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A Novel Approach in the WIMP Quest: Cross-Correlation of Gamma-Ray Anisotropies and Cosmic Shear

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Abstract

We present the cross-correlation angular power spectrum of cosmic shear and gamma-rays produced by the annihilation/decay of Weakly Interacting Massive Particle (WIMP) dark matter (DM), and by astrophysical sources. We show that this observable can provide novel information on the composition of the Extra-galactic Gamma-ray Background (EGB), since the amplitude and shape of the cross-correlation signal depend on which class of sources is responsible for the gamma-ray emission. If the DM contribution to the EGB is significant (at least in a definite energy range), although compatible with current observational bounds, its strong correlation with the cosmic shear (since both signals peak at large halo masses) makes such signature potentially detectable by combining Fermi-LAT data with forthcoming galaxy surveys, like Dark Energy Survey and Euclid.

Keywords: dark matter - extragalactic gamma rays background - weak gravitational lensing.

1 Introduction

The presence of gravitational anomalies at different scales (galactic, cluster, large scale structure, and cosmological scales) is observationally well-established. However, it is not fully understood yet whether such anomalies are due to a new form of matter (i.e., dark matter (DM)) or to a new form of interaction (e.g., a modification of the laws of gravity). Currently, the DM solution represents the mainstream, mainly because there is no theory of gravity which can account for all the anomalies at different scales simultaneously. For example, MOND (Modified Newtonian Dynamics) is a theory stating that acceleration is not linearly proportional to gravitational force at small accelerations, and seems to be quite successful in explaining galactic rotation curves. However, it cannot explain cluster dynamics without the addition of some DM components. On the other hand, it is possible that we just haven't been good enough to build the proper extension to Newtonian and Einstein gravity. Moreover, if DM interacts only gravitationally with ordinary matter, the two classes of solution are hardly distinguishable.

One of the best ways to settle the issue would be to detect a non-gravitational signal of DM coming from the regions with gravitational anomalies. In this talk, we will present a novel strategy in this direction. In particular, if DM is made by weakly interacting massive particles (WIMPs), they have weak but non-negligible interactions with ordinary matter, and one of the predictions of the model is sizable fluxes of γ-rays from DM halos.

Both cosmic shear and cosmological gamma-ray emission stem from the presence of DM in the Universe: DM structures are responsible for the bending of light in the weak lensing regime and while γ-rays can be produced by astrophysical sources hosted by DM halos (i.e. star-forming galaxies (SFG) or active galactic nuclei (AGN)), DM itself may be a source of γ-rays, through its self annihilation or decay, depending on the properties of the DM particle. Those γ-rays emitted by DM should therefore have the potential to exhibit strong correlation with the gravitational lensing signal.

The most recent measurement of the EGB was performed by the Fermi-LAT telescope in Abdo et al. (2010)a, covering a range between 200 MeV and 100 GeV: the emission is obtained by subtracting the contribution of resolved sources (both point-like and extended) and the Galactic foreground (due to cosmic rays interaction with the interstellar medium) from the whole Fermi-LAT data. Unresolved astrophysical sources like blazars or radio galaxies contribute to the EGB but the exact amount of their contribution is still unknown.

The γ-rays produced by DM annihilation or decay can also contribute to EGB (e.g., Ullio et al. (2002)). However, the fact that the EGB energy spectrum is compatible with a power-law, without any evident spectral feature, suggests that DM cannot play a leading role in the whole energy range, see Abdo et al. (2010)b.

In the angular anisotropies of the EGB emission, the DM also plays a subdominant role: indeed, a detection of a significant auto-correlation angular PS has been recently reported in Ackermann et al. (2012) (for multipoles $\ell > 100$, which is the range of interest for our analysis, since there the contamination of the Galactic foreground can be neglected), but the features of such a signal (in particular its independence on multipole and energy) seem to indicate an interpretation in terms of blazars, Harding & Abazajian (2012).

Both cosmic shear and γ-ray emission depend on the large scale structure of the Universe: because this is what generates the lensing effect and because those same structures can produce γ-rays. Here we will show how to use the lensing signal in order to possibly disentangle a DM signal in the EGB. A detection of such cross-correlation would demonstrate that the weak lensing observables are indeed due to particle DM matter and not to possible modifications of General Relativity. This presentation is based on Camera et al. (2012).

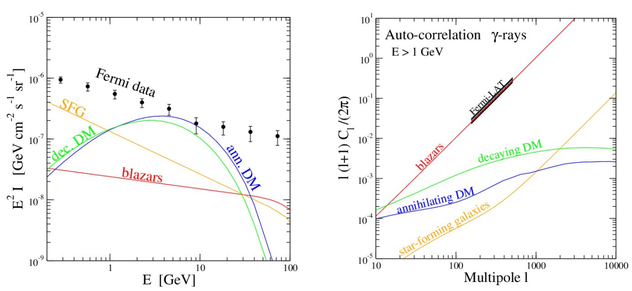

Figure 1: *Left*: EGB emission as a function of observed energy for the four extragalactic components described in the text. Data are from Abdo et al. (2010)a. *Right:* γ-ray angular PS at $E > 1$ GeV for the same models of the left panel. The observed angular PS is summarized by the black band from Ackermann et al. (2012). This figure is taken from Camera et al. (2012).

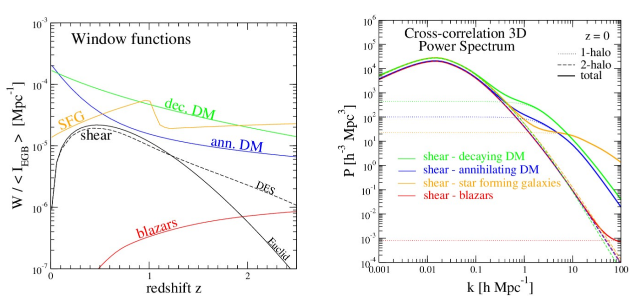

Figure 2: *Left*: Window functions vs. redshift. For γ-ray sources we consider the flux above 1 GeV normalized to the total EGB intensity measured by Fermi-LAT. *Right:* Three-dimensional PS of cross-correlation shear/γ-rays at $z = 0$. This figure is taken from Camera et al. (2012).

2 Theoretical Modeling

The source intensity along a given direction $\vec{n}$ can be written as:

$$I_g(\vec{n}) = \int d\chi\, g(\chi, \vec{n})\, \tilde{W}(\chi)\ , \tag{1}$$

where $\chi(z)$ is the radial comoving distance, g is the density field of the source, and $\tilde{W}$ is the window function (which does not depend on $\vec{n}$). We then define a normalized version $W = \langle g\rangle\, \tilde{W}$, so $\langle I_g\rangle = \int d\chi\, W(\chi)$. Expanding the intensity fluctuations of two source populations i and j in spherical harmonics, one can compute the cross-correlation angular PS (here in the dimensionless form):

$$C_\ell^{(ij)} = \frac{1}{\langle I_i\rangle\langle I_j\rangle} \int \frac{d\chi}{\chi^2} W_i(\chi)\, W_j(\chi) P_{ij}(k = \ell/\chi, \chi)\ . \tag{2}$$

The definition of the 3-dimensional PS P_{ij} is

$$\langle \hat{f}_{g_i}(\chi, \vec{k}) \hat{f}^*_{g_j}(\chi', \vec{k}')\rangle = (2\pi)^3 \delta^3(\vec{k} - \vec{k}') P_{ij}(k, \chi, \chi')\ , \tag{3}$$

where $f_g \equiv [g(\vec{x}|m, z)/\bar{g}(z) - 1]$ ($\hat{f}_g$ is its Fourier transform) and the Limber approximation ($k = \ell/\chi$) is assumed to hold. We consider the sources to be characterized by a parameter m (typically the mass), and $g(\vec{x}|m)$ is the density field of an object associated to m, while $\bar{g}(z) = \langle g(\vec{n}, z)\rangle$. P_{ij} can be computed following the so-called halo-model approach. The two-point correlation is given by the sum of two components, the 1-halo and 2-halo terms, i.e. $P_{ij} = P^{1h}_{ij} + P^{2h}_{ij}$, (Scherrer & Bertschinger (1991), Ando & Komatsu (2006)):

$$P^{1h}_{ij}(k) = \int dm\, \frac{dn}{dm} \hat{f}^*_i(k|m)\, \hat{f}_j(k|m) \tag{4}$$

$$P^{2h}_{ij}(k) = \left[\int dm_1\, \frac{dn}{dm_1} b_i(m_1) \hat{f}^*_i(k|m_1)\right] \times \left[\int dm_2\, \frac{dn}{dm_2} b_j(m_2) \hat{f}_j(k|m_2)\right] P^{\rm lin}(k) \tag{5}$$

where dn/dm is the number density distribution of sources, $P^{\rm lin}$ is the linear matter PS, and $b_i(m)$ is the linear bias between the object i and matter.

Note that the average of $\langle g\rangle$ is given by:

$$\bar{g}(z) = \langle g(\vec{n}, z)\rangle = \int dm\, \frac{dn}{dm} \int d^3\vec{x}\, g(\vec{x}|m, z)\ , \tag{6}$$

which implies that at small k (where $\hat{f} \sim \int d^3\vec{x}\, g(\vec{x}|m)/\bar{g}$) the terms in the square-brackets in Eq. (5) are ~ 1 (except in the case of a significant bias).

The 2-halo term is thus normalized to the standard linear matter PS at small k, which motivates the normalization of the window function introduced above.

We aim at cross-correlating the shear signal (source i in Eqs. (2–5)) with γ-rays emitted by DM, SFGs, and blazars (source j in Eqs. (2–5)).

3 Results

The above formalism can be applied to all the mentioned components, by considering the specific g, W, and dn/dm of each case. For the sake of clearness we will focus on a benchmark model for each component. They are described in Camera et al. (2012). In particular, we note that, although we take DM to provide a significant contribution of the EGB at $E \geq 1$ GeV in Fig. 1a, it is basically impossible to obtain an evidence for DM from the angular PS of γ-rays alone because the latter is dominated by the blazar contribution.

The contributions to the EGB and to the γ-ray auto-correlation APS of each components are shown in Fig. 1.

In Fig. 2 we show the ingredients of Eq. (2) for the computation of the shear/γ-ray cross-correlation angular PS: the window functions and 3D power spectra. The window function for the cosmic shear signal nicely overlaps with the DM window function, both for annihilating and decaying DM, while this happens only at intermediate redshifts for the SFG window function and only at high redshifts for the case of blazars. This suggests that a tomographic approach could be a powerful strategy to further disentangle different contributions in the angular PS (this will be explored in a forthcoming work, Camera et al. (in preparation)). The shear signal is stronger for larger DM masses. The same is true also for the γ-ray signal from DM and this fact gives a large 1-halo contribution which dominates in the range $k = 1-10\,h/\mathrm{Mpc}$ in Fig. 2b. Those wavenumbers correspond to $\ell \simeq 100 - 1000$. Galaxies have masses $\leq 10^{14} M_{\odot}$, thus they correlate with the shear signal of lower-mass halos and the 1-halo contribution becomes important at smaller scale $k \gg 1h/\mathrm{Mpc}$.

Thus, an important result is that, since both the shear and DM-induced γ-ray signals are stronger for larger halos, their cross-correlation is more effective with respect to the case of astrophysical sources at intermediate wavenumbers. This, together with the sizable overlapping of the DM γ-ray and shear window functions at low redshift, leads to the expectation of a sizable DM signal in the angular PS, which is indeed what we find in Fig. 3.

The observational forecasts for the cross-correlation between Dark Energy Survey (DES), Abbott et al. (2005), or Euclid, Laureijs et al. (2011), and Fermi-LAT are shown for the benchmark models considered in this work (for error estimates, we take observational performances from Atwood et al. (2009), Laureijs et al. (2011), and Abbott et al. (2005). Fig. 3 shows that a DM signal can be disentangled in the angular PS at $\ell \leq 10^3$. The same conclusion can be derived for DM models with different mass and annihilation/decay channels, provided the DM is a significant component of the total γ-ray EGB (at least in one energy bin) as in our assumptions.

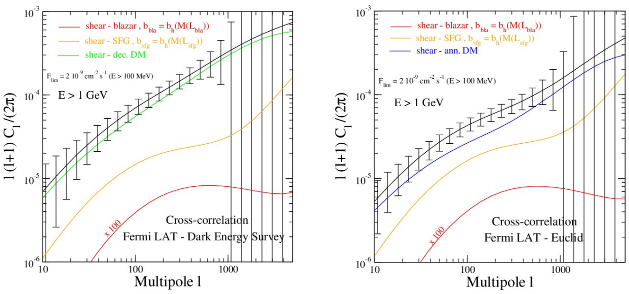

Figure 3: *Left*: Cross-correlation between cosmic shear and γ-ray emission, for the different classes of γ-ray emitters described in the text (with a γ-ray threshold expected for Fermi-LAT after 5 years of exposure). Each contribution is normalized by multiplying Eq. (2) by $\langle I_j \rangle / \langle I_{\mathrm{EGB}} \rangle$ to make them additive. DES is taken as the reference galaxy survey. Error bars are estimated for the total signal (in black). *Right:* Same as in the left panel but for annihilating DM, with Euclid as the reference galaxy survey. This figure is taken from Camera et al. (2012).

4 Conclusions

In this talk, we discussed the cross-correlation angular power spectrum of weak lensing cosmic shear and γ-rays produced by WIMP annihilations/decays and astrophysical sources. We showed that this method can provide novel information on the composition of the EGB. Since the shear signal is stronger for structures of larger masses and most of the γ-ray emission from decaying and annihilating DM is also produced in large mass halos, their cross-correlation is typically stronger than the case of astrophysical sources (which are associated to galactic-mass halos) for $\ell \simeq 100 - 1000$. The combination of Fermi-LAT with forthcoming surveys like DES and Euclid can thus potentially provide evidence for WIMPs.

Acknowledgement

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DISCUSSION

SERGIO COLAFRANCESCO: What are the effects of DM-density profiles and of the cross-correlation of DM halos with gamma-ray emitting galaxies on the results you have shown?

MARCO REGIS: DM density profiles in the inner part are model dependent; however this affects the cross-correlation angular power spectrum only at multipoles $\ell > 10^3 - 10^4$, so above the range of our interest.

Since the bulk of anisotropies from DM comes from very large halos, the galactic mass halos are not crucial in the estimate of the total DM signal.

JIM BEALL: How much of an improvement in the error bars do you need to better delimit the model?

MARCO REGIS: This changes with the overall normalization of the WIMP cross-correlation signal which depends on the (unknown) interaction rate. However, the bottom-line is that, provided the DM is one of the most relevant components of the EGB in at least a energy band, current and next future experiments, like Fermi-LAT and DES, would suffice.