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Resolving the Extragalactic γ-ray Background above 50 GeV with Fermi-LAT


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The Fermi Large Area Telescope (LAT) Collaboration has recently released a catalog of 360 sources detected above 50 GeV (2FHL). This catalog was obtained using 80 months of data reprocessed with Pass 8, the newest event-level analysis, which significantly improves the acceptance and angular resolution of the instrument. Most of the 2FHL sources at high Galactic latitude are blazars. Using detailed Monte Carlo simulations, we measure, for the first time, the source count and angular resolution of the instrument. Most of the 2FHL sources at high Galactic latitude are processed with Pass 8, the newest event-level analysis, which significantly improves the acceptance.

The EGB spectrum has been accurately measured, from 100 MeV to 820 GeV, by the Large Area Telescope (LAT) on board the Fermi Gamma-Ray Space Telescope.
sion [2]. Part of the EGB arises from the emission of resolved and unresolved point sources like blazars, star-forming and radio galaxies [e.g. 3–5], which are routinely detected in γ rays. A possible contribution to the EGB may also come from diffuse processes such as annihilating/decaying dark matter particles (see [6] for a review).

Here we show for the first time that Fermi-LAT is able to resolve the high-energy EGB into point-like sources. Indeed, thanks to the accrual of 80 months of data (see right panel of Fig. 1) and the increased acceptance and improved point-spread function delivered by the new event-level analysis dubbed Pass 8 [7], the LAT has recently performed an all-sky survey at >50 GeV resulting in the detection of 360 γ-ray sources that constitute the second catalog of hard Fermi-LAT sources [2FHL, 8].

Blazars, mostly belonging to the BL Lacertae (BL Lac) population, are the majority (74%) of the sources in the 2FHL catalog. At Galactic latitudes (b) larger than 10° about 70% of the detected sources are associated with BL Lacs. Only 7% of these high-latitude (|b| > 10°) sources are classified as something other than BL Lacs, 4% of which as Flat Spectrum Radio Quasars (FSRQs) and 3% as Radio Galaxies. Blazars of uncertain type and unassociated sources constitute the remaining 23% of the sample. The median of the synchrotron peak frequencies for blazars of uncertain type is very similar to that of BL Lacs (log_{10}(\nu_{\text{peak}}^b / \text{Hz}) = 15.7 vs. 15.6). The same holds for the median spectral index of unassociated sources (\Gamma =3.0 vs. 3.1). This is supporting the fact that blazars of uncertain type and unassociated sources are almost entirely BL Lacs. Therefore, the fraction of likely blazars in the high-latitude 2FHL sample is 97% (93% BL Lacs and 4% FSRQs).

In this paper, we derive the source detection efficiency of the 2FHL catalog analysis using accurate Monte Carlo simulations of the γ-ray sky. We then infer the intrinsic flux distribution \(dN/dS\) of sources located at a latitude \(|b| > 10^\circ\), where \(S\) is the photon flux (ph cm\(^{-2}\) s\(^{-1}\)) measured in the 50 GeV–2 TeV energy band.

The simulations were performed using the gtobssim tool, which is part of the Fermi Science Tools distribution, and using the same pointing and live time history and event selection as used in the 2FHL catalog. We have employed the PSR2_SOURCE_V6 instrument response function for the simulations and analysis and the Galactic and isotropic diffuse emission were simulated using the gll_iem_v06.fits and iso_P8R2_SOURCE_V6_v06.txt templates \(^1\). The last ingredient of the simulations is an isotropic population of point sources that has the characteristics of blazars (fluxes and spectra) as detected in 2FHL. The simulations described here were produced iteratively and ultimately rely on the source count distribution \(dN/dS \propto S^{-\alpha}\) as determined at the end of photon fluctuation analysis (see later), which is, a broken power law with a break flux \(S_0 = 1 \times 10^{-11}\) ph cm\(^{-2}\) s\(^{-1}\) and a Euclidean slope above the break, \(\alpha_1 = 5/2\), while below \(S_0\) the slope is \(\alpha_2 = 1.65\). Sources were generated with fluxes in the range \([S_{\text{min}}, S_{\text{max}}] = [10^{-14}, 10^{-9}]\) ph cm\(^{-2}\) s\(^{-1}\) and with power-law spectra of the form \(dN/dE \propto E^{-\Gamma}\). For each source the photon index \(\Gamma\) is drawn from a Gaussian distribution with average value 3.2 and standard deviation 0.7 (this reproduces the observed distribution as shown on the bottom panel of Fig. 2). Galactic sources are not considered in the simulations since we are interested in the flux distribution of blazars at \(|b| > 10^\circ\). We produced 10 simulations of the γ-ray sky following these prescriptions and in Fig. 1 the sky map of one simulation is shown together with the real one. Clearly visible in both maps are the diffuse emission along the Galactic plane, the Fermi-LAT bubbles [9], the emission from point sources and the isotropic diffuse emission.

The energy spectrum of the simulations is consistent within 10%, at all energies of interest and for photons detected at \(|b| > 10^\circ\), with that of the LAT observations. As clearly visible in Fig. 1, the spatial distribution of gamma rays of the real map is also correctly reproduced. The 10 simulations are analyzed exactly as the real data were for the 2FHL catalog. This starts from detecting source candidates using a sliding-cell algorithm and a wavelet analysis [10] then analyzing each with the standard Fermi Science Tools, in order to derive the γ-ray properties of detectable sources (see [8] for more details). As in the 2FHL catalog, detected sources are those with a test statistic (TS)>25 and at least 3 associated photons predicted by the likelihood fit. This leads to the detection, in the simulations, of 271 ± 18 sources at \(|b| > 10^\circ\), which is in good agreement with the 253 sources detected in the 2FHL. Moreover, the simulations show that the 2FHL catalog contains at most 1% of false detections.

In order to further validate our analysis we have performed two consistency checks on the simulations. The first compares the input source fluxes \(S_{\text{true}}\) with the fluxes \(S_{\text{meas}}\) measured with the Fermi Science Tools in the simulations. The result displayed in the top panel of Fig. 2 shows that for bright sources this ratio converges to 1 as expected in the absence of biases or errors. On the other hand \(S_{\text{meas}}/S_{\text{true}}\) for faint sources deviates systematically from 1. This effect is readily understood as caused by the Eddington bias, which is the statistical fluctuations of sources with a simulated flux below the threshold to a flux above the detection threshold [11]. Our second check compares of the average photon index distribution (\(dN/d\Gamma\)), as derived from the simulations, with the same distribution as derived from the 2FHL catalog. This is reported in the bottom panel of Fig. 2 and it shows that our description of the γ-ray sky and of the blazar population is faithful to the real one.

\(^1\) See http://fermi.gsfc.nasa.gov/ssc/
The results from analyzing the sources in the simulated data can be used to measure the detection efficiency $\omega(S)$, which is a weighting factor that takes into account the probability to detect a source as a function of flux. The detection efficiency is simply derived from the simulations measuring the ratio between the number of detected sources and the number of simulated ones as a function of measured source flux. The result reported in Fig. 3 shows that the LAT detects any source in the $|b| > 10^\circ$ sky for fluxes larger than $\approx 2 \times 10^{-11}$ ph cm$^{-2}$ s$^{-1}$, but misses 80–90 % of the sources with fluxes of $\approx 1 \times 10^{-11}$ ph cm$^{-2}$ s$^{-1}$ and many more below this flux. The peak ($\omega(S) > 1$) clearly visible at a flux of $\approx 2 \times 10^{-11}$ ph cm$^{-2}$ s$^{-1}$ is due to the Eddington bias. We have verified that our estimate of the detection efficiency is insensitive to the choice of break flux by repeating the analysis with breaks occurring at fluxes as low as $S_b \geq 5 \times 10^{-12}$ ph cm$^{-2}$ s$^{-1}$, i.e., well below the fitted range determined from the photon fluctuation analysis described later.

A reliable estimate of the detection efficiency is fundamental in order to correct the observed flux distribution of the 2FHL catalog and in turn to derive the intrinsic source count distribution, which is obtained as:

$$\frac{dN}{dS}(S_i) = \frac{1}{\Omega \Delta S_i} \frac{N_i}{\omega(S_i)} \, [\text{cm}^2 \text{ s deg}^{-2}], \quad (1)$$

where $\Omega$ is the solid angle of the $|b| > 10^\circ$ sky, $\Delta S_i$ is the width of the flux bin, $N_i$ is the number of sources in each flux bin and $S_i$ is the flux at the center of a given bin $i$. We verified through simulations that this method allows us to retrieve the correct source count distribution as long as the distribution used in the simulations is a faithful representation of the real one.

This is found to be consistent, down to the sensitivity of the 2FHL catalog ($\approx 8 \times 10^{-12}$ ph cm$^{-2}$ s$^{-1}$), with a power-law function with slope $\alpha_1 = 2.49 \pm 0.12$ (see bottom panel of Fig. 3). This best-fit value is consistent with the Euclidean expectation and motivated us to choose $\alpha_1 = 2.5$ in the simulations.

Fig. 4 shows the cumulative source count distribution that is defined as:

$$N(> S) = \int_{S}^{S_{\text{max}}} \frac{dN}{dS} \, dS' \, [\text{deg}^{-2}], \quad (2)$$

where $S_{\text{max}}$ is fixed to be $10^{-8}$ ph cm$^{-2}$ s$^{-1}$.

In order to infer the shape of the $dN/dS$ distribution below the flux threshold for detecting point sources we have performed a photon fluctuation analysis. This helps us to probe the source count distribution to the level where sources contribute on average 0.5 photons each. The photon fluctuation analysis has been successfully used in the past to predict the shape of $dN/dS$ below the sensitivity of ROSAT [16] before Chandra and XMM, about one decade later, detected those faint sources [17]. The analysis is performed by comparing the histogram of the pixel counts of the real sky with the ones obtained via Monte Carlo simulations and allows us to constrain the slope of the differential flux distribution below the threshold of the survey [16, 18]. We consider a differential flux distribution described as a broken power law where the slope above the break is $\alpha_1 = 2.5$ as determined in this work while below the break the slope varies in different simulations between $\alpha_2 \in [1.3, 2.7]$. For each value of the slope we derive the model pixel count distribution averaging over the pixel count distributions obtained from 20 simulations. The simulated and real maps have been pixelized using the HEALPix tool [19]. We have used a resolution of order 9, which translates into 3145728 pixels and an pixel size of about 0.11$^\circ$. Consistent results are obtained when using a resolution of order 8. We consider a single energy bin from 50 GeV to 2 TeV.

The model (averaged) pixel count distributions are compared to the real data using a $\chi^2$ analysis to deter-

2 See http://healpix.sourceforge.net
mine the most likely scenario. As expected, there is a
degeneracy between the best-fit value of the slope \( \alpha_2 \) and
the choice of the break flux, \( S_b \). The result of the analy-
ysis is that the break flux is limited to the range between
\( S_b \in [8 \times 10^{-12}, 1.5 \times 10^{-11}] \) ph cm\(^{-2}\) s\(^{-1}\) while the index
below the break is in the range \( \alpha_2 \in [1.60, 1.75] \). The
best configuration, which we refer to as our benchmark
model, has a break flux at \( 1 \times 10^{-11} \) ph cm\(^{-2}\) s\(^{-1}\) and
a slope \( \alpha_2 = 1.65 \) with a \( \chi^2 = 12.4 \) (for 12 degrees of
freedom). This implies that the source count distribution
must display a hard break \(|\alpha_1 - \alpha_2| \approx 0.9\) from the
Euclidean behavior measured at bright fluxes. We show
in Fig. 5, for the best-fit configuration, the comparison
between the pixel count distribution evaluated for the
average of 20 simulations, and the same quantity as derived
from the real data. The figure also shows the differences
between these two distributions.

The presence of a break at about \( 1 \times 10^{-11} \) ph cm\(^{-2}\)
s\(^{-1}\) is corroborated by the number of detected sources,
that for our benchmark source count distribution is found
to be consistent with the 2FHL (271 \( \pm 18 \) vs. 253 in the
2FHL). As soon as we move the position of the break
to lower fluxes, the expected number of detected sources

FIG. 2: Top Panel: ratio of the measured-to-simulated source
flux (as derived from the analysis of the simulations described
in the text) as a function of simulated source flux. Bottom
Panel: comparison between the photon index distributions of
sources detected in 2FHL (blue points) and the average of the
simulations (red points).

FIG. 3: Top Panel: detection efficiency \( \omega(S) \) (blue points) as a
function of source flux and normalized distribution of source
fluxes detected in 2FHL (grey shaded histogram). Bottom
Panel: intrinsic \( S^2 dN/dS \) distribution measured with two dif-
f erent cuts on the source \( TS \): 25 (black points) and 10 (red
points, for the lowest four flux bins only). The black solid line
shows our best-fit model, while the grey and cyan bands show
the 1\( \sigma \) and 3\( \sigma \) uncertainty bands from the photon fluctuation
analysis. The vertical brown dotted line represents the sensi-
tivity of the photon fluctuation analysis. The orange and red
curves indicate where 85\% and 100\% of the EGB intensity
above 50 GeV [2]. Taking the 100\% curve as an example, any
point on that curve, that is joined with a power law to the
measured source count distribution at \( S \approx 10^{-11} \) ph cm\(^{-2}\)
s\(^{-1}\), will give a source count distribution that produces 100\%
of the EGB.
becomes quickly incompatible with the values measured in the 2FHL, even when compensating by making $\alpha_2$ steeper (e.g., for $S_b = 5 \times 10^{-12}$ ph cm$^{-2}$ s$^{-1}$ and $\alpha_2 = 1.10$, we predict $318 \pm 20$ sources).

Alternatively, it is possible to probe directly flux values below the 2FHL detection threshold by applying a source TS cut lower than the nominal value of 25 used for the construction of the catalog. As long as the source detection efficiency is self-consistently derived, the intrinsic source count distribution is independent of the the TS cut and lower cut values translate into lower detection thresholds. By repeating the analysis with $TS > 10$ we were able to add a new point at about $6 \times 10^{-12}$ ph cm$^{-2}$ s$^{-1}$ that, albeit with a relatively large error, corroborates the presence of a break at $1 \times 10^{-11}$ ph cm$^{-2}$ s$^{-1}$ (see bottom panel of Fig. 3).

Finally, we have checked that the shape of the derived $dN/dS$ distribution is not significantly affected by a change of $\alpha_1$ within its error.

The lowest flux that the photon fluctuation analysis is sensitive to can be estimated by adding to the source count distribution one more break flux below that of the benchmark model. We fixed the slope below this second break to $\alpha_3 = 1.80$, which is at the edge of the derived range for $\alpha_2$, while the break flux is varied in the range $S_{\lim} \in [5 \times 10^{-13}, 5 \times 10^{-12}]$ ph cm$^{-2}$ s$^{-1}$ to register when a worsening of the $\chi^2$ (with respect to the best-fit one) is observed. The result of this analysis is that the fit worsened by more than $3\sigma$ for $S_{\lim} \gtrsim 1.3 \times 10^{-12}$ ph cm$^{-2}$ s$^{-1}$. The results of the photon fluctuation analysis are reported in Figs. 3 and 4, which show that this technique allows us to measure the source count distribution over almost three decades in flux. In the bottom panel of Fig. 3, we show the fluxes at which a source count distribution with any given slope $\alpha_2$ below $S_b = 1 \times 10^{-11}$ ph cm$^{-2}$ s$^{-1}$ would produce 100% (or 85%) of the EGB.

We have tested also the possibility that a new source population could emerge in the flux distribution with a Euclidean distribution, as might be expected, for example, from star-forming galaxies [20]. In this test we set $\alpha_3 = 2.50$ and follow the method described above to derive the maximum flux at which a possible re-steepening of the source counts might occur. This is found to be $S_{\lim} \approx 7 \times 10^{-13}$ ph cm$^{-2}$ s$^{-1}$ and the integrated emission of such a population would exceed at fluxes of $\approx 7 \times 10^{-14}$ ph cm$^{-2}$ s$^{-1}$ the totality of the EGB intensity.

Our best-fit model for the flux distribution $dN/dS$ is therefore, for $S \gtrsim 10^{-12}$ ph cm$^{-2}$ s$^{-1}$, a broken power-law with break flux in the range $S_b \in [0.8, 1.5] \times 10^{-11}$, slopes above and below the break of $\alpha_1 = 2.49 \pm 0.12$ and $\alpha_2 \in [1.60, 1.75]$, respectively and a normalization $K = (4.60 \pm 0.35) \times 10^{-19}$ deg$^{-2}$ ph$^{-1}$ cm$^2$ s. We believe this describes the source counts of a single population (blazars), because no re-steepening of the source count distribution is observed and because the large majority (97%) of the detected sources are likely blazars.

Fig. 4 reports the theoretical expectations for the source count distribution given by blazars [4, 13] and BL Lacs [12]. These models are consistent with the observations at bright fluxes, but are above the experimental $N(S)$ by about a factor of 2 at $S = 10^{-12}$ ph cm$^{-2}$ s$^{-1}$. We include in the same figure also the predicted 5 mCrab sensitivity reachable by CTA in 240 hours in the most sensitive pointing strategy [15]. At these fluxes the source density is $0.0194 \pm 0.0044$ deg$^{-2}$, which translates to the serendipitous detection of 200 $\pm 45$ blazars in one quarter of the full sky. It is also interesting to note that our analysis constrains the source count distribution to fluxes that are much fainter than those reachable by CTA in short exposures.

Once known, the source count distribution can be used to estimate the contribution of point sources to the EGB. This is performed by integrating the flux distribution $dN/dS$ as follows:

$$I = \int_{0}^{S_{\max}} S' \frac{dN}{dS} dS' \ [\text{ph cm}^{-2} \text{s}^{-1} \text{sr}^{-1}].$$

Choosing $S_{\max} = 10^{-8}$ ph cm$^{-2}$ s$^{-1}$ we find that the total integrated flux from point sources is $2.07^{+0.40}_{-0.34} \times 10^{-9}$ ph cm$^{-2}$ s$^{-1}$ sr$^{-1}$ which constitutes $80^{+16}_{-14}\%$ of the EGB above 50 GeV estimated in [2]. This validates $3$ The quoted range takes into account only the uncertainty on the photon fluctuation analysis and can extend above 100%. Indeed, it does not consider possible systematic correlations between the
the predictions of models [4, 5, 12]. This calculation contains an extrapolation of the derived source count distribution below the sensitivity of the pixel counting. Point sources with fluxes \( S > 1.3 \times 10^{-12} \text{ ph cm}^{-2} \text{ s}^{-1} \) produce \( 1.47^{+0.20}_{-0.24} \times 10^{-9} \text{ ph cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \) (61\% of the EGB), while \( 6.0^{+2.0}_{-1.0} \times 10^{-10} \text{ ph cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \) (25\% of the EGB) is produced by sources below that flux.

The \textit{Fermi}-LAT has measured the angular power spectrum of the diffuse \( \gamma \)-ray background at \( |b| > 10^\circ \) and in four energy bins spanning the 1-50 GeV energy range [21]. For multipol

The angular power due to unresolved sources at \( > 50 \text{ GeV} \) can be readily predicted from the source count distribution as:

\[
C_P = \int_0^{S_{\text{max}}} \left( 1 - \omega(S') \right) S'^2 \frac{dN}{dS'} dS' \left[ (\text{ph cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1})^2 \text{ sr}^{-1} \right],
\]

The angular power evaluates to \( C_P(E > 50 \text{ GeV}) = 9.4^{+1.0}_{-1.6} \times 10^{-22} \text{ (ph/cm}^2/\text{s})^2 \text{ sr}^{-1} \). This is the first observationally-based prediction of the angular power at \( > 50 \text{ GeV} \). Our estimation for \( C_P(E > 50 \text{ GeV}) \) is in good agreement with the extrapolation of the \textit{Fermi}-LAT angular power measurements [21] above 50 GeV and is consistent with the calculated anisotropy due to radio loud active galactic nuclei made in Refs. [22, 23].

In conclusion, the \textit{Fermi}-LAT collaboration has used the new event-level analysis Pass 8 to conduct an all-sky survey above 50 GeV. The resulting 2FHL catalog contains 253 sources at \( |b| > 10^\circ \) and closes the energy gap between the LAT and Cherenkov telescopes. We have thoroughly studied the properties of both resolved and unresolved sources in the 50 GeV–2 TeV band using detailed Monte Carlo simulations and a photon fluctuation analysis. This allowed us to characterize, for the first time, the source count distribution above 50 GeV, which is found to be compatible at \( \gtrsim 10^{-12} \text{ ph cm}^{-2} \text{ s}^{-1} \) with a broken power-law model with a break flux in the range \( S_b \in [0.8, 1.5] \times 10^{-11} \text{ ph cm}^{-2} \text{ s}^{-1} \), and slopes above and below the break of, respectively, \( \alpha_1 = 2.49 \pm 0.12 \) and \( \alpha_2 \in [1.60, 1.75] \). A photon fluctuation analysis constrains a possible re-steepening of the flux distribution to a Euclidean behavior (\( \alpha_3 = 2.50 \)) to occur at fluxes lower than \( \sim 7 \times 10^{-13} \text{ ph cm}^{-2} \text{ s}^{-1} \). Our analysis permits us to estimate that point sources, and in particular blazars, explain almost the totality (86\% of the EGB).

This might have a number of important consequences, since any other contribution, exotic or not, must necessarily be small. This bound might imply strong constraints for the annihilation cross section or decay time of high-mass dark matter particles producing \( \gamma \)-rays [4, 5]. Tight constraints could also be inferred on other \( \gamma \)-ray emission mechanisms due to other diffusive processes such as UHECRs [25, 26]. Finally, if the neutrinos detected by IceCube have been generated in hadronic cosmic-ray interactions, then the same sources producing the neutrino background will produce part of the sub-TeV \( \gamma \)-ray background [27]. Because blazars were found not to be responsible for the majority of the neutrino flux [28], the fact that the 50 GeV–2 TeV \( \gamma \)-ray background is almost all due to blazars constrains the contribution of other source classes to the neutrino background. Such constraints will be presented in a dedicated paper.

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