Intensity and origin of the extragalactic gamma-ray background.

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on behalf of the Fermi LAT collaboration

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The Extragalactic gamma-ray background (EGB).

Resolved point sources

Galactic diffuse emission
(CR interactions with the interstellar medium)

- Inverse Compton
- $\pi^0$-decay
- Bremsstrahlung

Residual charged cosmic rays
Protons, nuclei, electrons + positrons, misclassified as gamma-rays by event selection filters

$\gamma$-rays from the Earth limb
$\gamma$-rays $\ll 1$GeV with poor directional reconstruction

Isotropic extragalactic diffuse emission

LAT sky, $E > 1$GeV, 4 years

Orbit averaged $E^*\text{flux for background model}$
The origin of the EGB in the LAT energy range.

### Undetected sources

**Blazars**

Dominant class of LAT extragalactic sources. Many estimates in literature. EGB contribution ranging from 20% - 100%.

**Non-blazar active galaxies**

27 sources resolved in 2FGL 
~ 25% contribution of radio galaxies to EGB expected. (e.g. Inoue 2011)

**Star-forming galaxies**

Several galaxies outside the local group resolved by LAT. Significant contribution to EGB expected. (e.g. Pavlidou & Fields, 2002, Ackermann et al. 2012)

**GRBs**

**High-latitude pulsars**

Small contributions expected. (e.g. Dermer 2007, Siegal-Gaskins et al. 2010)

### Diffuse processes

**Intergalactic shocks**

Widely varying predictions of EGB contribution ranging from 1% to 100% (e.g. Loeb & Waxman 2000, Gabici & Blasi 2003)

**Dark matter annihilation**

Potential signal dependent on nature of DM, cross-section and structure of DM distribution (e.g. Ullio et al. 2002)

**Interactions of UHE cosmic rays with the EBL**

Dependent on evolution of CR sources, predictions varying from 1% to 100% (e.g. Kalashev et al. 2009)

**Extremely large Galactic electron halo** (Keshet et al. 2004)

**CR interaction in small solar system bodys** (Moskalenko & Porter 2009)
Derivation of the EGB spectrum.

> All-sky maximum likelihood fit (Galactic plane excluded)
  - LAT sky map compared to full model of gamma-ray emission.
  - Equal-area pixels with 0.8 deg$^2$ (HEALPix grid).
  - Point sources and diffuse emission fitted simultaneously.

> LAT gamma-ray sky model:
  - Diffuse Galactic emission templates based on GALPROP model.
  - Strong LAT sources individually fitted.
  - Weak LAT sources included as template.
  - Solar gamma-ray emission.
  - Local diffuse emission (e.g. Loop I).
  - Isotropic template.

> Isotropic emission = EGB + residual CR background.
First LAT EGB analysis published in 2010.

Spectrum can be fitted by power law: \( \gamma = 2.41 \pm 0.05 \).

Flux above 100 MeV: \( F_{100} = 1.03 \pm 0.17 \times 10^{-5} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \) (extrapolated).

Foreground modeling uncertainty not included in error bands (~ 30%).
EGB analysis improvements.

...since the first publication (Abdo et al., PRL 104).

> 44 months of LAT data, energy range 200 MeV - 820 GeV.

> Reprocessed with updated in-flight calibration.

> Separate low-energy (< 12.8 GeV) and high-energy (> 12.8 GeV) analysis.

> New super-low background event selection for high-energy analysis (P7TKRVETO).

> Residual CR background estimates based on large dedicated Monte Carlo production.

> Wider range of Galactic diffuse emission foreground models evaluated.

> 2FGL catalog sources included in sky model.

> Galactic plane mask derived from gas surveys.

> New template for gamma-ray emission from North Polar spur.
New event classification.

> **Updated event classification** in comparison to published analysis (PASS7 vs PASS6).
  - gains in effective area & lower systematic uncertainties.

> **Standard event class** P7ULTRACLEAN for low-energy analysis (<12.8 GeV).

> **Newly developed** P7TKRVETO event class for high-energy analysis (>12.8 GeV).
  - Based on P7ULTRACLEAN.
  - Uses part of the LAT tracker as additional veto against incoming CRs.
  - Removes a condition from P7ULTRACLEAN selection that is inefficient above \( \sim 500 \) GeV.
  - Relaxed constraints on Zenith angle.
  - Effective reduction of background: up to factor 2 vs. P7ULTRACLEAN above 12.8 GeV
  - No gain in background reduction at lower energies, therefore standard P7ULTRACLEAN with higher acceptance used there.
Background from charged cosmic rays.

> EGB intensity is 6 orders of magnitude lower than CR background intensity (@10 GeV).

> Comparison to high Galactic latitude LAT data to cross-check Monte Carlo predictions.

> ± 35 % systematic uncertainty on prediction.

> Large scale Monte Carlo production effort to determine residual CR background contamination in PASS7 event classes up to 1 TeV.
Energy range limit from event selection/reconstruction.

- EGB measurement impossible above ~800 GeV with current reconstructions.
- Current energy reconstruction does not handle saturated crystals well.
  - Strong bias in the energy response at 1 TeV and above.
- Track confusion at very high energies can result in CRs being classified as gamma rays.

- Both problems will be resolved in the next generation of event reconstruction and selection (Pass 8)
Model for the Galactic diffuse emission foreground.

\[ \gamma \text{-ray emission model} \]

\[ \gamma \text{-ray emission model} \]

\[ H_I + H_{II} \ (8 \text{kpc} < r < 10 \text{kpc}) \]

> Diffuse gamma-ray emission of Galaxy modeled using the \textbf{GALPROP code}.

> **Galactic plane** and all regions with significant contributions from \( H_2 \) and non-local \( H_I \) (\( r < 8 \text{kpc} \) or \( r > 10 \text{kpc} \)) are masked for EGB analysis.

> **Two dominant** high-latitude components fit to LAT data:

  - **Inverse Compton** emission (isotropic ISRF with approximate correction for anisotropy of radiation field).
  - **Bremsstrahlung and \( \pi^0\)-decay** from CR interactions with local (8kpc < \( r < 10\text{kpc} \)) atomic and ionized hydrogen (\( H_I + H_{II} \)).
> Default foreground model similar to models studied in Ackermann et al., ApJ 750, 3 (2012).

- **Cosmic-ray source distribution** follows Pulsar distribution.
- **5 kpc** cosmic-ray halo.
- **Diffusion & re-acceleration** of CRs in the interstellar medium.
- **Constant & isotropic diffusion** throughout Galaxy.
- **Interstellar gas distribution** from radial velocity measurement at radio frequencies.
- **Total gas column density** corrected using interstellar dust as tracer (E(B-V) map, Schlegel et al. 1998).
Galactic foreground (IC emission).

> **Shape of Galactic foreground** from IC emission depends heavily on the propagation model.

> **Important systematic uncertainty** for the foreground model subtraction.

> **Fit to LAT data** indicates that our understanding of the shape/spectrum of the diffuse IC emission is limited.

> **Evaluation of a larger class** of foreground models than for first publication.

- Diffusion coefficient not constant throughout Galaxy
- Different CR source populations
- Variations of the ISRF
- Variations of halo size
- ...
Low-energy analysis (<12.8 GeV)

- P7ULTRACLEAN event class.
- Intensity of each foreground model template is fitted in each single energy band.
- 2FGL sources (TS>200) are fitted individually

High-energy analysis (>12.8 GeV)

- P7TKRVETO event class.
- Foreground model spectrum is fixed, but normalization is rescaled
- 2FGL sources (TS>200) are fitted individually.
Low-energy vs. high-energy analysis.

For consistency checking low- and high-energy analysis is performed with significant overlap in energy.

> Fit results are consistent.
The preliminary LAT EGB spectrum.

- Preliminary EGB spectrum between 200 MeV to 410 GeV for default foreground model.
- Error bands include systematics from effective area uncertainty and CR background subtraction.
- ... but NOT systematics from foreground model uncertainties. (still under evaluation).

> Publication in preparation for EGB spectrum up to 820 GeV.
Comparison to older measurements.

- In agreement with published spectrum.
- Error bars predominantly systematic. Apparent features in the spectrum are **NOT** significant.
- Possible spectral softening at high energies?
Systematic uncertainties from foreground modeling.

> Still under investigation.

> Particular emphasis on the impact of foreground modeling on features in the EGB spectrum.

> Expect ~ 30% uncertainty on normalization, similar to published analysis.

Future improvements of the measurement of the EGB intensity rely on a better understanding of the Galactic diffuse emission.
The Origin of the EGB

Why is this important?

The Extragalactic Gamma-ray Background may encrypt the signature of the most powerful processes in astrophysics.

Blazars contribute 20-100% of the EGB (Stecker & Salomon 96, Mücke & Pohl 00, Narumoto & Totani 04, Dermer 07, Inoue & Totani 09).

Emission from star-forming galaxies (e.g. Pavlidou & Fields 02).

Emission from particles accelerated in Intergalactic shocks (Loeb & Waxmann 00).

73% Dark Energy

23% Dark Matter

4% Atoms

Emission due to the annihilation of Cosmological Dark Matter (e.g. Jungman + 96).
Unresolved source contributions to the EGB.

> The big questions:
  ▪ Which classes of unresolved sources contribute how much to the EGB?
  ▪ Can unresolved sources alone explain the bulk of the EGB intensity?

> Many models and estimates in literature, too many to give credit to all of them....

> **Star-forming galaxies:** Pavlidou & Fields 2002; Thompson et al. 2007; Bhattacharya & Sreekumar 2009; Makiya et al. 2011; Fields et al. 2010; Stecker & Venters 2011; etc.


> **Radio galaxies:** Stawarz et al. 2006; Inoue et al. 2008; Inoue & Totani 2009; Massaro & Ajello 2011; Inoue 2011

> **Millisecond pulsars / GRBs:** Casanova et al. 2007; Dermer 2007; Faucher-Giguere & Loeb 2010; Siegal-Gaskins et al. 2010; etc.
Contributions of star-forming galaxies.

> 4% - 23% contribution to EGB from star-forming galaxies (0 < z < 2.5)

> Gamma-ray emission from galaxies is assumed to follow either a rescaled Milky Way (1) or a power-law spectrum (2), observed for Starburst Galaxies.

> Talk by Keith Bechtol this morning.
Contributions from radio galaxies.

- Estimation of contribution of LAT detected radio galaxies to the EGB (Inoue 2011).
- EGB contribution estimated from radio luminosity function.
- Unresolved radio galaxies contribute ~ 25%.
Unresolved Blazars

Blazars are dominant extragalactic source population in the LAT energy band.

Extrapolation of source count distribution of resolved LAT Blazars allows estimate of their contribution to the EGB.

Total contribution of Blazars in 100 MeV - 100 GeV band: 23% ± 5% (stat) ±12% (syst)

Unresolved Blazars: FSRQ gamma-ray luminosity function.

- LAT resolved FSRQ population spans wide range in redshift and luminosity
- Allows to build gamma-ray luminosity function (GLF) based on LAT data alone
- Luminosity-dependent density evolution (LDDE) fits LAT population best
- Prediction of EGB contribution based on GLF + spectral modeling

Unresolved Blazars: BL Lac luminosity function.

- Difficult: 55% of LAT BL Lac lack reliable redshift measurements.
- Only loose constraints on redshifts exists.
- Sample BLLac redshifts from allowed range of redshifts.
- Create luminosity functions by averaging over many samples.

> Evidence for:
  > strong positive evolution
  > different evolutionary speeds for BL Lac of different luminosities
  > Redshift peak at \( \sim 0.75 \)

Ajello, 220th AAS meeting, Anchorage
Sum of contributions from unresolved sources.

> Total contribution from FSRQ + BL Lac + Radio galaxies + Star-forming galaxies: ~ 50% - 80%

> Keep in mind: ~ 30% foreground modeling uncertainty not included in EGB error bands
Summary.

> New EGB analysis on 44 months of LAT data performed. Many improvements with respect to first analysis.

> Preliminary EGB spectrum has been presented between 200 MeV and 410 GeV. Studies of the systematic uncertainties with respect to the foreground models still ongoing.

> New EGB spectrum is in agreement with published measurement in the overlapping energy range.

> Unresolved source contributions of different source populations can explain a large fraction of the intensity of the extragalactic gamma-ray background.

> BL Lac’s might dominate at very high energies (≥~ 100 GeV).
Background from charged cosmic rays.

- Primary cosmic rays + secondaries created in the Earth atmosphere.
- More than 6 orders of magnitude in CR background suppression is needed (at 10 GeV) for EGB analysis.
- Isotropic distribution assumed for long (>>1 day) observation periods.
- LAT cosmic-ray background model:

![Graph showing various particle intensities](image)

- Background suppression efficiency and remaining residual background needs to be carefully studied to allow its subtraction in the EGB analysis.
Solar template and Loop I template.
Contributions of star-forming galaxies.

- 8 galaxies detected by the LAT
- Almost linear correlation between gamma-ray luminosity and tracers of star formation
  - bolometric infrared luminosity
  - 1.4 GHz radio continuum emission
- Detection + upper limits can be used to constrain correlation
- Use gamma-ray / IR luminosity correlation to calculate EGB contribution based on IR luminosity function of galaxies.