Intensity and origin of the extragalactic gamma-ray background.

Fermi Gamma-ray Space Telescope

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on behalf of the Fermi LAT collaboration

4th Fermi Symposium
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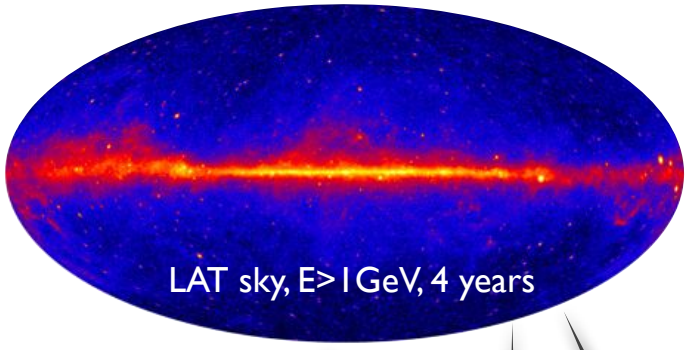
11/01/2012

HELMHOLTZ ASSOCIATION

DESY

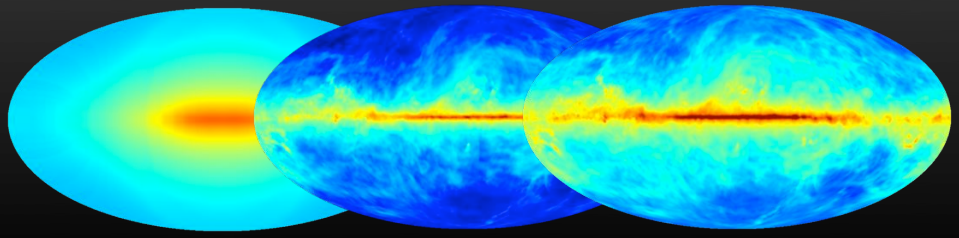
The Extragalactic gamma-ray background (EGB).



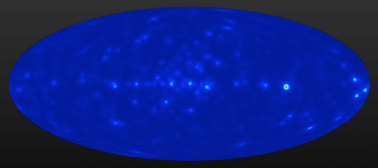
Galactic diffuse emission
(CR interactions with the interstellar medium)

Inverse Compton

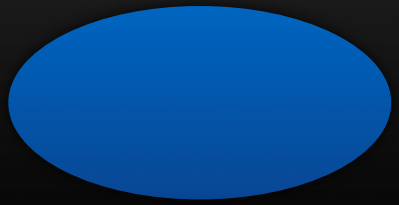
π^0-decay



Bremsstrahlung



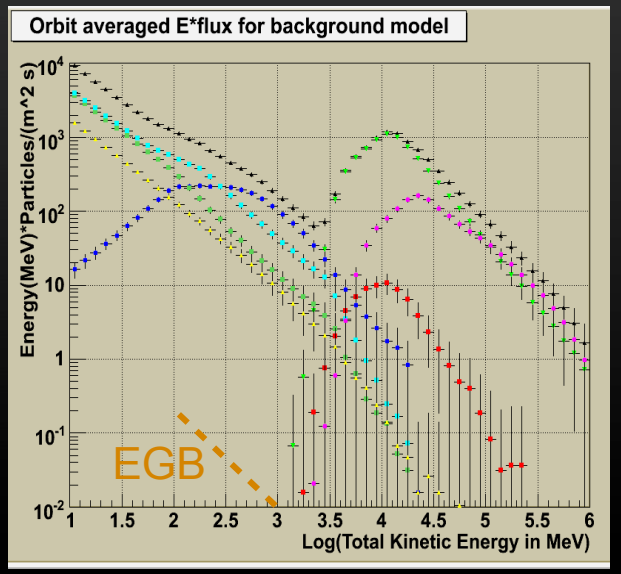
Resolved point sources



Isotropic extragalactic diffuse emission

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

γ-rays from the Earth limb
γ-rays << 1GeV with poor directional reconstruction



The origin of the EGB in the LAT energy range.

Undetected sources

Blazars

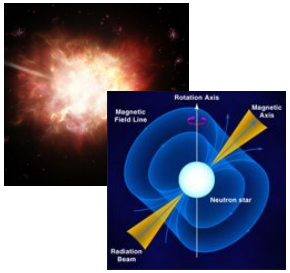
Dominant class of LAT extra-galactic sources. Many estimates in literature. EGB contribution ranging from 20% - 100%.

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

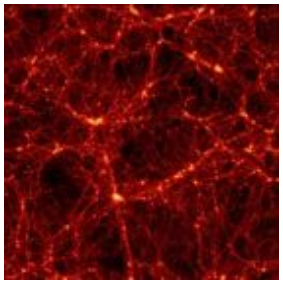
High-latitude pulsars

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

Diffuse processes

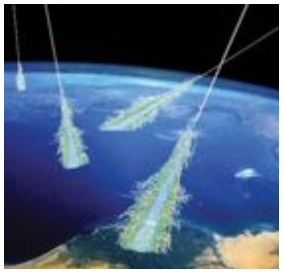
Intergalactic shocks

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)

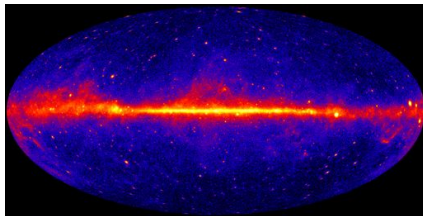
Extremely large Galactic electron halo (Keshet et al. 2004)

CR interaction in small solar system bodys (Moskalenko & Porter 2009)

DESY

Derivation of the EGB spectrum.

LAT sky



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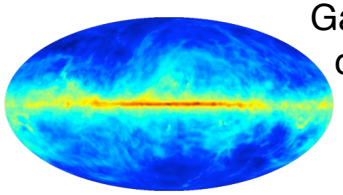

Galactic diffuse model

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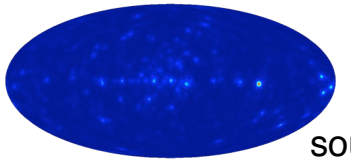

Point sources

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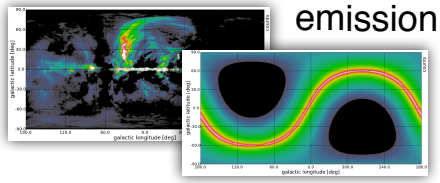
local & solar diffuse emission



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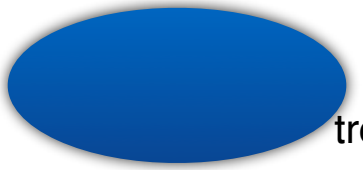


Iso-tropic

> All-sky maximum likelihood fit (Galactic plane excluded)

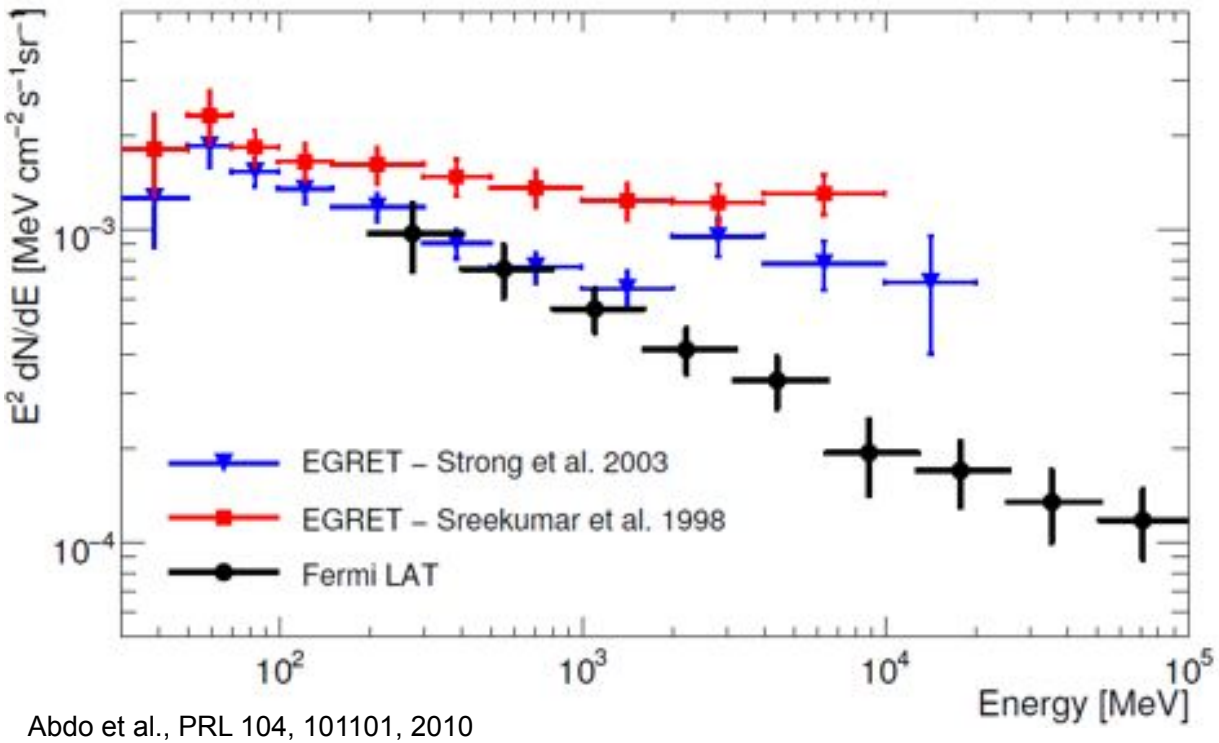
- LAT sky map compared to full model of gamma-ray emission.
- Equal-area pixels with 0.8 deg^2 (HEALPix grid).
- Point sources and diffuse emission fitted simultaneously.

> 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.



Abdo et al., PRL 104, 101101, 2010

- Spectrum can be fitted by power law: $\gamma = 2.41 \pm 0.05$.
- Flux above 100 MeV: $F_{100} = 1.03 \pm 0.17 \times 10^{-5}$ cm^{-2} s^{-1} sr^{-1} (extrapolated).
- Foreground modeling uncertainty not included in error bands (~ 30 %).

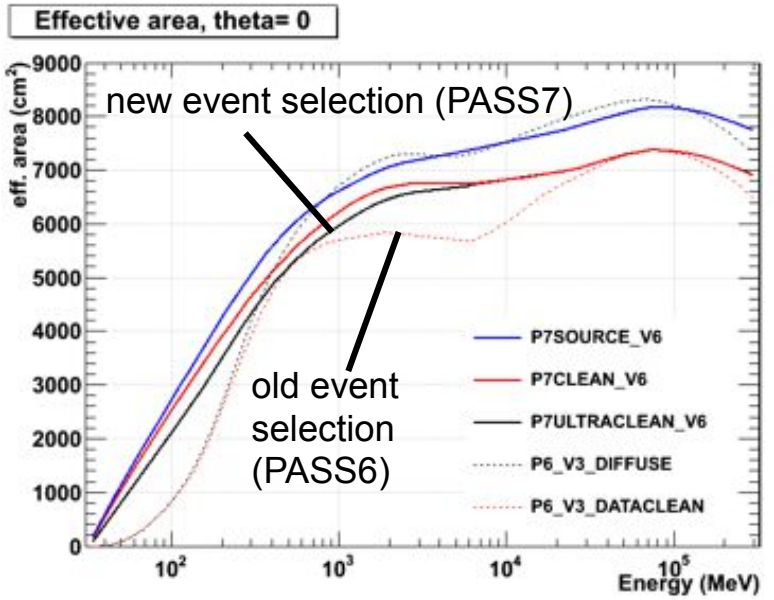
EGB analysis improvements.

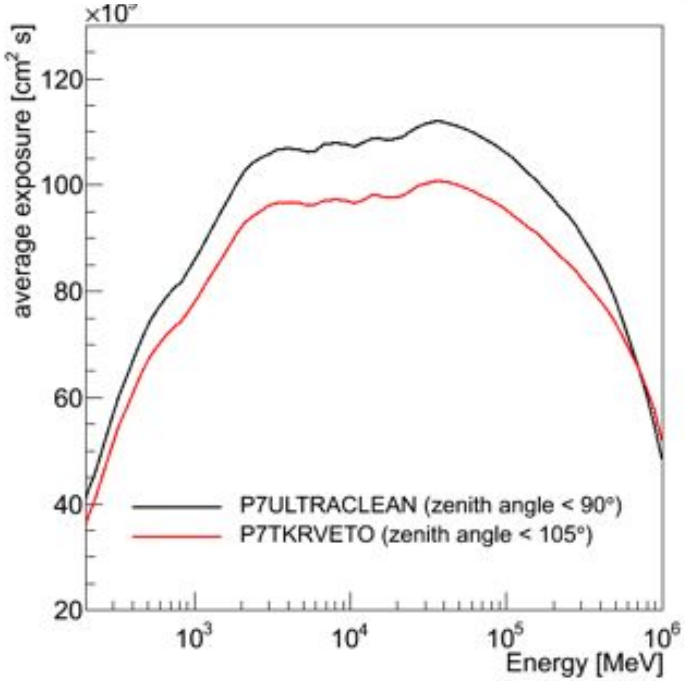
...since the first publication (Abdo et al., PRL 104).

- **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.

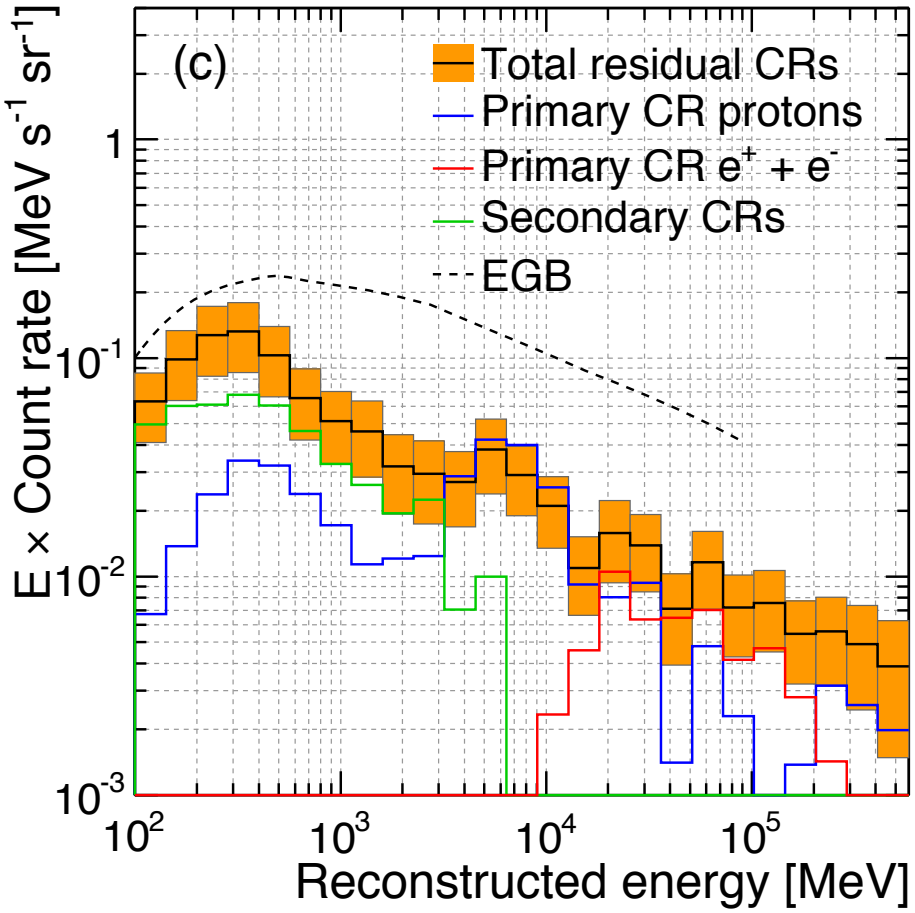
New event classification.

- **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 ~ 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.



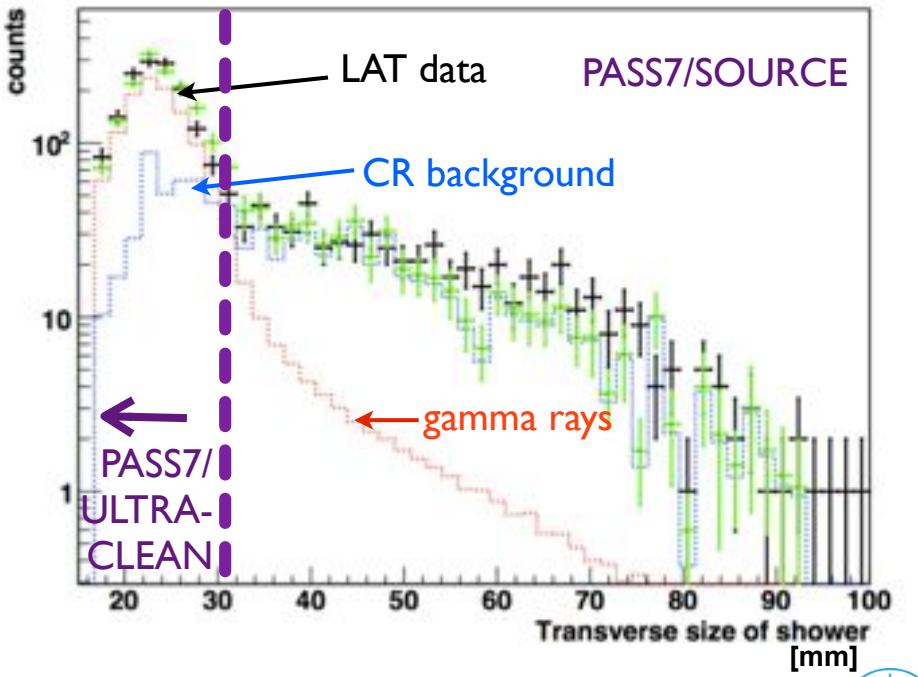


Background from charged cosmic rays.



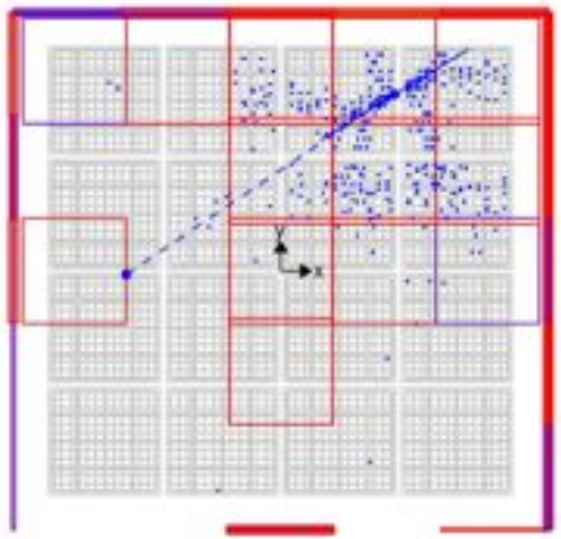
- Large scale Monte Carlo production effort to determine residual CR background contamination in PASS7 event classes up to 1 TeV.

- 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.

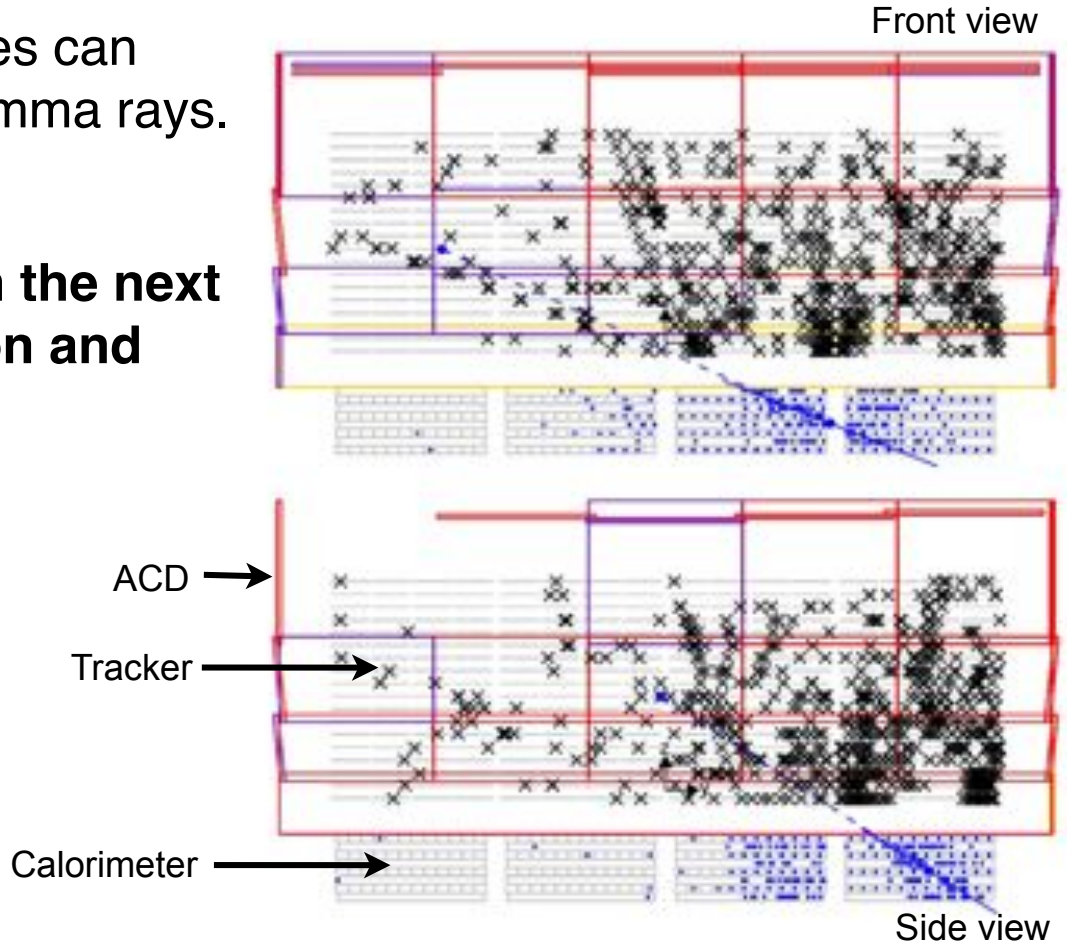


Energy range limit from event selection/reconstruction.

- 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)**



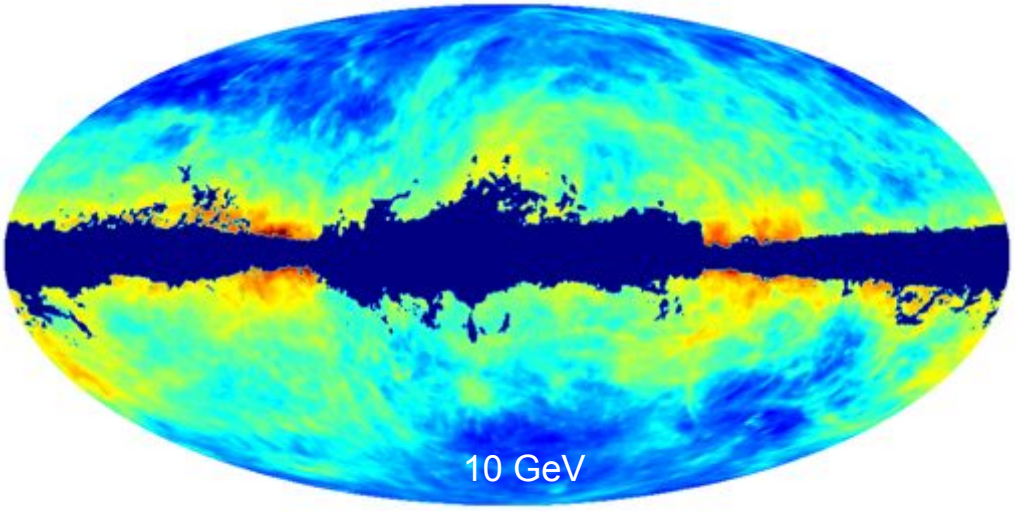
Top view



LAT view of a 920 GeV event

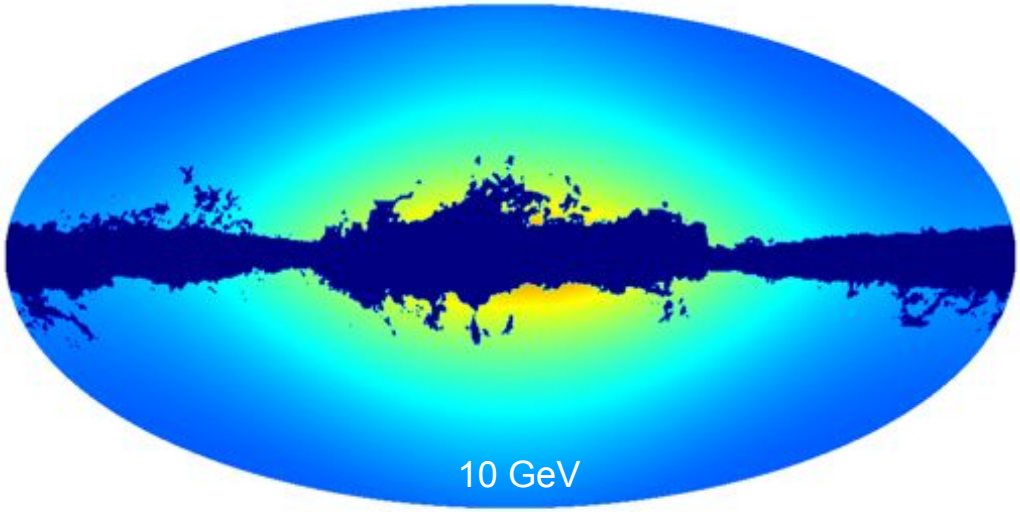
Model for the Galactic diffuse emission foreground.

γ-ray emission model



$H_I + H_{II}$ (8 kpc < r < 10 kpc)

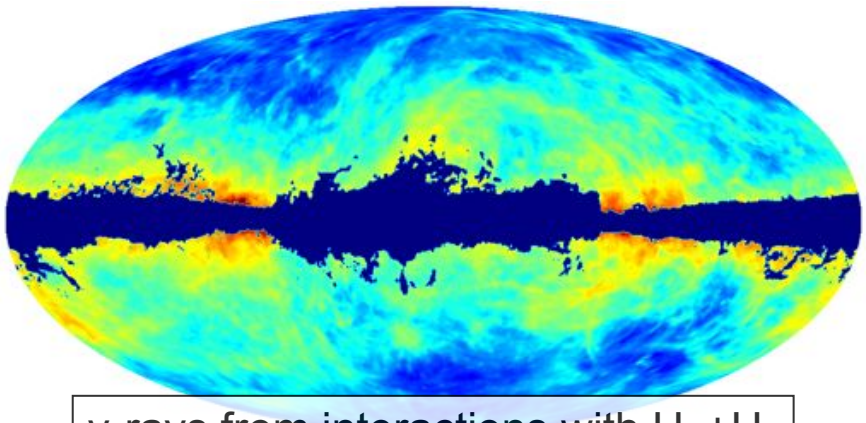
γ-ray emission model



Inverse Compton scattering

- Diffuse gamma-ray emission of Galaxy modeled using the **GALPROP code**.
- **Galactic plane** and all regions with significant contributions from H_2 and non-local H_I ($r < 8$ kpc or $r > 10$ 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 π0-decay** from CR interactions with local (8kpc < r < 10kpc) atomic and ionized hydrogen ($H_I + H_{II}$).

Galactic foreground.

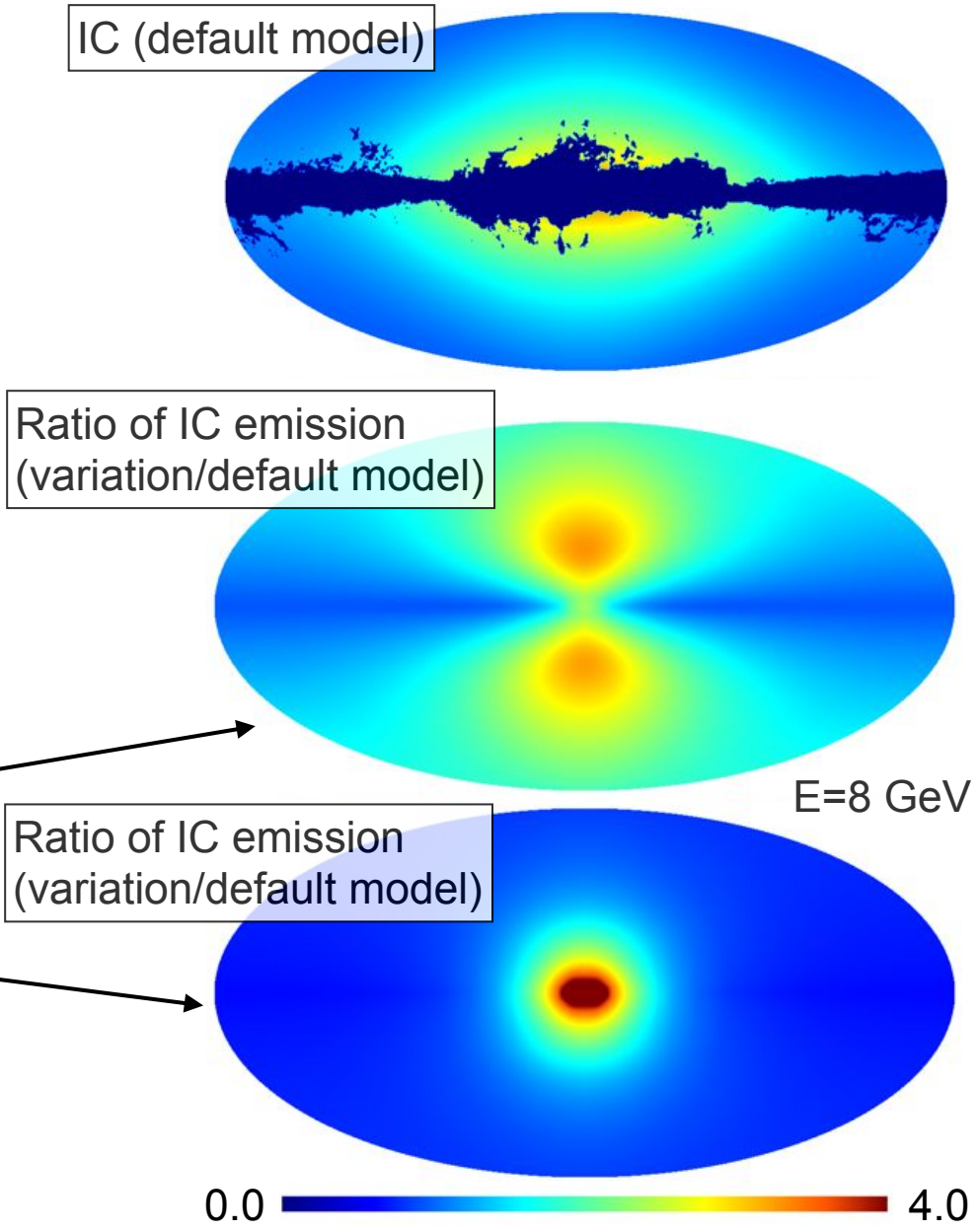


γ-rays from interactions with H_I +H_{II} (default model)

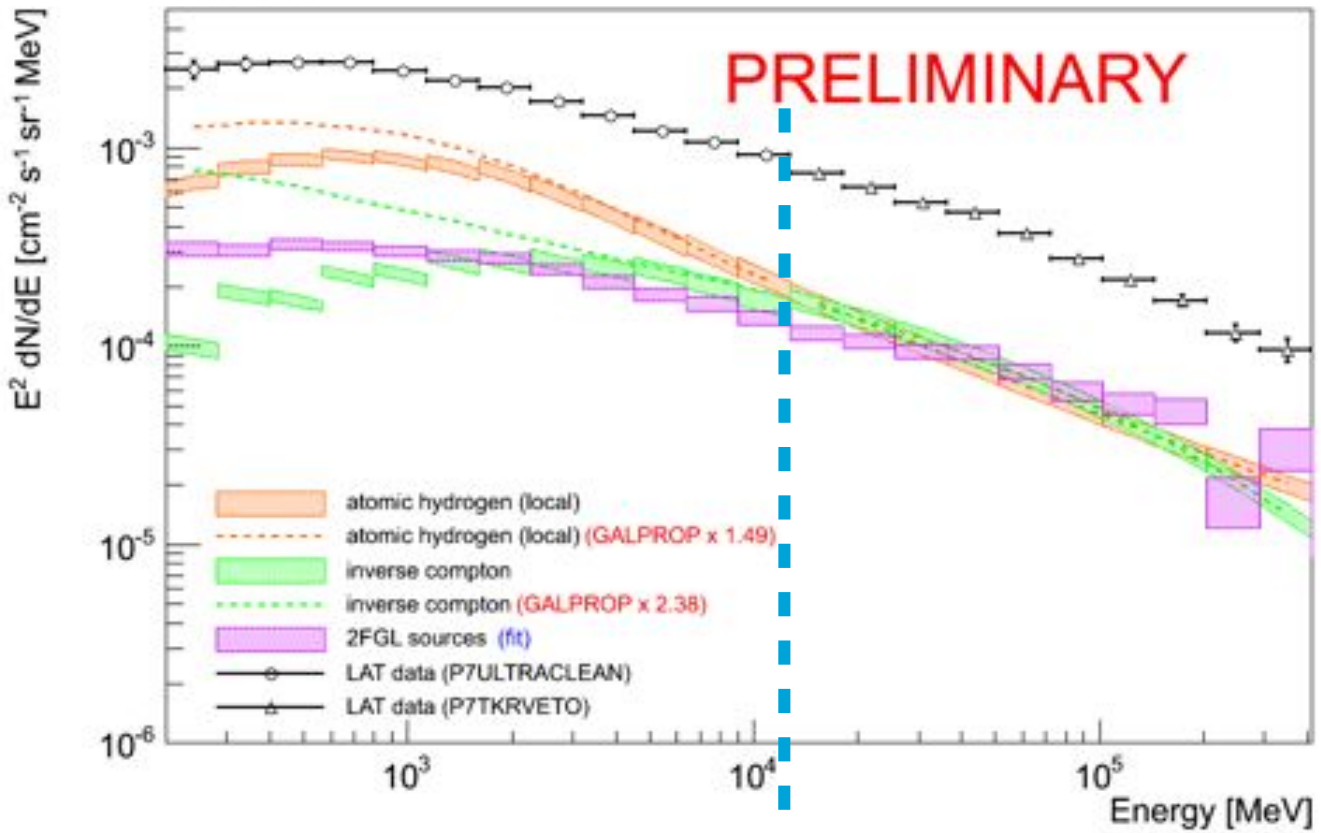
- **Default foreground model** similar to models studied in Ackermann et al., ApJ 750, 3 (2012).
  - **Cosmic-ray source distribution** follows Pulsar distribution.
  - **5 kpc** cosmic-ray halo.
  - **Diffusion & re-acceleration** of CRs in the interstellar medium.
  - **Constant & isotropic diffusion** 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 vs. high-energy analysis.



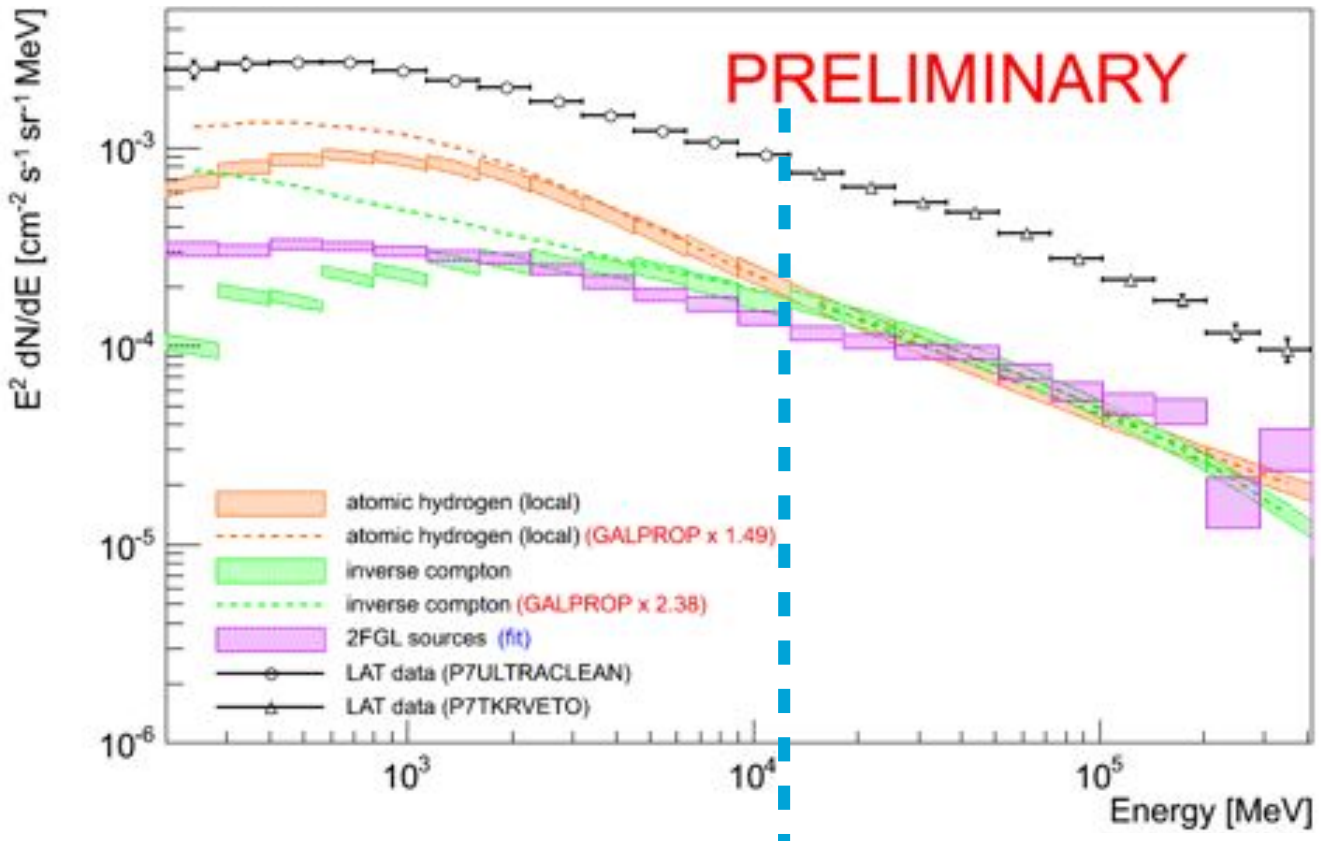
Low-energy analysis (<12.8 GeV)

- 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.

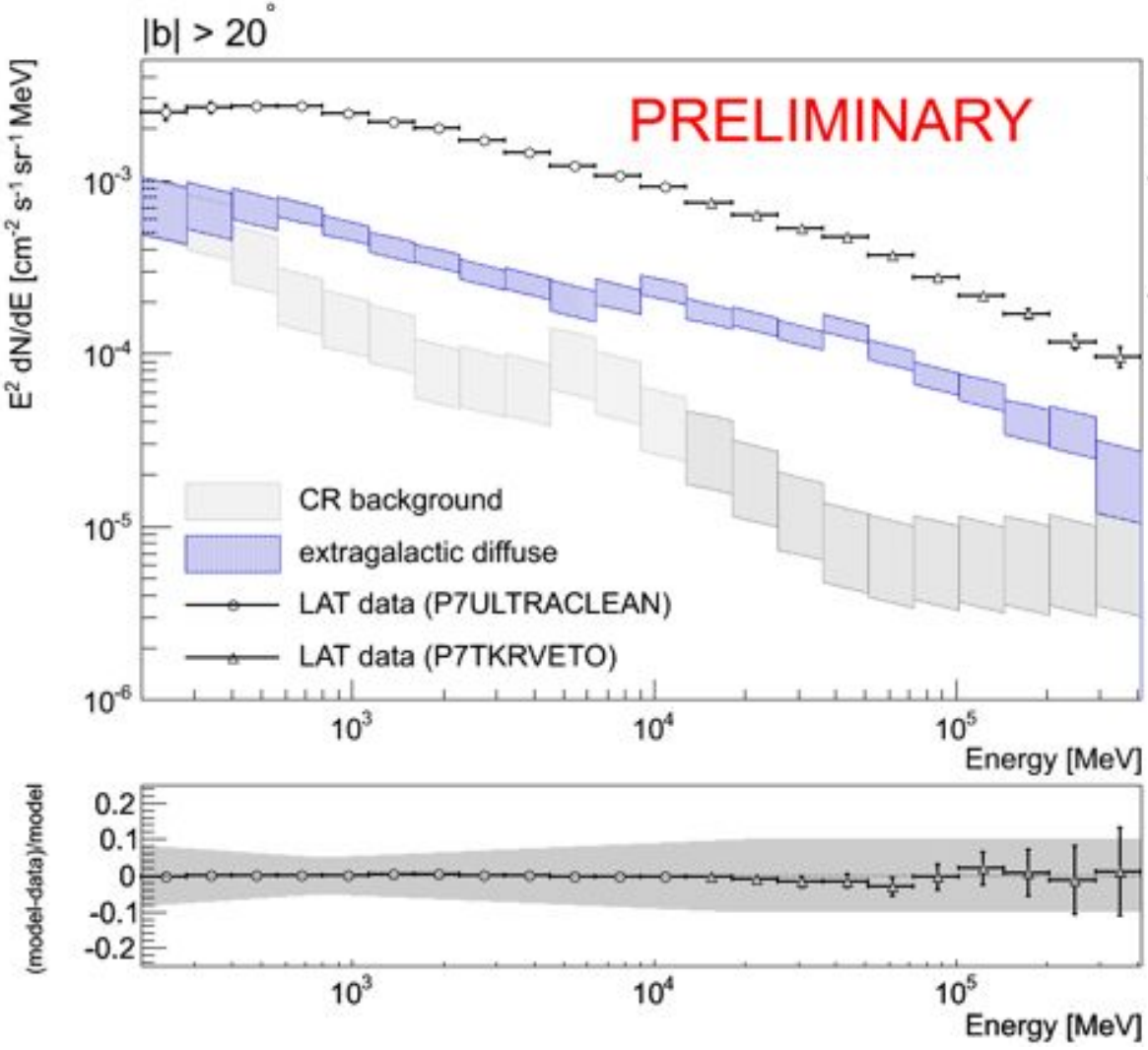
Low-energy vs. high-energy analysis.

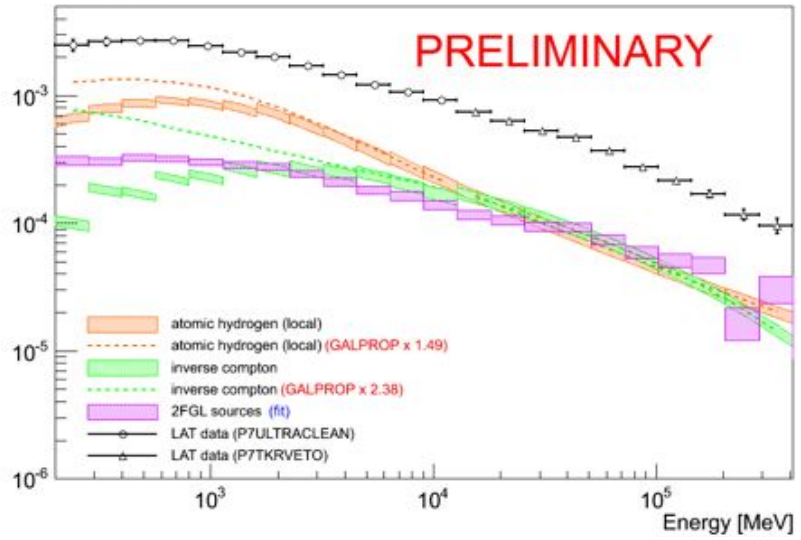


Low-energy analysis (<12.8 GeV) **High-energy analysis (>12.8 GeV)**

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

The preliminary LAT EGB spectrum.

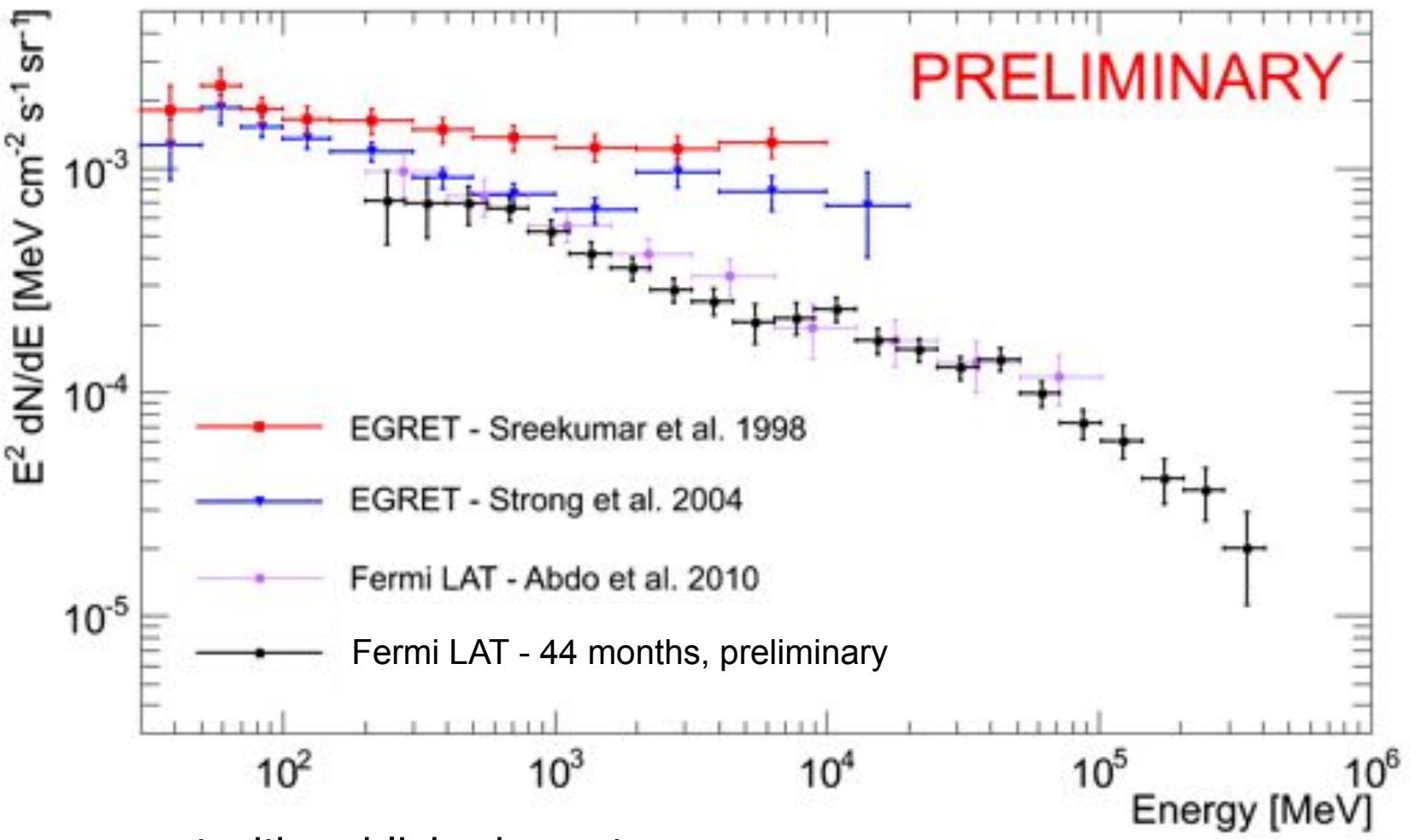




- Preliminary EGB spectrum between 200 MeV to 410 GeV for default foreground model.
- Error bands include systematics from effective area uncertainty and CR background subtraction.
- ... but **NOT** systematics from foreground model uncertainties. (still under evaluation).

- Publication in preparation for EGB spectrum up to 820 GeV.

Comparison to older measurements.



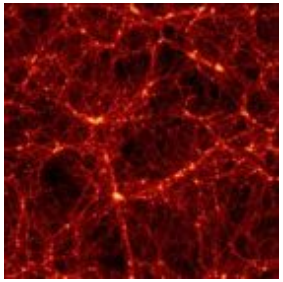
- In agreement with published spectrum.
- Error bars predominantly systematic. Apparent features in the spectrum are **NOT significant**.
- Possible spectral softening at high energies ?

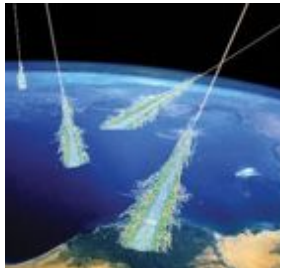
Systematic uncertainties from foreground modeling.

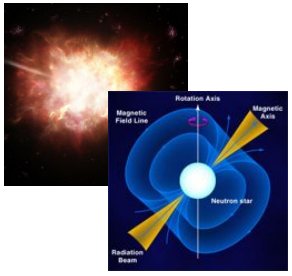
- Still under investigation.
- Particular emphasis on the impact of foreground modeling on features in the EGB spectrum.
- Expect ~ 30% uncertainty on normalization, similar to published analysis.

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

The Origin of the EGB





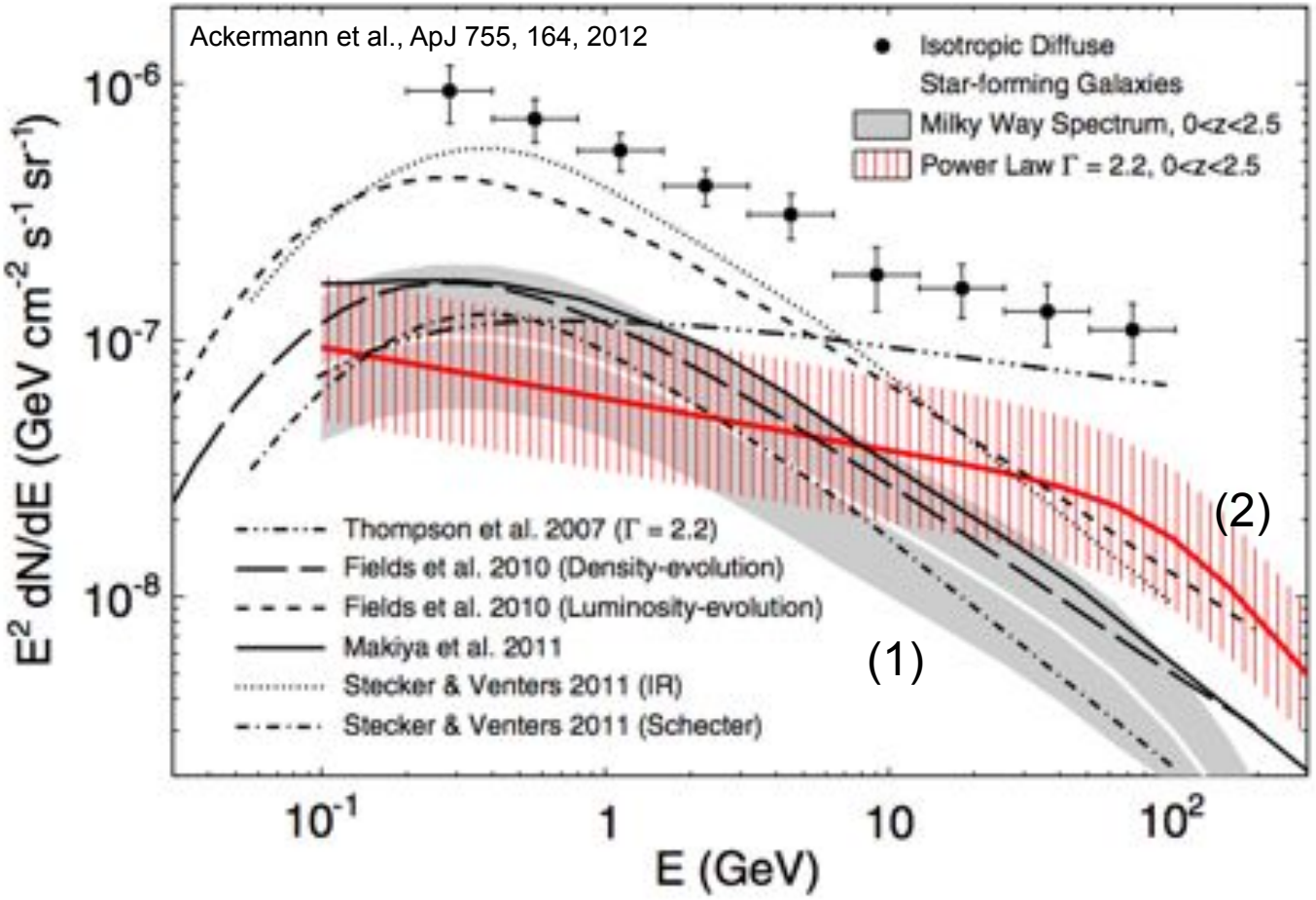


Unresolved source contributions to the EGB.

- 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 ....

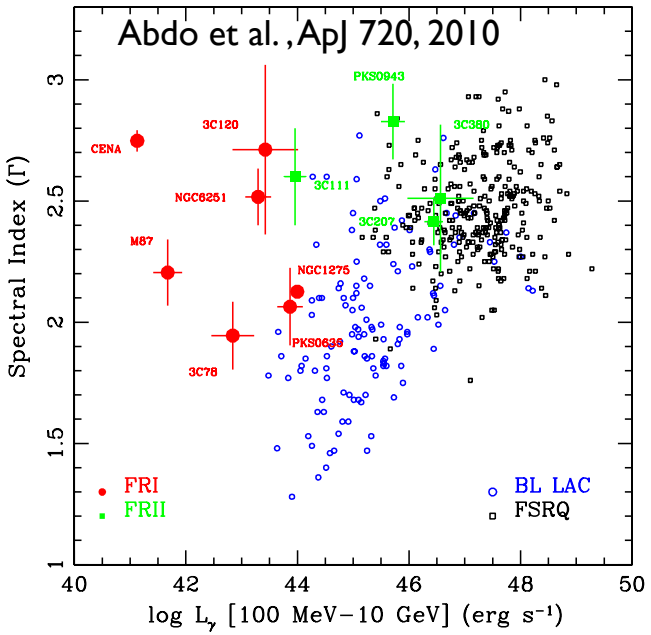
- **Star-forming galaxies**: Pavlidou & Fields 2002; Thompson et al. 2007; Bhattacharya & Sreekumar 2009; Makiya et al. 2011; Fields et al. 2010; Stecker & Venters 2011; etc.
- **Blazars**: Padovani et al. 1993; Stecker et al. 1993; Salamon & Stecker 1994; Chiang et al. 1995; Stecker & Salamon 1996; Chiang & Mukherjee 1998; Mukherjee & Chiang 1999; Muecke & Pohl 2000; Narumoto & Totani 2006; Giommi et al. 2006; Dermer 2007; Pavlidou & Venters 2008; Kneiske & Mannheim 2008; Bhattacharya et al. 2009; Inoue & Totani 2009; Abdo et al. 2010; Stecker & Venters 2010; 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.

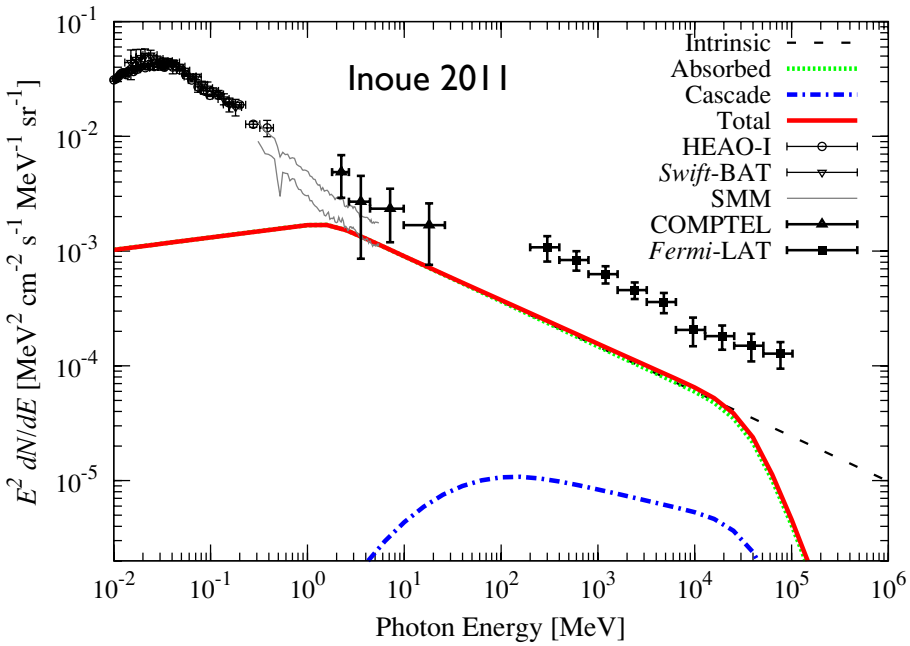


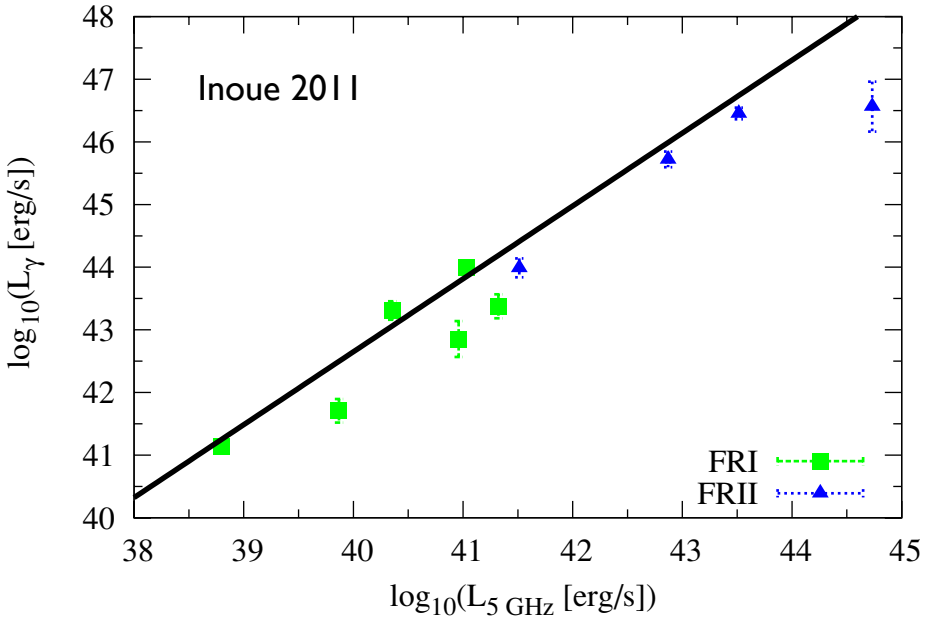
- 4% - 23% contribution to EGB from star-forming galaxies ($0 < z < 2.5$)
- Gamma-ray emission from galaxies is assumed to follow either a rescaled Milky Way (1) or a power-law spectrum (2), observed for Starburst Galaxies.
- Talk by Keith Bechtol this morning.

Contributions from radio galaxies.

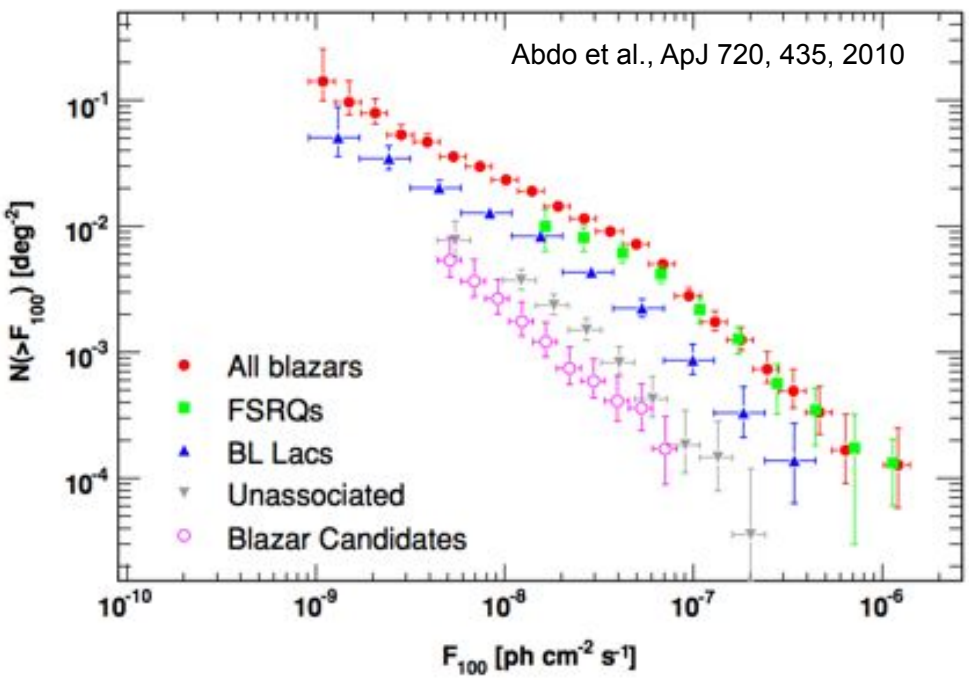


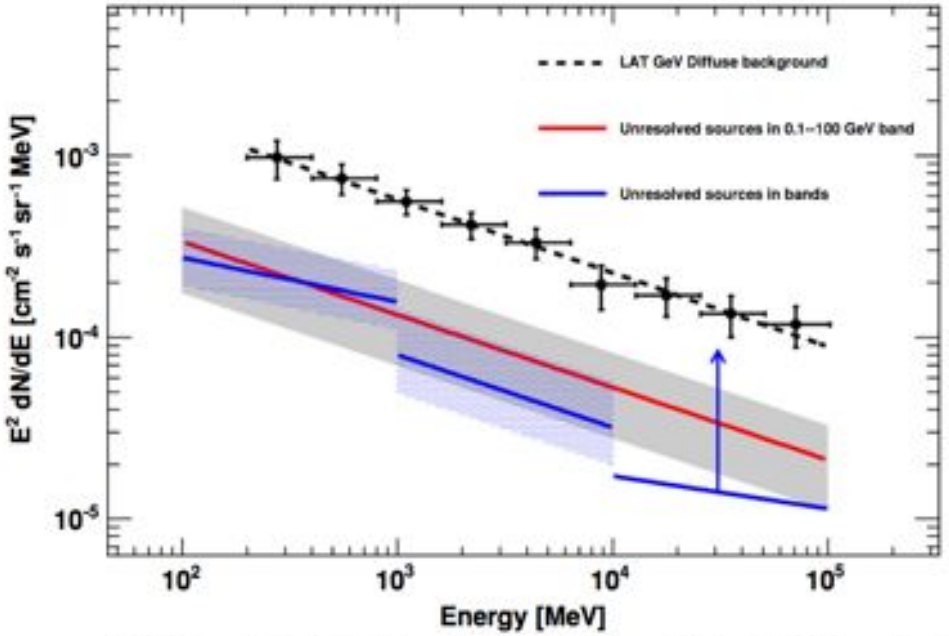
- Estimation of contribution of LAT detected radio galaxies to the EGB (Inoue 2011).
- Uses correlation of Radio/Gamma-ray luminosity based on 11 radio galaxies described in Abdo et al., ApJ 720, 2010.
- EGB contribution estimated from radio luminosity function.
- unresolved radio galaxies contribute ~ 25%.

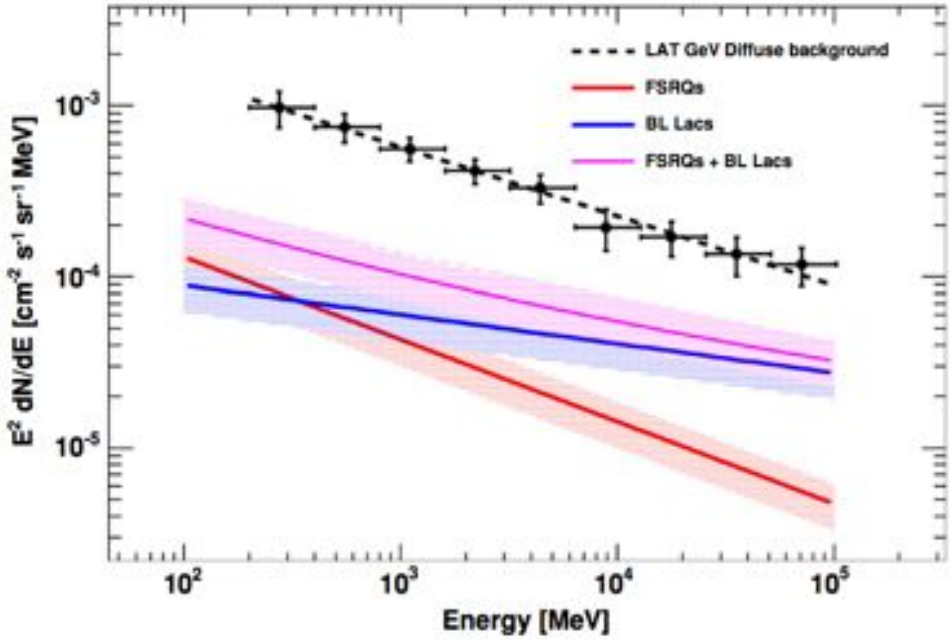




Unresolved Blazars.

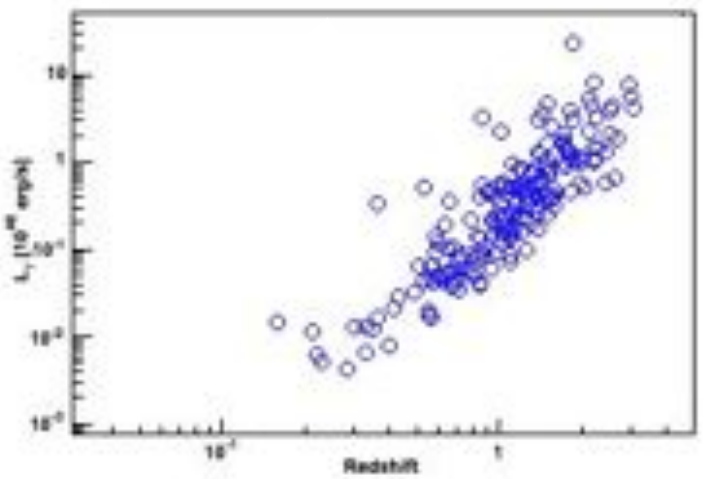






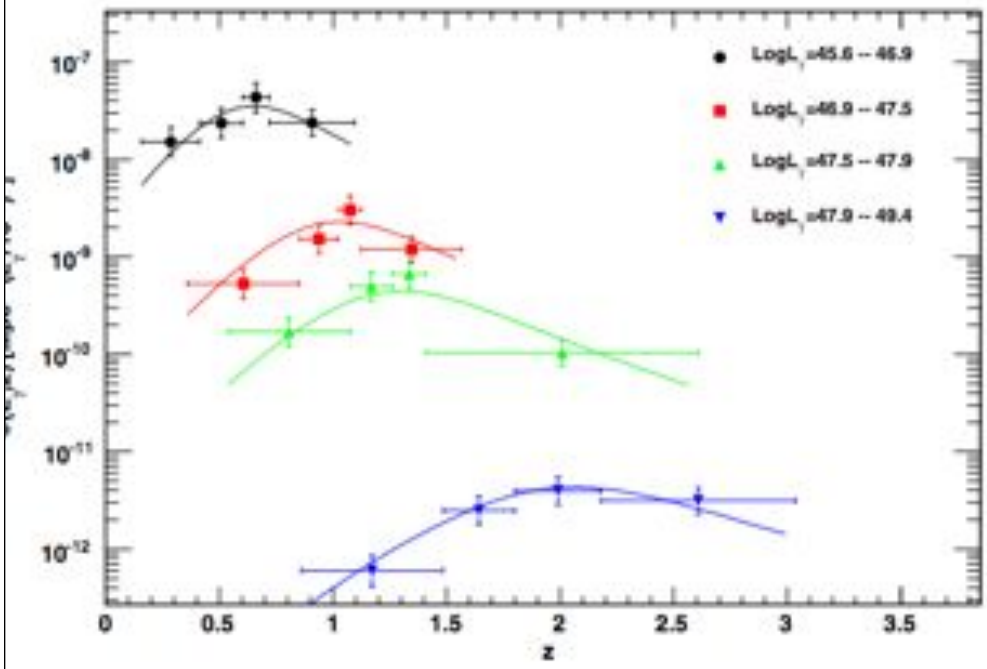
- Blazars are dominant extragalactic source population in the LAT energy band.
- Extrapolation of source count distribution of resolved LAT Blazars allows estimate of their contribution to the EGB.
- Total contribution of Blazars in 100 MeV - 100 GeV band: 23% ± 5% (stat) ±12% (syst)

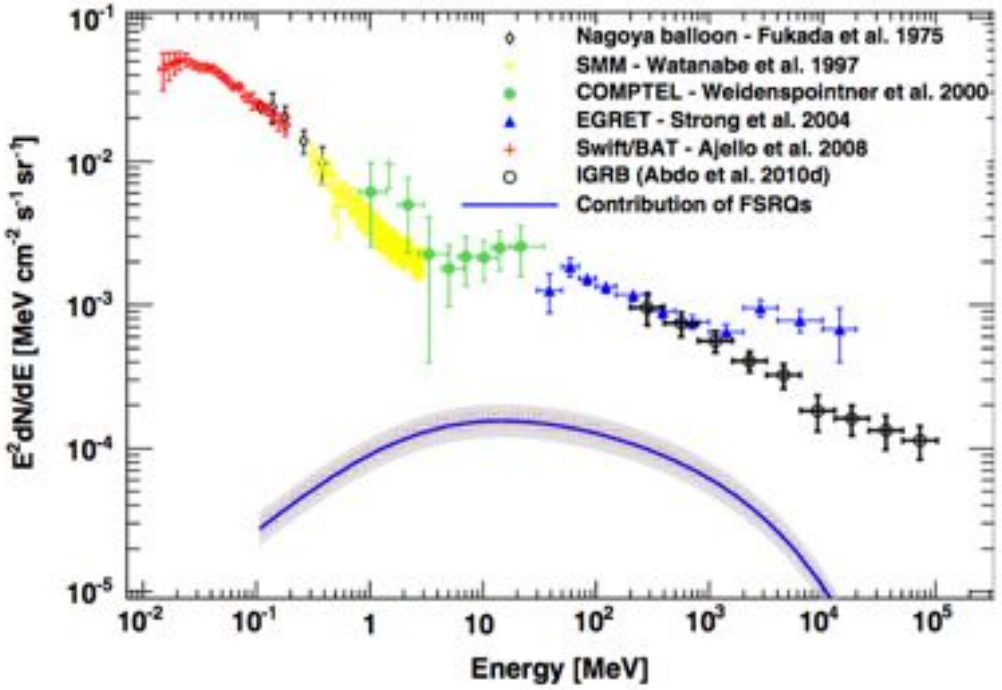
Unresolved Blazars: FSRQ gamma-ray luminosity function.



Ajello et al., ApJ 751, 108, 2012

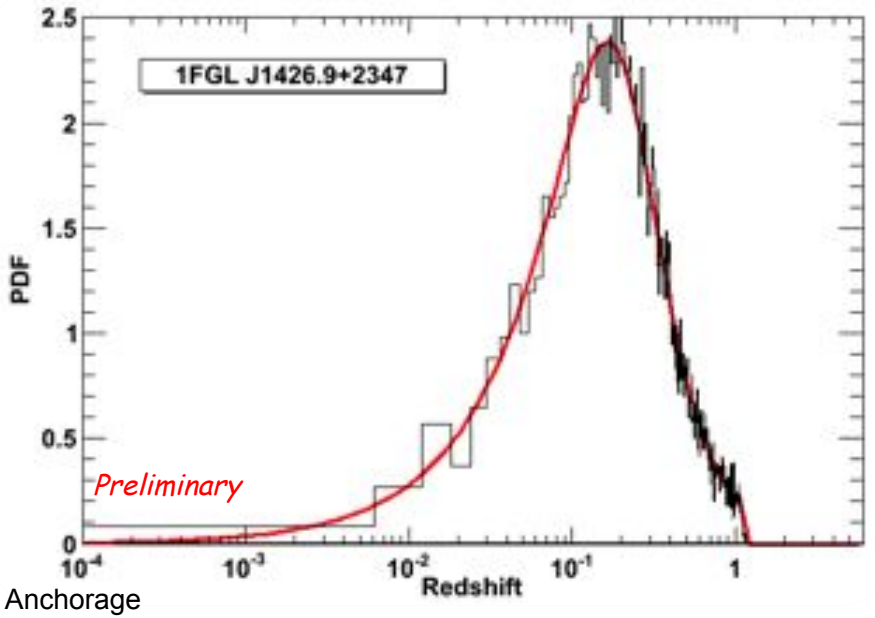
- LAT resolved FSRQ population spans wide range in redshift and luminosity
- Allows to build gamma-ray luminosity function (GLF) based on LAT data alone
- Luminosity-dependent density evolution (LDDE) fits LAT population best
- Prediction of EGB contribution based on GLF + spectral modeling



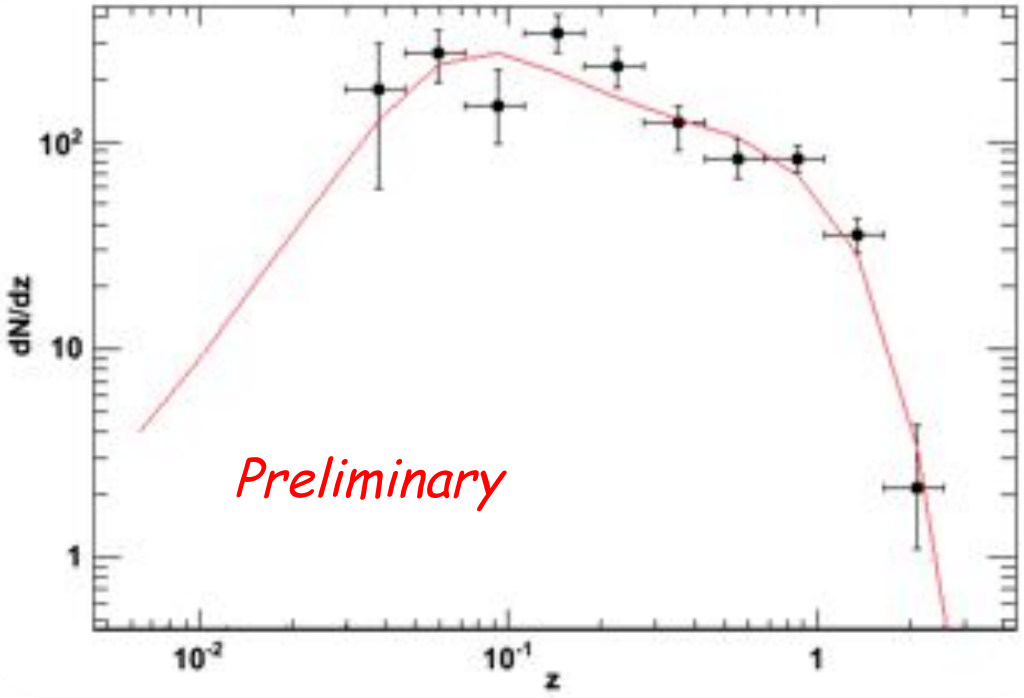


Unresolved Blazars: BL Lac luminosity function.

- 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.

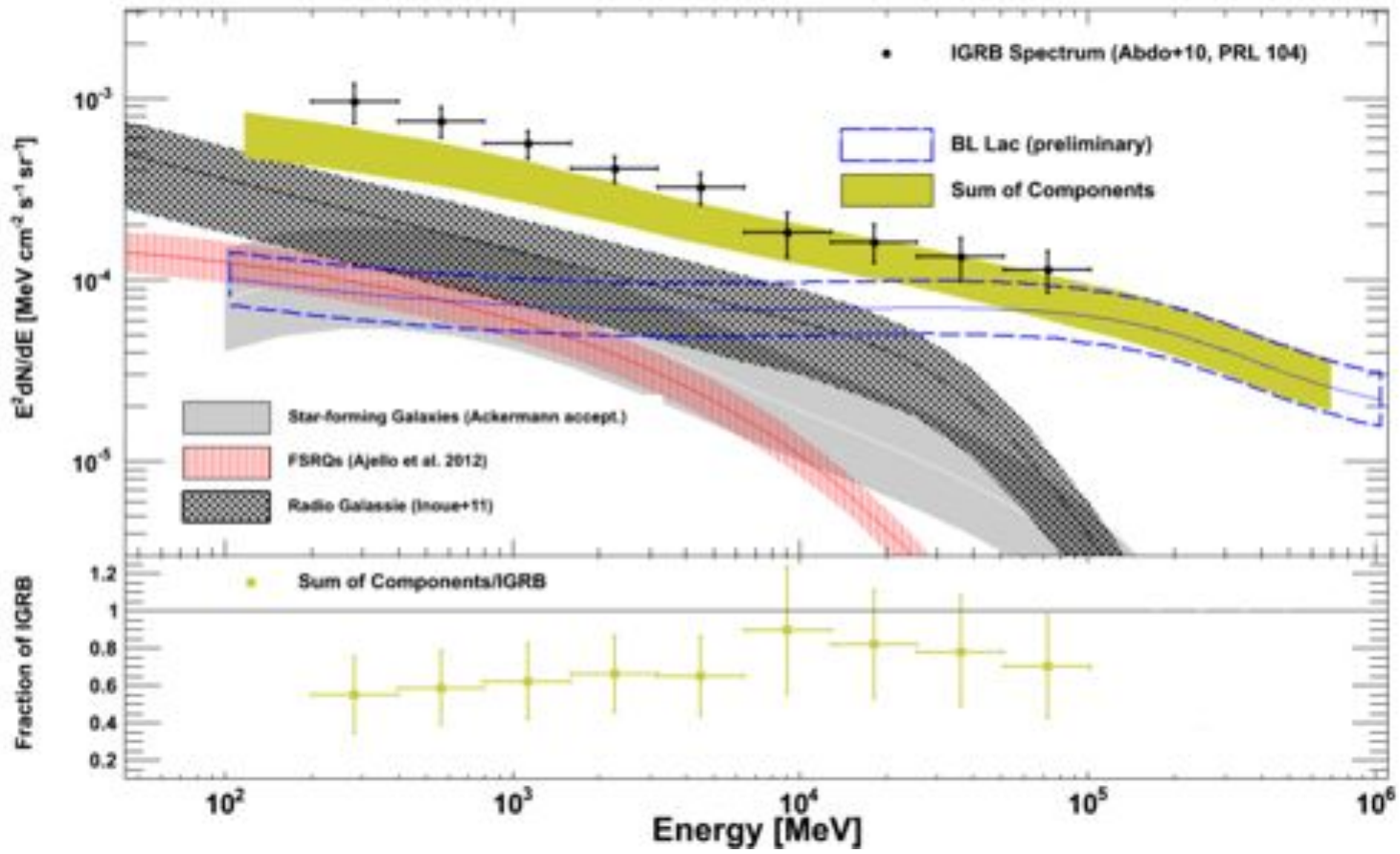


Ajello, 220th AAS meeting, Anchorage



- Evidence for:
  - strong positive evolution
  - different evolutionary speeds for BL Lac of different luminosities
  - Redshift peak at ~0.75

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

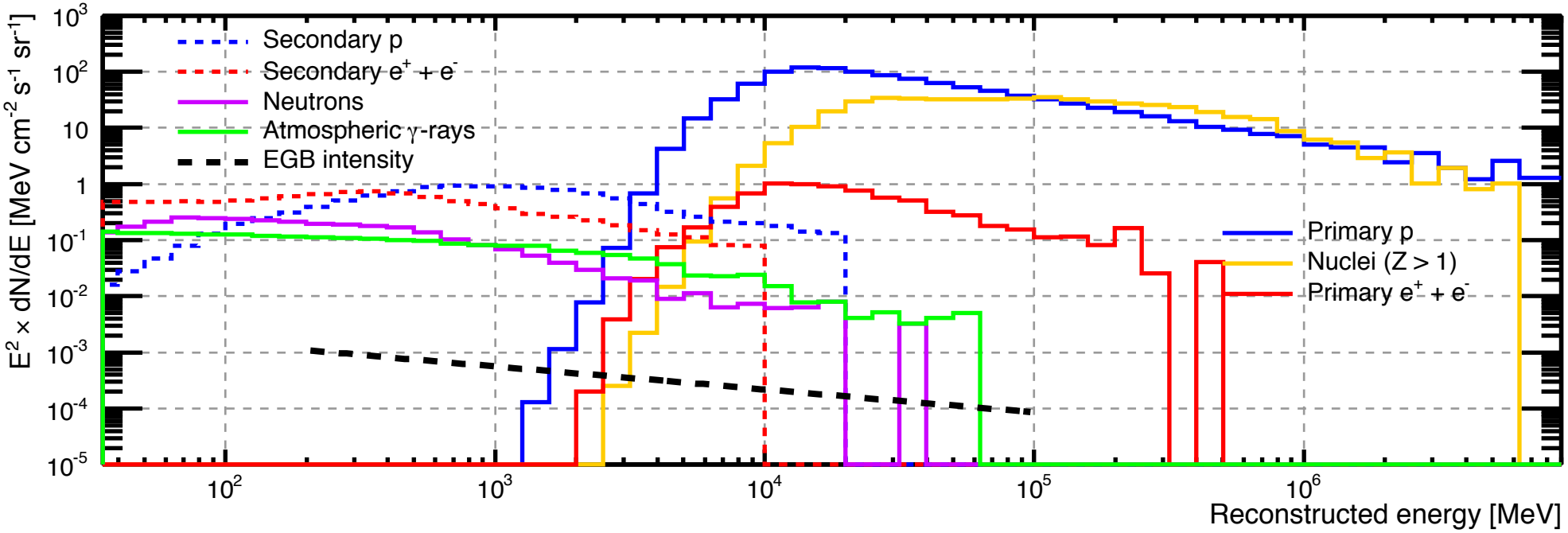
Summary.

- 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).

Backup.

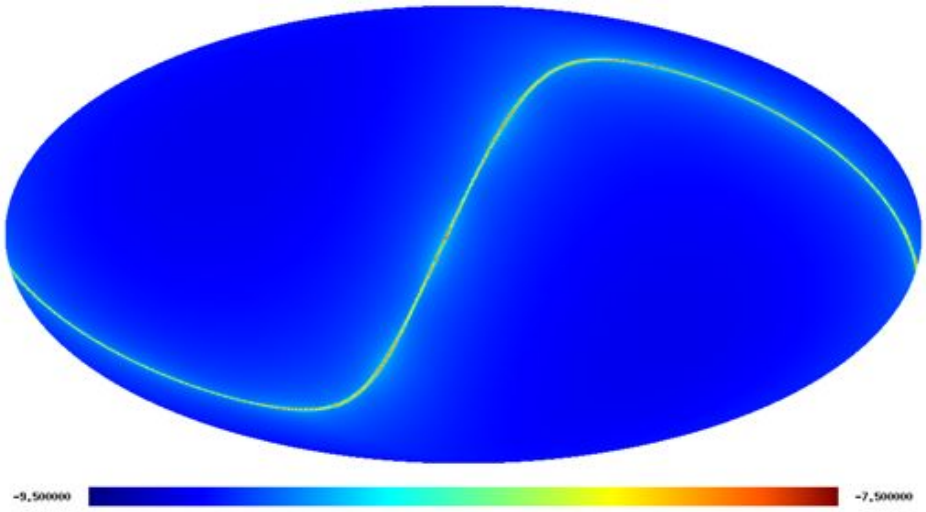
Background from charged cosmic rays.

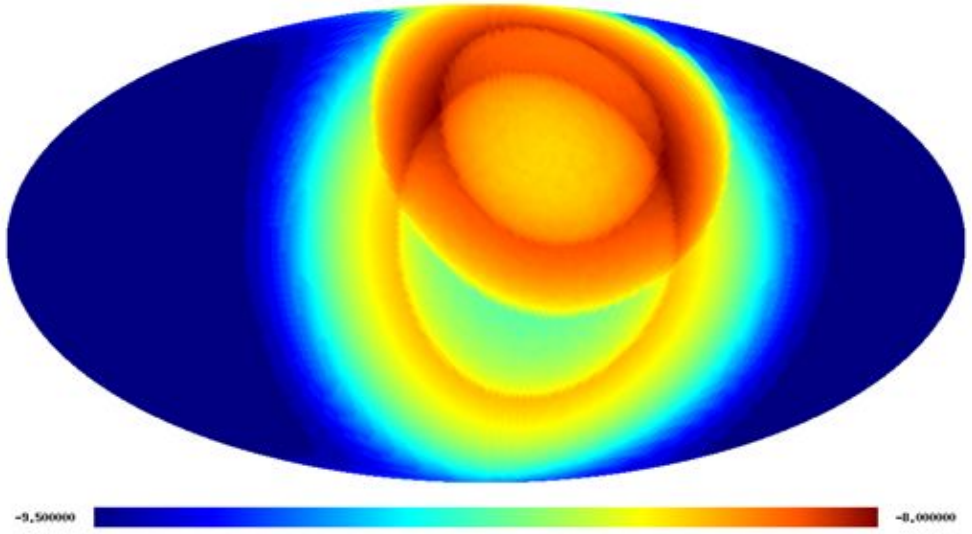
- Primary cosmic rays + secondaries created in the Earth atmosphere.
- More than 6 orders of magnitude in CR background suppression is needed (at 10 GeV) for EGB analysis.
- Isotropic distribution assumed for long (>>1 day) observation periods.
- LAT cosmic-ray background model:



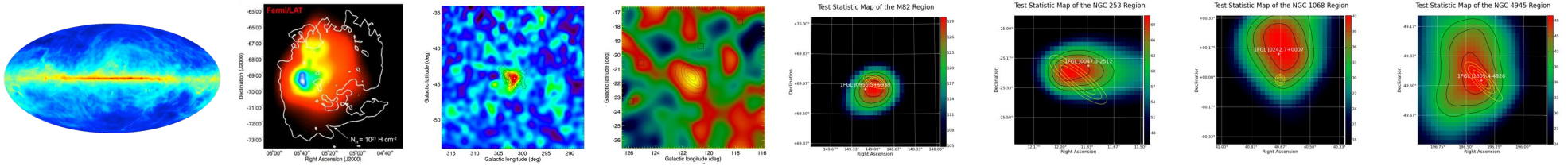
- Background suppression efficiency and remaining residual background needs to be carefully studied to allow its subtraction in the EGB analysis.

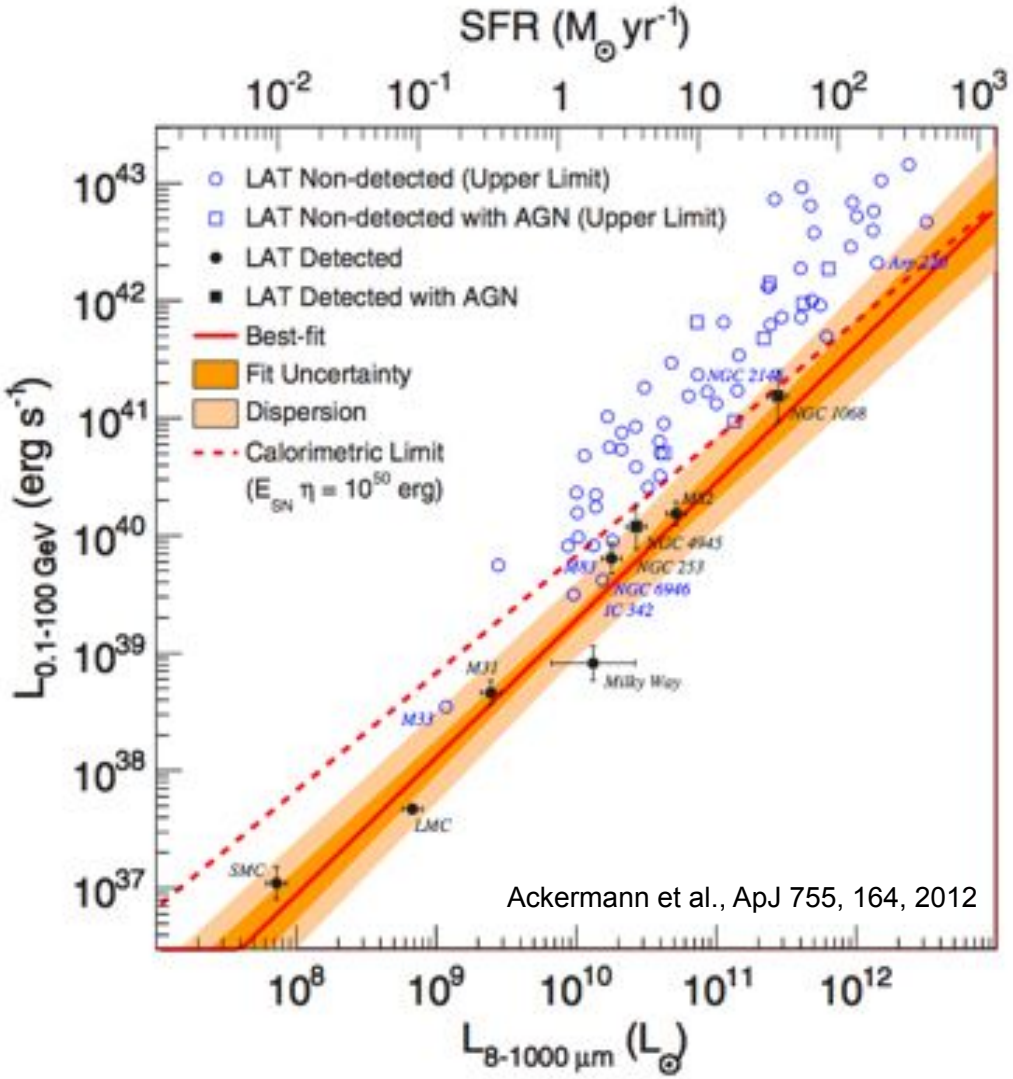
Solar template and Loop I template.





Contributions of star-forming galaxies.





Ackermann et al., ApJ 755, 164, 2012

- 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.