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# Detecting particle dark matter signatures by cross-correlating $\gamma$-ray anisotropies with weak lensing

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**Abstract.** The underlying nature of dark matter still represents one of the fundamental questions in contemporary cosmology. Although observations well agree with its description in terms of a new fundamental particle, neither direct nor indirect signatures of its particle nature have been detected so far, despite a strong experimental effort. Similarly, particle accelerators have hitherto failed at producing dark matter particles in collider physics experiments. Here, we illustrate how the cross-correlation between anisotropies in the diffuse $\gamma$-ray background and weak gravitational lensing effects represents a novel promising way in the quest of detecting particle dark matter signatures.

## 1. Introduction

Weakly Interacting Massive Particles (WIMPs), loosely characterised by a mass of the order of the GeV–TeV and by weak-scale interactions, are probably the most well-studied candidate to the rôle of particles of dark matter. This has happened because many extensions of the Standard Model of Particle Physics predict the existence of WIMPs. Moreover, it is quite natural for WIMPs to reproduce the dark matter density observed e.g. by *Planck* [1]. WIMP dark matter can either decay or annihilate into Standard Model particles, including $\gamma$ rays. The specific mechanisms of $\gamma$-ray emission depend on the dark matter candidate considered (see e.g. for a review [2]). They include: *i*) direct production of monochromatic $\gamma$ rays; *ii*) decay of neutral pions due to the hadronisation of the primary annihilation/decay products; *iii*) final state radiation; and *iv*) secondary emission by bremsstrahlung or inverse Compton scattering of primarily produced leptons. Hitherto, there is no observational confirmation of the existence of WIMPs. Since no dark matter source has been unambiguously detected so far, the entire WIMP-induced $\gamma$-ray emission may be unresolved and, thus, it contributes to the diffuse $\gamma$-ray background (DGRB).

## 2. Dark Matter and $\gamma$ Rays

The DGRB is the radiation remaining after resolved sources and Galactic foregrounds are removed from the total $\gamma$-ray emission [3]. Unresolved astrophysical sources are populations of $\gamma$-ray emitters, such as blazars, misaligned AGNs (MAGNs) or star-forming galaxies (SFGs),

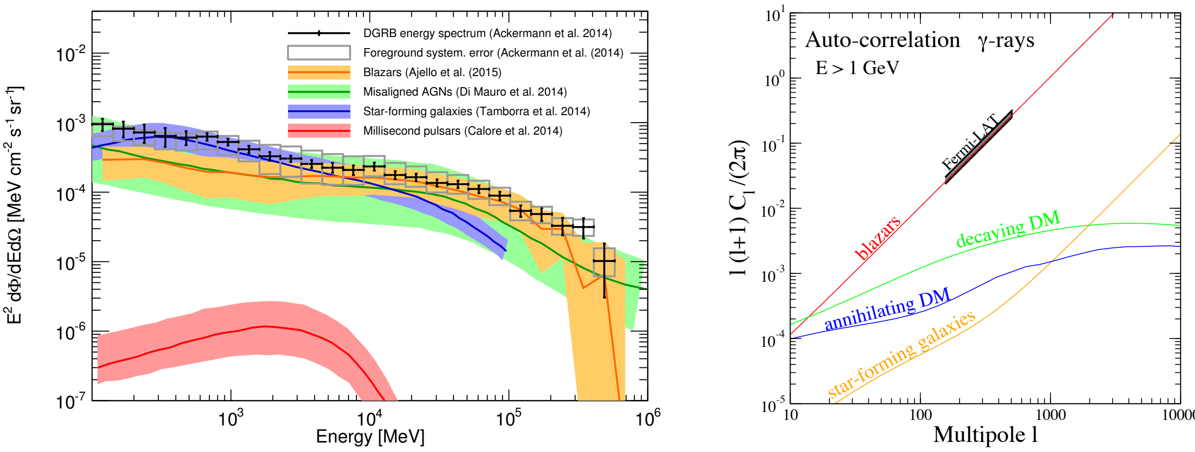


**Figure 1.** *Left panel from [3]:* The energy spectrum of the DGRB (black points) as recently measured by *Fermi* [4]. Grey boxes around each data point denote the uncertainty associated with the Galactic diffuse emission. Solid lines show the expected $\gamma$-ray emission from unresolved sources for different astrophysical populations: blazars (orange); MAGNs (green); SFGs (blue); and milli-second pulsars (red). Colour bands represent the corresponding uncertainties on the emission of each population. *Right panel from [6]:* $\gamma$-ray angular power spectrum at $E_\gamma > 1$ GeV for various contributions to the diffuse $\gamma$-ray background (coloured curves), including two viable WIMP dark matter candidates. Auto-correlation from *Fermi* data [5] (black band, left panel) favours an explanation in terms of unresolved astrophysical sources.

which cannot be detected as individual objects, but whose cumulative emission nonetheless contributes to the DGRB. Alongside such unresolved astrophysical sources, annihilations or decays of dark matter particles in principle also represent another component of the DGRB. The most recent measurements of the DGRB intensity performed by *Fermi* [4] showed that the upper limits that can be extracted on dark matter are, at least, competitive with other indirect detection strategies, as for example the observation of the dwarf Spheroidal galaxies. However, no relevant spectral features can be seen in the DGRB energy spectrum, which in turn appears to be well-described by a combination of various populations of unresolved astrophysical sources (see Fig. 1, left panel).

Other pieces of information can be extracted from the DGRB. Being contributed by a large number of faint sources at any scale, it is indeed intrinsically anisotropic. These anisotropies contain information on the distribution and type of $\gamma$-ray sources, and can be studied in terms of their statistical properties. The level of anisotropy of the DGRB intensity field has been measured by *Fermi* Collaboration [5], finding that the $\gamma$-ray angular power spectrum is compatible with emission from blazars just below detection threshold. This can be appreciated in the right panel of Fig. 1, where the auto-correlation angular power spectrum of DGRB anisotropies, $C_\ell^{\gamma\gamma}$, is shown for the two most important populations of unresolved astrophysical $\gamma$-ray emitters, as well as a viable decaying and an annihilating WIMP dark matter scenario, see [6] for details.

## 3. $\gamma$ Rays and Weak Gravitational Lensing

### *3.1. $\gamma$ Rays and Cosmic Shear*

Since the DGRB comprises the unresolved $\gamma$-ray emission up to cosmological distances, it is expected to correlate with any observable that traces the cosmic large-scale structure. This can occur for instance with the distribution of galaxies e.g. [7]. A major advantage of this

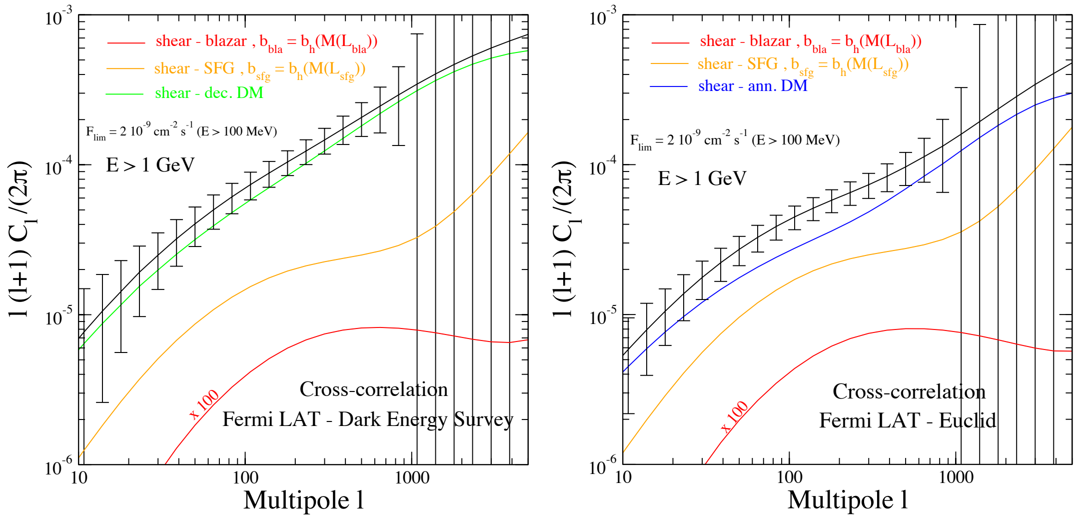


**Figure 2.** Forecasts for the combination of $\gamma$-ray from *Fermi* with cosmic shear from the DES (left panel) or *Euclid* (right panel) shows a total signal (black curves) not only detectable, but with a significantly subdominant contribution from astrophysics, thus leaving room for the detection of WIMPs from [6].

is that, if studies on the nature of DGRB based on its intensity energy spectrum or auto-correlation angular power spectrum are limited by the contamination from the Milky Ways emission, the cross-correlation with the large-scale structure is particularly informative since it will not be affected by this uncertainty. Recently, the first detection of a cross-correlation with the distribution of galaxies in four galaxy catalogues has been reported and analysed in terms of WIMP dark matter [8, 9, 10].

Camera et al. [6] has for the first time proposed to cross-correlate anisotropies in the DGRB with the weak lensing effect of cosmic shear. Cosmic shear and convergence—usually indicated with $\gamma$ and $\kappa$—are the two main weak lensing effects [11]. The former produces a coherent distortion in background galaxy images that results into an additional ellipticity to the intrinsic shape of the galaxies. By measuring correlations in background galaxy ellipticities over the sky, we can infer the amount of intervening matter along the line of sight, thus effectively mapping the large-scale distribution of matter in the Universe. It is straightforward to see the potential of this method in Fig. 2: the black curves depict the forecast signals for the cross-correlation of *Fermi* $\gamma$ rays with cosmic shear from, respectively, the Dark Energy Survey (DES) [12, 13] and the forthcoming European Space Agency's satellite *Euclid* [14]. The cross-correlation is not only detectable, as the error bars illustrate, but will most importantly have a contribution from astrophysical sources (red and yellow curves) much sub-dominant with respect to that of $\gamma$ rays from annihilating/decaying dark matter (blue and green curves).

More recently, Camera et al. [15] demonstrated that the cross-correlation signal is even more informative, if the full redshift and energy information is exploited. Results from such 'tomographic-spectral' approach can be appreciated by looking at Fig. 3. The left panel depicts forecast $1\sigma$ joint marginal error contours from $C_\ell^{\gamma\kappa}$ measured by *Euclid* and an envisaged successor of *Fermi* (dubbed *'Fermissimo'*) in the $m_{\rm DM} - \langle\sigma_a v\rangle$ parameter plane. The benchmark scenario is a WIMP with thermal cross-section and mass of 100 GeV. Different colours show the effect of redshift and/or energy binning, as compared to the unbinned case (magenta lines).In the right panel, the various curves show, as a function of the WIMP mass, the expected improvement in the $2\sigma$ bounds on the WIMP annihilation cross-section yielded by the use of $C_\ell^{\gamma\kappa}$, the cross-correlation angular power spectrum between *Fermi* 10-year $\gamma$-ray data and cosmic shear from

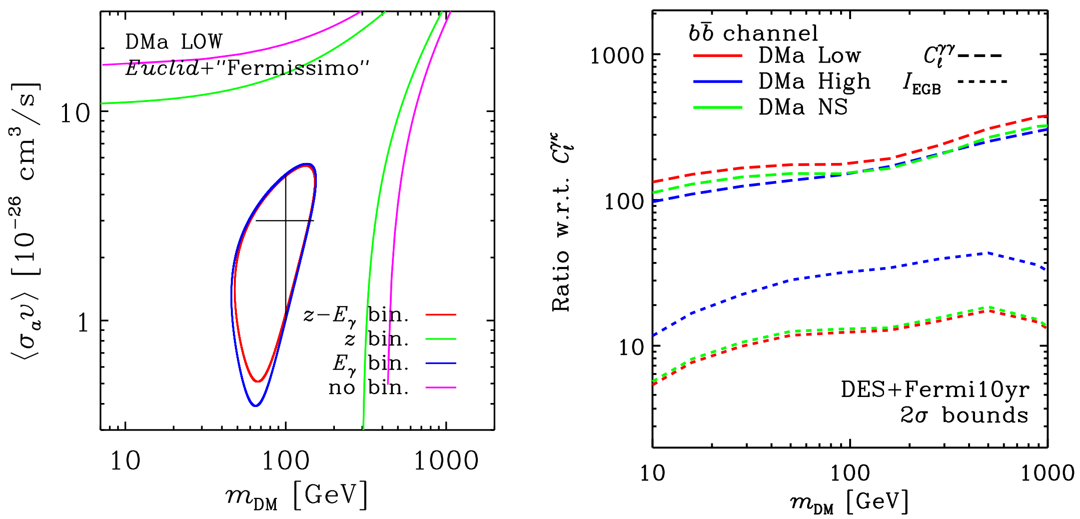


**Figure 3.** *Left panel from [15]:* Forecast $1\sigma$ joint marginal error contours from $C_\ell^{\gamma\kappa}$ measured by *Euclid* and an envisaged successor of *Fermi* (dubbed *'Fermissimo'*) in the $m_{\rm DM} - \langle\sigma_a v\rangle$ parameter plane for a WIMP with thermal cross-section and mass of 100 GeV. Different colours show the effect of redshift and/or energy binning, as compared to the unbinned case (magenta lines). *Right panel from [15]:* Comparison between the $2\sigma$ bounds on WIMP annihilation cross-section, $\langle\sigma_a v\rangle$, versus WIMP mass, $m_{\rm DM}$, that are expected with the $\gamma$-ray and cosmic shear cross-correlation, $C_\ell^{\gamma\kappa}$, with respect to those from the $\gamma$-ray auto-correlation, $C_\ell^{\gamma\gamma}$, and the $\gamma$-ray total intensity, $I_{\rm EGB}$.

the DES, compared to the use of either the $\gamma$-ray total intensity, $I_{\rm EGB}$, or the auto-correlation of DGRB anisotropies, $C_\ell^{\gamma\gamma}$. The combination of cosmic shear and $\gamma$ rays is 10 to 300 times more efficacious in putting bounds on dark matter particle physics properties, if no signal were to be found. Note that such bounds are highly complementary with other strategies for particle dark matter searches.

### *3.2. $\gamma$ Rays and CMB Lensing*

The first attempt to measure such a cross-correlation between the DGRB and the cosmic shear was attempted in with the data of the Canada-France-Hawaii Telescope Lensing Survey [16]. However, the survey small sky coverage ($\sim$154 sq. deg.) was not enough to reach a detection. Instead, Fig. 4 shows the first $> 3\sigma$ evidence of a cross-correlation between DGRB anisotropies and the lensing of the CMB [17]. Although CMB lensing is not the optimal probe for dark matter, this result nevertheless demonstrates that the proposed cross-correlation technique can be proficiently adopted for studying the DGRB.

## 4. Conclusions

The cross-correlation of anisotropies in the DGRB and the weak gravitational lensing of cosmic shear represent a novel, unique approach to quest of indirectly detecting WIMP signatures in the $\gamma$-ray sky. The potential of this method has been discussed at length [6, 15] and the first detection of the cross-correlation of $\gamma$-ray anisotropies and CMB lensing has been reported [17]. Now, the route ahead is to employ the technique with state-of-the-art cosmic shear data, such as that soon delivered by DES, as well as to plan synergies with future weak lensing surveys such as the *Euclid* satellite.

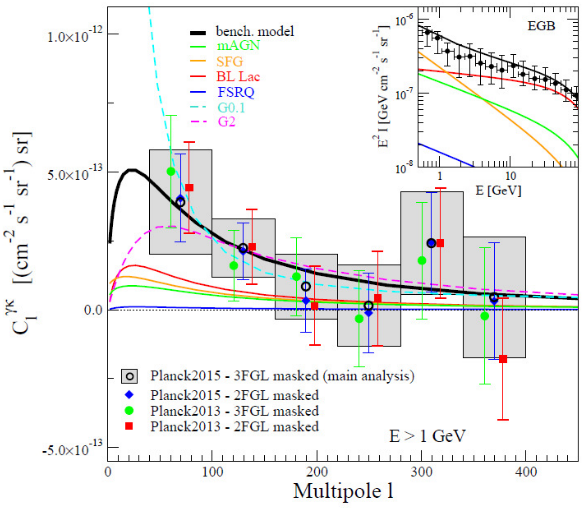


**Figure 4.** Cross-correlation angular power spectrum, $C_\ell^{\gamma\kappa}$, between DGRB anisotropies from Pass 7 *Fermi* data and *Planck* CMB lensing, as a function of the multipole, l, for $\gamma$-ray energies $E_\gamma > 1$ GeV. Four different analyses are shown, which combine two lensing maps (*Planck* 2013 and 2015 releases) and two $\gamma$-ray point-source masks (2FGL and 3FGL). The benchmark theoretical model (black curve) is the sum of contributions from various unresolved astrophysical $\gamma$-ray sources (coloured, solid curves). As a comparison, two generic models with Gaussian window functions normalised such as to provide the whole DGRB above 1 GeV and peaking at different redshifts (dashed lines) are also shown from from [17].

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## References

[1] Ade P *et al* (Planck) 2015 (*Preprint* arXiv:1502.01589)
[2] Bertone G, Hooper D and Silk J 2005 *Phys. Rept.* **405** 279–390 (*Preprint* arXiv:hep-ph/0404175)
[3] Fornasa M and Sánchez-Conde M A 2015 *Phys. Rept.* **598** 1–58 (*Preprint* arXiv:1502.02866)
[4] Ackermann M *et al* (Fermi-LAT) 2015 *JCAP* **1509** 008 (*Preprint* arXiv:1501.05464)
[5] Ackermann M *et al* (Fermi LAT Collaboration) 2012 *Phys. Rev.* **D85** 083007 (*Preprint* arXiv:1202.2856)
[6] Camera S, Fornasa M, Fornengo N and Regis M 2013 *Astrophys. J.* **771** L5 (*Preprint* arXiv:1212.5018)
[7] Ando S and Pavlidou V 2009 *Mon. Not. Roy. Astron. Soc.* **400** 2122 (*Preprint* arXiv:0908.3890)
[8] Xia J Q, Cuoco A, Branchini E and Viel M 2015 *Astrophys. J. Suppl.* **217** 15 (*Preprint* arXiv:1503.05918)
[9] Regis M, Xia J Q, Cuoco A, Branchini E, Fornengo N and Viel M 2015 *Phys. Rev. Lett.* **114** 241301 (*Preprint* arXiv:1503.05922)
[10] Cuoco A, Xia J Q, Regis M, Branchini E, Fornengo N and Viel M 2015 (*Preprint* arXiv:1506.01030)
[11] Bartelmann M and Schneider P 2001 *Phys. Rept.* **340** 291–472 (*Preprint* arXiv:astro-ph/9912508)
[12] The Dark Energy Survey Collaboration 2005 *ArXiv Astrophysics e-prints* (*Preprint* arXiv:astro-ph/0510346)
[13] Abbott T *et al* (DES) 2015 (*Preprint* arXiv:1507.05552)
[14] Laureijs R *et al* (Euclid Collaboration) 2011 *ESA-SRE* **12** (*Preprint* arXiv:1110.3193)
[15] Camera S, Fornasa M, Fornengo N and Regis M 2015 *JCAP* **1506** 029 (*Preprint* arXiv:1411.4651)
[16] Shirasaki M, Horiuchi S and Yoshida N 2014 *Phys. Rev.* **D90** 063502 (*Preprint* arXiv:1404.5503)
[17] Fornengo N, Perotto L, Regis M and Camera S 2015 *Astrophys. J.* **802** L1 (*Preprint* arXiv:1410.4997)