WIENER-FILTER INSPIRED CROSS-CORRELATION ANGULAR POWER SPECTRUM OF THE UNRESOLVED GAMMA RAY BACKGROUND AND GALAXIES IN A MULTITRACER FRAMEWORK (ABSTRACT ID: 244)

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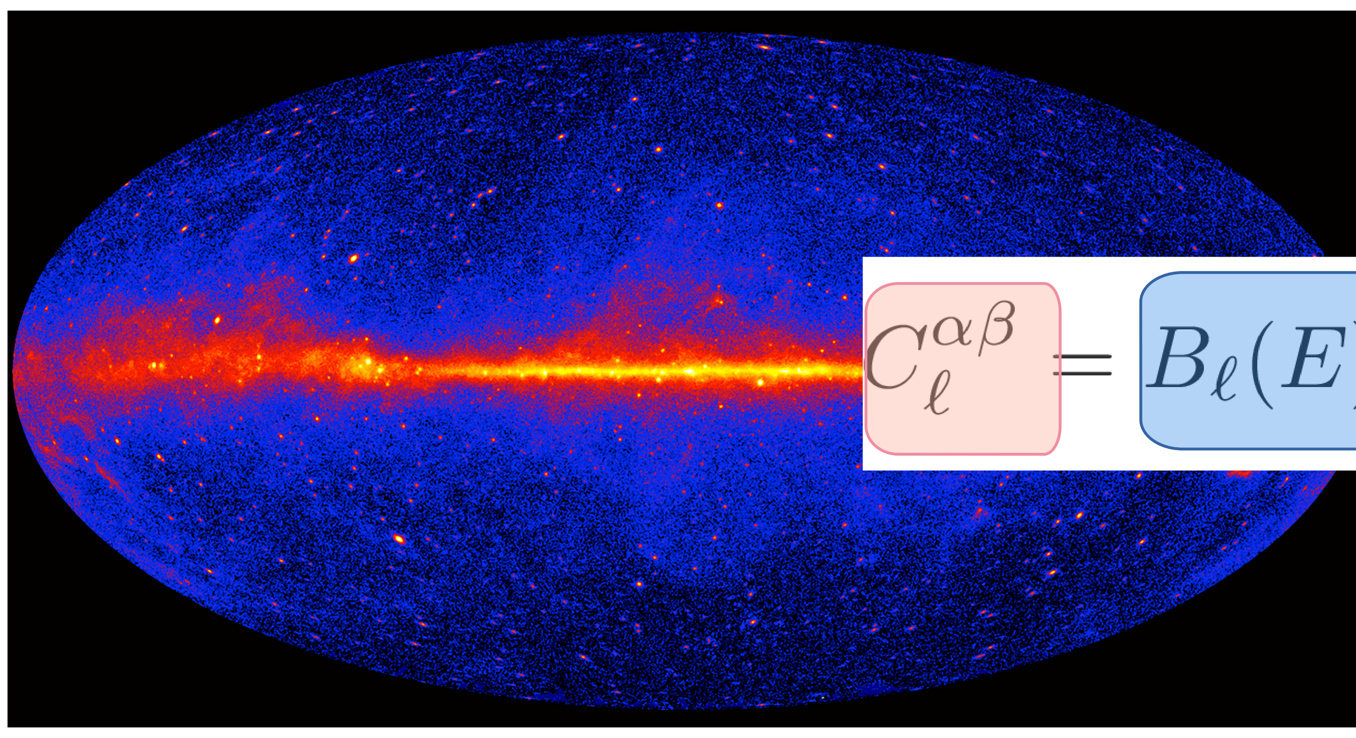
Cosmology and Particle Physics at the crossroad

The description of the Universe provided by Physical Cosmology is probably as powerful as problematic. The ΛCDM cosmological model, rooted in Einstein's general relativity theory and its description of gravity, is a **"concordance paradigm"**, able to accurately describe the evolution of the universe throughout $13 \cdot 10^9$ years of existence, starting from a Hot Big Bang, and across a wide number of metric and mass scales, from the Large Scale Structure (~100 Mpc – 1 Gpc) down to the galactic scale (~ 30 kpc). The prediction of the temperature anisotropies of the Cosmic Microwave Background is perhaps its largest success. Nevertheless, it postulates the existence of, and it is named after, two "dark" entities beyond the Standard Model of Particle Physics. Dark Energy (Λ, 68% of the matter – energy component today) and Cold Dark Matter (CDM 28% of the matter-energy component today). Known particles, from baryons to photons and neutrinos, just represent the last 4% of today's matter-energy component of the universe. Dark matter seems to be interacting exclusively through gravity: there is thus a certain **necessity** of demonstrating CDM's existence through other interaction channels, possibly via forces and particles belonging to the Standard Model.

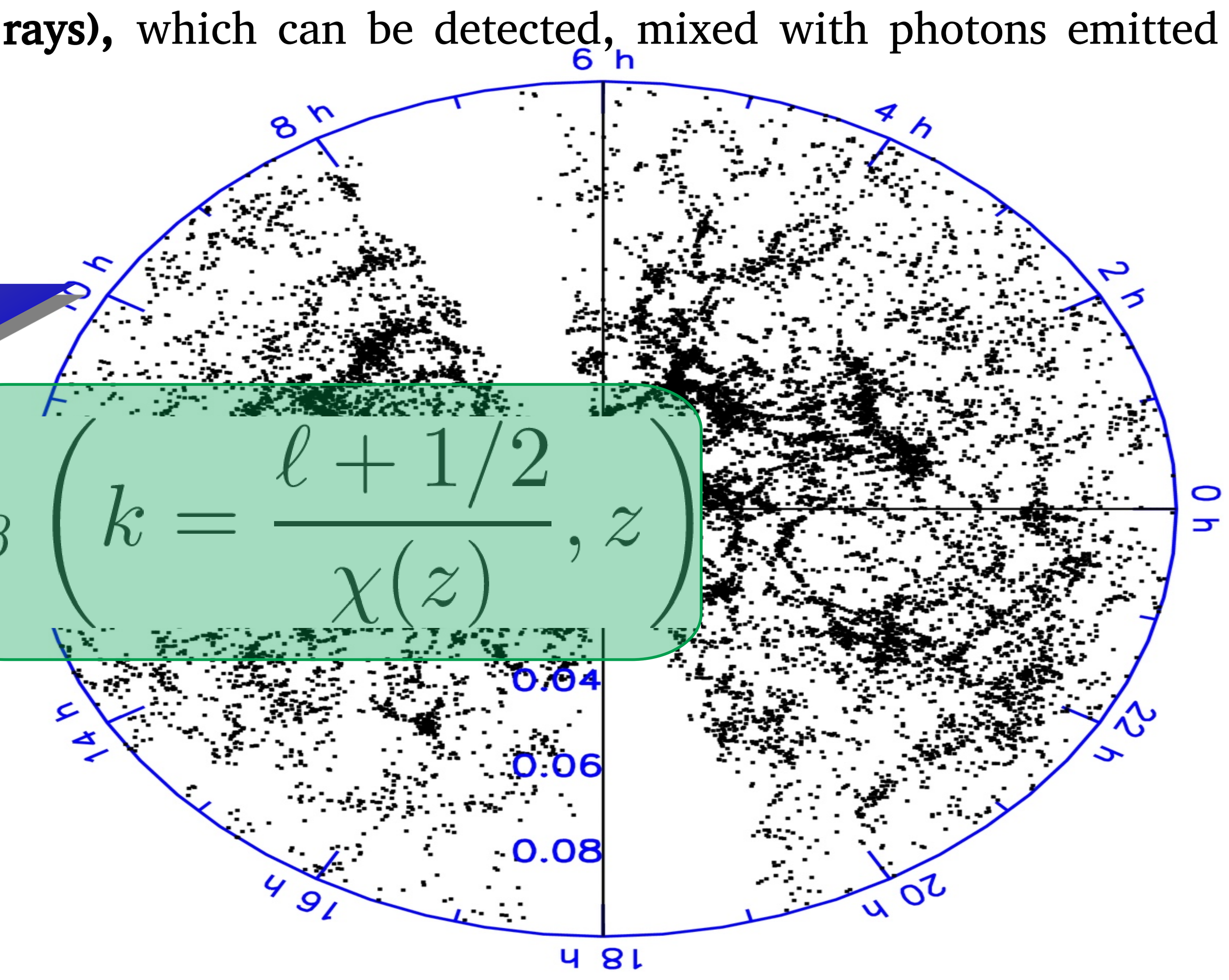
Dark Matter might decay or annihilate into some Standard Model particles, contributing to the cosmic rays budget: if we are able to identify the final states of such processes, we can claim some sort of **indirect detection**. The phenomenology of a candidate Cold Dark matter particle can be summarised into two parameters: its **mass** m_χ , and its **annihilation cross section** or its **decay rate** Γ. Among the several models, **WIMPs** (Weakly interactive massive particles) are a well-known model, setting the mass in the 0.1 GeV-several TeV interval, close to the weak force energy scales. Endowed with typical weak scale couplings, they rather easily reproduce the observed abundance of Dark Matter. Being so massive, they might decay or annihilate into **high energy photons (gamma rays),** which can be detected, mixed with photons emitted by astrophysical sources, by instruments as the Fermi-LAT telescope.



Galaxy - UGRB

$$C_\ell^{\alpha\beta} = B_\ell(E) \int \frac{c\,\mathrm{d}z}{H(z)} \frac{W_\alpha(z)\, W_\beta(z)}{\chi(z)^2} P_{\alpha\beta}\left(k = \frac{\ell + 1/2}{\chi(z)}, z\right)$$

Angular cross-correlation formalism



Looking for Dark Matter in its natural environment

Unresolved electromagnetic backgrounds at different energies permeate our Universe, a "fog" of photons not emitted by identified astrophysical sources. At the GeV-TeV scale, the emission is known as the **Unresolved gamma ray background** (**UGRB**):

- Its total intensity appears **dominated by Active Galactic Nuclei (AGNs) and Star Forming Galaxies (SFGs),** too distant or too faint to be individually resolved.
- There is **room for some additional process**, also of exotic origin. Decaying or annihilating dark matter contributions to the total UGRB can be investigated starting from its fundamental property: **dark matter clusters into gravitationally bound haloes.**
- Haloes are clouds of WIMPS, hosting galaxies and larger structures: γ emission of astrophysical origin also originates in haloes; yet if they are "glowing" by effect of Dark Matter itself, the signal should be distinctive at **low redshift and large angular scales.**

Angular power spectrum formalism: data and theory

C_ℓ

The quantity measures the anisotropy (variance per angular multipole ℓ) of a given signal. It is a bidimensional information, projecting the sources on the sky plane; there is no information on distances.

$W(z)$
Window function, Modelling the redshift distribution

$P(k,z)$
Power spectrum, modelling the spatial structure or brightness of the sources

$B_\ell(E)$
Beam factor, accounting for Fermi – LAT limitd resolution

Dark matter is clustered in an *anisotropic* cosmic web (the Large Scale Structure, LSS)

Dark matter can't be directly detected, but every LSS tracer (e.g. galaxies), shows some degree of cross correlation

Enhance anisotropy through cross-correlation

The UGRB is an *almost* isotropic signal. The degree of gamma *autocorrelation* anistropy is comparable with Blazar clustering (Ackermann et al., 2012; 2018).

UGRB is also, although weakly, tracing the LSS!

(Regis et al., 2015; Cuoco et al., 2015; Xia et al., 2015; Ando et al., 2013; Paopiamsap et al. 2023)

Room for improvement

- The story does not finish here. The astrophysical component dominates the anisotropy, yet uncertainties leave many points undecided, with poor constraining power on component amplitude and parameter degeneracies. We can try to put upper limits on WIMP phenomenological parameters.
- Need to increase the signal-to-noise ratio (SNR) with suitable techniques, like the Wiener filter.

First improvement

Matching the sources distribution: the Wiener filter technique

Assume that γ sources overdensities ~ linear combination of galaxies overdensities (Urban et al., 2005.0024) $y_{\gamma,DM+astro} = \mathbf{w}^{\mathbf{T}}(z)\mathbf{x}_{\mathbf{gal}}(z)$

Introduce weights $w(\chi)$in the galaxy window function

$$W_g(\chi) = \frac{\chi^2\, w(\chi)\, \bar{n}_g(\chi)}{\left[\int d\chi\, \chi^2\, w(\chi)\, \bar{n}_g(\chi)\right]}.$$

Find the explicit weighting expression

$$w(\chi) = \frac{\sum_i W_i(\chi)}{\chi^2 \bar{n}_{g,c}(\chi)} \left(\Theta\left(\chi - \chi_{\min}\right) - \Theta\left(\chi - \chi_{\max}\right)\right).$$

Theoretical Wiener filter estimator

Galaxy window function gets replaced with

$$W(z)_{\mathrm{gal,optimal}} = \frac{\sum_i W_i^{\gamma,\mathrm{trac}}(z)}{\int_{z_{\min}}^{z_{\max}} c\,\mathrm{d}z \sum_i W_i^{\gamma,\mathrm{trac}}(z)/H(z)} \left(\Theta\left(z - z_{\min}\right) - \Theta\left(z - z_{\max}\right)\right),$$

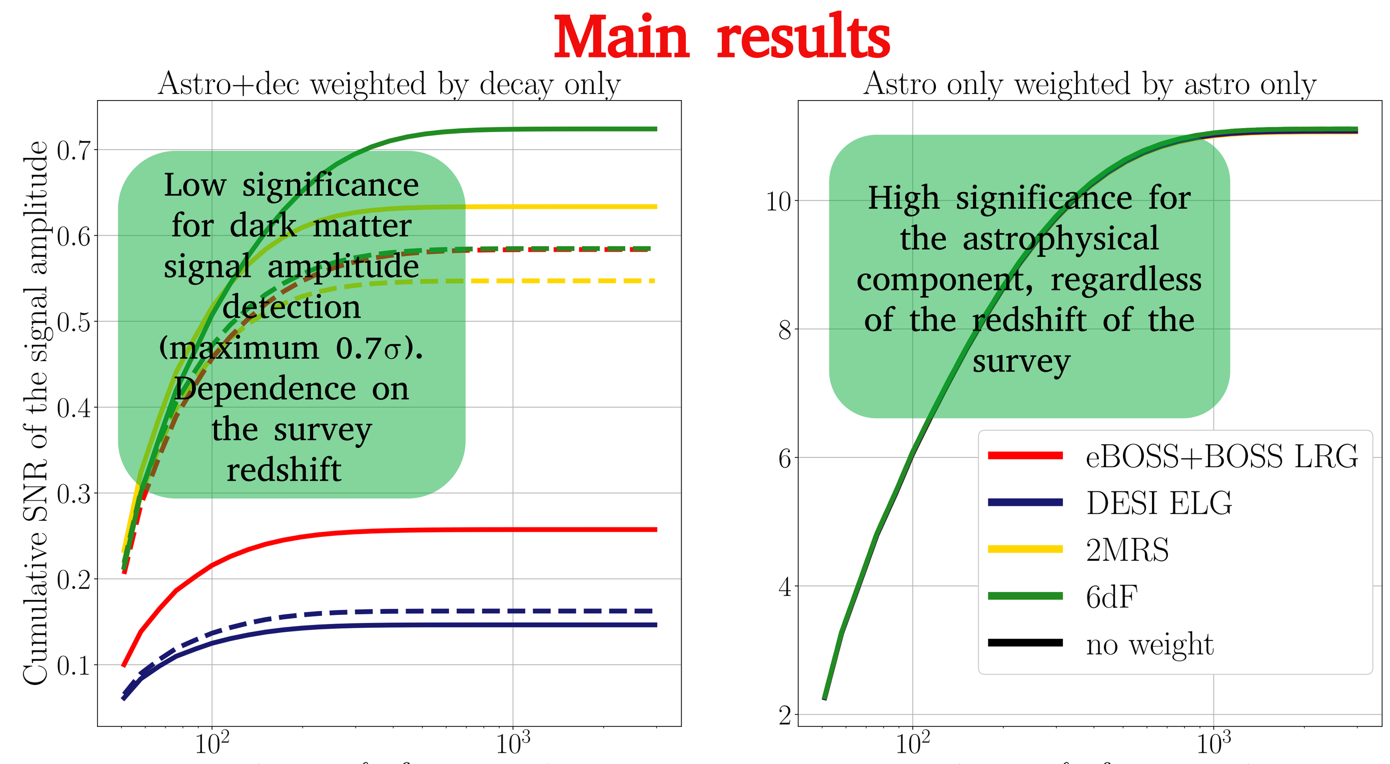
By construction: increased overlap between tracers. The increase of the final SNR is **not granted,** it is the result of the competition between the original and replaced kernels' widths and heights on integrated quantities, and on the recalculation of the galaxy shot noise

Second improvement

Complementing the information: a multitracer approach

This second improvement consists in calculating the SNR of a signal amplitude (either dark matter or astrophysics) in the Fisher formalism by simultaneously combining the autocorrelation galaxy, autocorrelation-γ and galaxy-γ cross-correlation power spectra in a single data vector: $\{C_\ell^{gg}, C_\ell^{g\gamma}, C_\ell^{\gamma\gamma}\}$. The power of the method (Seljak, 2009; Mc-Donald and Seljak, 2009; Abramo and Leonard, 2013; Barberi Squarotti et al., 2024; Kopana et al., 2023) relies on the different biasing level of the tracers with respect to the underlying dark matter field. This fact allows to overcome most of the shot-noise detrimental effects on the data covariance and yields a **granted improvement of the SNR.**

Main results



The Wiener Filter (dashed lines) outperforms non-filtered (solid) models when **surveys have low shot-noise levels (large number of galaxies in the survey, e.g DESI ELG)**. In those cases, the method is more effective on testing for dark matter presence (i.e., enhance a subdominant signal compared to astrophysics) albeit **only in relative improvement, not in absolute values.** On the astrophysics-only side, **the Wiener Filter does not improve** relative to the non-weighted case. Yet the **multitracer yields very high significance** to the detection of AGNS and SFGs as sources of the UGRB.