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Searching for secluded dark matter with H.E.S.S., Fermi-LAT, and Planck

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# Searching for Secluded Dark Matter with H.E.S.S., Fermi-LAT, and Planck

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**Abstract.** Short-lived mediators are often used to describe dark matter interactions with Standard Model particles. When the dark matter mass is heavier than the mediator's, it may self-annihilate into short-lived mediators, and in some cases this might be the dominant annihilation channel. This scenario is known as secluded dark matter. We use Fermi-LAT observations of dwarf spheroidal galaxies, H.E.S.S. data from the Galactic center, and Planck measurements of the Cosmic Microwave Background to constrain secluded dark matter. We explore the interplay between these experiments and we assess the impact of the mediator mass on our bounds, an often overlooked yet very important point. In particular, we exclude pair -annihilation cross section greater or on the order of  $\sigma v \sim 4 \times 10^{-27} \text{cm}^3/\text{s}$  for dark matter masses around 10 GeV and greater or on the order of  $\sigma v \sim 3 \times 10^{-25} \text{cm}^3/\text{s}$  for dark matter masses around the TeV. Our findings supersede previous constraints which use Fermi-LAT data, they constitute the first limits on secluded dark sectors using the H.E.S.S. telescope. We also show that one can fit TeV gamma-ray observations from the H.E.S.S. telescope with secluded dark matter annihilation, with the mediator mass impacting the best-fit dark matter particle mass. Our findings indicate that any assessment of secluded dark sectors in the context of indirect detection significantly depends on the choice of the mediator mass.

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## 1 Introduction

The nature of dark matter is one of the most exciting and important open questions in science [1–5]. The Standard Model (SM) does not have a fundamental particle capable of explaining the cold dark matter in our universe, which constitutes 27% of the entire energy-budget. Among proposed dark matter candidates, Weakly Interacting Massive Particles (WIMPs) stand out as uniquely well motivated, since via the thermal freeze-out they could naturally explain the observed dark matter abundance [6].

Among different detection techniques, indirect dark matter detection, the detection of the debris of dark matter annihilation or decay, has the remarkable advantage of connecting particle physics and astrophysics: a potential dark matter signal would pinpoint the dark matter mass and annihilation cross section, provided certain astrophysical inputs [7].

Typically, indirect searches for dark matter are focused on final states belonging to the SM spectrum such as quarks, leptons and gauge bosons [8–24]. However, it is also possible that WIMPs annihilate mostly into short-lived particles which later decay into SM particles [25–32]. This setup is very common for dark matter models in the context of the  $Z'$  portal when the dark matter is heavier than the  $Z'$  [25, 33–39], as well as in models where the dark matter is entirely confined to the dark sector but annihilates to particles that subsequently decay to SM products [29, 40].

Motivated by the presence of such “secluded annihilations” in several models, numerous studies have been performed in the context of indirect dark matter detection [41–48]. The present study differs from previous work in several key aspects:

(i) We do not focus on one specific dataset, and we consistently include Fermi-LAT, H.E.S.S. and Planck data to draw our conclusions;

(ii) We use seven years of Fermi-LAT data in the direction of dozens of dwarf spheroidal galaxies (dSphs) with the updated instrument response function (PASS8) [49];

(iii) We make use of 10 years of H.E.S.S. data, equivalent to 254h live-time exposure, on the Galactic center with the latitude region  $|b| < 3^\circ$  removed [50];

(iv) We account for Planck data on the CMB, as such data is rather sensitive to any injection of electromagnetically interacting particles capable of producing appreciable ionization and heat, thus severely constraining dark matter annihilation at early times [51, 52];

(v) We critically and quantitatively assess the impact of the mediator mass on our bounds. We show that the mass of the short-lived mediator does matter in the derivation of precise limits on the dark matter annihilation cross section and in the determination of best-fit regions of parameters. In the context of indirect dark matter detection, these mediators are typically assumed to be simply sufficiently heavier than the pair SM particles produced in their decay modes. However, if one departs from this particular assumption, the experimental limits significantly change;

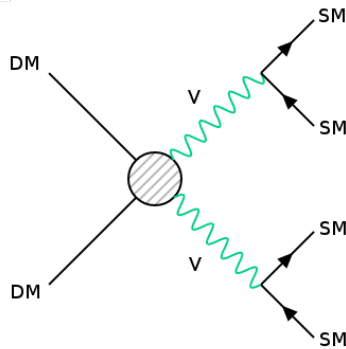
(vi) We discuss the possibility of explaining the TeV gamma-ray excess observed by the H.E.S.S. telescope in the Galactic center [53, 54] with secluded dark matter annihilation.

Our study is structured as follows: In *section 2*, we lay out the setup we focus on; in *section 3* we discuss how we derive the production of gamma-rays and ionization induced by dark matter annihilation; in *section 4* we describe the dataset we use; in *section 5* we present our limits, *section 6* we address the H.E.S.S. TeV excess in terms of secluded dark matter and finally, in *section 7*, we draw our conclusions.

## 2 Secluded Dark Matter

Secluded dark matter refers to a scenario where the dark matter particle annihilates preferentially to particles that do not belong to the SM particle content. Dark matter particles that annihilate directly into SM particles can be severely constrained by data since typically the same Feynman diagram that lead to dark matter annihilations is also responsible for dark matter-nucleon scattering, subject of intense and highly-constraining experimental searches [55–66]. There are ways to break this direct relation between annihilation and scattering such as via co-annihilations [67], multi-mediators [68], or velocity-dependent suppressions, among others [32, 69–71]. However, one interesting possibility that does not require the existence of extra fields is to simply enforce the dark matter mass to be heavier than the mediator’s mass. In this case, if

the coupling between the dark matter particle and the mediator is sufficiently large, the main annihilation channel can be into a pair of short-lived mediators, which constitutes a paradigmatic secluded dark matter setup [33, 68, 72–77]. Another viable secluded dark matter scenario occurs when the dark matter particle belongs to either an  $SU(N)$  group [78, 79], or a hidden valley setup [80, 81], or interacts with SM particle via the Chern-Simons portal [82]. Either way, dark matter annihilation into short-lived mediators occurs, and can be the most important final state. Therefore, one can constrain the parameter space of such secluded dark matter models by searching for the byproducts of this  $2 \rightarrow 4$  annihilation process (see Fig.1).



**Figure 1.** Feynman diagrams for dark matter annihilation into short-lived states that decay into SM particles.

There are several possible annihilation final states based on Fig.1. In order to cover many possibilities in this work, we will investigate the cases which the short-lived state decay either into leptons or into quarks, and also vary the mediator mass to assess how relevant its mass is in the derivation of the bounds on the dark matter annihilation cross section. We start first describing how we compute the dark matter signal.

### 3 Dark Matter Annihilation

#### 3.1 Gamma-rays

The presence of dark matter in our neighborhood motivates us to search for signs of dark matter annihilations in regions where the dark matter density is expected to be very high, such as the Galactic Center and dSphs. The differential flux for dark matter annihilation in an angular direction to be,

$$\frac{d\Phi_\gamma(\Delta\Omega)}{dE}(E_\gamma) = \frac{1}{4\pi} \frac{\sigma v}{2M_{DM}^2} \frac{dN_\gamma}{dE_\gamma} \cdot J_{ann} \quad (3.1)$$

where  $J_{ann}$  is the astrophysical J-factor with,

$$J_{ann} = \int_{\Delta\Omega} d\Omega \int \rho_{DM}^2(s) ds, \quad (3.2)$$

where  $s = s(\theta)$  is a line-of-sight variable and  $\theta$  is the angle between the line of sight and the line to the center of the dark matter halo,  $\sigma v$  is annihilation cross section today, i.e. non-relativistic,  $M_{DM}$  the dark matter mass, and  $\rho_{DM}$  the dark matter density profile which we will assume to be a Navarro-Frenk-White (NFW) profile [83] where,

$$\rho_{DM}(r) = \frac{\rho_s}{(r/r_s)(1+r/r_s)^2}, \quad (3.3)$$

where  $r_s$  and  $\rho_s$  are the scale radius and the characteristic density respectively. The integral in Eq.(3.2) is computed over the line of sight.

We are adopting an NFW profile because it is the same profile used by Fermi-LAT collaboration. Different profiles will induce an overall change in our limits by a constant factor depending whether a steeper [84] or more core-like profile is adopted [85, 86].

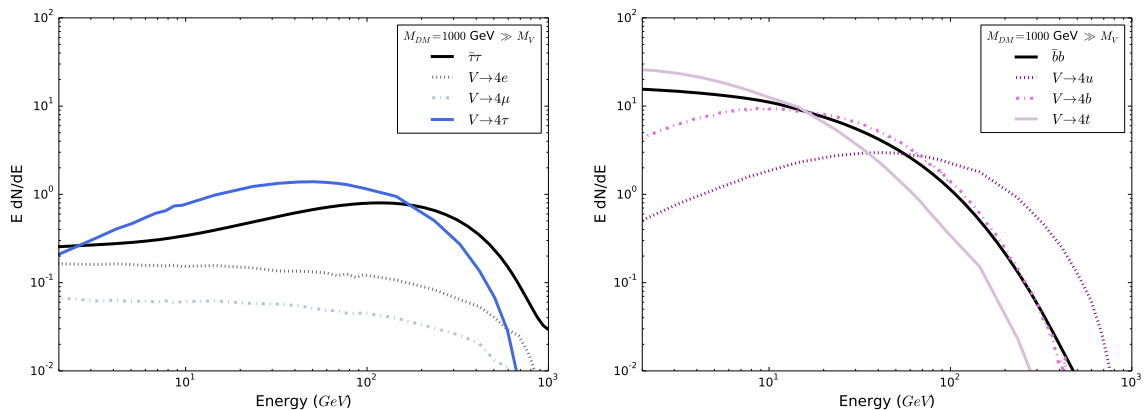
The key quantity in the derivation of our limits is the energy spectrum because we are focused on  $2 \rightarrow 4$  annihilations. The shape of the energy spectrum will allow us to understand the results we present further. We used the PPPC4DM code to compute the energy spectra when the  $V$  decays into charged leptons [87]. We emphasize that PPPC4DM by default assumed the mediator to be just a bit heavier than its decay products. In order to derive bounds for other hadronic channels and assess the importance of the mediator mass, we generated the energy spectra with Pythia 8 [88].

In fig.2 we show the energy spectra of a 1 TeV dark matter particle annihilating into short-lived mediators with them decaying into charged leptons (left-panel) or hadrons (right-panel). Thus far we are assuming the dark matter particle to be much heavier than the mediator, i.e.  $M_{DM} \gg M_V$ .

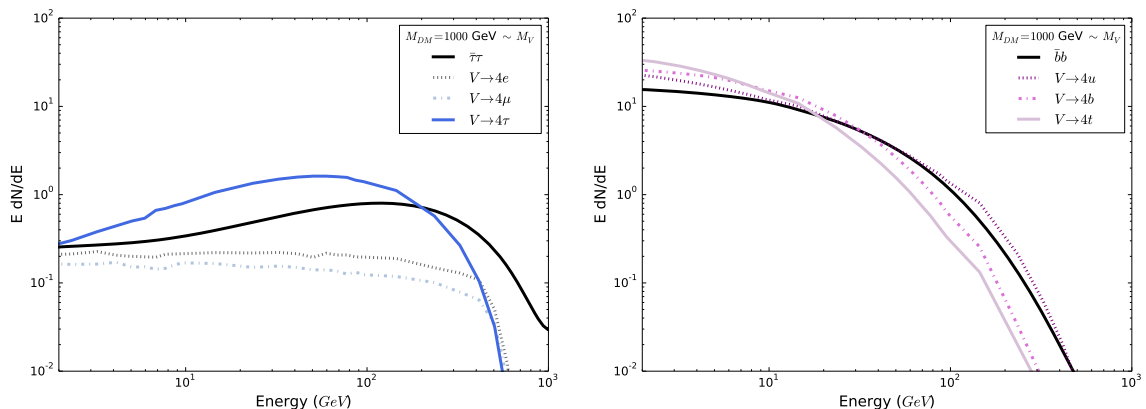
By comparing the energy spectra for the dark matter annihilations into  $2\tau$  and  $4\tau$  we notice that the energy spectrum is harder for the latter at lower energies between 1 – 100 GeV. This occurs for the annihilations into  $4b$  only during a smaller energy region,  $E = 20 - 100$  GeV, and it is much less prominent. In these figures, we took the mediator mass to be much heavier than its decay modes.

We will repeat the same procedure but take the mediator mass to be comparable to the dark matter mass. The result is displayed in Fig.3. For the leptonic case, the difference in the overall energy spectrum is mild, but for the case which the mediator decays into hadrons, the difference is clearly visible, making the annihilation into  $4b$  mimic the one into  $2b$ .

In order to have a clearer picture of the relevance of the mediator mass in our computation, in Fig.4, we derive the energy spectra for two leptonic decay modes of the mediator,  $e\bar{e}$  on the left-panel and  $\tau\bar{\tau}$  on the right-panel, and vary the mediator mass,



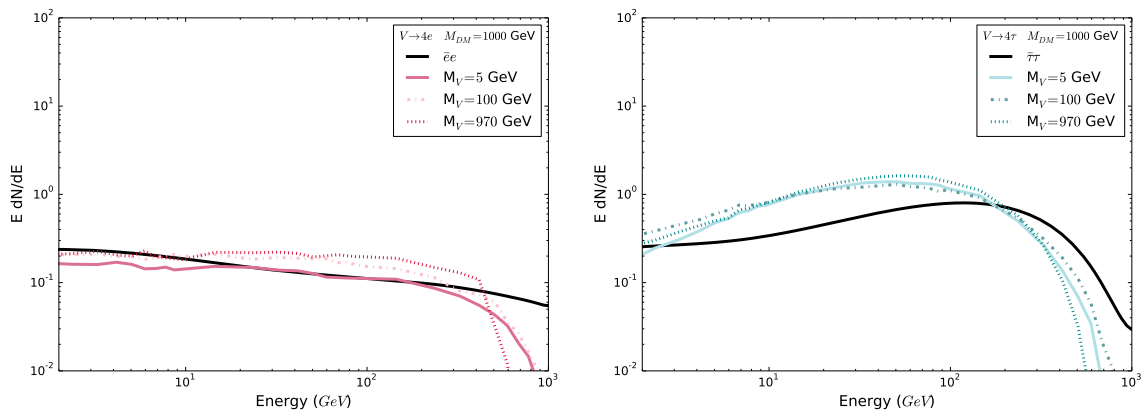
**Figure 2.** Energy spectrum for a 1 TeV dark matter annihilating into  $VV$ , with the  $V$  mass much larger than the final state's. Left-panel:  $V$  decays either into  $ee$  or  $\mu\bar{\mu}$  or  $\tau\bar{\tau}$ . Right-panel:  $V$  decays either into  $u\bar{u}$  or  $b\bar{b}$  or  $t\bar{t}$ . Moreover, we superimpose the direct annihilation channel  $DMDM \rightarrow \tau\bar{\tau}$  on the left-panel, and  $DMDM \rightarrow b\bar{b}$  on the right-panel for comparison.



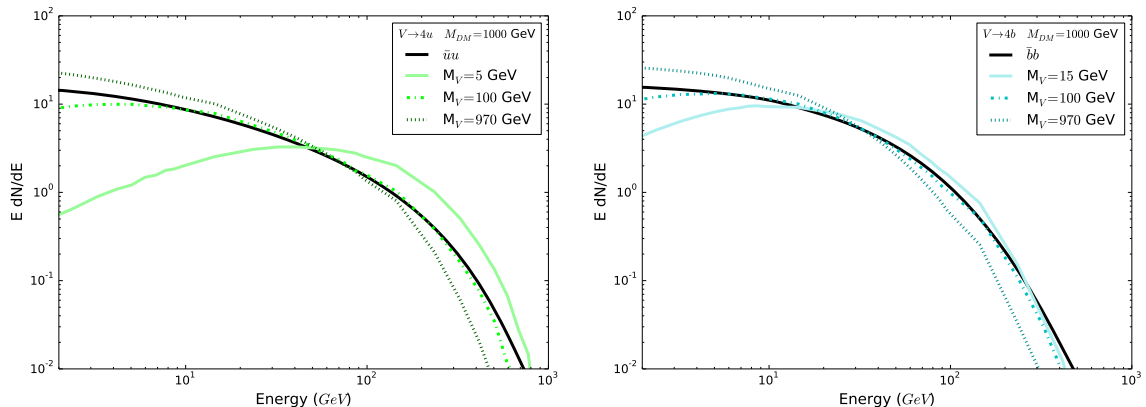
**Figure 3.** Energy spectrum for a 1 TeV dark matter annihilating into  $VV$ , with  $V$  being nearly degenerate in mass. Left-panel:  $V$  decays either into  $ee$  or  $\mu\bar{\mu}$  or  $\tau\bar{\tau}$ . Right-panel:  $V$  decays either into  $u\bar{u}$  or  $b\bar{b}$  or  $t\bar{t}$ . Moreover, we superimpose the direct annihilation channel  $DMDM \rightarrow \tau\bar{\tau}$  on the left-panel, and  $DMDM \rightarrow b\bar{b}$  on the right-panel for comparison.

while keeping  $M_{DM} = 1$  TeV. Notice that the mediator yields very mild difference into the energy spectra. We will see further that this does not hold true for annihilations into  $4e$  and  $4\mu$ . Moreover, when the  $V$  particle decays hadronically the mediator mass is very important. Notice in Fig.5 that the assumption made on the mediator mass can significantly change the energy spectra, especially towards lower energies. Therefore, any assessment of secluded dark sectors in the context of indirect detection cannot be regarded as model-independent since they rely significantly on choice for the mediator mass.

Now we have the gamma-ray yield for different dark matter annihilation setups,



**Figure 4.** Left-panel: energy spectrum for a 1 TeV dark matter annihilating into  $4e$  for  $M_V = 5, 100, 970$  GeV; Right-panel: energy spectrum for a 1 TeV dark matter annihilating into  $4\tau$  for  $M_V = 5, 100, 970$  GeV. We superimposed the direct annihilation channel  $\text{DM DM} \rightarrow e\bar{e}$  on the left-panel, and  $\text{DM DM} \rightarrow \tau\bar{\tau}$  on the right-panel for comparison.



**Figure 5.** Left-panel: energy spectrum for a 1 TeV dark matter annihilating into  $4u$  for  $M_V = 5, 100, 970$  GeV; Right-panel: energy spectrum for a 1 TeV dark matter annihilating into  $4b$  for  $M_V = 5, 100, 970$  GeV. We superimposed the direct annihilation channel  $\text{DM DM} \rightarrow u\bar{u}$  on the left-panel, and  $\text{DM DM} \rightarrow b\bar{b}$  on the right-panel for comparison.

we discuss dark matter signals in the CMB.

### 3.2 Cosmic Microwave Background

In the context of thermal freeze out, dark matter annihilations are efficient at dark ages,  $z \leq 1200$ . However, such energy injection produced by dark matter annihilation heats and ionizes the photon-baryon plasma perturbing the ionization history precisely measured Planck [89]. Such dark matter annihilations not necessarily capable of changing the redshift of recombination may alter the residual ionization after recombination which is subject to tight constraints.



These constraints are based on the following procedure: The energy density injection rate is determined by the product of the number density of pairs of DM particles which is  $n_{DM}/2$  for Majorana particles, the annihilation probability per time unit  $P_{ann} = \langle\sigma v\rangle n_{DM}$  and the energy released per dark matter annihilation  $E_{ann} = 2M_{DM}$ . Therefore, we get,

$$\frac{dE}{dt dV_{inj}}(z) = \left(\frac{n_{DM}}{2}\right) (\langle\sigma v\rangle n_{DM}) (2m_{DM}). \quad (3.4)$$

Assuming the dark matter particle to be non-relativistic and considering only the smooth cosmological dark matter halo we get,

$$n_{DM} = \rho_{DM} M_{DM} = \rho_c \Omega_{DM} M_{DM} = \rho_c \Omega_{DM o} (1+z)^3 M_{DM}, \quad (3.5)$$

where  $\Omega_{DM o}$  is the dark matter abundance today.

Substituting Eq.(3.5) into Eq.(3.6) we get,

$$\frac{dE}{dt dV_{inj}}(z) = \rho_c^2 \Omega_{DM o}^2 (1+z)^6 \left(\frac{\langle\sigma v\rangle}{M_{DM}}\right). \quad (3.6)$$

The injected energy is, however, not equal to the energy deposited in the intergalactic medium, because the response of the medium to energy injection does depend on the final states produced in the dark matter as well as when it took place. Hence, in order to account for this effect, we add an efficiency function which is redshift dependent,  $f(z)$ . In this way,

$$\frac{dE}{dt dV_{dep}}(z) = f(z) \frac{dE}{dt dV_{inj}}(z), \quad (3.7)$$

which means that the particle physics input of this effect is encompassed in  $f(z)\langle\sigma v\rangle/M_{DM}$ . However  $f(z)$  is non-trivial to compute. Recently, the redshift dependence has been averaged over and the efficiency deposition been separated from the energy spectrum [51] as follows,

$$f_{eff} = \frac{1}{2M_{DM}} \int_0^{M_{DM}} E dE \left( f_{eff}^\gamma(E) \frac{dN}{dE^\gamma} + 2f_{eff}^{e^+}(E) \frac{dN}{dE^{e^+}} \right), \quad (3.8)$$

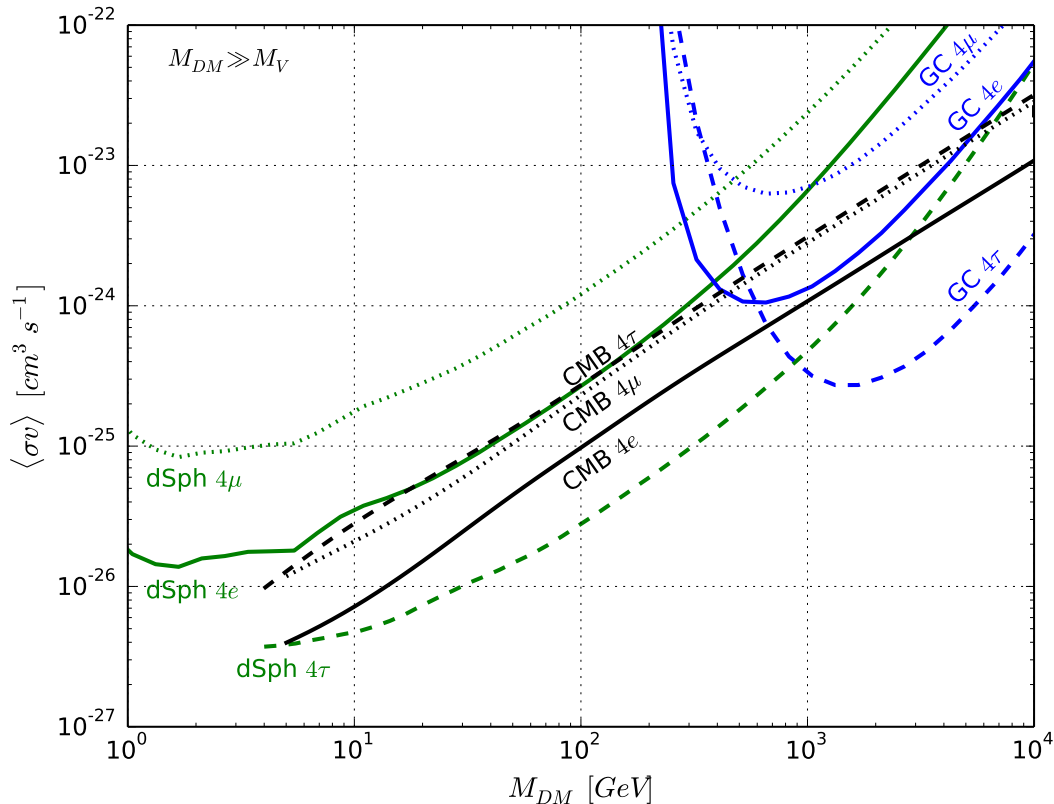
where the effect of dark matter annihilations on the CMB for any annihilation final states is determined by,

$$p_{ann} = f_{eff} \frac{\langle\sigma v\rangle}{m_{DM}}. \quad (3.9)$$

We highlight that  $\langle\sigma v\rangle$  in Eq.(3.9) is the thermally averaged dark matter annihilation cross section which can be very different from the dark matter annihilation cross section today that enters in gamma-ray flux.

In Eq.(3.8),  $E$  is the energy of the electron-positron or photon, and  $dN/dE^\gamma$  and  $dN/dE^{e^+}$  are the photon and positron energy spectra produced per dark matter annihilation. Throughout we assume that the electron and positron have the same energy spectra. The energy and positron spectra produced per dark matter annihilation depends on the dark matter mass and annihilation final state. For instance, dark matter annihilations into  $VV$  which eventually decay into  $e^+e^-$  produce an energy spectrum different from the direct annihilation into  $e^+e^-$ . In order to obtain CMB bounds for this  $2 \rightarrow 4$  annihilation process, we feed the energy spectrum obtained using Pythia [88] into the code presented in [51, 52] which computed the new physics effect on the CMB.

Now we have reviewed the dark matter annihilation signatures in gamma-rays and on the CMB, we describe the dataset used in our analysis.



**Figure 6.** 95% C.L. upper limits on the dark matter annihilation cross as a function of the dark matter mass for the process  $DM DM \rightarrow VV$ , with  $V$  decaying into  $e\bar{e}$ ,  $\mu\bar{\mu}$ ,  $\tau\bar{\tau}$ . We assumed  $M_{DM} \gg M_V$ , with the  $V$  mass being just sufficiently heavier than the decays modes.

## 4 Dataset

### 4.1 Fermi-LAT

Fermi-LAT, the NASA gamma-ray telescope, has given rise to a new area of gamma-rays studies due to the precision achieved, far better than its predecessors, and for making the data publicly available to the community via friendly user tools [90]. In the context of dark matter, several important steps have been given with the publication of several sensitivity studies to dark matter annihilations, for instance, in dSphs [49, 91–97].

Since dSphs are dark matter dominated objects and are located away from the large diffuse gamma-ray emission stemming from the galactic center, they are regarded as a “holy grail” as far as dark matter signals are concerned [98–105]. Be that as it may, there are still uncertainties on dark matter content in dSphs and these are subject of intense discussions [106–116]. Therefore, in order to gain statistics and perform a more robust analysis, the dataset of dSphs galaxies have been combined and treated using a maximum likelihood analysis [92]. After collecting seven years of gamma-ray data with energies between 500 MeV–500 GeV belonging to the event class P8R2SOURCEV6 using the up-to-date software PASS-8, no significant excess has been observed leading to the exclusion of the thermal dark matter annihilation cross section of  $3 \times 10^{-26}$  for dark matter masses below 100 GeV, for annihilations solely into  $b\bar{b}$  [49].

The collaboration has publicly shared individual likelihood functions which one can use to perform their own independent analysis for a given dSph<sup>1</sup>. However, we emphasize that such likelihood functions are for individual dSphs and since we are interested in repeating the Fermi-LAT procedure in a more robust way using a stacked analysis of the sample of 15 dSphs used by Fermi-LAT, we have to build a combined likelihood function following the receipt provided in [49]. Moreover, we build a likelihood function to marginalize the statistical uncertainties on the J-factor with the J-factor likelihood function defined as,

$$\mathcal{L}_J(J_i|J_{obs,i}, \sigma_i) = \frac{1}{\ln(10)J_{obs,i}\sqrt{2\pi}\sigma_i} \times \exp\left\{-\frac{(\log_{10}(J_i) - \log_{10}(J_{obs,i}))^2}{2\sigma_i^2}\right\},$$

where  $J_{obs,i}$  is the measured J-factor with statistical error  $\sigma_i$  of a dSph  $i$ , while  $J_i$  is the correct J-factor value.

Therefore, one can compute the joint-likelihood function by multiplying each individual likelihood, having in mind that the likelihood of an individual dSph  $i$  is,

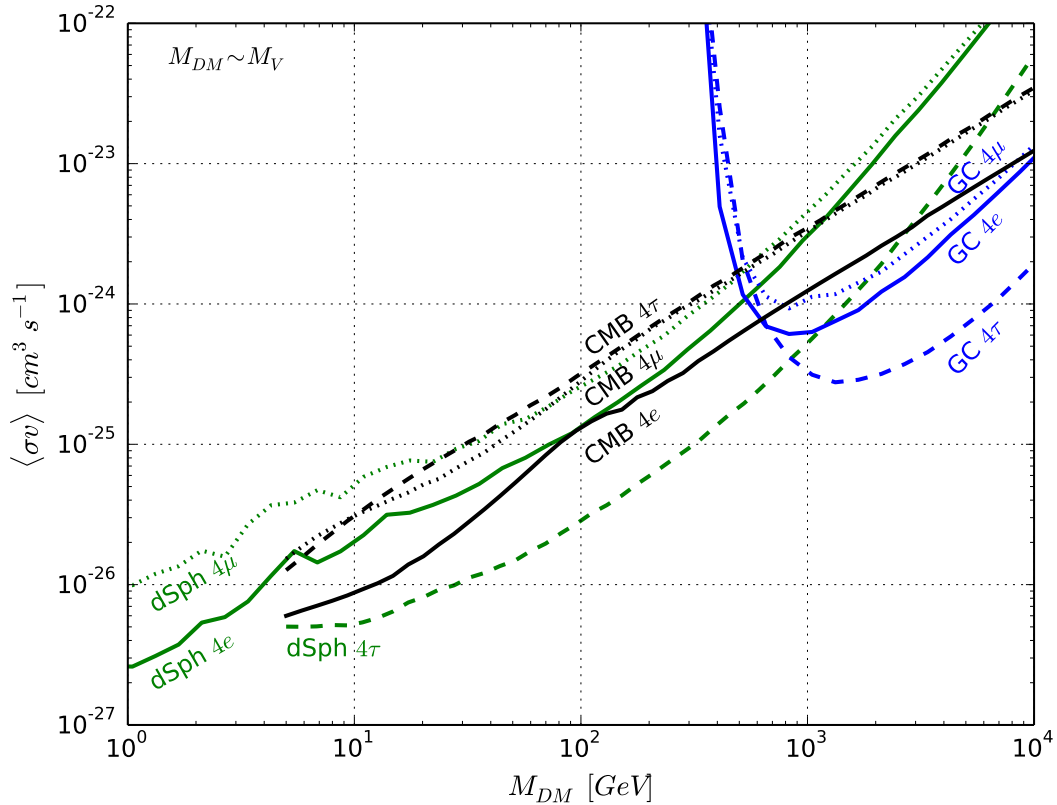
$$\tilde{\mathcal{L}}_i(\mu, \theta_i = \{\alpha_i, J_i\}|D_i) = \mathcal{L}_i(\mu, \theta_i|D_i)\mathcal{L}_J(J_i|J_{obs,i}, \sigma_i), \quad (4.1)$$

---

<sup>1</sup>[http://www-glast.stanford.edu/pub\\_data/1048/](http://www-glast.stanford.edu/pub_data/1048/)

where  $\mu$  accounts for particle physics input, dark matter mass and annihilation cross section,  $\theta_i$  for the set of nuisance parameters from the LAT study ( $\alpha_i$ ) as well as the J-factors of the dSphs  $J_i$ , where  $D_i$  is the gamma-ray data set used in the analysis. Thus, after performing a joint-likelihood function and accounting for the statistical errors on the J-factors with the likelihood function defined above we were able to do test statistic and obtain 95% C.L. upper limits on the dark matter annihilation cross section by finding a change in the log-likelihood of  $2.71/2$  as described in [49]. We highlight were able to nicely reproduce Fermi-LAT limits as shown in [21, 117].

In summary, we computed a joint-likelihood function for different energy spectra to take into account the fact we are now investigating secluded annihilations. The results are exhibit in green curves in Fig.6-9 for two different mass regimes,  $M_{DM} \gg M_V$  and  $M_{DM} \sim M_V$ .



**Figure 7.** 95% C.L. upper limits on the dark matter annihilation cross as a function of the dark matter mass for the process  $DM DM \rightarrow VV$ , with  $V$  decaying into  $e\bar{e}$ ,  $\mu\bar{\mu}$ ,  $\tau\bar{\tau}$ . We assumed  $M_{DM} \sim M_V$ .

## 4.2 H.E.S.S.

The H.E.S.S. telescope has expanded our knowledge concerning gamma-ray emitters for energies greater than 200 GeV. In comparison to Fermi-LAT, H.E.S.S. lacks in exposure but overcomes this fact with its large effective area. As far as dark matter searches are concerned the most stringent limits on the dark matter annihilation cross section comes from observation of the Galactic Center. In particular, with 112h of data, upper limits were placed on the dark matter annihilation cross section adopting an Einasto profile [118] still far from the thermal annihilation cross section. A more recent study, with 10 years of observation that is equivalent to 254h of live-time exposure, H.E.S.S. has significantly improved their sensitivity, excluding the thermal annihilation cross section for dark matter masses between 1 – 2 TeV, annihilating solely into  $\tau\bar{\tau}$  [50], again using a Einasto dark matter density profile. The substantial improvement on the bound is a result of the more statistics and an improved analysis of the signal and background events [119].

We duplicated the H.E.S.S. analysis and were able to reproduce their results, as demonstrated in [21]. We then fed the energy spectrum for secluded dark matter annihilations into the likelihood functions provided in [119] and changed the choice for the dark matter density profile to NFW, to put H.E.S.S. constraints on equal footing with Fermi-LAT's. By performing a test-statistic as described in [119] we derive 95% C.L. limits on the pair *dark matter annihilation cross section vs mass* for all channels here under consideration. The results are shown as blue curves in Fig.6-9 for various annihilation channels and two different mass regimes,  $M_{DM} \gg M_V$  and  $M_{DM} \sim M_V$ .

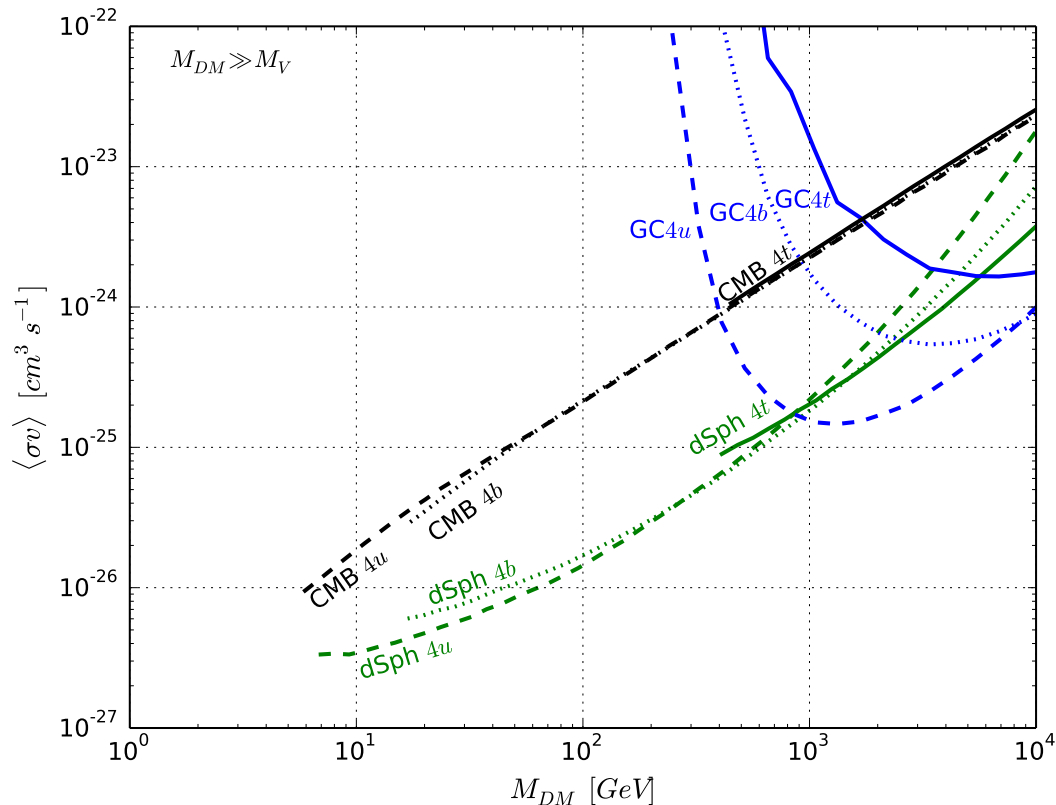
## 4.3 Planck

The precision achieved by Planck has greatly impacted our knowledge about the Universe's constituents. The precise measurements on the CMB have resulted in a very precise estimate of the dark matter abundance and allowed us to make robust assessments on the impact of new physics effects on the CMB [120–122].

In particular, the precise measurements on the CMB temperature and polarization angular power spectra severely restricts potential new physics contributions that might change the ionization history [89, 123–128]. After integrating out all the cosmological factors, this affect can be described in terms of the annihilation fact  $p_{ann}$  defined in Eq.(3.9). Currently, Planck places a 95% C.L. limit on this parameter that reads,

$$p_{ann} < 4.1 \times 10^{-28} cm^3 s^{-1} GeV^{-1}. \quad (4.2)$$

Therefore, one can use this bound to constrain the ratio  $\langle\sigma v\rangle/M_{DM}$  for a given energy spectrum. Using the code in [51, 52] we introduced the energy spectrum resulted from the various secluded dark matter scenarios we study, and compared to Eq.(4.2) to place 95% C.L. on the dark matter annihilation cross section. The limits are shown with black curves in Fig.6-9 under two different mass regimes,  $M_{DM} \gg M_V$  and  $M_{DM} \sim M_V$ .



**Figure 8.** 95% C.L. upper limits on the dark matter annihilation cross as a function of the dark matter mass for the process  $\text{DMDM} \rightarrow VV$ , with  $V$  decaying into  $u\bar{u}$ ,  $b\bar{b}$ ,  $t\bar{t}$ . We assumed  $M_{DM} \gg M_V$ , with the  $V$  mass being just sufficiently heavier than the decays modes.

## 5 Results

In Fig.6 we exhibit the 95% C.L. limits on the dark matter annihilation cross section for the case that  $M_{DM} \gg M_V$ , with the mediator being just sufficiently heavier than its decay channels. We remind the Reader that the CMB bounds are placed on the thermally averaged dark matter annihilation cross section, whereas Fermi-LAT and H.E.S.S. bounds are on the dark matter annihilation cross section today. In the figures, we keep the average dark matter annihilation in the y-axis, but the reader should interpret the plots wisely.

The bounds from CMB are shown in black lines for the  $4e$  (solid),  $4\mu$  (dotted) and  $4\tau$  (dashed) channels. A similar pattern is used for Fermi-LAT (green) and H.E.S.S. (blue) bounds.

As expected CMB is a powerful probe to dark matter annihilation into electron and muons. For annihilation into  $VV$ , with each  $V$  decaying into  $\bar{\tau}\tau$  Fermi-LAT takes

## Fermi-LAT PASS8

<b>dSph 4b, <math>M_{DM} = 100</math> GeV</b> $M_{DM} \gg M_V \rightarrow \sigma v \simeq 2 \times 10^{-26} \text{ cm}^3/\text{s}$ $M_{DM} \sim M_V \rightarrow \sigma v \simeq 2.8 \times 10^{-26} \text{ cm}^3/\text{s}$	<b>dSph 4b, <math>M_{DM} = 1</math> TeV</b> $M_{DM} \gg M_V \rightarrow \sigma v \simeq 2 \times 10^{-25} \text{ cm}^3/\text{s}$ $M_{DM} \sim M_V \rightarrow \sigma v \simeq 2 \times 10^{-25} \text{ cm}^3/\text{s}$
<b>dSph 4e, <math>M_{DM} = 100</math> GeV</b> $M_{DM} \gg M_V \rightarrow \sigma v \simeq 3 \times 10^{-25} \text{ cm}^3/\text{s}$ $M_{DM} \sim M_V \rightarrow \sigma v \simeq 1.5 \times 10^{-25} \text{ cm}^3/\text{s}$	<b>dSph 4e, <math>M_{DM} = 1</math> TeV</b> $M_{DM} \gg M_V \rightarrow \sigma v \simeq 7 \times 10^{-24} \text{ cm}^3/\text{s}$ $M_{DM} \sim M_V \rightarrow \sigma v \simeq 3.5 \times 10^{-24} \text{ cm}^3/\text{s}$

## H.E.S.S.

<b>GC 4b, <math>M_{DM} = 1</math> TeV</b> $M_{DM} \gg M_V \rightarrow \sigma v \simeq 2 \times 10^{-24} \text{ cm}^3/\text{s}$ $M_{DM} \sim M_V \rightarrow \sigma v \simeq 10^{-23} \text{ cm}^3/\text{s}$	<b>GC 4b, <math>M_{DM} = 10</math> TeV</b> $M_{DM} \gg M_V \rightarrow \sigma v \simeq 10^{-24} \text{ cm}^3/\text{s}$ $M_{DM} \sim M_V \rightarrow \sigma v \simeq 1.5 \times 10^{-24} \text{ cm}^3/\text{s}$
<b>GC 4e, <math>M_{DM} = 1</math> TeV</b> $M_{DM} \gg M_V \rightarrow \sigma v \simeq 1.5 \times 10^{-24} \text{ cm}^3/\text{s}$ $M_{DM} \sim M_V \rightarrow \sigma v \simeq 7 \times 10^{-25} \text{ cm}^3/\text{s}$	<b>GC 4e, <math>M_{DM} = 10</math> TeV</b> $M_{DM} \gg M_V \rightarrow \sigma v \simeq 6 \times 10^{-23} \text{ cm}^3/\text{s}$ $M_{DM} \sim M_V \rightarrow \sigma v \simeq 10^{-23} \text{ cm}^3/\text{s}$
<b>GC 4<math>\mu</math>, <math>M_{DM} = 1</math> TeV</b> $M_{DM} \gg M_V \rightarrow \sigma v \simeq 7 \times 10^{-24} \text{ cm}^3/\text{s}$ $M_{DM} \sim M_V \rightarrow \sigma v \simeq 10^{-24} \text{ cm}^3/\text{s}$	<b>GC 4<math>\mu</math>, <math>M_{DM} = 10</math> TeV</b> $M_{DM} \gg M_V \rightarrow \sigma v \simeq 1.8 \times 10^{-22} \text{ cm}^3/\text{s}$ $M_{DM} \sim M_V \rightarrow \sigma v \simeq 1.4 \times 10^{-23} \text{ cm}^3/\text{s}$
<b>GC 4<math>\tau</math>, <math>M_{DM} = 1</math> TeV</b> $M_{DM} \gg M_V \rightarrow \sigma v \simeq 4 \times 10^{-24} \text{ cm}^3/\text{s}$ $M_{DM} \sim M_V \rightarrow \sigma v \simeq 3 \times 10^{-24} \text{ cm}^3/\text{s}$	<b>GC 4<math>\tau</math>, <math>M_{DM} = 10</math> TeV</b> $M_{DM} \gg M_V \rightarrow \sigma v \simeq 3 \times 10^{-24} \text{ cm}^3/\text{s}$ $M_{DM} \sim M_V \rightarrow \sigma v \simeq 2 \times 10^{-24} \text{ cm}^3/\text{s}$

## Planck

<b>CMB 4b, <math>M_{DM} = 100</math> GeV</b> $M_{DM} \gg M_V \rightarrow \langle \sigma v \rangle \simeq 2.5 \times 10^{-25} \text{ cm}^3/\text{s}$ $M_{DM} \sim M_V \rightarrow \langle \sigma v \rangle \simeq 2.5 \times 10^{-25} \text{ cm}^3/\text{s}$	<b>CMB 4b, <math>M_{DM} = 1</math> TeV</b> $M_{DM} \gg M_V \rightarrow \langle \sigma v \rangle \simeq 3 \times 10^{-24} \text{ cm}^3/\text{s}$ $M_{DM} \sim M_V \rightarrow \langle \sigma v \rangle \simeq 2.5 \times 10^{-24} \text{ cm}^3/\text{s}$
<b>CMB 4e, <math>M_{DM} = 100</math> GeV</b> $M_{DM} \gg M_V \rightarrow \langle \sigma v \rangle \simeq 10^{-25} \text{ cm}^3/\text{s}$ $M_{DM} \sim M_V \rightarrow \langle \sigma v \rangle \simeq 1.5 \times 10^{-25} \text{ cm}^3/\text{s}$	<b>CMB 4e, <math>M_{DM} = 1</math> TeV</b> $M_{DM} \gg M_V \rightarrow \langle \sigma v \rangle \simeq 10^{-24} \text{ cm}^3/\text{s}$ $M_{DM} \sim M_V \rightarrow \langle \sigma v \rangle \simeq 1.5 \times 10^{-24} \text{ cm}^3/\text{s}$

**Table 1.** 95% C.L. limits on the dark matter annihilation cross section for several secluded dark matter scenarios. For easy comparison we show the bounds for  $M_{DM} \gg M_V$  and  $M_{DM} \sim M_V$ . All annihilations were individually analyzed, i.e. we assumed that the dark matter particle annihilates solely into each final state. Notice that Fermi-LAT and H.E.S.S. are sensitive to the dark matter annihilation cross section today, whereas CMB to the thermally averaged one.

the lead since  $\tau$  decays hadronically and efficiently produces gamma-rays. For dark matter masses above 400 GeV the complementarity among these three telescopes is fantastic. For annihilation into  $4e$  and  $4\mu$ , CMB is still more restrictive, but the one into  $4\tau$  Fermi-LAT bound is the most stringent for  $M_{DM} < 800$  GeV, with H.E.S.S.

taking the lead for larger masses.

Similarly to what has been typically assumed in the literature, we adopted  $M_{DM} \gg M_V$ . We now assume that the dark matter and the mediator are nearly mass degenerate and show the new bounds on the annihilation cross section in Fig.7. Our choice for this assumption of a mass degenerate regime is motivated by its presence in several dark sector models. On a theoretical note, if the dark matter particle has both vector and axial vector couplings to the mediator then we anticipate that the dark matter particle cannot be much heavier than the mediator, so not to spoil perturbativity unitarity [129, 130]. Thus is reasonable to assume that the dark matter and the mediator have comparable masses.

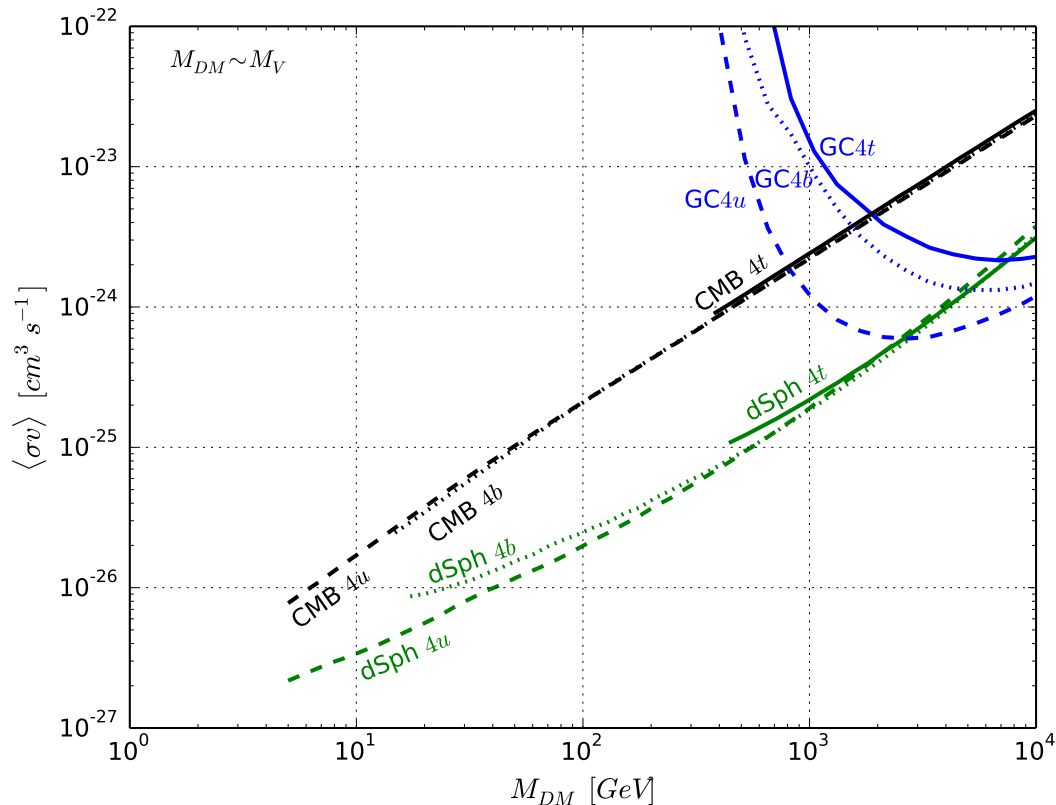
H.E.S.S. sensitivity to annihilations into  $4\tau$  is not much affected, but those into  $4e$  and  $4\mu$  are visibly changed. For instance, with  $M_{DM} = 1$  TeV, for  $e\bar{e}$  final state, H.E.S.S. could exclude  $\sigma v \simeq 1.5 \times 10^{-24} \text{cm}^3/s$  for  $M_{DM} \gg M_V$ , but with  $M_{DM} \sim M_V$  now excludes  $\sigma v \simeq 6 \times 10^{-25} \text{cm}^3/s$ . Moreover, still keeping  $M_{DM} = 1$  TeV, H.E.S.S. upper bound on dark matter annihilation cross sections goes from  $\sigma v \simeq 7 \times 10^{-24} \text{cm}^3/s$  for  $M_{DM} \gg M_V$ , to  $\sigma v \simeq \times 10^{-24} \text{cm}^3/s$  for  $M_{DM} \sim M_V$ , clearly showing that the mediator mass is important in the derivation of robust limits on the dark matter annihilation cross section. A similar reasoning can be applied to the other experiments. On Table 1 we show several benchmark models for comparison.

In Fig.8 we exhibit the 95% C.L. limits on the dark matter annihilation cross section into hadrons for the case that  $M_{DM} \gg M_V$ , with the mediator being just sufficiently heavier than its decay final states. The bounds from CMB are shown in black lines for the annihilations into  $4t$  (solid),  $4b$  (dotted) and  $4u$  (dashed) channels. A similar pattern is used for Fermi-LAT (green) and H.E.S.S. (blue) bounds.

For  $M_{DM} = 1$  TeV and annihilations into  $4b$  with  $M_{DM} \gg M_V$ , Fermi-LAT excludes  $\sigma v \simeq 2 \times 10^{-25} \text{cm}^3/s$ , Planck rules out  $\langle \sigma v \rangle \simeq 3 \times 10^{-24} \text{cm}^3/s$ , and lastly H.E.S.S. excludes  $\sigma v \simeq 2 \times 10^{-24} \text{cm}^3/s$ . If we ramp up the mediator mass to  $M_V \sim M_{DM}$ , H.E.S.S. sensitivity significantly changes, whereas Planck and Fermi-LAT sensitivities are mildly changed. In particular, H.E.S.S. upper bound on the dark matter annihilation cross section worsens now ruling out  $\sigma v \simeq \times 10^{-23} \text{cm}^3/s$ . A multitude of other setups are explicitly presented in Table 1 to facilitate the comparisons and easily assess the impact of the mediator mass in the derivation of the bounds.

In summary, one can see the mediator mass is more relevant for a heavy dark matter, with masses much larger than 100 GeV. In some cases, the difference in the upper limit on the dark matter annihilation cross section reaches a factor of seven, as in the  $M_{DM} = 1$  TeV case for annihilations into  $4\mu$ , for the H.E.S.S. telescope. To illustrate even further the importance of the mediator mass we paired the results for  $M_{DM} \gg M_V$  and  $M_{DM} \sim M_V$  for the  $4b$  and  $4\tau$  channels in Fig.10. As observed previously the upper limits change significantly specially for H.E.S.S. observation of the GC.



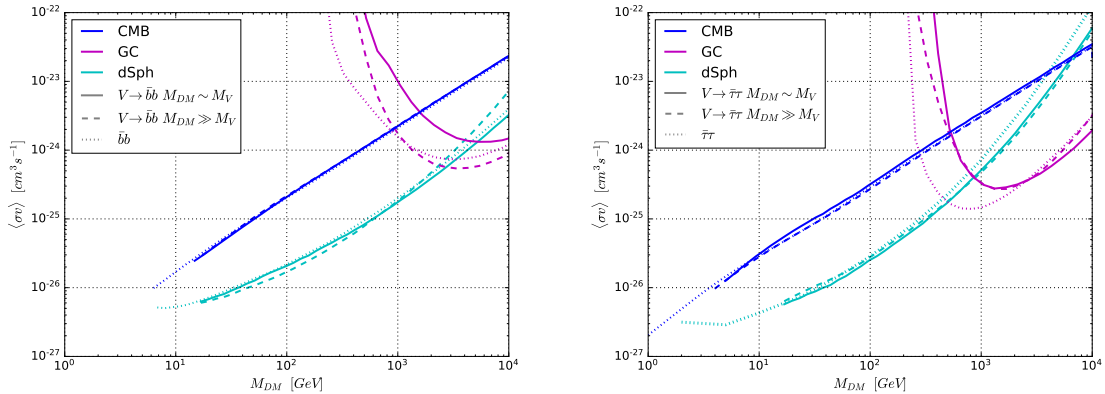


**Figure 9.** 95% C.L. upper limits on the dark matter annihilation cross as a function of the dark matter mass for the process  $DMDM \rightarrow VV$ , with  $V$  decaying into  $u\bar{u}$ ,  $b\bar{b}$ ,  $t\bar{t}$ . We assumed  $M_{DM} \sim M_V$ .

To summarize, our work derives new and updated limits on the dark matter annihilation cross section of secluded dark matter sector and shows that these bounds rely on the mass of the mediator.

## Discussion

CMB and gamma-ray constraints do not probe the same annihilation rates, as they probe annihilation rates at different times in the history of the universe. The annihilation cross section today drives gamma-ray signals, whereas the thermal averaged annihilation cross section at CMB decoupling drives CMB constraints. Some dark matter models feature velocity dependent annihilation rates, and in those models the assessment of which experiment is the most restrictive is model dependent [131–137]. Here, we have highlighted that bounds on the dark matter annihilation cross section do not depend on specific particle physics models and in this respect they can be regarded as model independent.



**Figure 10.** 95% C.L. upper limits on the dark matter annihilation cross section for  $M_{DM} \gg M_V$  and  $M_{DM} \sim M_V$  to easy comparison based on the observation from the CMB (blue), GC (magenta) and dSph (cyan). *Left-panel:* annihilation into  $4b$ ; *Right-panel:* annihilation into  $4\tau$ . We also overlay the canonical dark matter annihilation into  $2b$  and  $2\tau$  respectively.

## 6 TeV Gamma-ray Excess Observed by H.E.S.S.

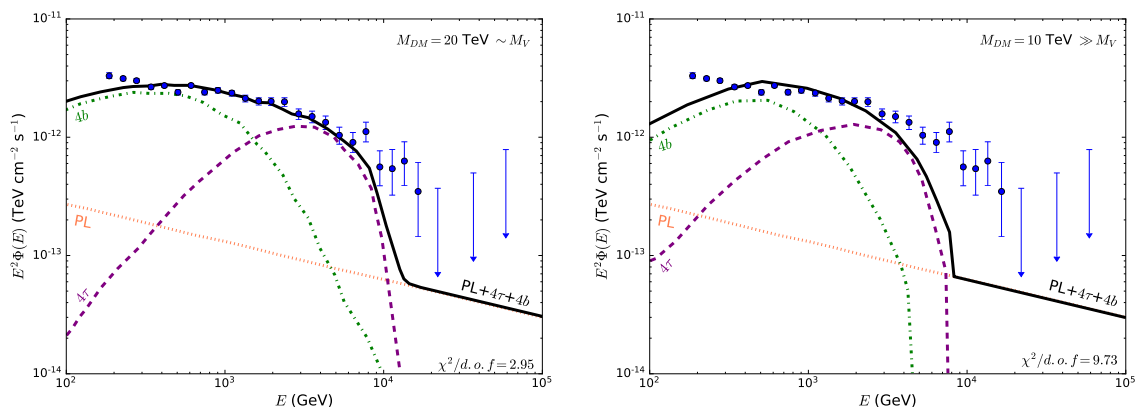
Gamma ray observations performed by the ground-based H.E.S.S. telescope within the 15 pc from the Galactic Center revealed a very-high-energy point-like source known as J1745-290 which features a significant deviation from a pure power-law (PL) emission in a few TeV energy region [53, 54].

We followed the procedure described in [54] and assumed that the annular region within  $0.15^\circ$  and  $0.45^\circ$  that has a solid angle of  $1.4 \times 10^{-4}$  sr is well-fitted by the PL spectrum  $dN/dE = A_b(E/1\text{TeV})^{\Gamma_b}$ , with  $A_b = (1.92 \pm 0.08_{stat} \pm 0.28_{sys}) \times 10^{-12} \text{cm}^{-2}\text{s}^{-1}\text{TeV}^{-1}$  and  $\Gamma_b = 2.32 \pm 0.05_{stat} \pm 0.11_{syst}$ . The result is shown with a dotted coral line in Fig. 11.

Moreover, we generated the energy spectrum of secluded dark matter annihilations using Pythia 8 [88] and derived the gamma-ray fluxes for dark matter annihilations into  $4\tau$  e  $4b$  for  $M_{DM} \sim M_V$  (left-panel) and  $M_{DM} \gg M_V$  (right-panel), as displayed in in Fig.11 with green and purple curves, respectively.

After summing the background contribution to the power-law emission above we obtain the black curve which is the gamma-ray flux produced by the dark matter plus background. In the left panel, where  $M_{DM} \sim M_V$ , the minimum  $\chi^2$  procedure yields  $\chi^2/d.o.f = 2.95$ . It favors  $\sigma v = 3.87 \times 10^{-26} \text{cm}^3\text{s}^{-1}$  and  $M_{DM} = 20$  TeV with annihilation branching ratio of 60% into  $4b$  and 40% into  $4\tau$ . We investigated the possibility to get improve the  $\chi^2$  for different branching ratios but the aforementioned scenario provided the best-fit.

In the right panel, where  $M_{DM} \gg M_V$ , the minimum  $\chi^2$  procedure yields  $\chi^2/d.o.f =$



**Figure 11.** H.E.S.S. TeV gamma-ray observation within 15 pc of the Galactic Center. In blue are the data points. The dotted coral line is the background emission assumed to be a simple PL. In black in the total gamma-ray emission obtained by summing the dark matter component with the background. In green (purple) the gamma-ray emission produced by the dark matter particle annihilating into  $4b$  ( $4\tau$ ). *Left-panel:* 20 TeV dark matter particle, with  $\sigma v = 3.87 \times 10^{-26} \text{cm}^3 \text{s}^{-1}$ , annihilating with 60% branching ratio into  $4b$  and 40% into  $4\tau$  for  $M_{DM} \sim M_V$ . *Right-panel:* 10 TeV DM particle, with  $\sigma v = 1.64 \times 10^{-26} \text{cm}^3 \text{s}^{-1}$ , annihilating 50% into  $4b$  and 50% into  $4\tau$  for  $M_{DM} \gg M_V$ . One can quantitatively see the impact of the mediator mass.

9.73. It favors  $\sigma v = 1.64 \times 10^{-26} \text{cm}^3 \text{s}^{-1}$  and  $M_{DM} = 10 \text{ TeV}$  with the branching ratio of 50% into  $4b$  and 50% into  $4\tau$ .

It is important to highlight that the dark matter annihilation cross section serves as an overall rescaling of the energy spectrum, whereas the dark matter mass changes the energy spectrum behavior at lower and larger energies. Furthermore, the dark matter annihilation in the mass degenerate case leads to a harder gamma-ray spectrum at lower energies proving a better fit to the data where the error is relatively smaller. The trade-off between dark matter mass, annihilation cross section, annihilation final states led to the best-fit parameters found above.

In summary, the TeV gamma-ray excess observed the H.E.S.S. telescope is also well-fitted by secluded dark matter annihilations, and mediator mass has an important impact on what dark matter mass provides a best-fit to the data, ratifying our conclusions.

A similar study but in the context of  $2 \rightarrow 2$  dark matter annihilations was carried out in [138, 139]. It is important to emphasize though that one could also nicely explain the H.E.S.S. observation by assuming that the background emission departs from the pure power-law spectrum, and it actually described by a power-law function with an exponential cut-off [140].

## 7 Conclusions

Secluded dark sectors are often investigated in a model-dependent fashion. Motivated by their relevance, we used seven years of Fermi-LAT observations of dwarf spheroidal galaxies, 10 years of H.E.S.S. data from the Galactic center, and the most recent Planck measurements on the Cosmic Microwave Background to constrain secluded dark sectors. We showed here that these datasets are highly complementary to each other, especially when the dark matter mass is above  $\sim 400$  GeV. We derived 95% C.L. limits on the dark matter annihilation cross section for several scenarios. We discussed sifted annihilations into  $4e, 4\mu, 4\tau, 4u, 4b, 4t$  and also assessed the impact of the mediator mass on our bounds. As far as indirect searches for dark matter are concerned, these mediators are often assumed to be very light and just sufficiently heavier than the decay modes' particle masses. We showed that their masses can lead to sizeable changes on the overall upper limits on the dark matter annihilation cross section. Our bounds supersede previous constraints using Fermi-LAT data, and they constitute the first limits on secluded dark sectors using H.E.S.S. telescope. We also showed that secluded dark matter can also fit the TeV gamma-ray observation observed by the H.E.S.S. telescope, with the mediator mass driving the best-fit points location.

In conclusion, our results clearly show that any robust assessment of secluded dark sectors in the context of indirect detection rely not only the dark matter annihilation cross section and annihilation final state, but also on the mediator mass.

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