Unresolved Gamma-Ray Sky through its Angular Power Spectrum

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The gamma-ray sky has been observed with unprecedented accuracy in the last decade by the *Fermi* Large Area Telescope (LAT), allowing us to resolve and understand the high-energy Universe. The nature of the remaining unresolved emission (Unresolved Gamma-Ray Background, UGRB) below the LAT source detection threshold can be uncovered by characterizing the amplitude and angular scale of the UGRB fluctuation field. This work presents a measurement of the UGRB autocorrelation angular power spectrum based on 8 years of *Fermi* LAT Pass 8 data products. The analysis is designed to be robust against contamination from resolved sources and noise systematics. The sensitivity to sub-threshold sources is greatly enhanced with respect to previous measurements. We find evidence (with $\sim 3.7\sigma$ significance) that the scenario in which two classes of sources contribute to the UGRB signal is favored over a single class. A double-power-law with exponential cutoff can explain the anisotropy energy spectrum well, with photon indexes of the two populations being 2.55 ± 0.23 and 1.86 ± 0.15.

I. INTRODUCTION

The Universe has a network of structures. The so-called cosmic web was formed by gravitational instabilities, starting from the tiny density fluctuations that originated during primordial inflation, which evolved into structures at very different scales, from stars to galaxies, up to galaxy clusters and filaments. Furthermore, this texture nurtures the formation of non-thermal astronomical sources.

In ten years of operation, the *Fermi* Large Area Telescope (LAT) has been providing an unprecedented census of non-thermal emitters in gamma rays. The most recent *Fermi*-LAT 8-year preliminary Point Source List (FL8Y[1]) contains 5524 objects detected with a significance greater than 4σ between 100 MeV and 1 TeV.

Gamma-ray sources that are too dim to be resolved individually by *Fermi*-LAT contribute cumulatively to the Unresolved Gamma-Ray Background (UGRB), see Ref. [7] for a recent review. Although the exact composition of the UGRB is still an open issue, high-latitude sources are expected to be mostly of extragalactic origin. Therefore they should follow the matter potential in the Universe (with some bias) and should be distributed anisotropically in the sky.

Different populations of gamma-ray emitters induce anisotropies in the UGRB with different amplitudes and different angular and energy spectra. A measurement

[1] `https://fermi.gsfc.nasa.gov/ssc/data/access/lat/fl8y/`

of the gamma-ray angular power spectrum (APS) can therefore constrain the nature of the UGRB in a complementary way with respect to the intensity energy spectrum and the 1-point photon count probability distribution [5]. A different but related approach based on two-point statistics is the cross correlation of the gamma-ray sky with independent probes tracing the large scale structures of the Universe [8–24].

The first detection of anisotropies in the UGRB was reported by the *Fermi*-LAT Collaboration in 2012 [25], and then updated in 2016, employing 81 months of Pass 7 *Fermi* LAT data from 0.5 to 500 GeV [26] (hereafter Fornasa et al.). The latter analysis revealed a hint that the measured APS might be due to more than one population of sources [27].

The raw APS (namely, the one that is measured directly from *Fermi*-LAT gamma-ray maps) is the sum of three contributions: a) a noise term, C_N, due to fluctuations of photon counts, showing no correlation between different pixels in the sky and thus producing a flat APS; b) the auto-correlation of fluctuations due to individual sources with themselves (C_P): in the limit of point-like sources and infinite angular resolution of the telescope, this term shows up only at zero angular separation in real space (which implies a flat APS), but the finite size of the point-spread function (PSF) makes the associated APS decrease at high multipoles; c) the correlation between fluctuations induced by sources located in different positions in the sky: this contribution is expected to trace the cosmic web. C_N is expected to become less and less relevant as the statistics grow. C_P decreases as the brightest sources become resolved. In the current state of gamma-ray searches, it is still the dominant physical contribution to the APS. The third term is expected to eventually take over once the sensitivity of the telescope is such that a sufficiently large number of bright sources are resolved (and so no longer contribute to the UGRB).

II. SIGNAL EXTRACTION

A study of morphological anisotropies requires data with a good angular resolution. The data selection used in this analysis is designed to obtain the purest event sample and to maximize both the precision of the reconstructed arrival directions and the total photon counts statistics. For these reasons we select Pass 8 [2] data of the P8R3_SOURCEVETO_V2 event class[3], and we reject the quartile of events with the worst PSF, which corresponds to all the events flagged as PSF0 type.

The data selection comprises 8 years and is performed using version v10r0p5 of the *Fermi* Science Tools. Data in the energy range between 100 MeV and 1 TeV is subdivided into 100 logarithmically spaced "micro" bins, and for each of them we produce a count map and an exposure map, whose ratio gives 100 flux maps. They are then summed in order to obtain intensity maps in 12 "macro" energy bins between 524 MeV and 1 TeV (see Tab. I). This choice minimizes the effects of the energy dependence of the exposure, and we exploited this fine binning in the estimation of the autocorrelation as will be explained in the next section. Data are spatially binned with HEALPix[4] order 9.

The flux maps are masked such that the majority of the Galactic interstellar emission is removed, as well as the contribution from the resolved sources listed in the FL8Y source list (adding sources from the 3FHL catalog [28] when considering energies beyond 10 GeV). The source mask is built taking into account both the brightness of each source and the energy dependence of the PSF. We tested the effectiveness of our masks performing several tests described in the Supplemental Online Material (SOM) [30]. Fig. 2 illustrates the mask built for the energy bin between 1.7 and 2.8 GeV.

In order to eliminate the residual Galactic contribution, we subtract the Galactic diffuse emission (GDE) with the model gll_iem_v6.fits described in [29]: in each micro energy bin, we perform a Poissonian maximum likelihood fit of data maps (considering only unmasked pixels) with the GDE model (with a free normalization) and a spatially constant term accounting for the UGRB and possible cosmic-ray residuals in the LAT; we find normalizations compatible with one within 1σ statistical uncertainty in each energy bin, and then we subtract the normalized GDE model from data maps. An example of masked map leaving only the UGRB in the energy bin (1.7–2.8) GeV is illustrated in the right panel of Fig. 2.

III. ANGULAR POWER SPECTRUM ANALYSIS

The APS of intensity fluctuation is defined as: $C_\ell^{ij} = \frac{1}{2\ell+1}\langle\sum_m a^i_{\ell m} a^{j*}_{\ell m}\rangle$, where the brackets indicate the average on the modes m, the indexes i and j label the i^{th} and the j^{th} energy bins. When $i = j$, we refer to autocorrelation, to cross-correlation otherwise. The coefficients $a_{\ell m}$ are given by the expansion in spherical harmonics of the intensity fluctuations, $\delta I_g(\vec{n}) = \sum_{\ell m} a_{\ell m} Y_{\ell m}(\vec{n})$, with $\delta I_g(\vec{n}) \equiv I_g(\vec{n}) - \langle I_g\rangle$ and $\vec{n}$ identifies the direc-

[2] https://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/Cicerone/Cicerone_Data/LAT_DP.html

[3] The new SOURCEVETO event class, currently under development in the LAT collaboration and planned for public release, has an acceptance comparable to P8R2_CLEAN_V6 with a residual contamination almost equal to that of P8R2_ULTRACLEANVETO_V6 at all energies.

[4] http://healpix.sourceforge.net

tion in the sky. The APS hence quantifies the amplitude of the anisotropy associated with each multipole ℓ, which roughly corresponds to a pattern "spot" size of $\lambda \simeq (180°/\ell)$.

We compute the APS with PolSpice [31, 32], a Fortran90 software tool which is based on the fast Spherical Harmonic Transform. PolSpice estimates the covariance matrix of the different multipoles taking into account the correlation effect induced by the mask with the algorithm described in [33, 34]. Prior to the measurement, we exploited the standard HEALPix routine to removed the monopole and the dipole terms from the intensity maps in order to eliminate possible spectral leakage (owing to the masking) of these large-scale fluctuations (which have large amplitudes) on the small scales we are interested in.

The resolution of the maps and the effect of the PSF are accounted for respectively by the pixel window function, $W^{\rm pix}(\ell)$, and the beam window function, $W^{\rm beam}(E,\ell)$, whose computation is described in the SOM. Any random noise would contribute to the signal when the autocorrelation in the $i^{\rm th}$ energy bin, $C_\ell \equiv C_\ell^{ii}$, is performed, hence it must be subtracted from the raw APS. We know that a Poissonian white noise would have a flat APS which can be estimated as in Fornasa et al.: $C_N = \frac{\langle n^i_{\gamma,\rm pix}/(\epsilon^i_{\rm pix})^2\rangle}{\Omega_{\rm pix}}$, $n^i_{\gamma,\rm pix}$ being the photon counts in the unmasked pixels, $\epsilon^i_{\rm pix}$ the exposure, and $\Omega_{\rm pix}$ the pixel solid angle. Considering this as the only noise term, any other random component not following a Poisson distribution would not be taken into account. Moreover, the above equation for $\hat{C}_N$ represents only an estimator of the true C_N. Indeed, we found evidence of an underestimation of the noise term above a few GeV, and devised a method to determine the autocorrelation APS without relying on the estimate of C_N. We exploit cross-correlations between different but closely adjacent micro energy bins: these are not affected by the noise term, since any kind of noise would not correlate between independent data samples. Also, we do not expect any effect due to the energy resolution of the instrument since the width of the micro bins is larger than the energy resolution, except for bins below 1 GeV (the first macro bin) whose result is anyway compatible with the one obtained by the standard autocorrelation method which is valid at those energies. As explained in the previous section, our macro energy bins are composed of a number N_b of micro energy bins. The APS computed in the macro bin can be seen as the sum of all the auto and cross APS computed for all the micro energy bins:

$$C_\ell = \sum_{\alpha=1}^{N_b} C_{\ell,\rm micro}^{\alpha\alpha} + 2\sum_{\substack{\alpha,\beta\\ \alpha>\beta}} C_{\ell,\rm micro}^{\alpha\beta} \tag{1}$$

where $\alpha,\beta = 1,...,N_b$.

Under the reasonable assumption that the contributing sources have a broad and smooth energy spectrum, the APS for each macro energy bin can be obtained as:

$$C_\ell = \frac{N_b}{N_b-1}\sum_{\substack{\alpha,\beta\\ \alpha\neq\beta}} \frac{C_{\ell,\rm micro}^{\alpha\beta,\rm Pol}}{W_{E_\alpha}(\ell)W_{E_\beta}(\ell)} \tag{2}$$

where $W_{E_\alpha}(\ell) = W^{\rm beam}_{E_\alpha}(\ell)W^{\rm pix}_{E_\alpha}(\ell)$ and N_b is the number of micro bins in each macro energy bin[5]. In this way, we avoid relying on the autocorrelation of the micro bins and therefore on the estimate of the noise. The SOM provides more details to support this approach.

A. Autocorrelation anisotropy energy spectrum

For each energy bin, we find no evidence for an ℓ-dependent APS. This flat behavior is expected if the anisotropy signal is dominated by unresolved point-like sources isotropically distributed in the sky. We therefore derive the level of anisotropy, C_P, for each energy bin by fitting the APS with a constant value: this provides the energy spectrum of the anisotropy signal due to gamma-ray point-like sources. Prior to this fit, each APS was binned to reduce the correlation among neighboring C_ℓ. To carry out the binning in the most effective way, we implemented the unweighted averaging procedure proposed in Fornasa et al., which was validated with Monte Carlo simulations (see Sec. IV-A of Fornasa et al.). The range of multipoles considered for the fitting procedure is determined taking into account several considerations: we exclude $l < 50$ where residual large-scale contributions from the foreground emission are significant and leakage from large-scale fluctuations still could be important; the beam window function correction is inaccurate when considering scales much smaller than the PSF: the upper limit in multipole depends on the PSF and on the photon statistics at a specific energy, and hence varies with the energy bin. Further details are provided in the SOM.

In Tab. I, we report the obtained C_P as a function of energy, as well as the fitting range of multipoles considered, and the systematics related to the uncertainty of the *Fermi*-LAT effective area $A_{\rm eff}$[6].

[5] Note that Eq. 2 returns a better approximation if the width of the micro bins decreases, and/or N_b increases, and/or the global spectrum of the underlying source population flattens. We calculated that when $N_b > 3$, considering our micro energy bin width and an anisotropy energy spectrum $\sim E^{-4}$, the difference between Eq. 1 and Eq. 2 is less than 1%. We use Nb = 6 for all but the two highest-energy macro bins, for which we use Nb = 11 and Nb = 12, respectively.

[6] This uncertainty is obtained doubling the systematic uncertainty of the instrumental $A_{\rm eff}$, since the APS is the square of the intensity. https://fermi.gsfc.nasa.gov/ssc/data/analysis/LAT_caveats.html

E_{min}-E_{max} [GeV]	Fit range [l_{min}-l_{max}]	$C_P \pm \delta C_P$ [$\mathrm{cm^{-4}s^{-2}sr^{-2}sr}$]	$C^{sys}_{P,A_{\rm eff}}$ [%]
$0.5-1.0$	$50-150$	(3.7 ± 1.5) E-18	20
$1.0-1.7$	$50-250$	(6.6 ± 1.6) E-19	20
$1.7-2.8$	$50-450$	(9.4 ± 1.8) E-20	20
$2.8-4.8$	$50-600$	(3.4 ± 0.63) E-21	20
$4.8-8.3$	$50-900$	(1.4 ± 0.18) E-21	20
$8.3-14.5$	$50-1000$	(4.3 ± 0.61) E-22	20
$14.5-22.9$	$50-1000$	(9.0 ± 2.1) E-22	20
$22.9-39.8$	$50-1000$	(2.1 ± 1.0) E-22	20
$39.8-69.2$	$50-1000$	(5.9 ± 4.0) E-23	20
$69.2-120.2$	$50-1000$	(3.1 ± 1.5) E-23	22
$120.2-331.1$	$50-1000$	(1.2 ± 0.73) E-23	25
$331.1-1000.0$	$50-1000$	(-4.4 ± 11) E-25	32

TABLE I. C_P values and the corresponding errors δC_P for each energy bin, as well as the range of multipoles considered in the fit of the APS and the systematic error associated to the instrumental effective area.

Fig. 1 shows our measurement of the anisotropy energy spectrum between 524 MeV and 1 TeV.

B. Cross-correlations between energy bins

A way to discriminate whether the signal is due to either a single class or multiple classes of point-like sources is to study the cross-correlations among energy bins: distinct populations of sources, presenting different energy spectra, reasonably lie in different sky positions.

Similarly to the autocorrelation APS, we find flat cross-APS when performing cross-correlations between macro energy bins. If the anisotropy cross signal is due to a single class of sources, then $C_P^{ij} = \sqrt{C_P^{ii}\, C_P^{jj}}$, where C_P^{ii} and C_P^{jj} are the autocorrelation anisotropy levels in the energy bins i and j respectively. The ratio $r_{ij} = C_P^{ij}/\sqrt{C_P^{ii}\, C_P^{jj}}$ is the cross-correlation coefficient: it should be compatible with 1 for each ij pair if the signal is due to a single class of sources. Fig. 3 (left panel) shows the r_{ij} matrix: low-energy bins clearly correlate with nearby bins, while correlate less with the high-energy ones, and *vice versa*, meaning that sources contributing to the signal at low energy are not located at the same positions (on the spherical sky projection along the line of sight) as those that contribute at high energy. Hence, more than one class of source is present.

IV. DISCUSSION

The global measurement, given by both the auto and the cross-correlations, can be exploited to perform a statistical test, in order to establish whether a double-population scenario is favored with respect to a single-population case. We compute the χ^2 for two models: a single power law with an exponential cutoff, sPLE (3 free parameters: normalization, spectral index and cutoff energy), and a double power law with an exponential cutoff, dPLE (5 free parameters: 2 normalizations, 2 indexes and the cutoff energy[7]). The analytical expressions of these two models are:

$$N_1 \times (E_i E_j)^{-\alpha} e^{\left(-\frac{E_i+E_j}{E_{\rm cut}}\right)} \tag{3}$$

$$\left[N_1 \times (E_i E_j)^{-\alpha} + N_2 \times (E_i E_j)^{-\beta}\right] e^{\left(-\frac{E_i+E_j}{E_{\rm cut}}\right)} \tag{4}$$

The fit is performed on the C_P^{ij} normalized by $E_i^2 E_j^2/[(\Delta E_i)(\Delta E_j)]$, where E_i and E_j refer to the logarithmic center of the $i^{\rm th}$ and $j^{\rm th}$ energy bins, and the resulting best-fit parameters are summarized in Tab. II. The results of the best fits for the autocorrelation amplitudes C_P are shown in Fig. 1.

The chi-square difference between the two best-fit configurations is $\Delta\chi^2 = \chi^2_{\rm sPLE} - \chi^2_{\rm dPLE} = 12.24$. In order to obtain the statistical significance of the result, we performed 10^7 Monte Carlo samplings of the null hypothesis (the sPLE model) and derived the distribution of the chi-square differences, from which we determine a preference for the dPLE model at the 99.98% CL (corresponding to $\sim 3.7\sigma$). Details about the Monte Carlo can be found in the SOM.

The two power-law indices resulting from the best fit of the dPLE model are -2.55 ± 0.23, for the low-energy component and -1.86 ± 0.15, for the one dominating above a few GeV.

The best fit for the dPLE model reveals a transition range between the two populations around 4 GeV. Separating the first 4 energy bins from the following 6 bins (we exclude the last 2 energy bins, which are completely beyond $E_{\rm cut}$, in order to avoid energies affected by absorption by the extragalactic background light), we define 4 sub-rectangles of the cross-correlation coefficient matrix, and evaluate the mean and the standard deviation of the mean for each sub-rectangle. The values are shown in the right-hand panel of Fig. 3: the off-diagonal region deviates from 1 at 4σ, which unequivocally favors a double population scenario.

While detailed modeling of the underlying source classes is left for upcoming work, our findings are compatible with most of the contributions being from blazar-like sources above a few GeV. At lower energies, a population with a softer spectrum, such as possibly misaligned AGNs [36] or a different type of blazars [37], appears to dominate the UGRB.

[7] For simplicity (i.e., to reduce the number of parameters) and since we expect the first population to be subdominant at high energy, we apply a single spectral cutoff.

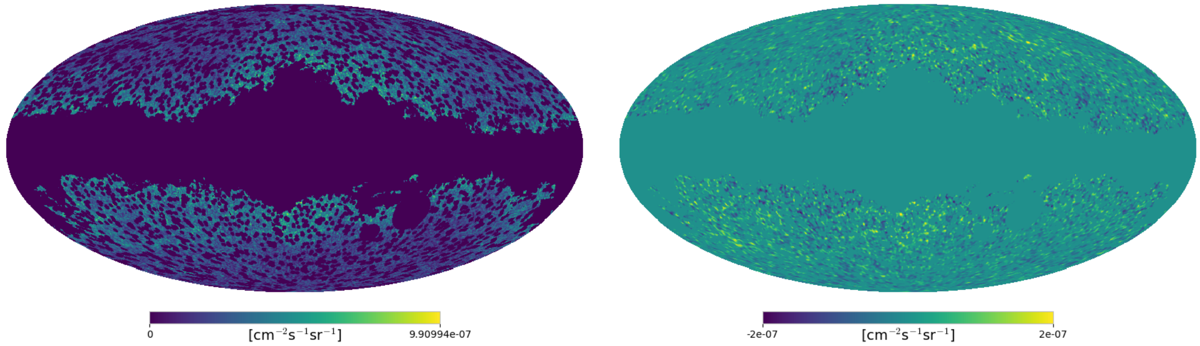

FIG. 2. Left: Mollweide projection of the all-sky intensity map for photon energies in the (1.7–2.8) GeV interval, after the application of the mask built for this specific energy bin; right: Mollweide projection of the UGRB map between (1.7–2.8) GeV. Masked pixels are set to 0; Maps have been downgraded to order 7 for display purposes and smoothed with a Gaussian beam with $\sigma = 0.5^\circ$ and $\sigma = 1^\circ$ respectively.

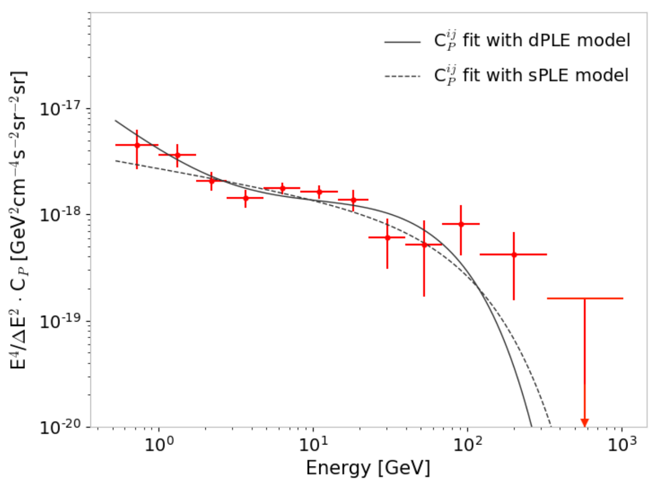

FIG. 1. Anisotropy energy spectrum $C_P(E)$, whose values are reported in Tab. I. We also show the best-fit models sPLE (single power law with exponential cutoff) and dPLE (double power law with exponential cutoff), and we stress that they have been obtained by considering the total set of C_P^{ij} from both auto- and cross-correlations between macro energy bins (see the last section for details about the fitting procedure).

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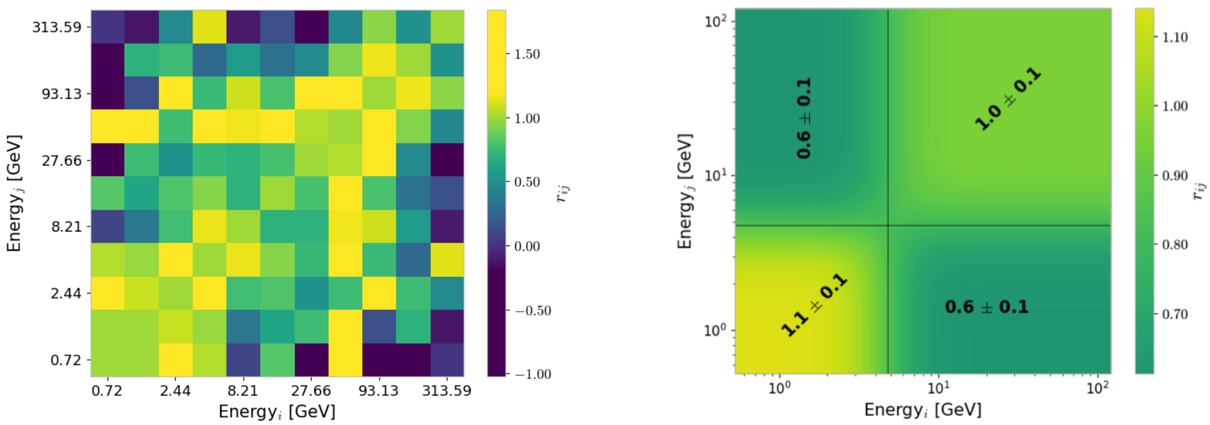

FIG. 3. Left: Cross-correlation coefficient r_{ij} matrix. This matrix is symmetric and has 1 on the diagonal by construction; the column and the row involving the last energy bin have been removed since the autocorrelation value is negative there and the corresponding r_{ij} values have negative roots. Right: mean values and standard deviation of the mean in each sub-rectangle of the r_{ij} matrix. If only one population contributed to the anisotropy signal, the mean values in the off-diagonal sub-rectangles would be values compatible with one, which is not the case.

Fit Parameters							
Model	N_1	α	N_2	β	$E_{\rm cut}$	χ^2	DoF
sPLE	(2.7±0.3)E-18	0.13±0.03	–	–	170±50	84.7	75
dPLE	(3.5±0.8)E-18	0.55±0.23	(7.6±6.4)E-19	−0.14±0.15	89±24	72.5	73

TABLE II. Parameters of the fit of the global C_P^{ij} energy spectrum for both a single power law with an exponential cutoff and for a double power law with an exponential cutoff. $E_{\rm cut}$ is in GeV, while N_1 and N_2 have the same dimension as $E^2{\rm C}_P^{ij}$. DoF is the difference between the number of ${\rm C}_P^{ij}$ considered $((12 \times (12+1))/2)$ and the number of free parameters of the model. Since the fit has been performed on the ${\rm C}_P^{ij}$ normalized by a factor whose global dimension is E^2, a factor of 2 should be added to the indices of the power laws to obtain the values in terms of intensity spectra.

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