event.	31
2.3	Hillas parameters overlaid on simulated LST camera image.	32
2.4	Cherenkov light in an extensive air shower, as seen in the atmo- sphere and the camera plane, with Hillas parameters indicated.	33

2.5	Reconstruction of an air shower.	34
2.6	VEGAS LT.	35
2.7	Observed candidate gamma-ray event compared to template from ITM.	37
2.8	Distributions of MSL, MSW, and shower maximum height.	39
2.9	Ring background method and reflected region method.	41
2.10	VERITAS energy bias.	47
2.11	VERITAS ITM energy resolution.	47
2.12	VERITAS flux spectra for each state, including the long-term spectrum.	52
2.13	VERITAS significance skymap for the long-term state.	53
2.14	VERITAS lightcurve.	55
2.15	<i>Fermi</i> -LAT SED for State A.	59
2.16	<i>Fermi</i> -LAT SED for State B.	59
2.17	<i>Fermi</i> -LAT SED for State C.	60
2.18	<i>Fermi</i> -LAT lightcurve.	61
2.19	Fits to η_H using an intrinsic powerlaw with Galactic and intrinsic absorption (iii).	65
2.20	Fits to η_H using an intrinsic log parabola with Galactic and intrinsic absorption (iv).	66
2.21	FLWO lightcurve.	77
2.22	Keck ESI spectrum.	78
2.23	Split normal distribution showing the uncertainty on the radio fluxes.	81
3.1	MWL SEDs for State A, State B, and State C.	85

3.2	Parameter best fits with all parameters freed.	90
3.3	Bjet_MCMC SEDs for State A with all parameters freed.	92
3.4	Bjet_MCMC SEDs for State B with all parameters freed.	93
3.5	Bjet_MCMC SEDs for State C with all parameters freed.	94
3.6	Bjet_MCMC SEDs for State A and State B and State C.	96
3.7	Flowchart for the Bj _{et} _MCMC modeling procedure of multiple epochs.	100
3.8	Flowchart for Bj _{et} _MCMC modeling procedure for one epoch. . . .	101
3.9	Parameter best fits with all parameters free for State B, and n_1 and B free for State A, State B and State C.	104
4.1	Thomson regime and Klein-Nishina regime.	109
4.2	Bjet_MCMC SEDs for State A, State B, and State C with n_1 and B free.	110
4.3	n_1 and B for State A, State B, and State C.	111
4.4	EED for State A, State B, and State C, with n_1 and B free. . . .	113
4.5	Corner plot for State A.	114
4.6	Corner plot for State B.	115
4.7	Corner plot for State C.	116
4.8	State B Bj _{et} _MCMC SED and M23 Epoch 4 SED.	123
5.1	Photon-initiated electromagnetic cascade.	127
6.1	Larmor radii.	142
6.2	Number density of EBL photons as a function of energy.	145
6.3	Number density of EBL photons as a function of redshift, for various energies.	146

6.4	CRPropa synchrotron energy loss lengths.	150
6.5	CRPropa photon interaction lengths at redshift $z = 0$	151
6.6	CRPropa electron interaction lengths at redshift $z = 0$	152
6.7	Impact of rigidity break condition on the tracked IC photons. . .	160
6.8	Magnetic field configuration ii (source in void).	165
6.9	Magnetic field configuration iii (observer in void).	166
6.10	Magnetic field configuration iv (constant B at every grid point). .	167
6.11	Magnetic field configuration ii (source in void) without a padded grid.	168
7.1	Angle β between the jet axis and LoS.	173
7.2	<i>Fermi</i> -LAT PSF.	174
7.3	Deflection angle δ between the LoS and $\hat{P}$	175
8.1	Illustration of the definitions of “all,” “detected” and “total” . . .	182
8.2	Illustration of “source in void” and “observer in void.”	183
8.3	Interaction lengths for PP with the EBL at various z	186
8.4	Interaction lengths for ICS at various z	187
8.5	Injected SEDs in the observer frame.	188
8.6	Estimate of the distance an electron travels in the CRPropa simu- lations.	190
8.7	Counts spectra of primary photon energies for a source at $z = 0.1$ for each magnetic field configuration.	192
8.8	Same as Figure 8.7 but for a source at $z = 0.4$	193
8.9	Same as Figure 8.7 but for a source at $z = 0.7$	194

8.10	Counts spectra of detected photons for a source at $z = 0.1$ for magnetic field configurations i, ii, iii, and iv.	196
8.11	Same as Figure 8.10, but for a source at $z = 0.4$	198
8.12	Same as Figure 8.10, but for a source at $z = 0.7$	200
8.13	Counts spectra of cascade photons in the case of $B = 0$	202
8.14	SED of detected cascade photons for a source at $z = 0.1$ with various ψ , for magnetic field configurations, ii, iii, and iv.	203
8.15	Total SEDs for a source at $z = 0.1$ for each magnetic field configuration.	206
8.16	Same as Figure 8.15 but for a source at $z = 0.4$	207
8.17	Same as Figure 8.15 but for a source at $z = 0.7$	208
8.18	Time delay of detected cascade photons.	211
8.19	Cascade flux as a function of time from a constant flux source. . .	212
A.1	Galactic photoelectric absorption.	227
A.2	<i>Swift</i> -XRT SEDs from each spectral model (i-iv).	231
A.3	<i>Swift</i> -XRT SEDs for State A.	232
A.4	<i>Swift</i> -XRT SEDs for State B.	233
A.5	<i>Swift</i> -XRT SEDs for State B.	234
A.6	Representative <i>Swift</i> -XRT SED for State A.	235
A.7	Representative <i>Swift</i> -XRT SED for State B.	236
A.8	Representative <i>Swift</i> -XRT SED for State C.	237
A.9	<i>Swift</i> -XRT lightcurve for State A.	238
A.10	<i>Swift</i> -XRT lightcurve for State B.	239

A.11 <i>Swift</i> -XRT lightcurve for State C.	240
A.12 Settling <i>Swift</i> -UVOT image, UVUM2 filter.	241
A.13 Settling <i>Swift</i> -UVOT image, UVW2 filter.	242
A.14 Non-settling <i>Swift</i> -UVOT image, B filter.	243
A.15 <i>Swift</i> -UVOT lightcurve for State A.	243
A.16 <i>Swift</i> -UVOT lightcurve for State B.	244
A.17 <i>Swift</i> -UVOT lightcurve for State C.	244
A.18 Representative <i>Swift</i> -UVOT SED for State A.	245
A.19 Representative <i>Swift</i> -UVOT SED for State B.	246
A.20 Representative <i>Swift</i> -UVOT SED for State C.	247
A.21 Host galaxy subtracted representative <i>Swift</i> -UVOT SED for State A.	248
A.22 Host galaxy subtracted representative <i>Swift</i> -UVOT SED for State B.	249
A.23 Host galaxy subtracted representative <i>Swift</i> -UVOT SED for State C.	250

List of Tables

2.1	MWL observation dates.	25
2.2	VEGAS analysis details.	53
2.3	VERITAS lightcurve analysis details.	56
2.4	<i>Fermi</i> -LAT analysis details.	60
2.5	Fastest observed variability.	73
3.1	Bjet_MCMC parameter summary for State A, State Band State C, with all parameters freed.	90
3.2	Bjet_MCMC χ^2/dof summary for State A, State Band State C, with all parameters freed.	95
3.3	χ^2 for various Bjet_MCMC fits with one free parameter.	102
3.4	χ^2 for various Bjet_MCMC fits with two free parameters.	102
4.1	Bjet_MCMC parameters for State A, State B, and State C with n_1 and B free.	112
4.2	Derived quantities from Bjet_MCMC fits.	117
4.3	Sample SSC parameter values for BL Lacs.	117
4.4	Significance of the difference between the best fit parameters to each state.	119

4.5	Comparison of M23 best fit parameters for Epoch 4 to the results in this thesis.	122
6.1	Parameters varied in CRPropa simulations.	156
7.1	CRPropa output.	170
7.2	Physical sizes involved in “detecting” simulation events.	172
8.1	Comoving distance along the LoS with $B = 0$	190
8.2	Ratio of the number of cascade photons at z to the number of cascade photons at $z = 0.1$	204
8.3	STeVECAt sources in 4LAC-DR3 and the void catalogs by Sutter et al. (2012, 2014) with $0.1 \leq z < 0.7$	217
A.1	χ^2 and degrees of freedom for the models fit to <i>Swift</i> -XRT data for State A.	228
A.2	Same as Table A.1 but for State B.	228
A.3	Same as Table A.1 but for State C.	229
A.4	<i>Swift</i> -XRT analysis details for State A.	229
A.5	Same as Table A.4 but for State B.	230
A.6	Same as Table A.4 but for State C.	230

Abstract

Multiwavelength Modeling of the Blazar 1ES 0647+250 and the Impact of
Cosmic Voids on the High-Energy Detection of Active Galactic Nuclei

by

Megan Spletstoesser

Multiwavelength spectra of active galactic nuclei (AGN) are affected by intrinsic AGN emission mechanisms fueled by the source environment and cosmic propagation along our line of sight (LoS), neither of which is fully understood. This thesis explores the former through multiwavelength data analysis and modeling of a particular blazar using a synchrotron-self-Compton model, and the latter—specifically LoS effects due to photon-induced electromagnetic cascades developing in and out of cosmic voids—through simulations of energetic ($E > 100$ MeV) photon propagation over cosmological distances.

Three very high-energy ($E > 100$ GeV) states of the distant ($z = 0.45^{+0.11}_{-0.10}$) blazar 1ES 0647+250 observed by the Very Energetic Radiation Imaging Telescope Array System are identified, and the emission zone is modeled using a leptonic synchrotron-self-Compton and blob-in-jet framework. It is found that one of the simplest scenarios that can describe the multiwavelength properties of the three states is a change in both the magnetic field strength of the emitting region's

environment and the spectral index (below the break energy) of the electron energy distribution.

Simulations of gamma-ray-emitting AGN at three redshifts ($z = 0.1, 0.4$, and $z = 0.7$) and in four cosmic void configurations are conducted, where a void is parameterized by a region with magnetic field strength $B_{\text{void}} = 0$ and a non-void is defined by $B_{\text{IGMF}} = 10^{-13}$ G; these are extreme assumptions about the magnetic field strength both in and out of voids. The spectral energy distributions of the detected photons show that the location of the void has a dramatic impact on the (detected) cascade flux under the extreme conditions considered in this thesis. An AGN in a void can result in a flux that is more than an order of magnitude greater than when the AGN is in a high-magnetic field $B_{\text{IGMF}} = 10^{-13}$ G environment. The cascade emission appears as an enhanced MeV to GeV spectrum, which can increase the number of AGN that are detected by the *Fermi* Large Area Telescope when compared to other AGN catalogs, provided the AGN lie along lines of sight that intersect a high void fraction.

Acknowledgments

This research is supported by grants from the U.S. Department of Energy Office of Science, the U.S. National Science Foundation and the Smithsonian Institution, by NSERC in Canada, and by the Helmholtz Association in Germany. This research used resources provided by the Open Science Grid, which is supported by the National Science Foundation and the U.S. Department of Energy's Office of Science, and resources of the National Energy Research Scientific Computing Center (NERSC), a U.S. Department of Energy Office of Science User Facility operated under Contract No. DE-AC02-05CH11231. We acknowledge the excellent work of the technical support staff at the Smithsonian Astrophysical Observatory's Fred Lawrence Whipple Observatory and at the collaborating institutions in the construction and operation of VERITAS.

This research used resources of the Hummingbird and Elkhorn shared high performance computing facility at the University of California, Santa Cruz. Support for Hummingbird is provided by Information Technology Services Division and the Office of Research.

This research has made use of data from the OVRO 40-m monitoring program (Richards, J. L. et al. 2011, ApJS, 194, 29), supported by private funding from the California Institute of Technology and the Max Planck Institute for Radio Astronomy, and by NSF grants AST2407603, AST2407604, AST-0808050, AST-

1109911, and NASA grants NNX09AU16G, NNX10AP16G, and NNX11AO13G.

The TELAMON program is using the Effelsberg 100-m telescope to monitor the radio spectra of active galactic nuclei (AGN) under scrutiny in astroparticle physics, namely TeV blazars and candidate neutrino-associated AGN.

We thank the observers Raja GuhaThakurta, Emily Cunningham, Yuting Feng, Grion Filho, and Eric Peng for collecting the Keck Echellette Spectrograph and Imager spectrum of 1ES 0647+250. Paolo Goldini analyzed the Keck spectrum.

We acknowledge the use of public data from the Swift data archive. This work made use of data supplied by the UK Swift Science Data Centre at the University of Leicester.

We thank the Swift Helpdesk and XSpec help for their guidance analyzing *Swift*-XRT data.

This research has made use of the SVO Filter Profile Service “Carlos Rodrigo”, funded by MCIN/AEI/10.13039/501100011033/ through grant PID2020-112949GB-I00.

Nomenclature

1FHL The First Fermi-LAT Catalog of Sources above 10 GeV (Ackermann et al., 2013)

2LAC The Second Catalog of Active Galactic Nuclei Detected by the Fermi Large Area Telescope (Ackermann et al., 2011)

4FGL-DR3 Fourth *Fermi*-LAT catalog: data release 3

4LAC-DR3 The Fourth Catalog of Active Galactic Nuclei Detected by the Fermi Large Area Telescope: Data Release 3 (Ajello et al., 2022)

AGN Active galactic nucleus/nuclei

BCU(s) Blazar candidate(s) of uncertain type

BL Lac BL Lacertae type object

BLR Broad line region

CMB Cosmic microwave background

CR Cherenkov radiation

EA Effective area

EAS Extensive air shower

EBL Extragalactic background light

EED Electron energy distribution

EM Electromagnetic

F14 Furniss et al. (2014)

F25 Furniss et al. (2025)

FADC Flash analog to digital converter

***Fermi*-LAT** *Fermi* Large Area Telescope

FLWO Fred Lawrence Whipple Observatory

FOV Field of view

HBL High-frequency synchrotron peaked BL Lacs

IACT Imaging atmospheric Cherenkov telescope

IC/ICS Inverse Compton/Inverse Compton scattering

IGMF Intergalactic magnetic field

ISM Interstellar medium

ITM Image template method

J26 Jackson et al. (2026)

KS test Kolmogorov-Smirnov test

λ Interaction mean free path; interaction length

LoS Line(s) of sight

LRG Luminous red galaxy

LT Lookup table

M23 MAGIC Collaboration et al. (2023)

MAGIC Major Atmospheric Gamma Imaging Cherenkov

MSL Mean-scaled length

MSW Mean-scaled width

MWL Multiwavelength

$n(\epsilon) \quad \frac{dn}{d\epsilon}$; differential background photon number density per energy interval

NLR Narrow line region

NSB Night sky background

OVRO Owens Valley Radio Observatory

PMT Photomultiplier tube

PP Pair production

PSF Point spread function

RBM Ring background method

RHV Reduced high voltage

RR Reflected region

S12 Sutter et al. (2012)

S14 Sutter et al. (2014)

SDSS-DR16 quasars: The Sloan Digital Sky Survey Quasar Catalog: Sixteenth
Data Release (Lyke et al., 2020)

SDSS-DR7 quasars The Sloan Digital Sky Survey Quasar Catalog. V. Seventh
Data Release (Schneider et al., 2010)

SDSS-DR7 This catalog consists of the main sample (Strauss et al., 2002) and
luminous red galaxy sample (Eisenstein et al., 2001)

SDSS Sloan Digital Sky Survey

SED Spectral energy distribution

SHV Standard high voltage

SMBH Supermassive black hole

SSC Synchrotron self-Compton

***Swift*-UVOT** *Swift* Ultra Violet/Optical Telescope

***Swift*-XRT** *Swift* X-ray Telescope

TELAMON TeV Effelsberg Long-term AGN Monitoring

UL Upper limit

URB Universal radio background

VEGAS VERITAS Gamma-ray Analysis Suite

VERITAS Very Energetic Radiation Imaging Telescope Array System

VHE Very high-energy; > 100 GeV

Voidiness $V_{\text{LoS}} = \frac{D_{\text{void}}}{D_{\text{LoS}}}$

Part I

Multiwavelength Modeling of the

Blazar 1ES 0647+250

Chapter 1

Observations of Very High-Energy Photons

1.1 Active Galactic Nuclei: Blazars

Active galactic nuclei (AGN) are an extremely luminous type of galaxy—the nucleus can be greater than 100 times more luminous than the rest of the galaxy (Stacy & Vestrand, 2003). The luminous nucleus is small (volume $< 1 \text{ pc}^3$) and usually unresolved (Krolik, 1999). At the center of an AGN, there lies a supermassive black hole (SMBH); approximately 15% of AGN have jets (Padovani et al., 2017), and the jets can be powered by the SMBH. The jets, which contain particles that are accelerated to relativistic energies, can be $\lesssim 1 \text{ AU}$ or $\gtrsim 1 \text{ Mpc}$ in

extent (Blandford et al., 2019) and are typically $\approx 10^5$ pc and remain collimated for hundreds of kpc (Romero, 2021).

An AGN has a broader spectrum than that of a normal galaxy; in the case of an AGN, the emission is observed across the full electromagnetic spectrum. AGN are often observed to have emission lines, and sometimes have absorption lines (Krolik, 1999). The spectra of AGN are observed to have broad lines and narrow lines. The regions of gas clouds that produce these are called the broad line region (BLR) and the narrow line region (NLR). The BLR moves faster than the NLR; therefore, the BLR is assumed to be closer to the SMBH than the NLR. This is inferred from the width of the lines, which is influenced by Doppler broadening, a velocity-dependent effect (Peterson, 1997a,b).

The BLR is denser than the NLR. In the NLR, emission lines that are forbidden by selection rules derived using the electric dipole approximation are, in fact, observed. These forbidden transitions can occur because in a low-density region an atom is less likely to become de-excited by other means (i.e., a collision) (Peterson, 1997a,b; Zettli, 2001).

Approximately 10% of jetted AGN are blazars (Prandini & Ghisellini, 2022), some of the most luminous objects that have been observed. Blazars are a class of AGN that have jets pointing $< 10^\circ$ to the observer's line of sight (Prandini & Ghisellini, 2022). Within the jets, particles are accelerated to relativistic energies,

so the emission is Doppler boosted. In the case of a discrete and isotropic source with flux density $F'_{\nu} \propto (\nu')^{-\alpha}$ (in the source frame) moving along the jet with velocity $\beta = v/c$ at angle θ to the line of sight, the observed flux density F_{ν} is Doppler boosted such that

$$F_{\nu}(\nu) = \delta^{3+\alpha} F'_{\nu'}(\nu), \quad (1.1)$$

where $\delta = \frac{1}{\Gamma(1 - \beta \cos \theta)}$, and Γ is the bulk Lorentz factor $\Gamma = (1 - \beta^2)^{-1/2}$ (Urry & Padovani, 1995). Therefore, Doppler boosting can have a dramatic effect on the observed flux, at all frequencies ν .

Blazar emission is variable on timescales as quick as minutes (see e.g. Blandford et al. (2019) and references therein). Short variability timescales indicate small emission regions (by causality); however, photon-photon interactions constrain the density of the region—the observed photons escaped the region, unabsorbed (Beckmann & Shrader, 2012a).

Blazar spectral energy distributions (SEDs) are observed to have two characteristic peaks; the lower energy peak is due to synchrotron emission by relativistic electrons, and the higher energy peak is thought to be the result of inverse Compton scattering (ICS). This emission is nonthermal (as in, it is neither a blackbody nor a spectrum characteristic of bremsstrahlung by a thermal electron distribution (Beckmann & Shrader, 2012b)). In the one-zone synchrotron self-Compton

(SSC) model, the same population of electrons is responsible for the synchrotron radiation and inverse Compton (IC) emission. Furthermore, in the one-zone SSC model, most of the luminosity is produced in this one region (Prandini & Ghisellini, 2022).

Blazars are further classified into two subtypes: BL Lacs (named after the prototype BL Lac, a galaxy called BL Lacertae) and flat-spectrum radio quasars (FSRQs). The host galaxies of both tend to be elliptical galaxies (Prandini & Ghisellini, 2022). FSRQs have lines with equivalent width $> 5 \text{ \AA}$ (Prandini & Ghisellini, 2022). Conversely, BL Lacs are defined by their characteristic weak or absent emission and absorption lines; therefore, it is difficult to measure their redshift. The frequency (in the observer frame) of the synchrotron peak $\nu_{\text{sync,peak}}$ in a blazar SED is used to further classify BL Lacs. Those with $\nu_{\text{sync,peak}} > 10^{15} \text{ Hz}$ are classified as high-frequency synchrotron peaked BL Lacs (HBLs) (Padovani & Giommi, 1996)—first called high-energy-peaked BL Lacs (Padovani & Giommi, 1995). In BL Lacs, the accretion disk emission is faint (Prandini & Ghisellini, 2022), and the lines from the BLR and NLR of BL Lacs are typically not observed because the nonthermal emission is dominant (Beckmann & Shrader, 2012c). This is in contrast to FSRQs, which generally have luminous accretion disks, strong BLR emission, and detectable NLR emission.

Gamma-ray-emitting blazars were first detected in the 1990s (Beckmann &

Shrader, 2012a). The focus of Part I of this work is a specific blazar, 1ES 0647+250 and several of its gamma-ray states.

1ES 0647+250 is classified as an HBL on TeVCat¹ and was identified as a candidate TeV HBL by Costamante & Ghisellini (2002). 1ES 0647+250 (MGC0648+2503) was first discovered in radio in the Second MIT-Green Bank 5 GHz Survey (Langston et al., 1990). Subsequently, it was observed in X-ray by the Einstein Slew Survey (Elvis et al., 1992). It was discovered in optical and classified as a BL Lac by Schachter et al. (1993). The first gamma-ray detection of 1ES 0647+250 was reported in Abdo et al. (2010), and it was discovered in very high-energy (VHE; > 100 GeV) by Lotto & the MAGIC Collaboration (2012), where MAGIC refers to the Major Atmospheric Gamma Imaging Cherenkov telescopes. The first Very Energetic Radiation Imaging Telescope Array System (VERITAS) detection of 1ES 0647+250 was reported in Dumm (2013).

The redshift of 1ES 0647+250 is not well determined, although there have been various attempts to measure it. MAGIC Collaboration et al. (2023) estimated $z = 0.45 \pm 0.05$ using GeV (*Fermi*-LAT) and TeV (MAGIC) spectra. There have been other attempts to determine its redshift, with estimates $z = 0.45^{+0.11}_{-0.10}$ (Meisner & Romani, 2010) and $z = 0.41 \pm 0.06$ (Kotilainen et al., 2011), as well as lower limits $z > 0.3$ (Falomo & Kotilainen, 1999), $z > 0.3$ (Scarpa et al., 2000), $z > 0.47$ (Sbarufatti et al., 2005), and $z > 0.29$ (Paiano et al., 2017). An additional

¹<http://tevcat.uchicago.edu>

attempt to measure the redshift is described in Section 2.7. According to TeVCat, adopting $z = 0.45^{+0.11}_{-0.10}$ (Meisner & Romani, 2010) makes 1ES 0647+250 one of the most distant known TeV HBLs.

In this work, several VHE states of 1ES 0647+250 are identified and modeled. The VHE photons are detected using methods described in what follows.

1.2 Imaging Atmospheric Cherenkov Telescopes (IACTs)

VHE photons can be indirectly detected with imaging atmospheric Cherenkov telescopes (IACTs). VERITAS is an IACT array and is shown in Figure 1.1. The current generation of IACTs use photomultiplier tubes (PMTs) to measure nanoseconds-long flashes of Cherenkov light (Cherenkov radiation is described in Section 1.2.1).

A photomultiplier tube creates an avalanche of electrons from an impinging photon. It does so using the photoelectric effect² which can create a clear signal from a single photoelectron. A PMT is shown in Figure 1.2 and described in the caption.

²The 1921 Nobel Prize in Physics was awarded to Einstein for the discovery of the photoelectric effect, and the 1923 Nobel Prize in Physics was awarded to Millikan for his work on the photoelectric effect, in part.



Figure 1.1: Image of VERITAS. Telescope 1 (T1) is at the front of the image. In the clockwise direction from T1 is T2, the prototype Schwarzschild-Couder telescope (red structure), then T4, and finally T3. Credit: Center for Astrophysics | Harvard & Smithsonian.

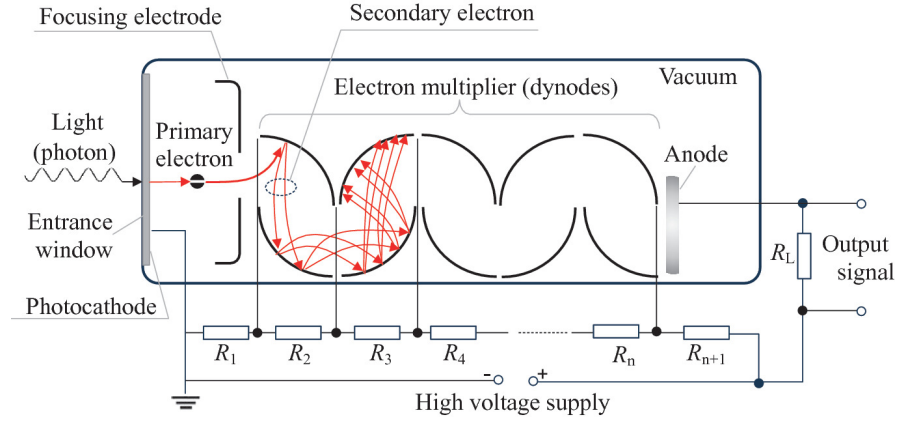


Figure 1.2: Photomultiplier tube schematic. The photocathode converts incident light into photoelectrons (p.e.s) via the photoelectric effect. The material of the photocathode is chosen to be sensitive to the wavelength of incident light that is to be observed. The focusing electrodes send the photoelectrons to the dynode via a potential difference (high voltage), which accelerates the photoelectrons (electrons flow from a lower potential to a higher potential). The dynodes amplify (multiply) the photoelectrons; when an electron collides with a dynode, it can liberate multiple electrons from the material (by ionizing it). This process repeats until the avalanche of electrons reaches the anode, which attracts the electrons and produces an output signal (a current) when the electrons exit the PMT. Image from Lin (2025).

1.2.1 Cherenkov Radiation (CR)

When a charged particle (hereafter simply called a “charge”) moves through a polarizable medium at a constant velocity $\vec{v}_q$ faster than the speed of light in said medium, the medium produces Cherenkov radiation (CR).³ In other words, CR is produced when $v_q > \frac{c}{n}$, where c is the speed of light in vacuum, n is the index of refraction of the medium, and $\frac{c}{n}$ is the speed of light in the medium.

A dielectric (that is, polarizable) medium cannot fully screen itself from an external electric field. Additionally, its electrons are tightly bound so that they can move only minutely. Therefore, in the presence of a charge and its corresponding electric field, the atomic electrons in the medium will rearrange themselves slightly to form dipoles, because the atomic electrons will be attracted to (or repelled by) the charge. After the charge passes, the electrons return to their initial configurations (Jelley, 1955), such that the dipole fields are impermanent and brief (Jelley, 1961). As the atoms in the medium return to their initial (unpolarized) state, they will radiate. The polarization is localized; atoms within $\sim \lambda_{\text{rad}}$, where λ_{rad} is the wavelength of the emitted radiation, are perturbed by the polarization (Jelley, 1961).

In the case of a charge traveling at $v_q < \frac{c}{n}$, the induced polarization of the

³The 1958 Nobel Prize in Physics was awarded to Cherenkov, Frank, and Tamm “for the discovery and the interpretation of the Cherenkov effect.”

medium is symmetric and the radiation destructively interferes, as shown in Figure 1.3. That there is destructive interference assumes that for every polarized atom there is another atom with opposite polarization in the vicinity, such that statistical fluctuations are negligible (Jelley, 1961); in other words, there are many atoms in the medium per λ_{rad} .

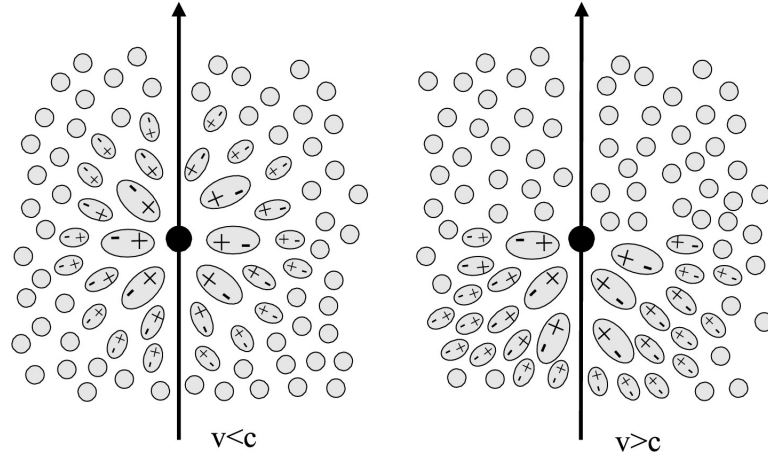


Figure 1.3: Polarization of atoms (shaded grey ellipses) in a medium in the case of a charge (shaded black) moving at constant velocity $\vec{v}$ (black arrow). The unpolarized atoms are shown as shaded grey circles. Left: Charge moving below the threshold, $v_q < \frac{c}{n}$, for Cherenkov radiation. The polarization is azimuthally symmetric (with respect to the moving charge). On average, the dipole fields constructively interfere. Right: Charge moving above the threshold, $v_q > \frac{c}{n}$, for Cherenkov radiation. In this case, the charge moves more quickly than its electric field, and so the atoms in front of it (in the direction of $\vec{v}$) are not polarized. Image from de Naurois & Mazin (2015).

However, if the charge travels at $v_q > \frac{c}{n}$ then it travels faster than radiation, which moves at $\frac{c}{n}$, and so the charge travels more quickly than its electric field can propagate. As a result, only the atoms behind the moving charge are polarized,

which will not result in destructive interference of the fields. The dipole radiation of the atoms in the medium interferes constructively, and produces a coherent wavefront in the shape of a cone at a distant point many wavelengths away from the moving charge (Jelley, 1961), as shown in Figures 1.4 and 1.5. The Cherenkov cone is described by

$$\cos \theta_C = \frac{ct/n}{v_q t}, \quad (1.2)$$

$$\cos \theta_C = \frac{ct/n}{\beta ct}, \quad (1.3)$$

$$\cos \theta_C = \frac{1}{\beta n}, \quad (1.4)$$

where θ_C is the half-opening angle of the emission cone, $\beta = \frac{v_q}{c}$, and t is an arbitrary travel time. Equation 1.4 is the condition for constructive interference and coherence (Jelley, 1955). At threshold, $v_q = \frac{c}{n}$, therefore $\theta_C = 0$, and the CR is in the same direction as the motion of the particle. The maximum angle of CR follows from Equation 1.4 and the fact that v_q cannot exceed the speed of light in vacuum, and is given by

$$\theta_{C,\max} = \arccos\left(\frac{1}{n}\right). \quad (1.5)$$

The condition $v_q > \frac{c}{n}$ enforces a threshold energy E_{th} for a charge to induce

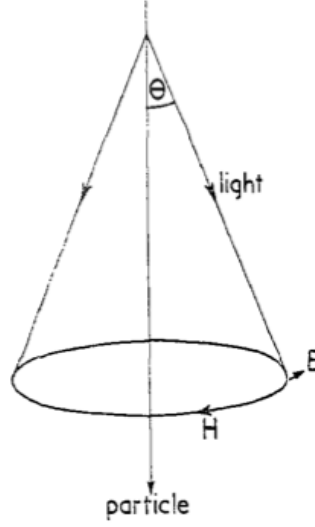


Figure 1.4: Cherenkov cone of angle θ (called θ_C in this work), showing the electric field $\vec{E}$ (perpendicular to the propagation of light) and magnetic field $\vec{H}$ (tangent to the Cherenkov cone). Image from Jelley (1955).

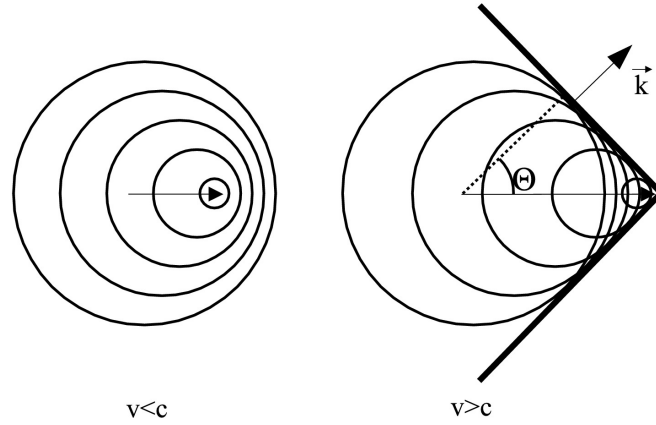


Figure 1.5: This image accompanies Figure 1.3. Left: Cherenkov wavefronts in the below-threshold case. Right: Cherenkov wavefronts in the above-threshold case, which produce CR due to constructive interference. The thick black line is the wavefront, which is perpendicular to the direction of propagation of light $\vec{k}$, by definition. Constructive interference produces the wavefront at angle Θ (called θ_C in this work) with respect to the velocity of the charge. Image from de Naurois & Mazin (2015).

CR, corresponding to $\beta_{\text{th}} > \frac{1}{n}$. A charge must have energy equal to at least

$$E_{\text{th}} = \Gamma mc^2, \quad (1.6)$$

$$= \frac{mc^2}{\sqrt{1 - \beta_{\text{th}}^2}}, \quad (1.7)$$

$$= \frac{mc^2}{\sqrt{1 - 1/n^2}}, \quad (1.8)$$

where m is the rest mass of the charge.

IACTs observe CR in the atmosphere. The index of refraction of the atmosphere is not constant; it is a function of atmospheric depth X and temperature. Therefore, the opening angle θ_C of CR produced in the atmosphere depends on the altitude of the moving charge, with θ_C increasing as altitude decreases. In air, the maximum angle is $\theta_{C,\text{max}} = 1.3^\circ$ (Jelley, 1961). This occurs at sea level, where the index of refraction of air is $n = 1.00029$ (Grieder, 2010a). The observed spectrum of CR in the atmosphere peaks at roughly $\lambda_{\text{rad}} \approx 325$ nm, as can be seen in Figure 1.6. Figure 1.6 shows a cutoff wavelength of the detected CR due to the absorption of Cherenkov light in the atmosphere. The energy loss per wavelength goes as $\lambda_{\text{rad}}^{-3}$ (Jelley, 1961). Altogether, this results in the characteristic blue of CR. Charged particles traveling through the atmosphere undergo more than CR; CR is one process that unfolds in extensive air showers.

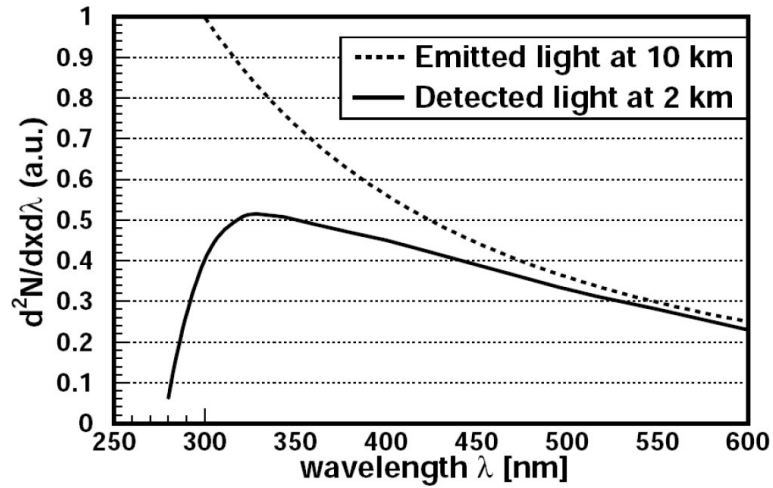


Figure 1.6: Spectrum of Cherenkov radiation in the atmosphere. The emitted Cherenkov light is absorbed by the atmosphere. See e.g. Voutsinas et al. (2026) for a description of absorption mechanisms of Cherenkov light in the atmosphere. Image from Prandini et al. (2022).

1.2.2 Extensive Air Showers (EAS)

IACTs such as VERITAS observe Cherenkov light from extensive air showers in the atmosphere. Gamma rays cannot be observed directly from Earth—the atmosphere is not transparent to gamma rays. An electromagnetic (EM) air shower, composed of photons and $e^\pm$, initiated by photons is shown in Figure 1.7 and unfolds as follows. A gamma ray γ and a nucleus $\mathcal{X}$ in the atmosphere can undergo Bethe-Heitler pair production (Bethe & Heitler, 1934) if the gamma ray has sufficient energy ($E_\gamma > 2m_e c^2$). This process, $\mathcal{X} + \gamma \rightarrow \mathcal{X} + e^+ + e^-$, is the first interaction shown in the EM shower in Figure 1.7. The electron-positron pair $e^\pm$ travels approximately in the same direction as the gamma ray; deviation from

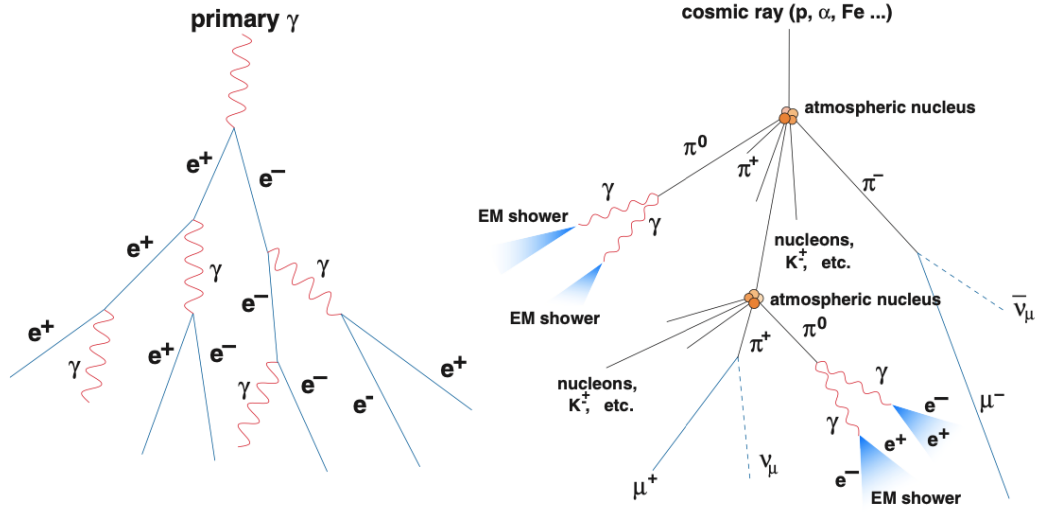


Figure 1.7: Electromagnetic air shower (left) and hadronic air shower (right). Image from Wagner (2006).

this approximation is negligible compared to the impact of Coulomb scattering (Grieder, 2010b), which scatters $e^\pm$ away from the central axis of the primary γ (Longair, 1992). The next process shown in the EM shower in Figure 1.7 is bremsstrahlung radiation, $\mathcal{X} + e^\pm \rightarrow e^\pm + \gamma$. The $e^\pm$ resulting from Bethe-Heitler pair production, each with energy $\sim E_\gamma/2$, can undergo a bremsstrahlung interaction which creates a high-energy photon. Thus, the processes of pair production and then bremsstrahlung can repeat. The bremsstrahlung radiation length X_B , the length over which the energy of the $e^\pm$ is reduced by a factor of $1/e$, is related to the pair production mean free path λ_{PP} via $X_B \approx \frac{7}{9}\lambda_{PP}$. Therefore, on average, an electron travels a shorter distance before bremsstrahlung radiating than

a photon does before pair producing. The cascade continues until the average electron energy reaches the critical energy $E_{\text{crit}} = 84 \text{ MeV}$, at which point the ionization losses are equal to the bremsstrahlung losses, which can be seen in Figure 1.8. Below E_{crit} , the air shower rapidly shrinks; the ionization losses dominate, thus the electrons rapidly lose energy and become nonrelativistic. Relativistic charges are necessary to meet the CR condition of $v_q > c/n$. The maximum number of particles in the air shower is $\sim \frac{E_\gamma}{E_{\text{crit}}}$; the height at which this occurs is the shower maximum X_{max} . The relativistic charges initiating Cherenkov radiation may be absorbed by the atmosphere, but the Cherenkov light makes it to the ground (Longair, 1992). As a result of Equation 1.8 the threshold energy for CR decreases as the charge gets closer to the ground (because n increases as altitude decreases). As an example of the amount of Cherenkov radiation, a 300 GeV gamma ray produces a few million photons within a cone of $1\text{-}2^\circ$, and the Cherenkov photon density near the shower axis is 7 m^{-2} (Longair, 1992). Figure 1.9 shows an air shower in the atmosphere and the same shower in the camera plane; the camera view is expanded on in Section 2.2.

In addition to EM showers, hadronic showers occur in the atmosphere, primarily initiated by protons in the atmosphere, as is shown in Figure 1.7. These constitute the background. However, the cascade develops differently, as can be seen in Figure 1.7; the secondary particles of hadronic showers have large transverse

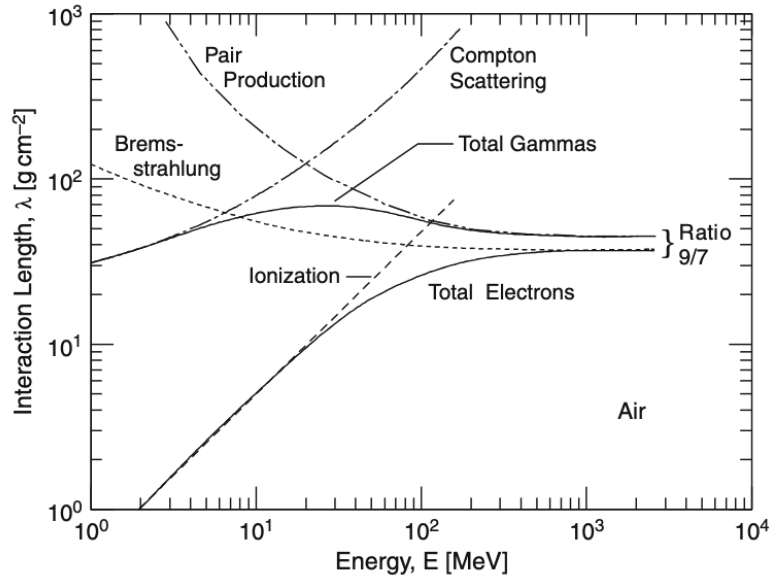


Figure 1.8: Interaction lengths relevant to electromagnetic air showers in the atmosphere. Image from Evans (1955) via Grieder (2010b).

momentum (see e.g. Grieder (2010c)). This allows for gamma-hadron separation (discussed in Section 2.2).

This work explores the emission mechanisms of the VHE-emitting blazar 1ES 0647+250 in the context of a synchrotron self-Compton model. Chapter 2 details the multiwavelength analysis of 1ES 0647+250. In Chapter 3, the multiwavelength modeling approach and methodology are described. The results are given in Chapter 4.

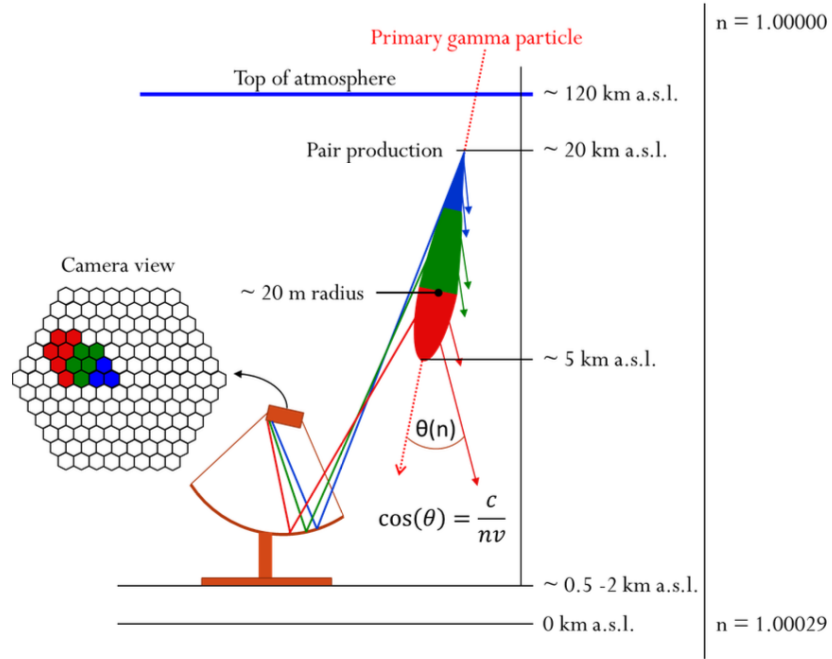


Figure 1.9: Cherenkov light in an extensive air shower, as seen in the sky and the camera. The cone opening angle increases with decreasing altitude due to the fact that $\theta_C = \arccos\left(\frac{1}{n\beta}\right)$. Image from Gadola (2013).

Chapter 2

Multiwavelength Analysis

This chapter describes the multiwavelength analysis of blazar 1ES 0647+250, from gamma ray to radio. The focus is on three epochs: State A, State B and State C.

2.1 Selection of States

States with sufficient quasi-simultaneous MWL data are selected. “Sufficient” MWL data are data at or around the SED peaks—optical, UV, and X-ray data for the synchrotron peak and high-energy ($100 \text{ MeV} < E < 100 \text{ GeV}$) and VHE data for the IC peak. This MWL coverage is assumed to be the minimum amount that may sufficiently constrain a SSC model. Three VERITAS observing seasons have sufficient MWL coverage: 2012-2013 (September 2012 to June 2013), 2020-

2021 (September 2020 to June 2021), and 2024-2025 (September 2024 to June 2025). From this, State A (from the 2012-2013 VERITAS observing season) and State B (from the 2020-2021 VERITAS observing season) are selected by considering VERITAS detections ($\geq 5\sigma$). In the case of State C (from the 2024-2025 VERITAS observing season), the author initiated a MWL campaign.

The multiwavelength coverage of State A, State B and State C is detailed in Table 2.1, and the states are described in Sections 2.1.1-2.1.3.

2.1.1 State A (2012)

Most of the VERITAS observing time and contribution to the significance of 1ES 0647+250 during the 2012-2013 observing season are in December 2012—specifically, December 8-21. Therefore, high-energy, X-ray, UV, optical, and radio data from the instruments described in Sections 2.3-2.9 overlapping this interval are considered. High-energy data (Section 2.3) in the range December 8-21 did not result in a detection (defined as test statistic $TS > 25$, which is approximately equivalent to significance $\sigma \geq 5$), so this interval was extended by adding two weeks (one week on both sides) until $TS > 25$; the result is 2012/11/17 00:00 to 2013/01/12 00:00. Radio data over the interval 2012 December 8-21 were requested from the Owens Valley Radio Observatory.

In summary, State A is defined as the time period from 2012 December 8 to

2012 December 22 with high-energy data spanning a longer time period from 2012 November 17 to 2013 January 12. The observation dates for each instrument are provided in Table 2.1.

2.1.2 State B (2020)

VERITAS observations of State B were prompted by Astronomer’s Telegrams. On 2020 December 13, the *Swift* X-ray Telescope observed an X-ray flare.¹ Subsequently, on 2020 December 15, the MAGIC telescopes detected a high flux VHE state.² VERITAS conducted follow-up observations beginning December 16. Most of the significance of 1ES 0647+250 in the 2020-2021 observing season is from observations in December. VERITAS detections ($\geq 5\sigma$) occur separately on the nights of December 16, 17, and 18. It is atypical for 1ES 0647+250 to be detected $\geq 5\sigma$ on nightly time scales. Thus, December 16-18 is an elevated VHE state. When uncertainties are considered, the flux during each of these nights is consistent with the flux during each of the others, and so the VERITAS data are combined into one steady VHE state that spans December 16-18. The closest *Swift* observations to the VERITAS detections begin on 2020 December 13—the day of the *Swift* X-ray Telescope Astronomer’s Telegram. Therefore, the selected high-energy data begin on 2020 December 13 00:00. Because this is three days before

¹<https://www.astronomersteletgram.org/?read=14264>

²<https://www.astronomersteletgram.org/?read=14268>

the start of the VHE high state, the selected end date of the high-energy data is three days after the end of the VHE high state: 2020 December 22 00:00. The time period December 13-22 is sufficient for a high-energy detection ($TS > 25$). Thus, the end date for *Swift* data is also chosen to be 2020 December 22 00:00. Radio data over the interval 2020 December 13-22 were requested from the Owens Valley Radio Observatory and the TeV Effelsberg Long-term AGN Monitoring program. In summary, State B is defined as the time period from 2020 December 13 to 2020 December 22. The observation dates for each instrument are provided in Table 2.1.

2.1.3 State C (2024)

In late 2024, the author initiated a MWL campaign for 1ES 0647+250, prompted by a call for proposals for sources in specific RA bands from the VERITAS Time Allocation Committee. The VERITAS proposal was awarded 25 hours to be collected over the time period 2024 November 27 to 2024 December 28. Therefore, high-energy, X-ray, UV, optical, and radio data (from the instruments described in Sections 2.3-2.9) taken over the time period of the VERITAS observations are selected. This time period results in a high-energy nondetection ($TS < 25$), so the interval was extended by adding two weeks (one week on both sides) until $TS > 25$; the result is 2024 November 13 to 2025 January 12.

In summary, State C is defined as the time period from 2024 November 27 to 2024 December 28 with high-energy data spanning a longer time period from 2024 November 13 to 2025 January 12. The observation dates for each instrument are provided in Table 2.1.

2.2 VERITAS Analysis with VEGAS

The Very Energetic Radiation Imaging Telescope Array System (VERITAS), located at the Fred Lawrence Whipple Observatory at $31^{\circ}40'$ N, $110^{\circ}57'$ W, 1268 m above sea level, is an array of four 12-meter diameter IACTs, each with 499 photomultiplier tubes (PMTs) which serve as imaging cameras (Holder et al., 2006). The instrument detects the nanoseconds-long flashes of Cherenkov light produced from air showers initiated by primary gamma rays in the approximate energy range of 85 GeV to 30 TeV interacting with the atmosphere. VERITAS has a 3.5° field of view, angular resolution (68% containment) of 0.1° at 1 TeV, and an energy resolution of 15-20% (Park & VERITAS Collaboration, 2015). The array can detect ($\geq 5\sigma$) a point source with 1% of the flux of the Crab Nebula within 25 hours.

The VERITAS Gamma-ray Analysis Suite (VEGAS) (Cogan, 2008) is one of the standard packages used to analyze VERITAS data. The other is `EventDisplay` (Maier & Holder, 2017). **VEGAS** results are presented in this work, and the results

	VERITAS	<i>Fermi</i> -LAT	<i>Swift</i>	FLWO	OVRO	TELAMON
State A (2012)	12/09	2012/11/17	12/12		12/18	
	12/10	to	12/13			
	12/11	2013/01/12	12/14			
	12/13		12/15			
	12/17		12/16			
	12/18		12/17			
	12/20		12/18			
	12/21		12/19			
State B (2020)			12/20			
	12/16	12/13	12/13		12/14	12/19
	12/17	to	12/16		12/17	
	12/18	12/22	12/17			
			12/19			
			12/20			
State C (2024)			12/21			
	11/27	2024/11/13	11/27	12/03	12/11	
	11/29	to	11/28	12/07	12/15	
	12/01	2025/01/12	11/29	12/11	12/18	
	12/02		11/30	12/23		
	12/03		12/01	12/24		
	12/05		12/02	12/25		
	12/06		12/03	12/26		
	12/08		12/04	12/27		
	12/09		12/05			
	12/22		12/06			
	12/24		12/07			
	12/27		12/08			
			12/09			

Table 2.1: MWL observing dates and cadence in MM/DD format with the year indicated in the header. Under State A all dates are in 2012, under State B all dates are in 2020, and under State C all dates are in 2024, unless otherwise indicated.

are confirmed by comparing them to the results of `EventDisplay`.³

This section details analysis as it is implemented in `VEGAS`, which has five stages of analysis: Stage 1, 2, 4, 5, and 6 (there is no longer a Stage 3). In this section, PMT and pixel are used interchangeably, and “camera” refers to the 499 PMTs in each telescope.

2.2.1 `VEGAS vaStage1`

`vaStage1` calibrates the raw data. The calibration is described in detail in Chromey (2022), O’Brien (2018), and Madhavan (2013), and references therein.

In brief, the raw data (a signal trace of digital counts versus time, measured from the flash analog to digital converter (FADC)) from each PMT are used to calculate timing offsets (between pixels), relative gains (between pixels), and the noise level of the night sky background (NSB). Due to different cable lengths and high-voltage settings, pixels have different transmission times. PMT gains may be different due to fatigue and dust buildup.

The relative timing and gain information are determined from the relevant calibration (“flasher”) observation. Each night of observations (and, if necessary, per voltage applied to the PMTs—standard high-voltage (SHV) or reduced high-voltage (RHV)), a two-minute “flasher” observation is taken, wherein the

³Dr. Pazit Rabinowitz graciously did the `EventDisplay` analysis to confirm the `VEGAS` results.

telescopes observe a dark patch of the sky while the flasher system is on. The current flasher system, which monitors the gain and timing of each PMT, is described in Hanna et al. (2010) (the former is described in Hanna (2007)). The flasher on each telescope consists of several blue light-emitting diodes (LEDs) pointed at the camera. The individual LEDs supply approximately the same amount of light (fixed brightness, measured in millicandela) simultaneously to the PMTs. The width of the LED current-pulse is adjusted so that it is a few nanoseconds, meant to mimic the pulses caused by Cherenkov photons, so that the flasher probes the PMTs in their observing conditions. The camera is flashed multiple times in a flasher observation and at different light levels by cycling the number of LEDs that are illuminated.

Using the fact that the signals from each LED arrive simultaneously at the PMTs, the timing offsets between pixels are calculated. The camera is flashed multiple times in a flasher observation; as such, each pixel has a distribution of event arrival times. The arrival time of each event is defined as the time corresponding to the half-maximum of the leading/rising edge of the signal trace (Madhavan, 2013). The mean of the arrival time distribution per pixel is applied in later **VEGAS** stages.

It is assumed that each PMT receives the same signal (same number of photons); therefore, assuming the same input, differences in the output signal s of

pixel p for each pulse i can be described as $\mathcal{G}_i = \frac{s_{p,i}}{\mathcal{S}_i}$, where $\mathcal{S}_i$ is taken to be the camera-average signal (Hanna et al., 2010), and $\mathcal{G}_i$ is termed the relative gain because it is normalized by $\mathcal{S}_i$ (Madhavan, 2013).

The relative gain describes signal differences between pixels in a camera; the absolute gain describes the signal gain from the mean μ_{pe} photoelectrons incident on the first PMT dynode to the mean charge μ_q read out from the PMT, described by Equation 2.1 and evaluated per telescope. The mean number of photoelectrons μ_{pe} on the first dynode follows a Poisson distribution with variance $\sigma_{\text{pe}}^2 = \mu_{\text{pe}}$. The signal (charge delivered to the PMTs) is

$$\mu_q = G\mu_{\text{pe}}e, \quad (2.1)$$

where e is the electron charge and G is the gain. The signal variance σ_q^2 is therefore

$$\sigma_q^2 = \left(\frac{\partial \mu_q}{\partial \mu_{\text{pe}}} \sigma_{\text{pe}} \right)^2, \quad (2.2)$$

$$= (Ge\sigma_{\text{pe}})^2, \quad (2.3)$$

$$= (Ge)^2 \mu_{\text{pe}}, \quad (2.4)$$

$$= Ge\mu_q. \quad (2.5)$$

The absolute gain per telescope is determined by fitting a line to Equation 2.5, where the charge variance σ_q^2 and mean charge μ_q are measured from the flasher

runs, the slope Ge gives the gain multiplied by the electron charge, and the intercept gives the variance of the pedestal noise.

Additional calibrations occur per observing (non-flasher) run. Per observing run, fixed pedestals (offsets) are injected into the PMT output signal in order to ensure the signal does not cross zero; this is necessary because the readout captures only positive signals, and so to measure fluctuations (both positive and negative) of the noise, an offset is used. Pedestal events are sampled at a rate of 1-3 Hz (Cogan, 2006) by artificially triggering the readout (using the software trigger system) in order to measure the pedestal. This information is used to discern Cherenkov signals from the noise.

2.2.2 VEGAS `vaStage2`

`vaStage2` applies the calibrations from `vaStage1` to observing runs, and cleans and parameterizes the camera images.

The FADC traces are corrected using the calibration information of `vaStage1` and then integrated to find the total charge in each pixel. Cogan (2006) contains a discussion of the integration algorithms.

As described in Daniel (2008), first (before image parameterization), each image is cleaned by retaining “picture pixels” and “boundary pixels.” Picture pixels are those with total charge $> 5\sigma_p$, where σ_p is the pedestal standard deviation in

that pixel p . Boundary pixels are adjacent to picture pixels and contain charge $> 2.5\sigma_p$. The charge of lone picture pixels is set to zero, and then the charge in the remaining non-picture and non-boundary pixels is set to zero. The image is now “clean.” At this point, an image like Figure 2.1 can be created (compared to the raw image in Figure 2.2), which contains the amount of charge in each pixel, after cleaning.

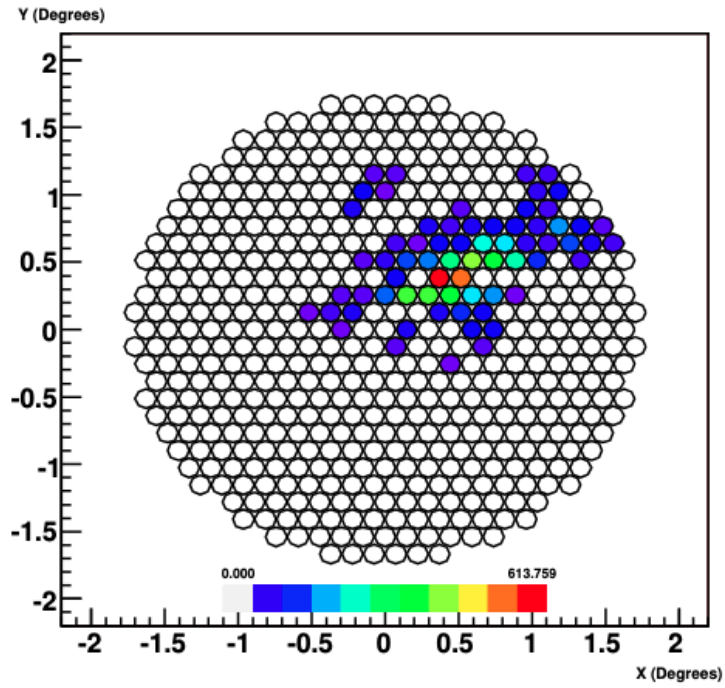


Figure 2.1: Cleaned VERITAS camera image of a real (not simulated) candidate gamma-ray event. The corresponding raw image is in Figure 2.2. Image from Cogan (2006).

The clean images are then parameterized using Hillas parameters (Hillas, 1985) which assign each image a length and a width related to the major and minor

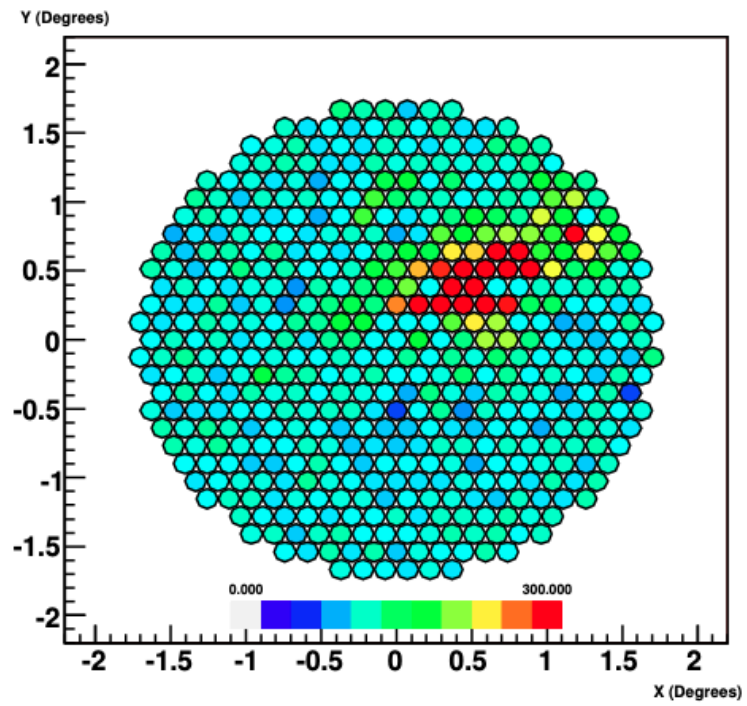


Figure 2.2: Raw VERITAS camera image of a real (not simulated) candidate gamma-ray event. Image from Cogan (2006).

axis of the image ellipse, as in Figure 2.3. The length and width describe the longitudinal and lateral properties of the air shower (Hillas, 1985), as shown in Figures 1.9 and 2.4.

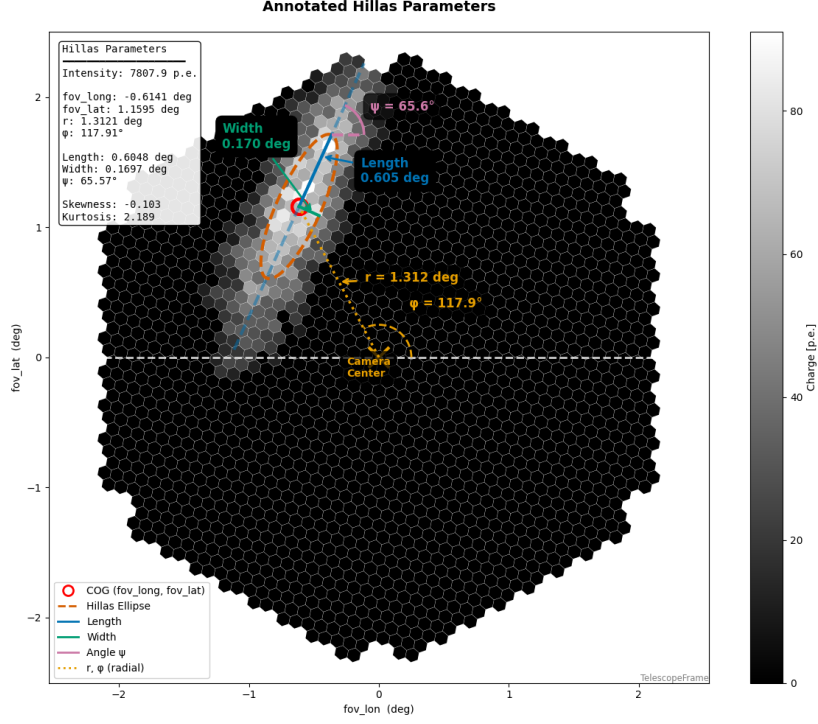


Figure 2.3: Hillas parameters (labeled Width and Length) of a simulated camera image from the Large-Sized Telescope (LST) of the Cherenkov Telescope Array Observatory (CTAO). Image from ctapipe developers (n.d.).

2.2.3 VEGAS vaStage4

Note that there is no VEGAS vaStage3 because it was merged into vaStage2. vaStage4 applies cuts to the images and stereoscopically reconstructs the properties of the primary event.

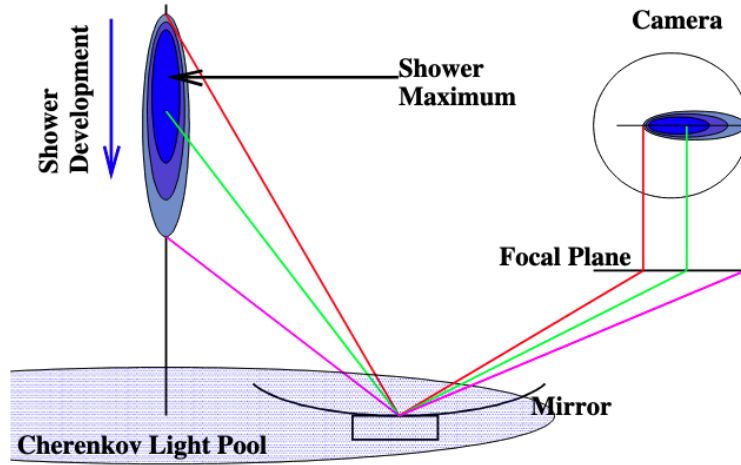


Figure 2.4: Cherenkov light in an extensive air shower, as seen in the atmosphere and the camera plane. Image from Cogan (2006).

Using the camera images from `vaStage2`, a minimum *size* (total charge) is enforced, and the cut value is dependent on the analysis. For the results presented in this work, $size > 400$ digital counts is used, corresponding to soft cuts (soft cuts are described in Section 2.2.6). In addition, at least five PMTs (≥ 5) are required for the image. At this point in the analysis, the photoelectrons (charges) have been converted to digital counts (for more information, see e.g. Kumar (2018)). Only images with a centroid that is $\leq 1.43^\circ$ from the camera center are kept to ignore images at the edge of the camera that are truncated (Daniel, 2008). From the remaining images, the shower core location (Section 1.2.2) is calculated by intersecting the major axes of the images (Cogan, 2006), as shown in Figure 2.5. The impact distance/parameter r is the distance between the shower core (on the ground) and the telescope.

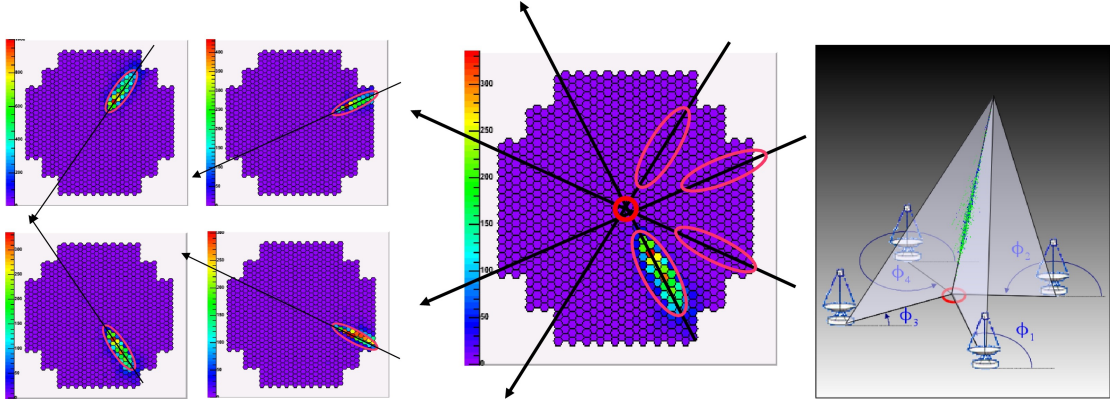


Figure 2.5: Reconstruction of an air shower. Left: Camera images of an event from an EAS. Middle: The primary particle direction is indicated by the red circle, the intersection of the individual main axes of the images on the left. Right: The shower core is circled in red, given by the intersection of the planes of the shower tracks. Image from de Naurois & Mazin (2015).

The image parameters (such as image length, width, total charge in the image (*size*), shower core location, impact distance/parameter) are used to “look up” primary event information using lookup tables (LTs). LTs are derived from simulations of air showers (via CORSIKA) and the instrument response (via GrISUDet and CARE), under a variety of observing conditions (e.g., zenith and azimuth angles, NSB, summer/winter atmosphere) (Chromey, 2022). The LTs output information such as the energy of the primary event, and the mean expected length and width of the image for gamma-ray showers. This is done at the telescope level. A LT for VEGAS is in Figure 2.6.

An event may be seen by multiple telescopes, in which case the quantity of interest (energy, length, or width) is taken to be an average of the estimates from

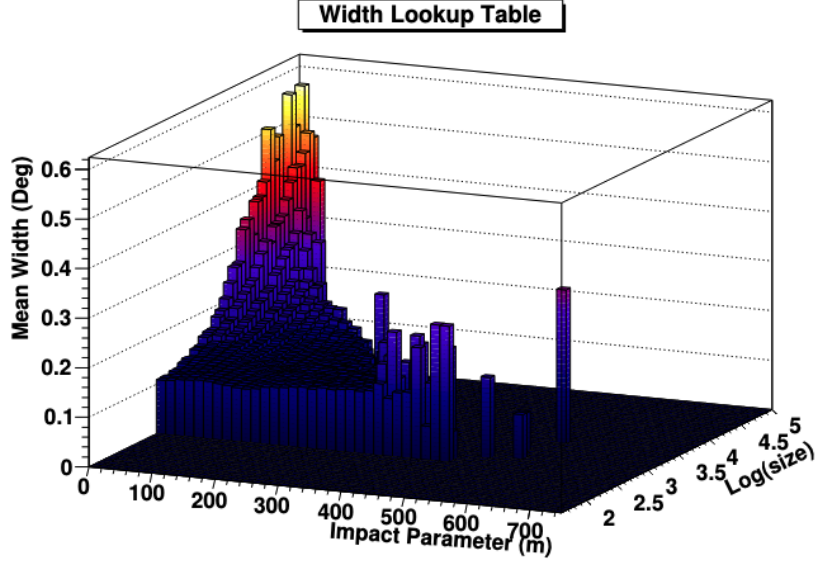


Figure 2.6: VEGAS LT for image width (for a fixed zenith angle). Image from Cogan (2006).

each of the telescopes that saw the event. The mean-scaled width (MSW) and mean-scaled length (MSL) are defined as

$$\text{MSW} = \frac{1}{N_{\text{tel}}} \sum_{i=1}^{N_{\text{tel}}} \frac{w_i}{\bar{w}_{\text{sim}}(\theta, \text{size}, r)}, \quad (2.6)$$

$$\text{MSL} = \frac{1}{N_{\text{tel}}} \sum_{i=1}^{N_{\text{tel}}} \frac{l_i}{\bar{l}_{\text{sim}}(\theta, \text{size}, r)}, \quad (2.7)$$

where the sum is over the number of telescopes N_{tel} that observed the event, w_i (l_i) is the width (length) of the image in telescope i , and $\bar{w}_i$ ($\bar{l}_i$) is the mean width (length) of simulation images in telescope i with a specific *size*, impact distance/parameter r and zenith angle θ of the observation (Daniel, 2008).

The primary event energy (cosmic ray or gamma ray) is calculated as

$$E_{\text{event}} = \frac{\sum_i^{N_{\text{tel}}} E_i \sigma_{E,i}^{-2}}{\sum_i^{N_{\text{tel}}} \sigma_{E,i}^{-2}} \quad (2.8)$$

where E_i is the mean energy of the bin corresponding to event size $size_i$ (s_i) and impact distance/parameter r_i , and $\sigma_{E,i}$ is the standard deviation of the bin.

Analysis presented in this work uses the image template method (ITM), which is described in Christiansen & VERITAS Collaboration (2017). ITM uses templates that contain the average number of photoelectrons (charge) in each camera pixel. Templates are constructed from simulations of gamma-ray-initiated air showers, and the simulations are conducted over ranges of the following parameters: energy (of the primary), zenith angle, shower core location (as in Figure 2.5), and depth of first interaction in the atmosphere X (where $X = 0$ corresponds to the top of the atmosphere) (Christiansen & VERITAS Collaboration, 2017). The templates are the predicted (simulated) average photoelectrons per pixel, and the ITM compares these to the observed Cherenkov photons. A calibration factor is applied to the observed signal to incorporate detector effects, as is described in Section 2.2.5.4. A comparison of a real image and a template image is shown in Figure 2.7.

The likelihood of the model (template) given the data (observed photoelectrons) is maximized over the parameters (energy, zenith angle, azimuth, core lo-

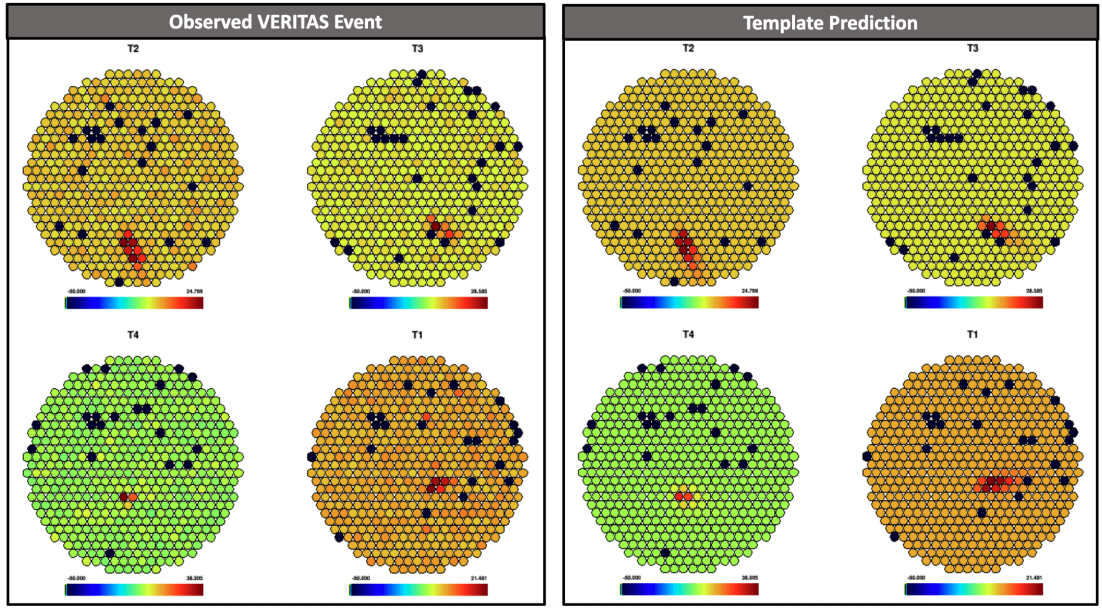


Figure 2.7: Observed candidate gamma-ray event (left) compared to template event (right) from ITM. The event has energy ≈ 150 GeV. Image from Christiansen & VERITAS Collaboration (2017).

cation, and X) to find the best fit parameters per event (Christiansen & VERITAS Collaboration, 2017). Before proceeding with the rather computationally expensive likelihood maximization, cuts on MSW and MSL (Equations 2.6 and 2.7) are applied so that only suspected gamma-ray images are reconstructed. In **VEGAS**, events with $\text{MSW} < 1.1$ and $\text{MSL} < 1.4$ are reconstructed via the ITM fitting algorithm. In the likelihood maximization procedure, the seed for the gamma-ray parameters is the value derived from the “standard” (Hillas) analysis described above, such as Equation 2.8.

2.2.4 **VEGAS vaStage5**

vaStage5 removes background events by applying cuts to the stereoscopic (array-level) event parameters derived in **vaStage4**. This background rejection is also called gamma-hadron separation—gamma being the signal and hadron referring to the background. “Box” cuts are applied; a box in the parameter space, bounded by optimized minimum and maximum values of MSW, MSL, and X_{max} (the height of the maximum shower development), is used to select events. For example, soft cuts (Section 2.2.6) accept events as signal if they have $0.05 \leq \text{MSW} \leq 1.1$, $0.05 \leq \text{MSL} \leq 1.3$, and $X_{\text{max}} \geq 7$ km (this set of cuts is applicable to data taken in both SHV and RHV observing conditions). Figure 2.8 illustrates the effectiveness of these cuts; the signal (gamma rays) and background (cosmic rays)

have markedly different distributions for the MSW and MSL. Note, however, as can be seen from Figure 2.8, after these cuts are applied, some background events will very likely still remain. At this point in the analysis, the remaining γ -ray-like background events must be removed, i.e., cosmic-ray background events which survive cuts. This is handled in `vaStage6`.

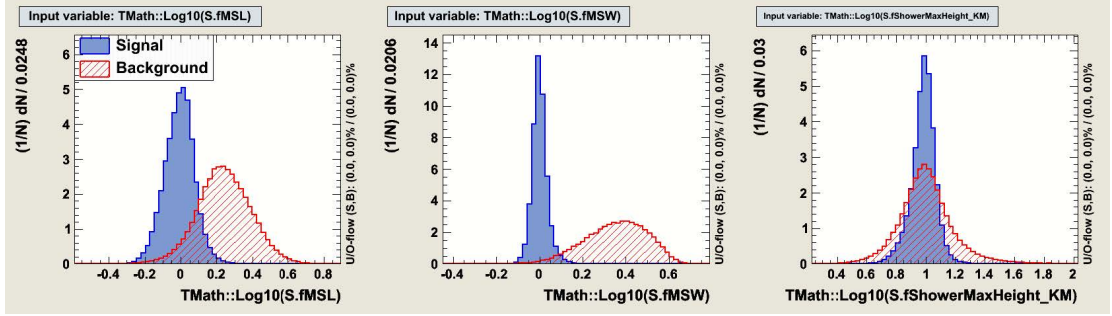


Figure 2.8: Sample distributions of MSL (left), MSW (center), and shower maximum height (right). The horizontal axis contains $\log_{10}$ of each quantity. Image from Ribeiro (2022).

2.2.5 VEGAS `vaStage6`

`vaStage6` ultimately produces science-ready results, such as significances, fluxes, and skymaps. Each is detailed in what follows. In this section, “center of the FOV” and “observation position” (looking ahead to Figure 2.9) are used interchangeably.

2.2.5.1 Excess Counts and Background Modeling

The observed signal (excess) counts N_S is given in Li & Ma (1983) (Equation 2) as

$$N_S = N_{\text{on}} - N_{\text{bkg}} = N_{\text{on}} - \alpha N_{\text{off}}, \quad (2.9)$$

where N_{bkg} is the number of background counts, N_{on} is the number of counts measured in the “On” region, N_{off} is the number of counts measured in the “Off” region, and α is the ratio of an “On” region exposure to an “Off” region exposure. The On region is a circular region in the FOV surrounding the source/target (or presumed source). For a point source (rather than an extended source), the size of the On region is chosen to be similar to the size of the PSF. In this work, the region size (`S6A_RingSize`) is 0.1° . The definition of the Off region(s), along with the definition of α , depend on the method of calculating the background, but no matter the method, known gamma-ray sources and bright stars are excluded from the Off region.

Two background modeling methods are implemented in **VEGAS**: the ring background method (RBM) and the reflected region (RR) method. Both are shown in Figure 2.9. RBM is favored for skymap production, and RR is favored for calculating spectra. As such, RR is used to produce the VERITAS spectra presented in this work, and RBM is used to create the VERITAS skymaps (displaying

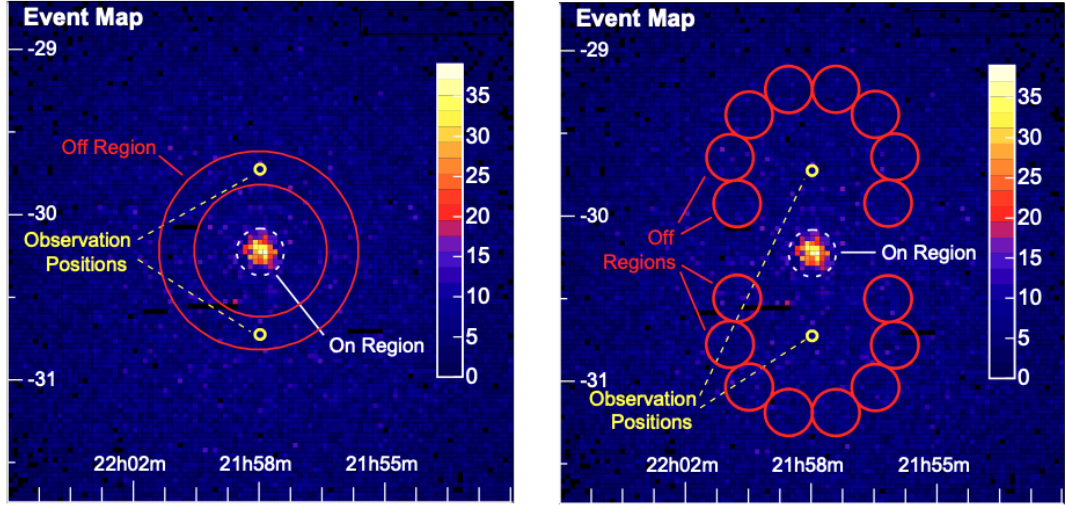


Figure 2.9: Left: Ring background method (RBM). Right: Reflected region (RR) method. These are wobble observations; the observation positions (solid yellow circles) are offset from the On region (dashed white circles). Image from Berge et al. (2007).

significance).

The RBM Off region is a ring (annulus) with center at the source position. In this work, the ring has inner annulus (`RBM_RingLowerRadius`) 0.6° and outer annulus (`RBM_RingUpperRadius`) 0.8° . The source is not necessarily at the center of the FOV; in wobble observations (most commonly utilized), the telescopes are not pointed directly at the source position and are instead pointed at an offset called a wobble angle (typically 0.5° , and the offset is cyclically in the North/South/East/West direction). This can be seen in Figure 2.9, where the center of the FOV (labeled “Observation Position”) is not aligned with the source (On region). All VERITAS data presented in this work are wobble observations.

To first order, the RBM $\alpha = \frac{\Omega_{\text{On}}}{\Omega_{\text{Off}}}$ is the ratio of the solid angle of the On region to that of the Off region (Berge et al., 2007), but α requires substantial corrections depending on the observation mode. As listed in Berge et al. (2007), some of the factors influencing the acceptance of an event are its offset (radial distance) from the FOV center and its (primary) energy, but the assumption of radial symmetry may be reasonable. For wobble observations, the RBM Off region is not radially symmetric about the center of the FOV, therefore, the energy dependence of the radial acceptance must be considered in the evaluation of α . In practice, the energy dependence is neglected, which introduces an additional uncertainty to measured energies, which in turn affects energy and flux measurements (O’Brien, 2018). For this reason, RBM is disfavored for producing spectra. RBM is favored for generating skymaps because it can be applied to the full FOV, unlike the RR method. Skymaps are built by placing test bins across the FOV and applying the background method to each test bin in order to compute significance (and excess counts) at multiple FOV locations. In the analysis presented here, the test bin has size (RBM_HistoBinSizeInDegrees) 0.0125° .

The RR method requires that wobble observations be conducted. In this way, the On region can be reflected about the center of the FOV to create n_{off} Off regions which are identical in size and shape to the On region, and where the On region and every Off region are an equal distance/radius from the observation

position (using the language of Figure 2.9) (Berge et al., 2007). The On and Off regions lie along a circle of radius $\mathcal{R}$, where $\mathcal{R}$ is the angular distance from the observation position to the center of the On region. Because the On region is reflected about the center of the FOV to create Off regions, the RR method is not defined at the center of the FOV—a test bin at the center is reflected to itself. In addition, as the test bin closely approaches the center of the FOV ($\mathcal{R}$ decreases), the number of viable reflected regions necessarily decreases because the perimeter of the circle decreases, and, eventually the reflected test region will overlap itself. For the RR method, $\alpha = n_{\text{off}}^{-1}$, because the On and Off regions are the same size and at the same radial distance from the FOV center; thus, there is no energy-dependent radial acceptance function to be applied. For this reason, RR is preferred for spectral analyses. In the analysis presented in this work, the size of the RR Off region $\theta = 0.1^\circ$.

2.2.5.2 Significance

The significance S of the deviation of an observational result from the null hypothesis that there is only background and no gamma-ray signal is derived in Li & Ma (1983) (Equation 17) as

$$S = \sqrt{2 \left(N_{\text{on}} \ln \left[\frac{1 + \alpha}{\alpha} \left(\frac{N_{\text{on}}}{N_{\text{on}} + N_{\text{off}}} \right) \right] + N_{\text{off}} \ln \left[(1 + \alpha) \left(\frac{N_{\text{off}}}{N_{\text{on}} + N_{\text{off}}} \right) \right] \right)}, \quad (2.10)$$

where Equation 2.10 was derived under the assumption that a detector observed N_{on} photons in one observation of duration $t_{\text{on}} = \alpha t_{\text{off}}$ pointed at a source, and then observed N_{off} photons in another observation of length t_{off} pointed at a background location. As noted in Li & Ma (1983), so long as N_{on} and N_{off} are not too few (both $\gtrsim 10$), Equation 2.10 is interpreted as the observation of an “ S standard deviation event.” To claim the detection of a new source, most commonly a threshold of 5σ ($5S$, or 5 standard deviations in excess of the background) is required.

The total significance of a source from i datasets (observations) is given in Aharonian et al. (2004) as

$$S = \sqrt{2} \left\{ \left[\sum_i N_{\text{on},i} \right] \ln \left(\frac{\left[\sum_i N_{\text{on},i} \right]}{\left[\sum_i \frac{\alpha_i}{1 + \alpha_i} (N_{\text{on},i} + N_{\text{off},i}) \right]} \right) + \left[\sum_i N_{\text{off},i} \right] \ln \left(\frac{\left[\sum_i N_{\text{off},i} \right]}{\left[\sum_i \frac{1}{1 + \alpha_i} (N_{\text{on},i} + N_{\text{off},i}) \right]} \right) \right\}^{1/2}. \quad (2.11)$$

This is derived in Appendix A.1.

2.2.5.3 Effective Area

The effective area (EA) is an instrument response function (IRF) that represents an instrument’s efficiency in reconstructing events, and depends on multiple fac-

tors, including, but not limited to, the number of telescopes active in the array, the epoch/season (summer or winter atmospheric profile), zenith angle of events, voltage applied to the PMTs (SHV or RHV), and camera offset from the target.

EAs are generated from simulations of gamma rays to incorporate combinations of the factors above.⁴ The EAs used in this work were derived from CORSIKA (Heck et al., 1998) (for air shower simulations and subsequent Cherenkov light), GrISUDet⁵ (for light collection in the camera), and CARE⁶ (using the camera light, which results in FADC traces). The simulations inject a hard spectrum with powerlaw index $\alpha = -2$ (using the convention E^α) for the source.

The EA is

$$A_{\text{eff}}(E) = A_{\text{total}} \frac{N_{\text{sel}}(E)}{N_{\text{total}}(E)}, \quad (2.12)$$

where $N_{\text{total}}(E)$ is the total number of simulated/injected gamma rays (at energy E), N_{sel} is the number of gamma-ray events which pass the selection cuts (Sections 2.2.3-2.2.4), and A_{total} is the total area over which the gamma rays are injected. In simulations, events are thrown randomly (Chromey, 2022) over an area $A_{\text{total}} = \pi R_{\text{thrown}}^2$ where a typical $R_{\text{thrown}} = 750$ m, which is larger than VERITAS's capability to detect events (Madhavan, 2013). The EA is evaluated

⁴The VEGAS Offline Analysis Working Group does not create 3-telescope effective areas by default. The work in this thesis required two 3-telescope effective areas, which were graciously generated by Dr. Alisha Chromey.

⁵<https://web.physics.utah.edu/~gammarray/>

⁶<http://otte.gatech.edu/care/>

in bins of true energy E_{true} .

The energy reconstruction is imperfect, and the difference between the true energies (known from simulations) and the reconstructed energies E_{rec} is nonzero. The difference, which probes the accuracy of reconstructed events, is quantified as

$$\delta E = \frac{E_{\text{rec}} - E_{\text{true}}}{E_{\text{true}}} \quad (2.13)$$

and is evaluated in bins of E_{true} (Park & VERITAS Collaboration, 2015). Within each bin, the median of δE is computed. The energy bias is defined as this median, and an example is shown in Figure 2.10. In each bin, the standard deviation (1σ , or 68% containment around the median is computed), and this is the energy resolution. The energy resolution is shown in Figure 2.11. In this work, an energy bias of $\delta E < 10\%$ is enforced.

In addition, due to the energy bias, when binned in energy, an event with E_{true} might be reconstructed with E_{rec} that is in a different energy bin (Madhavan, 2013). The simulations are reweighted according to the user-input spectrum and then a migration matrix M_{ij} records the fraction of events in bin i (true energy in bin i) that end up in bin j (reconstructed energy in bin j), and is applied to the EA, as detailed in Madhavan (2013).

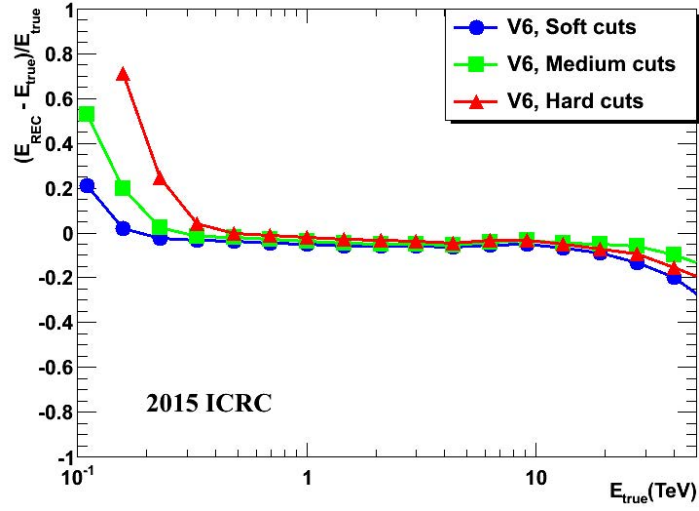


Figure 2.10: VERITAS energy bias. The simulations which produced these plots were for gamma rays at 20° zenith. V6 refers to the observing epoch and means data taken after July 2012. Image from Park & VERITAS Collaboration (2015).

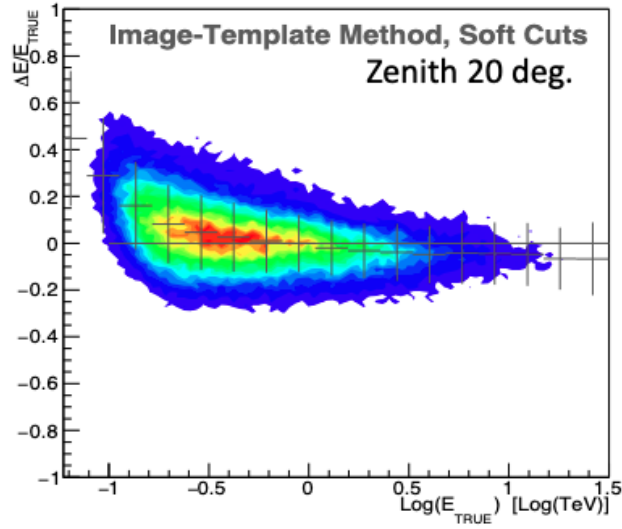


Figure 2.11: VERITAS energy resolution with ITM, where $\Delta E = E_{\text{rec}} - E_{\text{true}}$. Image from Christiansen & VERITAS Collaboration (2017).

2.2.5.4 Gain Throughput (GT) Factors

LTs, ITM templates, and EAs use gain and throughput (GT) factors to account for instrument degradation. “G” (for gain) pertains to the camera throughput, and “T” (for throughput) refers to the optical throughput. The camera throughput degradation refers to $g_i = \frac{G_i}{G_{i,\text{MC}}}$, the ratio between the average measured absolute gain G_i and the PMT gain used in simulations $G_{i,\text{MC}}$, for each telescope i . The optical throughput degradation refers to $t_i = \frac{T_i}{T_{i,\text{MC}}}$, the ratio between the average reflectivity T_i and the average reflectivity used for simulations $T_{i,\text{MC}}$, for each telescope i . A detailed study of GT factors is in Adams et al. (2022).

2.2.5.5 Flux

A flux is obtained from the signal counts N_S (Equation 2.9), the time T_{live} over which the counts are observed, and the EA over which the counts are collected.

T_{live} is the livetime of the observations, and excludes deadtime and accounts for quality cuts (e.g., observation times with poor weather are removed). Altogether, the differential photon flux is

$$\frac{dN(E)}{dE} = \frac{N_S(E)}{T_{\text{live}} A_{\text{eff}} dE}, \quad (2.14)$$

where in the analysis the quantity on the right-hand side is evaluated in bins of

size dE and, using the binned fluxes and the energy E_* (described below and given by Equation 2.17) of each bin, $\frac{dN(E)}{dE}$ is evaluated and then used for a model fit. Every VERITAS spectrum presented in this work is fit to a powerlaw model, so

$$\frac{dN(E)}{dE} = \kappa \left(\frac{E}{E_0} \right)^\alpha, \quad (2.15)$$

where the **VEGAS** convention of E^α (rather than $E^{-\alpha}$) is used, κ is the normalization (the differential photon flux at E_0), E_0 should be set equal to (or very nearly equal to) to the decorrelation energy and is a fixed parameter, and α is the spectral index. These quantities are reported with errors as $\kappa \pm \Delta_\kappa$ and $\alpha \pm \Delta_\alpha$. In **VEGAS** the decorrelation energy (also referred to as pivot energy) is calculated analytically as in Abdo et al. (2009)

$$E_d = E_0 \exp \left[-\frac{\text{cov}(\kappa, \alpha)}{\kappa \Delta_\alpha^2} \right] \quad (2.16)$$

where $\text{cov}(\kappa, \alpha)$ is the off-diagonal element of the covariance matrix and $\text{cov}(\kappa, \alpha) = \text{cov}(\alpha, \kappa)$ (Park, 2018; Taylor, 1997). The decorrelation energy is the energy at which the model flux uncertainty is the smallest. Accordingly, Equation 2.16 is obtained by minimizing the uncertainty on the model flux (Equation 2.15); this is derived explicitly in Section 5.3.3 of O’Brien (2018). E_d is the energy that minimizes the fractional uncertainty $\frac{F}{\Delta_F}$ (where $F \equiv \frac{dN}{dE}$) on the model flux and

uncorrelates the uncertainties Δ_α and Δ_κ (Abdo et al., 2010). **VEGAS** returns the decorrelation energy E_d , and at the next iteration (by hand), the user should set $E_0 = E_d$, and continue to iterate until the fit (including parameters κ and α) converges, and $E_0 = E_d$.

The energy flux is given by $E_*^2 \frac{dN}{dE}$, where in **VEGAS** the energy E_* of the bin is evaluated according to Lafferty & Wyatt (1995) (Equation 6). That is, the energy E_* of the bin bounded by $[E_l, E_u]$ is determined by

$$\left. \frac{dN(E)}{dE} \right|_{E_*} = \frac{1}{\Delta E} \int_{E_l}^{E_u} \frac{dN(E)}{dE} dE. \quad (2.17)$$

Therefore, in the case of a powerlaw (Equation 2.15)

$$E_*^\alpha = \frac{1}{E_u - E_l} \int_{E_l}^{E_u} E^\alpha dE. \quad (2.18)$$

Thus, E_* depends on the spectral index.

In summary, the SEDs are evaluated according to Equations 2.14 and 2.18. Lightcurves display the integral photon flux as a function of time; specifics are detailed in Section 2.2.6.

Provided A_{eff} , N_S , and T_{live} , a flux can always be determined from Equation 2.14. Whether or not this flux is an upper limit depends on the user-set significance threshold applied to each energy bin. Fluxes below this threshold are calculated

as upper limits using the “unbounded” method of Rolke & López (2001), which is the `VEGAS` default (`UL_RolkeBounded=0`). In this work, ULs are given at the 95% confidence level, in accordance with the modeling software, `Bjet_MCMC` (Chapter 3), requirements. To do so, `VEGAS` uses ROOT’s `TRolke` method. This is further detailed in Ribeiro (2022) and Rolke & López (2001).

2.2.6 1ES 0647+250 (VER J0650+250)

Data are analyzed with a set of cuts (“soft cuts”) optimized for soft sources with powerlaw $\left(\frac{dN}{dE} \propto E^\Gamma\right)$ indices of $-4 \leq \Gamma \leq -3.5$ with low energy thresholds (Park & VERITAS Collaboration, 2015).

From 2007 to 2011, 1ES 0647+250 was observed by VERITAS for a total of 1550 minutes (deadtime and quality-cuts corrected). This results in a significance of 2.1σ . Due to the low significance of this time period, the remaining data from 2012 to 2024 are used to construct a “long-term” SED, which contains all VERITAS data from October 2012 to December 2024, and has a significance of 18.0σ . The long-term SED is included in Figure 2.12, for reference. The corresponding skymap is in Figure 2.13. The best fit position to the (RA, Dec) of the excess in Figure 2.13 is $(102.70 \pm 0.06^\circ, 25.03 \pm 0.08^\circ)$ (equivalently, (06h 50m 48s, +25d 01m 48s)). This is consistent with the established optical source position (06h 50m 46.49s, +25d 02m 59.63s) of 1ES 0647+250.⁷ There-

⁷Position from Gaia DR3 via `simbad.cds.unistra.fr`

fore, the VERITAS catalog name for 1ES 0647+250 is VER J0650+250.

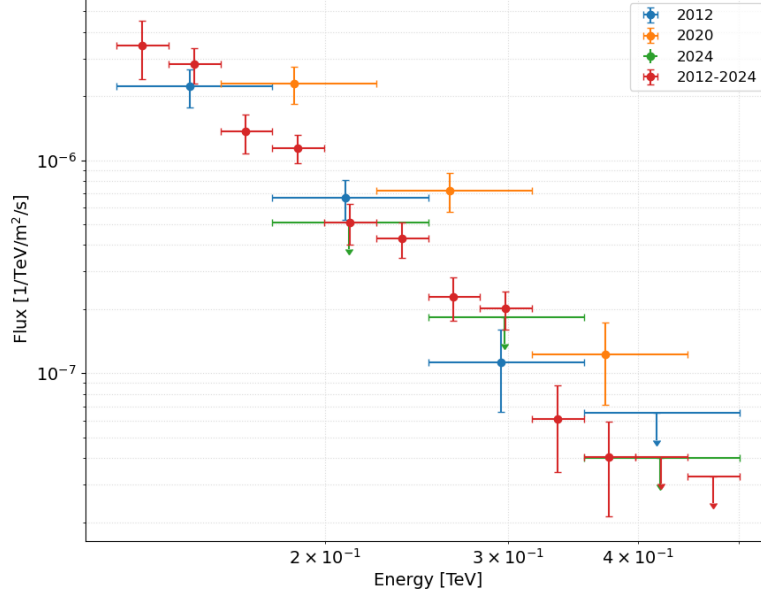


Figure 2.12: VERITAS flux spectra for each state: State A (blue), State B (orange), and State C (green). The long-term spectrum from 2012 to 2024 is also shown (red).

The VERITAS flux spectra for State A, State B, and State C are in Figure 2.12. The VERITAS spectrum for State C has solely upper limits because the `VEGAS` and `EventDisplay` results do not give a significant ($\geq 5\sigma$) detection; in this case, the significance threshold for an UL flux (in an energy bin b) is set to $\sigma_b = 4$. The other states, including the long-term SED, use the default of $\sigma_b = 2$.

The significance of each state, along with the exposure time, is in Table 2.2.

Figure 2.14 contains the long-term lightcurve, using time bins based on the

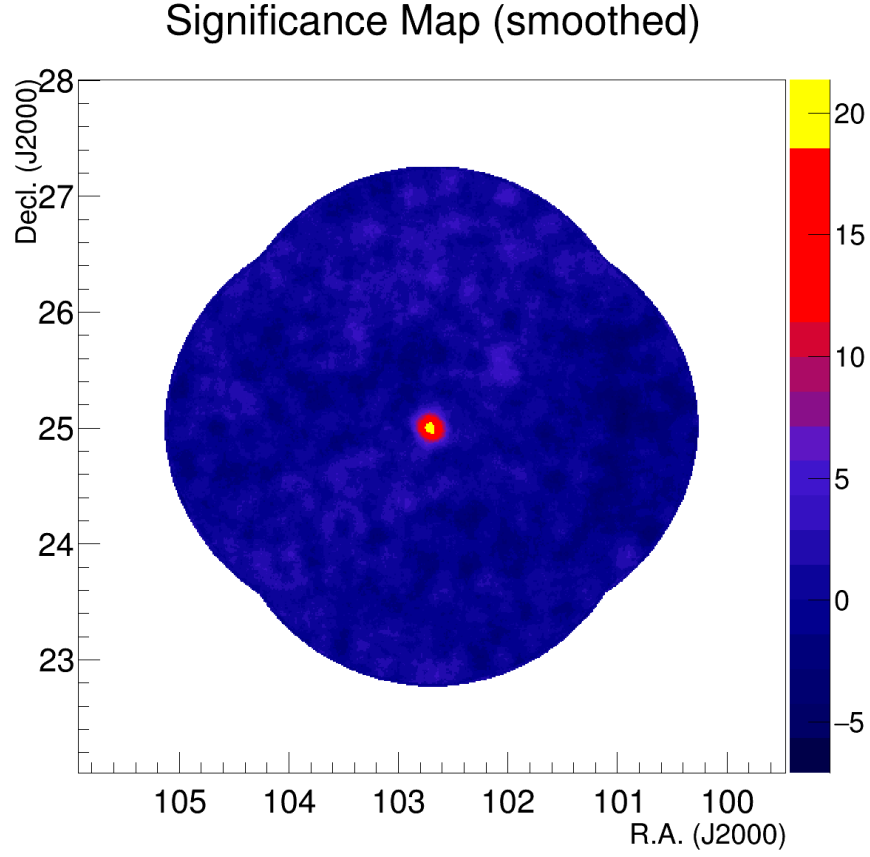


Figure 2.13: VERITAS significance skymap for the long-term state (2012-2024). The colorbar indicates the significance.

State	Exposure [minutes]	σ	κ [1/TeV/m ² /s]	α	E_0 [TeV]
State A	644	9.9	$(1.05 \pm 0.15) \times 10^{-6}$	-4.12 ± 0.51	0.18
State B	229	10.3	$(1.04 \pm 0.14) \times 10^{-6}$	-4.03 ± 0.50	0.23
State C	1116	4.2	-	-	-
Long-term	3689	18.0	$(6.13 \pm 0.43) \times 10^{-7}$	-4.12 ± 0.25	0.21

Table 2.2: VEGAS analysis details. The exposure time is deadtime corrected. The significance is indicated with σ . The spectral parameters correspond to a powerlaw $\frac{dN}{dE} = \kappa \left(\frac{E}{E_0} \right)^\alpha$. The long-term state spans 2012-2024. Dashes indicate that a fit could not be made due to insufficient statistics.

observing season. The observing season boundaries are specified in Table 2.3. The bin edges are the first and last observation dates in each observing season, but the source is not continually observed between these dates.

Lightcurves in this work display the integral flux computed from the integral of the histogram of flux data points, as suggested by Lyu (2026). The integral flux is given over a specific energy range $\mathcal{F}(> E_{\text{hist}})$. The integral flux is adjusted to a different common E_{min} of 0.15 TeV as necessary, using the powerlaw (Equation 2.15) best fit parameters κ and α , via

$$\mathcal{F}(> E_{\text{min}}) = \mathcal{F}(> E_{\text{hist}}) + \int_{E_{\text{min}}}^{E_{\text{hist}}} \frac{dN}{dE} dE \quad (2.19)$$

$$= \mathcal{F}(> E_{\text{hist}}) + \kappa \int_{E_{\text{min}}}^{E_{\text{hist}}} \left(\frac{E}{E_0} \right)^\alpha dE. \quad (2.20)$$

Specifically, the lightcurve in Figure 2.14 was obtained by fitting a powerlaw to each season, with fixed $E_0 = 0.21$ TeV and $\alpha = -4.18$; these parameters are the best fit to the long-term SED. The uncertainty on $\mathcal{F}(> E_{\text{min}})$ shown in the lightcurve is obtained from propagating uncertainties on κ and $\mathcal{F}(> E_{\text{hist}})$ using Equation 2.20.

The lightcurve in Figure 2.14 contains an upper limit flux $\mathcal{F}_{UL}(> E_{\text{min}})$ for February 2022 because the significance is $< 2\sigma$ (see Table 2.3). The upper limit integral flux $\mathcal{F}_{UL}(> E_{UL})$ is calculated using the Rolke method, and is adjusted

to a different common $E_{\min}$ of 0.15 TeV, through

$$\mathcal{F}_{UL}(> E_{\min}) = \mathcal{F}_{UL}(> E_{UL}) + K \int_{E_{\min}}^{E_{UL}} E^{\alpha} dE, \quad (2.21)$$

where

$$K = \mathcal{F}_{UL}(> E_{UL}) \left(\int_{E_{UL}}^{\infty} E^{\alpha} dE \right)^{-1}. \quad (2.22)$$

As can be seen in Figure 2.14, the VHE flux is variable and State B is one of the highest flux VHE states observed by VERITAS. State A and State C are relatively low VHE states.

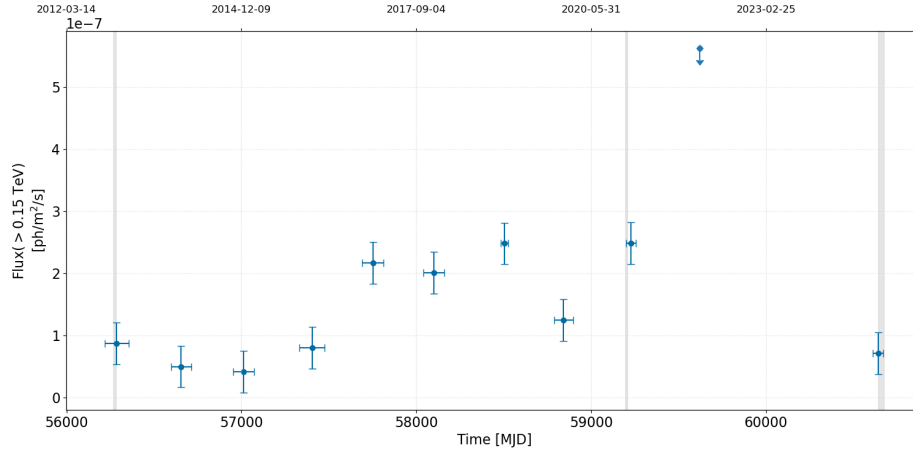


Figure 2.14: VERITAS lightcurve. The significance and exposure time corresponding to each point are in Table 2.3. The gray shaded regions indicate State A, State B, and State C (in that order).

Season	Significance [σ]	Exposure time [minutes]
2012 Oct to 2013 Mar	10.1	783
2013 Oct to 2014 Feb	2.7	116
2014 Oct to 2015 Feb	2.6	228
2015 Nov to 2016 Mar	3.9	190
2016 Oct to 2017 Mar	5.8	95
2017 Oct to 2018 Feb	7.1	195
2018 Dec to 2019 Feb	4.9	114
2019 Nov to 2020 Feb	4.7	423
2020 Dec to 2021 Feb	10.9	347
2022 Feb (only)	1.7	56
2024 Oct to 2024 Dec	4.3	1143

Table 2.3: VERITAS lightcurve analysis details. The exposure time is deadtime corrected.

2.3 *Fermi*-LAT

The *Fermi* Large Area Telescope (*Fermi*-LAT) is an imaging, pair-conversion, telescope which detects gamma rays from < 20 MeV to > 300 GeV with a field of view of 2.4 steradian (Atwood et al., 2009). *Fermi*-LAT orbits the Earth every ≈ 1.5 hours, with every two orbits reaching approximately uniform exposure of the sky. The on-axis angular resolution ranges from $\leq 0.15^\circ$ at > 10 GeV to 3.5° at 100 MeV.

1ES 0647+250 (4FGL J0650.7+250) *Fermi*-LAT data are analyzed with Fermipy v1.1.6 (Wood et al., 2017) and ScienceTools v2.2.0 (Fermi Science Support Development Team, 2019). The energy range spans 100 MeV to 1 TeV, because

the fourth source catalog data release 3 (4FGL-DR3; (Abdollahi et al., 2022)) reports SEDs up to 1 TeV. Initially, eight energy bins per decade are selected, although the bins are further combined prior to SED modeling, as is shown in Figures 2.15-2.17. Sources within 15° of 1ES 0647+250 are included in the likelihood model, which is, as recommended, larger than the region of interest (ROI) of 10° . Pass 8 Source Class (`evclass`: 128) events and photons converted in both the front and back of the instrument (`evtype`: 3) are selected. Events above 90° zenith (`zmax`) are excluded to reduce events from the direction of Earth’s limb (Abdollahi et al., 2022). The events are further classified into four components using PSF type (PSF0, PSF1, PSF2, PSF3) to apply a different instrument response function (IRF) to each component, based on the quality of the reconstructed event direction divided into quartiles.⁸ The `P8R3_SOURCE_V3` IRFs are used. The energy dispersion correction is applied with `edisp_bins`: -2 as recommended by Abdollahi et al. (2022), and the correction is disabled for the isotropic diffuse emission, because this already includes the energy dispersion.⁹ 4FGL-DR3 `gll_psc_v29.fit` is used as the base model catalog, `gll_iem_v07.fits` for the diffuse background template, and `iso_P8R3_SOURCE_V3_v1.txt` for the isotropic background. The normalization of all sources within 3° of 1ES 0647+250 is freed.

⁸https://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/Cicerone/Cicerone_Data/LAT_DP.html

⁹https://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/Pass8_edisp_usage.html

All parameters of sources (anywhere within 15° of 1ES 0647+250) with test statistic $TS \geq 10$ in the fit are freed, and the isotropic and galactic diffuse components are freed. The remaining parameters are fixed to their 4FGL-DR3 catalog values.

Fermi-LAT data are selected to be as contemporaneous as possible with the VERITAS and *Swift* data while still providing sufficient statistics to constrain SED fit parameters; see Section 2.1 for more details. The results of the *Fermi*-LAT analysis are in Table 2.4.

The lightcurves from the *Fermi*-LAT Light Curve Repository¹⁰ (Abdollahi et al., 2023) over the periods modeled in this work (State A, State B, State C) show steady integral fluxes integrated from 0.1 to 100 GeV, with the minimum and maximum flux (including upper limits) varying by a factor < 3 , on weekly timescales. A lightcurve with integral flux evaluated from 100 MeV to 1 TeV is in Figure 2.18, and was produced with Fermipy as described in the caption. The majority (more than half) of the bins are upper limits with test statistic $TS < 4$. Note that the dates overlapping with VERITAS observations of State C include a 3.3 day *Fermi*-LAT data outage starting 2024 December 16.¹¹

¹⁰<https://fermi.gsfc.nasa.gov/ssc/data/access/lat/LightCurveRepository/>

¹¹<https://fermi.gsfc.nasa.gov/ssc/library/news/>; Dec 19, 2024: “LAT Outage - Updated”

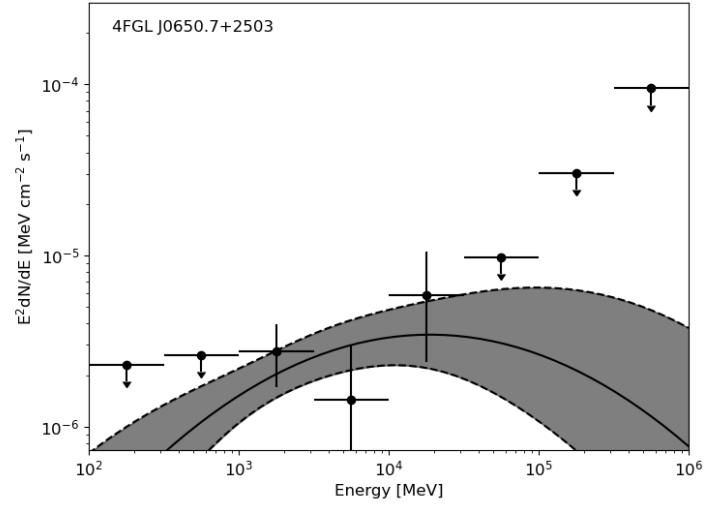


Figure 2.15: Rebinned *Fermi*-LAT SED for State A.

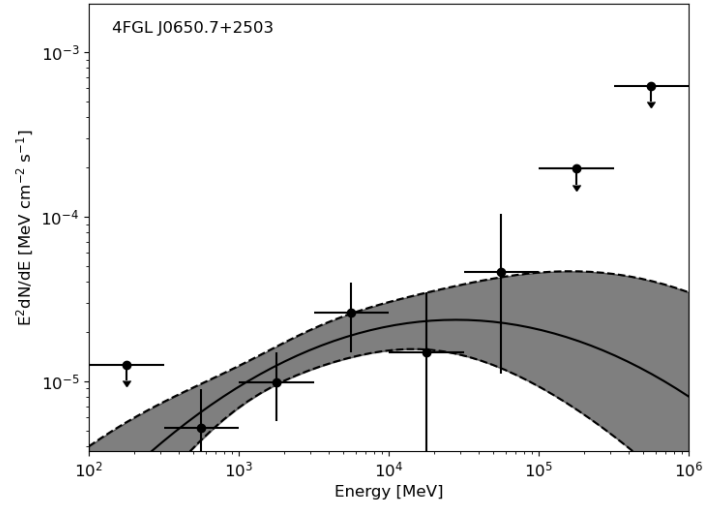


Figure 2.16: Rebinned *Fermi*-LAT SED for State B.

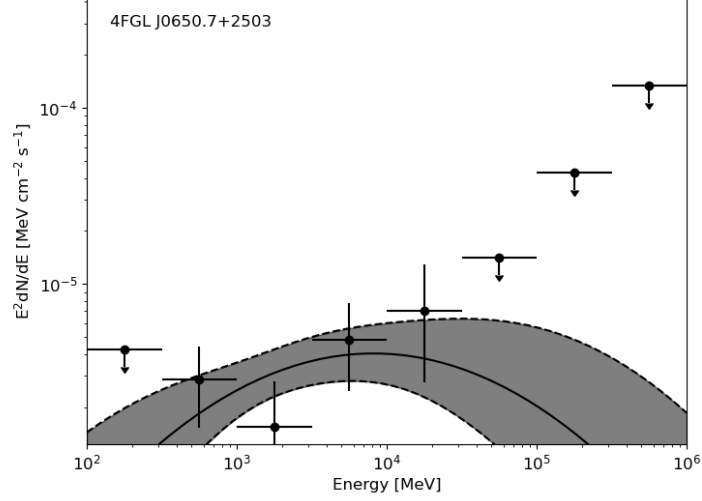


Figure 2.17: Rebinned *Fermi*-LAT SED for State C.

State	TS	N_0 [1/MeV/cm ² /s]	α	β
State A	32.8	$(5.06 \pm 1.86) \times 10^{-13}$	1.58 ± 0.31	0.10 ± 0.12
State B	79.6	$(3.11 \pm 9.54) \times 10^{-13}$	1.56 ± 0.26	0.08 ± 0.11
State C	37.5	$(7.67 \pm 2.75) \times 10^{-13}$	1.70 ± 0.33	0.11 ± 0.15
2012-2025	9417.2	$(1.10 \pm 0.03) \times 10^{-12}$	1.66 ± 0.02	0.04 ± 0.01

Table 2.4: *Fermi*-LAT analysis details for each state. The “2012-2025” state spans from 2012 August 1 to 2025 January 25 (56140.0-60700.0 MJD). The fit parameters correspond to a log parabola $\frac{dN}{dE} = N_0 \left(\frac{E}{E_b} \right)^{-(\alpha+\beta \ln(E/E_b))}$ with $E_b = 2066.80$ MeV; the spectrum of 1ES 0647+250 is classified as log parabola in the *Fermi* catalog.

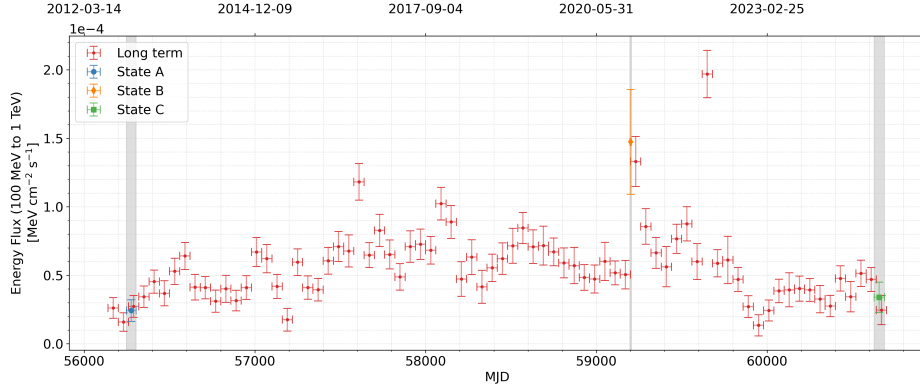


Figure 2.18: *Fermi*-LAT lightcurve. The gray shaded regions indicate the time ranges of State A, State B, and State C. The red points are 60-day bins with the normalization of all sources within 20° of 1ES 0647+250 free; all other parameters are fixed (to the 4FGL-DR3 values) in each bin, including the isotropic and galactic diffuse components. The blue, orange, and green points correspond to the fluxes of State A, State B, and State C, respectively, with one time bin per state; for the computation of these fluxes, the normalization of all sources within 20° of 1ES 0647+250 is free.

2.4 *Swift*-XRT

The *Swift* X-ray Telescope (*Swift*-XRT) is a focusing X-ray telescope that operates automatically in one of several modes—2D imaging Photon Counting (PC) mode or 1D imaging Windowed Timing (WT); the readout is automated as described in Hill et al. (2004). The instrument detects photons in the range 0.2-10 keV, has a 23.6×23.6 arcmin field of view, $2.36''$ pixel scale, $3''$ pointing accuracy, and PSF $18''$ ($22''$) half-power diameter angular resolution at 1.5 (8.1) keV (Burrows et al., 2005). At launch, the energy resolution was 140 eV at 5.9 keV (Burrows et al., 2005).

Spectra for individual *Swift*-XRT observations, specified with a unique observation ID (ObsID), are obtained from the online product generator “Build Swift-XRT products”¹² (Evans et al., 2009) via `swifttools` v3.0.23.¹³ The online product generator uses HEASoft v6.32 and corrects for pile-up (> 0.6 counts/sec) and bad columns, and identifies a suitable extraction region for each snapshot. The data products are re-grouped¹⁴ using `grppha` in HEASoft v6.30.1 (NASA High Energy Astrophysics Science Archive Research Center (Heasarc), 2014) to ensure a minimum of 20 counts per bin, because χ^2 statistics are used to evalu-

¹²https://www.swift.ac.uk/user_objects/

¹³<https://github.com/Swift-SOT/swifttools>

¹⁴As noted in the README.txt accompanying each product, the data “have had `group min 1` applied”, meaning there is a minimum of 1 count per bin.

ate the quality of the fits. Several spectral models are implemented using **XSpec** v12.12.1 (Arnaud, 1996):

- i Intrinsic powerlaw with Galactic absorption,
- ii Intrinsic log parabola with Galactic absorption (where log refers to $\log_{10}$ in the **XSpec** model),
- iii Intrinsic powerlaw with both Galactic and intrinsic absorption (using $z = 0.45$),
- iv Intrinsic log parabola with Galactic and intrinsic absorption (using $z = 0.45$).

The photoelectric absorption component(s) use the Tuebingen-Boulder interstellar medium (ISM) absorption model (**tbabs**) and ISM abundances (**abund wilm**) from Wilms et al. (2000). Photoelectric absorption is most relevant for X-rays with energy < 1 keV; in this interaction, photons with energy E_γ remove electrons with binding energies $E_e < E_\gamma$. The absorption component of the observed flux F_{obs} is given by $\exp(-n_H\sigma(E))$, such that i and ii are written

$$F_{\text{obs}} = f_{\text{int}} \exp(-n_H\sigma(E)), \quad (2.23)$$

where f_{int} is the intrinsic flux (e.g. powerlaw, log parabola), n_H is the Galactic hydrogen column density, and $\sigma(E)$ is the photoelectric cross section. The observed

flux, using iii and iv, is modeled as

$$F_{\text{obs}} = f_{\text{int}} \exp(-n_H \sigma(E)) \exp(-\eta_H \sigma(E(1+z))), \quad (2.24)$$

where $\exp(-\eta_H \sigma(E(1+z)))$ is the intrinsic absorption, η_H is the hydrogen column density in the host galaxy, and $\sigma(E(1+z))$ is the photoelectric cross section evaluated in the frame of the host galaxy. Most of the gas in the Milky Way is hydrogen, so although n_H is used as the total gas density in **XSpec** (with element abundances set by **abund wilm**), its value is set to the density of hydrogen gas in the ISM (in the Milky Way). The weighted average total Galactic hydrogen column density n_H , which includes atomic and molecular hydrogen, is found using the online tool “Calculate Galactic N_H ”¹⁵ to be $n_H = 0.157 \times 10^{22}$ atoms/cm² using the source name, which queried position (102.69371°, 25.04990°). In all cases i–iv, the Galactic hydrogen column density n_H is fixed to 0.157×10^{22} atoms/cm², the normalization energies are fixed to their **XSpec** defaults, and the remaining model parameters are kept free (with the exception of redshift).

For each observation considered in this thesis, the unfolded spectral points (**eeufspec**) of models i–iv are indistinguishable within uncertainties, and nearly identical in many cases. An example is in Figure A.2. For the majority of the ObsIDs (of State A, State B, and State C), the lowest reduced χ^2 corresponds

¹⁵<https://www.swift.ac.uk/analysis/nhtot/index.php>

to a log parabola with Galactic absorption (ii); the χ^2 values and degrees of freedom for each model are in Tables A.1-A.3. X-ray spectra do not commonly show absorption near the nuclei of blazars (Beckmann & Shrader, 2012b); in the case of 1ES 0647+250, a scan of the literature did not reveal measurements of η_H . Nonetheless, models with $\eta_H \neq 0$ were fit to 1ES 0647+250 data. The best fits to η_H from spectral models iii and iv are in Figures 2.19 and 2.20. The best fit range of η_H , $\eta_{H,\text{low}}$ to $\eta_{H,\text{high}}$, is large (in most cases, the uncertainty is $> 50\%$ of η_H); many of the fits find $\eta_{H,\text{low}}$ equal to 0, which is consistent with no substantial absorption in the host galaxy. In these cases, iii is consistent with i, and iv is consistent with ii. A simpler model (with one less degree of freedom) is preferred, so i is favored over iii, and ii is favored over iv. Thus, in this thesis, the results of the log parabola with Galactic absorption (ii) are used.

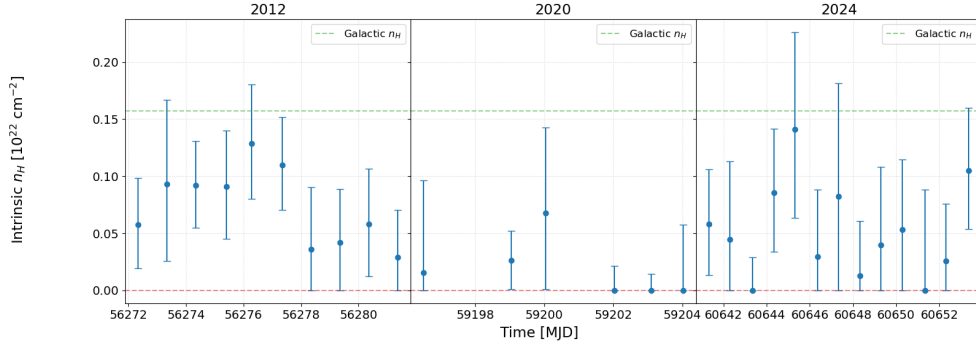


Figure 2.19: Fits to the host galaxy hydrogen column density η_H using iii for State A (left), State B (middle) and State C (right). The Galactic hydrogen column density (dashed green) and 0 (dashed red) are shown for reference.

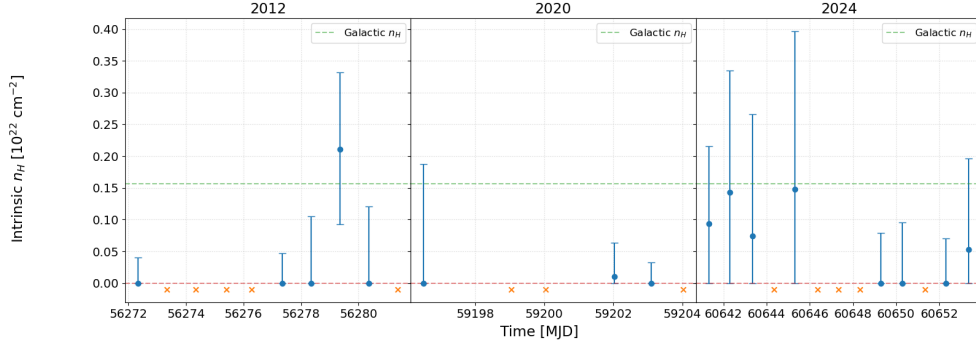


Figure 2.20: Similar to Figure 2.19, but for spectral model iv. Some fits failed to converge (orange $\times$ markers).

However, to emphasize, the choice of model (considering cases i–iv) has very little impact on the observed fluxes, and the model parameters (from fits to ii) are solely used to compute the fastest observed variability in Section 2.4.3, in an energy range (2–10 keV) where absorption is minimal. The impact of the model on the integral flux is summarized in Appendix A.2.3. The **intrinsic** fluxes f_{int} are used in the SED modeling in Chapter 3. Preliminary estimates (using symmetric and Gaussian errors on η_H , $\delta\eta_H = \frac{1}{2}(\eta_{H,\text{high}} - \eta_{H,\text{low}})$) show that once (the large) uncertainties on η_H are propagated to f_{int} , the intrinsic fluxes f_{int} of the models i–iv are in agreement within uncertainties. Therefore, the intrinsic fluxes derived from models i–iv are statistically distinguishable and unlikely to impact the modeling in Chapter 3 significantly.

To determine a single SED for each state, which is composed of many observations, representative SEDs, which reflect the variability of the source, are

constructed for each state using all the observations within the corresponding state, as follows.

2.4.1 Intrinsic SEDs via `nHDeabsorb`

Each individual SED (from model ii) is n_H -deabsorbed using `nHDeabsorb` (Splettstoesser, 2024) in order to isolate the intrinsic flux f_{int} .

`nHDeabsorb` uses `XSpec` to create a table of photoelectric absorption values at various energies for a specific hydrogen column density N_H ; that is, `nHDeabsorb` creates and uses a table of $\exp(-N_H\sigma(E))$ at various E . The photoelectric absorption at an arbitrary n_H is therefore given by

$$\exp(-n_H\sigma(E)) = \exp\left(-\frac{n_H}{N_H}N_H\sigma(E)\right) \quad (2.25)$$

$$= [\exp(-N_H\sigma(E))]^{n_H/N_H}. \quad (2.26)$$

For a given energy E , `nHDeabsorb` returns the absorption at a user-set n_H using Equation 2.26. In this way, the cross section and the element abundances are not directly required to compute the absorption—instead, the `XSpec` table encodes them. The photoelectric absorption relevant to this work (with $n_H = 0.157 \times 10^{22}$ atoms/cm²) is in Figure A.1.

The individual observations provide the observed flux $F_{\text{obs},i}$ in each energy bin

$E_i \pm \Delta E_i$. The energy bins $E_i \pm \Delta E_i$ are those set by **XSpec** by default, so they are the smallest possible bins. The deabsorbed flux (from model ii) in each bin is

$$f_{\text{int},i} = \frac{F_{\text{obs},i}}{\exp(-n_H\sigma(E))|_i} \quad (2.27)$$

where $\exp(-n_H\sigma(E))|_i$ is taken to be the average of the absorption values in the **nHDeabsorb** table in the energy bin $E_i \pm \Delta E_i$. An example of the energy bins of an individual observation, as well as the absorption, is in Figure A.1.

2.4.2 Representative SEDs

As shown in Figures A.3, A.4, and A.5, the source is somewhat variable in X-ray in each state. Each n_H -deabsorbed observation is considered in what follows, in order to produce a representative SED. For each state, initially, 16 equally log-spaced bins are created with edges from 0.3 keV to 10 keV. Let each bin edge be denoted $E_{\text{low},j}$ and $E_{\text{high},j}$. All individual observations for each state are considered, using the default bins from **XSpec**. Each individual observation has a series of **deabsorbed** fluxes $f_i \pm \delta f_i$ corresponding to energy bin $E_i \pm \Delta E_i$. Within each of the j log-spaced bins, the deabsorbed fluxes f_i which correspond to a central energy E_i in the bin ($E_{\text{low},j} \leq E_i < E_{\text{high},j}$) are used. Note that the individual SEDs are deabsorbed prior to binning due to the energy dependence of the absorption. Bins with fewer than five flux points are combined with the

previous bin. This results in < 16 bins; the final bin edges are in Figures A.6, A.7, and A.8. A weighted average flux $\bar{f}_b$ is computed from the deabsorbed fluxes in each bin, with weights $(\delta f_i)^{-2}$. The energy associated with the bin is taken to be the weighted average energy $\bar{E}_b$ of E_i , where the weights are $(\Delta E_i)^{-2}$, in order to weight the representative energy towards the energy where the majority of the fluxes truly lie. The difference between $\bar{E}_b$ and the log-spaced center $E_{\text{center,log}}$, evaluated as $\frac{|\bar{E}_b - E_{\text{center,log}}|}{E_{\text{center,log}}}$, is up to 15% for the highest energy bin, and $< 5\%$ for the other bins; the difference can be seen in Figures A.6-A.8. To capture the variability, in each bin, two flux RMS values and two combined uncertainties Δ are calculated,

$$\text{RMS}_{\text{low}} = \sqrt{\frac{\sum_{f_i < \bar{f}_b} (f_i - \bar{f}_b)^2}{N_{\text{low}}}}, \quad \text{RMS}_{\text{high}} = \sqrt{\frac{\sum_{f_i > \bar{f}_b} (f_i - \bar{f}_b)^2}{N_{\text{high}}}}, \quad (2.28)$$

$$\Delta_{\text{low}} = \frac{\sqrt{\sum_{f_i < \bar{f}_b} (\delta f_{i,b})^2}}{N_{\text{low}}}, \quad \Delta_{\text{high}} = \frac{\sqrt{\sum_{f_i > \bar{f}_b} (\delta f_{i,b})^2}}{N_{\text{high}}}, \quad (2.29)$$

where N_{low} (N_{high}) is the number of points in the bin below (above) the bin average $\bar{f}_b$. The combined error is evaluated separately for fluxes above and below the weighted average $\bar{f}_b$ (via Equation 2.29) in order to consider the same set of points for the comparison of Δ and RMS, and in order to account for the asymmetric distribution of fluxes about $\bar{f}_b$; the representative SED must reflect

this asymmetry. There are no instances where $f_i = \bar{f}_b$. As recommended by Hervet et al. (2024), in cases where the combined statistical uncertainty Δ_{high} (Δ_{low}) is greater than RMS_{high} (RMS_{low}), the combined uncertainty is used instead of the RMS as the uncertainty on the representative SED. The RMS is used in the vast majority of cases ($\approx 90\%$), rather than the combined uncertainty Δ .

In summary, the representative SED has a series of energies $\bar{E}_b$ with bin edges $E_{\text{low},j}$ and $E_{\text{high},j}$, and a representative flux $\bar{f}_b$ with uncertainties RMS_{low} (or Δ_{low}) and RMS_{high} (or Δ_{high}).

For State A, a representative SED is built using the ten observations between 2012 December 8 and 2012 December 22; there are ten PC mode observations, and there are no WT mode observations longer than a couple minutes, so these are not considered. For State B, a representative SED is built using the six observations between 2020 December 13 and 2020 December 22; these observations are of mixed modes. For State C, a representative SED is built using all 13 PC mode observations between 2024 November 27 and 2024 December 2. There are no WT mode observations longer than a couple minutes, so these are not considered. The representative SEDs, along with the individual (deabsorbed) SEDs, are in Figures A.6, A.7, and A.8. Appendix A.2 has more information about the *Swift*-XRT analysis.

2.4.3 Fastest observed variability

The modeling software used in Chapter 3, `Bjet_MCMC`, can use the fastest observed variability τ as an additional constraint. τ is determined from *Swift*-XRT lightcurves, which are in Appendix A.2.3. The integral fluxes are computed between 2 and 10 keV (via `flux` in `XSpec`) from model ii.

τ is taken to be the flux doubling time or flux halving time (as appropriate), using the two fluxes f_1, f_2 which appear to change the most drastically over each state. In the case of the flux doubling time, τ_{double} can be solved using the observed fluxes $f_1 \pm \delta f_1$ at time t_1 and $f_2 \pm \delta f_2$ at time t_2 , where $t_2 > t_1$, via

$$f_1 = A \cdot 2^{t_1/\tau_{\text{double}}} \quad (2.30)$$

$$f_2 = A \cdot 2^{t_2/\tau_{\text{double}}} \quad (2.31)$$

$$\frac{f_2}{f_1} = 2^{(t_2-t_1)/\tau_{\text{double}}} \quad (2.32)$$

$$\tau_{\text{double}} = \frac{t_2 - t_1}{\log_2(f_2/f_1)}. \quad (2.33)$$

Overall,

$$\tau = \begin{cases} \tau_{\text{double}} = \frac{t_2 - t_1}{\log_2(f_2/f_1)} & f_2 > f_1 \\ \tau_{\text{half}} = \frac{t_2 - t_1}{\log_{1/2}(f_2/f_1)} & f_2 < f_1. \end{cases} \quad (2.34)$$

The dates (t_1 and t_2) used in this calculation are indicated in Figures A.9, A.10,

and A.11.

The upper and lower uncertainties on τ are computed from the following differences $\Delta\tau$,

$$\begin{aligned}
\Delta\tau_{1+} &= \tau(f_1 + \delta f_1, f_2) - \tau(f_1, f_2), \\
\Delta\tau_{1-} &= \tau(f_1 - \delta f_1, f_2) - \tau(f_1, f_2), \\
\Delta\tau_{2+} &= \tau(f_1, f_2 + \delta f_2) - \tau(f_1, f_2), \\
\Delta\tau_{2-} &= \tau(f_1, f_2 - \delta f_2) - \tau(f_1, f_2),
\end{aligned} \tag{2.35}$$

where τ is given by Equation 2.34. Two of the above result in a positive number, and two result in a negative number. The upper 1σ uncertainty on τ , $\delta\tau_+$, is taken to be the square root of the two positive $\Delta\tau$ added in quadrature. The lower 1σ uncertainty, $\delta\tau_-$, is taken to be the square root of the two negative $\Delta\tau$ added in quadrature. As can be seen in Table 2.5, τ is not well-constrained (its uncertainties are large), so the 95% confidence level of τ , τ_{95} , is used as the fastest observed variability in `Bjet_MCMC`, to be conservative. The 95% confidence level (CL) is estimated assuming a normal distribution with mean τ and standard deviation $\delta\tau_+$. Note that the 95% CL computed is not the central 95%—it is the 95% percentile. The results, τ and τ_{95} , for each state are in Table 2.5.

The *Swift*-XRT analysis methods and tools used in this work and described in this section are loosely outlined at Splettstoesser (2025a).

State	τ [hours]	τ_{95} [hours]
State A	$\tau_{\text{half}} = 45^{+16}_{-10}$	71
State B	$\tau_{\text{double}} = 75^{+5}_{-5}$	81
State C	$\tau_{\text{double}} = 31^{+31}_{-10}$	83

Table 2.5: Fastest observed variability τ and corresponding 95% confidence level (percentile) τ_{95} for each state.

2.5 *Swift*-UVOT

The *Swift* Ultra-Violet/Optical Telescope (*Swift*-UVOT), a photon-counting instrument onboard the *Swift* Gamma-ray Observatory, is sensitive to photons in the range 170-600 nm (approximately 2.1 – 7.3 eV) and uses six filters (UVW1, UVM2, UVW2, U, B, and V); filter widths (FWHM) are in Roming et al. (2005). *Swift*-UVOT has pixels of size 0.5 arcsec, a 17×17 arcmin² field of view, and PSF 0.9'' (FWHM) at 350 nm and 0.3'' pointing accuracy (Roming et al., 2005).

Swift-UVOT observations (each with its own ObsID, as in Section 2.4) are analyzed individually with HEASoft v6.30.1 (NASA High Energy Astrophysics Science Archive Research Center (Heasarc), 2014), via `swift-uvot-analysis-tools` (Ribeiro et al., 2020), which uses the central wavelengths in Poole et al. (2008) to convert magnitudes to fluxes. The analysis in this work utilizes aperture photometry with source region radius 5'' centered¹⁶ on 1ES 0647+250, and a background region with radius 20'' located away from 1ES 0647+250 and not overlapping other

¹⁶The position is determined via `uvotdetect`.

sources.

`swift-uvot-analysis-tools` corrects for Galactic extinction using the York Extinction Solver¹⁷ (McCall, 2004) to obtain the extinction coefficients R_λ , and the dust reddening from Schlafly & Finkbeiner (2011) via the IRSA Galactic Dust Reddening and Extinction Service¹⁸. Hereafter, in this section, “de-extincted” flux refers to the observed fluxes with Galactic extinction removed.

For the observation on 2020 December 21 (ObsID 00032646039), the UVW2 and UVM2 filter images show that the spacecraft is rocking/settling (see Appendix A.3.1); thus, these observations are not used in the analysis.

Lightcurves are in Appendix A.3.2, which show that the flux in each state is relatively steady. The minimum and maximum flux in each state differ by a factor of < 1.5 . Therefore, a representative SED is constructed for each state, using a similar method to the one in Section 2.4.2. However, Section 2.4.2 describes creating energy bins; instead, for each *Swift*-UVOT filter, a weighted average de-extincted flux is computed using the i individual observations (ObsIDs) pertaining to the state. The resulting representative SEDs and individual SEDs are in Appendix A.3.3.

The contribution of the host galaxy is removed from the representative

¹⁷<https://www.cadc-ccda.hia-ihp.nrc-cnrc.gc.ca/en/community/YorkExtinctionSolver/>

¹⁸<https://irsa.ipac.caltech.edu/applications/DUST/index.html> via `astroquery.irsa_dust`

de-extincted *Swift*-UVOT fluxes using `SED_Host_Galaxy_Correction` v0.1.0 (Hervet, 2024a; Fioc & Rocca-Volmerange, 1999). This tool is used with the host galaxy *H*-band (AB) magnitude $m_{H,AB} = 16.9 \pm 0.2$, effective radius of the host galaxy $r_{\text{eff}} = 1.6''$, and Sersic index $N = 1.24$ ($m_{H,AB}$, r_{eff} , and N are reported in Kotilainen et al. (2011) and derived from Nordic Optical Telescope images), in addition to the redshift $z = 0.45$ given in Meisner & Romani (2010) and consistent with MAGIC Collaboration et al. (2023). Relevant *Swift*-UVOT and Nordic Optical Telescope filter information—effective filter wavelength λ_{eff} and effective filter width W_{eff} —is obtained from Rodrigo & Solano (2020) and Rodrigo et al. (2012). `SED_Host_Galaxy_Correction` reveals that the host galaxy contribution is faint, $< 16\%$ in all cases. The resulting de-extincted SEDs with the host galaxy contribution removed are in Appendix A.3.3 and are used for the SED modeling in Chapter 3.

2.6 FLWO

The Fred Lawrence Whipple Observatory (FLWO) has been using the 48" optical telescope¹⁹ to obtain blazar monitoring data for known VHE emitters. Blazars are imaged in up to four filters: SDSS r', SDSS i', Harris V, and Harris B.

State C is the only state with contemporaneous FLWO data, with observation

¹⁹<http://www.sao.arizona.edu/FLWO/48/48.html>

dates given in Table 2.1.

Piatra Lusen analyzed the FLWO data (Lusen, 2025). Magnitudes are determined using aperture photometry with 3.38'' aperture. Using each blazar image, the blazar's magnitude m_f is measured in addition to that of a "check star" which is used to evaluate the quality of the observation. This procedure is described in Archer et al. (2018) and Acharyya et al. (2026a). The resulting lightcurve is in Figure 2.21.

To obtain the intrinsic flux, the effects of dust extinction are removed from the observed magnitudes by subtracting the band extinction A^c at the source sky location²⁰ (Schlafly & Finkbeiner, 2011). The A^c which corresponds to the filter closest to each FLWO filter is selected: SDSS r A^c was used for SDSS r', SDSS i for SDSS i', CTIO V for Harris V, and CTIO B for Harris B. The resulting magnitude $m_f - A^c$ is converted to a flux using the central wavelength of each filter. The central wavelengths of the SDSS r' and SDSS i' filter are from the SDSS DR6 Photometric Flux Calibration website²¹ and the central wavelengths of the Harris V and Harris B filters are from Bessell (1979). A representative SED is constructed from the de-extincted data in the same way as in Sections 2.4 and 2.5. The host galaxy contribution is removed from the de-extincted representative SED, as is described in Section 2.5, using the effective wavelengths and effective widths from

²⁰Obtained from <https://irsa.ipac.caltech.edu/applications/DUST/>

²¹<https://classic.sdss.org/dr6/algorithms/fluxcal.php#sdss2flux>

Rodrigo & Solano (2020) and Rodrigo et al. (2012). The representative SED is steady; the minimum and maximum flux differ by a factor of < 1.4 in all filters.

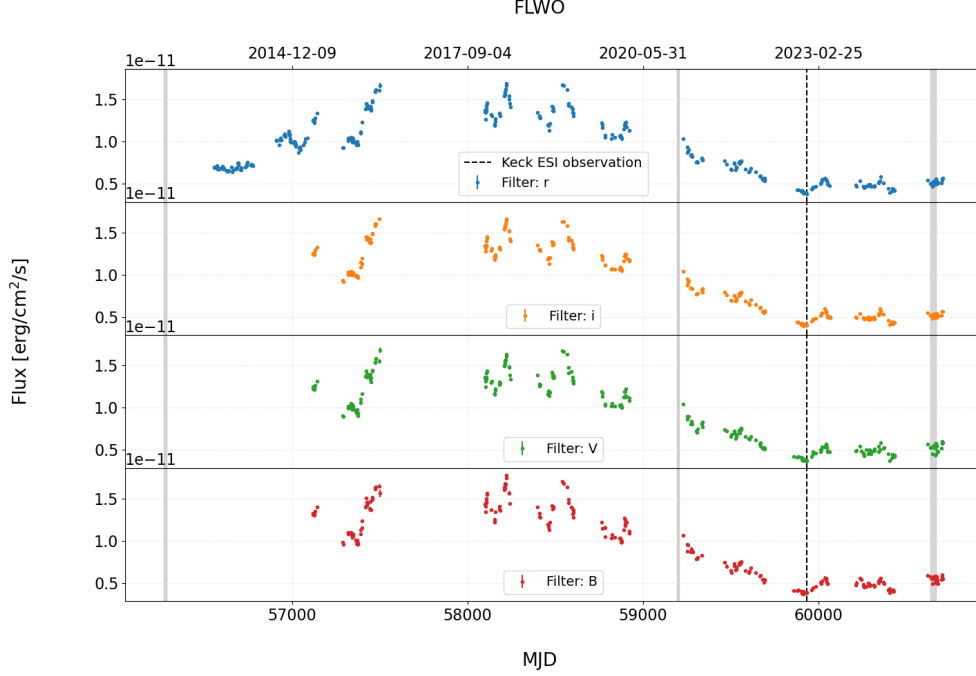


Figure 2.21: FLWO lightcurve for each filter. From the upper plot to the lower plot, the filters are SDSS r' , SDSS i' , Harris V, and Harris B. The gray shaded regions indicate State A, State B, and State C, respectively. The dashed black line is the date of the Keck ESI observation, which is discussed in Section 2.7.

2.7 Keck ESI

As discussed in Section 1.1, 1ES 0647+250 does not have a measured spectroscopic redshift. Therefore, when the source entered an optically dim state in November 2022 (see Figure 2.21), Raja GuhaThakurta, Emily Cunningham, Yuting Feng,

Grion Filho, and Eric Peng graciously obtained a spectrum of 1ES 0647+250 during their scheduled night of Keck Echellette Spectrograph and Imager (ESI) observations on 2022 December 24. The data were analyzed by Paolo Goldoni (Goldoni, 2023). The resulting spectrum is in Figure 2.22; no spectral lines from the host galaxy are detected. Thus, no redshift can be determined from this observation.

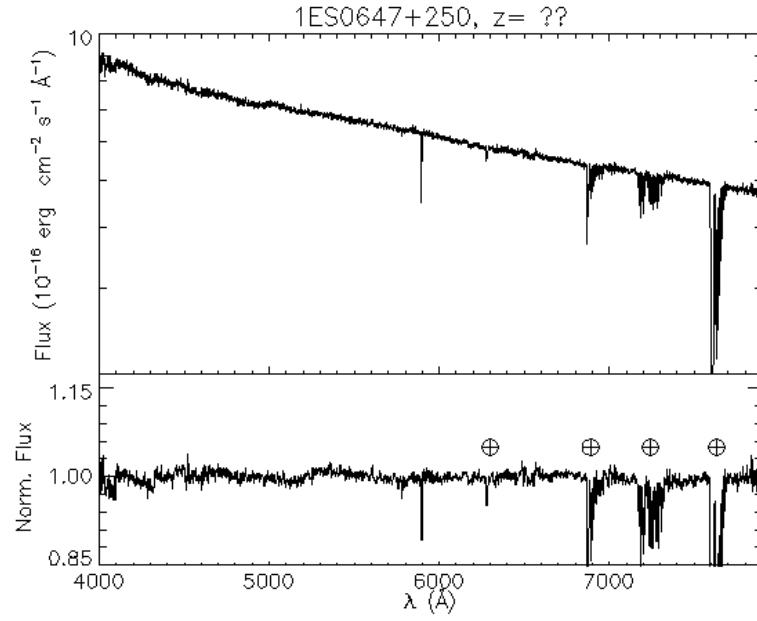


Figure 2.22: Keck ESI spectrum for 1ES 0647+250; image from Goldoni (2023). The signal-to-noise ratio is about 140. The Na I D (neutral sodium doublet) absorption lines at about 5900 Å are from the Milky Way. Absorption features due to Earth’s atmosphere are indicated by the symbol $\oplus$.

2.8 OVRO

The Owens Valley Radio Observatory (OVRO) began a blazar monitoring program with the 40-m telescope in 2007, to monitor > 1100 blazars with high cadence (typically biweekly) at 15.0 GHz with bandwidth 3.0 GHz (Richards et al., 2011). The 40-m has an “antenna” beam and “reference” beam with width (FWHM) $157''$. Details of the instrument, analysis, monitoring program, and its initial results from the first two years are in Richards et al. (2011).

The OVRO collaboration provided fluxes f with estimated uncertainty σ_f . The total uncertainty $\delta f = \sqrt{(0.05f)^2 + (\sigma_f)^2}$ includes the 5% absolute calibration error (Richards et al., 2011); at the advice of the OVRO collaboration, δf is the uncertainty used in this work.

The fluxes are steady over the periods under study, with the minimum flux and maximum flux varying by a factor of < 1.1 in each state.

OVRO data for 1ES 0647+250 (BL0647+250) overlaps State A with five observations, State B with two observations, and State C with three observations.

As is done with *Swift*-XRT, *Swift*-UVOT, and FLWO data, a representative SED is constructed, with uncertainties δ_{low} (Δ_{low} or RMS_{low}) and δ_{high} (Δ_{high} or RMS_{high}) calculated as in Section 2.4.2.

The OVRO radio data are treated similarly to an upper limit because the

radio flux includes contributions from the jet; see Abdo et al. (2011) for a brief discussion. The `Bjet_MCMC` SSC model includes the compact zone (“blob”) near the blazar nucleus, and not the jet (see Chapter 3). Therefore, the observed radio flux is the maximum flux from the blob, and the radio flux is treated similarly to an upper limit. However, `Bjet_MCMC` (v1.1.0) assigns an upper limit flux a step function probability with 95% probability below the upper limit and 5% probability above it. Thus, for a more accurate treatment (for better likelihood evaluation) the uncertainty on f is taken to be $f_{-10f}^{+\delta_{\text{high}}}$. The lower uncertainty of the flux is extended to $-10f$ to create a flat probability distribution below f , in order to ensure the fit is not overly skewed toward the upper limit f and to include the upper uncertainty as a part of the parameter space that can be explored by the walkers in `Bjet_MCMC`. The probability distribution is illustrated in Figure 2.23.

2.9 TELAMON

The TeV Effelsberg Long-term AGN Monitoring (TELAMON) program (Eppel et al., 2024) began a TeV-detected AGN monitoring program in 2020, which uses the Effelsberg 100-m telescope. This program also monitors candidate neutrino-associated AGN. Observations are with 20 mm (added in 2021), 14 mm, and 7 mm receivers, from 14 GHz to 45 GHz. There are further sub-bands for each

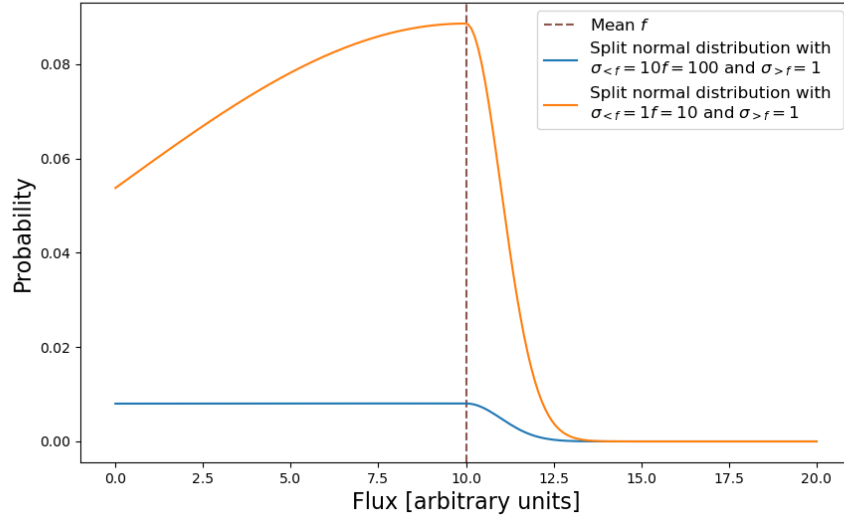


Figure 2.23: Split normal distribution with mean f (dotted brown), standard deviation below the mean $\sigma_{<f}$, and standard deviation above the mean $\sigma_{>f}$. Adopting an uncertainty of $f_{-f}^{\delta_{\text{high}}}$ results in a probability distribution (orange) which is not flat below the mean. An uncertainty $f_{-10f}^{\delta_{\text{high}}}$ results in a flat probability distribution (blue) below the mean. In this way, f is treated similarly to an upper limit, and the uncertainty δ_{high} is still considered in the fit; this is the uncertainty on the radio flux used in the MWL modeling in Chapter 3.

receiver, with centers at 19.25 GHz, 21.15 GHz, 22.85 GHz, and 24.75 GHz for the 14 mm (bandwidth 19-25 GHz), and centered at 36.25 GHz, 38.75 GHz, 41.25 GHz, 43.75 GHz for the 7 mm (bandwidth 36-44 GHz). More details, including instrument specifications, analysis, monitoring strategy, and initial results from the first 2.5 years, are in Eppel et al. (2024).

TELAMON data for 1ES 0647+250 overlaps the State B with one observation date, at 19.25 GHz, 21.15 GHz, and 24.75 GHz (the 14 mm receiver). No representative SED is created because there is one observation. The TELAMON fluxes are treated similarly to upper limits in the same way as the OVRO radio fluxes, as described in Section 2.8.

Chapter 3

Multiwavelength Modeling with Bjet_MCMC

This chapter details the methodology to understand which physical parameters are likely responsible for the changes in 1ES 0647+250 from State A to State B to State C. Bjet_MCMC provides the framework for modeling the physical parameters.

Bjet_MCMC (Hervet et al., 2024; Hervet, 2024b), where “Bjet” means “Blob-in-jet”, is a package that models multiwavelength SEDs of blazars with Markov chain Monte Carlo (MCMC) methods. The modeling is not time-dependent. The “blob” in Bjet_MCMC is a compact, spherical, high-energy emission zone of radius R moving relativistically along the blazar jet with bulk Lorentz factor Γ . The radius is constrained by the fastest observed variability via $R \leq R_{\max} = \frac{t_{\text{obs, min}} c \delta}{(1+z)}$.

The blob contains high-energy electrons, and a tangled magnetic field of constant magnitude B . The electrons in the blob are distributed isotropically and have a Doppler factor δ , where $\delta = \frac{1}{\Gamma(1 - \beta \cos \theta)}$, Γ is the blob's bulk Lorentz factor, β is the blob's velocity, and θ is the angle between the jet axis and the line of sight. In the blob frame, the electron energy distribution (EED) is a broken powerlaw,

$$N_e(\gamma) = \begin{cases} K\gamma^{-n_1} & \gamma_{\min} \leq \gamma \leq \gamma_{\text{break}} \\ N_e^{(2)}\gamma^{-n_2} & \gamma_{\text{break}} \leq \gamma \leq \gamma_{\max} \end{cases}, \quad (3.1)$$

where γ refers to the Lorentz factors of the particles $\gamma = \frac{E}{mc^2}$, $K \equiv N_e(1)$, and $N_e^{(2)} \equiv K\gamma_{\text{break}}^{n_2-n_1}$. Additional constraints are built in such that $\gamma_{\min} < \gamma_{\text{break}} < \gamma_{\max}$, and $n_2 > n_1$. In the one-zone synchrotron-self-Compton (SSC) model, the blob's radiation is the sole radiation considered.

Specifically, `Bjet_MCMC v1.1.0` (Hervet et al., 2024)¹ is used to fit a SSC model to State A (2012), State B (2020), and State C (2024). The observation dates composing each state are given in Table 2.1.

3.1 Overview of States

The states are described in Section 2.1. `Bjet_MCMC` is to be used with a period of time over which the SED is approximately steady; in addition, uncertainties on

¹Main branch cloned on 2025 March 14

the fluxes should capture any variability of the source over the period of interest (Hervet et al., 2024). Both of these points are discussed in Chapter 2.

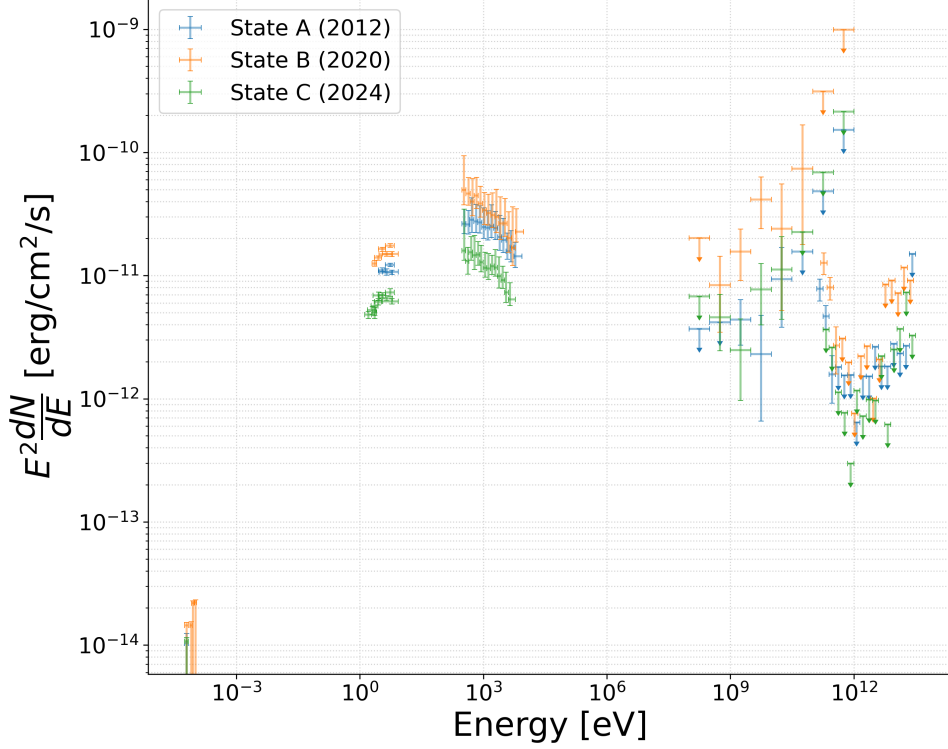


Figure 3.1: MWL SEDs for State A, State B, and State C.

Figure 3.1 shows the MWL SEDs for each of the states. State B has the highest flux at all wavelengths. State B is a higher state, and State A and State C are lower states. In radio, State C has a slightly higher flux than State A; however, the uncertainty on State A is larger. In optical, UV, and X-ray, State C has the lowest (synchrotron) flux. In high-energy (*Fermi*-LAT), within uncertainties, the fluxes of State A and State C agree. The VHE fluxes of State C are all ULs,

which can be seen more clearly in Figure 2.12. This makes definitive statements difficult. Debatably, the VHE flux of State C is lower than the VHE flux of State A.

3.2 Bjet_MCMC Configuration

The fluxes are obtained as described in Chapter 2. `Bjet_MCMC` models the intrinsic blazar emission, and `Bjet_MCMC` removes the attenuation of the SED due to extragalactic background light (EBL) absorption using the model of Franceschini & Rodighiero (2017). Thus, Sections 2.2 and 2.3 describe the observed high-energy and VHE emission only, and Sections 2.4, 2.5, and 2.6 describe the analysis leading to the intrinsic emission. As required by the `Bjet_MCMC` data format², upper limit fluxes are determined at the 95% confidence level.

The cosmology, viewing angle, and redshift are fixed as follows. The default `Bjet_MCMC` cosmology is used: flat Λ CDM, $H_0 = 69.9$ km/s/Mpc, $\Omega_M = 0.286$, and $\Omega_\Lambda = 0.714$ (Bennett et al., 2014). At the time of writing, there is no known viewing angle of 1ES 0647+250, so the `Bjet_MCMC` default 0.57° is used. Lastly, the redshift is set to $z = 0.45$ from Meisner & Romani (2010), calculated by treating the host galaxy as a standard candle.

A SSC model is considered for 1ES 0647+250 because SSC models typically fit

²https://bjet-mcmc.readthedocs.io/en/latest/data_format.html

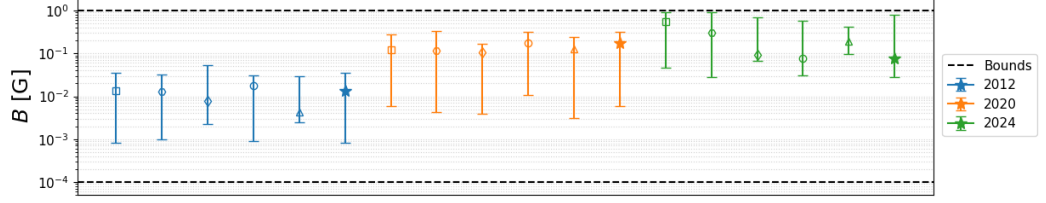
the SEDs of HBLs (see e.g. Hervet et al. (2024)). Parameters $K, n_1, n_2, \gamma_{\min}, \gamma_{\text{break}}$ and $\gamma_{\max}$ describe the EED (Equation 3.1), and δ, R , and B describe the blob. The parameters are further described in Table 1 of Hervet et al. (2024). The default parameter boundaries (found in Table 1 of Hervet et al. (2024)) are used and are shown explicitly in Figure 3.2. For the fastest observed variability, a 95% CL derived from *Swift*-XRT data is used, as described in Section 2.4.3.

3.3 SSC Model with All Parameters Freed

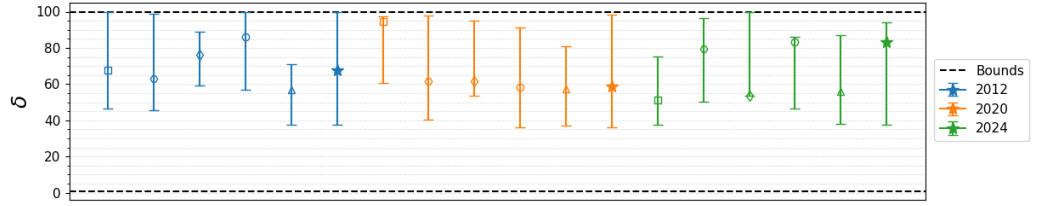
Initially, each state is modeled five times with `Bjet_MCMC` with all nine SSC parameters free. Each result is a possible solution, not a unique solution. The recommended³ ratio of number of steps to number of walkers, 120, is used such that there are 4800 steps and 40 walkers. Additionally, the first 200 steps are discarded in the burn phase.

The initial guess of each parameter is selected randomly by `Bjet_MCMC`. For each state, five identical jobs were submitted in order to incorporate the potential impact of this randomness. The five MCMC chains are concatenated (excluding the burn phase of each), and the concatenated chains are used to evaluate the best parameters and the SED. The concatenated result is created by concatenating the output (the MCMC chain, saved as “backend.h5” by `Bjet_MCMC`) of the five

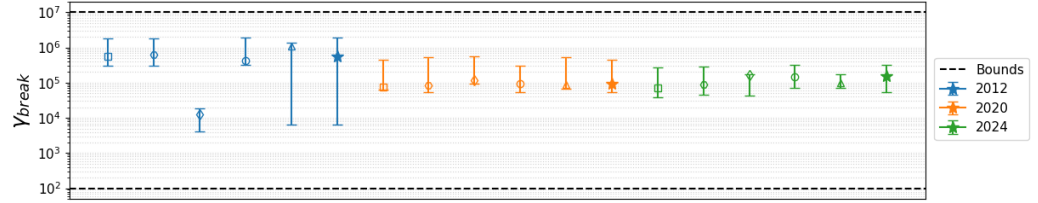
³<https://bjet-mcmc.readthedocs.io/en/latest/optimization.html>



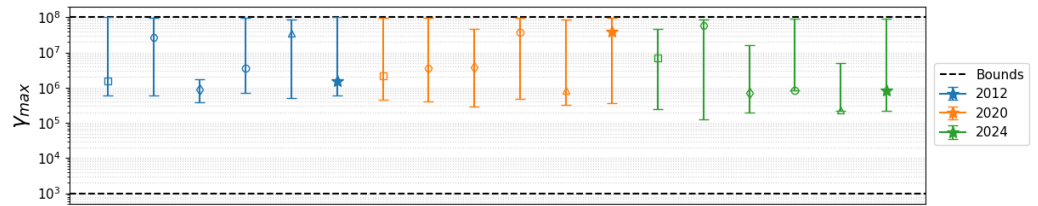
(a) Best fit values for blob magnetic field strength B .



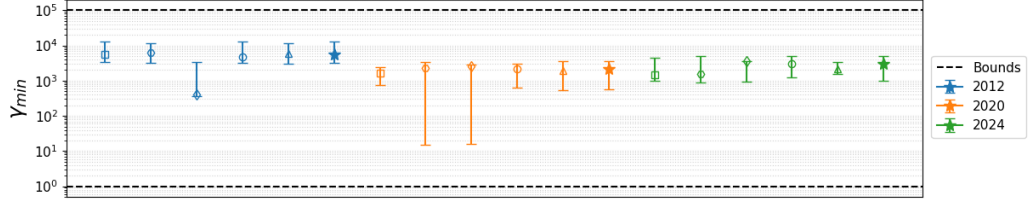
(b) Best fit values for blob Doppler factor δ .



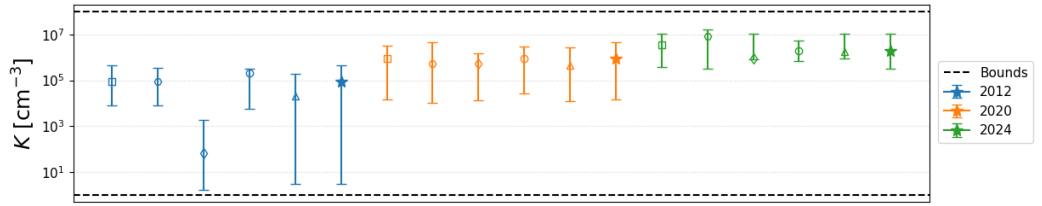
(c) Best fit values for electron distribution break energy γ_{break} .



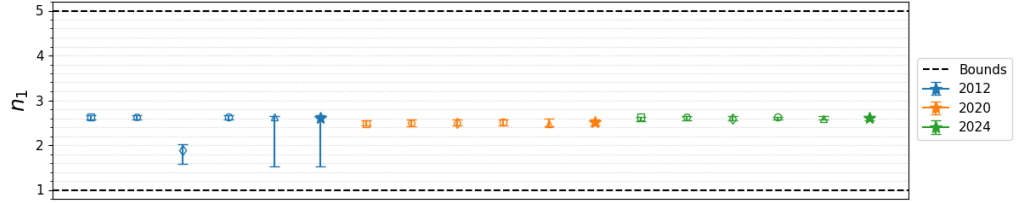
(d) Best fit values for electron distribution maximum energy γ_{max} .



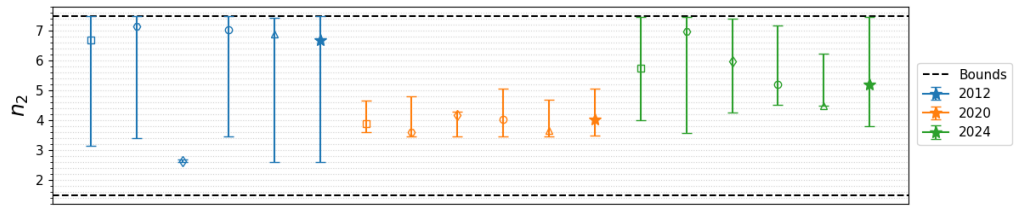
(e) Best fit values for electron distribution minimum energy γ_{min} .



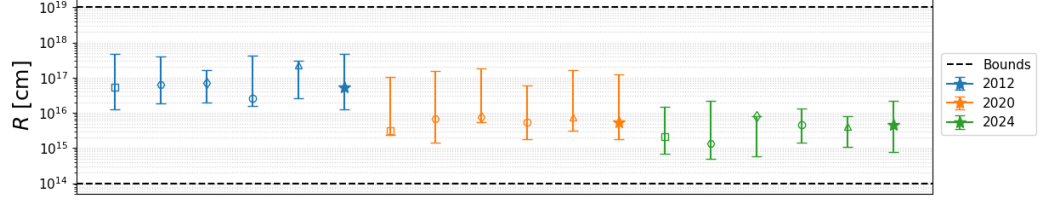
(f) Best fit values for electron distribution normalization K .



(g) Best fit values for electron distribution index below the break energy n_1 .



(h) Best fit values for electron distribution index above the break energy n_2 .



(i) Best fit values for radius of the blob R .

Figure 3.2: Parameter best fits from the five jobs with all parameters freed (un-filled markers) and the concatenated result (filled markers), for State A (blue), State B (orange), and State C (green). Dashed lines indicate the Bjet_MCMC parameter boundaries.

Parameter	Unit	State A	State B	State C
B	$\log_{10} \text{ G}$	$-1.88^{+0.42}_{-1.21}$	$-0.76^{+0.26}_{-1.47}$	$-1.12^{+1.03}_{-0.43}$
δ		$67.50^{+32.46}_{-29.84}$	$58.53^{+39.62}_{-22.31}$	$83.08^{+10.83}_{-45.63}$
γ_{break}	$\log_{10}$	$5.75^{+0.53}_{-1.95}$	$4.97^{+0.67}_{-0.24}$	$5.18^{+0.32}_{-0.45}$
γ_{max}	$\log_{10}$	$6.18^{+1.82}_{-0.41}$	$7.59^{+0.41}_{-2.03}$	$5.93^{+2.02}_{-0.58}$
γ_{min}	$\log_{10}$	$3.75^{+0.38}_{-0.24}$	$3.34^{+0.21}_{-0.59}$	$3.48^{+0.23}_{-0.48}$
K	$\log_{10} \text{ cm}^{-3}$	$4.96^{+0.69}_{-4.49}$	$5.95^{+0.70}_{-1.77}$	$6.28^{+0.75}_{-0.79}$
n_1		$2.62^{+0.05}_{-1.09}$	$2.51^{+0.07}_{-0.08}$	$2.62^{+0.04}_{-0.05}$
n_2		$6.69^{+0.80}_{-4.10}$	$4.02^{+1.04}_{-0.55}$	$5.20^{+2.26}_{-1.40}$
R	$\log_{10} \text{ cm}$	$16.74^{+0.93}_{-0.64}$	$15.73^{+1.38}_{-0.48}$	$15.65^{+0.68}_{-0.76}$

Table 3.1: Bjet_MCMC SSC fit parameter results, with all parameters freed. These values correspond to the concatenated results in Figure 3.2.

jobs (excluding each burn phase) and using `get_best_log_prob_and_params` and `min_max_params_1sigma`. Hereafter, results derived from the five concatenated chains are referred to as the “concatenated results.” The best fit parameters for each state, including those for each of the five jobs as well as the concatenated results, are in Figure 3.2; the parameter values for the concatenated results are also listed in Table 3.1. The corresponding SEDs are in Figures 3.3, 3.4, and 3.5.

Note that the SED “ 1σ contours” from `Bjet_MCMC` are determined using what is called the “min-max method,” and are not exact contours, because exact contours are too computationally expensive. The MCMC chain stores the parameter values and the log probabilities $\ln P$, where $\ln P = -\frac{1}{2}\chi^2$. Using this information, the “min-max method” searches for extreme parameter values considering models within $< \Sigma$ of the global best χ^2 ($\chi_{\min}^2$), where $\Sigma = \chi_{\text{ppf}}^2(p = 0.682, k)$ is the 68.2% containment (percentile, or percent point function) of the distribution $\chi^2(k)$ where there are $k = 9$ free parameters in the SSC model in the SEDs in this section, and χ^2 is the usual deviation of the model from the data.⁴ Considering this subset of models, for each parameter, the model line (the SED) with the maximum parameter value is saved. The same is done for the minimum of each parameter. With nine free parameters, up to 18 unique models are considered. The contours are built from the absolute maximum and minimum of these model lines. Hereafter, the contours are referred to as “approximate 1σ contours” to emphasize that they

⁴github.com/Ohervet/Bjet_MCMC/blazar_mcmc.py#L276

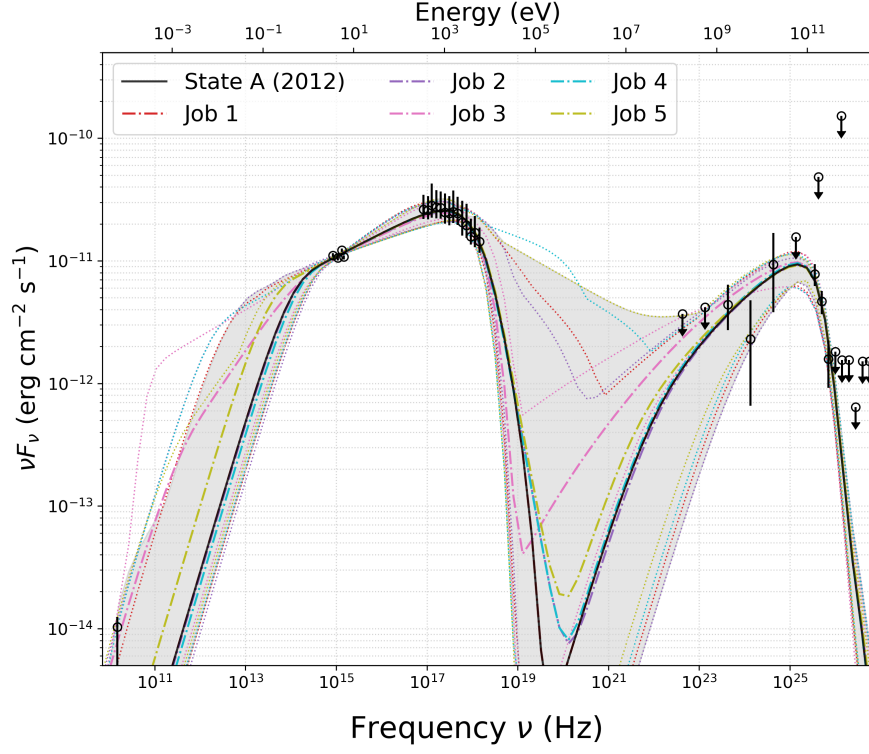


Figure 3.3: Best fit SEDs from the five jobs (in red, purple, pink, cyan, and olive) and the concatenated result (black) for State A (2012), with all parameters freed. The best fit of the concatenated result is a solid black line, and the approximate 1σ contour computed according to `Bjet_MCMC`'s min-max method is shaded. For the individual jobs, the best fit line is dashed-dotted, and the edges of the approximate 1σ contour are dotted (not shaded). Job 1 (red) corresponds to the rightmost point of the State A parameters in Figure 3.2 (the square markers), Job 2 corresponds to the next point (hexagon markers), and so on. The black line corresponds to the stars in Figure 3.2.

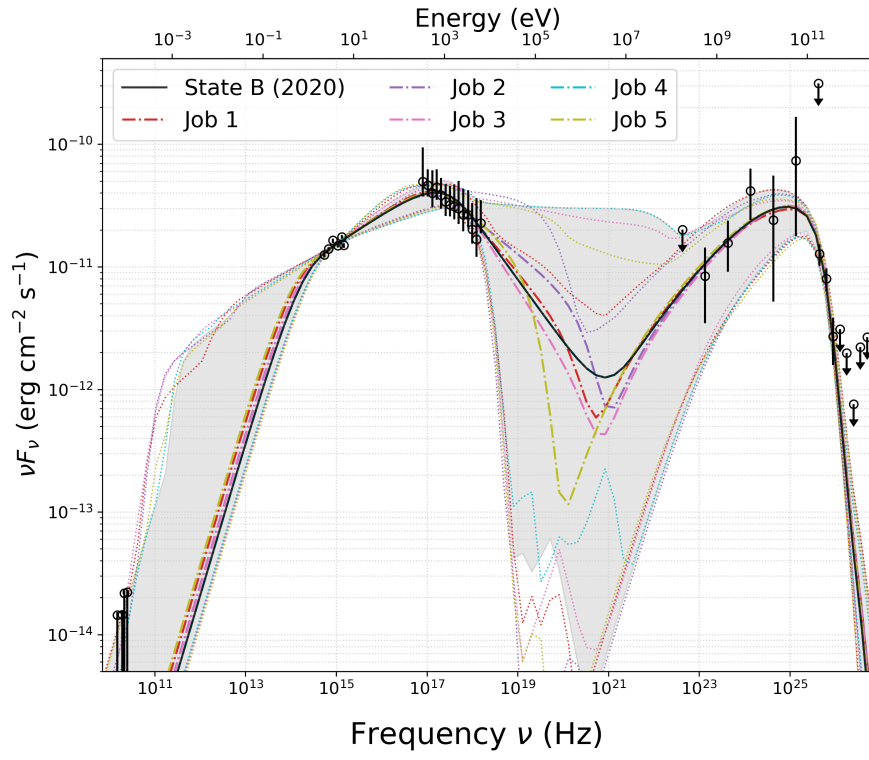


Figure 3.4: Same as Figure 3.3, but for State B.

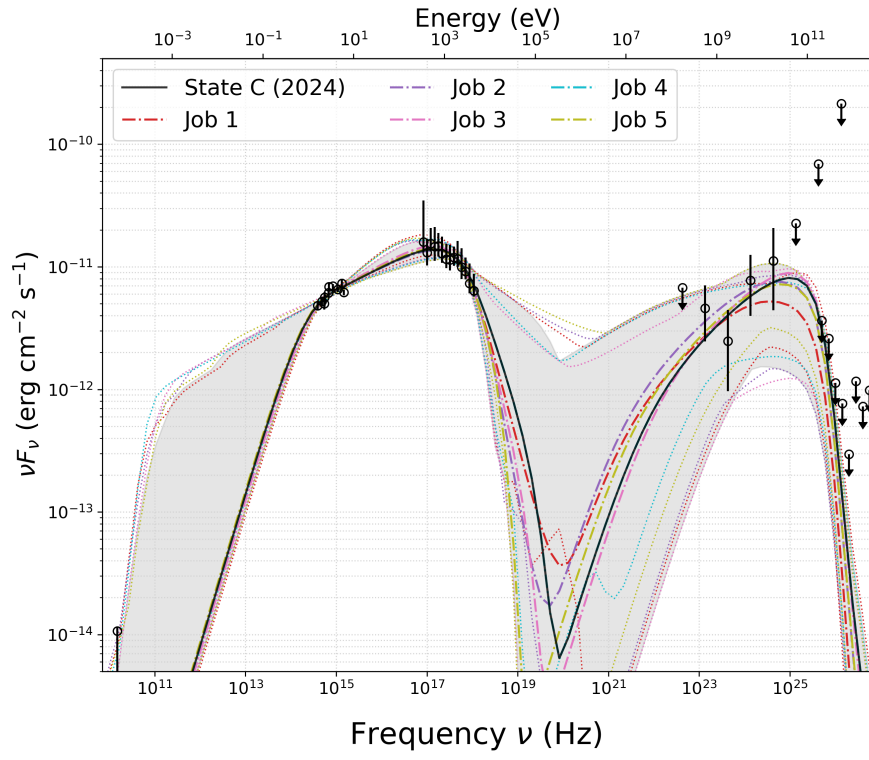


Figure 3.5: Same as Figure 3.3, but for State C.

are not exact contours.

The χ^2 values for the concatenated results are in Table 3.2, from which it can be inferred that a SSC model fits each state well.

Job	χ^2 (χ^2/dof)		
	State A	State B	State C
1	23.78 (0.70)	25.53 (0.67)	20.99 (0.54)
2	23.84 (0.70)	25.73 (0.68)	20.63 (0.53)
3	25.98 (0.76)	25.76 (0.68)	20.82 (0.53)
4	23.89 (0.70)	25.41 (0.67)	20.34 (0.52)
5	23.87 (0.70)	25.61 (0.67)	20.41 (0.52)
Concatenated result	23.78 (0.70)	25.41 (0.67)	20.34 (0.52)

Table 3.2: `Bjet_MCMC` χ^2 for each of the five jobs submitted and the concatenated results of each state. The reduced χ^2 is in parentheses. With nine free parameters, State A has 34 degrees of freedom (dof), State B has 38 dof, and State C has 39 dof.

The SEDs of each state are in Figure 3.6. Figure 3.6 shows that there is some sensitivity to the initial random guess of each parameter. But, in the case of State B and State C which are the most constraining datasets, the converged solutions for each parameter are consistent within uncertainties. However, in the case of State A, several parameters are inconsistent (within uncertainties) with at least one job: γ_{break} , K , n_1 , and n_2 . This highlights the degeneracy of the model. A smaller n_1 and n_2 (meaning a harder spectrum) can be compensated by, for example, a smaller K .

Figure 3.6 illustrates that the default `Bjet_MCMC` parameter boundaries are sensible for State A, State B, and State C. None of the parameter best fits are

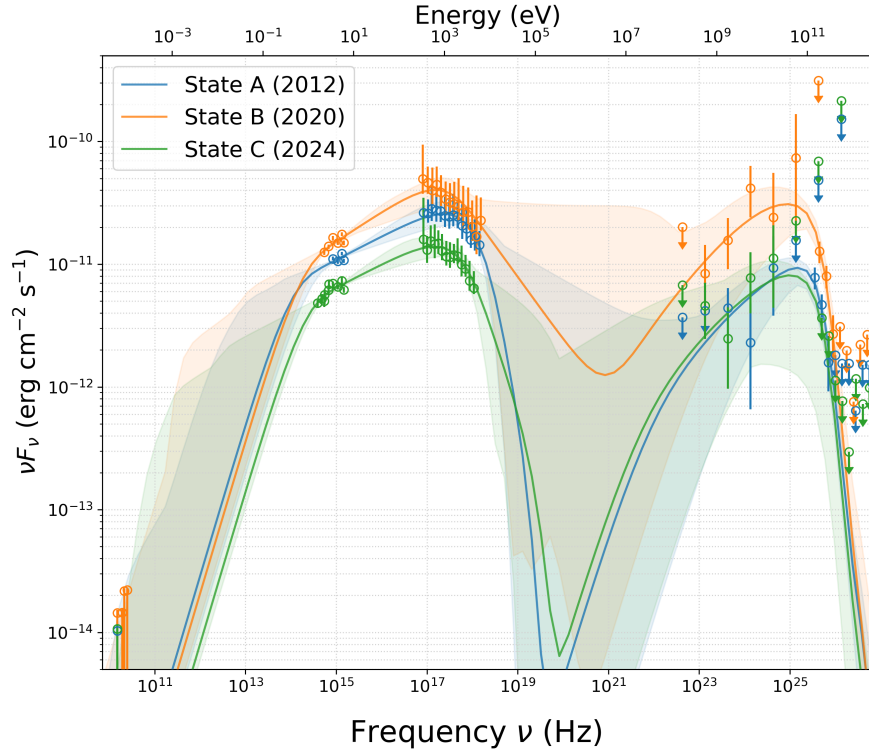


Figure 3.6: Best fit SEDs (the concatenated result) for each state: State A (blue), State B (orange), and State C (green). The shaded regions are the approximate 1σ contours computed according to `Bjet_MCMC`'s min-max method.

at a parameter boundary. For the parameters whose 1σ uncertainty extends to a boundary (the uncertainty on δ , $\gamma_{\max}$, and n_2 reaches the upper boundary), further increasing the boundary of these parameters is of little physical consequence or is constrained by physical reasons. Increasing the allowed upper boundary of $\gamma_{\max}$ is known to have a small impact on the SED because few electrons are at the highest energies (by virtue of Equation 3.1). Relatedly, increasing the upper range of n_2 creates a soft spectrum that effectively introduces a cutoff of $\gamma_{\max}$, so increasing it causes further degeneracies that are unlikely to improve the fit. Blazar SED modeling tends to adopt $\delta_{\max} = 100$ —see, e.g., Ghisellini et al. (2014). These authors specifically exclude $\delta < 1$ and $\delta > 100$ because they are regarded as extreme values. Population studies find average and median $\delta < 100$. Ghisellini et al. (1998) conduct MWL modeling of 51 gamma-ray-emitting blazars, and their modeling limits Doppler factors to ≤ 25 (consistent with observed superluminal motion), although the authors note that adequate fits can be achieved with $\delta \sim 100$. Zhang et al. (2020) estimate the Doppler factor of 350 *Fermi*-LAT blazars using the BLR luminosity and gamma-ray luminosity, and find that $\delta \leq 85.66$. As a last example, Löahtenmööaki & Valtaoja (1999) find $\delta < 100$ from radio data and an assumed maximum intrinsic brightness temperature and a calculated brightness temperature of a flare.

Although the SEDs in Figure 3.6 are markedly different, the parameters in

Figure 3.2 are in agreement, within uncertainties. Therefore, results are inconclusive as to which parameters can explain the change in the state of the blazar from State A to State B to State C. Section 3.4 describes a possible procedure for obtaining more definitive results.

3.4 Parameter Filtering

The large parameter uncertainties (given in Section 3.3) make statements about parameter differences between the State A, State B, and State C inconclusive, as evidenced by Figure 3.2 (specifically, the filled markers). However, the SEDs in Figure 3.1 are different; it appears that some physical properties have changed to cause these changes in the SEDs. In order to identify key parameters and determine if a simpler model can satisfactorily fit the data, a “parameter filtering” method is implemented using a likelihood ratio test ($\Delta\chi^2$ test) (Wilks, 1938) with nested models. An n -free parameter model (the null hypothesis) is compared to an $(n + 1)$ -free parameter model (the alternate hypothesis) using the likelihood ratio

$$\Delta\chi^2 = \chi_n^2 - \chi_{n+1}^2, \quad (3.2)$$

where χ^2 is calculated by `Bjet_MCMC` and $\Delta\chi^2$ follows a chi-squared distribution with degrees of freedom $\text{dof}_\Delta = \text{dof}_n - \text{dof}_{n+1} = (p - n) - (p - (n + 1)) = 1$ where p is the number of data points (see, e.g. Campos et al. (2023)). The number of free parameters n is increased (from $n = 1$) until the improvement in the fit is insignificant; that is, until $\Delta\chi^2 \lesssim 1$, because $\chi^2_{\text{pdf}}(0.682, \text{dof} = 1) \approx 1$. The method is summarized in Figures 3.7 and 3.8 and described below. State B is the state with the smallest uncertainties on the data points; for this reason, fits to State A and State C are conducted with parameter values frozen to those of State B (specifically, the concatenated results, the “State B” column of Table 3.1).

Firstly, fits with one free parameter ($n = 1$) are performed for each of the nine SSC parameters. The fit with the best (lowest) χ^2 indicates that the corresponding free parameter has the largest impact on the fit (out of the fits considered). The resulting χ^2 for each free parameter is in Table 3.3 for State A and State C. In both cases, n_1 , the index of the electron spectrum below the break energy γ_{break} , results in the lowest χ^2 (compared to the other fits with one parameter free).

Next, fits with two free parameters ($n = 2$) are performed, where one of the free parameters is always n_1 . Table 3.4 shows the resulting χ^2 for each parameter combination. In the fits with two free parameters to State A and State C, the lowest χ^2 corresponds to the fit with n_1 and B free. This suggests that in both State A and State C, n_1 and B are key parameters and can play a dominant role

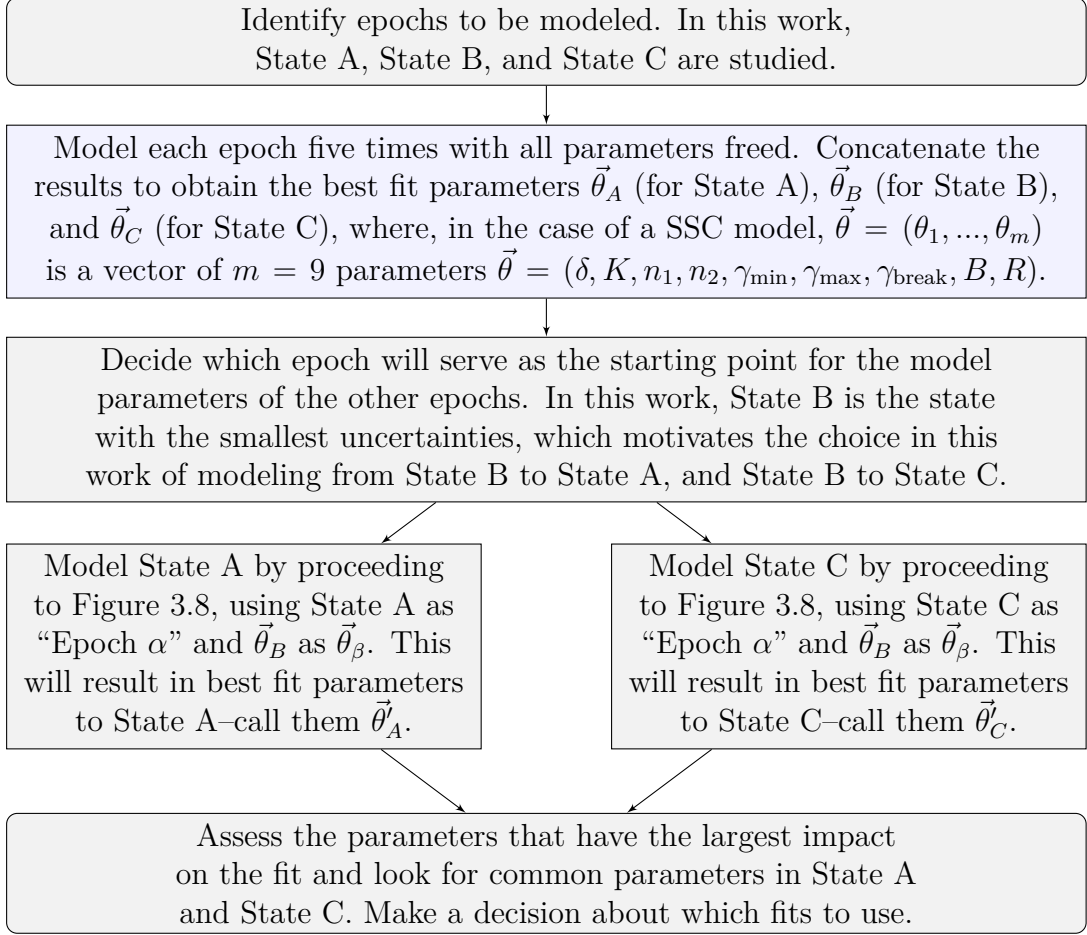


Figure 3.7: Flowchart for the `Bjet_MCMC` modeling procedure implemented in this work. This flowchart assumes three epochs: State A, State B, and State C. Blue shaded boxes indicate `Bjet_MCMC` modeling. This procedure is not intended to be definitive; users must apply their own judgment when using `Bjet_MCMC`, which was done in this work; as discussed in Section 3.4, n_1 and B were found to have the largest impact on the fits to State A and State C, so the choice was made to utilize fits with n_1 and B free.

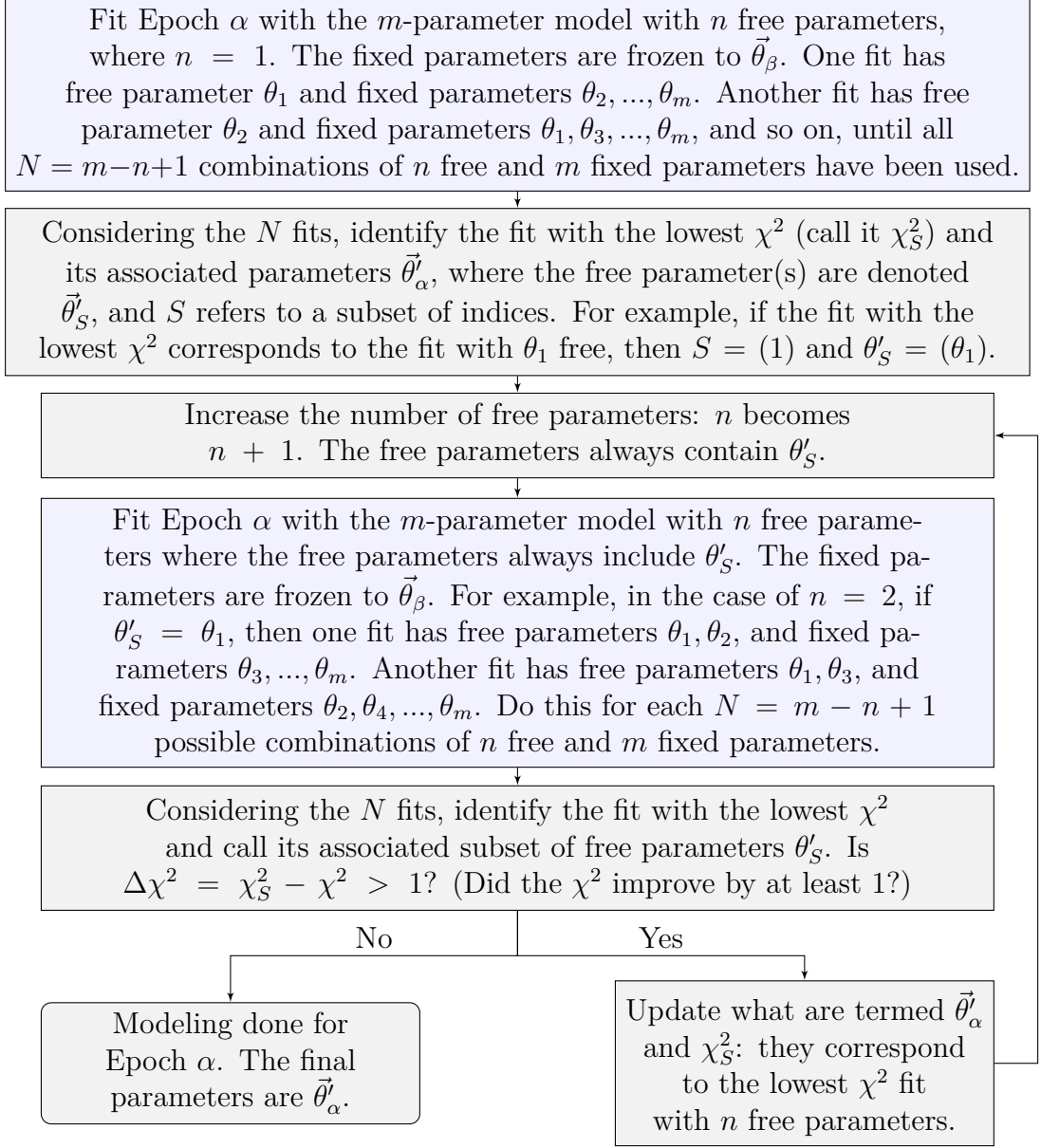


Figure 3.8: Flowchart for **Bjet_MCMC** modeling procedure for one epoch, Epoch α , which is a dataset that will be fit with an m -parameter model. θ_β is a vector of parameters $\vec{\theta} = (\theta_1, \dots, \theta_m)$ that was derived from **Bjet_MCMC** fits to Epoch β (distinct from Epoch α). n is the number of free parameters. Blue shaded boxes indicate **Bjet_MCMC** modeling.

Free parameter	χ^2 (χ^2/dof)	
	State A	State C
B	125.55 (2.99)	33.08 (0.70)
δ	115.92 (2.76)	34.02 (0.72)
γ_{break}	432.33 (10.29)	683.8 (14.55)
γ_{max}	1037.68 (24.71)	5992.7 (127.50)
γ_{min}	291.12 (6.93)	875.63 (18.63)
K	49.83 (1.19)	34.66 (0.74)
n_1	45.3 (1.08)	23.56 (0.50)
n_2	1007.00 (23.98)	6009.27 (127.86)
R	92.46 (2.20)	33.28 (0.71)

Table 3.3: χ^2 for fits to State A and State C with one parameter free. The reduced χ^2 is in parentheses. Fixed parameters for State A, State B, and State C are frozen to State B results with all parameters freed, i.e., the “State B” column of Table 3.1. Bold text indicates the best χ^2 . With one free parameter, State A has 42 dof and State C has 47 dof.

in the change of state.

Free parameters		χ^2 (χ^2/dof)		
		State A	State B	State C
B	n_1	32.04 (0.78)	23.55 (0.56)	21.62 (0.47)
δ	n_1	32.51 (0.79)	-	21.99 (0.48)
γ_{break}	n_1	44.82 (1.09)	-	23.53 (0.51)
γ_{max}	n_1	45.17 (1.10)	-	23.15 (0.50)
γ_{min}	n_1	39.24 (0.96)	-	23.28 (0.51)
K	n_1	45.14 (1.10)	-	23.46 (0.51)
n_2	n_1	44.88 (1.09)	-	23.40 (0.51)
R	n_1	35.50 (0.87)	-	23.01 (0.50)

Table 3.4: Same as Table 3.3 but for fits with two free parameters. With two free parameters, State A has 41 dof, State B has 45 dof, and State C has 46 dof. A dash indicates that the fits with the corresponding set of free parameters were not conducted.

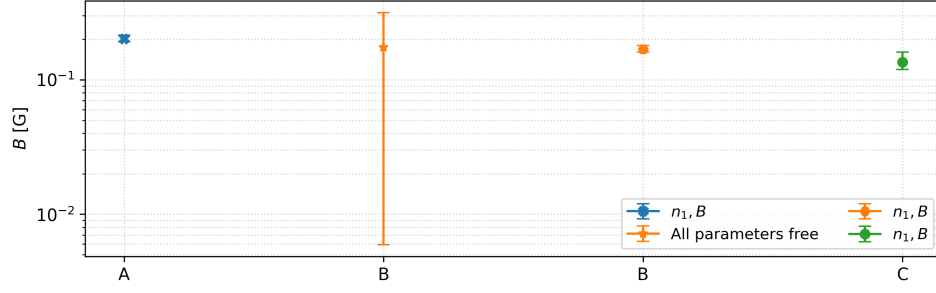
Fits to State C with three free parameters (two of which are always n_1 and

B) did not result in any χ^2 improving by > 1 (compared to $\chi^2 = 21.62$ from the fit with n_1 and B free), so the results with three parameters are not shown or considered in this work.

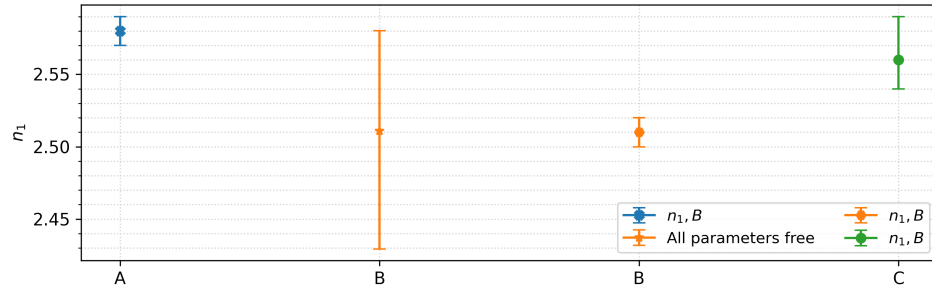
The fit to State A with three free parameters n_1 , B , and γ_{break} improves the χ^2 by 1.08 ($\chi^2 = 30.96$ with n_1 , B , and γ_{break} free, compared to $\chi^2 = 32.04$ with n_1 and B free). Combined with the fact that an improvement in χ^2 of 1.08 is only marginally better than 1, and the reduced χ^2 of the fit with n_1 and B free is 0.78, which indicates a satisfactory fit, the choice is made to examine the results of n_1 and B free. These are the results presented in Chapter 4.

When comparing the fits of State A and State C with n_1 and B free to those of State B with all parameters free, the large uncertainties on State B still make for inconclusive results. This is shown in Figure 3.9.

Motivated by a search for the simplest scenario that can be applied to State A, State B, and State C, and to derive uncertainties on n_1 and B in fits to State B under the same conditions as State A and State C, a fit to State B is performed with n_1 and B free (with the remaining parameters fixed to the concatenated results of State B). The results are shown in Figure 3.9, and the reduced uncertainties of the fit to State B with two free parameters (rather than nine) are evident. This too highlights the degeneracy of the model—extreme values of one parameter can be compensated by extreme values of another, degenerate



(a) Best fit values to magnetic field strength B .



(b) Best fit values to electron index below the break energy n_1 .

Figure 3.9: Parameter best fits for State A with n_1 and B free (blue), State B with all parameters free (orange star), State B with n_1 and B free (orange hexagon), and State C with n_1 and B free (green).

parameter. Table 3.4 includes the resulting χ^2 ; the reduced χ^2 of 0.56 indicates a satisfactory fit to State B with n_1 and B free. Therefore, the choice is made to frame the physical interpretation of Chapter 4 around the results of fits to State A, State B, and State C with n_1 and B free, and seven fixed parameters frozen to the values of the concatenated results of State B with all parameters free.

Results of this modeling are given and discussed in Chapter 4.

Chapter 4

Results and Discussion

This chapter describes `Bjet_MCMC` results corresponding to SSC fits with n_1 (index of the blob’s electron distribution before the break energy—see Equation 3.1) and B (magnetic field strength in the emitting region) free in State A (a lower state), State B (a higher state), and State C (a lower state), and the remaining parameters fixed to the concatenated results of State B. In this chapter, electron Lorentz factor γ is used interchangeably with electron energy E_e because $\gamma = \frac{E_e}{m_e c^2}$ where m_e is the electron mass. The `Bjet_MCMC` parameters for State A are denoted with a subscript A ($n_{1,A}$ and B_A), those for State B are denoted with a subscript B , and those for State C are denoted with a subscript C .

4.1 Overview of Relevant Parameters

In a SSC model, the magnetic field B is presumed to already exist in the emitting region, and there are no assumptions about the drivers of the electron energy distribution (EED; Equation 3.1) parameters. Tavecchio et al. (1998) use a SSC model with electrons distributed according to a broken powerlaw (as does `Bjet_MCMC`) to derive relationships between physical parameters of TeV blazars; in this framework, the dominant synchrotron power is typically emitted by electrons with energy $\gamma \approx \gamma_{\text{break}}$, and the energy of the electrons that dominate the IC emission depends on the energy of the (incident) photon in the electron rest frame E'_{ph} , which defines the Thomson regime ($E'_{\text{ph}} \ll m_e c^2$) and the Klein-Nishina regime ($E'_{\text{ph}} \gg m_e c^2$). E'_{ph} depends on the electron Lorentz factor γ and speed β , where $E'_{\text{ph}} = \gamma E_{\text{ph}}(1 - \beta \cos \theta) = \gamma E_{\text{ph}}(1 + \beta)$ in the case of a head-on collision (in which the angle between the electron velocity and photon velocity $\theta = \pi$). Therefore, an interaction in the Klein-Nishina regime can occur with a sufficiently high-energy electron (high γ) or a sufficiently high-energy photon (high E_{ph}); this is shown in Figure 4.1. In the Thomson regime, in SSC models, the dominant IC flux is often emitted by electrons with $\gamma \approx \gamma_{\text{break}}$. In the Klein-Nishina regime, ICS is increasingly inefficient because the cross section decreases as E'_{ph} increases (see, e.g., Tavecchio et al. (1998) and Aharonian (2004)). For TeV BL Lacs, it is important

to consider Klein-Nishina effects (Tavecchio et al., 1998). In the SSC framework, the synchrotron photons are the seed photons for inverse Compton scattering. Therefore, E_{ph} is the synchrotron photon energy, and γ is the electron energy (from the EED, Equation 3.1). In a blazar SED, the prominence of the Klein-Nishina regime manifests as a reduced IC peak compared to the Thomson regime prediction (see, e.g., Hervet, O. et al. (2015); Kino et al. (2002)). The synchrotron photons can also be absorbed by the electrons in a process called synchrotron self-absorption. The absorption coefficient for this process sharply decreases as the photon frequency ν_{ph} increases, such that the lowest-energy synchrotron photons are absorbed and therefore do not escape the “blob”; this typically occurs at radio energies (see, e.g., Kino et al. (2002) Figure 1).

The EED spectral index n_1 and the magnetic field B can be degenerate because both can impact the production of synchrotron photons. A decrease in solely n_1 (with all other EED parameters in Equation 3.1 fixed) produces a harder EED, which increases the relative number of electrons with energy $\approx \gamma_{\text{break}}$, which creates more synchrotron photons near the synchrotron peak. An increase in solely B can achieve a similar effect by increasing the synchrotron power $P \propto B^2 \gamma^2$ (see, e.g., Rybicki & Lightman (1979)). An increase in the synchrotron emission tends to increase the IC emission. When all other SSC parameters are fixed, n_1 more strongly impacts the slopes of the synchrotron and IC emission, and B impacts

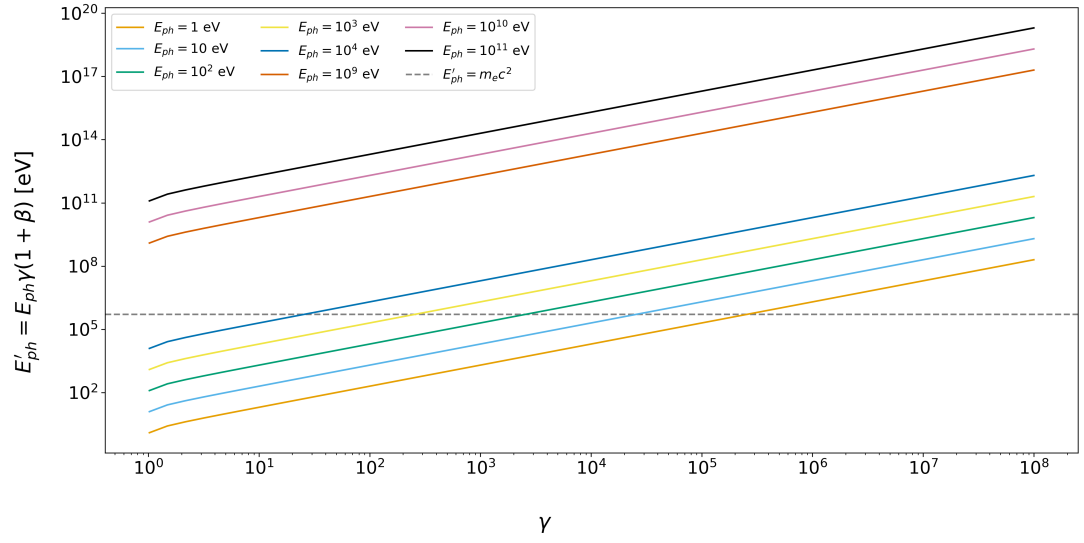


Figure 4.1: The Thomson regime ($E'_{\text{ph}} \ll m_e c^2$) and the Klein-Nishina regime ($E'_{\text{ph}} \gg m_e c^2$) are separated by $E'_{\text{ph}} = m_e c^2$ (dotted gray line). The solid lines show the photon energy in the electron frame E'_{ph} for various photon energies E_{ph} , as a function of the electron Lorentz factor $\gamma = (1 - \beta^2)^{-1/2}$, for a head-on collision where $E'_{\text{ph}} = E_{\text{ph}} \gamma (1 + \beta)$.

the synchrotron peak and therefore the IC peak.

4.2 SSC Model and Implications

The SEDs of State A, State B, and State C with n_1 and B free are in Figure 4.2; the associated parameters are in Figure 4.3 and Table 4.1.

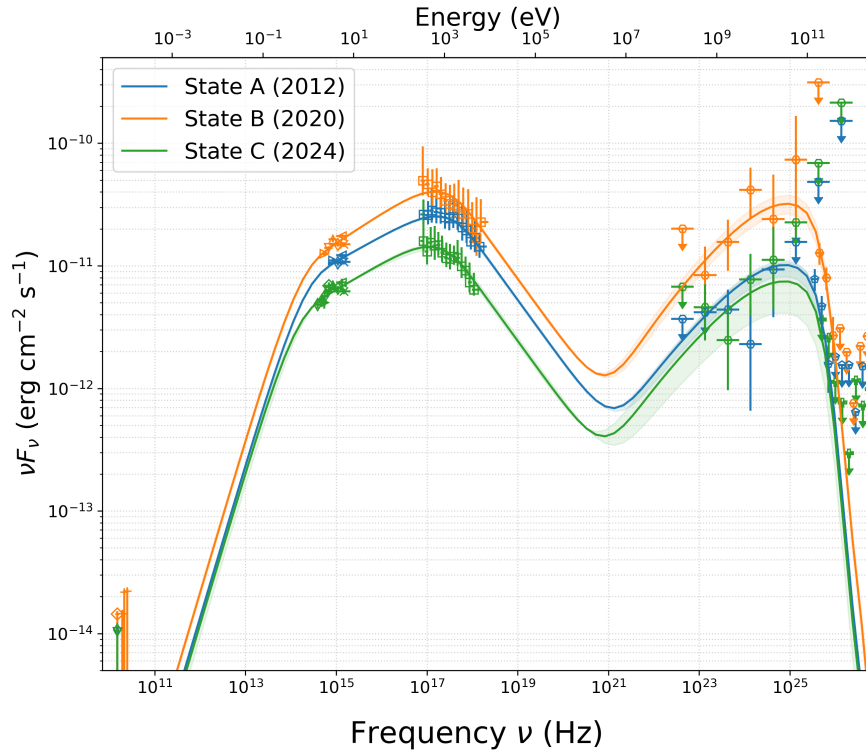
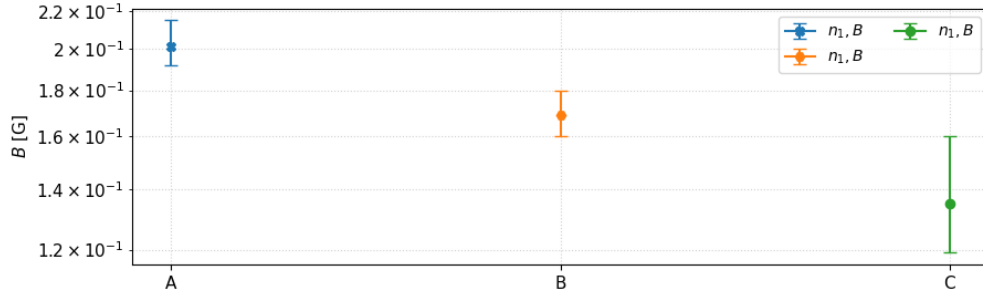


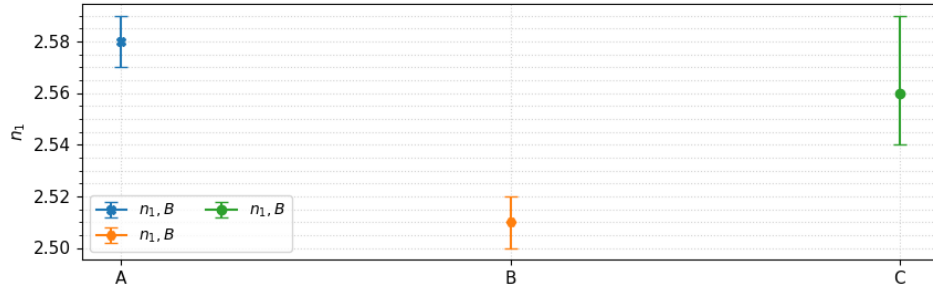
Figure 4.2: Best fit SEDs to State A (2012; blue), State B (2020; orange), and State C (2024; green), with n_1 and B free. These approximate 1σ contours were made with $\chi^2_{\text{ppf}}(k=2)$ because there are $k=2$ free parameters.

a data-driven constraint (e.g., the synchrotron peak).

As can be seen in Figure 4.2, the highest synchrotron flux is that of State



(a) Best fit values to magnetic field strength B .



(b) Best fit values to electron index below the break energy n_1 .

Figure 4.3: Results of fits to State A (blue), State B (orange), and State C (green) with n_1 and B free.

Parameter	Unit	State A	State B	State C
B	$\log_{10} \text{ G}$	$-0.70^{+0.03}_{-0.02}$	$-0.77^{+0.03}_{-0.02}$	$-0.87^{+0.04}_{-0.05}$
n_1		$2.58^{+0.01}_{-0.01}$	$2.51^{+0.01}_{-0.01}$	$2.56^{+0.04}_{-0.02}$
δ			58.53	
γ_{break}	$\log_{10}$		4.97	
γ_{max}	$\log_{10}$		7.59	
γ_{min}	$\log_{10}$		3.34	
K	$\log_{10} \text{ cm}^{-3}$		5.95	
n_2			4.02	
R	$\log_{10} \text{ cm}$		15.73	

Table 4.1: **Bjet_MCMC** SSC fit parameter results with n_1 and B free. The other parameters are fixed to the best fit values for State B. The remaining parameters are fixed to those of State B with all parameters free and are included in this table for reference.

B. This could be caused by an increase in B or a decrease in n_1 (hardening of the EED). Indeed, although State B does not have the strongest magnetic field strength B , State B has the smallest n_1 (see Figure 4.3 and Table 4.1). That State A has a higher synchrotron flux than State C (both of which are low states) can be attributed to a stronger magnetic field during State A, which is seen in Figure 4.3. Figure 4.3 shows that State B has the hardest spectrum (lowest n_1). The corresponding electron spectra are in Figure 4.4. Because the normalization K (which is fixed) is defined at $\gamma = 1$ (the minimum allowed γ), there are more electrons per energy for all energies in the State B EED, as is shown in Figure 4.4.

The corner plots for the MCMC fits are in Figures 4.5-4.7. The best parameter

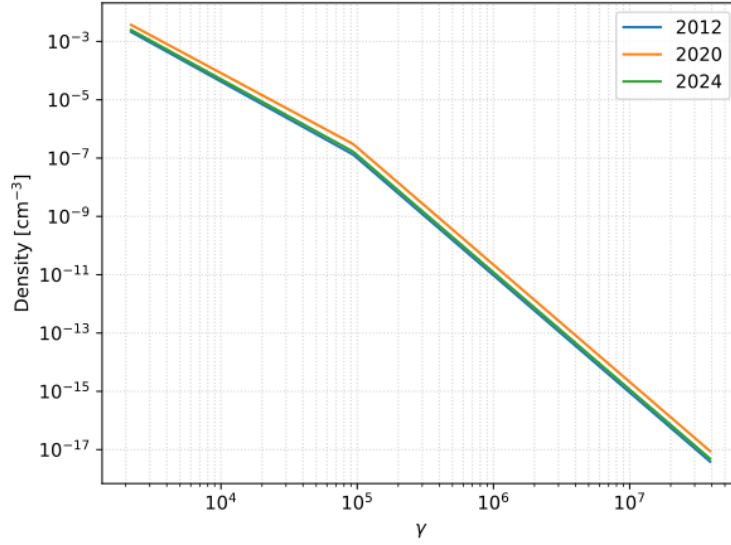


Figure 4.4: EED for State A (2012; blue), State B (2020; orange), and State C (2024; green), with n_1 and B free. The normalization K is the same for each state, although this is only visible at $\gamma = 1$ because $K \equiv N_e(1)$ where $N_e(\gamma)$ is given by Equation 3.1.

is determined from the global best χ^2 of the walkers and steps, which is not necessarily the peak of the posterior/likelihood distribution. In Figures 4.5-4.7, however, it is.

Additional quantities derived from the best-fit model are in Table 4.2. Recall that τ_{95} , which is used as an upper limit on the size of the emitting region $R_{\max}$ (Section 2.4.3), is different for each state. Each $R_{\max}$ is larger than the fixed $\log_{10}(R/\text{cm}) = 15.73$. For each state, Table 4.2 also gives the Lorentz factor at which the escape time equals the synchrotron cooling time. Using $\mu_0 = 1$ units,

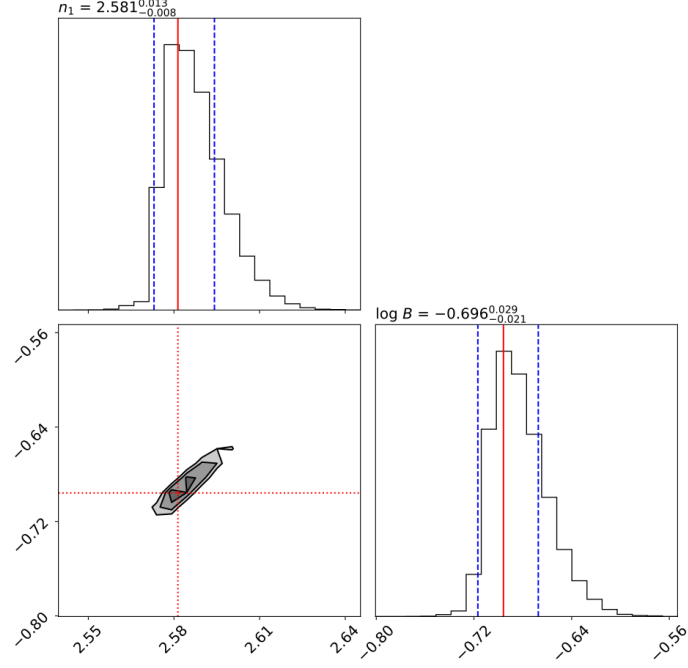


Figure 4.5: Corner plot for State A. The histograms show the likelihood profile—the number of walkers (including all steps aside from the burn phase) in each parameter bin. The red line is the best fit value. The dashed blue lines indicate $\pm 1\sigma$. The dotted red lines on the corner plot indicate the best fit values. The shaded contours show the `corner.py` defaults: the 0.118, 0.393, 0.675, and 0.864 confidence levels (corresponding to the 0.5σ , 1σ , 1.5σ , and 2σ confidence levels of a 2D Gaussian). The 0.118 confidence region is so small it does not appear on the plot.

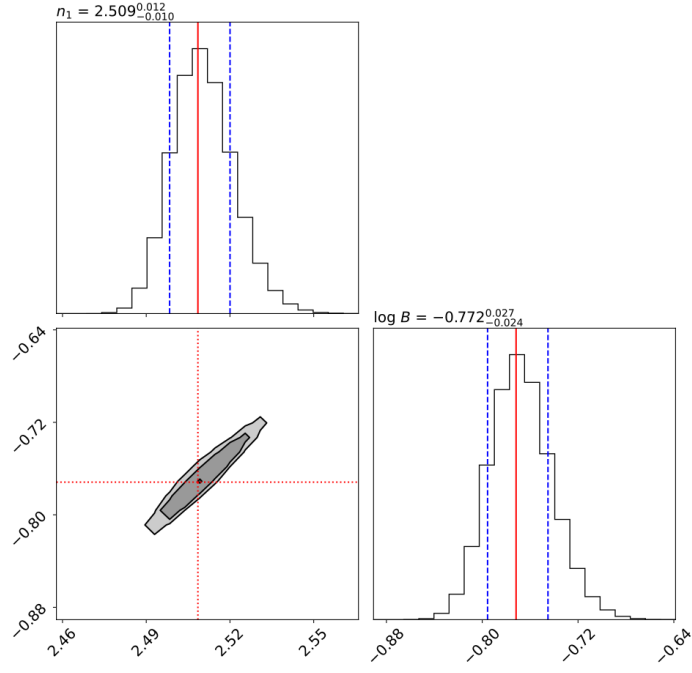


Figure 4.6: Same as Figure 4.5, but for State B.

this is

$$\gamma_c = \frac{3\pi m_e c^2}{\sigma_T B^2 R}, \quad (4.1)$$

where σ_T is the Thomson cross section (see, e.g., Abdo et al. (2011)). Above γ_c , the synchrotron cooling time is shorter than the escape time, and the electrons cool significantly (lose a significant amount of energy) before escaping. For all states, $\gamma_{\text{break}} \simeq \gamma_c$ (within an order of magnitude). Therefore, the break in the EED γ_{break} may potentially be due to electron cooling. Recall that `Bjet_MCMC` is a stationary model in which it is assumed the particle injection mechanisms are in equilibrium with the cooling processes (Hervet et al., 2024); γ_{break} is a fit

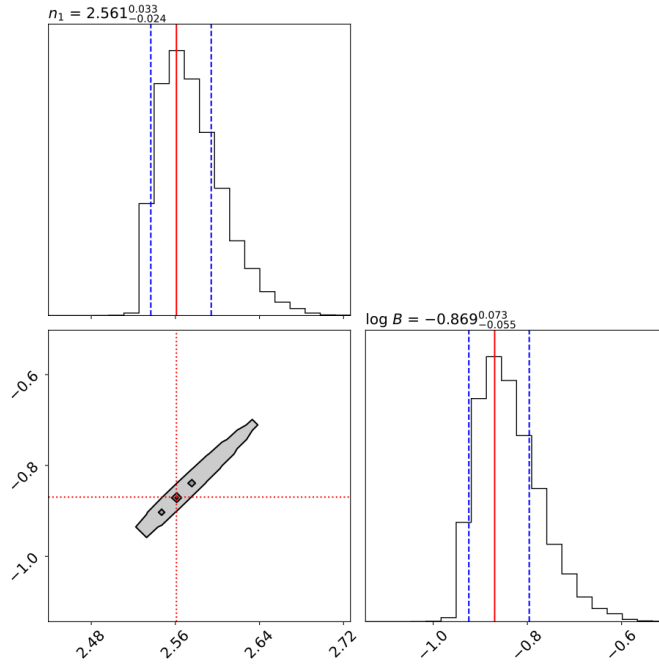


Figure 4.7: Same as Figure 4.5, but for State C.

parameter and is not derived from γ_c . Lastly, Table 4.2 contains the magnetic energy density U_B and electron density U_e (in the blob frame); these quantities are output from `Bjet_MCMC`. Each state is particle dominated ($U_B < U_e$), which is typical of BL Lacs (Tavecchio & Ghisellini, 2015).

Some sample values for SSC parameters fit to BL Lacs in Tavecchio et al. (2010) are given in Table 4.3. With the exception of n_1 and δ , the parameters in Table 4.1 are consistent with the sample from Tavecchio et al. (2010). The values of n_1 (free for each state) and δ (fixed to 58.53 from State B) are somewhat unusual, but not unheard of—see, e.g., Qin et al. (2018). Qin et al. (2018) examined 46 GeV-TeV BL Lacs and fit the SEDs with a one-zone SSC model (with the same

Parameter	Units	State A	State B	State C
$R_{\max}$	$\log_{10} \text{ cm}$	17.49	17.55	17.46
U_e	erg cm^{-3}	1.32×10^{-2}	2.55×10^{-2}	1.59×10^{-3}
U_B	erg cm^{-3}	1.62×10^{-3}	1.14×10^{-3}	7.26×10^{-4}
U_B/U_e		1.23×10^{-1}	4.47×10^{-2}	4.58×10^{-2}
γ_c	$\log_{10}$	5.53	5.67	5.87

Table 4.2: Derived quantities from the **Bjet_MCMC** fits. $R_{\max} = \frac{c\delta\tau_{95}}{1+z}$ is the upper limit on R imposed by causality, and τ_{95} is given in Table 2.5 for each state. The electron energy density U_e and magnetic energy density U_B in the blob frame are provided by **Bjet_MCMC**. γ_c is the Lorentz factor at which the escape time equals the synchrotron cooling time (Equation 4.1).

parameters as **Bjet_MCMC**) using MCMC methods. They find that the Doppler factors tend to be around 11.6, but 13 of the 46 objects have $\delta > 58.53$. They find that only a couple of objects are best fit with $n_1 > 2.51$ (the lowest n_1 in this work is $n_{1,B} = 2.51 \pm 0.01$); however, the majority of their n_2 values are harder than 4.02 (the fixed value of n_2 used in this work).

Parameter	Unit	Range from Tavecchio et al. (2010)	
		Low	High
B	$\log_{10} \text{ G}$	−3.30	0.30
n_1		1.8	2.3
δ		2.0	47.0
γ_{break}	$\log_{10}$	2.95	6.70
γ_{max}	$\log_{10}$	4.48	7.60
γ_{min}	$\log_{10}$	0.00	5.88
K	$\log_{10} \text{ cm}^{-3}$	2.28	5.98
n_2		3.1	4.9
R	$\log_{10} \text{ cm}$	15.00	16.78

Table 4.3: Sample SSC parameter values fit to BL Lacs detected at TeV and not detected at TeV (at the time of writing of Tavecchio et al. (2010)).

Degeneracies in the SSC model make a unique solution and interpretation impossible. The SSC parameters cannot definitively determine the acceleration mechanism (e.g., first-order Fermi acceleration at a shock front, see Abdo et al. (2011)). The solution presented in this work indicates that the SED fit is most sensitive to n_1 and B . The significance of the difference between the best fit parameters to each state is in Table 4.4. With the seven other SSC parameters fixed, n_1 and B differ by $< 3\sigma$ for each state, with the exception of the State A and State B n_1 . However, the largest difference is $n_{1,C} - n_{1,B} = 0.08$, which is not a very dramatic change in the EED (see Figure 4.4), so the acceleration process may be consistent at each of these snapshots. The fits to the snapshot SEDs of State A, State B, and State C prefer progressively smaller B when $\delta, K, n_2, \gamma_{\min}, \gamma_{\text{break}}, \gamma_{\max}$, and R are fixed. This is not definitive and unambiguous evidence that B evolved, due to the degeneracies in the model. But if it is interpreted in this framework, other works have attributed a decreasing B to the blob moving down the jet (e.g. Aleksić, J. et al. (2015)), where the magnetic field decrease is consistent with the evolution of the shock in the jet (Marscher & Gear, 1985; Romero et al., 1997).

The first long-term MWL study of 1ES 0647+250 is MAGIC Collaboration et al. (2023) (hereafter “M23”). M23 focuses on SED modeling of four VHE epochs of 1ES 0647+250 and extensive MWL correlation analysis. The authors test a one-zone SSC model and conclude that a one-zone model cannot reproduce

Parameter	States	Difference [σ]
n_1	State A & State B	5.0
	State A & State C	2.2
	State B & State C	0.6
B	State A & State B	2.3
	State A & State C	2.5
	State B & State C	0.2

Table 4.4: Significance of the difference between the best fit parameters to each state.

the radio emission, and so they fit the SEDs with a two-component model (two spherical emitting regions), where one component produces the X-ray and VHE emission, and the other component produces the radio and optical emission. The radio emission is not reproduced by the one-zone SSC model in this work (see, e.g., Figure 4.2); because the radio data are treated similarly to an upper limit, this is not in tension with the model lines in Figure 4.2. The radio data are treated similarly to an upper limit because they include contributions from the jet, whereas solely the blob is modeled by `Bjet_MCMC` (see Section 2.8 for more details). If M23 were to treat the radio data as an upper limit, their one-zone SSC fit is acceptable. Relevant to the work in this thesis is the M23 one-zone SSC model, which uses a homogeneous spherical blob with radius R , Lorentz factor Γ (which determines the Doppler factor through $\delta \sim \Gamma$), and magnetic field B , with

the electrons distributed according to a smoothly broken powerlaw,

$$k(\gamma) = k_1 \gamma^{-n_1} \left(1 + \frac{\gamma}{\gamma_{\text{break}}} \right)^{n_1 - n_2}, \quad \gamma_{\text{min}} \leq \gamma \leq \gamma_{\text{max}}. \quad (4.2)$$

State B (59196.0-59205.0 MJD) is approximately coincident with Epoch 4 (hereafter “E4,” as is done in M23) from 59198.0 to 59208.0 MJD. The datasets for State B and E4 are similar. The OVRO data are identical. The selected *Swift* and *Fermi*-LAT data have substantial overlap but are not identical, and the VHE facility data (VERITAS and MAGIC) have different observing dates, times, and cadence. M23 uses $z = 0.41$, whereas this work uses $z = 0.45$. The modeling results of M23 that are presented in Table 4.5 are from a visual fit and therefore do not have associated errors. The digitized best-fit SED from M23 is in Figure 4.8, which shows a sharp drop in the SED between the synchrotron and IC peaks compared to the fit to State B (which is a similar dataset). This is most likely caused by combinations of several parameters, such as the closeness of γ_{break} and γ_{max} . Shown also in Figure 4.8 is the State B SED. Recall that the fixed State B values were determined from State B fits (with all parameters free). The SEDs are somewhat compatible, but the best fit parameters (Table 4.5) differ significantly. This is in part due to the parameter degeneracies: dissimilar parameters can result in somewhat similar SEDs. Additionally, the fitting procedures are fundamentally different: M23 scans the parameter space by hand, whereas this

work uses `Bjet_MCMC` to explore the parameter space. It is not surprising that the parameters differ.

Regarding the long-term variability of 1ES 0647+250, M23 concludes that the MWL lightcurves (which cover the time period ~ 2009 -2021) are variable over long timescales. M23 note that the VHE flux in M23 is increasing; the VERITAS lightcurve presented in Figure 2.14 has different observing coverage than M23 and shows a generally increasing flux until ~ 2019 , when it decreases, and then increases again in 2020 (State B). M23 suggests that the long-term (timescales of years) variability could be associated with particle injection near the SMBH, rather than acceleration and cooling, which are typically thought to be the source of fast variability. The focus of this thesis is not long-term variability trends derived from lightcurves but three snapshot SEDs separated by eight years (between State A and State B) and four years (between State B and State C); each SED is a snapshot at one point during the long-term variability. Therefore, limited comparisons can be made, but in general, the SEDs of State A, State B, and State C are in agreement with the M23 observations that the high-energy (*Fermi*-LAT) data are increasing over time and that the optical and X-ray data are significantly variable over timescales of years.

Parameter	Unit	State B	M23 Epoch 4
Time interval	MJD	59196.0-59205.0	59198.0-59208.0
Exposure time	Hours	3.82	13.5
Significance	σ	10.3	22.9
z		0.45	0.41
$\gamma_{\min}$	$\log_{10}$	3.34	3.40
γ_{break}	$\log_{10}$	4.97	4.67
$\gamma_{\max}$	$\log_{10}$	7.59	5.70
n_1		$2.51^{+0.01}_{-0.01}$	2.0
n_2		4.02	3.12
B	$\log_{10}$ G	$-0.77^{+0.03}_{-0.02}$	-0.80
$N(\gamma = 1)$	$\log_{10}$ cm $^{-3}$	5.95	3.65
R	$\log_{10}$ cm	15.73	16.48
δ		58.53	17
U_B/U_e		2.22×10^{-3}	0.09

Table 4.5: Comparison of M23 best fit parameters for Epoch 4 to the results in this thesis. The redshift $z = 0.41$ used in M23 is from Kotilainen et al. (2011), and the M23 the EBL model is from Franceschini et al. (2008). The redshifts have uncertainties, but they are not included in the table to emphasize that the uncertainties on z are not considered in the modeling. Note that the electron distribution parameters in the third column pertain to a piecewise broken power-law (Equation 3.1), and the electron distribution parameters in the fourth column refer to a smoothly broken powerlaw (Equation 4.2). For M23, $N(\gamma = 1)$ is evaluated using Equation 4.2 and the best fit parameters. In M23, the Doppler factor is deduced from $\Gamma \sim \delta$, where $\Gamma = 17$ is determined from the fit.

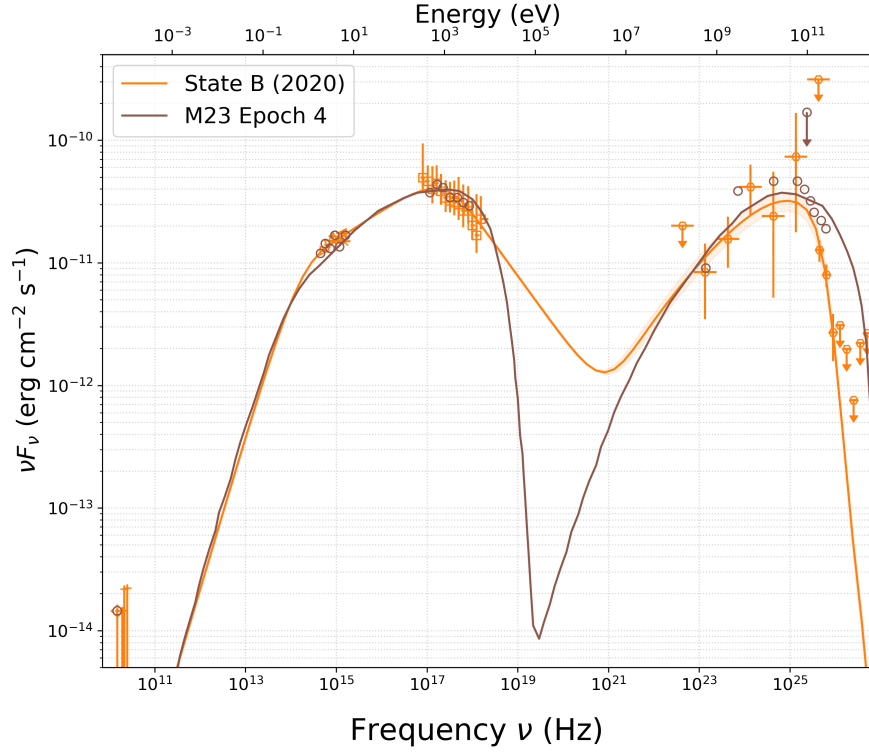


Figure 4.8: State B SED and data (orange) and M23 Epoch 4 SED and data (brown). The M23 results were digitized with Rohatgi (2019) and the error bars on the data were excluded; this is an approximate reconstruction. The *Swift* and *Fermi*-LAT datasets are not identical, but there is substantial overlap.

4.3 Conclusion

A component of Part I involved developing a possible (not definitive) and statistically motivated strategy for using `Bjet_MCMC` to model blazars, particularly in the case where little is known about the blazar that can constrain its parameters, such as the viewing angle and Doppler factor. This strategy is summarized in the flowcharts in Figures 3.7 and 3.8, but it is emphasized that this procedure is not the only reasonable approach, and ultimately the `Bjet_MCMC` technique is at the discretion of the user.

This work found that the possible driving parameters for the change in snapshot SEDs of 1ES 0647+250 from State A (lower state) to State B (higher state) to State C (lower state) are the magnetic field B and the EED index below the break energy n_1 . Specifically, a decrease in the magnetic field strength ($B_A > B_B > B_C$) and a modest variation in the first EED index n_1 (of $n_{1,A} > n_{2,B}, n_{1,B} < n_{1,C}, n_{1,A} > n_{1,C}$) can describe the blazar SED. This can be due to the blob moving down the jet to a region with a weaker magnetic field, which can be expected in the case of a relativistic shock propagating down the jet. However, it must be emphasized that this is not a unique solution nor is it a definitive interpretation.

Part II

Simulations of High-Energy and Very High-Energy Photon Propagation

Chapter 5

Cosmic Voids and Active Galactic Nuclei

Cosmic voids, the under-dense regions of the universe, were first reported in Gregory & Thompson (1978), using a wide-angle 3D map of galaxies which revealed large, mostly empty regions in the galaxy distribution. These under-dense regions are termed voids, and are the largest structures in the universe by volume. Voids have several properties relevant to this work. The EBL density in voids is expected to be lower than the EBL density in environments outside of voids (such as galaxy clusters, filaments, and sheets); because the EBL is the light emitted from stars and galaxies over all cosmic time, it is expected that under-dense regions, which contain fewer stars and galaxies by definition, have

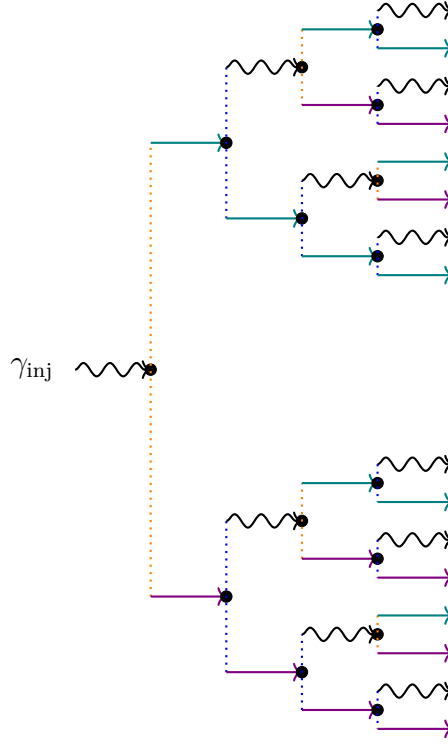


Figure 5.1: An electromagnetic cascade, as it unfolds in the **CRPropa** simulations, initiated by an injected gamma ray. Electrons are teal, and positrons are magenta. Gamma-ray photons are drawn as black wavy lines. The background photons are drawn as black dots; in all interactions (in Section 6.2.2) except triplet pair production, the energy of the background photon is neglected. Orange dotted lines indicate Breit-Wheeler pair production, and blue dotted lines represent inverse Compton scattering. As is shown, in **CRPropa** the secondaries in the simulation initially travel in the same direction as the primaries.

a lower EBL density (see e.g. Furniss et al. (2014)). Additionally, the magnetic field strength in voids is predicted to be small (see e.g. Beck et al. (2013)).

AGN were discussed in Section 1.1.

The work in this thesis builds upon and complements Jackson et al. (2026) (hereafter “J26”), Furniss et al. (2025) (hereafter “F25”), and Furniss et al. (2014) (hereafter “F14”). J26, F25, and F14 studied the “voidiness” of AGN detected by

Fermi-LAT and quasars detected by the optical instrument SDSS (Sloan Digital Sky Survey). As defined in F14, the voidiness along the line of sight (LoS) is

$$V_{\text{LoS}} = \frac{D_{\text{void}}}{D_{\text{LoS}}} = \frac{\sum D_{\text{void},i}}{D_{\text{LoS}}}, \quad (5.1)$$

where D_{void} is the total ($\sum D_{\text{void},i}$) comoving distance which intersects voids and D_{LoS} is the comoving distance to the AGN. The voidiness is a proxy for the density along the LoS, where $V_{\text{LoS}} = 1$ corresponds to a LoS that is entirely composed of voids and presumed to be maximally under-dense. V_{LoS} is calculable using parameters from the void catalogs of Sutter et al. (2012) (hereafter “S12”) and Sutter et al. (2014) (hereafter “S14”), which use SDSS-DR7 and SDSS-DR9 data to determine voids, respectively. Loosely speaking, each work (J26, F25, and F14) finds that AGN (the majority of which are blazars) detected by *Fermi*-LAT tend to lie along lines of sight that have a higher V_{LoS} than quasars detected by SDSS. In addition, each work remarks that this observation is likely attributed to, at least in part, substantial electromagnetic cascade emission. Such an electromagnetic cascade is shown in Figure 5.1. The expected small magnetic field strength in voids could result in enhanced secondary gamma-ray emission near the LoS. Gamma rays can $e^\pm$ pair produce with background photons, most likely via Breit-Wheeler single pair production with the extragalactic background light (EBL). The pairs have the potential to inverse Compton up-scatter background photons to gamma-

ray energies. In the case of weakly deflected pairs due to a weak magnetic field strength, the electromagnetic cascades remain closer to the LoS, allowing more of the secondary flux to be observed at Earth. Any cascade emission is impacted by both lower EBL density in voids and lower magnetic field strength in voids; in this thesis, only the latter is explored, and existing EBL models are utilized.

F14 used the full S12 catalog¹—full meaning that voids near the survey boundary were included. The S12 void catalog is derived from SDSS-DR7. SDSS-DR7 consists of the “main sample” (Strauss et al., 2002) out to $z = 0.2$, and the “luminous red galaxy sample” out to $z = 0.44$ (Eisenstein et al., 2001). The main sample and LRG (luminous red galaxy) sample are distinct from the quasar sample; the main sample and LRG sample are not intended to include quasars. The selection criteria are described in e.g. Strauss et al. (2002) for the main sample, Eisenstein et al. (2001) for the LRG sample, and Schneider et al. (2010) for the quasar sample. F14 examined the voidiness of sources in various samples, as listed below, and selected sources with spectroscopic redshifts $0.05 < z < 0.36$ (sources with only photometric redshifts were not utilized).

- SDSS-DR7 quasar catalog (Schneider et al., 2010). This is non-overlapping with the SDSS-DR7 sources (the main sample and LRGs). 3901 of the SDSS-DR7 quasars are included in F14.

¹The 2014.11.04 release

- 2LAC: The Second Catalog of Active Galactic Nuclei Detected by the Fermi Large Area Telescope (Ackermann et al., 2011). The majority of these sources are blazars (see Table 5 of Ackermann et al. (2011)). 51 of the 2LAC sources are included in F14.
- 1FHL: The First Fermi-LAT Catalog of Sources above 10 GeV (Ackermann et al., 2013). 28 of the 1FHL sources are included in F14, after one source (1ES 0806+524) was removed because it has significant variability > 10 GeV. The 1FHL catalog defines “VHE candidates” as sources with all of the following properties:
 - i Above 50 GeV, the flux is greater than $10^{-11} \text{ ph cm}^{-2} \text{ s}^{-1}$.
 - ii Above 10 GeV, the spectral index is less than 3.
 - iii Source significance Sig_{30} is greater than 3, where $\text{Sig}_{30}^2 = TS_{30-100} + TS_{100-500}$ and TS_{30-100} ($TS_{100-500}$) is the test statistic from 30 – 100 GeV (100 – 500 GeV).
- “VHE-like”: 1FHL sources satisfying criteria i, ii, and iii; this results in sources that are either detected at VHE or are VHE-emitting candidates identified by 1FHL. There are 19 VHE-like sources included in F14.
- Randomly generated: 10^5 locations which are uniformly randomly distributed throughout the SDSS-DR7 survey region. Note that the random

locations do not trace the large-scale structure of the universe.

The 2LAC, 1FHL, and VHE-like catalogs share many of the same sources. F14 did not directly utilize TeVCat² sources because IACT observations tend to be biased by high flux states. The authors note that the selected sources from the SDSS quasar, 2LAC, 1FHL, VHE-like, and randomly generated catalogs are distributed similarly in the universe, with a similar percentage of each catalog’s sources lying in voids: 18% for SDSS quasars, 25% for 1FHL, 26% for VHE-like, and 21% for randomly generated. In each catalog, the percentage of sources within voids is consistent (within $\approx 10\%$) with that of the randomly generated sources. Therefore, the catalogs do not appear to target sources that are in or out of voids—they are all consistent with random.

The voidiness is calculated as in Equation 5.1, where, in F14, $D_{\text{void},i}$ is calculated as $\frac{4}{3}R_{\text{eff}}$, which corresponds to the average length of random intersections through a sphere of radius R_{eff} (Coleman, 1989), and S12 provides the effective radius of each void, via

$$R_{\text{eff}} = \left(\frac{3}{4\pi} V_t \right)^{1/3}, \quad (5.2)$$

where V_t is the total volume of the Voronoi cells (which are polyhedra; see e.g., Neyrinck (2008)) defining the void.

The voidiness distribution is the normalized fraction of sources (in a given

²<http://tevcat.uchicago.edu/>

population) as a function of voidiness V_{LoS} . F14 examined the voidiness distribution of the sources in each population bulleted above by performing two-sample Kolmogorov-Smirnov (KS) tests, which test the null hypothesis that two samples are from the same distribution. The significance level derived from the KS test represents the probability that the null hypothesis can be rejected, in other words, the level of confidence that the two distributions are **not** the same.

The (voidiness) distribution of SDSS quasars is strongly (12.5σ) inconsistent with that of the randomly generated sources; this is expected because the large sample of 3901 SDSS quasars traces the large-scale structure, and so the voidiness distribution is not expected to be that of random chance. The distribution of VHE-like sources was found to have marginal (2.4σ) evidence of not being drawn from the same distribution as SDSS quasars.

Altogether, the VHE-like sources in particular emerge as the sources that are most significantly (but still not significantly) able to reject the null hypothesis that they are from the same distribution as the SDSS quasars. Therefore, on average, VHE-like sources (specifically, blazars) tend to lie along more underdense LoS than SDSS quasars. F14 speculate that this may be due to a lower EBL density in voids, a lower magnetic field strength in voids, or a combination of both; if the local EBL density and local magnetic field strength are determined by the local density, then voids may have lower than average EBL density and magnetic

field strength. The preference for underdense LoS (rather than overdense LoS) is evident from Figure 1 of F14, which contains the V_{LoS} distribution for each sample, and shows that there is a higher fraction of VHE-like sources than SDSS quasars at higher V_{LoS} (and a lower fraction of VHE-like sources than SDSS quasars at lower V_{LoS}).

Extending the work of F14, F25 utilized the S12 and S14 void catalogs to study the voidiness of the samples bulleted below, including sources within the void footprint and $0.1 \leq z < 0.7$.

- 4LAC-DR3: The Fourth Catalog of Active Galactic Nuclei Detected by the Fermi Large Area Telescope: Data Release 3 (Ajello et al., 2022). This catalog contains sources with $E > 50$ MeV. Sources without redshifts were excluded from F25 (and redshift information from Goldoni et al. (2021) was used). Only sources with spectroscopic redshifts are included. This left 160 sources with $0.1 \leq z < 0.4$, and 143 sources with $0.4 \leq z < 0.7$. The majority of sources are blazars.
- SDSS-DR16 quasars: SDSS-IV quasar catalog from Data Release 16 of the extended Baryon Oscillation Spectroscopic Survey (Lyke et al., 2020). There are 3,326 sources with $0.1 \leq z < 0.4$ and 16,425 sources with $0.4 \leq z < 0.7$ within the void catalog.
- “Redshift-matched” sample of SDSS quasars: Randomly selected SDSS-

DR16 quasars chosen so that the redshift distribution matches that of 4LAC-DR3 (see Figure 1 of F25). This is done separately for the two redshift intervals, $0.1 \leq z < 0.4$ and $0.4 \leq z < 0.7$. Five hundred redshift-matched samples are created.

- Randomized populations: 500 randomized populations are made using 4LAC-DR3, and 500 are made using SDSS-DR16 quasars. For each randomized population, N random RA and Dec coordinates (that lie within the void catalog footprint) are generated, where N is the size of the catalog ($N = 303$ for 4LAC-DR3 and $N = 19,751$ for SDSS-DR16 quasars).

Results are reported in two redshift intervals (“nearby” $0.1 \leq z < 0.4$, and “distant” $0.4 \leq z < 0.7$) in order to abate redshift-voidiness bias. Sources with $z < 0.1$ are excluded from the study as a potential source of bias because they have systematically lower voidiness; roughly half of the galaxies at $z < 0.1$ have $V_{\text{LoS}} \approx 0$ (nearly none of the LoS intersects a void). S12 notes an observational bias of void size tending to increase as redshift increases.

In F25, the distance (in Mpc) along the line of sight which interests voids (D_{void} in Equation 5.1) is computed as the union of LoS segments within voids, where the void size is described by the effective radius (Equation 5.2) in the void catalogs. As in F14, a two-sample KS test was used to compute p-values and significances. As in F14, the SDSS-DR16 quasars are strongly inconsistent with

the randomly generated sample, as expected.

The (voidiness) distribution of 4LAC-DR3 AGN in the distant ($0.4 \leq z < 0.7$) redshift interval was inconsistent with the distribution of the 500 samples of redshift-matched SDSS quasars, at 4.1σ using the median p-value (of the 500 samples). BL Lacs dominate the contribution to this observation, with a significance of 3.8σ , (compared to 0.3σ for flat spectrum radio quasars (FSRQs) and 2.7σ for blazar candidates of uncertain type (BCUs)). The identification of BCUs is described in Ajello et al. (2022). However, the sources within the nearby ($0.1 \leq z < 0.4$) redshift bin do not produce the same result; that is, the nearby 4LAC-DR3 AGN and 500 samples of redshift-matched SDSS quasars are consistent with being drawn from the same underlying voidiness distribution. This echoes the result of F14.

J26 expands on the work of F25 and examines the same sources as F25 (that is, the same subset of sources in 4LAC-DR3 and SDSS-DR16), and the same void catalogs (from S12 and S14). As in F25, J26 generated 500 “redshift-matched” samples of SDSS quasars, adhering to the same criteria as F25.

J26 considered the total void intersecting distance $D_{\text{void}} = V_{\text{LoS}} D_{\text{total}}$ (via Equation 5.1). D_{void} was computed using the voidiness V_{LoS} values from F25, and the analysis of F25 was repeated by comparing the distributions of D_{void} for the various samples using a two-sample KS test. The conclusions of J26

(which used D_{void}) are the same as those of F25 (which used V_{Los}); namely, that when comparing 4LAC-DR3 sources and 500 samples of redshift-matched SDSS-DR16 quasars, the distant ($0.4 \leq z < 0.7$) sources are unlikely to be drawn from the same D_{void} distribution (with a p-value of 2.3×10^{-5}); however, the nearby ($0.1 \leq z < 0.4$) sources have consistent D_{void} distributions (p-value 0.327).

As in F25 and F14, the SDSS quasars are inconsistent with randomly generated sources. A hypothetical sample that contains **all** gamma-ray emitting AGN is expected to be strongly inconsistent with randomly generated sources because AGN trace the large-scale structure; however, F25 found that the (D_{void}) distribution of 4LAC-DR3 sources (**detected** gamma-ray AGN) is consistent with randomly generated sources, (p-value > 0.05) as was also found in F25.

J26 finds that more 4LAC-DR3 AGN are within voids than SDSS-DR16 quasars, $28 \pm 3\%$ compared to $19.1 \pm 0.3\%$, where the uncertainty on the fraction of sources in voids $\frac{n}{N}$ is $\frac{\sqrt{n}}{N}$, and determine that this fact cannot explain the modest statistical difference in D_{void} distributions between 4LAC-DR3 and SDSS-DR16 sources. By examining the source environment (that is, in a void or not in a void), J26 concludes that the source location, whether within a void or outside a void, is unlikely to be the primary cause for the difference in voidiness distribution between 4LAC-DR3 AGN and SDSS-DR16 quasars.

In Part II of this work, gamma-ray flux enhancement due to secondary pho-

tons created in electromagnetic cascades as the primary photons traverse lines of sight with various voidiness (parameterized by magnetic field strength) and length (redshift) is explored. This work estimates extreme cases of flux enhancement. Primary photons are simulated and propagated through various magnetic fields using `CRPropa` as described in Chapter 6; simulations mimic sources that are in voids and behind voids. Simulation outputs are analyzed as described in Chapter 7. Results, such as SEDs, are presented and discussed in Chapter 8.

Chapter 6

CRPropa Simulations

CRPropa uses Monte Carlo methods to propagate high-energy particles over cosmological distances. CRPropa 3.2.1 (Alves Batista et al., 2022; Heiter et al., 2018), via `simCRpropa` (Meyer & Splettstoesser, 2025), was utilized to inject high-energy photons and study the subsequent electromagnetic cascades.

6.1 Cosmology

In CRPropa the cosmology is a flat universe with cosmological constant Ω_Λ and $\Omega_{\text{total}} = 1 = \Omega_\Lambda + \Omega_m$ (Batista et al., 2016). In addition, cosmology in the matter dominated regime ($z \lesssim 10^3$) is used, such that the Hubble rate is $H(z) = H_0 \sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda}$ (Armengaud et al., 2007). For consistency (with Equation 5.1), the CRPropa simulations in this work use the same cosmology as was used to

calculate the comoving distances in the void catalogs of Sutter et al. (2012, 2014) (see Chapter 5), i.e., $h = 0.71$ and $\Omega_m = 0.27$.

6.2 Particle Interactions and Propagation

6.2.1 Propagation

Charged particles in magnetic fields are propagated in **CRPropa** by solving the following equations¹ of motion in comoving coordinates via numerical integration:

$$\begin{pmatrix} \frac{d\vec{r}}{dt} \\ \frac{d\vec{p}}{dt} \end{pmatrix} = \begin{pmatrix} c\hat{p} \\ q \left[\frac{d\vec{r}}{dt} \times \vec{B} \right] \end{pmatrix}, \quad (6.1)$$

which can also be written as

$$\begin{pmatrix} \frac{d\vec{r}}{dt} \\ \frac{d\hat{p}}{dt} \end{pmatrix} = \begin{pmatrix} c\hat{p} \\ \frac{qc^2}{E_q} [\hat{p} \times \vec{B}] \end{pmatrix}, \quad (6.2)$$

where $\vec{r}$ is the position of the particle with charge q and mass m , Γ its Lorentz factor, $\vec{p} = \Gamma m \vec{v}$ its relativistic momentum and $\hat{p}$ the associated unit vector, c the speed of light, and $\vec{B}$ the magnetic field. In **CRPropa**, particles are assumed to be ultra-relativistic so that $v = c$, and the rest mass is ignored. Equation 6.2 uses

¹Equation 6.1 is Equation 5 of <https://github.com/CRPropa/CRPropa2/blob/master/doc/UserGuide.tex>.

the fact that the energy of the charged particle is $E_q = \Gamma mc^2$, $\vec{v} = c\hat{v} = c\hat{p}$, and $\frac{d\Gamma}{dt} = 0$ (because $\vec{v}$ is perpendicular to $\frac{d\vec{v}}{dt}$). The energy E_q is updated each time an interaction occurs (as is detailed in Section 6.2.2).

Simulations use the Boris push (Boris & Shanny, 1972) algorithm (implemented in `CRPropa` 3.2) to solve the equations of motion in Equation 6.1. This method is for the case of ballistic propagation/transport of single particles (versus diffusive transport). The Boris push method intrinsically conserves energy when the electric field $\vec{E} = 0$ and therefore maintains the correct momentum components (Alves Batista et al., 2022). That is, the component of momentum parallel to the magnetic field $\Gamma mv_{\parallel}$ is constant ($\vec{F} \propto \vec{v} \times \vec{B} = \vec{F}_{\perp} + \vec{F}_{\parallel} = [\vec{v}_{\perp} + \vec{v}_{\parallel}] \times \vec{B} \Rightarrow \vec{F}_{\parallel} = \vec{v}_{\parallel} \times \vec{B} = 0$). The Boris push method is utilized in this work because it is in general recommended by `CRPropa` developers due to both its accuracy and computation time². However, the Boris push method does not preserve the phase; that is, the position and momentum vectors are not necessarily perpendicular at each step in the propagation, and, as noted in Alves Batista et al. (2022), this may impact the Larmor frequency. Nevertheless, the method has a globally constrained error, and therefore possesses long-term accuracy, and so it is the preferred method for most simulations (Alves Batista et al., 2022).

For each particle, the distance to the next interaction Δx_1 is calculated using a

²See https://crpropa.github.io/CRPropa3/pages/example_notebooks/propagation_comparison/Propagation_Comparison_CK_BP.html for a detailed comparison of the propagation methods.

random number r uniformly distributed between 0 and 1 via $\Delta x_1 = -\lambda_{\text{tot}} \ln(1-r)$ where λ_{tot} is the total mean free path (also called interaction length) and accounts for all possible interaction channels via $\lambda_{\text{tot}}^{-1} = \sum \lambda_i^{-1}$. If the particle travels far enough to interact, then an interaction occurs. The specific interaction is determined according to another random number w between 0 and 1 (inclusive) using the condition $\sum_a^i \frac{\lambda_{\text{tot}}}{\lambda_a} > w$, where the subscript a denotes the different interaction channels and the first i that satisfies the inequality selects the specific interaction (e.g. inverse Compton scattering off the CMB; see Section 6.2.2 for the interactions). Secondary particles initially travel in the same direction as the energetic parent, the one that is not a background photon. The propagation algorithm, including how the step size is selected, is described in far more detail in Kampert et al. (2013).

The propagation module (**PropagationBP**) configuration parameters are as follows. The Boris push tolerance (i.e integrator accuracy³, or relative error⁴) was set to 10^{-9} as in Aharonian et al. (2023). The minimum step size was set to 0.3 pc, also as in Aharonian et al. (2023), to capture variability timescales of 1 year; it is also less than 1 pc, the approximate smallest expected Larmor radius for the simulation conditions, shown in Figure 6.1. The propagation module proposes a step size; if this step size does not satisfy the requested tolerance, then the

³<https://github.com/CRPropa/CRPropa2/blob/master/doc/UserGuide.tex>

⁴github.com/CRPropa/CRPropa3/PropagationBP.h#L57

proposed step size is decreased, and this continues until either the tolerance is achieved or the minimum step size is reached. The maximum step size was set to the approximate smallest interaction length 10^{-3} Mpc (see Figure 6.6). The selected maximum step size, minimum step size, and tolerance resolve the Larmor radius for the extremes of the simulation conditions⁵.

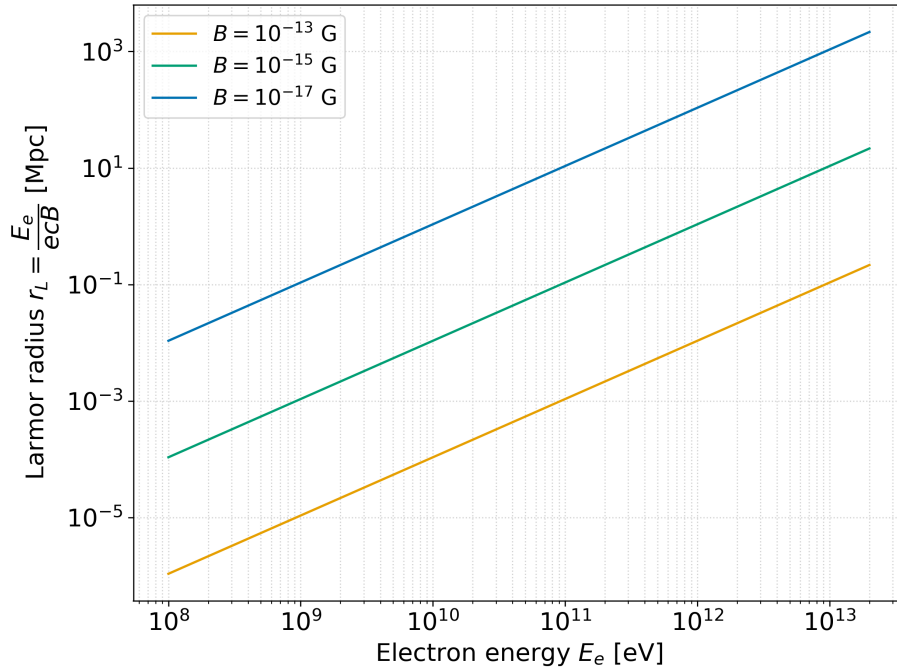


Figure 6.1: Larmor radii r_L for several magnetic field strengths B , as a function of electron energy E_e . The Larmor radius is $r_L = \frac{E_e}{ecB}$ assuming the pitch angle is $\Theta = 90^\circ$ ($r_L = \frac{\gamma m v_\perp}{eB}$ where $v_\perp = c \sin \Theta$ and Θ is measured with respect to $\vec{B}$).

In addition, the thinning is set to the minimum $\eta = 0$ such that all secondary

⁵<https://github.com/spletts/PhDThesisHB>

particles are accepted, propagated, and tracked, so long as they pass the break conditions in Section 6.5.

6.2.2 Interactions

6.2.2.1 Photon Background Fields

Simulations include three photon background fields: the cosmic microwave background (CMB), discovered by Penzias & Wilson (1965), the extragalactic background light (EBL) model of Saldana-Lopez et al. (2021), and the universal radio background (URB) model of Nițu et al. (2021).

As the equations of motion are solved in comoving coordinates, the cosmological evolution (redshift dependence) of the background fields is accounted for within **CRPropa**. The interaction rates λ^{-1} for each interaction are tabulated for redshift $z = 0$ (the inverse, the interaction length, is shown in Figures 6.5 and 6.6), and **CRPropa** interpolates these tables at run time. The tabulated interaction rates are calculated using the comoving differential background photon number density per energy interval $\frac{dn}{d\epsilon} = n(\epsilon, z = 0)$ (Alves Batista et al., 2022). The CMB was produced instantaneously at one redshift $z \sim 1100$ (Armengaud et al., 2007) and so it is scaled as

$$n(\epsilon, z) = (1 + z)^2 n(\epsilon(1 + z)^{-1}, z = 0), \quad (6.3)$$

using dimensional analysis of $n(\epsilon)$ with units of $[\text{energy}]^{-1}[\text{length}]^{-3}$, where physical length scales as $(1+z)$ with respect to comoving length, and energy scales as $(1+z)^{-1}$. The redshift evolution of other photon fields (the EBL and URB) is approximated with an additional scaling factor $s(z)$ (specific to each model) applied to the interaction rate λ^{-1} , where $s(z)$ is defined as

$$s(z) = \frac{\int n(\epsilon, z) d\epsilon}{\int n(\epsilon, z=0) d\epsilon}, \quad (6.4)$$

and the integral is over the energy range of the model (Batista et al., 2016). It is assumed that the shape of n is independent of z in the comoving frame. For the CMB, this relation is exact, so $s(z) = 1$. It is not exact for the EBL nor URB. The dependence of the EBL number density on energy is shown in Figure 6.2 for the redshifts used in this work. The dependence of the EBL number density on redshift is shown in Figure 6.3 for several relevant energies. The number density is that of Saldana-Lopez et al. (2021) and obtained via `ebtable` (Meyer, n.d.). Therefore, beyond the cosmological evolution of $n(\epsilon)$, there is additional redshift dependence through $s(z)$.

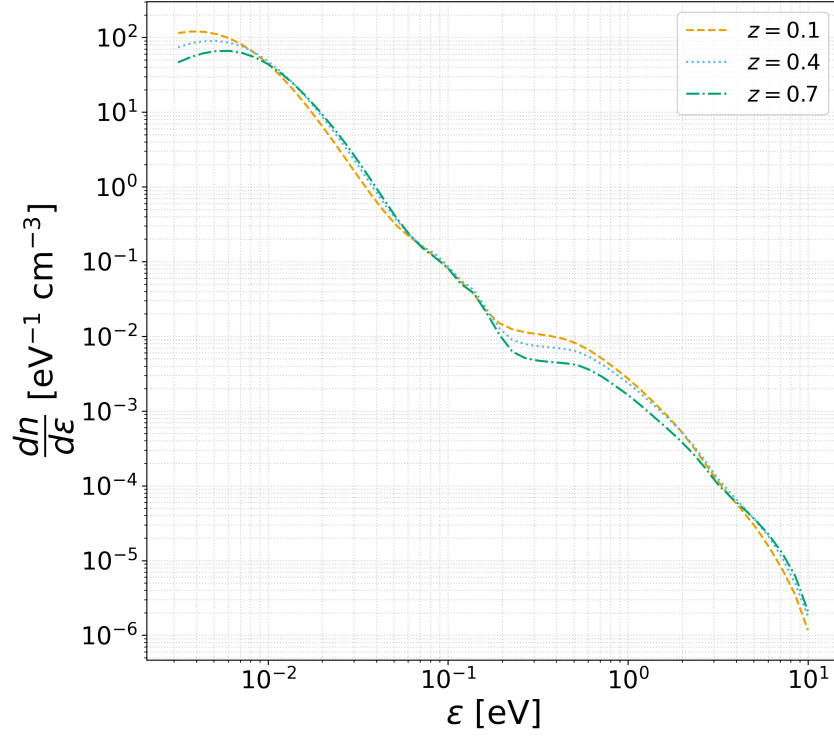


Figure 6.2: Number density of EBL photons $\frac{dn}{d\varepsilon}$ as a function of EBL photon energy ε for various redshifts used in this work. The EBL model is that of Saldana-Lopez et al. (2021).

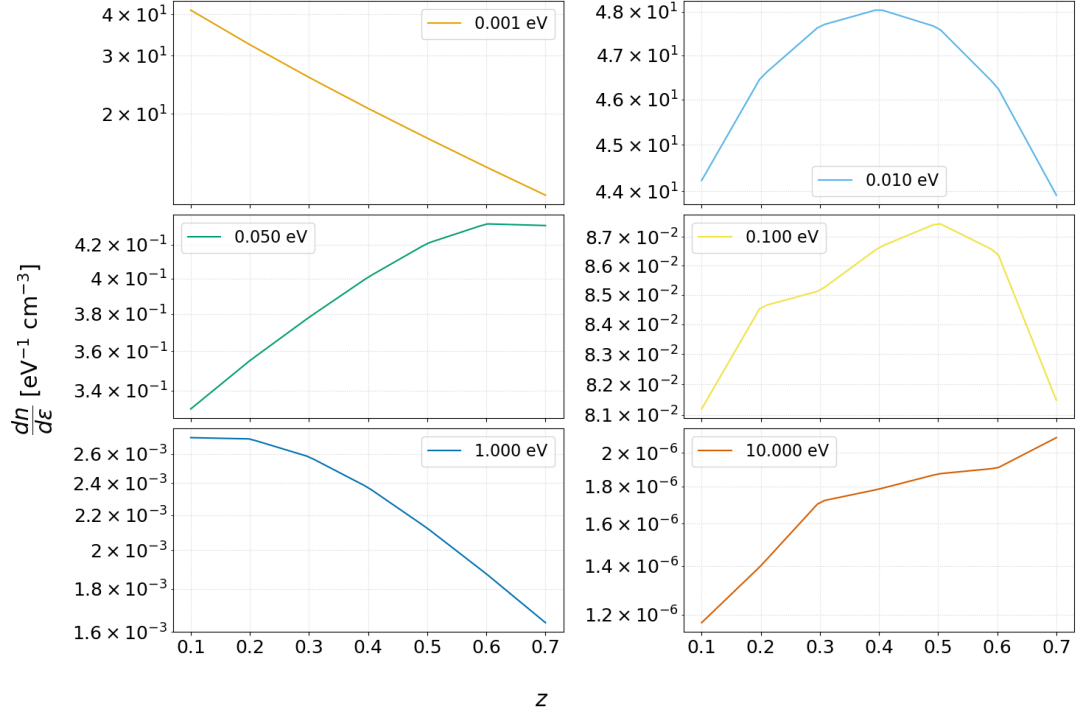


Figure 6.3: Number density of EBL photons $\frac{dn}{d\varepsilon}$ as a function of redshift z for various EBL photon energies. Note that the vertical axis is on a linear scale. The EBL model is that of Saldana-Lopez et al. (2021).

6.2.2.2 Enabled Interactions

In what follows, the background CMB, EBL, and URB photons are represented as γ_{bkg} and have energy ϵ . The interaction rates (at $z = 0$) are calculated as

$$\lambda^{-1}(E) = \frac{1}{8\beta E^2} \int_0^\infty \frac{n(\epsilon)}{\epsilon^2} \int_{s_{\text{th}}}^{s_{\text{max}}} \sigma(s)(s - m^2 c^4) ds d\epsilon \quad (6.5)$$

where $n(\epsilon) = \frac{dn}{d\epsilon}$ is the differential number density per energy interval of the background photon field, and $\sigma(s)$ is the cross section for the particular interaction as a function of the squared center of momentum energy $s = m^2 c^4 + 2\epsilon E$ (Heiter et al., 2018). s_{th} is the minimum s for secondaries to be produced. $s_{\text{max}} = 4E\epsilon + m^2 c^4$ is the case of a head-on collision. E and m refer to the energy and mass of cosmic rays with velocity $\beta \approx 1$. In this work, the cosmic rays are photons, electrons, or positrons. The (differential) interaction rate is calculated at any redshift z and energy E (of the primary) as

$$\lambda^{-1}[E, z] = (1 + z)^2 s(z) \lambda^{-1}[E(1 + z), z = 0], \quad (6.6)$$

(Heiter et al., 2018), where $s(z)$ is given by Equation 6.4.

The simulations in this work include the interactions below, which are described in detail in Heiter et al. (2018). The dominant interactions are indicated

with $\star$; interactions without a preceding $\star$ are extremely unlikely to occur because of the large interaction lengths λ .

i $\star$ (**EMInverseComptonScattering**) Inverse Compton scattering (ICS) of electrons/positrons off background photons: $e^\pm + \gamma_{\text{bkg}} \rightarrow e^\pm + \gamma$. The energy of γ , E_γ , is calculated by neglecting the energy of the background photon (the most energetic of which has energy $10^{-3} \text{ eV} \lesssim \epsilon_{\text{EBL}} \lesssim 10 \text{ eV}$ corresponding to far-infrared and ultraviolet energies) such that $E_{e^\pm} = E_\gamma + E'_{e^\pm}$, where $E'_{e^\pm}$ is the final electron/positron energy. s and $\frac{E'_{e^\pm}}{E_{e^\pm}}$ are sampled to determine the up-scattered photon energy.

ii $\star$ (**EMPairProduction**) Breit-Wheeler $e^\pm$ pair production (PP): $\gamma + \gamma_{\text{bkg}} \rightarrow e^+ + e^-$. The energy of the background photon is neglected such that the energy of the positron is calculated via $E_{e^+} = E_\gamma - E_{e^-}$ (Heiter et al., 2018). The cosmic ray photon is destroyed. s and $\frac{E_\gamma}{E_{e^-}}$ are sampled to determine the electron energy E_{e^-} .

iii (**EMDoublePairProduction**) Double $e^\pm$ pair production (DPP): $\gamma + \gamma_{\text{bkg}} \rightarrow e^+ + e^- + e^+ + e^-$. In the implementation in **CRPropa**, one of the electrons (positrons) receives no energy and the other electron (positron) receives half the energy E_γ of γ such that $E_{e_2^\pm} = 0$ and $E_{e_1^\pm} = \frac{E_\gamma}{2}$, where once again $\epsilon = 0$ has been used. The result is that one of the pairs is not tracked in the simulations because at rest they lie below the break energy (see Section

6.5 about break conditions); however, this is inconsequential to the work presented in this thesis because the interaction is incredibly unlikely for the photon energies under consideration. Note that there is no sampling of the secondary electron/positron energy in this interaction.

iv (EMTripletPairProduction) Triplet $e^\pm$ pair production: $e^\pm + \gamma_{\text{bkg}} \rightarrow e^\pm + e^+ + e^-$. In the interaction, $e^\pm$ loses energy ΔE corresponding to a fraction of its initial energy E , which creates an electron-positron pair with equal energies $E_{e^-} = E_{e^+}$ such that $\Delta E = 2E_{e^-}$. The electron/positron energies $E_{e^\pm}$ are calculated assuming a head-on collision, which is the most likely case. s is sampled to determine the energy of the background photon ϵ , which then determines $E_{e^\pm}$.

v (SynchrotronRadiation) In CRPropa the expression for the synchrotron energy loss of ultra-relativistic particles is used. Because the energy loss is $\propto \Gamma^2$, where Γ is evaluated as $\frac{E}{mc^2}$, this process depends strongly on the energy of the charged particle; therefore, this process is important only for ultra-high-energy electrons. For the energy ranges and magnetic fields considered in the simulations in this work (see Sections 6.3 and 6.6), it is impossible for a synchrotron photon to be produced, as shown in Figure 6.4.

vi $\star$ (FutureRedshift) Adiabatic energy loss due to expansion of the universe

(Alves Batista et al., 2015) via $\frac{dE}{dz} = \frac{E}{1+z}$.⁶

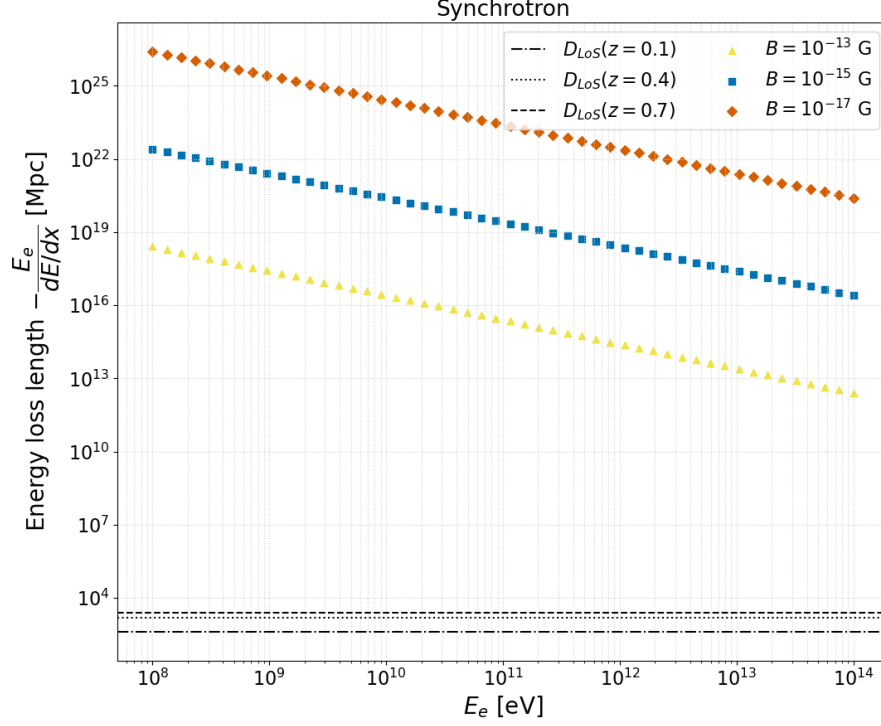


Figure 6.4: Synchrotron energy loss lengths $\frac{-E_e}{dE/dx}$ as a function of electron energy E_e on the horizontal axis.

Figures 6.5 and 6.6 contain the interaction lengths (at $z = 0$) for interactions initiated by energetic photons and initiated by energetic electrons, respectively. Figure 6.4 shows the energy loss lengths, the distance over which the electron/positron energy is reduced by $1/e$, where e is Euler's number. Note that the dominant interactions—ICS, PP, and adiabatic energy loss due to the expan-

⁶github.com/CRPropa/CRPropa3/Redshift.cpp#L52

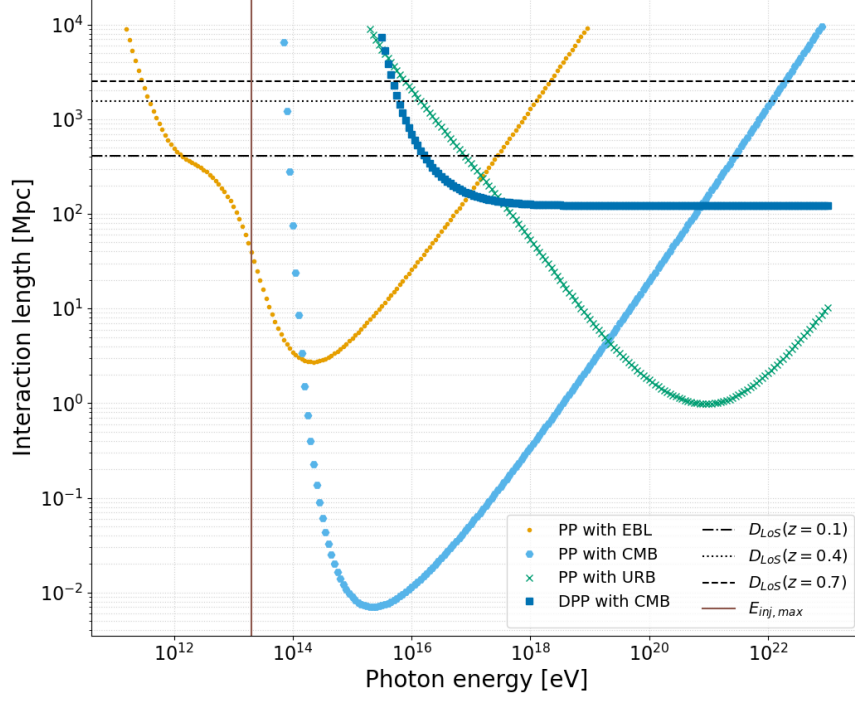


Figure 6.5: CRPropa’s tabulated photon interaction lengths (at $z = 0$) for pair production (PP) and double pair production (DPP) off background CMB, EBL and URB photons. The EBL model is from Saldana-Lopez et al. (2021). The universal radio background (URB) model is that of Nițu et al. (2021). The horizontal lines indicate comoving distance $D_{\text{LoS}}(z)$ to a source at $z = 0.1$ (dashed-dotted black), $z = 0.4$ (dotted black), and $z = 0.7$ (dashed black). The maximum energy of the injected photons is $E_{\text{inj,max}}$ (brown solid line).

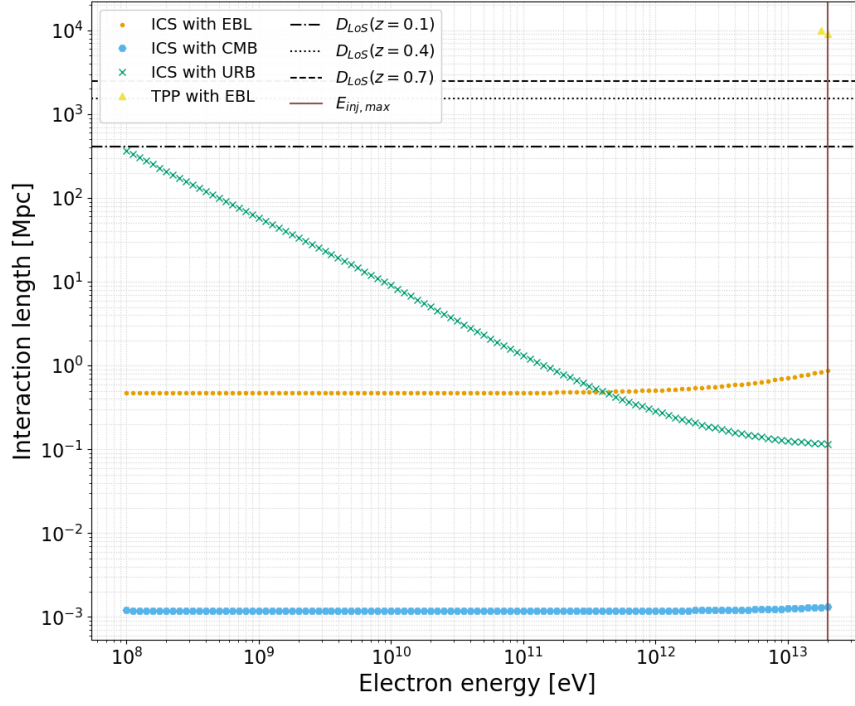


Figure 6.6: **CRPropa**’s tabulated electron interaction lengths (at $z = 0$) for inverse Compton scattering (ICS) and triplet pair production (TPP). Interactions with large energy loss lengths (that is, synchrotron radiation) are not shown on this plot. The maximum energy of the injected **photons** is $E_{\text{inj,max}}$.

sion of the universe—do not depend on the magnetic field $\vec{B}$; these interactions are neither enhanced nor diminished as a result of $\vec{B}$. $\vec{B}$ solely controls the deflection of charges and consequently the launching direction of secondary (IC) photons.

CRPropa samples the energies of the background photon ϵ from the probability distribution function (in this case the differential interaction rate) $\text{PDF} \propto \frac{d\lambda^{-1}(E_\gamma)}{d\epsilon}$, where E_γ is the energy of the high-energy primary cosmic ray (Heiter et al., 2018).

For pair production, inverse Compton scattering, and triplet pair production, first s is sampled from $\frac{d\lambda^{-1}}{ds(s, E_\gamma)}$. For pair production, once s is sampled, the energy of the electron E_e is determined by sampling $x = \frac{E_\gamma}{E_e}$ from $\frac{d\sigma_{PP}}{dx}$ where σ_{PP} is the pair production cross section. For triplet pair production, after s is sampled, it then determines the energy of the background photon via $\epsilon = \frac{s - m_e^2 c^4}{4E_\gamma}$, and lastly $E_{e^\pm}$ is calculated according to $E_{e^\pm} = 0.57m_e \left(\frac{\epsilon}{m_e c^2}\right)^{-0.56} \left(\frac{E_\gamma}{m_e c^2}\right)^{0.44}$ (Heiter et al., 2018). In inverse Compton scattering interactions, s is sampled, then $x = \frac{E'_{e^\pm}}{E_{e^\pm}}$ (the ratio of initial $e^\pm$ energy to final $e^\pm$ energy) is sampled from $\frac{d\sigma_{IC}}{dx}$. The up-scattered photon energy is determined from $E_\gamma = E_e - E'_e$ and again ϵ is ignored.

The default tables for λ^{-1} within **CRPropa** extend at lowest to 10^9 eV. For most of the interactions described in this section, below 10^9 eV the interaction length is much further than the comoving distances studied in this work (see Table

6.1). This is shown in Figures 6.5 and 6.6. However, the inverse Compton cross sections do not vanish around 10^9 eV, and below these energies the interaction is still important. Using `CRPropa3-data`⁷ (`calc_electromagnetic.py`) the inverse Compton tables were extended⁸ down to 10^8 eV (the lower energy range of *Fermi*-LAT) with the same number of bins per decade as the default tables (i.e. the default tables spanned 10^9 - 10^{23} eV and the tables were remade from 10^8 - 10^{22} eV with the same number of bins).

6.3 Sources

Each source, which describes the properties of the injected particles, is placed at a given redshift z (`SourceRedshift`), at location $\vec{X}_0 = \vec{0}$ in simulation coordinates. Photons are injected using particle type 22, according to the Particle Data Group Monte Carlo numbering scheme⁹. Photons are injected with a powerlaw spectrum (`SourcePowerLawSpectrum`) $\frac{dN}{dE} \propto E^\alpha$ from $E_{\min} = 10^8$ eV to $E_{\max} = 2 \times 10^{13}$ eV, with index $\alpha = -1.5$; a rather hard spectral index of -1.5 is selected in order to probe an extreme case. Of the *Fermi*-LAT AGN used in F25 and J26, the average 4LAC-DR3 powerlaw (photon) index is $\alpha \approx -2.1$. The initial momenta of the injected photons are dictated by a cone (i.e., jet) of half-opening angle $\psi = 0.1^\circ$

⁷<https://github.com/CRPropa/CRPropa3-data/>

⁸Verified at <https://github.com/CRPropa/CRPropa3/issues/528>

⁹https://pdg.lbl.gov/2012/mcdata/mc_particle_id_contents.html

with central axis along $\hat{x}$ in simulation coordinates (`SourceEmissionCone`). The choice of ψ is somewhat arbitrary but it is selected to be a realistic blazar half-opening angle. Jorstad et al. (2017) report an average $\psi \lesssim 2^\circ$ for a sample of 36 gamma-ray bright AGN (21 FSRQs, 12 BL Lac blazars, and 3 radio galaxies). Using a sample of 161 blazars, Hervet et al. (2016) determine that the majority of the sample have $\psi < 1^\circ$. A small angle is also required to achieve the desired voidiness V_{LoS} —this is discussed in Section 6.6. Note that ψ , in part, determines which photons are “detected,” and a smaller ψ means a smaller (more realistic) collection area—this is discussed in Chapter 7. The impact of the choice of ψ is explored in Section 8.3.4. The emission is uniform¹⁰ within the cone. For each simulation configuration, a total of 5×10^5 particles were injected.

The source parameters that are varied in different simulations are in Table 6.1.

6.4 Observer

The observer is a large sphere (`ObserverSurface(Sphere)`) with center at the source location $\vec{0}$ and radius equal to the comoving distance to the source D_{LoS} , where D_{LoS} is calculated by `CRPropa (redshift2ComovingDistance)` using the source redshift z and the cosmology in Section 6.1. The large observer sphere framework is standard for `CRPropa` simulations (see e.g. Aharonian et al. (2023)).

¹⁰crpropa.github.io/SourceEmissionCone

z	D_{LoS} [Mpc]	Magnetic field	IGMF [G]	ℓ [Mpc]	$\frac{dN}{dE}$	ψ [deg]
0.1	413.5	i, ii, iii, iv	10^{-13}	1	$E^{-1.5}$	0.1
0.4	1543.0	i ii, iii, iv	10^{-13}	1	$E^{-1.5}$	0.1
0.7	2505.3	i	N/A	50	$E^{-1.5}$	0.1
0.7	2505.3	ii, iii, iv	10^{-13}	1	$E^{-1.5}$	0.1

Table 6.1: Varied simulation parameters. The source is injected at redshift z (which gives the comoving distance to the source D_{LoS}) and assigned a half-opening angle ψ . The redshifts correspond to the redshift interval boundaries from Furniss et al. (2025). The magnetic field geometries are given in Section 6.6. The IGMF is the magnetic field strength outside voids; in voids, $B = 0$ is used. ℓ is the coherence length of the magnetic field and is used as the length of each side of the grid cell in the magnetic field grid. This table summarizes the assumptions made about the sources and magnetic fields used in the simulations in this work.

However, as is discussed in Section 7.1, not all particles on the observer sphere are “detected” (Figures 7.1 and 7.3 illustrate two of the three detection criteria). The observer collects photons that cross the observer sphere, and other particles ($e^\pm$, nuclei) are vetoed (`ObserverElectronVeto`, `ObserverNucleusVeto`). Likewise, *Fermi*-LAT has an anti-coincidence detector which rejects charged particles (Atwood et al., 2009). The extensive air showers initiated by $e^\pm$ would be detected as gamma rays by IACTs, such as VERITAS, due to the similarity of the air shower development. However, $e^\pm$ lose energy through ICS interactions with the CMB (see Figure 6.6), so very few $e^\pm$ are expected to reach the observer sphere, and a negligible amount would be “detected” if $e^\pm$ were collected (Chapter 7). Lastly, the focus of this work is the contribution of cascade emission to fluxes in the energy range of *Fermi*-LAT, not IACTs.

The photons on the observer sphere were identified as primary (injected) or secondary (cascade) particles using the interaction type (logged by using `CRPropa`'s `CandidateTagColumn`). This was done because the time delay τ alone may not be enough to identify which particles are secondaries, due to the following three facts: secondary particles are initially launched in the same direction as their energetic parent, all particles move at the speed of light in `CRPropa`, and the simulations have large volumes with $B = 0$. Therefore, it is possible for cascade photons to arrive at the same time as primary photons, corresponding to $\tau = 0$.

6.5 Break Conditions

Via `setDeactivateOnDetection`, all particles are tracked until they cross the observer sphere, unless they meet any of the conditions below.

Particles are tracked for a maximum distance of $(1.5D_{\text{LoS}}) \times 10^3$ where D_{LoS} is the comoving distance to the source (in Mpc).

Particles with energies equal to or below 10^8 eV are not tracked.

`simCRpropa` calculates the minimum electron/positron rigidity R_{break} such that electrons/positrons with rigidity below R_{break} , on average, create photons via ICS (with the CMB) with energy below E_{break} . The rigidity R of a relativistic electron

of energy $E_e = \Gamma m_e c^2$ is

$$R = \frac{pc}{e} \approx \frac{E_e}{e} = \frac{\Gamma m_e c^2}{e}. \quad (6.7)$$

The electron Lorentz factor is computed using the average IC scattered photon energy E_{IC} , which is given by (Equation 2.14 of Coppi & Blandford (1990)),

$$E_{\text{IC}} \approx \frac{4}{3} \Gamma^2 E_{\text{bkg}}, \quad (6.8)$$

where the IC photon is produced by an electron with Lorentz factor Γ and a background photon of energy E_{bkg} . To calculate R_{break} , $E_{\text{IC}} = E_{\text{break}} = 10^8$ eV is adopted to determine the electron Γ and therefore E_e . Altogether,

$$R_{\text{break}} \approx \sqrt{\frac{3E_{\text{break}}}{4E_{\text{bkg}}}} \frac{m_e c^2}{e}, \quad (6.9)$$

where the `simCRpropa` default takes E_{bkg} to be the average energy of the CMB, rather than the EBL or URB. Although the interaction length for ICS with the CMB is three orders of magnitude shorter than that for ICS with the EBL, using the typical CMB energy as E_{bkg} does cause a small number of (would-be) IC photons with energy $> E_{\text{break}}$ to be lost to the break conditions, because their parent electron is not tracked (if it lies below R_{break}). The `simCRpropa`-determined

$R_{\text{break}} = 55.6$ GV, and to be slightly more conservative, particles with rigidity below 50 GV are not tracked. The impact of this choice is investigated with two small `CRPropa` simulations, each of which injects 500 electrons at $z = 0.1$ and solely allows them to ICS with the CMB, EBL, and URB—there is no energy loss due to the expansion of the universe, and the electrons travel through $B = 0$. The injected electrons have a flat energy distribution obtained by assigning each one an energy from a log-spaced distribution from $5 \times 10^{10} - 10^{13}$ eV. In one simulation, the electrons are tracked until $R_{\text{break}} = 100$ MV, which is aligned with $E_{\text{break}} = 10^8$ eV, and in the other the electrons are tracked until $R_{\text{break}} = 50$ GV. Note that the interactions in the simulation are not identical: the occurrence, if any, of an interaction, as well as the secondary IC photon energy, are randomly sampled. The result is in Figure 6.7. When the electrons are tracked until $R = 100$ MV, there is $\approx 66\%$ increase in the number of IC photons produced by interactions with the EBL than when electrons are tracked until $R = 50$ GV. This difference is moderate, but insignificant when compared to the number of IC photons produced by interactions with the CMB: $\mathcal{O}(10^4)$ for ICS off EBL versus $\mathcal{O}(10^6)$ for ICS off CMB. Therefore, $R_{\text{break}} = 50$ GV is used, rather than a lower value; this choice decreases computation time.

The minimum redshift sets the lower bound of the observer time window¹¹ and is set to $z_{\text{min}} = -10^{-3}$, corresponding to a comoving distance of 413 Mpc

¹¹ github.com/CRPropa/CRPropa3/sim4D.ipynb#L19

using the cosmology of 6.1, which ensures that particles $\approx 1.4 \times 10^7$ years into the future are tracked. This also satisfies the detection criteria outlined in Chapter 7, including cuts on the time delays of events.

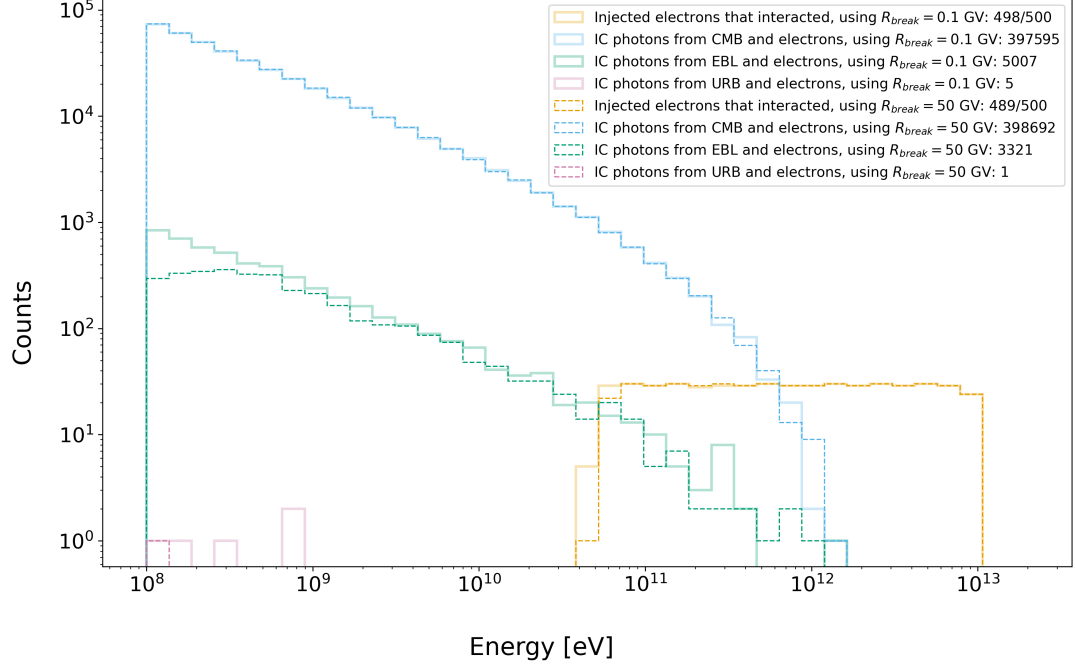


Figure 6.7: Counts spectra of simulated injected electrons (orange) and the counts spectra of secondary inverse Compton (IC) photons created by the injected electrons and the CMB (blue), EBL (green), and URB (pink). The dashed lines indicate events that are collected when using $R_{\text{break}} = 50$ GV. The solid, thicker, and reduced opacity lines indicate events that are collected when using $R_{\text{break}} = 100$ MV. The injected spectrum has no dependence on R_{break} , but the distinction between the two simulations is made in this figure as a reminder that the interactions are randomly sampled.

6.6 Magnetic Fields and their Evolution and Evaluation

`CRPropa` accounts for the evolution of magnetic fields via

$$B(z) = (1+z)^2(1+z)^m B(z=0), \quad (6.10)$$

where $(1+z)^2$ dilutes the field $B(z=0)(1+z)^m$ due to the expansion of the universe (Batista et al., 2016), m is (optionally) set by the user to incorporate additional redshift dependence (using `MagneticFieldEvolution`), and $B(z=0)$ is set by the user at each point on the comoving grid. In order to ensure the magnetic field is independent of redshift (that is, the magnetic field strength at the source is the same as the magnetic field strength at the observer), $m = -2$ is used. Altogether,

$$B(z) = B(z=0). \quad (6.11)$$

The result is that B is independent of redshift. $B(0)$ is set at each grid point in what follows.

The simulations specify a magnetic field value (magnitude and direction) at locations on a Cartesian grid, as the use of Cartesian coordinates is required by `CRPropa`. The functions that fill the grid are within `simCRpropa` (Meyer &

Splettstoesser, 2025). When a magnetic field grid is created in **CRPropa**, it must be created with either reflective or periodic boundary conditions. In this work, the grid starts at $\vec{0}$ (the location of the source) and unfolds in the first octant. Boundary conditions are applied in order to assign a magnetic field strength to grid points in all eight octants. The length of each side of a grid cell is set to ℓ (given in Table 6.1). In the case of $B = 0$ (i) and $z = 0.7$ a coherence length of $\ell = 50$ Mpc is used because the grid size is irrelevant (the field at an arbitrary point always evaluates to zero) and $\ell = 50$ Mpc drastically reduces the simulation time (several hours versus a couple of days). For the remaining simulations, $\ell = 1$ Mpc. A coherence length of $\ell = 1$ Mpc is used in **CRPropa** simulations in Aharonian et al. (2023) and Acharyya et al. (2026b), and is the assumed coherence length in Archambault et al. (2017). The center¹² of each cell is assigned the magnetic field $\vec{B}$ with a given magnitude B and a randomly chosen unit direction. The random directions are chosen with the same random seed¹³ (2541004132) to ensure reproducibility. In **CRPropa**, the grid is interpolated using trilinear interpolation (Alves Batista et al., 2022) in order to compute the magnetic field at any position $\vec{X}$ using the 8 grid points $\vec{B}(\vec{X}_i)$ nearest to the point $\vec{X}$. Note that the trilinear interpolation implemented in **CRPropa**¹⁴ does not

¹²https://crpropa.github.io/CRPropa3/api/classcrpropa_1_1Grid.html

¹³The random number was selected in accordance with best practices given by <https://blog.scientific-python.org/numpy/numpy-rng/>

¹⁴<https://paulbourke.net/miscellaneous/interpolation/>, as noted in **CRPropa** comments

preserve the vector magnitude. In the case of the constant magnitude $\mathcal{B}$ field set at each grid point, the trilinear interpolation tends to decrease $\mathcal{B}(\vec{X})$ at arbitrary $\vec{X}$ by $\approx 40 - 60\%$ ¹⁵.

The magnetic field configurations of the simulations are as follows.

- i Voidiness $V_{\text{LoS}} = 1$ with $B = 0$ everywhere.
- ii Voidiness $V_{\text{LoS}} \approx 0.50$ with $B = 0$ near the source and $B = 10^{-13}$ G near the observer; the source is in a void. The region with $B = 10^{-13}$ G is a rectangular prism. The field is shown in Figure 6.8. $B = 10^{-13}$ G is chosen as an extreme value for the IGMF. Note that ψ (defined in Section 6.3) must be small in order to satisfy $V_{\text{LoS}} \approx 0.50$ for every injected photon. The injected photons are launched with angle Ψ with respect to $\hat{x}$ (the central axis of the cone of injected photons), where $\Psi \leq \psi$; therefore, $V_{\text{LoS}} = \frac{1}{2 \cos \Psi}$.
- iii Voidiness $V_{\text{LoS}} \approx 0.50$ with $B = 10^{-13}$ near the source and $B = 0$ G near the observer; the observer is in a void. The region with $B = 10^{-13}$ G is a rectangular prism. The field is shown in Figure 6.9. In this case,

$$V_{\text{LoS}} = 1 - \frac{1}{2 \cos \Psi}.$$

- iv Voidiness $V_{\text{LoS}} = 0$ with $B = 10^{-13}$ G at every grid point. To reiterate,

due to trilinear interpolation, the magnitude B is not necessarily preserved

¹⁵https://github.com/spletts/PhDThesis/blob/main/trilinear_interpolation_coefficient_impact.ipynb

when evaluated at arbitrary grid locations.

Configurations ii and iii mimic half of the line of sight containing a void. Reflective (rather than periodic) boundary conditions are applied to the first octant to ensure that in one case the volume surrounding the source of injected photons has $B = 0$ (Figure 6.8), and in another case that the volume near the observer sphere has $B = 0$ (Figure 6.9). To probe the extreme case (maximal flux enhancement along the LoS within voids), the magnetic field in voids is set to $B_{\text{void}} = 0$. This was also done in Tjemsland et al. (2024). For comparison, the magnetic field strength in clusters is $\sim \mu\text{G}$ (Armengaud et al., 2007). Beck et al. (2013) state that the minimum magnetic field in voids is 10^{-15} G on Mpc scales. The field outside of voids is set to a large IGMF value, $B = 10^{-13}$ G, in order to study an extreme case. In each configuration i-iv, the grid is “padded” by two cells to prevent unwanted effects of interpolation (i.e., nonzero B assigned to locations on the edge of the grid and $B = 0$ assigned to locations at the center of the grid, which interpolates to $B \neq 0$ at the center—see Figure 6.11). Specifically, the grid is constructed with $\text{ceil}(D_{\text{LoS}}/\ell) + 2$ cells on each side. In the case of configuration ii, the edge of the grid is padded with two cells with $B = 0$. In the case of configuration iii, the edge of the grid is padded with two cells with $B = 10^{-13}$ G. When the grid is not padded, the resulting magnetic field in the case of ii is that of Figure 6.11. In the case of configuration i and iv, a constant B is supplied at each grid point, and the

grid is padded with two cells, each with magnetic field strength B .

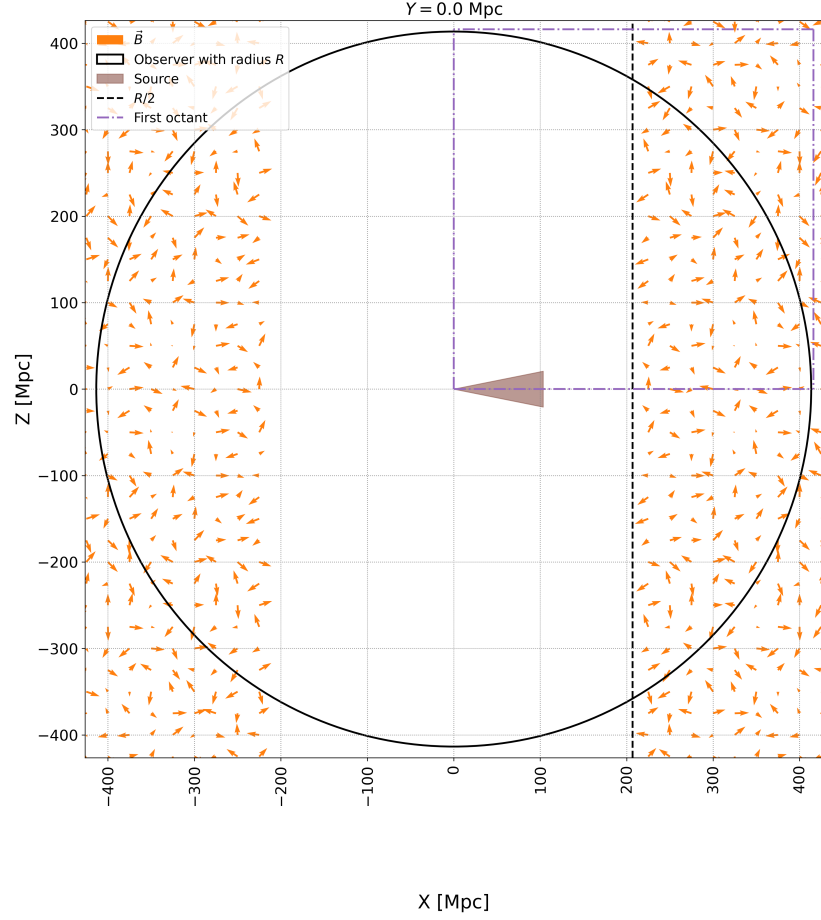


Figure 6.8: 2D slice in the XZ plane ($Y = 0$ Mpc) of magnetic field configuration ii for a magnetic field with coherence length $\ell = 1$ Mpc, constructed for a source at $z = 0.1$. The black circle represents the observer sphere (of radius $R = D_{\text{LoS}}$), the surface on which the photons are collected; particles are no longer tracked once they cross this surface. The brown triangle represents the source emission cone with central axis $+\hat{x}$ and an exaggerated opening angle. The magnetic field directions are indicated in orange. A magnetic field value is assigned to grid points in the first octant (dash-dotted purple) and reflective boundary conditions assign magnetic field values to the remaining octants.

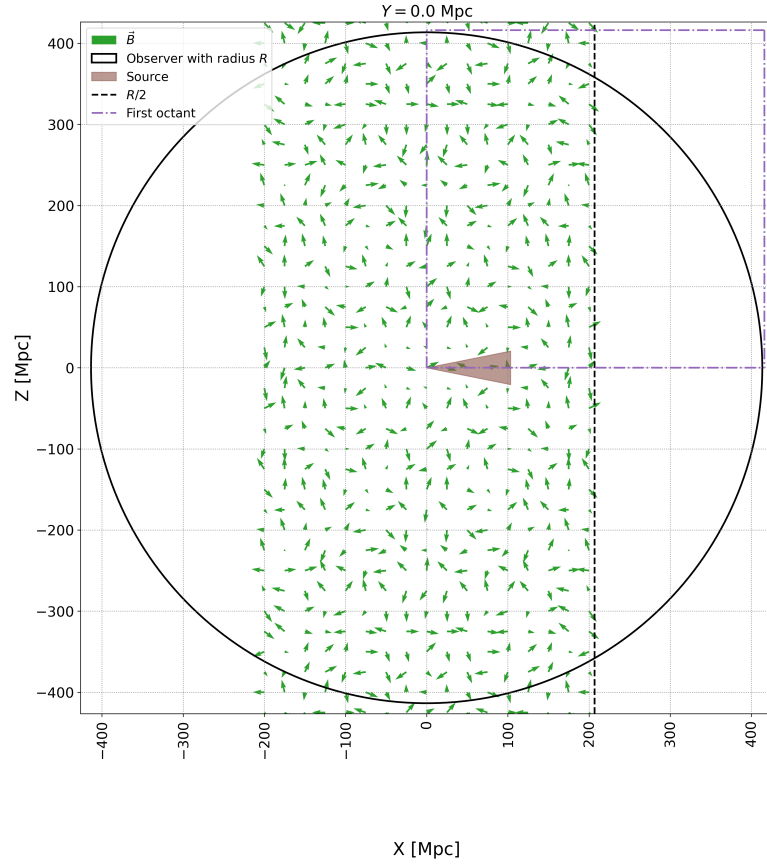


Figure 6.9: 2D slice of magnetic field configuration iii for a magnetic field with coherence length $\ell = 1$ Mpc, constructed for a source at $z = 0.1$.

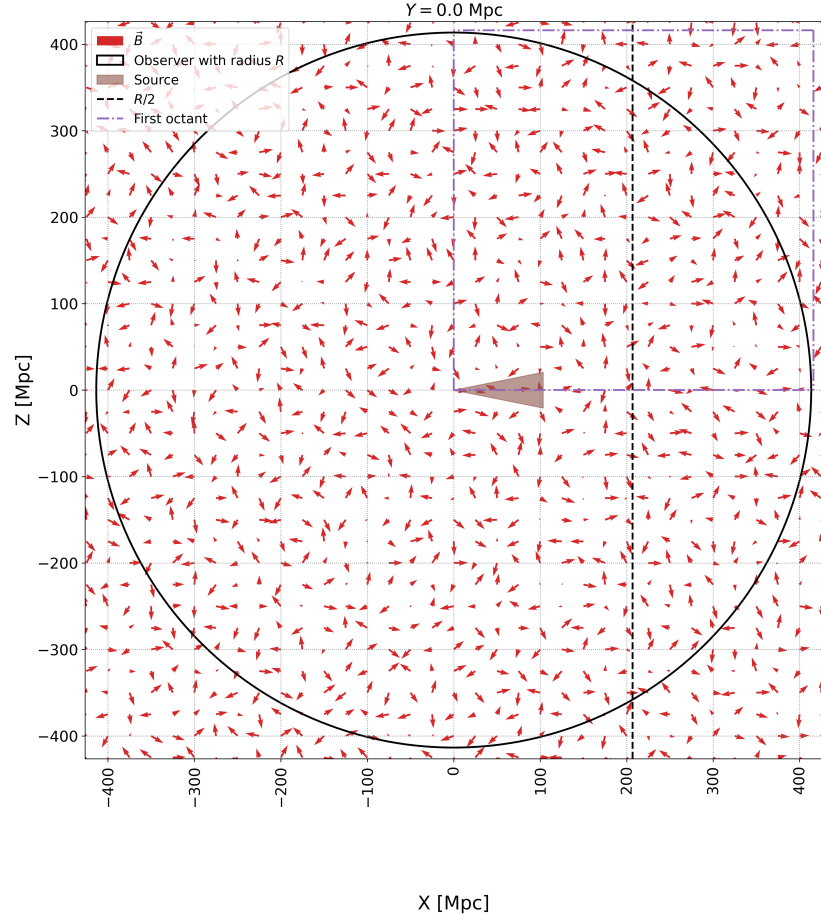


Figure 6.10: 2D slice of magnetic field configuration iv for a magnetic field with coherence length $\ell = 1$ Mpc, constructed for a source at $z = 0.1$.

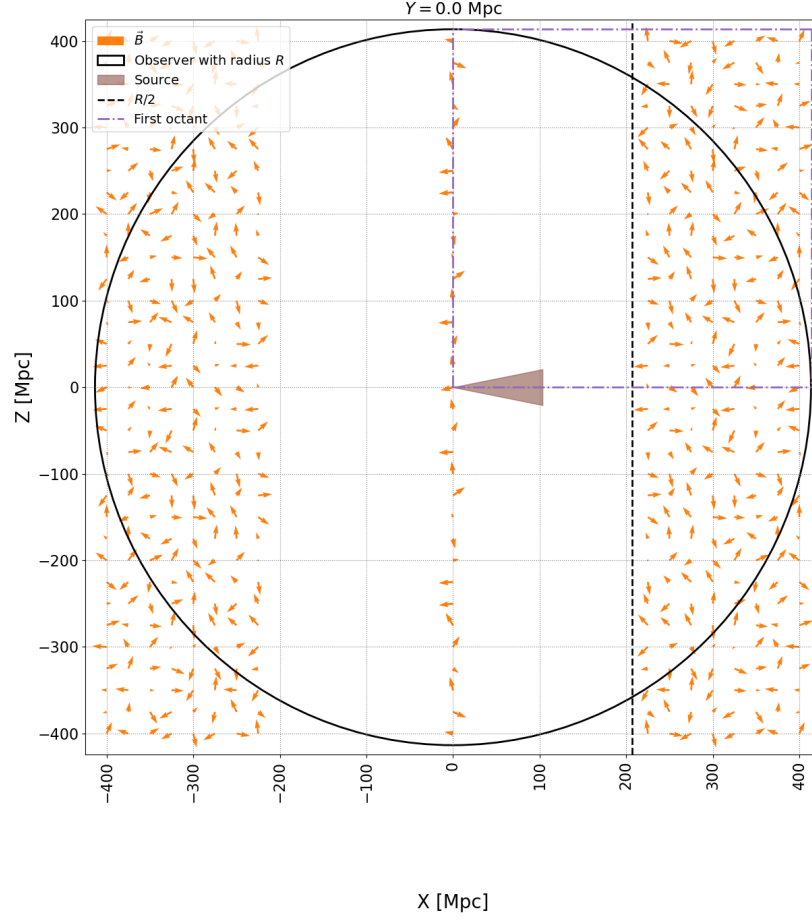


Figure 6.11: Similar to Figure 6.8, but without a padded grid. In this case, the nonzero magnetic field at the grid edges is interpolated to a nonzero field at the center of the grid.

Chapter 7

Analysis of CRPropa Simulations

When each event photon i hits the observer sphere, its position on the sphere $\vec{X}_i$, observed energy E_i , (unit vector) arrival momentum $\hat{P}_i$ (in units of $c = 1$), position of the injected primary photon $\vec{X}_{0,i}$ (which ultimately resulted in the photon event i), and (unit vector) momentum of the injected primary photon $\hat{P}_{0,i}$ are recorded, among other quantities given in Table 7.1. This work uses the terminology of **CRPropa** in which $\hat{P}$ is referred to as a momentum, but note that it is a unit vector indicating the momentum direction. Every photon is injected with $\vec{X}_{0,i} = \vec{0}$, the location of the “source” (Section 6.3). The photons are injected with momenta within a cone of half-opening angle ψ and central axis $\hat{x}$, where $\hat{x}$ is the standard Cartesian unit vector (see Section 6.3 for details about the injected source). This information is used to select events for detection using constraints

on their position, deflection angle, and time delay.

The code used for the analysis described in this chapter is `ana_simCRpropa` (Splettstoesser, 2025b).

Parameter	Description
D	Trajectory length [Mpc]
ID	Particle ID
E	Energy [eV]
$\vec{X} = (X, Y, Z)$	Position [Mpc]
$\hat{P} = (P_x, P_y, P_z)$	Unit vector of momentum
E_0	Energy at source [eV]
$\vec{X}_0 = (X_0, Y_0, Z_0)$	Position at source [Mpc]
$\hat{P}_0 = (P_{x,0}, P_{y,0}, P_{z,0})$	Unit vector of momentum at source
ID1	Particle ID at point of creation
W	Weights; because thinning $\eta = 0$, $W = 1$
tag	Indicates if the event is a primary or secondary

Table 7.1: Output quantities from `CRPropa` via `simCRpropa`. The user sets which parameters are included in the output file, as well as the corresponding units. A subscript 0 ($\vec{X}_0$, $\hat{P}_0$ and E_0) indicates that the quantity refers to its value at the source. No subscript (D , ID, E , $\vec{X}$, $\hat{P}$) indicates that the quantity is current (that is, its value at the observer sphere). The definitions are from the header of `CRPropa`’s `TextOutput` file.

7.1 “Detection” of Events on the Large Observer Sphere

Events on the observer sphere were selected as “detected” if they met the following criteria:

- i The event i is on the surface of the spherical cap (the cyan surface in Figure 7.1) formed by the observer sphere and source emission cone of half-opening angle ψ (the cone that defines the momentum of injected photons). That is, $\beta = \arccos(\hat{x} \cdot \hat{r}_i) \leq \psi$, where $\hat{r}_i$ is the radial spherical unit vector that points along the line of sight from $\vec{X}_{0,i}$ to $\vec{X}_i$; $\hat{r}_i = \frac{\vec{X}_i - \vec{X}_{0,i}}{|\vec{X}_i - \vec{X}_{0,i}|}$. The angle β is depicted in Figure 7.1.
- ii The deflection angle δ_i , defined as the angle between the arrival momentum and the line of sight, is within the *Fermi*-LAT 95% acceptance weighted total PSF. The PSF is plotted in Figure 7.2, and the deflection angle is illustrated in Figure 7.3. Mathematically, the criterion is: $\delta_i = \arccos(\hat{P}_i \cdot \hat{r}_i) \leq \text{PSF}(E_i)$, where $\text{PSF}(E_i)$ is the energy-dependent *Fermi*-LAT PSF.
- iii The time delay $\tau = \frac{D - D_{\text{LoS}}}{c}$ satisfies $\tau \leq 10^7$ years, where D is the total trajectory length and $D_{\text{LoS}} \equiv D_{\text{LoS}}(z)$ is the direct distance from the source to the observer.

By definition, all primary photons that reach the observer sphere satisfy criterion i. The central axis of the source emission cone (**SourceEmissionCone**) is $\hat{x}$, the unit vector from the injected photon to the event on the observer sphere is

$\hat{r}_i$, and the angle β_i between these vectors is

$$\cos \beta_i = \hat{x} \cdot \hat{r}_i = \hat{x} \cdot \frac{\vec{X}_i - \vec{X}_{0,i}}{|\vec{X}_i - \vec{X}_{0,i}|}. \quad (7.1)$$

The condition for an event to be within the source emission cone is $\beta_i \leq \psi$. The physical sizes (cone radii and collection surface area) involved in collecting events on observer spheres of different radii are in Table 7.2.

Redshift z	Cone radius [Mpc]	Collection area [Mpc ²]
0.1	0.7	1.6
0.4	2.7	22.8
0.7	4.4	60.1

Table 7.2: Physical sizes involved in “detecting” events on the large observer sphere. The cone radius $D_{\text{LoS}} \sin \psi$ is its radius at the intersection of the observer sphere. The observer sphere has radius D_{LoS} . The cosmology used to calculate D_{LoS} is stated in Section 6.1. The collection area is the surface area of the spherical cap $2\pi D_{\text{LoS}}^2 (1 - \cos \psi)$.

Criterion ii concerns the deflection angle δ_i , the angle between the line of sight $\hat{r}_i$ and the arrival momentum $\hat{P}_i$, as shown in Figure 7.3. The deflection is given by

$$\cos \delta_i = \hat{P}_i \cdot \hat{r}_i = \hat{P}_i \cdot \frac{\vec{X}_i - \vec{X}_{0,i}}{|\vec{X}_i - \vec{X}_{0,i}|}. \quad (7.2)$$

The PSF describes the ability of the instrument to reconstruct the arrival direction of gamma rays emitted from a point source, so events with deflection angle within

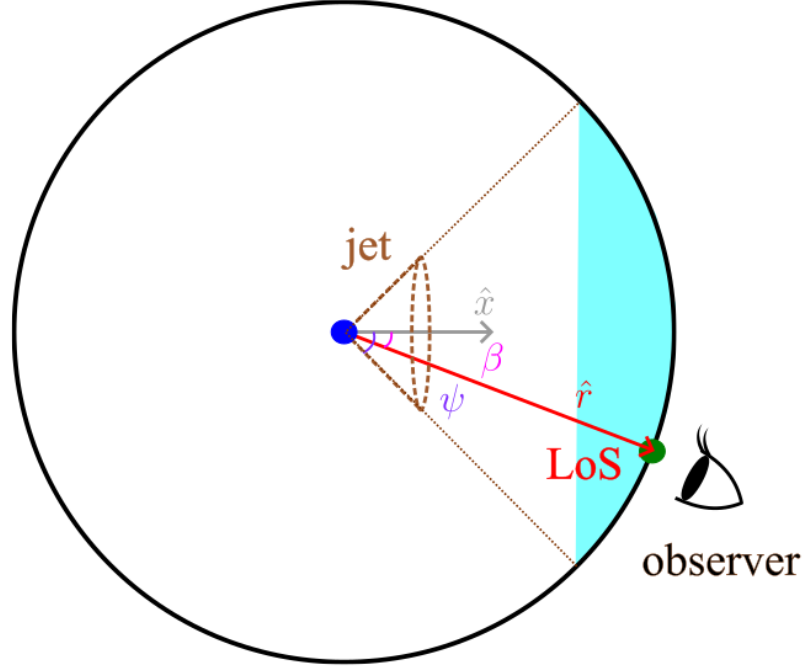


Figure 7.1: Illustration of the angle β (magenta) between the jet axis $\hat{x}$ (grey) and the line of sight $\hat{r}$ (red) for a photon event at the location marked in green on the observer sphere. The primary photon is injected at the location indicated in blue ($\vec{0}$). The half-opening angle of the jet is ψ (purple), and the jet (**SourceEmissionCone**) itself is bounded by dashed brown lines. The spherical cap (cyan) is the surface formed by the intersection of the cone (of injected photons) with the large observer sphere. The sides of the cone are extended (dotted brown) to better show the intersection with the sphere. Detection criterion i requires $\beta \leq \psi$.

the *Fermi*-LAT 95% acceptance weighted total PSF are selected, via $\delta_i \leq \text{PSF}(E_i)$.

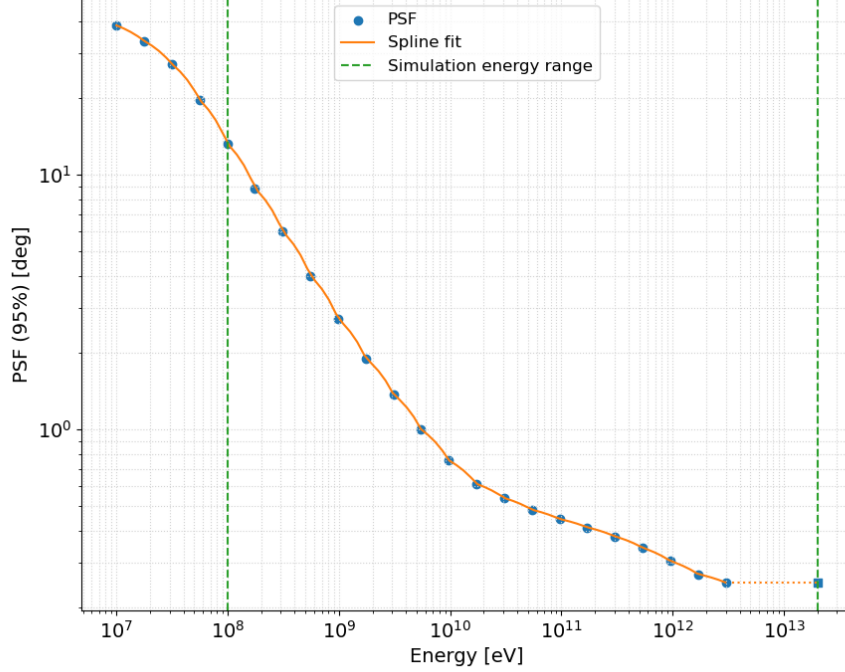


Figure 7.2: *Fermi*-LAT 95% acceptance weighted PSF (blue circles), obtained from Maldera et al. (2021). The blue square shows the PSF extrapolation. The orange solid line is the interpolated fit to the PSF (`scipy.interpolate.InterpolatedUnivariateSpline` with polynomial order $k = 1$) used in criterion ii. The orange dotted line illustrates that the spline fit at the corresponding energies is extrapolated beyond the extent of the *Fermi*-LAT PSF. The dashed green lines indicate the minimum and maximum injected energy in the simulations.

The extent of the *Fermi*-LAT 95% PSF is $E_{\text{max}} = 3$ TeV; in this work, above 3 TeV the PSF is extrapolated as a constant equal to the value of the PSF at E_{max} , where $\text{PSF}(E_{\text{max}}) \approx 0.251^\circ$. The extrapolation of the PSF impacts very few events; the number of events above 3 TeV that reach the observer sphere

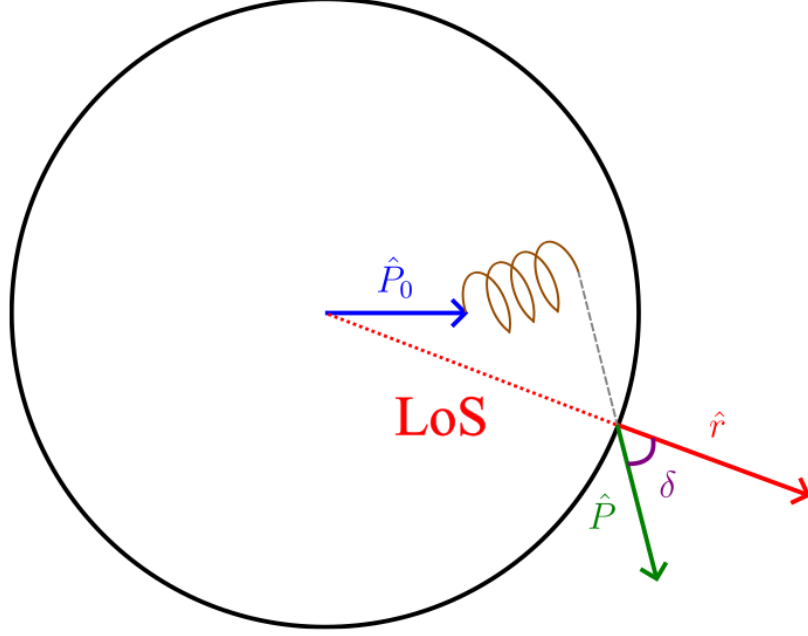


Figure 7.3: Illustration of the deflection angle δ (purple), defined as the angle between the line of sight $\hat{r}$ (red) and the arrival photon momentum $\hat{P}$ (green). At the center of the observer sphere (black) is the source. An injected primary photon travels in direction $\hat{P}_0$ (blue line) for some distance before pair producing, at which point the path of one of the charged particles in the pair is shown (in brown), assuming a constant magnetic field (magnitude and direction). The charged particle travels until it IC scatters, and the resulting IC photon travels (along the dotted grey line) until it reaches the observer sphere with arrival momentum along $\hat{P}$ (assuming the IC photon itself does not PP). Detection criterion ii requires $\delta \leq \text{PSF}(E)$ for an event with energy E .

and satisfy criterion i is less than 200 in all simulations considered in this work. Simulations of sources at $z \geq 0.4$ did not result in any events above 3 TeV meeting criterion i.

The effective area of the *Fermi*-LAT is not considered, meaning that a 100% detector efficiency is assumed, neglecting instrument deadtime as well as the dependence of effective area on energy and incidence angle.

Note that, as defined by `CRPropa`, $\hat{P}_i$ should be a unit vector. However, `CRPropa`'s `TextOutput` saves numbers to five digits after the decimal place.¹ In addition, due to the limitations of representing 64-bit floating-point numbers, a typical magnitude of this vector is, for example, 1.0000000167262335. Therefore, Equations 7.1 and 7.2 are evaluated as

$$\cos \beta_i = \frac{\hat{x} \cdot \hat{r}_i}{|\hat{x}| |\hat{r}_i|} \quad (7.3)$$

and

$$\cos \delta_i = \frac{\hat{P}_i \cdot \hat{r}_i}{|\hat{P}_i| |\hat{r}_i|}, \quad (7.4)$$

respectively. Then, the dot products are clamped (via `numpy.clip`) such that $\cos \delta_i > 1$ is set to 1, and $\cos \delta_i < -1$ is set to -1 (and similarly for $\cos \beta_i$).

¹github.com/CRPropa/CRPropa3/TextOutput.cpp#L175

The time delay τ of “detected” events is constrained to $\tau \leq 10^7$ years, which was done in Aharonian et al. (2023). It is assumed that the source of injected photons is steadily emitting and does not undergo flaring states.

In summary, events are accepted if they are on the spherical cap formed by the large observer sphere and the source emission cone, if their deflection angle is within the *Fermi*-LAT 95% confidence level (containment angle) PSF, and if their time delay is $\leq 10^7$ years. **ELMAG** (Blytt et al., 2020) is another Monte Carlo code that propagates high-energy photons and models their interactions over cosmological distances; ELMAG discards events that do not meet criterion i, and defines the deflection angle as in ii. Therefore, **ELMAG** supports the use of the criteria i and ii. However, through criterion i, the choice of the cone half-opening angle ψ impacts the area over which cascade photons are selected (and potentially detected). The impact of this on the results presented in Chapter 8 is discussed in Section 8.3.4.

7.2 Energy Flux Per Decade

The binned energy flux per decade $E^2 \frac{dN}{dE}$ is calculated in arbitrary units as follows². The number of events $\mathcal{N}$ within an energy bin bounded by $[E_{\text{low}}, E_{\text{high}}]$

²The calculation follows the CRPropa documentation, https://crpropa.github.io/CRPropa3/pages/example_notebooks/photon_propagation/cascade_1d.html.

is

$$\mathcal{N} = \int_{E_{\text{low}}}^{E_{\text{high}}} \frac{dN}{dE} dE, \quad (7.5)$$

and if $\frac{dN}{dE}$ does not vary much within the individual bins, the midpoint rule is applicable,

$$\mathcal{N} = \left. \frac{dN}{dE} \right|_{E_{\text{center}}} \Delta E \quad (7.6)$$

(for further reading see e.g. Freedman & Diaconis (1981); Wasserman (2006)).

Logarithmic bins are constructed; that is, bins which are equally spaced in $\log_{10}$ space are constructed. Within each bin, the number of events $\mathcal{N}$ within the bin is computed (using `numpy.histogram`), by changing variables from Equation 7.5 ($E \rightarrow \log_{10} E$) and applying the approximation in Equation 7.6,

$$\mathcal{N} = \int_{\log_{10}(E_{\text{low}})}^{\log_{10}(E_{\text{high}})} \frac{dN}{d(\log_{10} E)} d(\log_{10} E) \quad (7.7)$$

$$\mathcal{N} = \left. \frac{dN}{d(\log_{10} E)} \right|_{E_{\text{center}}} \Delta(\log_{10} E) \quad (7.8)$$

$$\Rightarrow \left. \frac{dN}{d(\log_{10} E)} \right|_{E_{\text{center}}} = \frac{\mathcal{N}}{\Delta(\log_{10} E)}. \quad (7.9)$$

To compute the energy flux per decade,

$$E^2 \frac{dN}{dE} = E^2 \frac{dN}{d(\log_{10} E)} \frac{d(\log_{10} E)}{dE} \quad (7.10)$$

$$= E^2 \frac{dN}{d(\log_{10} E)} \frac{1}{E \ln(10)} \quad (7.11)$$

$$= E \frac{dN}{d(\log_{10} E)} \frac{1}{\ln(10)} \quad (7.12)$$

$$= E \frac{\mathcal{N}}{\Delta(\log_{10} E)} \frac{1}{\ln(10)} \quad (7.13)$$

$$= E \frac{\mathcal{N}}{\log_{10}(E_{\text{high}}) - \log_{10}(E_{\text{low}})} \frac{1}{\ln(10)} \quad (7.14)$$

where E is chosen to be the linear bin center E_{center} , following **CRPropa** documentation³. For the SEDs presented in this work, with 40 bins, the difference between the linear bin center E_{lin} and log bin center E_{log} , $\frac{|E_{\text{lin}} - E_{\text{log}}|}{E_{\text{lin}}}$, is $< 2\%$. Altogether,

$$E^2 \frac{dN}{dE} = \left(\frac{E_{\text{high}} + E_{\text{low}}}{2} \right) \frac{\mathcal{N}}{\log_{10}(E_{\text{high}}/E_{\text{low}})} \frac{1}{\ln(10)}. \quad (7.15)$$

The energy fluxes per decade presented in this work are calculated using Equation 7.15.

³As in https://crpropa.github.io/CRPropa3/pages/example_notebooks/photon_propagation/cascade_1d.html

7.3 Injected Spectrum

In total, N_T primary events are injected from $E_{\min}$ to $E_{\max}$ with index $\alpha = -1.5$ (see Section 6.3) according to $\frac{dN}{dE} \propto E^\alpha$, where the **CRPropa** convention of E^α (rather than $E^{-\alpha}$) is used. In the source frame, $\frac{dN}{dE} = KE^\alpha$. The normalization K of the injected spectrum is therefore

$$N_T = \int_{E_{\min}}^{E_{\max}} \frac{dN}{dE} dE \quad (7.16)$$

$$N_T = K \int_{E_{\min}}^{E_{\max}} E^\alpha dE \quad (7.17)$$

$$\Rightarrow K = N_T \left(\int_{E_{\min}}^{E_{\max}} E^\alpha dE \right)^{-1}. \quad (7.18)$$

In the observer frame, using $E_{\text{obs}} = (1+z)^{-1}E$ and $dE_{\text{obs}} = (1+z)^{-1}dE$, where E is the energy in the source frame, the energy flux per decade of the injected spectrum in the observer frame is given by

$$E^2 \frac{dN}{dE} \Big|_{\text{obs}} = [(1+z)E]^2 \frac{dN}{(1+z)dE} \quad (7.19)$$

$$= (1+z) \left(KE^{2+\alpha} \right). \quad (7.20)$$

The intrinsic energy fluxes per decade in this work are plotted in the observer frame (using Equation 7.20) versus $(1+z)E$.

Chapter 8

Results and Discussion

This chapter contains the results of the **CRPropa** simulations outlined in Table 6.1 and analyzed as described in Chapter 7.

In this chapter, “detected” photons are defined as photons that pass the criteria in Section 7.1. “All” photons include both detected and not-detected photons, such that “all cascade photons” refers to all cascade photons on the observer sphere. The “total” refers to the total contribution from both primary and cascade photons. This terminology is depicted in Figure 8.1. “Primary” photons implicitly refer to the primary photons that reached the observer sphere (which is distinct from the injected photons). When a source is said to be “in a void,” this refers to configuration ii (from Section 6.6), meaning the source is in a magnetic field as pictured in Figure 6.8, with $V_{\text{LoS}} = 0.50$ and $B = 10^{-13}$ G near the observer.

Similarly, when the observer is said to be “in a void,” this refers to configuration iii (from Section 6.6), meaning the source is in a magnetic field as pictured in Figure 6.9, with $V_{\text{LoS}} = 0.50$ and $B = 10^{-13}$ G near the source. Figure 8.2 portrays “source in void” and “observer in void.” Lastly, in this chapter, “electrons” refers to both electrons and positrons.

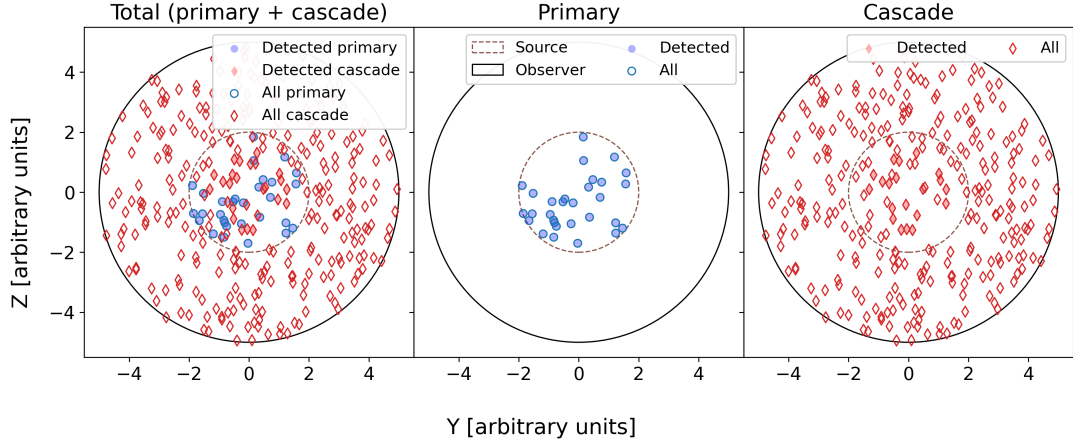


Figure 8.1: Illustration (with fake events) of the definitions of “all,” “detected” and “total” used in this chapter. Left: “All total photons” (unfilled markers) and “detected total photons” (filled markers) on the observer sphere. “Total” includes both the primary ($\circ$ markers) photons and the cascade ($\diamond$ markers) photons. “All total photons” refers to each and every photon on the observer sphere. “All detected photons” are a subset of all total photons. Middle: “All primary photons” (unfilled $\circ$) and “detected primary photons” (filled $\circ$). Every primary photon is necessarily detected. The observer sphere is indicated with a black circle. The brown dashed circle indicates criterion i (from Section 7.1). Right: “All cascade photons” (unfilled $\diamond$) and “detected cascade photons” (filled $\diamond$).

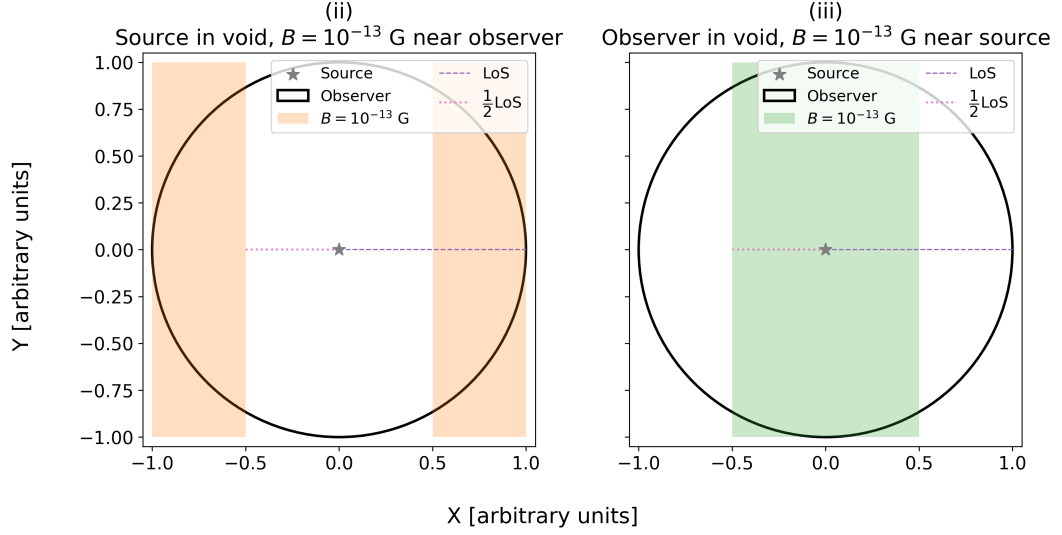


Figure 8.2: Illustration of “source in void” (ii; left) and “observer in void” (iii; right). The shaded regions indicate where $B \neq 0$, and the unfilled regions indicate $B = 0$. The line of sight (dashed purple) extends from the source (gray star) to any point on the observer sphere (black circle). The distance of half the line of sight $\frac{1}{2}\text{LoS}$, which is the same as $\frac{1}{2}D_{\text{LoS}}$, is shown (dotted pink) to emphasize $V_{\text{LoS}} = 0.50$. Note that ii is shaded in orange because in this chapter spectra pertaining to ii are in orange, and iii is shaded in green because spectra pertaining to iii are in green.

8.1 Overview of Dominant Interactions and Relevant Distances

8.1.1 Impact of Magnetic Field

Recall from Section 6.2.2 that the dominant interactions (ICS, PP, and expansion of the universe) do not require a magnetic field in order to occur, so in the simulations described in Chapter 6 the exclusive role of the magnetic field is deflecting charged particles. The deflection depends on the (random) direction of $\vec{B}$ and the electron energy E_e , which determine the Larmor radius r_L . r_L decreases with decreasing energy—see Figure 6.1—and therefore the momentum direction changes more quickly for a low-energy electron than a high-energy electron. For a fixed redshift, the SED of primary photons in each magnetic field configuration is expected to be nearly identical because the interactions governing the energy loss of primary photons do not depend on the magnetic field—this is explored more in Section 8.2. Additionally, for a fixed redshift and without constraint on the time delay τ (which is constrained by $z_{\min}$ of Section 6.5 and criterion iii of Section 7.1), the number of “all” cascade photons arriving at the observer sphere does not depend on $\vec{B}$.

8.1.2 Impact of Redshift

The interactions are redshift-dependent. The interaction length $\lambda(z)$ depends on redshift z because the photon fields are denser at earlier times (larger redshifts) and because of the cosmological evolution of the EBL and CMB (Equation 6.4); at larger z , the PP and ICS interactions are more frequent, as shown in Figures 8.3 and 8.4. The redshift dependence means that λ is not constant along the LoS; primary photons are injected at $z > 0$, and so λ is shorter (and interactions more frequent) near the source than near the observer. Additionally, due to the energy dependence of λ (particularly λ_{PP}), a greater number of the injected photons are likely to PP at larger z : Figure 8.3 shows that at $z = 0.7$ photons with energy $\gtrsim 10^{11}$ eV have PP interaction lengths shorter than the distance remaining to the observer, whereas at $z = 0.1$ photons with energy $\gtrsim 10^{12}$ eV meet the same criterion. Lastly, more photons are injected at 10^{11} eV than 10^{12} eV because the injected spectrum is $\frac{dN}{dE} \propto E^{-1.5}$. These effects enhance the entire cascade at larger z . However, detected particles that were injected at larger z lose more energy due to the expansion of the universe than those created at smaller z . This is illustrated in Figure 8.5. The impact of z on the total number of cascade photons on the observer sphere is discussed in Section 8.3.3.

Of course, the redshift also determines the comoving distance a particle must travel before reaching the observer sphere.

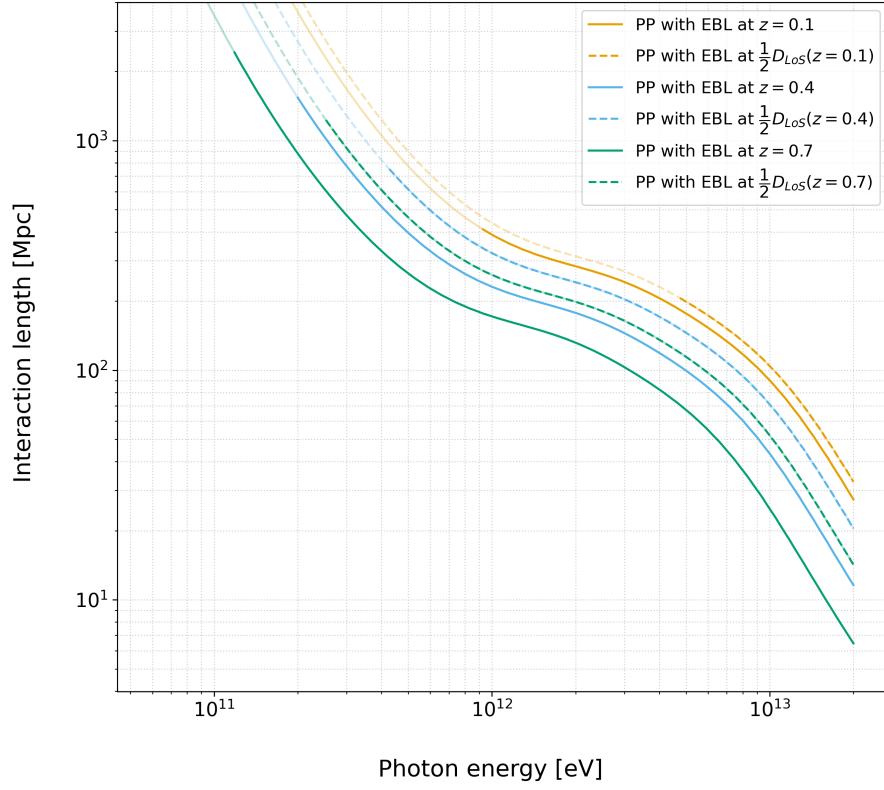


Figure 8.3: Interaction lengths λ for pair production (PP) with the EBL at various z . The solid lines correspond to λ at the source: $z = 0.1$ (orange), $z = 0.4$ (blue), and $z = 0.7$ (green). The dotted lines correspond to λ at the comoving distance halfway between the source and the observer: $\frac{1}{2}D_{\text{LoS}}(z)$. The lines have reduced opacity where λ is larger than the distance remaining to the observer.

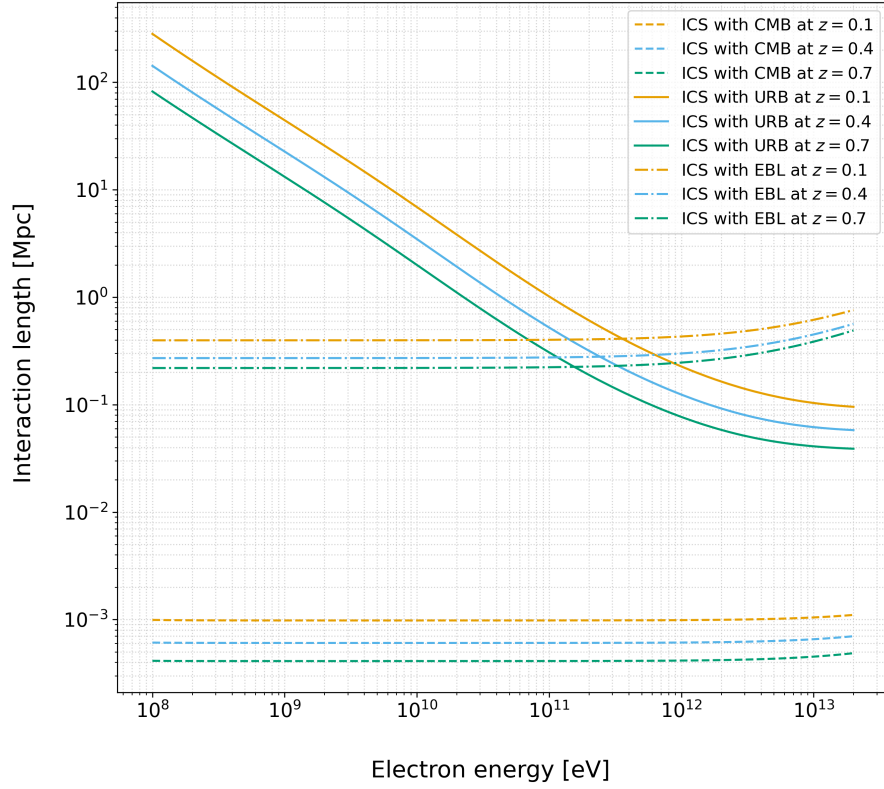


Figure 8.4: Interaction lengths for inverse Compton scattering (ICS) of electrons off CMB photons (dashed), ICS off URB photons (solid), and ICS off EBL photons (dashed-dotted) at various redshifts: $z = 0.1$ (orange), $z = 0.4$ (blue), and $z = 0.7$ (green).

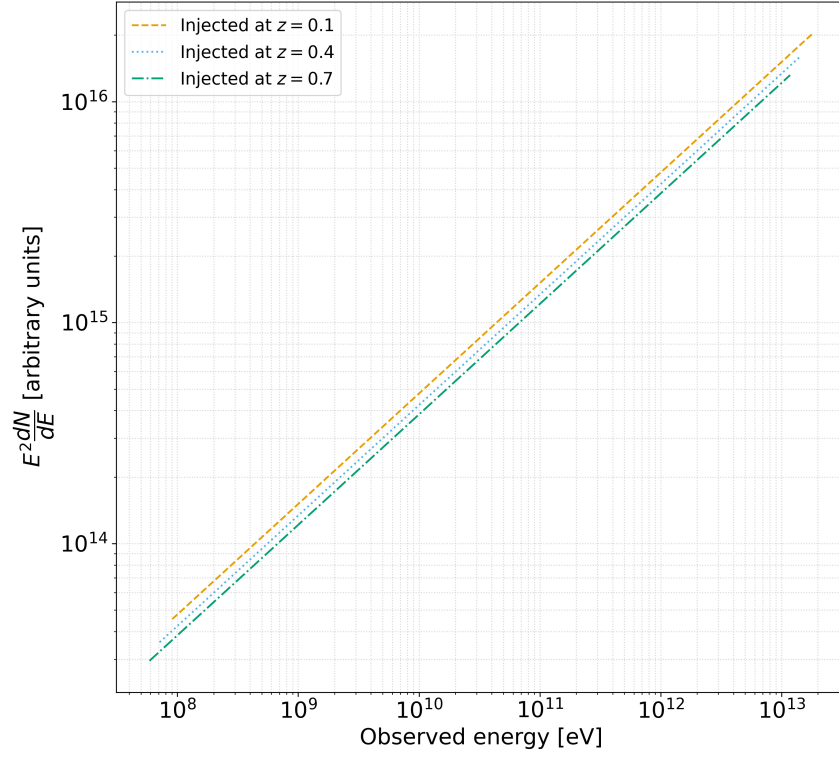


Figure 8.5: Injected SEDs in the observer frame for a source at $z = 0.1$ (dashed orange), $z = 0.4$ (dotted blue), and $z = 0.7$ (dashed-dotted green). The injected SED is given by Equation 7.20.

8.1.3 Impact of Distance Traveled

For a fixed voidiness $V_{\text{LoS}} = 0.50$, each source redshift corresponds to a different comoving distance traveled through $B = 0$ and $B \neq 0$, and therefore a different volume over which a charge will be deflected. Table 8.1 gives the comoving distance along the LoS with $B = 0$ for each redshift and for each magnetic field configuration, and grid cells of side length $\ell = 1$ Mpc; ℓ sets the resolution of the magnetic field grid and the maximum distance over which B drops to zero when interpolated between a cell with $B = 10^{-13}$ G and $B = 0$. Of interest is the approximate distance an electron travels in the **CRPropa** simulations. An approximation of this distance is achieved with a small **CRPropa** simulation of 1,000 electrons with solely ICS (off the EBL, CMB, and URB) enabled, and each electron tracked until the break conditions in Section 6.5 are reached. Once an electron is created, it travels $\lesssim 1$ Mpc before the first ICS interaction, and it can produce up to $\approx 10^3$ photons with energy $> 10^8$ eV (E_{break}) via ICS, depending on the electron's initial energy. The resulting distance an electron travels in the simulations is shown in Figure 8.6, which suggests that most travel > 1 Mpc. Therefore, in the case of ii and iii, electrons created in an environment where $B = 0$ can travel to an environment where $B \neq 0$ and ICS. If ICS begins in one half of the LoS, it is not necessarily limited to that half of the LoS.

z at source	z at $\frac{1}{2}D_{\text{LoS}}$	D_{void} in Magnetic Field Configuration [Mpc]			
		i	ii	iii	iv
0.1	0.05	413.5	206.7	206.7	0
0.4	0.19	1543.0	771.5	771.5	0
0.7	0.32	2505.3	1252.7	1252.7	0

Table 8.1: For a source at redshift z , D_{void} is the comoving distance along the LoS with $B = 0$ (which is a proxy for the amount of void along the LoS) in each magnetic field configuration (i-iv from Section 6.6). The second column is the redshift at which the comoving distance is equal to $\frac{1}{2}D_{\text{LoS}}$, which, in the case of ii and iii, corresponds to the approximate distance from the source at which the magnetic field changes from $B = 0$ to $B \neq 0$ (or vice versa).

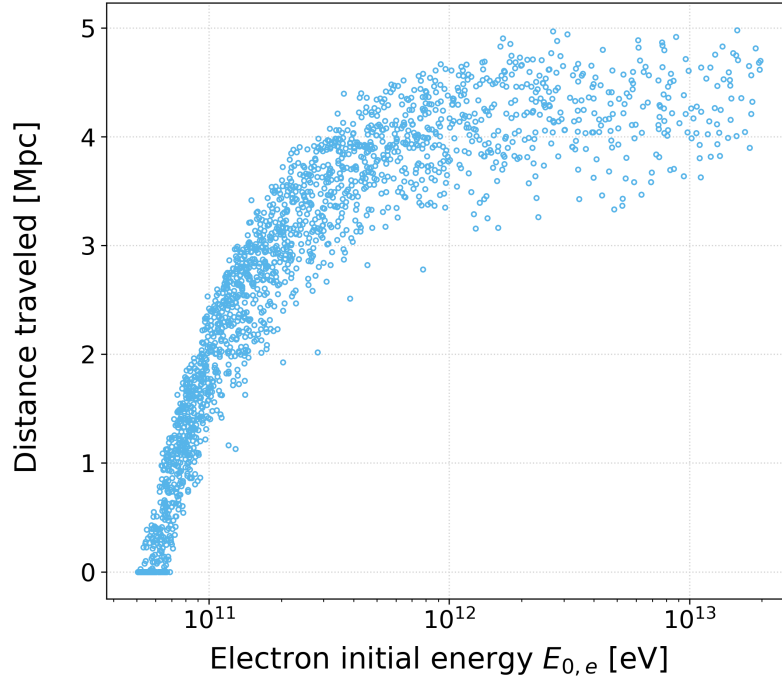


Figure 8.6: Estimate of the distance an electron with initial $E_{0,e}$ travels between the first and last tracked ICS interaction—tracked using the break conditions of Section 6.5.

8.2 (Detected) Primary Photons

By the criteria established in Section 7.1, all primary photons that reach the observer sphere are detected. The creation and launching of secondary photons in `CRPropa` have several random components. Although the number of primary photons is unaffected by $\vec{B}$, different interactions occur in different simulations. Therefore, the SEDs of primary photons from simulations with magnetic field configurations i-iv (from Section 6.6) may not be identical at energies above the threshold for PP with the EBL due to the randomness involved in selecting when and if PP occurs (see Section 6.2.2). Furthermore, in PP interactions, both the squared center-of-mass energy of the interaction and the electron's energy are sampled randomly¹. The injected photon energy of each photon is also randomly² selected, but this effect ought to be negligible when a large number of particles are injected. For completeness, Figures 8.7-8.9 contain the counts spectra of primary photons for each magnetic field configuration for redshifts $z = 0.1$, $z = 0.4$, and $z = 0.7$, respectively, as well as the difference in counts. Figures 8.7-8.9 illustrate that the series of interactions in each simulation is not identical.

¹github.com/CRPropa/CRPropa3/EMPairProduction.cpp#L200,
github.com/CRPropa/CRPropa3/EMPairProduction.cpp#L161

²github.com/CRPropa/CRPropa3/Source.cpp#L142

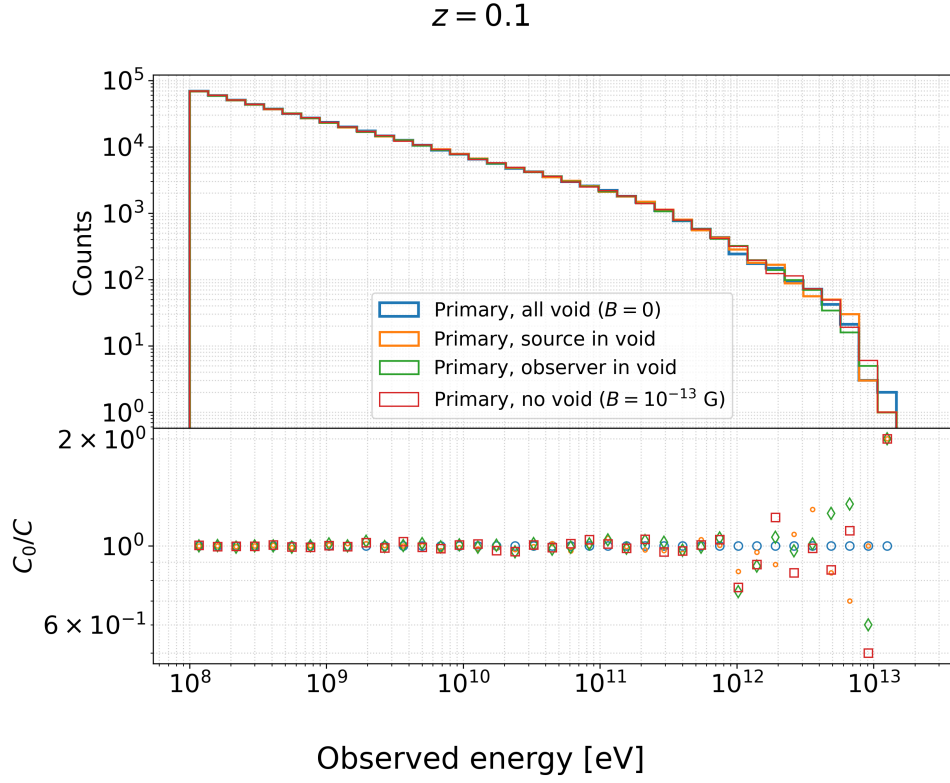


Figure 8.7: Upper: Counts spectra of primary photon energies for a source at $z = 0.1$, for each magnetic field configuration: i (blue), ii (orange), iii (green) and iv (red) for a source at $z = 0.1$. Lower: Ratio of the counts C_0 in the $B = 0$ configuration (i) to the counts C in each magnetic field configuration, indicated with the same color as the upper plot.

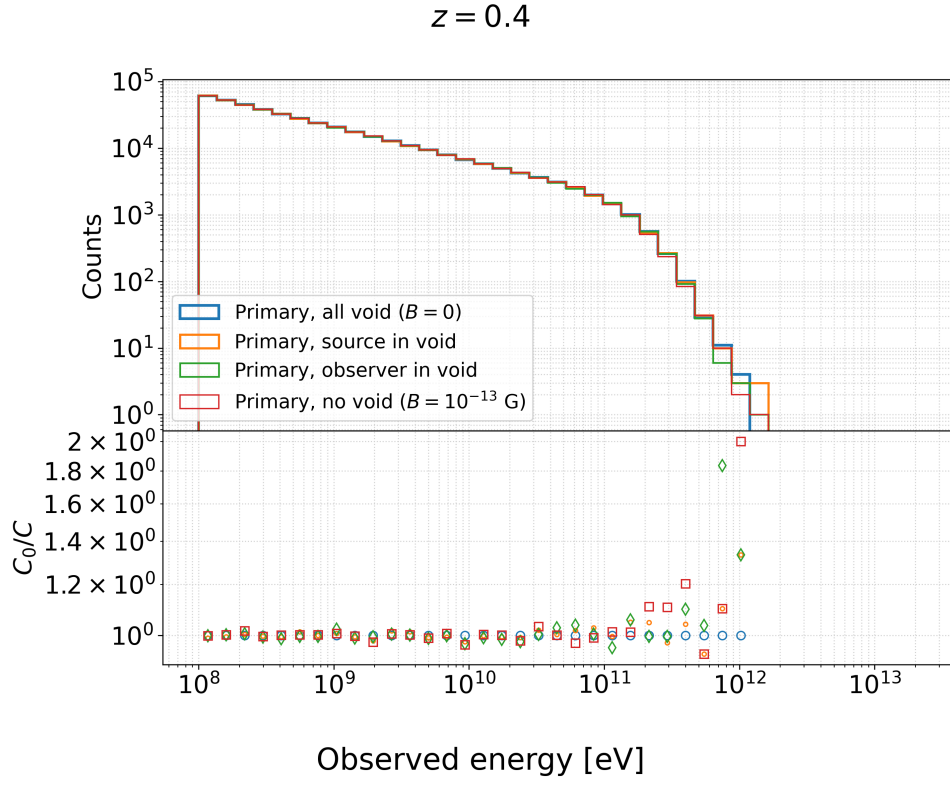


Figure 8.8: Same as Figure 8.7 but for a source at $z = 0.4$.

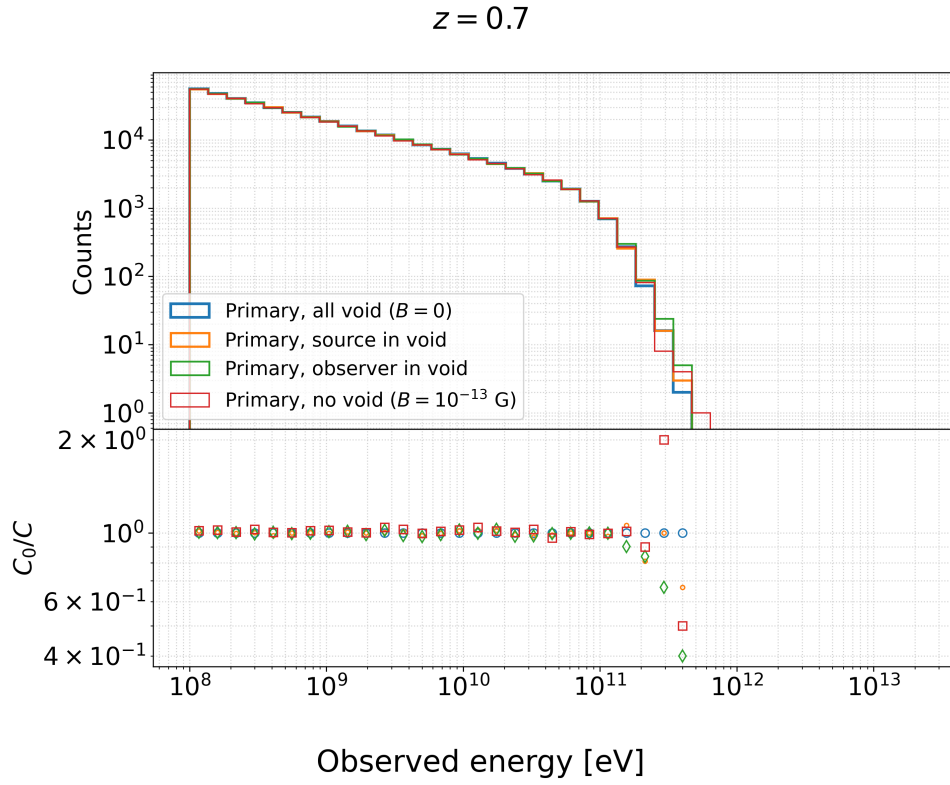


Figure 8.9: Same as Figure 8.7 but for a source at $z = 0.7$.

8.3 Detected Cascade Photons

Because, for a fixed source redshift, the SED of primary photons does not depend on $\vec{B}$, only one primary SED is shown in the figures in this section and onward (rather than one per magnetic field configuration). The SED of **detected** cascade photons depends on $\vec{B}$ because of the detection criteria of Section 7.1. If no detection constraints and no break conditions (e.g., $z_{\min}$) are enforced such that **all** cascade photons are considered, the SEDs of cascade photons from simulations with each of the magnetic field configurations are very similar for a fixed redshift.

Recall that, as discussed in Section 6.2.2, a PP interaction destroys the gamma ray; therefore, an injected photon can undergo maximally one PP interaction. Further, the first interaction must be a PP interaction; no electrons exist in the simulations until they are created by PP.

8.3.1 Sources at $z = 0.1$

Figure 8.10 contains the counts spectra of detected cascade photons for the magnetic field configurations i, ii, iii, and iv, for a source at $z = 0.1$. In Figure 8.10, the extreme cases of $B = 0$ (no deflection; i) and $B = 10^{-13}$ G (maximal deflection; iv) bracket the intermediate cases of source in void (ii) and observer in void (iii). More electrons are produced near the source than near the observer due to

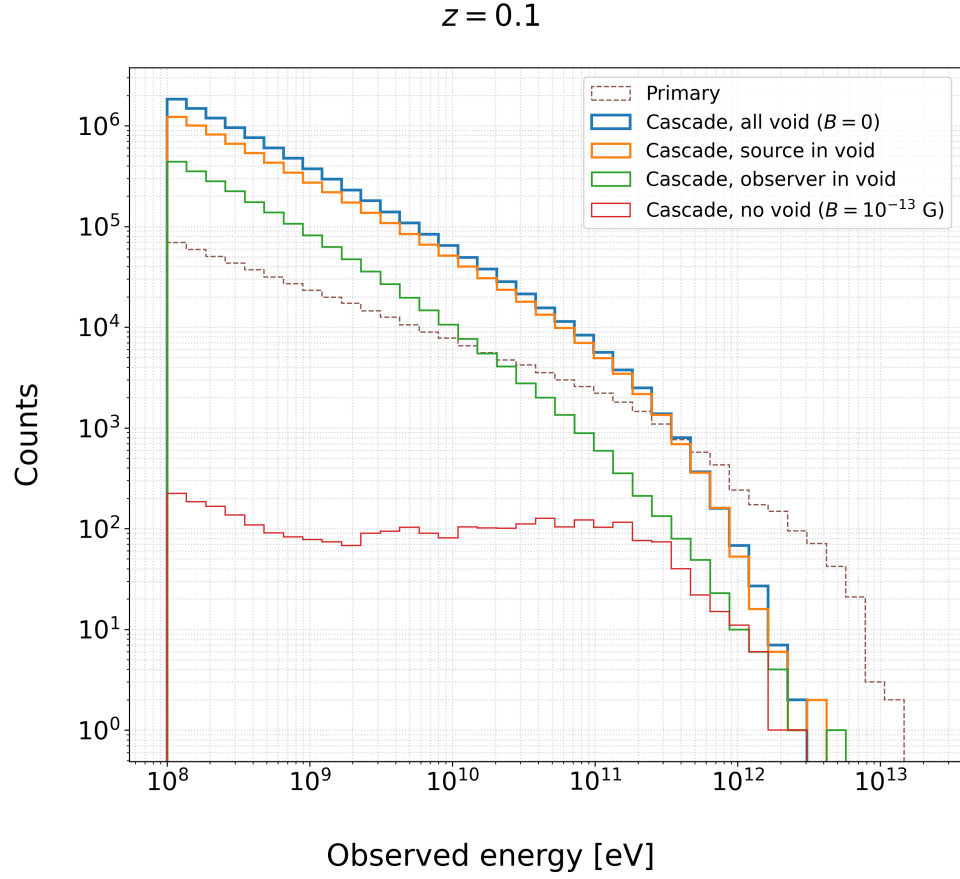


Figure 8.10: Counts spectra of detected photons for a source at $z = 0.1$ in various magnetic field configurations. The SED of primary photons (dashed brown) is independent of the magnetic field; thus, only one primary SED is shown. The SEDs of detected cascade photons (solid lines) are heavily dependent on the magnetic field. Shown in this figure is magnetic field i (blue), ii (orange; Figure 6.8), iii (green; Figure 6.9), and iv (red).

several factors: the dependence of λ on z and E , expansion of the universe, and the depletion of the injected photon spectrum through PP. Both ii and iii have substantial cascade flux above the primary flux (although to varying degrees) because in both cases sufficient PP occurs in regions where $B = 0$; sufficient PP occurs along the full LoS. The IC photons themselves can PP, and due to the long interaction length and short distance to the observer at $z = 0.1$, this is likely to occur further along the LoS, nearer to the observer than the source. This too contributes to the cascade flux being above the primary flux in the case of ii (source in void), particularly at lower energies because, in general, there are more low-energy secondary photons as the cascade develops.

8.3.2 Sources at $z = 0.4$ and $z = 0.7$

Figures 8.11 and 8.12 show the counts spectra of detected cascade photons for a source at $z = 0.4$ and $z = 0.7$, respectively. Again, the flux in the case of i ($B = 0$) and iv ($B = 10^{-13}$ G) surrounds the flux in the cases of ii and iii. And in the case of iii (observer in void), much of the cascade develops where $B \neq 0$, so much of the cascade is deflected, and this cascade flux is lower than the cascade flux in the case of ii (source in void). This is expected no matter the redshift of the source.

In the case of iii (observer in void) and a source at $z = 0.4$, the cascade flux

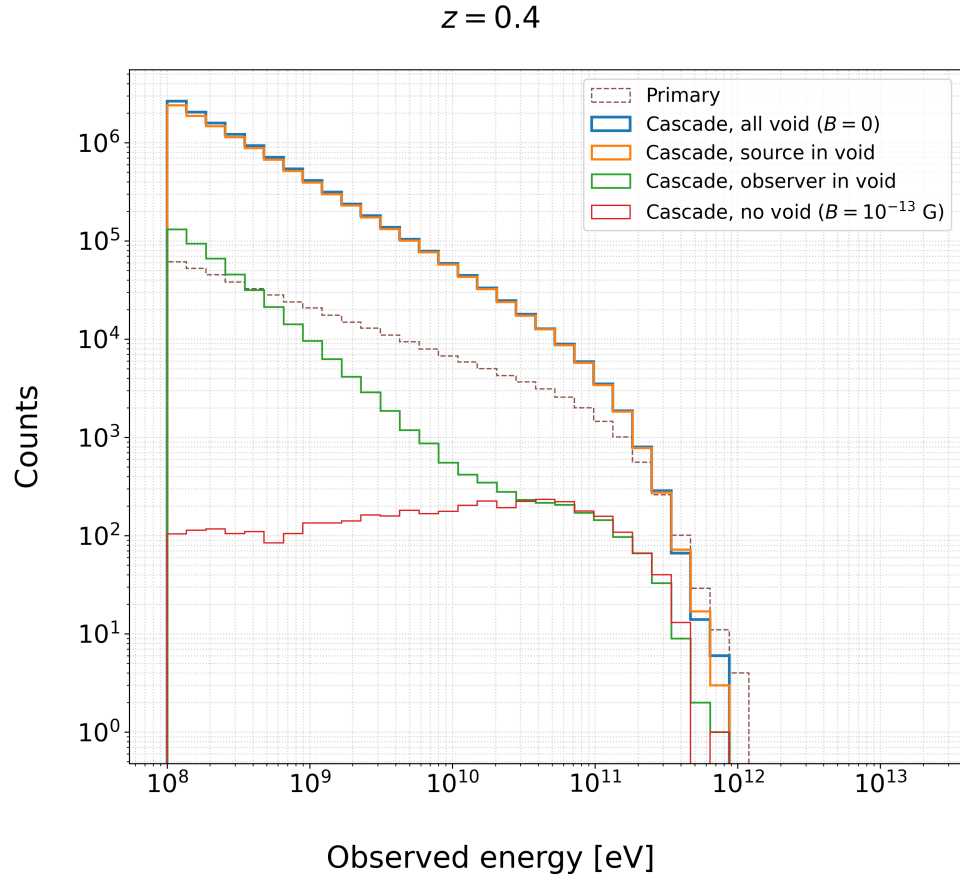


Figure 8.11: Same as Figure 8.10, but for a source at $z = 0.4$.

from $\approx 10^8 - 3 \times 10^8$ eV is dominant over the primary flux. In contrast, in the case of iii and a source at $z = 0.7$, the cascade flux is subdominant to the primary flux at all energies. Because the LoS distance is much larger in the case of $z = 0.7$ than $z = 0.4$ which is in turn larger than the case of $z = 0.1$ (see Table 8.1) and $\lambda(z = 0.7) > \lambda(z = 0.4) > \lambda(z = 0.1)$, more PP interactions can occur in the case of a source at $z = 0.7$ than $z = 0.4$ which is in turn larger than $z = 0.1$. Furthermore, most of the cascade develops along the LoS nearer to the source, so that the number of PP interactions in the half of the LoS near the source (call it N_s) is greater than the number of PP interactions in the half of the LoS near the observer (call it N_o), and the ratio of these numbers N_s/N_o increases with z ; as the size of half of the LoS increases and $\lambda(z)$ decreases, the number of PP interactions that can occur increases.

The cases of iii (observer in void) and iv ($B = 10^{-13}$ G) differ strongly at energies $\lesssim 3 \times 10^{10}$ eV for a source at $z = 0.4$ and $\lesssim 3 \times 10^9$ eV for a source at $z = 0.7$, because the fraction of PP interactions that occur in each half of the LoS N_s/N_o is greater for $z = 0.7$. Additionally, $\frac{1}{2}D_{\text{LoS}}(z)$ is larger for $z = 0.7$, so the lower-energy primaries have more distance to pair produce, which creates lower-energy secondaries. Lastly, the start of the cascade is more energetic than the end. As expected, the cases of iii (observer in void) and iv ($B = 10^{-13}$ G) are different because iv results in every pair being deflected, which makes it far less

likely that their secondary photons will be detected by the criteria in Section 7.1.

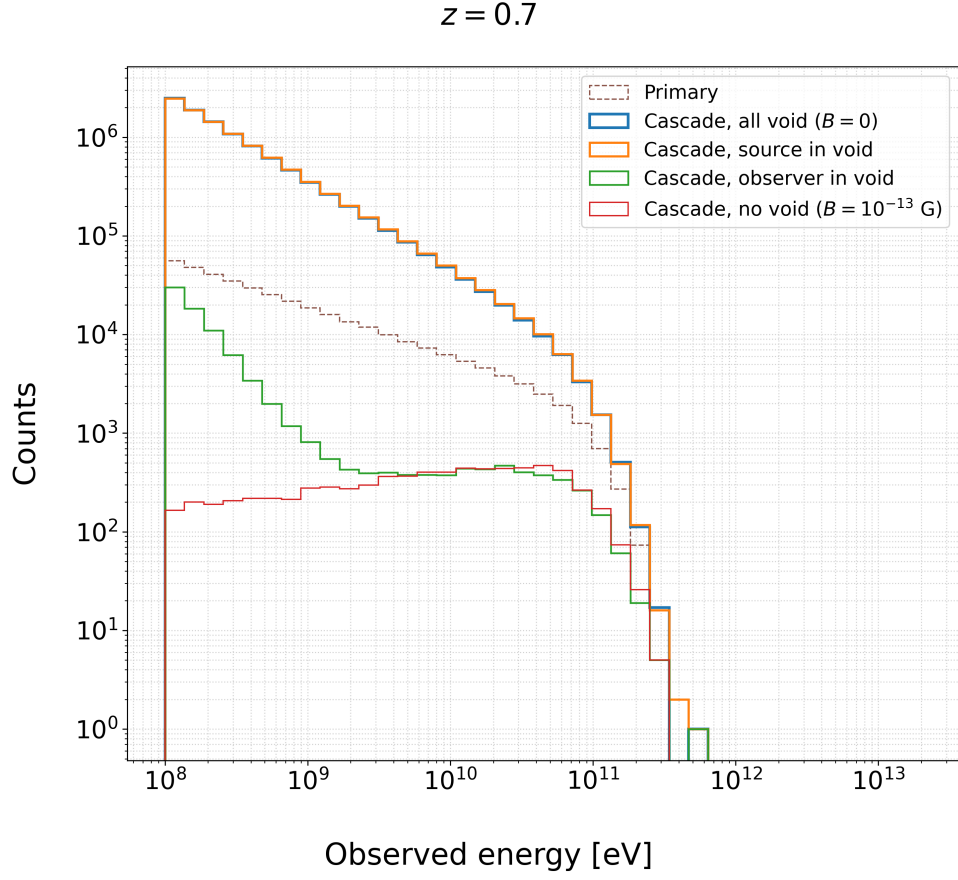


Figure 8.12: Same as Figure 8.10, but for a source at $z = 0.7$.

8.3.3 Sources in $B = 0$

In the case of $B = 0$ (i), **every** cascade photon is detected by the definition in Section 7.1—no particles are deflected, and each arrives with time delay $\tau = 0$. Thus, these results provide a good approximation of the number of “all” cascade photons produced by a source at redshift z that make it to the observer sphere.

Figure 8.13 and Table 8.2 illustrate all the cascade photons in the case of $B = 0$, for each redshift in this study. Figure 8.13 shows the expected imprint of EBL absorption, which more strongly impacts the photons (both primary and secondary) from a source at $z = 0.7$ than a source at $z = 0.1$.

Table 8.2 encodes the combined impacts of PP, ICS, and the expansion of the universe, and shows that, for the simulations in this work, the total number of cascade photons for a source at $z = 0.1$ versus $z = 0.4$ versus $z = 0.7$ differs by, at most, $\approx 30\%$. This suggests that (for the simulations presented in this thesis) redshift has a moderate impact on the number of cascade photons (with energy above $E_{\text{break}} = 10^8$ eV) that ultimately reach the observer sphere (and necessarily pass break conditions). This is primarily due to the break conditions and the injected spectrum. Due to the fact that $\lambda(z = 0.7) > \lambda(z = 0.4) > \lambda(z = 0.1)$, $D_{\text{LoS}}(z = 0.7) > D_{\text{LoS}}(z = 0.4) > D_{\text{LoS}}(z = 0.1)$, and a larger range of photon energies is likely to PP at larger z (see Figure 8.3), it is expected that more secondaries will be created for sources at larger z . However, each generation of particles is less energetic than the last, so the more interactions there are, the more likely it is that the secondaries fall below $E_{\text{break}} = 10^8$ eV. This is particularly relevant for the simulations with a source at $z = 0.4$ and $z = 0.7$ in which IC photons are likely to PP. Conversely, in the case of a source at $z = 0.1$, for most of the injected energies E , $\lambda(E, z \leq 0.1) \sim D_{\text{LoS}}(z \leq 0.1)$ so an IC photon pair-

producing is far less likely. However, depending on the magnetic field, not all cascade photons are detected.

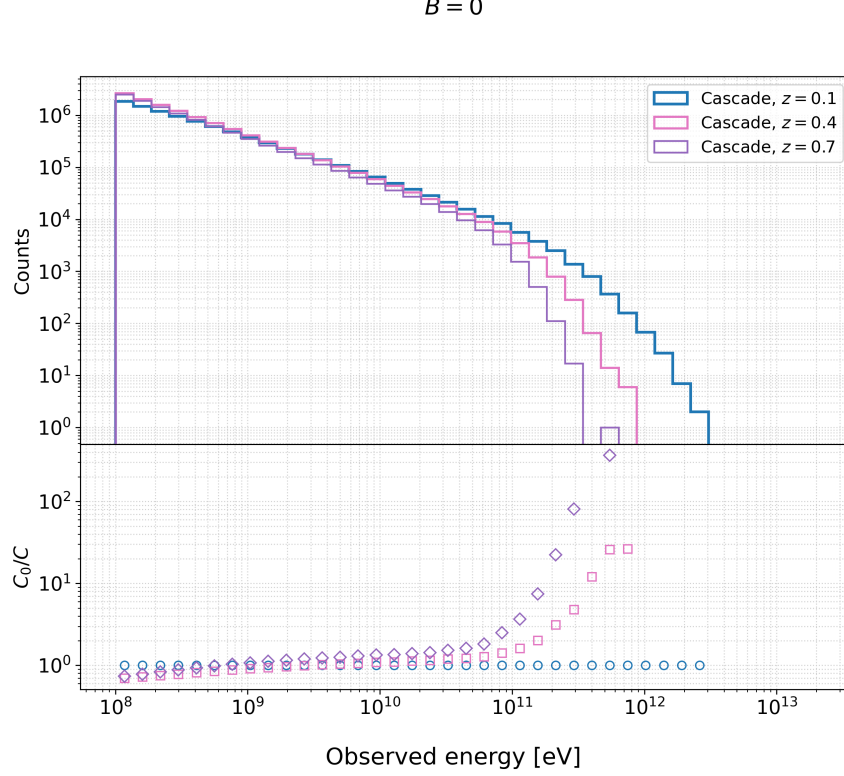


Figure 8.13: Upper: Counts spectra of detected cascade photons in the case of $B = 0$ (i) for $z = 0.1$ (blue), $z = 0.4$ (pink), and $z = 0.7$ (purple). Lower: Ratio of the counts C_0 at $z = 0.1$ to the counts C at z indicated with the same color as the upper plot.

8.3.4 Impact of the Cone Half-Opening Angle ψ

The cone half-opening angle ψ determines the surface area over which cascade photons can be detected via criterion i (this criterion is also implemented by EL-MAG, a package similar to `CRPropa`). That the choice of ψ can impact simulation

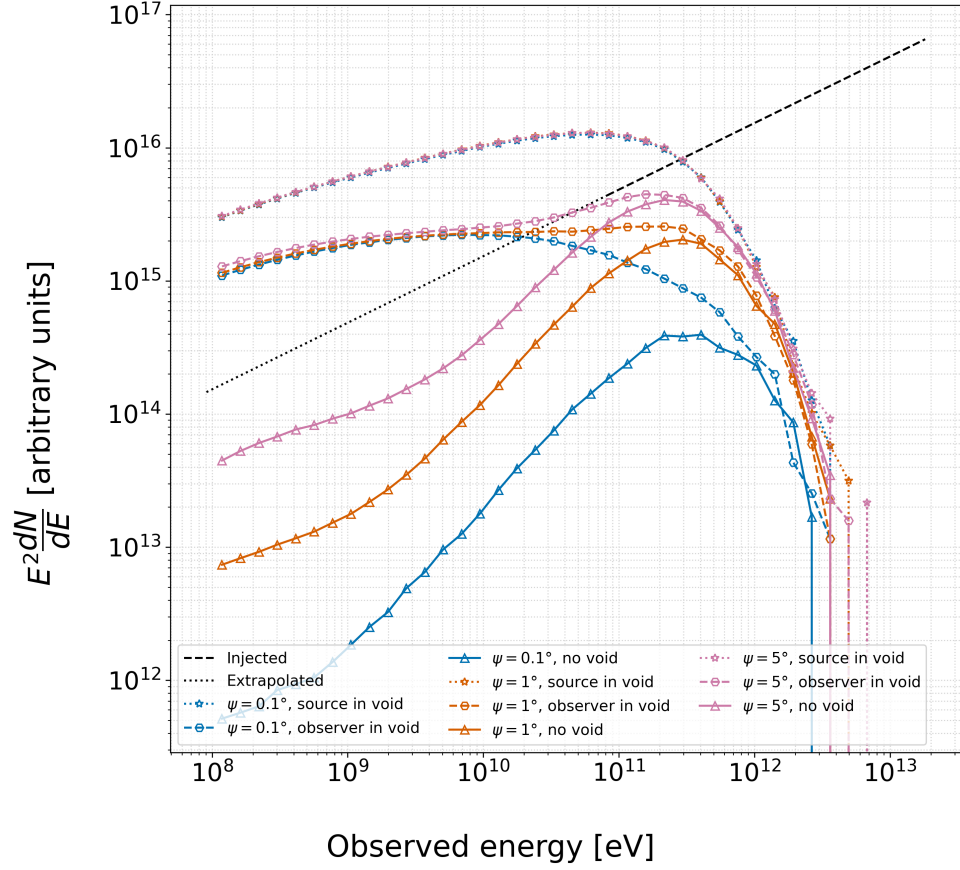


Figure 8.14: SED of detected **cascade** photons for a source at $z = 0.1$ with various ψ : $\psi = 0.1^\circ$ (blue; used in this work), $\psi = 1^\circ$ (orange), and $\psi = 5^\circ$ (pink). Shown in this figure is magnetic field ii (star markers; Figure 6.8), iii (hexagon markers; Figure 6.9), and iv (triangle markers). The injected spectrum (dashed black line) is extended to lower energies (black dotted line) showing what the flux of the primaries would be, if they were injected.

z	Ratio r of cascade photons
0.1	1.00
0.4	1.27
0.7	1.14

Table 8.2: r is the ratio of the number of cascade photons at z to the number of cascade photons at $z = 0.1$. These numbers were derived in the case of $B = 0$, but for a fixed z are representative of the number of all cascade photons produced in each magnetic field configuration. There are 9.0×10^6 cascade photons in the case of a source at $z = 0.1$.

results has been previously noted by, e.g., Ackermann et al. (2018), a study which uses ELMAG to simulate AGN with $\psi = 0.5^\circ, 1.5^\circ, 3^\circ$, and $\psi = 5^\circ$ and with $0.1 \lesssim z \lesssim 0.3$ to constrain the IGMF. The authors find that, when imposing that the time delay $\tau \leq 10^7$ years, the choice of $\psi = 3^\circ$ and $\psi = 5^\circ$ yield comparable results on the IGMF strength. However, with $\tau \leq 10^7$ years, the choice of $\psi = 0.5^\circ$ versus $\psi = 3^\circ$ decreases the IGMF constraints by a factor of 1/2 because more cascade photons are discarded in the case of $\psi = 0.5^\circ$. When $\tau \leq 10$ years is used, the IGMF limits are independent of the choice of ψ .

To estimate the impact of ψ on the detected cascade emission in this work, several small simulations were conducted for a source at $z = 0.1$ with $\psi = 0.1^\circ$, 1° , and 5° ; for blazars, $\psi \lesssim 5^\circ$ (Prandini & Ghisellini, 2022). The simulations are nearly identical to those described in Chapter 6, aside from the fact that $N_{\text{inj}} = 10^5$ photons are injected and $E_{\text{min}} = 9 \times 10^{10}$ eV (a cascade is typically initiated by a photon above this energy, via Figure 6.5). The resulting SEDs of

detected photons (analyzed as described in Chapter 7) are in Figure 8.14. Note that the normalization is not the same as that of Figure 8.10 because a different number of photons was injected between 9×10^{10} eV and 2×10^{13} eV. The choice of ψ has a negligible impact on the detected photons in the case of ii (source in void), a moderate impact at high energies in the case of iii (observer in void), and a significant impact in the case of iv ($B = 10^{-13}$ G). Further investigation of the impact of ψ for sources at additional redshifts ($z = 0.4, 0.7$) is beyond the scope of this work. However, the choice of ψ in future work (Section 8.4) may be driven by a real source and observed jet half-opening angle (if known from observations).

8.4 Detected Total Photons and Implications for F25 and J26

In a real observation, the primary and cascade photons are indistinguishable. As such, the SEDs (Equation 7.15) of the total detected photons are presented in Figures 8.15-8.17. Under the extreme conditions (of voidiness, magnetic field strength, and spectral index) probed in this work, the location of voids has a drastic impact on the number of cascade photons. Specifically, when a source at $z = 0.1, 0.4$ or $z = 0.7$ is in a void (ii), there is substantial cascade flux that contributes to the total detected flux. When the observer is in a void (iii), the

cascade flux still leaves a notable imprint on the total detected flux at the lower energy range of *Fermi*-LAT; this is true for sources at $z = 0.1$, $z = 0.4$, and $z = 0.7$, although the imprint is smaller (in both flux and energy extent) for sources at larger z .

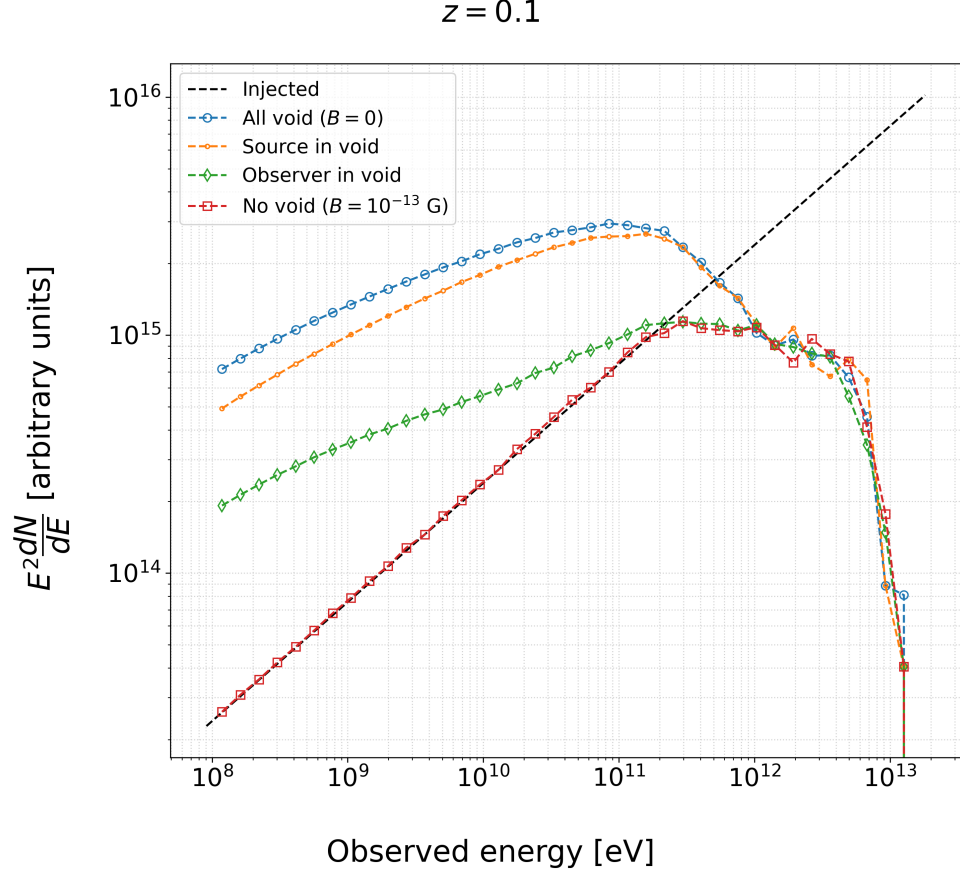


Figure 8.15: Total SEDs for each magnetic field configuration: i (blue), ii (orange), iii (green) and iv (red) for a source at $z = 0.1$.

The cascade photons impact the shape and normalization of the total SEDs.

When the source is in a void (ii), the total spectrum below $\approx 5 \times 10^{10}$ eV is

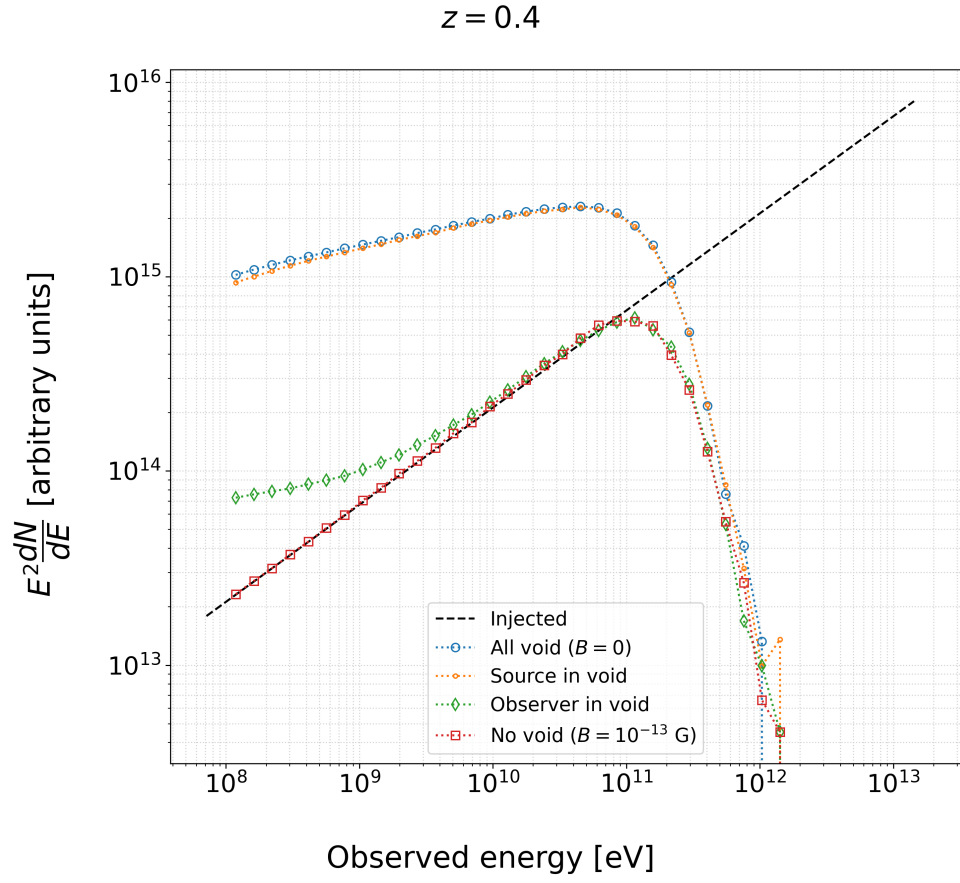


Figure 8.16: Same as Figure 8.15 but for a source at $z = 0.4$.

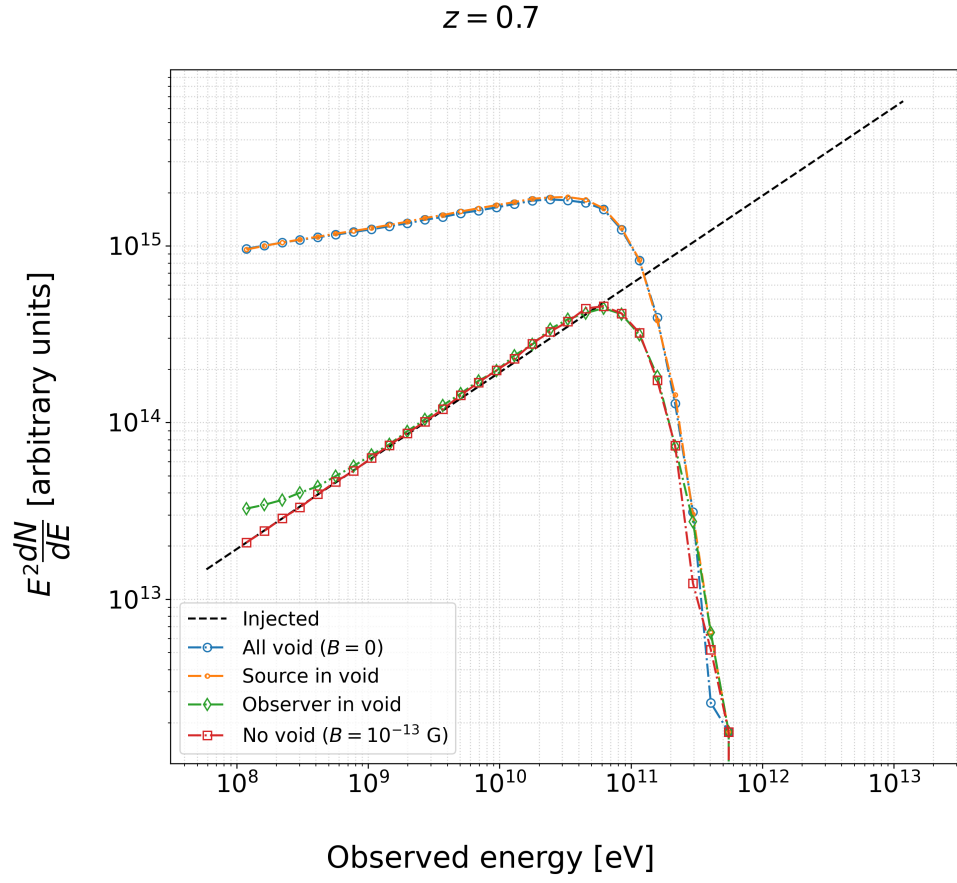


Figure 8.17: Same as Figure 8.15 but for a source at $z = 0.7$.

softened (the observed photon index α in $E^2 \frac{dN}{dE} \propto E^{\alpha+2}$ decreases) when compared to the primary spectrum, and its normalization is increased. For a relatively nearby source at $z = 0.1$, even when the observer is in a void (iii), cascade emission noticeably softens the spectrum below $\approx 10^{11}$ eV, compared to the primary spectrum. Even though these are noticeable signatures, the intrinsic spectrum of a source is unknown. Additionally, blazars (which compose the majority of the AGN sample used in J26 (Jackson et al., 2026) and F25 (Furniss et al., 2025)) tend to be variable objects.

The cascade emission cannot be observed to be variable over some observable timescale t_{obs} , provided the cascade emission has a distribution of time delays $\tau \gg t_{\text{obs}}$. In reality, the cascade emission and primary emission cannot be isolated, and so the dominance of one over the other is unknown. Independent of whether the primary or cascade emission dominates, a rather abrupt change in its observed SED cannot be attributed to the cascade emission; the cascade emission is steady and so any change must be due to the intrinsic SED (if $\tau \gg t_{\text{obs}}$). Although the cascade emission can change in response to a change in the (unknown) intrinsic emission of a source, this change is spread out over time τ and so will not be observed as an abrupt change (again, so long as $\tau \gg t_{\text{obs}}$). The time delays of the detected cascade photons from all simulation results presented in this chapter are shown in Figure 8.18. Note that τ depends heavily on the strength of the

magnetic field, and this work uses $B_{\text{IGMF}} = 10^{-13}$ G. Figure 8.18 is the result of a simulation in which all photons were injected at one time. Unlike the simulations in this work in which a source emits photons at one instant in time, a real AGN is continuously emitting, and so the cascade (and primary) emission is continually contributing to the observed flux. To probe the cascade flux (and its time average) from a real, continuously emitting source, consider the observed cascade flux $F_c(t)$ arriving at time t (see e.g. Equation 1 of Acciari et al. (2023)),

$$F_c(t) = \int G(E_{\gamma,0}, E_{\gamma}, t - \tau, \tau) F_s(t) d\tau \quad (8.1)$$

where $E_{\gamma,0}$ is the energy of the injected primary event that results in a cascade photon of energy E_{γ} arriving with time delay τ , F_s is the source flux, and G is the Green's function. Under the assumption of constant flux (constant $F_s(t)$, which is common—see Dermer et al. (2011) and references therein), Figure 8.19 illustrates the detected cascade emission from a source that starts emitting photons at $t = 0$ and continues at a constant rate for 10^8 years; the cascade emission is smeared out over a long time. If the intrinsic spectrum changes over some (observable) timescale t_{var} , so too will the cascade, but not promptly (provided $\tau \gg t_{\text{var}}$). For reference, *Fermi*-LAT was launched in 2008 ($t_{\text{var,max}} \sim 20$ years) and so for the simulations in this work $\tau \gg t_{\text{var}}$; the cascade emission is observed to be steady even if the primary emission is variable.

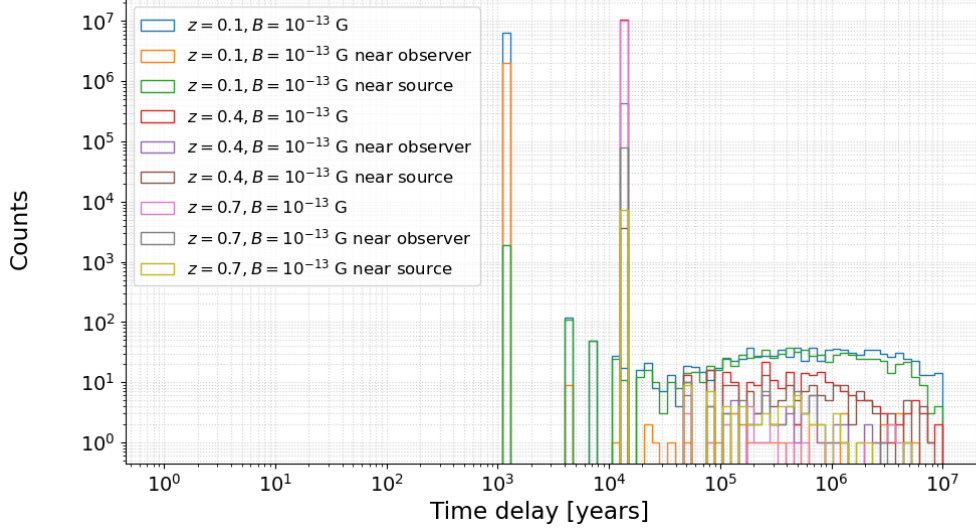


Figure 8.18: Time delay $\tau = \frac{D - D_{\text{LoS}}}{c}$ of detected cascade photons from a simulated source that injects all its photons at one instant in time. The simulations with $B = 0$ (i) are not shown because $\tau = 0$ for every photon. No photons arrive at exactly $\tau = 0$ due to the limited precision of the **CRPropa** output: D_{LoS} is calculated by **redshift2ComovingDistance** to 13 decimal places, but the distance D is truncated to $\mathcal{O}(10^{-3})$ Mpc (for a source at $z = 0.1$) or $\mathcal{O}(10^{-2})$ Mpc (for a source at $z = 0.4$ or $z = 0.7$), which results in a precision of $\approx 3.2 \times 10^3$ years and $\approx 3.2 \times 10^4$ years, respectively.

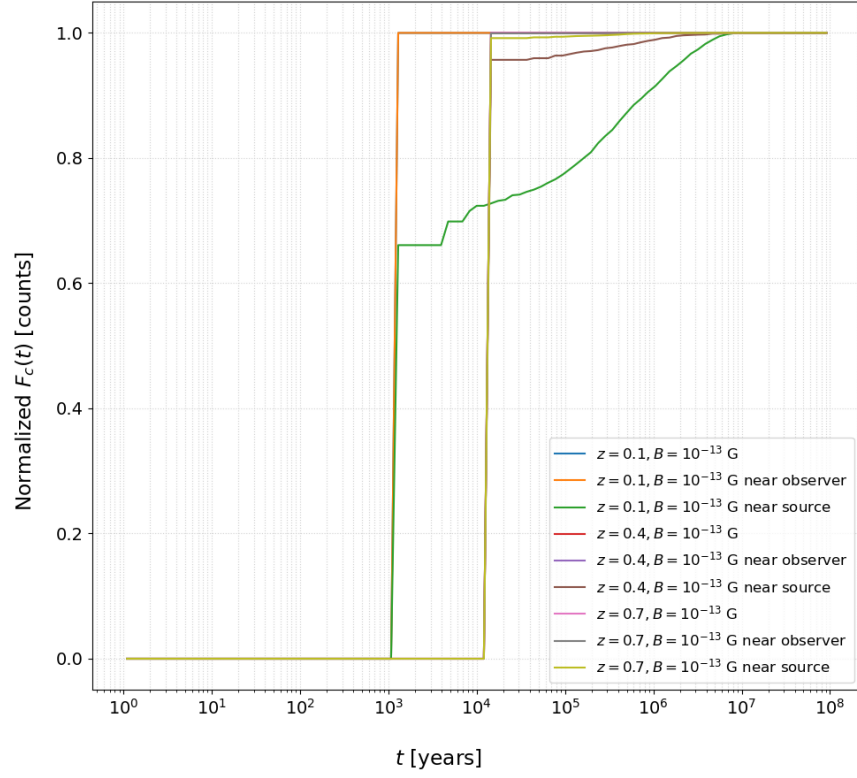


Figure 8.19: Cascade flux $F_c(t)$ (Equation 8.1) as a function of time from a constant flux source that starts emitting photons at $t = 0$ and continues for 10^8 years. The cascade flux is steady and slowly varying when taking into account the source's emitting history.

However, a sudden change in the shape of the spectrum can be attributed to an intrinsic process in the blazar (e.g., in the context of SSC model, a change in the electron distribution’s $\gamma_{\min}$, which could be driven by a change in the efficiency of the acceleration mechanism due to a relativistic shock—see, e.g. Aleksić et al. (2012)). *Fermi*-LAT evaluates the variability of AGN using a “variability index”. **Variability_Index** is a test statistic (TS_{var}) determined from Equation 6 of Abdollahi et al. (2020), from which the corresponding confidence level is calculated. TS_{var} compares the N_{int} -year average flux (in 4LAC-DR3, $N_{\text{int}} = 12$) to the yearly fluxes (Abdollahi et al., 2020). In 4FGL-DR3, if **Variability_Index** (TS_{var}) is greater than 24.72 (over 12 intervals), then the source has $< 1\%$ chance of being steady (Abdollahi et al., 2022) on yearly timescales. This describes the variability of the **integral** flux, so it does not necessarily describe the variability of specifically, e.g., the lower-energy range of *Fermi*-LAT. Of the 303 4LAC sources studied in F25 and J26, 87 have $TS_{\text{var}} > 24.72$.

This work, which assumes that the sources are steadily emitting photons, suggests that the location of voids has a drastic impact on the amount of cascade emission, with sources in voids (ii) having significant cascade emission. This is true for each redshift. However, for $z = 0.1$, the location of the void has a less drastic impact.

F25 studied V_{LoS} and found that high-energy-emitting sources at $0.4 \leq z < 0.7$

tend to lie along LoS with higher voidiness than optical sources, but did not find the same to be true of sources at $0.1 \leq z < 0.4$. Independent of voidiness, in the extreme cases studied in this thesis, more cascade flux is produced by sources at $z = 0.4$ and $z = 0.7$ than by a source at $z = 0.1$. Although not all of the cascade photons are detected, this fact can contribute to the findings of F25. J26 studied D_{void} , the comoving distance along the LoS that intersects a void, and found the same conclusions: the high-energy-emitting (4LAC) sources in the distant redshift interval ($0.4 \leq z < 0.7$) tend to intersect a larger void distance D_{void} than the optical (SDSS) sources. This was not found for the sources at $0.1 \leq z < 0.4$. This thesis shows that, for a fixed redshift and a fixed D_{void} (ii and iii have the same D_{void} for a fixed z), for the sources at $z = 0.4$ and $z = 0.7$, the location of the top-hat D_{void} can either greatly enhance (ii) or minorly enhance (iii) the observed flux due to cascade emission. For a source at $z = 0.1$, the location of the top-hat D_{void} is less important, and both cases ii and iii result in a modest flux enhancement from cascade emission. Lastly, this work shows that the void location is crucial; note that voidiness V_{LoS} does not contain information about where the voids are along the LoS.

The work in this thesis studied $V_{\text{LoS}} = 0, 0.50, 1$, and $z = 0.1, 0.4, 0.7$. $V_{\text{LoS}} = 0.50$ can be attained in many ways; this work utilizes a step function (ii, iii). To further this work and better compare it to F25 and J26, future simulations should

vary V_{LoS} as well as the location of the voids. More realistic simulations should include a small but nonzero magnetic field in voids and a less extreme IGMF strength. Additionally, the simulations do not correspond to any particular source because the intent of Part II is to study the extreme cases to understand if more realistic simulations could be illuminating. Therefore, the SEDs are not fit to any data in this work.

Selecting particular sources can guide the injection spectrum and magnetic field grid (by way of the source’s voidiness). Potential sources are selected by identifying AGN in both STeVECat (Gréaux et al., 2023a,b) and the catalog used in J26 and F25, which contains 4LAC-DR3 sources with $0.1 \leq z < 0.7$ and within the footprint of the SDSS DR7 and DR9 void catalogs (Sutter et al., 2012, 2014). Sources in both catalogs are identified by matching RA and Dec using STILTS (Taylor, 2006) with maximum separation 0.1° via `catalog_matcher` (Splettstoesser, 2025c) where the smallest separation match is selected. The default maximum separation in `catalog_matcher` is 0.1° because the 68% containment radius of IACTs can be $\mathcal{O}(10^1)$ arcmin (see e.g. Figure 4 of Park & VERITAS Collaboration (2015)). The resulting catalog of matched sources was then checked to ensure the *Fermi* names from both catalogs are identical. If the *Fermi* names are not identical, then identifiers given by SIMBAD (Wenger et al., 2000) and the alternate names given in STeVECat were checked for duplication to ensure

the sources are in fact matches. These checks are included in `catalog_matcher`. Potential sources are given in Table 8.3, as well as their variability index, which must be considered. The *Fermi*-LAT and VHE data of these sources can inform CRPropa simulations. If the source is steady, the simultaneity of the VHE data and the *Fermi*-LAT data should be irrelevant. Sources with $TS_{\text{var}} < 24.72$ are preferable (because the 4LAC catalog spectra can simply be used). Table 8.3 shows that 8 out of 11 potential sources have $< 1\%$ probability of being steady. Therefore, in order to utilize these sources, care needs to be taken to identify a period of time over which *Fermi*-LAT and VHE fluxes can be considered approximately steady. STeVECat supplies the published spectra of TeVCat³ sources observed with imaging atmospheric Cherenkov telescopes within the years 1992-2021; the variability of these spectra should be investigated if they are to be used. Finally, more realistic spectra can be injected by using CRPropa’s `SourceGenericComposition` or by re-weighting an arbitrarily injected spectrum. A summary of the simulation parameters which might be adjusted to accommodate a specific blazar is in Table 6.1. With all this, CRPropa simulation results can be fit and compared to VHE and *Fermi*-LAT spectra.

³<http://tevcat.uchicago.edu>

Name	<i>Fermi</i> catalog name	Variability Index
H 1426+428	4FGL J1428.5+4240	18.6
RX J0847.1+1133	4FGL J0847.2+1134	20.8
B2 1420+32	4FGL J1422.5+3223	9817.7
1H 1013+498	4FGL J1015.0+4926	338.9
4C +21.35	4FGL J1224.9+2122	25039.4
1ES 1440+122	4FGL J1442.7+1200	21.1
PG 1553+113	4FGL J1555.7+1111	168.6
W Comae	4FGL J1221.5+2814	339.3
B2 1215+30	4FGL J1217.9+3007	645.8
PG 1218+304	4FGL J1221.3+3010	116.6
PKS 1424+240	4FGL J1427.0+2348	370.9

Table 8.3: STeVECcat sources in 4LAC-DR3 and the void catalogs by Sutter et al. (2012, 2014), with $0.1 \leq z < 0.7$. The 4LAC variability index TS_{var} is given in the last column.

8.5 Conclusion

Part II examines the enhancement of the detected high-energy emission of AGN due to electromagnetic cascades, using **CRPropa** simulations of injected high-energy photons propagating through various voidiness configurations, where the voids were parameterized as regions with $B_{\text{void}} = 0$ and non-voids were parameterized with $B_{\text{IGMF}} = 10^{-13}$ G, extreme cases for both. The voidiness configurations studied corresponded to voidiness $V_{\text{LoS}} = 0, 0.50, 1$, and the case of $V_{\text{LoS}} = 0.50$ was achieved with two configurations of the void as a step-function—one where the source is in a void and the other where the observer is in a void. Simulated sources were assigned a steady emission spectrum $E^{-1.5}$ and placed at different

redshifts: $z = 0.1, 0.4$, and 0.7 . This work found extreme flux enhancements when the source is in a void, for sources at all three redshifts. The flux enhancement is small but not insignificant at the low-energy tail of the *Fermi*-LAT energy range when the observer is in a void and the source is at $z = 0.4$ or $z = 0.7$. For a source at $z = 0.1$, there is substantial cascade emission both in the case of the source in a void and in the case of the observer in a void. The flux enhancement specifically manifests in the energy range of *Fermi*-LAT (about 100 MeV to 1 TeV), which can make AGN along voidy LoS easier for *Fermi*-LAT to detect, thus enhancing the number of voidy AGN in the *Fermi*-LAT catalog compared to other AGN catalogs (e.g., SDSS quasar catalogs). The simulations in this work indicate that this statement applies to each redshift $z = 0.1, 0.4$, and $z = 0.7$, whereas F25 isolates 4LAC-DR3 AGN in the redshift interval $0.4 \leq z < 0.7$ as tending to lie along LoS of higher voidiness. The simulation results in this chapter show that the amount of flux enhancement due to voidy LoS is very sensitive to the location of the voids for sources at $z = 0.4$ and $z = 0.7$, and sources at $z = 0.1$ have significantly enhanced emission whether the observer is in a void or the source is in a void. To compare this work to the results of J26 and F25, additional simulations are necessary and warranted, given the results of this thesis.

Appendix

Appendix A

Appendix for Part I

A.1 Significance of Multiple Datasets

Equation 2.11 follows from Li & Ma (1983) by adjusting the null hypothesis and alternative hypothesis accordingly.¹ The null hypothesis is that all counts are background counts (that is, the expected number of source counts $\langle N_S \rangle = 0$). Thus, under the null hypothesis, the number of counts in the On region is a measurement of the expected number of background counts in the On region. Equation 7 of Li & Ma (1983) gives the expected number of background counts in time t_{on} , which becomes, in the case of multiple datasets and a fluctuating

¹Henrike Fleischhack and Stephane Vincent, private communication

background,

$$\langle \hat{N}_{B,i} \rangle = \frac{N_{\text{on},i} + N_{\text{off},i}}{t_{\text{on},i} + t_{\text{off},i}} t_{\text{on},i} \quad (\text{A.1})$$

$$\langle \hat{N}_B \rangle = \sum_i \langle \hat{N}_{B,i} \rangle \quad (\text{A.2})$$

$$\langle \hat{N}_B \rangle = \sum_i \frac{\alpha_i (N_{\text{on},i} + N_{\text{off},i})}{1 + \alpha_i}, \quad (\text{A.3})$$

where $\alpha_i = \frac{t_{\text{on},i}}{t_{\text{off},i}}$ has been used. Li & Ma (1983) define $\alpha = \frac{t_{\text{on}}}{t_{\text{off}}}$, which implies $\alpha_i = \frac{t_{\text{on},i}}{t_{\text{off},i}}$. The number of background counts in time t_{off} is

$$\langle \hat{n}_{B,i} \rangle = \frac{N_{\text{on},i} + N_{\text{off},i}}{t_{\text{on},i} + t_{\text{off},i}} t_{\text{off},i} \quad (\text{A.4})$$

$$\langle \hat{n}_{B,i} \rangle = \frac{N_{\text{on},i} + N_{\text{off},i}}{\alpha_i t_{\text{off},i} + t_{\text{off},i}} t_{\text{off},i} \quad (\text{A.5})$$

$$\langle \hat{n}_B \rangle = \sum_i \frac{N_{\text{on},i} + N_{\text{off},i}}{\alpha_i + 1}. \quad (\text{A.6})$$

Under the null hypothesis, $\sum_i \langle N_{\text{on},i} \rangle = \langle N_{\text{on}} \rangle = \langle \hat{N}_B \rangle$ and $\sum_i \langle N_{\text{off},i} \rangle = \langle N_{\text{off}} \rangle = \langle \hat{n}_B \rangle$. Therefore, the likelihood of the null hypothesis L_0 becomes

$$\begin{aligned} L_0 = & P \left(\sum_i N_{\text{on},i} \middle| \langle N_{\text{on}} \rangle = \sum_i \frac{\alpha_i (N_{\text{on},i} + N_{\text{off},i})}{1 + \alpha_i} \right) \\ & \times P \left(\sum_i N_{\text{off},i} \middle| \langle N_{\text{off}} \rangle = \sum_i \frac{N_{\text{on},i} + N_{\text{off},i}}{1 + \alpha_i} \right). \end{aligned} \quad (\text{A.7})$$

The likelihood of the alternative hypothesis L is

$$L = P\left(\sum N_{\text{on},i} \middle| \langle N_{\text{on}} \rangle = \sum N_{\text{on},i}\right) P\left(\sum N_{\text{off},i} \middle| \langle N_{\text{off}} \rangle = \sum N_{\text{off},i}\right). \quad (\text{A.8})$$

From now on, the following variables will be used

$$n_i \equiv N_{\text{on},i} \quad (\text{A.9})$$

$$n \equiv \sum_i n_i \quad (\text{A.10})$$

$$m_i \equiv N_{\text{off},i} \quad (\text{A.11})$$

$$m \equiv \sum_i m_i. \quad (\text{A.12})$$

Equation 17 of Li & Ma (1983) defines the significance (of a deviation from the expectation for background alone) as

$$S = \sqrt{-2 \ln \lambda} = \sqrt{2 \ln(\lambda^{-1})}, \quad (\text{A.13})$$

where (using Equation 14 of Li & Ma (1983))

$$\lambda = \frac{L_0}{L}. \quad (\text{A.14})$$

The counts follow a Poisson distribution, thus

$$P(x|\langle x \rangle = y) = \frac{y^x e^{-y}}{x!}. \quad (\text{A.15})$$

Therefore, Equation A.8 becomes

$$L = P(n|\langle n \rangle = n) \times P(m|\langle m \rangle = m) = \frac{n^n e^{-n}}{n!} \frac{m^m e^{-m}}{m!}, \quad (\text{A.16})$$

and similarly for Equation A.7,

$$L_0 = P\left(n|\langle n \rangle = \sum_i \frac{\alpha_i(n_i + m_i)}{1 + \alpha_i}\right) P\left(m|\langle m \rangle = \sum_i \frac{n_i + m_i}{1 + \alpha_i}\right) \quad (\text{A.17})$$

$$= \frac{1}{n!} \left(\sum_i \frac{\alpha_i(n_i + m_i)}{1 + \alpha_i}\right)^n \exp\left[-\sum_i \frac{\alpha_i(n_i + m_i)}{1 + \alpha_i}\right] \frac{1}{m!} \left(\sum_i \frac{n_i + m_i}{1 + \alpha_i}\right)^m \quad (\text{A.18})$$

$$\times \exp\left[-\sum_i \frac{n_i + m_i}{1 + \alpha_i}\right] \quad (\text{A.19})$$

$$= \frac{1}{n!m!} \left(\sum_i \frac{\alpha_i(n_i + m_i)}{1 + \alpha_i}\right)^n \left(\sum_i \frac{n_i + m_i}{1 + \alpha_i}\right)^m \quad (\text{A.20})$$

$$\times \exp\left[-\sum_i \frac{\alpha_i n_i + n_i + \alpha_i m_i + m_i}{1 + \alpha_i}\right] \quad (\text{A.21})$$

$$= \frac{1}{n!m!} \left(\sum_i \frac{\alpha_i(n_i + m_i)}{1 + \alpha_i}\right)^n \left(\sum_i \frac{n_i + m_i}{1 + \alpha_i}\right)^m \exp\left[-\sum_i \frac{1 + \alpha_i}{1 + \alpha_i}(n_i + m_i)\right] \quad (\text{A.22})$$

$$= \frac{1}{n!m!} \left(\sum_i \frac{\alpha_i(n_i + m_i)}{1 + \alpha_i}\right)^n \left(\sum_i \frac{n_i + m_i}{1 + \alpha_i}\right)^m \exp[-(n + m)] \quad (\text{A.23})$$

$$= \frac{e^{-n}e^{-m}}{n!m!} \left(\sum_i \frac{\alpha_i(n_i + m_i)}{1 + \alpha_i}\right)^n \left(\sum_i \frac{n_i + m_i}{1 + \alpha_i}\right)^m. \quad (\text{A.24})$$

Therefore,

$$\lambda^{-1} = \frac{L}{L_0} \quad (\text{A.25})$$

$$= \frac{n^n m^m e^{-n} e^{-m}}{n! m!} \quad (\text{A.26})$$

$$= \frac{e^{-n} e^{-m}}{n! m!} \left(\sum_i \frac{\alpha_i (n_i + m_i)}{1 + \alpha_i} \right)^n \left(\sum_i \frac{n_i + m_i}{1 + \alpha_i} \right)^m$$

$$= \left(\frac{n}{\sum_i \frac{\alpha_i (n_i + m_i)}{1 + \alpha_i}} \right)^n \left(\frac{m}{\sum_i \frac{n_i + m_i}{1 + \alpha_i}} \right)^m. \quad (\text{A.27})$$

Altogether,

$$\ln(\lambda^{-1}) = n \ln \left(\frac{n}{\sum_i \frac{\alpha_i (n_i + m_i)}{1 + \alpha_i}} \right) + m \ln \left(\frac{m}{\sum_i \frac{n_i + m_i}{1 + \alpha_i}} \right) \quad (\text{A.28})$$

$$= \left(\sum_i n_i \right) \ln \left(\frac{\sum_i n_i}{\sum_i \frac{\alpha_i (n_i + m_i)}{1 + \alpha_i}} \right) + \left(\sum_i m_i \right) \ln \left(\frac{\sum_i m_i}{\sum_i \frac{n_i + m_i}{1 + \alpha_i}} \right) \quad (\text{A.29})$$

$$= \left(\sum_i N_{\text{on},i} \right) \ln \left(\frac{\sum_i N_{\text{on},i}}{\sum_i \frac{\alpha_i (N_{\text{on},i} + N_{\text{off},i})}{1 + \alpha_i}} \right) \quad (\text{A.30})$$

$$+ \left(\sum_i N_{\text{off},i} \right) \ln \left(\frac{\sum_i N_{\text{off},i}}{\sum_i \frac{N_{\text{on},i} + N_{\text{off},i}}{1 + \alpha_i}} \right), \quad (\text{A.31})$$

which, in $S = \sqrt{2 \ln(\lambda^{-1})}$, recovers Equation 2.11.

A.2 *Swift*-XRT Analysis

A.2.1 Galactic Absorption

Figure A.1 shows the Galactic absorption due to the ISM that impacts the observed X-ray flux of 1ES 0647+250. The elements corresponding to the absorption edges can be found in Owens et al. (1997). Overlaid in Figure A.1 is also an example of default `XSpec` bins, over which the Galactic absorption is averaged in order to deabsorb SEDs.

A.2.2 *Swift*-XRT SEDs

Four models were fit to each *Swift*-XRT SED: i-iv, from Section 2.4. The resulting χ^2 and degrees of freedom for each are in Tables A.1-A.3. The model parameters for the fit utilized in this work (ii from Section 2.4) are in Tables A.4-A.6.

Figure A.2 contains the observed fluxes from all models (i-iv in Section 2.4) that are fit to one observation (ObsID 00041535067). This illustrates that, of the models considered, the choice of model has a small impact on the observed flux. Although one observation is shown, this holds true for each observation considered in this thesis.

Figures A.3, A.4, and A.5 show the fluxes (from model ii) from each of the observations contained in State A, State B, and State C, respectively. There is

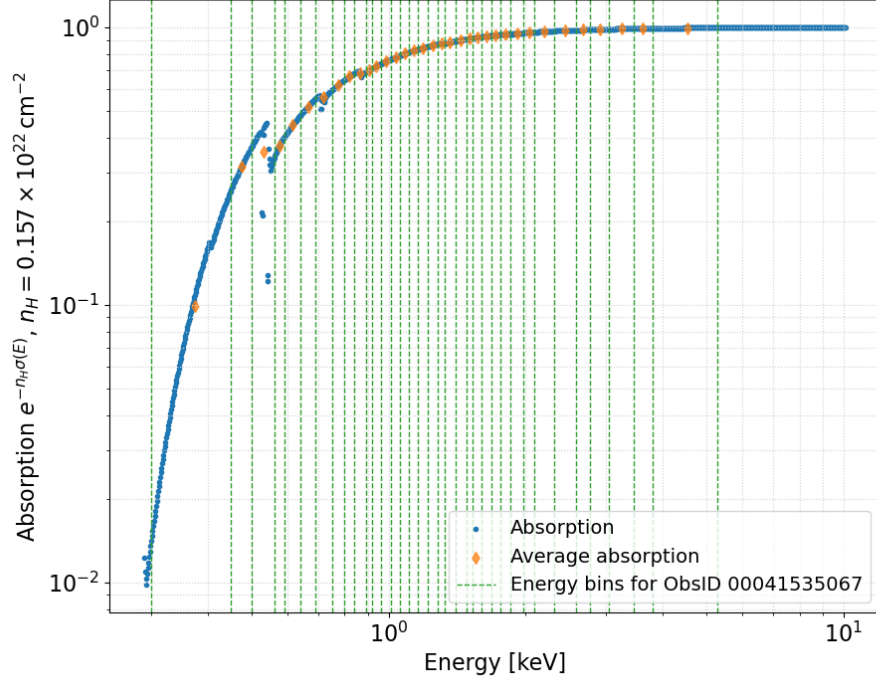


Figure A.1: Galactic photoelectric absorption for the n_H corresponding to the coordinates of 1ES 0647+250 (blue circles); this is one of the outputs of **nHDeabsorb**. Another output is the average absorption in each bin (orange diamonds). The default XSpec bin edges (green dashed lines) for ObsID 00041535067 from State C are also shown. The default bins vary per observation.

ObsID	χ^2 (χ^2/dof)			
	Model i	Model ii	Model iii	Model iv
00032646001	54.02 (0.95)	49.69 (0.89)	51.71 (0.92)	49.69 (0.90)
00032646002	21.70 (0.83)	18.77 (0.75)	19.73 (0.79)	-
00032646003	89.46 (1.28)	80.74 (1.17)	82.71 (1.20)	-
00032646004	68.03 (1.42)	59.29 (1.26)	63.80 (1.36)	-
00032646005	68.28 (1.39)	58.56 (1.22)	60.40 (1.26)	-
00032646006	82.06 (1.32)	69.41 (1.14)	73.35 (1.20)	69.41 (1.16)
00032646007	29.26 (0.79)	28.50 (0.79)	28.75 (0.80)	28.50 (0.81)
00032646008	46.19 (1.05)	46.11 (1.07)	45.29 (1.05)	42.84 (1.02)
00032646009	32.18 (0.73)	30.24 (0.70)	30.52 (0.71)	30.24 (0.72)
00032646010	61.67 (1.08)	60.90 (1.09)	61.14 (1.09)	-

Table A.1: χ^2 and χ^2/dof (degrees of freedom) for the models introduced in Section 2.4, i-iv, fit to State A. Dashes indicate that the fit did not converge in **XSpec** after 20 trials.

ObsID	χ^2 (χ^2/dof)			
	Model i	Model ii	Model iii	Model iv
00032646033	10.37 (0.65)	10.28 (0.69)	10.33 (0.69)	10.28 (0.73)
00032646034	145.74 (0.97)	144.55 (0.97)	144.66 (0.97)	-
00032646035	35.07 (1.35)	30.90 (1.24)	34.03 (1.36)	-
00032646037	183.86 (1.00)	183.85 (1.01)	183.86 (1.01)	183.81 (1.02)
00032646038	142.39 (1.10)	142.24 (1.11)	142.39 (1.11)	142.24 (1.12)
00032646039	13.12 (1.09)	12.26 (1.11)	13.12 (1.19)	-

Table A.2: Same as Table A.1 but for State B.

ObsID	χ^2 (χ^2/dof)			
	Model i	Model ii	Model iii	Model iv
00041535055	34.77 (0.79)	33.58 (0.78)	33.07 (0.77)	32.97 (0.79)
00041535056	16.76 (0.73)	16.56 (0.75)	16.28 (0.74)	15.95 (0.76)
00041535057	21.87 (1.21)	20.48 (1.20)	21.87 (1.29)	20.32 (1.27)
00041535058	46.84 (1.14)	39.20 (0.98)	43.97 (1.10)	-
00041535059	26.17 (1.31)	23.02 (1.21)	22.65 (1.19)	22.65 (1.26)
00041535060	42.23 (1.24)	41.15 (1.25)	41.94 (1.27)	-
00041535061	28.72 (1.51)	27.02 (1.50)	27.88 (1.55)	-
00041535062	55.78 (1.36)	54.40 (1.36)	55.70 (1.39)	-
00041535063	31.06 (1.11)	30.01 (1.11)	30.68 (1.14)	30.01 (1.15)
00041535064	32.24 (1.07)	30.76 (1.06)	31.35 (1.08)	30.76 (1.10)
00041535065	11.53 (0.89)	11.38 (0.95)	11.53 (0.96)	-
00041535066	34.03 (0.90)	33.32 (0.90)	33.74 (0.91)	33.32 (0.93)
00041535067	45.06 (1.37)	40.56 (1.27)	40.57 (1.27)	40.41 (1.30)

Table A.3: Same as Table A.1 but for State C.

ObsID	K [ph/cm ² /keV/s]	a	b
00032646001	$1.96^{+0.06}_{-0.06} \times 10^{-2}$	$2.16^{+0.07}_{-0.07}$	$0.29^{+0.15}_{-0.14}$
00032646002	$1.62^{+0.08}_{-0.08} \times 10^{-2}$	$2.10^{+0.10}_{-0.11}$	$0.47^{+0.30}_{-0.28}$
00032646003	$1.54^{+0.05}_{-0.05} \times 10^{-2}$	$2.050^{+0.06}_{-0.07}$	$0.39^{+0.14}_{-0.14}$
00032646004	$1.67^{+0.06}_{-0.06} \times 10^{-2}$	$2.06^{+0.08}_{-0.08}$	$0.44^{+0.16}_{-0.16}$
00032646005	$1.95^{+0.07}_{-0.07} \times 10^{-2}$	$2.01^{+0.08}_{-0.08}$	$0.47^{+0.17}_{-0.16}$
00032646006	$2.07^{+0.07}_{-0.07} \times 10^{-2}$	$2.08^{+0.07}_{-0.07}$	$0.47^{+0.15}_{-0.14}$
00032646007	$2.01^{+0.09}_{-0.09} \times 10^{-2}$	$2.06^{+0.09}_{-0.09}$	$0.17^{+0.21}_{-0.20}$
00032646008	$1.60^{+0.06}_{-0.06} \times 10^{-2}$	$2.24^{+0.07}_{-0.07}$	$0.05^{+0.18}_{-0.17}$
00032646009	$1.20^{+0.05}_{-0.05} \times 10^{-2}$	$2.18^{+0.07}_{-0.08}$	$0.25^{+0.19}_{-0.18}$
00032646010	$1.53^{+0.05}_{-0.05} \times 10^{-2}$	$2.16^{+0.07}_{-0.07}$	$0.13^{+0.16}_{-0.15}$

Table A.4: *Swift*-XRT analysis details for State A. The spectral parameters correspond to a log parabola (ii from Section 2.4) $\frac{dN}{dE} = K \left(\frac{E}{E_0} \right)^{-a-b \log_{10}(E/E_0)}$, where $E_0 = 1$ keV.

ObsID	K [ph/cm ² /keV/s]	a	b
00032646033	$2.17^{+0.14}_{-0.14} \times 10^{-2}$	$2.40^{+0.11}_{-0.12}$	$0.10^{+0.34}_{-0.32}$
00032646034	$1.84^{+0.04}_{-0.04} \times 10^{-2}$	$2.38^{+0.04}_{-0.04}$	$0.10^{+0.09}_{-0.09}$
00032646035	$1.66^{+0.08}_{-0.08} \times 10^{-2}$	$1.92^{+0.12}_{-0.13}$	$0.46^{+0.25}_{-0.23}$
00032646037	$2.99^{+0.05}_{-0.05} \times 10^{-2}$	$2.28^{+0.04}_{-0.04}$	$-0.01^{+0.07}_{-0.07}$
00032646038	$2.73^{+0.06}_{-0.06} \times 10^{-2}$	$2.30^{+0.04}_{-0.05}$	$-0.04^{+0.09}_{-0.09}$
00032646039	$2.03^{+0.16}_{-0.16} \times 10^{-2}$	$2.00^{+0.14}_{-0.15}$	$-0.39^{+0.42}_{-0.39}$

Table A.5: Same as Table A.4 but for State B.

ObsID	K [ph/cm ² /keV/s]	a	b
00041535055	$9.06^{+0.36}_{-0.35} \times 10^{-3}$	$2.24^{+0.07}_{-0.08}$	$0.19^{+0.18}_{-0.17}$
00041535056	$9.25^{+0.51}_{-0.51} \times 10^{-3}$	$2.39^{+0.10}_{-0.10}$	$0.12^{+0.27}_{-0.25}$
00041535057	$7.11^{+0.44}_{-0.43} \times 10^{-3}$	$2.42^{+0.11}_{-0.12}$	$-0.30^{+0.25}_{-0.23}$
00041535058	$8.62^{+0.34}_{-0.34} \times 10^{-3}$	$2.13^{+0.09}_{-0.09}$	$0.54^{+0.21}_{-0.20}$
00041535059	$9.78^{+0.61}_{-0.60} \times 10^{-3}$	$2.26^{+0.11}_{-0.12}$	$0.60^{+0.37}_{-0.35}$
00041535060	$8.34^{+0.37}_{-0.37} \times 10^{-3}$	$2.19^{+0.09}_{-0.10}$	$0.22^{+0.23}_{-0.21}$
00041535061	$8.51^{+0.53}_{-0.52} \times 10^{-3}$	$2.20^{+0.12}_{-0.13}$	$0.47^{+0.39}_{-0.36}$
00041535062	$7.12^{+0.29}_{-0.28} \times 10^{-3}$	$2.28^{+0.08}_{-0.09}$	$0.23^{+0.20}_{-0.19}$
00041535063	$6.85^{+0.34}_{-0.34} \times 10^{-3}$	$2.17^{+0.10}_{-0.11}$	$0.25^{+0.25}_{-0.24}$
00041535064	$7.48^{+0.36}_{-0.36} \times 10^{-3}$	$2.36^{+0.09}_{-0.10}$	$0.28^{+0.24}_{-0.23}$
00041535065	$9.02^{+0.73}_{-0.71} \times 10^{-3}$	$2.34^{+0.12}_{-0.13}$	$-0.20^{+0.53}_{-0.49}$
00041535066	$7.87^{+0.33}_{-0.33} \times 10^{-3}$	$2.21^{+0.08}_{-0.09}$	$0.17^{+0.21}_{-0.20}$
00041535067	$8.16^{+0.37}_{-0.36} \times 10^{-3}$	$2.10^{+0.09}_{-0.09}$	$0.41^{+0.21}_{-0.20}$

Table A.6: Same as Table A.4 but for State C.

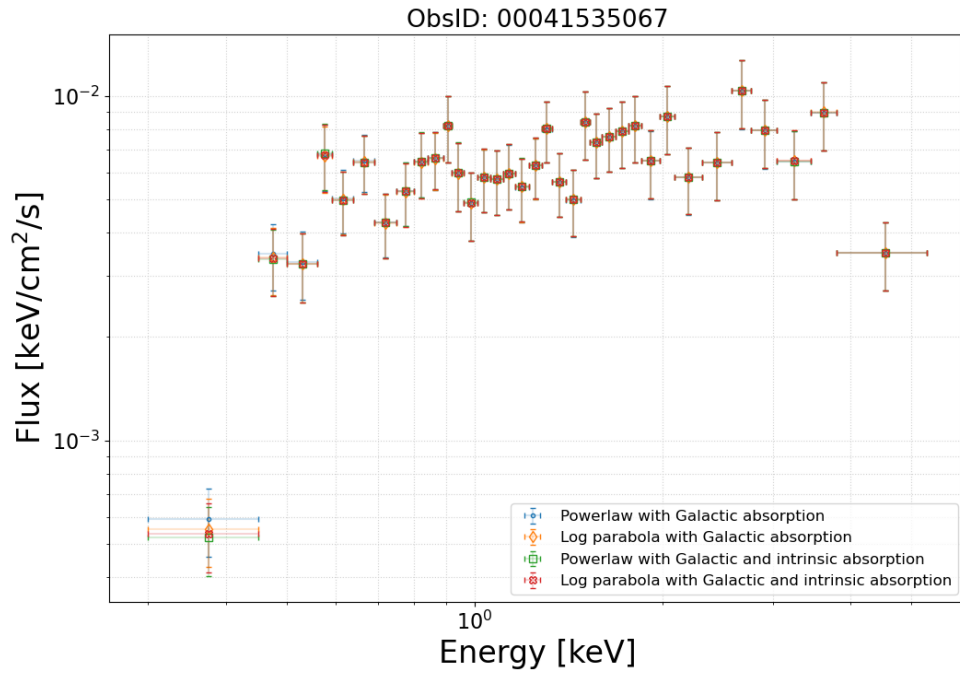


Figure A.2: Observed *Swift*-XRT fluxes from the following spectral models fit to ObsID 00041535067 from State C: i (blue), ii (orange), iv (green), and iv (red). Within error bars, the fluxes agree.

some variability among the fluxes.

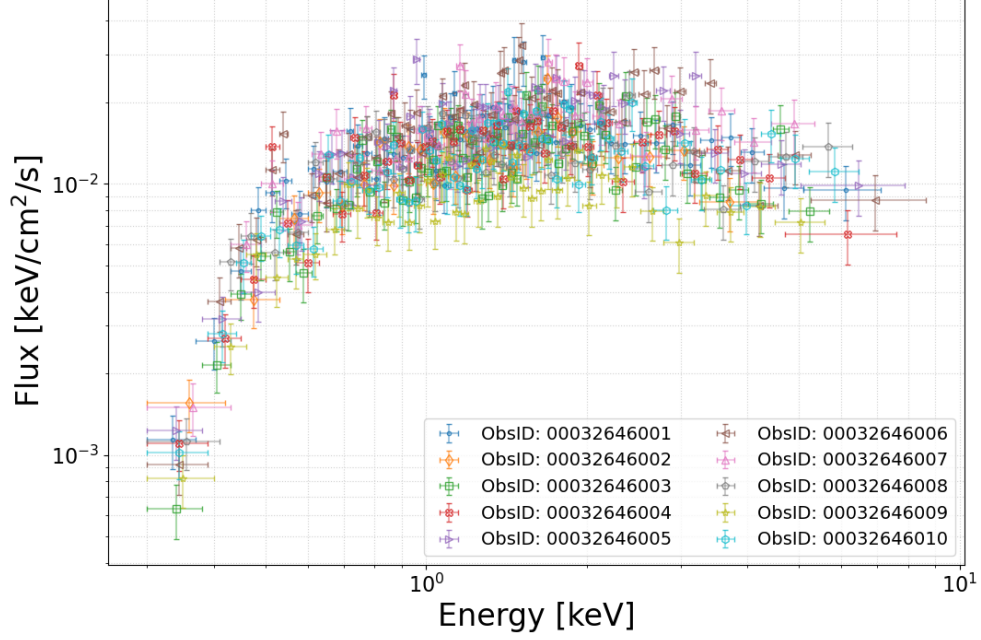


Figure A.3: All observed *Swift*-XRT fluxes within State A. The spectral model used is ii from Section 2.4.

Figures A.6, A.7, and A.8 show the representative SED and deabsorbed fluxes of State A, State B, and State C.

A.2.3 *Swift*-XRT Lightcurves

Figures A.9, A.10, and A.11 are *Swift*-XRT lightcurves for all models considered (i-iv, in Section 2.4). The lightcurves display the observed integral fluxes (as opposed to the intrinsic/deabsorbed fluxes). The integral fluxes are computed

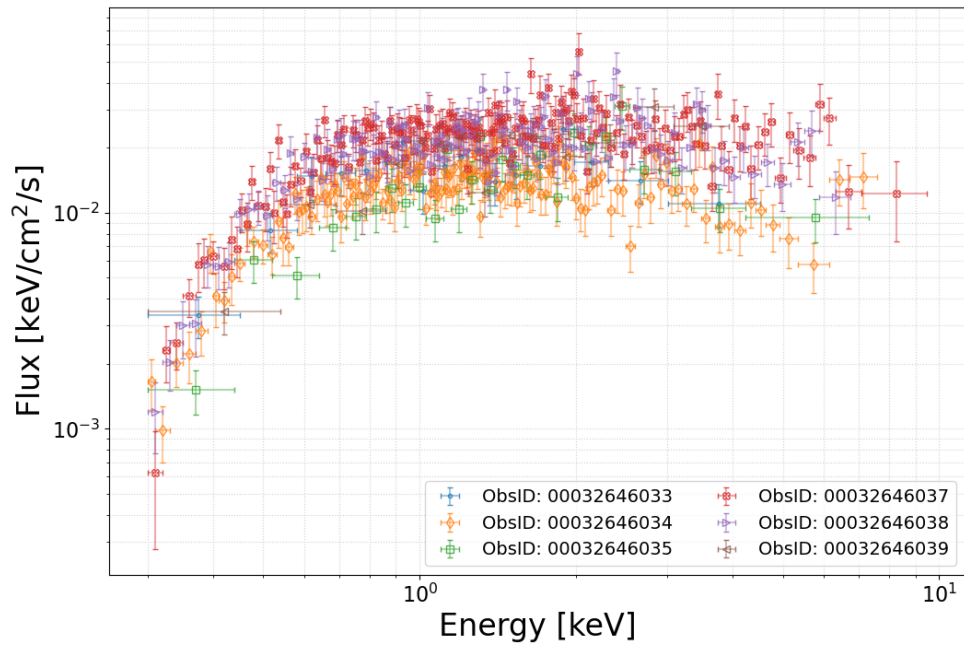


Figure A.4: Same as A.3, but for State B.

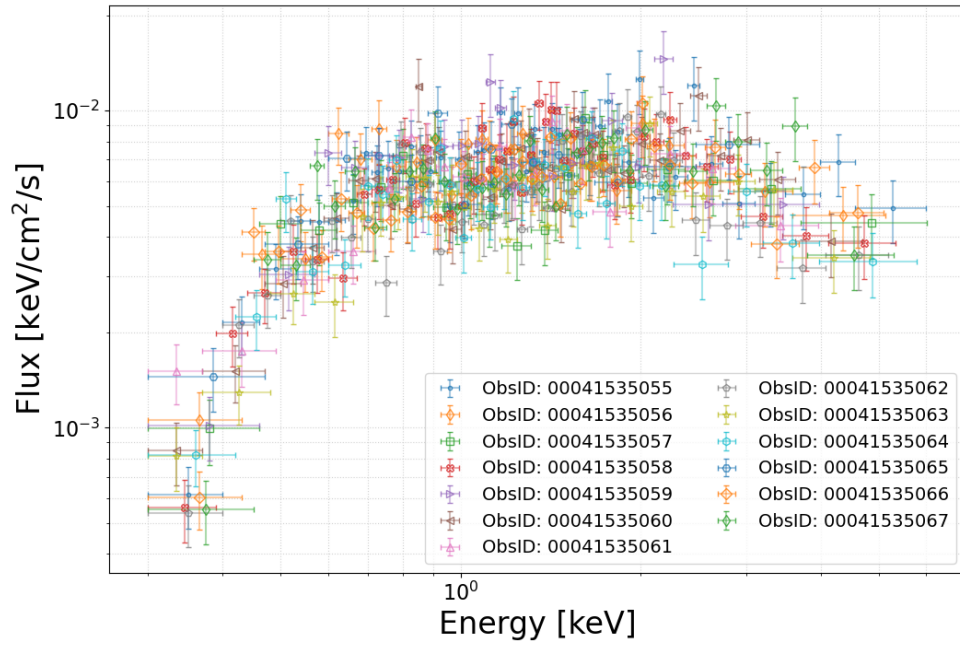


Figure A.5: Same as A.3, but for State C.

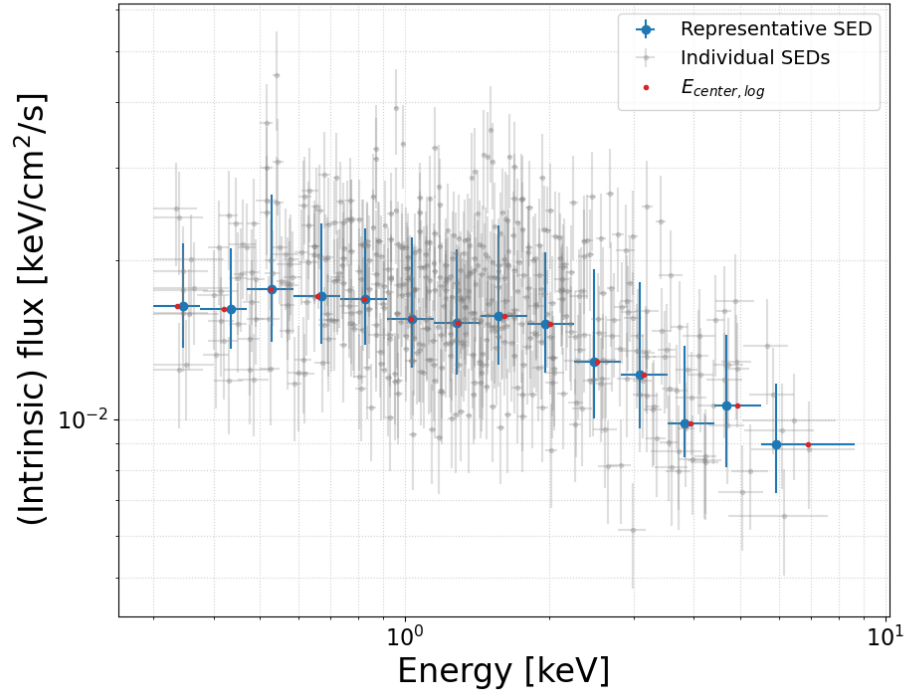


Figure A.6: Representative *Swift*-XRT SED (blue) for State A, as well as the individual SEDs (gray). Note that the gray SEDs are the SEDs in Figure A.3. The fluxes correspond to ii from Section 2.4, and have been n_H -deabsorbed via `nHDeabsorb`. The center of each energy bin in log space (red) is shown for reference.

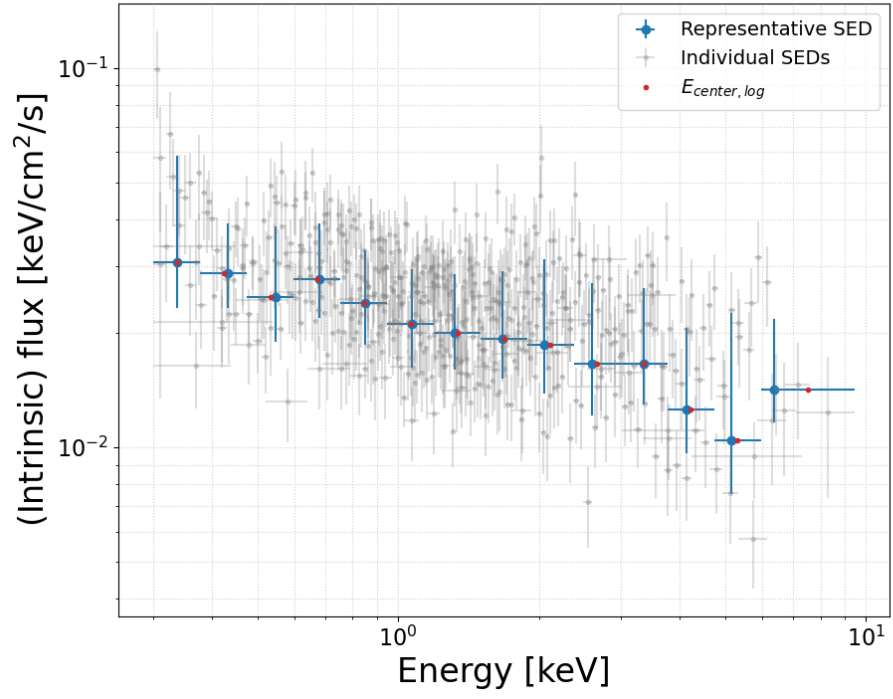


Figure A.7: Same as A.6, but for State B. Note that the gray SEDs are the SEDs in Figure A.4.

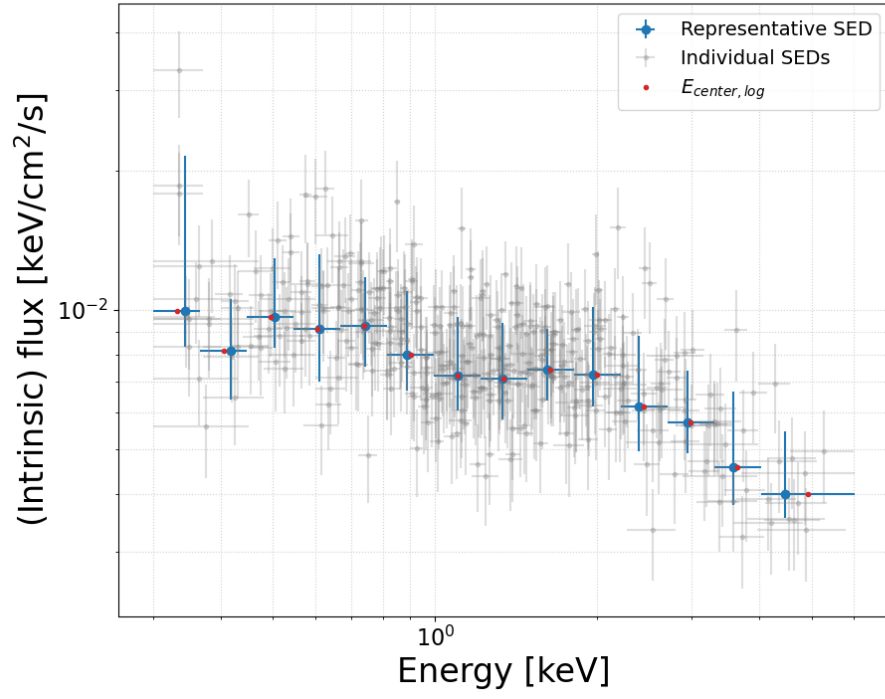


Figure A.8: Same as A.6, but for State C. Note that the gray SEDs are the SEDs in Figure A.5.

from 2 to 10 keV; above 2 keV, the absorption is minuscule, as shown in Figure A.1. Four models were tested. In some cases, the fit to the model in *XSpec* did not converge after the default number of trials (20); in these instances, the corresponding model is not included in the lightcurve.

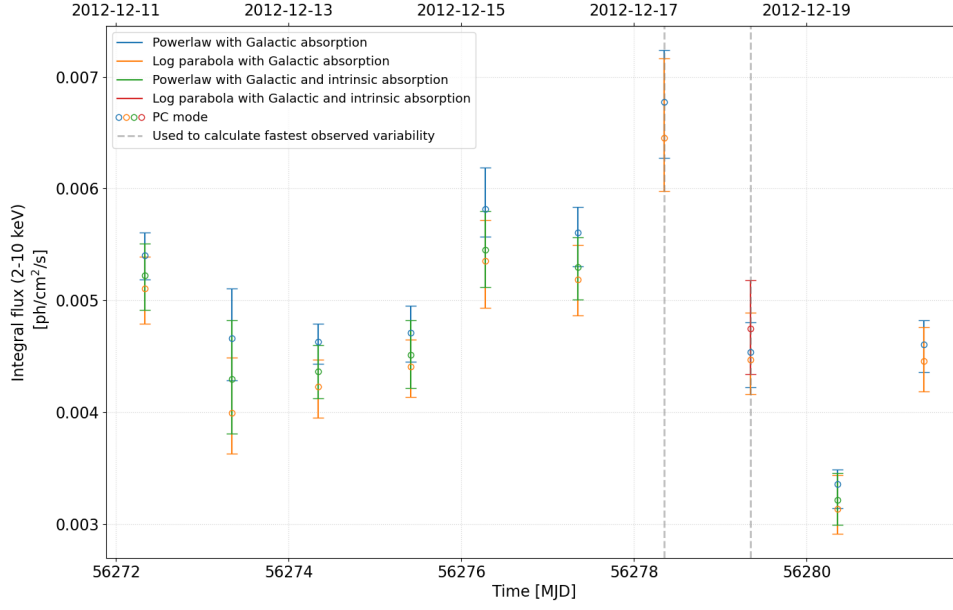


Figure A.9: *Swift*-XRT lightcurve for State A obtained from spectral model i (blue), ii (orange), iv (green), and iv (red). The dashed gray lines indicate the observations used to compute the fastest observed variability τ in Section 2.4.3.

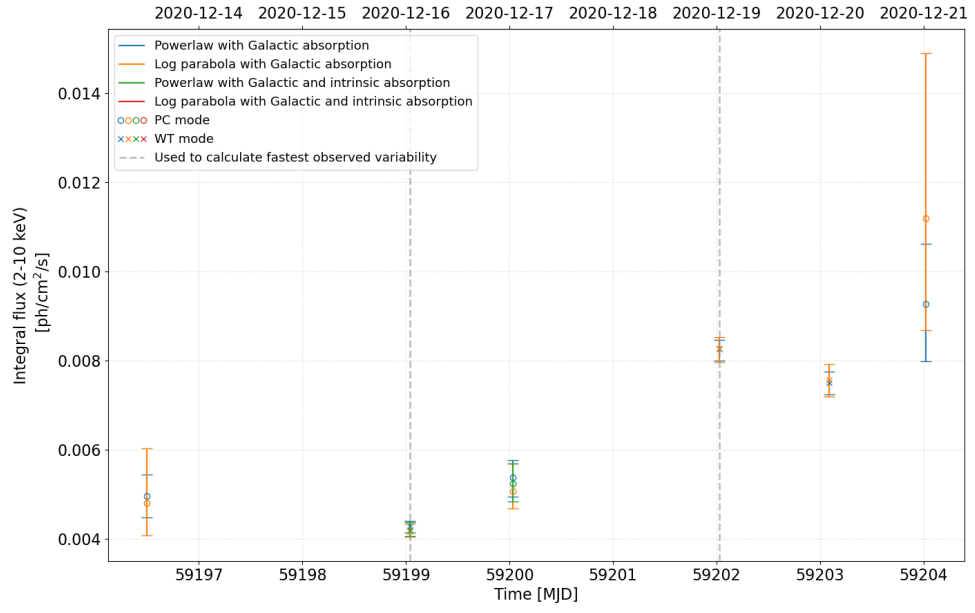


Figure A.10: Same as A.9, but for State B. The points selected for the calculation of τ have small uncertainties, so they produce a well-constrained τ_{95} .

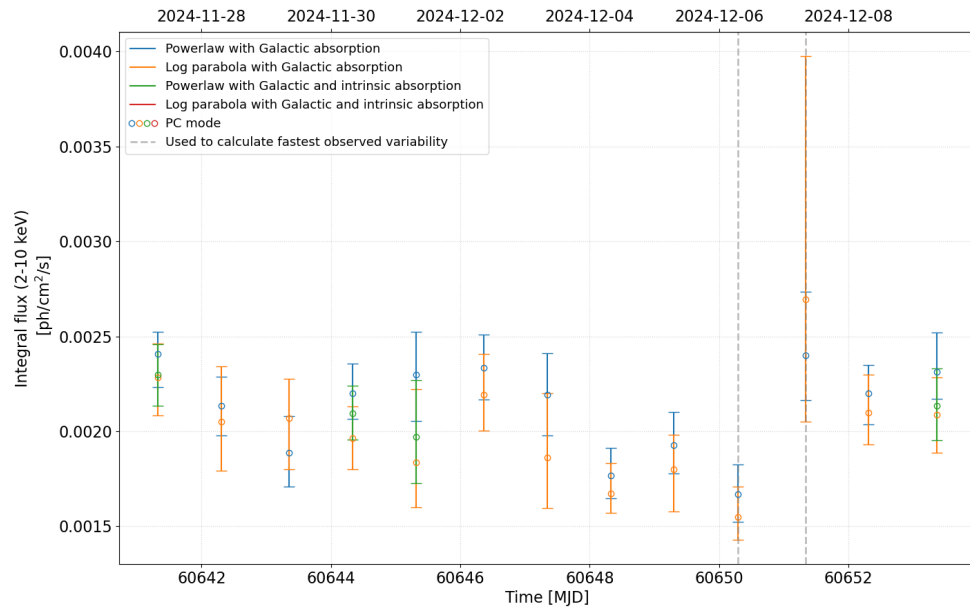


Figure A.11: Same as A.9, but for State C.

A.3 *Swift*-UVOT Analysis

A.3.1 *Swift*-UVOT Rocking

Figures A.12 and A.13 show images in which the spacecraft is rocking. For reference, Figure A.14 shows a steady image.

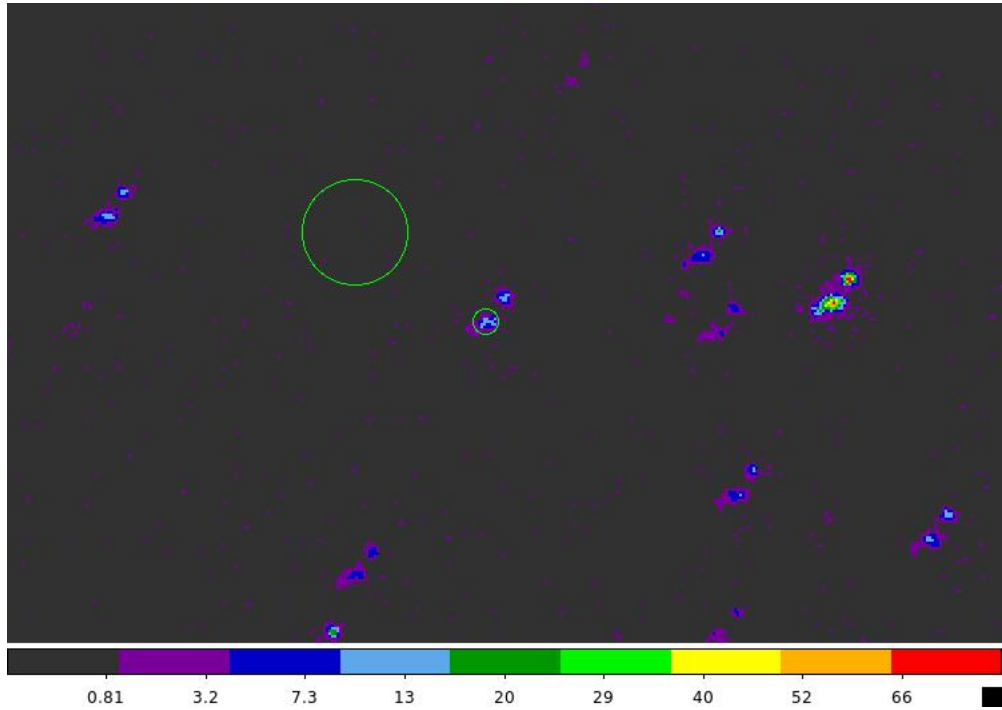


Figure A.12: Settling *Swift*-UVOT image, UVUM2 filter, ObsID 00032646039. The green circles indicate the source and background regions; however, this observation is not used in the analysis, so the regions are irrelevant.

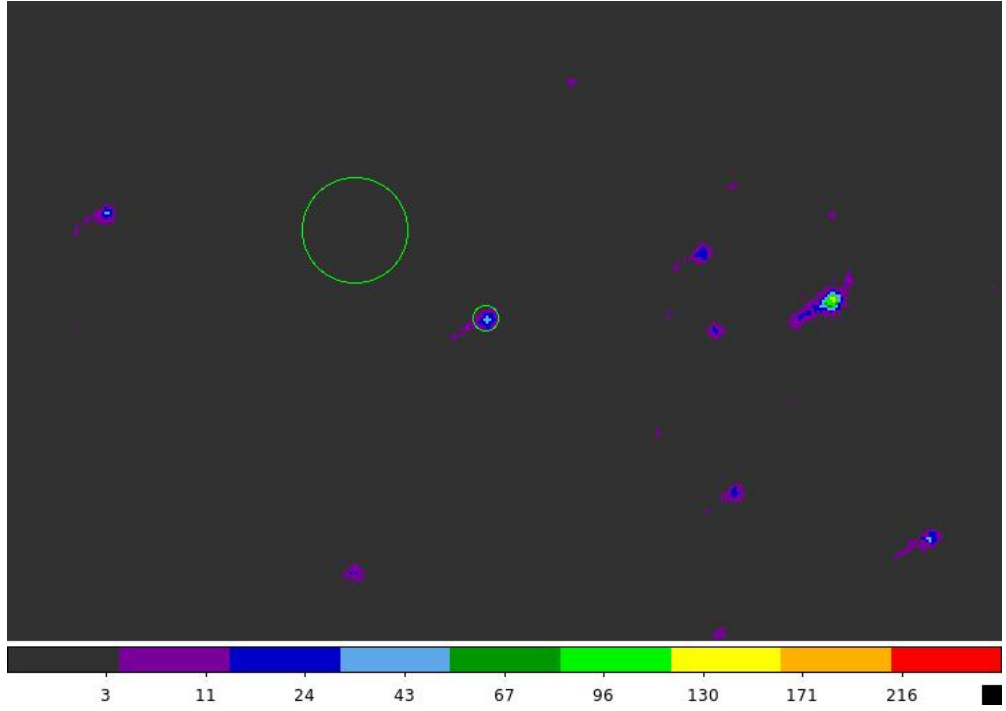


Figure A.13: Same as Figure A.12, but for the UVW2 filter.

A.3.2 *Swift*-UVOT Lightcurves

Figures A.15, A.16, and A.17 contain lightcurves with the observed fluxes (i.e., including Galactic extinction and the host galaxy contribution). An observation does not necessarily include data from every filter, which can be seen Figure A.15.

A.3.3 *Swift*-UVOT SEDs

De-extincted representative SEDs are in Figures A.18, A.19, and A.20. De-extincted and host galaxy subtracted representative SEDs are in Figures A.21, A.22, and A.23.

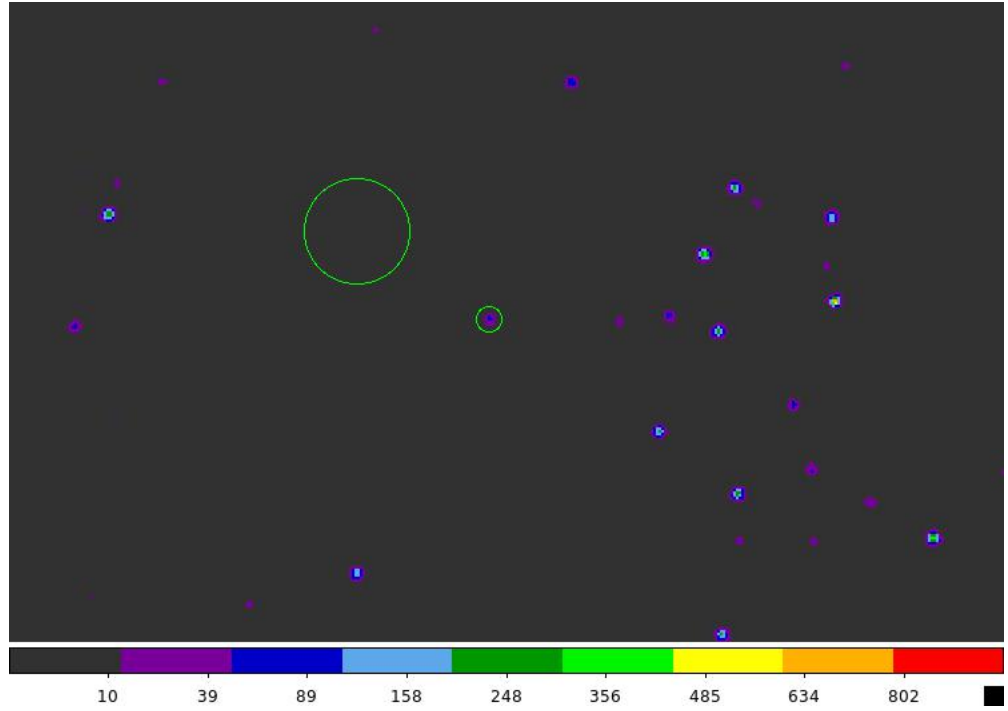


Figure A.14: Non-settling *Swift*-UVOT image, B filter, ObsID 00032646039. The green circles indicate the source and background regions.

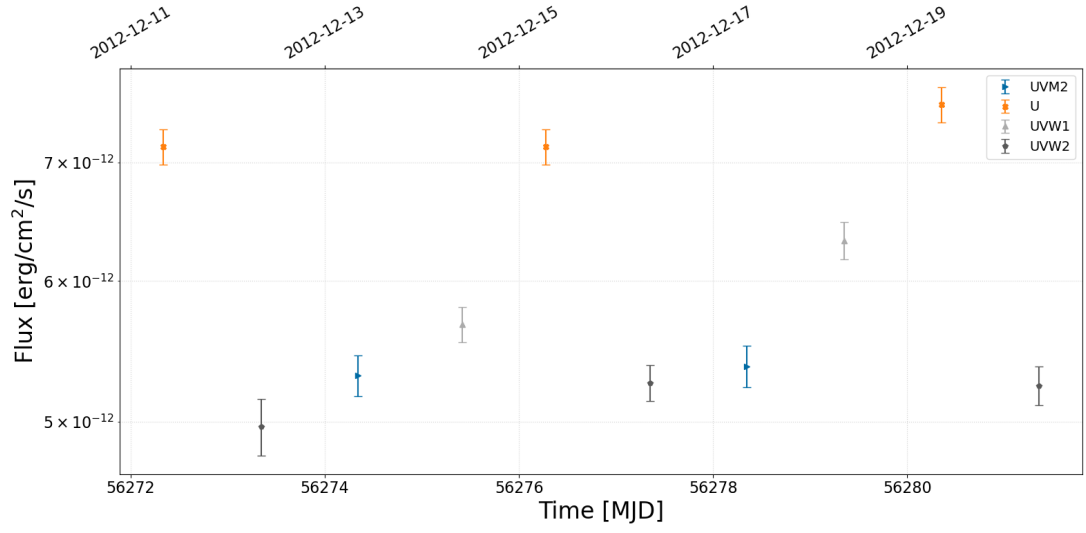


Figure A.15: *Swift*-UVOT lightcurve for State A. The legend indicates the filter.

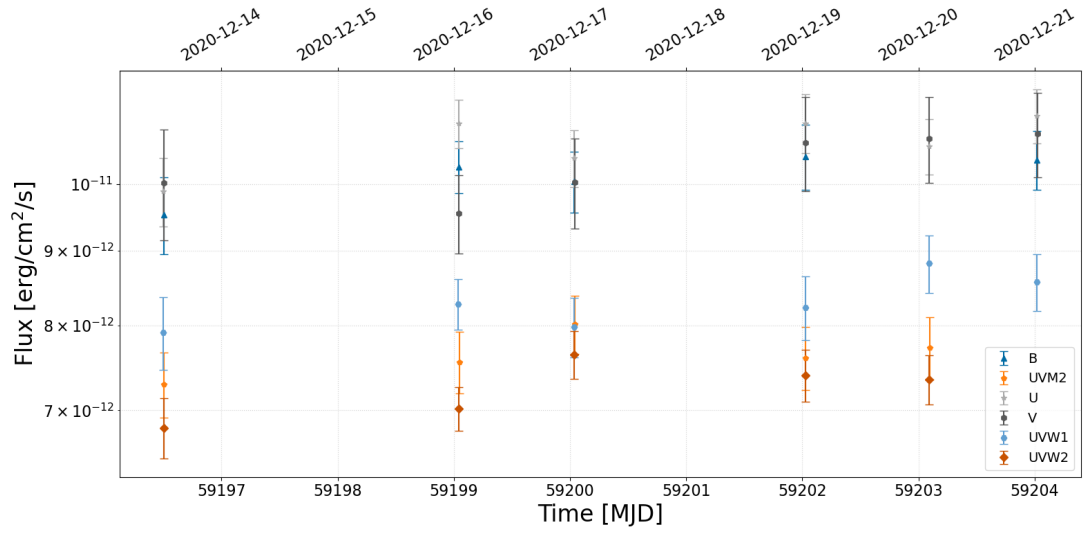


Figure A.16: Same as A.15, but for State B.

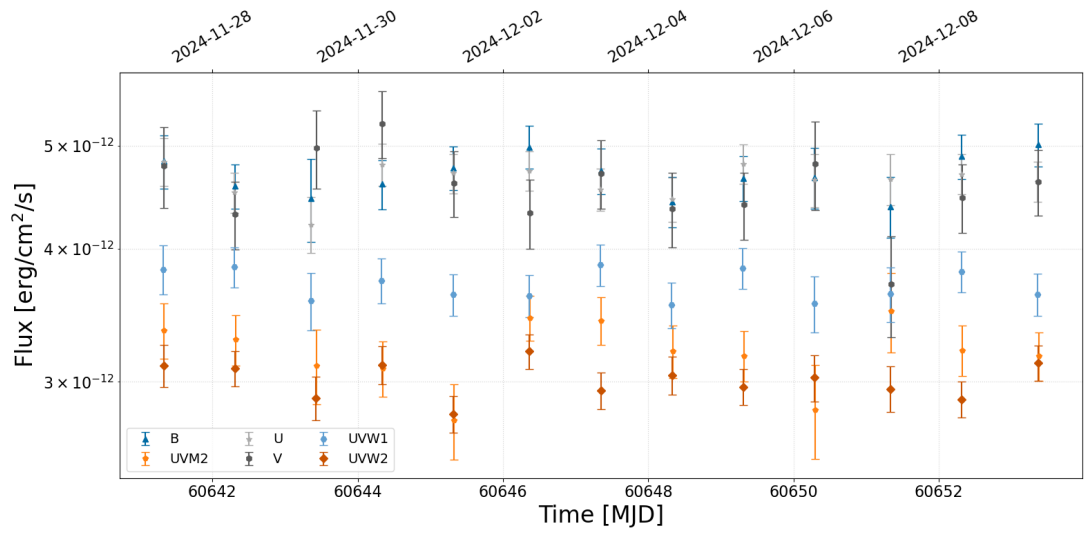


Figure A.17: Same as A.15, but for State C.

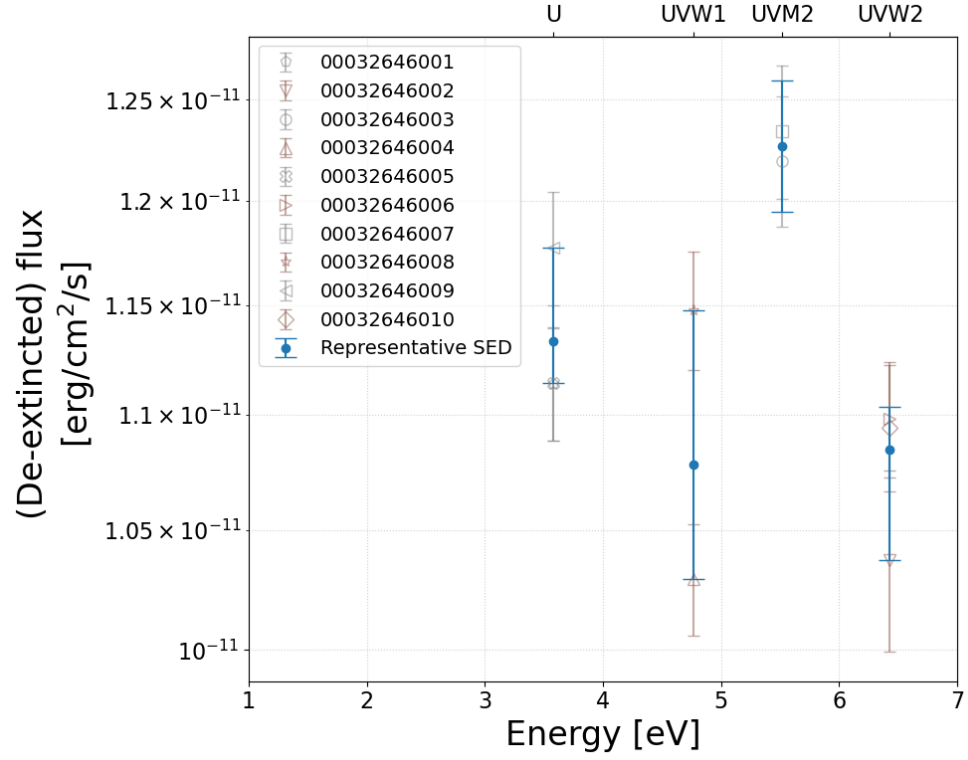


Figure A.18: Representative *Swift*-UVOT SED (blue) for State A, and the individual SEDs (gray and brown). The fluxes are de-extincted (that is, the Galactic extinction is removed), but the (faint) contribution from the host galaxy is still included. The numbered legend labels indicate the ObsID. The top axis contains the *Swift*-UVOT filter.

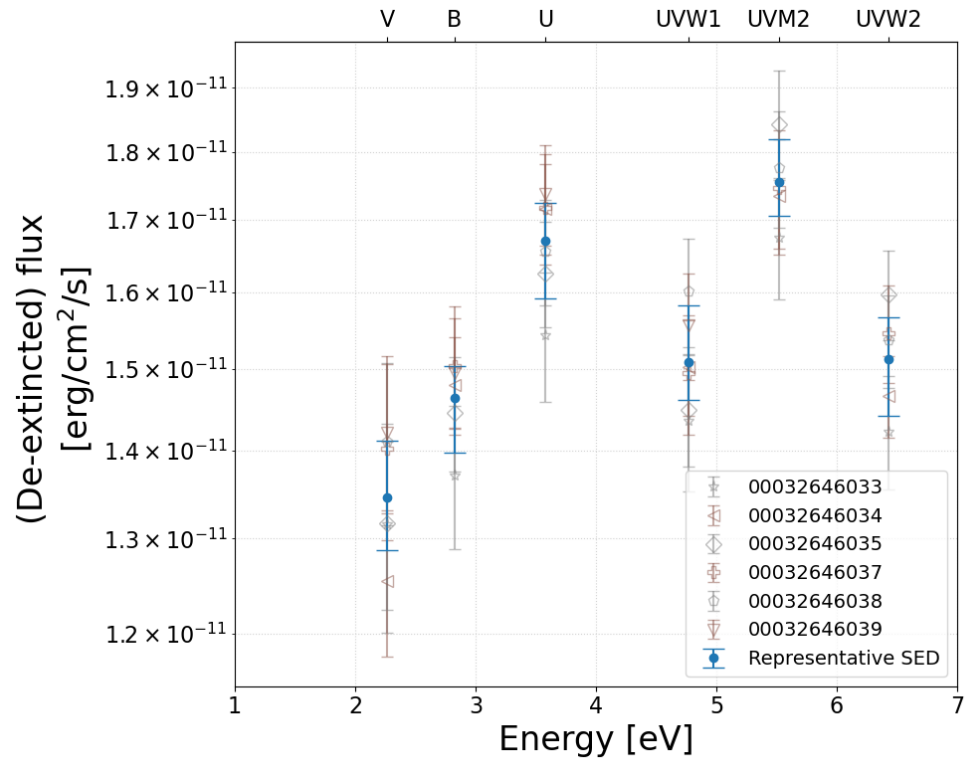


Figure A.19: Same as A.18, but for State B.

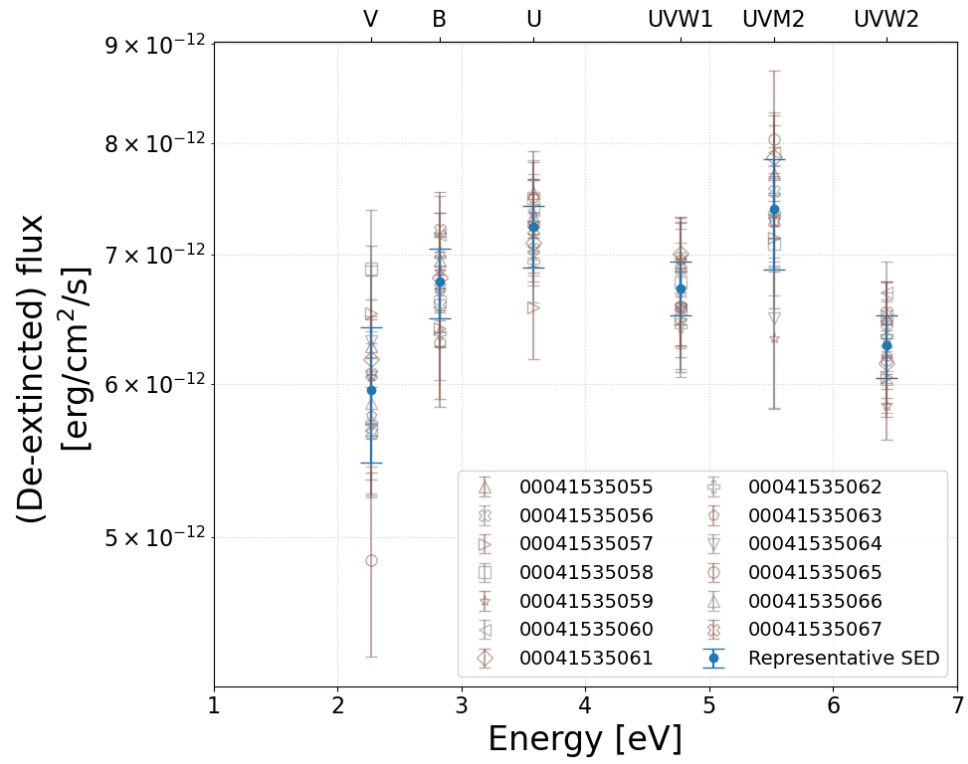


Figure A.20: Same as A.18, but for State C.

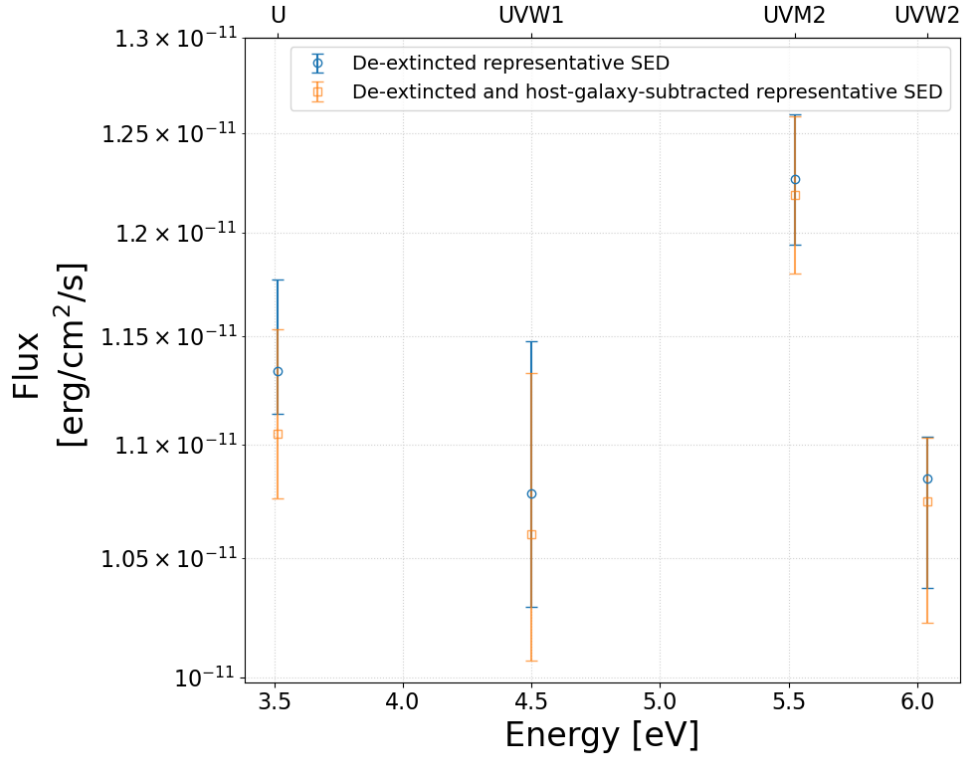


Figure A.21: De-extincted representative *Swift*-UVOT SED (blue) for State A, in addition to the SED with the host galaxy contribution removed from the representative fluxes (orange). The latter are used in the SED modeling in Chapter 3.

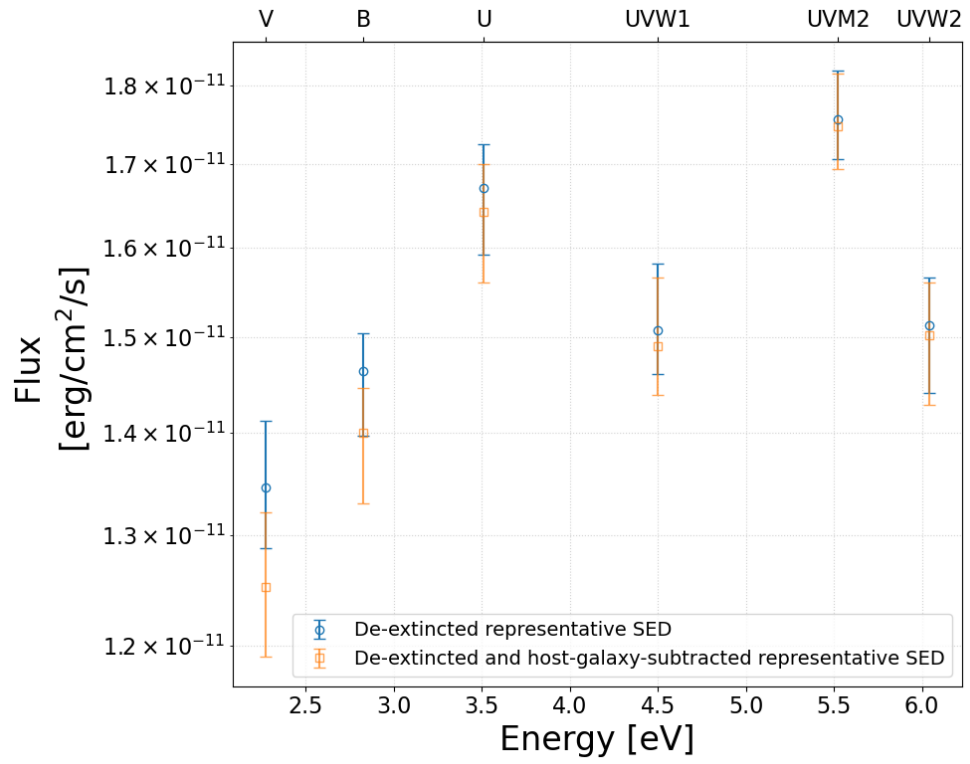


Figure A.22: Same as A.21, but for State B.

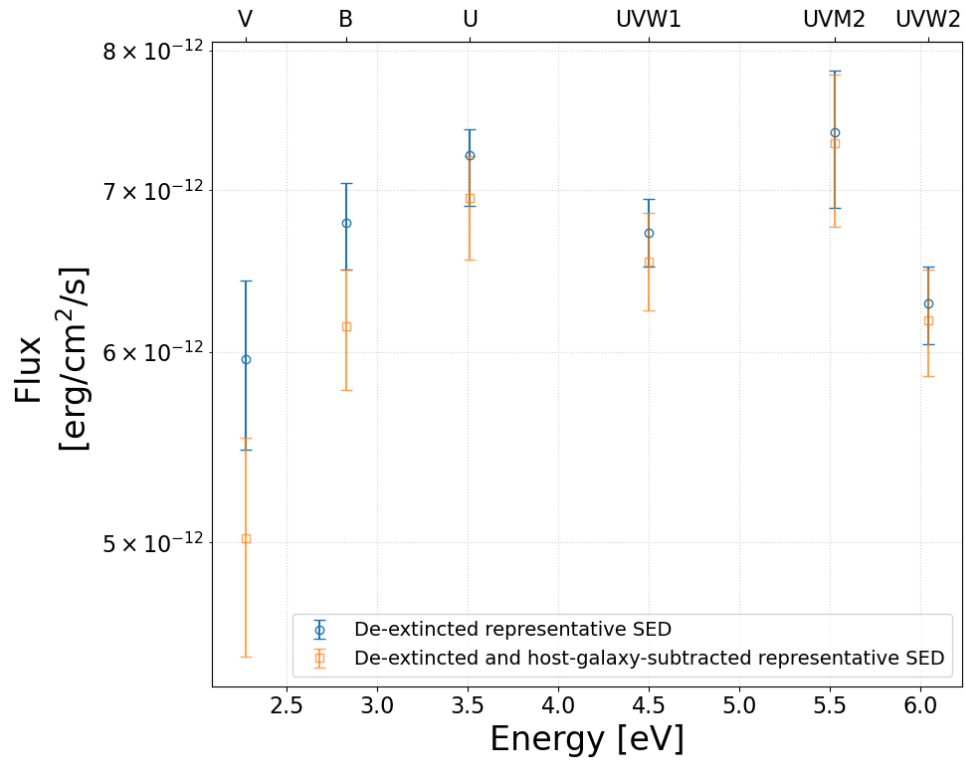


Figure A.23: Same as A.21, but for State C.

Bibliography

- Abdo, A. A., Ackermann, M., Ajello, M., et al. 2009, *The Astrophysical Journal*, 707, 1310, doi: 10.1088/0004-637X/707/2/1310
- Abdo, A. A., Ackermann, M., Ajello, M., et al. 2010, *ApJS*, 188, 405, doi: 10.1088/0067-0049/188/2/405
- . 2011, *ApJ*, 736, 131, doi: 10.1088/0004-637X/736/2/131
- Abdollahi, S., Acero, F., Ackermann, M., et al. 2020, *The Astrophysical Journal Supplement Series*, 247, 33, doi: 10.3847/1538-4365/ab6bcb
- Abdollahi, S., Acero, F., Baldini, L., et al. 2022, *The Astrophysical Journal Supplement Series*, 260, 53, doi: 10.3847/1538-4365/ac6751
- Abdollahi, S., Ajello, M., Baldini, L., et al. 2023, *ApJS*, 265, 31, doi: 10.3847/1538-4365/acbb6a
- Acciari, V. A., Agudo, I., Aniello, T., et al. 2023, *Astronomy & Astrophysics*, 670, A145, doi: 10.1051/0004-6361/202244126
- Acharyya, A., Archer, A., Bangale, P., et al. 2026a, arXiv e-prints, arXiv:2607.15435. <https://arxiv.org/abs/2607.15435>
- . 2026b, *ApJ*, 996, 38, doi: 10.3847/1538-4357/ae1d72
- Ackermann, M., Ajello, M., Allafort, A., et al. 2011, *ApJ*, 743, 171, doi: 10.1088/0004-637X/743/2/171
- . 2013, *ApJS*, 209, 34, doi: 10.1088/0067-0049/209/2/34
- Ackermann, M., Ajello, M., Baldini, L., et al. 2018, *The Astrophysical Journal Supplement Series*, 237, 32, doi: 10.3847/1538-4365/aacdf7
- Adams, C. B., Benbow, W., Brill, A., et al. 2022, *A&A*, 658, A83, doi: 10.1051/0004-6361/202142275

- Aharonian, F., Akhperjanian, A., Beilicke, M., et al. 2004, *A&A*, 421, 529, doi: 10.1051/0004-6361:20035764
- Aharonian, F., Aschersleben, J., Backes, M., et al. 2023, *The Astrophysical Journal Letters*, 950, L16, doi: 10.3847/2041-8213/acd777
- Aharonian, F. A. 2004, *Large Scale Jets of Radio Galaxies and Quasars* (World Scientific)
- Ajello, M., Baldini, L., Ballet, J., et al. 2022, *The Astrophysical Journal Supplement Series*, 263, 24, doi: 10.3847/1538-4365/ac9523
- Aleksić, J., Alvarez, E. A., Antonelli, L. A., et al. 2012, *A&A*, 544, A142, doi: 10.1051/0004-6361/201219133
- Aleksić, J., Ansoldi, S., Antonelli, L. A., et al. 2015, *A&A*, 578, A22, doi: 10.1051/0004-6361/201424811
- Alves Batista, R., Erdmann, M., Evoli, C., et al. 2015, *EPJ Web of Conferences*, 99, 13004, doi: 10.1051/epjconf/20159913004
- Alves Batista, R., Becker Tjus, J., Dörner, J., et al. 2022, *J. Cosmology Astropart. Phys.*, 2022, 035, doi: 10.1088/1475-7516/2022/09/035
- Archambault, S., Archer, A., Benbow, W., et al. 2017, *ApJ*, 835, 288, doi: 10.3847/1538-4357/835/2/288
- Archer, A., Benbow, W., Bird, R., et al. 2018, *ApJ*, 862, 41, doi: 10.3847/1538-4357/aacbd0
- Armengaud, E., Sigl, G., Beau, T., & Miniati, F. 2007, *Astroparticle Physics*, 28, 463–471, doi: 10.1016/j.astropartphys.2007.09.004
- Arnaud, K. A. 1996, in *Astronomical Society of the Pacific Conference Series*, Vol. 101, *Astronomical Data Analysis Software and Systems V*, ed. G. H. Jacoby & J. Barnes, 17
- Atwood, W. B., Abdo, A. A., Ackermann, M., et al. 2009, *The Astrophysical Journal*, 697, 1071, doi: 10.1088/0004-637X/697/2/1071
- Batista, R. A., Dundovic, A., Erdmann, M., et al. 2016, *Journal of Cosmology and Astroparticle Physics*, 2016, 038–038, doi: 10.1088/1475-7516/2016/05/038
- Beck, A. M., Hanasz, M., Lesch, H., Remus, R. S., & Stasyszyn, F. A. 2013, *MNRAS*, 429, L60, doi: 10.1093/mnrasl/sls026

- Beckmann, V., & Shrader, C. R. 2012a, *The Central Engine* (John Wiley & Sons, Ltd), 35–88, doi: <https://doi.org/10.1002/9783527666829.ch3>
- . 2012b, *AGN through the Electromagnetic Spectrum* (John Wiley & Sons, Ltd), 141–207, doi: <https://doi.org/10.1002/9783527666829.ch5>
- . 2012c, *AGN Types and Unification* (John Wiley & Sons, Ltd), 89–140, doi: <https://doi.org/10.1002/9783527666829.ch4>
- Bennett, C. L., Larson, D., Weiland, J. L., & Hinshaw, G. 2014, *ApJ*, 794, 135, doi: [10.1088/0004-637X/794/2/135](https://doi.org/10.1088/0004-637X/794/2/135)
- Berge, D., Funk, S., & Hinton, J. 2007, *A&A*, 466, 1219, doi: [10.1051/0004-6361:20066674](https://doi.org/10.1051/0004-6361:20066674)
- Bessell, M. S. 1979, *Publications of the Astronomical Society of the Pacific*, 91, 589, doi: [10.1086/130542](https://doi.org/10.1086/130542)
- Bethe, H., & Heitler, W. 1934, *Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences*, 146, 83, doi: [10.1098/rspa.1934.0140](https://doi.org/10.1098/rspa.1934.0140)
- Blandford, R., Meier, D., & Readhead, A. 2019, *ARA&A*, 57, 467, doi: [10.1146/annurev-astro-081817-051948](https://doi.org/10.1146/annurev-astro-081817-051948)
- Blytt, M., Kachelrieß, M., & Ostapchenko, S. 2020, *Computer Physics Communications*, 252, 107163, doi: [10.1016/j.cpc.2020.107163](https://doi.org/10.1016/j.cpc.2020.107163)
- Boris, J., & Shanny, R. 1972, *Naval Research Laboratory*
- Burrows, D. N., Hill, J. E., Nousek, J. A., et al. 2005, *Space Sci. Rev.*, 120, 165, doi: [10.1007/s11214-005-5097-2](https://doi.org/10.1007/s11214-005-5097-2)
- Campos, A., Samuroff, S., & Mandelbaum, R. 2023, *Monthly Notices of the Royal Astronomical Society*, 525, 1885–1901, doi: [10.1093/mnras/stad2213](https://doi.org/10.1093/mnras/stad2213)
- Christiansen, J., & VERITAS Collaboration. 2017, in *International Cosmic Ray Conference*, Vol. 301, 35th International Cosmic Ray Conference (ICRC2017), 789, doi: [10.22323/1.301.0789](https://doi.org/10.22323/1.301.0789)
- Chromey, A. J. B. 2022, PhD thesis, Iowa State University
- Cogan, P. 2006, PhD thesis, University College Dublin
- Cogan, P. 2008, in *International Cosmic Ray Conference*, Vol. 3, International Cosmic Ray Conference, 1385–1388, doi: [10.48550/arXiv.0709.4233](https://doi.org/10.48550/arXiv.0709.4233)

- Coleman, R. 1989, *Canadian Journal of Statistics*, 17, 27, doi: <https://doi.org/10.2307/3314760>
- Coppi, P. S., & Blandford, R. D. 1990, *MNRAS*, 245, 453, doi: [10.1093/mnras/245.3.453](https://doi.org/10.1093/mnras/245.3.453)
- Costamante, L., & Ghisellini, G. 2002, *A&A*, 384, 56, doi: [10.1051/0004-6361:20011749](https://doi.org/10.1051/0004-6361:20011749)
- ctapipe developers. n.d., Event Display with Hillas Parameters. https://ctapipe.readthedocs.io/en/latest/auto_examples/visualization/hillas.html#hillas-parameters
- Daniel, M. K. 2008, in *International Cosmic Ray Conference*, Vol. 3, International Cosmic Ray Conference, 1325–1328, doi: [10.48550/arXiv.0709.4006](https://doi.org/10.48550/arXiv.0709.4006)
- de Naurois, M., & Mazin, D. 2015, *Comptes Rendus Physique*, 16, 610, doi: <https://doi.org/10.1016/j.crhy.2015.08.011>
- Dermer, C. D., Cavadini, M., Razzaque, S., et al. 2011, *The Astrophysical Journal*, 733, L21, doi: [10.1088/2041-8205/733/2/L21](https://doi.org/10.1088/2041-8205/733/2/L21)
- Dumm, J. 2013, Highlights from the VERITAS Blazar Program. <https://arxiv.org/abs/1308.0287>
- Eisenstein, D. J., Annis, J., Gunn, J. E., et al. 2001, *AJ*, 122, 2267, doi: [10.1086/323717](https://doi.org/10.1086/323717)
- Elvis, M., Plummer, D., Schachter, J., & Fabbiano, G. 1992, *ApJS*, 80, 257, doi: [10.1086/191665](https://doi.org/10.1086/191665)
- Eppel, F., Kadler, M., Heßdörfer, J., et al. 2024, *A&A*, 684, A11, doi: [10.1051/0004-6361/202348262](https://doi.org/10.1051/0004-6361/202348262)
- Evans, P. A., Beardmore, A. P., Page, K. L., et al. 2009, *MNRAS*, 397, 1177, doi: [10.1111/j.1365-2966.2009.14913.x](https://doi.org/10.1111/j.1365-2966.2009.14913.x)
- Evans, R. D. 1955, *The atomic nucleus*, International series in pure and applied physics (New York: McGraw-Hill)
- Falomo, R., & Kotilainen, J. K. 1999, *A&A*, 352, 85, doi: [10.48550/arXiv.astro-ph/9910106](https://doi.org/10.48550/arXiv.astro-ph/9910106)
- Fermi Science Support Development Team. 2019, *Fermitools: Fermi Science Tools, Astrophysics Source Code Library*, record ascl:1905.011

- Fioc, M., & Rocca-Volmerange, B. 1999, arXiv e-prints, astro, doi: 10.48550/arXiv.astro-ph/9912179
- Franceschini, A., & Rodighiero, G. 2017, A&A, 603, A34, doi: 10.1051/0004-6361/201629684
- Franceschini, A., Rodighiero, G., & Vaccari, M. 2008, A&A, 487, 837, doi: 10.1051/0004-6361:200809691
- Freedman, D., & Diaconis, P. 1981, Zeitschrift für Wahrscheinlichkeitstheorie und Verwandte Gebiete, 57, 453, doi: 10.1007/BF01025868
- Furniss, A., Amador, J. N., Hervet, O., Jackson, O., & Williams, D. A. 2025, ApJ, 980, L15, doi: 10.3847/2041-8213/adae9d
- Furniss, A., Sutter, P. M., Primack, J. R., & Domínguez, A. 2014, Monthly Notices of the Royal Astronomical Society, 446, 2267, doi: 10.1093/mnras/stu2196
- Gadola, A. 2013, PhD thesis, University of Zurich, doi: 10.5167/uzh-85743
- Ghisellini, G., Celotti, A., Fossati, G., Maraschi, L., & Comastri, A. 1998, MNRAS, 301, 451, doi: 10.1046/j.1365-8711.1998.02032.x
- Ghisellini, G., Tavecchio, F., Maraschi, L., Celotti, A., & Sbarrato, T. 2014, Nature, 515, 376, doi: 10.1038/nature13856
- Goldoni, P. 2023, private communication
- Goldoni, P., Pita, S., Boisson, C., et al. 2021, A&A, 650, A106, doi: 10.1051/0004-6361/202040090
- Gréaux, L., Biteau, J., Hassan, T., et al. 2023a, STeVECat, the Spectral TeV Extragalactic Catalog, version 1, <https://doi.org/10.5281/zenodo.8152245>, Zenodo, doi: 10.5281/zenodo.8152245
- . 2023b, arXiv e-prints, arXiv:2304.00835, doi: 10.48550/arXiv.2304.00835
- Gregory, S. A., & Thompson, L. A. 1978, ApJ, 222, 784, doi: 10.1086/156198
- Grieder, P. K. 2010a, Atmospheric Cherenkov Radiation (Berlin, Heidelberg: Springer Berlin Heidelberg), doi: 10.1007/978-3-540-76941-5_4
- . 2010b, Electromagnetic Interactions and Photon–Electron Cascades (Berlin, Heidelberg: Springer Berlin Heidelberg), 147–203, doi: 10.1007/978-3-540-76941-5_4

- . 2010c, *Hadrons* (Berlin, Heidelberg: Springer Berlin Heidelberg), 683–739, doi: 10.1007/978-3-540-76941-5_13
- Hanna, D. 2007, Calibration Techniques for VERITAS. <https://arxiv.org/abs/0709.4479>
- Hanna, D., McCann, A., McCutcheon, M., & Nikkinen, L. 2010, *Nuclear Instruments and Methods in Physics Research A*, 612, 278, doi: 10.1016/j.nima.2009.10.107
- Heck, D., Knapp, J., Capdevielle, J. N., Schatz, G., & Thouw, T. 1998, CORSIKA: a Monte Carlo code to simulate extensive air showers.
- Heiter, C., Kuempel, D., Walz, D., & Erdmann, M. 2018, *Astroparticle Physics*, 102, 39, doi: 10.1016/j.astropartphys.2018.05.003
- Hervet, O. 2024a, Ohervet/SED_Host_Galaxy_Correction: First release, v0.1.0, Zenodo, doi: 10.5281/zenodo.10800919
- . 2024b, Ohervet/Bjet_MCMC: v1.0.0: New EIC process for the multi-zone model and multiple updates, v1.0.0, Zenodo, doi: 10.5281/zenodo.13129296
- Hervet, O., Boisson, C., & Sol, H. 2016, *A&A*, 592, A22, doi: 10.1051/0004-6361/201628117
- Hervet, O., Johnson, C. A., & Youngquist, A. 2024, *The Astrophysical Journal*, 962, 140, doi: 10.3847/1538-4357/ad09c0
- Hervet, O., Boisson, C., & Sol, H. 2015, *Astronomy & Astrophysics*, 578, A69, doi: 10.1051/0004-6361/201425330
- Hill, J. E., Burrows, D. N., Nousek, J. A., et al. 2004, in *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, Vol. 5165, X-Ray and Gamma-Ray Instrumentation for Astronomy XIII, ed. K. A. Flanagan & O. H. W. Siegmund, 217–231, doi: 10.1117/12.505728
- Hillas, A. M. 1985, in *International Cosmic Ray Conference*, Vol. 3, 19th International Cosmic Ray Conference (ICRC19), Volume 3, ed. F. C. Jones, 445
- Holder, J., Atkins, R., Badran, H., et al. 2006, *Astroparticle Physics*, 25, 391–401, doi: 10.1016/j.astropartphys.2006.04.002
- Jackson, O., Furniss, A., Hervet, O., Splettstoesser, M., & Williams, D. A. 2026, arXiv e-prints, arXiv:2604.01492, doi: 10.48550/arXiv.2604.01492

- Jelley, J. V. 1955, *British Journal of Applied Physics*, 6, 227, doi: 10.1088/0508-3443/6/7/301
- . 1961, *Contemporary Physics*, 3, 45, doi: 10.1080/00107516108204445
- Jorstad, S. G., Marscher, A. P., Morozova, D. A., et al. 2017, *The Astrophysical Journal*, 846, 98, doi: 10.3847/1538-4357/aa8407
- Kampert, K.-H., Kulbartz, J., Maccione, L., et al. 2013, *Astroparticle Physics*, 42, 41, doi: <https://doi.org/10.1016/j.astropartphys.2012.12.001>
- Kino, M., Takahara, F., & Kusunose, M. 2002, *The Astrophysical Journal*, 564, 97, doi: 10.1086/323363
- Kotilainen, J. K., Hyvönen, T., Falomo, R., Treves, A., & Uslenghi, M. 2011, *A&A*, 534, L2, doi: 10.1051/0004-6361/201117800
- Krolik, J. H. 1999, *What Are Active Galactic Nuclei? And Why Does Anyone Care?* (Princeton, N.J: Princeton University Press), 3–21
- Kumar, S. 2018, PhD thesis, University of Delaware
- Lafferty, G. D., & Wyatt, T. R. 1995, *Nuclear Instruments and Methods in Physics Research A*, 355, 541, doi: 10.1016/0168-9002(94)01112-5
- Langston, G. I., Heflin, M. B., Conner, S. R., et al. 1990, *ApJS*, 72, 621, doi: 10.1086/191427
- Li, T.-P., & Ma, Y.-Q. 1983, *ApJ*, 272, 317, doi: 10.1086/161295
- Lin, X. 2025, *VL Detectors* (Cham: Springer Nature Switzerland), 31–46, doi: 10.1007/978-3-031-64475-7_3
- Löahtenmöäki, A., & Valtaoja, E. 1999, *The Astrophysical Journal*, 521, 493, doi: 10.1086/307587
- Longair, M. S. 1992, *High energy astrophysics. Vol.1: Particles, photons and their detection* (Cambridge University Press)
- Lotto, B. D., & the MAGIC Collaboration. 2012, *Journal of Physics: Conference Series*, 375, 052021, doi: 10.1088/1742-6596/375/1/052021
- Lusen, P. 2025, private communication
- Lyke, B. W., Higley, A. N., McLane, J. N., et al. 2020, *The Astrophysical Journal Supplement Series*, 250, 8, doi: 10.3847/1538-4365/aba623

- Lyu, Y. 2026, Bachelor’s thesis, University California Santa Cruz
- Madhavan, A. 2013, PhD thesis, Iowa State University
- MAGIC Collaboration, Acciari, V. A., Aniello, T., et al. 2023, *A&A*, 670, A49, doi: 10.1051/0004-6361/202244477
- Maier, G., & Holder, J. 2017, Eventdisplay: An Analysis and Reconstruction Package for Ground-based Gamma-ray Astronomy. <https://arxiv.org/abs/1708.04048>
- Maldera, S., Wood, M., Caputo, R., et al. 2021, Fermi LAT Performance. https://www.slac.stanford.edu/exp/glast/groups/canda/lat_Performance.htm
- Marscher, A. P., & Gear, W. K. 1985, *ApJ*, 298, 114, doi: 10.1086/163592
- McCall, M. L. 2004, *AJ*, 128, 2144, doi: 10.1086/424933
- Meisner, A. M., & Romani, R. W. 2010, *ApJ*, 712, 14, doi: 10.1088/0004-637X/712/1/14
- Meyer, M. n.d., example_ebl.ipynb: Example EBL usage notebook, https://github.com/me-manu/ebtable/blob/main/notebooks/example_ebl.ipynb
- Meyer, M., & Splettstoesser, M. 2025, simCRpropa. <https://github.com/splettts/simCRpropa>
- NASA High Energy Astrophysics Science Archive Research Center (Heasarc). 2014, HEASoft: Unified Release of FTOOLS and XANADU, Astrophysics Source Code Library, record ascl:1408.004
- Neyrinck, M. C. 2008, *Monthly Notices of the Royal Astronomical Society*, 386, 2101–2109, doi: 10.1111/j.1365-2966.2008.13180.x
- Nițu, I., Bevins, H., Bray, J., & Scaife, A. 2021, *Astroparticle Physics*, 126, 102532, doi: 10.1016/j.astropartphys.2020.102532
- O’Brien, S. 2018, PhD thesis, University College Dublin
- Owens, A., Denby, M., Wells, A., et al. 1997, *The Astrophysical Journal*, 476, 924, doi: 10.1086/303628
- Padovani, P., & Giommi, P. 1995, *ApJ*, 444, 567, doi: 10.1086/175631

- Padovani, P., & Giommi, P. 1996, *Monthly Notices of the Royal Astronomical Society*, 279, 526, doi: 10.1093/mnras/279.2.526
- Padovani, P., Alexander, D. M., Assef, R. J., et al. 2017, *The Astronomy and Astrophysics Review*, 25, doi: 10.1007/s00159-017-0102-9
- Paiano, S., Landoni, M., Falomo, R., et al. 2017, *ApJ*, 837, 144, doi: 10.3847/1538-4357/837/2/144
- Park, K. I. 2018, *Fundamentals of Probability and Stochastic Processes with Applications to Communications*, 1st edn. (Cham: Springer International Publishing)
- Park, N., & VERITAS Collaboration. 2015, in *International Cosmic Ray Conference*, Vol. 34, 34th International Cosmic Ray Conference (ICRC2015), 771, doi: 10.22323/1.236.0771
- Penzias, A. A., & Wilson, R. W. 1965, *ApJ*, 142, 419, doi: 10.1086/148307
- Peterson, B. M. 1997a, *The Broad-Line Region* (Cambridge University Press), 67–92
- . 1997b, *The Narrow-Line Region* (Cambridge University Press), 93–109
- Poole, T. S., Breeveld, A. A., Page, M. J., et al. 2008, *MNRAS*, 383, 627, doi: 10.1111/j.1365-2966.2007.12563.x
- Prandini, E., Dialektopoulos, K., & Strišković, J. 2022, in *Proceedings of Corfu Summer Institute 2021 “School and Workshops on Elementary Particle Physics and Gravity” — PoS(CORFU2021)*, CORFU2021 (Sissa Medialab), 319, doi: 10.22323/1.406.0319
- Prandini, E., & Ghisellini, G. 2022, *Galaxies*, 10, doi: 10.3390/galaxies10010035
- Qin, L., Wang, J., Yang, C., et al. 2018, *PASJ*, 70, 5, doi: 10.1093/pasj/psx150
- Ribeiro, D. 2022, PhD thesis, Columbia University
- Ribeiro, D., O’Brien, S., & Shahinyan, K. 2020, *swift-uvot-analysis-tools*. https://github.com/deividribeiro/swift-uvot-analysis-tools/tree/remove_ds9
- Richards, J. L., Max-Moerbeck, W., Pavlidou, V., et al. 2011, *The Astrophysical Journal Supplement Series*, 194, 29, doi: 10.1088/0067-0049/194/2/29

- Rodrigo, C., & Solano, E. 2020, in XIV.0 Scientific Meeting (virtual) of the Spanish Astronomical Society, 182
- Rodrigo, C., Solano, E., & Bayo, A. 2012, SVO Filter Profile Service Version 1.0, IVOA Working Draft 15 October 2012, doi: 10.5479/ADS/bib/2012ivoa.rept.1015R
- Rohatgi, A. 2019, WebPlotDigitizer, 5.2. <https://automeris.io>
- Rolke, W. A., & López, A. M. 2001, Nuclear Instruments and Methods in Physics Research A, 458, 745, doi: 10.1016/S0168-9002(00)00935-9
- Romero, G. E. 2021, Astronomische Nachrichten, 342, 727, doi: 10.1002/asna.202113989
- Romero, G. E., Combi, J. A., Benaglia, P., et al. 1997, A&A, 326, 77
- Roming, P. W. A., Kennedy, T. E., Mason, K. O., et al. 2005, Space Sci. Rev., 120, 95, doi: 10.1007/s11214-005-5095-4
- Rybicki, G. B., & Lightman, A. P. 1979, Radiative processes in astrophysics (New York: Wiley)
- Saldana-Lopez, A., Domínguez, A., Pérez-González, P. G., et al. 2021, MNRAS, 507, 5144, doi: 10.1093/mnras/stab2393
- Sbarufatti, B., Treves, A., & Falomo, R. 2005, ApJ, 635, 173, doi: 10.1086/497022
- Scarpa, R., Urry, C. M., Falomo, R., Pesce, J. E., & Treves, A. 2000, ApJ, 532, 740, doi: 10.1086/308618
- Schachter, J. F., Stocke, J. T., Perlman, E., et al. 1993, ApJ, 412, 541, doi: 10.1086/172942
- Schlafly, E. F., & Finkbeiner, D. P. 2011, ApJ, 737, 103, doi: 10.1088/0004-637X/737/2/103
- Schneider, D. P., Richards, G. T., Hall, P. B., et al. 2010, AJ, 139, 2360, doi: 10.1088/0004-6256/139/6/2360
- Splettstoesser, M. 2024, nHDeabsorb. <https://github.com/spletts/nHDeabsorb>
- . 2025a, xrt_workflow. https://github.com/spletts/xrt_workflow
- . 2025b, ana_simCRpropa. https://github.com/spletts/ana_simCRpropa

- . 2025c, *catalog_matcher*. https://github.com/spletts/catalog_matcher
- Stacy, J., & Vestrand, W. 2003, in *Encyclopedia of Physical Science and Technology* (Third Edition), third edition edn., ed. R. A. Meyers (New York: Academic Press), 397–432, doi: <https://doi.org/10.1016/B0-12-227410-5/00274-X>
- Strauss, M. A., Weinberg, D. H., Lupton, R. H., et al. 2002, *AJ*, 124, 1810, doi: [10.1086/342343](https://doi.org/10.1086/342343)
- Sutter, P. M., Lavaux, G., Wandelt, B. D., & Weinberg, D. H. 2012, *The Astrophysical Journal*, 761, 44, doi: [10.1088/0004-637X/761/1/44](https://doi.org/10.1088/0004-637X/761/1/44)
- Sutter, P. M., Lavaux, G., Wandelt, B. D., et al. 2014, *Monthly Notices of the Royal Astronomical Society*, 442, 3127, doi: [10.1093/mnras/stu1094](https://doi.org/10.1093/mnras/stu1094)
- Tavecchio, F., & Ghisellini, G. 2015, *Monthly Notices of the Royal Astronomical Society*, 456, 2374–2382, doi: [10.1093/mnras/stv2790](https://doi.org/10.1093/mnras/stv2790)
- Tavecchio, F., Ghisellini, G., Ghirlanda, G., Foschini, L., & Maraschi, L. 2010, *MNRAS*, 401, 1570, doi: [10.1111/j.1365-2966.2009.15784.x](https://doi.org/10.1111/j.1365-2966.2009.15784.x)
- Tavecchio, F., Maraschi, L., & Ghisellini, G. 1998, *The Astrophysical Journal*, 509, 608–619, doi: [10.1086/306526](https://doi.org/10.1086/306526)
- Taylor, J. R. 1997, *An introduction to error analysis: the study of uncertainties in physical measurements*, second edition. edn. (Sausalito, California: University Science Books)
- Taylor, M. B. 2006, in *Astronomical Society of the Pacific Conference Series*, Vol. 351, *Astronomical Data Analysis Software and Systems XV*, ed. C. Gabriel, C. Arviset, D. Ponz, & S. Enrique, 666
- Tjemsland, J., Meyer, M., & Vazza, F. 2024, *ApJ*, 963, 135, doi: [10.3847/1538-4357/ad22dd](https://doi.org/10.3847/1538-4357/ad22dd)
- Urry, C. M., & Padovani, P. 1995, *Publications of the Astronomical Society of the Pacific*, 107, 803, doi: [10.1086/133630](https://doi.org/10.1086/133630)
- Voutsinas, G., Dalchenko, M., Gaug, M., et al. 2026, *Molecular absorption of Cherenkov light at CTAO*. <https://arxiv.org/abs/2603.02833>
- Wagner, R. M. 2006, PhD thesis, Max-Planck-Institute for Physics, Munich
- Wasserman, L. 2006, *Density Estimation* (New York, NY: Springer New York), 125–144, doi: [10.1007/0-387-30623-4_6](https://doi.org/10.1007/0-387-30623-4_6)

- Wenger, M., Ochsenbein, F., Egret, D., et al. 2000, *A&AS*, 143, 9, doi: 10.1051/aas:2000332
- Wilks, S. S. 1938, *The Annals of Mathematical Statistics*, 9, 60. <http://www.jstor.org/stable/2957648>
- Wilms, J., Allen, A., & McCray, R. 2000, *ApJ*, 542, 914, doi: 10.1086/317016
- Wood, M., Caputo, R., Charles, E., et al. 2017, in *International Cosmic Ray Conference*, Vol. 301, 35th International Cosmic Ray Conference (ICRC2017), 824, doi: 10.22323/1.301.0824
- Zettili, N. 2001, *Quantum Mechanics: Concepts and Applications* (Wiley)
- Zhang, L., Chen, S., Xiao, H., Cai, J., & Fan, J. 2020, *The Astrophysical Journal*, 897, 10, doi: 10.3847/1538-4357/ab9180