Fermi-LAT Observations of Active Galactic Nuclei

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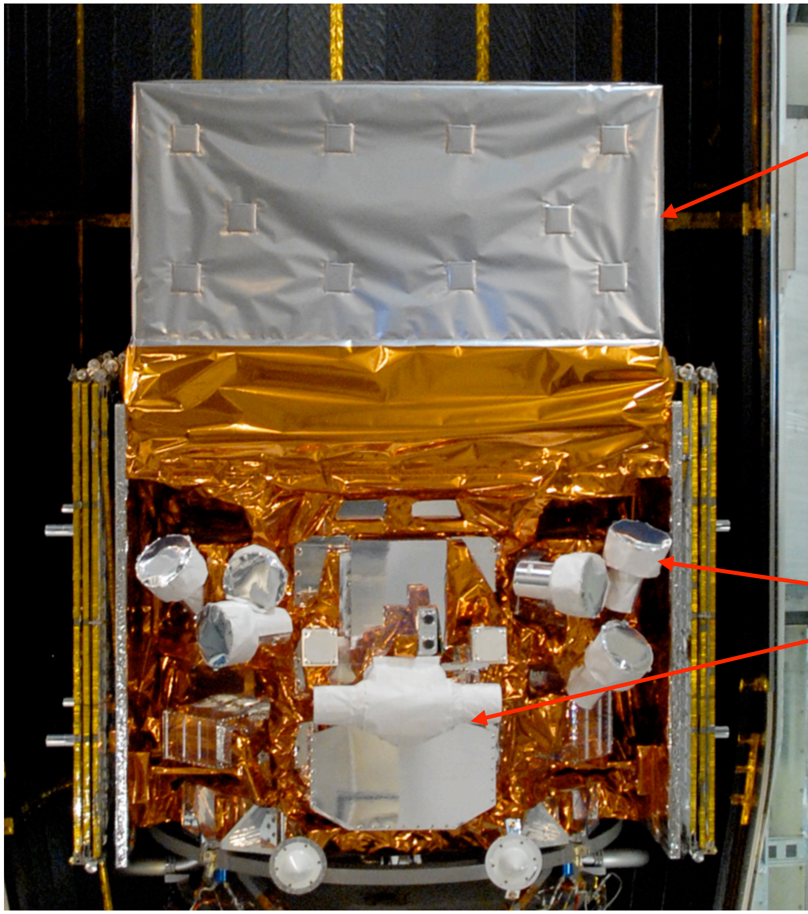
Stanford U. & KIPAC

on behalf of the Fermi-LAT Collaboration


June 11, 2008
Circular orbit at 565 km
Inclination 25.6°
Lifetime ≥5 years

Fermi instruments



Large Area Telescope (LAT):

- 20 MeV - >300 GeV (including unexplored region 10-100 GeV)
- 2.4 sr FoV (scans entire sky every ~3hrs)

Gamma-ray Burst Monitor (GBM)

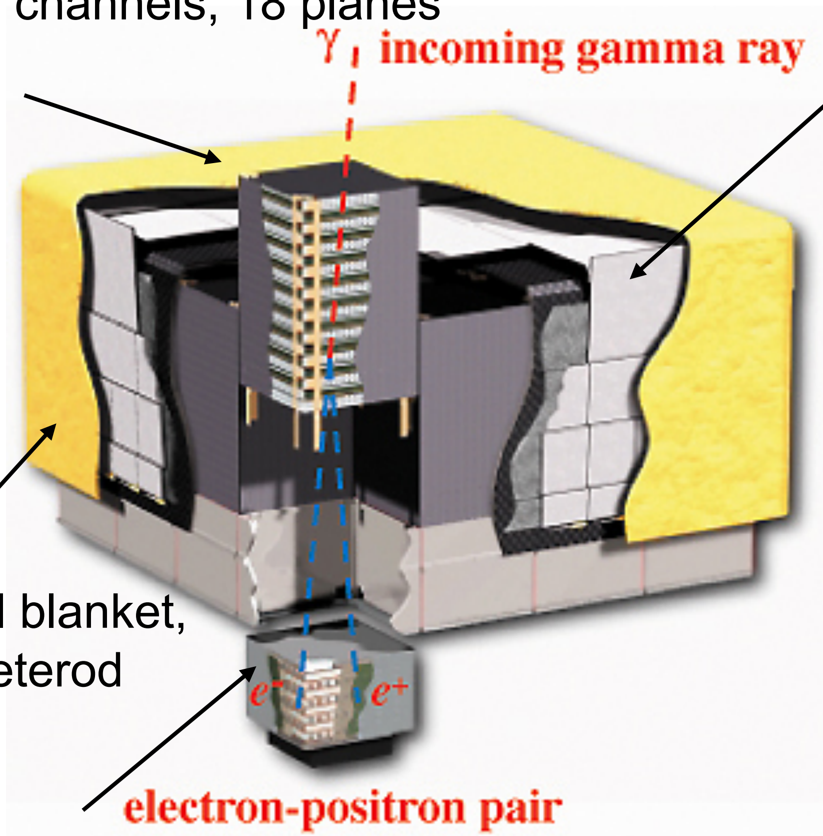
- 8 keV - 40 MeV
- views entire unocculted sky

- **Large leap in all key capabilities, transforming our knowledge of the gamma-ray universe. Great discovery potential.**

Fermi-LAT systems

Si Tracker with Tungsten foils (pair conversion): pitch = 228 μm, 8.8×10^5 channels, 18 planes

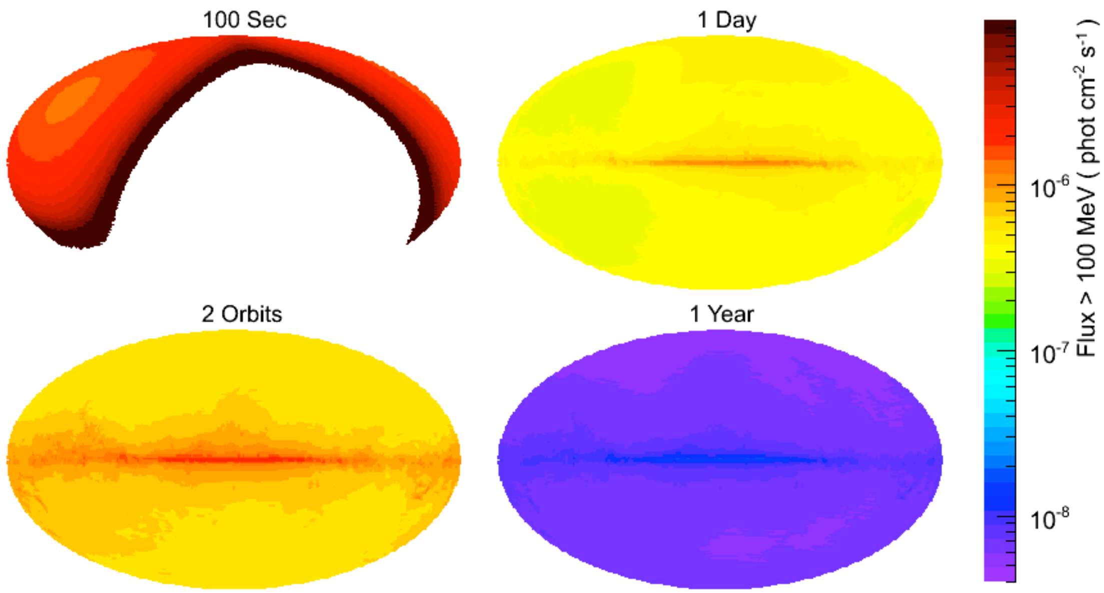
Anti-Coincidence Detector (ACD) – segmented scintillator tiles



Thermal blanket, micrometerod shield

CsI Calorimeter – hodoscopic array (8 layers) of 1536 crystals

Operations and observing modes



LAT sensitivity on 4 different timescales: 100 s, 2 orbits (2x96 min), 1 day and 1 year

- Almost all observations in survey mode - the LAT observes the entire sky every two orbits (~3 hours), each point on the sky receives ~30 mins exposure during this time.
  - 35 deg rocking angle to Sept 2 2010, 50 deg thereafter.
- Autonomous repoints (~1/month)
  - 5 hour pointed mode observations in response to bright GBM detected GRB (duration now reduced to 2.5 hours)
- LAT Calibrations (16 hours), Engineering (5 days)
  - Very high ontime!

LAT Collaboration

- France
  - CNRS/IN2P3, CEA/Saclay
- Italy
  - INFN, ASI, INAF
- Japan
  - Hiroshima University
  - ISAS/JAXA
  - RIKEN
  - Tokyo Institute of Technology
- Sweden
  - Royal Institute of Technology (KTH)
  - Stockholm University
- United States
  - Stanford University (SLAC and HEPL/Physics)
  - University of California, Santa Cruz - Santa Cruz Institute for Particle Physics
  - Goddard Space Flight Center
  - Naval Research Laboratory
  - Sonoma State University
  - The Ohio State University
  - University of Washington

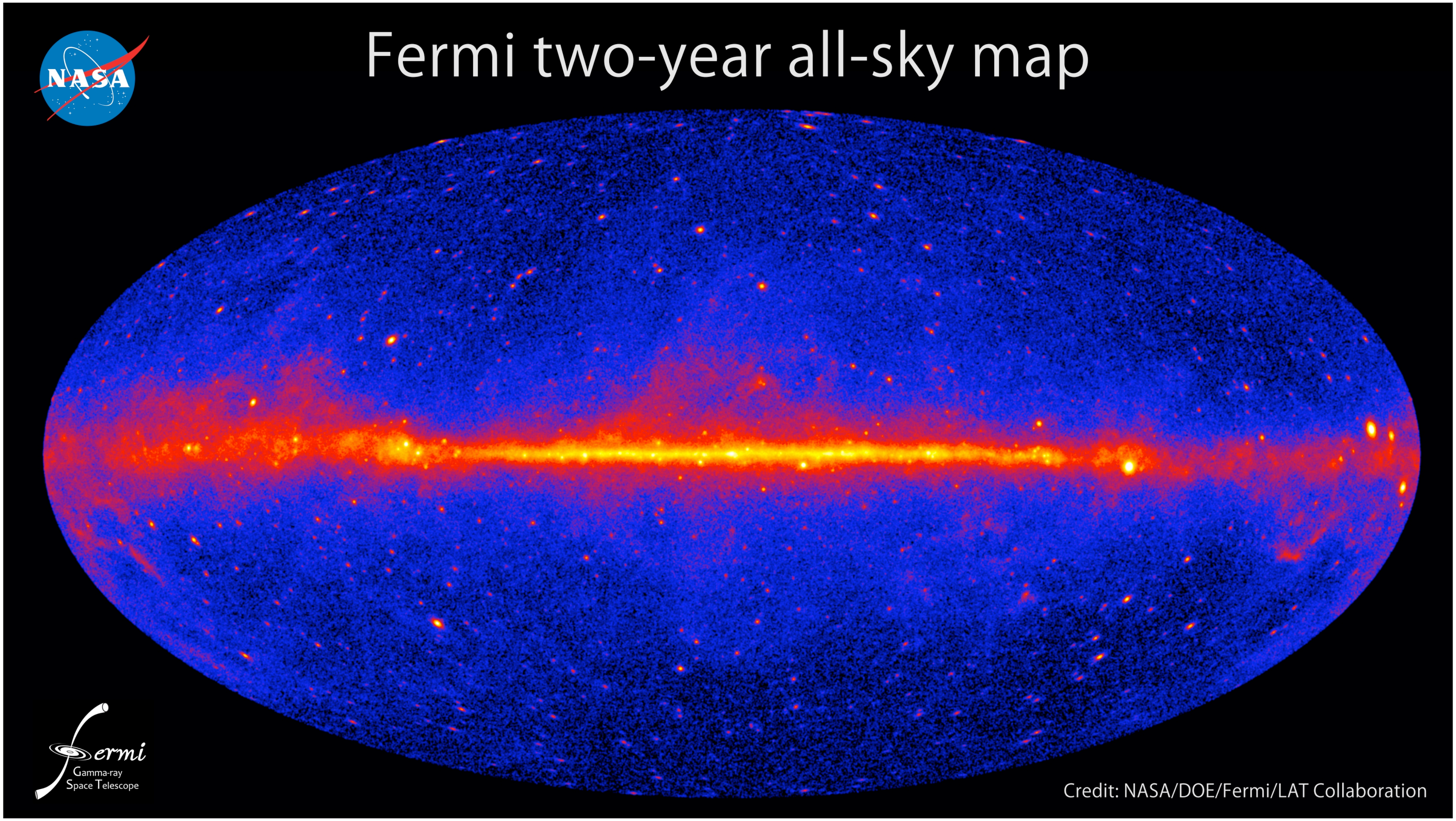
PI: Peter Michelson
(Stanford)

~400 Scientific Members (including 96 Affiliated Scientists, plus 68 Postdocs and 105 Students)

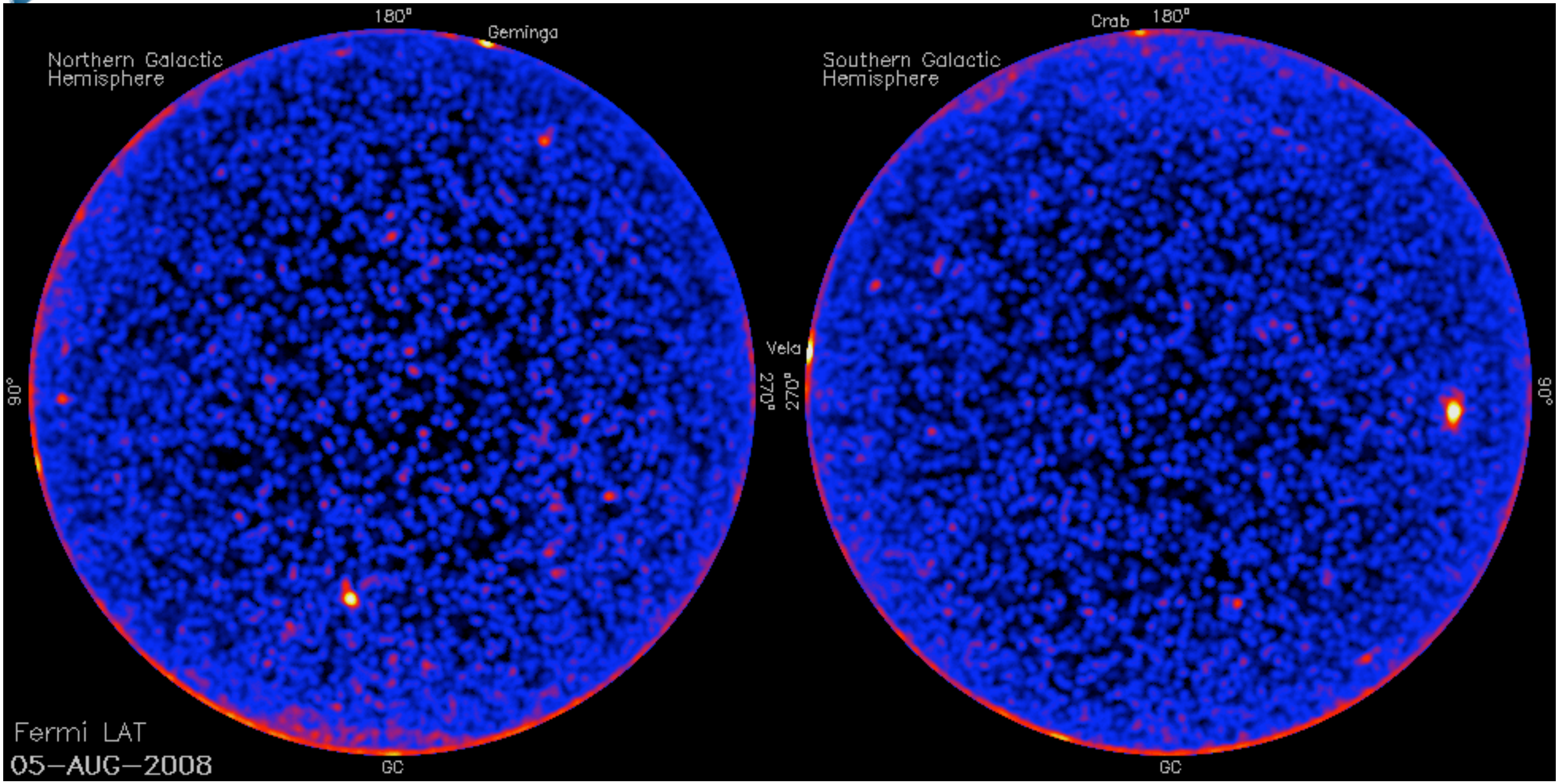
Cooperation between NASA and DOE, with key international contributions from France, Italy, Japan and Sweden.

Project managed at SLAC.

The >1 GeV Sky

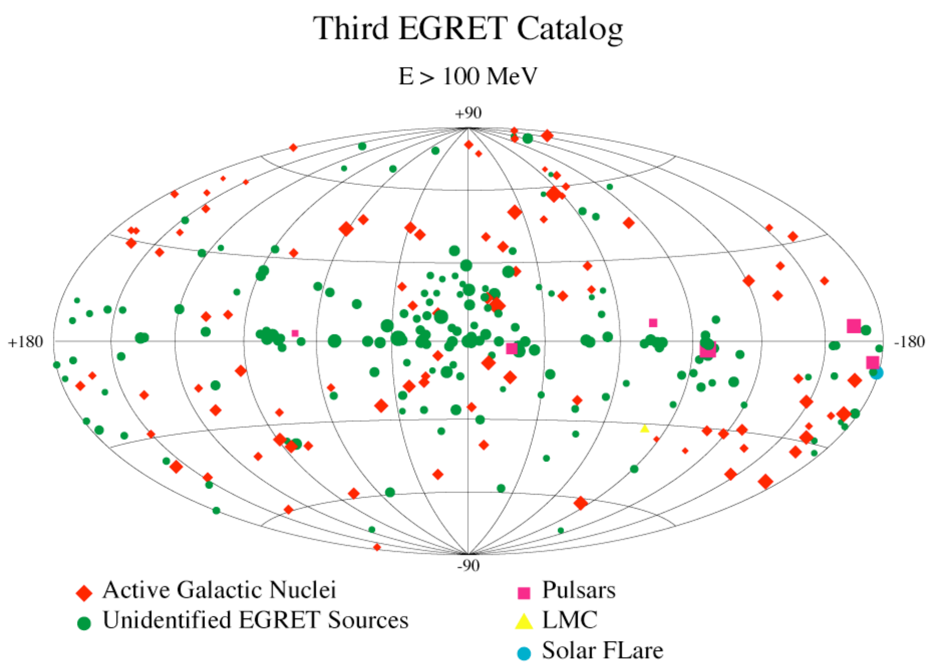

Fermi two-year all-sky map
Credit: NASA/DOE/Fermi/LAT Collaboration

First 1 year of LAT data



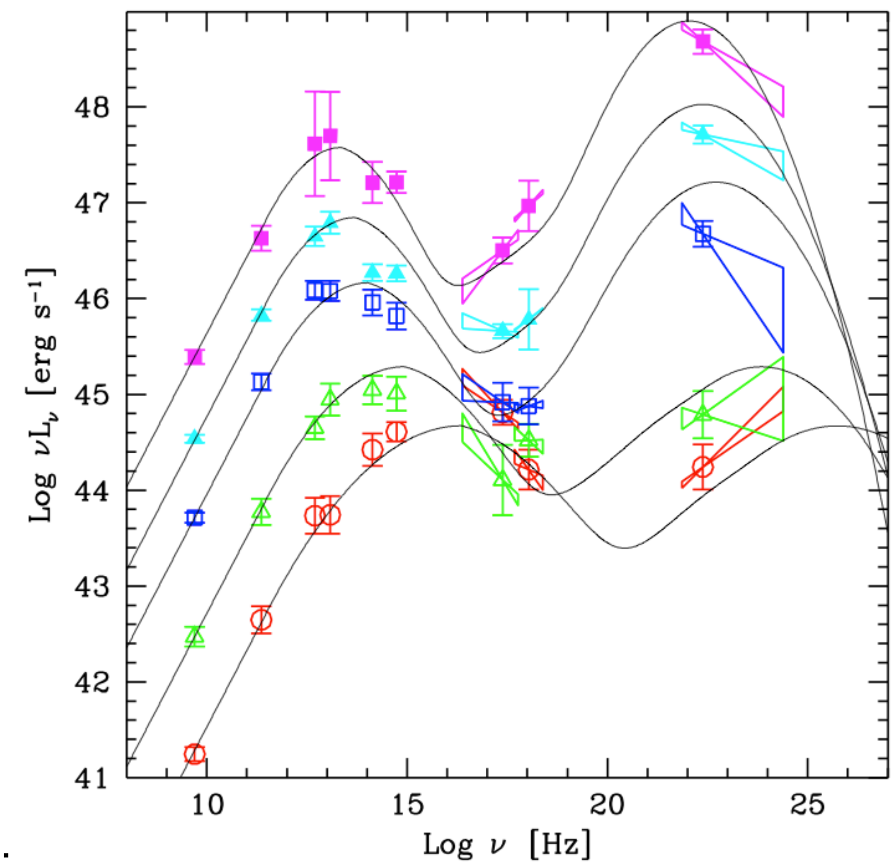
First movie in gamma rays ever shot!

EGRET Gamma-Ray Sky



EGRET has shown that AGN dominate the extragalactic MeV- GeV sky

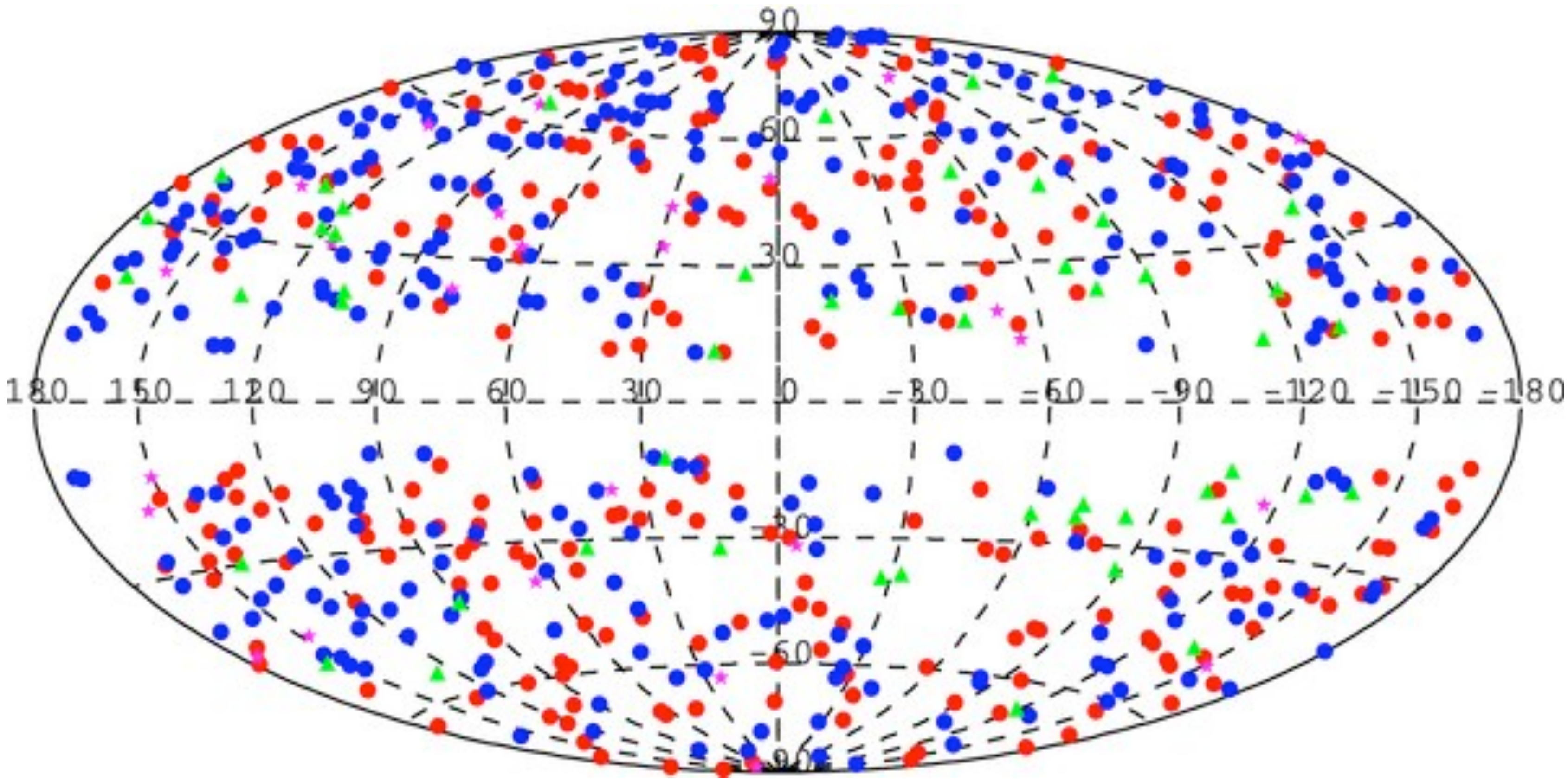
- ~70 Blazars (3rd Catalog, Hartman et al 1999;
- >100 (Sowards-Emmerd et al. 2003,2004);
- marginal detection of a couple of radio-galaxies



SED with two main components:

- Synchrotron at low energies
- Inverse Compton and/or "hadronic" at higher energies

Fermi-LAT AGN Skymap

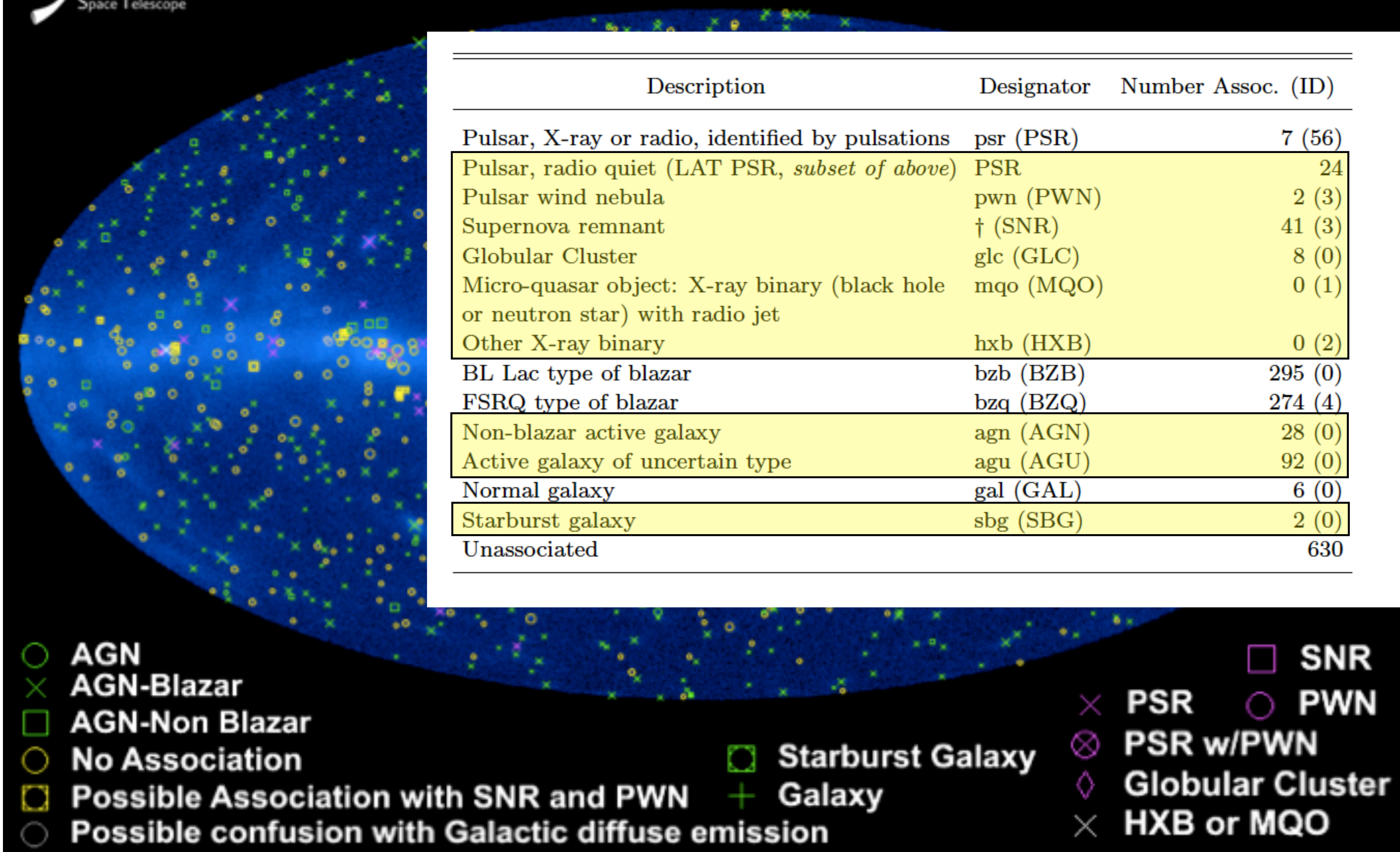


Locations of the sources (~700) in the clean sample. Red circles: FSRQs, blue circles: BL Lacs, magenta stars: radio galaxies, green triangles: AGNs of unknown type.

The Fermi LAT 1FGL Source Catalog

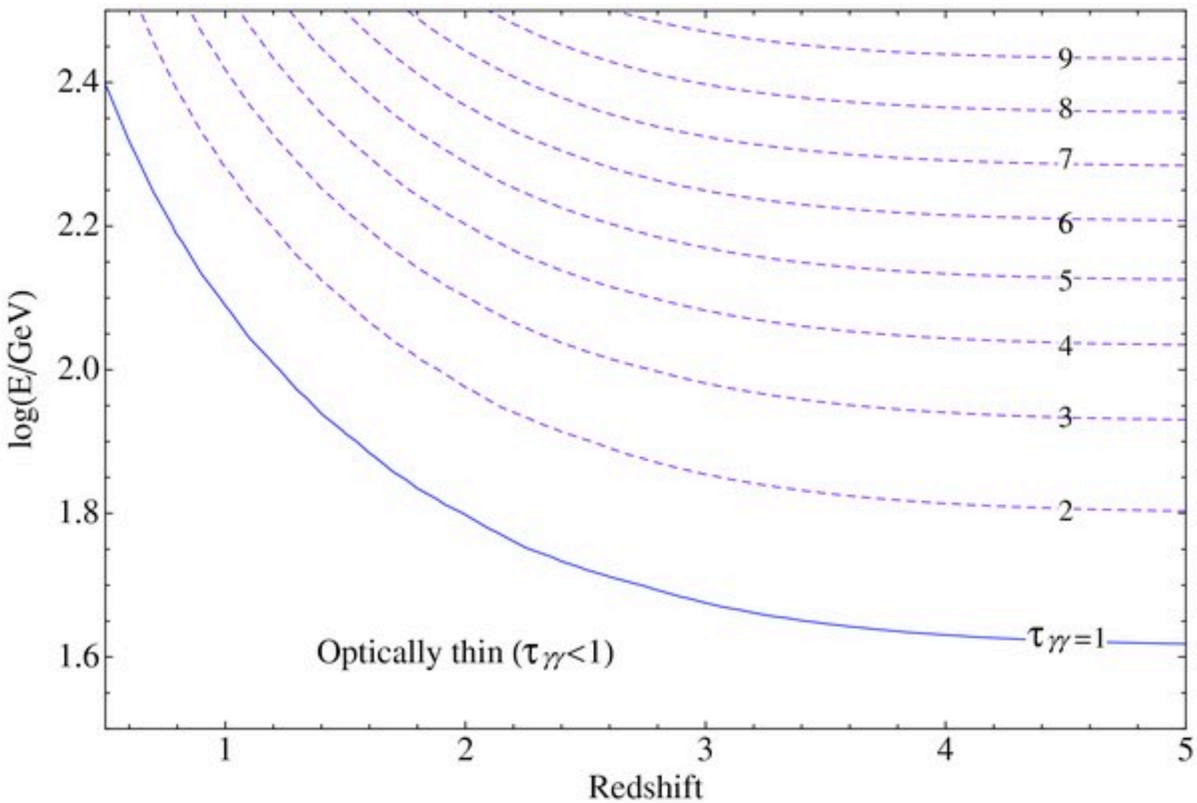
1,451 sources

Description	Designator	Number Assoc. (ID)
Pulsar, X-ray or radio, identified by pulsations	psr (PSR)	7 (56)
Pulsar, radio quiet (LAT PSR, *subset of above*)	PSR	24
Pulsar wind nebula	pwn (PWN)	2 (3)
Supernova remnant	† (SNR)	41 (3)
Globular Cluster	glc (GLC)	8 (0)
Micro-quasar object: X-ray binary (black hole or neutron star) with radio jet	mqo (MQO)	0 (1)
Other X-ray binary	hxb (HXB)	0 (2)
BL Lac type of blazar	bzb (BZB)	295 (0)
FSRQ type of blazar	bzq (BZQ)	274 (4)
Non-blazar active galaxy	agn (AGN)	28 (0)
Active galaxy of uncertain type	agu (AGU)	92 (0)
Normal galaxy	gal (GAL)	6 (0)
Starburst galaxy	sbg (SBG)	2 (0)
Unassociated		630



Credit: *Fermi* Large Area Telescope Collaboration

Gamma-Ray Opacity of the Universe



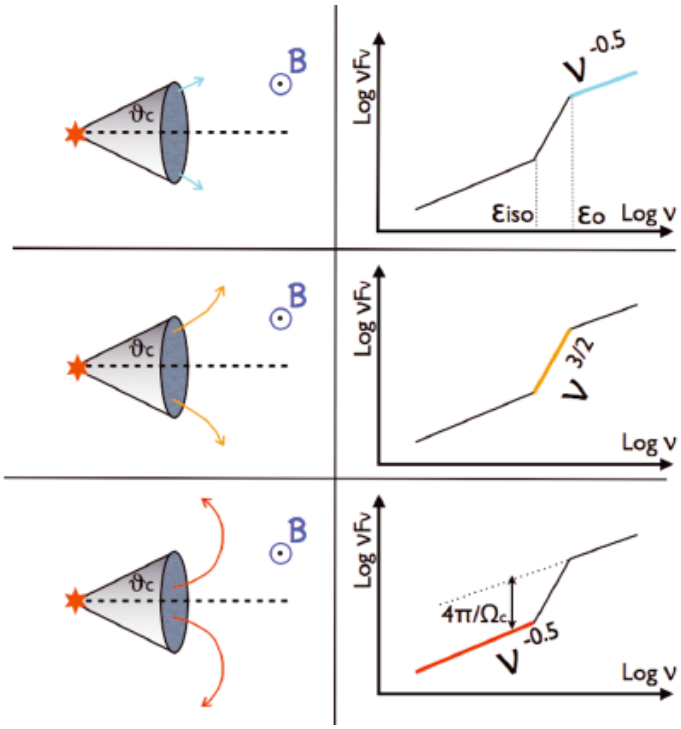
Gamma-ray opacity contours in the E-z plane using the EBL fit (Razzaque+'2009). The $\tau_{\gamma\gamma}$ = 1 contour plotted here is known as the Fazio-Stecker (1970) relation and represents a γ-ray horizon of the universe.

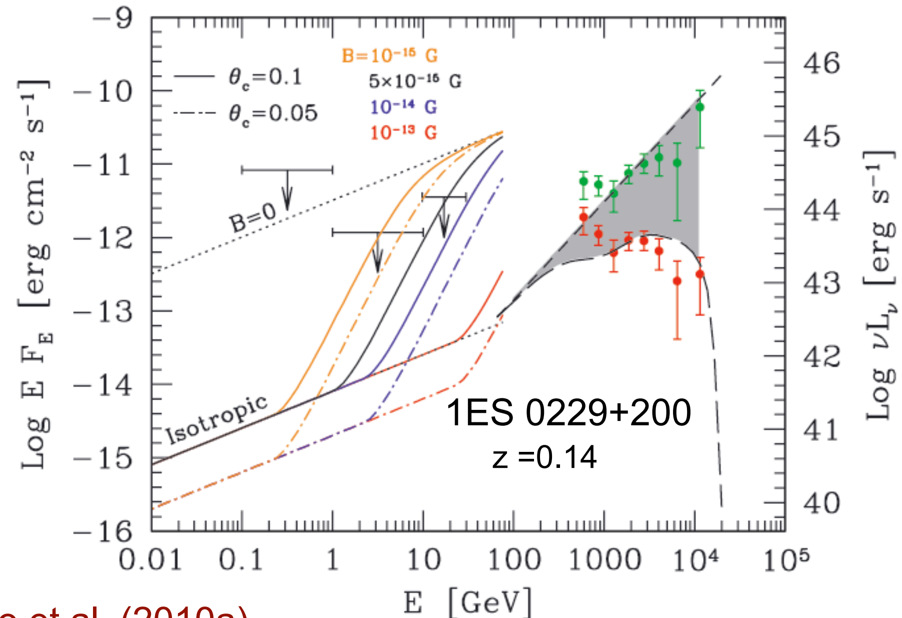
Dermer+'09

AGN as Probes of Intergalactic Magnetic Field

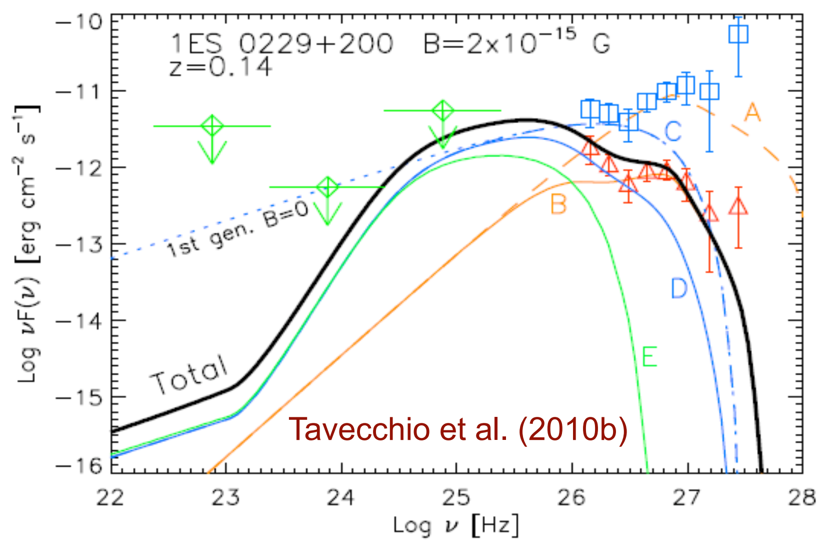
- Formation of pairs cascades by TeV photons on CMB & EBL
  - Extended gamma-ray halos
  - Spectral change in the GeV-TeV energy range
  - Surface brightness vs. energy
  - Time delays
- Approach
  - Observe TeV emitters at higher redshifts
  - Low-redshift sources are important to test the emission models
  - Measurements in 10-100 GeV range are critical
- Impact
  - Reprocessed TeV emission may contribute to isotropic background at MeV-GeV energies
  - Propagation of UHECR
  - Magneto-genesis

Spectral Model of Halo Emission





Tavecchio et al. (2010a)



Cooling spectrum $\nu F_\nu \propto \nu^{1/2}$

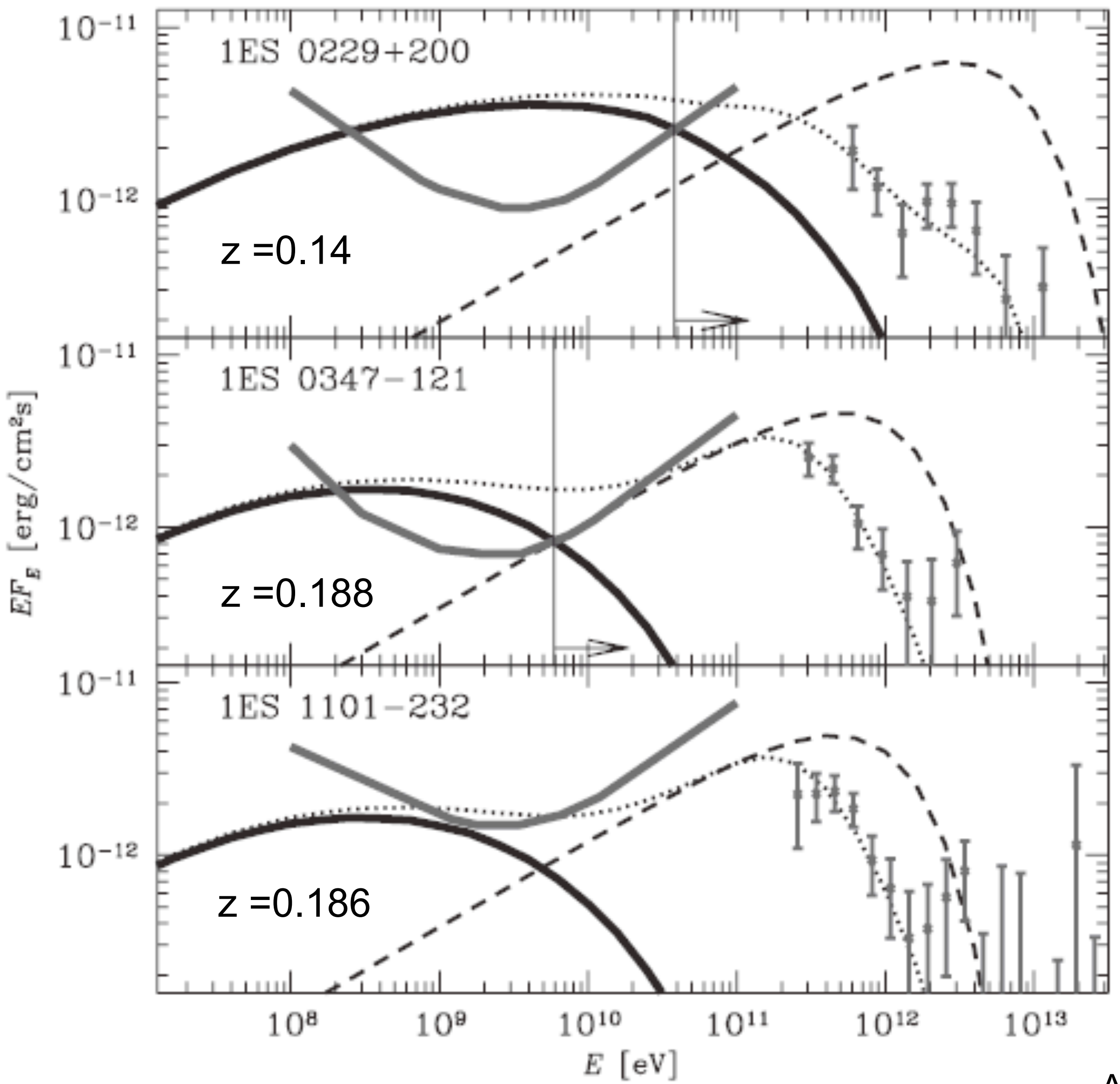
Compton-scattered spectrum $\nu F_\nu \propto \nu^{3/2}$

Isotropized spectrum $\nu F_\nu \propto \nu^{1/2}$

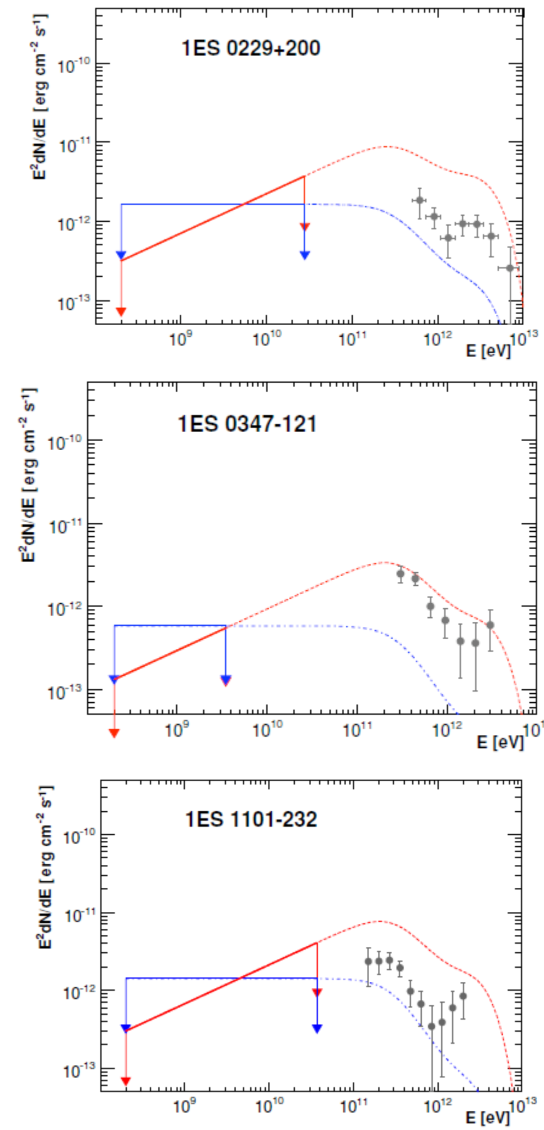
Neronov and Vovk and Tavecchio et al. assume persistent TeV blazar activity

Fermi Gamma-ray Space Telescope

Limits on IGMF from Spectra



B> 3x10^{-16} G, Neronov & Vovk (2010)



Abdo et al. 2009, ApJ, 707, 1310

IGMF
coherence length λ_{coh}
volume filling factor

Magnetic fields and structure formation

Magnetic fields in thick disk of Milky Way: ~3μG
(Lyne and Smith 1989)

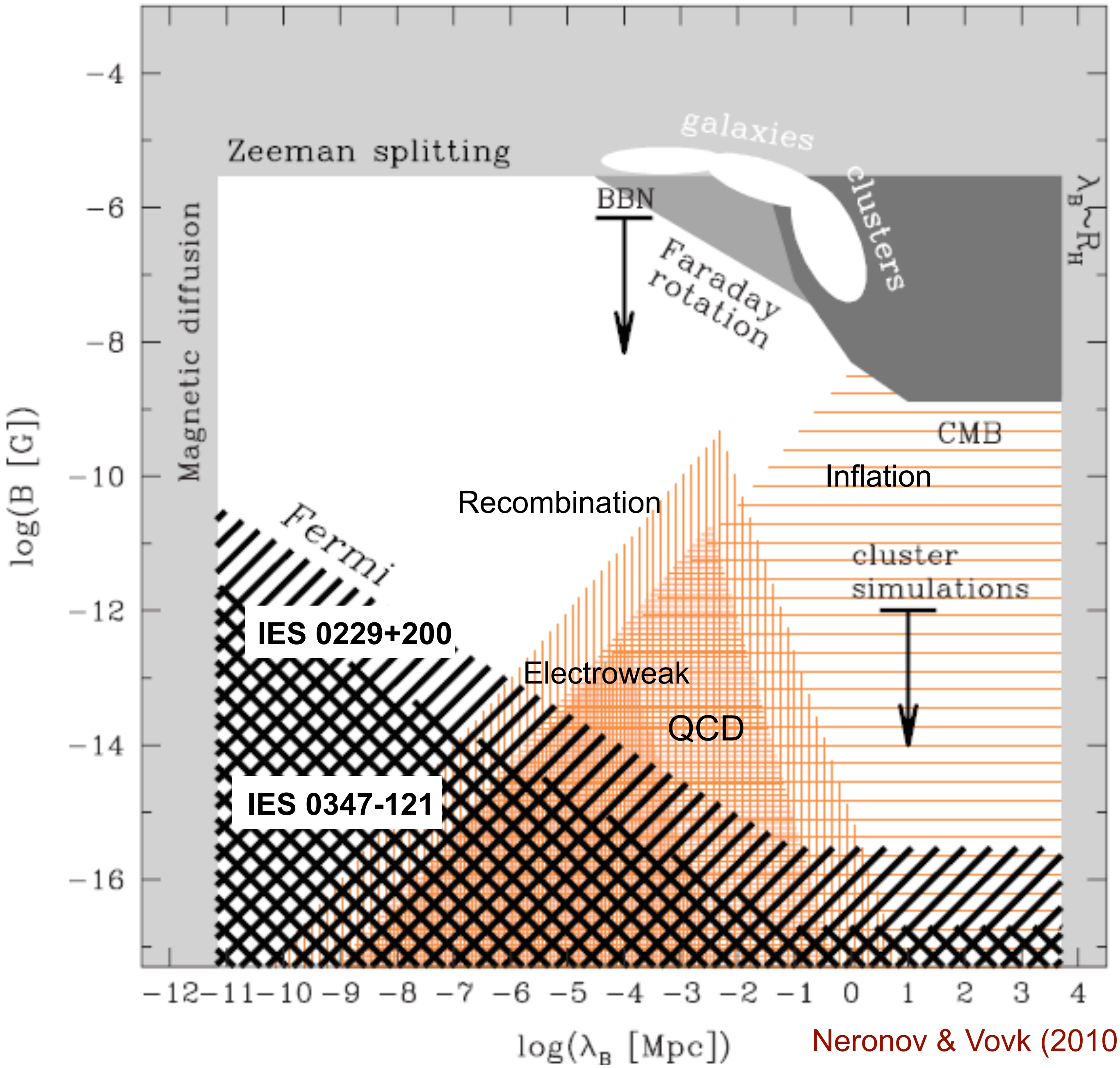
Halo of the Galaxy:
~0.1 μG – several μG?

Intergalactic space:
<< 10 nG / Z

λ_{coh} smaller than horizon size, larger than dissipation scale

(see Neronov & Semikoz 2009 for more detail and references)

Limits on IGMF and Correlation Length

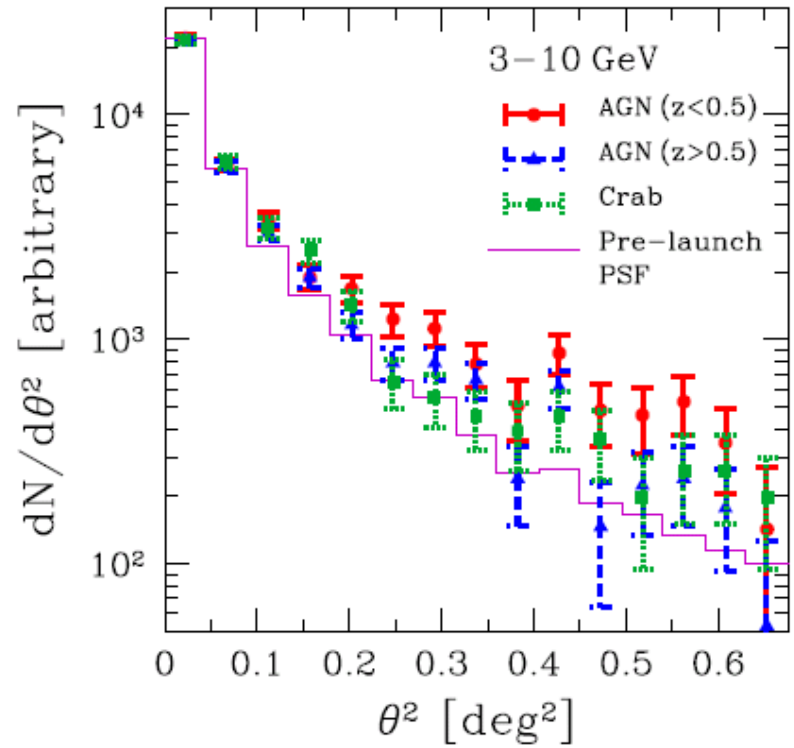


Neronov & Vovk (2010)

Pair Halos

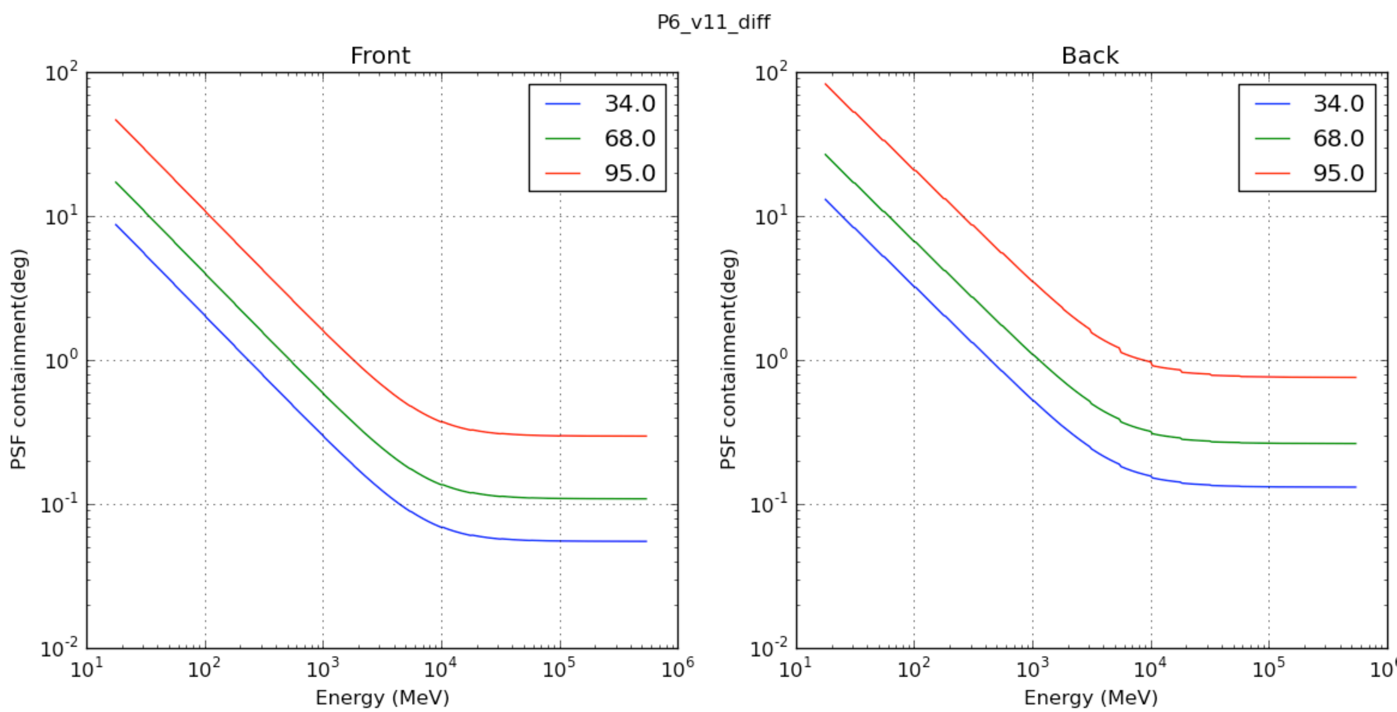
Ando and Kusenko (2010)

- Use Crab as PSF
- Count differences between the Crab and stacked AGN distributions 0.5-0.8 degrees away from sources
- Measure excess and test significance
  - $\delta = \mathrm{Front}_{excess}/\mathrm{Front}_{psf} + \mathrm{Back}_{excess}/\mathrm{Back}_{psf}$
  - 3-10 GeV
    - δ = 1.4 +/- 0.5 +/- 0.2
    - 2.7 σ
  - 10-100 GeV
    - No quoted δ
    - 1 σ



Marshall Roth was not able to reproduce their results

Example Profile



- Plot shows the angle for 34, 68, and 95% containment of signal photons
- Power law dependence: b ~ 0.8 < 1
- “Gaussianity”: γ ~ 2.15 tails much broader than Gaussian
- “Front” is nearly a factor of 3 narrower than “Back”

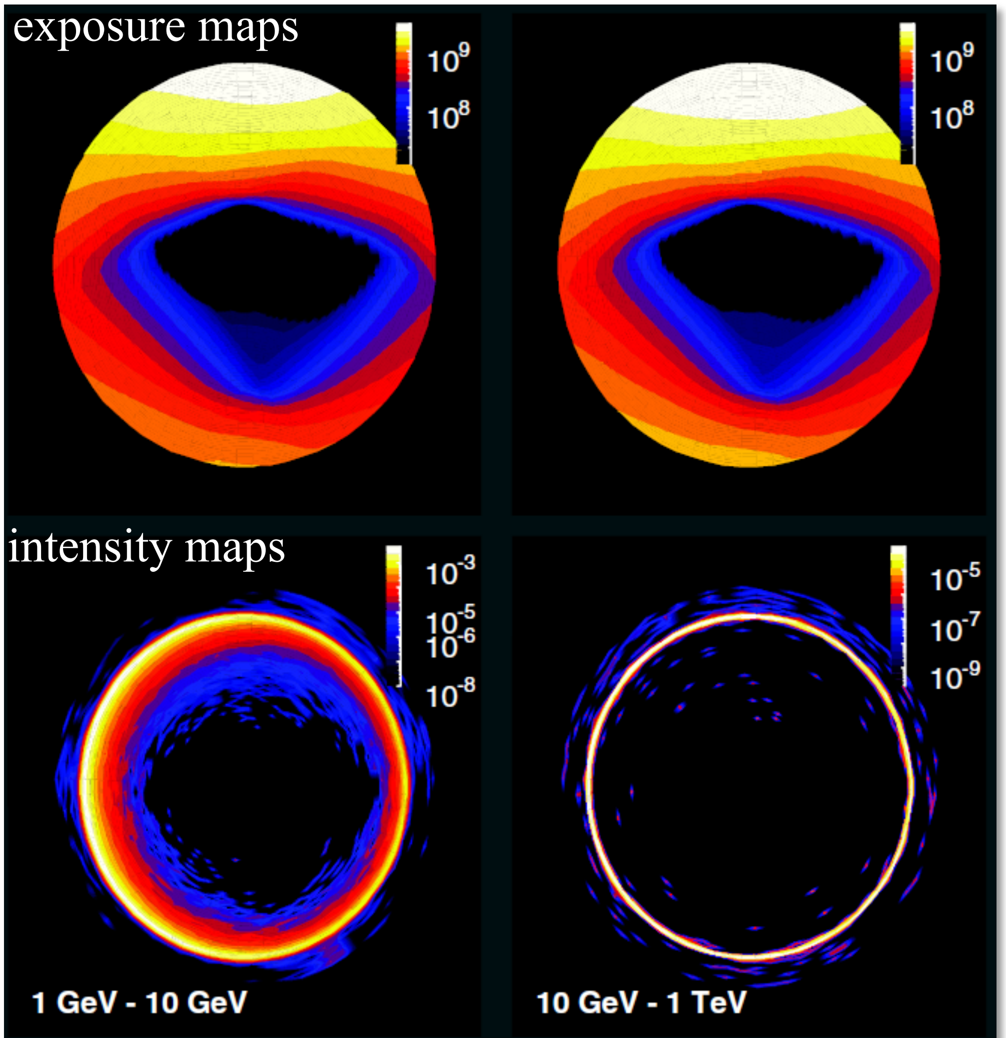
MC vs On-orbit

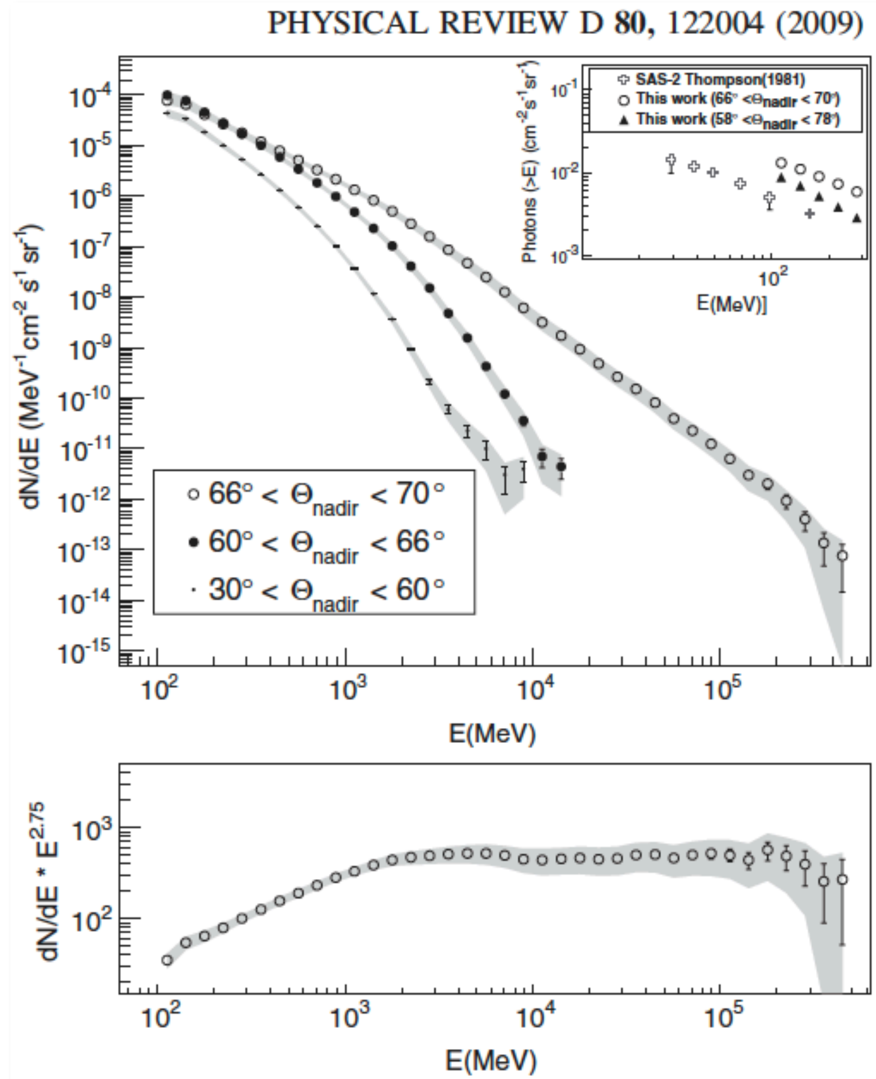
Validation

- Effective Area, Energy Dispersion, and even the PSF were all done through GEANT4-like simulations and beam data.
- Large effort went into finding calibration sources on orbit for verifying MC reflected on-orbit performance.
- Three main calibration sources
  - Earth limb (grazing cosmic rays)
    - Well known spectrum and very narrow
    - More useful in effective area validation
  - Pulsars
    - Vela: brightest DC source, highest signal-to-noise from phase selection
    - Crab: IC component emits into the TeV !
  - AGN
    - Hard blazars with spectral indices < 2 !
    - Significant flux above 10 GeV

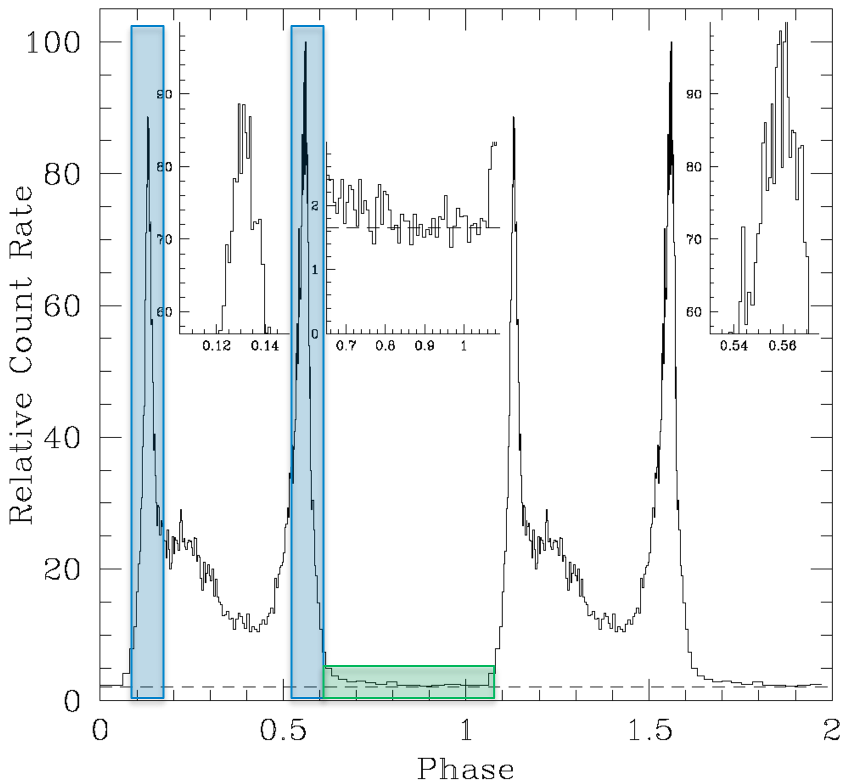
Earth albedo observations and energy response

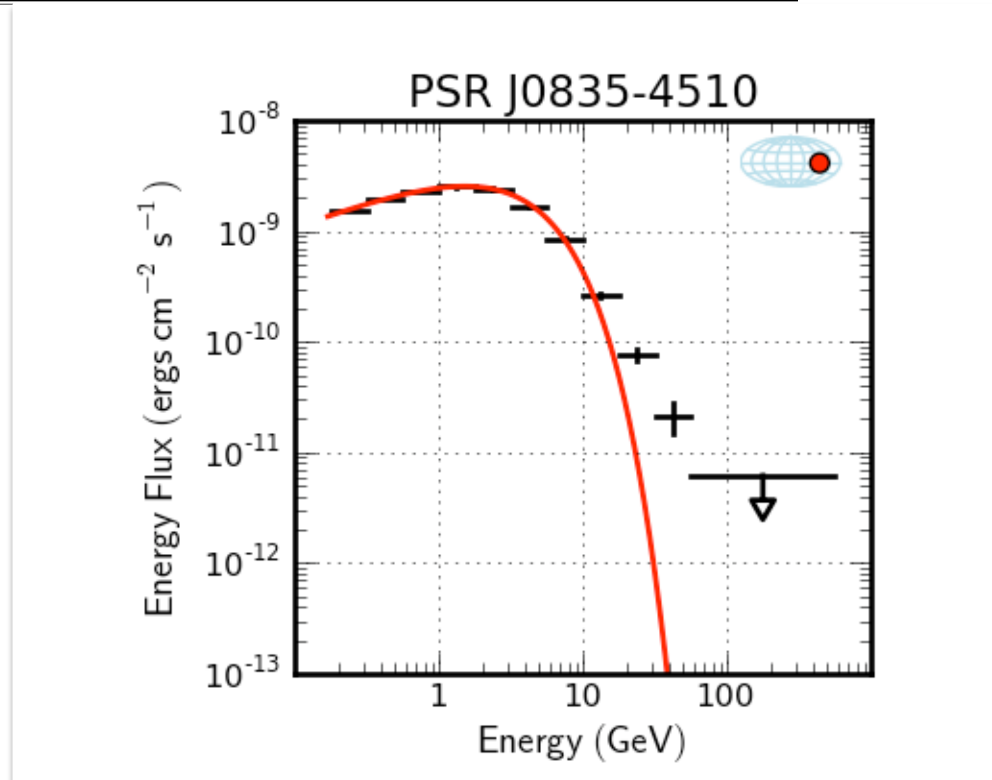
- Earth's gamma-ray albedo from CR interactions in the atmosphere
- Expect a power-law from the limb above ~5 GeV following the CR spectrum





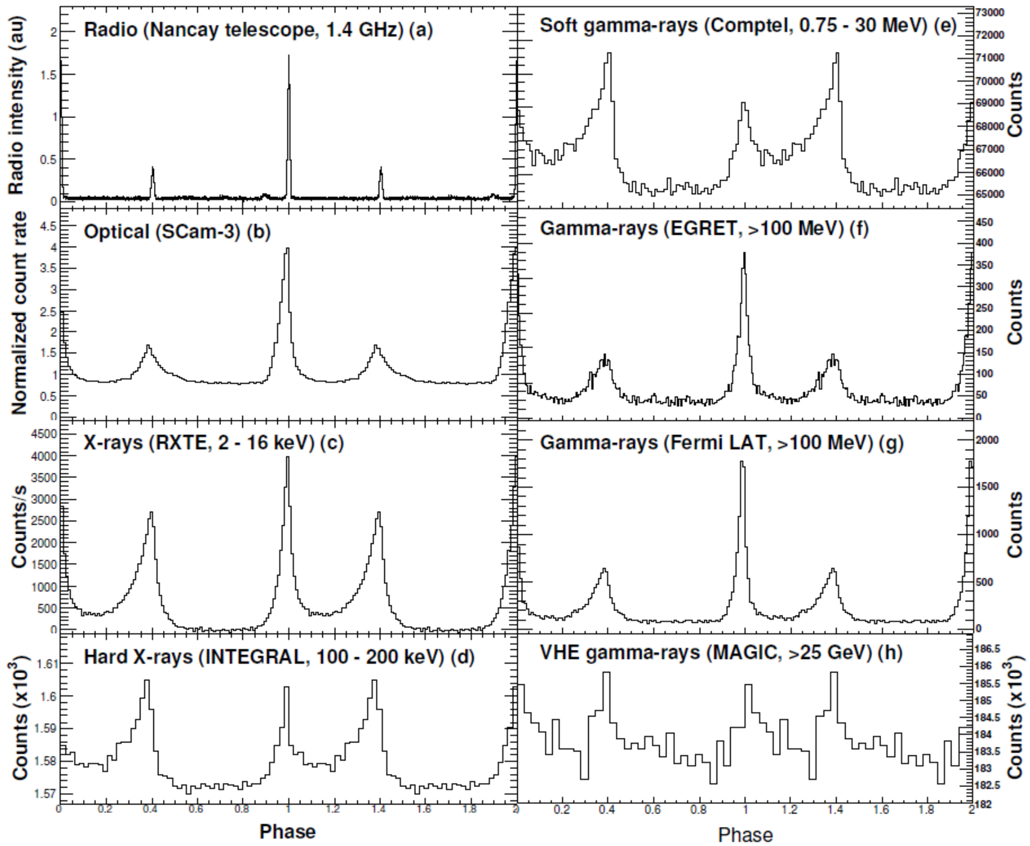
Pulsars

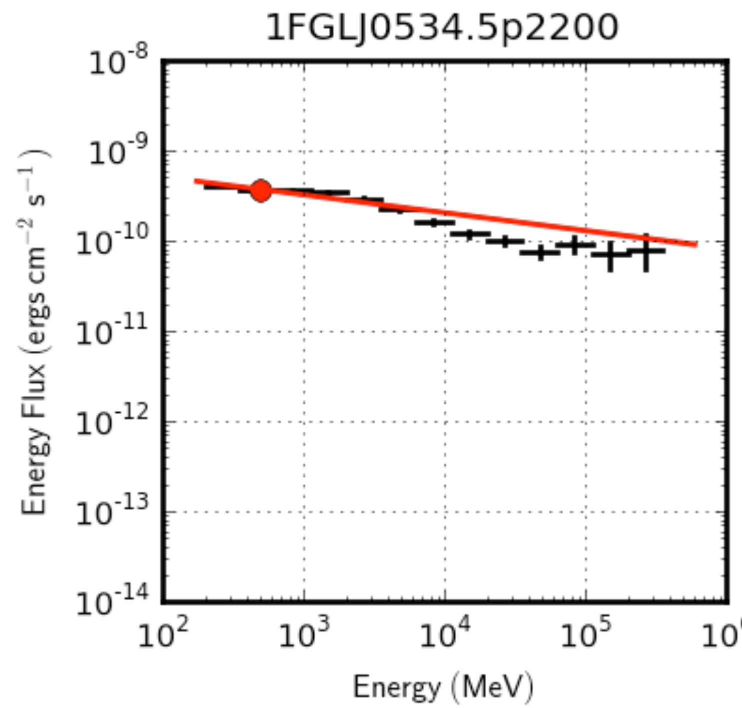




- Vela phase profile, pulsar turns completely off!
- One can easily subtract off the angular profile when pulsar is not pulsing to determine the angular structure of background
- Part of the PSF calibration, right plot shows background subtracted angular profiles as a function of energy for “Front” events
- Caveat: Pulsar spectra cuts off (exponentially) at ~10 GeV, need another calibration source to get to 100 GeV!

The Crab

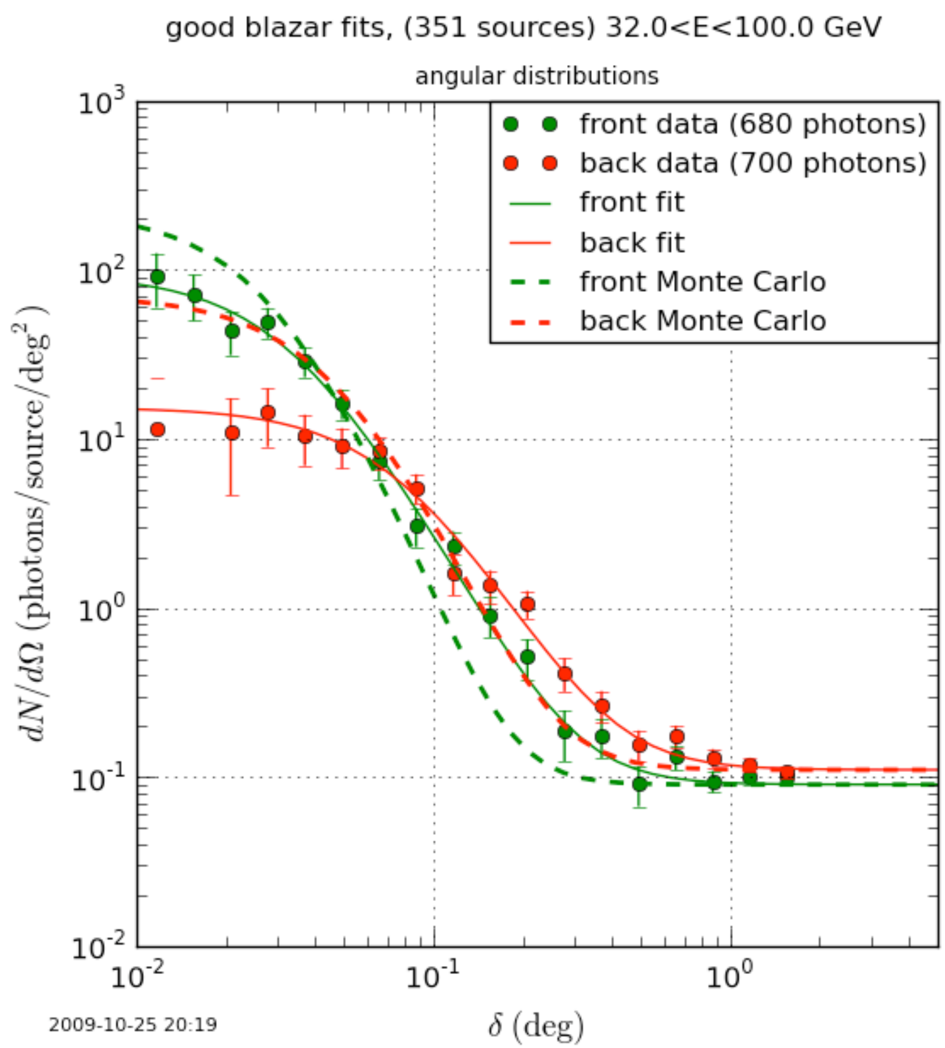




- Significant emission in nearly every energy band
- Spectrum still relatively hard, but background subtraction is troublesome, the IC component is essentially always on and appears point-like!

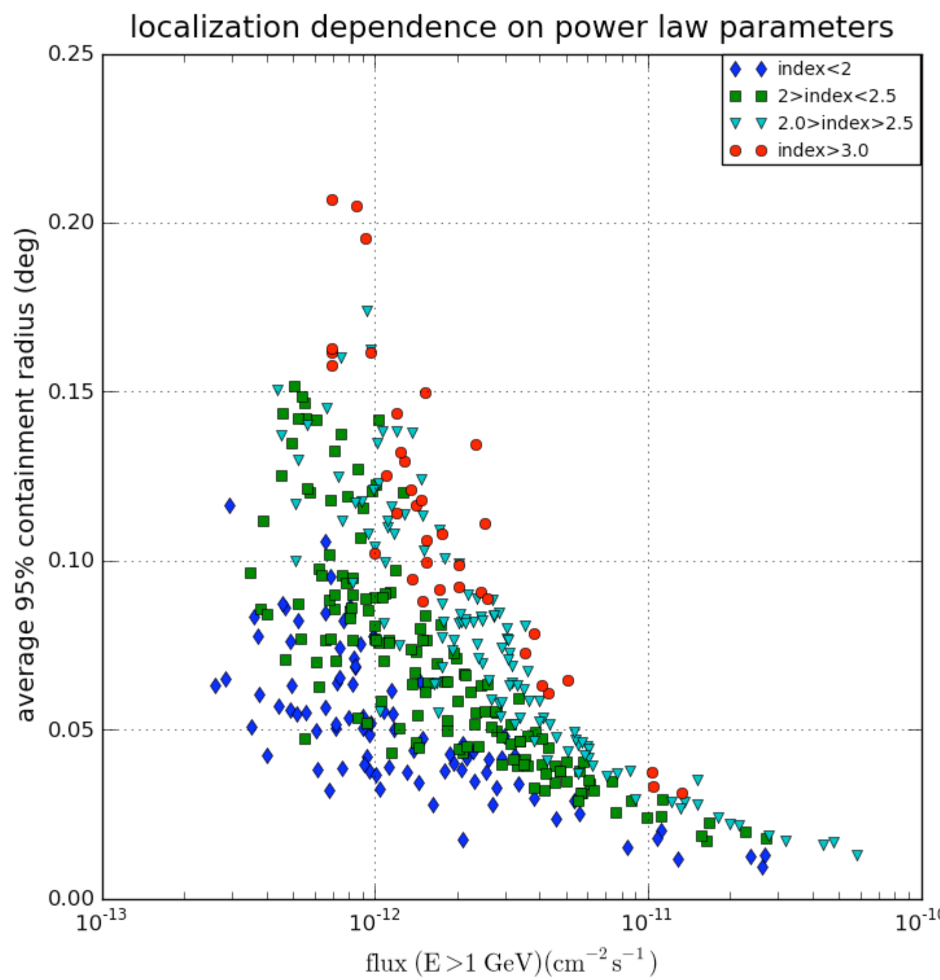
Direct Measurement of the PSF Using Blazars

- The discrepancy implied by the need for the fudge factor can be verified by a direct measurement of the PSF.
- This is a preliminary plot for E>32 GeV, using the same selected sources with ΔTS<9. It shows that the PSF determined from the data is up to ~x2 wider than the Monte Carlo prediction at the highest energies for which we can measure it.



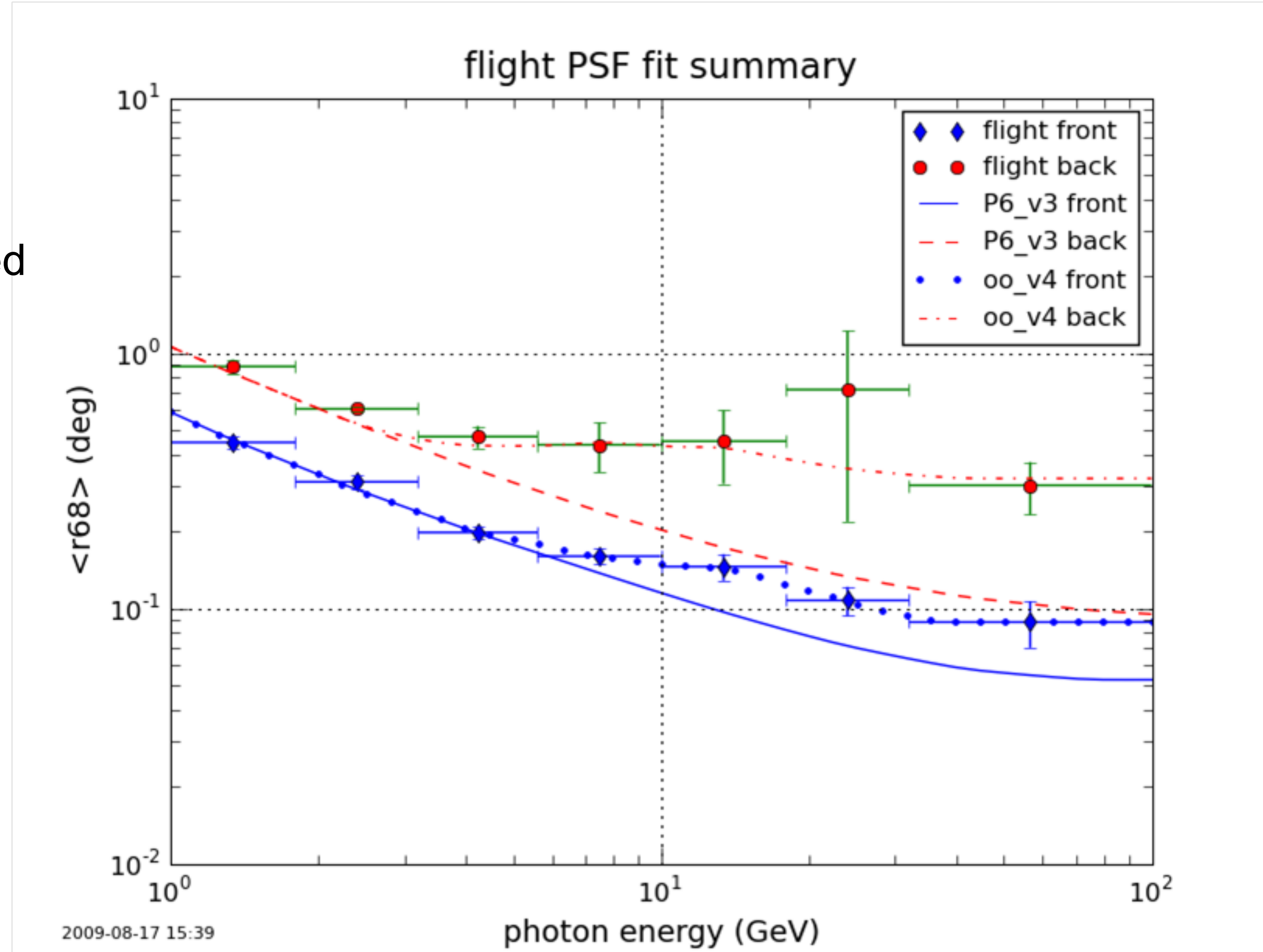
Size of Source Location Region vs. Spectral Fit Parameters

Since the PSF is strongly energy-dependent, the “error box” depends on the spectral shape. The circular confidence radius plotted below is the geometric mean of the elliptical axes. Note that the dependence on flux is consistent with an inverse square root.



High Energy PSF summary

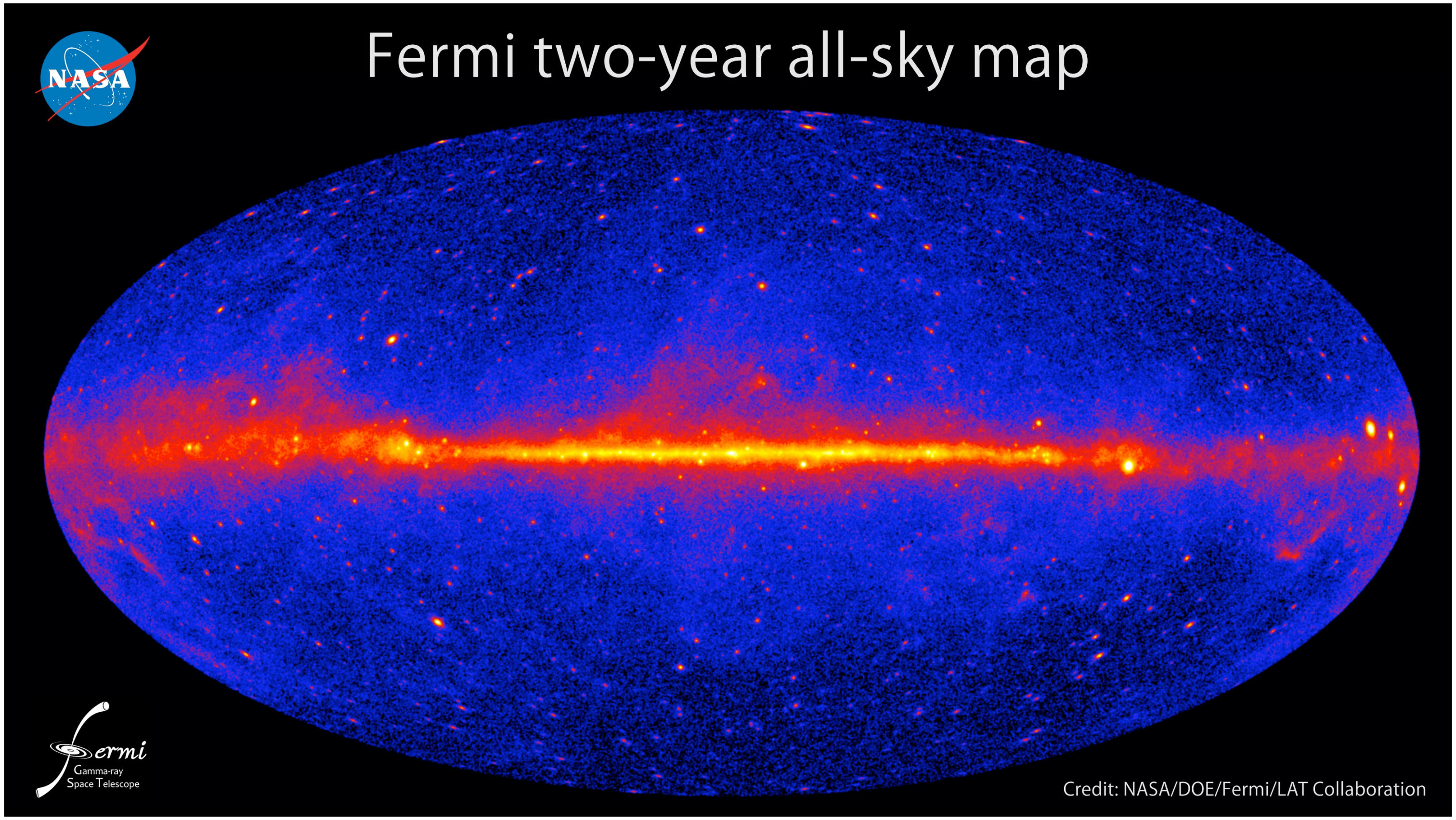
The solid and dashed lines represent the Monte Carlo PSF prediction for front and back. (The „oo_v4" curves correspond to a proposed PSF)



Official Statement from the LAT Team

- The LAT team confirms that the photon distributions in the stacked analysis of blazars that Ando & Kusenko performed are indeed broader than expected based on the P6_V3 Diffuse point-spread function (PSF), which is used in current team publications and released by the team via the FSSC
- We had recognized that the PSF in flight was broader than expected at high energies; this was suggested in the caveats posted at the FSSC and noted in the 1FGL catalog paper
- We are confident that the PSF at high energies is being mis-modeled in our Monte Carlo (MC) simulations of the LAT because we find similarly-broadened profiles in a stacked analysis of bright pulsars (Vela, Crab, and Geminga). The caveats posted on the FSSC page are being updated with this information
- We have recently uncovered a deficiency in our MC simulation that may explain most, if not all, of the mismatch. We are working to deliver rapidly an 'in-flight' PSF that corrects for the effect while we proceed to fix the MC issue. Further instrument performance improvements are also under development
- The redshift dependence of the photon distributions that Ando & Kusenko (2010) report can be understood in terms of spectral evolution of blazars (the $z>0.5$ blazars having softer spectra on average than for $z<0.5$), and the above-mentioned inaccuracy of the P6_V3 Diffuse PSF at high energies

More Caveats



- The background, Galactic diffuse emission, is structured and not very easy to account
- GeV-TeV observations are often non-simultaneous

Relevant Fermi-LAT Observations

Abdo et al.(2009), ApJ, 700, 597 Bright Active Galactic Nuclei Source List from the First Three Months of the Fermi Large Area Telescope All-Sky Survey

Abdo et al.(2009), ApJ, 699, 817 Early Fermi Gamma-ray Space Telescope Observations of the Quasar 3C 454.3

Abdo et al. (2009), ApJ, 707, 1310 Fermi Observations of TeV-Selected Active Galactic Nuclei

Abdo et al.(2009), ApJ, 699, 31 Fermi Discovery of Gamma-ray Emission from NGC 1275

Aharonian et al.(2009), ApJL, 696, L150 Simultaneous Observations of PKS 2155-304 with HESS, Fermi, RXTE, and Atom: Spectral Energy Distributions and Variability in a Low State

Abdo et al.(2009), ApJ, 707, 55 Fermi Large Area Telescope Gamma-Ray Detection of the Radio Galaxy M87

Abdo et al.(2009), ApJ, 699, 976 Fermi/Large Area Telescope Discovery of Gamma-Ray Emission from a Relativistic Jet in the Narrow-Line Quasar PMN J0948+0022

Abdo et al.(2009, ApJ, 697, 934 Fermi/Large Area Telescope Discovery of Gamma-Ray Emission from the Flat-Spectrum Radio Quasar PKS 1454-354

Abdo et al.(2009), ApJL, 707, L142 Radio-Loud Narrow-Line Seyfert 1 as a New Class of Gamma-Ray Active Galactic Nuclei

Abdo et al.(2009), ApJ, 700, 1059 Pulsed Gamma-rays from PSR J2021+3651 with the Fermi Large Area Telescope

Abdo et al.(2010), ApJL, 709, L152 Detection of Gamma-Ray Emission from the Starburst Galaxies M82 and NGC 253 with the Large Area Telescope on Fermi

Abdo et al.(2010), ApJ, 715, 429 The First Catalog of Active Galactic Nuclei Detected by the Fermi Large Area Telescope

Abdo et al.(2010), ApJ, 710, 810 PKS 1502+106: A New and Distant Gamma-ray Blazar in Outburst Discovered by the Fermi Large Area Telescope

Abdo et al. (2010), ApJ, 716, 30 The Spectral Energy Distribution of Fermi Bright Blazars

Acciari et al.(2010), ApJL, 708, L100 Discovery of Very High Energy Gamma Rays from PKS 1424+240 and Multiwavelength Constraints on Its Redshift

Abdo et al.(2010), Nature, 463, 919 A change in the optical polarization associated with a gamma-ray flare in the blazar 3C279

Abdo et al.(2010), ApJ, 722, 520 Gamma-ray Light Curves and Variability of Bright Fermi-detected Blazars

Abdo et al.(2010), Science, 328, 725 Fermi Gamma-Ray Imaging of a Radio Galaxy

Abdo et al.(2010, A&A, 512, A7 Observations of the Large Magellanic Cloud with Fermi

Abdo et al.(2010), ApJ, 708, 1310 Fermi Observations of the Very Hard Gamma-ray Blazar PG 1553+113

Abdo et al.(2009), ApJ, 707, 727 Multiwavelength Monitoring of the Enigmatic Narrow-Line Seyfert 1 PMN J0948+0022 in 2009 March-July

Abdo et al.(2010), 712, 1209 Fermi Large Area Telescope Observations of PSR J1836+5925

Ackermann et al.(2010), ApJ, 721, 1383 Fermi Gamma-ray Space Telescope Observations of Gamma-ray Outbursts from 3C 454.3 in 2009 December and 2010 April

Abdo et al.(2010), ApJL, 714, L73 Fermi-Large Area Telescope Observations of the Exceptional Gamma-ray Outbursts of 3C 273 in 2009 September

Abdo et al.(2010), ApJ, 720, 912 Fermi Large Area Telescope Observations of Misaligned Active Galactic Nuclei

Abdo et al.(2010),ApJ, 719, 1433 Fermi Large Area Telescope View of the Core of the Radio Galaxy Centaurus A

Abdo et al.(2010, ApJ, 721, 1425 Fermi Large Area Telescope and Multi-wavelength Observations of the Flaring Activity of PKS 1510-089 between 2008 September and 2009 June

Acciari et al.(2010), ApJL, 715, L49 The Discovery of {γ}-Ray Emission from the Blazar RGB J0710+591

Abdo et al.(2010), A&A, 523, L2 Fermi Large Area Telescope observations of Local Group galaxies: detection of M 31 and search for M 33

Abdo et al.(2010), A&A, 523, A46 Detection of the Small Magellanic Cloud in gamma-rays with Fermi/LAT

Abdo et al.(2010, ApJ, 716, 835 Suzaku Observations of Luminous Quasars: Revealing the Nature of High-energy Blazar Emission in Low-level Activity States

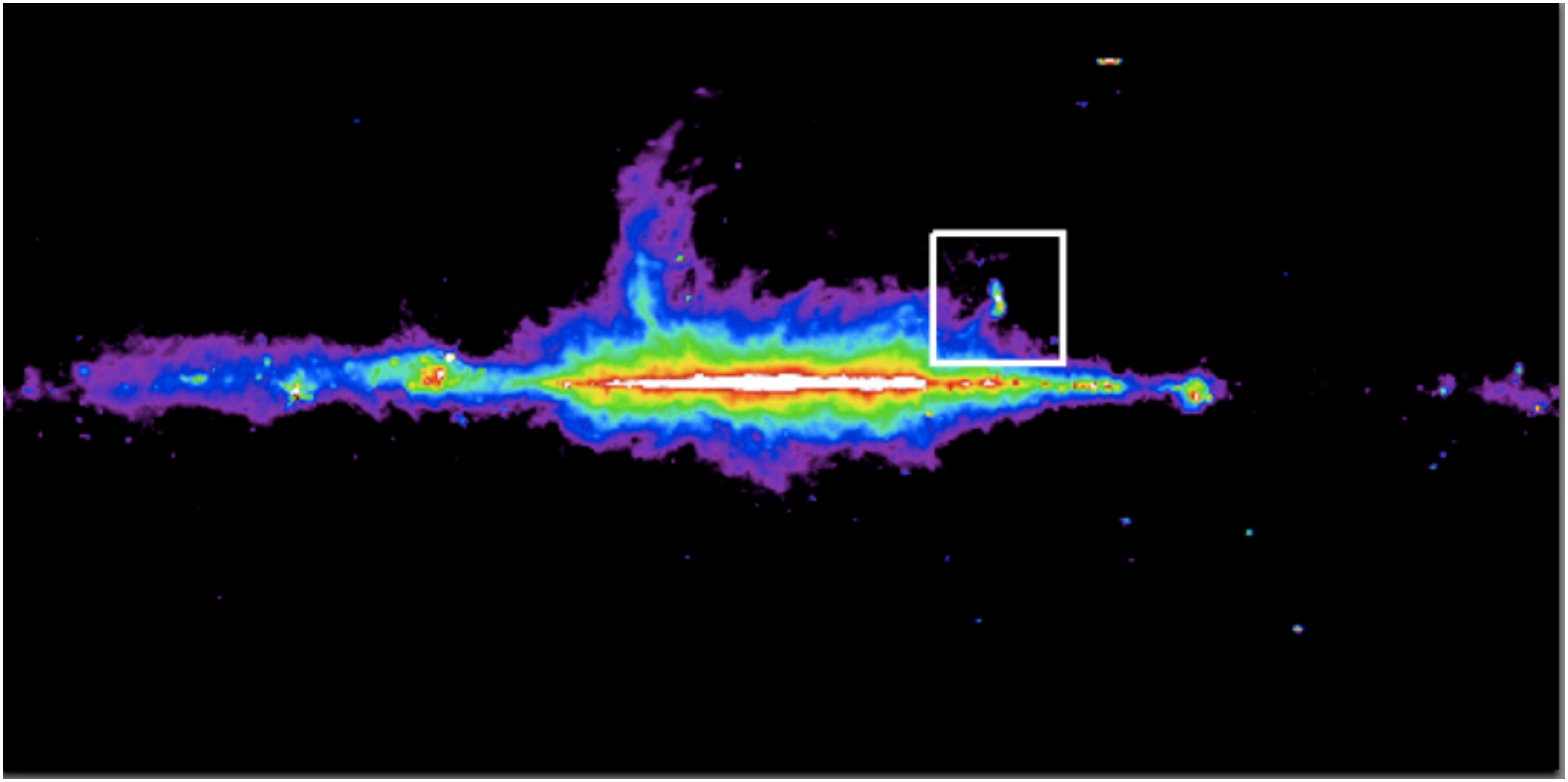
Abdo et al.(2010), ApJ, 710, 1271 Spectral Properties of Bright Fermi-Detected Blazars in the Gamma-Ray Band

Cen A Summary

- Confirms pre-launch expectation that radio lobes can produce **inverse Compton γ-ray emission**
- Cen A is (uniquely) large enough ~10^{o} to directly image with Fermi-LAT
- Require 0.1-1 TeV electrons in giant 'relic' lobes: accelerated in-situ or efficient transport from center
- Estimate E_{tot} = 10^{58} erg, jet power ~10^{43} erg s^{-1} (~10^{-3} L_{edd}), non-thermal/ thermal plasma pressures comparable
- Implication for emission region/ mechanism in LAT radio galaxies?

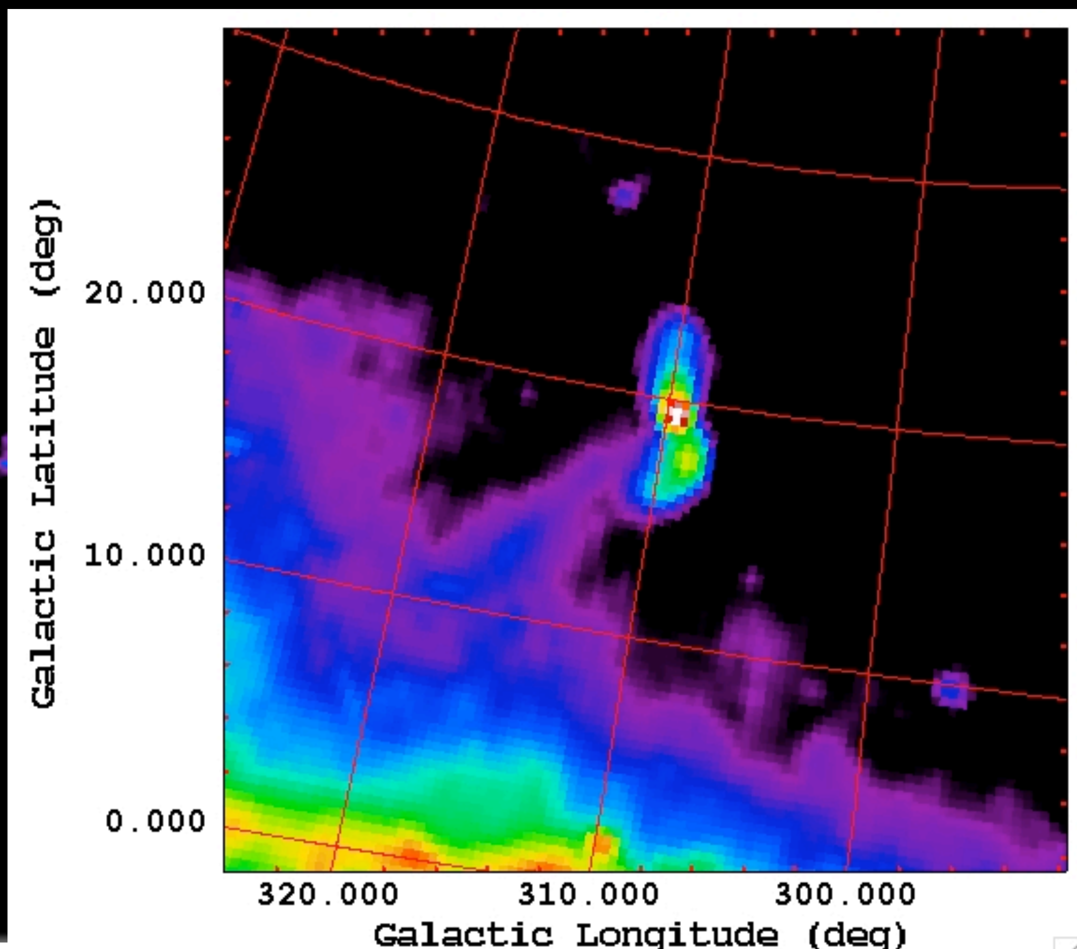
NASA/DOE/Fermi-LAT Collab., Capella Obs.

Cen A the Radio Galaxy

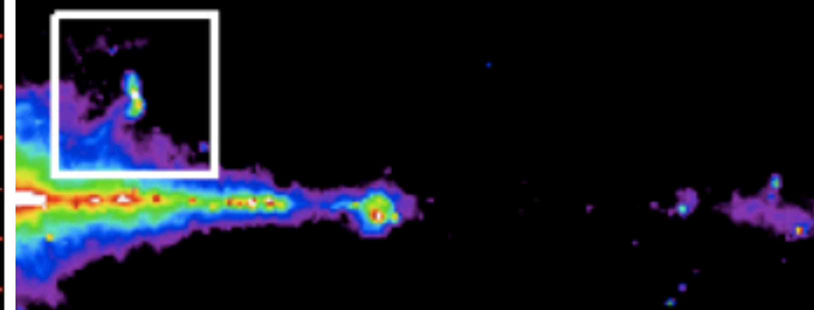


All-sky 408 MHz (Haslam et al. 1982)

Cen A the Radio Galaxy



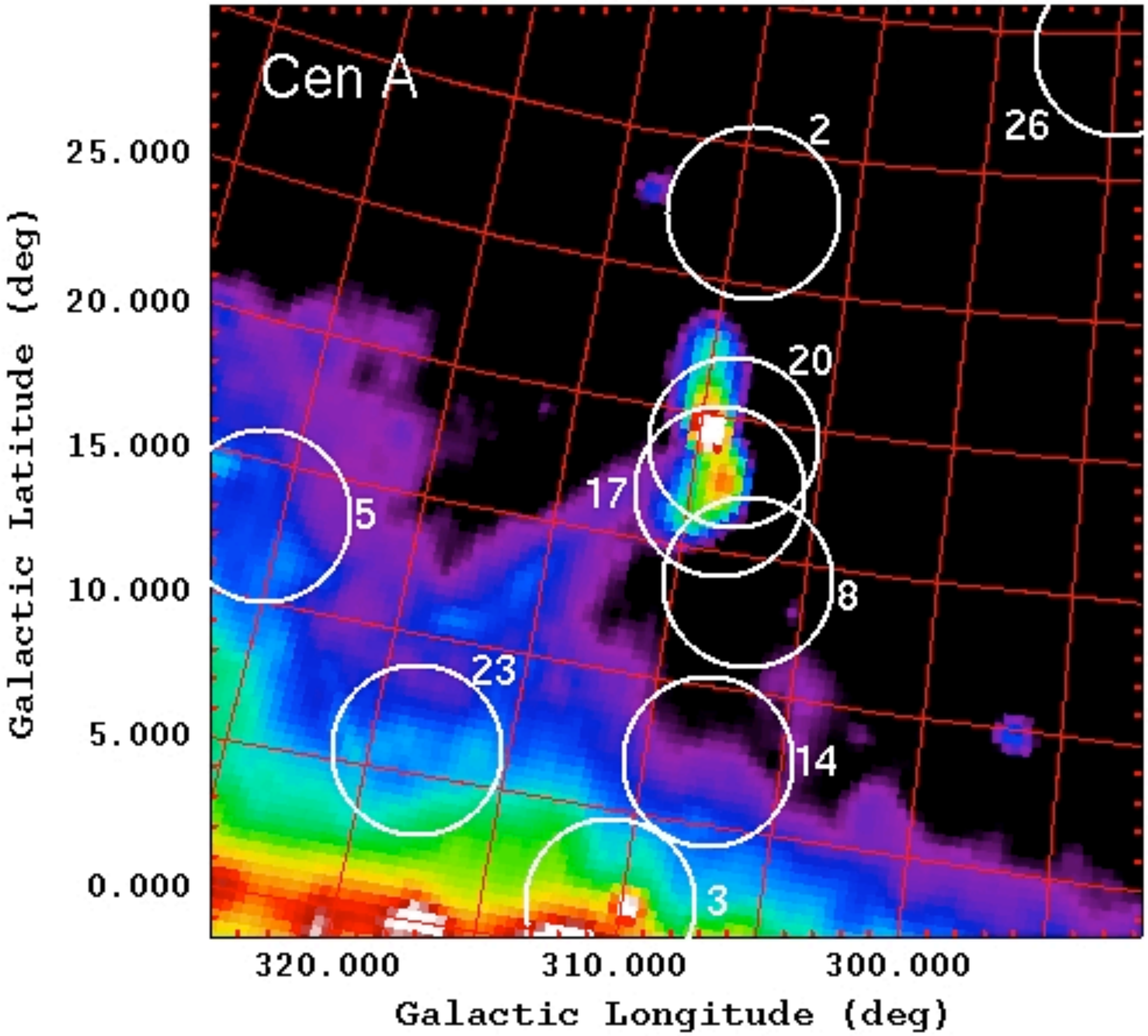
- Nearest Radio-loud AGN
- Radio source extent ~10°
- At D=3.7 Mpc, *L*=600 kpc



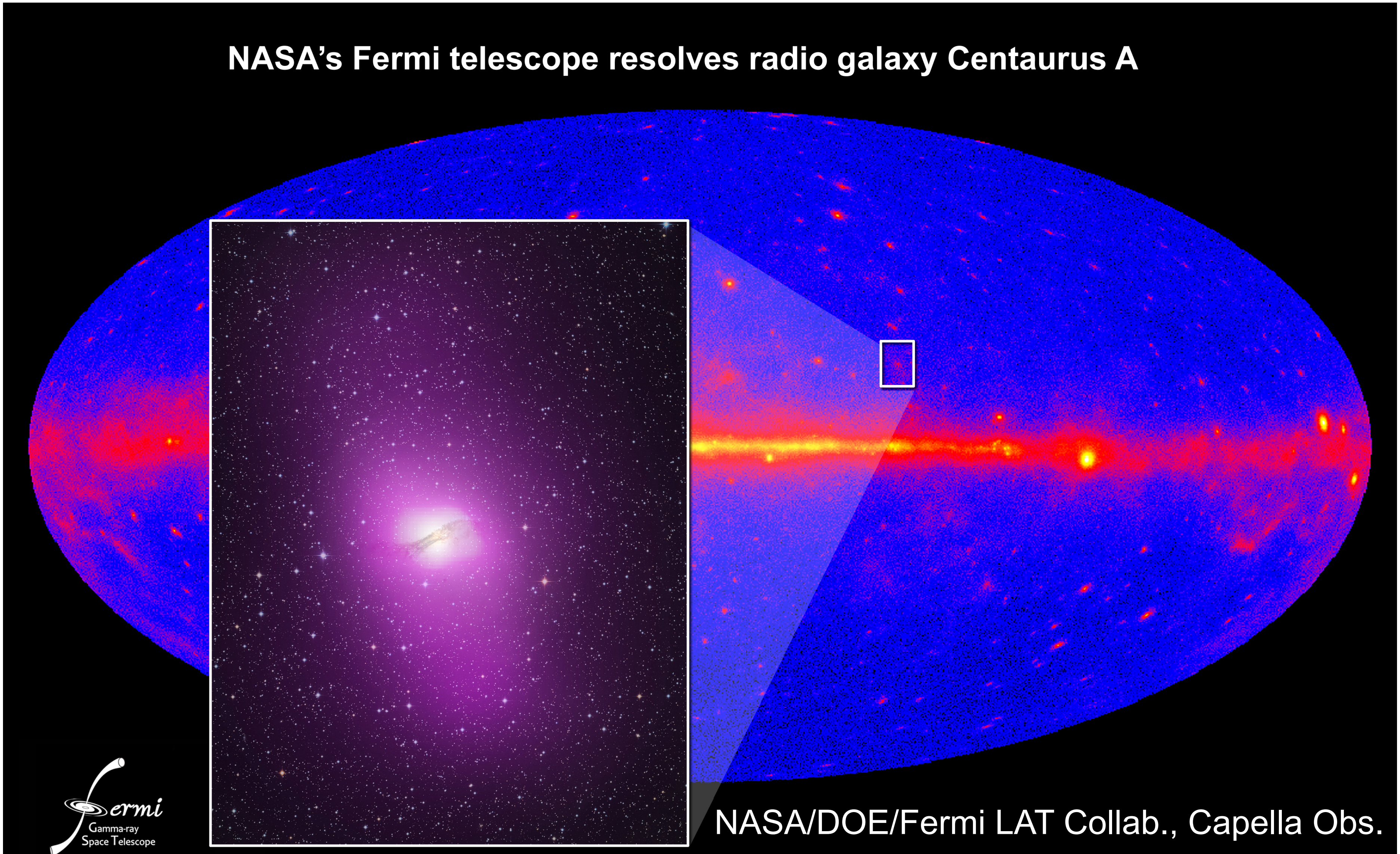
- Non-blazar GeV/TeV AGN
  - LAT resolution = 0.8° at 1GeV: can *image* radio lobes

All-sky 408 MHz (Haslam et al. 1982)

Clustering of UHECR Events (Auger)

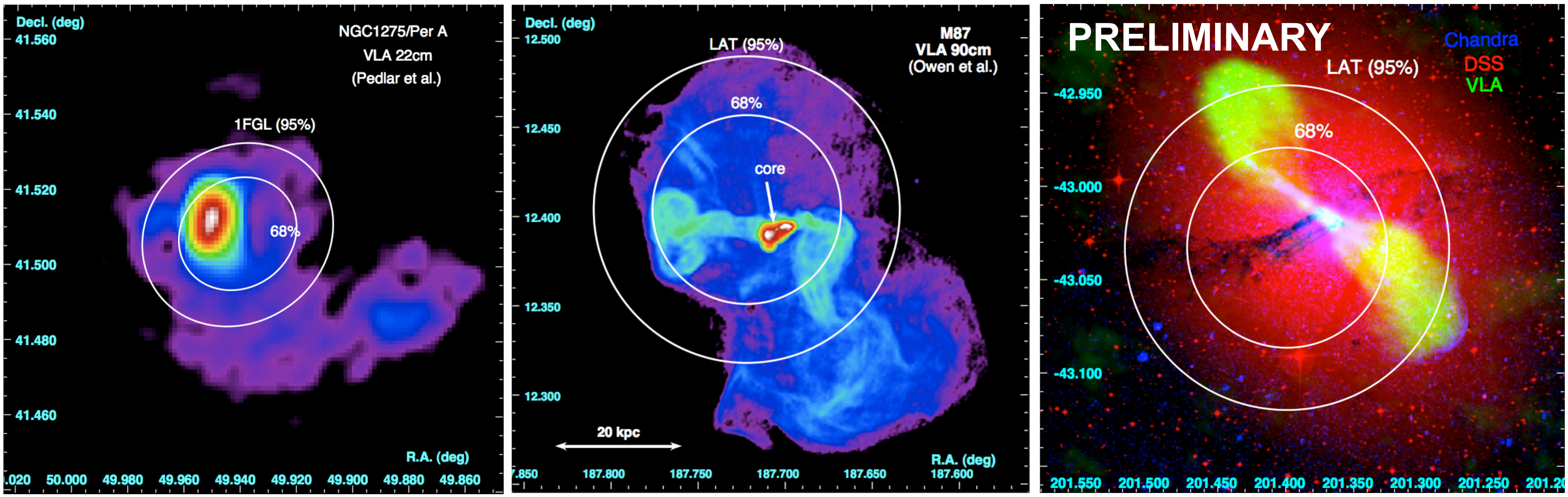


Cen A the Gamma-ray Galaxy



LAT Associations: *Precise* γ-ray Localizations

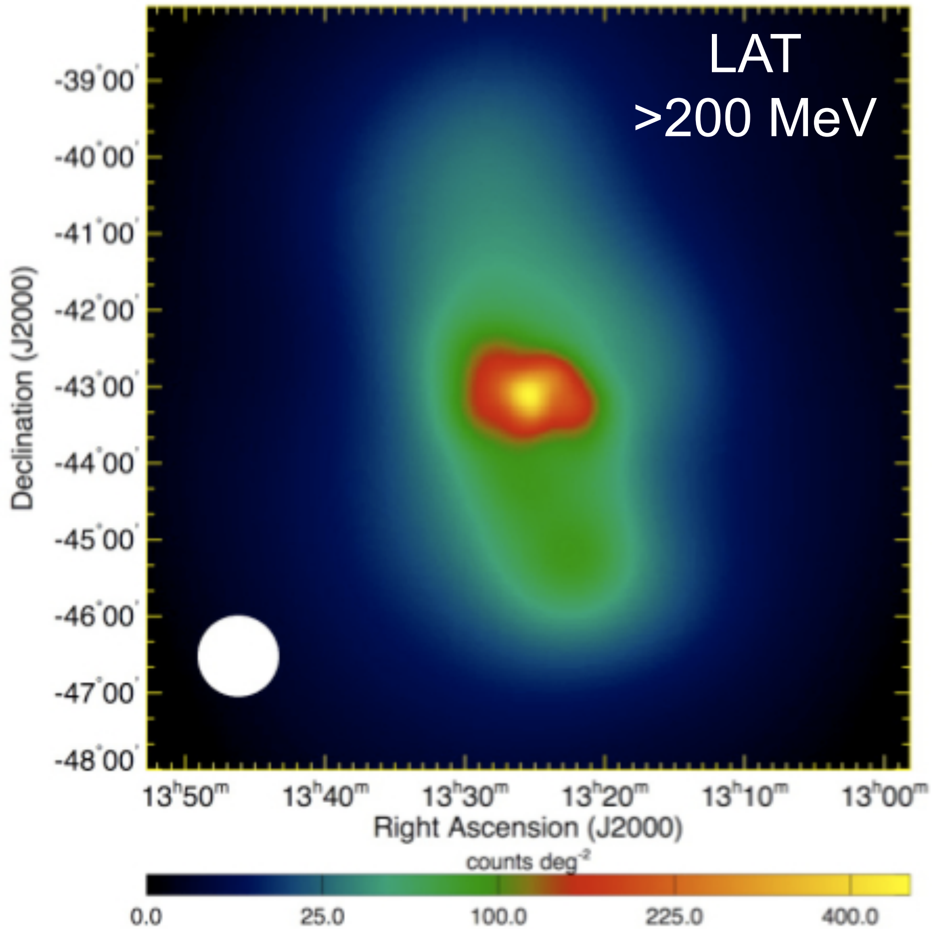
- LAT γ-ray localizations, *radii* (95%) ~ 1.5 – 5 arcmin correspond to ~5-25 kpc for nearest radio galaxies



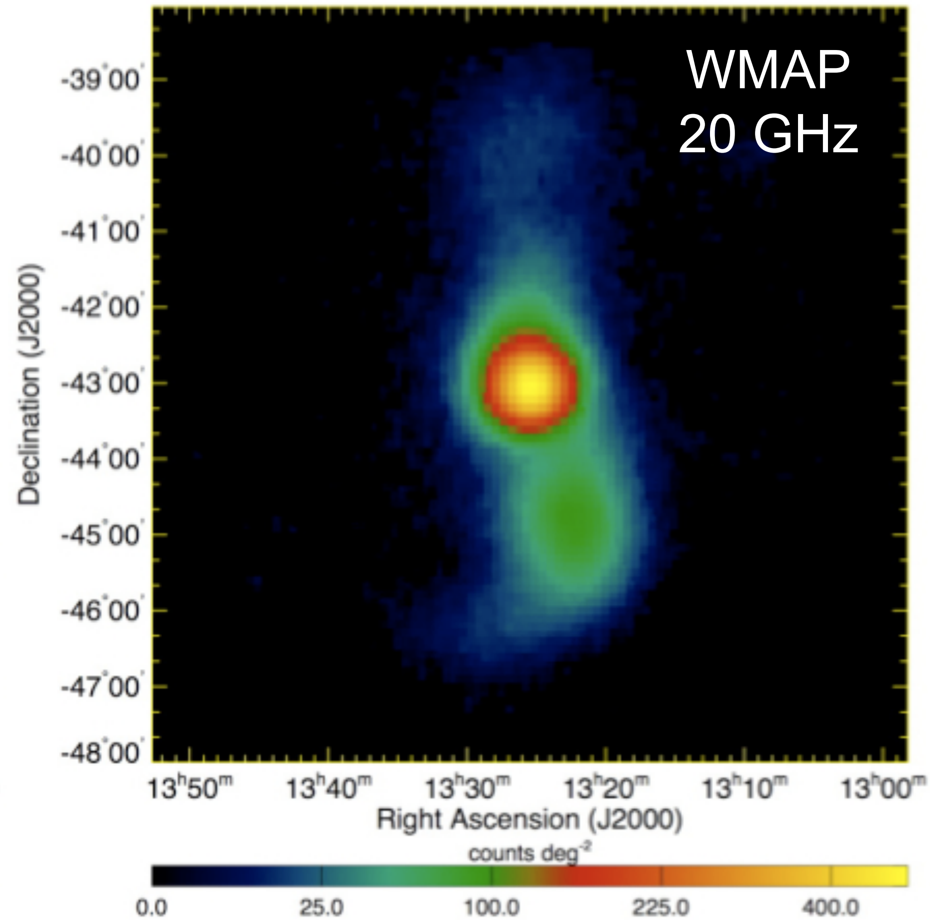
Pictured are LAT 68% and 95% confidence ellipses on radio images (+optical/X-ray in Cen A)

First γ-ray Imaging of Radio Galaxy Lobes

Over ½ of the total >100 MeV observed LAT flux in the lobes



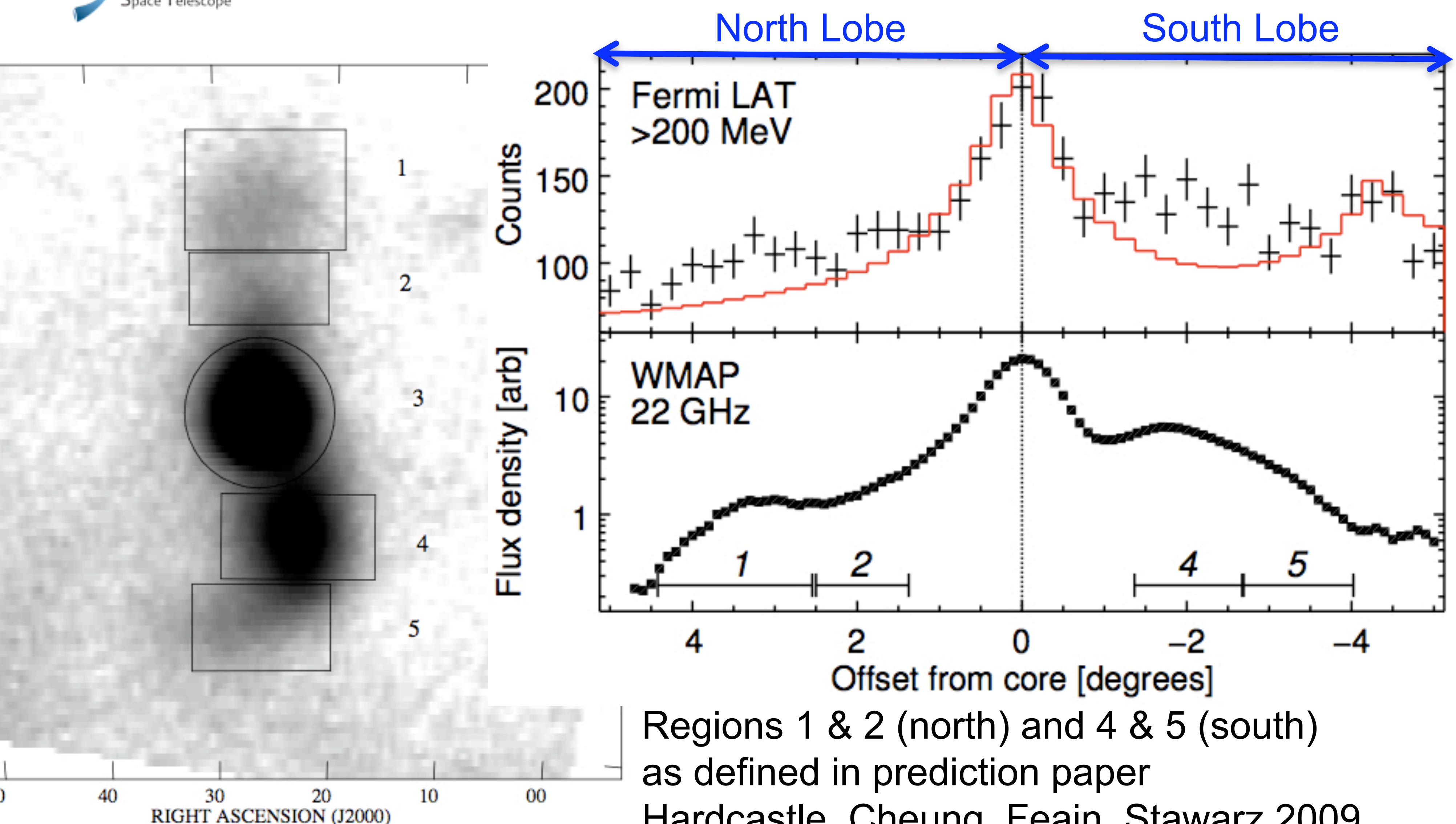
Background & point sources subtracted



From Nils Odegard (GSFC)

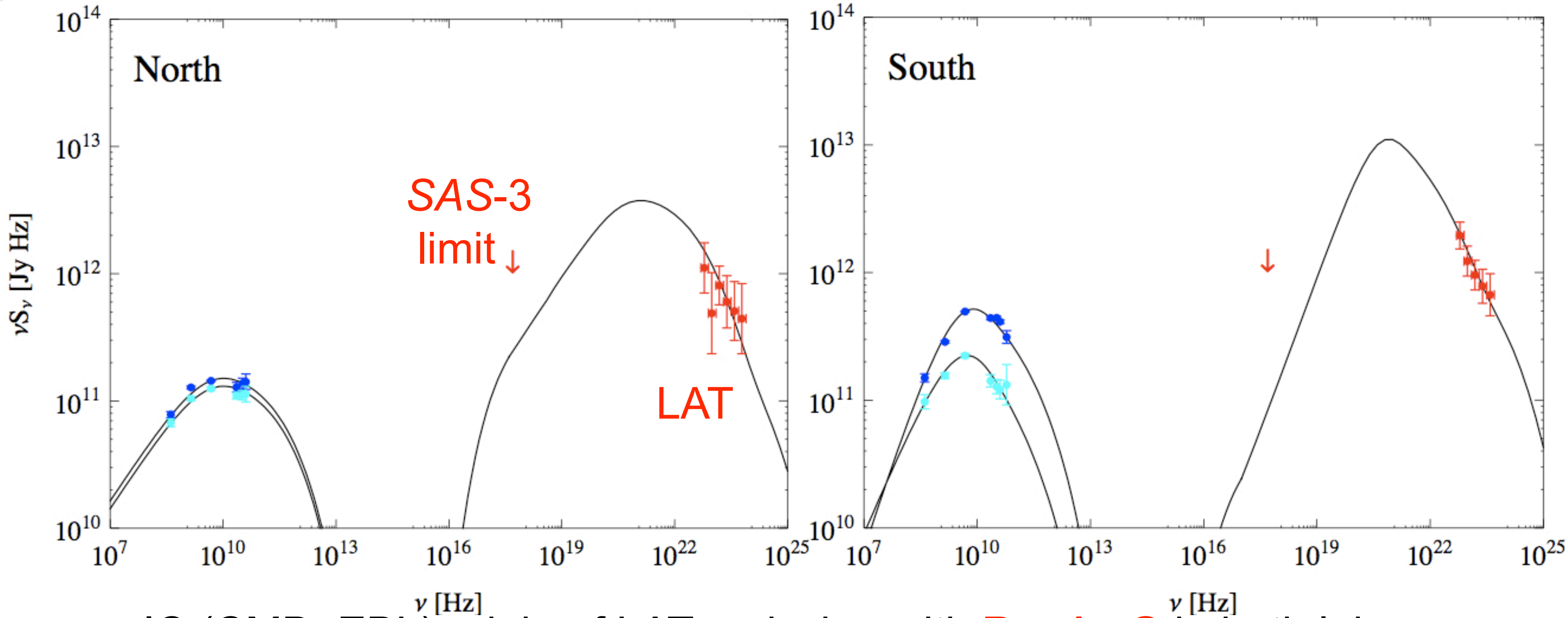
2010 Science, 328, 725; Leads: Cheung, Fukazawa, Knodlseder, Stawarz

Gamma-ray and Radio Counts Profiles



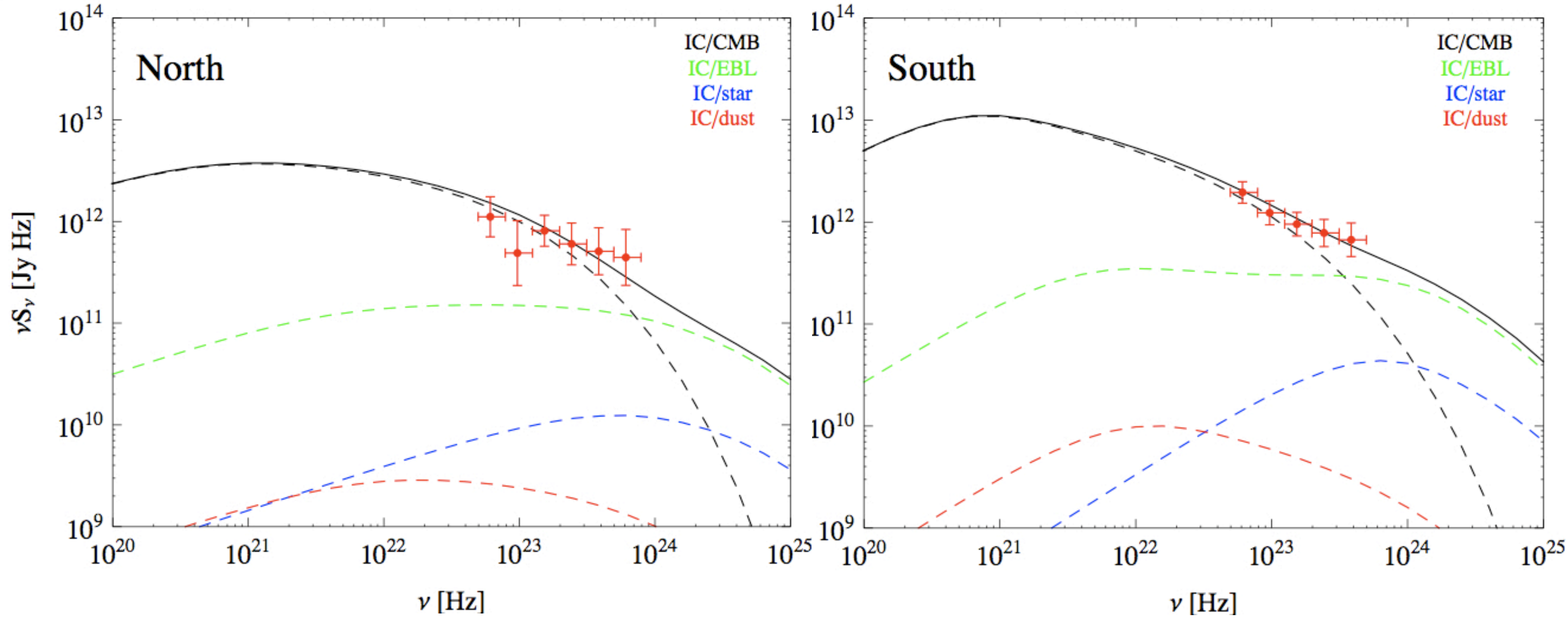
Regions 1 & 2 (north) and 4 & 5 (south) as defined in prediction paper Hardcastle, Cheung, Feain, Stawarz 2009

Imaging Inverse Compton γ-ray Emission



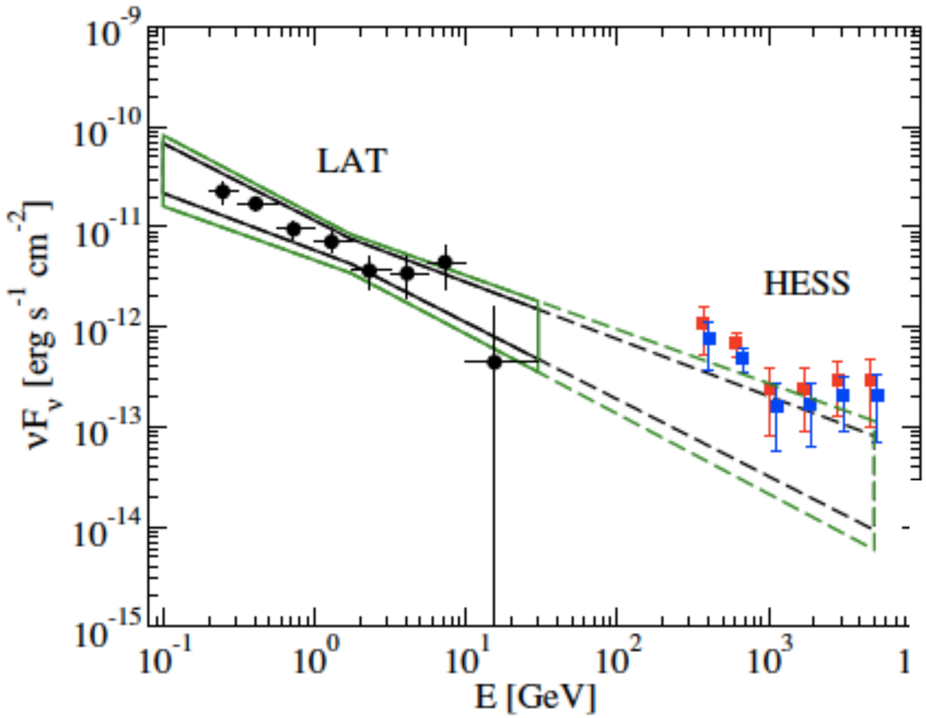
- IC (CMB+EBL) origin of LAT emission with **B ~ 1 μG** in both lobes, near equipartition
- IC component dominant, U_{CMB}/U_B **~ 10** -- 'requires' the lower *B*-field in Cen A lobes than typical in other (more powerful) examples
- **First inverse Compton lobe measurements in γ-rays!**

Inverse Compton Emission: Close-up

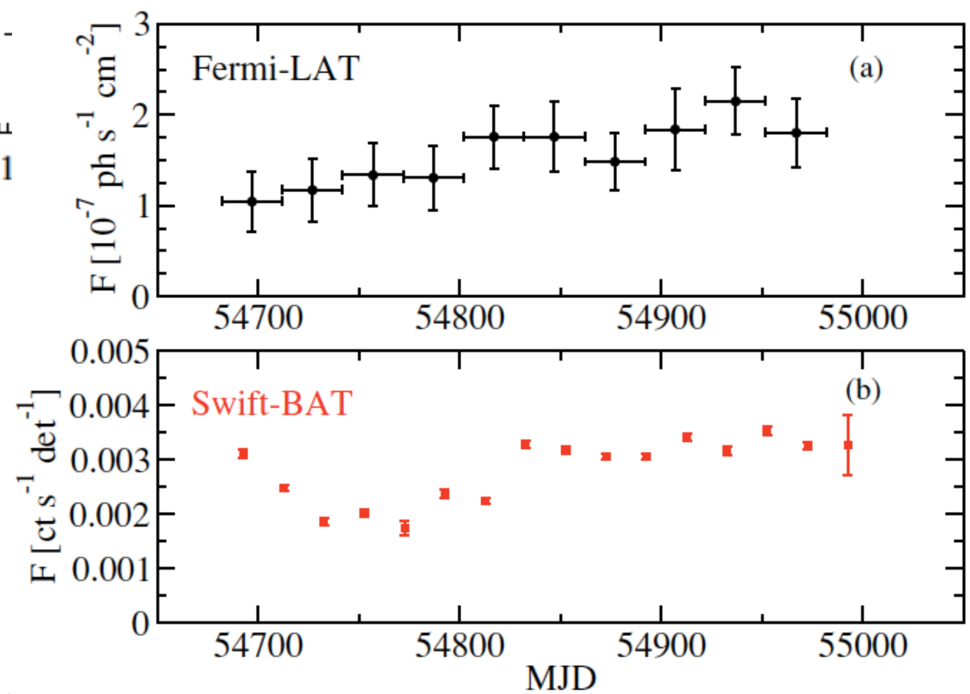


- LAT γ−ray emission dominated by IC/CMB component for the modeled electron energy spectra (broken power-law + exponential)
- Can uniquely probe EBL which dominates here at higher-energies, >GeV (cf., Georganopoulos et al. 2008 for Fornax A)
- Host galaxy + dust components negligible at >100's kpc from center

Cen A Core: Fermi-LAT vs. HESS

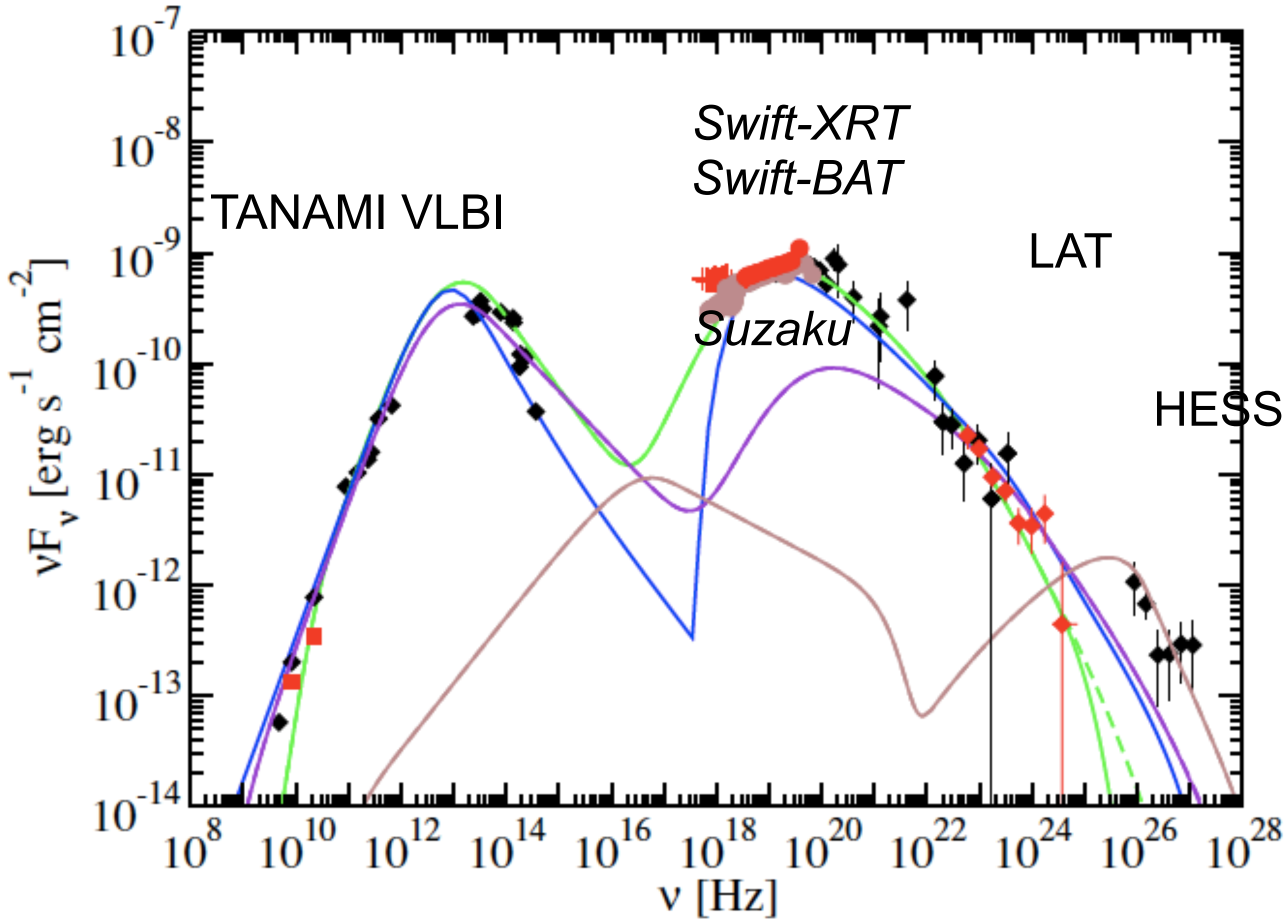


- The flux does not show large variations and compatible with const, meanwhile long-term variations of the TeV flux can not be excluded



- Fermi-LAT and HESS non-simultaneous observations are marginally compatible when HESS data are shifted by their systematic error

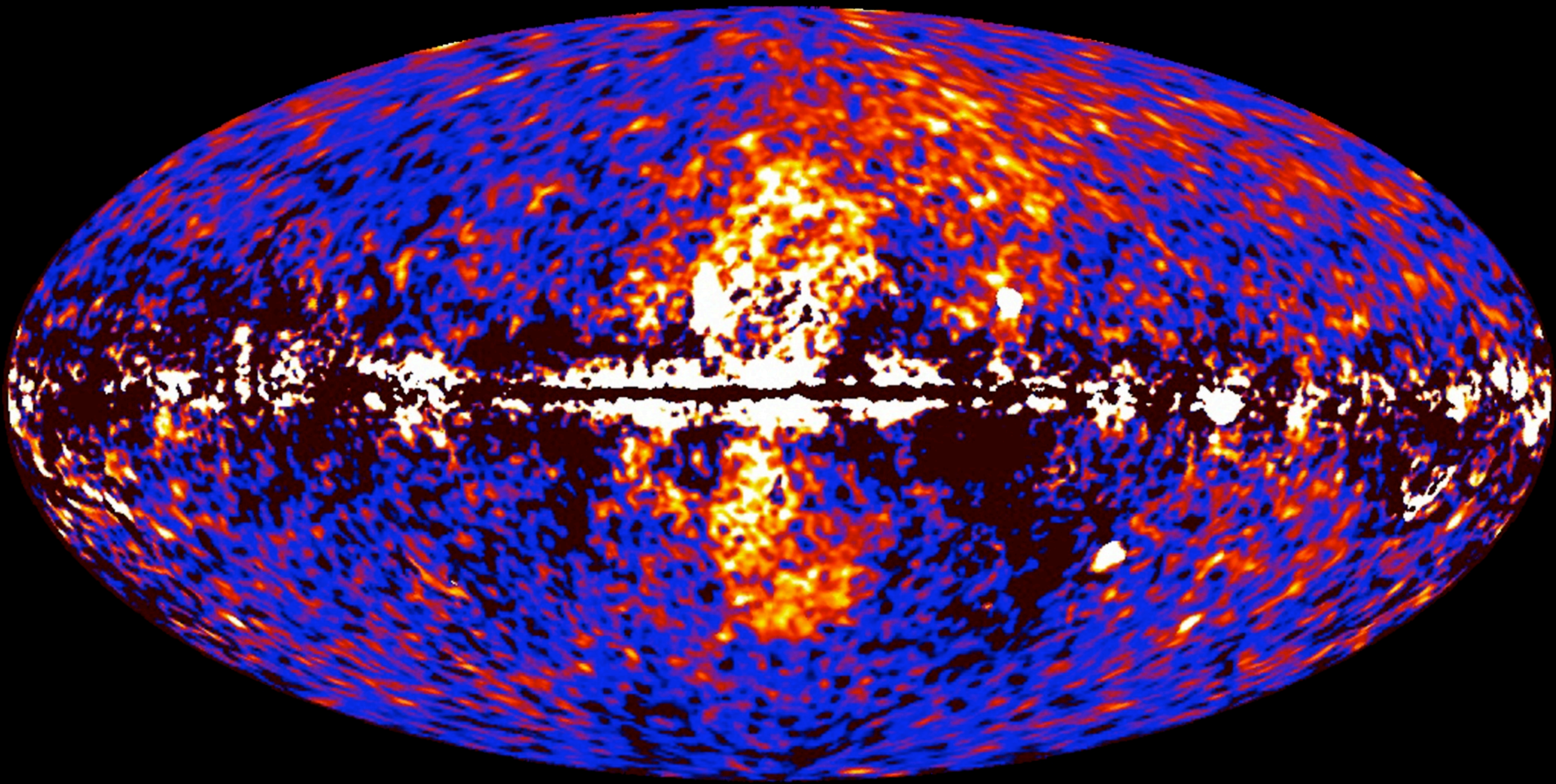
Cen A Core: SED Modeling



HESS data does not fit into the model and require a separate component

Curves are model fits to nuclear region of Cen A. The green curve is a synchrotron/*SSC fit to the entire data set. The dashed green curve shows this* model without *γγ attenuation. The* brown curve is designed to fit the HESS data while not overproducing the other data in the SED.

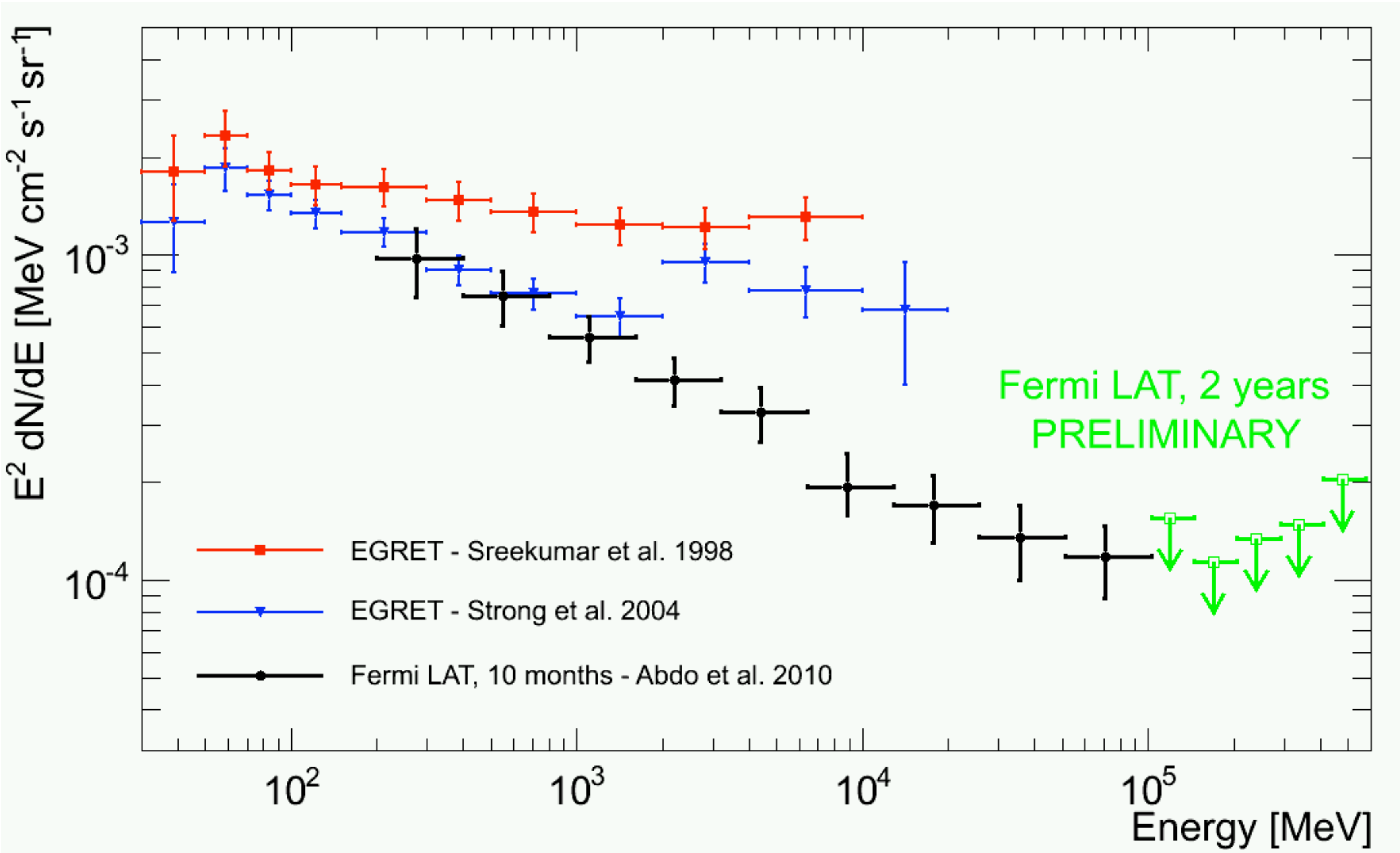
Gamma-Ray Lobes



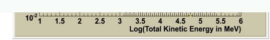
The new structure consists of enormous bubbles extending about 50° north and south of the galactic center.

Su, Slayter and Finkbeiner, 2010

Isotropic extragalactic diffuse emission



DataClean photon sample was necessary



Residual instrumental bkg (MC)

3rd Fermi Symposium

May 9-12, 2011 in Rome, Italy.

http://fermi.gsfc.nasa.gov/science/symposium/2011/


Ikonos, Paris, 1 metre Pan-sharpened
Thank you!
eurimage