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Searching for WIMP signals with galaxies - gamma ray cross correlations: optimal weights in the angular power spectrum

Andrea Rubiola,[a,b,*] **Stefano Camera**[b] **and Nicolao Fornengo**[b]

[b] *Department of Physics, Università di Torino, via Pietro Giuria 1, Turin, Italy*

[a] *Department of Physics, Università di Trento, Via Sommarive 14, Povo (Trento), Italy*

E-mail: andreamaria.rubiola@unito.it

Although one of the two namesakes of the ΛCDM cosmological model, the hypothesis of cold dark matter existence still chiefly relies on its gravitational effects, whilst both direct and indirect detection via non-gravitational signatures have not yet been achieved. Weakly interacting massive particles (WIMP) are a candidate cold relic with a mass from 0.1 GeV to several TeV: they might then annihilate or decay in γ photons and contribute to the unresolved gamma-ray background (UGRB) detected by experiments such as Fermi – LAT. Even if dominated by an isotropic shot-noise component, a degree of anisotropy was detected in the past already in the autocorrelation angular power spectrum. The subsequently detected UGRB-galaxies angular power spectrum cross-correlation further enhances such anisotropy, showing a link between the UGRB and the large scale structure of the Universe (LSS), and allows a better understanding of its composition: some classes of astrophysical objects, like Active Galactic Nuclei, are the most likely sources, but dark matter contributions are not excluded; at low redshifts, the astrophysical contribution should even be subdominant compared to WIMP annihilation or decay signatures, as shown in previous works. Within this general framework, we present a weighting scheme of the galaxy tracer distribution which proved effective in enhancing the anisotropic contribution of other shot-noise-dominated LSS tracers, such as cosmic rays and gravitational waves, and assess its efficiency in terms of signal-to-noise ratio and constraining power on the WIMP mass and its annihilation or decay cross-sections.

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*Speaker

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1. Introduction: WIMPs and the Fermi Unresolved Gamma Ray Background

Cold Dark Matter (CDM) is assumed to be the main driver of the large scale structure (LSS) clustering: such hypothesis urges particle physicists to figure out ways to demonstrate its existence through interactions different from the gravitational effects it exerts on astrophysical objects. Three main categories of detection mechanisms have thus been devised, namely: DM being produced by interaction of standard model (SM) particles; DM interaction with SM particles (direct detection) and, finally, the possibility for DM particles to annihilate or decay in SM particles (indirect detection).

Different models assume different interaction channels and production mechanisms: focusing on the indirect detection case, the final states can be modelled depending on the preferred DM model, requiring the specification of the particle mass m_χ and either its annihilation cross section $\langle\sigma v\rangle$ or its decay rate Γ. Among the many DM candidates, weakly interacting massive particles (WIMPs) are of particular interest: they are quite massive (0.1 GeV to several TeV) and assumed to be produced in the early universe phase under thermal equilibrium conditions. Endowed with such mass values and typical weak-scale couplings for their annihilation cross-sections, they can reproduce the measured DM abundance $\Omega_{\mathrm{DM}} \approx 0.27$, leaving room for the possibility that a single particle, to be added to the SM ones, could represent the whole of DM, whose "coldness" property arises from its large mass value.

WIMPs being so massive, they are likely to decay or annihilate into γ photons as final states: due to this emission, the LSS should therefore be "glowing", and the emitted photons might be contributing to the unresolved γ-ray background (UGRB) detected by the Fermi-LAT instrument, comprising all high energy photons not emitted by individually resolved astrophysical sources. The UGRB is substantially isotropic, whilst the DM field constituting the LSS is organised in an anisotropic cosmic web, as shown by different tracers such as galaxies or neutral hydrogen. If at least part of the UGRB signal is indeed sourced by DM clustered in halos, we therefore need to recover an anisotropic component, which might be enhanced by statistically cross-correlating it with some LSS tracer [1]. In the last decade, the existence of the global UGRB-LSS cross-correlation has indeed been demonstrated on data [2, 3]: four classes of astrophysical sources are found to dominate the signal, namely BL Lac quasars (BL Lac), flat spectrum radio quasars (FSRQ), misaligned Active Galactic Nuclei (mAGN) and star-forming galaxies (SFG), to which exotic sources like decaying or annihilating DM signal can be added [4]. In particular, DM alone may source most of the signal at $z \leq 0.1$, whilst, at higher z, the well-established astrophysical contribution at small angular scales contrasts with broad uncertainties at the largest ones [5]. This prevents a firm assessment of DM contribution, potentially the dominant one there. Many aspects remain so far undecided: enhancing the signal-to-noise ratio is thus crucial for this line of research, and an improvement strategy of the latter is the main topic of this contribution.

2. Angular power spectrum formalism and the Wiener filtering technique

The angular cross-correlation power spectrum between any γ source (dubbed with γ as well) and galaxies as LSS tracers measures the signal's degree of anisotropy per Fermi energy bin ($C_\ell(E)$)

at every given angular scale $\ell \approx \pi/\theta$, reading [6]:

$$C_\ell^{\gamma\,\mathrm{gal}}(E) = \int \frac{c\,\mathrm{d}z}{H(z)} \frac{W_\gamma\,(z,E)\;\;W_{\mathrm{gal}}\,(z)}{\chi(z)^2} P_{\gamma\,\mathrm{gal}} \left(k = \frac{\ell + 1/2}{\chi(z)}, z\right). \tag{1}$$

The following quantities enter Eq. (1): the comoving radial distance, χ; the window functions, W, shaping the redshift intensity distribution of the γ sources or the galaxies number density; finally, the three-dimensional power spectrum $P_{\gamma\,\mathrm{gal}}$. The latter is derived within the halo model formalism: it describes the spatial shape of the sources in terms of the density profiles or halo occupation distributions (HOD) for DM and galaxy surveys respectively, or the brightness profile for the astrophysical sources. The finite resolution of the Fermi-LAT instrument is also taken into account under the simplified hypothesis of a Gaussian beam, depending on both energy and angular multipole, which multiplies the C_ℓ obtained with Eq. (1). The large size of the uncertainties hindering the resolution of different signal contributions we mentioned above can be tackled by means of the Wiener filter (based on [7]). Its meaning can be sketched as follows: if galaxies and γ emitters are actually tracing the same field, we might thus weight galaxies according to their redshift so that their window function optimally matches that of the UGRB. Operatively, the optimal weighting implies the substitution of the galaxy window function with the combination of all the γ tracers' windows, as follows:

$$W\,(E,z)^{\mathrm{opt}}_{\mathrm{gal}} = \frac{\sum_i W^{\gamma_i}\,(E,z)}{\int_{z_{\min}}^{z_{\max}} c\,\mathrm{d}z\, \sum_i W^{\gamma_i}\,(E,z)\,/H(z)} \left(\Theta\,(z - z_{\min}) - \Theta\,(z - z_{\max})\right), \tag{2}$$

where z_{min} and z_{max} are the original galaxy surveys' minimum and maximum redshifts, $\Theta(z)$ represents the Heaviside's theta function and the i index runs through all the sources constituting the UGRB, including either annihilating or decaying DM. The two tracers are now endowed with the same window function (modulo the normalisation denominator in the optimised one); we can therefore find cases for which the reshaped argument of Eq. (1) indeed provides more signal than the standard configuration.

3. Preliminary results and discussion

In the full case, the cross-correlation signal $S_\ell\,(E)$ is linked to the cross-correlation power spectra as follows: $S_\ell\,(E) = \sum_i C_\ell^{\gamma_i\,\mathrm{g}}\,(E)$, with i again encompassing BL Lac, FSRQ, mAGN, SFG, and either annihilating or decaying DM. Although unrealistically, this first test setup assumes for simplicity that the whole signal S_ℓ is sourced by decaying DM, i.e. $S_\ell\,(E) = C_\ell^{\mathrm{DM\ gal}}\,(E)$. The cumulative signal-to-noise (SNR) acts as a reference figure-of-merit:

$$SNR^{\mathrm{cum}}_{\ell^{\min},\ell^{\max}}\,(E) = \sqrt{\sum_{\ell=\ell^{\min}}^{\ell=\ell^{\max}} \left(\frac{S_\ell\,(E)}{\sigma_\ell\,(E)}\right)^2}, \tag{3}$$

from which we see that the filtering is an actual boost – on all or some multipoles ℓ – if the enhancement is stronger for the signal at the numerator than for the uncertainties $\sigma_\ell\,(E)$ at denominator. The latter are also a function of the Wiener filter, since they read:

$$\sigma_\ell\,(E) = \sqrt{\frac{\left(C_\ell^{\mathrm{g\,g}}(E) + \mathcal{N}_\ell^{\mathrm{g}}(E)\right)\left(C_\ell^{\gamma\gamma,\mathrm{tot}}(E) + \mathcal{N}_\ell^{\gamma}(E)\right) + \left(S_\ell(E)\right)^2}{(2\ell+1)\;\Delta\ell\;f_{\mathrm{sky}}(E)}}, \tag{4}$$

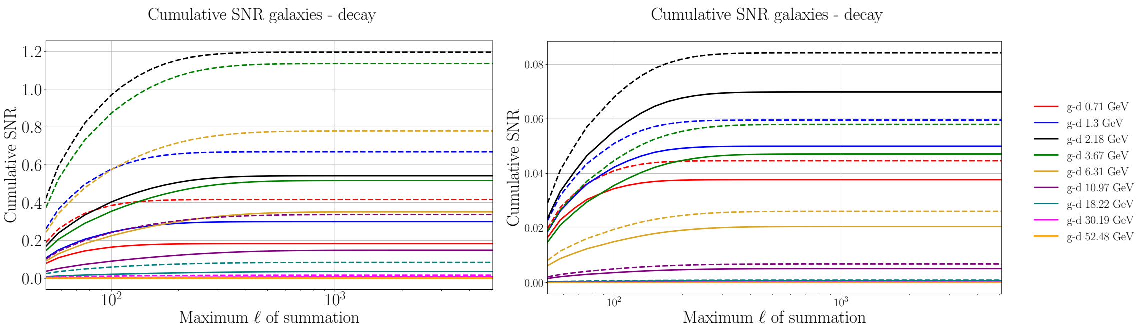

Figure 1: Cumulative SNR for the non-optimised (solid) and optimised (dashed) galaxies-decaying DM cross-correlation signal, for $m_\chi = 100$ GeV and $\Gamma = 10^{-27}$ s^{-1}. Left: the weighting scheme is applied to the 6dFRS survey. Right: the eBOSS Emission Light Galaxies sample is considered.

where C_ℓ^{gg} is the galaxy autocorrelation angular power spectrum, $\mathcal{N}_\ell^g$ is the galaxy shot-noise power spectrum, $C_\ell^{\gamma\gamma,\mathrm{tot}}$ is the total UGRB autocorrelation power spectrum (defined in equation 3.4 of [8]), $\mathcal{N}_\ell^\gamma$ is the γ shot-noise power spectrum, $\Delta\ell$ is the multipole bin width and f_{sky} is the sky fraction constituting the UGRB as a function of energy (all energy dependencies in the angular power spectra of Eq. 4 have been omitted for simplicity). C_ℓ^{gg} and $\mathcal{N}_\ell^g$ also get modified by the Wiener filter. Since the Milky Way contribution to the UGRB is non-negligible at small ℓ [9], we set $\ell^{min} = 50$ and stop the summation at $\ell^{max} = 5000$; we show the results of Eq. 3 in Fig. 1, considering the same binning in energy used in [9]; its saturation at high multipoles indeed shows that the information is mostly retained for $\ell \lesssim O(1000)$. Fig. 1 also compares the results for a low-redshift survey (6dFRS, left, $0 \le z \le 0.15$. The survey's redshift distribution function is taken from [10], whilst the HOD is specified in [11]) and a high-redshift one (eBOSS Emission Light Galaxies, right, $0.6 \le z \le 1.1$. The survey's redshift distribution is taken from [12], whilst the HOD is modelled in [13]). In both cases the SNR gets improved by a factor of some units compared to the non-optimal case, but only 6dFRS displays a SNR above 1, because the DM window function is peaked at low z, whilst in the second case the integral only intercepts its final tail.

4. Conclusions

In summary, the application of the Wiener filter signal processing technique to the window functions used for calculating the cross-correlation angular power spectrum between γ sources and galaxy surveys proves effective in terms of SNR *multiplicative increase*, even though the attained *absolute* values are rather modest. The degree of success depends on the properties of the selected galaxy surveys and on the fact we use an integrated quantity: both their being centered at low rather than high redshift and their width are relevant. Based on the assumption of decaying DM as unique γ source, the boost is in the order of some units. In general, there is a direct scaling relation between the chosen m_χ and Γ values and the final SNR. The development and completion of this work will contemplate the inclusion of astrophysical sources, testing the framework on more galaxy surveys and assessing the methodology's constraining power on the fundamental parameters $\langle\sigma v\rangle$, Γ and m_χ, regulating the amplitude of the model signal, to be compared with the exclusion limits set by the hitherto accumulated observational evidence. SNR might then be further enhanced by leveraging on the power of statistical methods: for instance, by cumulating the SNR across the energy bins or the application of multi-tracer approaches, as well as by devising other optimisation schemes.

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