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Cross-correlating CMB temperature fluctuations with high-energy γ-ray flux from Dark-Matter annihilation

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Summary. — In this paper we compute the Integrated Sachs-Wolfe effect due to the presence of dark-matter structures on cosmological scale. We cross-correlate the CMB temperature fluctuations with the extragalactic high-energy γ-ray flux map obtained with FERMI-LAT. We find a null signal consistent with the theory and conclude that the presence of halos and subhalos at galactic and extragalactic scale, if not excluded, will be hardly discoverable.

PACS 95.35.+d – Dark matter (stellar, interstellar, galactic, and cosmological).
PACS 98.35.Gi – Galactic halo.

1. – Introduction

The nature of the dark matter (DM) is still unknown. Indeed, no exotic signal proven to be due to the presence of DM has been observed so far, beyond its gravitational effects. In the hunt for the DM particle, indirect detection seemed a promising way in the last few years, because of the launch of experiments such as Fermi and Pamela, with enough sensitivity to test a large number of possible models in the hypothetical framework with a weakly interacting DM particle at the electroweak scale.

The issue of the spatial distribution of DM is also still an open question. N-body simulations are the best way to study the highly non-linear processes involved in the evolution of substructures. Unfortunately, they can only probe a limited range of halo masses and scales. The evolution of micro-halos with size close to the free-streaming mass can only be studied by simulating a small region at very high redshifts. The modeling of a Milky Way (MW)—sized DM halo has limited resolution but such information can be interpolated in a consistent way with that coming from the simulation of the smallest-sized halos [1] in order to have a handful of self-consistent models reproducing the local and extragalactic environment, which can be used when inferring predictions for fluxes of particles deriving from DM annihilation.

Following the results of numerical simulations and the theory of hierarchical structure formation, the DM distribution in the MW halo consists of two separate phases: a smoothly distributed component (main halo) and a clumpy component made of virialized substructures (subhalos). The same structure is also mirrored at cluster scales, where a smooth component comes together with a clumpy one.

The possible influence on particle fluxes and angular correlations due to the huge number of small-sized DM halos has been investigated and found to be hardly observable [1-4].

In this work, we make use of the results of [5]. In that paper, maps of the residual isotropic γ-ray emission have been derived, starting from 21 months of data from the Fermi-Large Area Telescope (LAT). A large portion of such an emission is being thought to be due to the extragalactic emission (EGB). The authors searched for the Integrated Sachs-Wolfe (ISW) signature by cross-correlating the Fermi-LAT maps with the WMAP7-Cosmic Microwave Background map, finding a cross-correlation consistent with zero. Finally, they cross-correlated the Fermi-LAT maps with the angular distributions of objects that may contribute to the EGB: QSOs in the SDSS-DR6 (Sloan Digital Sky Survey-Data Release 6) catalog, NRAO VLA Sky Survey (NVSS) galaxies, Two Micron All Sky Survey (2MASS) galaxies and Luminous Red Galaxies (LRGs) in the SDSS catalog. The results obtained are in any case consistent with zero, in agreement with theoretical expectations.

Since a large portion of the EGB may be contributed by DM annihilation, in this paper we cross-correlate the Fermi-LAT maps with the angular distribution of DM structures at cosmological level. We use the formalism of [2] applyed to the analysis of [1] to model the extragalactic DM environment and we refer to these papers for the relative bibliography.

2. – Integrated Sachs-Wolfe effect from DM structures

To compute the cross-correlation signals we model the expected fluctuations of the γ-ray flux. These fluctuations arise from local deviations from the γ-ray luminosity density $\rho_\gamma(z)$. The authors of [5] also assume that the γ-ray sources trace the underlying fluctuations in the mass density according to some linear biasing prescription that may depend on the redshift: $\delta_{n_\gamma}(z,\mathbf{x}) \equiv b_\gamma(z)\delta_m(z,\mathbf{x}) = b_\gamma(z)(\rho_m(z,\mathbf{x})-\rho_m(z))/\rho_m(z)$,where ρ_m indicates the mass density and $b_\gamma(z)$ is called the biasing function.

Putting all together, the expected fluctuation in γ-ray energy flux is

$$\delta I(\mathbf{n}) \equiv \frac{I(\mathbf{n})-I}{I} = \frac{\int (1+z)^{-\Gamma} H(z)^{-1} \rho_\gamma(z) b_\gamma(z) \delta_m(z,\mathbf{x}) \mathrm{d}z}{\int (1+z)^{-\Gamma} H(z)^{-1} \rho_\gamma(z) \mathrm{d}z}, \tag{1}$$

where $I \equiv I(>E)$ indicates the γ-ray mean flux and $I(\mathbf{n}) \equiv I(>E,\mathbf{n})$ is the energy flux along the generic direction $\mathbf{n}$.

The general expression for the two-point angular correlation is then

$$\langle \delta I(\mathbf{n_1}) \delta J(\mathbf{n_2}) \rangle = \sum_l \frac{2l+1}{4\pi} C_l^{I,J} P_l[\cos(\theta)], \tag{2}$$

where I and J are the two fields and the angular spectrum is given by

$$C_l^{I,J} = 4\pi \int_{k_{\min}}^{k_{\max}} \frac{\mathrm{d}k}{k} \Delta^2(k) [G_l^I(k)][G_l^J(k)]. \tag{3}$$

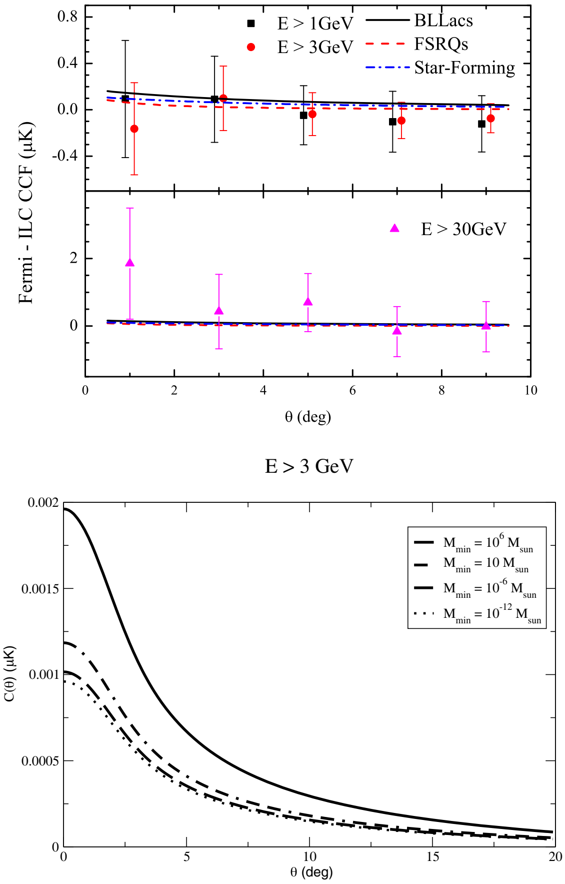

Fig. 1. – Upper panel: cross-correlation estimated from the WMAP7 ILC map and the 21-month Fermi-LAT EGB map with $|b| > 20^\circ$ in three energy bands. The three symbols refer to 3 energy cuts $E > 1\,\mathrm{GeV}$, $E > 3\,\mathrm{GeV}$ (upper panel) and $E > 30\,\mathrm{GeV}$ (lower panel). Model predictions for different types of sources are represented by continuous curves: FSRQs (black, continuous), BLLacs (red, dashed), star-forming galaxies (blue, dot-dashed). Figure from [5]. Lower panel: cross-correlation for energy $E > 3\,\mathrm{GeV}$ for different DM halo models with different free-streaming minimum halo mass.

$\Delta^2(k)$ is the logarithmic matter power spectrum today as a function of the wave number k:

$$\Delta^2_\delta(k) = \frac{k^3}{2\pi^2} P_\delta(k) = A\delta^2_H \left(\frac{ck}{H_0}\right)^{3+n} T^2_f(k). \tag{4}$$

We used $\delta_H = 1.6728$. The reference values of cosmological parameters are those of WMAP 7. The matter transfer function, $T_f(k)$, was computed using CMBfast [6] and was linearly extrapolated to smaller scales. We have checked that extrapolating with a fix slope of -2 does not change our results.

In our case, $I = E$ represents the EGB signal, with

$$G^E_l(k) = \frac{\int (1+z)^{-\Gamma} H(z)^{-1} \rho_\gamma(z) b_\gamma(z) D(z) j_l[k\eta(z)]\mathrm{d}z}{\int (1+z)^{-\Gamma} H(z)^{-1} \rho_\gamma(z) \mathrm{d}z}, \tag{5}$$

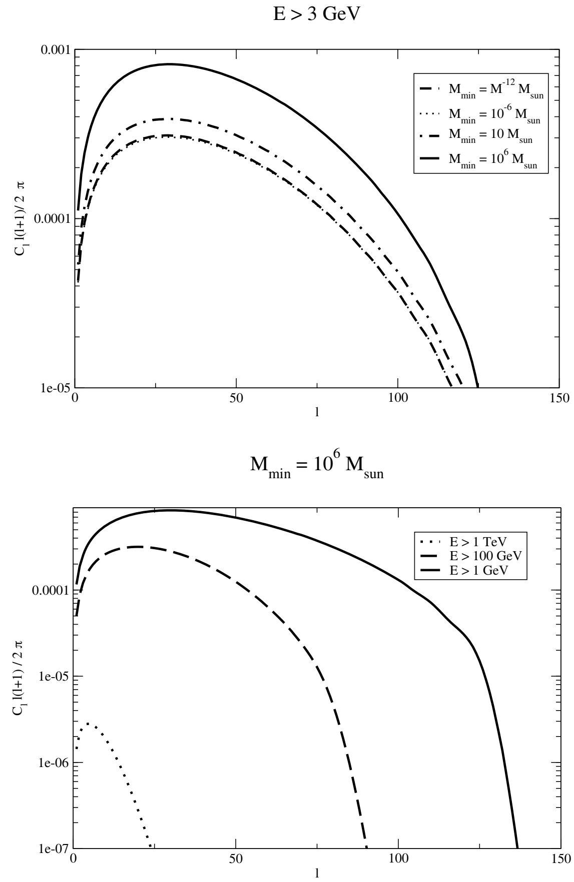

Fig. 2. – Upper panel: angular power spectrum derived for energy $E > 3\,\mathrm{GeV}$ for different DM halo models with different free-streaming minimum halo mass. Lower panel: angular power spectrum for one halo model at different threshold energies.

where $j_l[k\eta(z)]$ are spherical Bessel functions, $D(z)$ is the linear growth factor of density fluctuations and $\eta(z)$ is the comoving distance to redshift z, and $b_\gamma(z)$ represents the mean bias factor of the sources, which we compute according to [7, 8].

The second filter function represents the temperature fluctuation field obtained from the CMB maps ($J = T$). We have computed it according to [9]:

$$G_l^T(k) = 3T_{\mathrm{CMB}}\Omega_m \left(\frac{H_0}{ck}\right)^2 \int \frac{\mathrm{d}[D(z)(1+z)/D(0)]}{\mathrm{d}z} j_l[k\,\eta(z)]\mathrm{d}z. \tag{6}$$

Equation (6) holds for linear perturbations, *i.e.* for $k \ll 1$, therefore in [9] it has been checked for a set of multipoles l that the cross-correlation function obtained using the power spectrum of CMB temperature perturbation given by CMBfast are well approximated by setting in eq. (3) $k_{\max} = 0.02\,\mathrm{Mpc}^{-1}$.

In the upper panel of fig. 1 we show the figure of [5] regarding the results of cross-correlation with astrophysical sources.

When computing $\rho_\gamma(z)$ we make use of the same methodology as in [1, 2] with the only variance that the opacity of the Universe to high-energy γ-rays has been computed using the results of [10].

Our results for the angular power spectrum derived from eq. (3) are shown in fig. 2. In the upper panel we plot the result for four different values of the free-streaming mass of the DM halo, all compatible with the state-of-the-art of knowledge. In the lower panel we fix the free-streaming mass and we change the energy threshold of the detected photons. We observe that, the larger is the free-streaming mass of the DM model, the larger is the effect on the angular power spectrum. Also, such effect is larger for lower energy thresholds.

Finally, the results of the cross-correlation computed according to eq. (2) are shown in the lower panel of fig. 1. Our results are compatible with zero, in accordance with theoretical expectations.

3. – Discussion

The presence of DM halos and subhalos on galactic and extragalactic scale has not got a big impact on the indirect detection. Yet, their presence is still compatible with observations and therefore not ruled-out.

Although this last attempt shows that at lower energies there may be some interesting effect to be investigated, we think that the larger satellites as the Dwarf Galaxies are still the most promising objects to look for.

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