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Francesca Calore, Valentina De Romeri, and Fiorenza Donato

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Conservative upper limits on WIMP annihilation cross section from Fermi-LAT γ-rays

Francesca Calore*
II. Institute for Theoretical Physics, University of Hamburg, Luruper Chaussee 149, 22761 Hamburg, Germany

Valentina De Romeri†
Astroparticle and High Energy Physics Group, IFIC (CSIC - Universidad de Valencia) - Edificio Institutos de Investigacion, C/ Catedratico Jose Beltran 2, E-46980 Paterna (Valencia), Spain

Fiorenza Donato‡
Dipartimento di Fisica Teorica, Università di Torino and INFN, Via P. Giuria 1, 10122 Torino, Italy

The spectrum of an isotropic extragalactic γ-ray background (EGB) has been measured by the Fermi-LAT telescope at high latitudes. Two new models for the EGB are derived from the subtraction of unresolved point sources and extragalactic diffuse processes, which could explain from 30% to 70% of the Fermi-LAT EGB. Within the hypothesis that the two residual EGBs are entirely due to the annihilation of dark matter (DM) particles in the Galactic halo, we obtain stringent upper limits on their annihilation cross section. Severe bounds on a possible Sommerfeld enhancement of the annihilation cross section are set as well. Finally, we consider models for DM annihilation depending on the inverse of the velocity and associate the EGBs to photons arising from the annihilation of DM in primordial halos. Given our choices for the EGB and the minimal DM modelling, the derived upper bounds are claimed to be *conservative*.

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I. INTRODUCTION

The indirect search for dark matter (DM) through its annihilation products in rare charged cosmic rays (CRs) and in multi-wavelength channels requires very accurate measurements and an unambiguous estimation of all the possible backgrounds to the DM signal. In the last years, dedicated experiments have provided unprecedented results by extending the energy ranges of the measured cosmic species as well as the precision of the data [1–7]. Further data are expected by the Fermi-LAT and Pamela on-going missions, and by the AMS-02 experiment on board the International Space Station. From the theoretical side, many efforts have been addressed to a better and increasingly detailed modellization of the astrophysical processes which shape, at different levels, the observed fluxes. Data from cosmic antiprotons [5, 6] have been shown to be compatible with the standard production from CRs impinging on the interstellar gas [8]. The anomalous increasing positron fraction measured by Pamela [1, 2] and confirmed by Fermi-LAT [9] may be explained by emission from near pulsars over-imposed to a standard CR population [10, 11]. Alternatively, a DM component with very high cross section or sources concentration has been invoked [12–15]. Unprecedented γ-ray measurements by Fermi-LAT have boosted interpretation of diffused and point sources emission in terms of exotic components from DM annihilation in the halo of the Milky Way, in extragalactic near objects or in cosmological structures [7, 16–18]. The very signature would be the monochromatic line, which nevertheless provides tiny signal on a remarkable background [19].

The high latitude γ-ray emission measured by Fermi-LAT [7], given its reduced contamination by galactic sources, can be a powerful tool to set limits on the contribution of DM to the measured flux. The data are indeed the result of a non trivial subtraction procedure and show a high isotropic feature.

The aim of the present research is to set *conservative* upper limits on the galactic weakly interacting massive particle (WIMP) DM annihilation cross section into γ-rays. Several upper limits have been obtained through different and complementary indirect research means [8, 18, 20–28]. However, it is usually not straightforward to compare these results, given the model dependence, the different assumptions on the astrophysical backgrounds, and the theoretical uncertainties. We will confront the γ-rays coming both from the DM halo and high-redshift protohalos with the background observed by Fermi-LAT at high latitudes. The conservative approach is achieved - in addition to prudent assumptions on the particle physics model and DM distribution in the Galaxy - through the comparison of the putative DM signal with a high latitude diffuse emission spectrum (i.e. EGB) obtained with minimal subtractions of known unresolved sources.

Our paper proceeds as follows. In Sect. 2 we discuss the possible contributions to the high latitude γ-ray emission from unresolved point sources and truly diffuse processes. We subtract the non-negligible fluxes to the Fermi-LAT

*Electronic address: francesca.calore@desy.de
†Electronic address: deromeri@ific.uv.es
‡Electronic address: donato@to.infn.it

data and draw two possible scenarios for the high latitude emission. In Sect. 3 we derive conservative upper limits to the DM annihilation cross section by identifying the residual γ-ray flux with γ-rays from DM annihilation in the galactic halo and in primordial DM small halos at high redshift. In the latter case, we study models in which the DM annihilation cross section has an explicit dependence on the inverse of the velocity. We discuss also a possible Sommerfeld enhancement of the annihilation cross section and derive limits on its amplitude. In Sect. 4 we draw our conclusions.

II. THE EXTRAGALACTIC γ-RAY BACKGROUND

A diffuse γ-ray emission has been measured by the Fermi-LAT detector at high latitudes ($|b| > 10^o$) [7]. The spectrum has been obtained after the subtraction from the data of the sources resolved by the telescope, the (indeed model dependent) diffuse galactic emission, the CR background in the detector and the solar γ-ray emission. The resulting flux decreases with a power law of the photon energy with spectral index 2.41 ± 0.05. It shows a highly isotropic sky distribution and is generically classified as an extragalactic γ-ray background (EGB).

The 1451 sources listed in the First Fermi-LAT catalog (1FGL) [29] represent the best-resolved survey of the sky in the 100 MeV to 100 GeV energy range. For each low–flux source there may be a large number of *unresolved* point sources which have not been detected because of selection effects, or too low emission. Most of the unassociated high latitude sources are blazars, a class of Active Galactic Nuclei (AGNs), and their pile to the EGB with the largest flux [30]. Galactic resolved pulsars and Milli-Second Pulsars (MSPs) represent the second largest population in the Fermi-LAT catalog [29, 31] and they are expected to contribute significantly to the putative EGB. A non-negligible γ-ray flux seems to be guaranteed by unresolved normal star-forming galaxies [32]. Ultra-high energy CRs (UHECRs) may induce secondary electromagnetic cascades, originating neutrinos and γ-rays at Fermi-LAT energies [33]. Contributions from unresolved blazars and MSPs are believed to contribute at least few percent to the Fermi-LAT EGB, while predictions for star-forming galaxies and UHECRs are highly model dependent.

Other astrophysical sources may emit in the high latitude γ-ray sky: i) radio-quiet AGN [34, 35], and Fanaroff and Riley radio galaxies of type I and II [36–38] whose contribution is strongly model dependent and likely bound to few percent of the EGB; ii) γ-ray bursts (GRBs), estimated less than 1% of the diffuse extragalactic γ-ray background [39]; iii) star-burst and luminous infrared galaxies. The relevant flux may cover a significant fraction of the EGB ($\leq 20\%$) [40], but the model dependence is such to prevent firm statements on the relevance of this extragalactic source; iv) nearby clusters of galaxies, which could yield about $1\% - 10\%$ of the EGRET EGB [41–43]; v) gravitational induced shock waves, produced during cluster mergers and large-scale structure formation, whose fluxes are quite model dependent and may reach few percent [44, 45]. All these γ-ray sources have been shown to contribute to less than 1% of the Fermi-LAT EGB or to be too highly model dependent. In the latter case, a very high uncertainty band would be associated with the γ-ray source, whose lower limit likely gives a negligible contribution to the Fermi-LAT EGB. They will therefore be neglected in rest of our paper.

In the following, we describe few classes of γ-ray emitters whose unresolved flux is firmly estimated in a non-negligible Fermi-LAT EGB percentage. In a conservative scenario (Model I), we will subtract AGN and MSPs to the Fermi-LAT EGB as derived in Ref. [7]. A more relaxed model (Model II) will be drawn by the further subtraction of a minimal flux from star-forming galaxies and CRs at the highest energies.

1. *BL Lacs and FSRQs*

Blazars constitute the class of γ-ray emitters with the largest number of identified members. Therefore, unresolved blazars are expected to have a sizable contribution to the EGB, [46]. The largest uncertainties in determining the blazars contribution are their unknown spectral energy distribution and luminosity function [35, 47]. In addition to phenomenological predictions, an analysis of the observed source count distribution through Monte Carlo simulations has been performed in Ref. [30]. The reliability of the algorithm relies onto a good agreement with the real data, from the comparison of reconstructed γ-ray fluxes and spectral properties of the sources. The energy spectrum is well described by a power-law for both FSRQs (softer) and BL Lacs one (harder), being the intersection between the two fluxes at about 400 MeV. Following our conservative approach - which is meant to consider the minimum unavoidable contribution to the EGB from unresolved astrophysical sources - we will adopt blazar contributions from the curves delimiting the lower uncertainty bands displayed in Fig. 20 of Ref. [30]. The ensuing flux is displayed in our Fig. 1 as dotted (dot-dashed) line for BL Lacs (FSRQs) contribution.

2. *Pulsars and MSPs*

As a result of their short periods, typical MSPs may be brighter in the γ-rays and much older than ordinary pulsars [48]. The ages of MSPs generally exceed the oscillation time across the galactic disk by a large factor so that MSPs are expected to be more prevalent at high latitudes. On the contrary young, energetic ordinary pulsars are more concentrated close to the Galactic plane, where they were born. In the first year of Fermi-LAT observations [29], 63 pulsars have been identified. Among them: (i) 16 pulsars at $|b| > 10^o$, of which 11 are MSPs; (ii) 5 MSPs at $|b| > 40^o$ and (iii) 1 MSP at $|b| > 60^o$. We estimate a minimal but not negligible contribution of the unresolved MSPs population to the γ-ray flux at high latitudes. We adopt an empirical prescription outlined in Ref. [49], which is based on the spectra of the eight MSPs detected by Fermi in the first 9 months [50] of operation. The differential energy spectra of the Fermi-detected MSPs are well described by a truncated power law:

$$\frac{dN}{dE} = KE^{-\Gamma}e^{-E/E_{cut}}. \quad (1)$$

Γ and E_{cut} are assumed to be $\langle\Gamma\rangle = 1.5$ and $\langle E_{cut}\rangle = 1.9$ GeV, while K has been obtained for $|b| \geq 40^o$.

In order to evaluate Eq. (1) for different observational regions - namely changing the normalization K - we follow the prescriptions given in Ref. [48]. Assuming a disk-like latitude profile, the ratio of the average intensities at different latitudes is given by:

$$\frac{I_{MSP}(|b| \geq b_1)}{I_{MSP}(|b| \geq b_2)} = \frac{\ln[(\sin|\mathrm{b}_1|)^{-1}]}{\ln[(\sin|\mathrm{b}_2|)^{-1}]}, \quad (2)$$

where $I_{MSP}(|b| \geq b_i)$, $i = 1, 2$, is the average MSP intensity over a solid angle $\Omega = 4\pi(1 - \sin|b_i|)$ defined by the integration from the minimal latitude b_i up to 90^o, written as:

$$I_{MSP} \equiv \frac{S_{tot}}{\Omega} = \frac{S_{min}}{\Omega}\cdot\left(\frac{\delta-1}{\delta-2}\right)\cdot\left(\frac{S_{min}}{S_{th}}\right)^{1-\delta}\cdot N(S > S_{th}). \quad (3)$$

S_{min} refers to the assumed Euclidean logN-logS flux distribution of the galactic MSP population, which is parametrized by a power-law with spectral index $\delta = 2.5$ for $S \geq S_{min}$. According to [48], we set $S_{min} = 10^{-10}$ ph s^{-1} cm^{-2}. $N(> S_{th})$ is the number of resolved sources above a given flux threshold S_{th}. We update the estimation for I_{MSP} in Ref. [48] with the more recent observations for $|b| \geq 10^o$ reported in Ref. [50], where 8 MSPs have been found above $S_{th} = 2 \cdot 10^{-8}$ ph s^{-1} cm^{-2} (lowest detected MSP flux). We find:

$$I_{MSP}(|b| \geq 10^o, E > 100\,\mathrm{MeV}) = 6.54\cdot 10^{-7}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}. \quad (4)$$

K is then derived from:

$$I_{MSP} = \int_{E_{min}}^{E_{max}} \frac{dN}{dE} dE \ , \quad (5)$$

where $\frac{dN}{dE}$ refers to Eq. (1). Cross-checking the average MSP intensities obtained with the prescription outlined above, and the results in Ref. [49] for $|b| \geq 40^o$, we find a relative difference of about 30%, due to the theoretical uncertainties on the assumed logN-logS and the latitude profile. We consider such a discrepancy as an empirical theoretical uncertainty on the determination of K, and fix the unresolved MSPs contribution subtracting a 30% uncertainty from the estimated average intensity. The MSP contribution is shown in Fig. 1 as a double dot-dashed line.

3. *Star-forming Galaxies*

Unresolved normal star-forming galaxies are expected to give a guaranteed contribution to the high latitude isotropic diffuse γ-ray background. Fermi-LAT has identified the source of the diffuse emission from our Galaxy due to the collisions of CRs with interstellar gas, leading to γ-rays from π^0 decay in flight. This observation provides a ground to estimate the γ-ray luminosity of star-forming galaxies, by scaling the CR flux with the massive star formation rate and fixing the amount of the gas in the external galaxy. Theoretical predictions are greatly affected by uncertainties in the determination of the star formation rate of the galaxies and their gas content [32, 47, 51]. Given the uncertainty surrounding key elements of the determination of this contribution, in our strictly conservative approach we do not take into account this component. In a more relaxed perspective, we consider the lowest predicted contribution from star-forming galaxies [32]. It is derived assuming an increase in the number of star forming galaxies with the redshift. The adopted emission corresponds to the long dashed curve in Fig. 2.

4. *UHECRs*

UHECRs accelerated in astrophysical objects produce secondary electromagnetic cascades during their propagation in the cosmic microwave and infrared backgrounds. Ref. [33] shows that if the primary CRs are dominated by protons, such cascades can contribute between 1% and 50% of the GeV-TeV diffuse photon flux measured by the EGRET experiment. In Ref. [52], the EGB spectrum from UHECRs (normalized to the HiRes data) has been obtained through a Monte Carlo simulation of the cascade development and compared with the measurement of the EGB by Fermi-LAT. In our more relaxed, whether conservative scenario, we will subtract the ankle model contribution to the Fermi-LAT EGB [52], which we show in Fig. 2. This γ-ray component has the peculiar behaviour to slightly increase with increasing energy, and at 100 GeV may account 8% of the Fermi-LAT measured EGB.

A. Models for the EGB

As a result of the previous analysis, we now proceed by subtracting from the Fermi-LAT EGB [7] additional contributions from unresolved sources at latitudes $|b| > 10^o$. The contributions to the EGB that we will remove from the Fermi-LAT spectrum are minimal. In fact, as extensively explained in the previous sections, the predictions that we will take into account for the relevant unresolved sources are the lowest ones according to the literature. In addition, for MSPs we have lowered existing calculations by updating them to the Fermi-LAT observations.

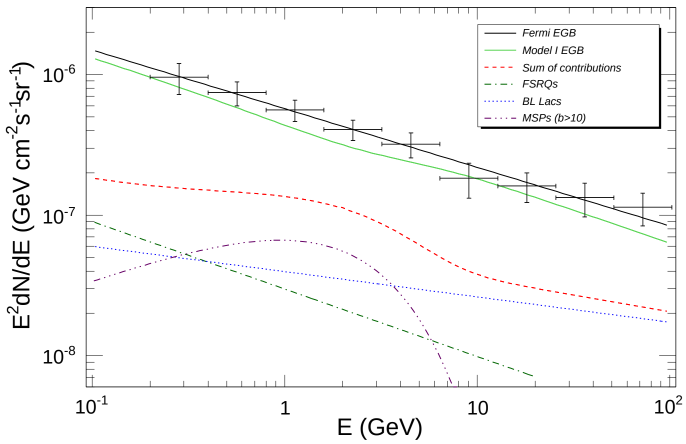

FIG. 1: γ-ray spectrum for $|b| > 10^o$ latitudes. Fermi-LAT data points are displayed along with their power–law fit (solid black curve) [7]. The dotted (blue), dot-dashed (green) and double dot-dashed (purple) curves correspond to BL Lacs, FSRQs and MSPs contribution, respectively. The dashed (red) curve is the sum of the previous three fluxes. The solid (lower, green) curve is derived by subtracting the three contributions to the Fermi-LAT result (Model I).

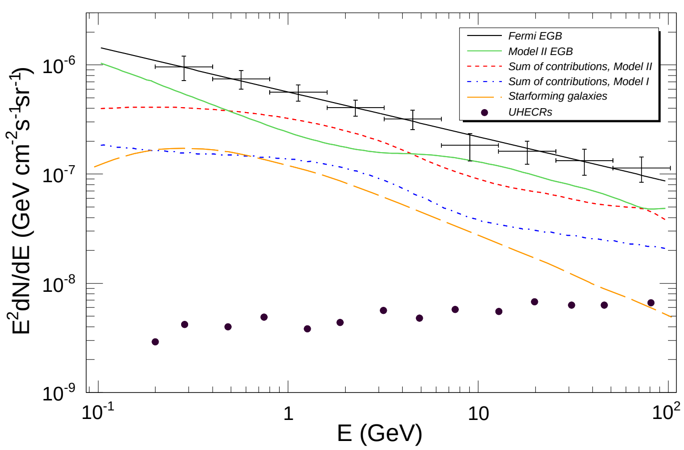

FIG. 2: γ-ray spectrum for $|b| > 10^o$ latitudes. Fermi-LAT data points are displayed along with their power–law fit (solid black curve) [7]. Dots and long dashed-curve (light blue) correspond to the UHECRs and star-forming galaxies γ-ray fluxes, respectively. The short-dashed (red) curve corresponds to the sum of BL Lacs, FSRQs and MSPs contribution (see Fig. 1), the short-dashed (blue) to the sum of the previous components with the star-forming galaxies and UHECRs ones. The solid (lower, green) curve is derived by subtracting all the contributions to the Fermi-LAT result (Model II).

In what we label Model I, we subtract from the Fermi-LAT EGB [7] the unresolved contributions for both BL Lacs and FSRQs as outlined in Sect. II 1, and the unresolved MSPs flux obtained according to the prescription Sect. II 2. The results are shown in Fig. 1, where the Fermi-LAT EGB data [7] are shown along with our power–law fit. The contributions from BL Lacs, FSRQs and MSPs are identified by dotted, dot-dashed and double dotted-dashed curves, respectively. The fluxes from the blazar populations follow power–laws, with softer (harder) spectrum for the FSRQs (BL Lacs). The crossing point for the two curves is around 300 MeV: above this energy BL Lacs flux dominates over the FSRQs one. The γ-rays from unresolved MSPs show a peculiar spectrum peaked at about 1 GeV and dominate over the blazar spectra from 300 MeV up to 3-4 GeV. The sum of the three contributions reflects the MSPs flux shape with a mild bump. At about 100 MeV the three sources explain 10% of the Fermi-LAT EGB and 30% above 1 GeV. The residual flux Model I, obtained by subtracting the sum of the three contributions (dashed curve) to the Fermi-LAT best fit flux is identified by the lower solid curve. It is not a net power law due to the dip in the GeV region introduced by the MSPs flux.
Fig. 2 refers to the scenario where the additional contributions from star-forming galaxies (long dashed line) and UHECRs (solid points) as outlined in Sect. II 3 and Sect. II 4 add to explaining the Fermi-LAT EGB. These two further contributions add with the previous ones (blazars and MSPs of Model I) and the total sum is displayed by the dashed red line. The solid (green) curve derives from the subtraction of all these contributions from the Fermi-LAT EGB (solid black line fitting the data points) and is labelled Model II hereafter. Notably, the contribution from star-forming galaxies turns out to be relevant for $E \leq 1$ GeV, whereas the γ-rays from UHECRs give non-negligible fluxes only at the high-end of the energy spectrum. We notice that at 100 MeV Model II explains about 70% of the Fermi-LAT EGB, while above 1-2 GeV they count about 50% of the total. To consider additional astrophysical components to the EGB further decreases the residual flux (lower solid line) with respect to the Fermi-LAT EGB (upper solid line) and shrinks the room left to potential exotic sources, like DM annihilations.

III. UPPER BOUNDS ON DM ANNIHILATION CROSS SECTION

In this Section we derive conservative upper limits on the WIMP annihilation cross section. We make the hypothesis that the residual fluxes we have derived in Sect. II A are entirely provided by the γ-rays produced by thermalized WIMP DM in the halo of the Milky Way.

A. γ-rays from DM annihilation

The flux of γ-rays $\Phi_\gamma(E_\gamma, \psi)$ originated from WIMP pair annihilation in the galactic halo [53–55] and coming

Halo profile	Isothermal a = 3.5 kpc	NFW [59] a = 25 kpc $r_c = 0.01$ pc	Einasto [60] $\alpha = 0.142$ $r_{-2} = 26.4$ pc $\rho_{-2} = 0.05$ GeV cm^{-3}
$\lvert b\rvert > 10^o$	2.389	2.400	2.833
$10^o < \lvert b\rvert < 20^o$	4.020	4.166	5.752
$\lvert b\rvert > 60^o$	1.226	1.283	1.232

TABLE I: Values for $I_{\Delta\Omega}$ in units of GeV^{2}cm^{-6}kpc. For all these profiles $\rho_l = 0.4$ GeV cm^{-3} , $R_{Sun} = 8.2$ kpc.

from the angular direction ψ is given by:

$$\Phi_\gamma(E_\gamma, \psi) = \frac{1}{4\pi}\frac{\langle\sigma v\rangle}{m_\chi^2}\frac{dN_\gamma}{dE_\gamma}\frac{1}{2}I(\psi)\,, \tag{6}$$

where $\langle\sigma v\rangle$ is the annihilation cross section times the relative velocity mediated over the galactic velocity distribution function, and dN_γ/dE_γ is the energy spectrum of γ-rays originated from a single DM pair annihilation. In particular, we may identify WIMP candidates with neutralinos in the Minimal Supersymmetric Standard Model (see Ref. [55] and refs. therein).
The photon spectrum in the continuum originates from the production of fermions, gauge bosons, Higgs bosons, and gluons from the annihilation of WIMP pairs. The spectra dN_γ/dE_γ from DM final states into $b\bar{b}$, $\mu^+\mu^-$ and $\tau^+\tau^-$ have been taken from Refs. [56, 57]. The extrapolation down to m_χ=10 GeV seems guaranteed within 10% of uncertainty for all the annihilation channels [58] (a more careful derivation being beyond the scope of the paper).
The quantity $I(\psi)$ is the integral performed along the l.o.s. of the squared DM density distribution:

$$I(\psi) = \int_{l.o.s.} \rho^2(r(\lambda, \psi))d\lambda\,. \tag{7}$$

with ψ being the angle between the l.o.s. and the direction pointing toward the galactic center (GC) and defined in function of the galactic coordinates so that $\cos\psi = \cos b \cos l$. When comparing with experimental data, Eq. (7) must be averaged over the telescope observing solid angle, $\Delta\Omega$:

$$I_{\Delta\Omega} = \frac{1}{\Delta\Omega}\int_{\Delta\Omega} I(\psi(b,l))d\Omega\,. \tag{8}$$

The integral of the squared DM density over the line-of-sight depends from the choice on $\rho(r)$. When including the galactic center in the integration (Eq. (7)), different DM distributions may lead to very different results for $I(\psi)$. However, since our analysis is applied to high latitude regions, the various descriptions for $\rho(r)$ point to very similar values for $I(\psi)$. We neglect any clumpiness effects and assume a smooth distribution of DM in the galactic halo. The results for $I_{\Delta\Omega}$ for different DM density distributions and observational regions are reported in Table I. All the DM profiles provide very similar results for latitudes well above the galactic plane. Hereafter, the results will be provided for the cored isothermal density profile.

B. Results on annihilation cross section

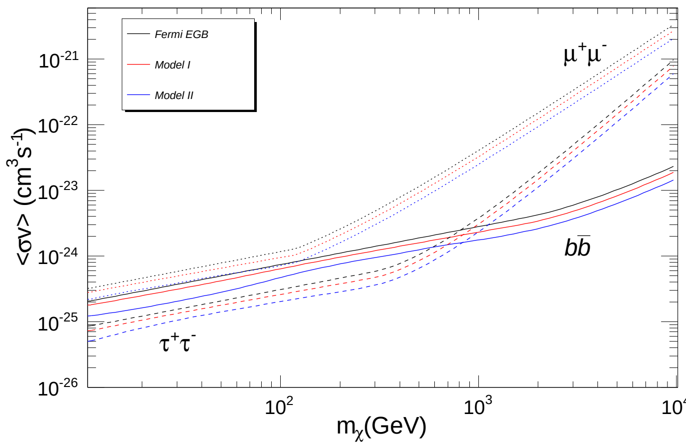

FIG. 3: Upper bounds on $\langle\sigma v\rangle$ from γ-ray in the high latitude galactic halo, as a function of the DM mass. From top to bottom, solid lines refer to 90% C.L. limits from the comparison with Fermi-LAT EGB (black lines), Model I (red lines), Model II (blue lines) (see text for details). Dotted, solid and dashed lines correspond DM annihilation into $\mu^+\mu^-$, $b\bar{b}$, $\tau^+\tau^-$, respectively.

In this Section we derive upper bounds at 90% C.L. on the WIMP annihilation cross section from the γ-ray Fermi-LAT EGB and the EGB residual fluxes identified as Model I and II in Sect. II A.

For the Fermi-LAT EGB [7], the upper bounds at 90% C.L. on $\langle\sigma v\rangle$ are obtained by requiring that the DM signal calculated according to Eq. 6 does not exceed the measured flux plus 1.28σ (one-sided upper limit on the $\langle\sigma v\rangle$ parameter). The corresponding constraints are plotted as black lines in Fig. 3. From the same data we have then subtracted the unresolved blazars and MSPs minimal contribution, as described at length in Sect. II A, and derived the upper bounds on $\langle\sigma v\rangle$ corresponding to Model I (red lines). Similarly, upper bounds for the Model II EGB are obtained from the further subtraction of the minimal flux from star forming galaxies and UHECRs (blue lines). In Fig. 3 we display the conservative upper bounds on the thermal annihilation DM cross section at 90% C.L., derived within the previous assumptions. From top to bottom, each bunch of lines refer to the limits on $\langle\sigma v\rangle$, arising from the comparison with the Fermi-LAT 90% C.L. EGB, Model I and Model II. Dotted, solid and dashed lines correspond DM annihilation into $\mu^+\mu^-$, $b\bar{b}$, $\tau^+\tau^-$, respectively. Given the scaling of the DM flux $\propto m_\chi^{-2}$, constraints on $\langle\sigma v\rangle$ increase with the mass and span about two orders of magnitude in the considered mass interval. It is evident from Fig. 3 that the subtraction of the minimal amount of γ-rays from unresolved sources lowers the limits on $\langle\sigma v\rangle$ by at least 50%. The Fermi-LAT data for the EGB are available also for latitudes $10^o < |b| < 20^o$ and $|b| > 60^o$ [7]. The flux in Eq. (6) changes for the mere normalization factors given in Table I. However, given the intensity of the measured fluxes our upper limits do not change if derived for the other high latitude regions.

Given the theoretical uncertainties affecting the DM content and the astrophysical backgrounds, the results in Fig. 3 are of the same order of magnitude or lower than the bounds on $\langle\sigma v\rangle$ from cosmological DM [18], from the galactic center [26], or from inverse Compton processes evaluated from γ-rays in different portions of the sky [20]. Very recently (during the review process of the present paper) the Fermi-LAT collaboration performed a combined analysis on ten Milky Way satellite galaxies [27], corroborated by the analysis in Ref. [28]. The absence of DM signals from these objects leads to upper limits on $\langle\sigma v\rangle$ which are close to 10^{-26} for masses about 10 GeV and 10^{-24} for m_χ=1 TeV. These bounds are close to the ones established in the present work for the high mass side, and stronger for the low mass range. The two results, given unavoidable modelling in the extraction of the upper bounds, strengthen each other in disfavouring a DM candidate with an annihilation cross section much higher than the electroweak reference value $3 \cdot 10^{-26}$ cm^3/s for very low WIMP masses. We make notice that the EGB spectra we have obtained in Model I and II could be further reduced, whether by the subtraction of additional components or by increasing the predictions for each contribution, set at the minimum in the present work. A smaller γ-ray flux at high latitudes could therefore be as powerful as the measurements from the dwarf spheroidal galaxies.

We emphasize that our limits are almost model independent: little dependence on the DM distribution, being at high latitudes, and mild differences due to final states.

Our limits are *conservative*: it is very unlikely that a higher $\langle\sigma v\rangle$ be compatible with Fermi-LAT EGB. Similarly, our upper limits could be lowered only with assumptions on non-homogeneous DM distributions or, of course, comparing to a smaller EGB residual.

C. Bounds on the Sommerfeld enhancement for $\langle\sigma v\rangle$

Recent claims on the excess of CR positrons [1] have stimulated the interpretation of data in terms of annihilating DM with fairly large annihilation cross sections of the order of $10^{-23} - 10^{-22}$ cm^3/s. These numbers are at least three orders of magnitude larger than the value indicated by observations of the DM abundance due to thermal production. One way to boost the annihilation cross section is through the Sommerfeld effect [14, 61–65], generically due to an attractive force acting between two particles, *i.e.* a Yukawa or a gauge interaction. In the case of DM particles, the main effect of such an attractive force would be to enhance $\langle\sigma v\rangle$ by a factor proportional to $1/\beta = c/v$, where v is the velocity of the DM particle ($1/v$ enhancement). The net result on the annihilation cross section writes as $\langle\sigma v\rangle = \mathrm{S}\ \langle\sigma v\rangle_0$, where S sizes the Sommerfeld enhancement of the annihilation amplitude. We have evaluated the Sommerfeld enhancement S using the approximation of the Yukawa potential by the Hulthen potential, for which an analytic solution is possible [66, 67] (and checked that the solution coincides with the numerical one). The Sommerfeld enhancement factor behaves as $1/v$ and for very small velocities it saturates to constant values. Given α the coupling constant and m_ϕ the mass of the new force carrier, if the quantity $m_\phi/m_\chi \cdot \alpha$ is close to the values that make the Yukawa potential have zero-energy bound states, the enhancement is much larger; indeed, the enhanced cross section shows resonances at $m_\chi = \frac{4 m_\phi n^2}{\alpha}$ (n $= 1, 2, 3...$), which grow as $1/v^2$, up to the point where they get cut off by finite width effects.

In Fig. 4 we show the Sommerfeld enhanced cross sections for $\alpha = \frac{1}{4\pi}$, $\beta = 10^{-8}$ and a force carrier of mass m_ϕ = 1 GeV (upper curve) and m_ϕ = 90 GeV (lower curve). We over-impose the upper bounds obtained in the previous Section from the residual EGB Model I and Model II and already displayed in Fig. 3. Our results show that a Sommerfeld enhancement due to a force carrier of m_ϕ < 1 GeV ($\alpha = \frac{1}{4\pi}$) is strongly excluded by Model I and II for the Fermi-LAT EGB data. For a massive force carrier (90 GeV) only the resonant peaks above the TeV mass are excluded. The result holds for $\beta = 10^{-8}$ up to $\beta = 10^{-3}$. Comparable constraints have been obtained in [21, 68] through the analysis of perturbations to the CMB angular power spectrum

Therefore, high latitude γ-ray observations interpreted as due to DM annihilation in the Milky Way halo bound the Sommerfeld enhancement of the annihilation cross section to a factor of 3-10-50-200 for m_χ=10-100-1000-5000 GeV, respectively. In case a Yukawa-like potential describes this non-relativistic quantum effect, a force carrier heavier than 1 GeV is definitely required.

D. Bounds from the high-redshift protohalos

A possible way to boost the annihilation rate is to modify the particle theory and make the ansatz that the annihilation cross section depends on the inverse of the velocity [69]. A boosted production of γ-rays in models with $\langle\sigma v\rangle \propto 1/v$ has been proposed for the first bound objects formed in the early phases of the universe [70, 71]. After the matter-radiation equality is reached, DM perturbations start growing via gravitational instability and form the first bound protohalos at a redshift of about 140. The birth of these protohalos depends on the properties of the

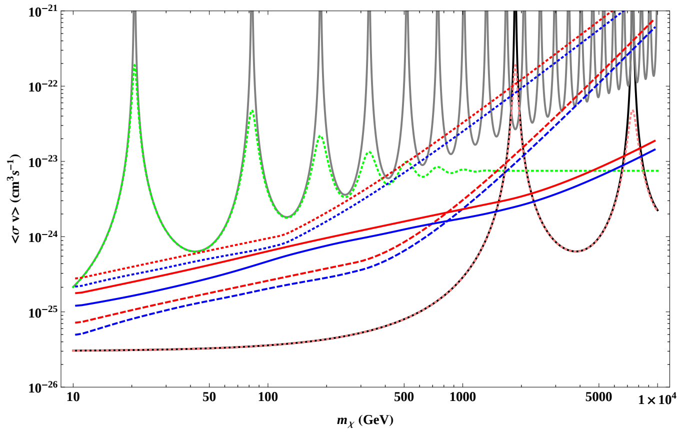

FIG. 4: Sommerfeld enhancement of the annihilation cross section as a function of the DM mass, for $\alpha = \frac{1}{4\pi}$. Solid curves are for $\beta = 10^{-8}$, dotted ones for $\beta = 10^{-3}$. The upper (lower) resonant curve is obtained for a force carrier of mass $m_\phi = 1$ GeV (90 GeV). The upper (lower) dotted, solid and dashed curves correspond to the upper bounds for EGB Model I (Model II) derived from WIMPs annihilating in the high latitude galactic halo in $\mu^+\mu^-$, $b\bar{b}$, $\tau^+\tau^-$, respectively (see Fig. 3.)

DM particles, since they are responsible of the primordial inhomogeneities. The complete decoupling of DM particles from the thermal bath happens later with respect to the freeze-out temperature T_f, at a temperature of kinetic decoupling T_{kd}, because scattering events with SM particles keep the WIMPs close to thermal equilibrium. For $T \leq T_{kd}$, free-streaming and acoustic oscillations compete to damp the power spectrum of matter density fluctuations, which sets in turn the mass M_c of primordial DM structures [72–75]. For very small values of M_c, the details of the QCD phase transition could further slightly damp the actual cutoff mass [76]. In general, however, both the thermal and kinematic decouplings from cosmic plasma are heavily linked to the WIMP nature and interactions with SM particles. The velocity dispersion of the first protohalos that collapse at redshift z_C is estimated to be very small ($\beta \sim 10^{-8}$) [71]. Therefore, models for $\langle\sigma v\rangle$ depending on the inverse of v predict a boosted flux of DM annihilation products. The photons arising from WIMP annihilations in very early halos can freely propagate with their energy redshifting and reach the Earth in the range $\sim$ keV - TeV, while photons emitted out of this transparency window are absorbed by the intergalactic medium.

The $1/v$ enhancement of the annihilation cross section may be simply parameterized by writing [71]:

$$\langle\sigma v\rangle = \langle\sigma v\rangle_0 \frac{c}{v} \ \text{cm}^3/\text{s}. \tag{9}$$

The energy density in photons today from WIMP annihilation in the primordial halos can be theoretically predicted by:

$$\rho_\gamma = 5.28{\cdot}10^6 \left(\frac{M_c}{M_\oplus}\right)^{-1/3} \langle\sigma v\rangle_0 B_{2.6} \left(\frac{m_\chi}{\text{TeV}}\right)^{-1} \text{GeVcm}^{-3}, \tag{10}$$

where the cosmological boost factor B, normalized to 2.6 ($B_{2.6} = B/2.6$) takes into account that the DM is distributed according to a Navarro-Frenk-White (NFW) density profile with the lowest concentration parameter [71]. Eq. (10) can be compared with the experimental photon density inferred for the Fermi-LAT EGB [7] and for our two EGB models derived in Sect. II A, which is obtained by integrating the photon flux on the Fermi-LAT energy range (100 MeV - 100 GeV). We obtain:

$$\rho_\gamma \simeq 6.62{\cdot}10^{-16} \left(\frac{E_\gamma}{\text{GeV}}\right)^{-0.41} \text{GeV cm}^{-3} \ (\text{Fermi}-\text{LAT}) \tag{11}$$

$$\rho_\gamma \simeq 5.65 \cdot 10^{-16} \left(\frac{E_\gamma}{\text{GeV}}\right)^{-0.41} \text{GeV cm}^{-3} \ (\text{Model I}) \tag{12}$$

$$\rho_\gamma \simeq 4.5 \cdot 10^{-16} \left(\frac{E_\gamma}{\text{GeV}}\right)^{-0.46} \text{GeV cm}^{-3} \tag{13}$$

$$(\text{Model II}, \text{E}_\gamma > 8 \text{ GeV})$$

We constrain $\langle\sigma v\rangle_0$ by comparison of the theoretical expression 10 with the experimental γ-ray density. The results are displayed in Fig. 5 as a function of the WIMP mass. The three central lines bound the $\langle\sigma v\rangle_0$ (Eq. (9)) parameter from Fermi-LAT photon density given in Eq. (11), Eq. (12) and Eq. (14) respectively, from top to bottom, when $M_c = M_\oplus$. The upper (dotted) and the lower (dashed) bounds are derived for Model II when $M_c = 10^2 M_\oplus$ (upper) and $10^{-2} M_\oplus$ (lower). The bounds on $\langle\sigma v\rangle_0$ are strong: for WIMP masses below 100 GeV it is forced to be $< 10^{-33}$ cm^3/s. Upper bounds grow to $< 10^{-32}$ cm^3/s for $m_\chi \simeq 1$ TeV and sets to $< 10^{-31}$ cm^3/s at 10 TeV. We make notice that they are more stringent than limits obtained from primordial light elements abundance and CMB anisotropies [77] and significantly improve the bounds of Ref. [71].

The 1/v behaviour of the $\langle\sigma v\rangle$ may be identified with the Sommerfeld effect for velocities $\beta \gg (m_\phi/m_\chi)^{1/2}$ [62]. For lower velocities, as are the ones typical for protohalos, the series of resonances appears (see Sect. III C) and the Sommerfeld enhancement S behaves as $1/v^2$ close to the peaks. In this case, the upper bounds on the annihilation cross section may be obtained by rescaling $\langle\sigma v\rangle$=$\langle\sigma v\rangle_0$S with a factor $1/\beta \cdot m_\phi/m_\chi$. From Eqs. 10 - 14 it is straightforward to notice that the bounds on a Sommerfeld enhanced $\langle\sigma v\rangle$ derived from a overproduction of γ-rays in protohalos, are much weaker than the ones imposed by annihilation in the high-latitude galactic halo.

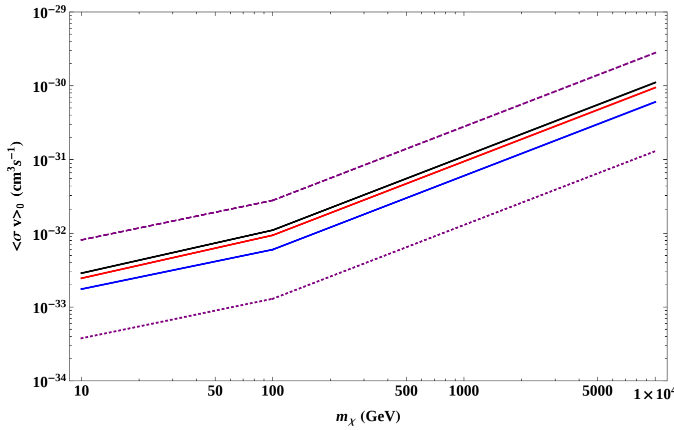

FIG. 5: Bounds on $\langle \sigma v \rangle_0$ from Eq. (9), as a function of the DM mass. The central three bounds are obtained for $M_c = M_\oplus$, and from Eqs. (11) (black line), (12) (red line) and (14) (blue line) respectively, from top to bottom. The upper (lower) purple lines are derived from Eq. (14) for Model II EGB and $M_c = 10^2 M_\oplus (10^{-2} M_\oplus)$.

IV. CONCLUSIONS

The γ-ray EGB measured by Fermi-LAT [7] likely includes contributions from galactic and extragalactic *unresolved* sources. We have explored possible non-negligible diffuse contributions from unresolved blazars, MSPs, star-forming galaxies and UHECRs. Lead by a conservative attitude, we have considered the minimal contribution for all sources, and neglected those objects whose high latitude flux is not excluded to be less than 1% of Fermi-LAT EGB. Two residual EGB fluxes have been derived by subtraction of the additional fluxes from the Fermi-LAT EGB: Model I is obtained after the subtraction of unresolved BL Lacs, FSRQs and galactic MSPs, while Model II is the residual flux after the further subtraction of star-forming galaxies and UHECRs.
From our new residual EGB fluxes, we have set upper limits on the DM annihilation cross section into γ-rays. A conservative upper bound on $\langle \sigma v \rangle$ is derived by assuming that the Model I and II EGB are entirely due to WIMPs pair-annihilating in the halo of our Galaxy. Values for $\langle \sigma v \rangle \gtrsim 10^{-25}$ cm^3/s are strongly excluded for $m_\chi \simeq 10$ GeV, while for $m_\chi \simeq 100$ GeV (1 TeV) the annihilation rate is bounded to $3 \cdot 10^{-25}$ cm^3/s (10^{-24} cm^3/s). This results holds for DM annihilating into $b\bar{b}$. Stronger limits below m_χ= 1 TeV are derived for annihilation into the leptonic τ annihilating channel, while for the μ channel the limits are close to the $b\bar{b}$ below m_χ= 100 GeV, and weaker above this mass. Annihilation into leptons is therefore excluded at a level which strongly disfavours the interpretation of cosmic positron fraction data in terms of leptophilic DM with small cosmological boost factors. The latter boost factors are in turns strongly limited by antiproton data [8].
The bounds on $\langle \sigma v \rangle$ have been interpreted in terms of Sommerfeld enhancement of the annihilation cross section. A Sommerfeld enhancement due to a force carrier of $m_\phi < 1$ GeV ($\alpha = \frac{1}{4\pi}$) is strongly excluded by Model I and II for the Fermi-LAT EGB data. For a massive force carrier (90 GeV) only the resonant peaks above the TeV mass are excluded. High latitude γ-ray observations interpreted as due to DM annihilation in the Milky Way halo bound the Sommerfeld enhancement of the annihilation cross section to a factor of 3-10-50-200 for m_χ=10-100-1000-5000 GeV, respectively, and in case an annihilation into light quarks occurs. For $m_\chi \lesssim$ 6-700 GeV these limits are reduced by a factor of few for the pure $\tau^+\tau^-$ annihilation channel. In case a Yukawa-like potential describes this non-relativistic quantum effect, a force carrier heavier than 1 GeV is definitely required.
Finally, we have explored the possibility that the residual γ-ray EGB is entirely due to cosmological annihilation of DM in protohalos at high redshift. Within the hypothesis that $\langle \sigma v \rangle$ is inversely proportional to the WIMP velocity, very severe limits are derived for the velocity-independent part of the annihilation cross section, depending on the protohalo mass.

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