Frascati Physics Series Vol. 64 (2016)
Frontier Objects in Astrophysics and Particle Physics
May 22-28, 2016

THE LARGE SCALE STRUCTURE PATH TO THE HIGH ENERGY UNIVERSE

Enzo Branchini
Department of Mathematics and Physics. University Roma Tre. Rome. Italy.
INFN. Sezione di Roma Tre. Rome. Italy.

Abstract

We illustrate the importance of the Large Scale Structure of the Universe beyond the usual perimeter of observational cosmology by means of two case studies, traditionally investigated within the framework of high energy astrophysics: the nature of the unresolved extragalactic γ-ray background and the search for the missing baryons in the intergalactic medium.

1 Introduction

The large scale structure [LSS] of the Universe is emerging as one of the most effective probes to investigate the nature of Dark Matter [DM] and that of Dark Energy. As these are probably the most important open problems in Cosmology and Fundamental Physics a number of large galaxy surveys are being designed to trace the LSS over increasingly large volumes of the Universe across a wide range of epchs. These datasets will contain a tremendous amount of information that will impact many areas of astrophysics beyond observational cosmology, including high energy phenomena.

In this work we briefly illustrate how the LSS can be exploited to address two outstanding problems: *(i)* the nature of the diffuse γ-ray background and *(ii)* the missing baryons problem. We shall show and discuss the most recent results based on the available data and highlight the impact that next generation surveys will have on both issues.

The layout of the paper is as follows. In Section 2 we use the cross-correlation between the LSS and the unresolved γ-ray background to investigate the origin of the latter. In Section 3 we show that the filamentary structures in the LSS is an effective signposts for the elusive Warm Hot Intergalactic Medium [WHIM], i.e. the likely reservoir of the atoms that are missing from the baryon budget. We summarise the main results and consideration in Section 4.

2 The nature of the γ-ray background and Dark Matter.

Our understanding of the extragalactic γ-ray sky has improved dramatically thanks to the Large Area Telescope (LAT) on board of the Fermi satellite. We now know that most of the resolved extragalactic sources are blazars. What we still don't know is whether these sources also account for the unresolved Diffuse Gamma-Ray Background (DGRB) [2]. The analysis of its energy spectrum has shown that blazars, misaligned AGNs and star forming galaxies [SFGs] can indeed explain a large fraction of the DGRB. However, current data neither clarify the relative contributions of these sources nor rule out the possibility that some other type of $\gamma-$ray source, like annihilating (or decaying) DM particles contribute to the DGRB. [1, 4]

Additional, independent constraints can be obtained by studying the angular correlation properties of the DGRB. Unfortunately, the standard auto-correlation analysis so successfully applied to the microwave background, is not very effective here. The reason is that uncertainties in the Galactic γ-ray emission models, do not guarantee an accurate subtraction of the Galactic foreground so that residuals can generate a spurious correlation signal. An effective way to overcome this problem is to cross-correlate the DGRB with any catalogue of extragalactic objects that trace the same LSS in which the extragalactic γ-ray sources reside and do not correlate with the local Galactic ccf_NVSS.pdf

Figure 1: *2-point DGRB-NVSS angular cross correlation function at $E > 0.5$ GeV computed with and without cleaning the Galactic γ-ray foreground.*

foreground.

This is the idea behind the suite of analyses that we have performed, in which we cross-correlated the Fermi-LAT DGRB maps with several different catalogs of extragalactic sources spanning different redshift ranges [6].

More specifically, we have considered the 5-year Fermi DGRB maps obtained after subtracting the contribution of resolved γ-ray sources, Galactic diffuse emission generated in the disk and off the Galactic plane in the Fermi bubble and Loop I structures. Events have been divided in three energy bins with $E > 0.5$, > 1 and > 10 GeV and maps have been further cleaned by removing multipoles with $\ell > 10$. Then we considered maps of discrete extragalactic sources obtained from five different datasets: *(i)* the SDSS DR6 quasar catalog, *(ii)* the 2MASS galaxy catalogue, *(iii)* the radio sources of the NVSS catalogue, *(iv)* the luminous red galaxies in the SDSS DR8 catalog and *(v)* the main galaxy sample from the SDSS DR8 catalogue. Finally, we computed the 2-point cross correlation function between the objects in each of the catalogues and the flux in the DGRB map. The typical result, plotted in Fig. 1, is that of a positive cross-correlation signal on angular scales below 1°.

To understand the nature of this cross-correlation we compared these measurements with the following model cross-angular power spectrum

$$C_\ell^{(\gamma g)} = \int \frac{d\chi}{\chi^2} W_\gamma(\chi)\, W_g(\chi)\, P_{\gamma g}\left(k = \ell/\chi, \chi\right) \ , \qquad (1)$$

where C_ℓ is the amplitude of the power spectrum at the multipole ℓ, χ is the radial co-moving distance, $P_{\gamma g}(k)$ is the 3D cross-power spectrum between γ-ray emitters and the discrete source (e.g. 2MASS galaxies) and $W(\chi)$ is the so-called window function that characterizes the distribution of objects and γ-ray emitters along the line of sight. To model the 3D spectrum we used the so-called halo model. $P_{\gamma g}(k)$ encodes the information on the relative clustering between LSS tracers and γ-ray emitters. W_γ represents the γ-ray intensity along the line of sight and depends on the intrinsic properties and redshift distribution of different types of γ-ray emitters: blazars, misaligned AGNs, SFGs and more exotic sources like DM particles that can annihilate or decay into γ-photons. $W_g(\chi)$ weights the contribution of the discrete sources at various redshifts and, therefore, depends on the observed redshift distribution of the objects in each of the catalogues listed above.

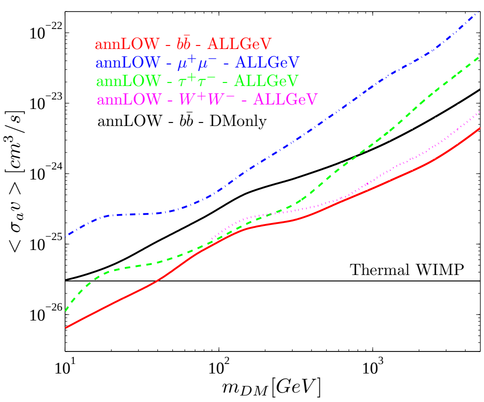

Figure 2: *95% C.L. upper limits on the DM annihilation rate as a function of its mass for different final states ($b\bar{b}$, $\mu^+\mu^-$, $\tau^+\tau^-$, $W + W^-$). The more conservative estimate (black curve) is obtained by assuming that only the DM contributes to the DGRB. The more realistic case of a DGRB contributed by all plausible astrophysical sources is shown by a red curve.*

Eq. 1 reveals the important tomographic aspect of the cross-correlation analysis. Different γ-ray emitters peaks their emission at different redshifts so that for each type of γ-ray source W_γ is significantly different from zero in a different redshift-range. As a consequence, one check whether a particular emitter does contribute to the DGRB by choosing an LSS-tracer with a window function W_g that overlap with that of the potential emitter. The possibility of measuring the cross-correlation in different energy bins, further sharpens the possibility to disentangle the various contributions.

Comparing the model with the measured cross-correlation signal allows one to constrain the contribution of the known astrophysical γ-ray sources to the EGB *as well as* the DM properties. For example one can constrain the mass and the annihilation cross-section for annihilation, as shown in Fig. 3. These constraints are consistent and competitive with those obtained by other indirect DM detection strategies targeting local dwarf galaxies of the Galactic center [7].

3 Searching for the missing baryons.

In the current framework of LSS formation, coherent structures build up over time forming the filaments of the cosmic web. At $z < 1$ their density contrast is sufficiently large to shock-heat the baryon component to temperatures 10^5–10^7 K, forming the so called WHIM. The experimental evidence for such component is scarce and its detection and characterisation is a major target of several, ongoing observational campaigns. The expected association between the WHIM and the LSS filaments has now some experimental support from X-ray observations of the outskirts of galaxy clusters, i.e. the nodes of the cosmic web connecting the filaments [3]. It is therefore clear that filamentary structures in the LSS can be used as effective signpost for the WHIM detection.

The volumes probed by current galaxy redshift survey is already large enough to trace the filamentary structures in the galaxy distribution, A typical example is illustrated in Fig. in which we show the filaments detected in the distribution of galaxies in VIPERS, a recently completed galaxy redshift survey of $\sim 90,000$ objects at $z \sim 0.8$.

We have proposed a new approach that uses galaxy luminosity density as a tracer of the WHIM. Using hydrodynamical simulations we have shown that the large scatter in the already known correlation between WHIM gas over-density, $\delta_{\rm whim}$, and galaxy luminosity over-density, $\delta_{\rm LD}$, becomes significantly tighter and consistent with linear ($\delta_{\rm whim} = 0.7 \pm 0.1 \times \delta_{\rm LD}^{0.9\pm0.2}$) when is restricted to filaments [5].

This confirms that filaments in the galaxy distribution are preferential location for the WHIM. To test this hypothesis we considered the filaments along the line of sight to the blazar H2356-309 and used the measured galaxy luminosity density to predict position and density of the WHIM. We found evidence for the WHIM in correspondence of the Sculptor Wall and Pisces-Cetus superclusters in agreement with the redshifts and column densities of the tentative WHIM detections already obtained.

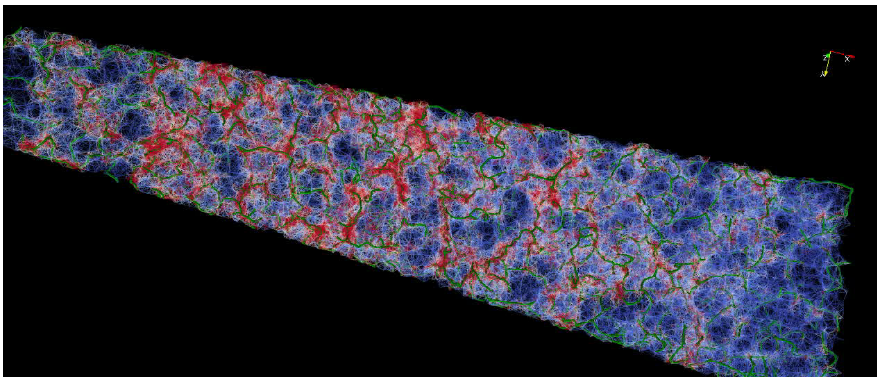

Figure 3: *Filaments (green) in the spatial distribution of the VIPERS galaxies. The red and blue areas highlight regions of high and low galaxy number density, respectively. Courtesy of N. Malavasi and S. Arnouts.*

4 Conclusions

In this paper we have worked out two examples that illustrate the importance of the LSS as tool not only for cosmology but also for high energy astrophysics. In the first example we have shown that LSS can be used to investigate the nature of the extragalactic DGRB. Using wide, redshift surveys of extragalactic objects to trace the LSS at different redshifts it has been possible to investigate the nature, abundance and redshift distribution of the unresolved sources that contribute to the DGRB, including DM. In fact, the constraints on the mass and annihilation cross section (or decay time) of the DM particle that one derives by cross correlating the LSS with the DGRB maps are competitive with the best indirect DM detection techniques proposed so far. Yet, current catalogues allows one to span a wide redshift range but with a limited resolution. Next generation surveys like Euclid, DESI or SKA will be large enough to significantly increase the number of redshift bins and, consequently, improve the quality of the constraints.

The second example uses the LSS to locate the elusive WHIM. We have shown that once the filamentary structures in the spatial distribution of galaxies are traced, then one can use the local galaxy luminosity to predict the location, the density of the WHIM gas and, consequently, the probability of its detection with X-ray observations. Also in this case, the advent of the next generation redshift surveys will greatly enhance our ability to detect and, eventually, characterize the WHIM in the X-ray band, both in emission and in absorption, with the planned Athena satellite mission.

References

1. M. Ackermann *et al*, Phys. Rev. Lett., **116**, 1105 (2016)
2. M.R. Ajello *et al*, ApJ, **780**, 73 (2014)
3. D. Eckert *et al*, Nature, **528**, 105 (2015)
4. D. Hooper *et al*, arXiv:1604.08505 (2016)
5. J. Nevalainen *et al*, Astron. & Astrophys., **538**, 142 (2015)
6. J.-Q. Xia *et al*, ApJ Suppl., **217**, 15 (2015)
7. M. Regis *et al*, Phys. Rev. Lett., **114**, 1301 (2015)
8. M.B. Green, Superstrings and the unification of forces and particles, in: Proc. fourth M. Grossmann Meeting on General Relativity (ed. R. Ruffini, Rome, June 1985), **1**, 203 (North-Holland, Amsterdam, 1986).