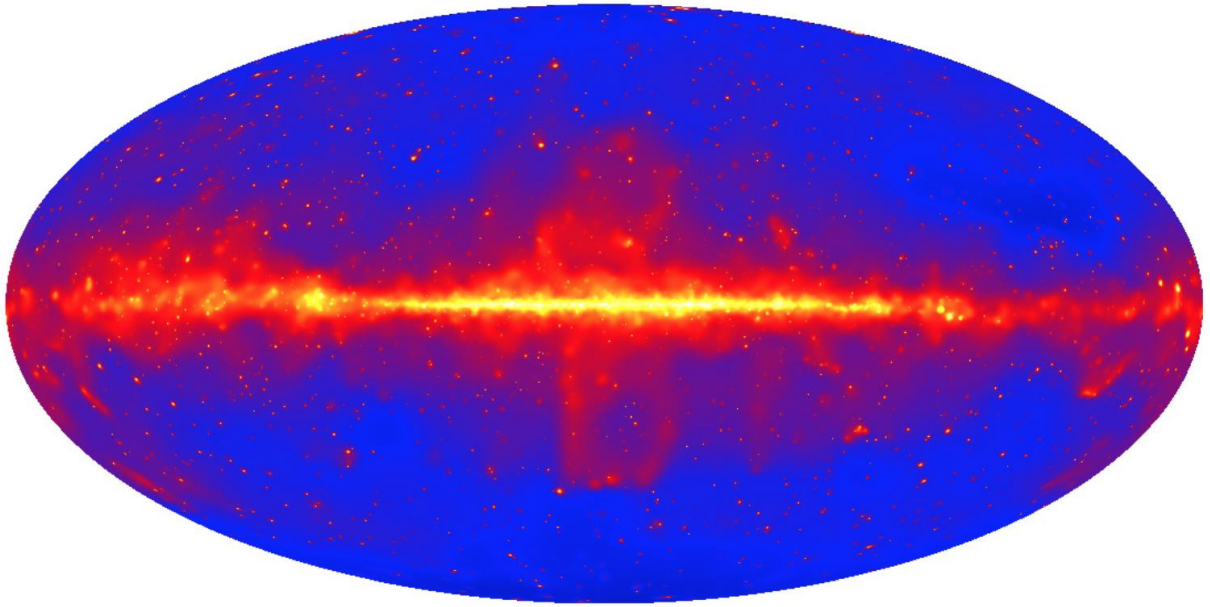
Resolving the Extragalactic γ-ray Background



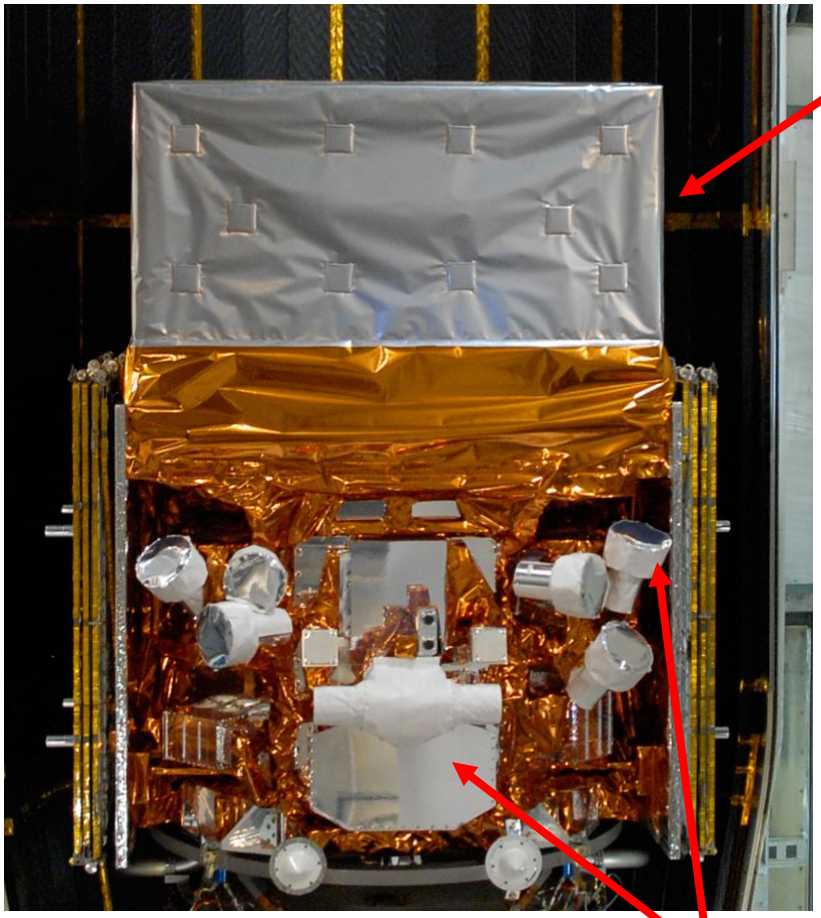
Marco Ajello
Clemson University
On behalf of the Fermi-LAT collab.

(with a few additions by Jack)

Ackermann+2015, ApJ, 799, 86
Ajello+2015, ApJL, 800,27
Ackermann+2016, PRL, 116, 151105

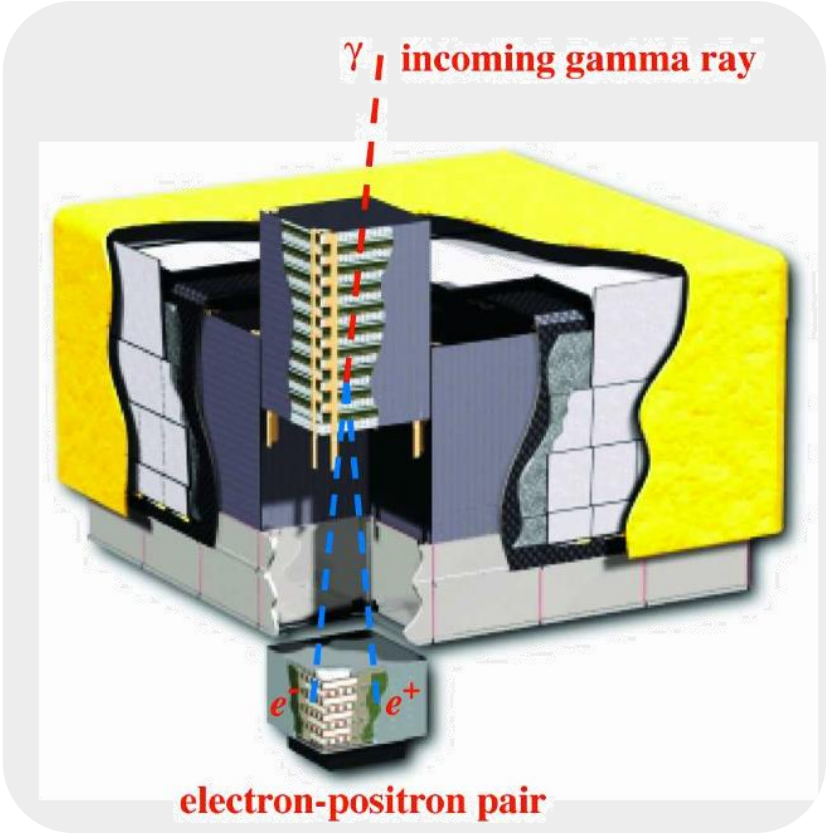
Singal 2015, MNRAS, 115,112
Singal+2014, ApJ, 786,109
Singal+2012, ApJ, 753, 45

Fermi: Bigger, Sharper, Faster



Large Area Telescope (LAT):

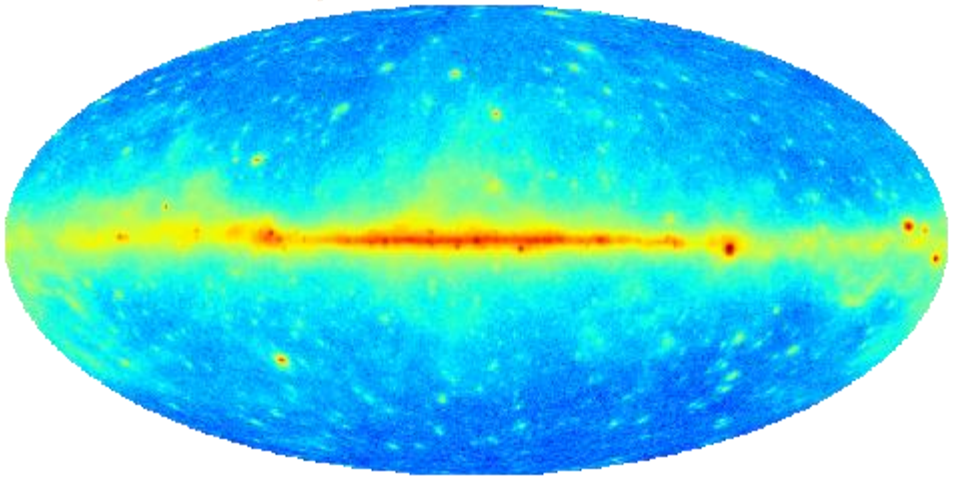
- 100 MeV - > >500 GeV
- 2.4 sr FoV (scans entire sky every ~3hrs)

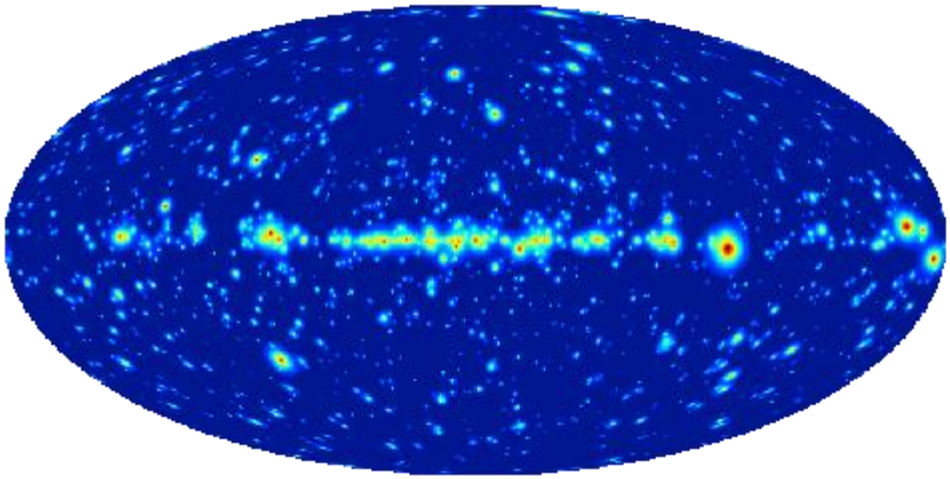


Gamma-ray Burst Monitor (GBM)

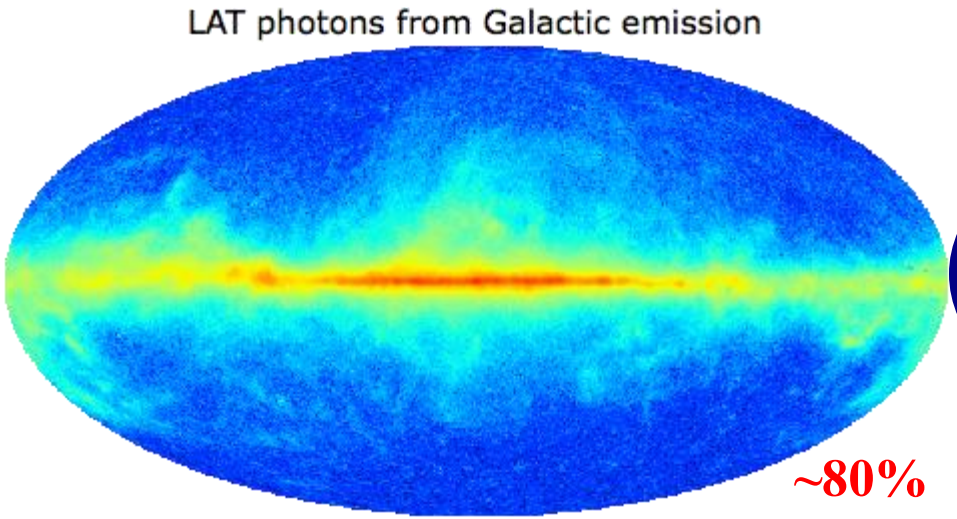
- 8 keV - 40 MeV
- views entire unocculted sky

The Gamma-ray Sky as Seen by *Fermi*





~10%

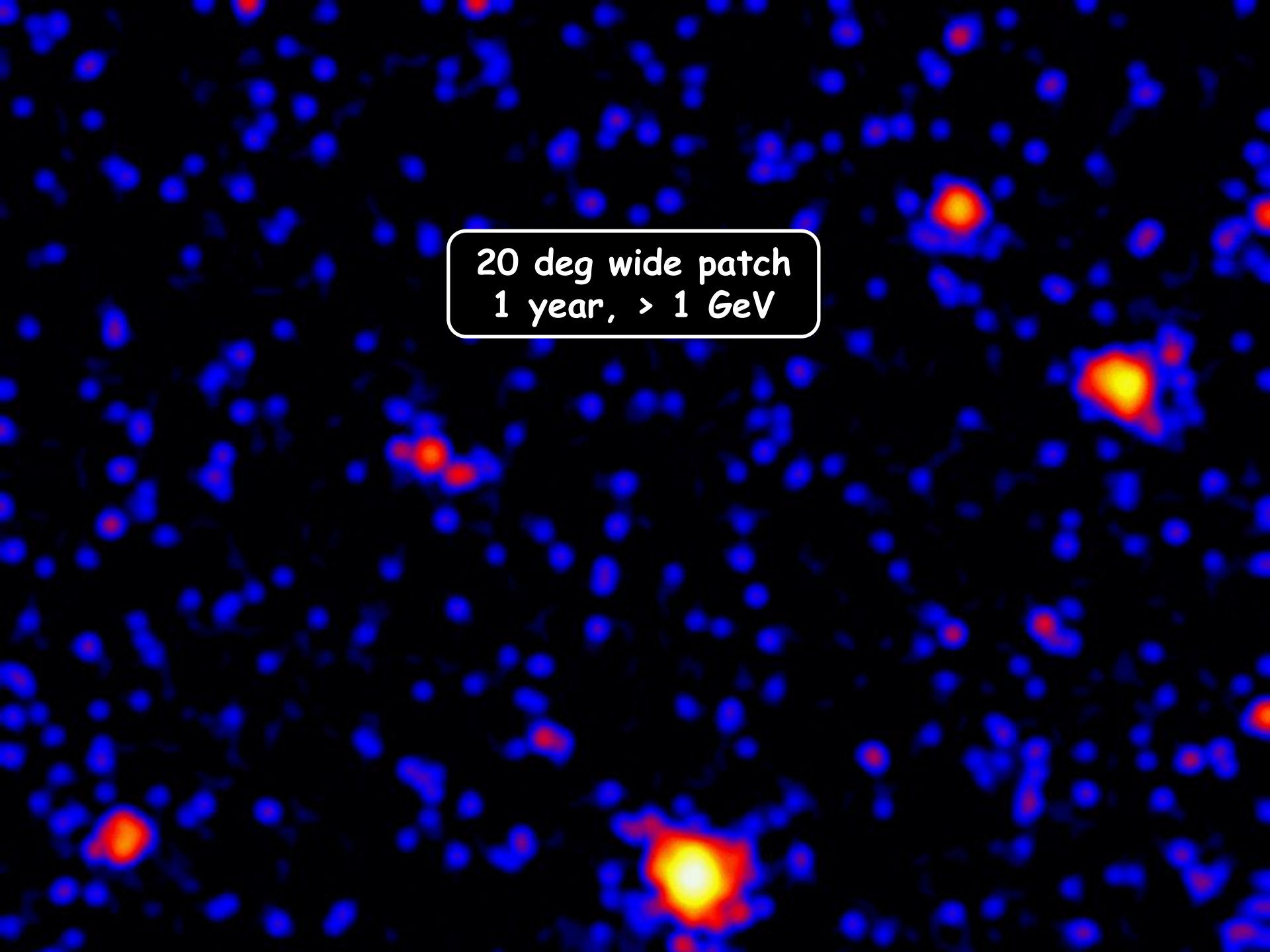


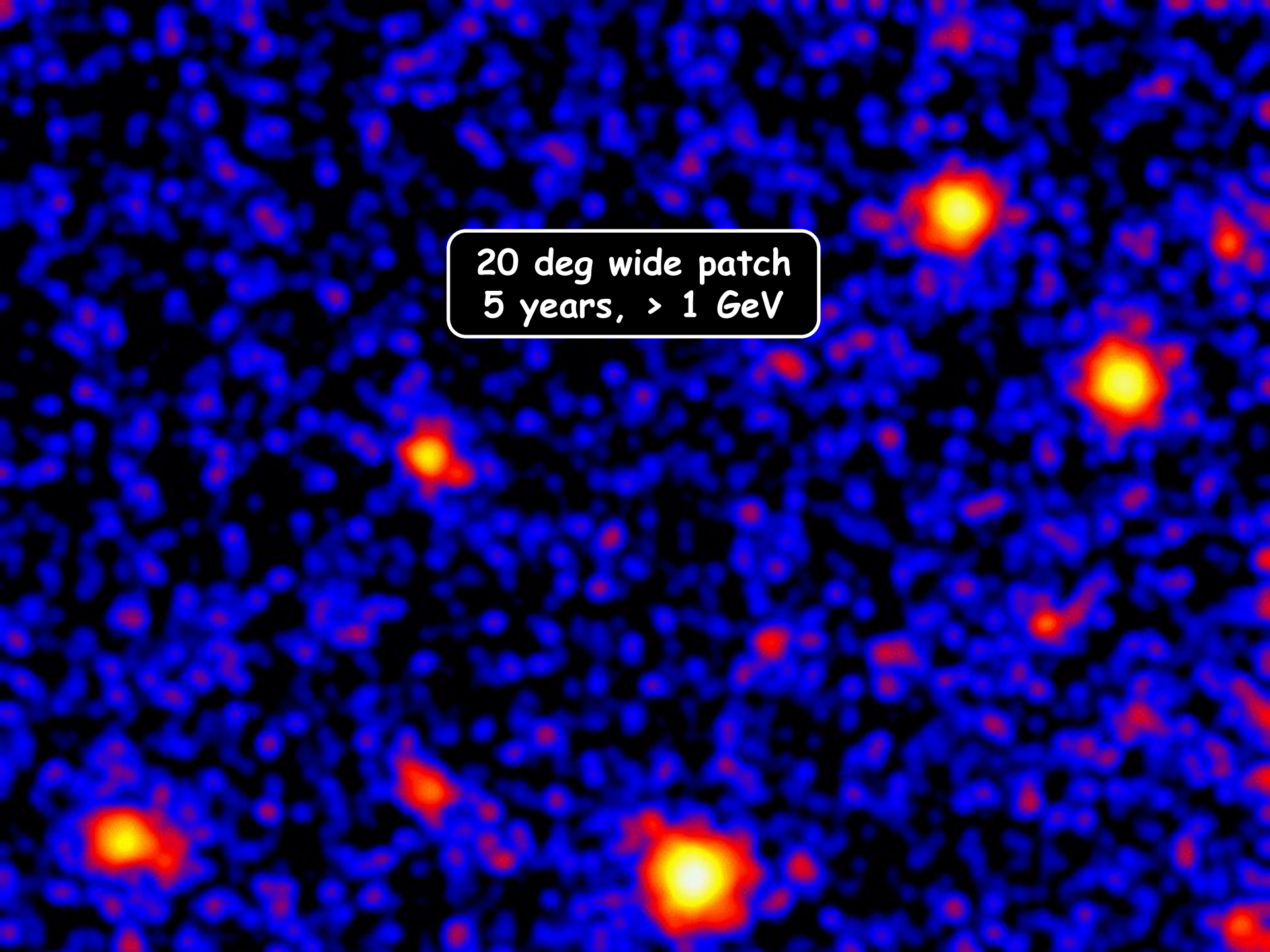
~80%

Nearly isotropic all-sky component (includes residual cosmic-ray background)

~10%

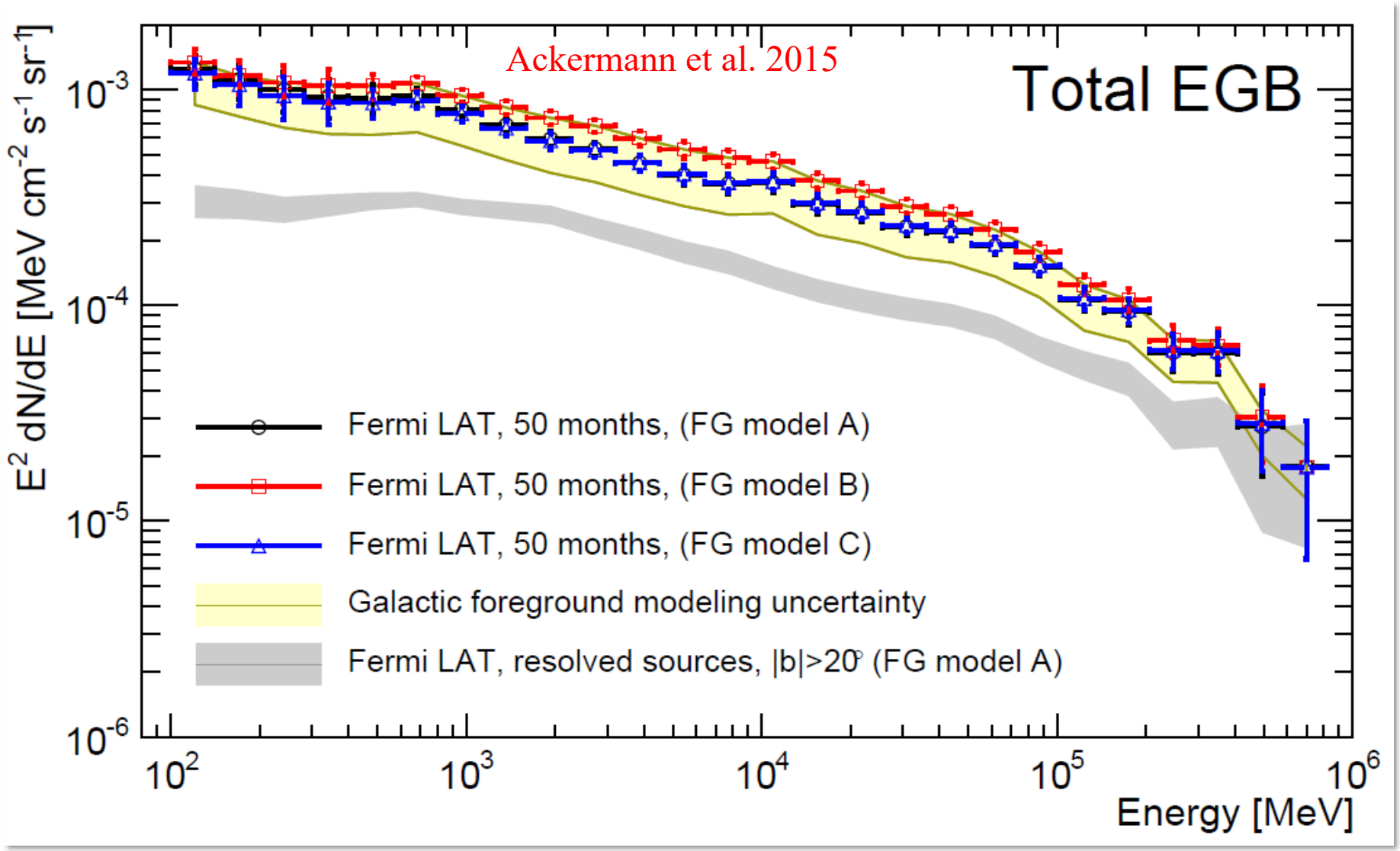
Galactic emission is 2 body process so very highly concentrated in plane
Suppressed in halo


20 deg wide patch
1 year, > 1 GeV


20 deg wide patch
5 years, > 1 GeV

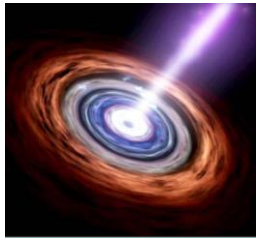
Total Extragalactic Gamma-ray Background

Systematic uncertainty from Galactic foreground represented by yellow band



EGB: Why is it important ?

Undetected sources



Blazars

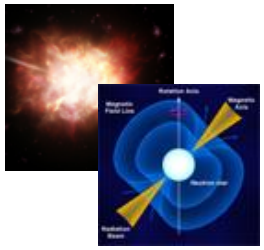
Dominant class of LAT extra-galactic sources. Many estimates in literature. EGB contribution ranging from 20% - 100%.

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)

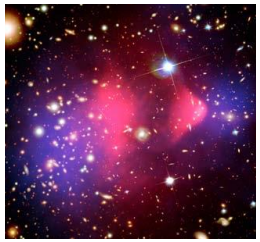


GRBs

High-latitude pulsars

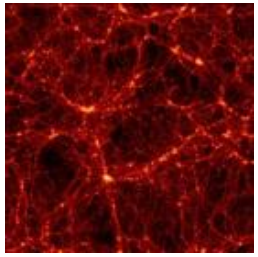
Small contributions expected. (e.g. Dermer 2007, Siegal-Gaskins et al. 2010)

Diffuse processes



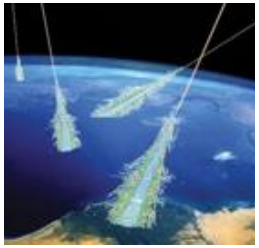
Intergalactic shocks

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

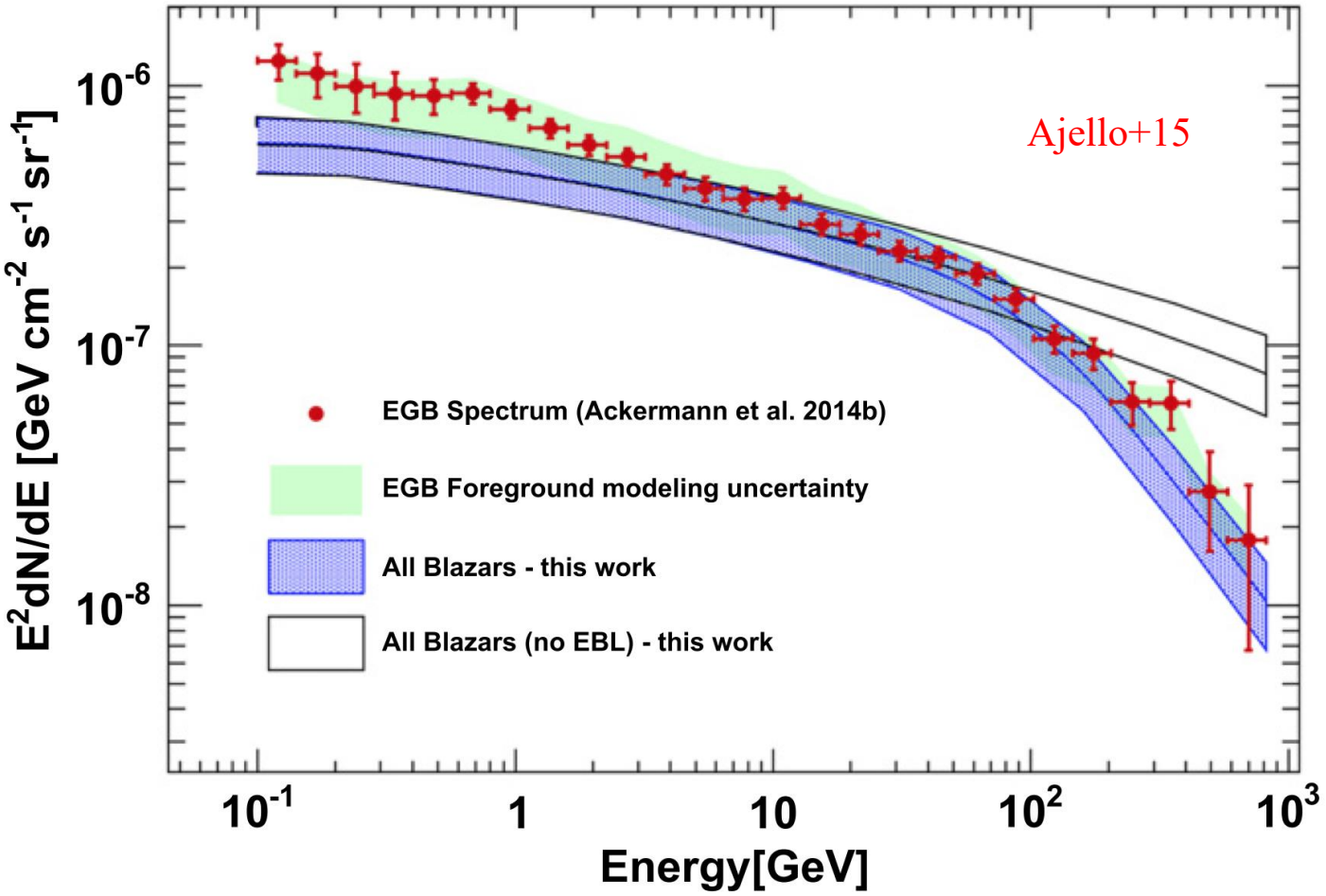
Dependent on evolution of CR sources, predictions varying from 1% to 100 % (e.g. Kalashev et al. 2009)

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

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

Blazars

- Blazars contribute a grand-total of $(5\text{-}7) \times 10^{-6}$ ph cm^{-2} s^{-1} sr^{-1}
  1. Blazars produce ~50% of the EGB
  2. Blazars + EBL are responsible for the cut-off of the EGB spectrum



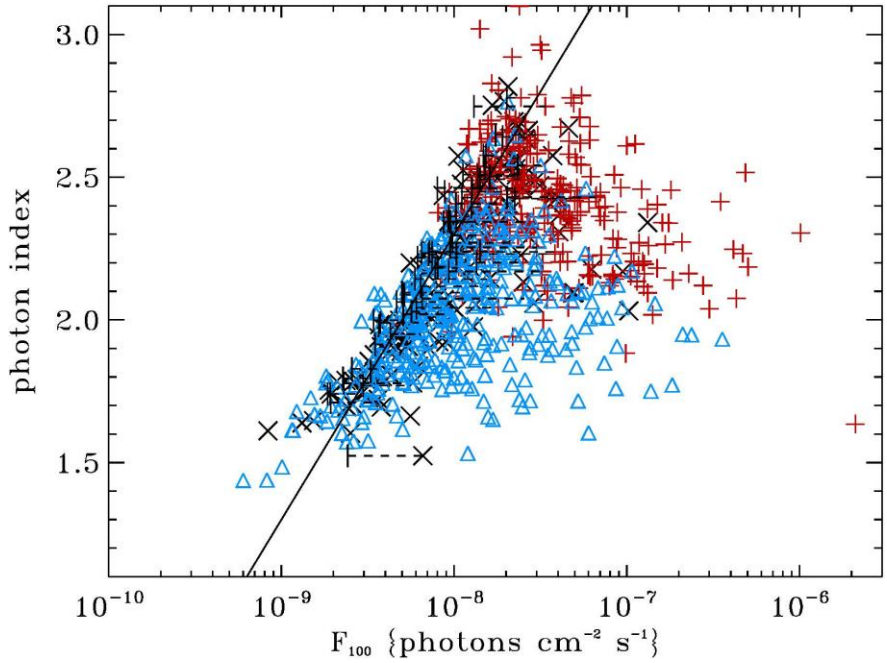
Blazars (JS)

- Ways to calculate
  1. Use blazar source counts

     Advantage: straightforward to determine at fluxes observed

     Disadvantage: Unknown below flux cutoff

     Flux cutoff is photon energy dependent



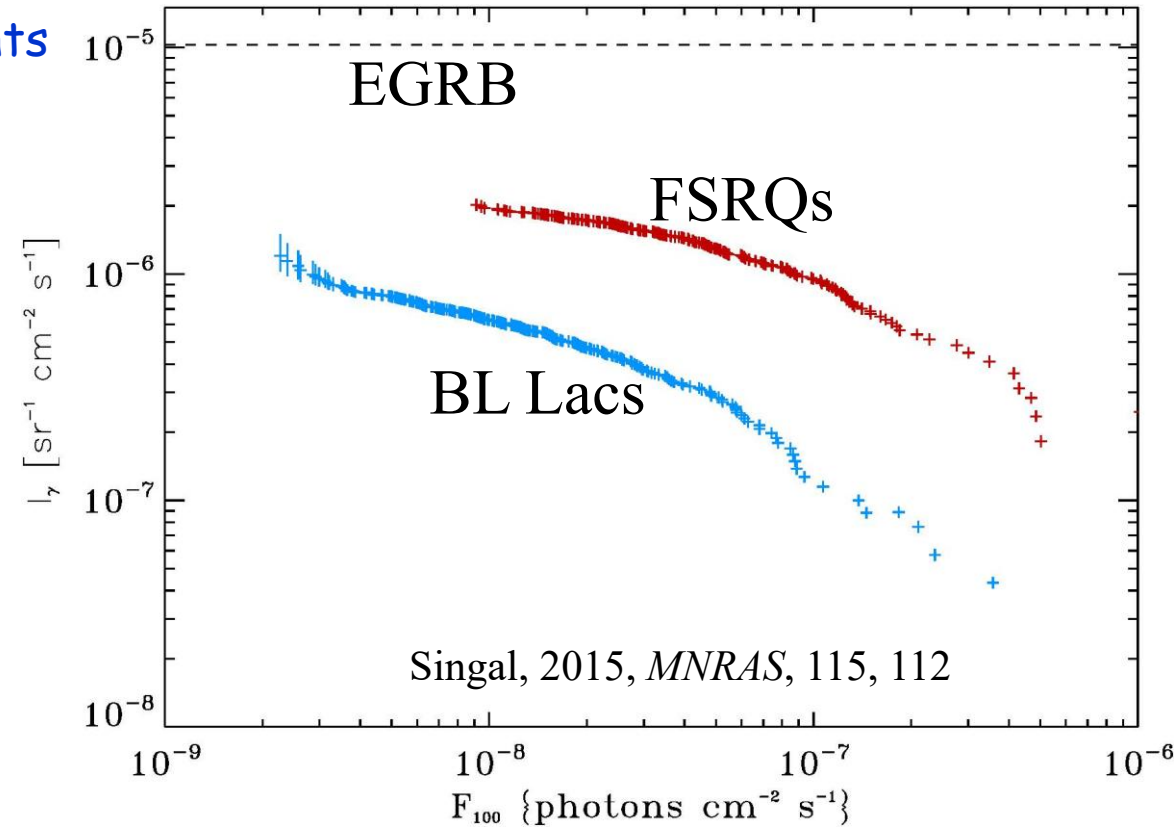
  2. Use blazar luminosity functions

     Advantage: more straightforward to extrapolate Lum fn. down than source counts

     Disadvantage: more complicated integration to get total

Blazars (JS)

- Ways to calculate
  1. Use blazar source counts



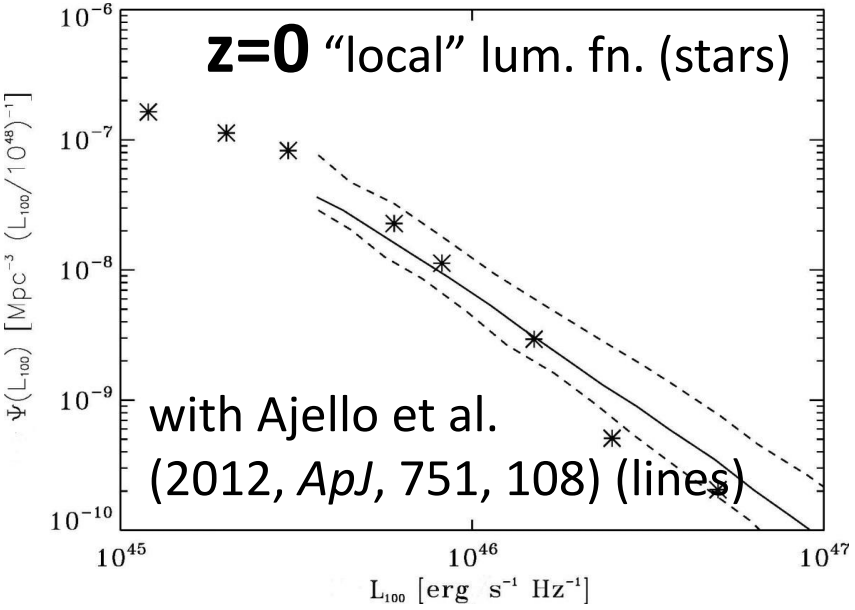
100 Mev-100 GeV	FSRQs %	BL Lacs %	Total %
Probed	20	10	30
Extrapolated	35 (+35/-9)	17 (+44/-12)	52 (+all/-15)

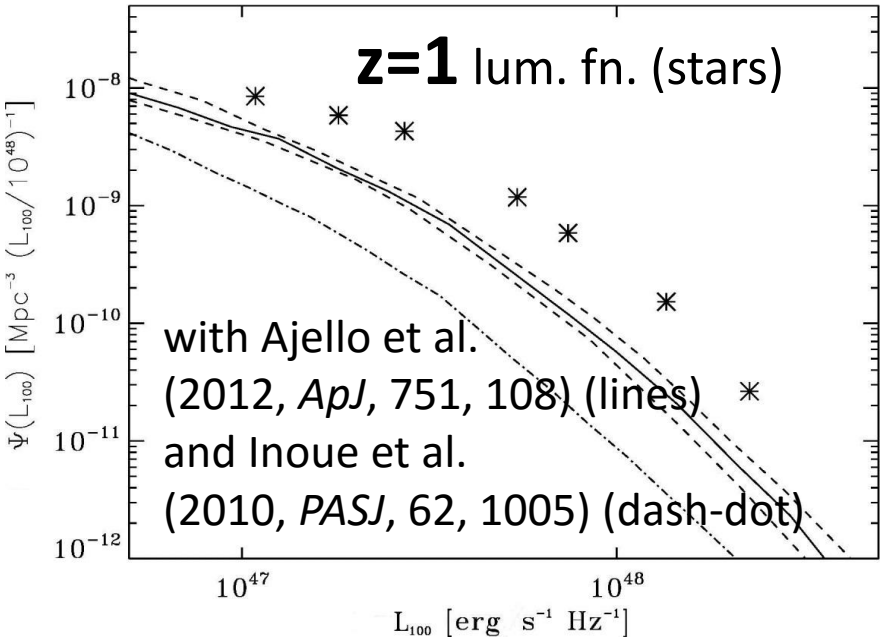
Blazars (JS)

- Ways to calculate
  2. Use blazar luminosity functions

$$\Psi_{L\gamma}(L_\gamma, z) = \rho(z) \times \psi_{L\gamma}(L'_\gamma) / g_{L\gamma}(z)$$

Singal, Ko, & Petrosian, 2014, *ApJ*, 786, 109 **FOR FSRQs**





$$\mathcal{I}_{\gamma:\mathrm{FSRQs}} = \int_z dz \int_{\Gamma=-\infty}^{\infty} d\Gamma \int_{L_\gamma=0}^{\infty} dL_\gamma \quad \frac{1}{4\pi {D_L}^2 K_L} \rho(z) \frac{dV}{dz} \Phi_{L'_\gamma}\left(\frac{L_\gamma}{g_{L_\gamma}(z)}, z\right) h(\Gamma)$$

Here FSRQs in toto account for $22(^{+10}/_{-4})$% of the EGB in 100 Mev- 100 GeV

Blazars (JS)

- How did we calculate the source counts or luminosity function?

Lynden-Bell method modified with the use of associated sets for truncated data

$$\Psi_{L\gamma}\left(L_\gamma, z\right) = \rho(z) \times \psi_{L\gamma}\left(L_\gamma^{'}\right) / g_{L\gamma}(z)$$

$$\Phi_k\left(L'\right) = \prod_k \left(1 + \frac{1}{n(k)}\right)$$

Cumulative lum. fn. Determined by modified Lynden-Bell (1971, *MNRAS*, 155, 95) modified with associated sets (e.g. Singal et al., 2012, *ApJ*, 764, 43)

Blazars

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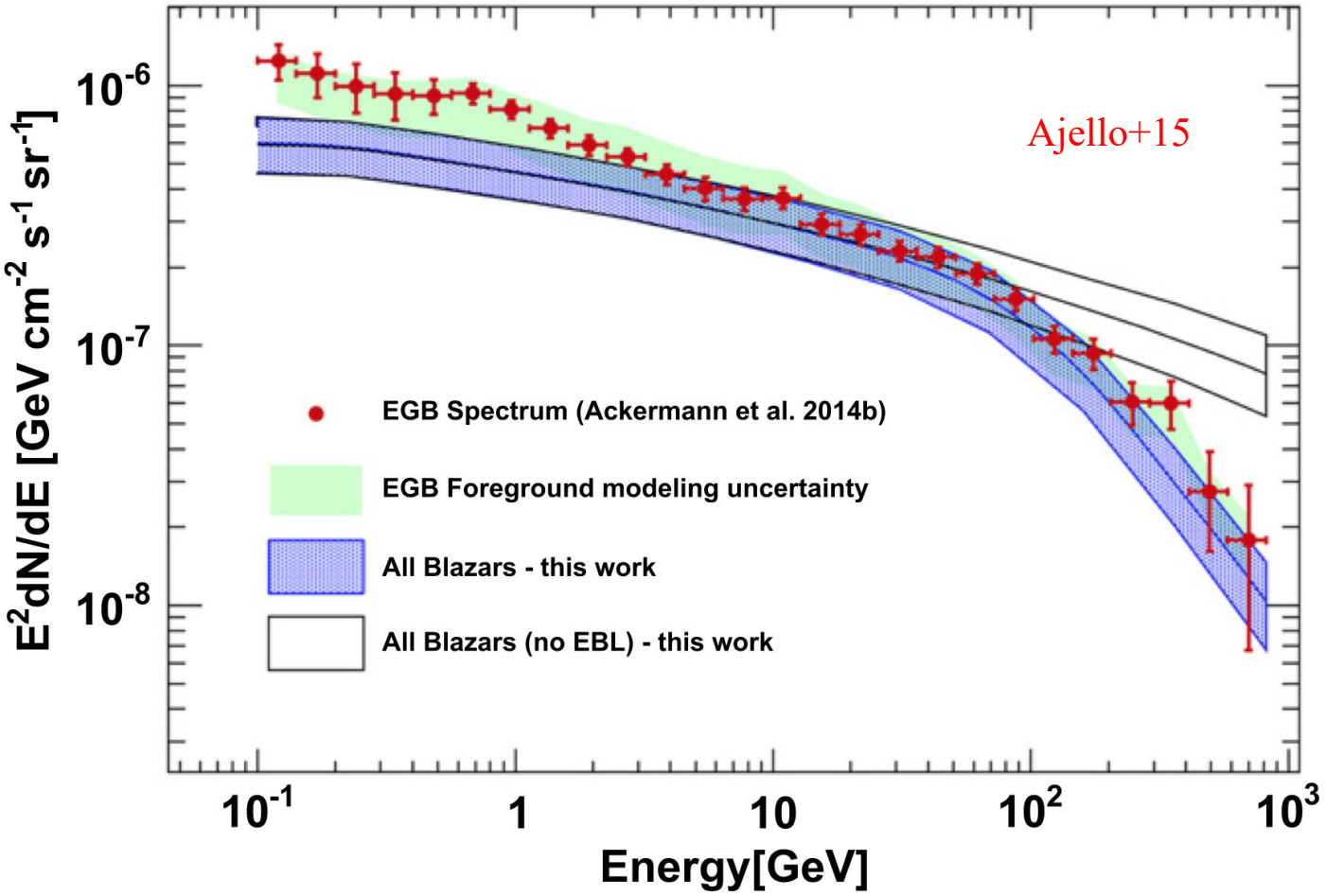
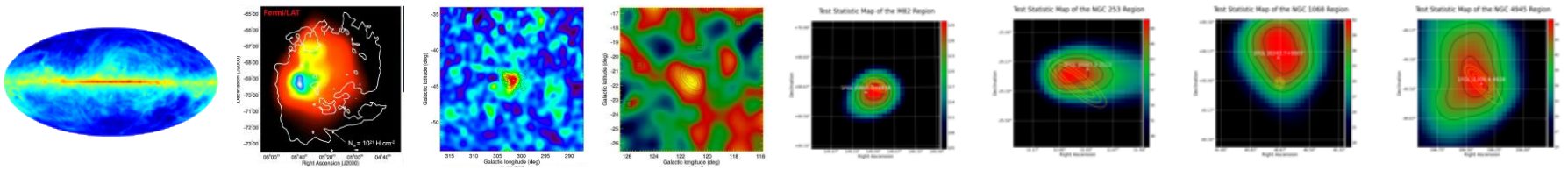
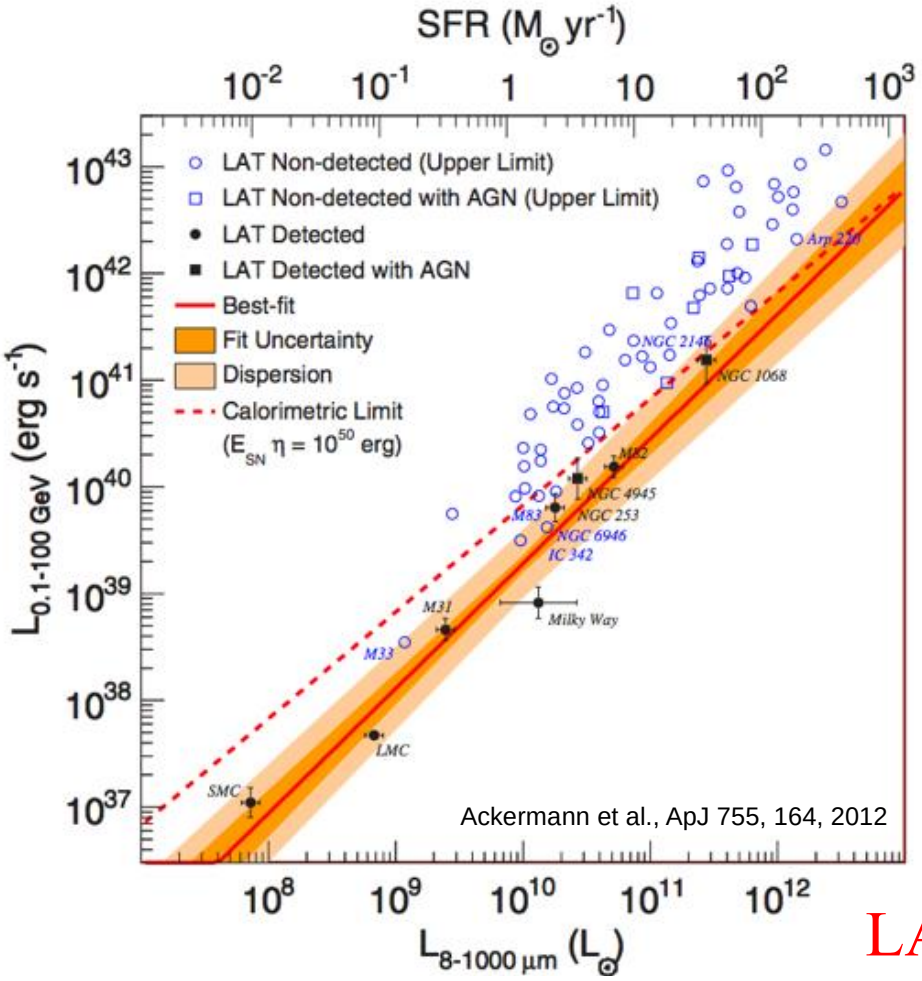


Star forming galaxies



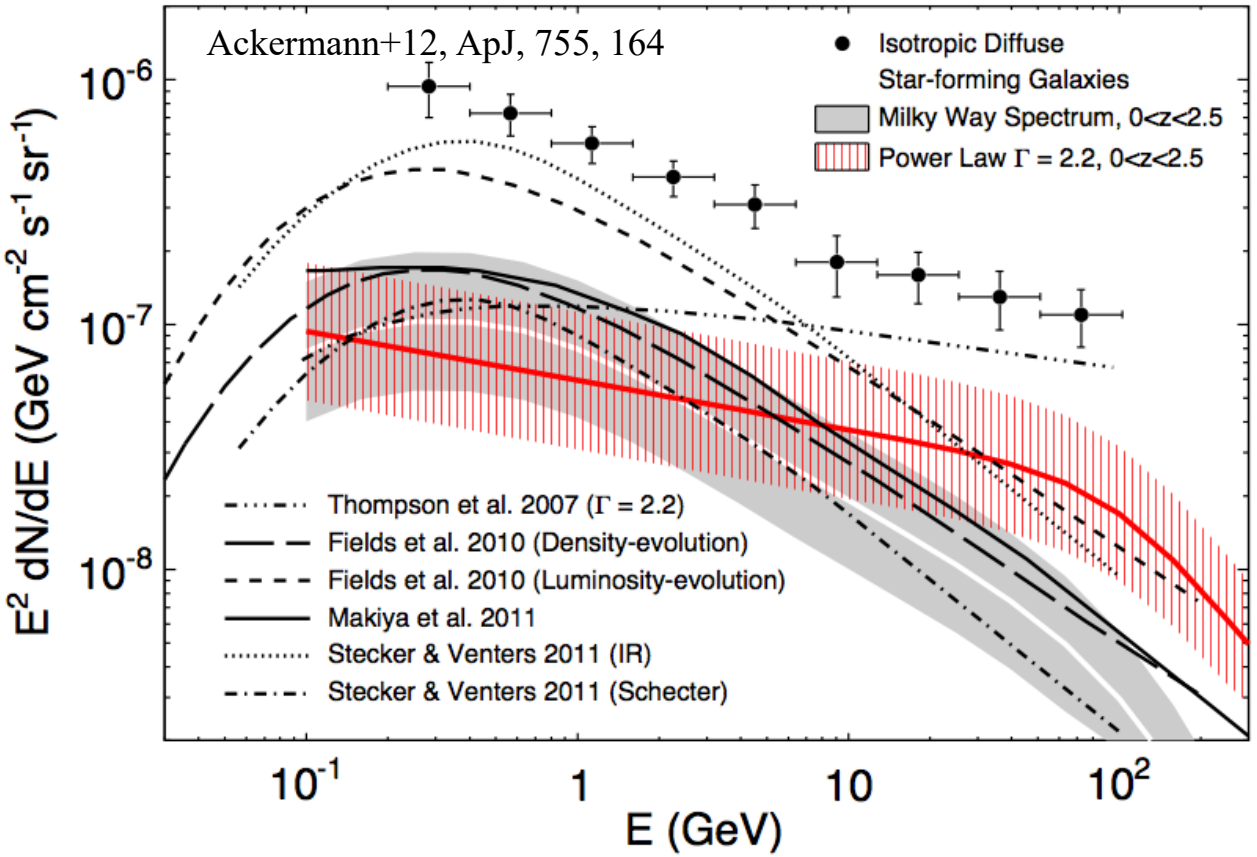


Ackermann et al., ApJ 755, 164, 2012

- 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.

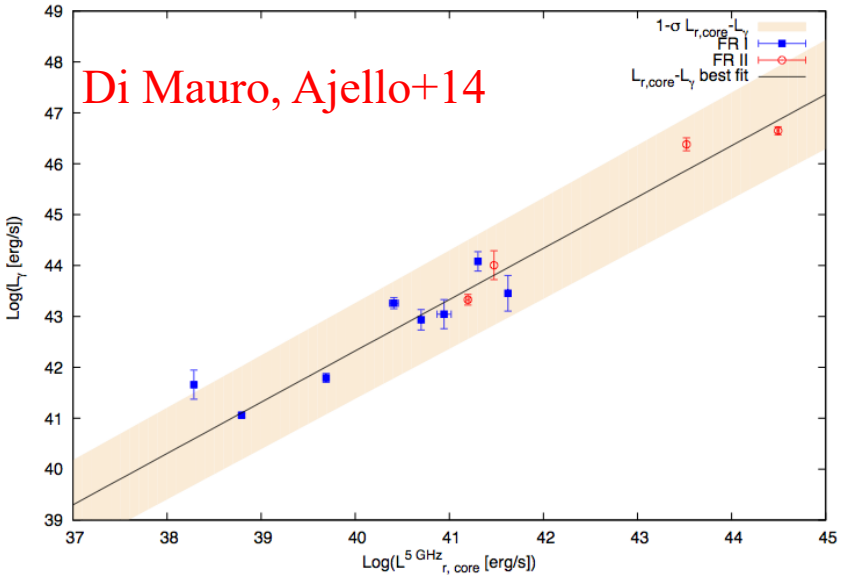
LAT detects all famous C-Thick AGN

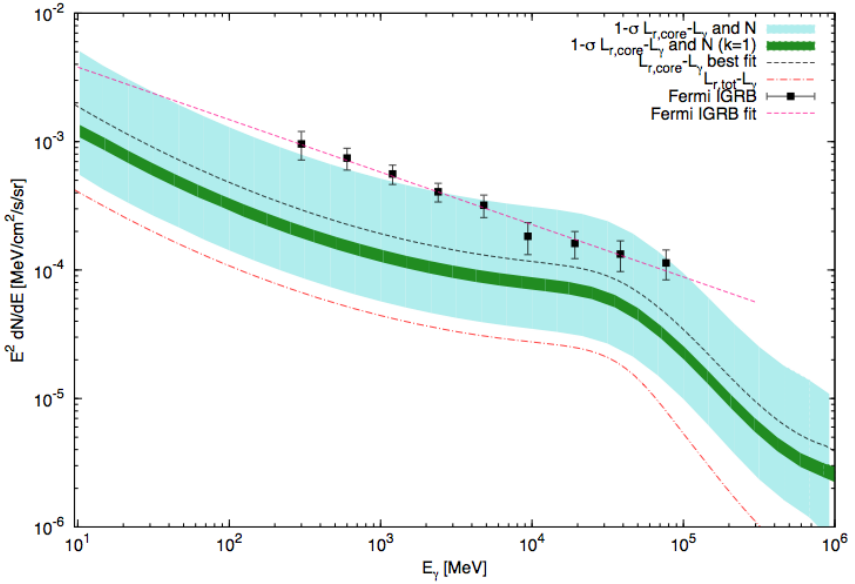
Star forming Galaxies



- Star-forming galaxies contribute 13%(±9%) of the EGB

Radio Galaxies

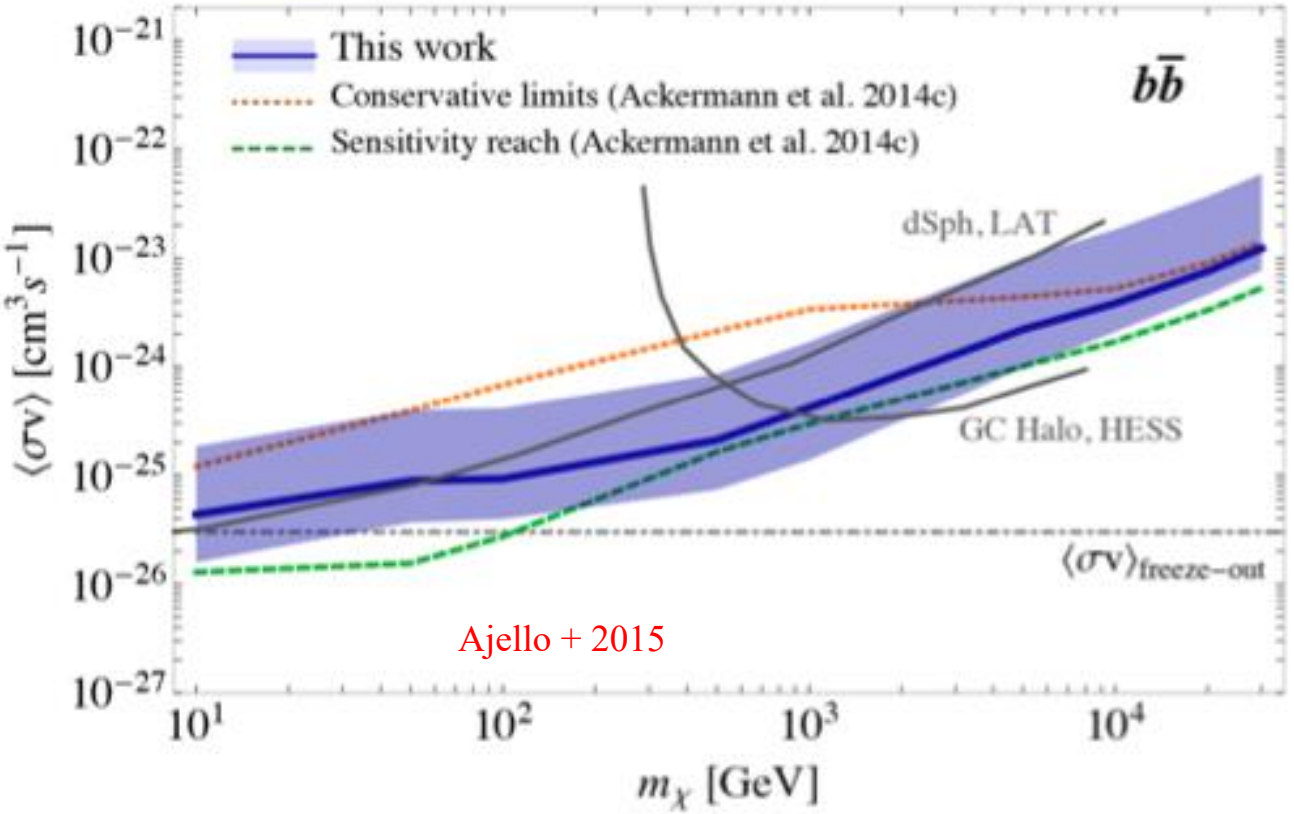




- *Fermi* has detected 15 radio galaxies (Abdo+10, ApJ 720, 912 and Nolan+12, ApJS, 199, 31)
- A correlation exists between the g-ray and the core luminosity
- Using the Willott+01 Luminosity Function, the contribution to the IGRB is: 25% (+58%/-16%)

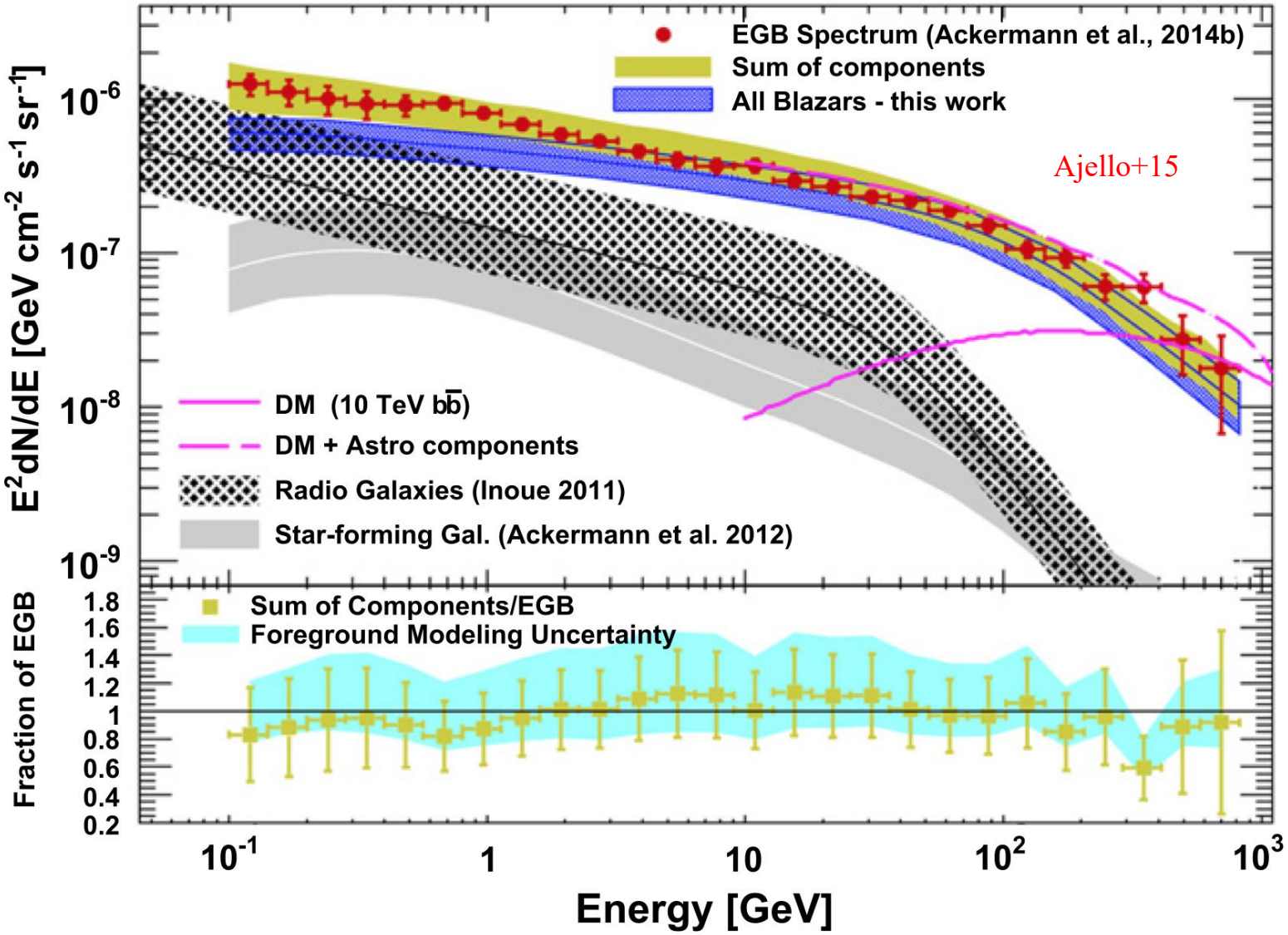
Dark Matter Limits

- DM limits reach higher masses due to the high-energy reach (820 GeV) of the EGB measurement
- Decreasing the uncertainties on source contributions can improve the limits by a factor of 5



Ajello + 2015

Summing Everything Up



Conclusion

- Fermi-LAT
  - Among the few instruments able to measure and resolve a cosmic background at the same time
- EGRB:
  - It can be explained entirely (between 100 MeV and 800 GeV) by known source populations
  - Blazars (FSRQs > BL Lacs) > SFGs > Radio Galaxies > DM
- EGRB is an important tool in multi-messenger astrophysics