Frascati Physics Series Vol. 69 (2019)
PHOTON 2019 - International Conference on the Structure and the Interactions of the Photon
June 3-7, 2019

UNVEILING THE UNRESOLVED GAMA-RAY SKY THROUGH ITS ANISOTROPIES

Michela Negro
INFN Sez. di Torino - Via P. Giuria 1, 10125 Torino

Abstract

The gamma-ray sky has been revealed in the last decade by the *Fermi* Large Area Telescope (LAT), offering an outstanding picture of our Universe at the highest energies. The majority of this gamma-ray emission has been attributed to known processes involving cosmic-ray interactions with the interstellar medium within our Galaxy. Another important contribution is represented by the gamma-ray emission of known Galactic and extragalactic astrophysical sources. However, still an important fraction ($\sim$20%) of the total gamma-ray emission remains unresolved, and therefore we referred to it as the unresolved gamma-ray background (UGRB). Guaranteed contribution to this component is the cumulative emission of gamma-ray sources that are too faint to be resolved separately and hence lie below the current instrumental sensitivity. On the other hand, even more exotic scenarios involving dark matter particles may contribute as well, making the exact composition of the UGRB one of the main unanswered questions in gamma-ray astrophysics. The unprecedented large sample of high quality gamma-ray photons provided by the *Fermi*-LAT opened a new window on this study: the measurement and characterization of UGRB spatial anisotropies. In this talk I will give an overview of all the different techniques employed in the effort to give a definitive answer to the question of the UGRB composition.

1 Introduction

The UGRB is *nearly* isotropic, and this kind of topology can be easily explained by the cumulative emission of randomly distributed γ-ray sources whose flux is below the sensitivity of *Fermi*-LAT. Hence, these sources are too faint to be resolved separately, and this results in a global diffuse glow. Contribution from well-known extragalactic astrophysical source populations, such as blazars [1, 4] and misaligned AGNs (mAGNs) [2, 3] is guaranteed, them being quite rare objects generally speaking, but the brightest and the most numerous seen in γ-rays. Also, a non-negligible contribution is expected from SFGs [4, 5, 6], which are not very bright in the γ-band but extremely abundant in the Universe and may contribute mostly at low energies ($<$ 10 GeV). Minor contributions from an unresolved population of Galactic millisecond pulsars (MSPs) can be expected [7, 8], as well as from galaxy clusters [9, 10, 1], Type Ia supernovae [11, 12], and GRBs [13, 14]. Furthermore, more exotic scenarios may contribute as well: despite a huge current experimental effort aimed to search for evidence of annihilating or decaying WIMPs through the detection of γ-rays (primarily or secondarily produced), no signal has been robustly associated with DM up to now, so if present it is most probably unresolved and contributes to the UGRB. The first measurement of the UGRB, (as opposed to the EGB, which was measured already by EGRET and SAS-2) in terms of intensity energy spectrum, was performed by the *Fermi*-LAT collaboration in 2010 [15], and from that time on there has been a wide interest to interpret the results, even more accentuated when new measurements, also exploiting different approaches than the intensity spectrum (as we will see in the next section), have been released. Despite the extensive interpretation campaign, the exact composition of the UGRB remains one of the main unanswered questions of γ-ray astrophysics. The interest in finding a definitive answer is attributable to the need to constrain the faint end of the luminosity function of the UGRB contributors, which could also tell something about the cosmological evolution of the classes of objects involved. Since these objects, as we said before, are too faint to be resolved individually, the study of the UGRB may represent the only source of information about them. In addition, the UGRB characterization might shed some light on the nature of DM, constraining the parameter space of mass and annihilation cross-sections or decay lifetimes of weakly interacting massive particles (WIMPs).

2 Autocorrelation

In addition to the mean flux of the UGRB one could extract valuable information from the study of the angular scale and the amplitude of its intensity fluctuations. The technique exploited to perform this analysis is the autocorrelation, both in terms of auto-correlation function (ACF) and angular power spectrum (APS). The final result of this study is an anisotropy energy spectrum, which is sensitive to all the components of the UGRB whose distribution carries a non-negligible small-scale anisotropy content. In Fig. 1 it is reported the result from [20], in which *Fermi*-LAT data between 0.5 GeV and 1 TeV have been analyzed by means of a sophisticated tool to compute the angular power spectrum from UGRB maps. The analysis not only includes the autocorrelation of the unresolved background with itself for each energy bin, but also encompasses all the cross-correlations between different energy bins. The results supports the scenario in which two major and distinct populations are responsible for the observed tiny intensity fluctuations. The two populations emerge at different energies, the transition occurring at ~ 4 GeV. In particular the best-fit model given by a double power law with exponential cutoff, suggests the presence of a bulk of BL Lac type blazars above a few GeV, while at lower energies, a population with a softer spectrum, like possibly misaligned AGNs, FSRQs, SFGs, or even more likely a combination of them, appears to dominate the UGRB. The detection of the high-energy cutoff, once confirmed that it is due to the absorption of energetic γ rays from the EBL, might shed light about the cosmic evolution of the particular contributors dominating at those energies. A proper physical interpretation of this measurement is still a work in progress.

3 Cross-correlation with LSS probes

In addition to the estimation of global UGRB quantities (resulting from the previously listed techniques), it is possible to benefit from an extremely powerful tool to directly characterize the unresolved content, namely cross-correlations of the UGRB with other observables. This technique estimates both cross-correlation functions (CCF) and cross-correlation angular power spectra (CAPS), looking for a non-null signal, which would give immediate evidence of whether the considered observable contributes or not to the UGRB. Cross-correlations with the UGRB have been done considering different large scale structures (LSS) probes, such as galaxy catalogs, galaxy cluster catalogs, cosmic shear and lensing potential of the cosmic-microwave background (CMB).

Cross-correlation with galaxy catalogs. Literature counts several works devoted to the evaluation of the cross-correlation signal between the UGRB and different galaxy catalogs, e.g. [16], [17], [18], and [19]. In particular in [18] exploited a tomographic approach to study the evolution of the cross-correlation signal with the redshift (namely the distance of the galaxies). They clearly detected a change over redshift in the spectral and clustering behavior of the γ-ray sources contributing to the UGRB. In [19] it is presented the cross-correlation between the *Fermi*-LAT sky maps and the 2MPZ catalog through which they investigated the nature of the local $z < 0.2$ γ-ray Universe. They went beyond the tomographic approach by investigating the cross-correlation of the UGRB with different sub-selections of the 2MPZ catalog: three bins in absolute B-band luminosity to investigate the star formation activity, three bins in K-band luminosity to trace the mass of the objects and a low-B/high-K sample as ideal target for DM searches (objects with high-K and low-B luminosities being massive and with a low level of star formation activity). They found that the signal was dominated by AGN emission, while blazars and SFGs provide a subdominant contribution.

Cross-correlation with galaxy cluster catalogs. Clusters of galaxies are the product of hierarchical structure formation processes driven by gravitational instability. Clusters of galaxies are not isolated objects, but live in the nodes of a complex cosmic web, surrounded by filaments that host populations of astrophysical objects. Currently several catalogs of galaxy clusters are available, and in particular in [21] the cross-correlation signal with three different catalogs has been investigated: WHL12 ($0.05 < z < 0.8$), redMaPPer ($0.08 < z < 0.55$), and PlanckSZ ($z < 0.5$). They detected a clear non-zero cross-correlation signal for all the catalogs considered and quantified the statistical significance in terms of number of sigmas in the three energy bins: for WHL12 they found $N_\sigma = 3.7, 4.4$, and 2.9; for redMaPPer they found $N_\sigma = 3.3, 5.0$, and 2.7; for PlanckSZ, due to the limited number of clusters, they opted for considering one single energy bin ($E > 1$ GeV) finding $N_\sigma = 3.7$. Another recent work, [22], investigated the cross-correlation of the UGRB with the Subaru Hyper Suprime-Cam (HSC) catalog, which provides a wide and homogeneous measurement of the large-scale structure distribution up to redshift 1.1. They investigated the cross-correlation signal in two different redshift bins ($0.1 < z < 0.6$ and $0.6 < z < 1.1$). They found a signal with a significance of $2.0 - 2.3\sigma$ for all redshift and low-redshift cluster samples, and a weaker signal with significance of $1.6 - 1.9\sigma$ for the high-redshift sample.

Cross-correlation with cosmic shear. The cosmic shear is a statistical measurement of the distortion of images of distant galaxies due to weak lensing. The same distribution of matter responsible for the lensing traces the γ-ray emission, either because of DM annihilation (and/or decay) or because of astrophysical γ-ray emitters hosted by DM structures, hence one expects correlation between the two fields. The first measurement of the cross-correlation of the extragalactic gamma-ray sky with cosmic shear was performed by [23], and recently the same group published the updated results exploiting the

Subaru Hyper Suprime-Cam (HSC) SSP survey [24]. The conclusion of that work was that given the current statistical significance of the signal results are compatible with having no signal, the hope being to get more information from the HSC final data. Ref [25] is an investigation of the cross-correlation of the UGRB with other galaxy cluster surveys, in particular: the Canada-France-Hawaii Telescope Lensing Survey (CFHTLenS), the Red Cluster Sequence Lensing Survey (RCSLenS), and the Kilo Degree Survey (KiDS). They found no cross-correlation signal and no improvement was achieved by exploiting of a tomographic approach. A very recent work related to this measurement is [26], which exploiting 9 years of Fermi-LAT data and the Dark Energy Survey (DES), for the first time has detected a non-null cross-correlation signal. In particular, based on a signal-to-noise ratio of 4.5, their results show that the signal is mostly localized at small angular scales and high γ-ray energies, with a hint of correlation at extended separation.

Cross-correlation with CMB. CMB photons traveling toward us from the last scattering surface encounters a super-clusters and super-voids of matter along its journey, and undergo the so-called *integrated Sachs-Wolfe* (ISW) effect, caused by the expansion of the Universe at late cosmological time, when the Universe itself became Dark Energy (DE)-dominated. The net result of this effect is that the CMB temperature appear slighlty warmer/colder in correspondence of a super-cluster/super-void than it would otherwise. The same superclusters being expected to produce γ-rays, measuring the cross-correlation between the CMB map and the UGRB can potentially probe the properties of DE in the local Universe. This was investigated in [16] for the first time. Unfortunately they found a cross-correlation signal consistent with zero; the poor data statistics of the γ data (at that time) may have contributed to this negative result, and we cannot exclude that a future more updated work could lead to a non-null correlation. Recently [27] explored the possibility to find correlation between the UGRB and the *lensing potential* of the CMB: the gravitational lensing induced by LSS perturbs the statistical properties of the CMB and imprints some distortions on its anisotropy pattern, in such a way that the radiation detected today is not exactly that emitted at recombination. They found a preference for a signal with the correct features expected from the extragalactic γ-ray emission with a 3.0σ significance.

Fig. 2, therefore, shows the significance of cross-correlation signals between the UGRB and several LSS probes denoted by different colors: the widths of the bars illustrate the redshift ranges considered and beside each bar we indicate the energy range relative to the found cross-correlation signal.

4 Conclusion

The great interest in unveiling the UGRB composition is evident from the several different techniques that have been exploited to achieve that goal. We mentioned the study of its intensity energy spectrum, but other techniques, which exploits the statistical features of the field, are the 1-point probability distribution function (or 1-point PDF), the autocorrelation, and the cross-correlation with other observables tracing the large scale structures of the Universe. In this contribution we focused on the autocorrelation measurement and the cross-correlations of the UGRB with galaxy catalogs, galaxy cluster catalogs, CMB, CMB lensing potential and weak lensing. Combining all the results from those analyses will be the ultimate effort towards the unveiling of the nature of the unresolved gamma-ray emission.

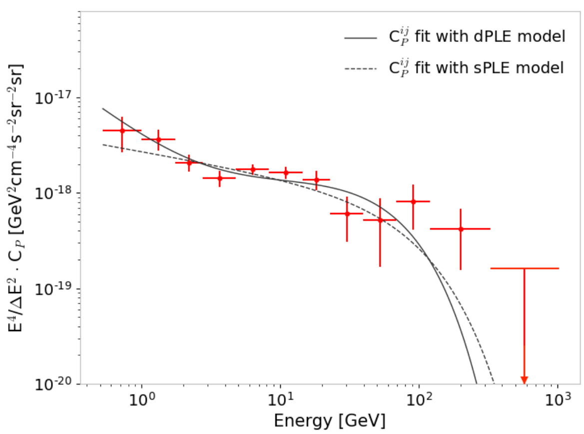

Figure 1: *UGRB Autocorrelation energy spectrum.*

5 Acknowledgements

The *Fermi*-LAT Collaboration acknowledges support for LAT development, operation and data analysis from NASA and DOE (United States), CEA/Irfu and IN2P3/CNRS (France), ASI and INFN (Italy), MEXT, KEK, and JAXA (Japan), and the K.A. Wallenberg Foundation, the Swedish Research Council and the National Space Board (Sweden). Science analysis support in the operations phase from INAF (Italy) and CNES (France) is also gratefully acknowledged. This work performed in part under DOE Contract DE-AC02-76SF00515.

References

1. Ando, S. *et al*, Mon. Not. Roy. Astron. Soc., 376, 4 (2007).
2. Inoue Y., Ap. J., 733, 66 (2011).
3. Di Mauro, M. *et al*, Ap. J., 780, 161 (2014).
4. Stecker, F. W. and Venters, T. M., Ap. J., 736 (2011).
5. Fields, B. D. *et al*, Phys. Rev. Lett. **13**, 138 (1964).
6. Makiya, R. *et al*, Ap. J., 728 (2011).
7. Siegal-Gaskins, J. M. *et al*, Mon. Not. Roy. Astron. Soc., 415 (1964).
8. Calore, F. *et al*, Ap. J., 796 (2014).
9. Miniati, F., Mon. Not. Roy. Astron. Soc., 337 (2002).
10. Keshe, U. *et al*, Ap. J., 585 (2003).
11. Ahn, K. *et al*, Phys. Rev. D17, 12 (2005).

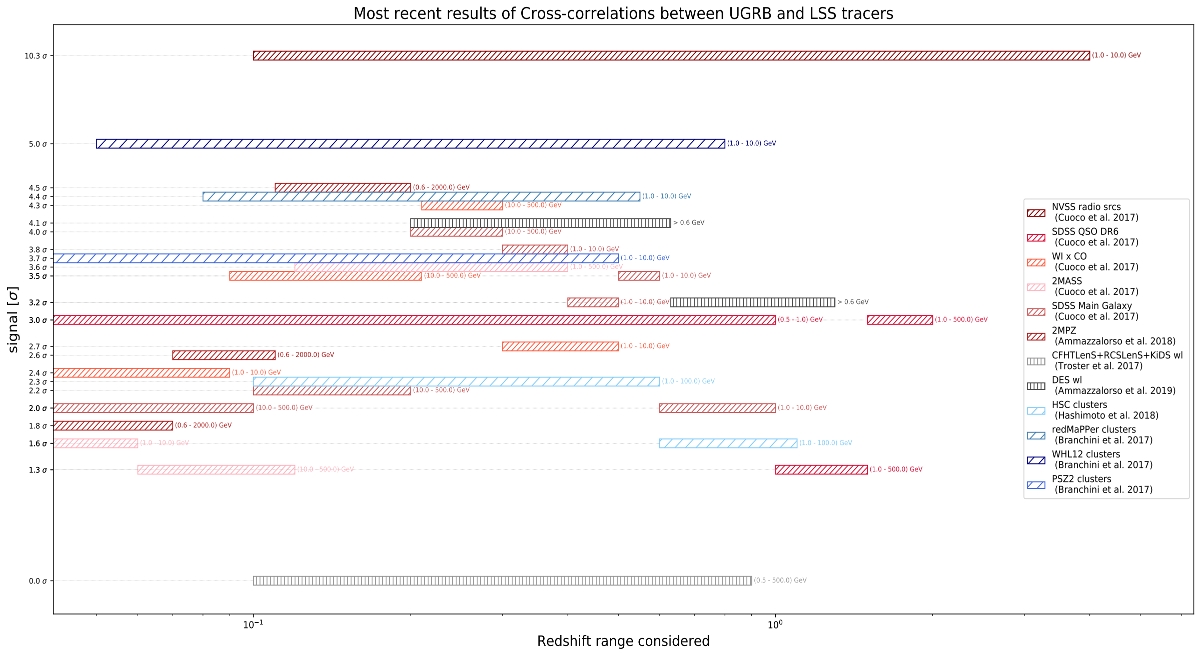

Figure 2: *Summary of Cross-Correlation signal between the extragalactic gamma-ray sky and LSS probes.*

12. Rasera, Y. *et al*, Phys. Rev. D74, 10 (2006).

13. Casanova, S. *et al*, Proceedings: Gamma-Ray Bursts 2007, 1000 (2008).

14. Ando, S. *et al*, Ap. J., 689 (2008).

15. Abdo, A.A. *et al*, Phys. Rev. Lett., 104 (2010).

16. Xia, J.-Q. *et al*, Mon. Not. Roy. Astron. Soc., 416 (2011).

17. Xia, J.-Q. *et al*, Ap. J. Suppl., 217 (2015).

18. Cuoco, A. *et al*, Mon. Not. Roy. Astron. Soc., 416 (2017).

19. Ammazzalorso, S. *et al*, Phys. Rev. D98, 10 (2018).

20. Ackermann, M. *et al*, Phys. Rev. Lett. 121, 24 (2018).

21. Branchini, E. *et al*, Astrophys. J. Suppl. 228, (2017).

22. Hashimoto, D. *et al*, Mon. Not. Roy. Astron. Soc., 448, 4 (2019).

23. Shirasaki, M. *et al*, Phys. Rev. D90 (2014).

24. Shirasaki, M. *et al*, Phys. Rev. D97, 12 (2018).

25. Tröster, T. *et al*, Mon. Not. Roy. Astron. Soc., 467 (2017).

26. Ammazzalorso, S. and others., arXiv:1907.13484 (2019)

27. Fornengo, N. *et al*, Ap. J 802 (2015)