

Intensity and origin of the extragalactic gamma-ray background.

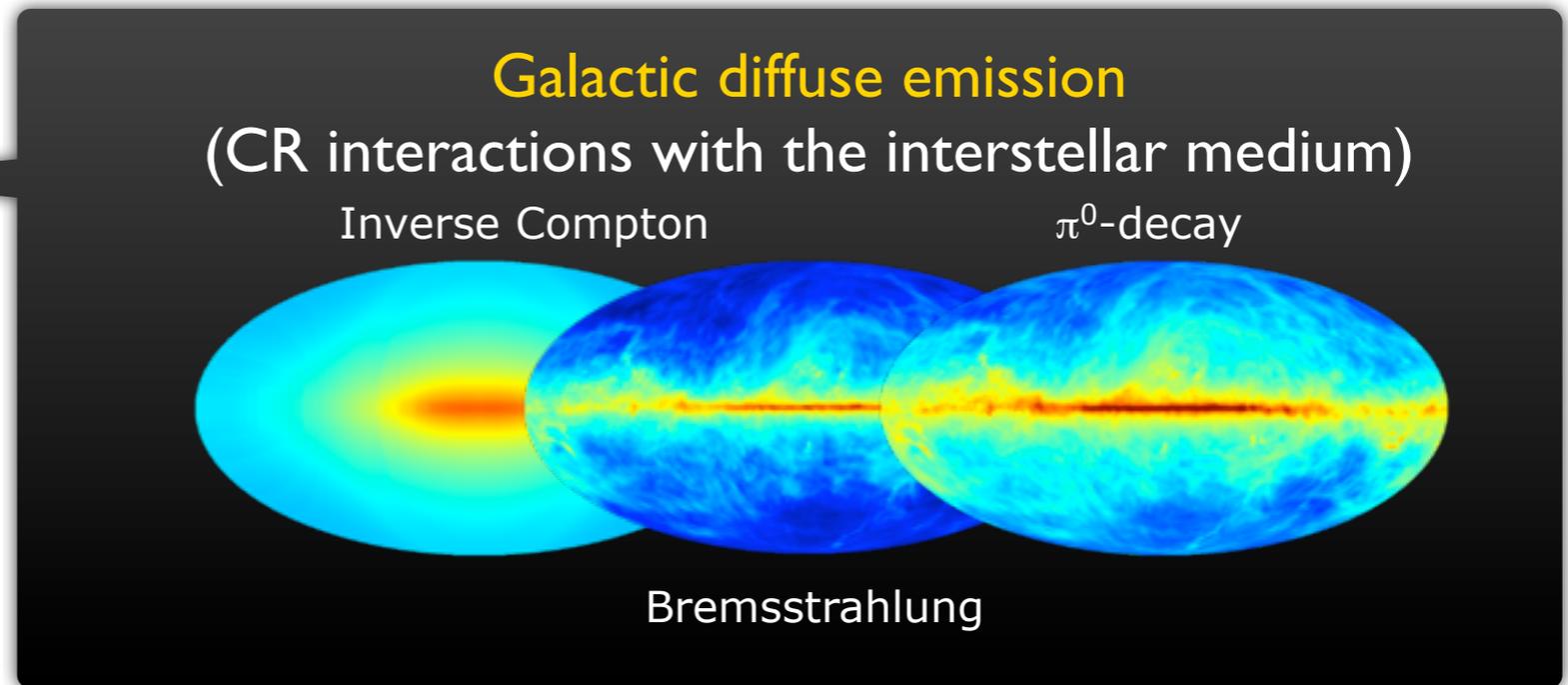
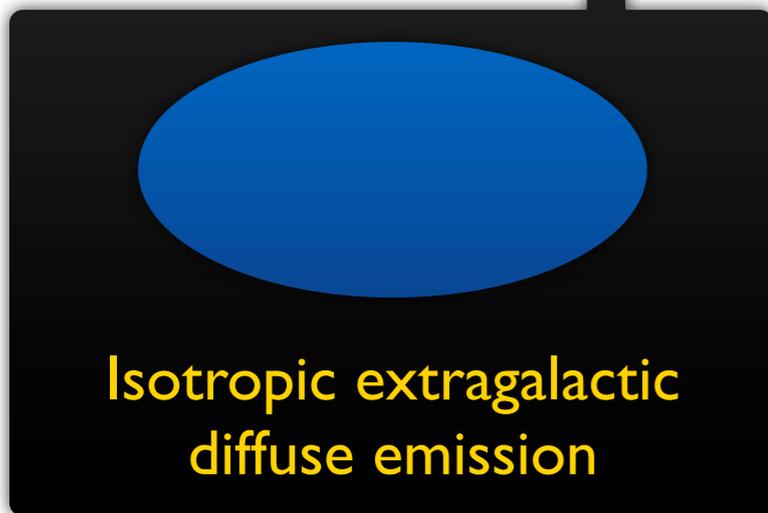
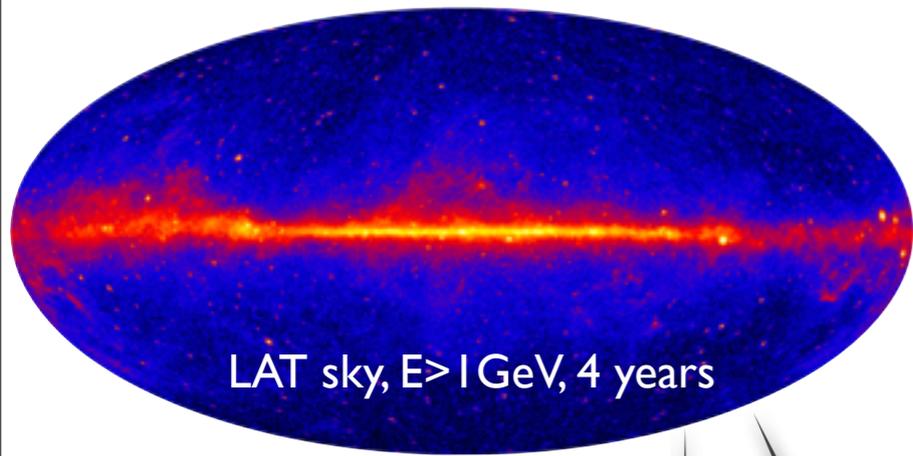


Markus Ackermann
on behalf of the Fermi LAT collaboration

4th Fermi Symposium
Monterey, California
11/01/2012

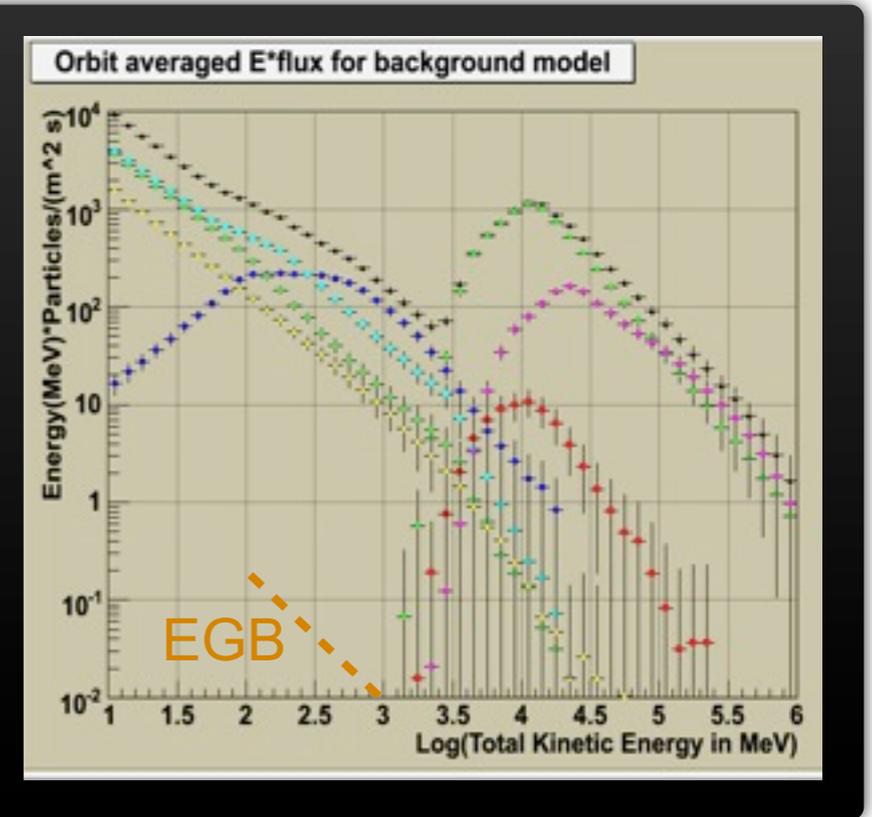


The Extragalactic gamma-ray background (EGB).



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

γ -rays from the Earth limb
 γ -rays $\ll 1 \text{ GeV}$ with poor directional reconstruction



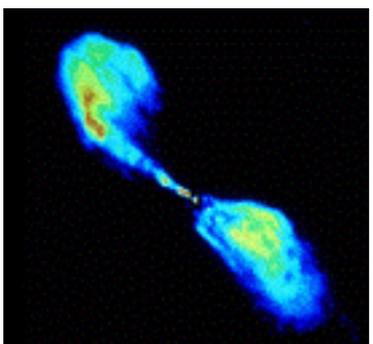
The origin of the EGB in the LAT energy range.

Undetected sources



Blazars

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



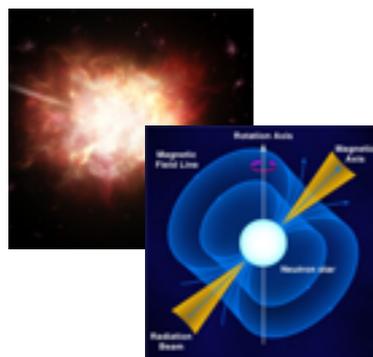
Non-blazar active galaxies

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

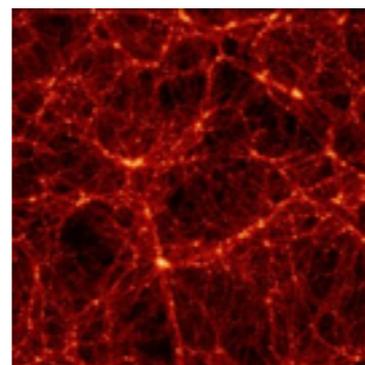
Small contributions expected. (e.g. Dermer 2007, Siegal-Gaskins et al. 2010)

Diffuse processes



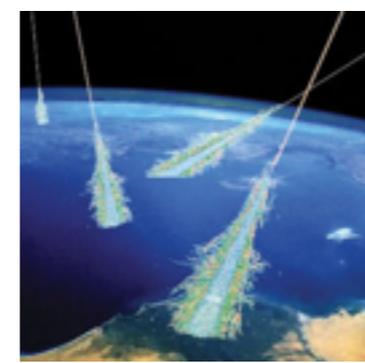
Intergalactic shocks

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)

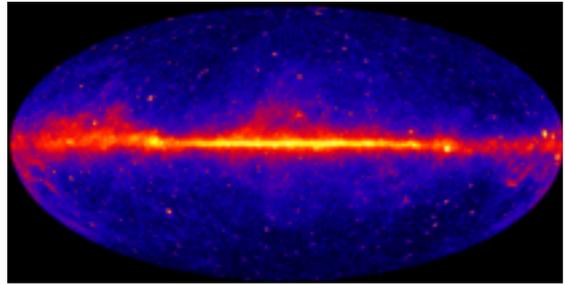


Extremely large Galactic electron halo (Keshet et al. 2004)

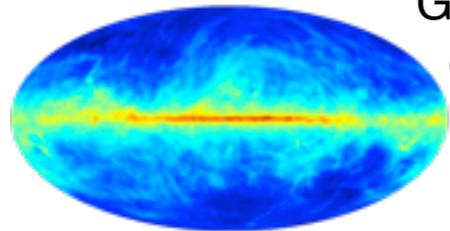
CR interaction in small solar system bodies (Moskalenko & Porter 2009)

Derivation of the EGB spectrum.

LAT sky

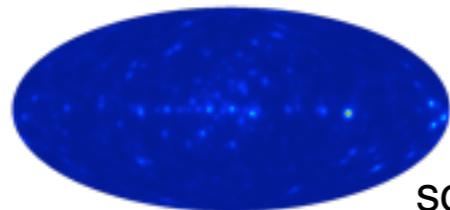


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Galactic diffuse model

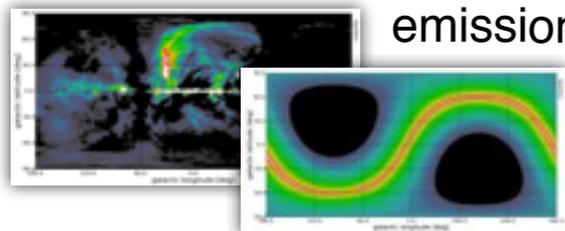
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Point sources

+

local & solar diffuse emission



+



Isotropic

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

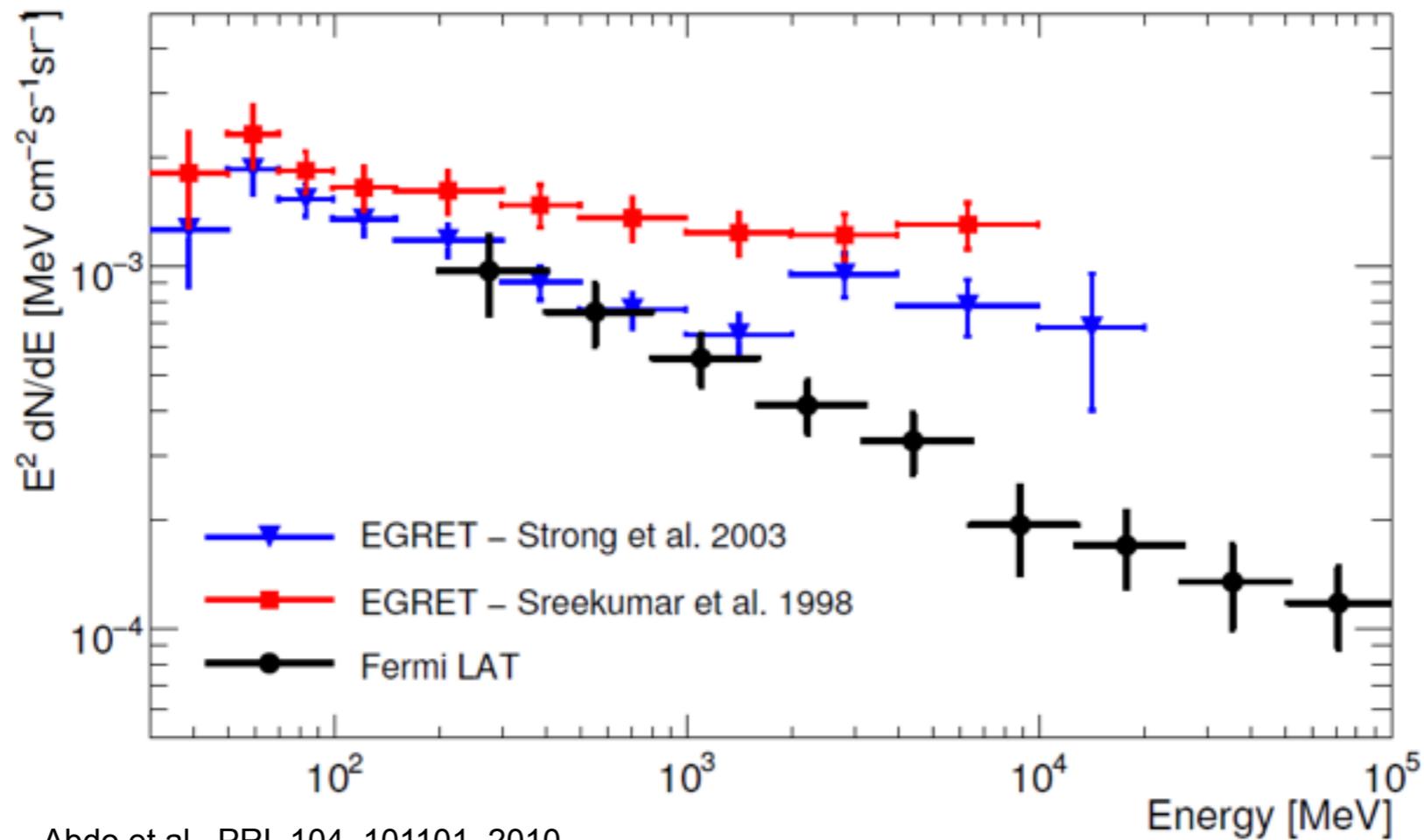
- LAT sky map compared to full model of gamma-ray emission.
- Equal-area pixels with 0.8 deg^2 (HEALPix grid).
- Point sources and diffuse emission fitted simultaneously.

> 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 ($\sim 30\%$).

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.



EGB analysis improvements.

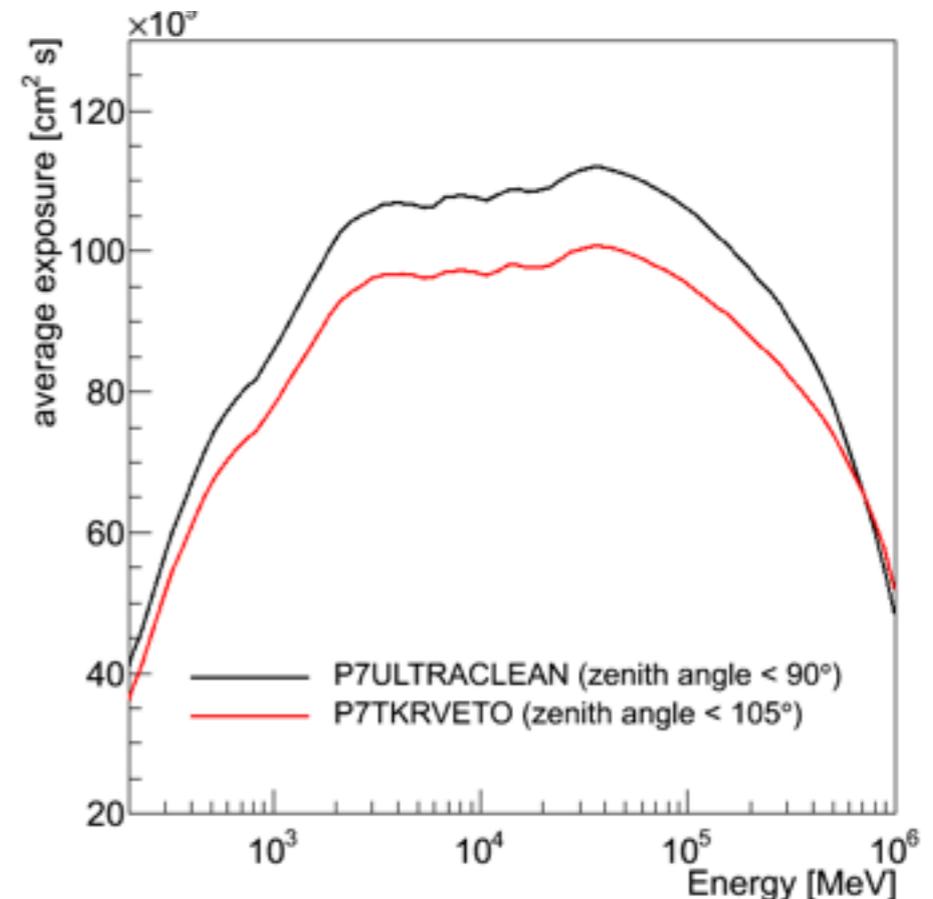
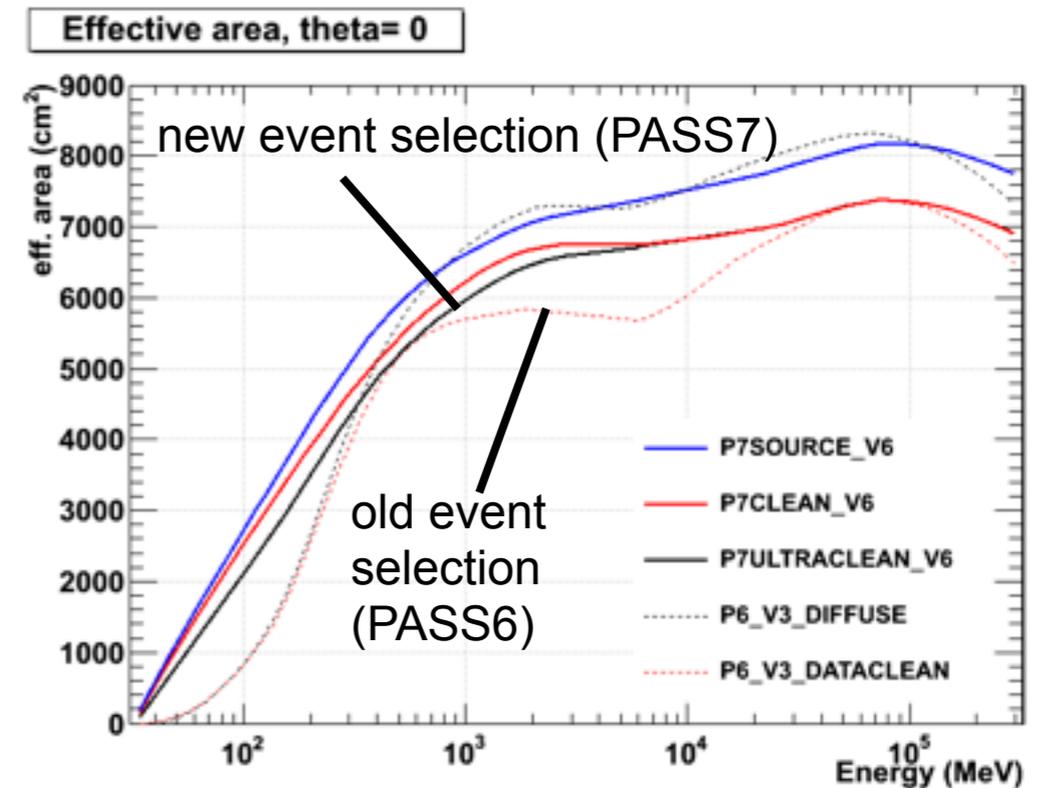
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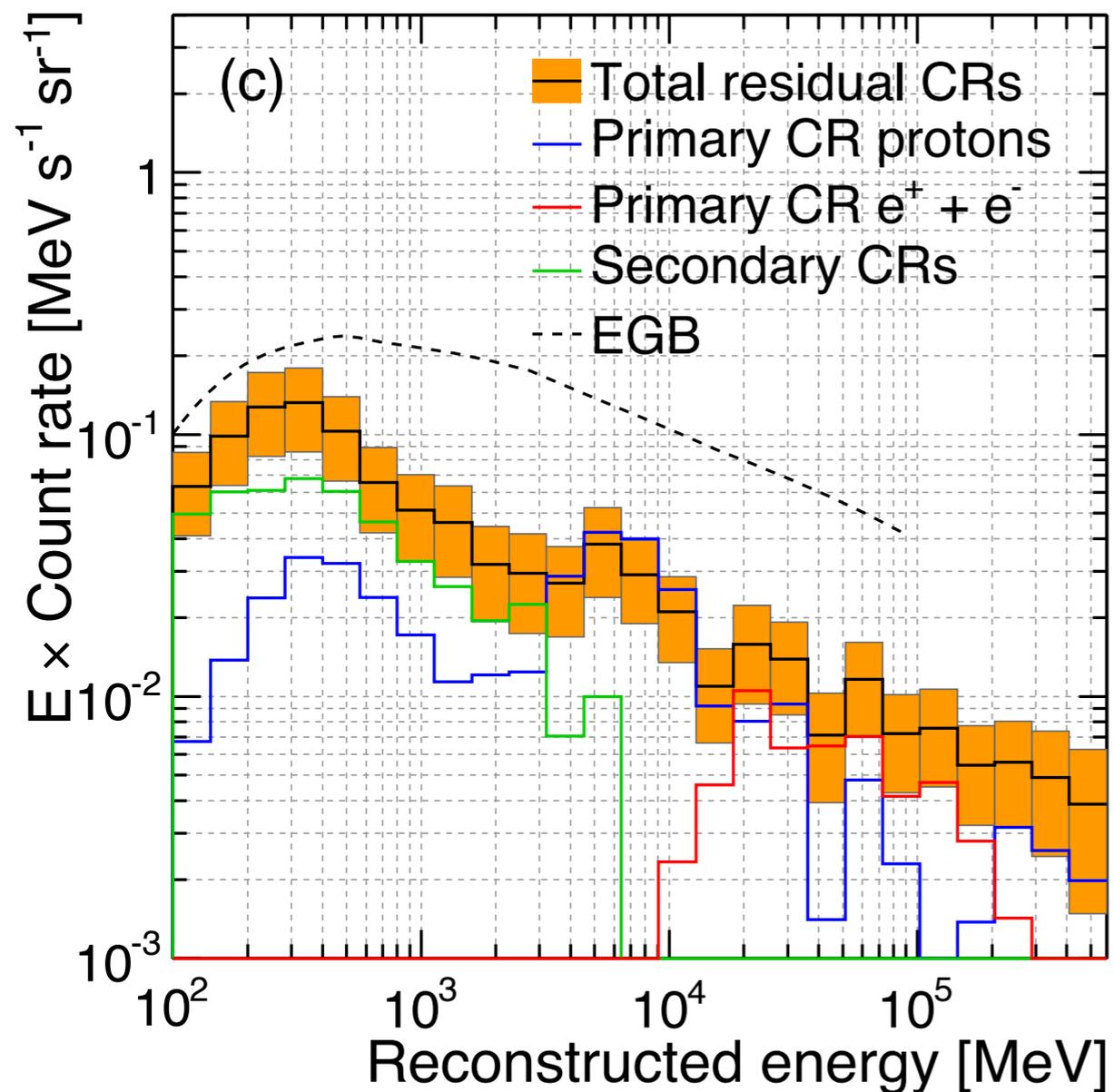


New event classification.

- > **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.

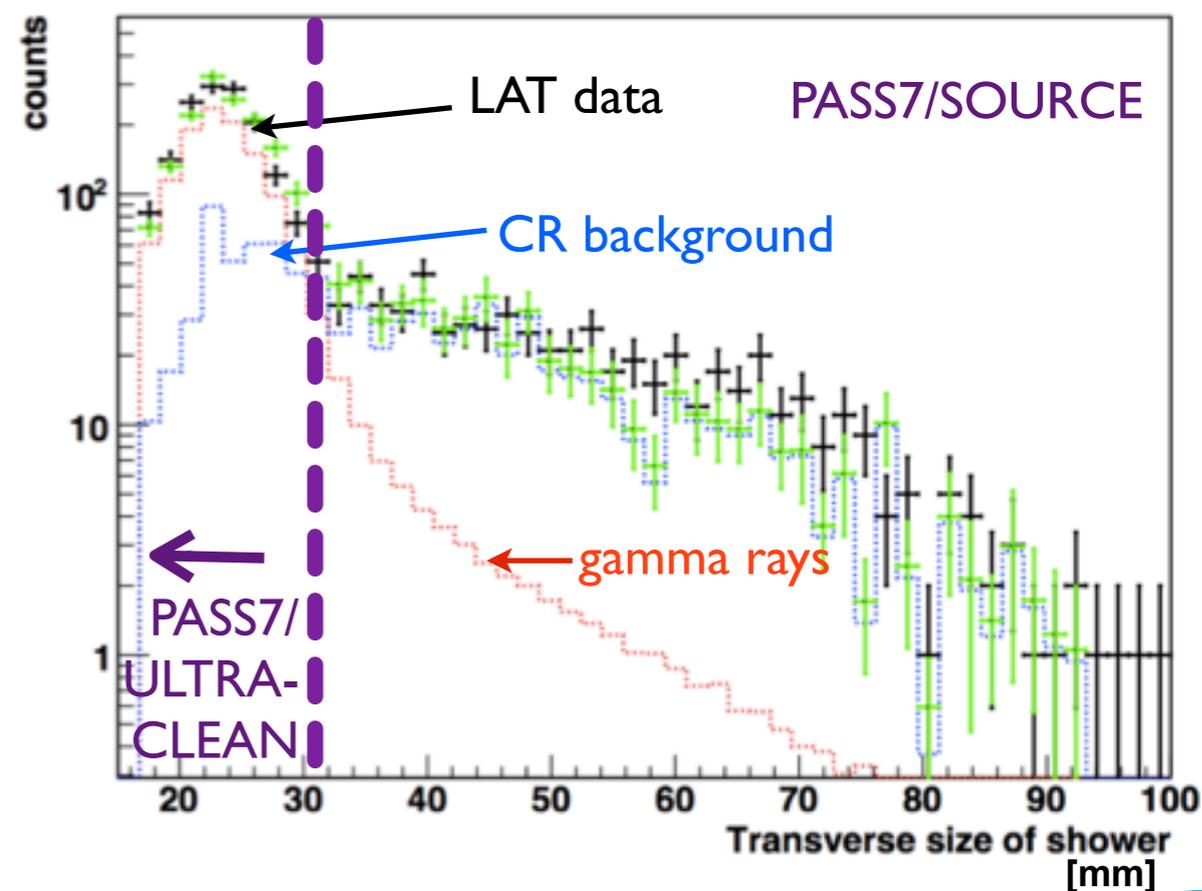


Background from charged cosmic rays.



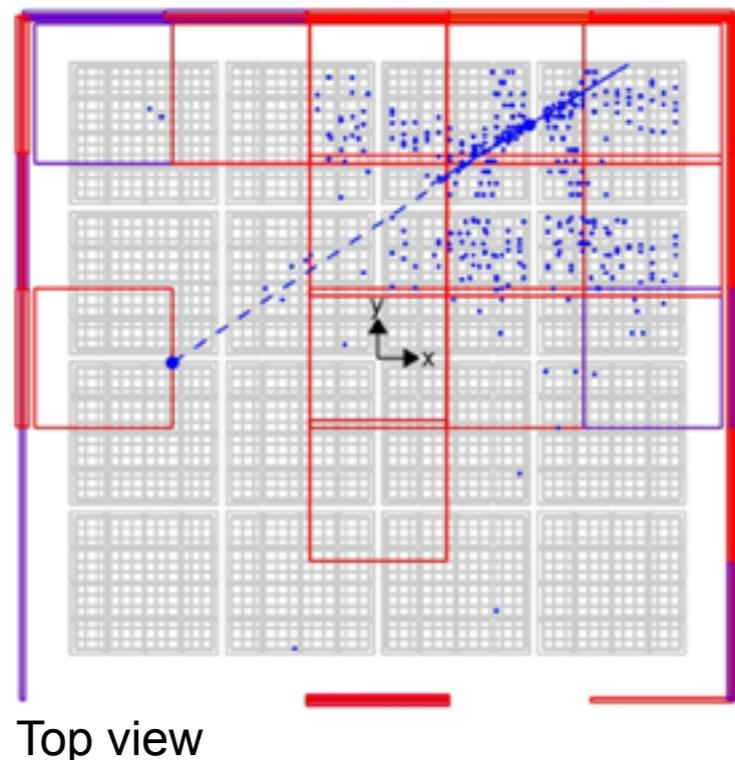
- Large scale Monte Carlo production effort to determine residual CR background contamination in PASS7 event classes up to 1 TeV.

- 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.
- $\pm 35\%$ systematic uncertainty on prediction.



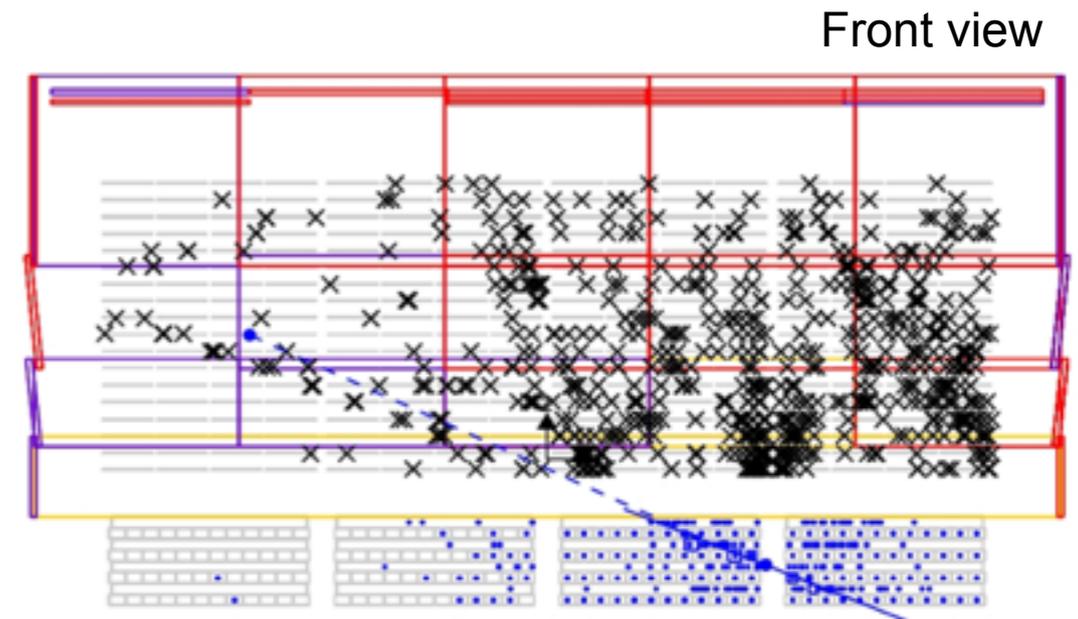
Energy range limit from event selection/reconstruction.

- > 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)**

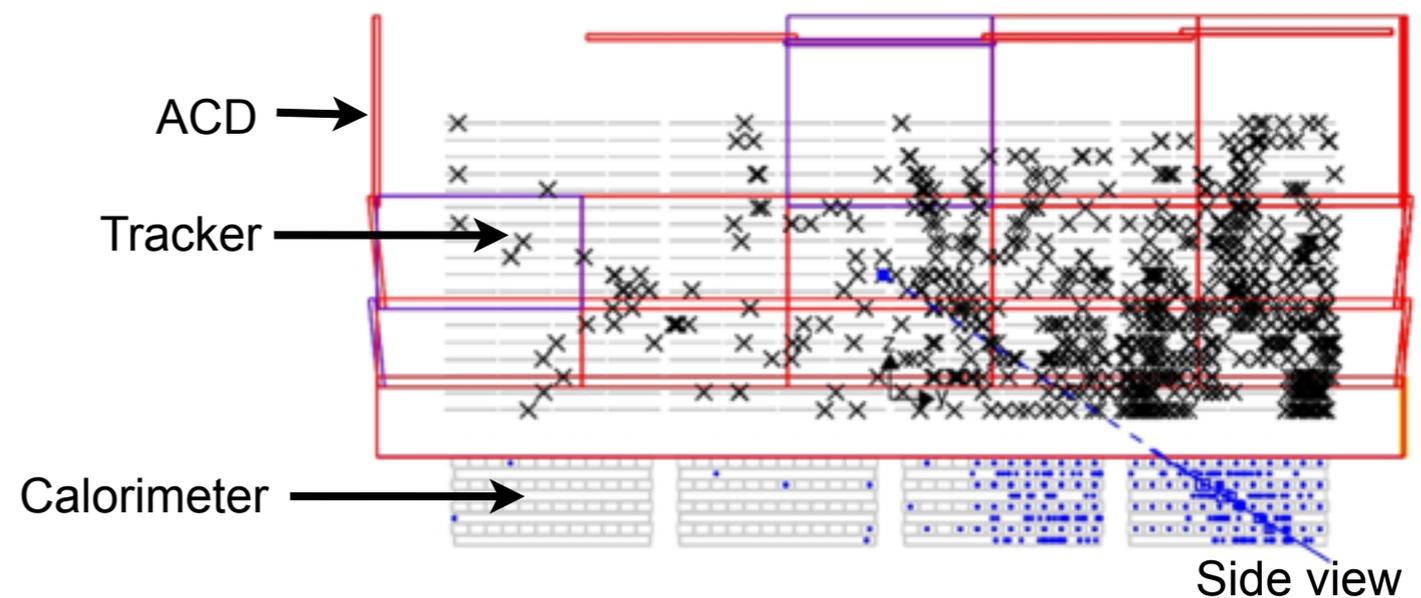


Top view

LAT view of a 920 GeV event



Front view

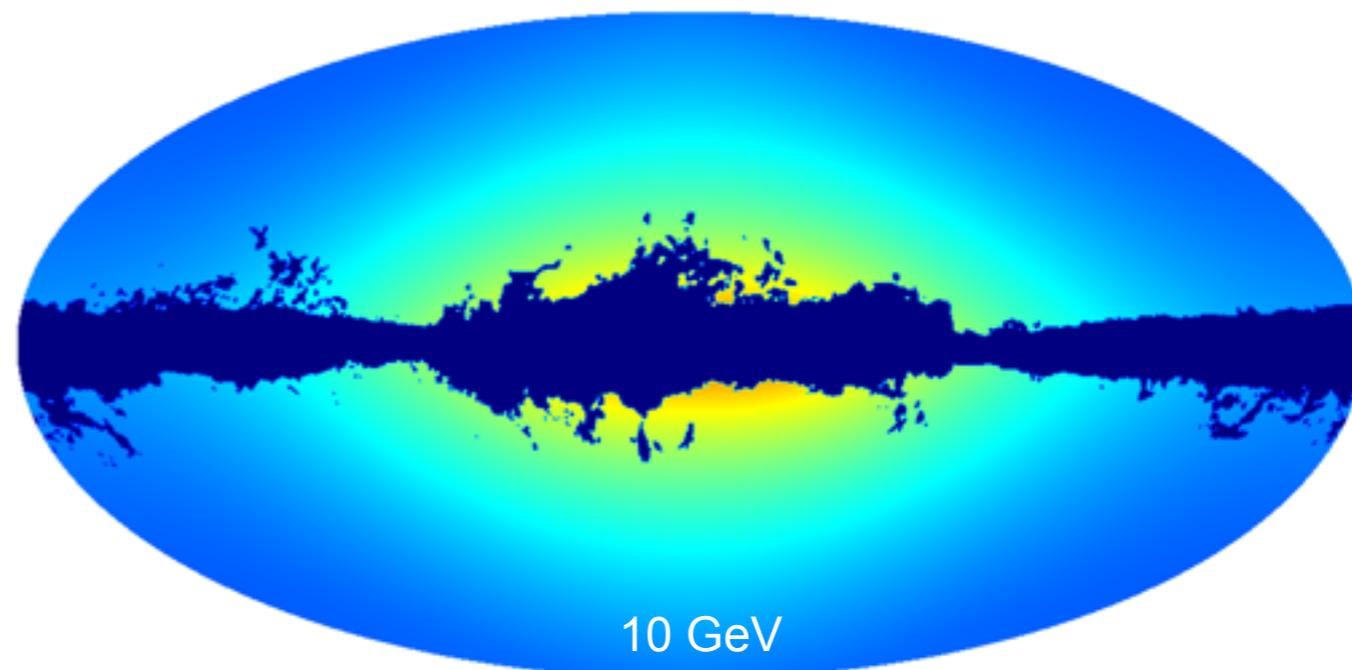
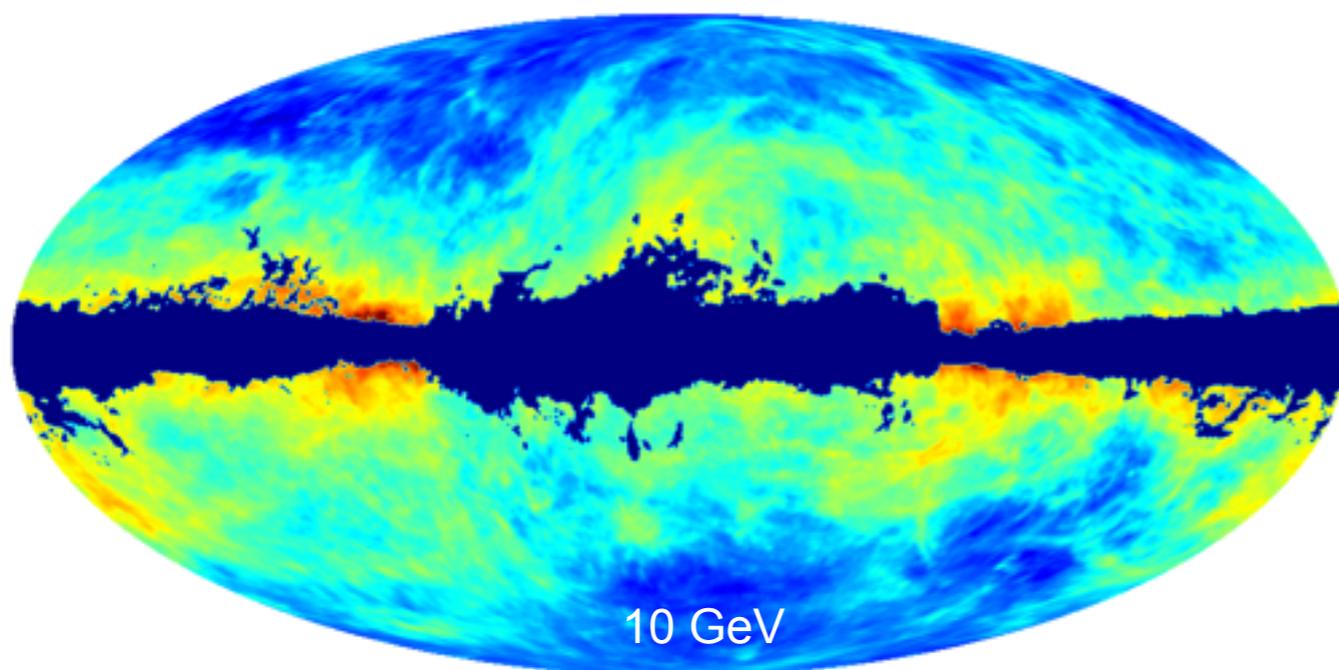


Side view

Model for the Galactic diffuse emission foreground.

γ -ray emission model

γ -ray emission model



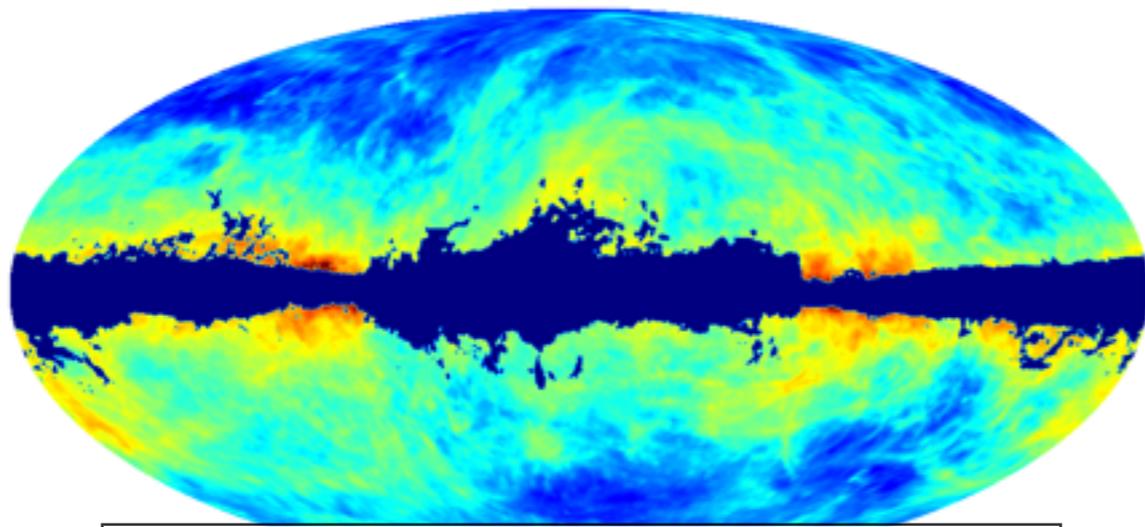
$H_I + H_{II}$ ($8 \text{ kpc} < r < 10 \text{ kpc}$)

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 ($r < 8 \text{ kpc}$ 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 π^0 -decay** from CR interactions with local ($8 \text{ kpc} < r < 10 \text{ kpc}$) 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).

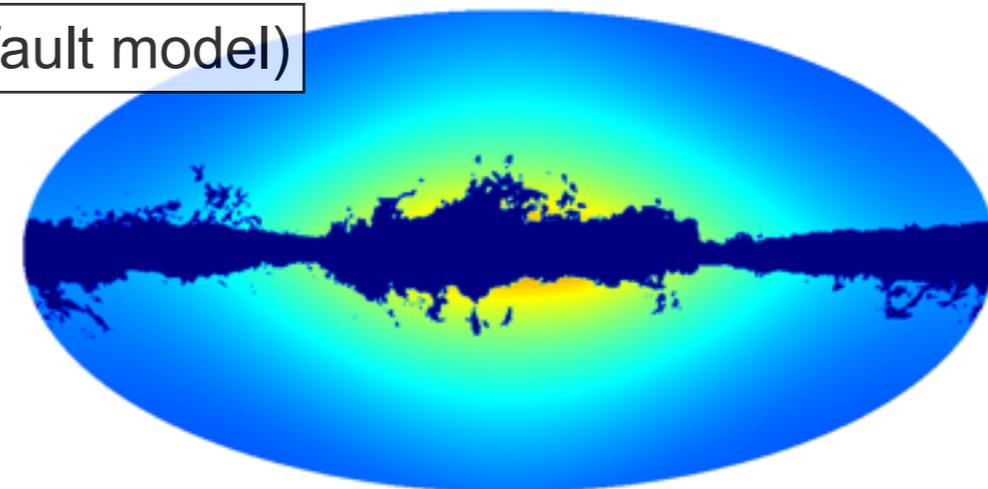


γ -rays from interactions with $H_I + H_{II}$
(default model)

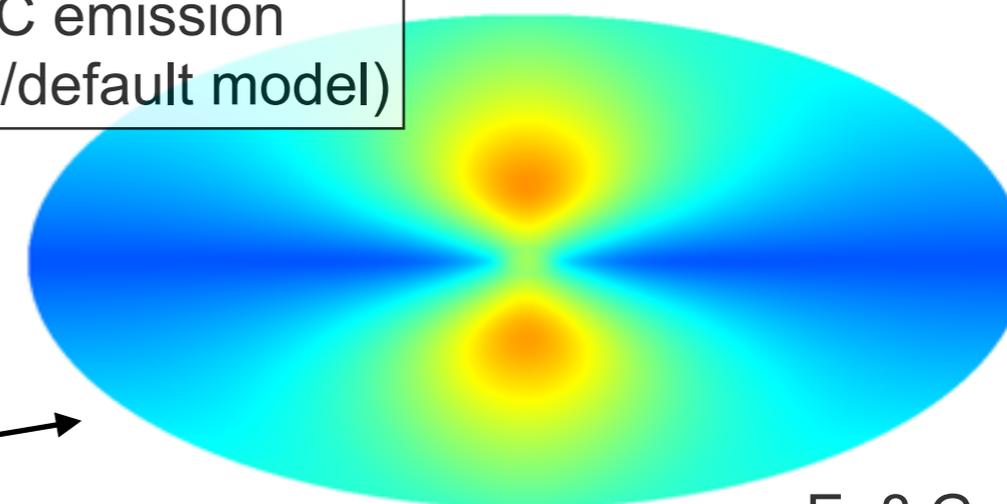
Galactic foreground (IC emission).

- > **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
 - ...

IC (default model)

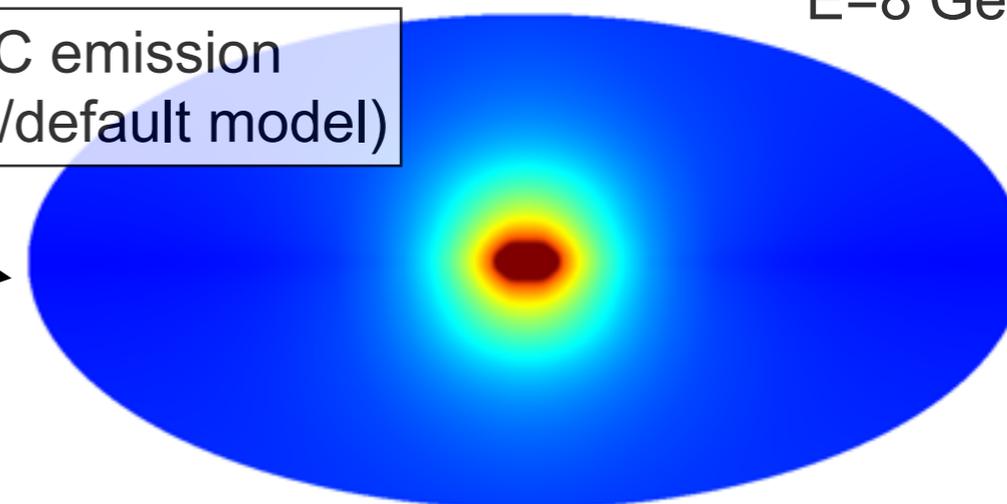


Ratio of IC emission (variation/default model)



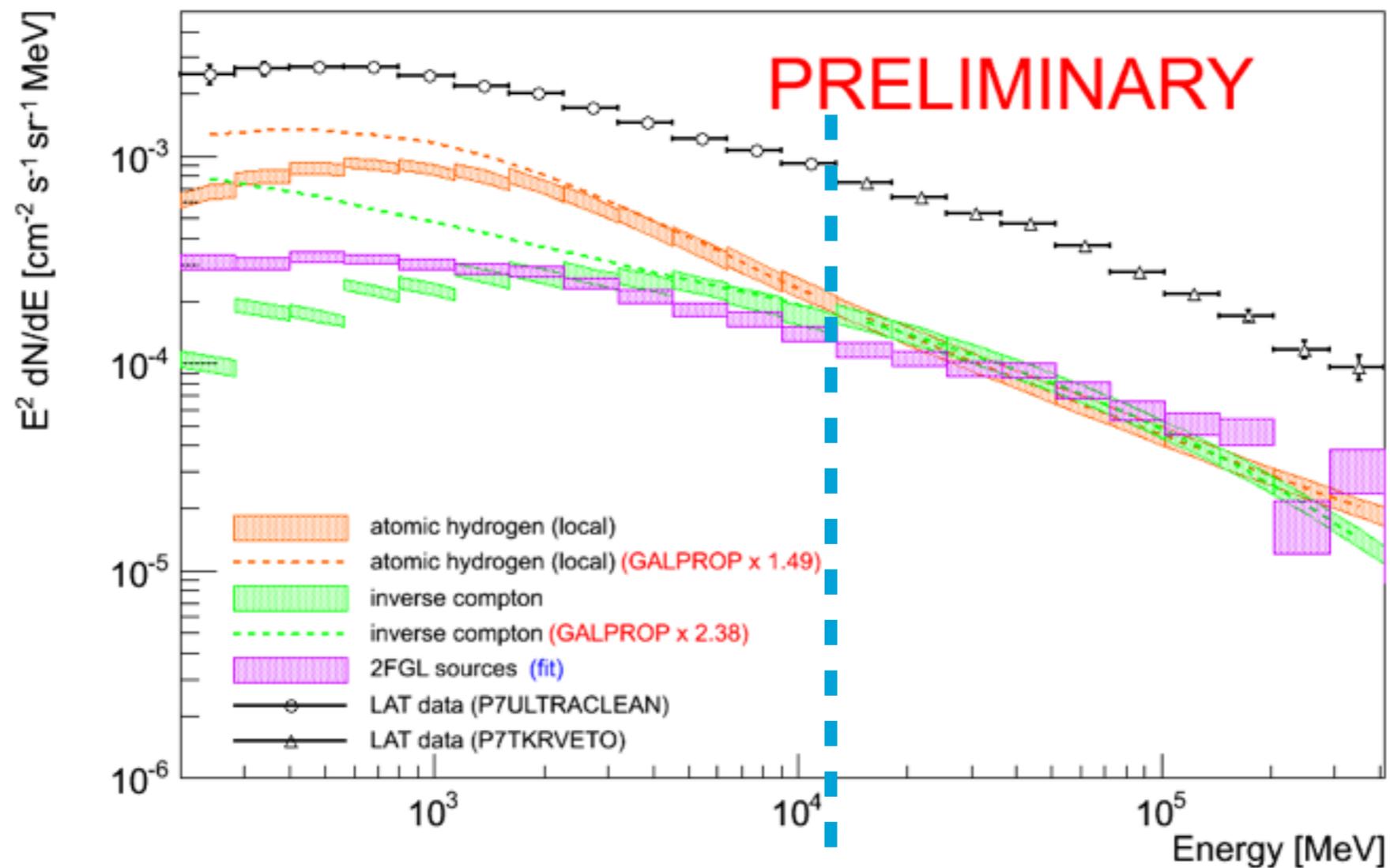
E=8 GeV

Ratio of IC emission (variation/default model)



0.0 4.0

Low-energy vs. high-energy analysis.



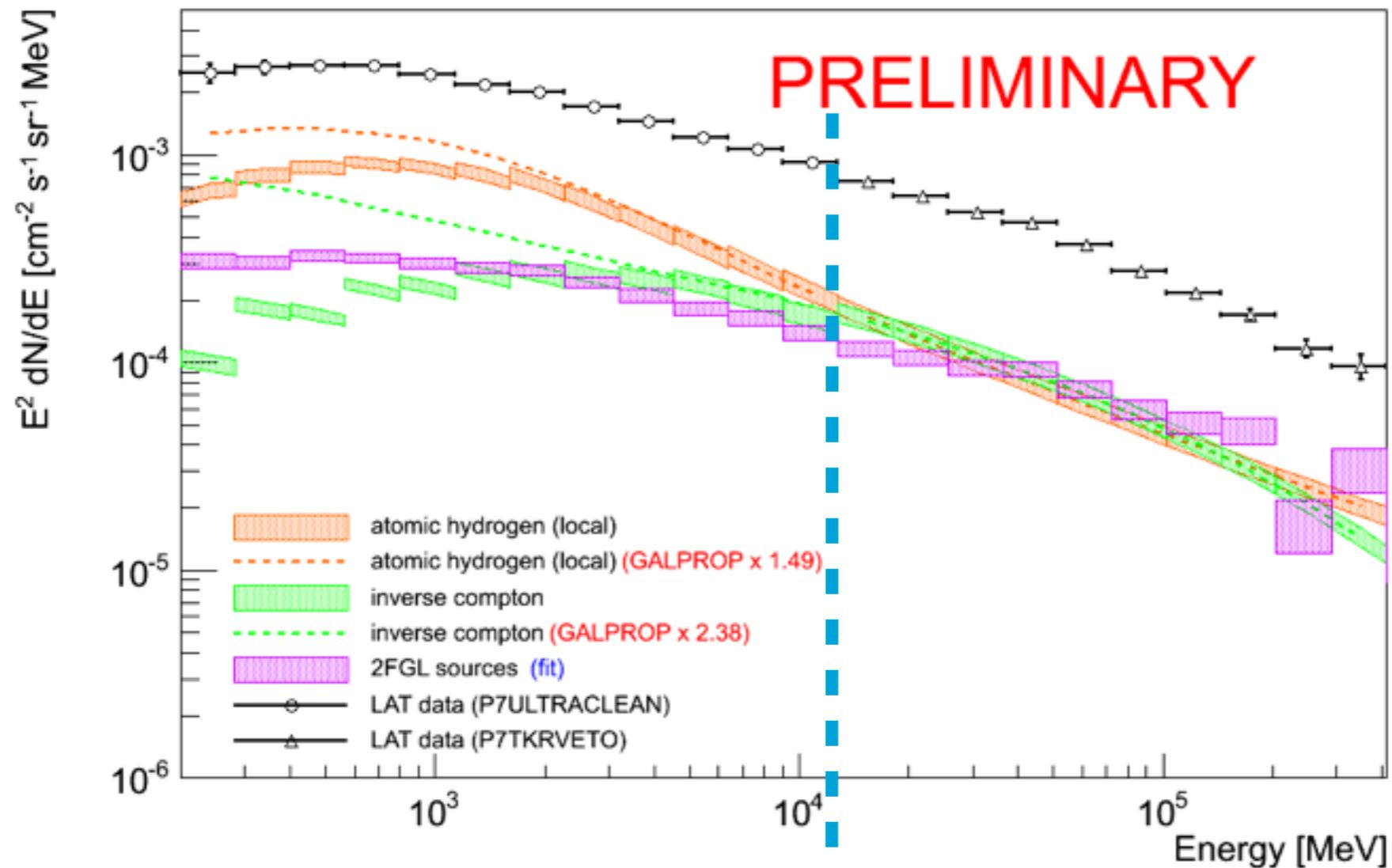
Low-energy analysis (<12.8 GeV)

- ▶ 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.

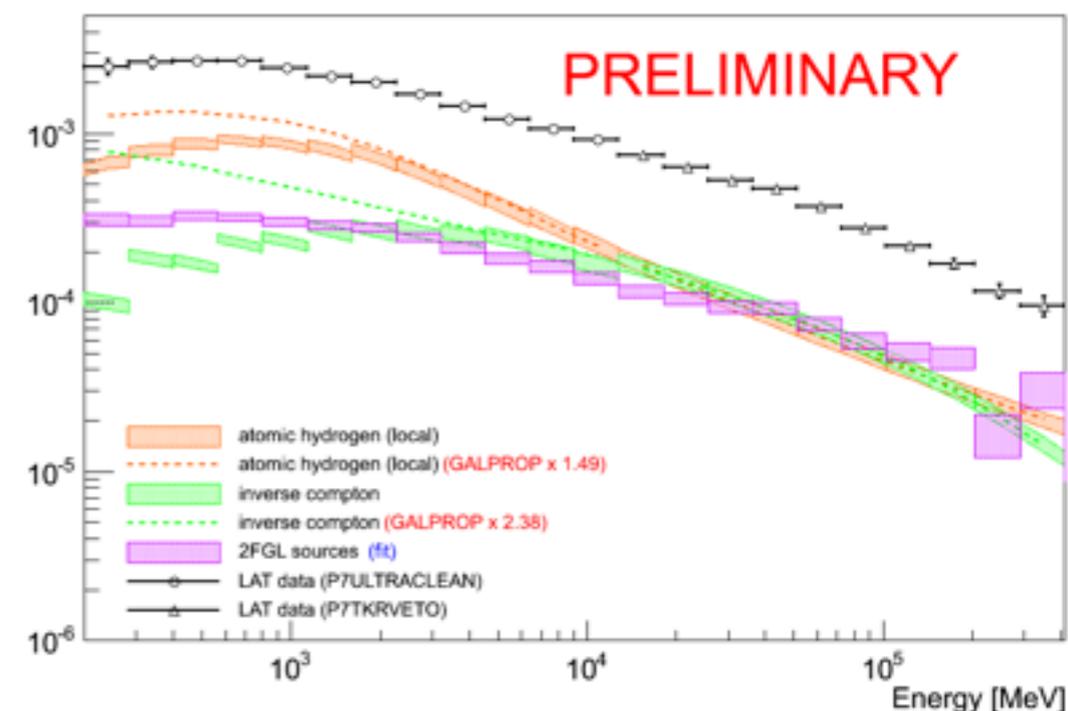
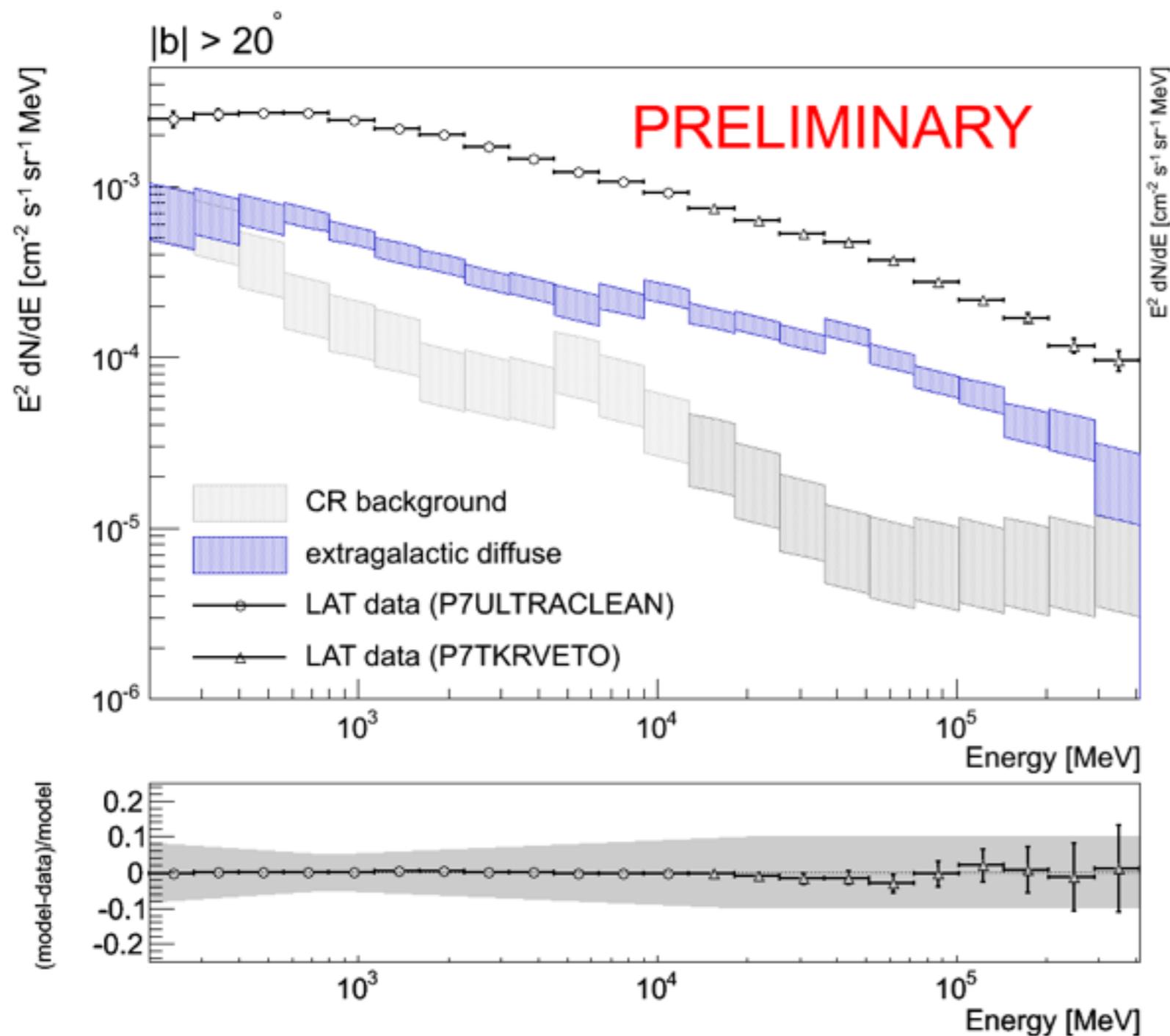


Low-energy analysis (<12.8 GeV)

High-energy analysis (>12.8 GeV)

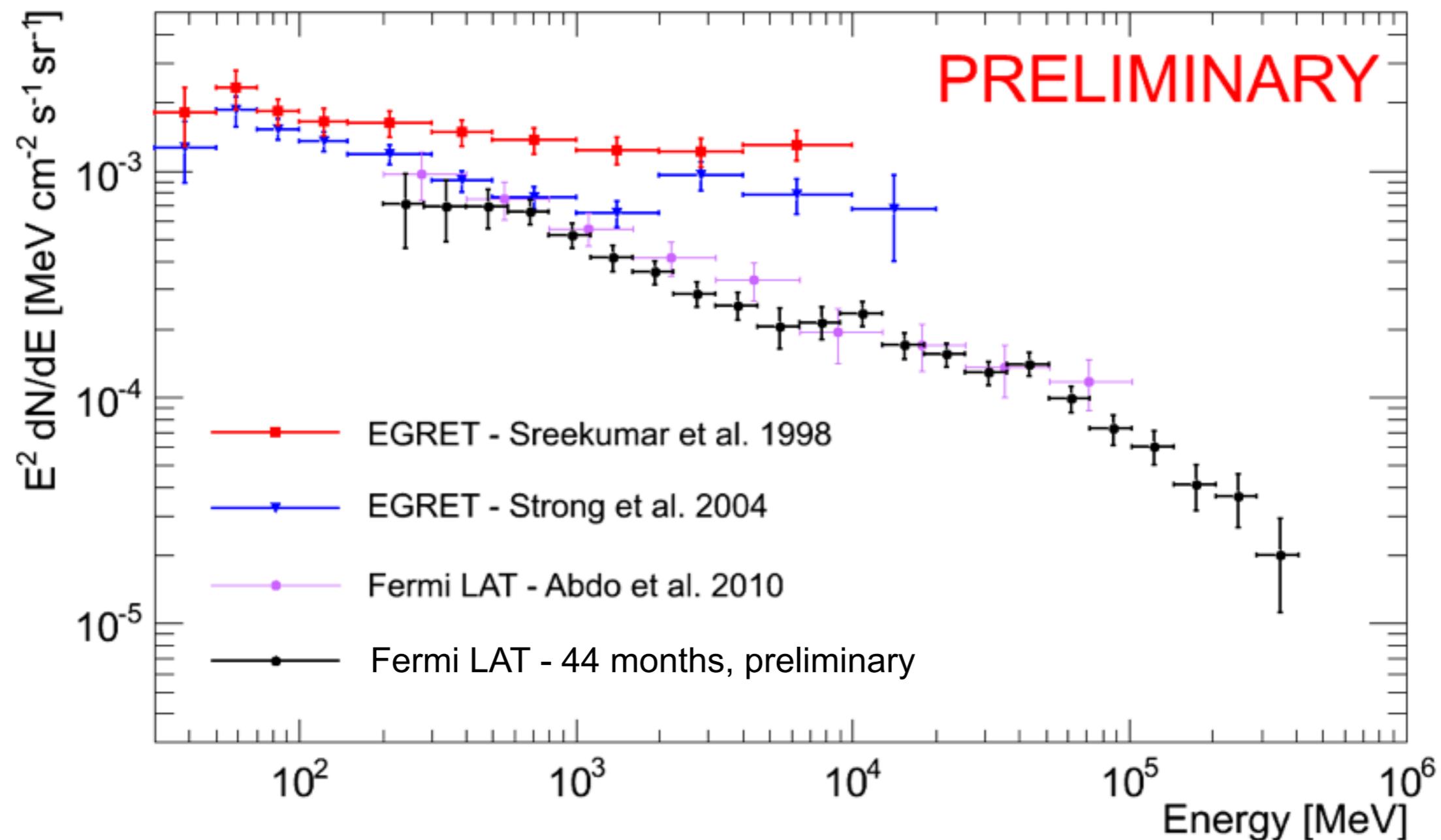
- > For consistency checking low- and high-energy analysis is performed with significant overlap in energy.
- > Fit results are consistent.

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.

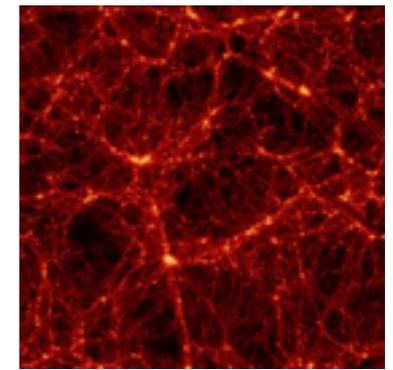
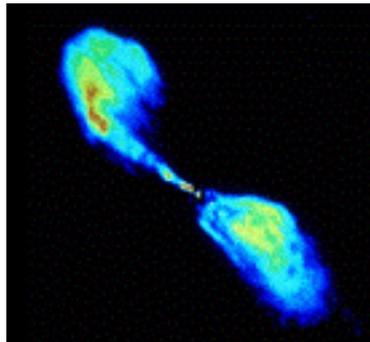
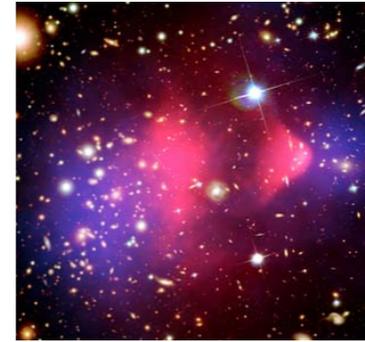
Comparison to older measurements.



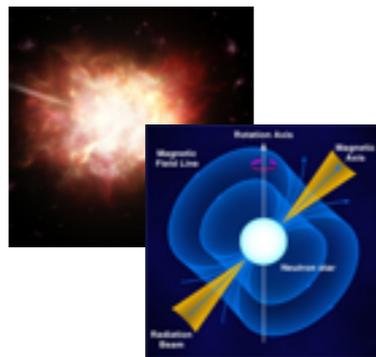
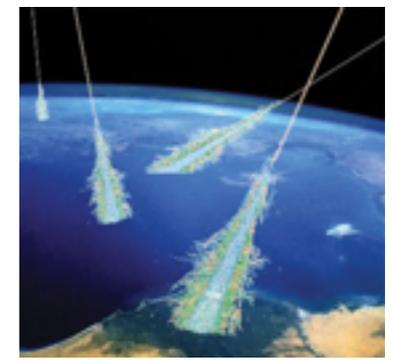
- > In agreement with published spectrum.
- > Error bars predominantly systematic. Apparent features in the spectrum are **NOT significant**.
- > Possible spectral softening at high energies ?

- > Still under investigation.
- > Particular emphasis on the impact of foreground modeling on features in the EGB spectrum.
- > Expect $\sim 30\%$ 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.

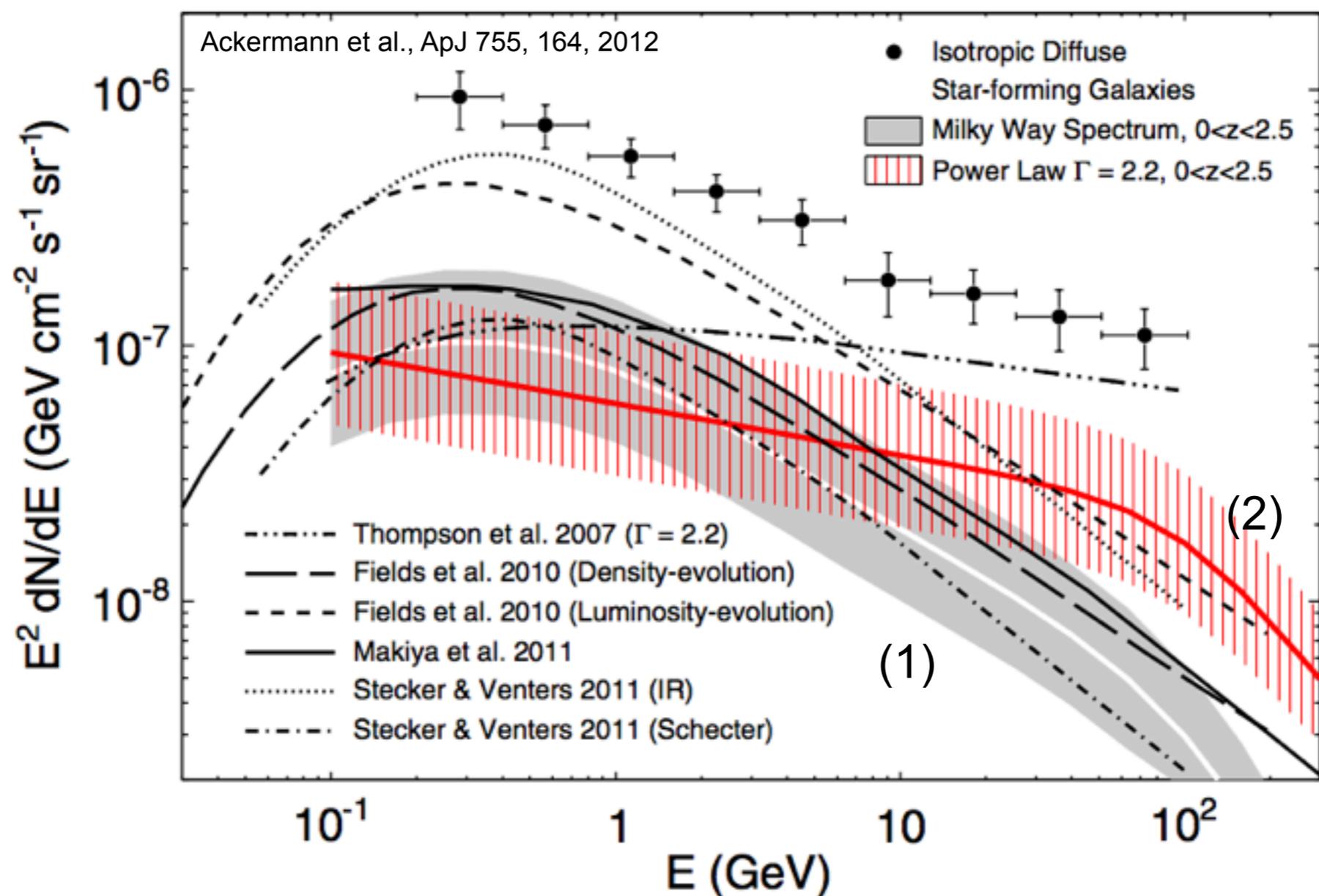
> **Blazars:** Padovani et al. 1993; Stecker et al. 1993; Salamon & Stecker 1994; Chiang et al. 1995; Stecker & Salamon 1996; Chiang & Mukherjee 1998; Mukherjee & Chiang 1999; Muecke & Pohl 2000; Narumoto & Totani 2006; Giommi et al. 2006; Dermer 2007; Pavlidou & Venters 2008; Kneiske & Mannheim 2008; 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.



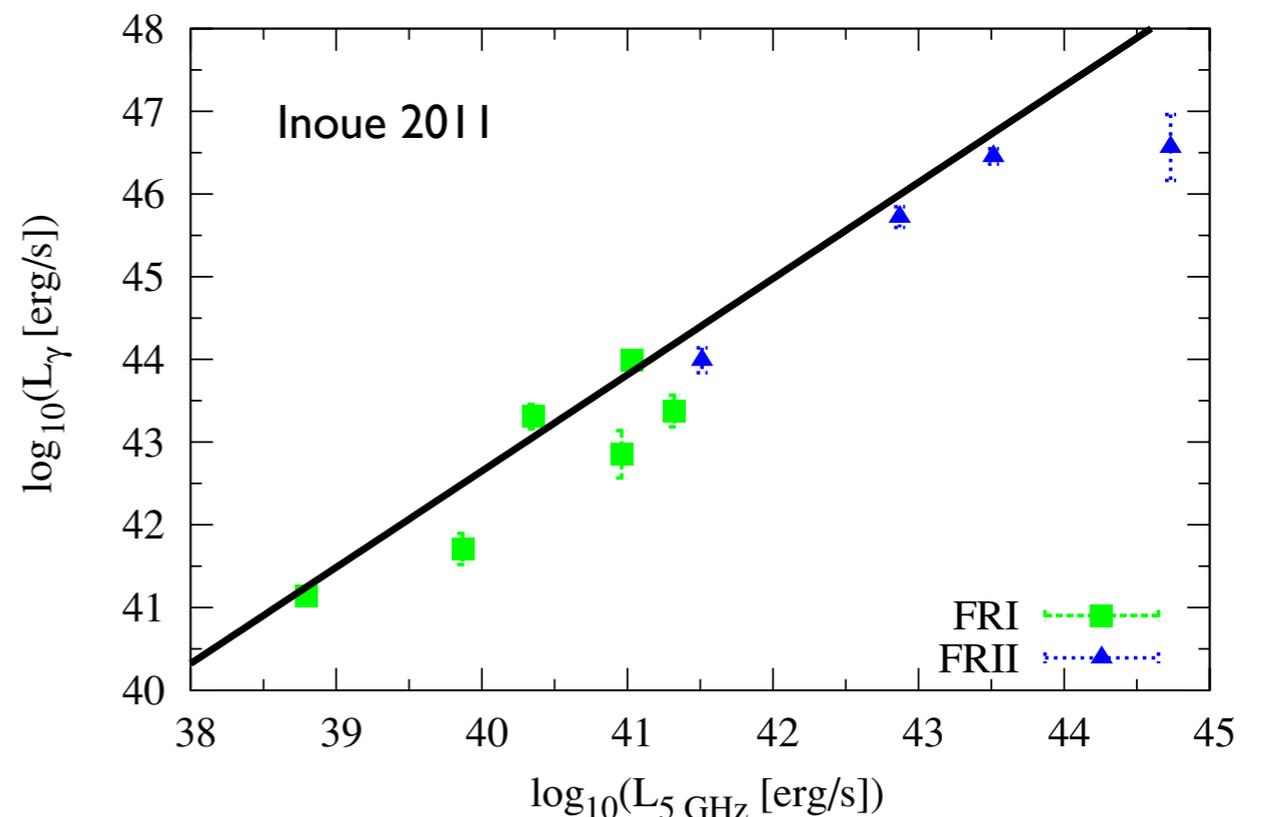
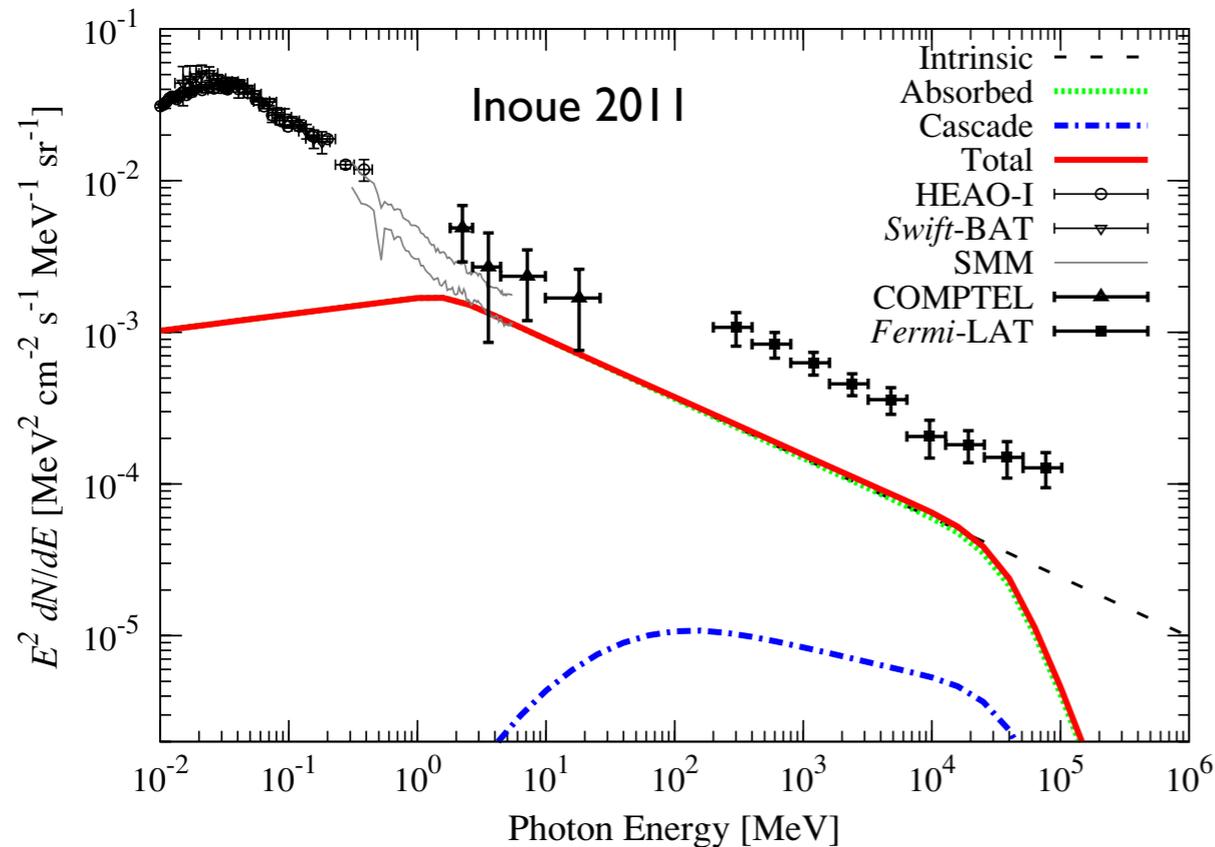
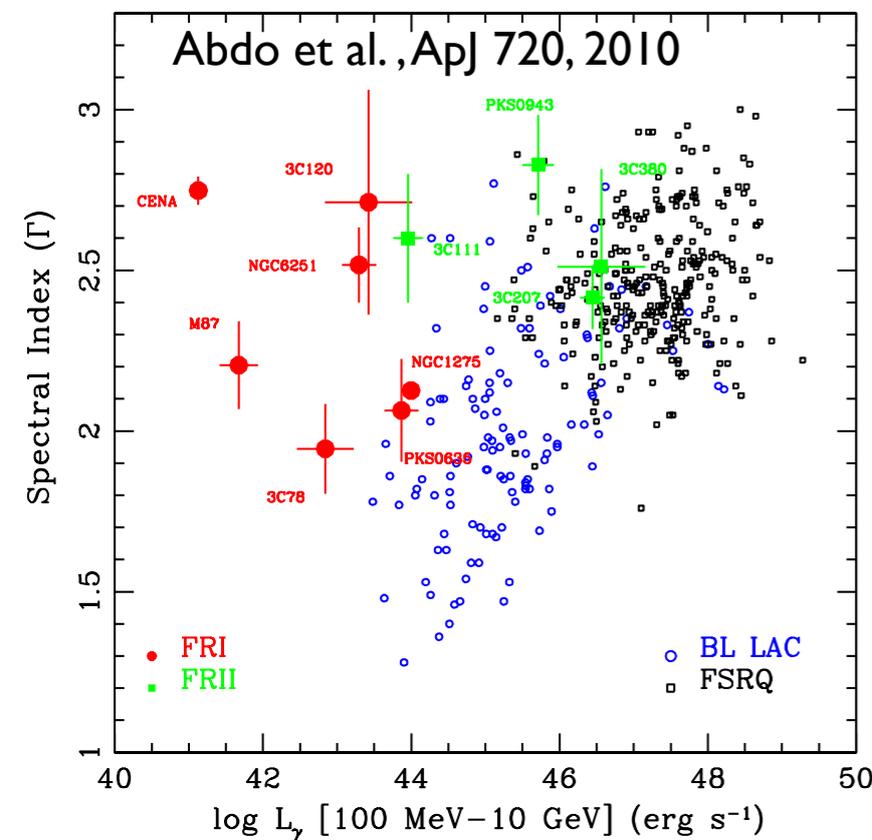
Contributions of star-forming galaxies.



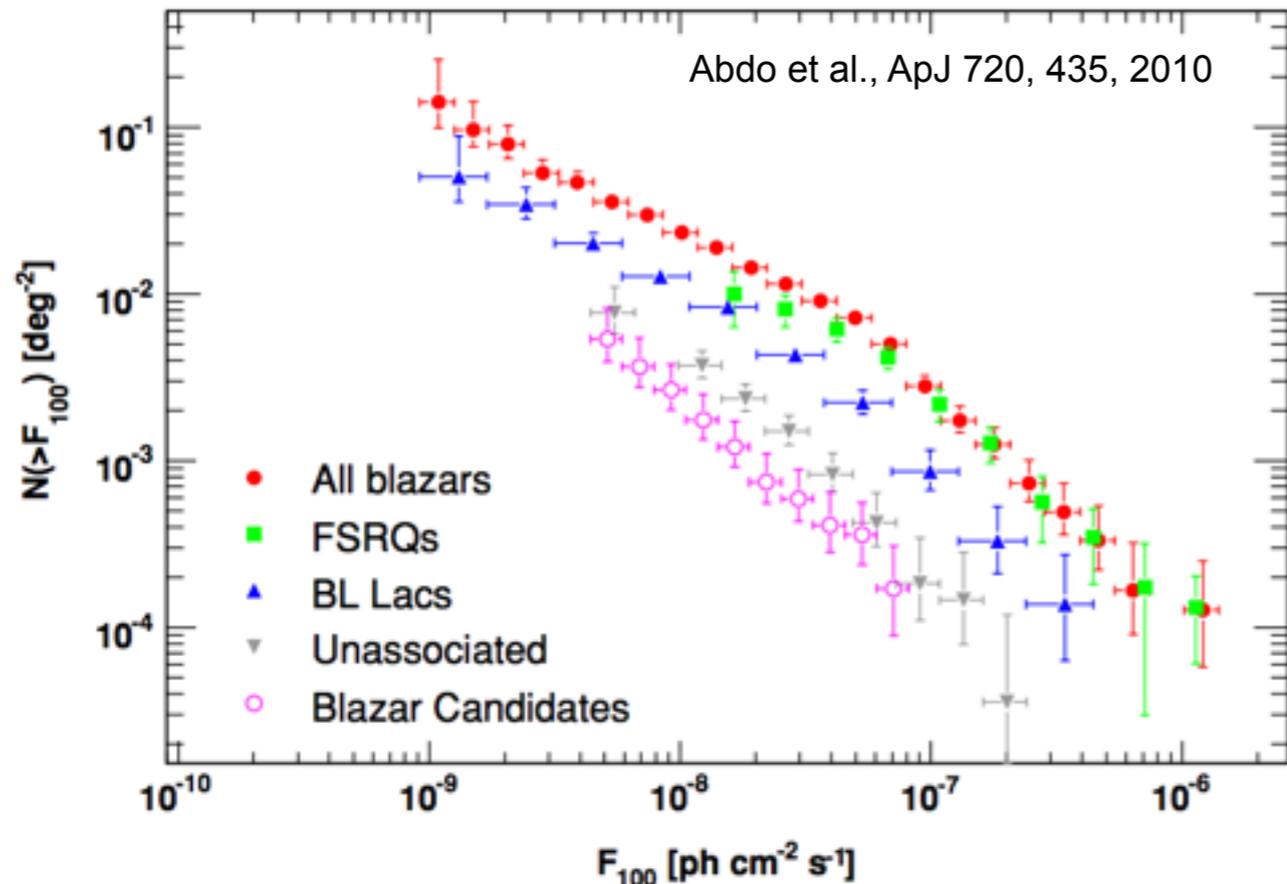
- > 4% - 23% contribution to EGB from star-forming galaxies ($0 < z < 2.5$)
- > Gamma-ray emission from galaxies is assumed to follow either a rescaled Milky Way (1) or a power-law spectrum (2), observed for Starburst Galaxies.
- > Talk by Keith Bechtol this morning.

Contributions from radio galaxies.

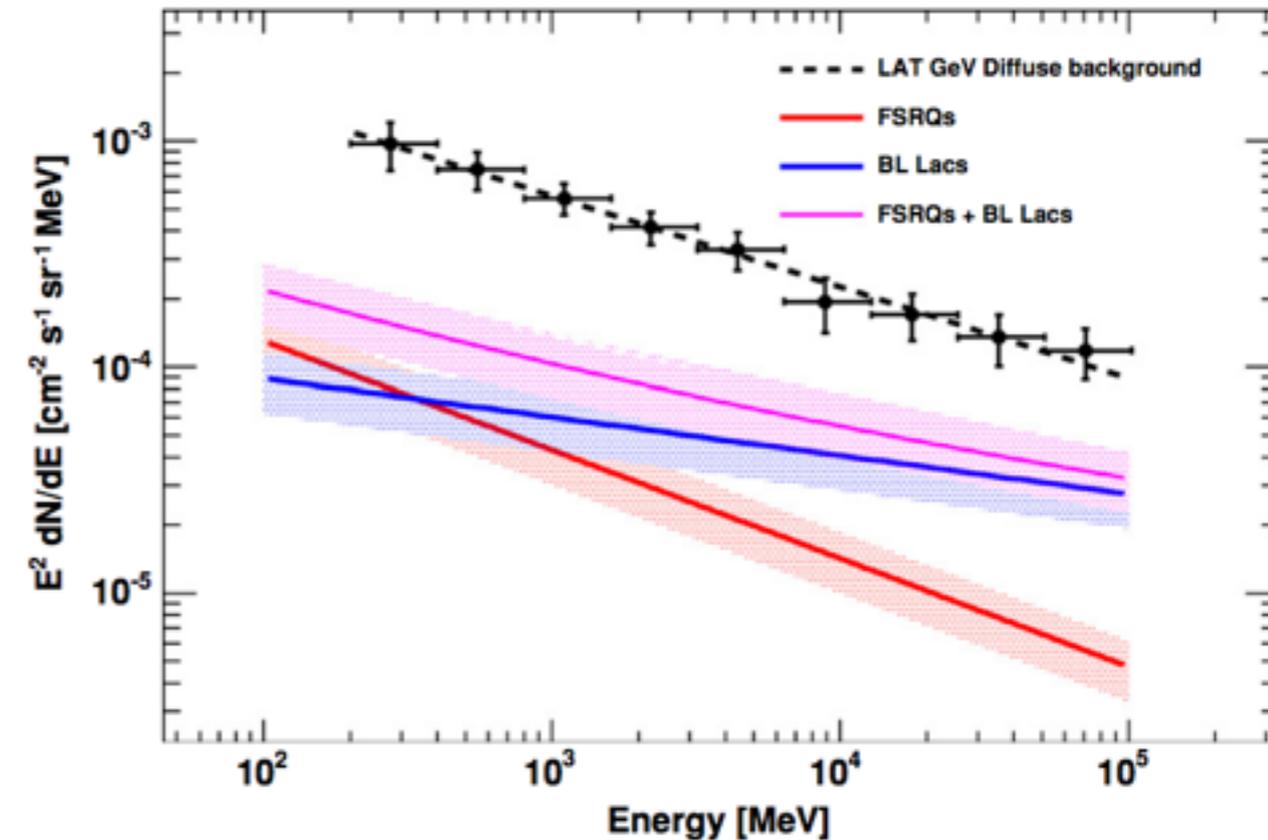
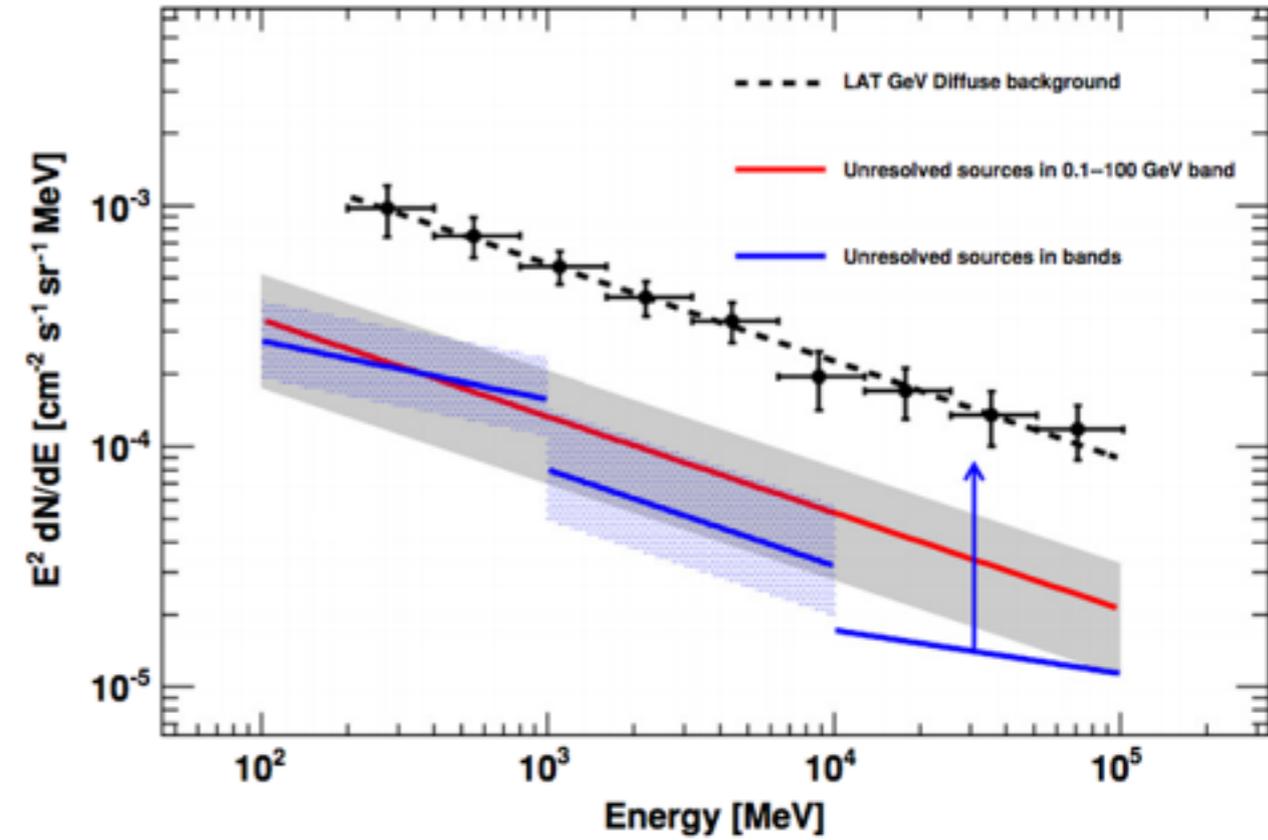
- Estimation of contribution of LAT detected radio galaxies to the EGB (Inoue 2011).
- Uses correlation of Radio/Gamma-ray luminosity based on 11 radio galaxies described in Abdo et al., ApJ 720, 2010.
- EGB contribution estimated from radio luminosity function.
- unresolved radio galaxies contribute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



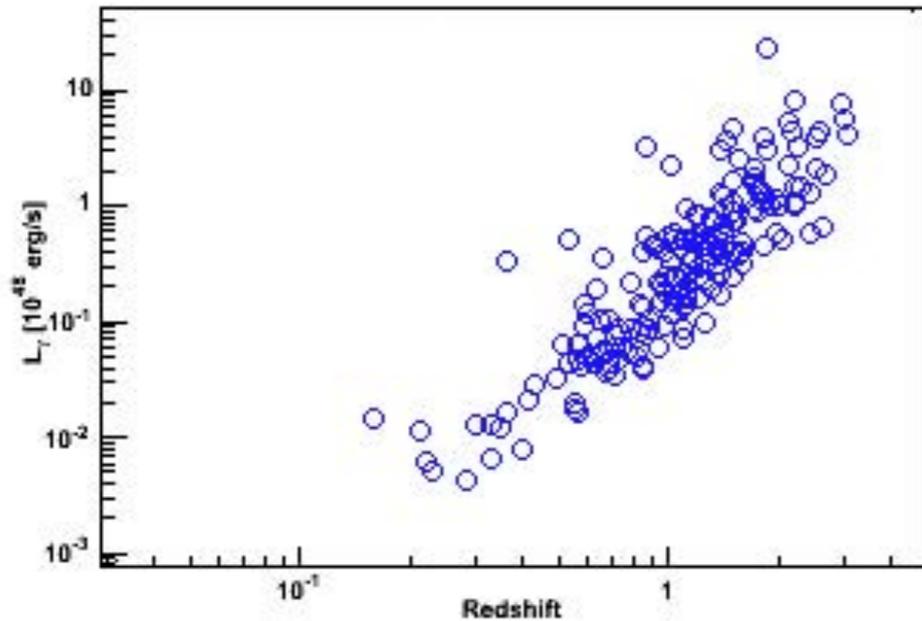
Unresolved Blazars



- 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)

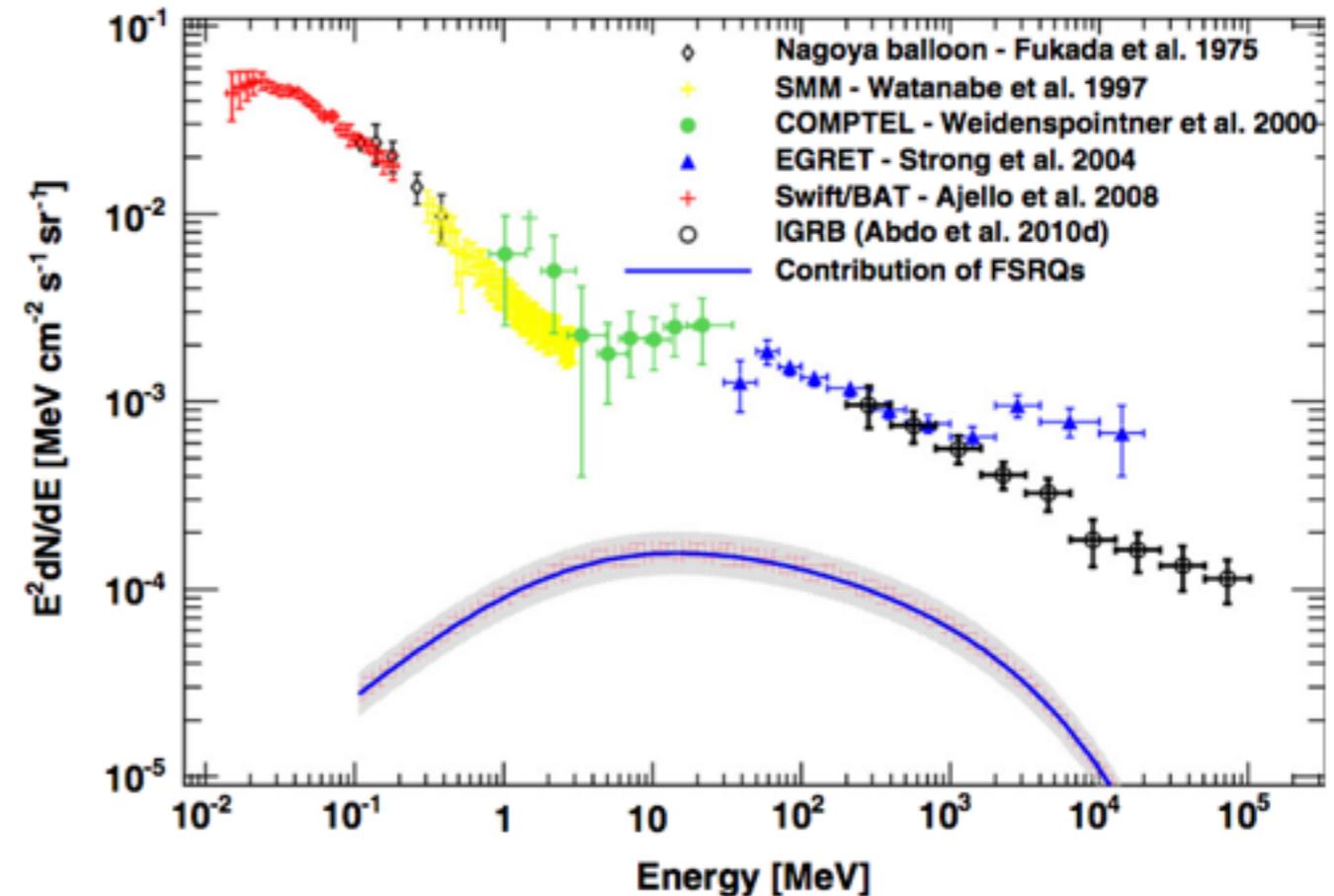
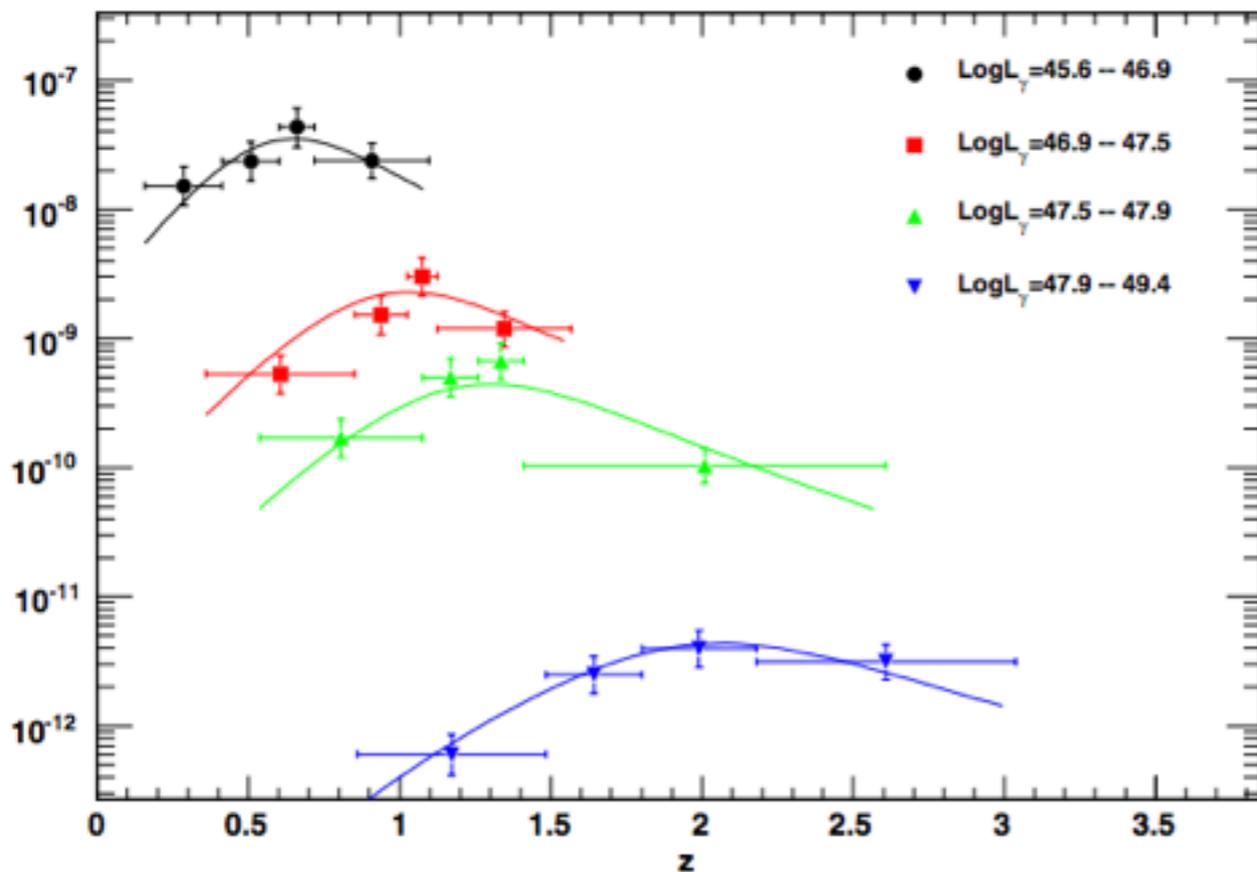


Unresolved Blazars: FSRQ gamma-ray luminosity function.



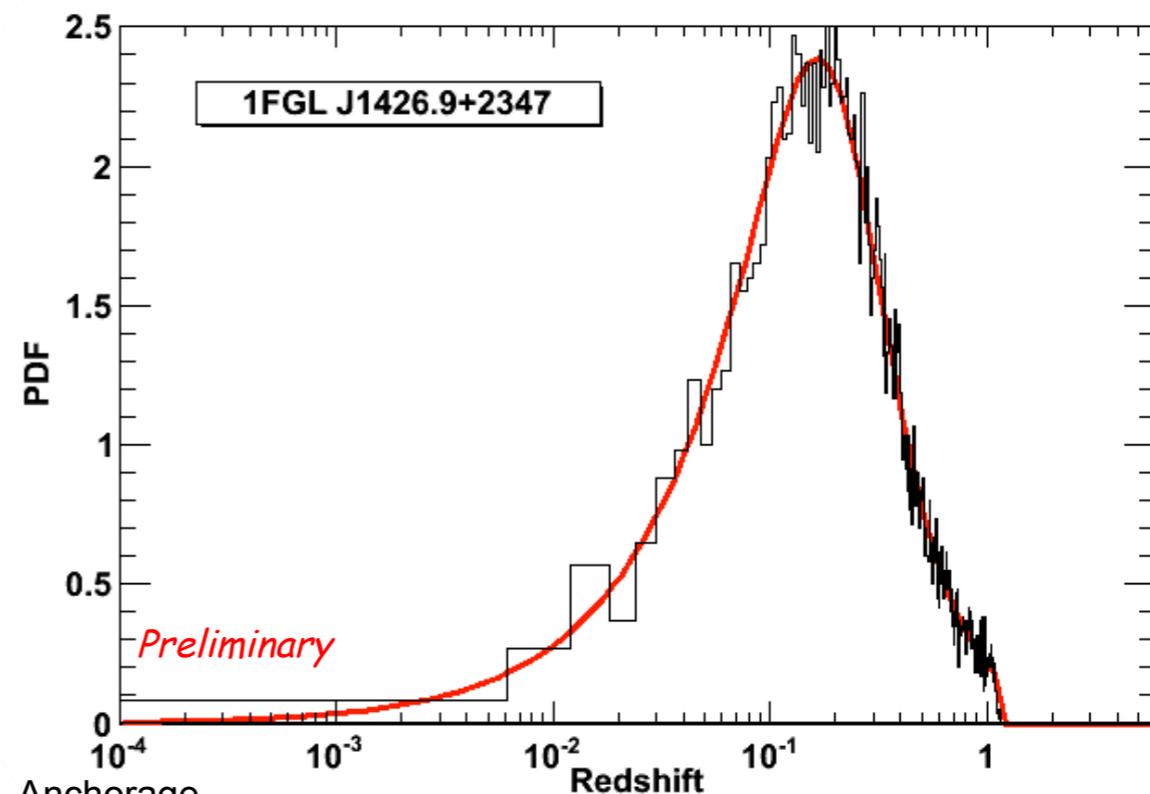
Abdo et al., ApJ 751, 108, 2012

- > 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

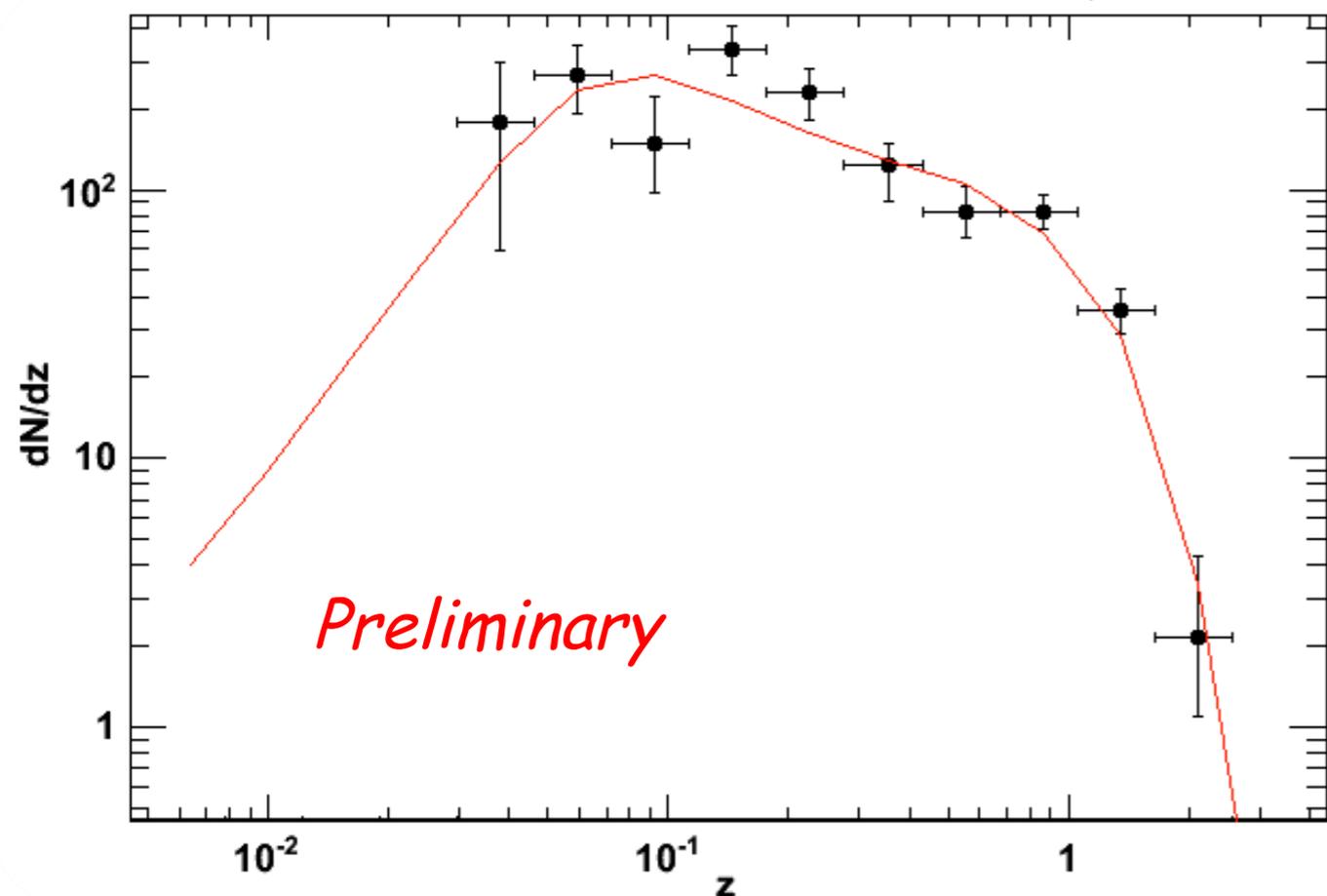


Unresolved Blazars: BLLac luminosity function.

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

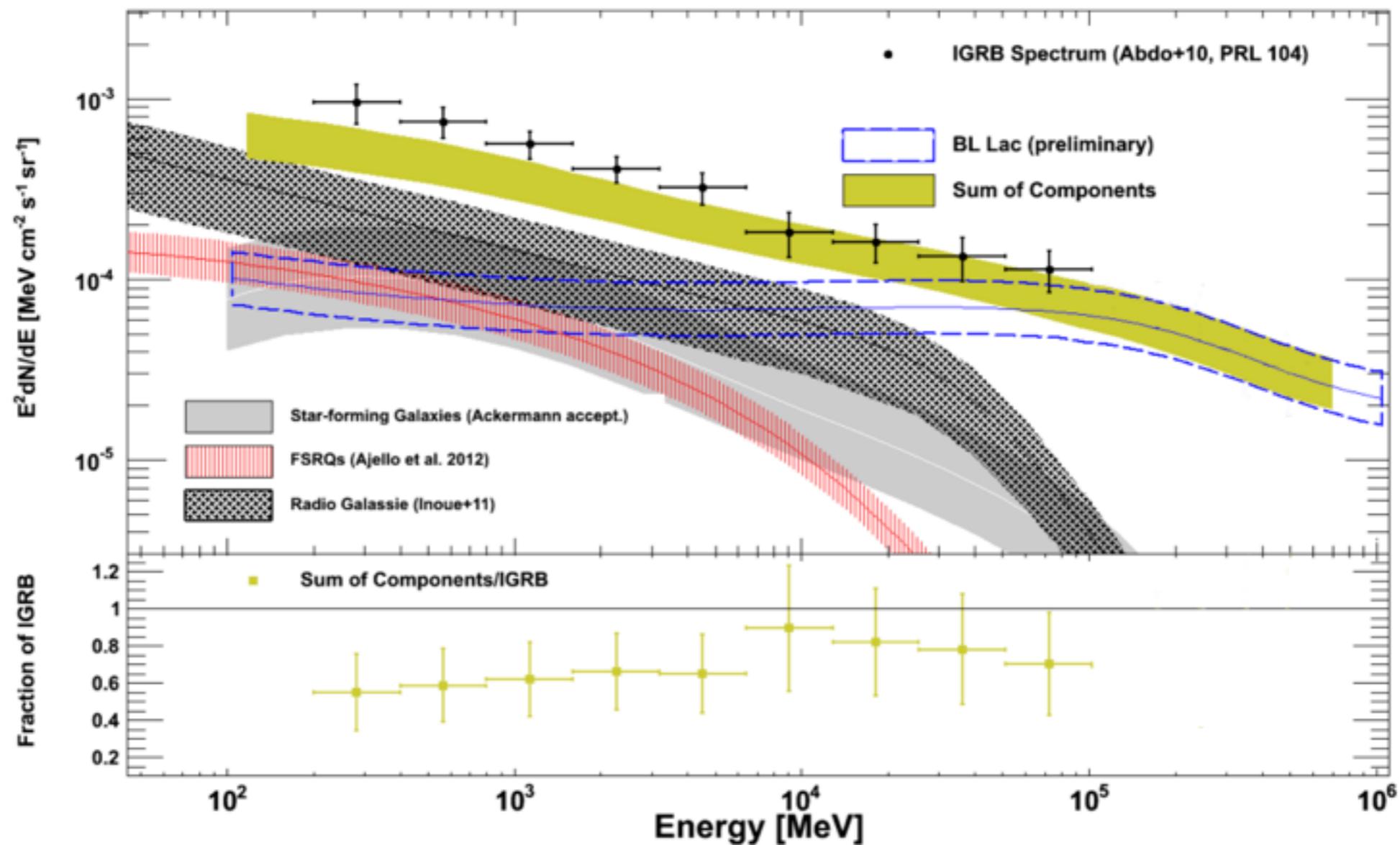


Ajello, 220th AAS meeting, Anchorage



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

Sum of contributions from unresolved sources.



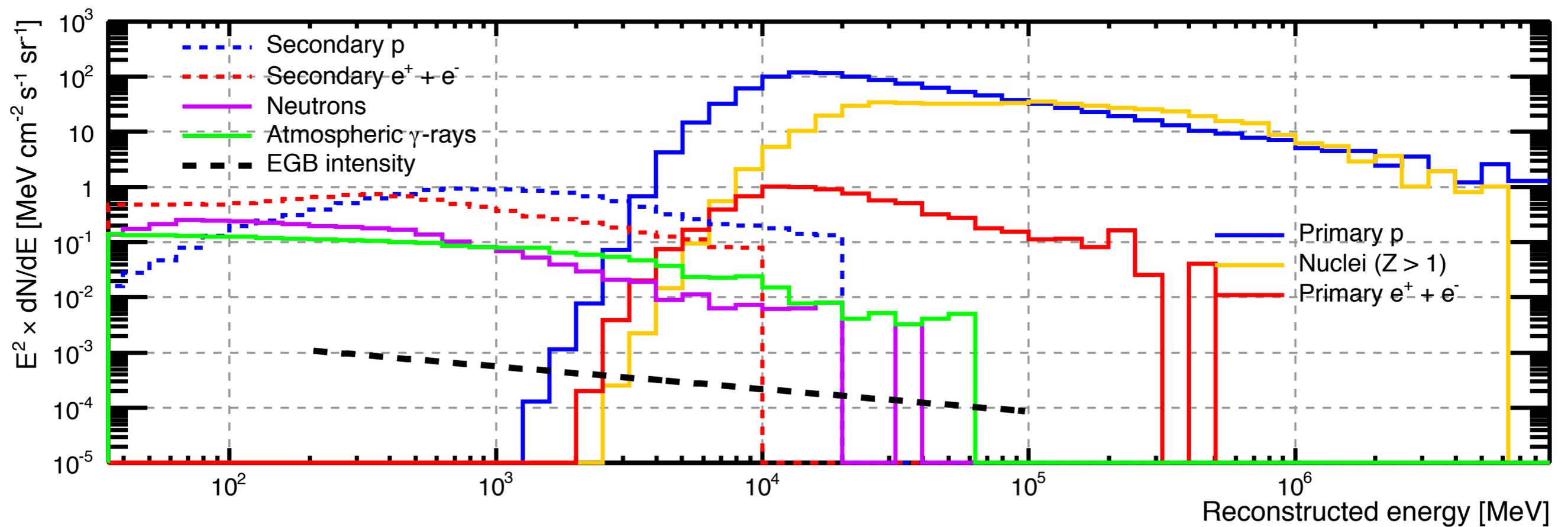
- Total contribution from FSRQ + BL Lac + Radio galaxies + Star-forming galaxies: $\sim 50\% - 80\%$
- Keep in mind: $\sim 30\%$ foreground modeling uncertainty not included in EGB error bands

- > 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.
- > BLLac's might dominate at very high energies ($>\sim 100$ GeV).



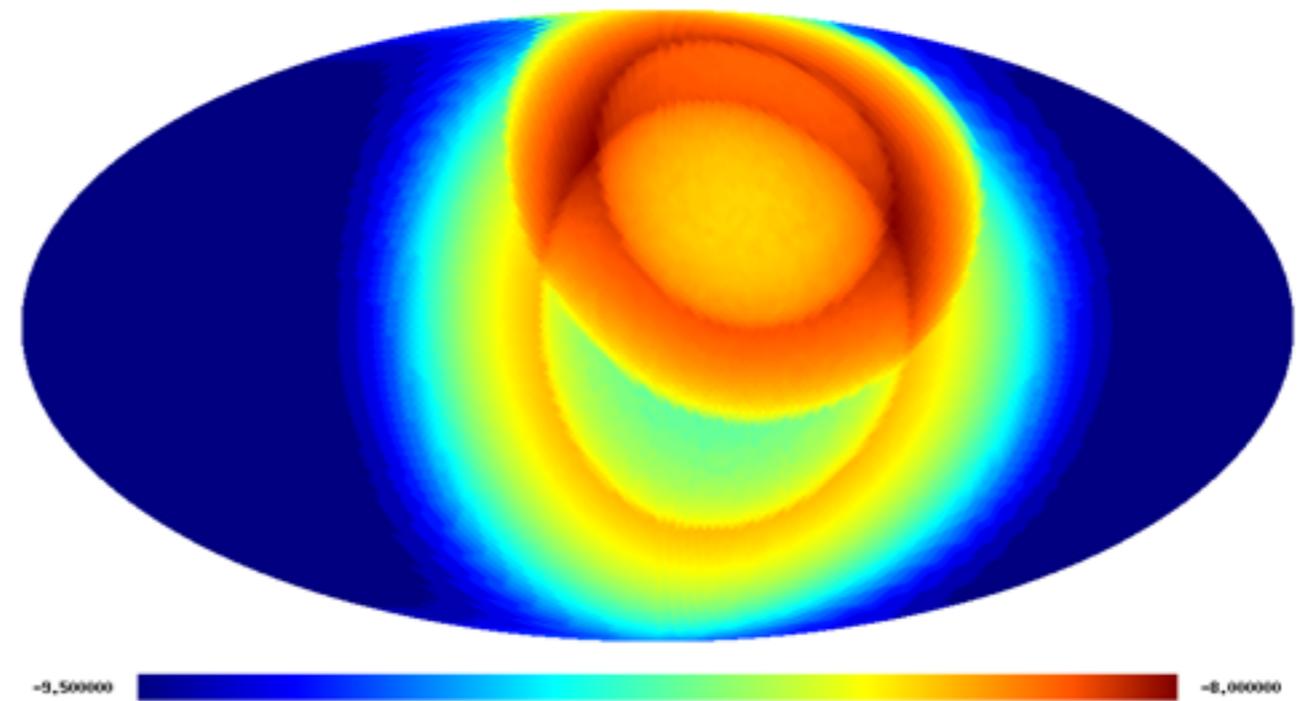
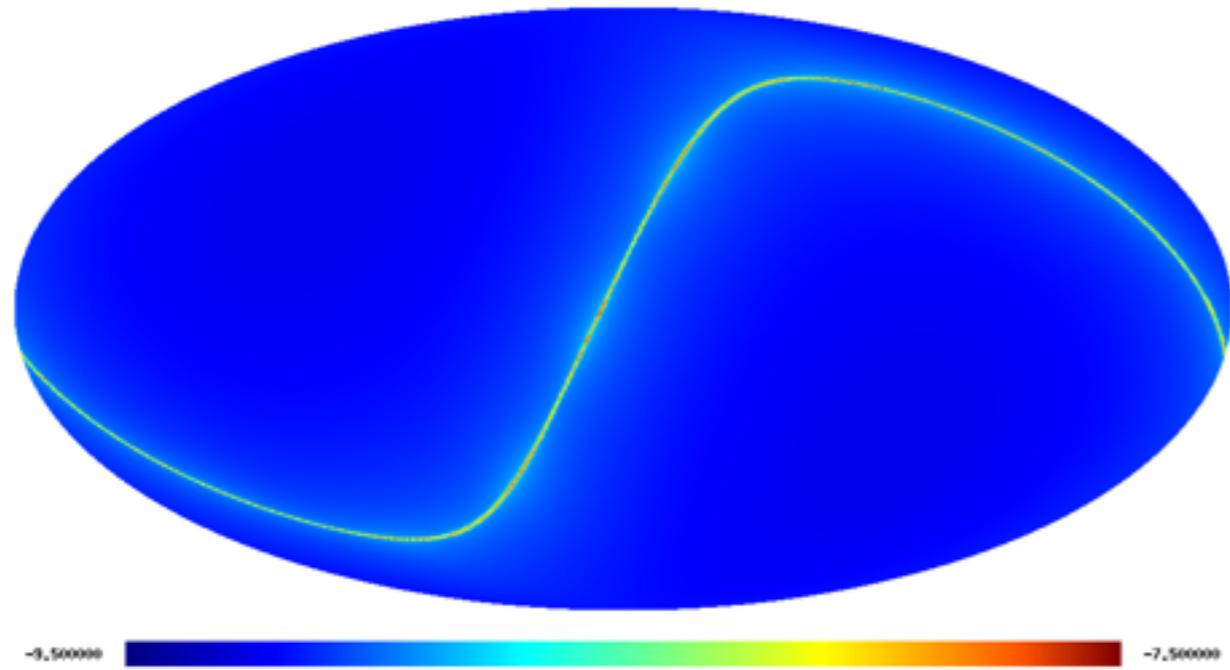
Background from charged cosmic rays.

- 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 ($\gg 1$ day) observation periods.
- LAT cosmic-ray background model:

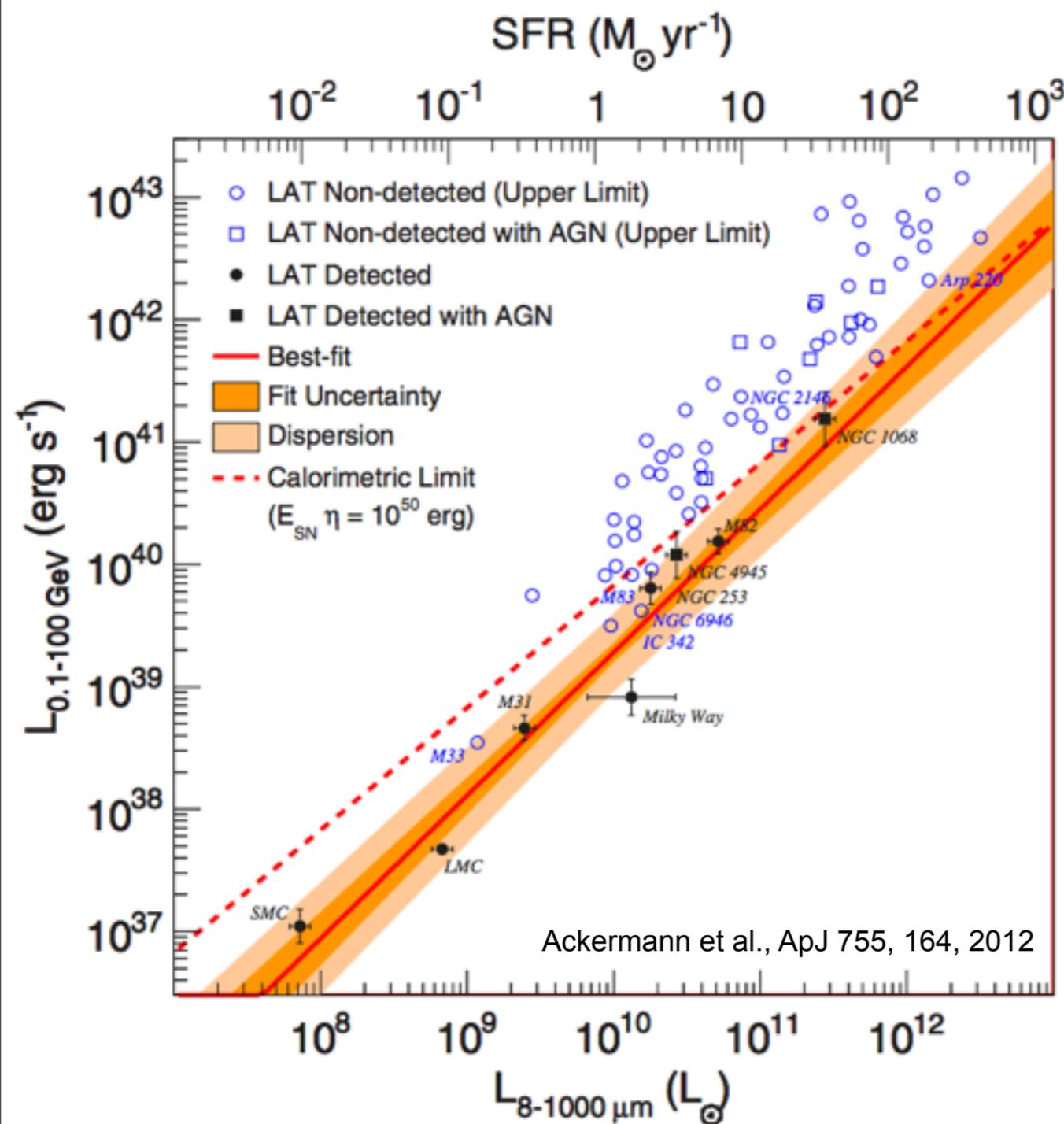
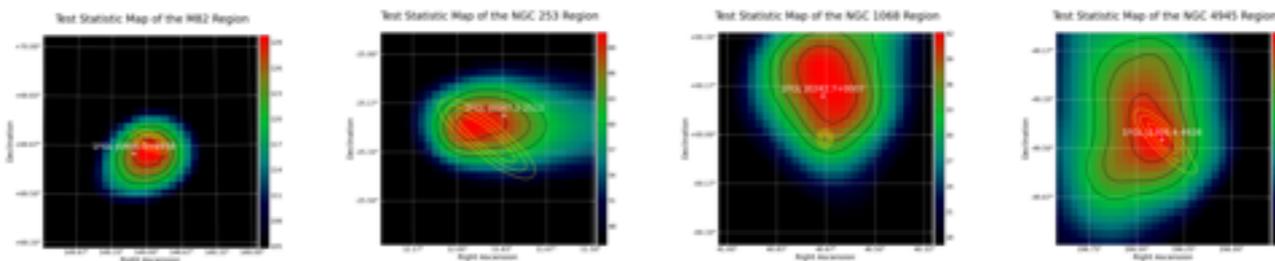
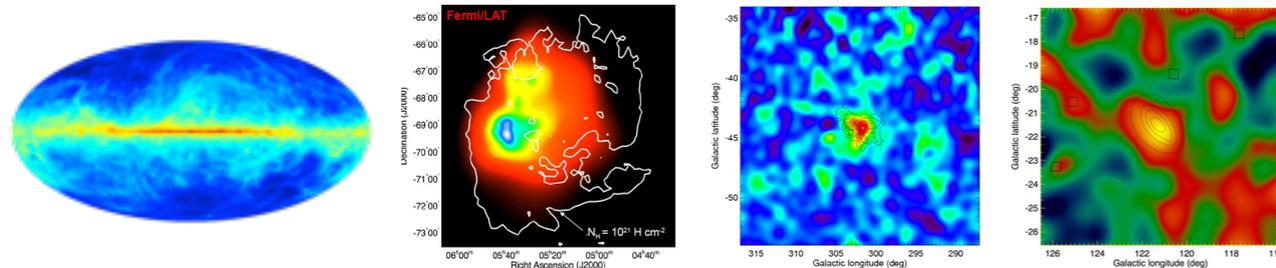


- Background suppression efficiency and remaining residual background needs to be carefully studied to allow its subtraction in the EGB analysis.

Solar template and Loop I template.



Contributions of star-forming galaxies.



- > 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.