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Cosmological Large Scale Anisotropies in the high-energy gamma-ray sky

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Abstract: The interactions that characterize the propagation of γ photons in the TeV energy range introduce a cosmological horizon at the distance of few hundreds Mpc, implying a correlation with the local Large Scale Structures. We provide detailed predictions of the expected anisotropies based on the map of the local universe from the PSCz astronomical catalogue. We then discuss the chances to detect the predicted signal with the forthcoming satellite observatory Glast and the extensive air showers detectors Milagro, and HAWC.

Gamma Astronomy

The 0.1–10 TeV range represents one of the "last" photonic windows yet to be explored at large distances. Besides single sources, wide field of view instruments like the extensive air showers detectors (EAS) Milagro, Argo and the planned HAWC and satellite-based observatories like GLAST are sensitive to diffuse γ-ray emissions.

A particularly interesting emission is the extragalactic diffuse γ-ray background (in the following, cosmic gamma background, or CGB). The CGB is a superposition of all unresolved sources emitting γ-rays in the Universe and provides an interesting signature of energetic phenomena over cosmological time-scales. While a clear detection of this background has been reported by the EGRET mission [1], its origin is still uncertain, despite the fact that many models have been proposed. The most likely contribution is the one from unresolved blazars, i.e. beamed population of active galactic nuclei, with (probably sub-leading) components from ordinary galaxies, clusters of galaxies, and gamma ray bursts. However, exotic possibilities like dark matter annihilation have been proposed, that are compatible with existing data and constraints. It is extremely difficult to test such models as long as the only observable is the energy spectrum. Recently, it was proposed to use the peculiar small-scale anisotropy encoded in the MeV-GeV gamma sky to probe dark matter [2, 3] or astrophysical [4, 5] contributions to the CGB. We further study this topic, with particular emphasis on the large scale anisotropy in the energy range 0.1-10 TeV. The lower part of this range will be probed by the GLAST telescope [6], while the energy window above the TeV is in principle accessible to EAS detectors like Milagro [7] and Argo [8]. Different candidates to explain the CGB predict distinctive large scale features, even when similar energy spectra are expected. This is a consequence of the combined effect of a cutoff distance after which γ of energy starting from about 100 GeV (the very-high energy regime, VHE) can travel undamped to us, and of the anisotropic distribution of matter in the local universe (i.e., within a few hundred Mpc from us), the local Large Scale Structures (LSS). We shall then use the redshift Point Sources Catalogue (PSCz) [9] as tracer of the real structures in the nearby universe, thus producing maps of the VHE gamma sky.

It is interesting to note that a similar horizon (and a similar correlation with LSS) is expected for cosmic rays particles of energy $\gtrsim 10^{19}$ eV (the so called ultra-high energy (UHE) regime) [10] (see also [11]). Indeed, possibly a fraction of CGB could be associated to the γ cascades produced

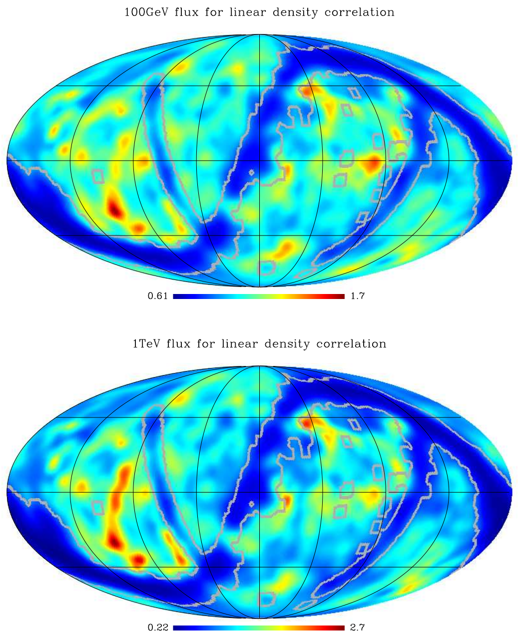

Figure 1: Equatorial density γ sky maps from the PSCz catalogue for $E_{\rm cut} = 100$ GeV and 1 TeV. The color scale is linear and the average flux outside the mask of the PSCz is normalized to 1 so that to represent adimensional maps. The mask of the PSCz survey is indicated by the thick grey contour.

by the energy losses from the propagation of UHE hadrons [12].

For a more complete and detailed discussion of the present issues we refer the reader to the paper [13].

Sky maps and forecast

In Fig. 1 we plot the resulting γ maps from the PSCz catalogue in equatorial coordinates for $E_{\rm cut} = 100$ GeV and 1 TeV. For the case of the map with $E_{\rm cut} = 100$ GeV, modulo the “hole” due to the mask the pattern is quite isotropic, with some hot spots like e.g. from the Virgo and Perseus Clusters. Other structures which appear are the Shapley concentration and the Columba cluster (for a key of the local cosmological structures see [10]). Given the limited statistics of GLAST at high energies, the TeV map is of interest especially for the EAS gamma detectors like MILAGRO. We see in this case that the nearest structures, forming the Super-Galactic Plane, dominate. Of course, from the Northern emisphere (where all the present or planned EAS instruments are located) only the upper part of the map is visible. Here, the Virgo Cluster and the Perseus cluster offer the strongest anisotropy.

To obtain the maps the effects of the propagation of the particles through the relevant Infrared/Optical and Microwave backgrounds have been properly taken into account. Further details can be found in the paper [13].

What are the real chances to detect these anisotropies with the data from the forthcoming experiments? To answer the question we have performed an harmonic decomposition of the maps $f(\hat{\Omega}) = \sum_{lm} a_{lm} Y_{lm}(\hat{\Omega})$ and then assessed the predicted shot noise errors on the a_{lm} due to the finite statistics collected by a given experiment. In particular, the errors read as $\sigma^2_{a_{lm}} = 4\pi f_{\rm sky}/N_\gamma\,(1 + N_{\rm CR}/N_\gamma)$ where N_γ and $N_{\rm CR}$ are respectively the numbers of photons and background events collected and $f_{\rm sky}$ is the fraction of the sky accessible to the experiment (assumed with uniform acceptance over this region).

In Fig. 2 we report the coefficients a_{lm}'s up to $l_{\rm max} = 10$ calculated from the PSCz gamma maps of Fig.1, with the relative errors for a 4 year exposure of the GLAST mission and 10 years for the EAS Milagro and HAWC. Performing the analysis in terms of the harmonics coefficients a_{lm} instead of angular power spectrum C_l's has the advantage of exploiting the full information present in the map (for an angular scale of order $\theta = \pi/l$) without the limit imposed by cosmic variance.

GLAST should be able to detect some structures above 100 GeV at the 2σ level, while, on the contrary, instruments like MILAGRO may hardly find hints of structures at 1 TeV (gray band in the bottom panel of Fig. 2). We note that the intensity of the anisotropies increases sensibly from the 100 GeV energy band to 1 TeV, but, despite the increased signal and statistics collected, ground arrays have an hard task in detecting the CGB fluctuations. The signal detected by EAS arrays is infact buried under an heavy background of Cosmic Rays events that overwhelms the gamma signal typically by a factor of order 10^5! Rejection capability helps in removing part of the background. Note that GLAST is expected to have an excellent background identification, so that only cosmic rays in the amount of $\sim 6\%$ of the gamma flux pass the cuts. On the other hand, EAS experiments have a poor rejection capability, which increases typically the gamma content of the diffuse flux by no more than one order of magnitude. Therefore even after gamma/hadron separation, the anisotropies of the gamma sky have to be identified against a *quasi*-isotropic background which is $\sim 10^4$ larger than the gamma flux.

It is further worth to notice that for an EAS detector the error on the a_{lm}'s scales as $\sqrt{N_{\rm CR}}/N_\gamma$. Therefore the reduction of the shot-noise error goes like $(t \cdot A_{\rm eff})^{-1/2}$ (both $N_{\rm CR}$ and N_γ grow linearly with $t \cdot A_{\rm eff}$, the collecting time times the effective area of the experiment), or equivalently as $\sqrt{h_{\rm cut}}/g_{\rm cut}$ (where $g_{\rm cut}$ and $h_{\rm cut}$ are the fraction of γ's and hadrons that survive after the trigger cuts): improving the exposure is equally important as improving the gamma/hadron separation capability. A simple inspection of Fig. 2 reveals that for a realistic detection of the features in the VHE sky one would need the improvement in effective area planned to be reached by instruments like HAWC [14] (see inner green band in the bottom panel of Fig. 2). An instrument like ARGO is expected to have performances in between MILAGRO and HAWC, and may have some chance especially if a significant improvement in hadron rejection can be made. Also, note that due to their altitude HAWC and ARGO have a significant acceptance of sub-TeV events. While the gamma/hadron separation is less efficient at lower energies, the higher statistics may help in revealing these structures. Let's also note that these estimates are somewhat conservative: summing the power at different l's may favor the detection (see e.g. [5]), and cross-correlating directly with the maps we have produced would eventually rely on the whole information.

Finally, the ultimate limitation in detecting anisotropies in the gamma sky with EAS observatories is expected to come from the understanding of the intrinsic anisotropy in the CR background that are generally measured at the level of few$\times 10^{-4}$ and are then comparable to the expected intrinsic γ anisotropy. One possible strategy to tackle this problem, could consist in reversing the gamma cut and thus enriching the sample in hadronic showers thus helping in identifying and removing non-gamma anisotropies.

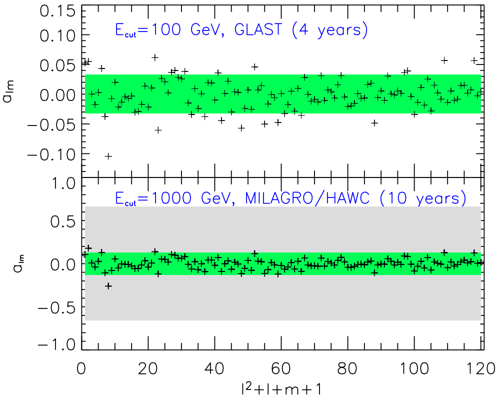

Figure 2: The coefficients a_{lm} up to $l_{\rm max} = 10$ calculated from the PSCz gamma maps of Fig. 1. The shaded band shows the 1-σ shot noise error; in the bottom panel the inner shaded region refers to HAWC, the outer one to MILAGRO.

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