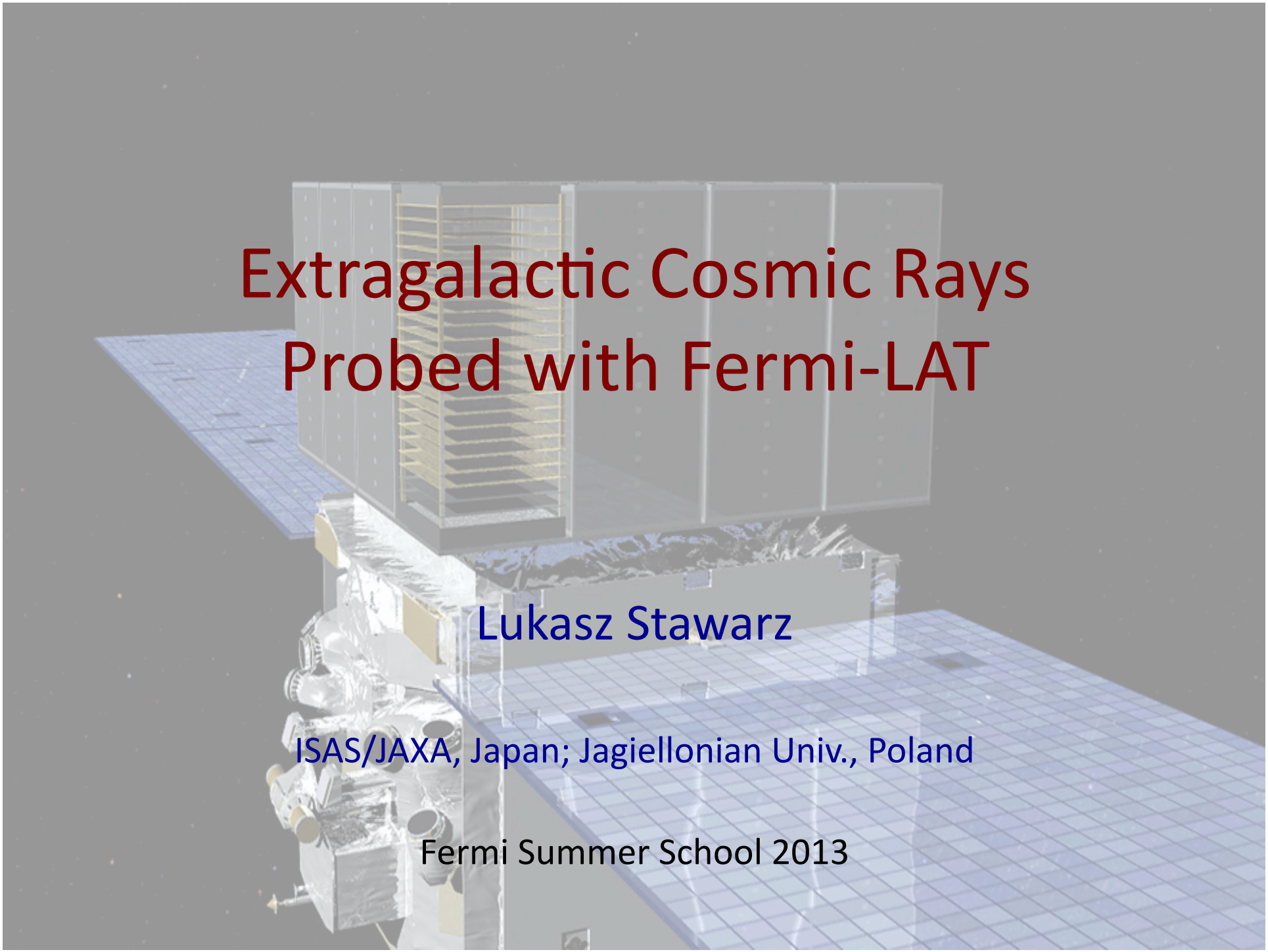


# Extragalactic Cosmic Rays Probed with Fermi-LAT

Lukasz Stawarz

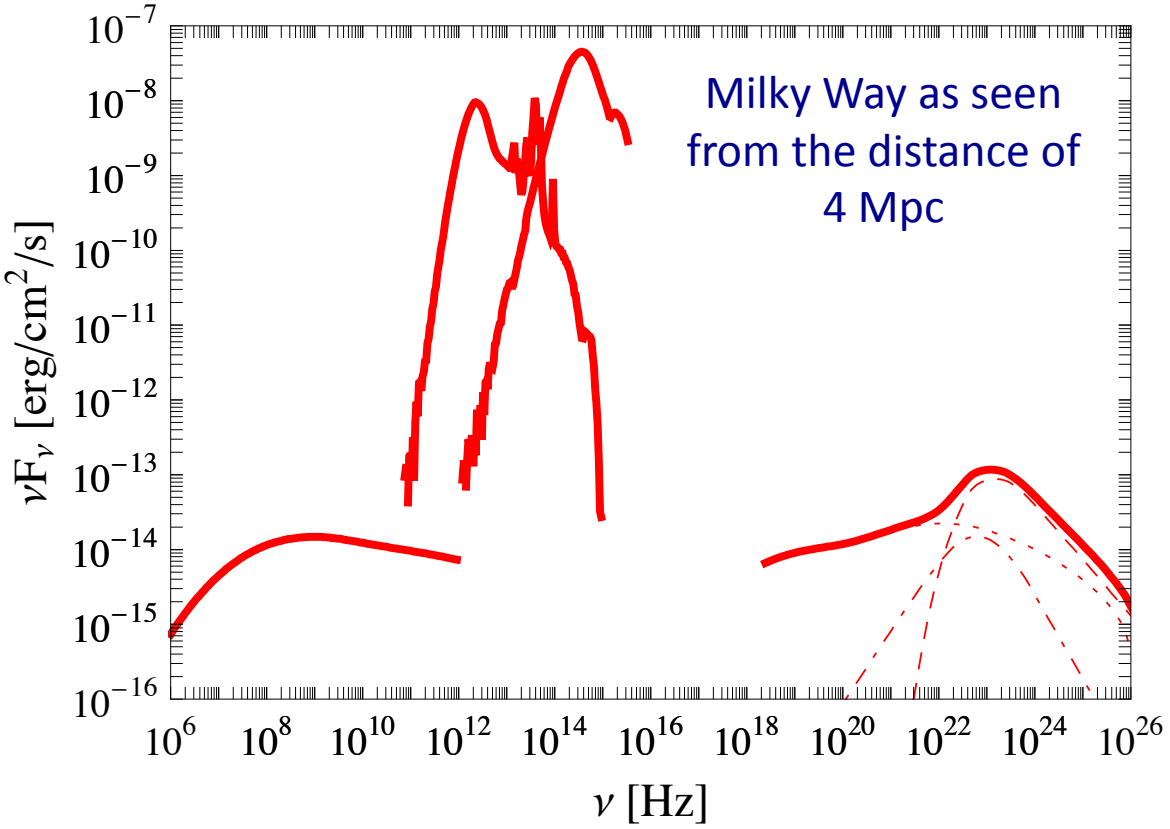
ISAS/JAXA, Japan; Jagiellonian Univ., Poland

Fermi Summer School 2013

# Outline

- Starbursts
- Blazars
- Extended Lobes
- Radio-Quiet AGN?
- Galaxy Clusters
- Gamma-Ray Bursts

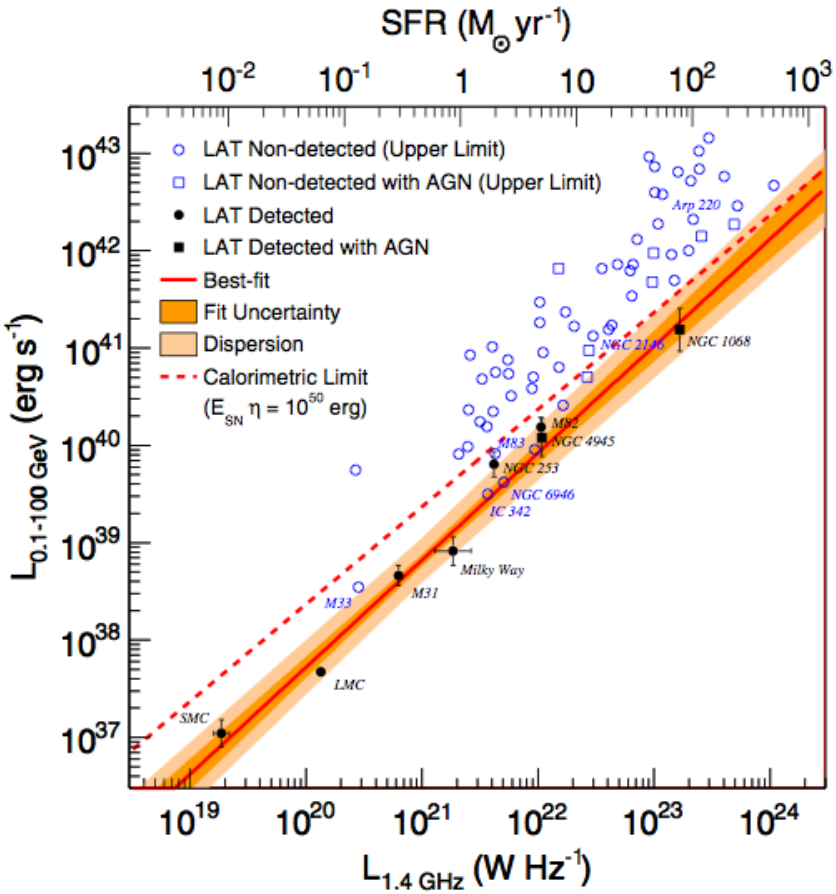
# Starbursts

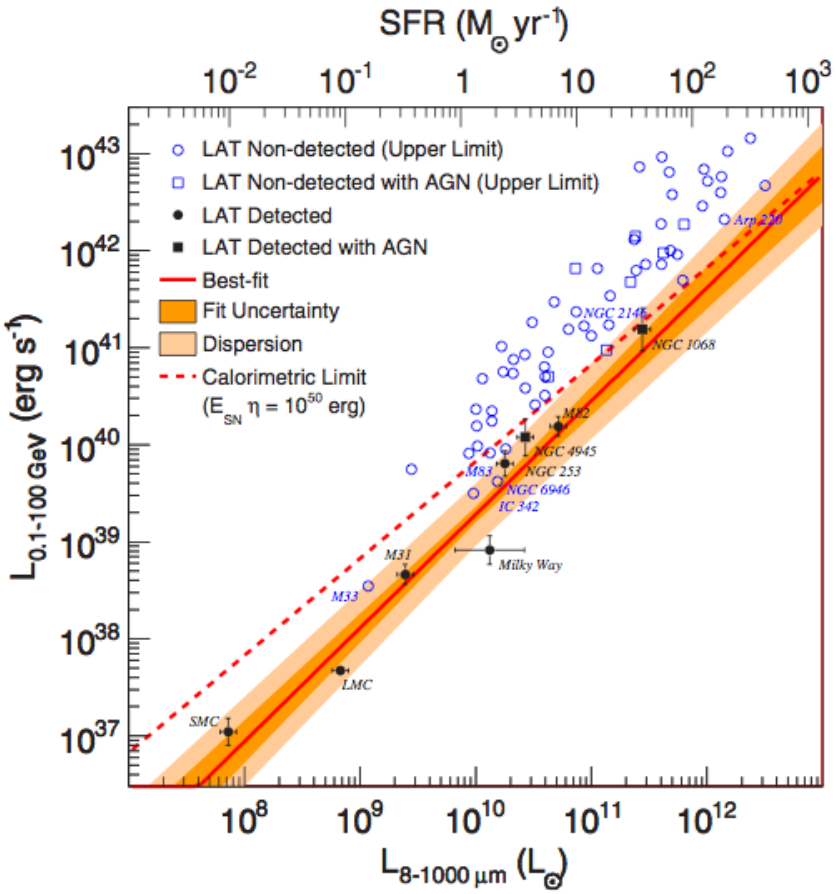



GLAPROP model developed by Moskalenko & Strong (1998) and Strong & Moskalenko (1998). This model assumes injection of a power-law electrons and nuclei by SNRs, and follows their spatial and energy evolution under the influence of different losses processes (Coulomb losses, synchrotron and IC cooling, proton-proton collisions, etc.), taking also into account the relevant interactions of charged particles with the interstellar turbulent magnetic field (with the assumed Kolmogorov spectrum) in a quasi-linear approximation regime.

# Starbursts

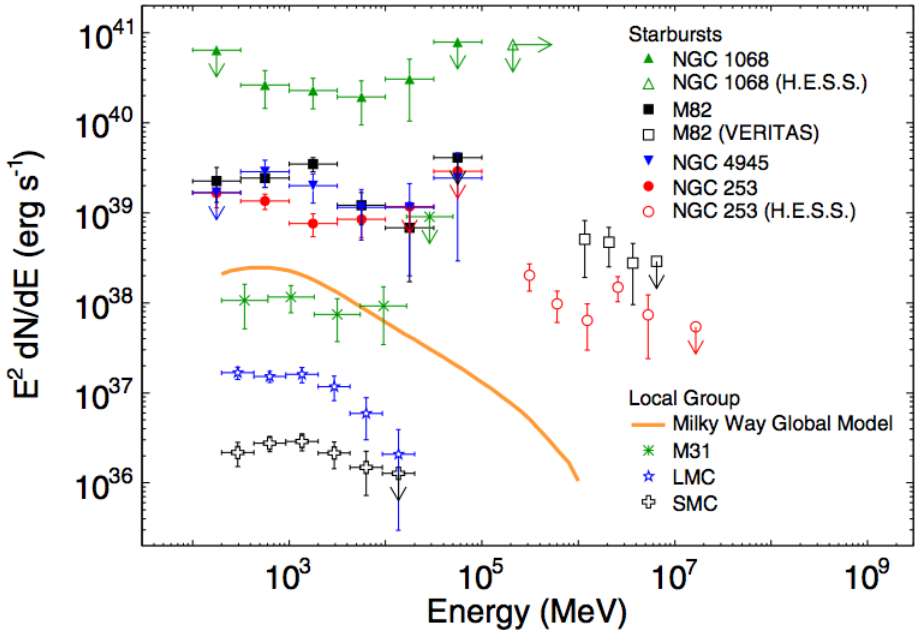
Abdo et al. 2010, ApJL 709, Ackermann et al. 2012, ApJ, 755:
detections of nearby starbursts galaxies with LAT, together the observations of Local Group galaxies, suggest a scaling between different tracers of the starformation rate and $L_\gamma$ .

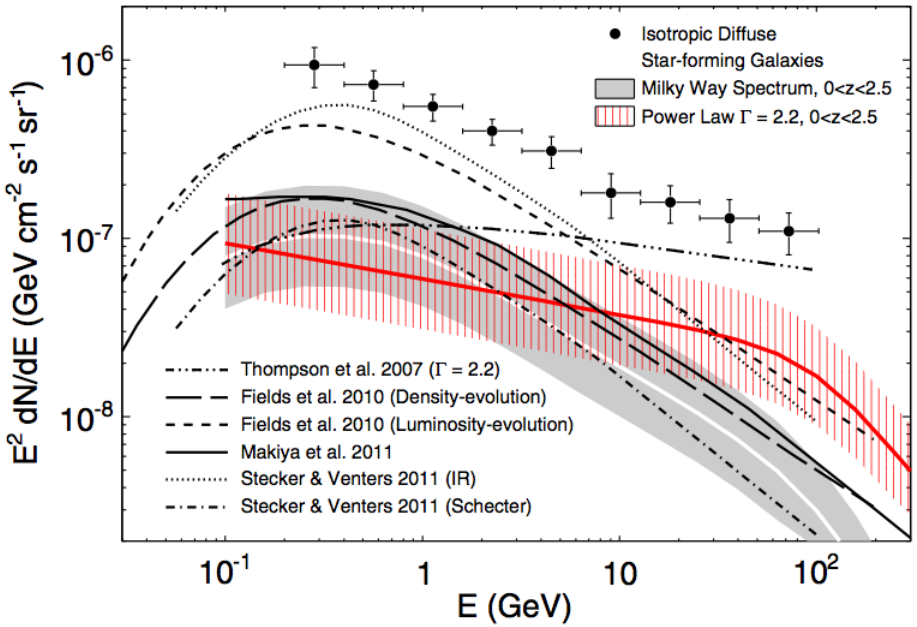


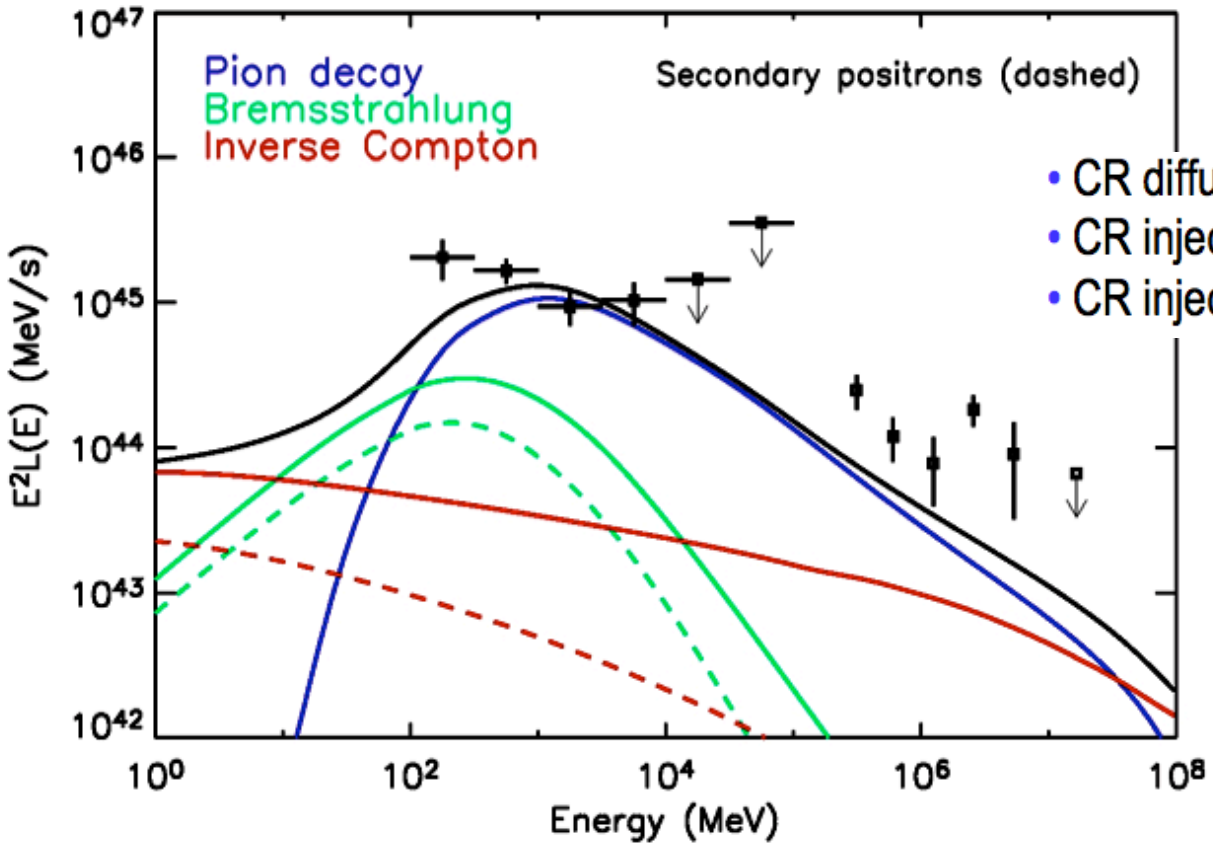
# Starbursts

Ackermann et al. 2012, ApJ, 755: starforming and starbursts systems may contribute to the unresolved extragalactic gamma-ray background at the level 5% - 25%.



# Starbursts

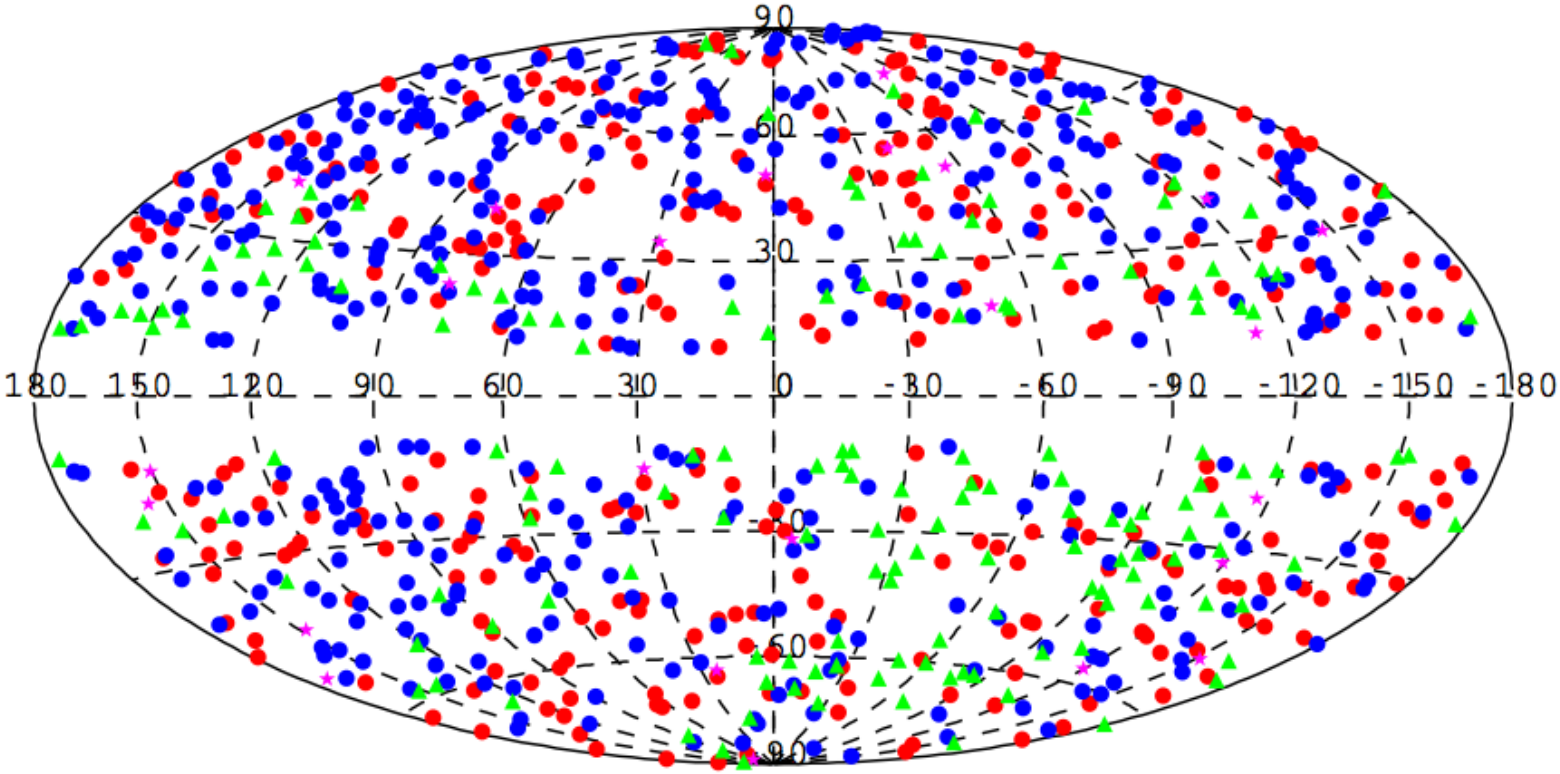



- CR diffusion as in MW
- CR injection spectra as in MW
- CR injection luminosity is 2.0x the MW value

*The case of NGC 253 (from a presentation by Pierrick Martin)*

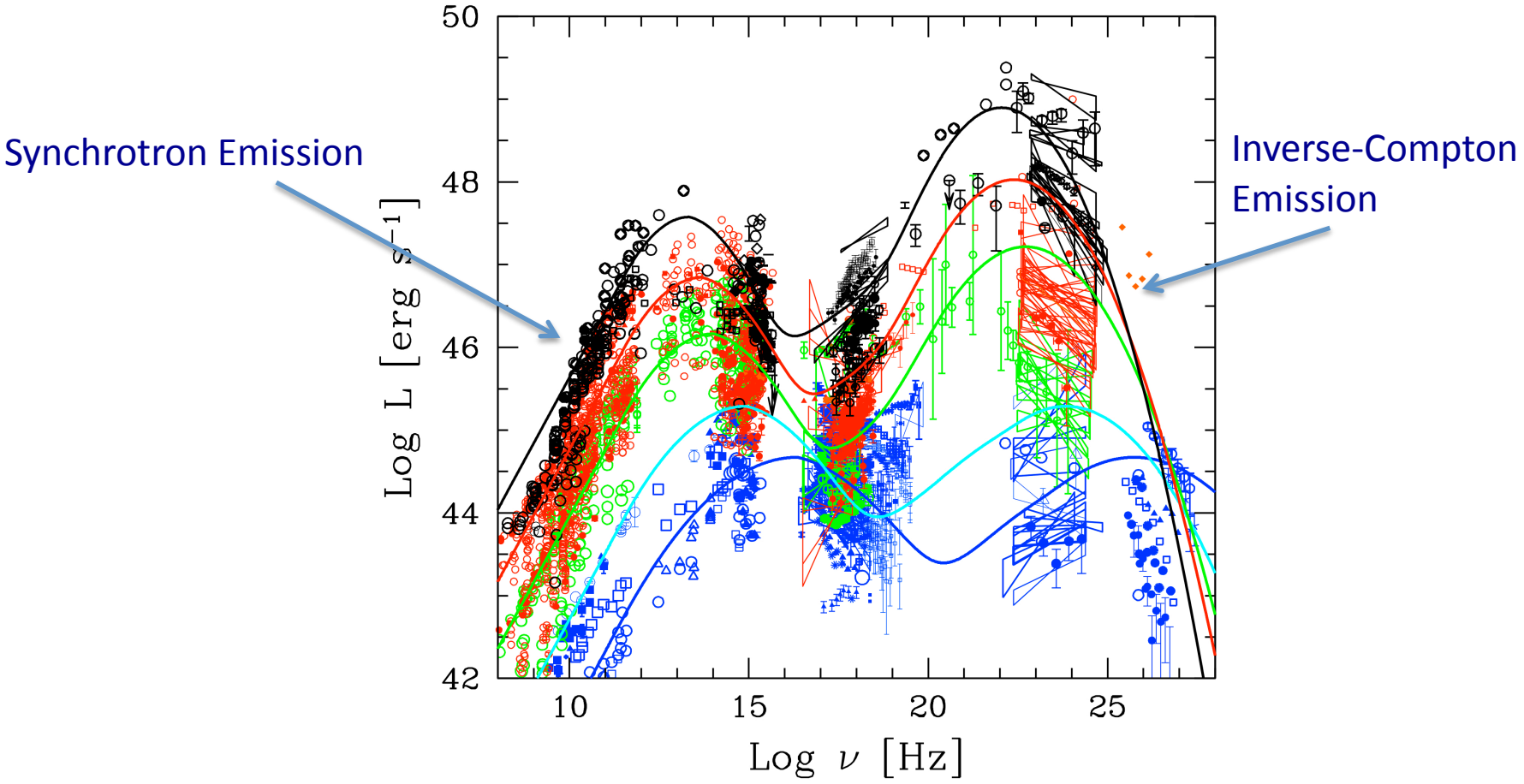
Energy spectra of CRs in other starforming galaxies detected in the GeV and TeV ranges are flatter than expected based on the GALPROP modeling

# Blazars



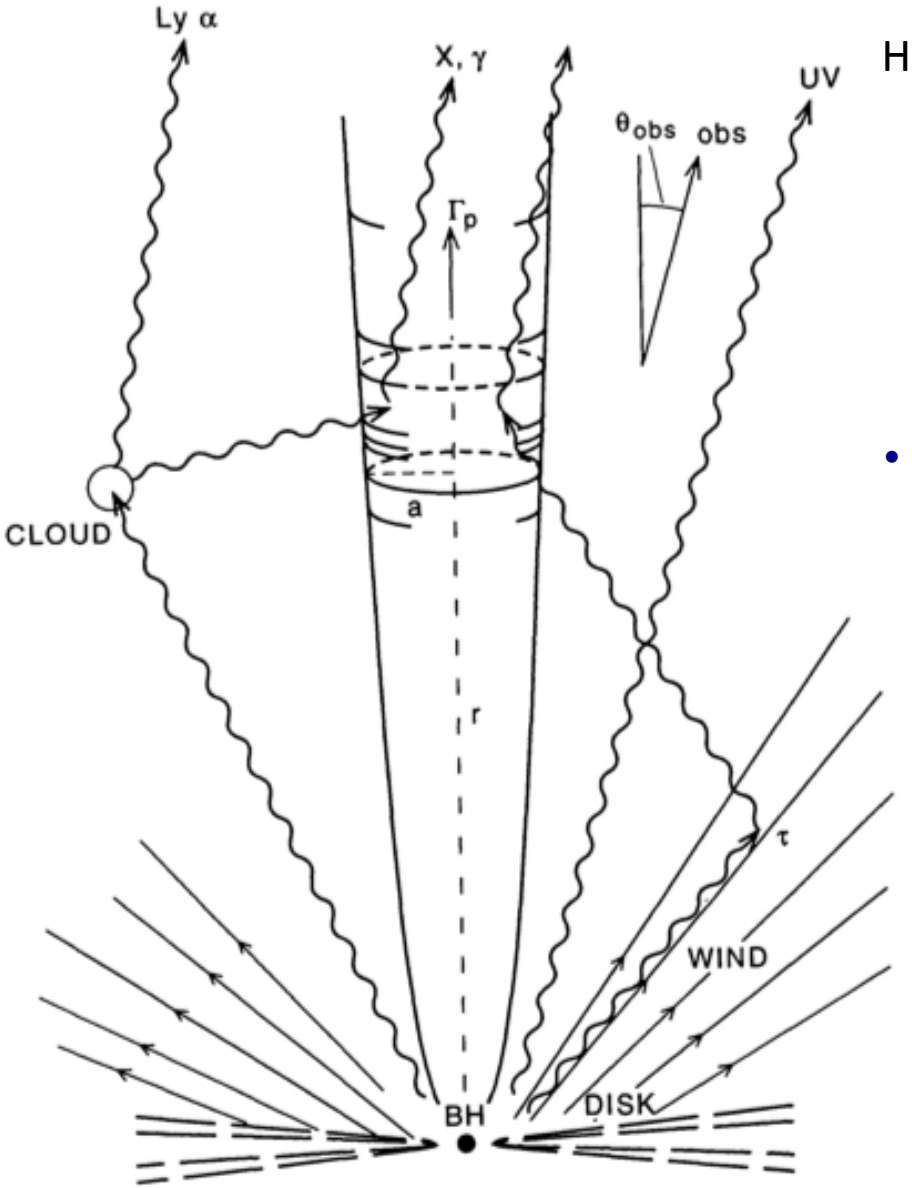

Ackermann et al. 2011, ApJ 743: The second LAT AGN Catalog (2LAC) corresponds to 24 months of data collected in scientific operation mode; includes 1016 sources located at high Galactic latitudes (|b|>10°) that are detected with a test statistic greater than 25 and associated statistically with active galaxies; there are 885 AGN in a "clean sample" comprising 395 BL Lacs, 310 flat-spectrum radio quasars, 22 AGN of other types, and 156 AGN of unknown type.

# Blazars



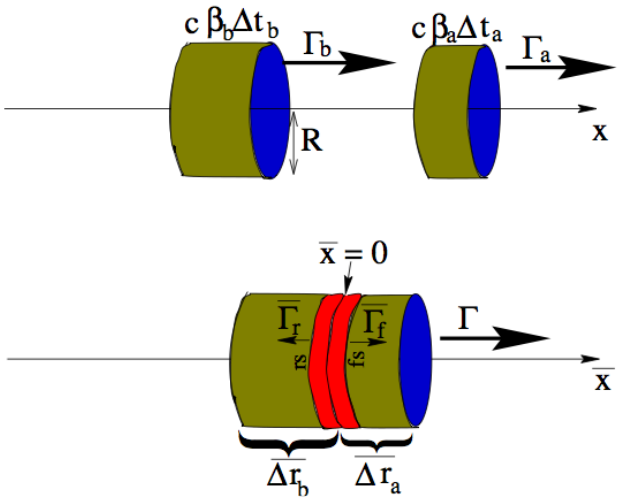

Blazars: BL Lacertae objects and Flat Spectrum Radio Quasars

# Blazars

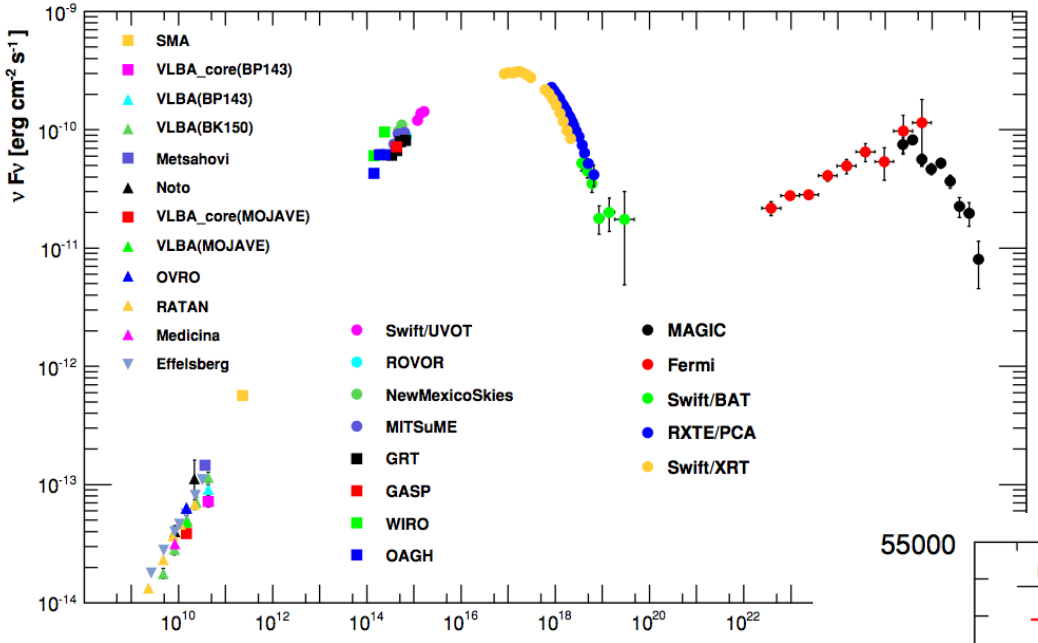


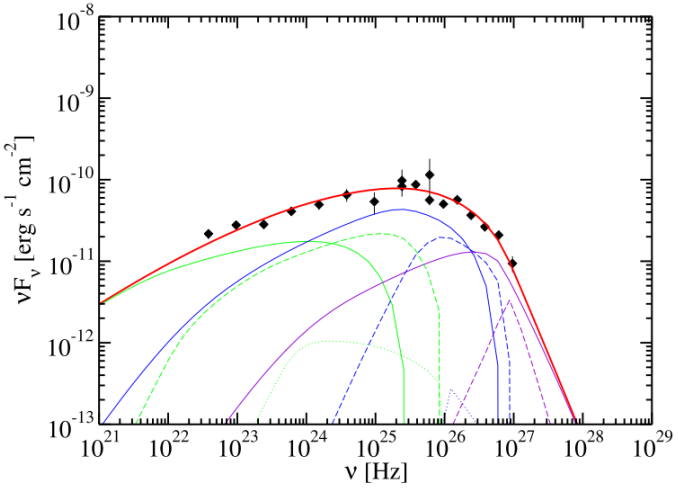

Homogeneous one-zone leptonic models; internal shocks scenario (e.g., Sikora et al. 1994)

- very successful in explaining many observed properties of blazar sources;
- location of the blazar emission zone rather uncertain (from <0.01pc up to >1pc);
- many underlying assumptions (e.g., acceleration process injecting power-law spectrum of the radiating electrons).



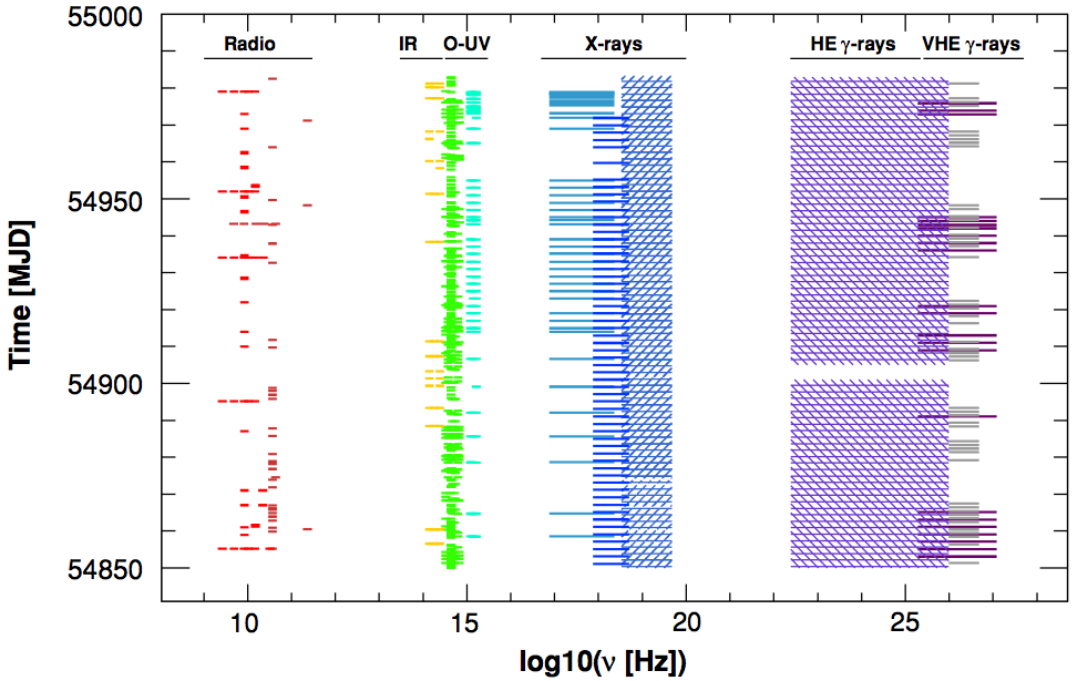
# Blazars



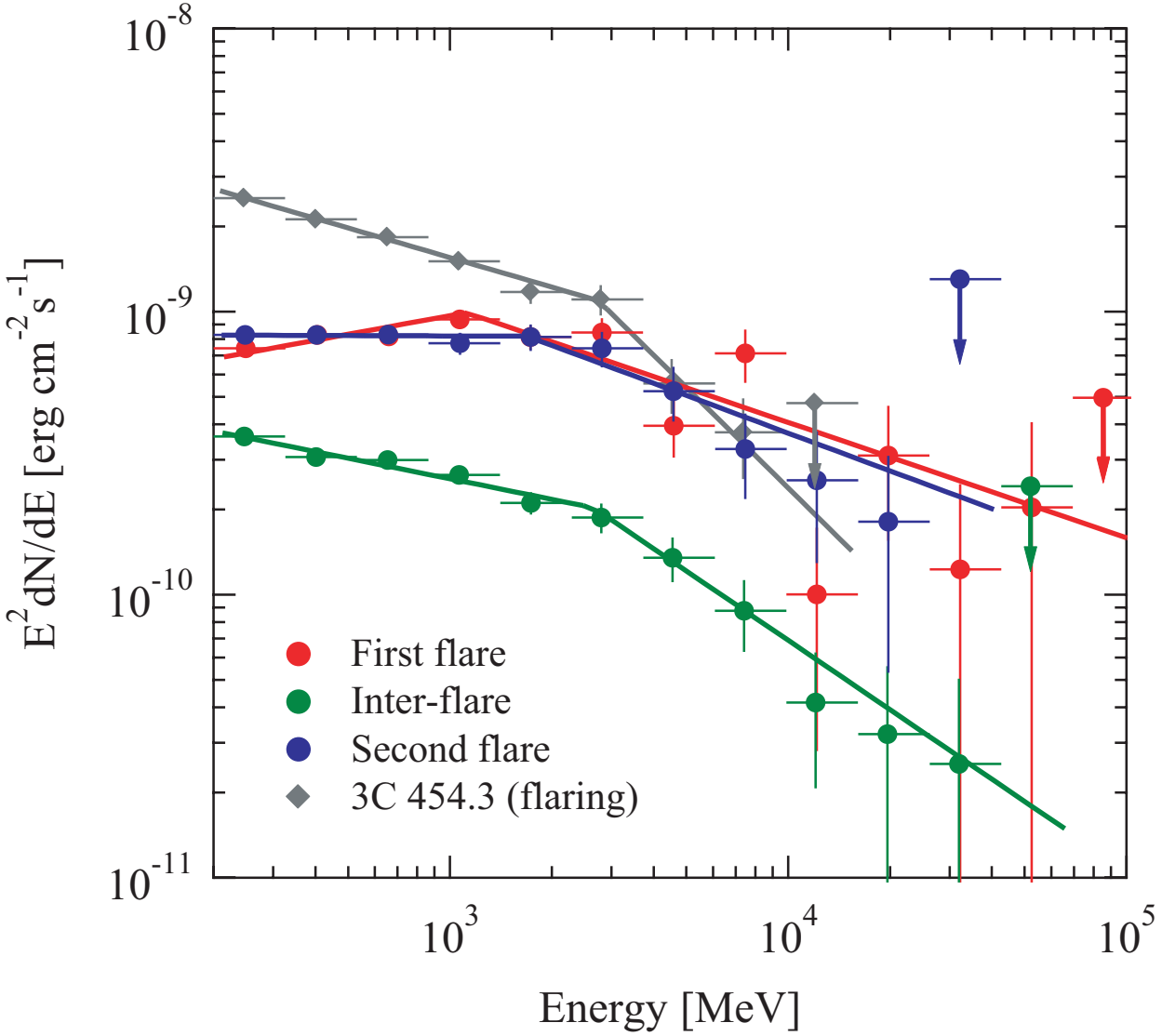




Abdo et al. 2011, ApJ, 727, 736:

MWL Campaigns on bright TeV blazars **Mrk 421** and **Mrk 501** and the averaged broad-band spectra



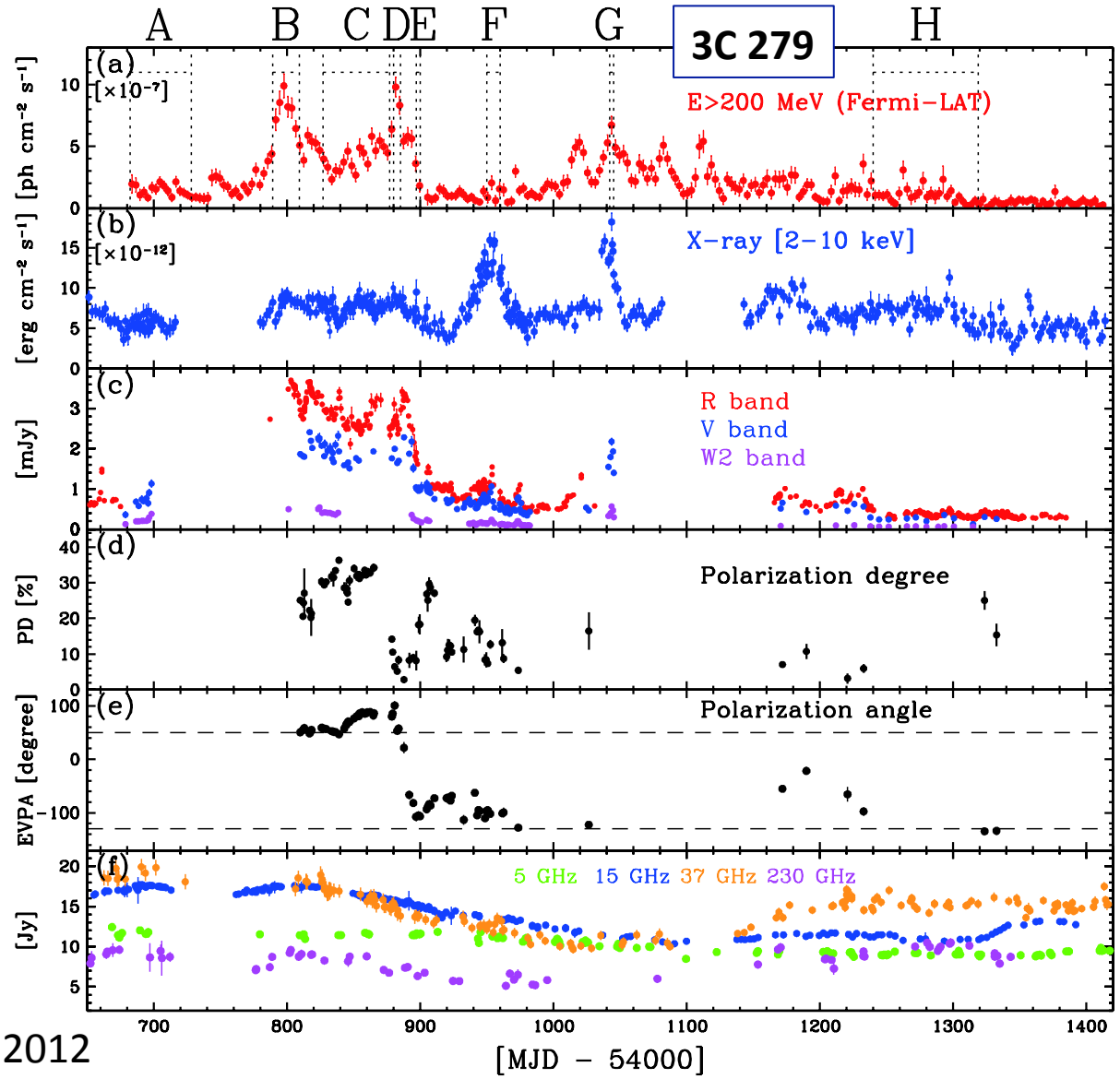
# Blazars




Tanaka et al. 2011
PKS 1222+216

Break consistent with annihilation of the GeV photons on HI and HeII Lyman recombination continuum and line emission inside the zone of the highest ionization of the broad line region, within 0.1 pc (see Poutanen & Stern 10).

# Blazars

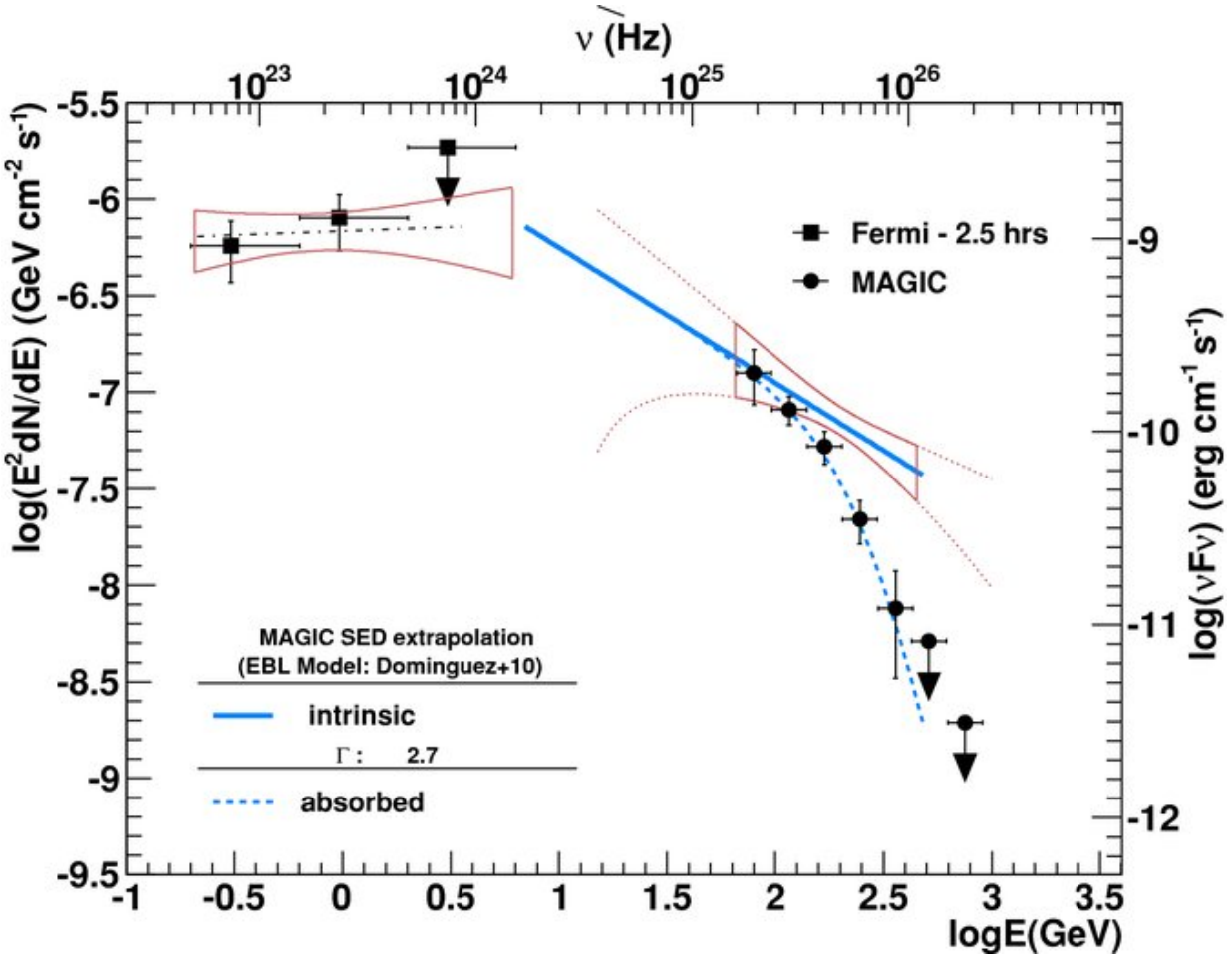



???

???

Hayashida et al. 2012

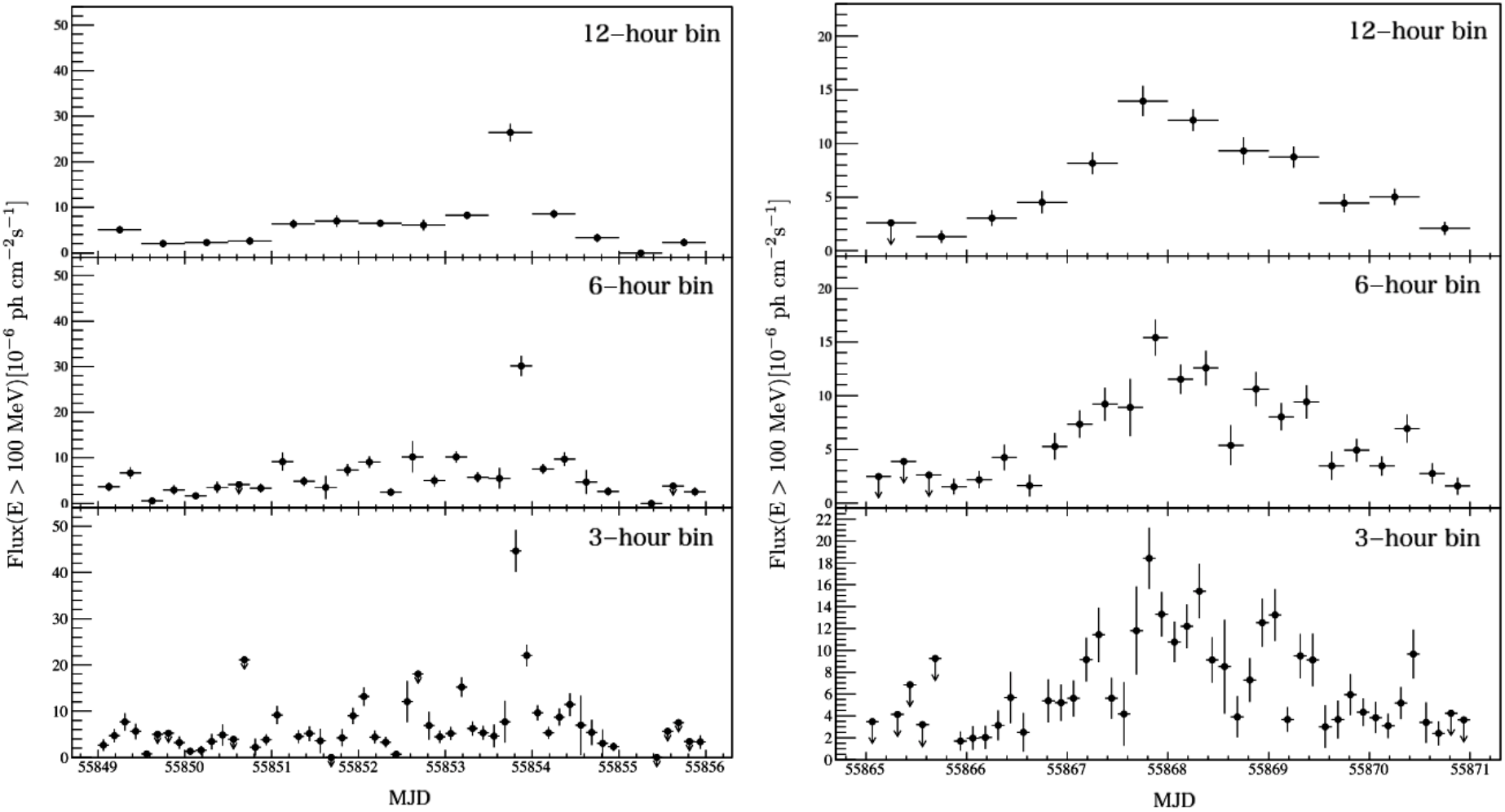
# Blazars




Aleksic et al. 2011

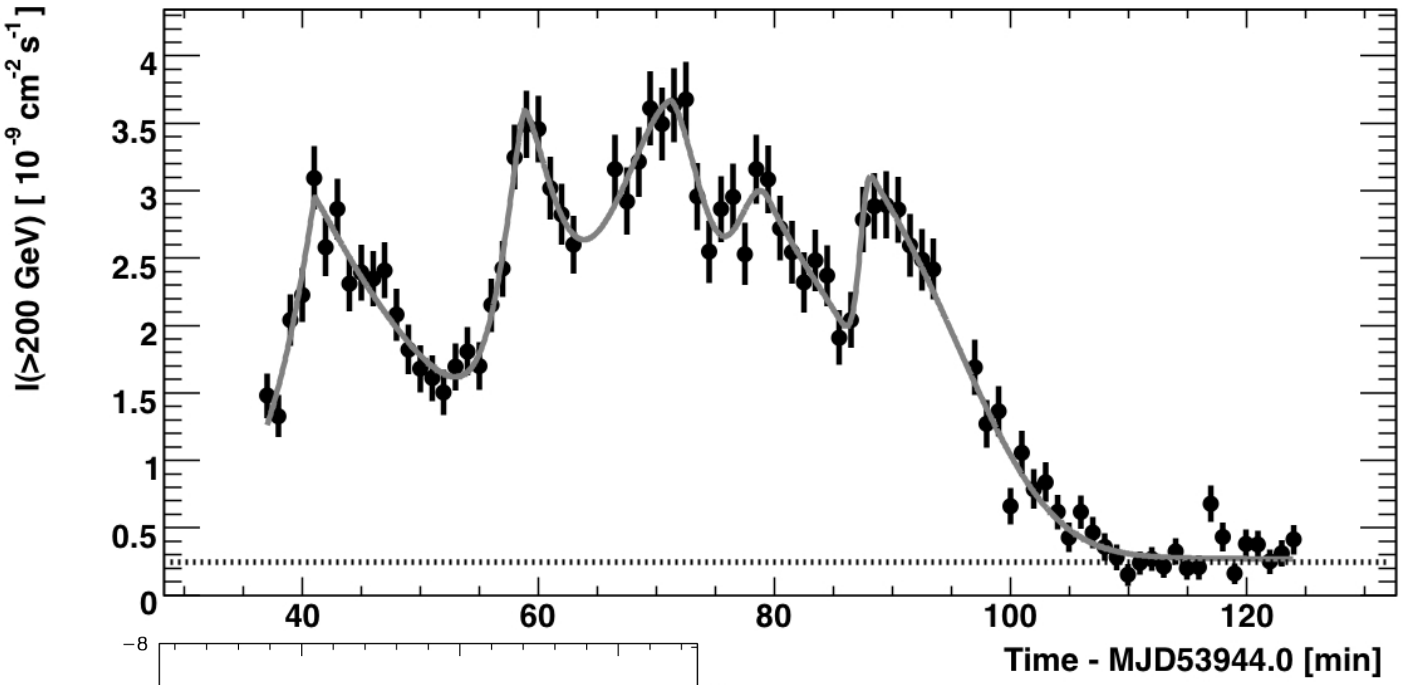
$$\tau_{\gamma\gamma}(1\,\mathrm{TeV}) \simeq \frac{\sigma_{\mathrm{T}}\,\xi_{\mathrm{HDR}}\,L_{\mathrm{disk}}}{12\pi\,R_{\mathrm{HDR}}\,c\,E_{\mathrm{HDR}}} \sim 100\left(\frac{\xi_{\mathrm{HDR}}}{0.1}\right)$$

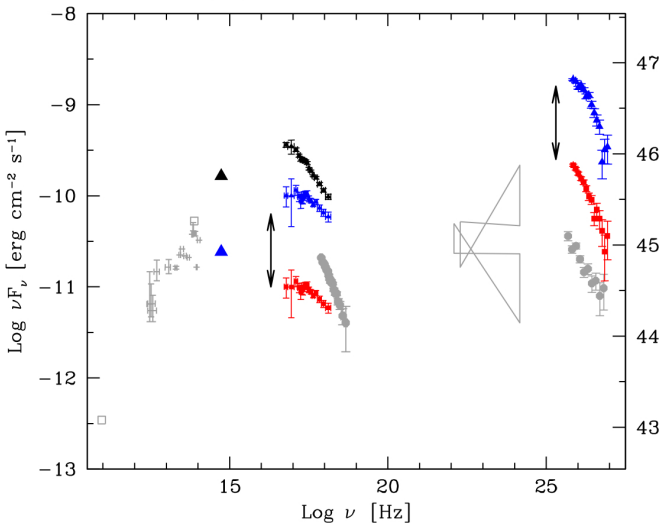
# Blazars




Saito et al. 2013: flux doubling timescale <1h implies huge power dissipated radiatively within very compact emission regions ~$10^{15}$ cm ~ $\Gamma_j \times R_g$.

# Blazars

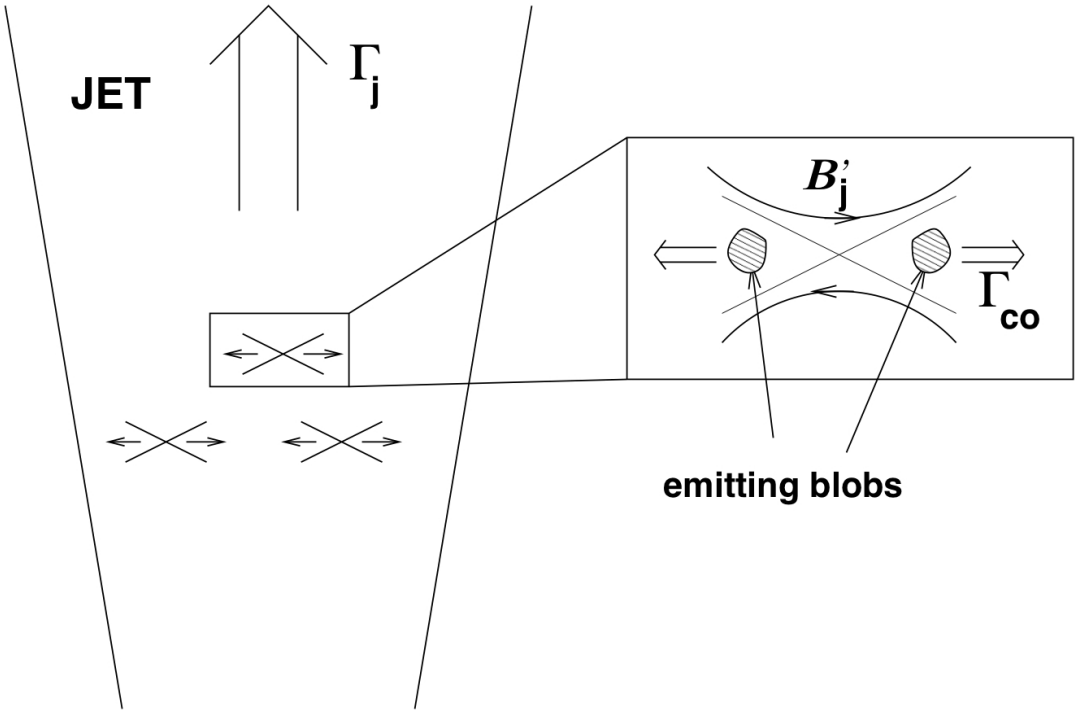


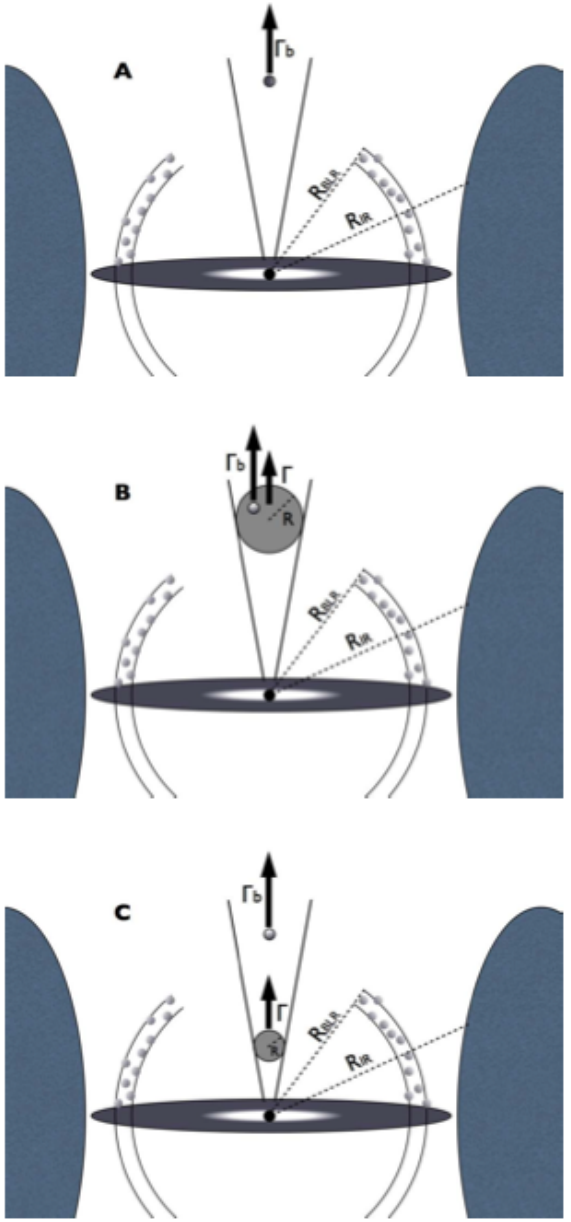




Aharonian et al. 2007/09:

TeV variability of BL Lac-type blazar PKS 2155-304 with flux doubling timescale, $t_{var}$ ~ 200 s…

# Blazars



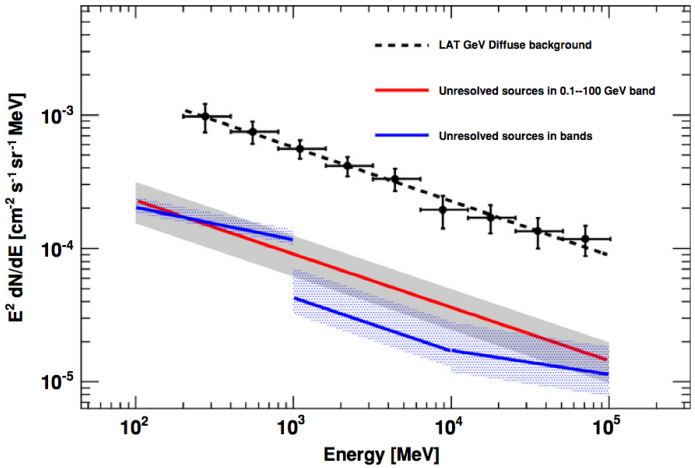

Structured jet models (Giannios et al. 2009, Tavecchio et al. 2011, etc., etc., etc.).

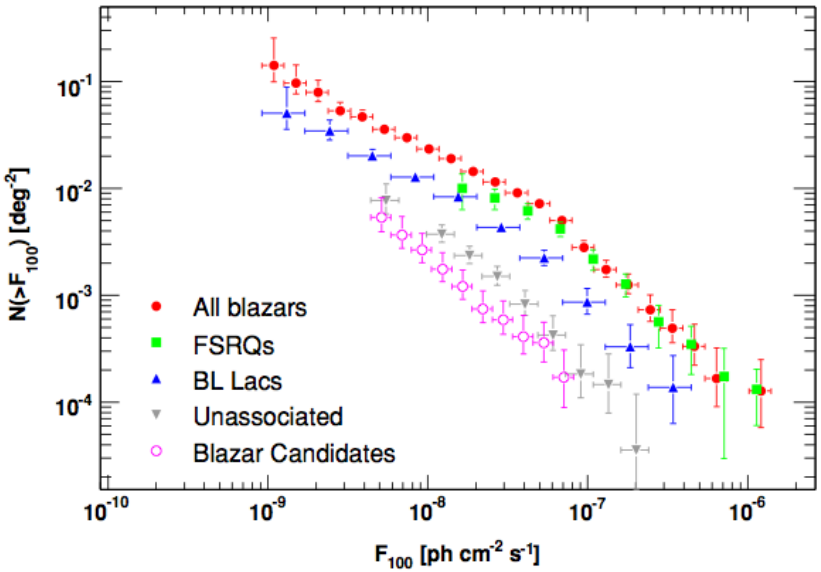
Magnetic reconnection? Turbulent (stochastic) acceleration?

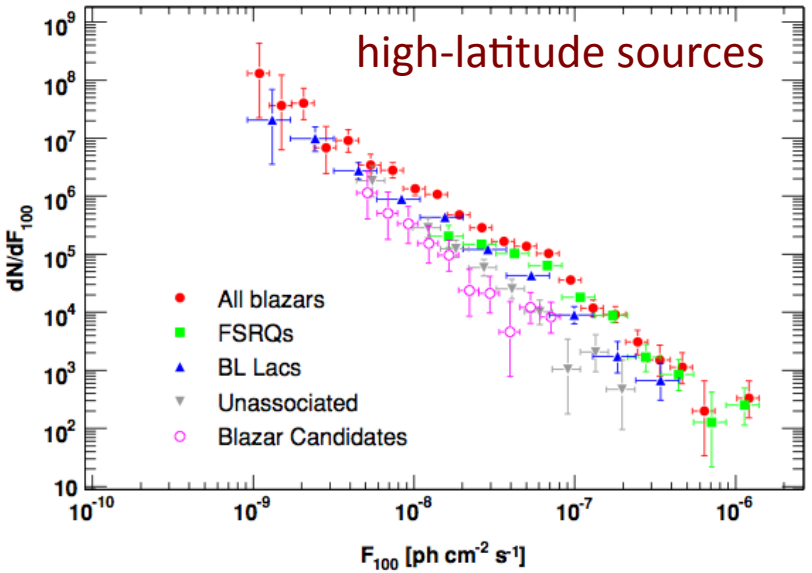
# Blazars

Abdo et al. 2010, ApJ 720:

- Fermi is already sampling the part of the blazar luminosity function that shows negative evolution;
- most of the unassociated high-latitude sources are likely to be blazars (dN/dS analysis);
- The average intrinsic spectrum of blazars is in a good agreement with the spectrum of EGB.
- Blazars may account only for <40% of the extragalactic background (see also anisotropies in the EGB, Ackermann et al. 2012, PRD 85)

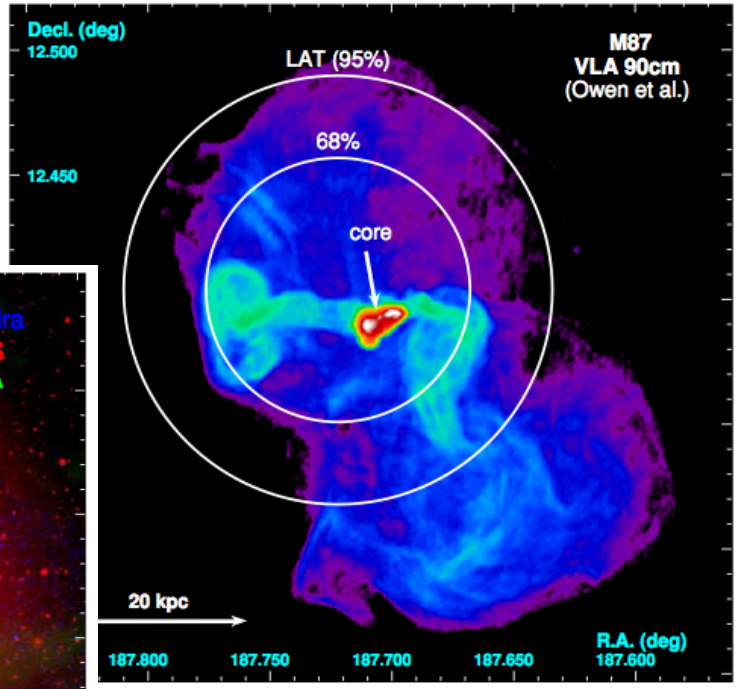


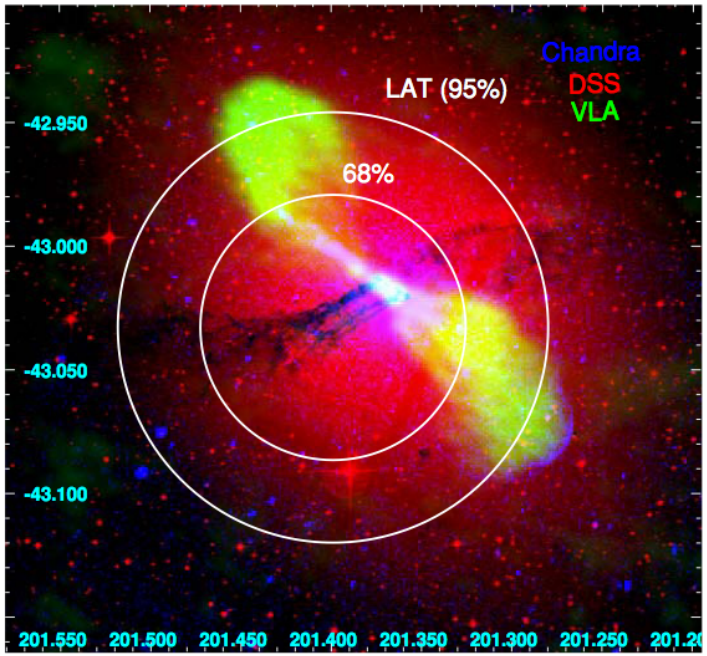



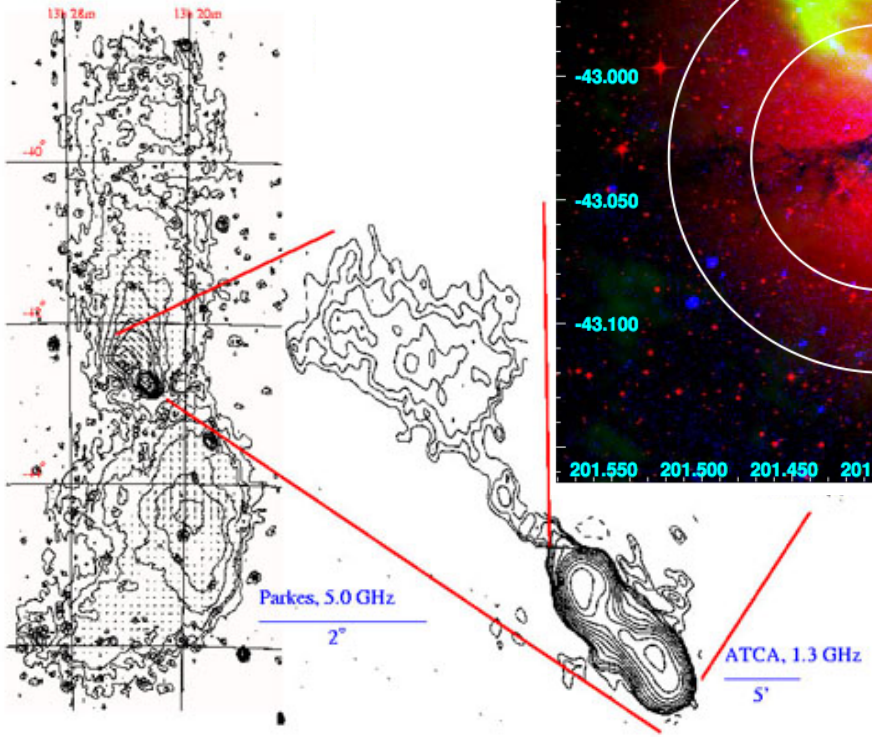



# Extended Lobes

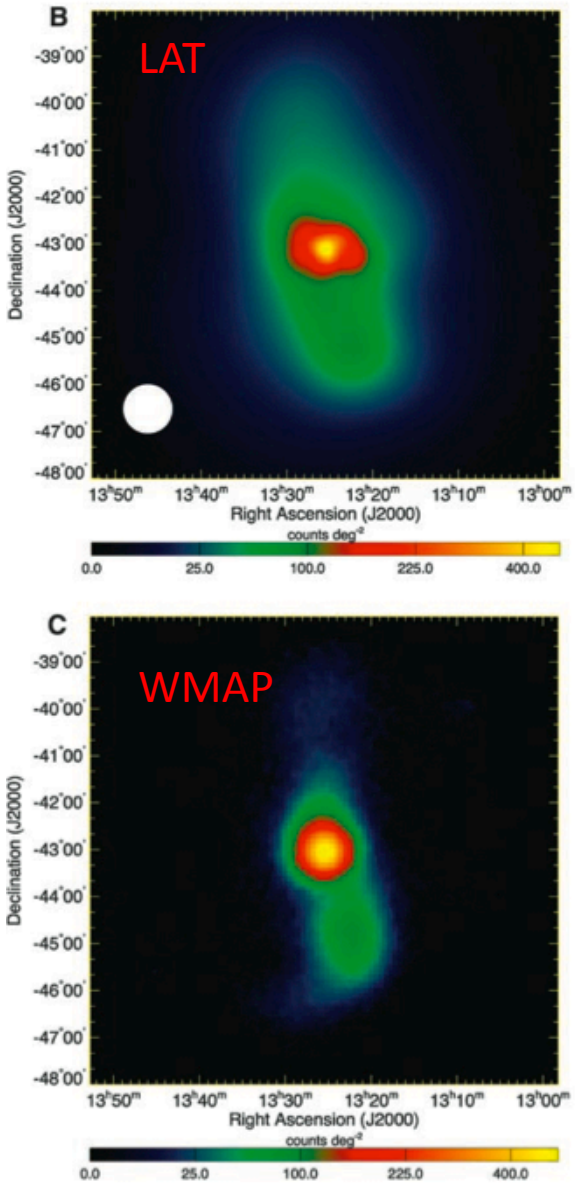
Abdo et al. 2009/10, ApJ 699, 707, 719, 720:
Famous radio galaxies (e.g., **M87, Centaurus A**) detected with LAT



# Extended Lobes

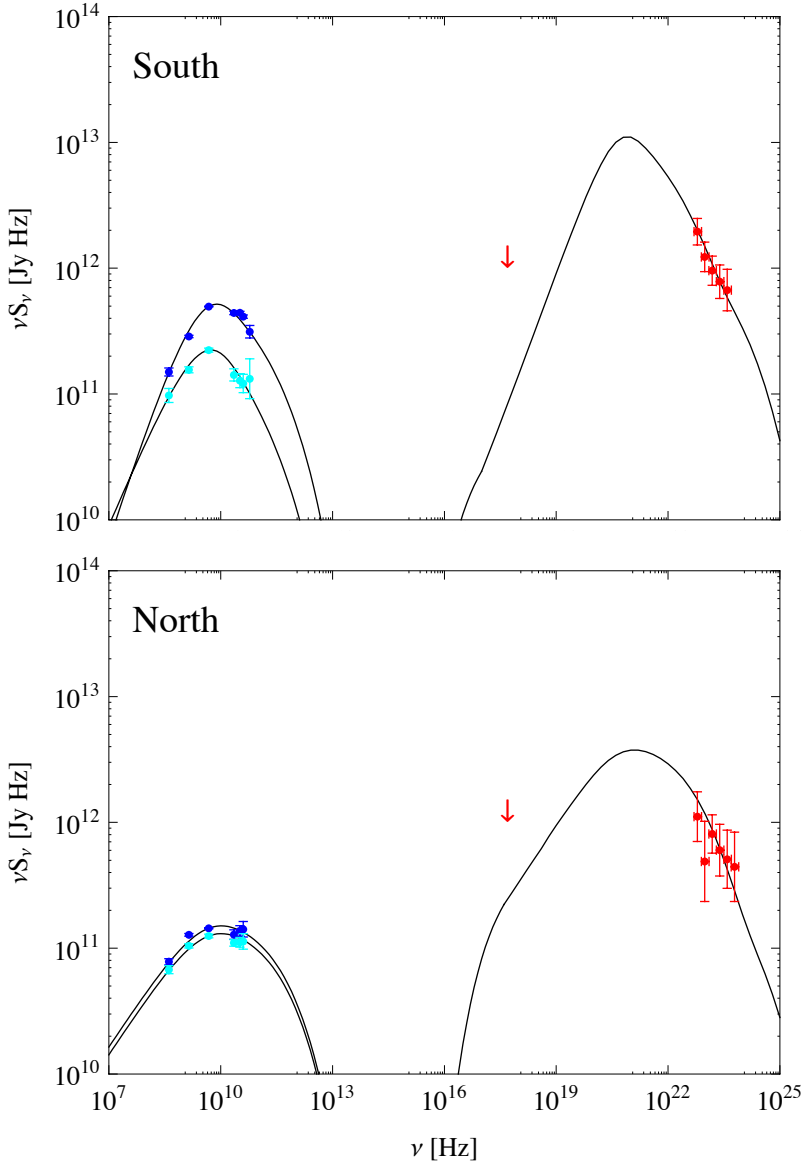



Abdo et al. 2010, Science 328:
Fermi-LAT resolves giant lobes
of the radio galaxy **Cen A**.

~100 times larger than Fermi Bubbles!

LAT observations imply that the lobes contribute ~50% of the GeV luminosity of the system, are in a pressure equilibrium between radiating electrons and magnetic field, and are the sites of in-situ particle acceleration (see also Yang et al. 2012)

# Extended Lobes

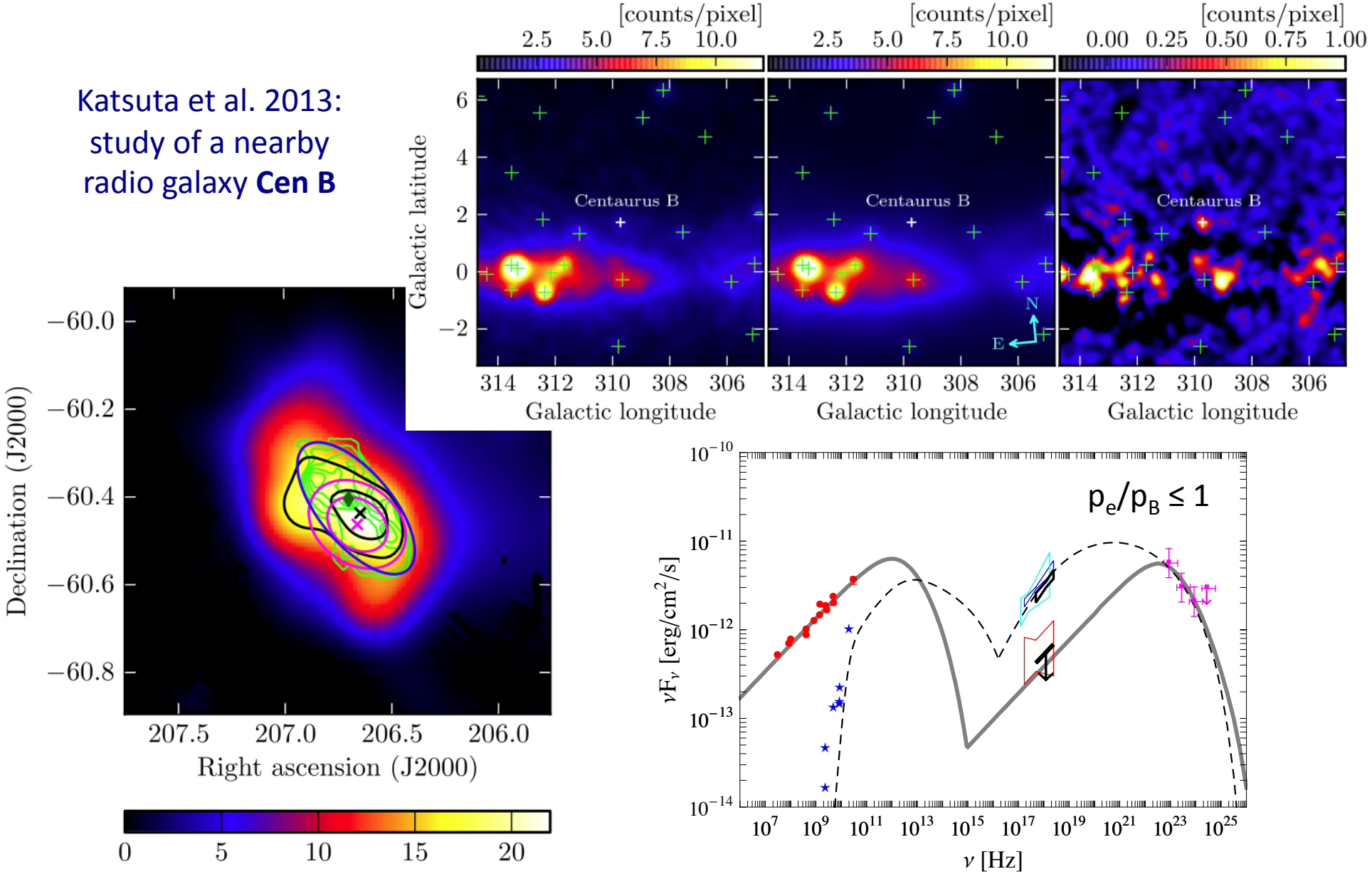




B ~ 1 μG

$p_e/p_B$ ~ 1

# Extended Lobes

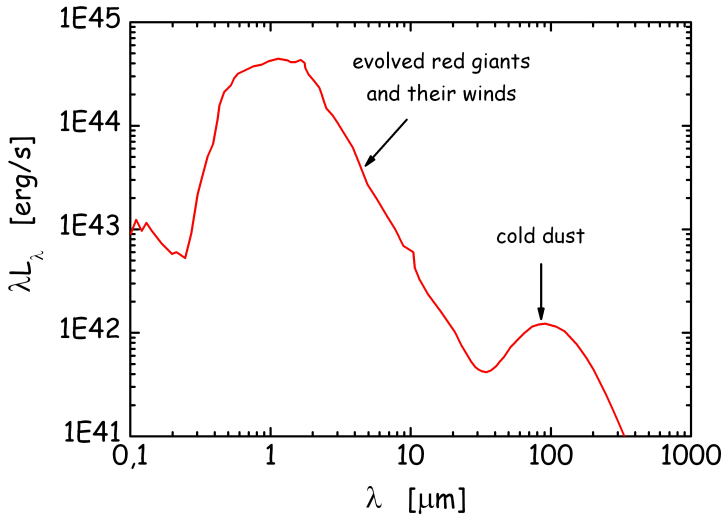
Katsuta et al. 2013:
study of a nearby
radio galaxy **Cen B**

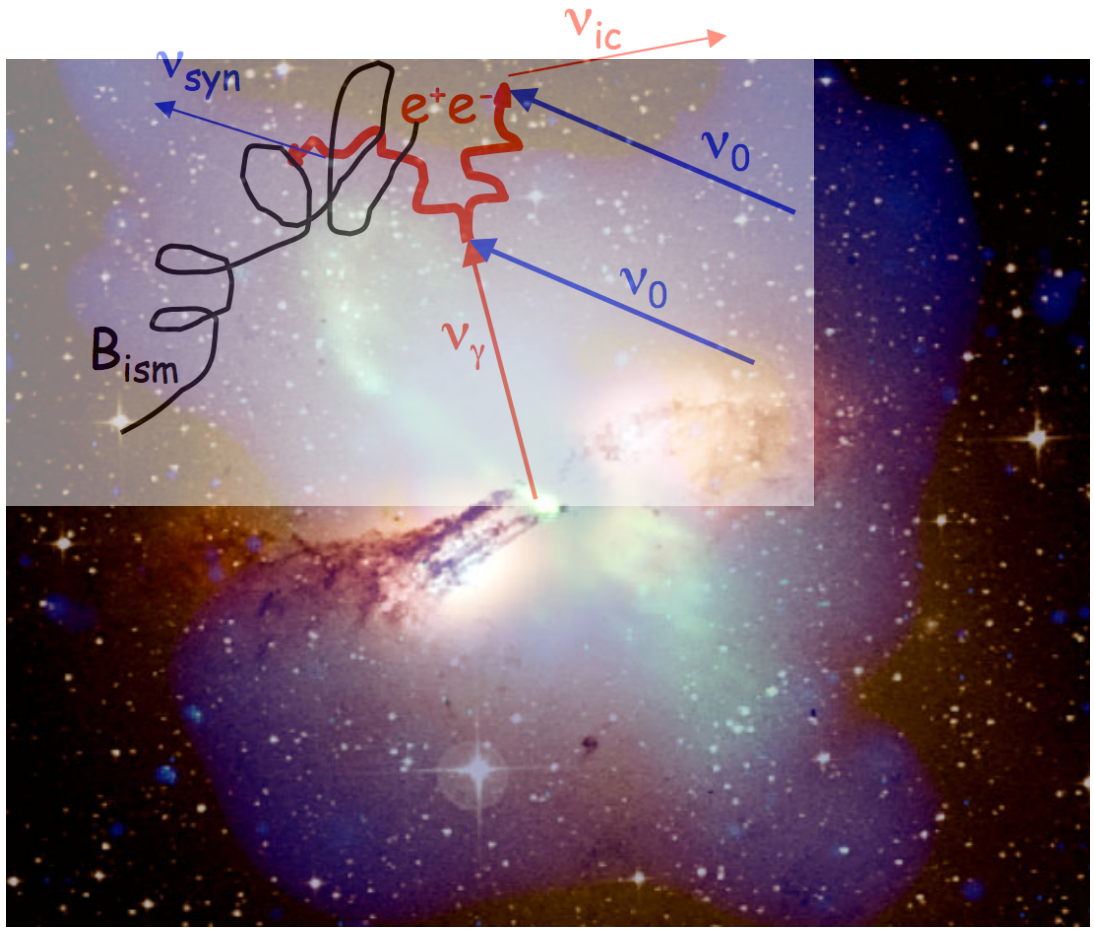


# Extended Lobes

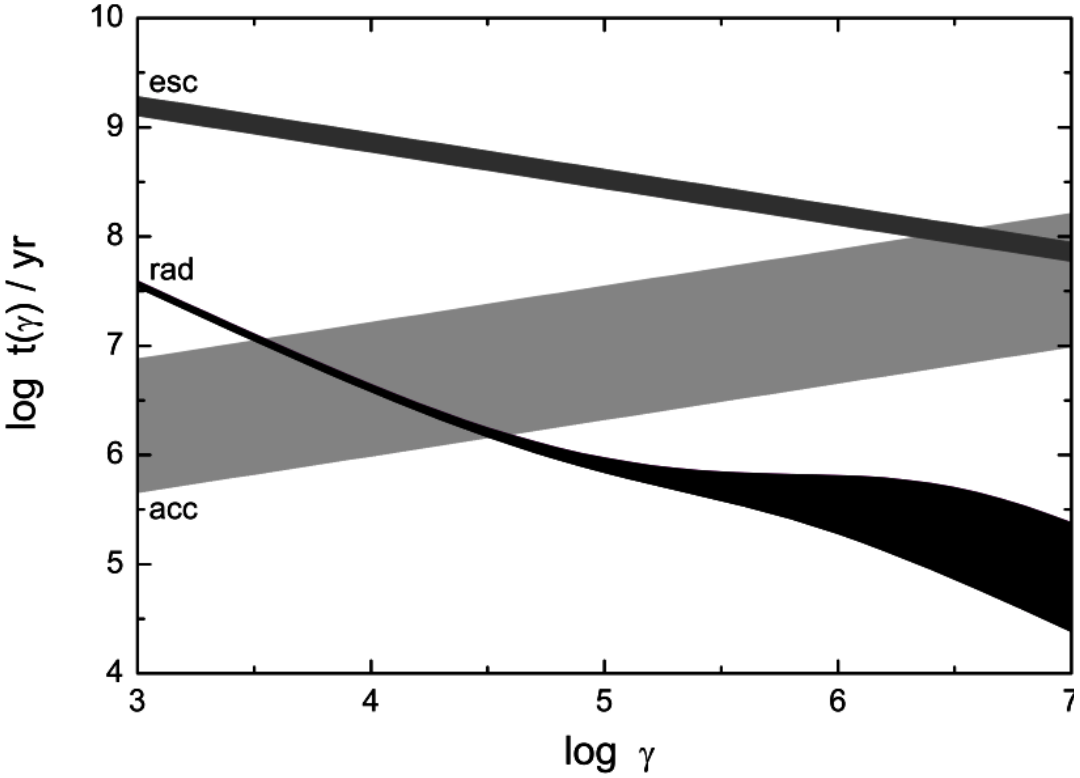
LS et al. 2006:

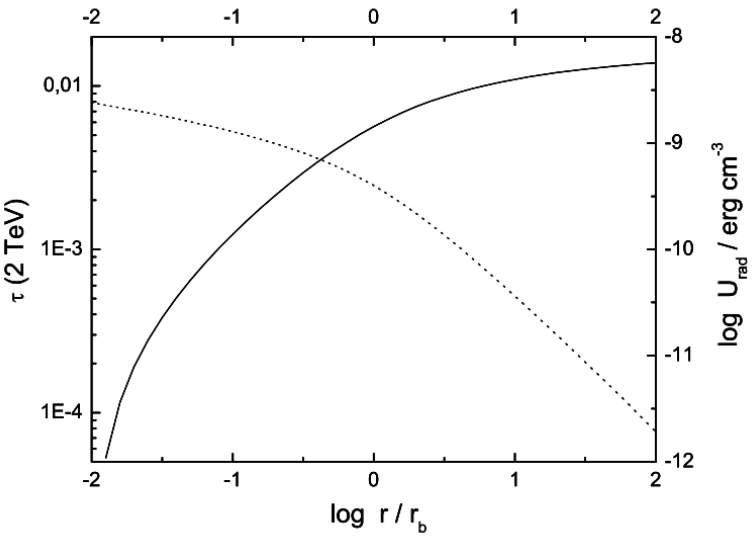
Absorption of TeV photons in radio-loud AGN by starlight of elliptical hosts ($\tau \sim 0.01$).

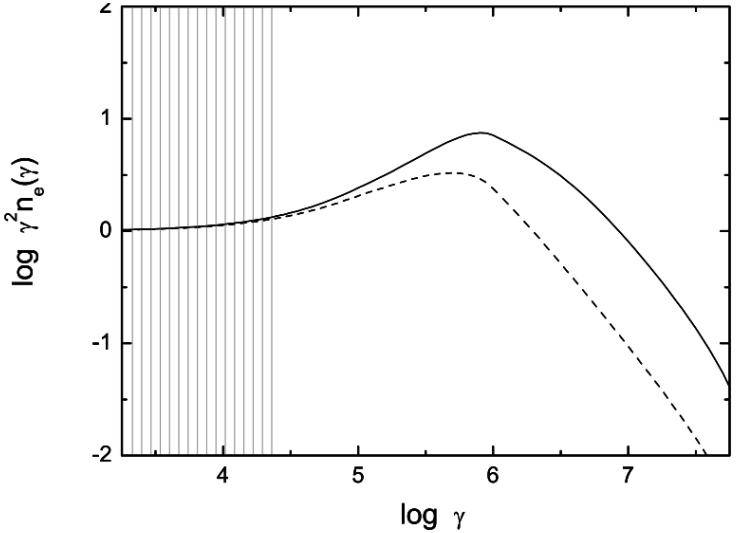


# Extended Lobes

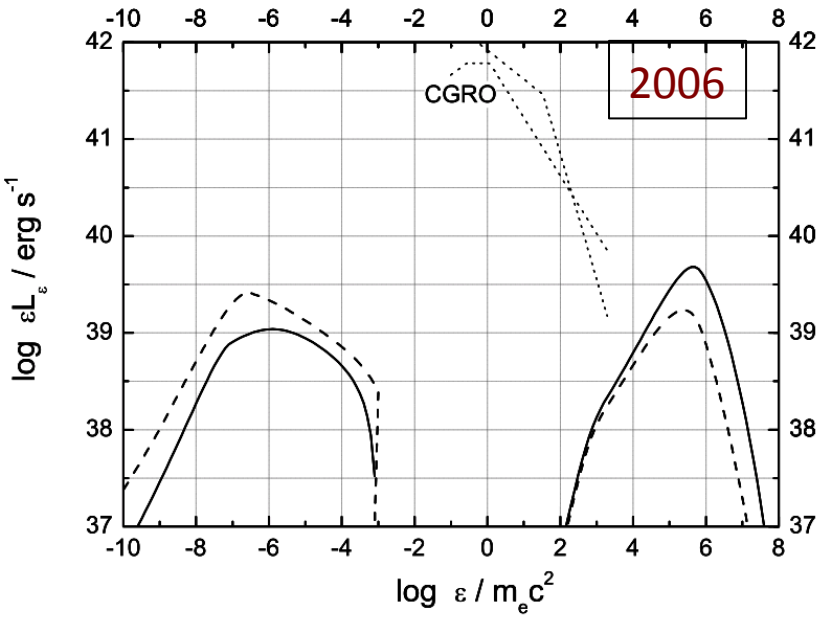


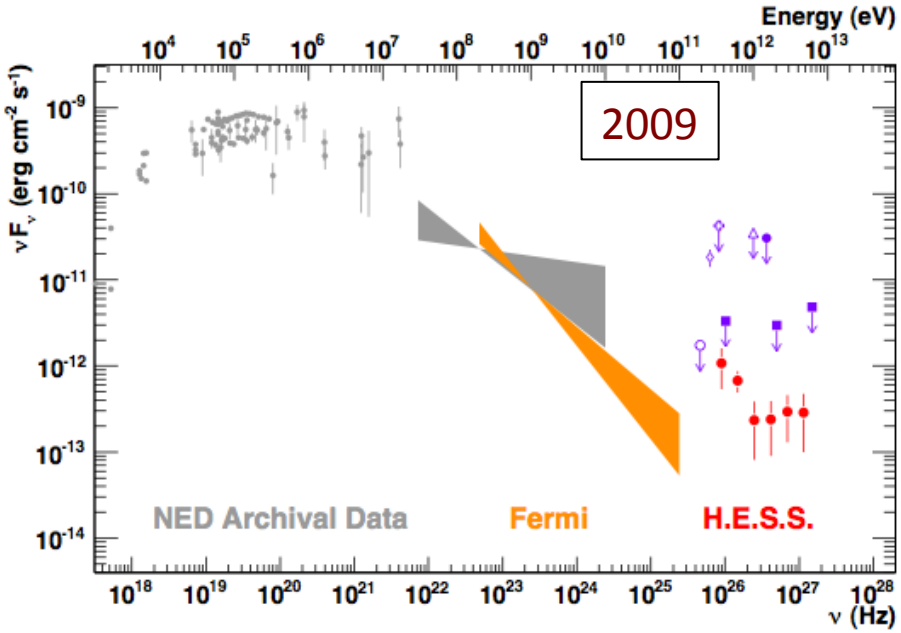




Created ~TeV energy e± pairs are isotropized by the ISM magnetic field before they cool radiatively (predominantly in the KN regime)

# Extended Lobes

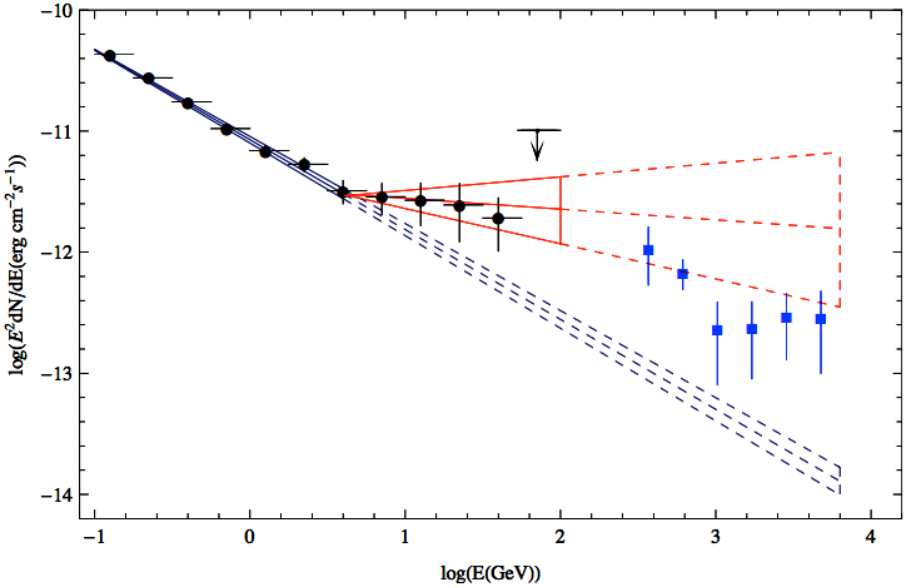



Theoretical prediction for an isotropic kpc-scale pair halos in elliptical host of Cen A

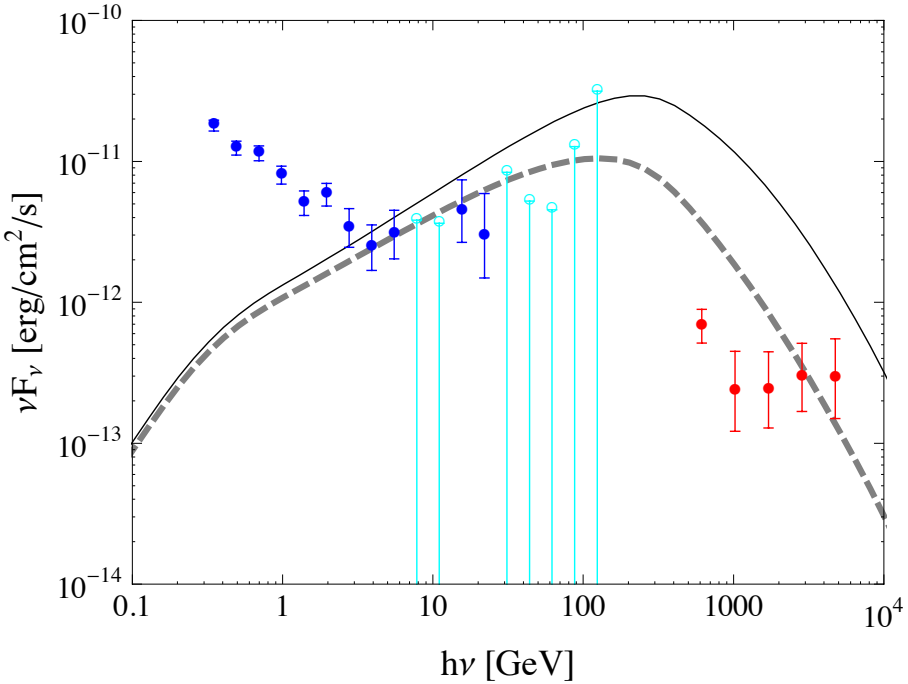



Broad-band γ-ray spectrum of the central regions of Cen A system after the HESS and Lat detections

# Extended Lobes




Sahakyan et al. 2013:
Reanalysis of the LAT data for the Centaurus A nucleus

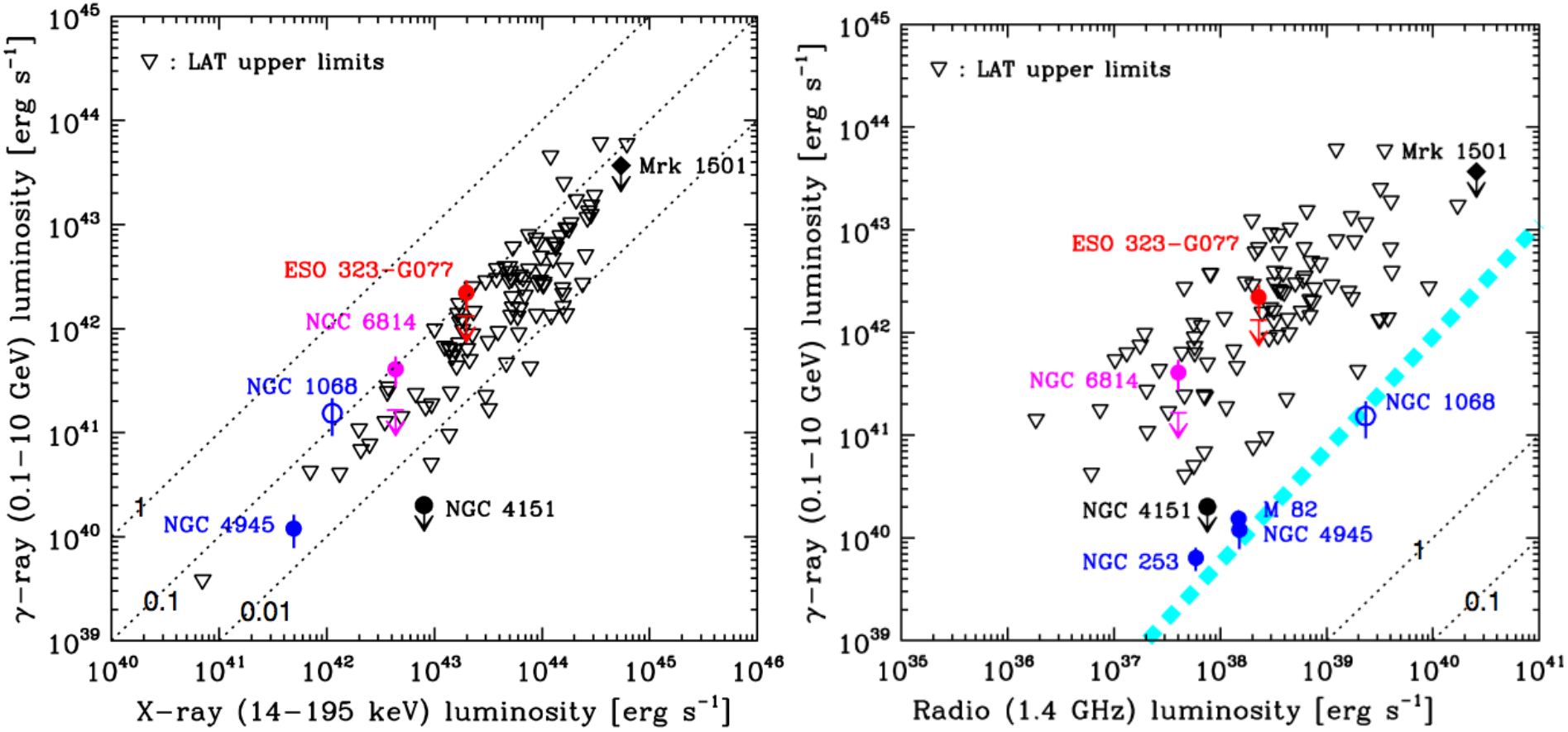



Our previous reanalysis of the LAT data for the Centaurus A nucleus together with the model lines from LS et al. 2006

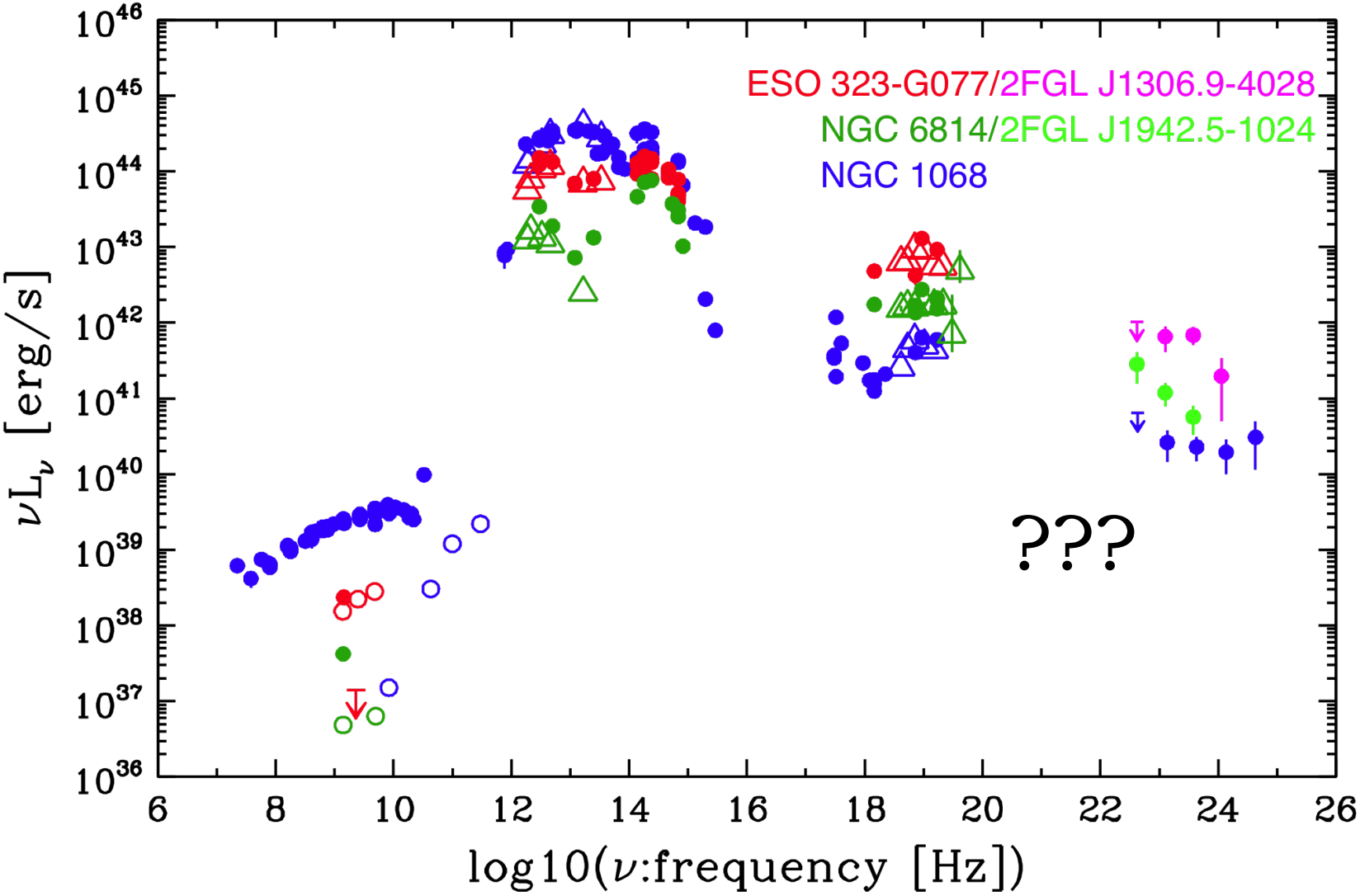
# Radio-Quiet AGN?

Ackermann et al. 2012, ApJ, 747:

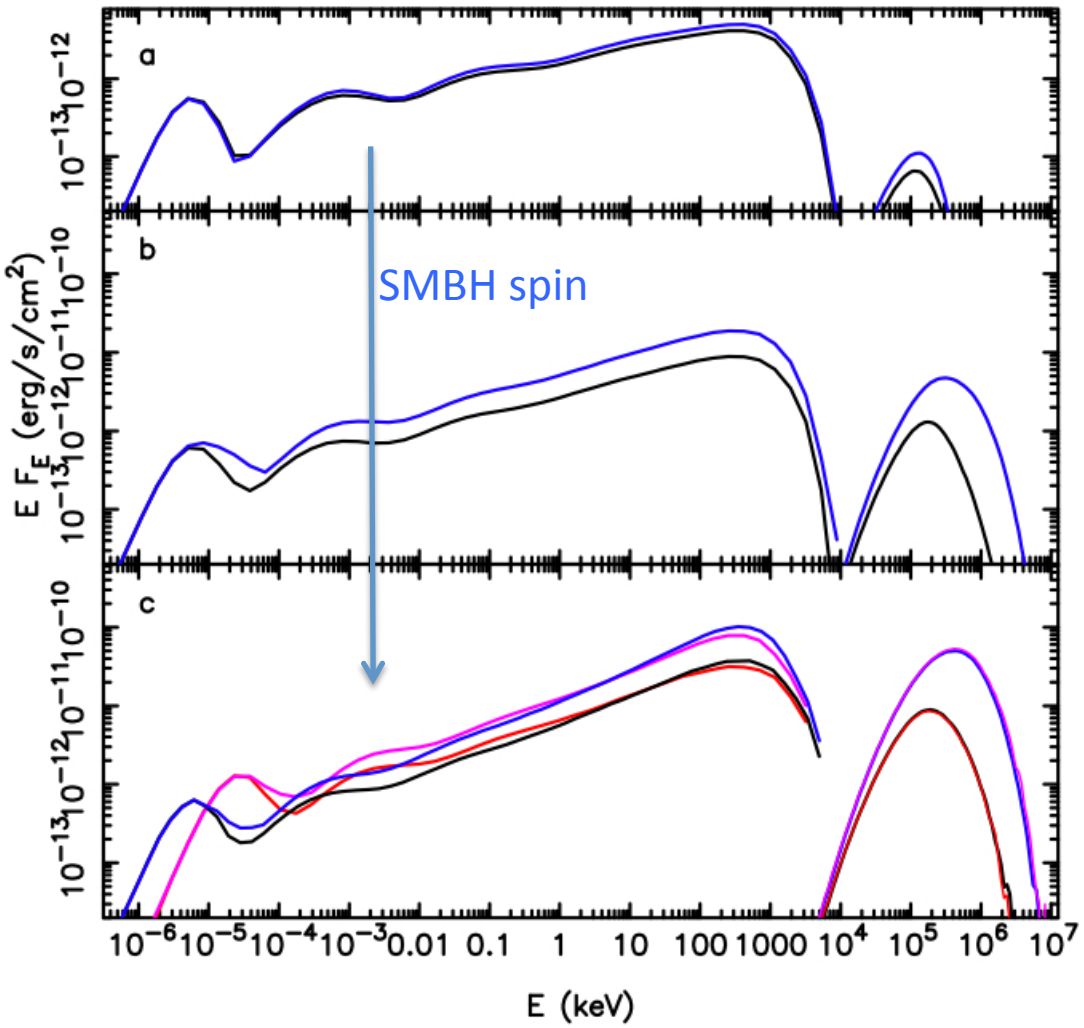
Fermi-LAT studies of hard X-ray bright AGN indicate that **radio-quiet Seyfert** galaxies are gamma-ray quiet as a class.



# Radio-Quiet AGN?



# Radio-Quiet AGN?

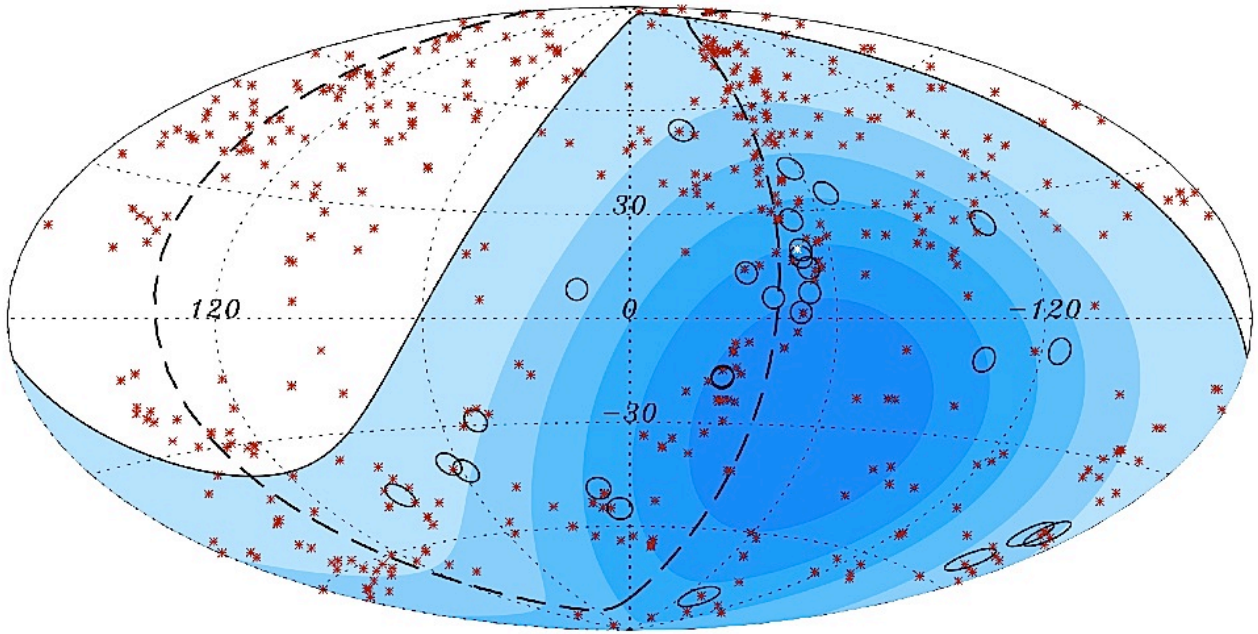



Niedziwiecki et al. 2009:

In active galaxies, proton-proton interactions within accretion flows may result in a significant emission component in the 0.1 – 10 GeV range, possibly constituting up to 10% of the disk/disk corona X-ray luminosity for a particular (preferred) range of the accretion rate, typically corresponding to advection-dominated ("hot") accretion flow, and a maximally spinning supermassive black hole.

# Radio-Quiet AGN?

Radio-quiet AGN: acceleration sites of UHECRs, or just tracers of the matter distribution in the local Universe (Moskalenko et al. 2009)?

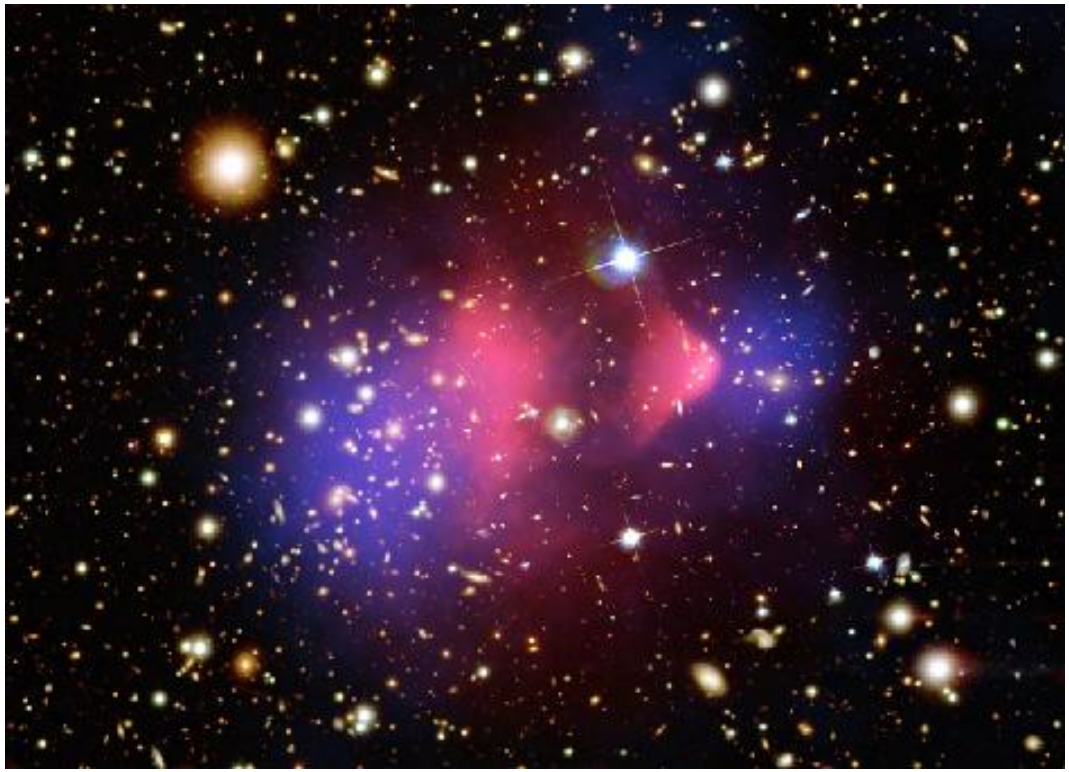


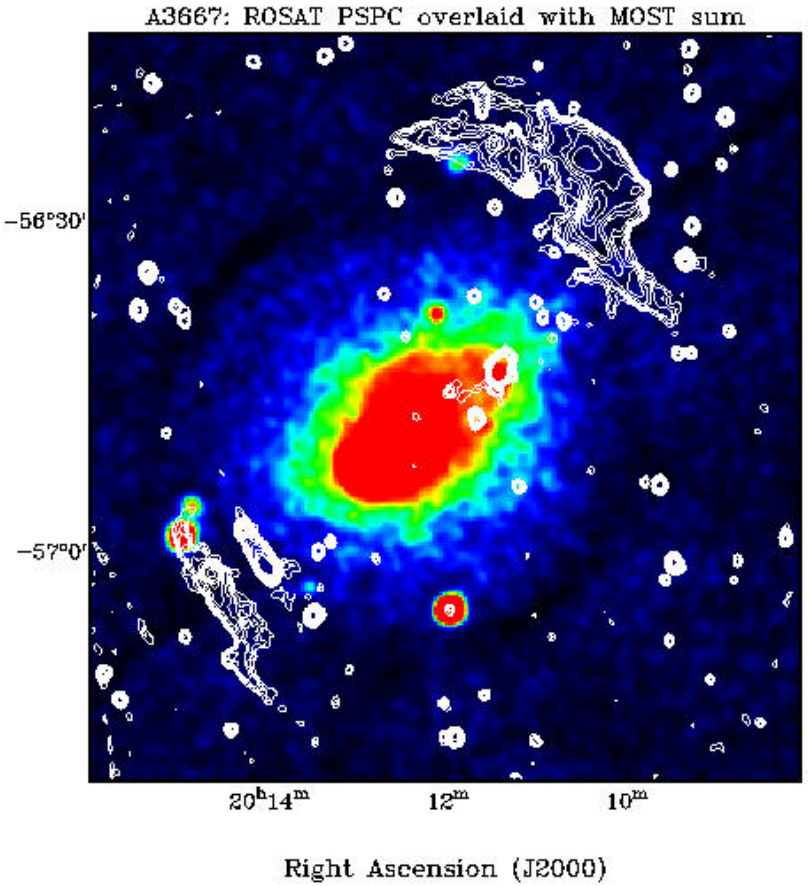

*Abraham et al. 2007: Using data collected at the P. Auger Observatory during the first 3.7 years, a correlation between the arrival directions of cosmic rays with energy above 6 x $10^{19}$ eV and the positions of AGN within 75 Mpc was claimed.*

# Clusters of Galaxies

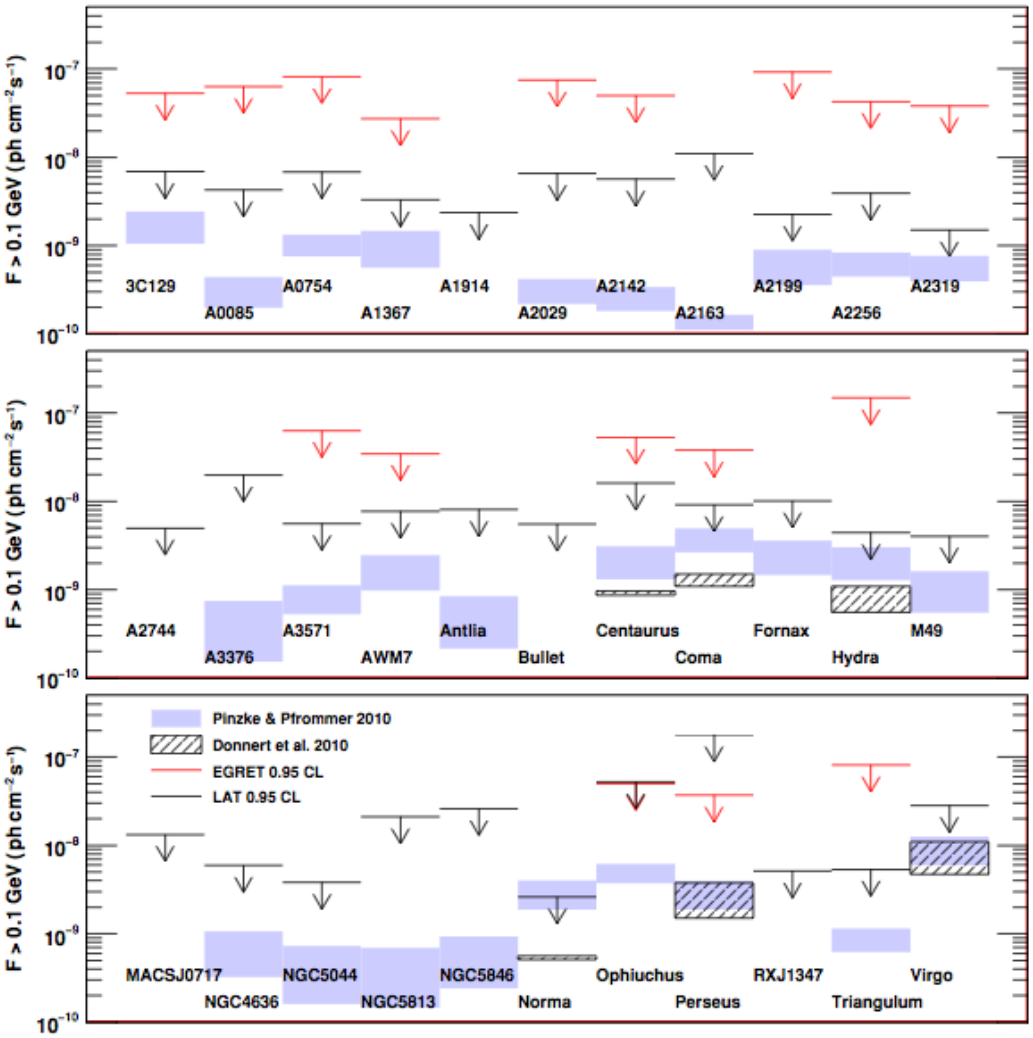
Merging processes leading to the formation of clusters of galaxies release huge amounts of gravitational energy ($\geq 10^{64}$ erg) on timescales of the order of ~Gyr.

While much of this energy is contained in thermal plasma with temperatures 10 keV emitting X-ray photons via the bremsstrahlung process, part of it may be channelled to accelerate a small fraction of particles from the thermal pool to ultrarelativistic energies.





# Clusters of Galaxies

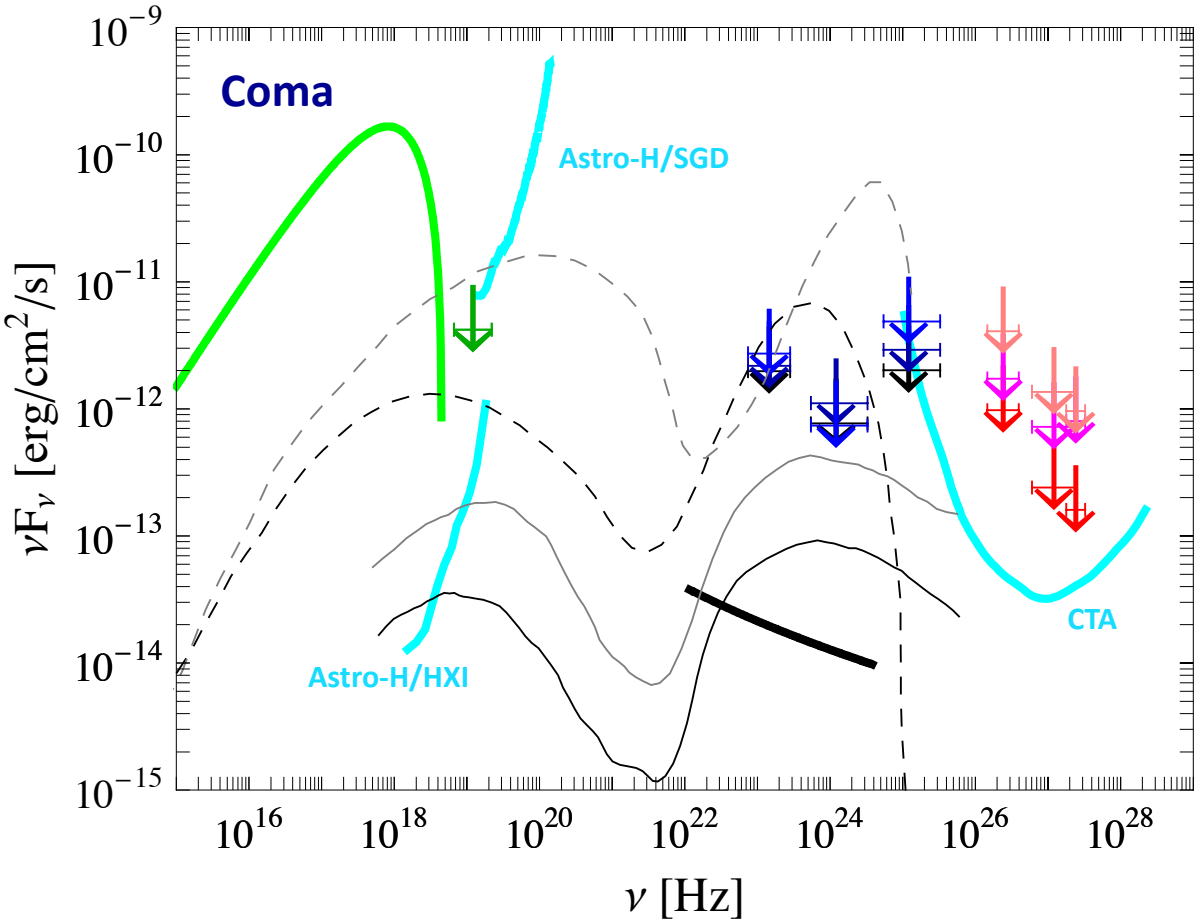



Ackermann et al. 2010, ApJ, 717

Model predictions for the gamma-ray emission of clusters very uncertain!

- Dark matter annihilation
- CR protons accelerated at merging shocks
- CR electrons accelerated by ICM turbulence

# Clusters of Galaxies



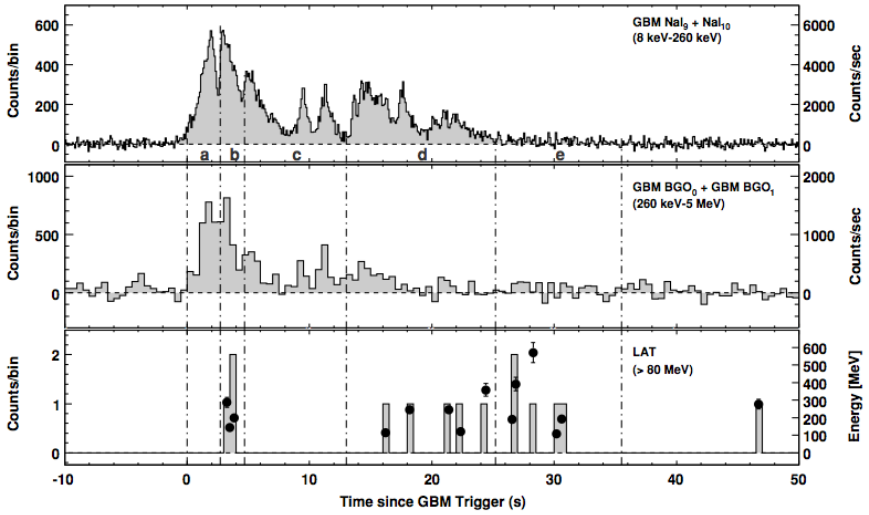

Takahashi et al. 2013, APh, 49

Current hard X-ray, GeV and TeV upper limits excludes weak ICM magnetic fields (B > 0.3 mG), and also a significant contribution of CR hadrons to the total ICM pressure ($p_{CR}/p_{th} < 0.1$).

# Gamma-Ray Bursts

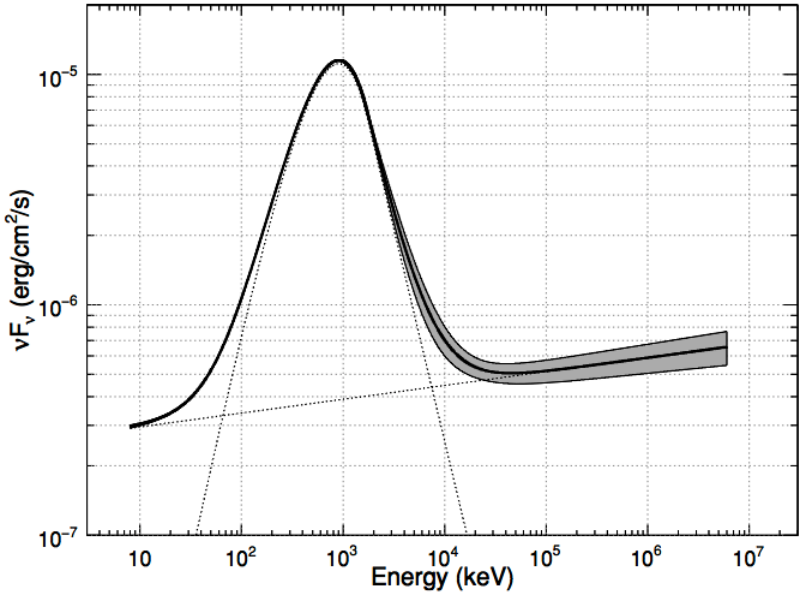
Abdo et al. 2009, ApJ 707:

the first GRB detected by LAT, **GRB 080825C**, shows a hint of a time delay between the onset of the high-energy (>100 MeV) emission relative to the low-energy (sub-MeV) emission.




Abdo et al. 2009, ApJ 706:

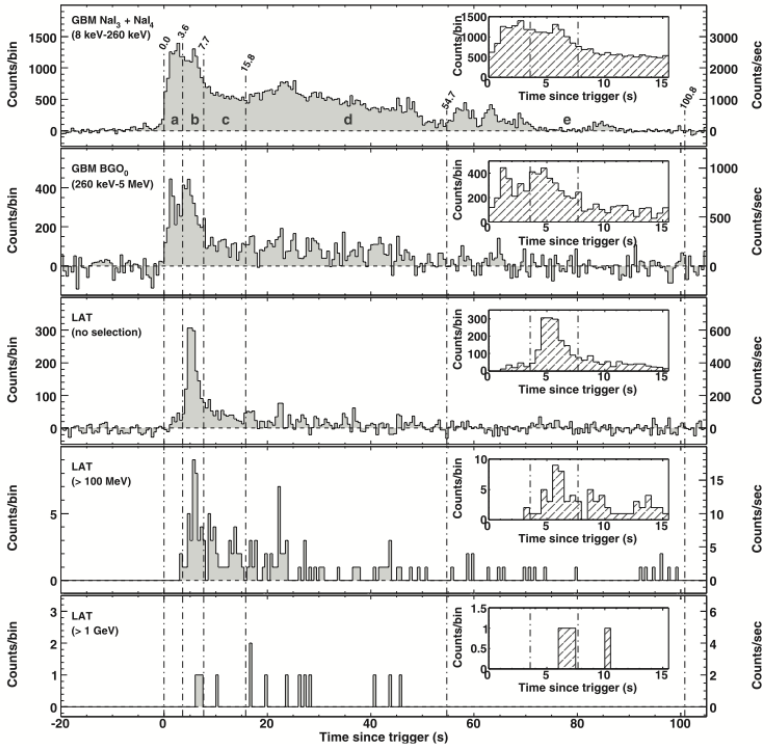
**GRB 090902B** shows clear evidence of excess power-law emission both at low (<50 keV) and high energies (>100MeV). Internal opacity requires the bulk Lorentz factor $\Gamma \sim 1000$.

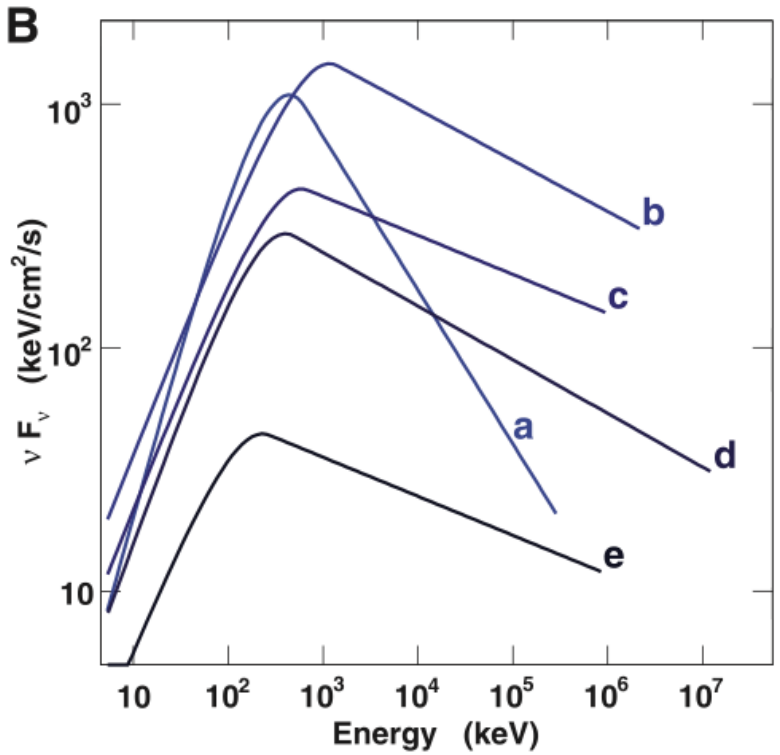


# Gamma-Ray Bursts

Abdo et al. 2009, Science 323:

exceptionally luminous **GRB 080916C** (z=4.35). The high-energy gamma rays are observed to start later and persist longer than the lower energy photons. Internal opacity requires the minimum bulk Lorentz factor $\Gamma \geq 890$. The delayed onset of LAT pulse, which coincides with the rise of the second peak in the GBM light curve suggests a common origin in a region spatially distinct from the first GBM pulse. The lack of two distinct emission components in the spectra throughout the burst suggests synchrotron origin of the radiation from keV up to ≥10 GeV.



# Conclusions

• Excellent gamma-ray data provided by Fermi-LAT and ground-based Cherenkov Telescopes (H.E.S.S., Magic, VERITAS).
• Good multiwavelength coverage enabled by the modern X-ray satellites, optical telescopes, and radio interferometers.

• Variety of astrophysical sources of high-energy emission and particles, from stellar binary systems and SNRs to Mpc-scale structures (lobes, clusters of galaxies).
• Variety of emission and particle acceleration processes involved (not only DSA!).

• A need for a cross-disciplinary, MWL approach.
• Progress driven by the data, many previously developed models to be abandoned.