Contribution of blazars and other source classes to the Extragalactic Gamma-ray Background

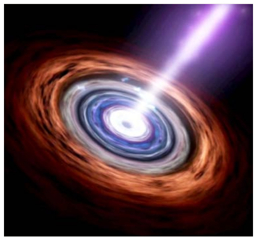
Marco Ajello[1],
Roger Romani[2], Dario Gasparrini[3]
on behalf of the Fermi-LAT collaboration

[1]Clemson, [2]Stanford, [3]ASI Data Center

Based on:
Fermi-LAT Collab. in prep.
Ajello et al., *2014*, *ApJ*, *780*, *73*
Ajello et al., *2012*, *ApJ*, *751*, *108*

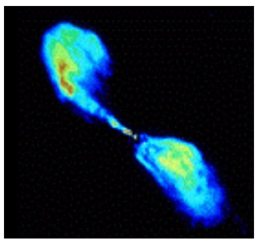
EGB: Why is it important ?

Undetected sources



Blazars

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

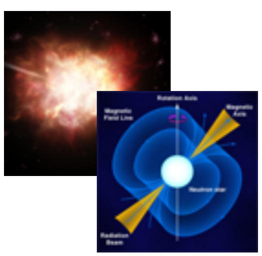


Non-blazar active galaxies

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)



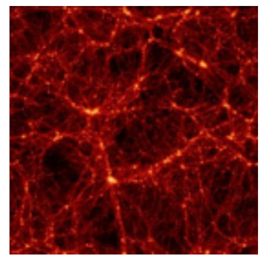
GRBs
High-latitude pulsars

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

Diffuse processes

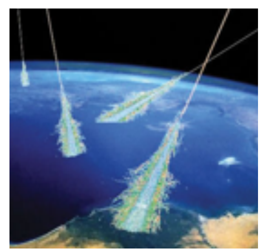
Intergalactic shocks

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)

Source Contribution to EGB

- The Big Question:
  - Which class of source contributes how much to the EGB ?
  - Can unresolved sources explain the bulk of the EGB ?
- Many models in the literature:

> **Blazars**: Stecker+93, Padovani+93, Salomon&Stecker94, Chiang&Mukherjee+98, Mukherjee&Chiang99, Muecke&Pohl00, Narumoto&Totani06, Giommi+06, Dermer07, Pavlidou&Venters08, Kneiske&Mannheim08, Bhattacharya et al. 2009, Inoue&Totani 09, Abod et al. 2010, Stecker & Venters 2010, Abazajan+10, Singal+10, Harding & Abazajan 2012, Di Mauro+14, Singal+14

> **Star forming galaxies**: Pavlidou & Fields 2002, Thompson+07, Bhattacharya&Sreekumar09, Makiya+11, Fields+10, Stecker&Venters+11, Lacki+14

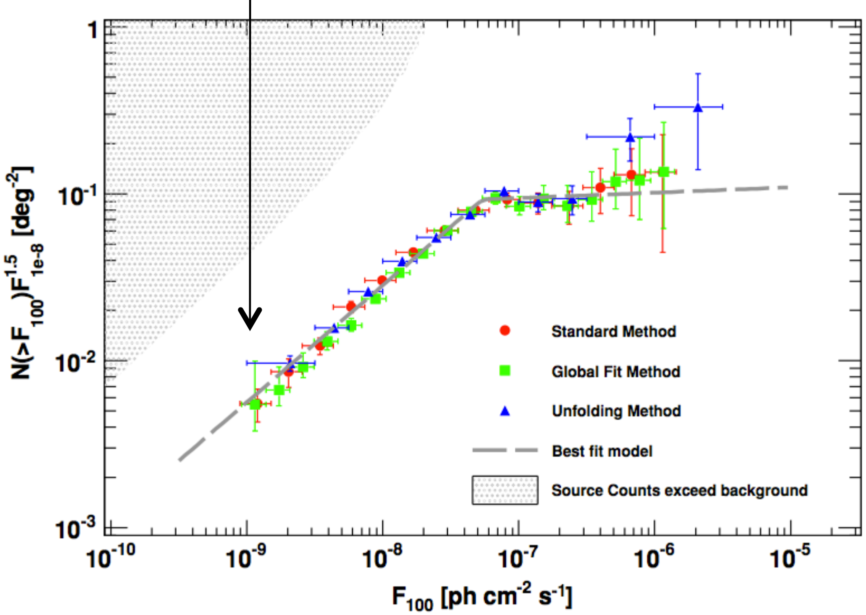
> **Radio galaxies**: Stawarz+06, Inoue+08, Inoue11, Massaro&Ajello11, DiMauro+13

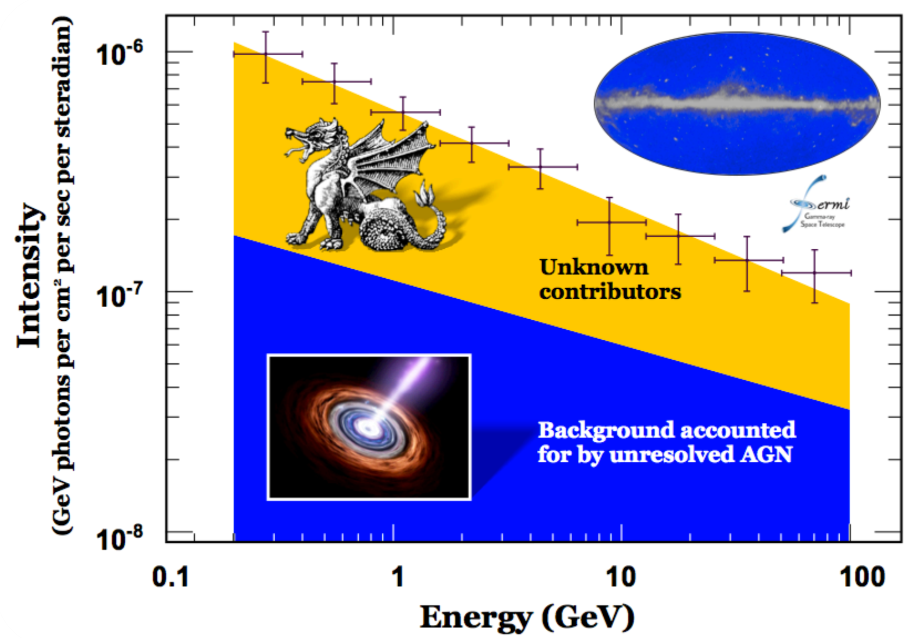
> **Milli-second pulsars/GRBs**: Fauchere-Giguere & Loeb10, Siegal-Gaskins+10/ Dermer07

IGRB as of 2010

- Unresolved blazars make a small fraction (≤30%) of the IGRB (Abdo et al. 2010, ApJ, 720, 435)

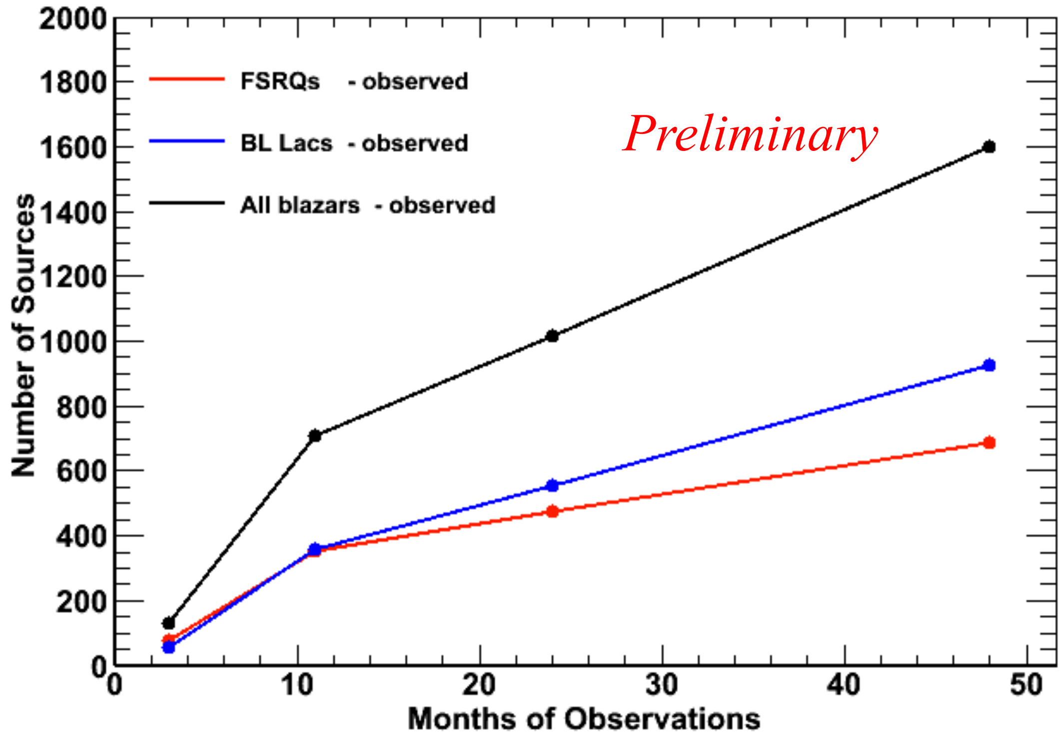
Unresolved (with F>1e-9 ph cm^{-2} s^{-1}) sources make ~16 %





Blazars

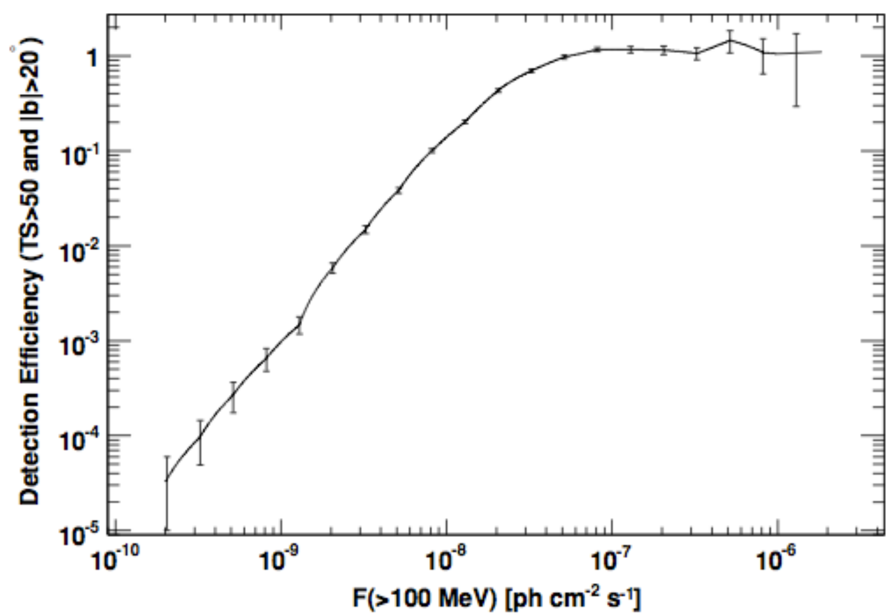
- Blazars are (by far) the largest population of sources detected by *Fermi*
  - Represent 85%-90%
  - Numbers steadily increasing (BSL, 1LAC, 2LAC, 3LAC)
  - BL Lacs have taken over the FSRQs



Blazars

- Goal: Revise Blazar contribution to the EGB
  – Model the population as a whole (relying on larger statistics)
  – Adopt improved SED modeling

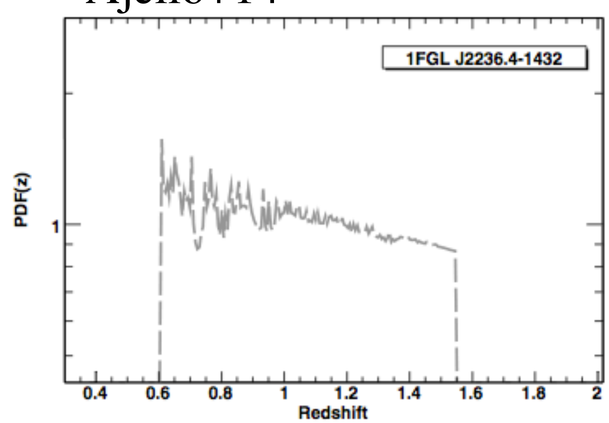
- Start from the sample of Abdo et al. 2010, ApJ 720, 435
  – 410 blazars
  – 211 BL Lacs / 199 FSRQs
  – 10% incompleteness

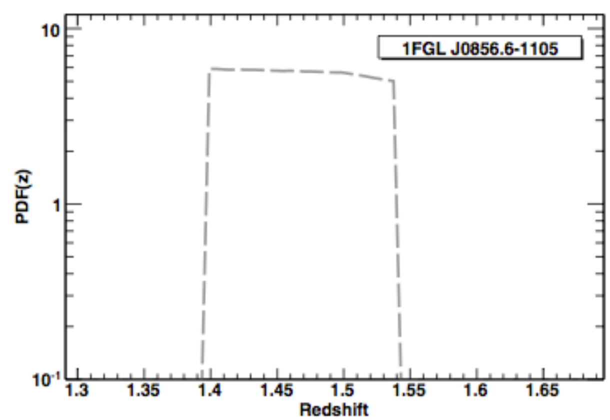


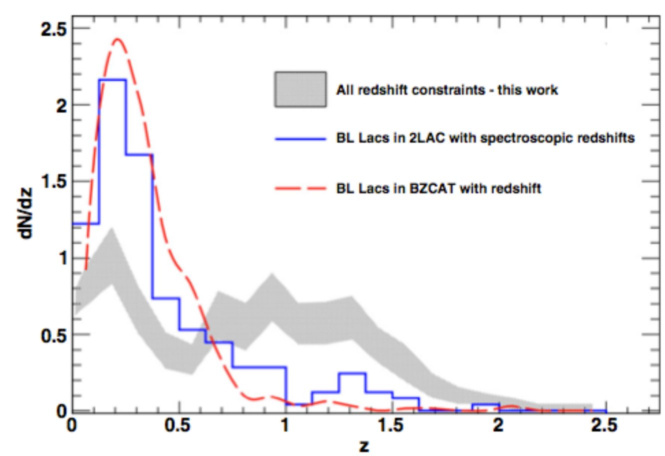
Redshift for BL Lacs

- Sample of ~211 BL Lacs with full redshift information:
  - ~100 with spectroscopic redshifts
  - ~100 with redshift contraints
    - Spectroscopic lower limits due absorption lines caused by intervening systems (Shaw+13)
    - Photometric upper limits due to lack of neutral hydrogen absorption (Rau+12)
    - Spectroscopic upper limits (z<2) due to absence of Lyman-α absorption (Shaw+13)
    - Host galaxy fitting lower limits (Shaw+13)

Ajello+14







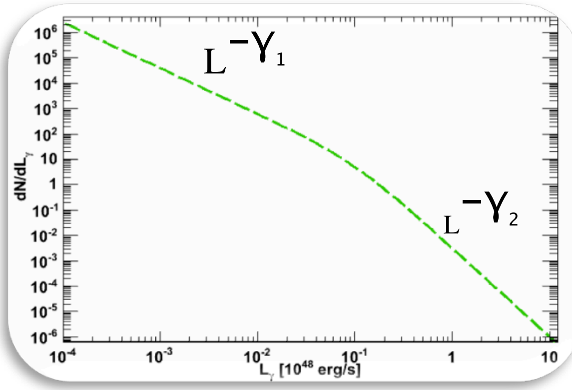
Modeling the Luminosity Function

Luminosity Function

$$\Phi(L_\gamma, z) = \Phi(L_\gamma/e(z), z=0)$$

=

Local Luminosity Function



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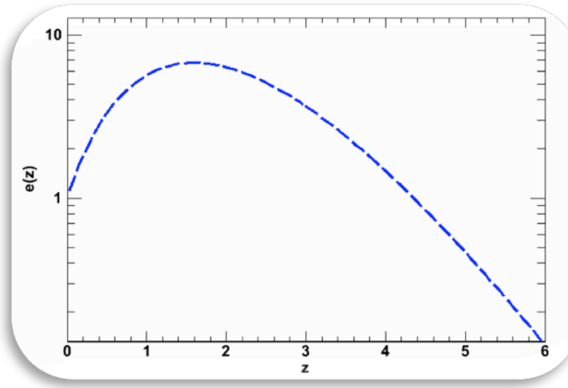
Evolutionary Factor



$$\Phi(L_\gamma, z=0) \propto \left[\left(\frac{L_\gamma}{L_*}\right)^{\gamma_1} + \left(\frac{L_\gamma}{L_*}\right)^{\gamma_2}\right]$$

Typical double power law

$$e(z) = (1+z)^k e^{z/\gamma}$$

Evolution in luminosity as a power-law with index k and a cut-off after z_{cut}=-1-kγ

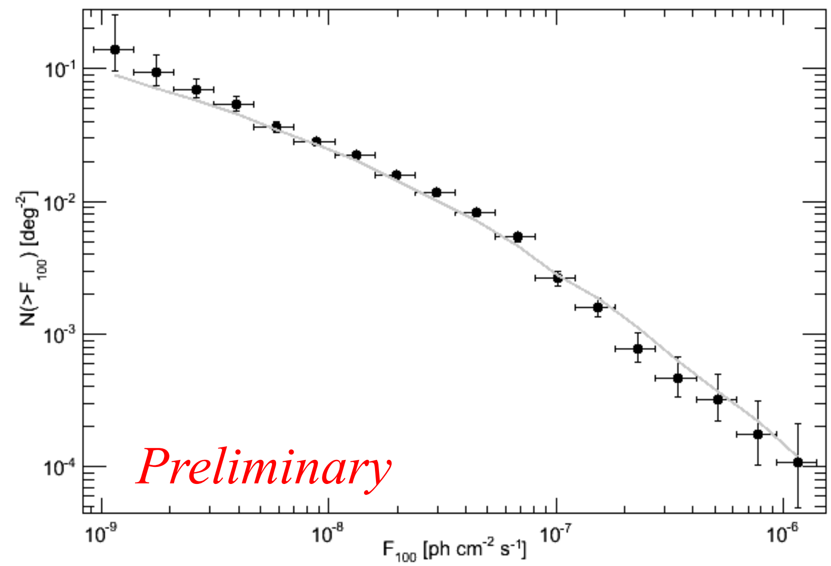
$$k = k_d + \tau(\log L - 46)$$

Accounts for the different speeds of evolution

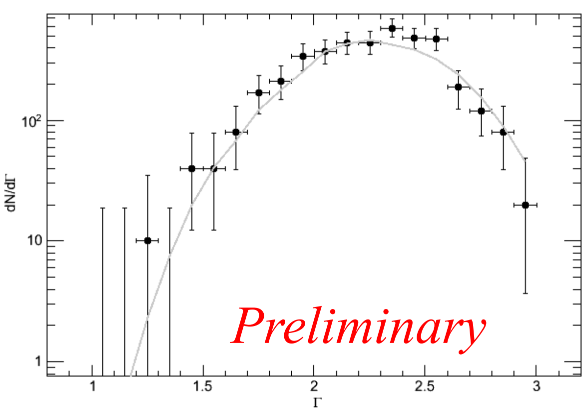
kd	~10
τ	~2.9
γ	-0.1

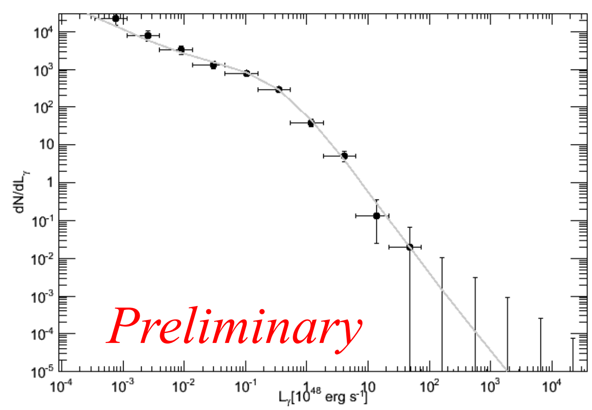
Method & Results

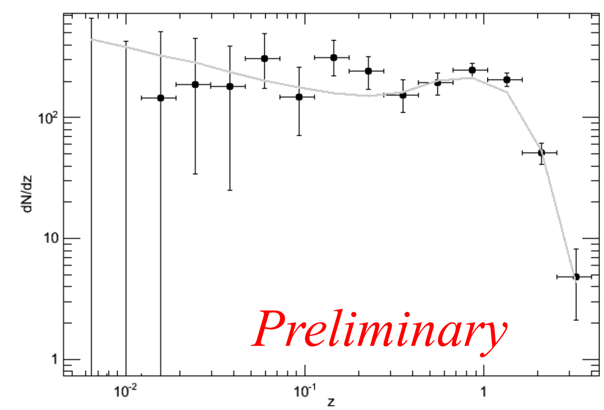
- Bootstrap method as in Ajello+14
  - Relies on 500 MC samples
  - Takes into account the error on redshift
  - Robust error estimate in general



- DE model does a reasonable job in describing the available dataset
  - LDDE does a good job as well
  - Contribution to EGB robust against changes of LF parameterization (as long as LFs reproduce all data)



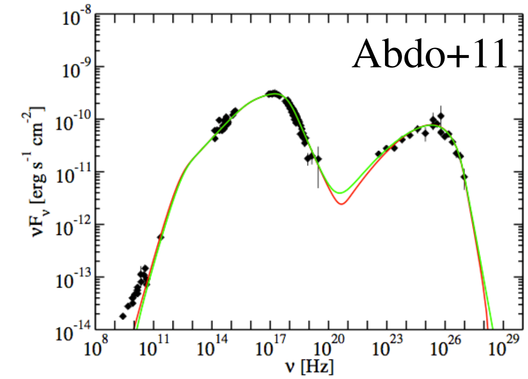




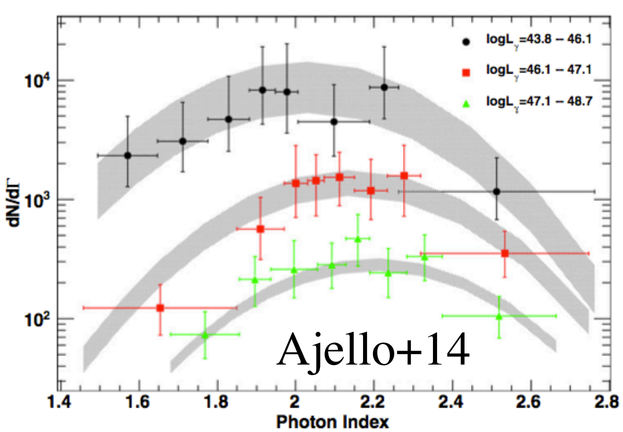
SED Modeling

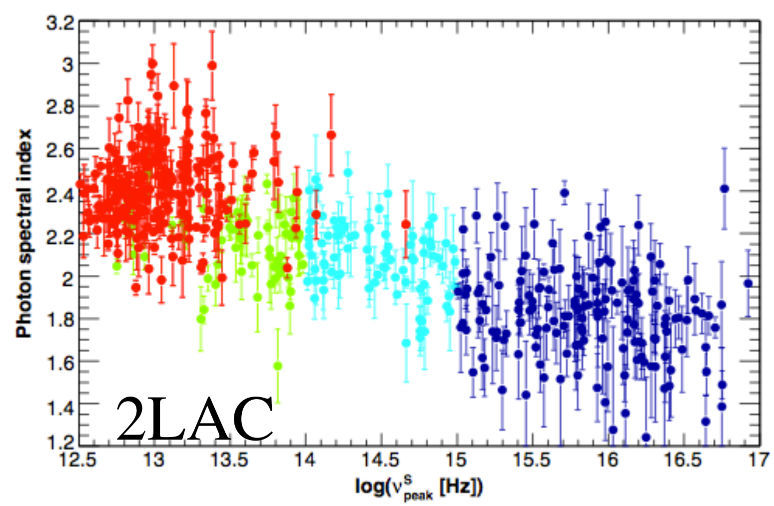
- We adopt a double power law absorbed by the EBL:

$$\frac{dN}{dE} = \frac{A}{\left(\frac{E}{E_b}\right)^a + \left(\frac{E}{E_b}\right)^b} * e^{-\tau(E,z)}$$



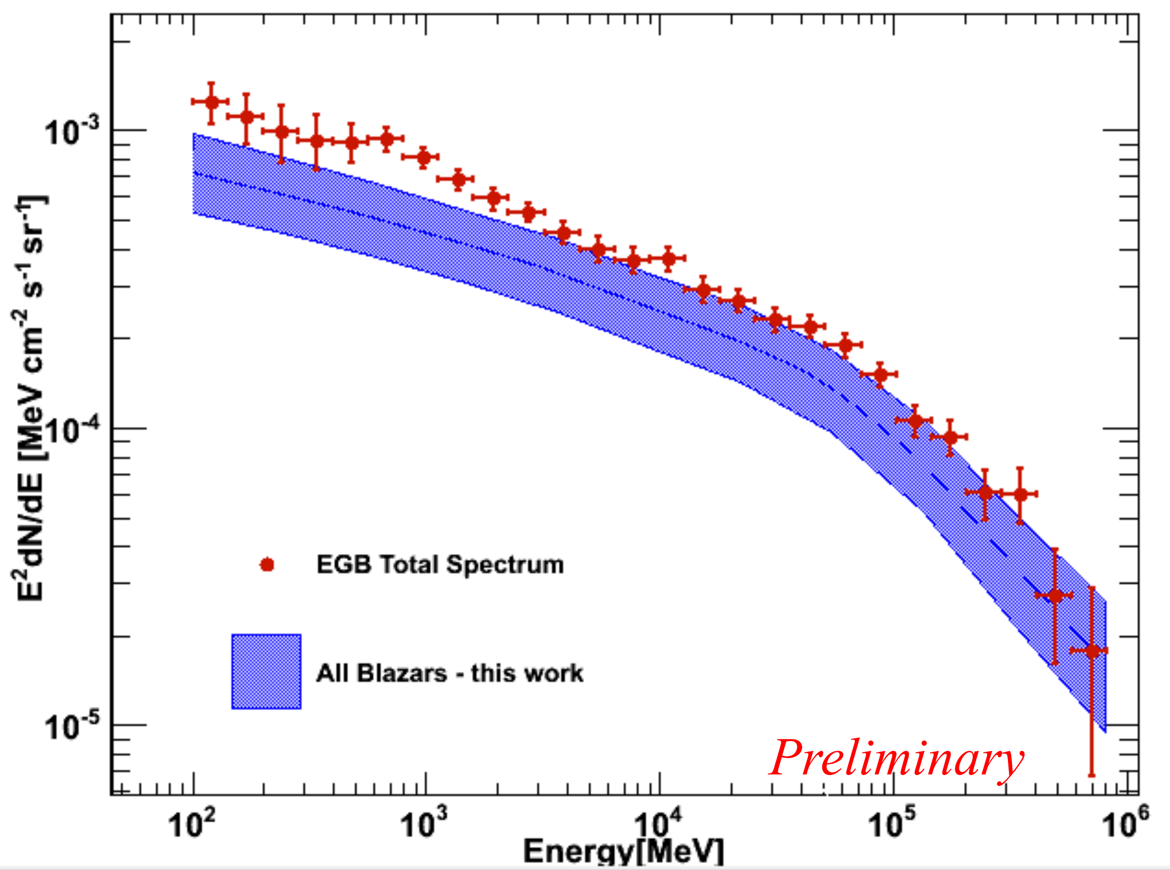
  - with $a \approx 1.7$ and $b \approx 2.6\text{-}3.0$
  - E_b is a function of measured photon index Γ, calibrated via simulations
  - since Γ=Γ(L), spectra naturally get softer for increasing luminosity (a la 'blazar sequence' of Ghisellini+09, adopted by Inoue et al. 2009, and Abazajian+10)



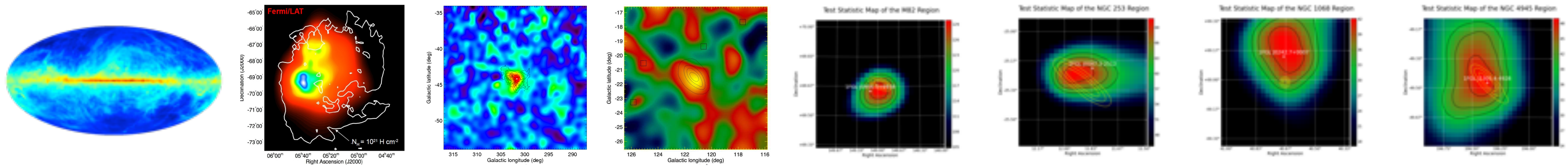


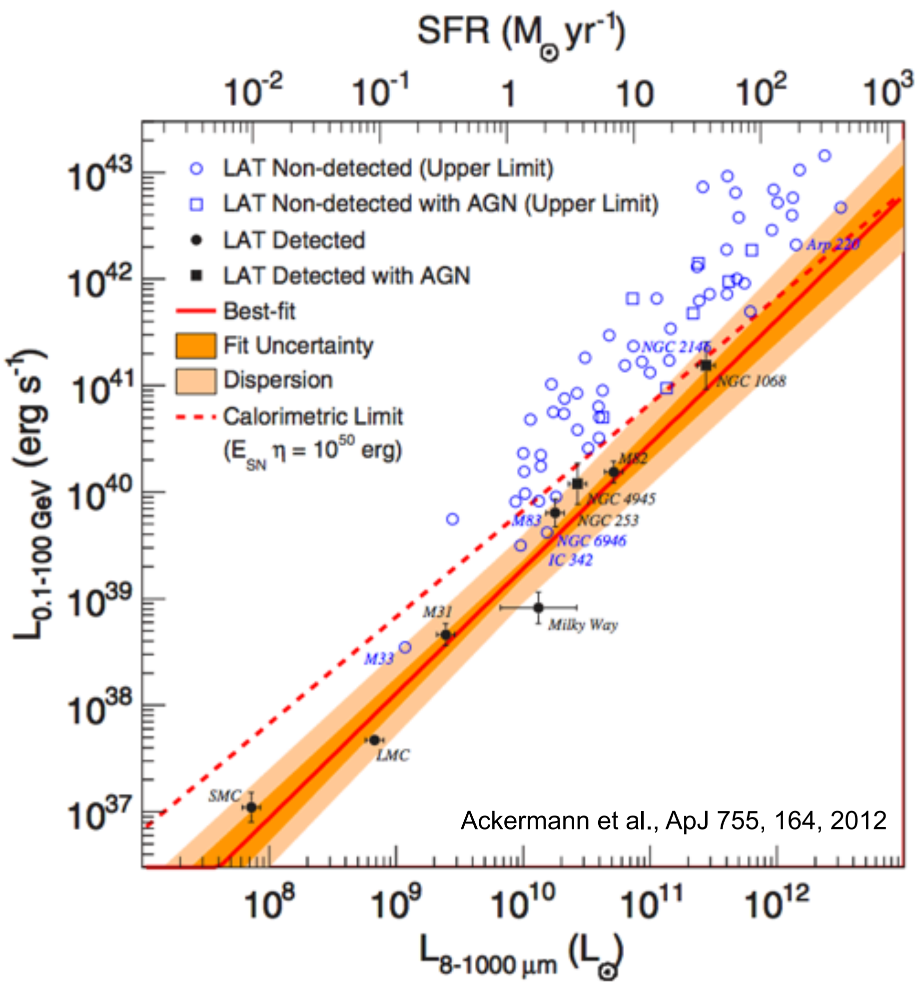
Results

- EGB total intensity of 1.1×10^{-5} ph cm^{-2} s^{-1} sr^{-1}
- Blazars contribute a grand-total of $(5\text{-}7)\times10^{-6}$ ph cm^{-2} s^{-1} sr^{-1}
  – Resolved sources : $\sim4\times10^{-6}$ ph cm^{-2} s^{-1} sr^{-1}
  – Unresolved blazars: $\sim(2\text{-}3)\times10^{-6}$ ph cm^{-2} s^{-1} sr^{-1} (in agreement with Abdo+10)



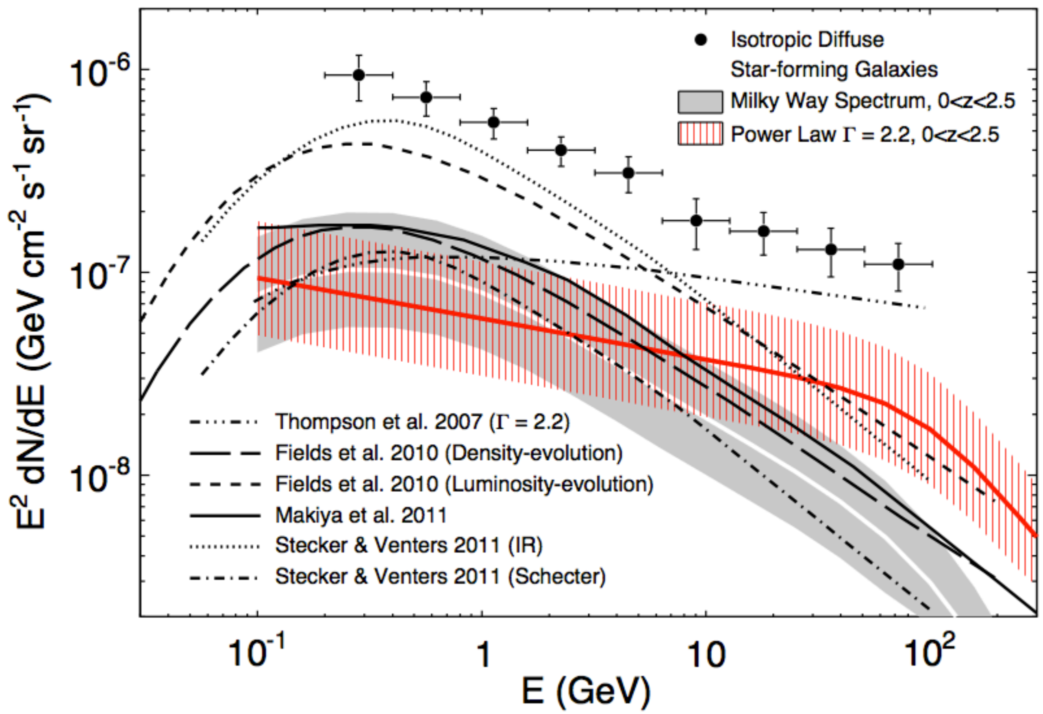
Star forming galaxies





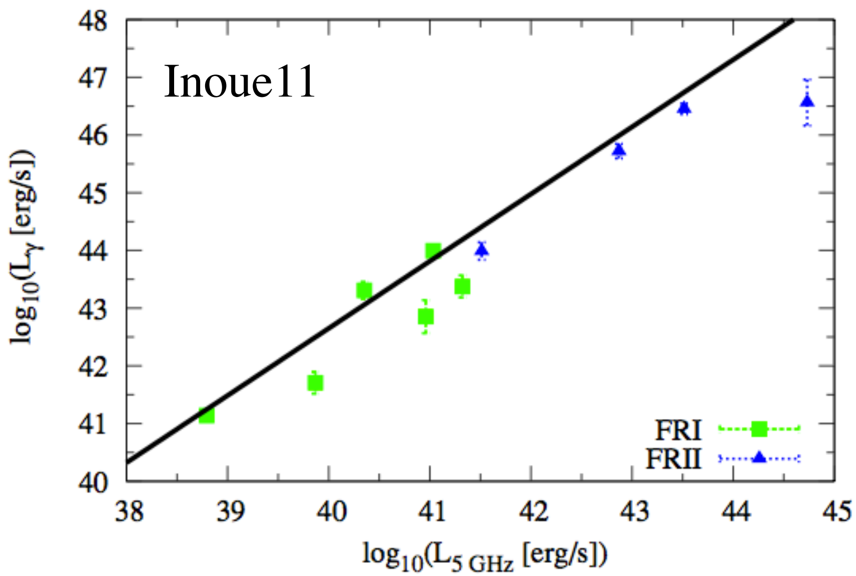
- 8 galaxies detected by the LAT
- Almost linear correlation between gamma-ray luminosity and tracers of star formation
  - bolometric infrared luminosity
  - 1.4 GHz radio continuum emission
- Detection + upper limits can be used to constrain correlation
- Use gamma-ray / IR luminosity correlation to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

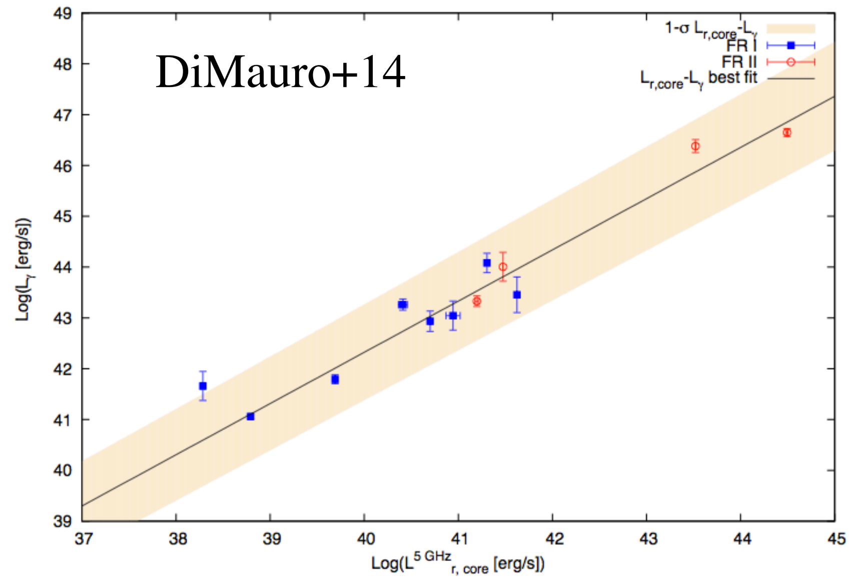
Star-forming Galaxies



- Unresolved star-forming galaxies produce 0.2-2.4 $\times 10^{-6}$ ph cm^{-2} s^{-1} sr^{-1}
  - E.g. 4% - 24% of the total EGB

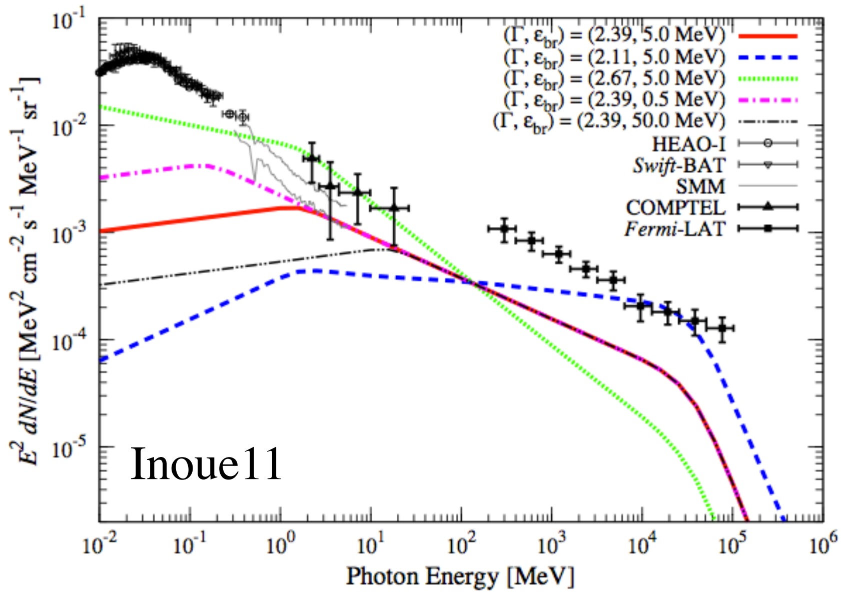
Radio Galaxies

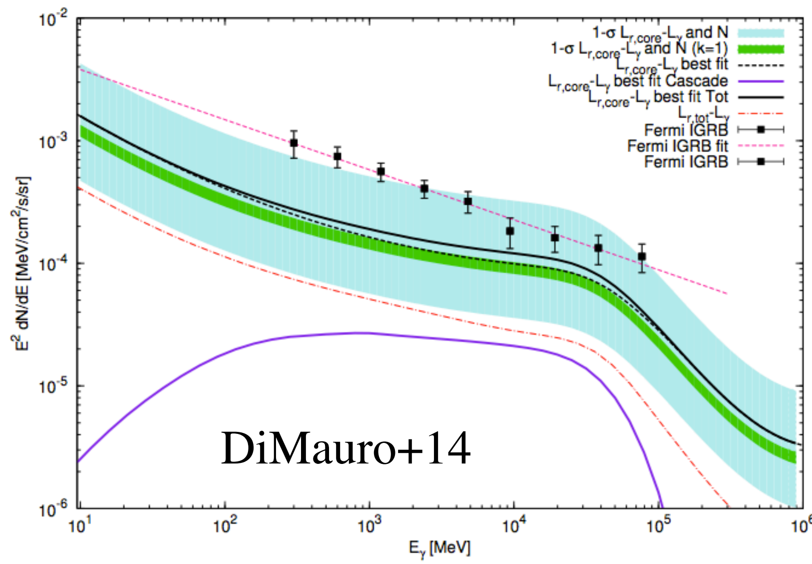




- *Fermi* has detected 15 radio galaxies (Abdo+10, ApJ 720, 912 and Nolan+12, ApJS, 199, 31)
- A correlation between the g-ray and the radio (core) luminosity has been found
- Using a radio luminosity function (e.g. Willott+01) the contribution to the EGB can be estimated: 20-100% of the EGB

Radio Galaxies





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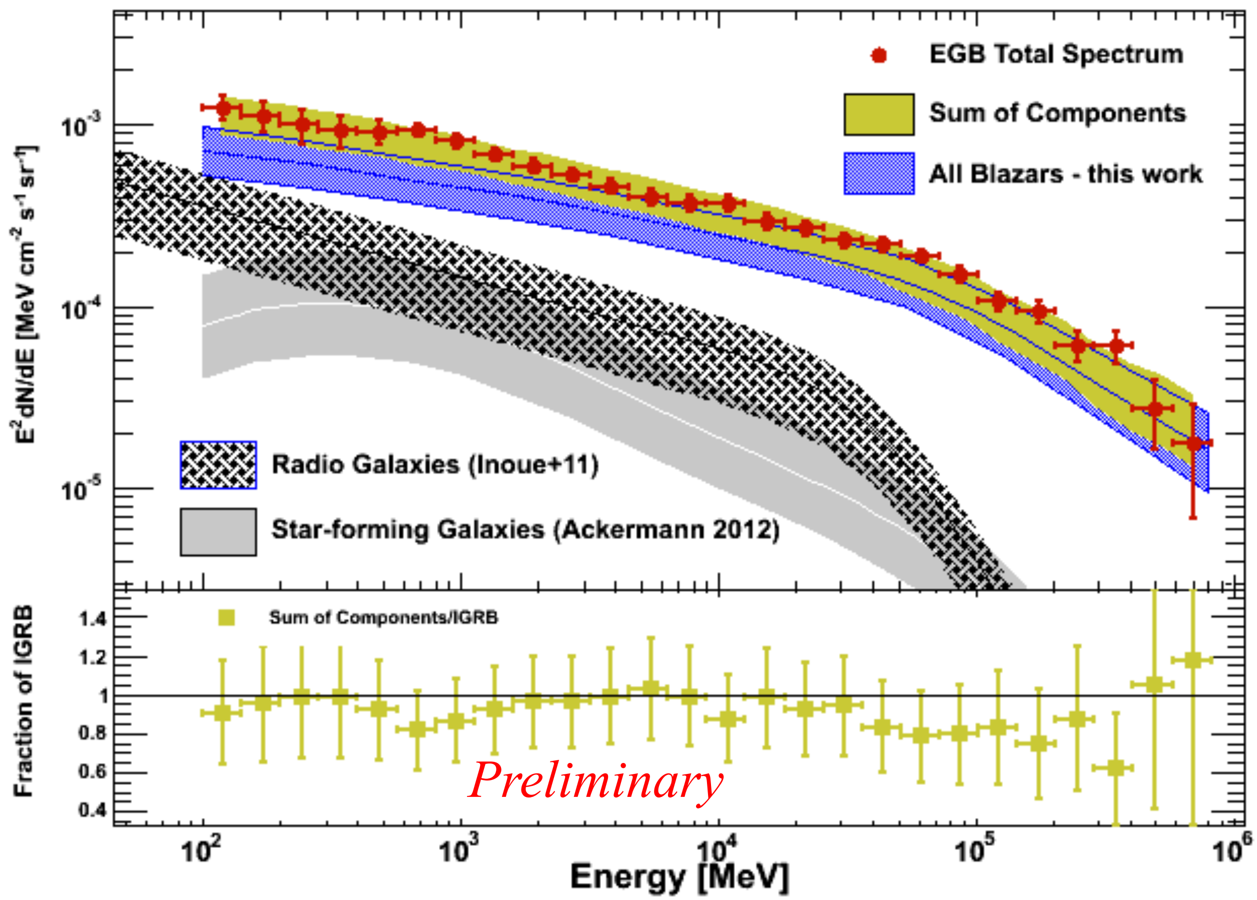
Sum of Components

- Blazars, star-forming galaxies and radio galaxies can explain the intensity and the spectrum of the EGB



As usual: it does not include the systematic uncertainty on the EGB

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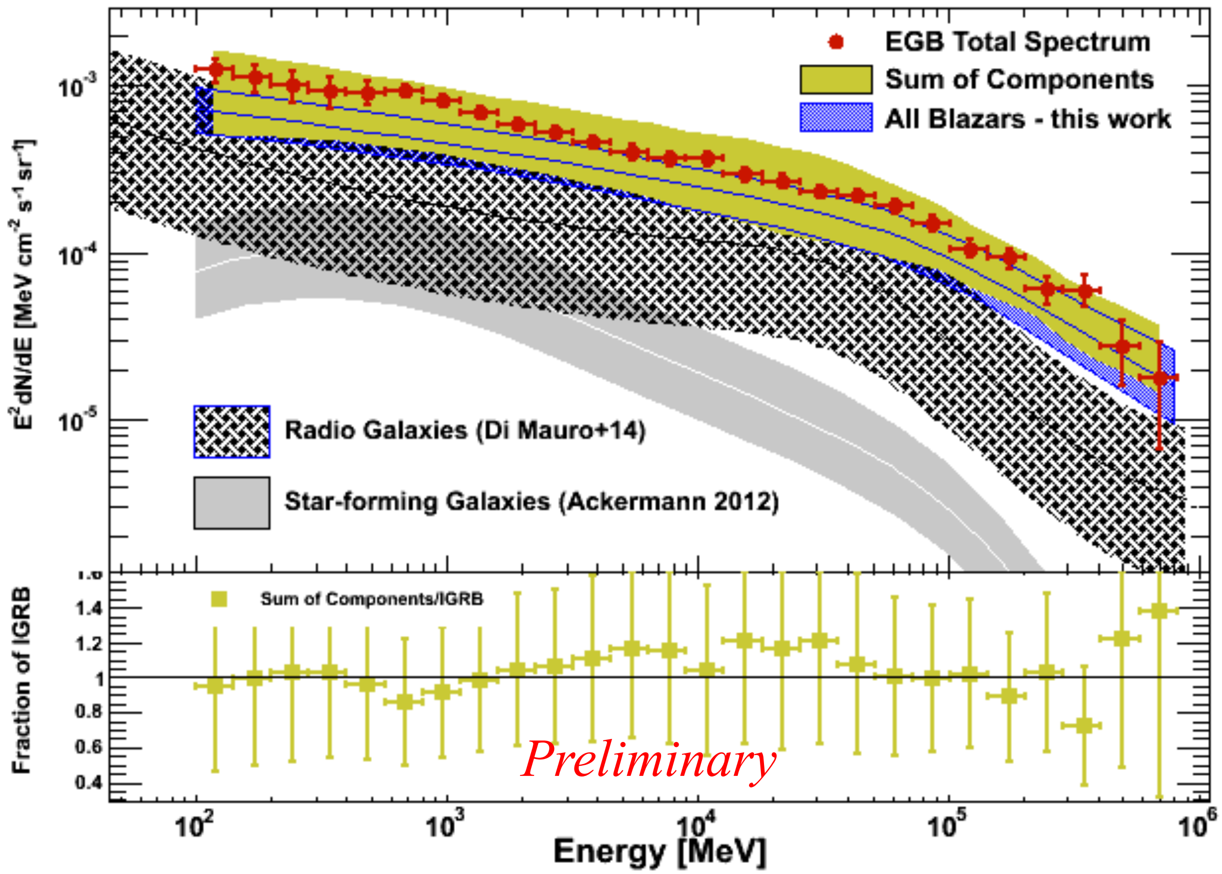

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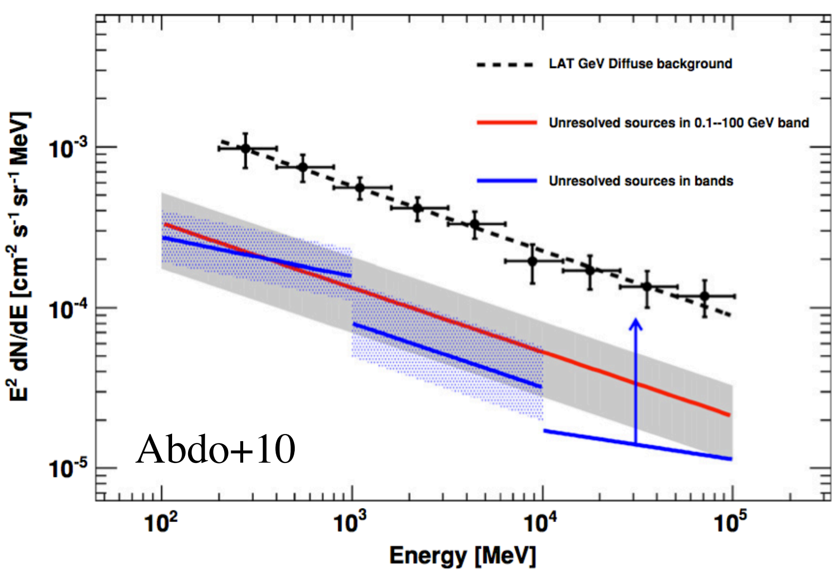
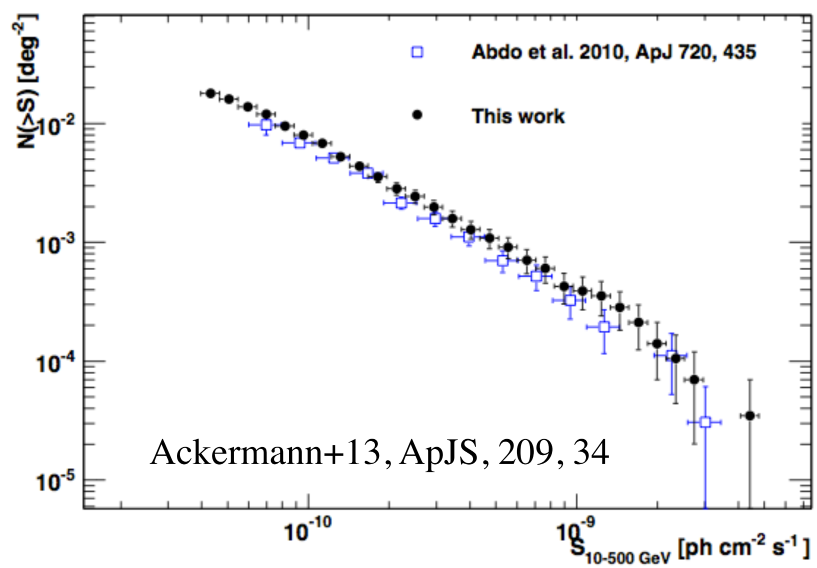
Some thoughts on blazars

- Resolved flux (>100 MeV) in *Fermi* Catalogs (at |b| > 15deg):
  - 1FGL -> 4.2×10^{-6} ph cm^{-2} s^{-1} sr^{-1}
  - 2FGL -> 4.4×10^{-6} ph cm^{-2} s^{-1} sr^{-1}
  - 3FGL -> 4.8×10^{-6} ph cm^{-2} s^{-1} sr^{-1}

- *Fermi* is not going to reduce the EGB much further
  - Except at >10 GeV where the LogN-LogS is steep and sensitivity increases faster than $T^{-0.5}$





Conclusions

- The *Fermi* (new) total EGB can be explained as a sum of :
  - Blazars : 45-65%
  - Star forming galaxies: 4-24%
  - Radio galaxies: ~20%

- Blazars are the largest contributors, and *Fermi* has resolved a substantial fraction of their emission

- Reducing the uncertainty in the radio galaxies estimate and star forming galaxies might be the next important task

- Outlook for blazars:
  - Improved response will favor detection of soft sources and hard sources
  - Expect a 4yr logN-logS which will rely on ~1600 sources
  - Expect as well new luminosity functions (depending on redshift coverage)

Thank You !