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# An Empirical Determination of the Intergalactic Background Light from UV to FIR Wavelengths Using FIR Deep Galaxy Surveys and the Gamma-ray Opacity of the Universe

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## ABSTRACT

We have previously calculated the intergalactic background light (IBL) as a function of redshift in the far ultraviolet to near infrared range, based purely on data from deep galaxy surveys. Here we utilize similar methods to determine the mid- and far infrared IBL out to a wavelength of  $850 \mu\text{m}$ . Our approach enables us to constrain the range of photon densities, based on the uncertainties from observationally determined luminosity densities and colors. By also including the effect of the 2.7 K cosmic background photons, we determine 68% confidence upper and lower limits on the opacity of the universe to  $\gamma$ -rays up to PeV energies.

Our direct results on the IBL are consistent with those from complimentary  $\gamma$ -ray analyses using observations from the *Fermi*  $\gamma$ -ray space telescope and the H.E.S.S. air Čerenkov telescope. Thus, we find no evidence of previously suggested processes for the modification of  $\gamma$ -ray spectra other than that of absorption by pair production alone.

*Subject headings:* diffuse radiation – galaxies: observations – gamma-rays: theory

## 1. Introduction

Past work on estimating the spectral and redshift characteristics of the intergalactic photon density (IBL) (with the  $z = 0$  IBL usually referred to as the EBL), has depended on various assumptions as to the evolution of stellar populations and dust absorption in galaxies (see below). There have also been attempts to probe the EBL using studies of blazar  $\gamma$ -ray spectra (Ackermann et al. 2012; Abramowski et al. 2013; Biteau & Williams 2015), an approach originally suggested by Stecker, De Jager & Salamon (1992).

We have previously pursued a *fully empirical* approach to calculating the IBL to wavelengths up to  $5 \mu\text{m}$  by using deep galaxy survey data (Stecker, Malkan & Scully 2012 (hereafter SMS12); and Scully, Malkan & Stecker 2014 (hereafter SMS14); for a similar approach, see also Helgason & Kashlinsky (2012) and Khaire & Srianand (2015). In this paper we extend our previous results from SMS12 and SMS14 on the  $\gamma$ -ray opacity of the Universe to encompass higher multi-TeV energies that are accessible to ground-based air Čerenkov telescopes. We do this by using very recent deep galaxy survey data at far infrared (FIR) wavelengths where galaxy emission is produced by dust re-radiation rather than starlight. We also include the  $\gamma$ -ray opacity from photons of the 2.7 K cosmic background radiation (CBR), thus extending our previous range of  $\gamma$ -ray opacities of the Universe beyond PeV energies.

Observations at wavelengths greater than  $24 \mu\text{m}$ , have been covered by the Multiband Imaging Photometer on the *Spitzer* space telescope (MIPS), now being dramatically advanced by the availability of data from the Photoconductor Array Camera and Spectrometer (PACS) and Spectral Photometric Imaging Receiver (SPIRE) instruments on the *Herschel* space telescope, the *Planck* space telescope, and by ground based observations from the Atacama Large Millimeter Array (ALMA) and observations from the Balloon-borne Large Aperture Submillimeter Telescope (BLAST). We stress that our approach, being

completely observationally based, is *model independent*, relying only on published luminosity functions. The observations of high-redshift galaxies are now sufficiently sampled to enable us to interpolate between observationally determined luminosity densities obtained for specific wavebands.

Our empirically based approach is superior to model-based methods, as it enables a determination of both the IBL *and its observational uncertainties* without modeling or making any assumptions about how the galaxy luminosity functions evolve, as some approaches require (*e.g.* Malkan & Stecker 1998, 2001; Kneiske, Mannheim & Hartmann, 2002; Stecker, Malkan & Scully 2006 (SMS06); Franceschini et al. 2008; Finke, Razzaque, & Dermer, 2010; Kneiske & Dole 2010) or by using semi-analytic models that make assumptions concerning galaxy evolution, stellar population synthesis models, star formation rates, and dust attenuation, particularly for redshifts greater than 1 (*e.g.*, Salamon & Stecker 1998; Gilmore et al. 2009; Somerville et al. 2011; Dominguez et al. 2011).

Our method of determining the expected  $\gamma$ -ray opacity of the Universe is complementary to the technique of using  $\gamma$ -ray observations directly (see above), because the intrinsic (unabsorbed) emission spectra of the  $\gamma$ -ray sources are uncertain.

Our final results give the  $\gamma$ -ray opacity as a function of energy and redshift to within an observationally determined 68% confidence band. Therefore, a direct comparison with  $\gamma$ -ray spectral data allows an independent determination of whether the previously suggested effects of secondary  $\gamma$ -ray production generated by: (1) cosmic-ray interactions along the line of sight to the source (Essey & Kusenko 2014) and (2) line-of-sight photon-axion oscillations during propagation (*e.g.*, De Angelis et al. 2007; Mayer & Horns 2013) are required to explain the  $\gamma$ -ray spectra of distant blazars. Both of those processes can produce additional modifications of the opacity derived from  $\gamma$ -ray observations, whereas

our method singles out only the modification of  $\gamma$ -ray spectra from pair-production alone.

In our conclusion section we compare our results with those obtained by the other methods in the some of the papers mentioned above. We also discuss the implications of our results.

## 2. Calculating the Infrared IBL

We have previously calculated the intergalactic background light (IBL) as a function of redshift in the far ultraviolet to near infrared range, based purely on data from deep galaxy surveys (SMS12; SMS14). Here we utilize similar methods to extend the calculation into the mid- and far infrared IBL out to a wavelength of 850  $\mu\text{m}$ .

### 2.1. Determining the Luminosity Densities from Empirical Luminosity Functions

In our previous work the observationally tolerated ranges of photon densities were determined from the luminosity densities (LDs),  $\rho_{L_\nu}$ , themselves, with errors provided by the various authors at wavelengths ranging from the far UV to the 5  $\mu\text{m}$  wavelength in the near IR. The LDs are computed by integrating fits to the observationally determined luminosity functions:

$$\rho_{L_\nu} = \int_{L_{min}}^{L_{max}} dL_\nu L_\nu \Phi(L_\nu; z) \quad (1)$$

Cases where authors did not directly compute the LDs were excluded because properly estimating their error requires knowledge of the covariance of the errors in the fit parameters of the luminosity functions (LFs) and also knowledge of any observational biases. To provide comprehensive redshift coverage of the LDs, SMS12 and SMS14 made use of continuum colors between the wavelength bands to fill in any gaps.

At wavelengths greater than  $5 \mu\text{m}$  very few studies provide determinations of luminosity densities (LDs) directly, as most authors are more concerned with calculating the *total* IR density, integrated over all wavelengths. This is because the total IR density is an observable which correlates to the star formation rate. Therefore, in this paper we used observer-given analytic fits to the LFs at various wavelengths. When those fits were not provided, we ourselves fit the observed infrared galaxy LFs at various wavelengths and redshifts and then use equation (1) to obtain the LDs.

Galaxy LFs typically have characteristic shapes that are flatter at lower luminosities but fall off more steeply at the highest luminosities. However, at wavelengths greater than  $5 \mu\text{m}$  the Schechter function, commonly used at optical wavelengths, does not provide a good fit to the LFs, being too flat at the faint end. Most observers instead fit their LFs to a broken power-law function that describes the data better. The transition region between the power law that holds at low luminosities and that holding at high luminosities is usually referred to as the *knee* of the LF. The luminosity at the knee is usually designated as  $L_*$ . The bulk of the LD comes from galaxies with luminosities in the vicinity of the knee; much fainter galaxies do not contribute much to the LD and the much brighter ones are quite rare. Thus, it is critical to determine the location of the knee in order to estimate the LDs with any accuracy.

For the cases where we were required to determine our own fits, we chose a double power-law fitting function of the form:

$$\Phi(L) = \frac{c}{L_* \left( \left( \frac{L}{L_*} \right)^{-a} + \left( \frac{L}{L_*} \right)^{-b} \right)} \quad (2)$$

Here, the negative parameters  $a$  and  $b$  are the indices of the power-law fits in the low luminosity and high luminosity ranges respectively. The overall normalization of the LF is given by the parameter  $c$ , which has the dimension of luminosity per  $Mpc^3 dex$ . To compute

the LDs, we integrate equation (1) over the galaxy luminosities between  $4 \times 10^7 L_{\odot}$  and  $10^{14} L_{\odot}$ . The resulting values that obtained for  $\rho_{L\nu}$  are not particularly sensitive to our chosen luminosity limits, since the bulk of the LD comes from galaxies with luminosities near  $L_*$ .

In order to accurately compute the errors in the LDs as derived from the fit parameters, which is essential for our calculation, we must do so in a way that includes terms involving the off-diagonal elements of the error matrix of the fits so as to account for covariance. In cases where the authors provided their own fits, we have therefore re-derived the fits of the LFs to generate the error matrix, retaining the same choice of fitting function and fixed parameters, if given.

Our goal, as in SMS12 and SSM14, was to compute the observationally tolerated ranges of luminosity densities. This requires that we represent the error on these quantities as best we can. The statistical error is determined by properly propagating the fit parameter errors accounting for covariance, lest we overestimate the error. To compute the total error on each LD, we further added in quadrature an additional systematic error that accounts for cosmic variance. We compute cosmic variance based on the field sizes of the individual studies. For the *AKARI Wide Field IR Survey Explorer (WISE)* and *GOODS* fields this value is typically of order of 10%. In determining the LDs, for consistency, all observational LFs are scaled to a Hubble parameter of  $h = 0.7$

Our new additions to our observationally determined LDs extend our coverage of rest frame galaxy photon production from the near IR to  $850 \mu\text{m}$  in the far IR, with enough determinations at each wavelength band to span the redshift range  $0 \leq z \leq 2 - 3$ . Using published results derived from observations by the *Spitzer* and *Herschel* space telescopes, sufficient redshift coverage was found for wavelength bands of 8, 12, 15, 24, 35, 60, 90, and  $250 \mu\text{m}$ .



There were two cases where we were required to combine LFs from different observational studies in order to provide enough coverage to discriminate the location of  $L_*$  particularly for redshifts greater than 1. At 12  $\mu\text{m}$  we combined the results of Perez-Gonzalez et al. (2005) and Rodighiero et al. (2010) to compute LDs in redshift bins centered on redshifts of 1.2, 1.6, and 2.0. In order to achieve sufficient redshift coverage at 90  $\mu\text{m}$  we combined some of the higher redshift 100  $\mu\text{m}$  data from Lapi et al. (2011) with that of the 90  $\mu\text{m}$  data from Gruppioni et al. (2013). This gains us additional coverage at redshifts of 1.4, 2.2, and 3.0.

At 160, 350, 500, and 850  $\mu\text{m}$ , LF data only exists for the very nearby redshifts. We therefore assumed that their redshift evolution closely follows that of the 250  $\mu\text{m}$  band (Lapi et al. 2011; Marchetti et al. 2016). We use local LDs calculated in those bands as a normalization to this evolution. This assumption is justified because the emission in this wavelength region is dominated by warm dust. At 160  $\mu\text{m}$  we used the local LF given by Patel et al. (2013). At 350 and 500  $\mu\text{m}$ , we used the combined local LF data of Marchetti et al. (2016) from *Herschel*/SPIRE, the *Herschel*/SPIRE estimate of Vaccari et al. (2010), and the *Planck* satellite data from Negrello et al. (2013). At 850  $\mu\text{m}$  we computed the local LD from the LF provided by Negrello et al. (2013). Figures 1 and 2 show the resulting derived values for  $\rho_{L_\lambda}(z)$  and their errors together with the observationally determined  $\pm 1 \sigma$  confidence bands for the 8, 12, 15, 24  $\mu\text{m}$  bands and those of 35, 60, 90, and 250  $\mu\text{m}$  respectively.

Our calculations of LDs at mid-IR to far-IR wavelengths presented here is an extension of the work done in SMS12 and SSM14. Thus, the results given in those papers for wavelengths less than 5  $\mu\text{m}$  is almost unchanged from the results presented here. However, we have updated the far UV calculations to include the more recent work from Bouwens et al. (2015) for LDs in the redshift range of 4 to 7. Even though the shape of the far UV band

can affect other bands when filling in for redshift gaps using colors, the overall calculation yields results that are qualitatively the same as those presented in SMS12 and SSM14, as the newer data do not significantly change the general trend.

In order to place 68% upper and lower limits from the observational data on  $\rho_{L_\nu}$  we make as few assumptions about the luminosity density evolution as possible. In SMS12 and SMS14 we utilized a robust rational fitting function in the form of a broken power-law dependent on  $(1+z)$  in order to generate the confidence bands. We find that the data for wavelengths greater than  $5 \mu\text{m}$  are well described by a fitting function of the form of a single power-law proportional to  $(1+z)^p$  for wavebands where the LDs continuously rise with  $z$  ( $60, 90$  and  $250 \mu\text{m}$ ) or a broken power-law, also dependent upon  $1+z$ , where the LDs peak ( $8, 12, 15, 24,$  and  $35 \mu\text{m}$ ). We take the 68% confidence ranges of these fits in each waveband as the  $\pm 1 \sigma$  confidence bands for the LDs. At redshifts beyond the redshift at the peak of star formation, the LDs decline with redshift. In accord with recent studies of the evolution of rest frame LFs in the UV that trace the star formation rate (Finkelstein et al. 2015), we conservatively assume upper and lower limit power-law functions in redshift to represent the rate of this decline as the highest redshifts. In the upper limit case, we assume a decline proportional to  $(1+z)^{-2}$ . In the lower limit case, we adopt a steeper decline proportional to  $(1+z)^{-4}$ . These assumptions have almost no impact on the derivation of the opacity confidence bands that we determined. Figures 1 and 2 show our results for LDs as a function of redshift at various wavelengths.

## 2.2. Taking account of PAH emission

At wavelengths greater than  $\sim 20 \mu\text{m}$  the LDs between the bands can be determined by smoothly interpolating between our observationally based LDs at specific wavelengths, since the spectral energy distributions (SEDs) from galaxies in this wavelength range are

smooth modified blackbody spectra produced by dust re-radiation. However, in the 5 – 20  $\mu\text{m}$  range the situation is more complex.

In star-forming galaxies, emission between 7 and 13  $\mu\text{m}$  is dominated primarily by polycyclic aromatic hydrocarbons (PAHs). These PAH molecules are found in very small dust grains in intergalactic media. They absorb the UV photons emitted by hot young *O* and *B* stars and reemit them in molecular emission bands in the mid-IR. They are thus a strong signature of active star formation in galaxies (Peeters, Spoon & Tielens 2004). In this regard, we note that luminous star forming galaxies at higher redshift have more prominent PAH emission features. The importance of PAH features in the mid-IR at redshifts  $0.5 \leq z \leq 2.5$  has been shown by Lagache et al. (2004).

The average SED of nearby star-forming galaxies (from Spoon et al. 2007, see also Smith et al. 2007) is shown in Figure 3 normalized to our best fit low redshift LD confidence band. One can see that there is a relative "valley" between 9 and 11  $\mu\text{m}$ . A simple direct interpolation between our 8 and 12  $\mu\text{m}$  bands would therefore obtain an incorrectly high value for the LD in this wavelength range. Since we do not have wavelength coverage in this regime, we take this feature into account by lowering our interpolated LDs by a factor of 3 for the upper limit and a factor of 5 for the lower limit at 10  $\mu\text{m}$ . The factor of 5 is chosen as a lower limit based on the difference between the peak at 8  $\mu\text{m}$  and the depth of the valley near 10  $\mu\text{m}$  from the SED. For the upper limit, we relax the depth of this feature because, while star forming galaxies make up the bulk of the IBL, contributions from other galaxy types have a less pronounced PAH feature. Since, at high redshifts, PAH emission correlates with the star formation rate (Shipley et al. 2016), we assume that our relative PAH shape factors of 3 and 5 coevolve with redshift.

### 3. The Extragalactic Background Light

At wavelengths above  $\sim 100 \mu\text{m}$  the FIRAS and DIRBE instruments aboard the *Cosmic Background Explorer* (COBE) have measured the EBL (Fixsen et al. 1998; Lagache et al. 1999). This diffuse background has now been in large part resolved by recent galaxy count studies using the *Herschel* telescope (Berta et al. 2010; Béthermin et al. 2012; Viero et al. 2015) along with ground based studies using *ALMA* (Fujimoto et al. 2016) and *BLAST* (Marsden et al. 2011). These more recent studies strongly support the COBE results.

However, there are no direct measurements of the EBL in the infrared range below  $\sim 100 \mu\text{m}$  owing to the dominance of foreground of Zodiacal light from interplanetary dust re-radiation. The flux of Zodiacal light is approximately two orders-of-magnitude larger than the EBL flux (Spiesman et al. 1995). In this region only lower limits obtained from galaxy counts exist.

Using our calculations of the LDs in the mid-IR and far-IR as a function of wavelength, we have constructed a 68% confidence band for the spectral energy distribution of the cosmic diffuse infrared background light (the IBL at  $z = 0$ ). Figure 4 shows our new results, combined with our previous results at shorter wavelengths, taken from SMS12 and SMS14. The light shaded band shows the maximum effect of PAH emission. It can be seen that taking account of the details of the PAH spectrum does not significantly affect our EBL results. Figure 4 also shows the observational lower limits on the EBL obtained from galaxy counts (in blue), extrapolations of mid-IR galaxy counts from *Spitzer*, and direct measurements (in black).

## 4. The Optical Depth of the Universe to Gamma-Rays from $\gamma + \gamma \rightarrow e^+ + e^-$ Interactions

### 4.1. The Optical Depth from Interactions with IBL Photons

The co-moving radiation energy density for wavelength  $\lambda$  at redshift  $z$ ,  $u_\nu(z)$ , where  $\nu = c/\lambda$ , is the time integral of the co-moving luminosity density  $\rho_\nu(z)$ ,

$$u_\nu(z) = \int_z^{z_{\max}} dz' \rho_{\nu'}(z') \frac{dt}{dz}(z'), \quad (3)$$

where  $\nu' = \nu(1+z)/(1+z')$  and  $z_{\max}$  is the redshift corresponding to initial galaxy formation (Salamon & Stecker 1998), and

$$\frac{dt}{dz}(z) = [H_0(1+z)\sqrt{\Omega_\Lambda + \Omega_m(1+z)^3}]^{-1}, \quad (4)$$

with  $\Omega_\Lambda = 0.72$  and  $\Omega_m = 0.28$ .

The upper and lower limits on our co-moving energy densities, derived using equation (3), are shown in Figures 5 and 6.

We note that in calculating the  $\gamma$ -ray opacities we use the quantities for the photon energy  $\epsilon_\nu = h\nu$  and the photon density  $n_\nu = \rho_\nu/\epsilon$ .

The cross section for photon-photon scattering to electron-positron pairs can be calculated using quantum electrodynamics (Breit & Wheeler 1934). The threshold for this interaction is determined from the frame invariance of the square of the four-momentum vector that reduces to the square of the threshold energy,  $s$ , required to produce twice the electron rest mass in the c.m.s.:

$$s = 2\epsilon E_\gamma(1 - \cos \theta) = 4m_e^2 \quad (5)$$

This invariance is known to hold to within one part in  $10^{15}$  (Stecker & Glashow 2001; Jacobson, Liberati, Mattingly & Stecker 2004).

With the co-moving energy density  $u_\nu(z)$  evaluated, the optical depth for  $\gamma$ -rays owing to electron-positron pair production interactions with photons of the stellar radiation background can be determined from the expression

$$\tau(E_0, z_e) = c \int_0^{z_e} dz \frac{dt}{dz} \int_0^2 dx \frac{x}{2} \int_0^\infty d\nu (1+z)^3 \left[ \frac{u_\nu(z)}{h\nu} \right] \sigma_{\gamma\gamma}[s = 2E_0hc/\lambda x(1+z)], \quad (6)$$

(Stecker, De Jager, & Salamon 1992).

In equations (5) and (6),  $E_0$  is the observed  $\gamma$ -ray energy at redshift zero,  $\lambda$  is the wavelength at redshift  $z$ ,  $z_e$  is the redshift of the  $\gamma$ -ray source at emission,  $x = (1 - \cos \theta)$ ,  $\theta$  being the angle between the  $\gamma$ -ray and the soft background photon, and the pair production cross section  $\sigma_{\gamma\gamma}$  is zero for center-of-mass energy  $\sqrt{s} < 2m_e c^2$ ,  $m_e$  being the electron mass. Above this threshold, the pair production cross section is given by

$$\sigma_{\gamma\gamma}(s) = \frac{3}{16} \sigma_T (1 - \beta^2) \left[ 2\beta(\beta^2 - 2) + (3 - \beta^4) \ln \left( \frac{1 + \beta}{1 - \beta} \right) \right], \quad (7)$$

where  $\sigma_T$  is the Thompson scattering cross section and  $\beta = (1 - 4m_e^2 c^4/s)^{1/2}$  (Jauch & Rohrlich 1955).

It follows from equation (5) that the pair-production cross section has a threshold at  $\lambda = 4.75 \mu\text{m} \cdot E_\gamma(\text{TeV})$ .

## 4.2. The Optical Depth of the Universe to Gamma-Rays from Interactions with the Cosmic Microwave Background

The optical depth of the universe to the CMB is given by

$$\tau_{CBR} = 5.00 \times 10^5 \sqrt{\frac{1.11 \text{PeV}}{E_\gamma}} \int_0^z \frac{dz' (1+z') e^{-\left(\frac{1.11 \text{PeV}}{E_\gamma(1+z')^2}\right)}}{\sqrt{\Omega_\Lambda + \Omega_m(1+z')^3}} \quad (8)$$

where we have updated the formula in Stecker (1969) using  $T_{CBR} = 2.73$  K and we have taken a  $\Lambda$ CDM universe with  $h = 0.7$ . In all of our calculations we use  $\Omega_\Lambda = 0.7$  and  $\Omega_m = 0.3$ .

### 4.3. Opacity results

Figure 7 shows the 68% confidence opacity bands for interactions with IBL photons given for sources at  $z = 0.1, 0.5, 1, 3$  and  $5$ , calculated using the methods described above, along with the opacity produced by interactions of  $\gamma$ -rays with photons of the 2.7 K cosmic background radiation. Note that at the higher energies and redshifts where the opacity is dominated by interactions with CRB photons, the uncertainty band becomes a very thin line, since the CBR-dominated opacity is exactly determined by equation (8).

## 5. Discussion and Conclusions

### 5.1. Comparison with our previous backward evolution model

Ten years ago we made estimates the diffuse infrared background when hardly any mid-IR and far-IR luminosity functions had been observationally determined at high redshifts (SMS06). That work was therefore based on the assumptions of a “backward evolution” model. Starting from the well-determined local ( $z=0$ ) LF at  $60\mu\text{m}$ , we assumed that the average locally determined transformations between different mid-IR and far-IR wavelengths applied, unchanged, at all redshifts. The luminosity function used was a double power-law, similar to that of equation (2) with the parameters  $a = -1.35, b = -3.6$  and

$L_* = 8.5 \times 10^{23}$  W/Hz at  $z = 0$  as determined at  $60 \mu\text{m}$ , which was the wavelength for which the most complete galaxy LF existed. We then assumed that the effect of redshift evolution could be taken account purely by the evolution of  $L_*$ , as described in SMS06.

We have compared the predictions of the SMS06 backwards evolution model with the recently observed IR LFs as used in this paper. If we make relatively small improvements in the assumed LF parameters, the backwards evolution model agrees with the new observations surprisingly well. The data favor a slightly flatter LF, with a low-luminosity slope of  $a = 1.25$  and a high-luminosity slope of  $b = 3.25$ , provided that we compensate by slightly decreasing the normalization of the LF at  $L_*$  and  $z = 0$  to  $3.5 \times 10^{-3}$  Mpc $^{-3}$  dex $^{-1}$ . We then match the observed LFs at higher redshifts, by assuming that  $L_*$  increases as  $(1 + z)^{3.0}$  for  $0 < z < 2.0$ , with  $L_*$  constant at higher redshifts. In this way, we can obtain a good fit between the backward evolution model and the observational data.

Although this slightly modified backwards evolution reproduces the observed LFs at all redshifts well, there are a few discrepancies, in either direction. The most substantial disagreement is with the  $8\mu\text{m}$  observations of Huang et al. (2007) at  $z = 0.15$ . Below the knee of the LF the observed LF the data are up to 0.3 dex higher than the LF of our backwards evolution model. On the other hand, our best-fitting model overpredicts the  $15 \mu\text{m}$  LFs by up to 0.25 dex at luminosities above the knee as compared with the data of Pozzi et al. (2004), Le Floch et al (2005), and Rodighiero et al. (2010). The likely explanation of both of these discrepancies is that our previously proposed simple model SEDs are based on average  $12\mu\text{m}$  luminosities as derived from the  $60 \mu\text{m}$  observations. Therefore, they do not include the strong contributions from the PAH bands (See section 2.2). Thus our SEDs will overpredict the dust continuum on either side of the PAH bump feature as shown in Figure 3. Correspondingly, if we lower the normalization to better fit the shorter and longer wavelengths, we under-estimate the broadband fluxes at  $8\mu\text{m}$  rest wavelength.



Of course, our new observationally-based calculation presented in this paper avoids the problems of backward evolution models, since here we use directly observed LFs at 8, 15, and 24  $\mu\text{m}$ . These data include the effect of the PAH emission features and show their significance.

## 5.2. Our present results and comparison with other work

Figure 8 shows our 68% confidence band computed for the  $z = 0$  EBL along with EBL SEDs obtained from the models of Franceschini et al. (2008) and Domínguez et al. (2011). Figure 9 shows our 68% opacity bands for  $z = 0.1, 0.5, 1, 3$  and 5, in comparison with the opacity curves of Franceschini et al. (2008) and Domínguez et al. (2011). We note that Franceschini et al. (2008) used data only up to 8  $\mu\text{m}$  that were available at the time and did not include a PAH component in their model. The model of Domínguez et al. (2011) assumes a redshift evolution at redshifts greater than  $\sim 1$  that follows the evolution in the  $K$ -band given by Cirasuolo et al. (2010).

## 5.3. Conclusion

In our previous papers (SMS12 and SMS14), we presented observationally based results for the IBL as a function of wavelength and redshift for wavelengths below of 5  $\mu\text{m}$ . Based on those results, we computed the  $\gamma$ -ray opacity of the universe up to a  $\gamma$ -ray energy of  $1.6/(1+z)$  TeV. In this paper we extend our determinations of 68% confidence bands for the IBL, giving upper and lower limits on the IBL out to 850  $\mu\text{m}$ . This model-independent determination is again based on observationally derived luminosity functions from local and deep galaxy survey data, including results from *Spitzer*, *Herschel* and *Planck*. We then use these results to calculate the opacity of the Universe to  $\gamma$ -rays out to PeV energies. In

doing so, we also take account of interactions of  $\gamma$ -rays with photons of the 2.7 K cosmic background radiation (CBR) (Stecker 1969), since the opacity from interactions with CBR photons dominates over that from interactions with IBL photons at the higher  $\gamma$ -ray energies and redshifts.

Figure 10 shows an energy-redshift plot of the highest energy photons from extragalactic sources at various redshifts from *Fermi* as given by Abdo et al. (2010) along with our 68% confidence band for  $\tau = 1$ , extending our result from SMS down to a redshift of  $z = 0.2$ .

Our direct results on the IBL are consistent with those from complimentary  $\gamma$ -ray analyses using observations from the *Fermi*-LAT  $\gamma$ -ray space telescope and the H.E.S.S. air Čerenkov telescope. Figure 11 indicates how well our opacity results for  $z = 1$  overlap with those obtained by the *Fermi* collaboration (Ackermann et al. 2012). Our results are also compatible with those obtained from higher energy  $\gamma$ -ray observations using H.E.S.S. (Abramowski et al. 2013). This overlap of results from two completely different methods strengthens confidence that both techniques are indeed complimentary and supports the concept that the spectra of cosmic  $\gamma$ -ray sources can be used to probe the IBL (Stecker et al. 1992).

Thus, we find no evidence for modifications of  $\gamma$ -ray spectra by processes other than absorption by pair production, either by cosmic-ray interactions along the line of sight to the source (Essey & Kusenko 2014) or line-of-sight photon-axion oscillations during propagation (*e.g.*, De Angelis et al. 2007; Mayer & Horns 2013). In this regard, we note that the *Fermi* Collaboration has very recently searched for irregularities in the  $\gamma$ -ray spectrum of NGC 1275 that would be caused by photon-axion oscillations and reported negative results (Ajello et al. 2016).

We conclude that modification of the high energy  $\gamma$ -ray spectra of extragalactic sources occurs dominantly by pair production interactions of these  $\gamma$ -rays with photons of the

IBL. They therefore support the concept of using the future *Čerenkov Telescope Array* instruments to probe the cosmic background radiation fields at infrared wavelengths. This method can be used in conjunction with future deep galaxy survey observations using the near infrared and mid-infrared instruments aboard the *James Webb Space Telescope*.

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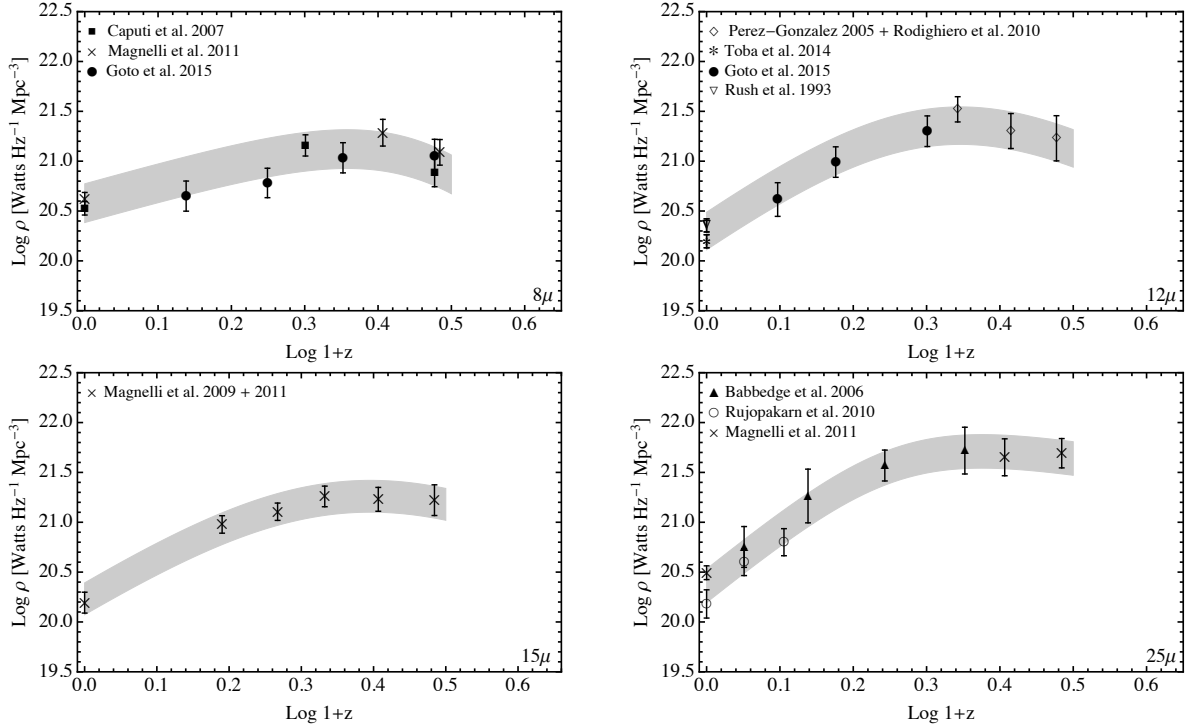


Fig. 1.— The luminosity densities for 8, 12, 15, and 24  $\mu$ m wavebands. Data are from several sources. Some *Spitzer* data from all 4 wavebands are from Rodighiero et al. (2010). *AKARI* 8 and 12  $\mu$ m data are from Goto et al. (2015), *Spitzer* data at 8  $\mu$ m are from Huang et al. (2007) and Caputi et al. (2007). *Spitzer* data at 8 and 24  $\mu$ m are from Babbedge et al. (2006). *Spitzer* data at 15  $\mu$ m are from Le Floc’h et al. (2005). *Spitzer* data at 24  $\mu$ m are from Pérez-González et al. (2005). The grey shading represents the 68% confidence bands (see text).



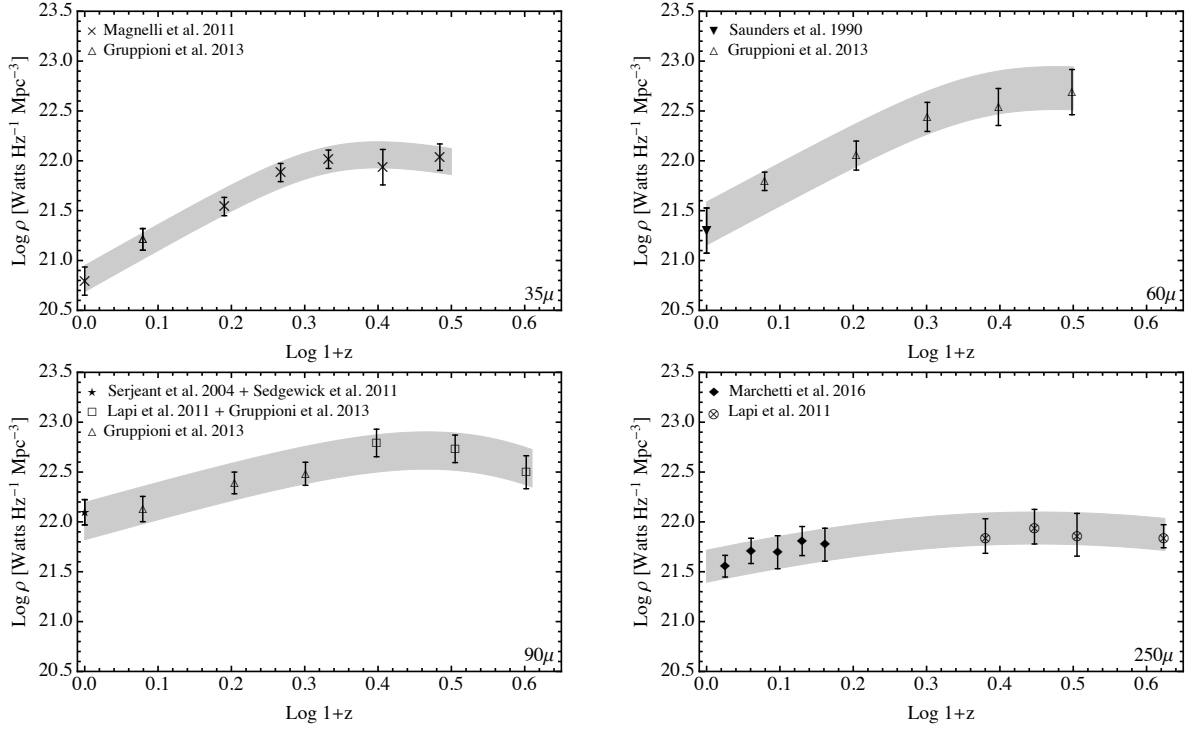


Fig. 2.— The luminosity densities for the 35, 60, 90, and 250  $\mu$ m wavebands. The grey shading represents the 68% confidence bands. *Herschel* data at 35, 60, and 90  $\mu$ m are from Gruppioni et al. (2013). Also 100  $\mu$ m data from Lapi et al (2011) are plotted on the 90  $\mu$ m graph. *Herschel* data at 250  $\mu$ m are from Eales et al. (2010), Dye et al. (2010) and Smith et al. (2012) (see text).

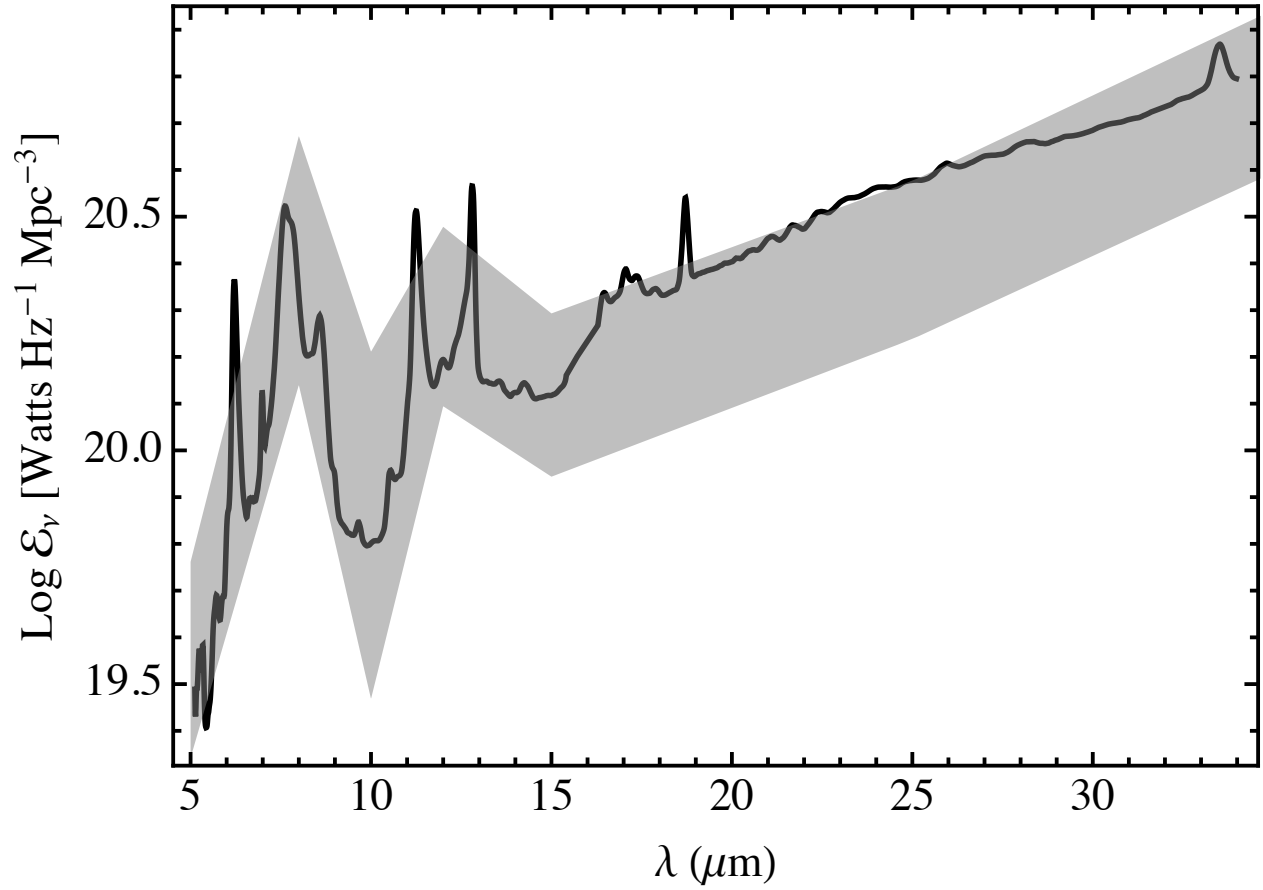


Fig. 3.— Average low redshift galaxy SED at MIR wavelengths based on the Class 1C SED of Spoon et al. (2007) normalized to our low redshift LDs from Figures 1 and 2, as indicated by the shaded region.

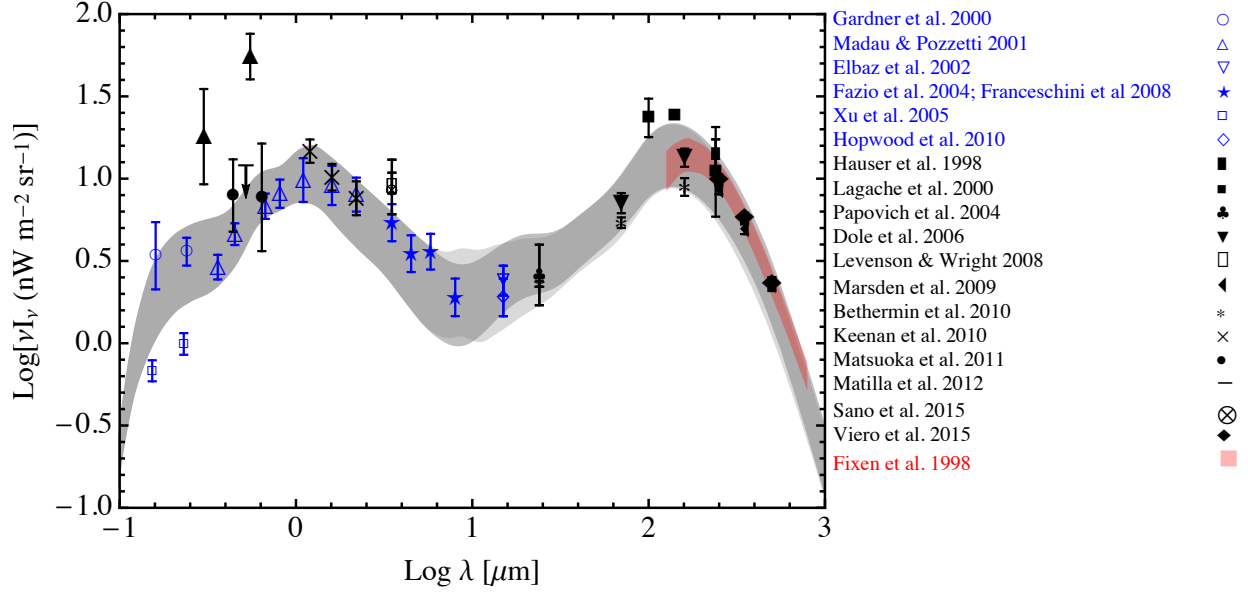


Fig. 4.— Our spectral energy distribution of the EBL together with empirical data based on our mid-IR LDs and far-IR LDs and the results of SMS12 and SMS14. The light shaded area between  $\sim 10 \mu\text{m}$  and  $\sim 30 \mu\text{m}$  indicates the maximum effect of the PAH bands (see Sect. 2.2). The lower limits from galaxy counts are shown in blue; direct measurements and extrapolations from galaxy counts in the mid-IR are shown in black. References for the empirical data before 2012 are given by Lagache et al. (2005) and Dwek & Krennrich (2012). A  $3.5 \mu\text{m}$  point is from Sano et al. (2016). The red shaded area is based on the *COBE-FIRAS* results of Fixsen et al. (1998) with limits described by modified black body spectra.

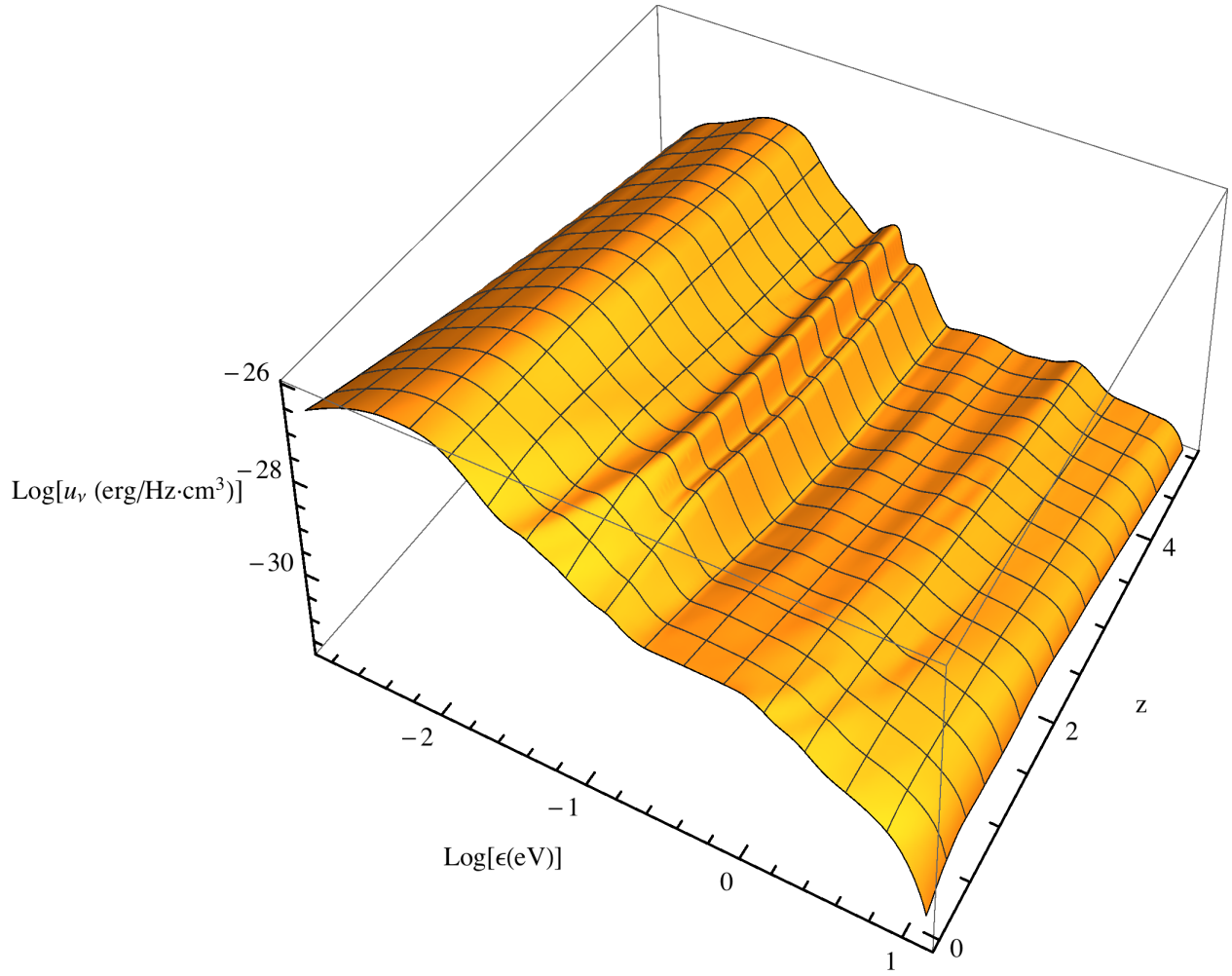


Fig. 5.— Upper limit envelope on the co-moving energy density as a function of energy and redshift.

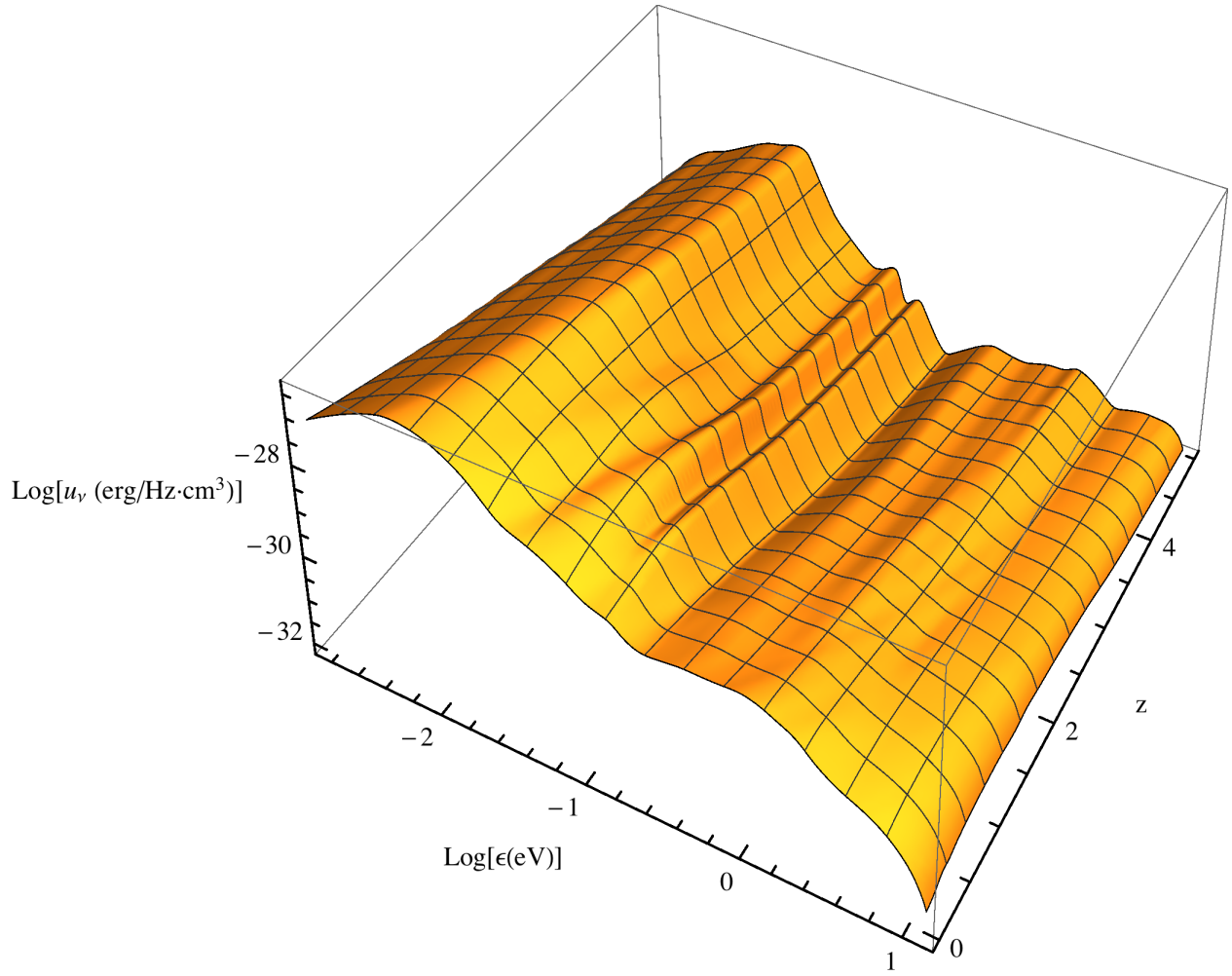


Fig. 6.— Lower limit envelope on the co-moving energy density as a function of energy and redshift.

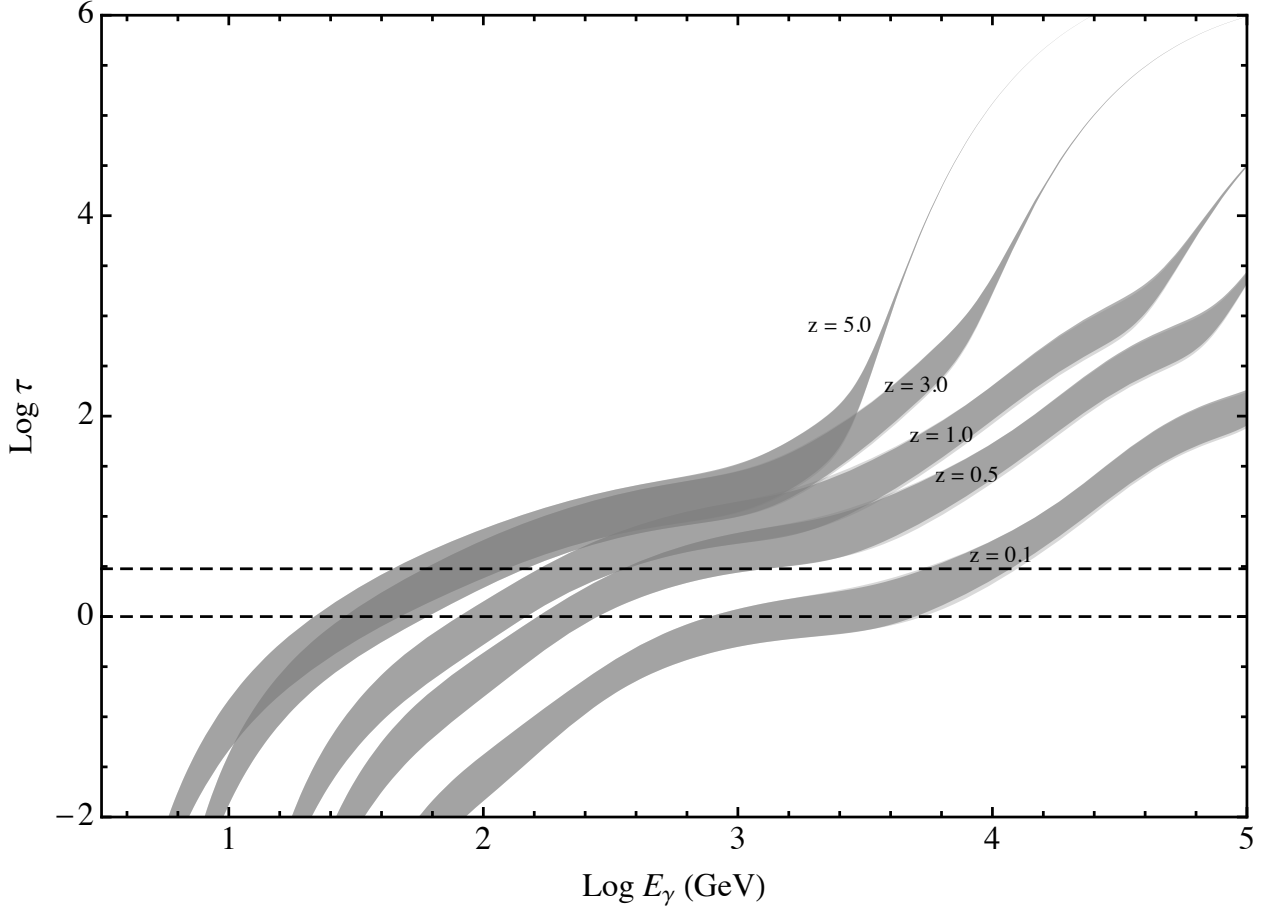


Fig. 7.— The optical depth of the universe from the IBL and the CBR as well as the total optical depth as a function of energy, given for redshifts of 0.1, 0.5, 1, 3, 5. It can be seen that the contribution to the optical depth from the IBL dominates at lower  $\gamma$ -ray energies and redshifts and that from the CBR photons dominates at the higher energies and redshifts. The optical depth from CBR photons is an exact function of energy as given by equation (8) and therefore the confidence band becomes a thin line. The dashed lines indicate the opacities  $\tau = 1$  and  $\tau = 3$ .

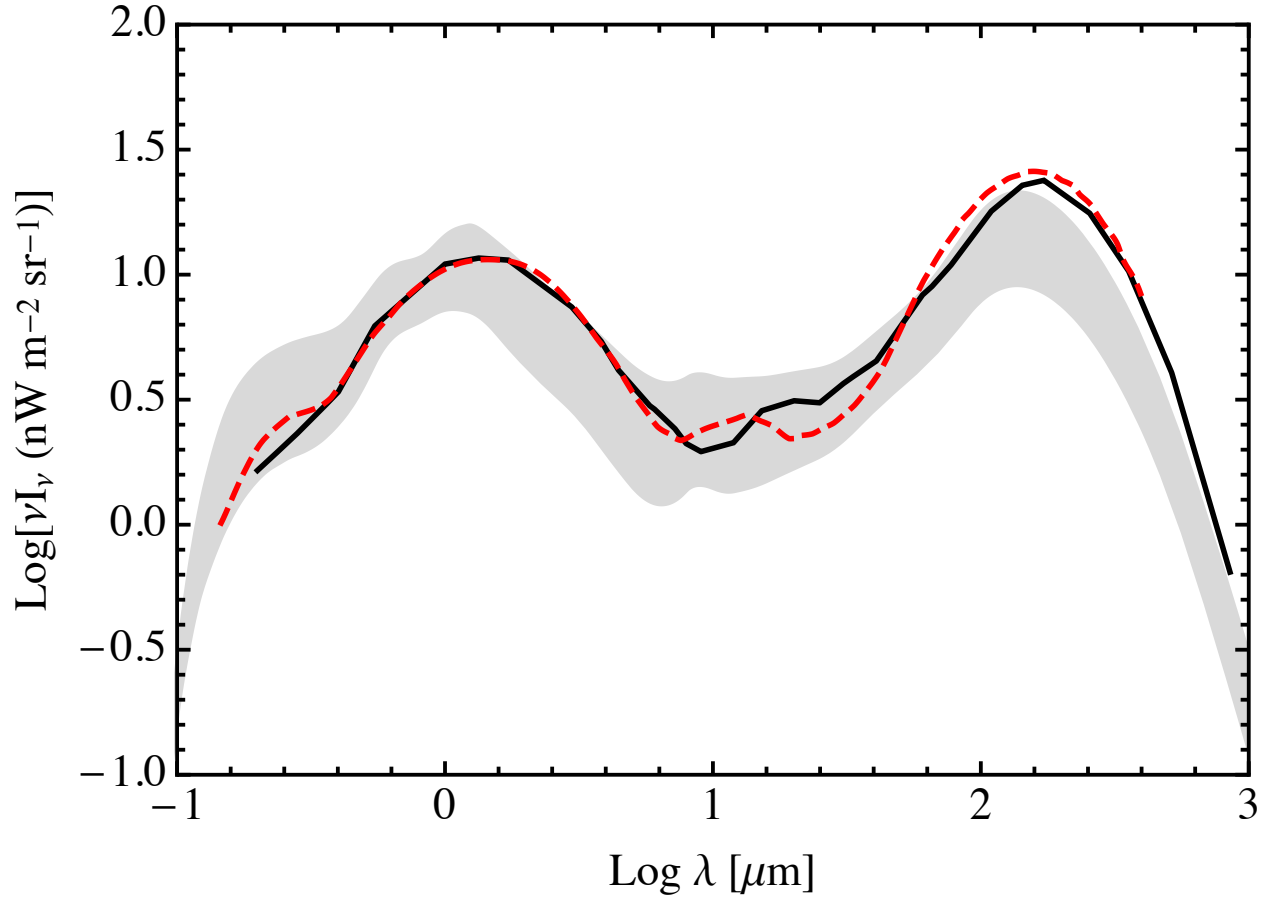


Fig. 8.— A comparison of our confidence band with the models of Franceschini et al. (2008) (solid black line) and Domínguez et al. (2011) (red dashed line).

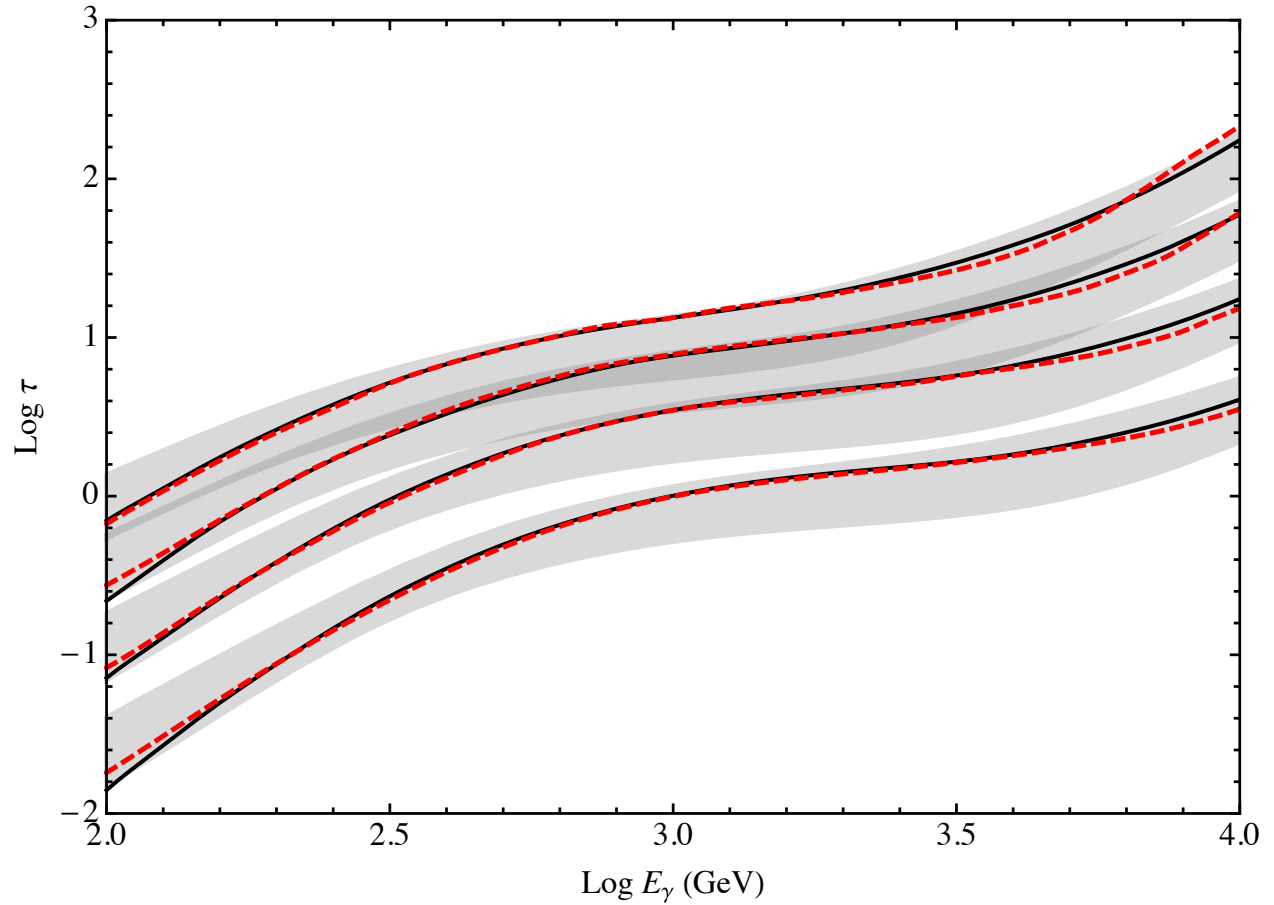


Fig. 9.— Comparison of our opacity results with those obtained by the models of Franceschini et al. (2008) (solid black line) and Domínguez et al. (2011) (red dashed line).



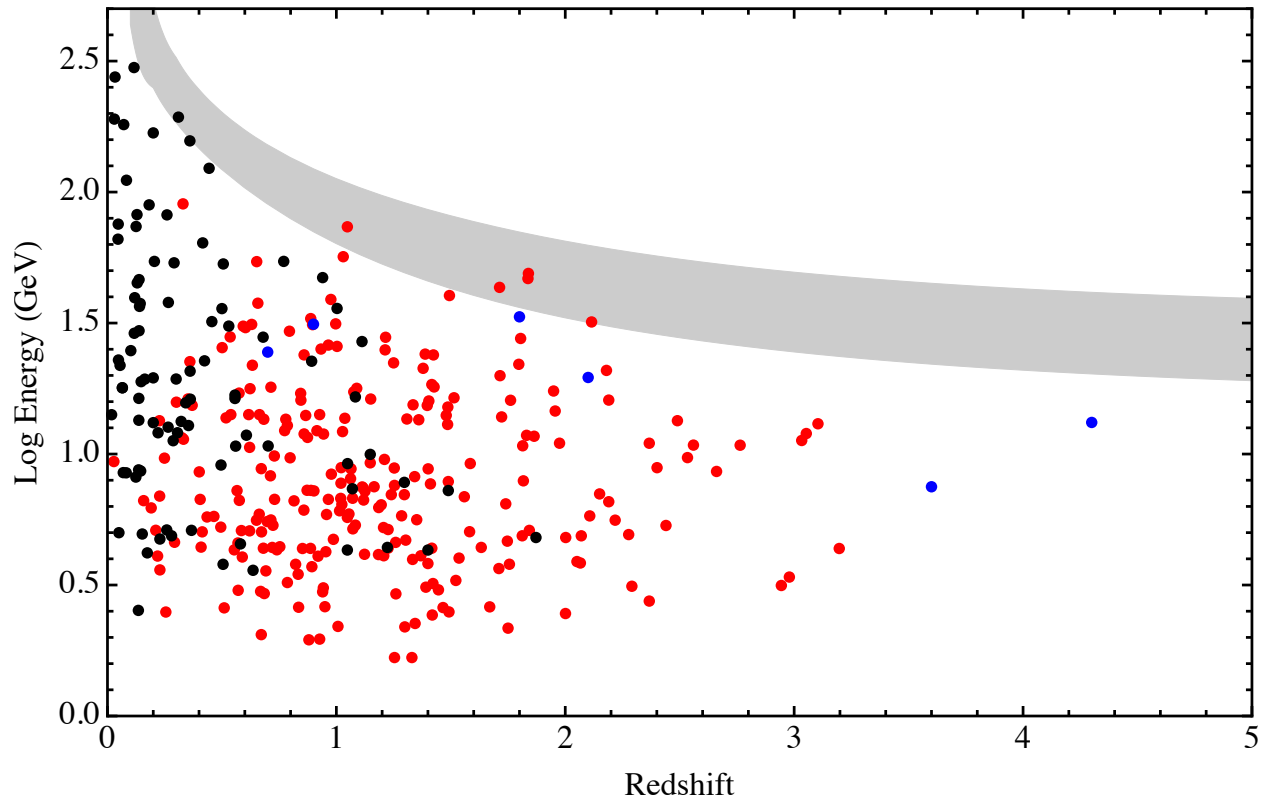


Fig. 10.— A  $\tau = 1$  energy-redshift plot (Fazio & Stecker 1970) showing our uncertainty band results compared with the *Fermi* plot of their highest energy photons from FSRQs (red), BL Lacs (black) and GRBs (blue) *vs.* redshift (from Abdo et al. 2010).

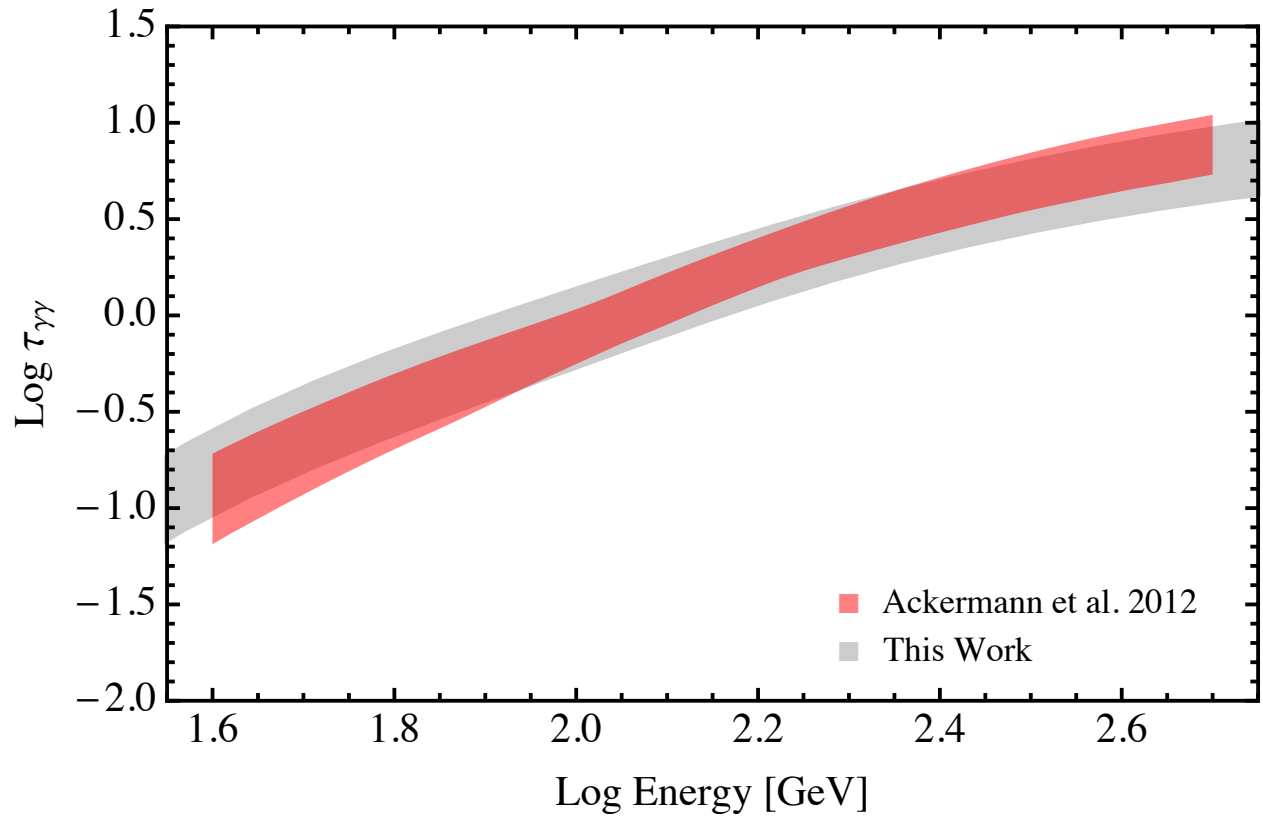


Fig. 11.— Comparison of our results for  $z = 1$  with those obtained from an analysis of blazar  $\gamma$ -ray spectra (Ackermann et al. 2012)