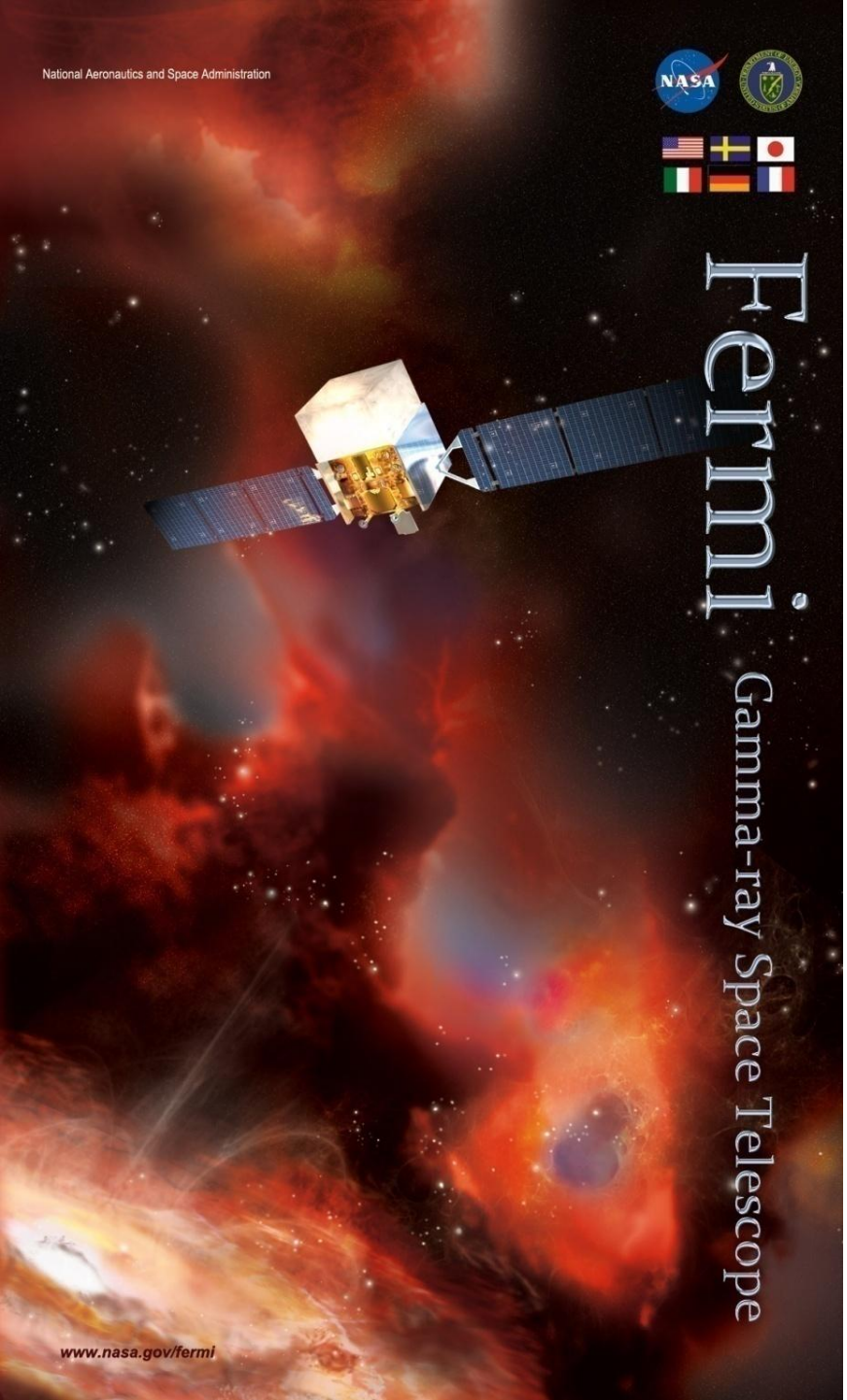


Selected *Fermi*-LAT Results from the Past Year

Keith Bechtol[1]

on behalf of the

***Fermi*-LAT Collaboration**

1 Kavli Institute for Cosmological Physics, University of Chicago

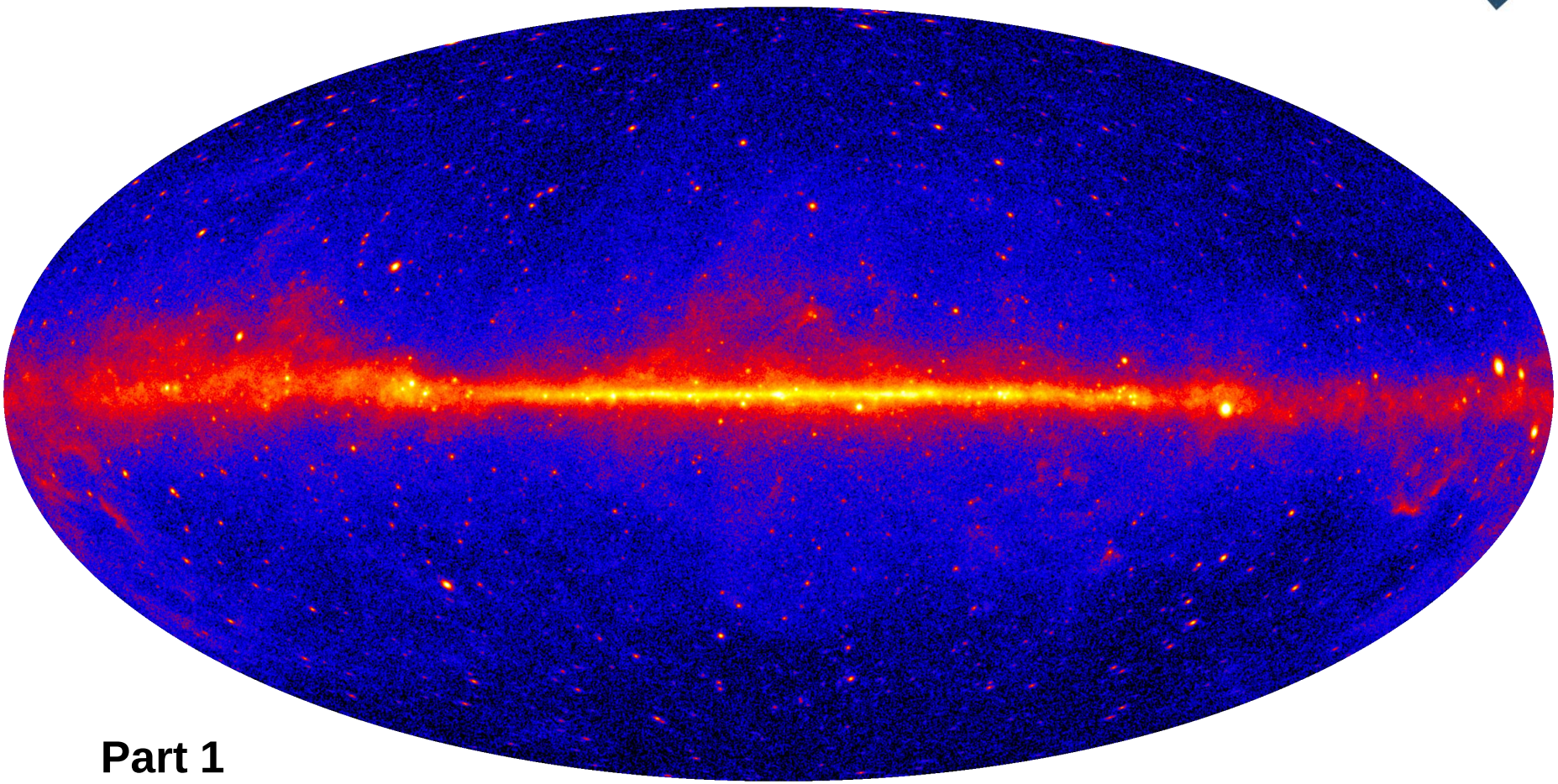
IceCube

Particle Astrophysics Symposium

14 May 2013

Fermi-LAT Talks at IPA Symposium 2013

- **Indirect Searches for Dark Matter with the *Fermi* LAT**
  - **Andrea Albert**
- **Galactic Sources in *Fermi***
  - **Liz Hays**
- **Gamma-Ray Bursts with *Fermi***
  - **Nicola Omodei**



Part 1

Mission Update

4-year counts map >1GeV
P7V6 Source class events
Front-converting only

Nearly 5 Years of Smooth Operations

As of Feb 2013:

- **99.7% uptime**
- **>280 billion triggers, >56 billion events to ground, ~250 million source event class photons available at the *Fermi Science Support Center***

Observation mode updates:

- **Still mainly sky-survey (50 deg rocking)**
- **Weekly 2-orbit pole observations added Sep 2012 (Earth limb)**
- **Nadir observations (TGFs)**
- **Alternatives to sky survey have been considered and white papers submitted in late April***

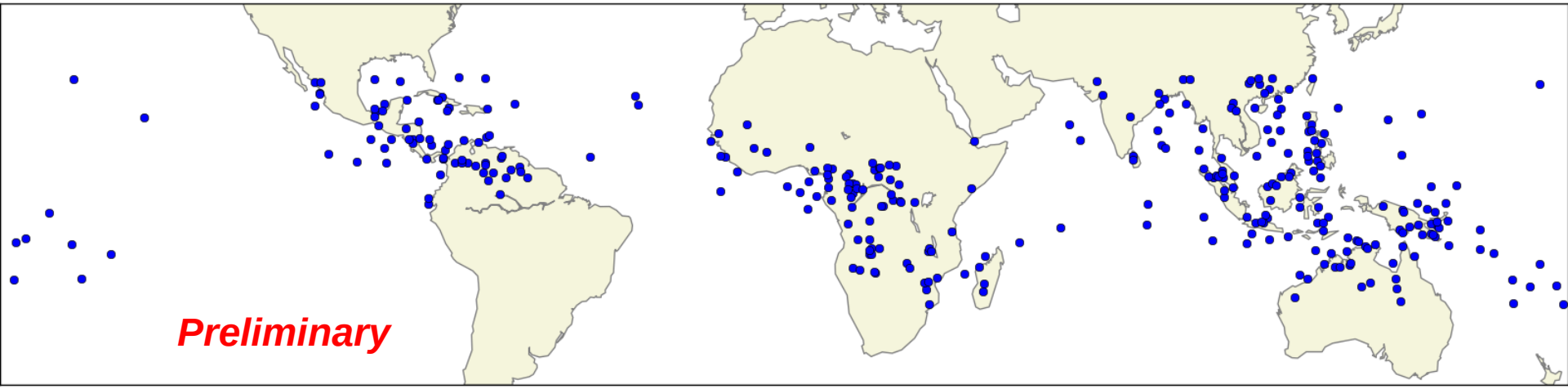
  "Multiple ideas, or combinations thereof may ultimately be implemented. Continuing dialogs between any groups involved and the Fermi Project are also encouraged."

11 Jun 2008

* http://fermi.gsfc.nasa.gov/ssc/proposals/alt_obs/obs_modes.html

Terrestrial Gamma-ray Flashes

- **Approved Cycle 4 and 5 Guest Investigator programs,**
  - **25 nadir observations each season (~1% duty cycle)**
  - **Program extends through Aug 2013**
- **Status**
  - **22 TGFs from first season of nadir observations**
  - **319 high confidence TGFs from sky-survey up to Jun 2012**
  - **Trigger request rates >1MHz, high-multiplicity events**



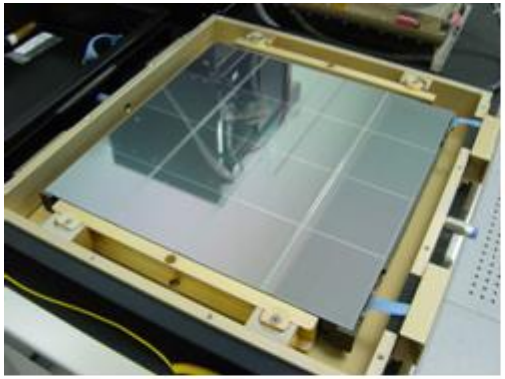
Location of LAT at time of TGF correlates with active thunderstorm regions, season

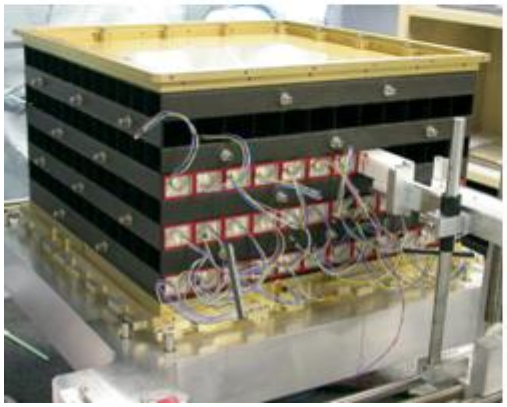
Fermi-LAT Hardware

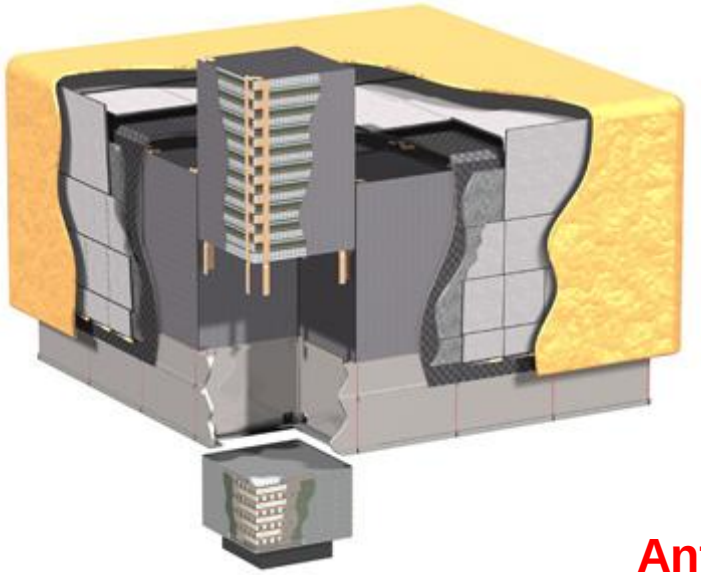
Precision Converter and Tracker

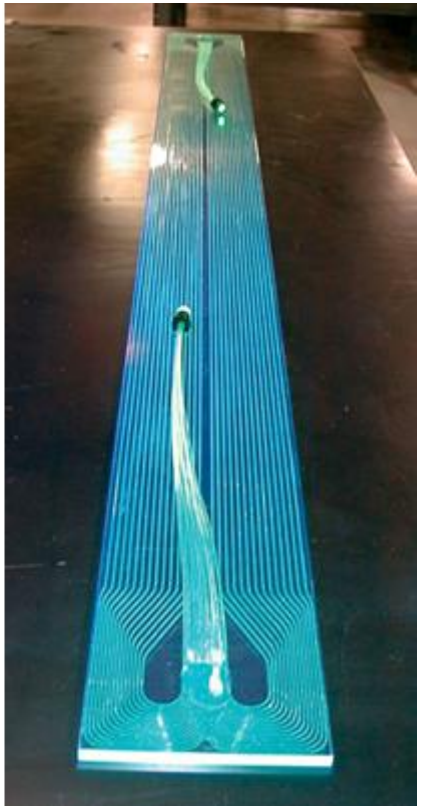
- Single sided SSD (40 cm, 228 um) ~ 80 m^2
- W foil interleaved (12x3% RL, 4x18% RL)
- 18 xy planes
- 1.5 RL

Thin/Front Thick/Back









Imaging Calorimeter

- 8.6 R.L.
- 1536 CsI crystals
- Hodoscopic (12 x 8 layers)

(+ Data Acquisition System)

- 500 Hz sent to ground

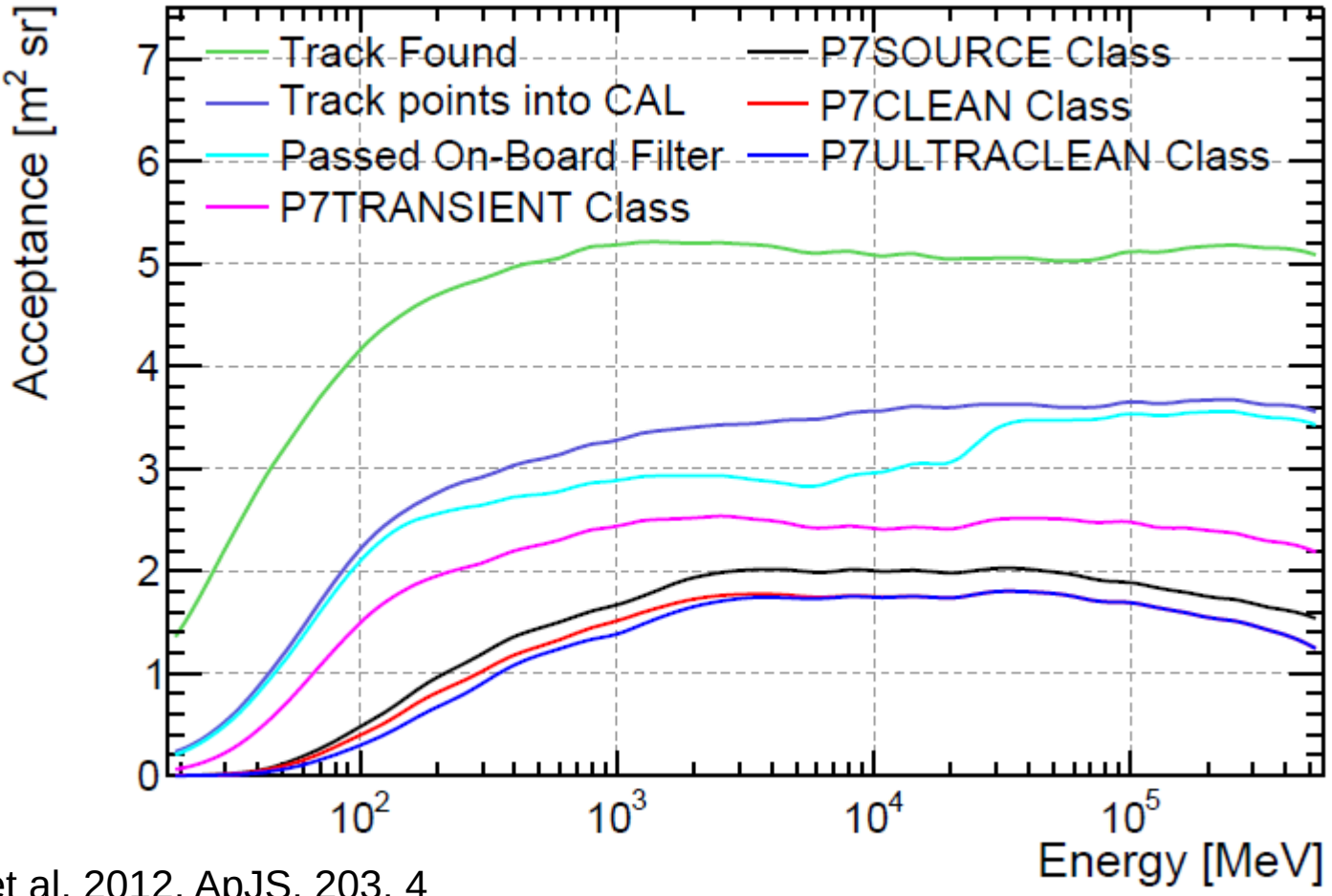
Anti-Coincidence Detector

- 4% RL
- Segmented (89 plastic scintillator tiles, 8 ribbons)
- 0.9997 efficiency

Atwood et al. 2009, ApJ, 697, 1071

LAT Performance Paper

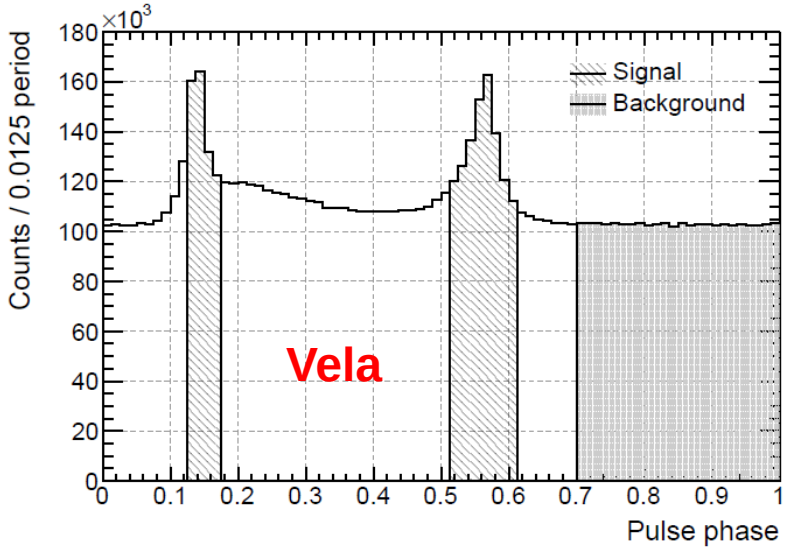
Detailed discussion of **data processing, event selections, instrument response** (effective area, PSF, energy resolution, background contamination), and **on-orbit validation studies,** as well as propagation of uncertainties into high-level analysis for the Pass 7 event reconstruction and classification

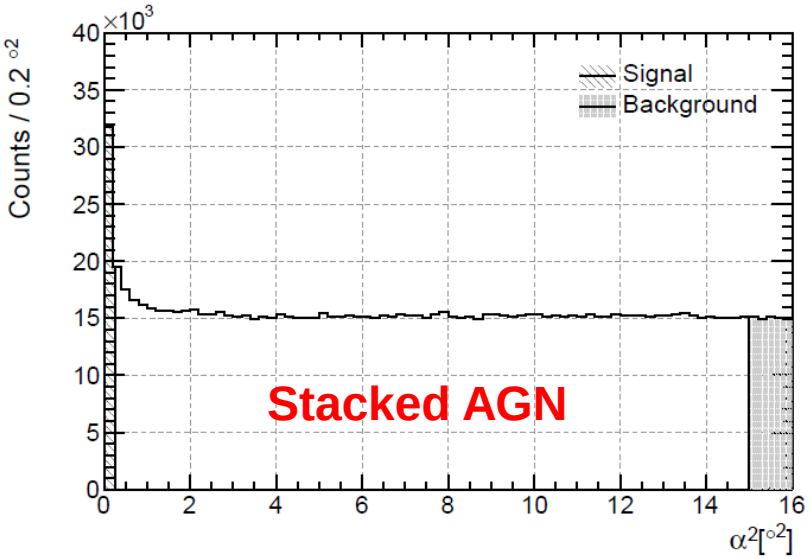


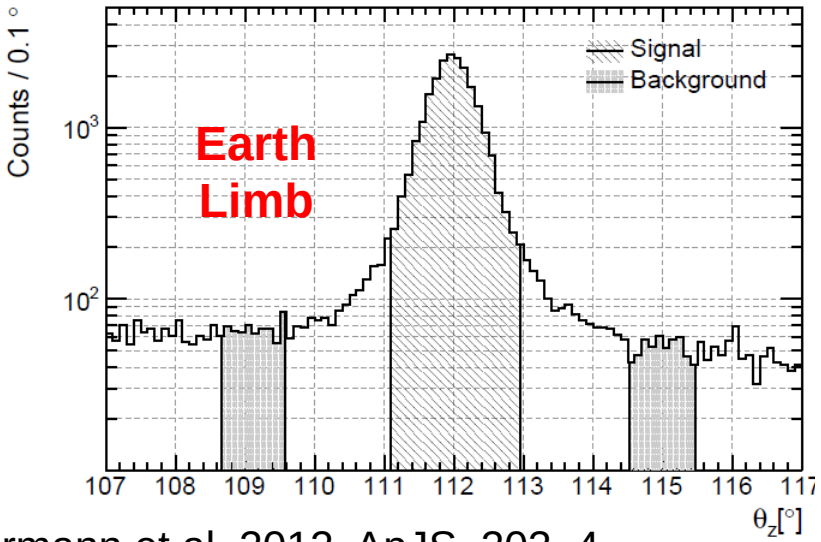
Ackermann et al. 2012, ApJS, 203, 4

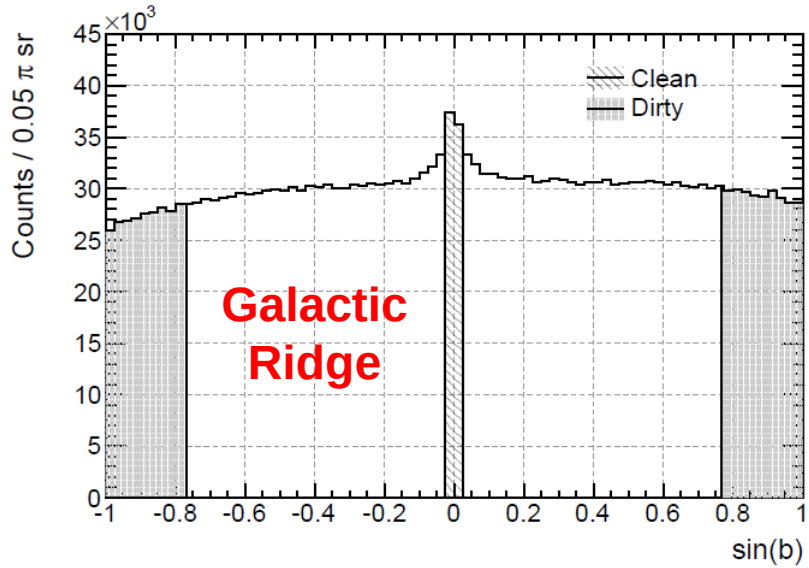
LAT Performance Paper

Example: 4 signal-rich calibration "sources" to validate effective area/PSF



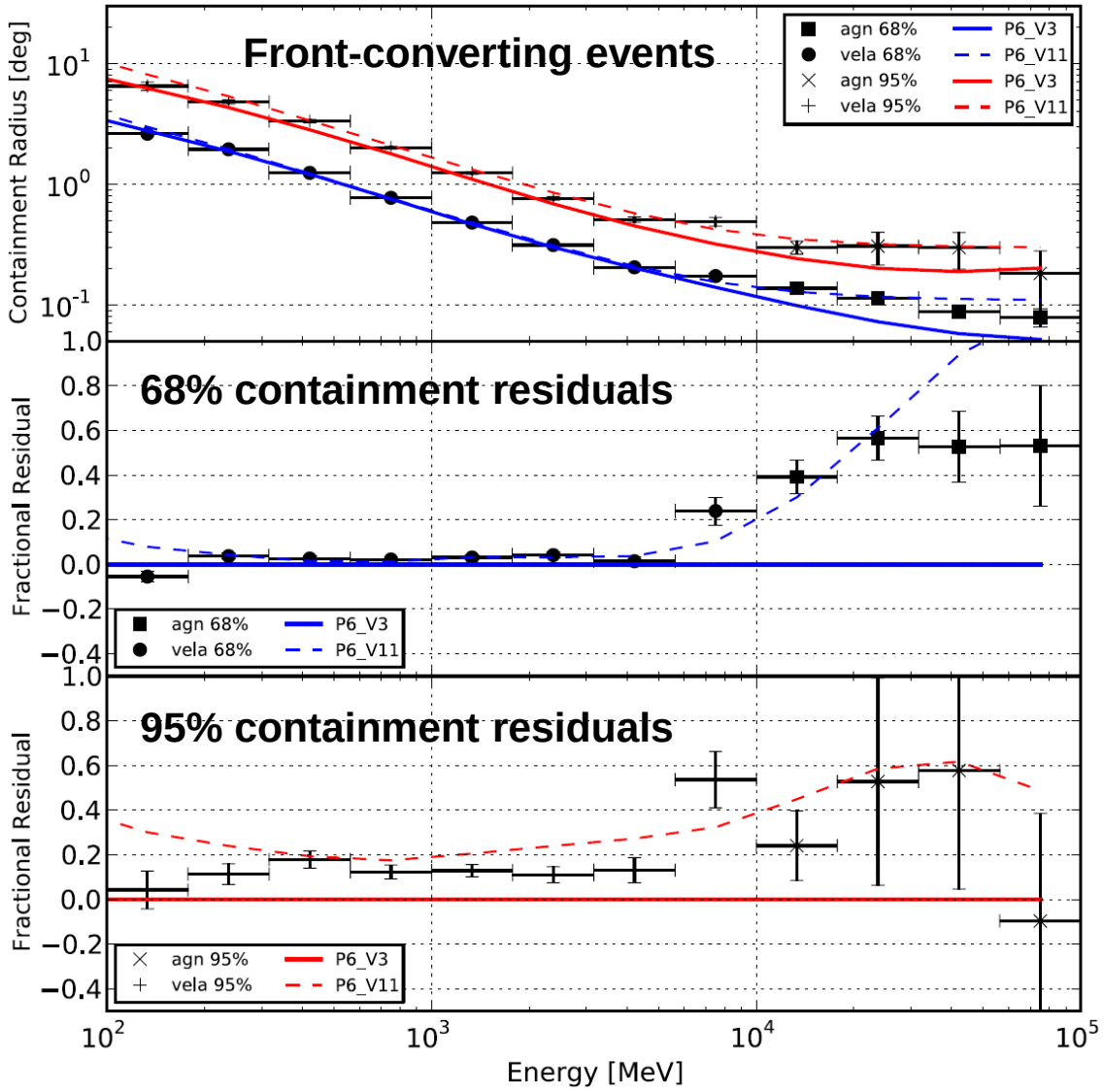






Ackermann et al. 2012, ApJS, 203, 4

On-orbit PSF Calibration (and search for pair halos around AGN)



On-orbit PSF >3GeV measured to be larger than pre-launch PSF estimated through beam tests and MC simulations

Several physical processes have been proposed which could create extended halos around AGN

- IC of CMB by secondary e^+e^-
- TeV photons or UHECRs could create secondary cascades
- Physical extension depends on intergalactic magnetic field

No significant extension beyond the PSF is found. Set upper limits on halo amplitude for stacked images of z>0.5 BL Lacs, and the TeV blazars 1ES0229+200 and 1ES0347-121

Ackermann et al. 2013, ApJ, 765, 54

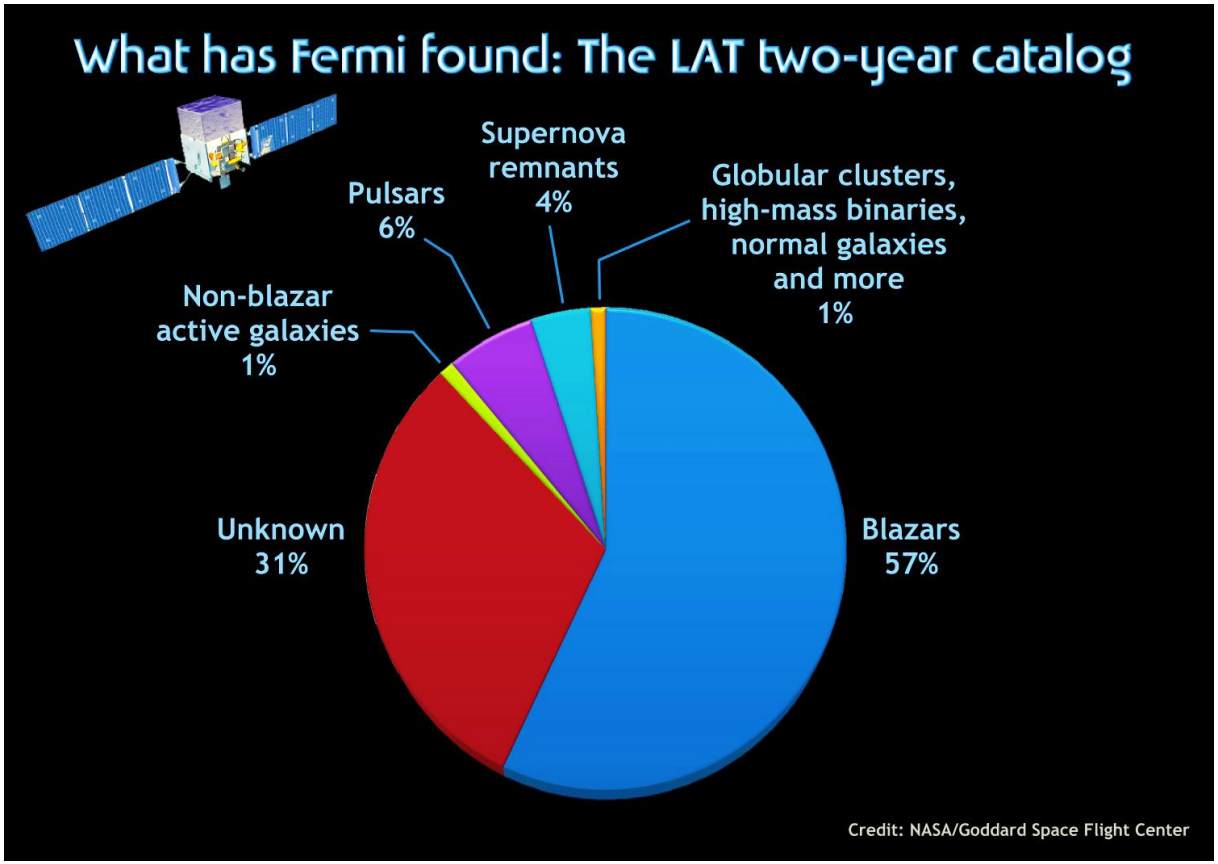
New Event Selections and Data Reprocessing

- **LAT Low Energy (LLE)**
  - **Especially suited for studying transient phenomena, such as Gamma-Ray Bursts and Solar Flares**

- **Pass 7 reprocessing (P7REP)**
  - **Expect public release in late spring 2013**
  - **See arXiv:1304.5456 for details**

- **Pass 8 work is ongoing**
  - **Comprehensive revision of the entire event-level analysis, based on the experience gained since launch**
  - **See arXiv:1303.3514 for details**

***Fermi Science Support Center* is the authoritative source for recommendations regarding the analysis of *Fermi* data**



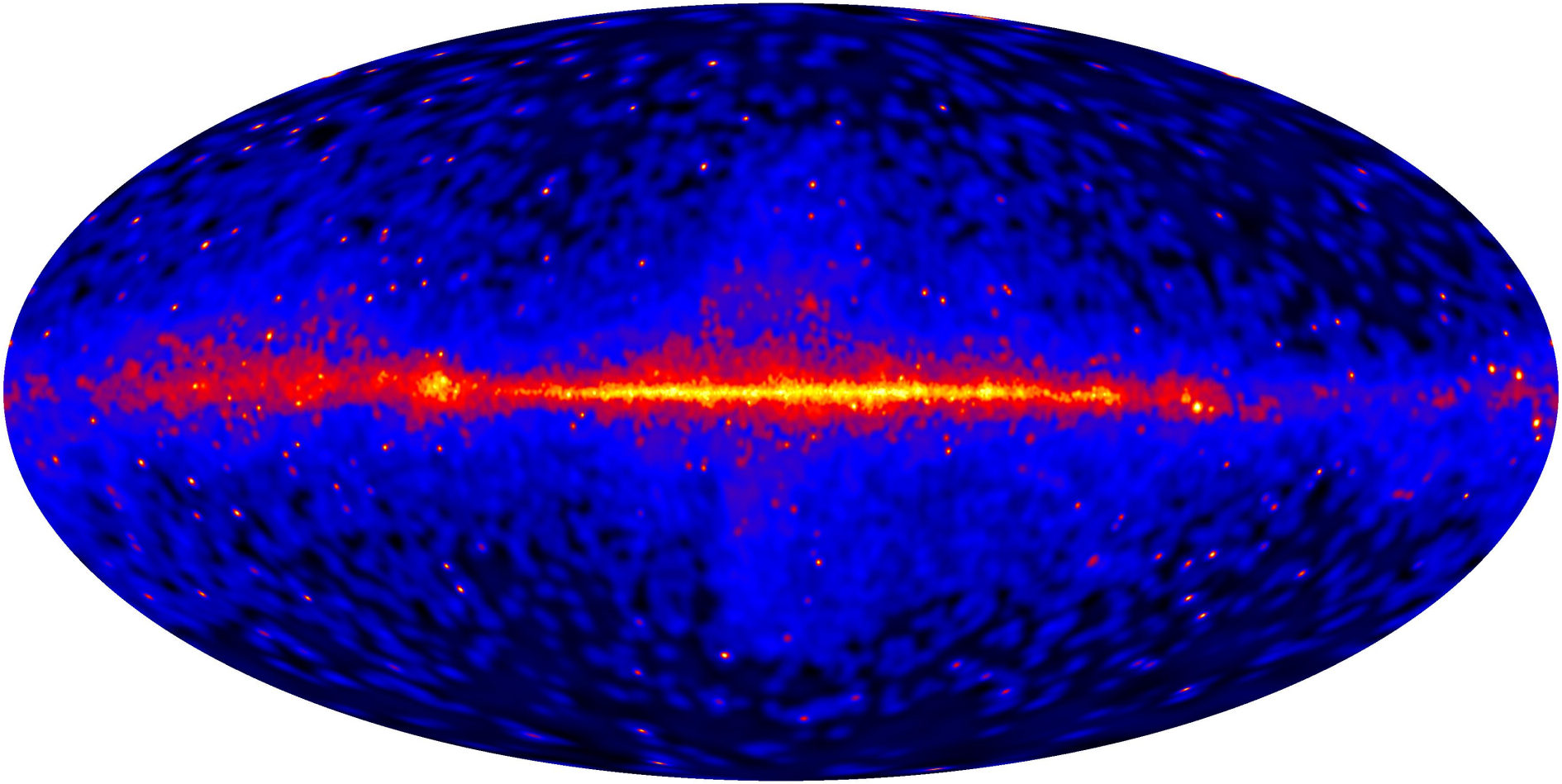
Part 2

New Source Catalogs to Supplement 2FGL

1873 sources in 2FGL

Nolan. et al. 2012, ApJS, 199, 31

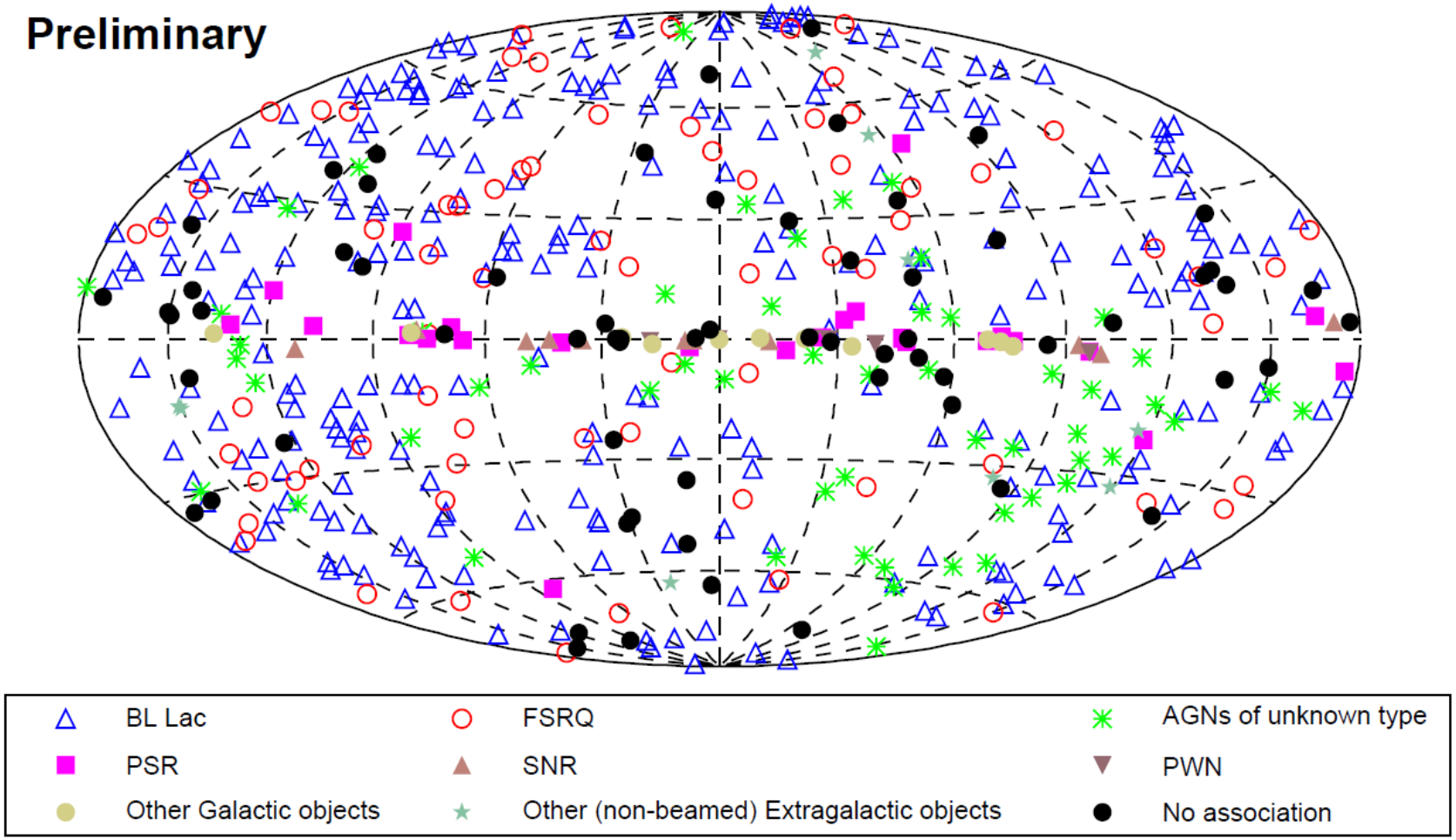
Hard Sources (Detected >10 GeV; 1FHL)



4 years, Source class, >10 GeV, adaptively smoothed

Hard Sources (Detected >10 GeV; 1FHL)

514 Sources in First *Fermi*-LAT Catalog of Sources Above 10 GeV (1FHL)

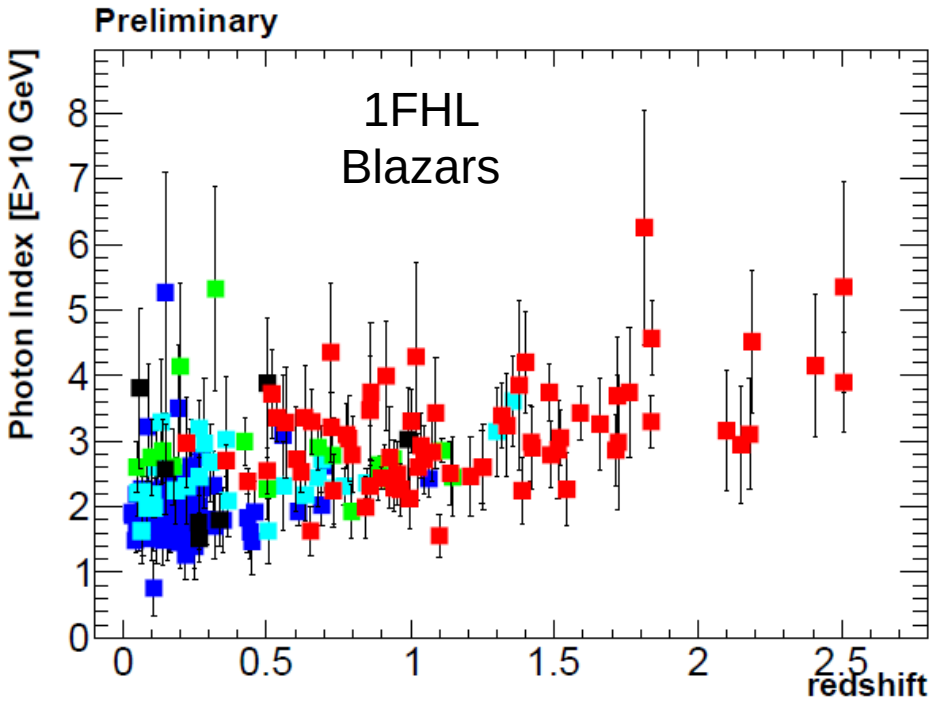


3 years, 10 – 500 GeV, P7 Clean events

arXiv:1304.4153

Hard Sources (Detected >10 GeV; 1FHL)

Class	#	Fraction of 1FHL (%)
Blazar BL Lac	259	50.4
Blazar FSRQ	71	13.8
Unknown type AGN	55	10.7
Pulsar	27	5.2
SNR	11	2.1
PWN	6	1.2
Other Galactic	11	2.1
Other extragalactic	9	1.8
Unassociated	65	12.7



BL Lacs are most abundant source type

54 1FHL sources not in 2FGL

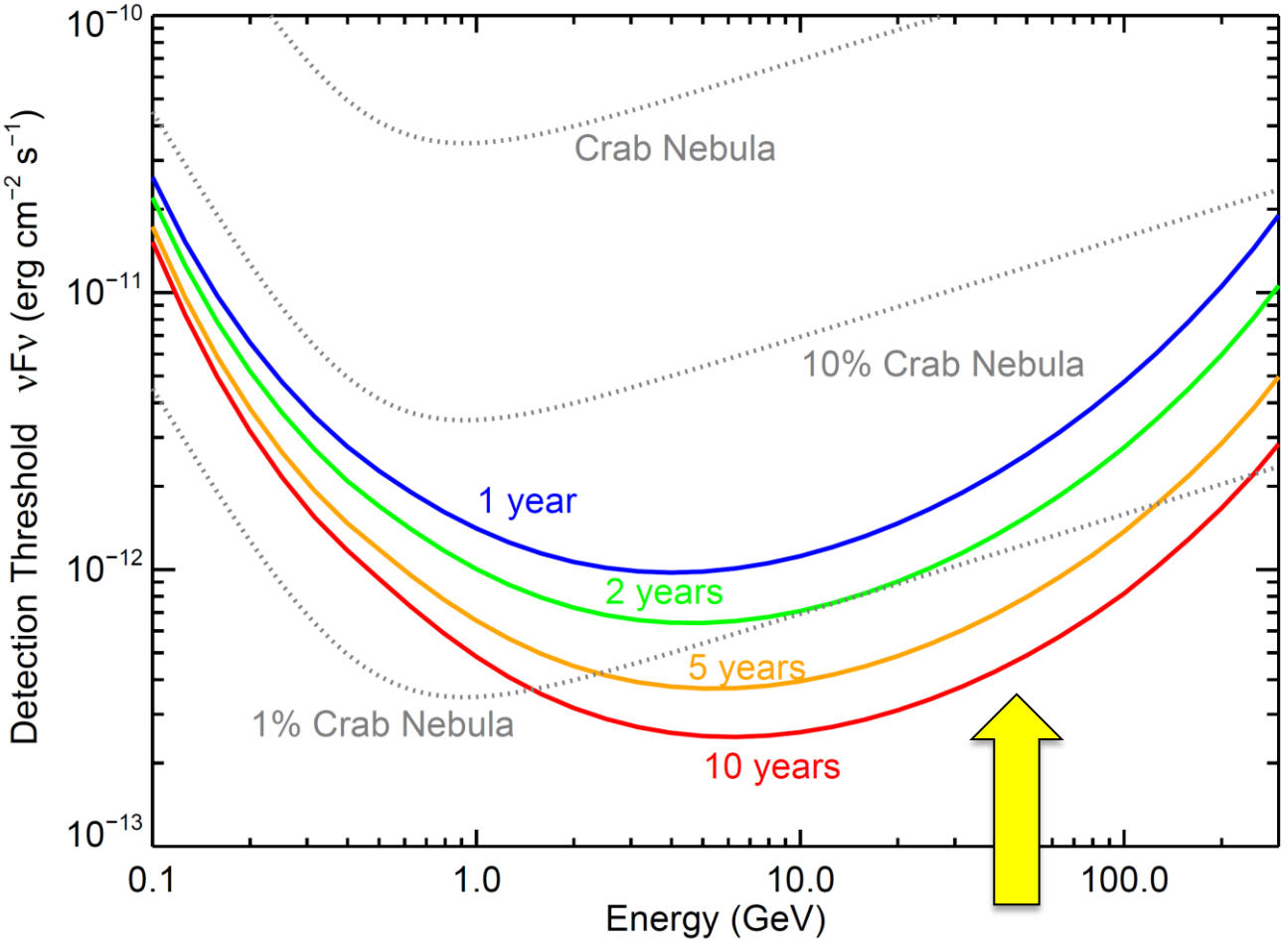
84 1FHL sources associated with known VHE sources

213 1FHL sources identified as good candidate VHE emitters

arXiv:1304.4153

Hard Sources (Detected >10 GeV; 1FHL)

Envelope of the minimum detectable power-law spectra over the full LAT band when varying the photon index. NOT a differential sensitivity plot.

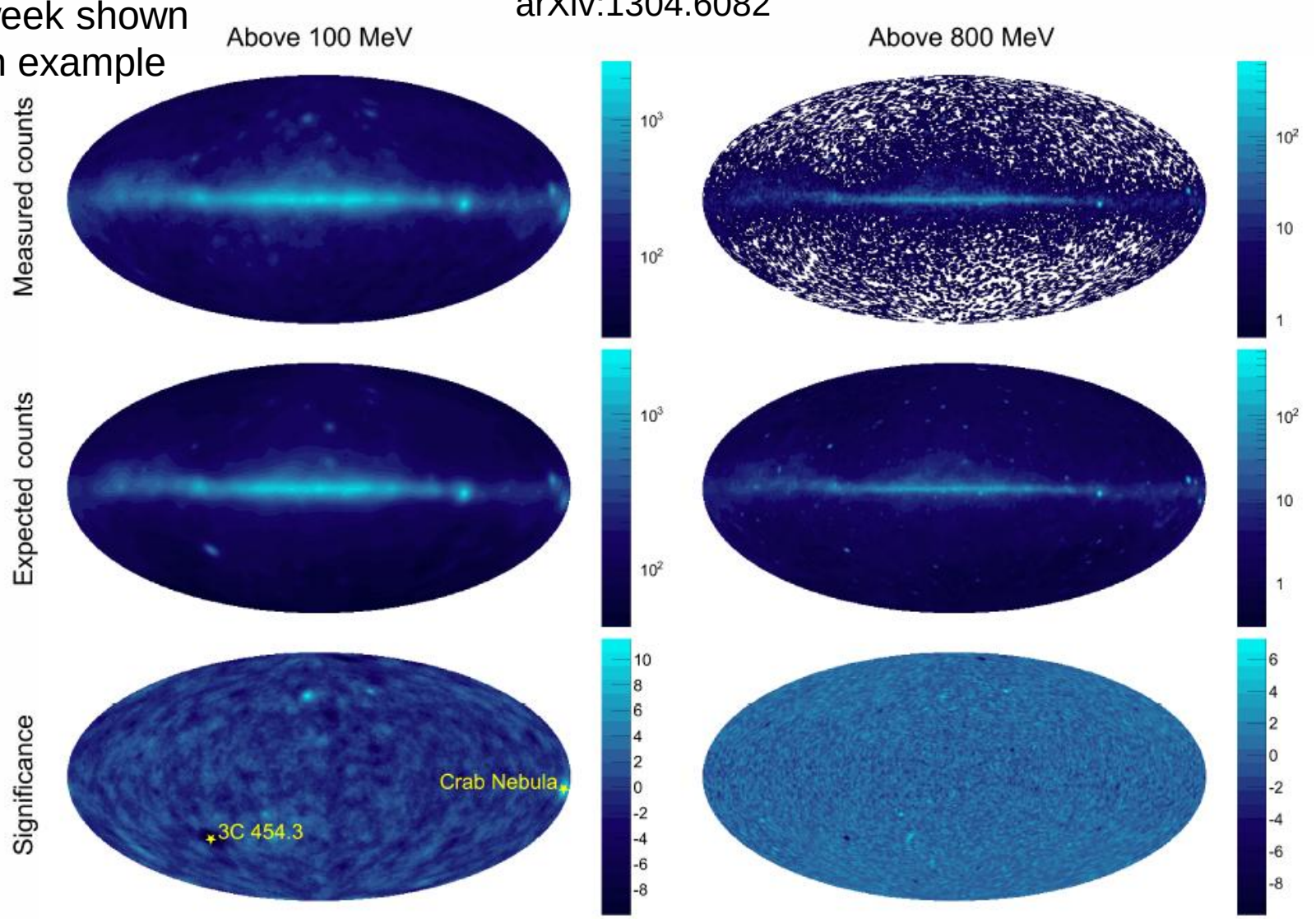


Sensitivity for hard sources increases more rapidly with accumulating exposure than for soft sources

Variable Sources (1FAV)

One week shown as an example

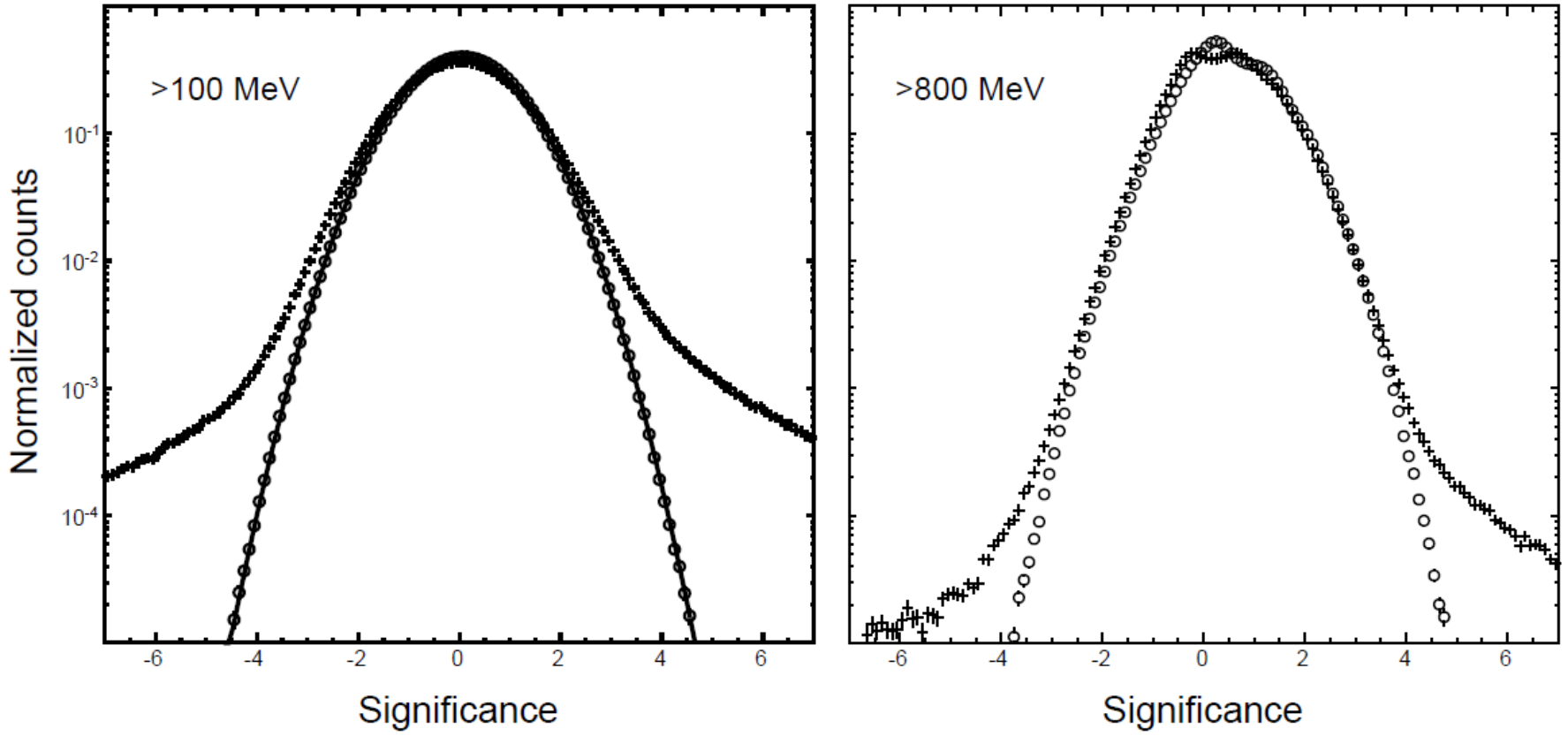
arXiv:1304.6082



Automated search for weekly variability relative to long-term average

Variable Sources (1FAV)

Distribution of flux variation significance in 2 energy bands



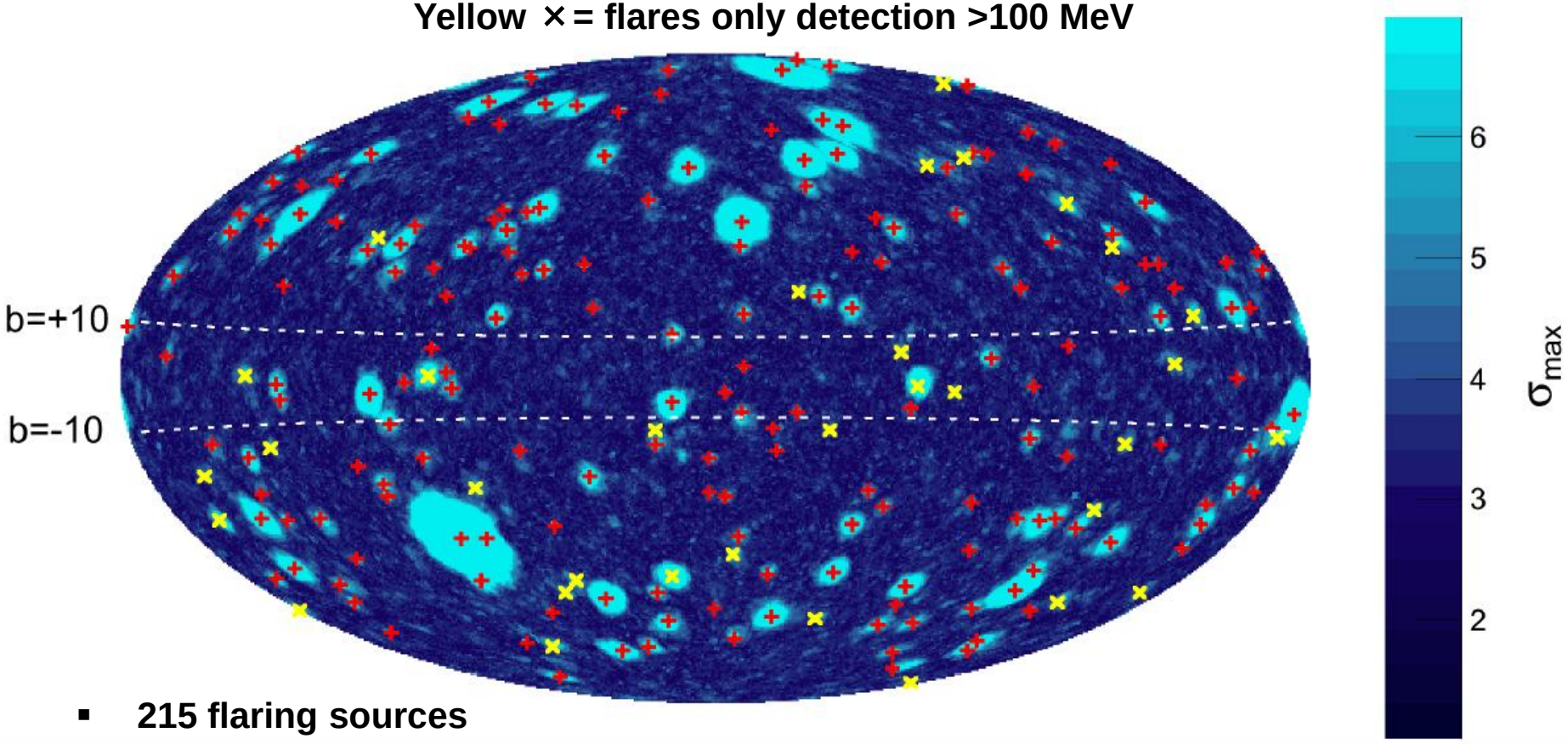
Open circles are simulations of a constant gamma-ray sky
Crosses are first 47 months of LAT observations

arXiv:1304.6082

Variable Sources (1FAV)

Red + = at least 1 flare detected >800 MeV

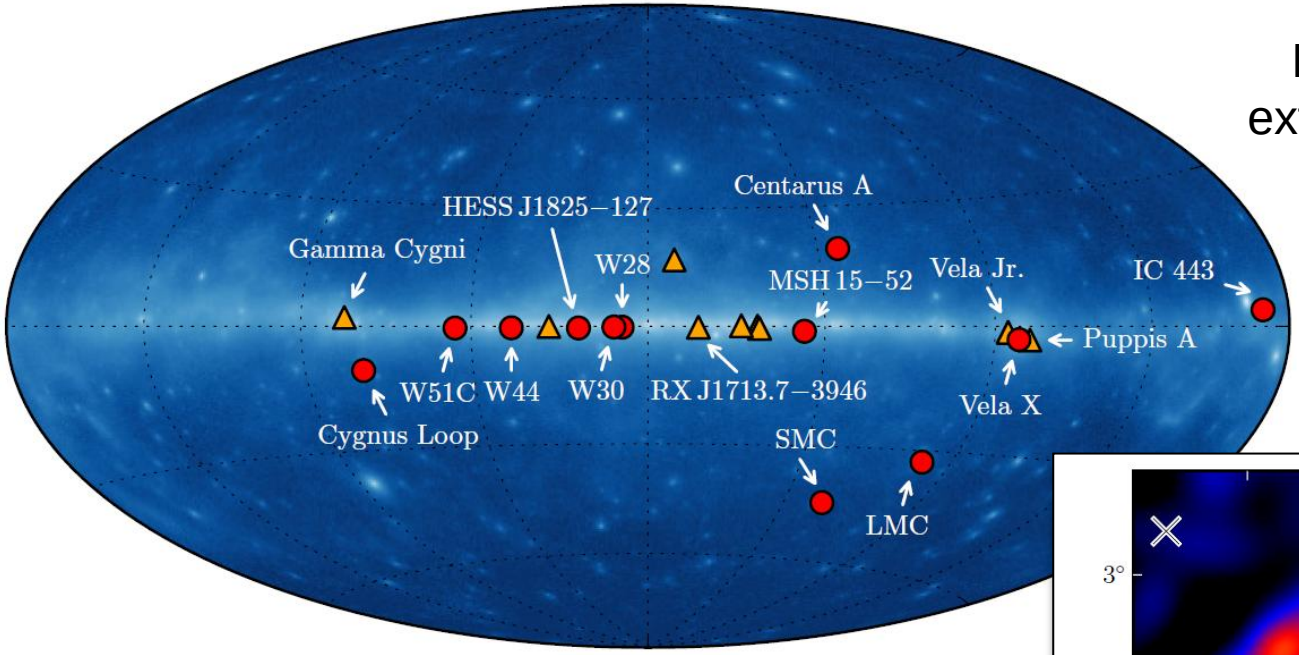
Yellow × = flares only detection >100 MeV



- **215 flaring sources**
  - **177 associated with AGN, FSRQs more variable than BL Lacs**
- **27 at |b| < 10 deg**
  - **7 known Galactic sources: Crab, Cyg X-3, LSI +61 303, PSR B1259-63, V407 Cygni + 2 nova candidates (no new Galactic transient sources)**
  - **19 positional coincidences with AGN**

arXiv:1304.6082

Spatially Extended Sources



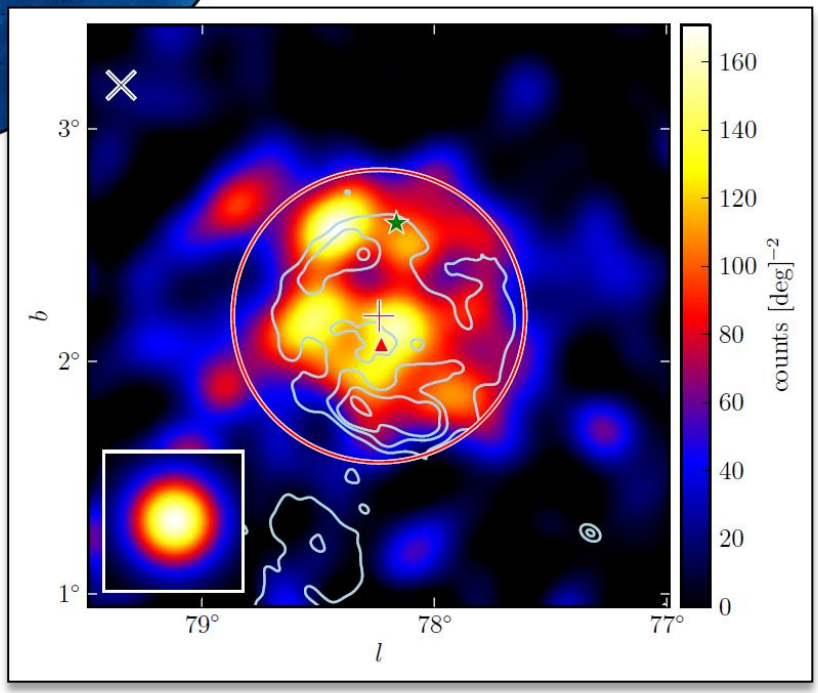
Identify 2FGL sources extended beyond the PSF

12 extended sources reported in 2FGL
6 SNRs (W51C, IC 443, W28, W44, Cygnus Loop, W30), 3 PWNe (Vela-X, MSH 15-52, HESS J1825-137), LMC, SMC, Cen A

+ Vela Jr. and RXJ 1713.7-3946 SNRs

+ 7 new spatially extended GeV sources including the Puppis A and Gamma Cygni SNRs

e.g., Gamma Cygni SNR



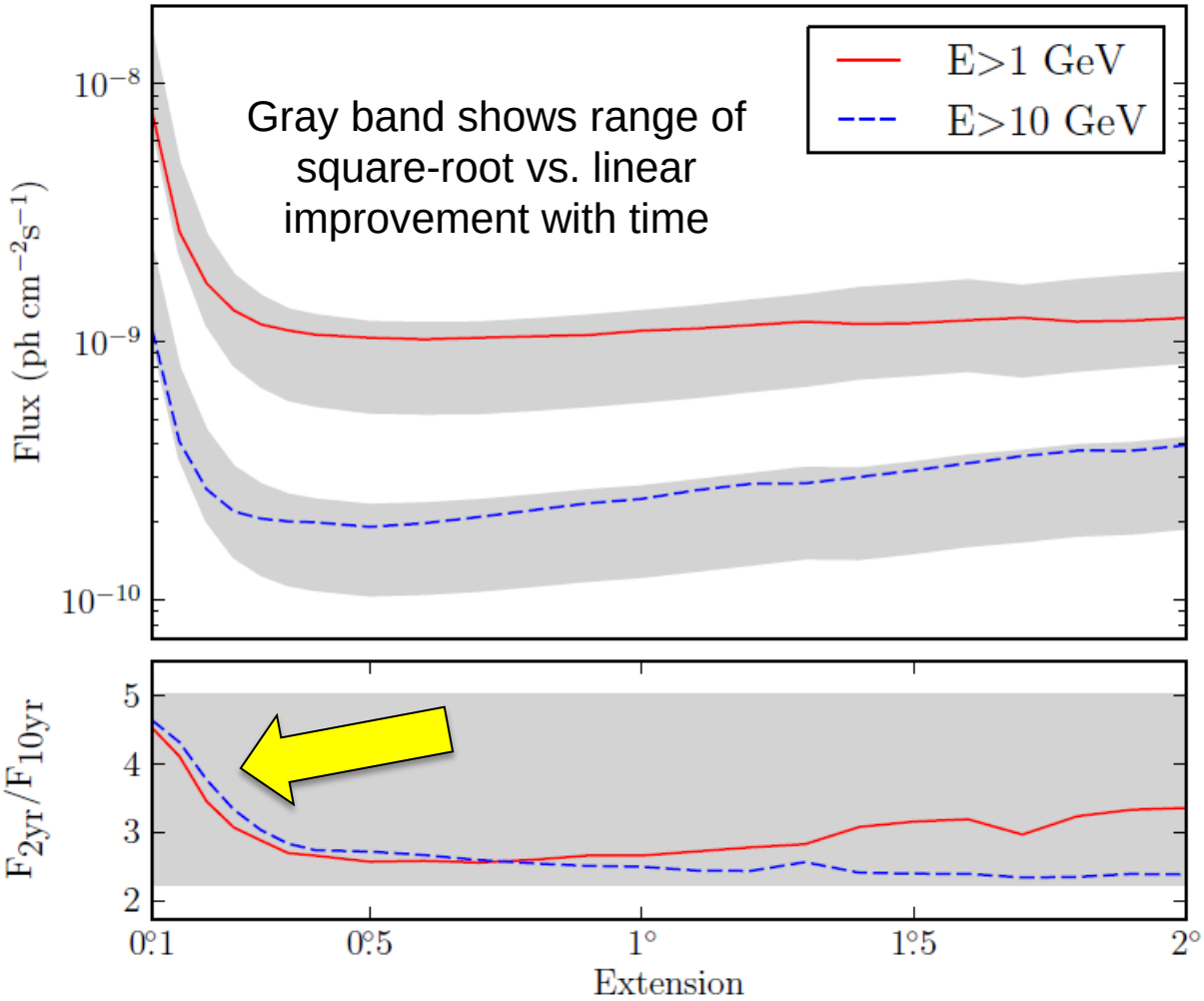
Lande et al. 2012, ApJ, 756, 5

Spatially Extended Sources

Ability to identify spatial extension improves almost linearly with exposure for small extended sources (~0.1 deg)

Minimum flux for which a source could be identified as extended after 10 years (spectral index 2, against 10x isotropic background)

Factor increase in sensitivity between 2 and 10 years



True Extension

Lande et al. 2012, ApJ, 756, 5

Population Studies / Catalogs for Individual Source Classes

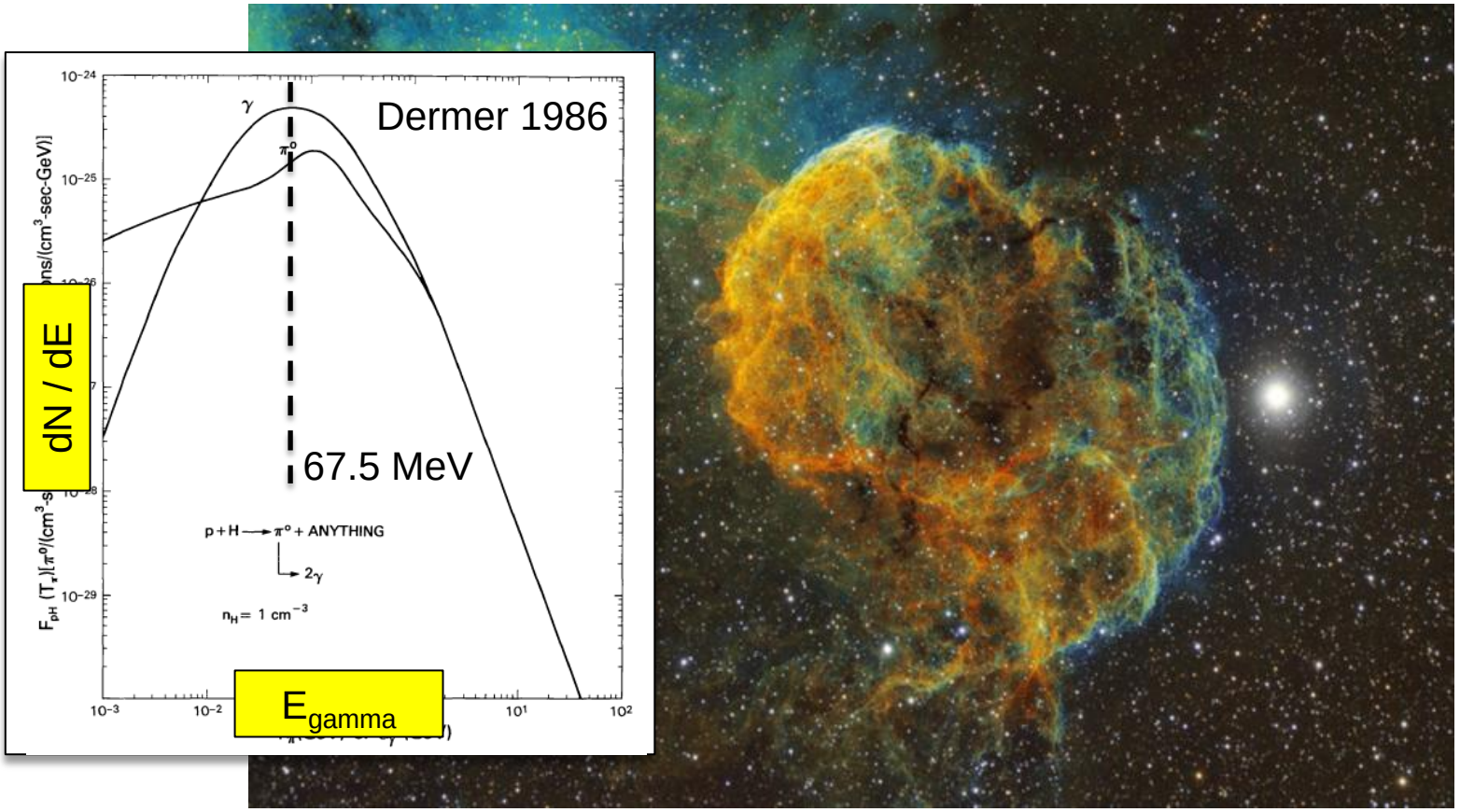
Trend towards population studies as mission progresses…

- Pulsars (2nd catalog submitted, 2PC)
- SNRs (1st catalog in prep)
- TeV PWNe and UnIDs (submitted)
- GRBs (1st catalog, arXiv:1303.2908)
- Star-forming galaxies (Ackermann et al. 2012, ApJ, 755, 164)
- AGN (2nd catalog , 2LAC, Ackermann et al. 2011, ApJ, 743, 171)
- Globular clusters (Abdo et al. 2010, A&A, 524, A75)

Several candidate source classes yet to be detected…

- Radio-quiet AGN (Ackermann et al. 2012, ApJ, 747, 104)
- Galaxy clusters (Ackermann et al. 2010, ApJL, 717, L71; Ackermann et al. 2010, JCAP, 05, 025; revised analysis in prep)
- Satellite galaxies (Ackermann et al. 2012, ApJ, 747, 121; Ackermann et al. 2011, Phys. Rev. Lett., 107, 241302)
- …

*Only showing papers from the LAT Collaboration in this list, but many other relevant works should be noted

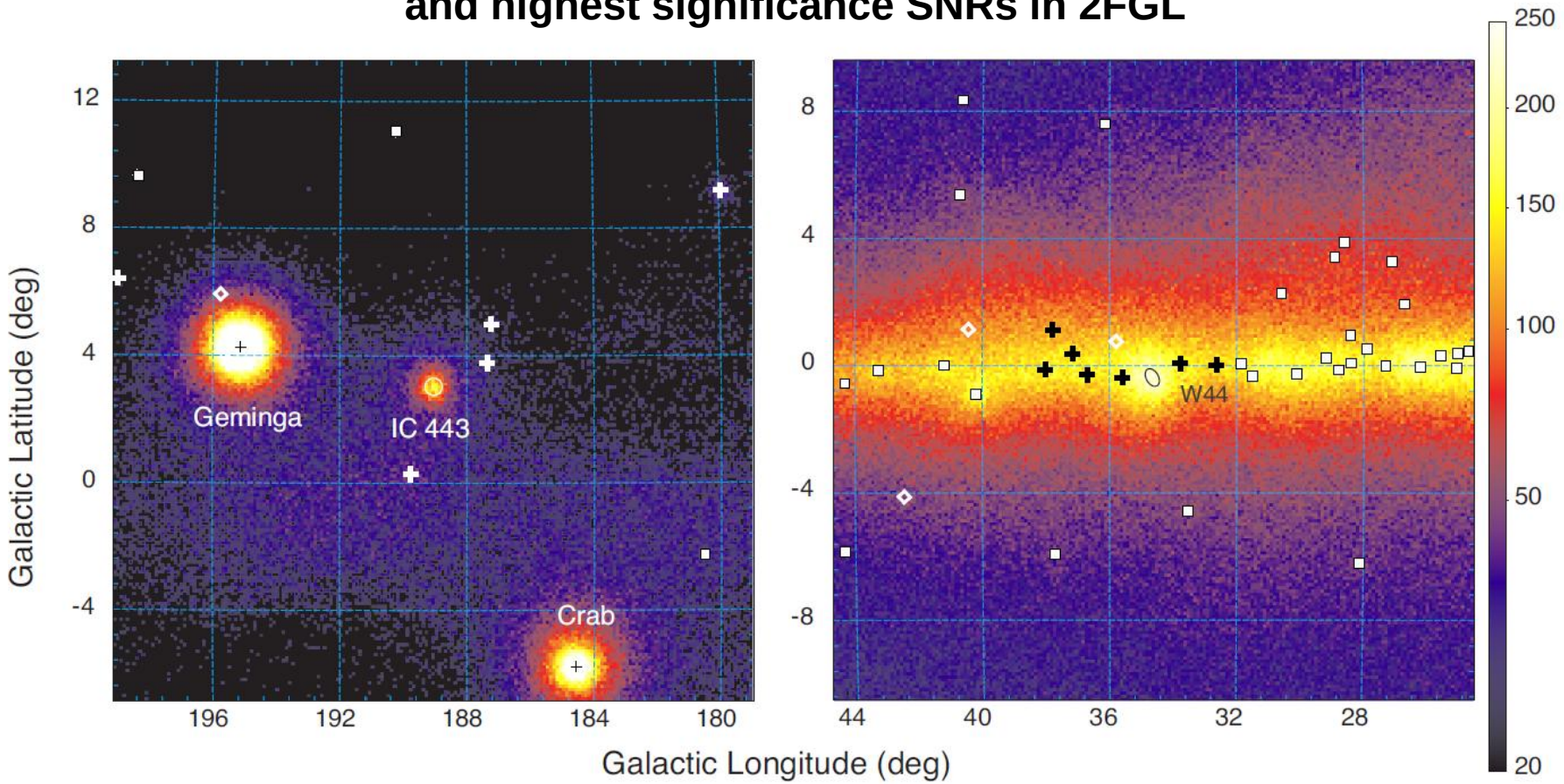


Part 3

Detection of the pion-decay cutoff in Supernova remnants

Top SNR Candidates: IC 443 & W44

Both SNRs interacting with clouds, ages of ~10^4 years, and highest significance SNRs in 2FGL



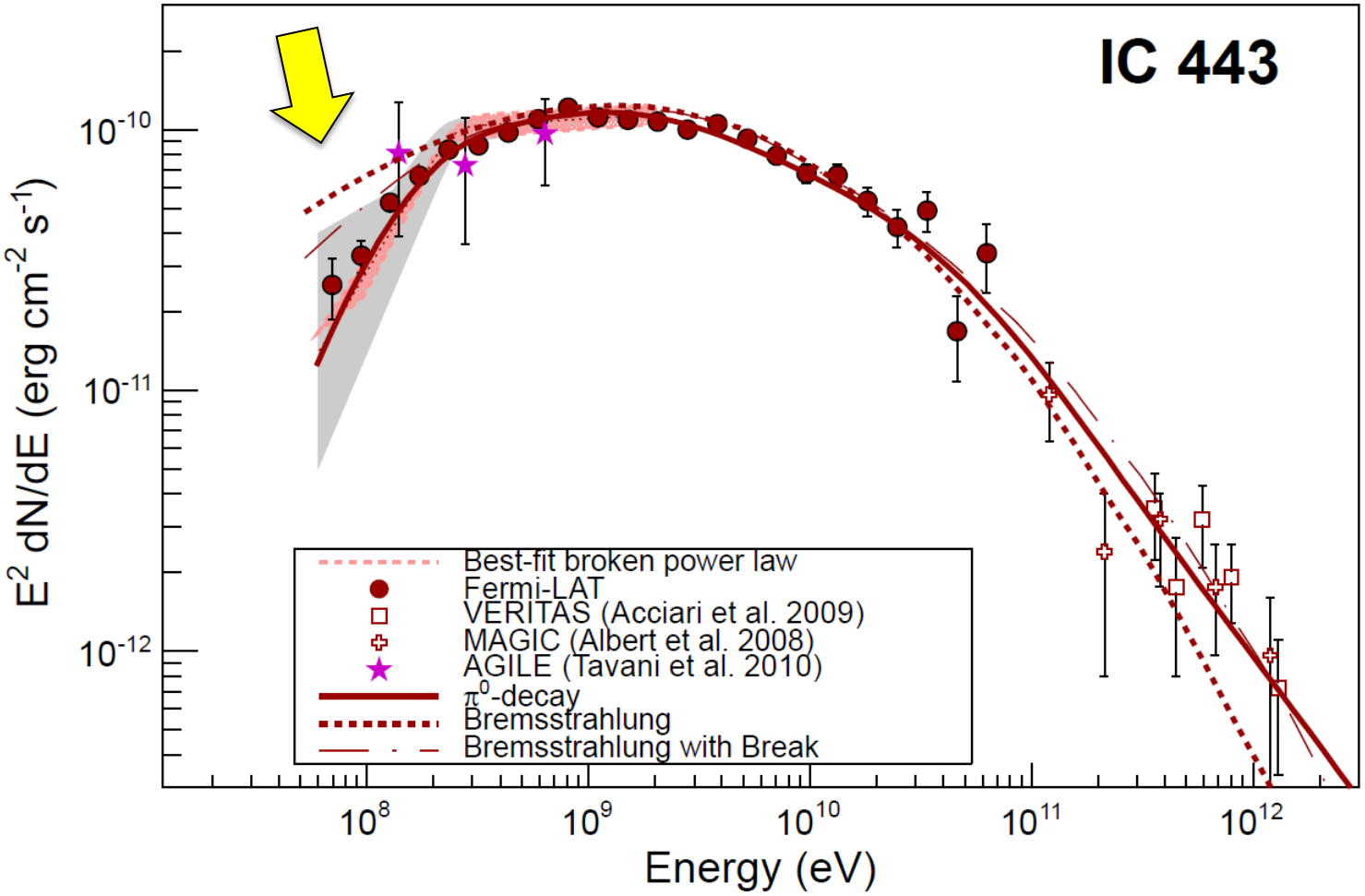
Counts map in 0.1 deg x 0.1 deg pixels, 60 MeV – 2 GeV

Diamonds indicate previously undetected sources

Crosses and diamonds indicate sources with normalization free in the fit

Ackermann et al. 2013, Science, 339, 807

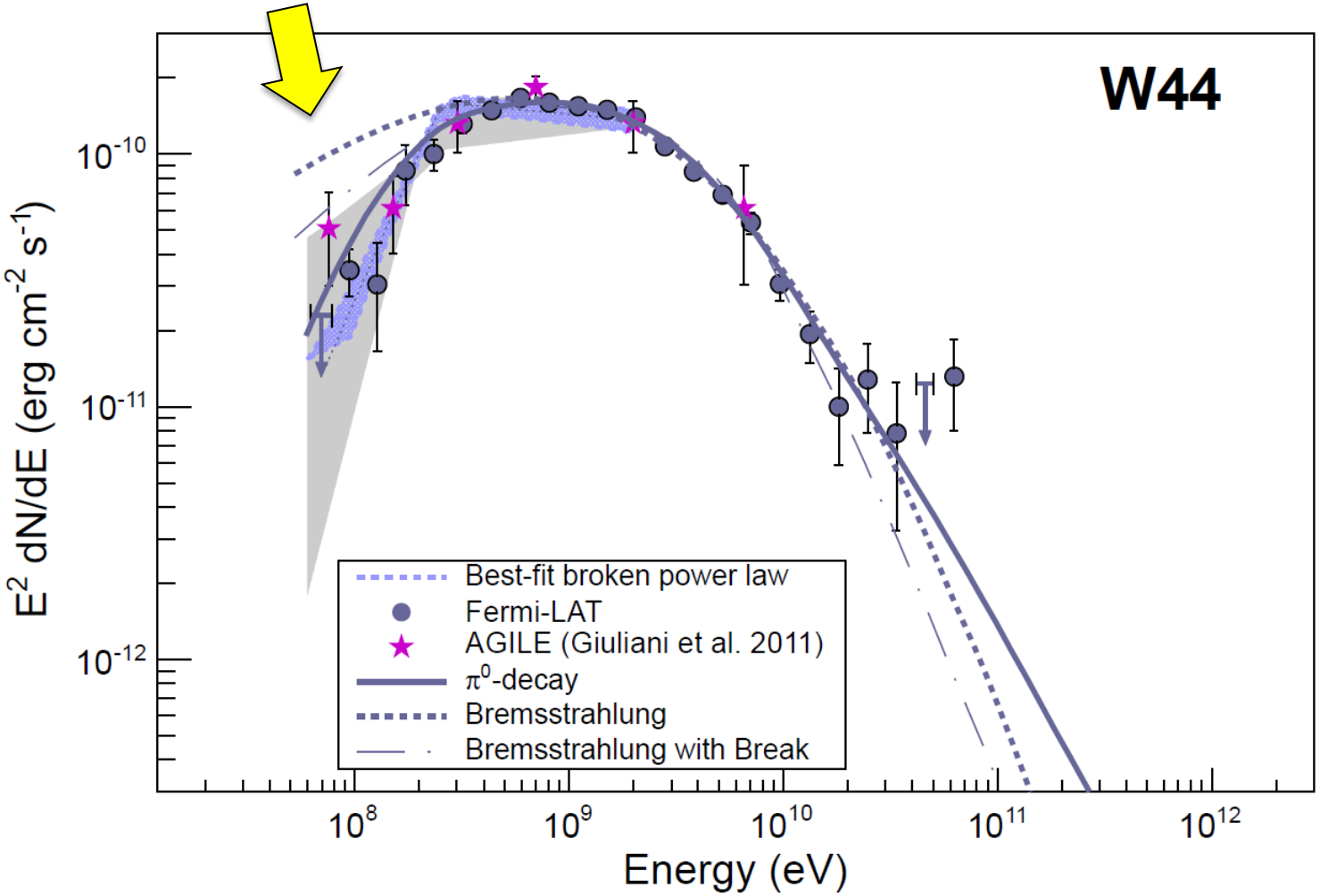
Gamma-ray Spectrum IC 443



Color (Gray) shaded region indicates statistical (systematic) uncertainty < 2 GeV. Systematic uncertainty associated with Galactic diffuse modeling was estimated by using several alternative diffuse models based on GALPROP.

Ackermann et al. 2013, Science, 339, 807

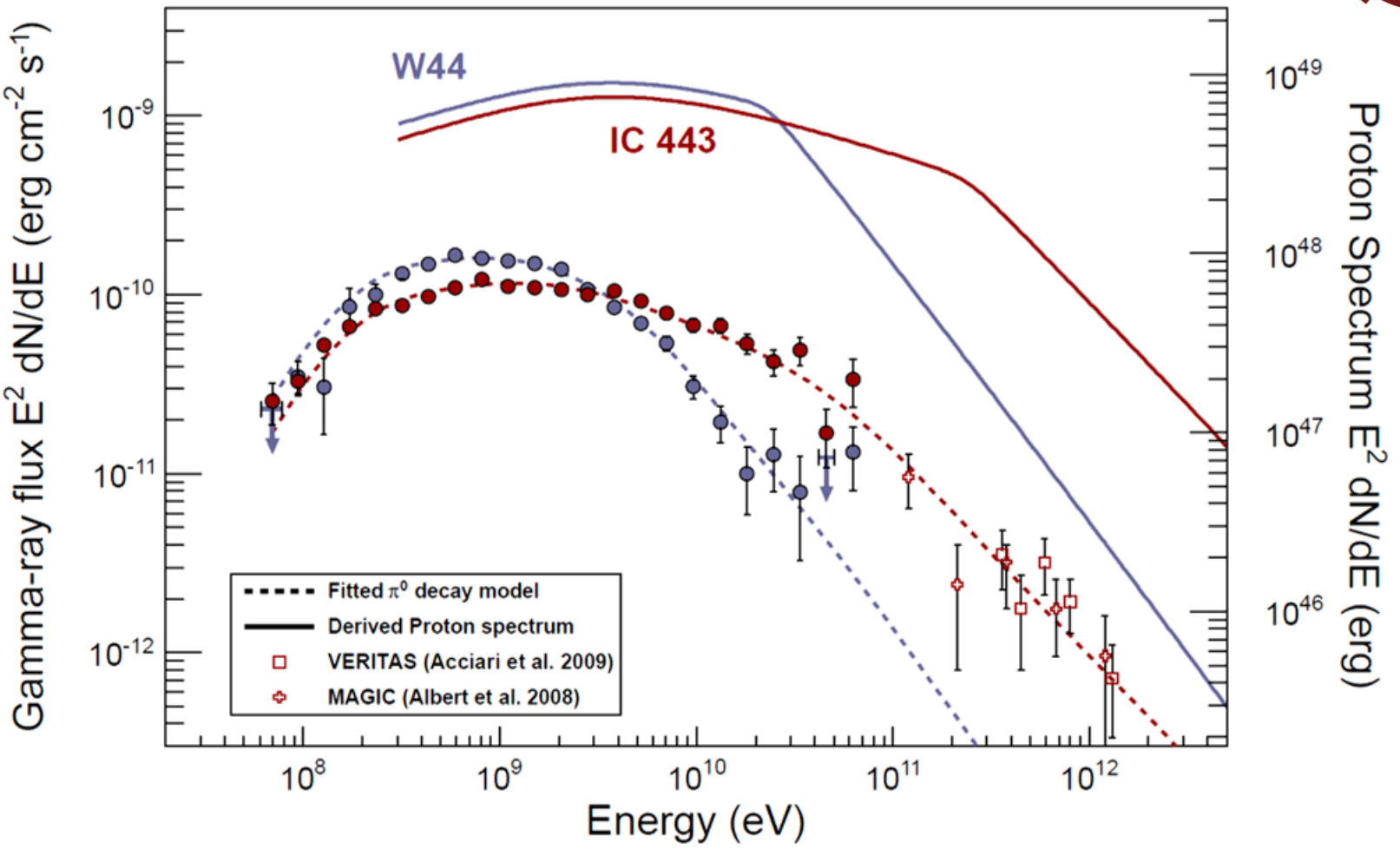
Gamma-ray Spectrum W44



Color (Gray) shaded region indicates statistical (systematic) uncertainty < 2 GeV. Systematic uncertainty associated with Galactic diffuse modeling was estimated by using several alternative diffuse models based on GALPROP.

Ackermann et al. 2013, Science, 339, 807

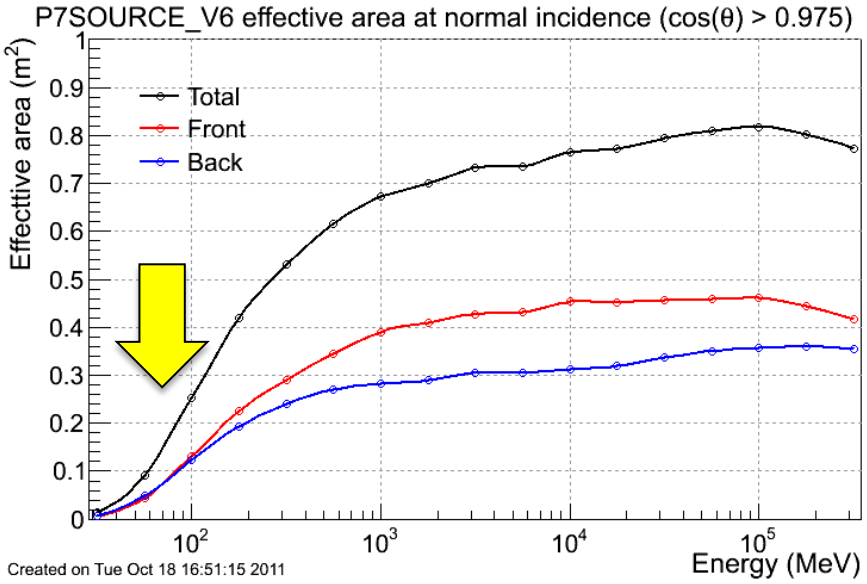
Gamma-ray and Inferred Proton Spectra

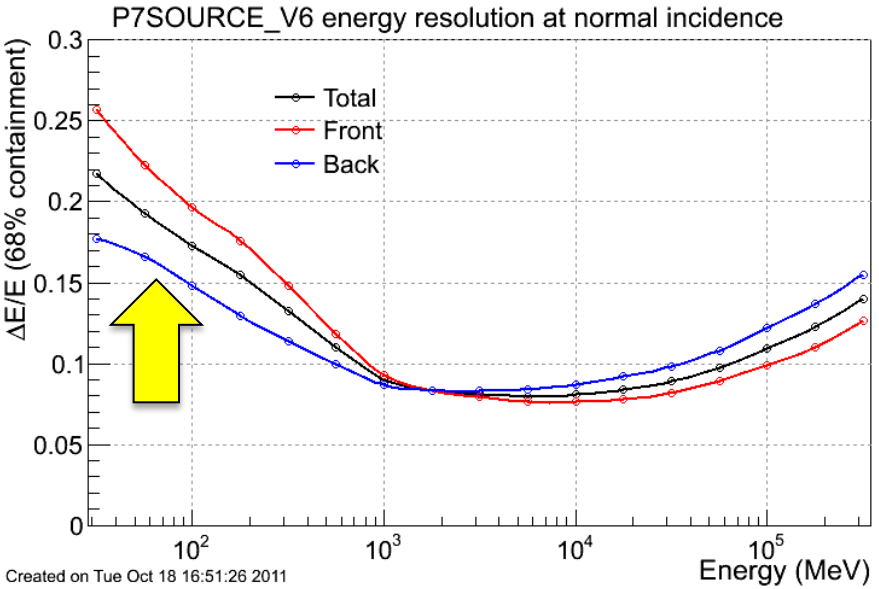


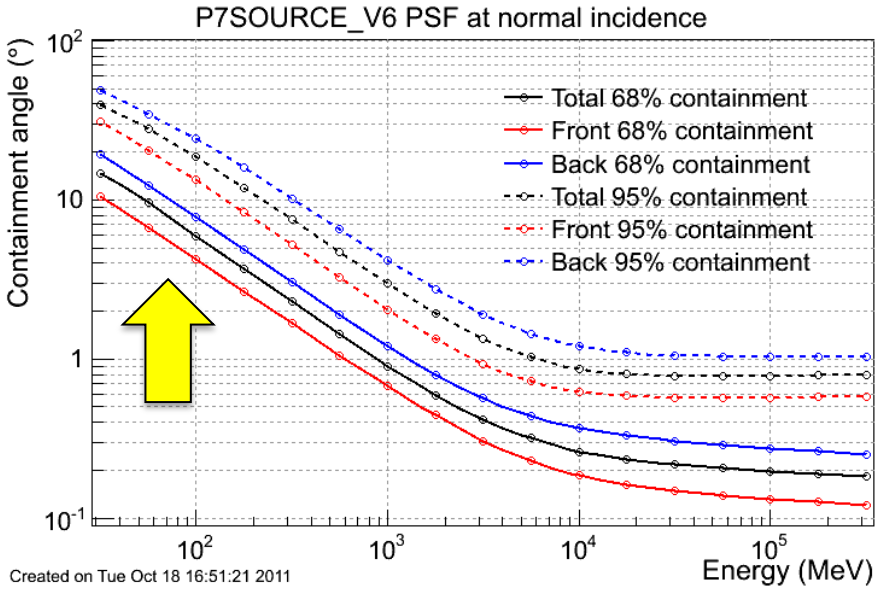
Assume average gas densities of 20 cm^{-3} (IC 443) and n = 100 cm^{-3} (W44) and distances of 1.5 kpc (IC 443) and 2.9 kpc (W44), factor 1.85 enhancement from heavier nuclei. Inferred CR acceleration efficiencies of 1-10% (protons with p > 0.8 GeV c^{-1}).

Ackermann et al. 2013, Science, 339, 807

Challenges of Spectral Analysis < 100 MeV



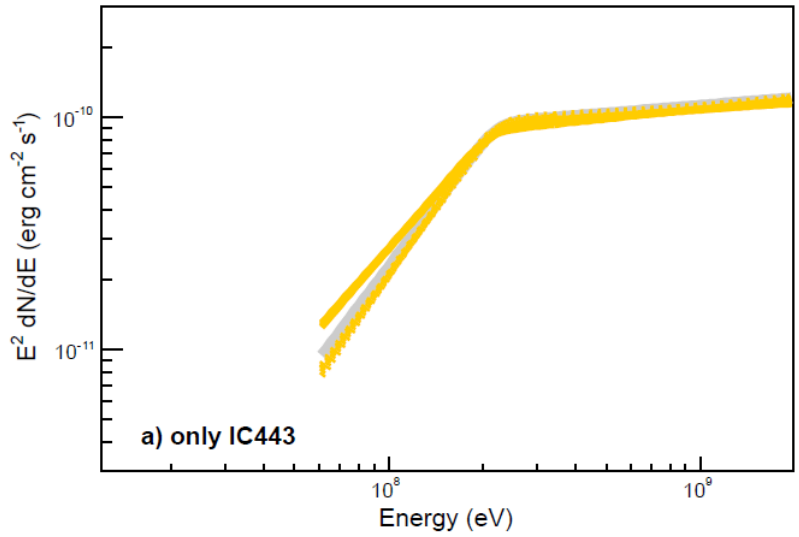


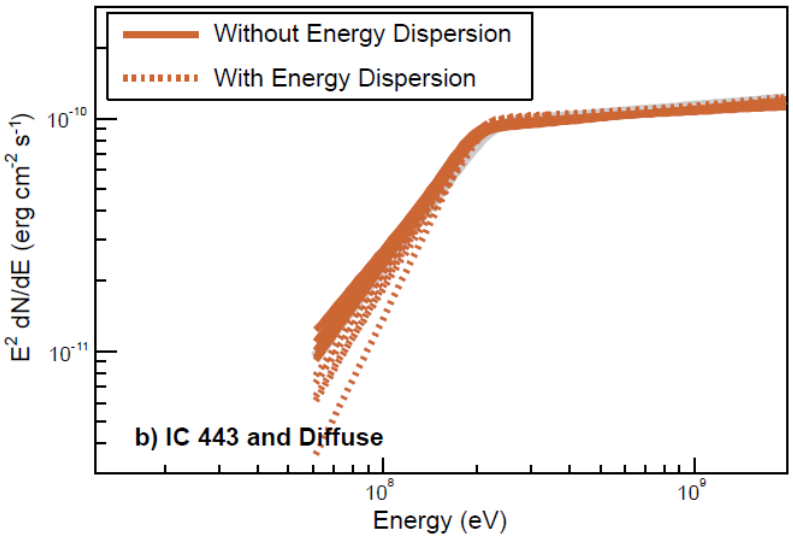


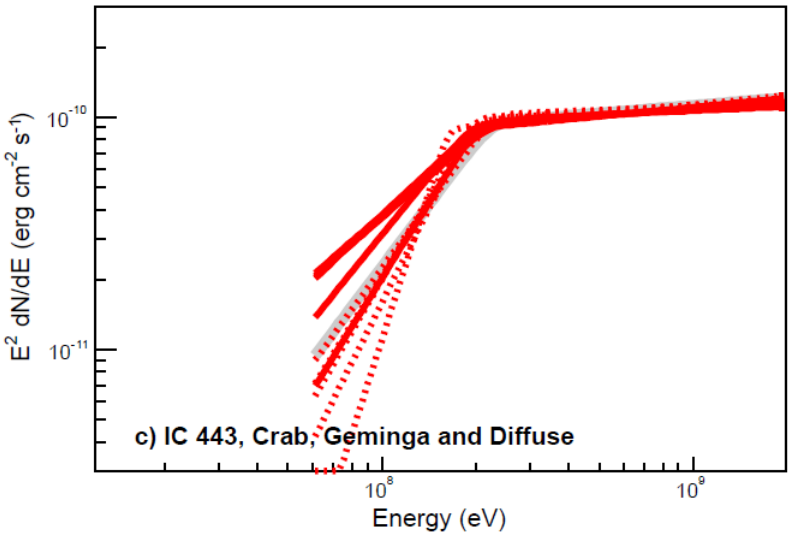
Rapidly changing effective area, increasing energy dispersion, and an enlarged PSF (which can couple nearby sources + diffuse to target source)

Cutoff Robust Against Energy Dispersion

Use simulations to explore the effect of energy dispersion in 60 MeV – 2 GeV range







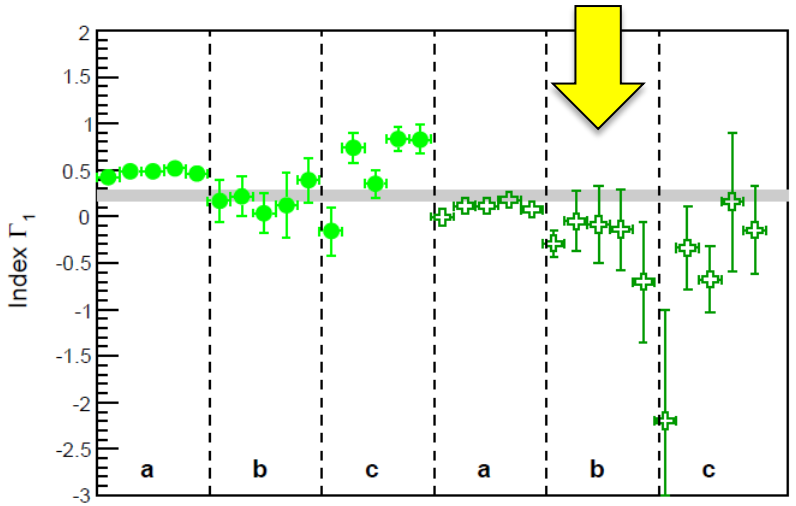
5 realizations for each case:
Solid (dashed) is analyzing without (with) energy dispersion
Gray is input spectrum

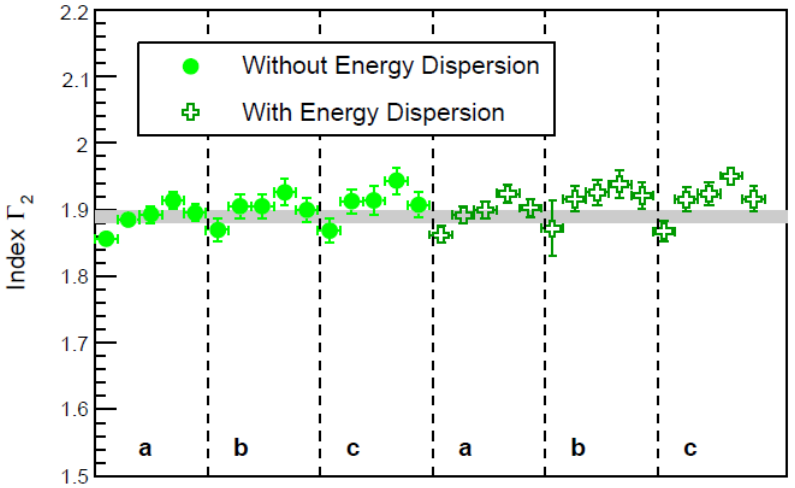
Including energy dispersion would make break even more pronounced

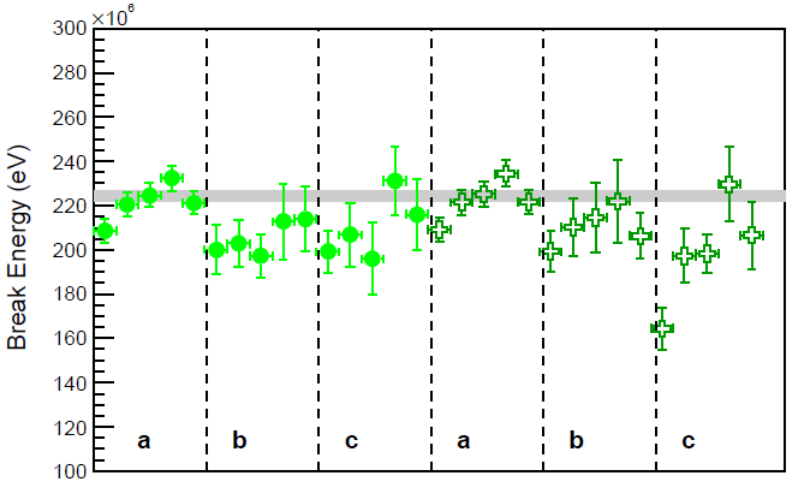
Ackermann et al. 2013, Science, 339, 807

Cutoff Robust Against Energy Dispersion

Including energy dispersion makes fitted low-energy spectra index *harder*, i.e., cutoff feature becomes *stronger* (minimal effect on other parameters)



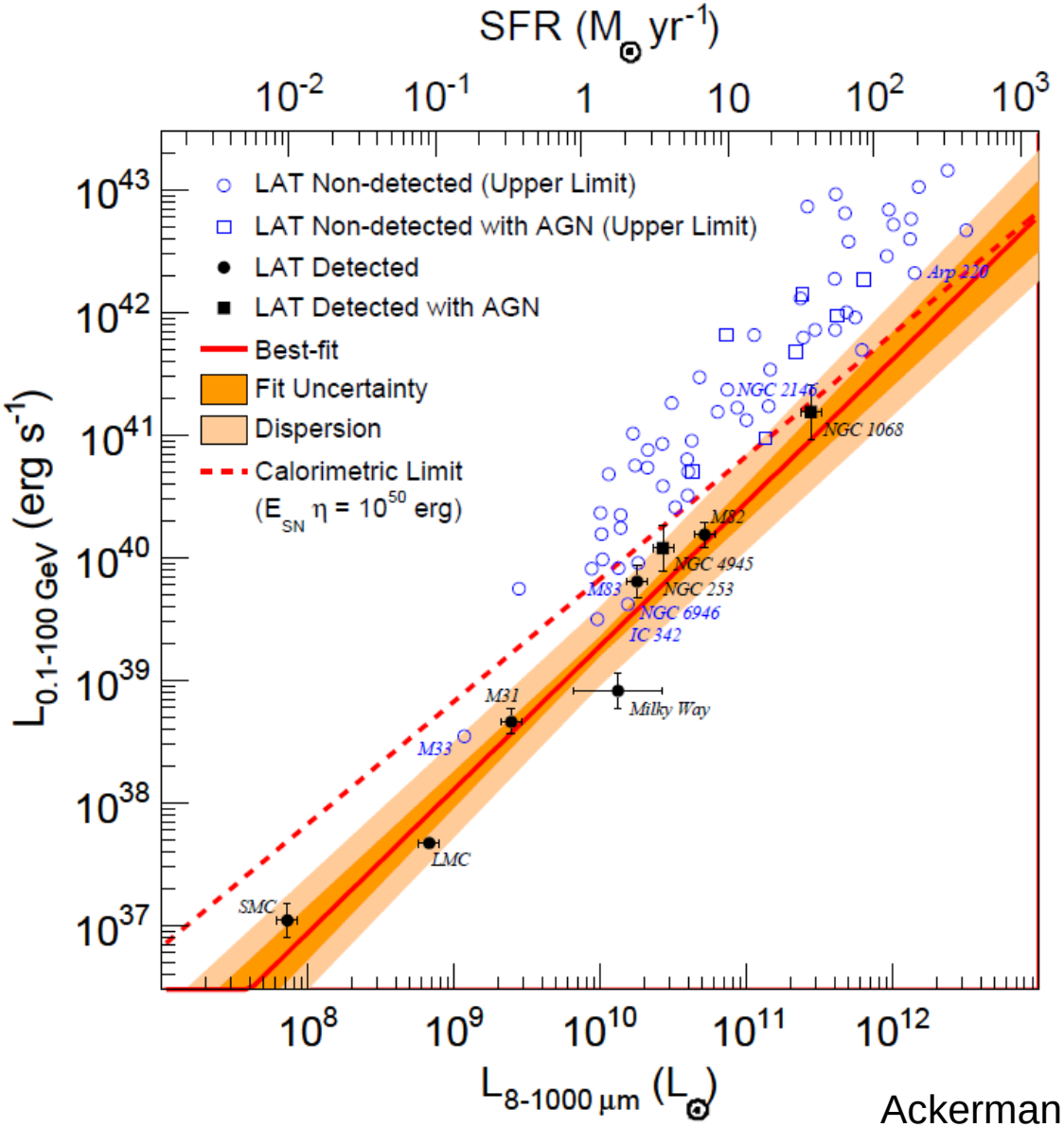




(a) IC 443 only
(b) IC 443 + diffuse
(c) IC 443, Crab, Geminga + diffuse

Ackermann et al. 2013, Science, 339, 807

Cosmic Rays On Galaxy Scales



If SNRs are indeed the accelerators of Galactic CRs…

Notice that **gamma-ray luminosity of nearby galaxies scales ~linearly with tracers of the star formation rate** (e.g., total IR luminosity or radio continuum luminosity at 1.4 GHz)

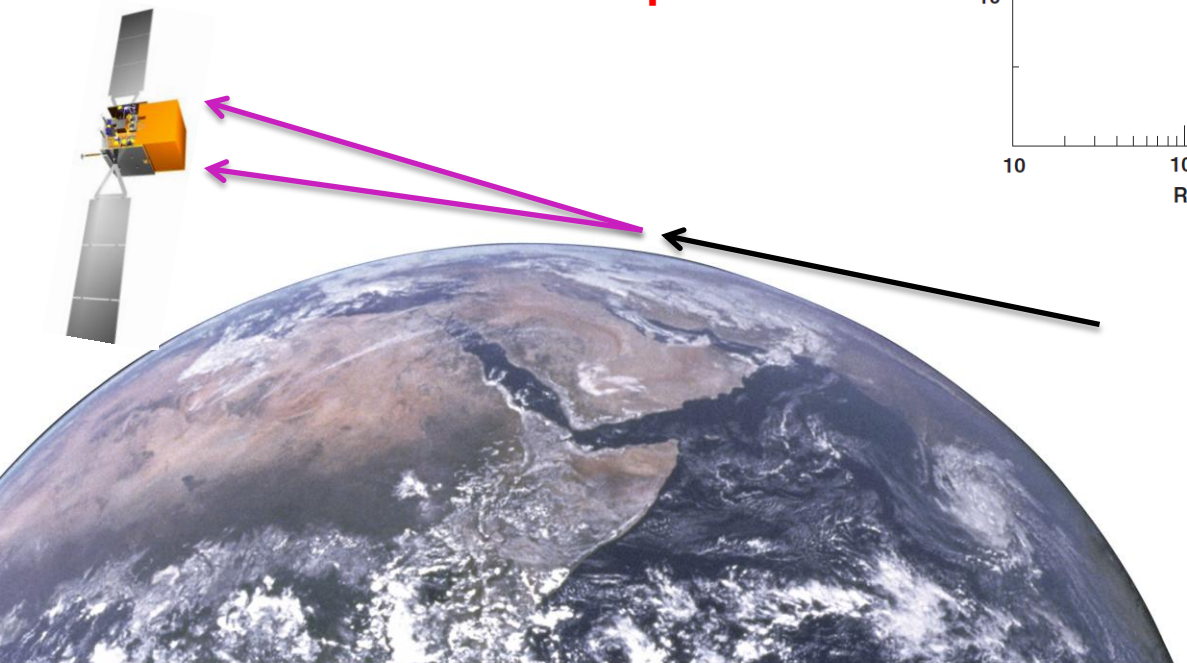
Consistent with SNR paradigm in which Galactic CRs are mainly injected by the explosions of short-lived massive stars

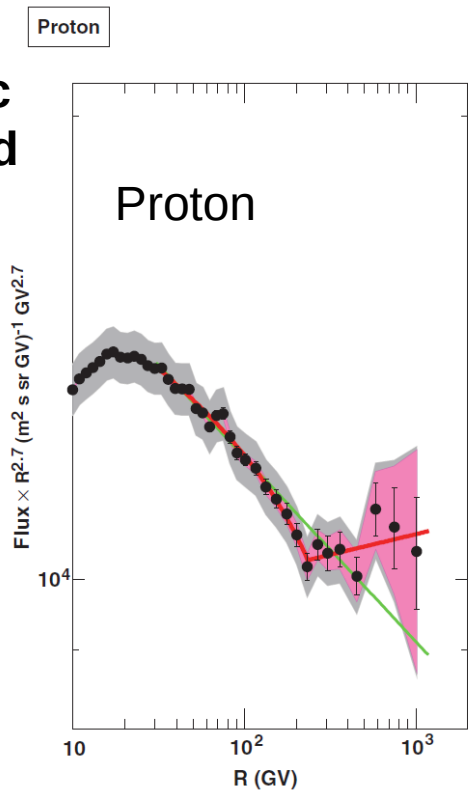
Ackermann, M. et al. 2012, ApJ, 755, 164

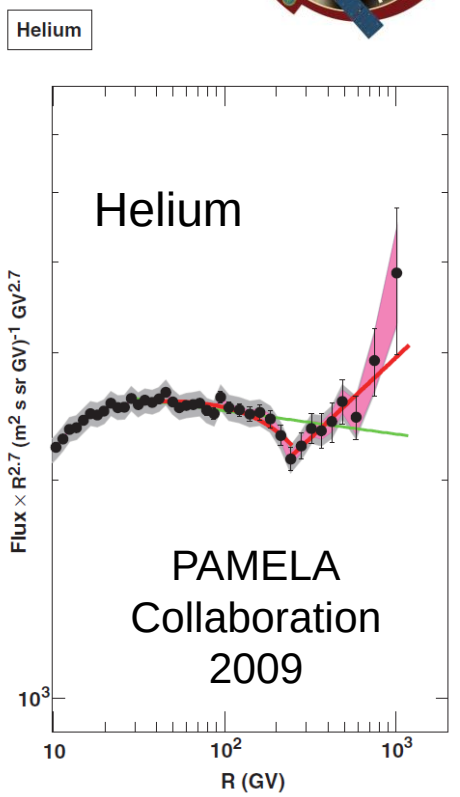
More Cosmic-ray Clues from *Fermi*

Can *Fermi* LAT confirm break in Galactic CR spectrum at rigidity ~240 GV reported by ATIC-2, CREAM, & PAMELA?

Take advantage of the brightest gamma-ray source available –
Galactic CRs interacting in the Earth's atmosphere!



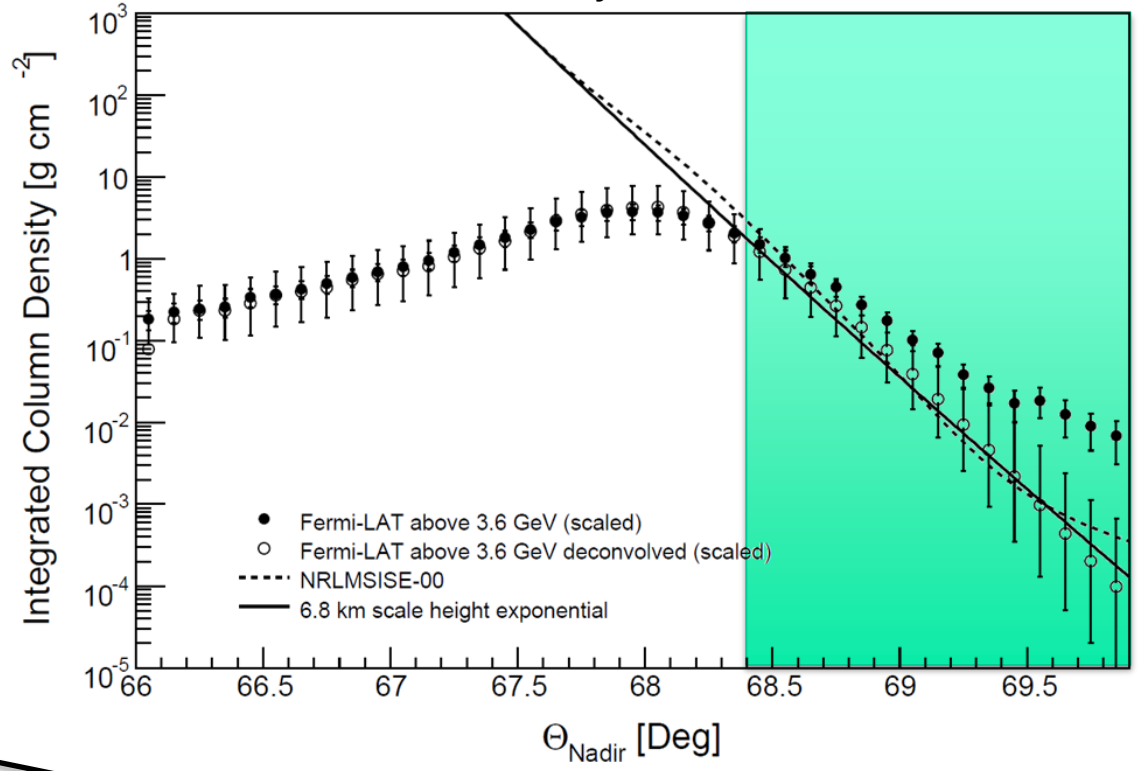


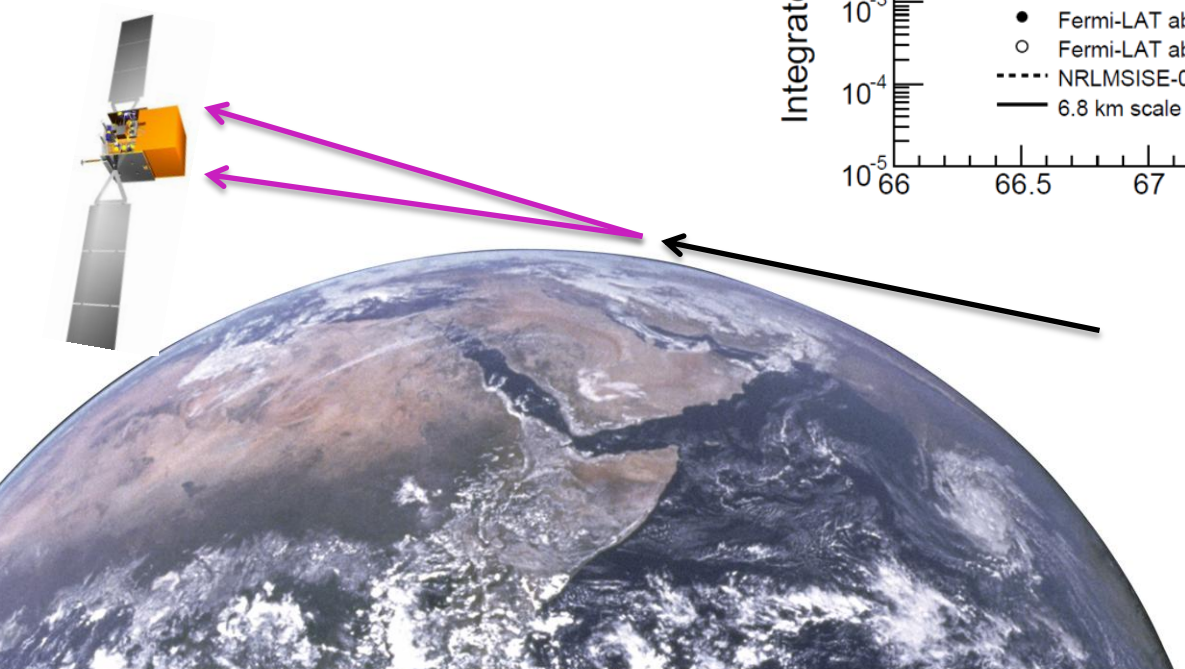


More Cosmic-ray Clues from *Fermi*

Abdo et al. 2009, Phys. Rev. D, 80, 122004

In thin target regime (integrated column density < 3 g cm^{-2}), secondary gamma-ray spectrum resulting from π^0 and K^0 decay repeats CR proton spectrum above few GeV

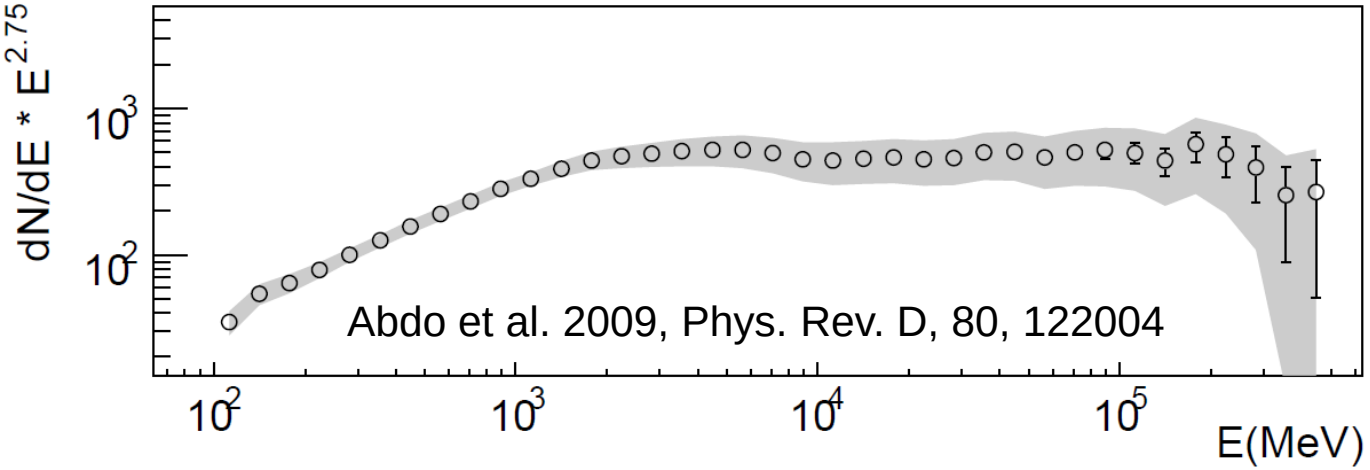


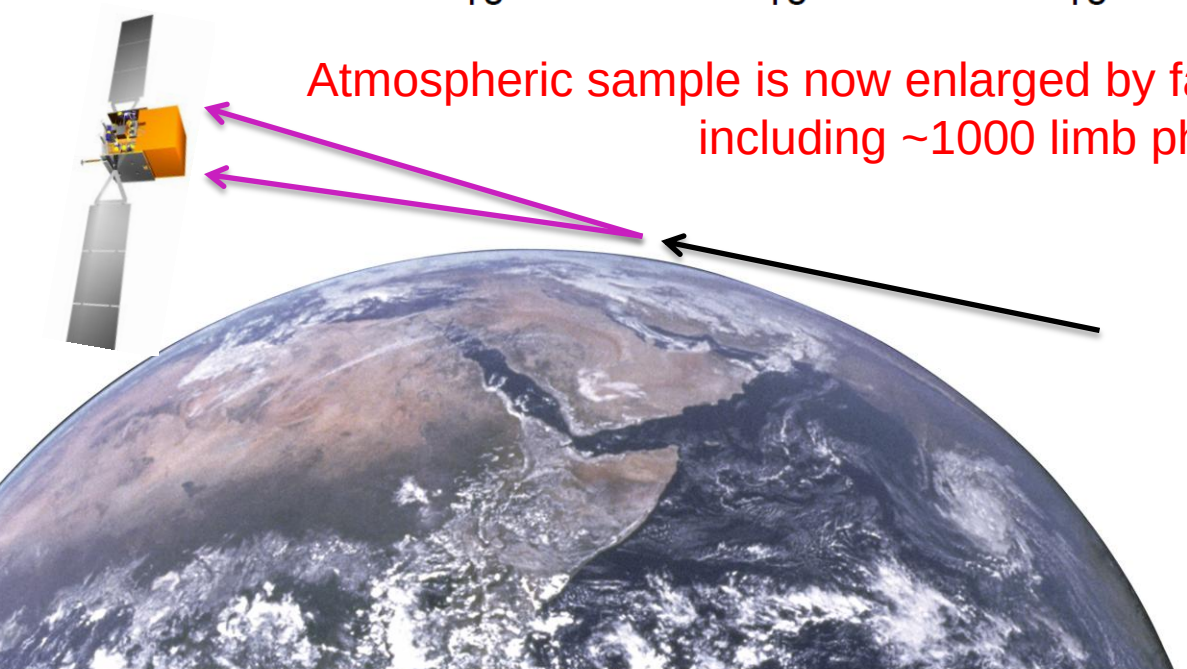


Select photons from nadir angles 68.4 – 70 deg

More Cosmic-ray Clues from *Fermi*

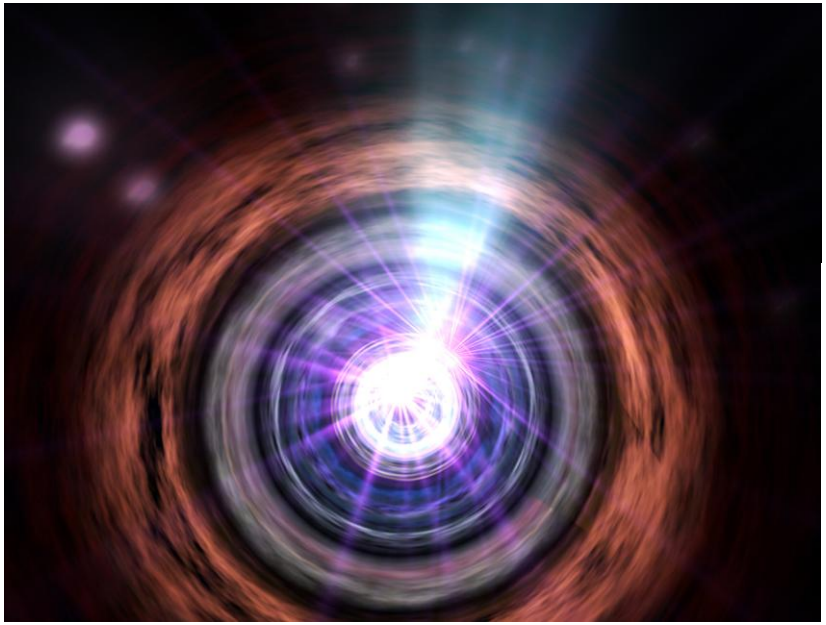
Gamma-ray spectrum from full “Limb” region (nadir angles 66-70 deg) measured from ~10 days of observations during commissioning period

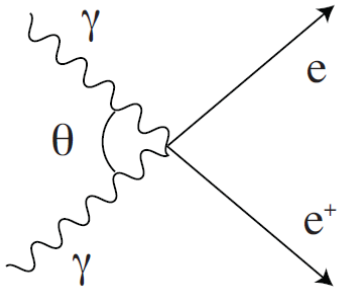




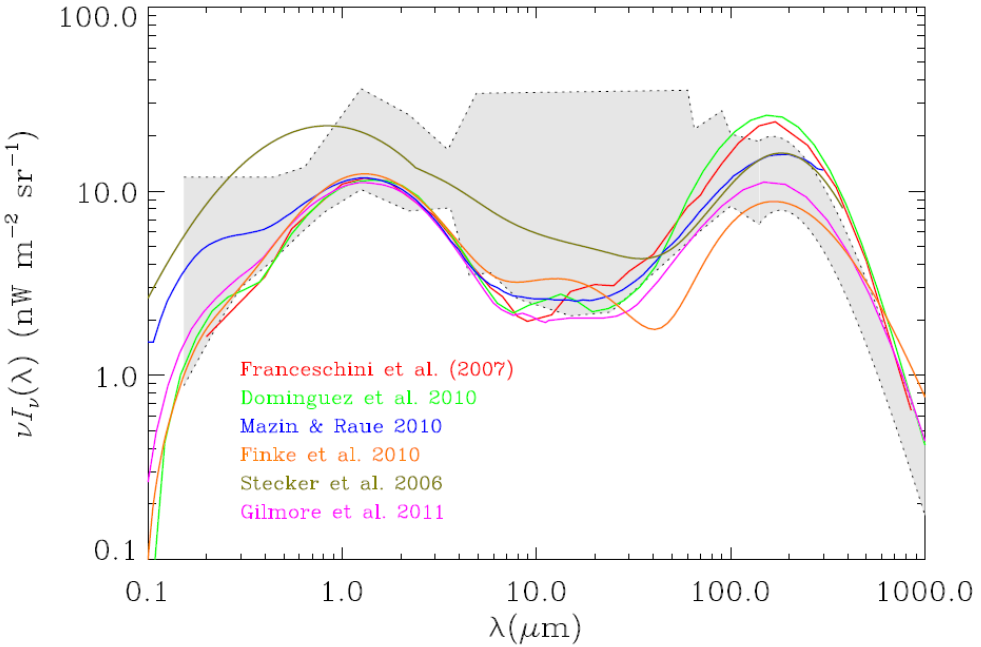
Atmospheric sample is now enlarged by factor > 30 after 4 years of *Fermi*, including ~1000 limb photons between 100 GeV.- 1 TeV

LAT publication reporting CR proton spectrum 90 GeV – 6 TeV (derived from 15 GeV – 1 TeV photons) in prep





Reviewed by
Dwek & Krennrich 2012

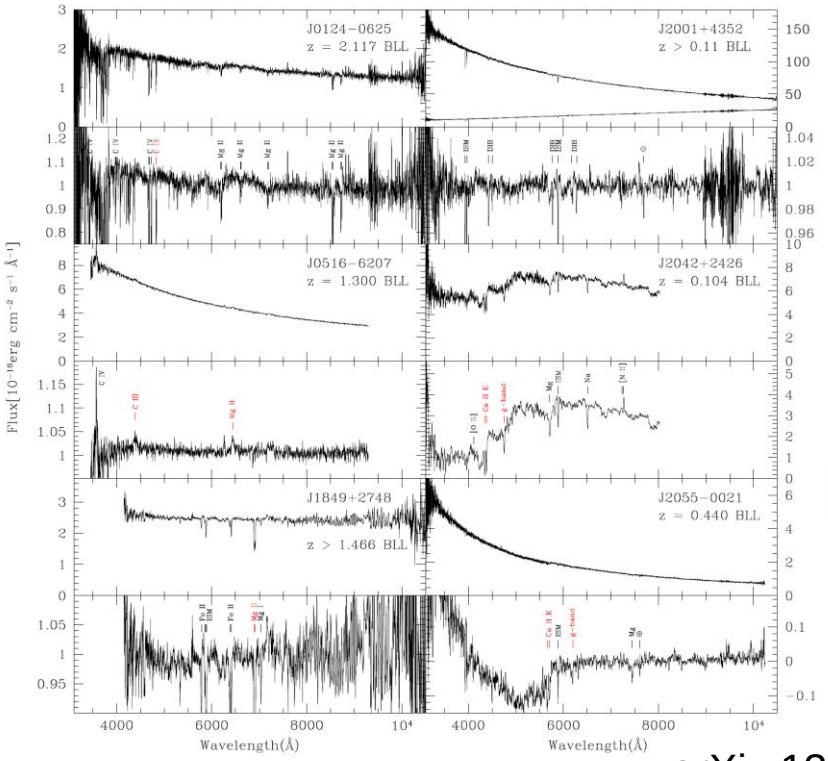


Part 4

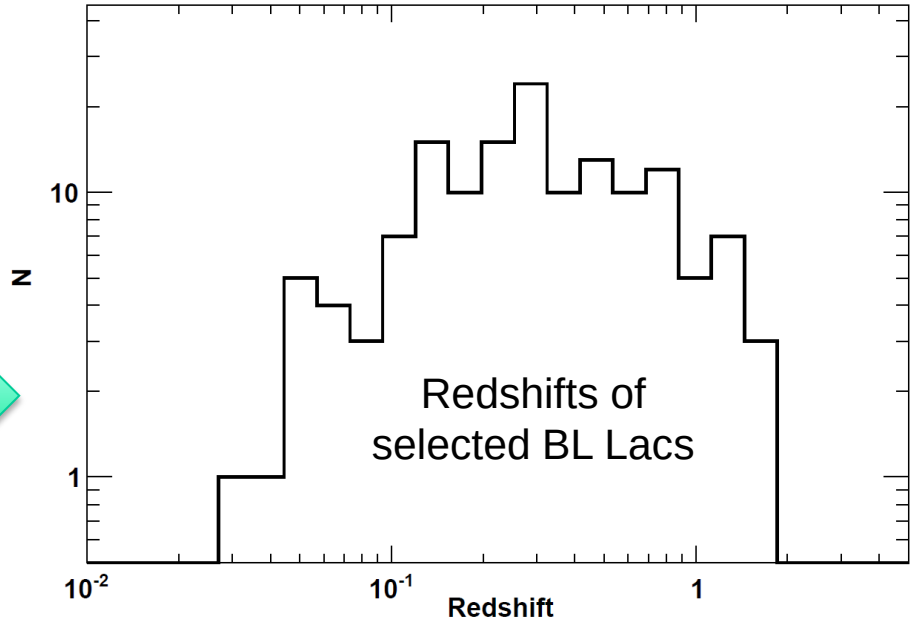
Blazars and the Extragalactic Background Light

Key Ingredient: BL Lac Redshifts

- **BL Lacs are source class of choice because their spectra are generally free of intrinsic absorption (unlike FSRQs)**
  - **But this makes redshifts difficult to obtain…**
- **Extensive optical follow-up program (Shaw et al. 2013)**
  - **Select subset of 150 *Fermi*-detected BL Lacs at 0.03 < z < 1.6**



Ackermann et al. 2012, Science, 338, 1190

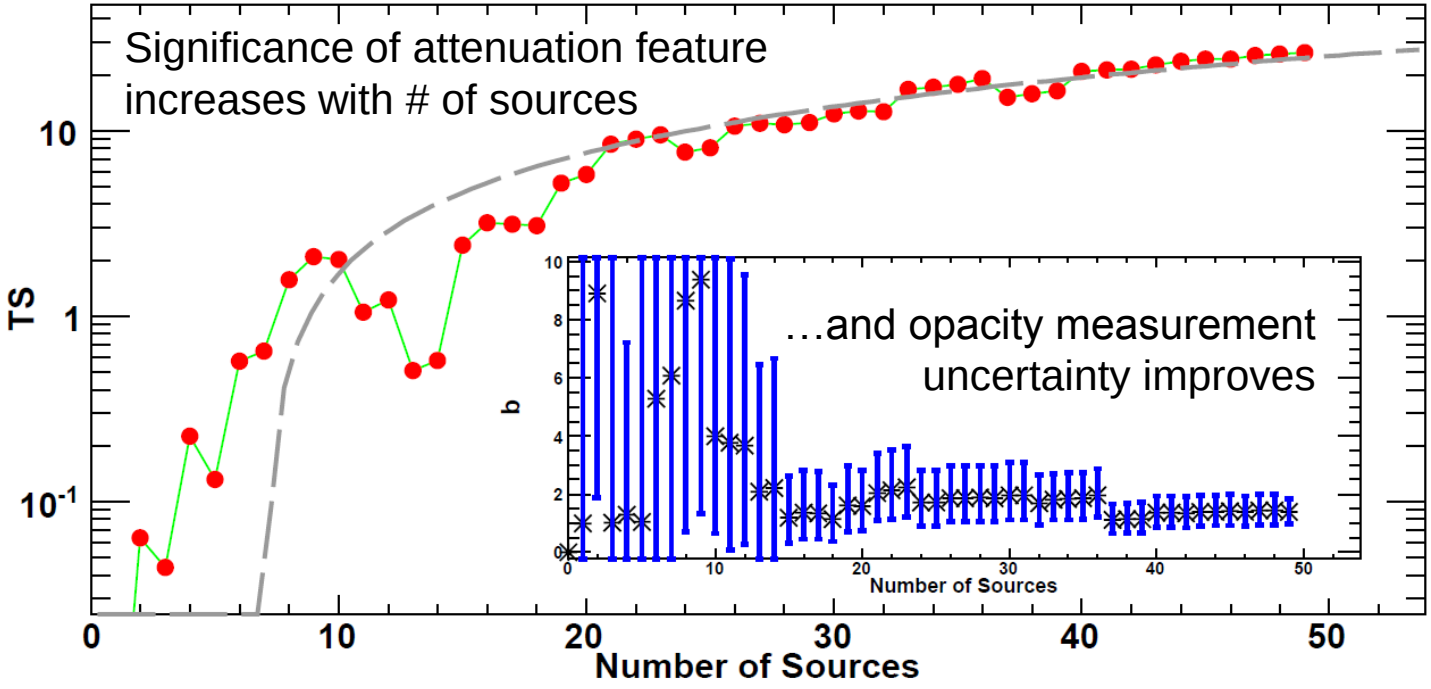


arXiv:1301.0323

Composite Likelihood Approach

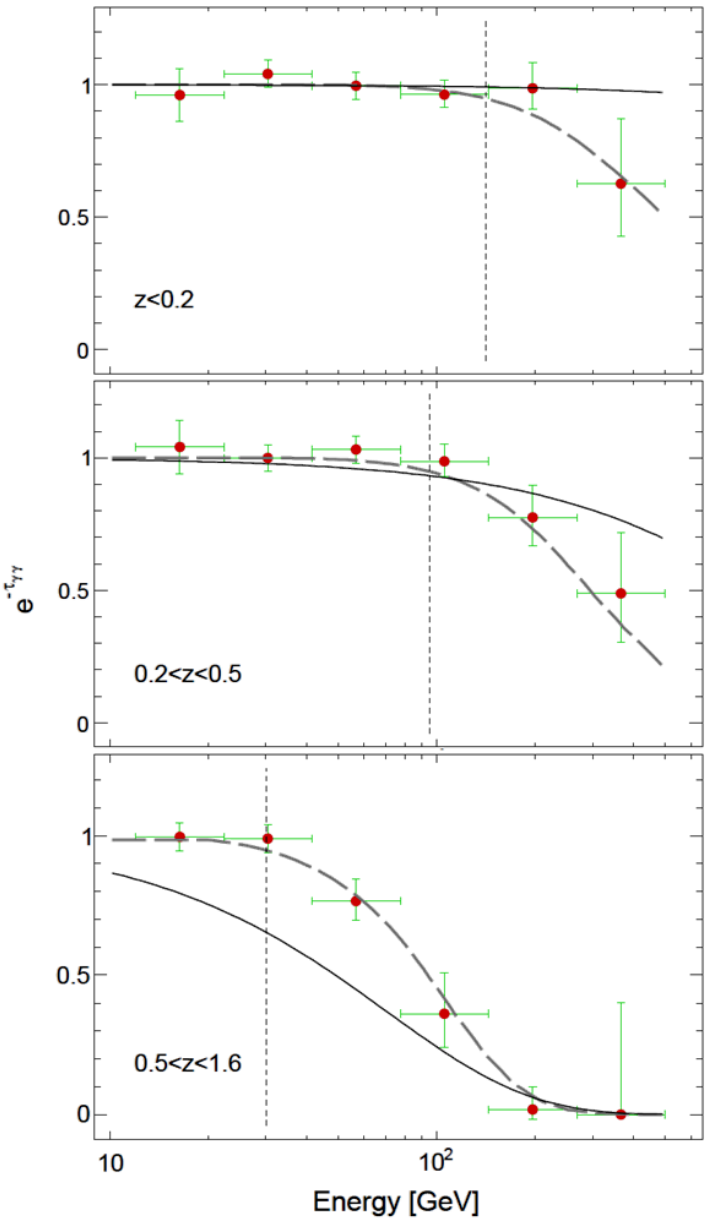
- **Model intrinsic blazar spectra by extrapolating the log-parabola fit at energies below the critical energy (< 5% attenuation expected from EBL model)**
- **Shared opacity parameter (*b*) fit simultaneously using all sources**

Attenuation $\exp(\tau_{\gamma\gamma}(E,z))$ with optical depth $\tau_{\gamma\gamma}(E,z) = b \cdot \tau_{\gamma\gamma}^{\mathrm{model}}(E,z)$



Ackermann et al. 2012, Science, 338, 1190

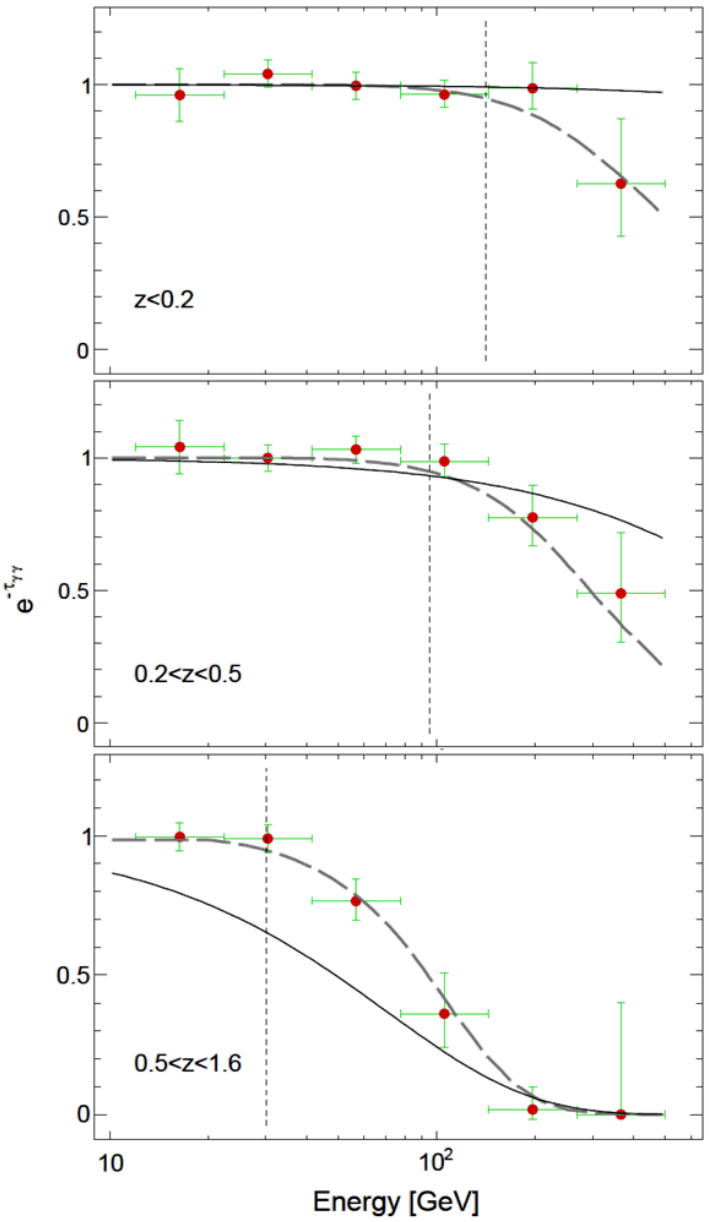
Fitting EBL Opacity in 3 Redshift Ranges



- **Attenuation feature as function of energy**
- **Vertical dashed line = critical energy below which < 5% of source photons are absorbed**
- **Long dashed line = EBL model of Franceschini et al. 2008**
- **Solid line = best-fit model assuming sources have intrinsic exponential cutoff, and follow blazar sequence model**

Ackermann et al. 2012, Science, 338, 1190

Fitting EBL Opacity in 3 Redshift Ranges



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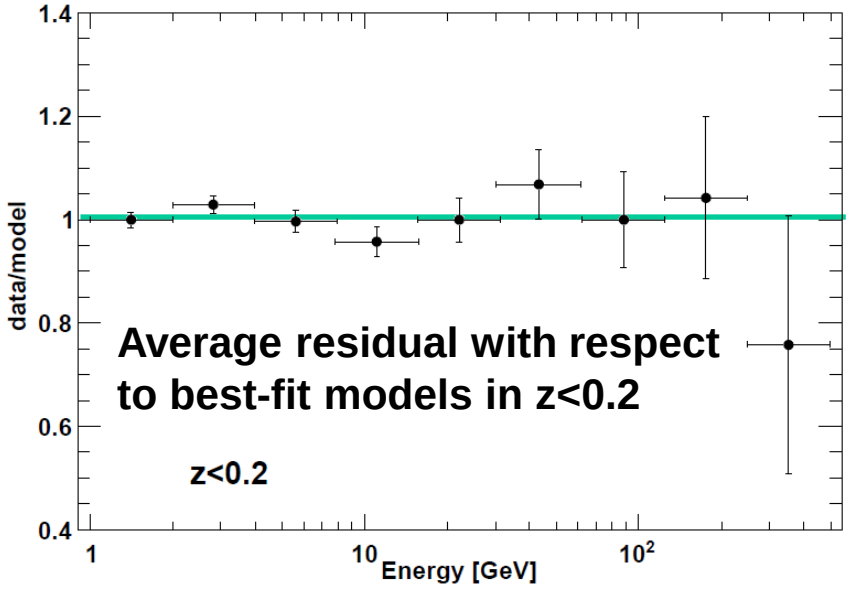
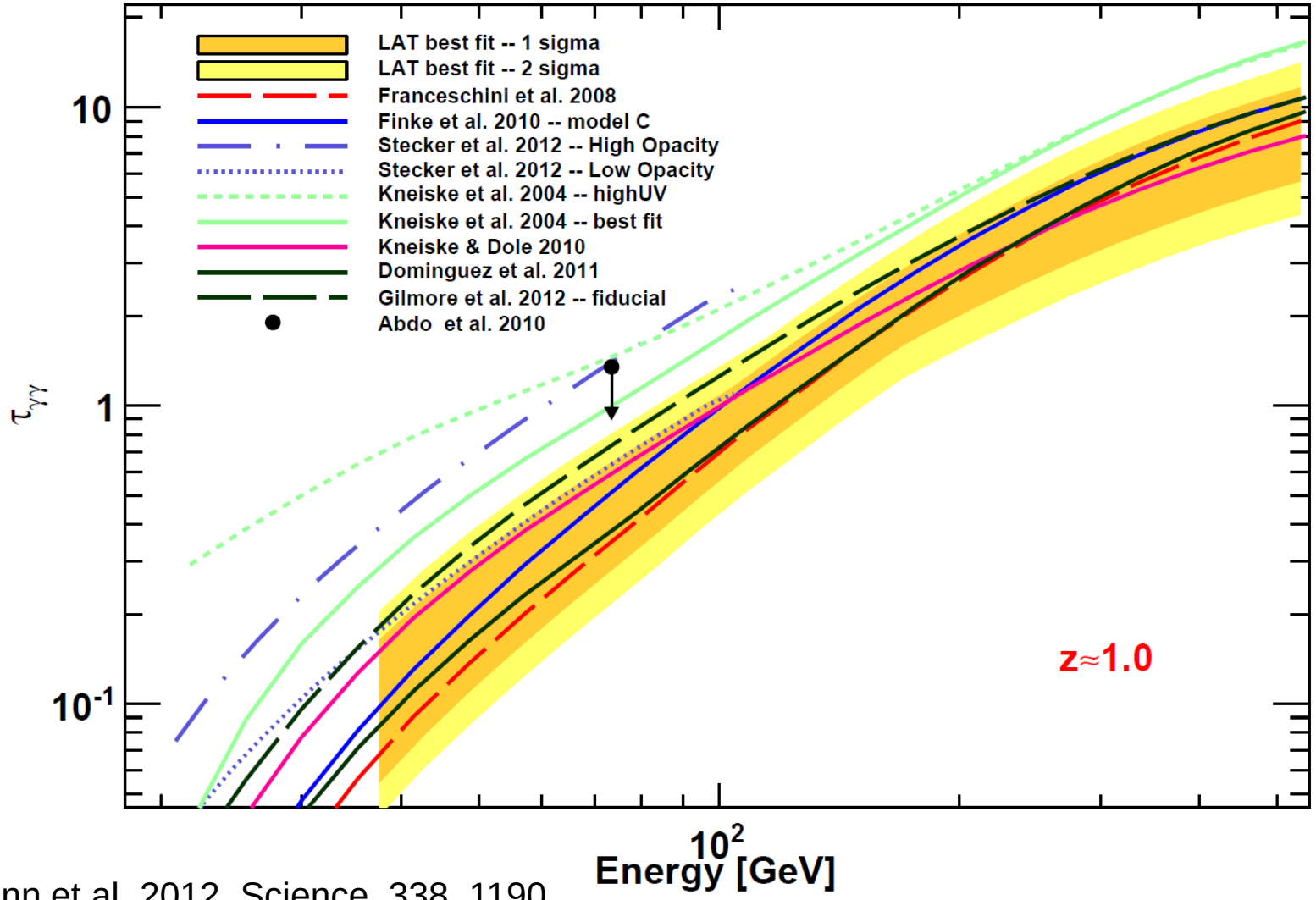


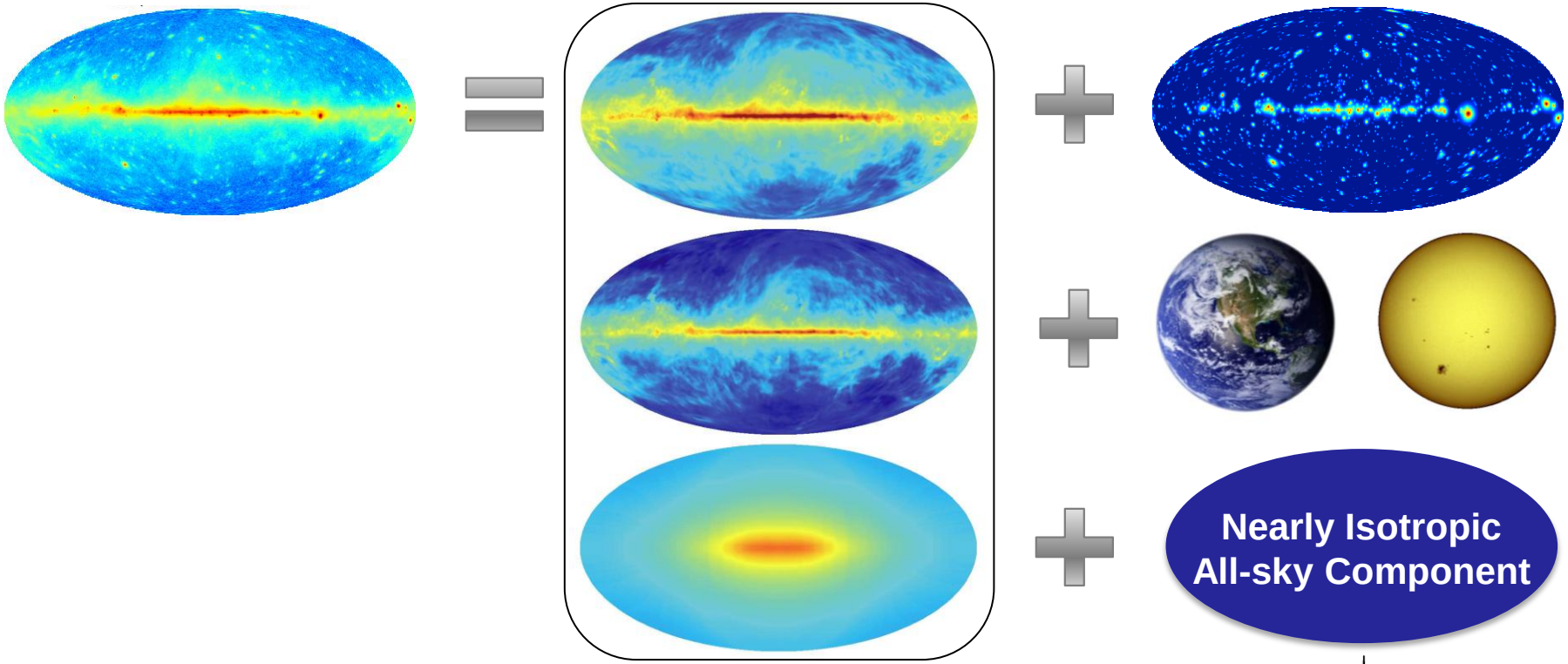
Ackermann et al. 2012, Science, 338, 1190

Opacity Comparison with EBL Models

LAT results consistent with "minimal" optical-UV EBL models based on observed galaxy counts



Ackermann et al. 2012, Science, 338, 1190

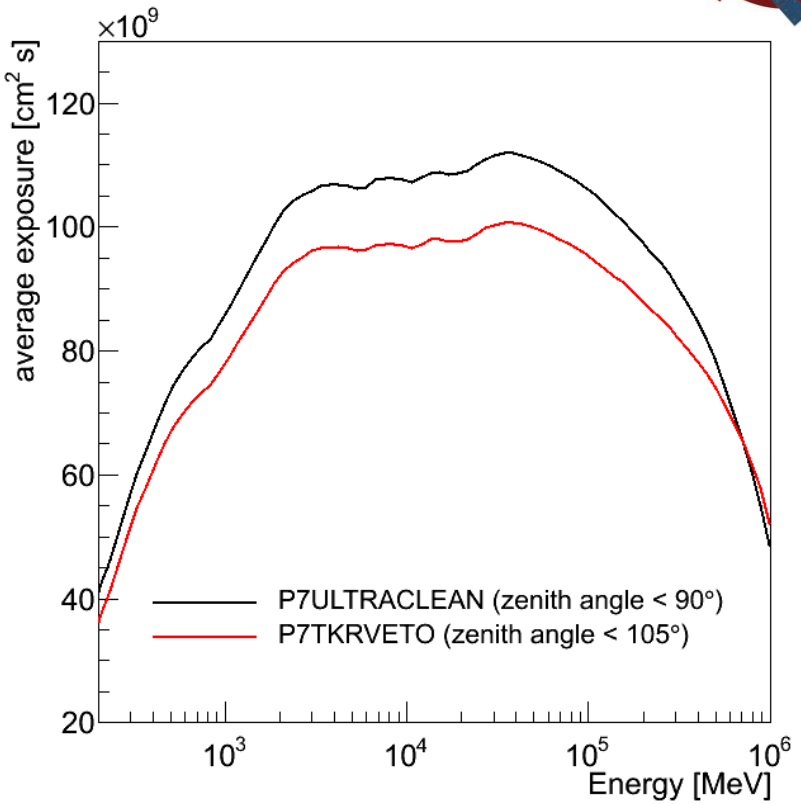


Part 5

Isotropic Diffuse Gamma-ray Background

IGRB Analysis Updates

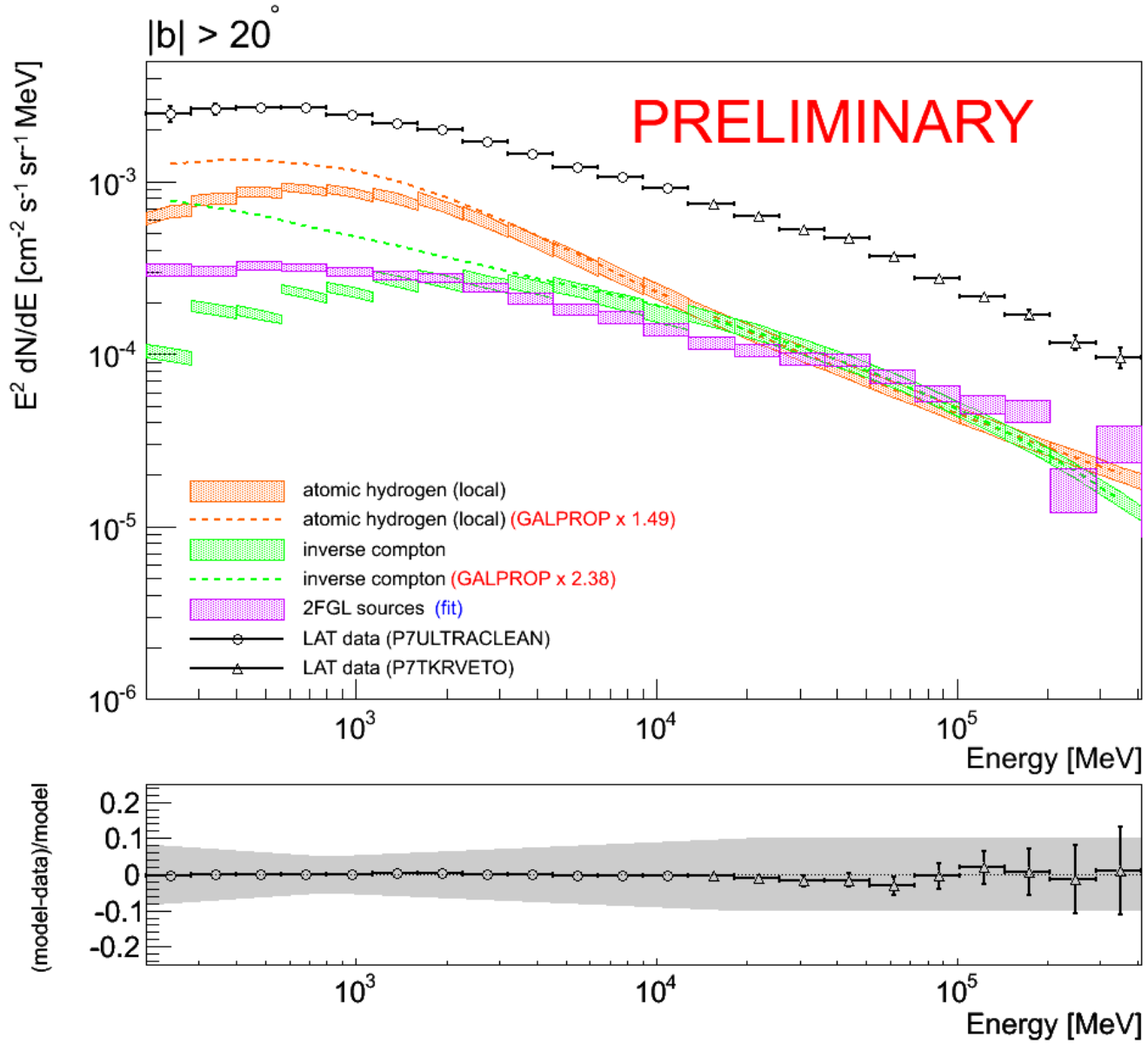
- **Event selection**
  - 44 months data, 0.2 – 820 GeV
  - Reprocessed Pass 7 events (P7REP)
  - Separate low-energy (<12.8 GeV) and high-energy analyses (>12.8 GeV)
  - New super-low background event selection for high-energy analysis
  - Residual particle background up to 1 TeV evaluated from large-scale MC simulations
- **Celestial model components**
  - Further studies of uncertainty from Galactic foreground models
  - Galactic plane mask
  - New North Polar spur template
  - 2FGL sources
  - Updated Earth emission model



P7TKRVETO (using part of tracker as additional veto) reduces CR background by factor ~2 relative to P7ULTRACLEAN above 12.8 GeV

Limited by energy reconstruction and track confusion >800 GeV (to be addressed in Pass 8)

IGRB Analysis Updates

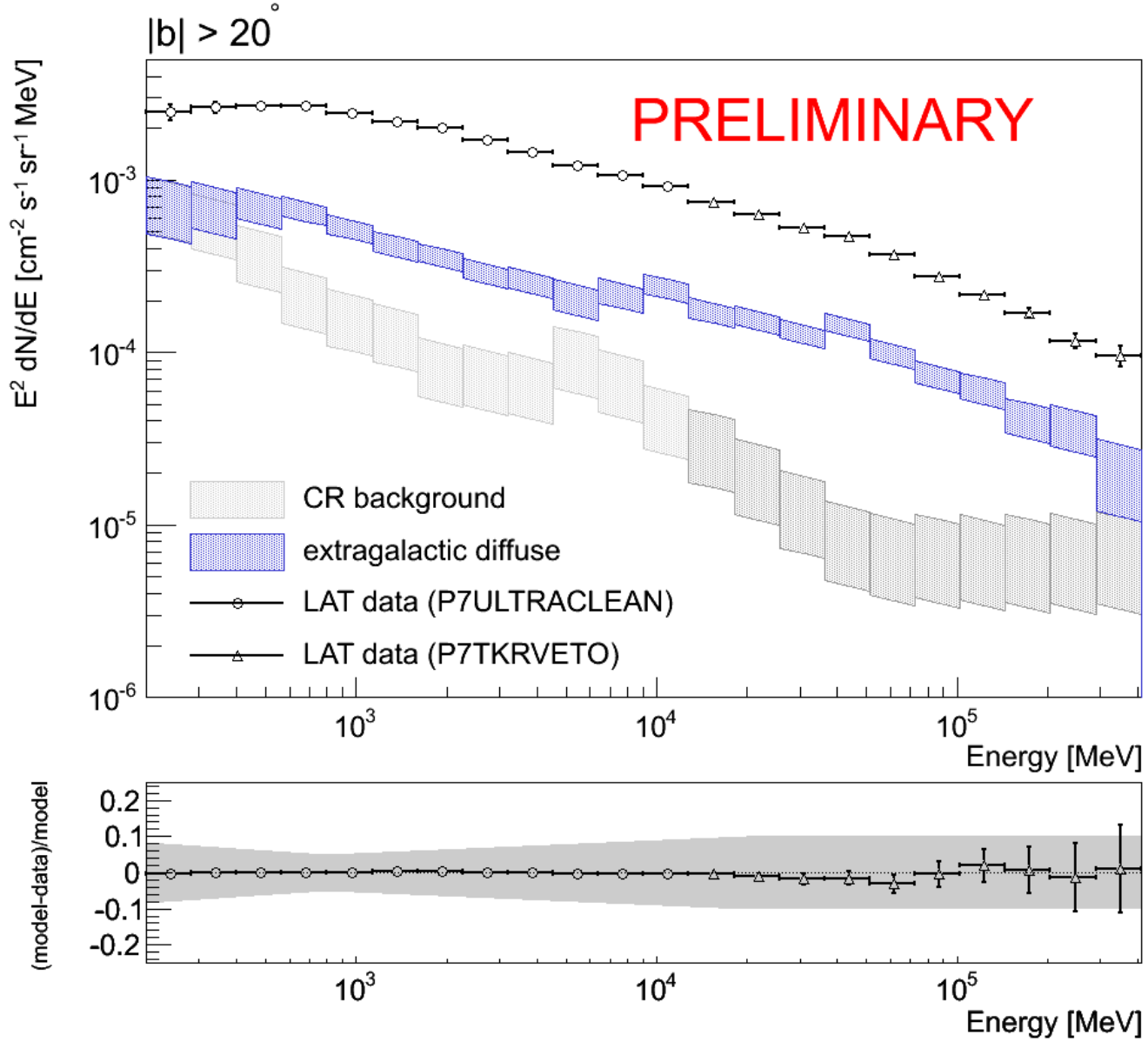


Default Galactic foreground model similar to those studied in Ackermann et al., ApJ 750, 3 (2012)

Fit to LAT data shows our understanding of IC component is incomplete; consider models with

- **Varying diffusion coefficients throughout Galaxy**
- **Different CR source populations**
- **Different interstellar radiation fields**
- **Different halo sizes**

IGRB Analysis Updates



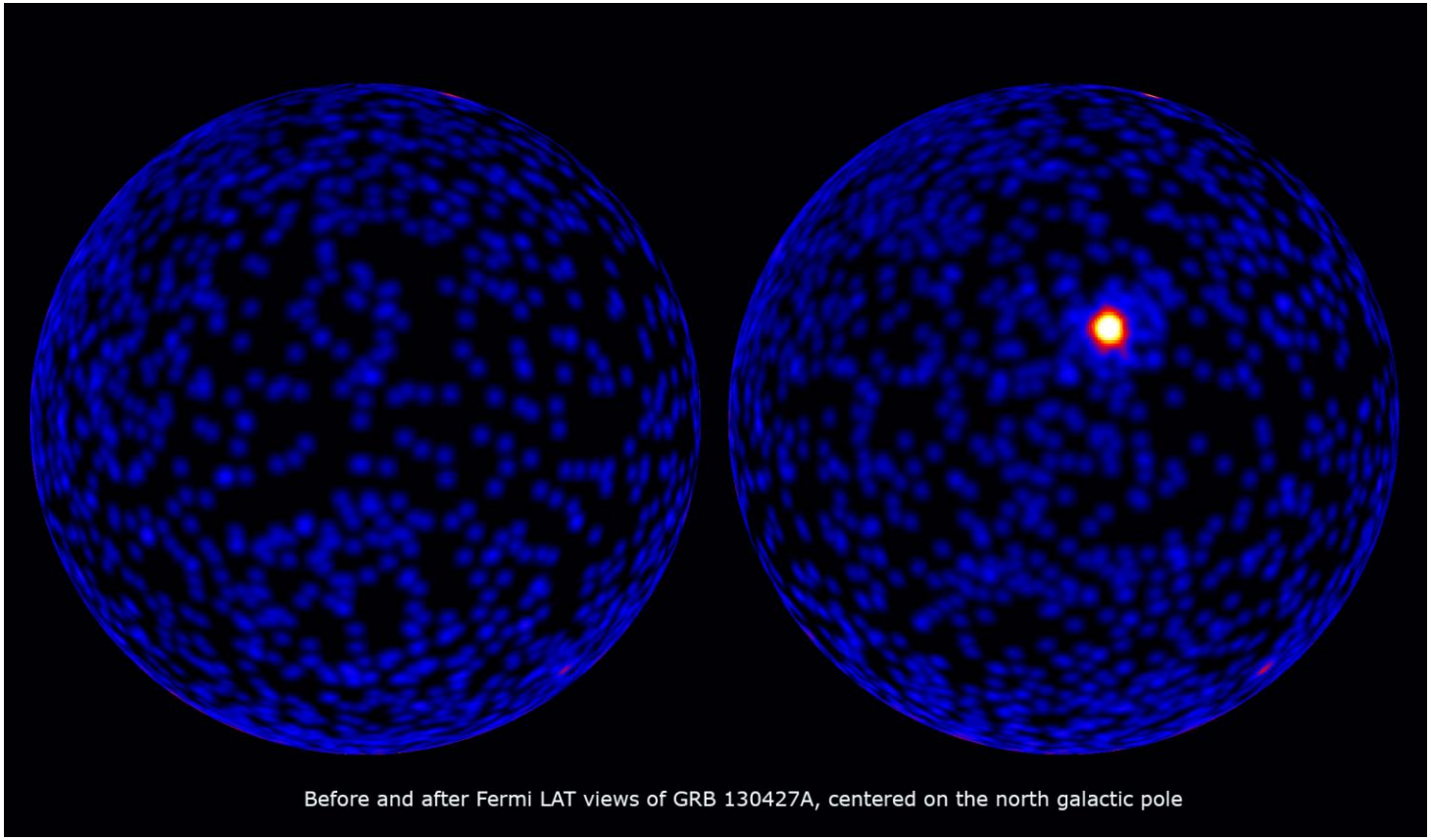
***Preliminary* 0.2 – 410 GeV IGRB spectrum shown**

Low and high energy analyses agree in overlap energy range

Uncertainties reflect statistical + systematic uncertainty (from effective area calibration and CR background subtraction)

..but NOT uncertainty from diffuse foreground models

Expect ~30% overall uncertainty on normalization



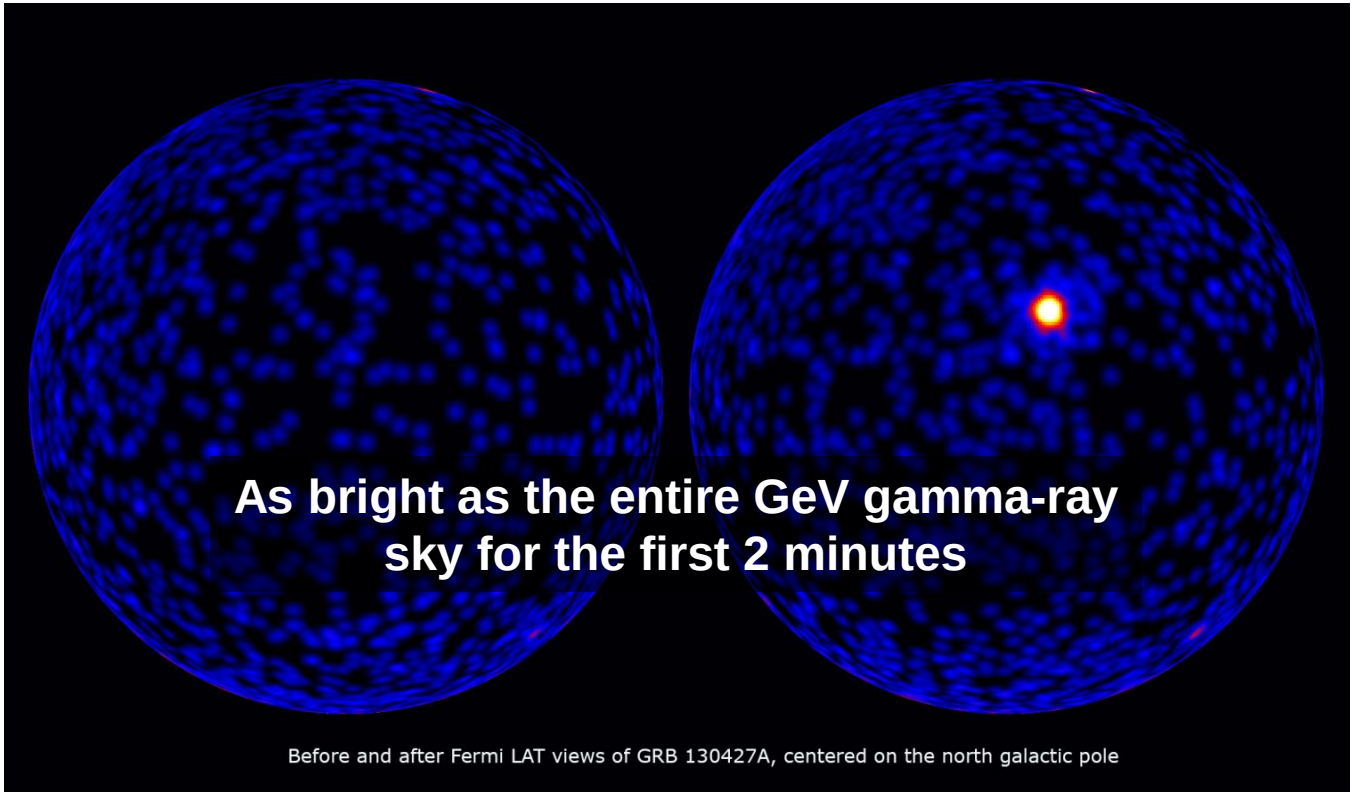
News

Record-breaking GRB 130427A!

>100 MeV, Source class, centered on North Galactic Pole, smoothed with 2 deg FWHM Gaussian, exposure corrected. *Left*: 5.5 - 2.5 hrs before. *Right*: 2.5 hrs before to 0.5 hr after.

Record Breaking GRB 130427A

- **Brightest burst yet for LAT and GBM**
- **Highest energy photon ever (94 GeV)**
- **Longest lasting GeV emission ever detected (~day)**
- **z = 0.34 (among closest 5% of GRBs)**

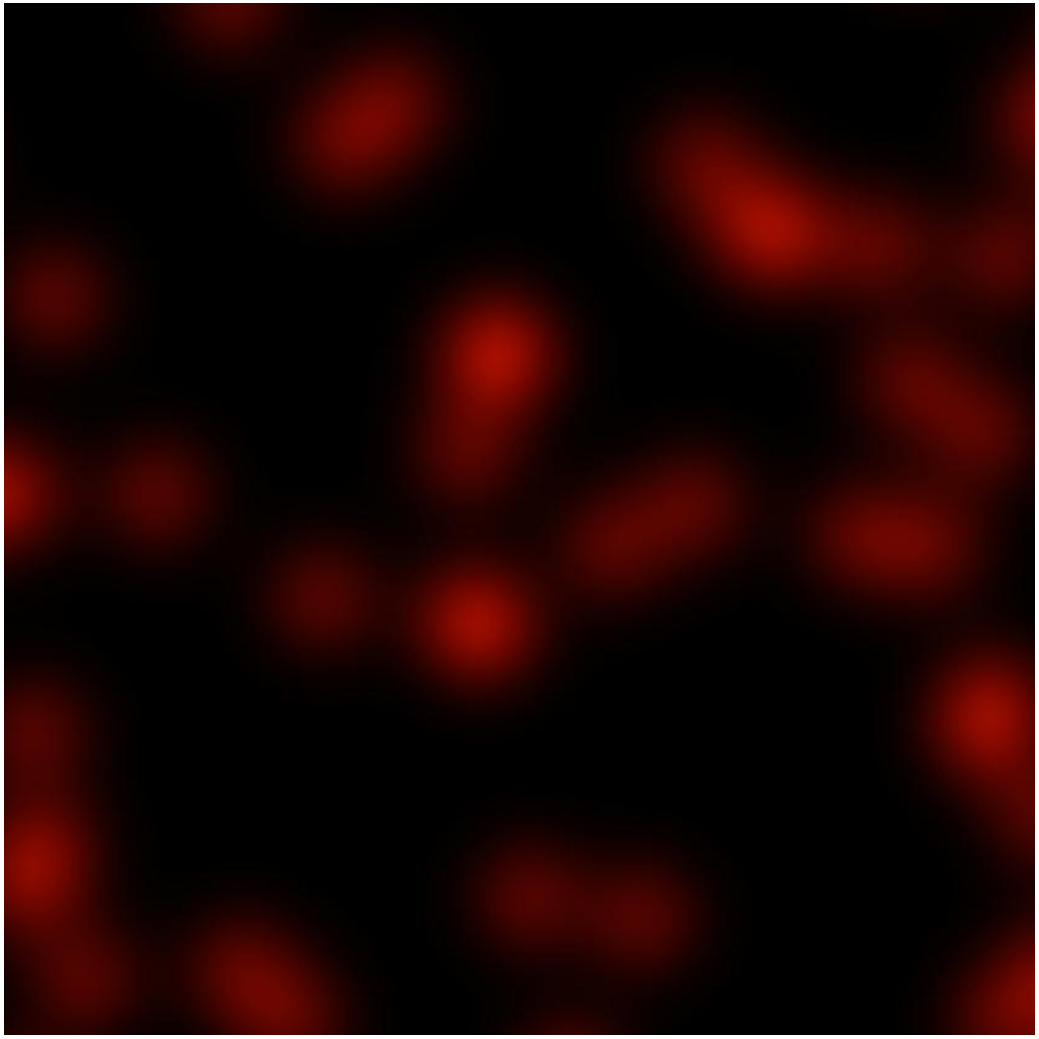


Before and after Fermi LAT views of GRB 130427A, centered on the north galactic pole

Record Breaking GRB 130427A

Sequence of smoothed counts maps from 0.1 to 100 GeV in a 20 deg wide region

Time period extends from 3 min before burst to 14 hrs after



>70 GCN Circulars!

Two LAT Circulars (14471, 14508)

IceCube Circular (14520)

HAWC Circular (14549)

Circular 14471: "The highest energy LAT photon has an energy of 94 GeV"

Extra

Back-up Slides