Particle dark matter searches outside the Local neighborhood

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If dark matter (DM) is composed by particles which are non-gravitationally coupled to ordinary matter, their annihilations or decays in cosmic structures can result in detectable radiation. We show that the most powerful technique to detect a particle DM signal outside the Local Group is to study the angular cross-correlation of non-gravitational signals with low-redshift gravitational probes. This method allows to enhance signal-to-noise from the regions of the Universe where the DM-induced emission is preferentially generated. We demonstrate the power of this approach by focusing on GeV-TeV DM and on the recent cross-correlation analysis between the 2MASS galaxy catalogue and the Fermi-LAT gamma-ray maps. We show that this technique is more sensitive than other extragalactic gamma-ray probes, such as the energy spectrum and angular autocorrelation of the extragalactic background, and emission from clusters of galaxies. Intriguingly, we find that the measured cross-correlation can be well fitted by a DM component, with thermal annihilation cross section and mass between 10 and 100 GeV, depending on the small-scale DM properties and gamma-ray production mechanism. This solicits further data collection and dedicated analyses.

I. INTRODUCTION

The origin of cosmic structures is well understood in terms of evolution of matter perturbations arising after the inflationary period. Inhomogeneities starting off with higher-than-average density grow through gravitational instability. DM is a necessary ingredient to the process, as it provides the potential-wells where standard matter is accreted after decoupling and protohalos form. As structure formation evolves, DM halos of increasing size form in a bottom-up fashion.

If DM is in form of particles which exhibit non-gravitational couplings to ordinary matter, a certain level of emitted radiation is expected. Photons can be produced from interactions of DM with the ambient medium (e.g., through scatterings) or from DM annihilation or decay by means of direct emission or through the production of intermediate particles. The non-gravitational signal associated to decay is proportional to the DM density: it is stronger at low redshift, because the produced radiation is diluted by the expansion of the Universe more rapidly than its source, i.e. the DM particle density. The DM annihilation signal, which is proportional to the density squared, is also peaked at low redshift since the density contrast associated to cosmic structures grows nonlinearly.

DM constitutes the backbone of all cosmic structures and DM halos represent, collectively, a potential source of DM decay or annihilation signals. This means that even if the radiation originating from DM annihilations or decays in a single halo is too faint to be detected, their cumulative signal and its spatial coherence could be. In addition, since the DM signal is expected to peak at $z < 0.3$, it can be separated by more mundane astrophysical processes that typically trace the star formation history and peak at higher redshifts.

To increase the sensitivity to non-gravitational DM sources one needs to isolate the annihilation/decay signal produced at low redshift. An effective way to filter out any signal that is not associated to DM-dominated structures or that is originated at high redshift is to cross-correlate the radiation field with bona fide low-redshift DM tracers [1–7]. In the following, we adopt this approach in the specific and yet very relevant framework of weakly interacting massive particles (WIMP) that may either annihilate or decay. We will use the results of the cross-correlation analysis between $\gamma$-ray maps from Fermi-LAT [8] and the 2MASS catalogue of relatively nearby galaxies [9] presented in [10].

II. DATA AND MODELS

The cross angular power spectrum (CAPS) between the unresolved $\gamma$-ray sky observed by Fermi-LAT and the
distribution of 2MASS galaxies can be written as \[3\]:

\[ C_\ell^{(\gamma g)} = \int \frac{d\chi}{\chi} W_\gamma(\chi) W_g(\chi) P_{\gamma g} (k = \ell / \chi, \chi) , \] (1)

where \( \chi(z) \) denotes the radial comoving distance, \( W_\gamma(\chi) \) represent the window functions described below, \( P_{\gamma g}(k, z) \) is the three-dimensional cross power spectrum (PS), \( k \) is the modulus of the wavenumber, and \( \ell \) is the multipole. Indices \( \gamma \) and \( g \) refer to \( \gamma \)-ray emitters and extragalactic sources in 2MASS, respectively. In Eq. (1) we used the Limber approximation [11], since \( P_{\gamma g} \) varies (relatively) slowly with \( k \).

The (differential in energy) window function for \( \gamma \)-ray emission from DM annihilation \( W_\gamma(z) \) is [3]:

\[ W_\gamma^a(z) = \frac{\Omega_{\Delta DM} c^2}{8\pi m_{DM}^2} (1 + z)^3 \Delta^2(z) \frac{dN_a}{dE_\gamma} e^{-\tau(z, E_\gamma(z))}, \] (2)

where \( \Omega_{\Delta DM} \) is the DM mean density in units of the critical density \( \rho_c \), \( \Delta^2(z) \) is the clumping factor, \( m_{DM} \) is the mass of the DM particles, and \( \langle \sigma v \rangle \) denotes the velocity-averaged annihilation rate. \( dN_a/dE_\gamma \) indicates the number of photons produced per annihilation and determines the \( \gamma \)-ray energy spectrum. The exponential damping quantifies the absorption due to extra-galactic background light [13].

The window function for DM decay is [3]:

\[ W_\gamma^d(z) = \frac{\Omega_{\Delta DM} c^2}{4\pi m_{\Delta DM}} \frac{dN_d}{dE_\gamma} e^{-\tau(z, E_\gamma(z))} , \] (3)

where \( \Gamma_d = 1/\tau_d \) is the DM decay rate.

The window function of 2MASS galaxies is \( W_g(z) \equiv H(z)/c dN_g/dz \) and their redshift distribution \( dN_g/dz \) is [14]:

\[ \frac{dN_g}{dz}(z) = \frac{\beta}{\Gamma(m+1)} \frac{z^m}{z_0^{m+\beta}} \exp \left[ -\left( \frac{z}{z_0} \right)^\beta \right] , \] (4)

with \( m = 1.90, \beta = 1.75 \) and \( z_0 = 0.07 \).

The PS \( P_{\gamma g} \) in Eq. (1) is computed within the halo-model framework, as the sum of a one-halo plus a two-halo terms. For more details, see [3, 7]. Both the PS and the clumping factor \( \Delta^2(z) \) in Eq. (2) depend on a number of DM properties: the halo mass function, that we take from Ref. [15], the halo density profile, for which we assume a Navarro-Frenk-White model [16], the minimum halo mass, that we set equal to \( 10^{-6} M_\odot \), and the halo mass-concentration relation \( c(M, z) \), that we adopt from Ref. [17]. The theoretical uncertainty of these quantities is rather small for halos larger than \( 10^{10} M_\odot \), because they can be constrained by observations and simulations. Since the DM decay signal is mainly contributed by large structures, the theoretical predictions are relatively robust. This is not the case for the annihilation signal which is preferentially produced in small halos and in substructures within large halos. Consequently, theoretical uncertainties on the annihilation signal are larger. For the subhalo contribution we consider two scenarios (LOW and HIGH) to bracket theoretical uncertainty. The LOW case follows the model of Ref. [18] (see their Eq. (2), with a subhalo mass function \( dn/dM_{\text{sub}} \propto M_{\text{sub}}^{-2} \)). The HIGH scenario is taken from Ref. [19], with the halo mass-concentration relation extrapolated down to low masses as a power law.

In our CAPS model (Eq. 1), we add a constant term \( C_{1h} \) (one-halo correction term) to correct for possible unaccounted correlations at very small-scales, within the Fermi-LAT Point Spread Function (PSF). The value of \( C_{1h} \) will be determined by fitting the data, and we anticipate that we find a \( C_{1h} \) value compatible with zero. Thus, the inclusion of this term does not change significantly the results. For an extensive discussion on this term, see Refs. [5, 7].
The measured CAPS $\hat{C}_\ell^{(\gamma g)}$ is a convolution of the true CAPS and the effective beam window function $W_\ell^B$ that accounts for the PSF of the instrument and the pixelization of the $\gamma$-ray map. Both quantities depend on energy. We use the $W_\ell^B$ derived in Ref. [10] and model the observed spectrum as $\hat{C}_\ell^{(\gamma g)} = W_\ell^B C_\ell^{(\gamma g)}$.

In the following, we shall consider the angular cross correlation function (CCF) rather than the spectrum. To model the CCF, we Legendre-transform the CAPS:

$$CCF^{(\gamma g)}(\theta) = \sum_\ell \frac{2\ell + 1}{4\pi} \hat{C}_\ell^{(\gamma g)} P_\ell[\cos(\theta)],$$

where $\theta$ is the angular separation and $P_\ell$ are the Legendre polynomials.

To compare model and observed CCFs, we estimate the $\chi^2$ difference defined as:

$$\chi^2 = \sum_{n=1}^{3} \sum_{\theta_i, \theta_j} (d^n_{\theta_i} - m^n_{\theta_i}(A)) [C^{-1}_{n\theta_i, \theta_j} (d^n_{\theta_j} - m^n_{\theta_j}(A)),$$

where $m$ and $d$ indicate model and data, $n$ identifies each one of the three overlapping energy ranges considered ($E > 0.5, 1$, and $10$ GeV) and the indices $\theta_i$ and $\theta_j$ run over 10 angular bins logarithmically spaced between $\theta = 0.1^\circ$ and $100^\circ$. $C^{-1}_{n\theta_i, \theta_j}$ is the covariance matrix that quantifies the errors of the data and their covariance among the angular bins. Data and covariance matrix are taken from Ref. [10]. The parameter vector for annihilating DM is $A = [m_{DM}, \langle \sigma v \rangle, C_{1h}]$, whereas for the decaying DM is $A = [m_{DM}, \tau_d, C_{1h}]$.

### III. RESULTS

In Fig. 1 we show a comparison between the measured CCF in one of the considered energy bins ($E > 500$ MeV) and the best fitting annihilating and decaying DM models obtained from the analysis discussed below. Error bars are given by the diagonal elements of the covariance matrix. DM models fit the measured CCF remarkably well (for best fitting model, $\chi^2_{BF} = 16.7$ with 26 d.o.f.). It is also noteworthy that the level of annihilation/decay rate provides a minor contribution to the Isotropic Gamma Ray Background (IGRB) measured by the Fermi-LAT [20], as shown in the inset of the figure. This implies that the cross-correlation technique can detect a DM signals too faint to show up in the total intensity measurement (for a review of the IGRB properties, see Ref. [21]).

The preferred regions of DM mass and annihilation/decay rate for various final states are shown in Fig. 2. Contours are drawn at $1\sigma$ and $2\sigma$ confidence levels and marginalizing over $C_{1h}$. Note that, although we use only three energy bins, they are sufficient to constrain the DM mass which induces a small but characteristic signature in the energy spectrum. In the low scenario the $1\sigma$ region lies just above the thermal annihilation rate $\langle \sigma v \rangle = 3 \times 10^{-26}$ cm$^3$ s$^{-1}$. In the high case, the DM signal increases by a factor of $\sim 10$ and consequently regions shift down by one order of magnitude. Therefore, given the current uncertainty in modeling DM structures we conclude that the thermal cross section is well within the allowed regions for $m_{DM} \lesssim 200$ GeV.

This cross-correlation measurement can alternatively be used to derive $95\%$ C.L. upper bounds on the annihilation/decay rate. We stress that these bounds are con-
schemes are shown for WIMPs annihilating into

FIG. 3. Left: 95% C.L. upper limits on the DM annihilation rate as a function of its mass. Both high and low clustering schemes are shown for WIMP’s annihilating into $b\bar{b}$ (with the impact of different energy bins reported for the latter case). Other final states of annihilation ($\mu^+\mu^-$, $\tau^+\tau^-$, $W^+W^-$) are shown in the low scenario only, for clarity. Right: 95% C.L. lower limits on the DM lifetime as a function of its mass, for different final states of decay.

Conservative and robust, since we assume here that DM is the only source of the $\gamma$-ray signal, without introducing additional assumptions on astrophysical components which would make the constraints stronger but also more model dependent. The 95% C.L. upper bounds on the WIMP annihilation (decay) rate as a function of WIMP mass are shown in the left-hand (right-hand) panel of Fig. 3. For $b\bar{b}$ and $\tau^+\tau^-$ final states, the thermal annihilation rate is excluded for masses below 10 (100) GeV in the low (high) scenario. In the case of $\mu^+\mu^-$, the bounds degrade by about one order of magnitude.

In Fig. 4 we compare the sensitivity of our cross correlation method with that of other extragalactic $\gamma$-ray probes. We focus on these probes since they are similarly affected by uncertainties in modeling DM halo and subhalos properties. This allows to compare various techniques in a homogeneous and robust way, something that cannot be done with local DM tracers (Galactic regions, dwarf galaxies) or early Universe probes, which have different systematic uncertainties. For illustrative purposes, we selected the low substructure scheme and $b\bar{b}$ final states case. We verified that different choices provide little differences and the results are robust to both the DM clustering model and the annihilation/decay channel. We consider again the simplest case (where most conservative bounds can be derived), in which the astrophysical contribution is set to zero in all observables and only DM is contributing as $\gamma$-ray source.

The bound corresponding to the IGRB energy spectrum has been derived using the IGRB estimated by the Fermi-LAT Collaboration [20] and adding up in quadrature statistical and systematic errors given in their Table 3. For the autocorrelation bound, we considered the angular spectrum estimated in four energy bins in Ref. [22].

IV. CONCLUSIONS

We compared the predicted angular cross-correlation between the $\gamma$-ray emission induced by DM annihilation or decay and the distribution of 2MASS galaxies with the measured CCF between these objects and the Fermi-LAT $\gamma$-ray maps.

The contribution of astrophysical sources to the IGRB is assumed to be subdominant at low redshift and not included in the model prediction, so to derive conservative bounds on DM. We found that in the low [18] and high [19] scenarios the “thermal” annihilation cross-section is

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FIG. 4. Ratio $\xi = \langle \sigma v \rangle_i / \langle \sigma v \rangle_X$ (in the annihilating DM case) and $\xi = \frac{\tau_i}{\tau_X}$ (in the decaying DM case) between the 95% C.L. bounds derived with method discussed in this work (cross-correlation of $\gamma$-rays with 2MASS catalogue, labeled with $X$) and from other extragalactic $\gamma$-ray probes ($i$ stands for total IGRB intensity, angular autocorrelation or clusters). The plot refers to the $b\bar{b}$ final state and (for the annihilating DM case) the low substructure scheme.

excluded at 95% C.L. up to DM masses of 10 and 100 GeV, respectively, for final state of annihilation into $b\bar{b}$ and $\tau^+\tau^-$. We demonstrated that the cross-correlation technique is significantly more sensitive to a DM signal than all other extragalactic $\gamma$-ray probes used so far. This was done by comparing the bounds of our cross-correlation analysis with the most recent results from IGRB, angular autocorrelation and clusters, finding an improvement of a factor ranging from a few up to 100 for both annihilating and decaying DM.

We showed that a WIMP DM contribution can fully explain the observed cross correlation. A canonical WIMP with a mass in the 10–100 GeV range, annihilation rate around the thermal value, and realistic model for DM halo and sub-halo properties reproduce both size and shape of the measured angular cross-correlation. This intriguing possibility deserves further investigation within a more comprehensive framework that include contributions from astrophysical sources and additional data.

Future investigation employing the Pass8 release of Fermi-LAT and forthcoming surveys at low/intermediate redshift [31] will therefore provide remarkable insights to the particle DM quest.

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