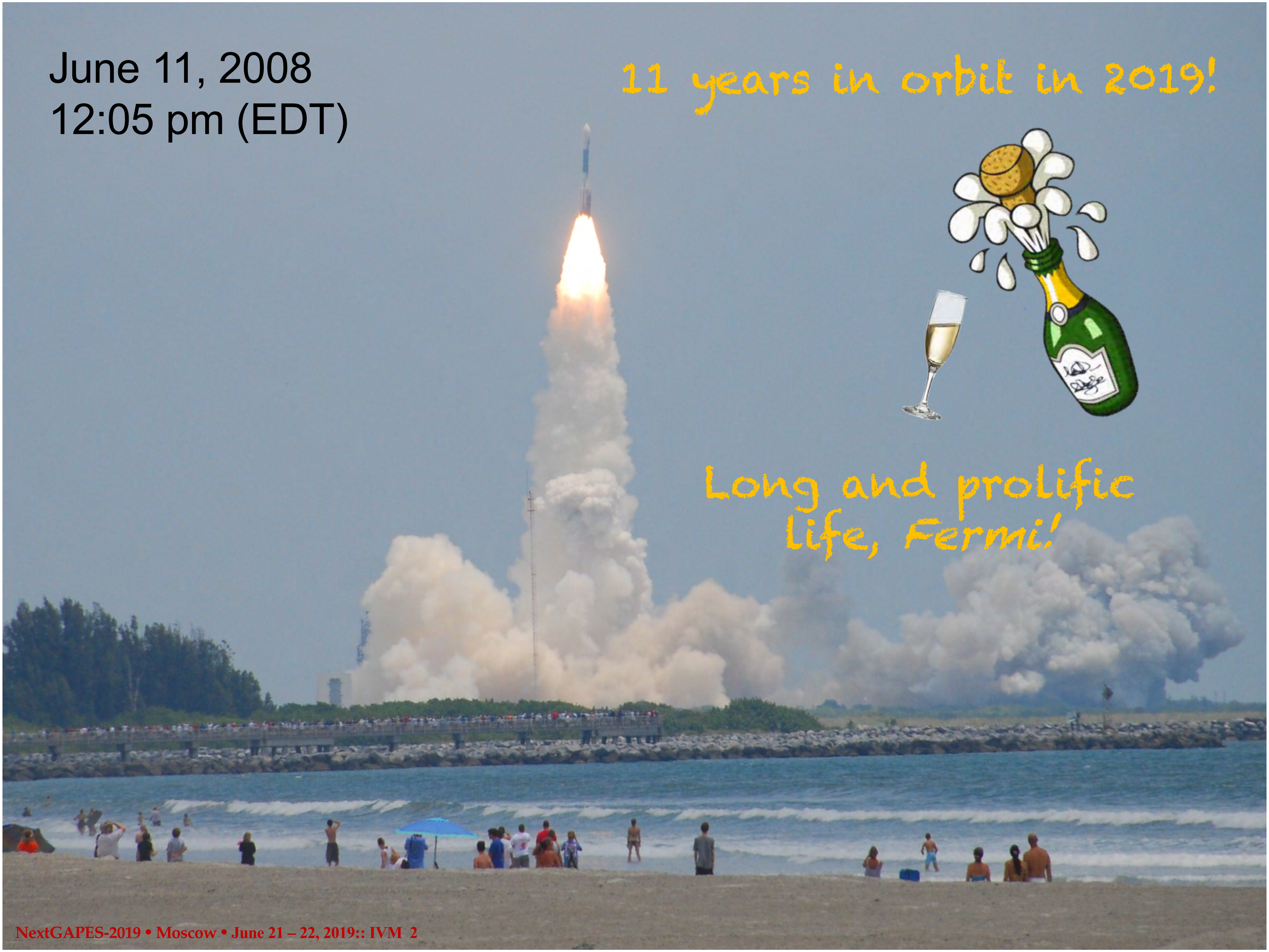
Fermi @ 11

Igor V. Moskalenko
Stanford University

On behalf of the Fermi LAT Collaboration

Next Generation AstroParticle Experiments in Space
NextGAPES-2019, Moscow, June 21-22, 2019

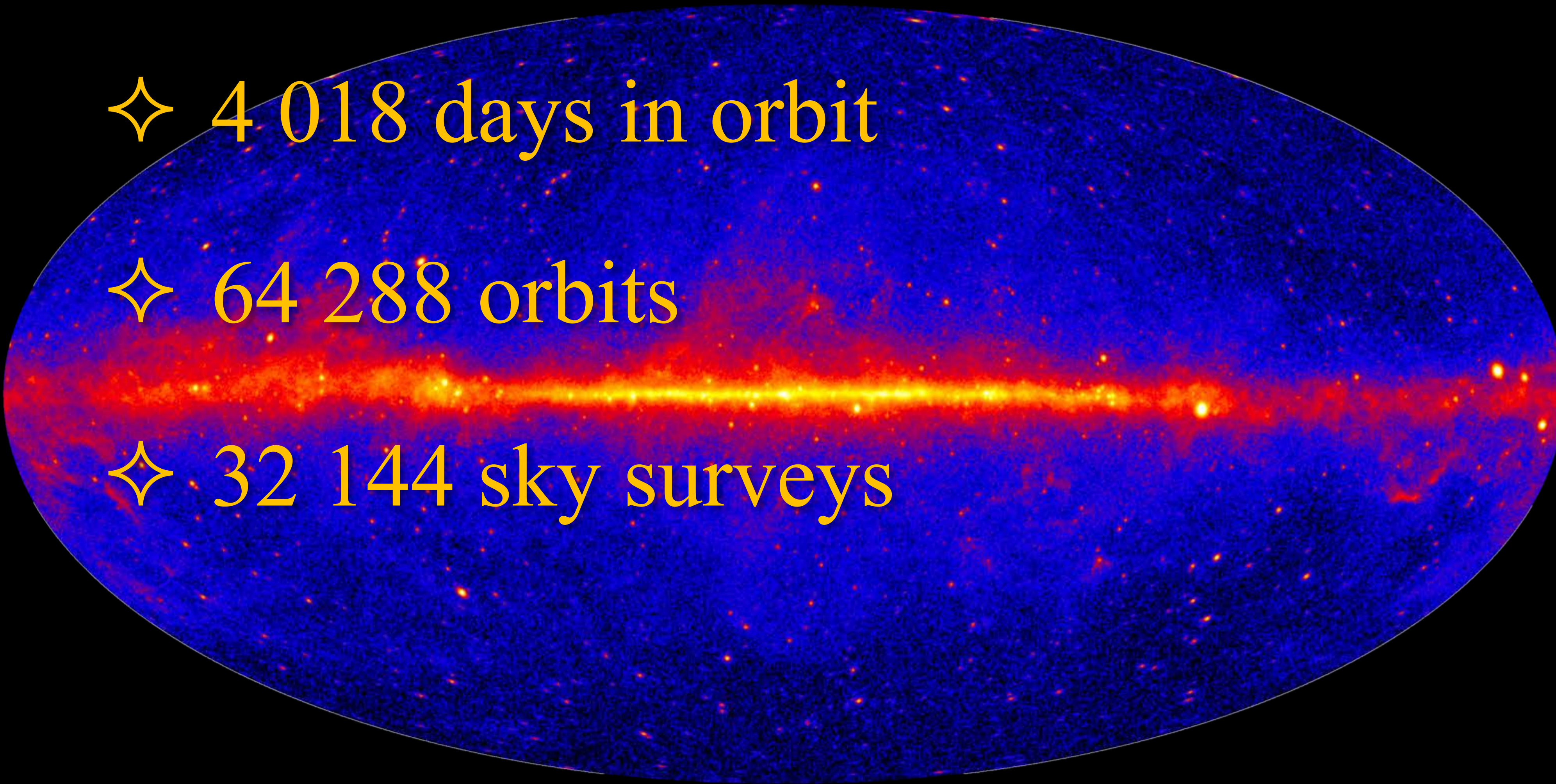

June 11, 2008
12:05 pm (EDT)
11 years in orbit in 2019!
Long and prolific
life, Fermi!

Fermi @ 11:

✧ 4 018 days in orbit

✧ 64 288 orbits

✧ 32 144 sky surveys

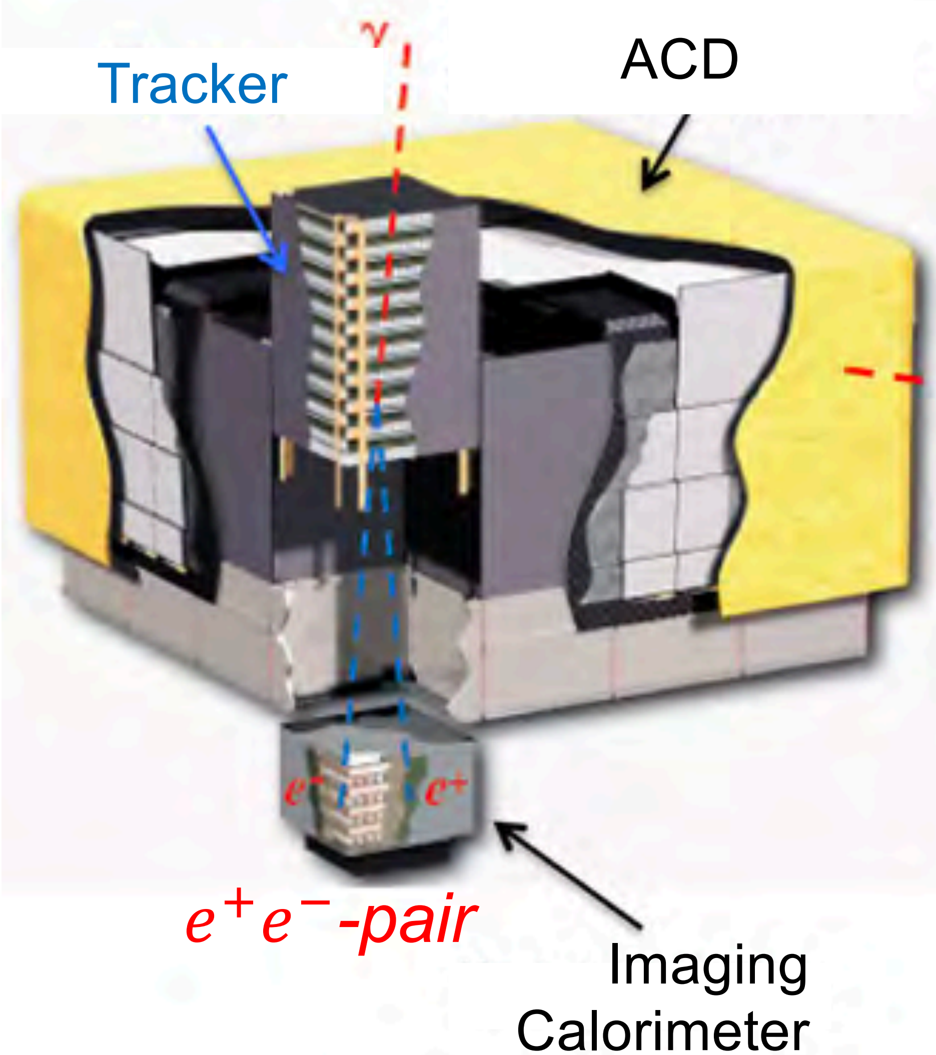


Fermi-LAT skymap >1 GeV, 48 months

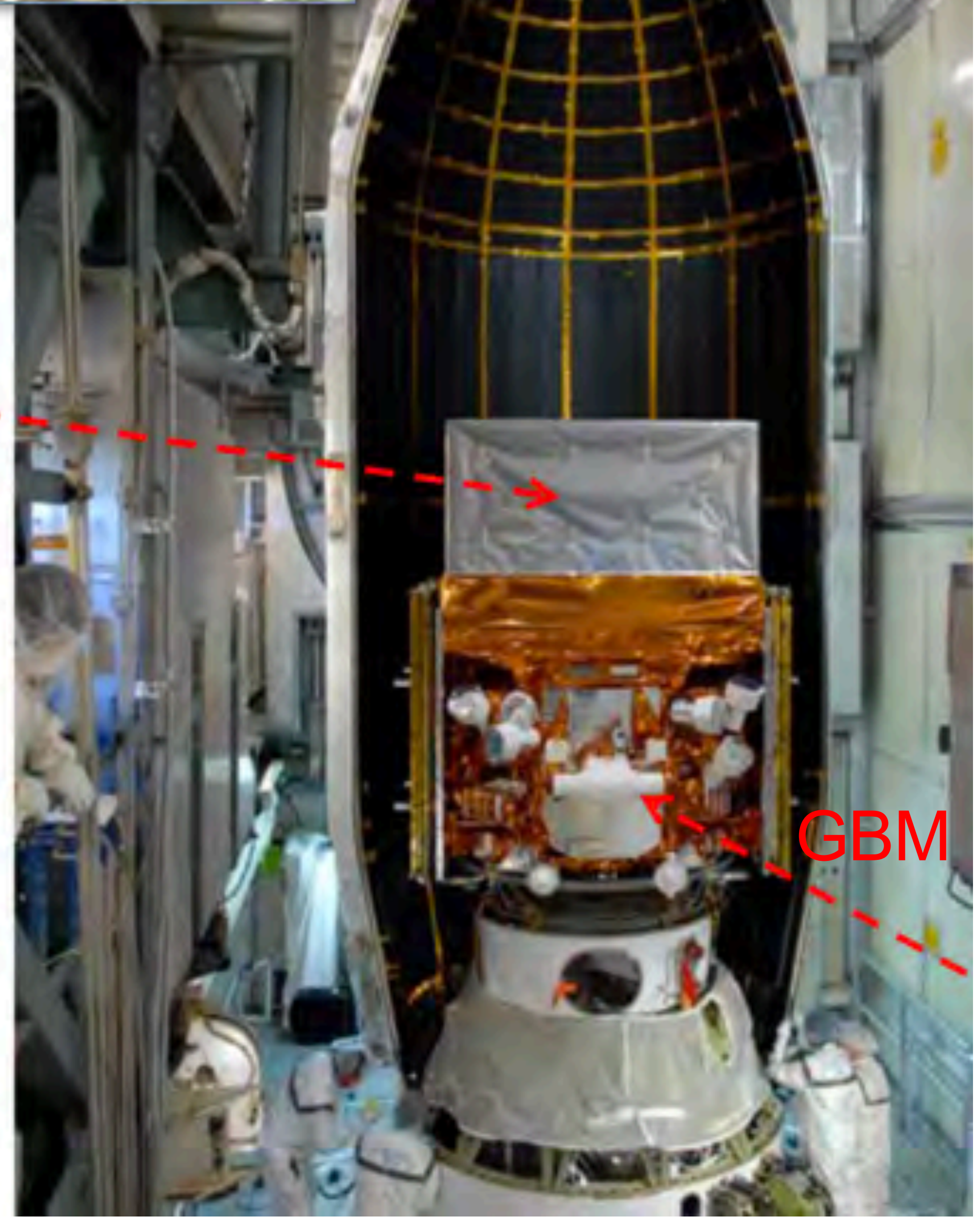
GLAST/Fermi-LAT

LAT: 20 MeV – >300 GeV

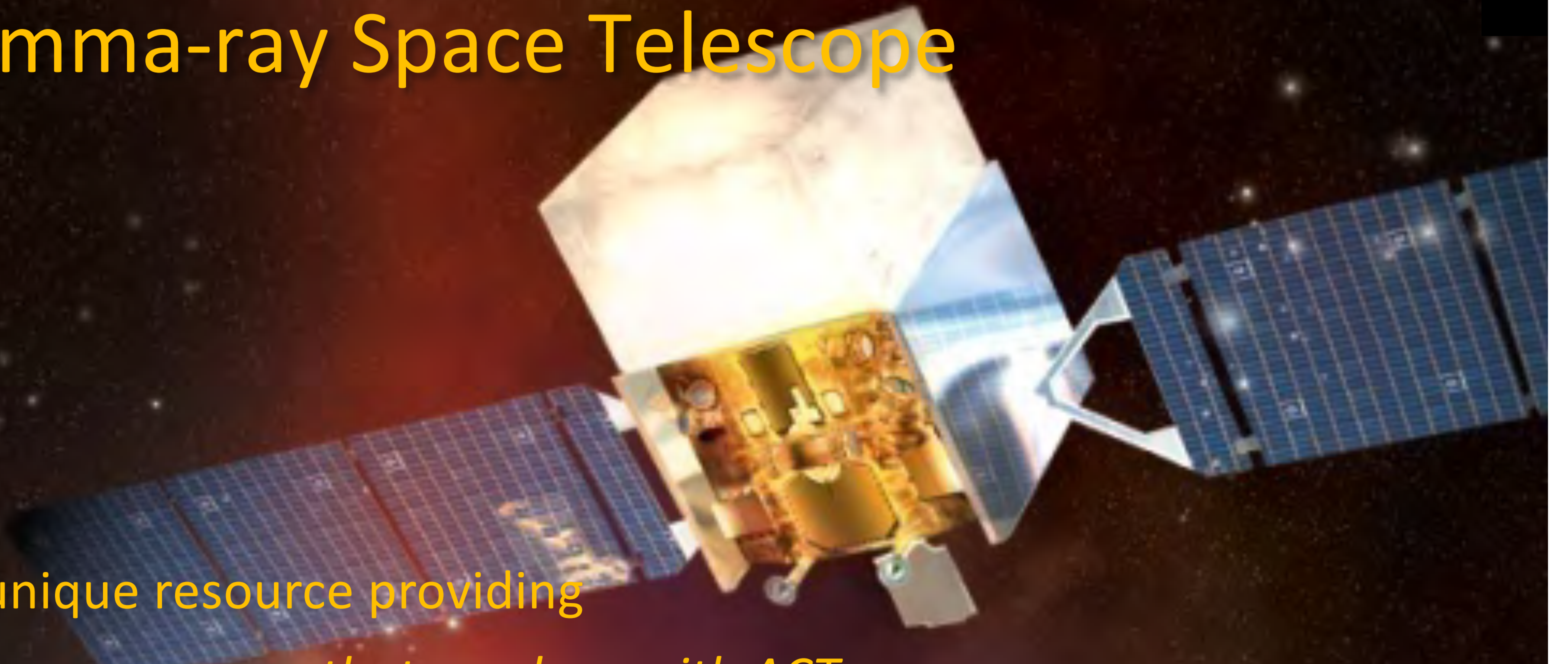
GBM: 10 keV – 30 MeV



4×4 = 16 identical towers

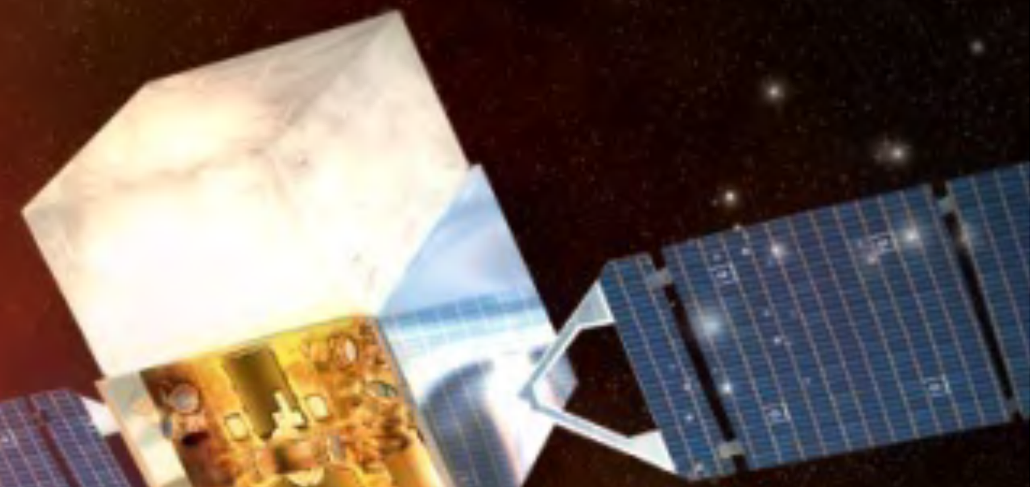


Fermi Gamma-ray Space Telescope



- The LAT is a unique resource providing
  - *Broad energy coverage that overlaps with ACTs*
  - *Large FoV: all-sky coverage every 3 hours – transients*
- Observatory is operating smoothly
  - *Instruments and spacecraft operate as designed, no degradation in science performance since launch*
  - *Minor issue: One solar panel is stuck*
- Observation Modes
  - *Dec 2013 – Dec 2014 in Galactic Center biased survey mode*
  - *Return to the standard rocking sky survey in Dec. 2018*
- Next NASA's senior review in 2019

Glitches etc.

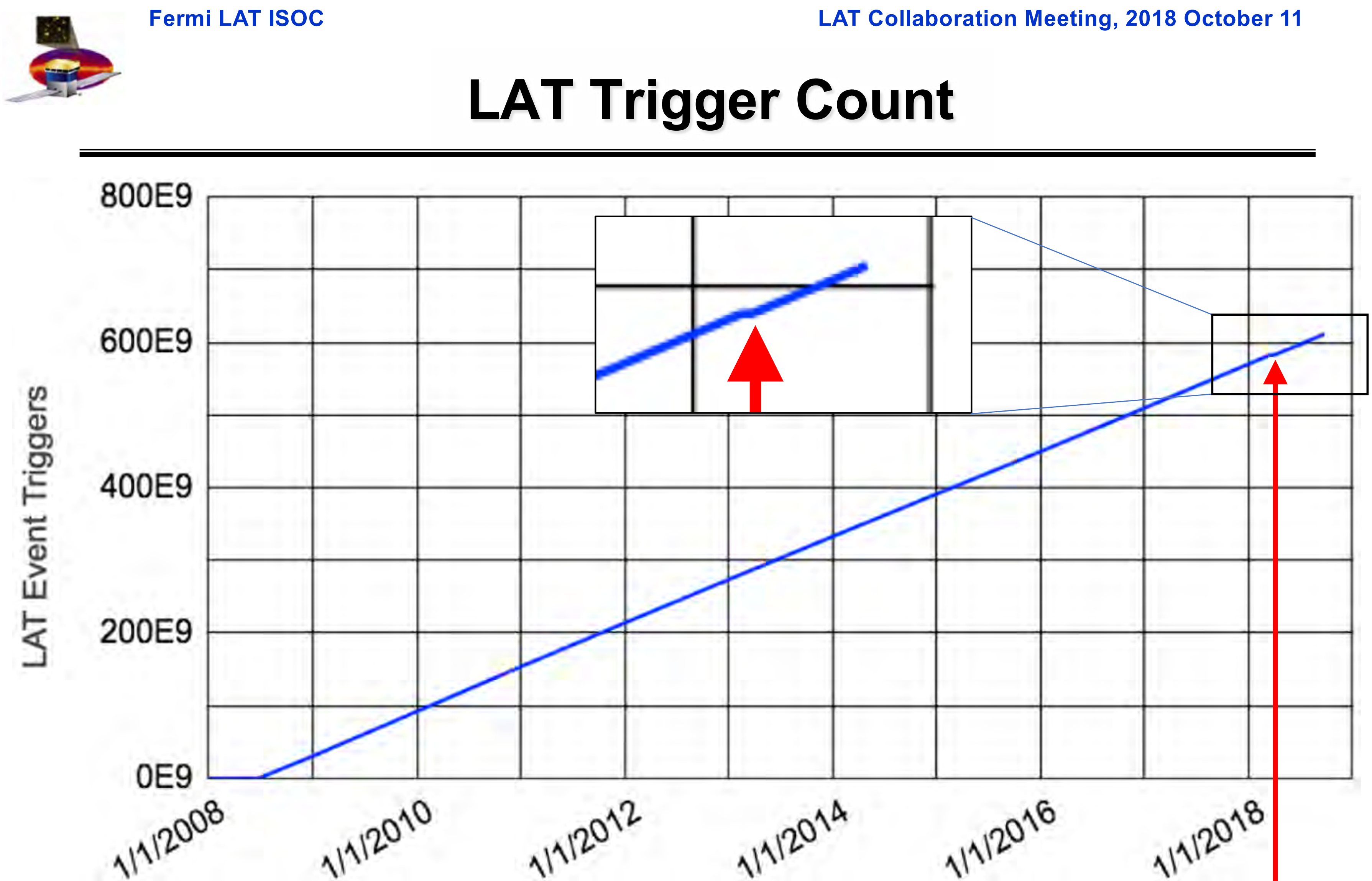


- Very smooth operations
- Only 2 incidents that resulted in powering down instruments
  - 2009 – reboot of LAT and SC cpus (addressed with FSW patch)
  - 2018 – Failure in –Y Solar Array Drive Assembly (SADA) on March 16

- An anomaly of the Solar Array Drive Assembly (SADA) for –Y solar array
  - Solar array itself remains fully operational, but one solar panel currently stuck at an angle of 17.5 deg, pointing downward
  - Resumed GBM operations on March 27
  - Resumed LAT observations on April 4

- Resumed normal +50/-50 deg rocking profile for part of the time and sine profile for the rest; practically full sky coverage

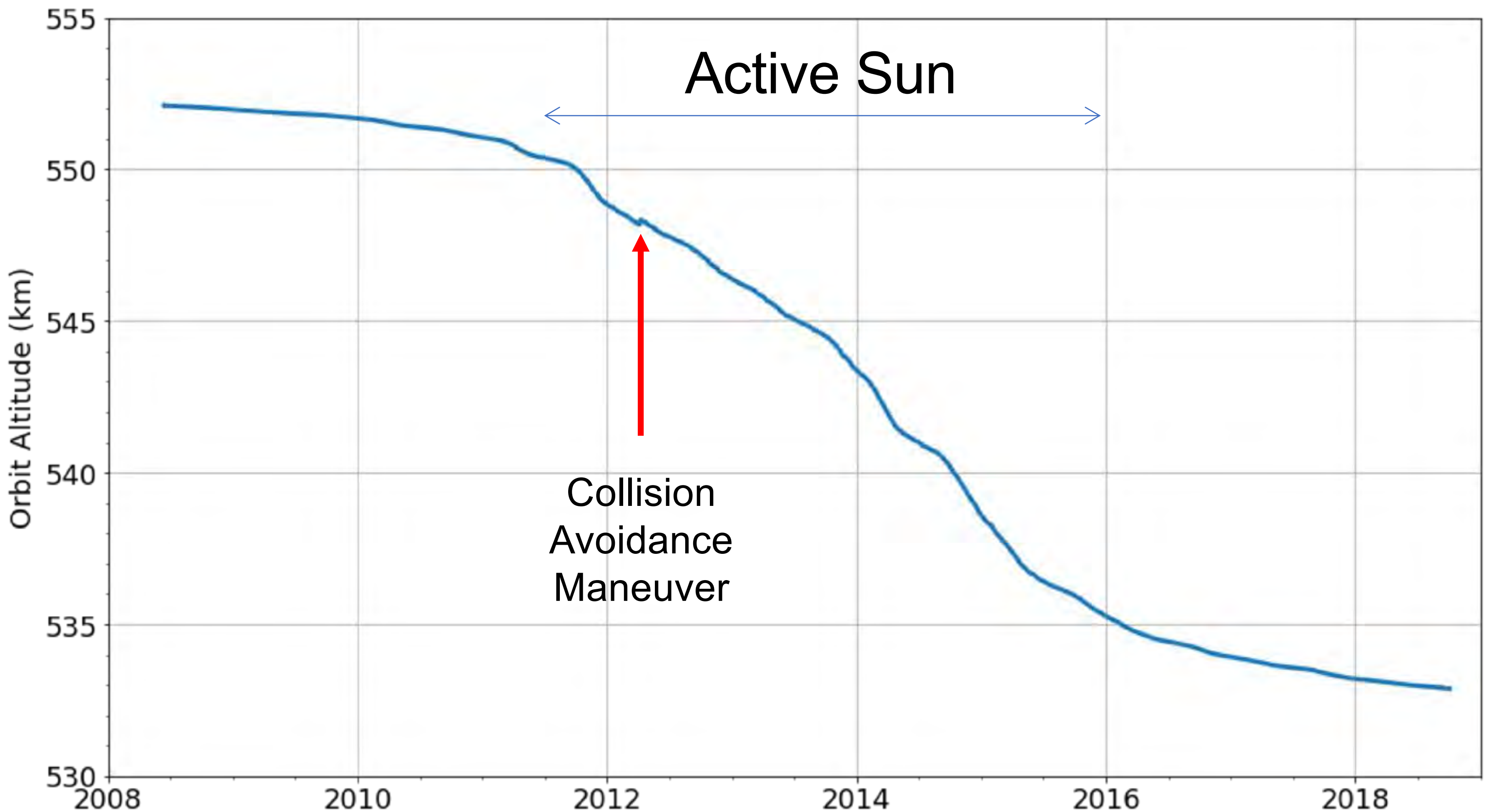
Effect on the event count



18 day interruption to data-taking is barely visible feature

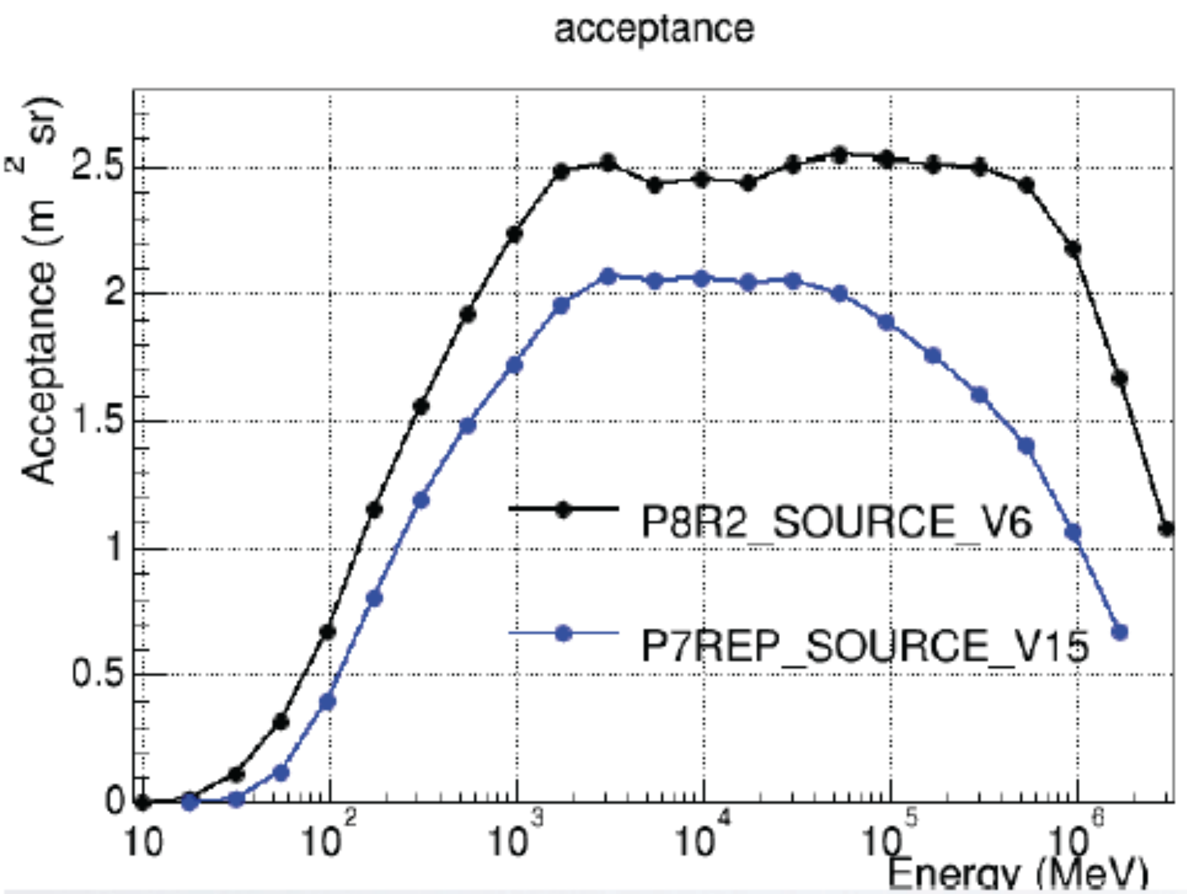
Fermi Orbit Altitude

Orbit altitude of Fermi is currently decreasing at ~1km / year



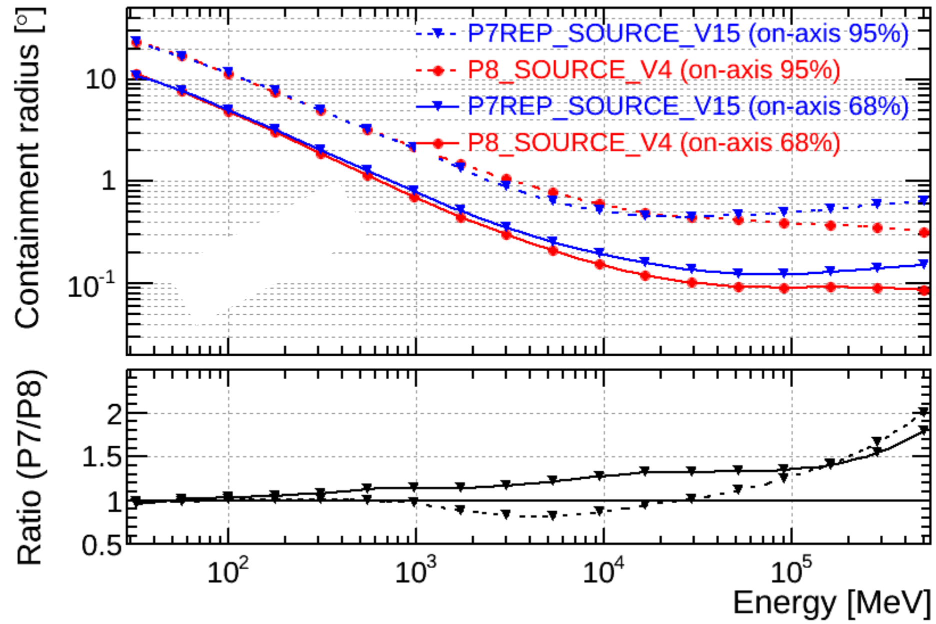
Pass 8 is here!

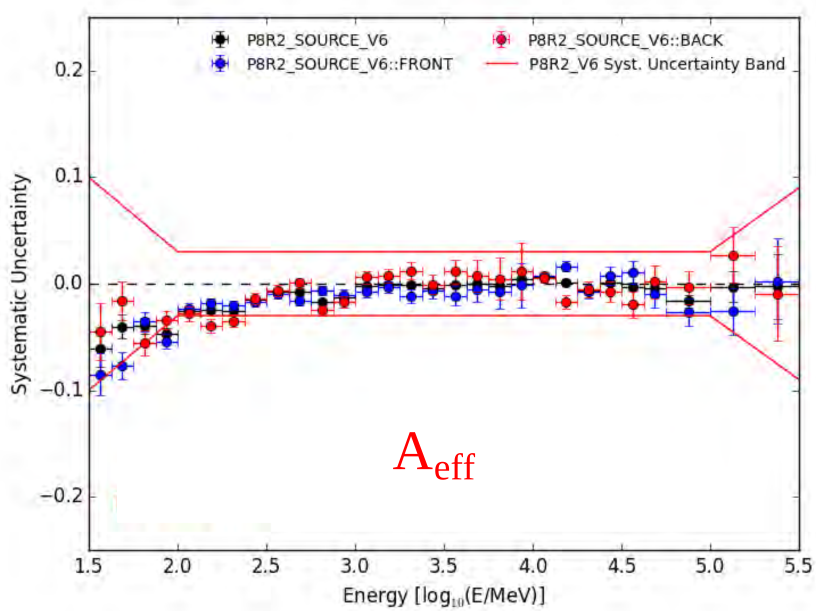
- Provided a substantial improvement in the capabilities of the LAT
  - 40% increase in point-source sensitivity
  - Up to ×2 gain in acceptance at very low (<100 MeV) and very high (>100 GeV) energies
- Updates: data and software releases
  - In-flight IRFs
  - Cal-only event class
  - New Science Tool features

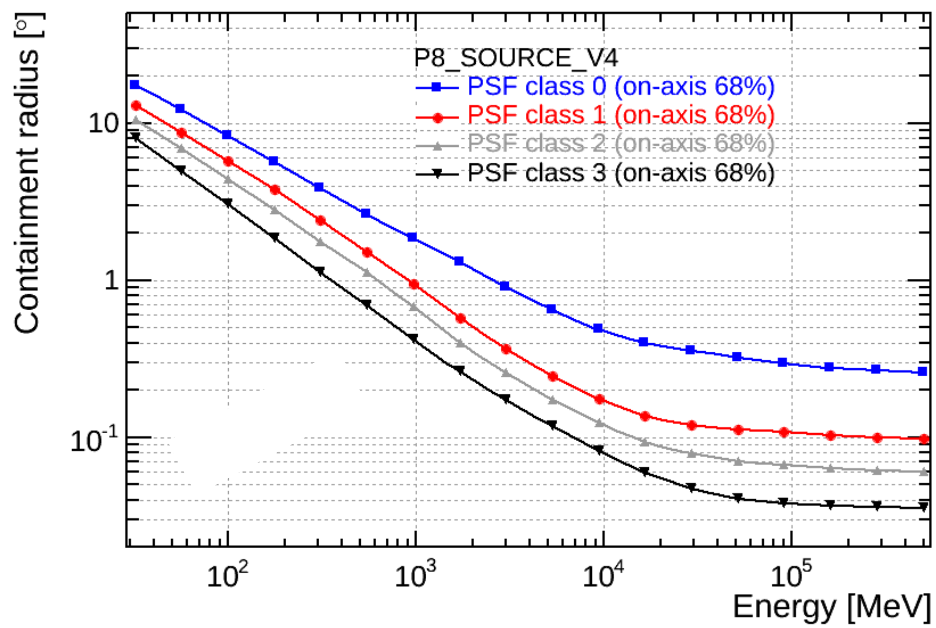


Pass 8 Performance

- Significant improvement in the angular resolution
- Additional event selection classes
- On-axis 68% containment (class 3)
  - 3° at 100 MeV
  - 0.4° at 1 GeV
  - 0.07° (~4.2') at 10 GeV
  - 0.035° (~2.1') at >100 GeV
- Cf. HESS 2 angular resolution is ~0.05° at best
- Significant reduction in the systematic uncertainty of the Effective Area





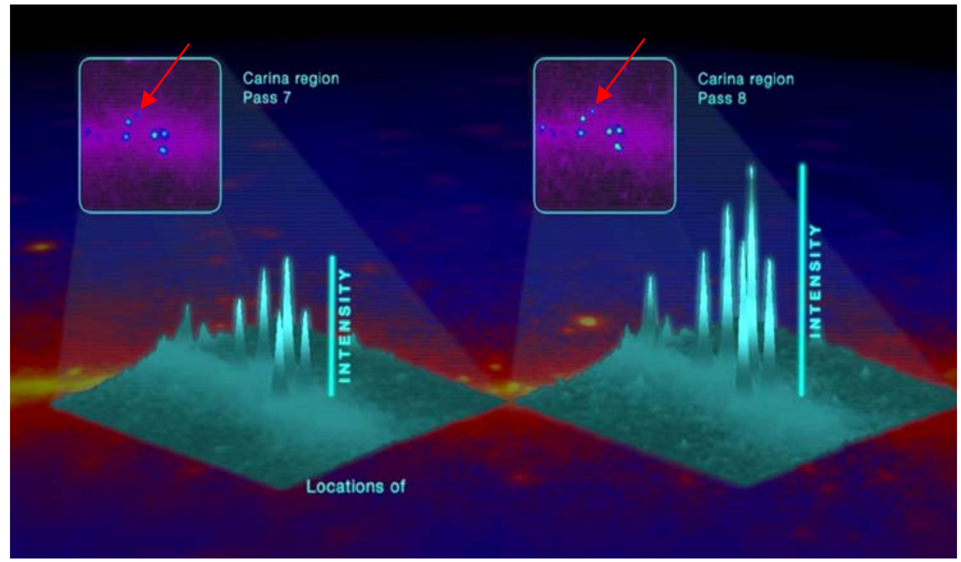


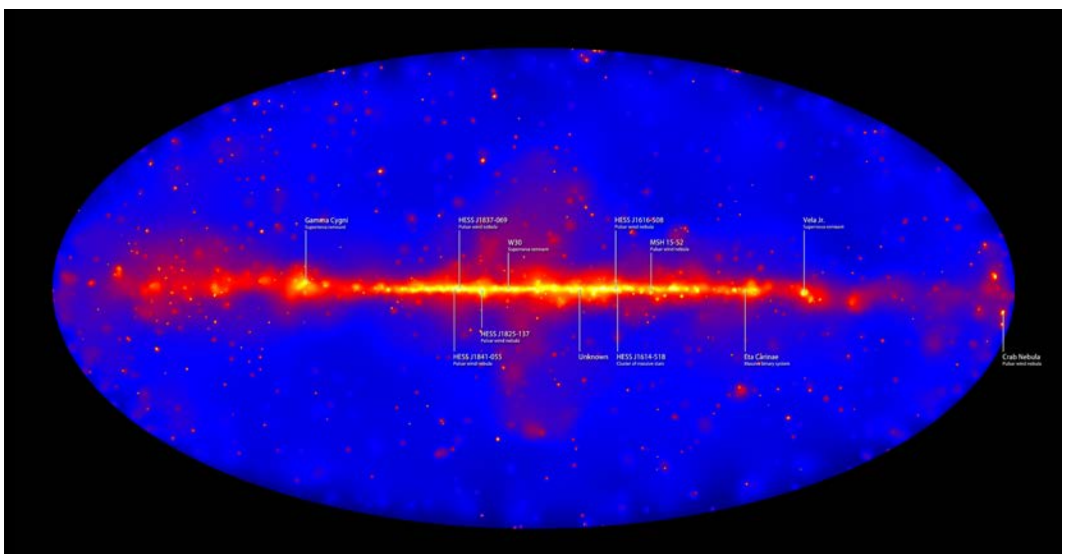
Reconstruction improvements

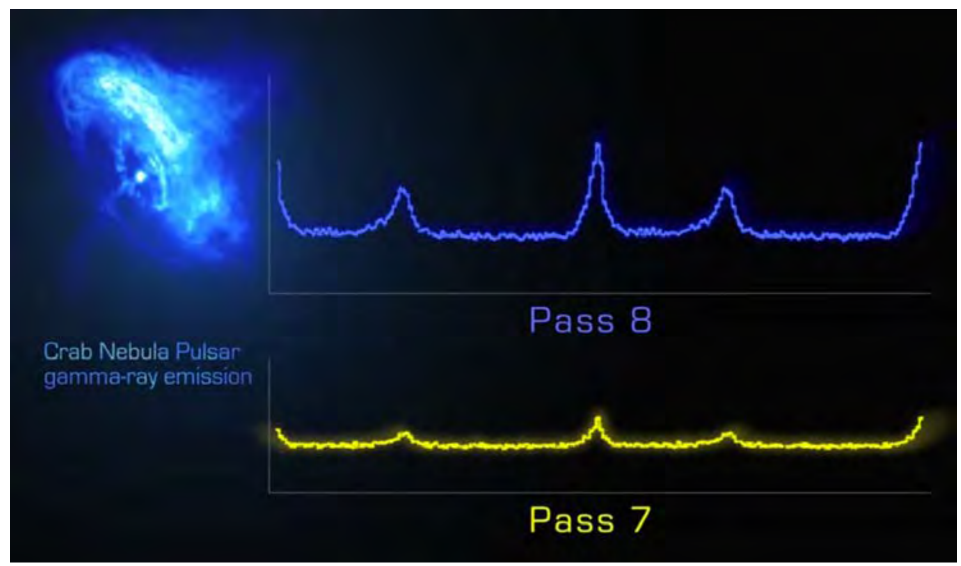
J.McEnery

- Pass 8 was a major revamp of the data processing pipeline produces sharper images (right) and more gamma-rays (lower right) dramatically improving Fermi Large Area Telescope performance
- Expanded Fermi-LAT coverage to higher energies allows the first census of the sky between 50 GeV and 2 TeV (below)

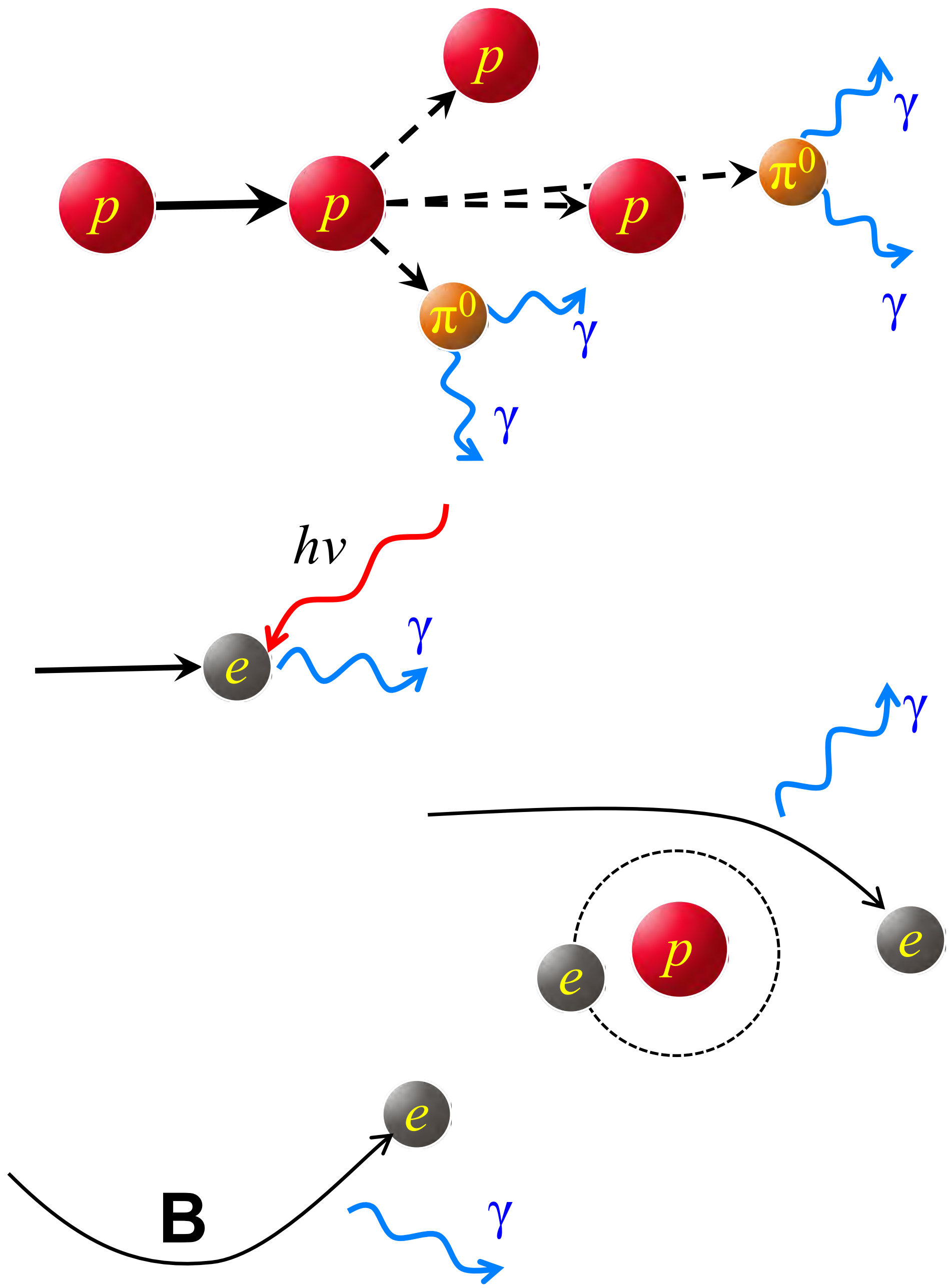
Another release is coming soon, further reducing the background!





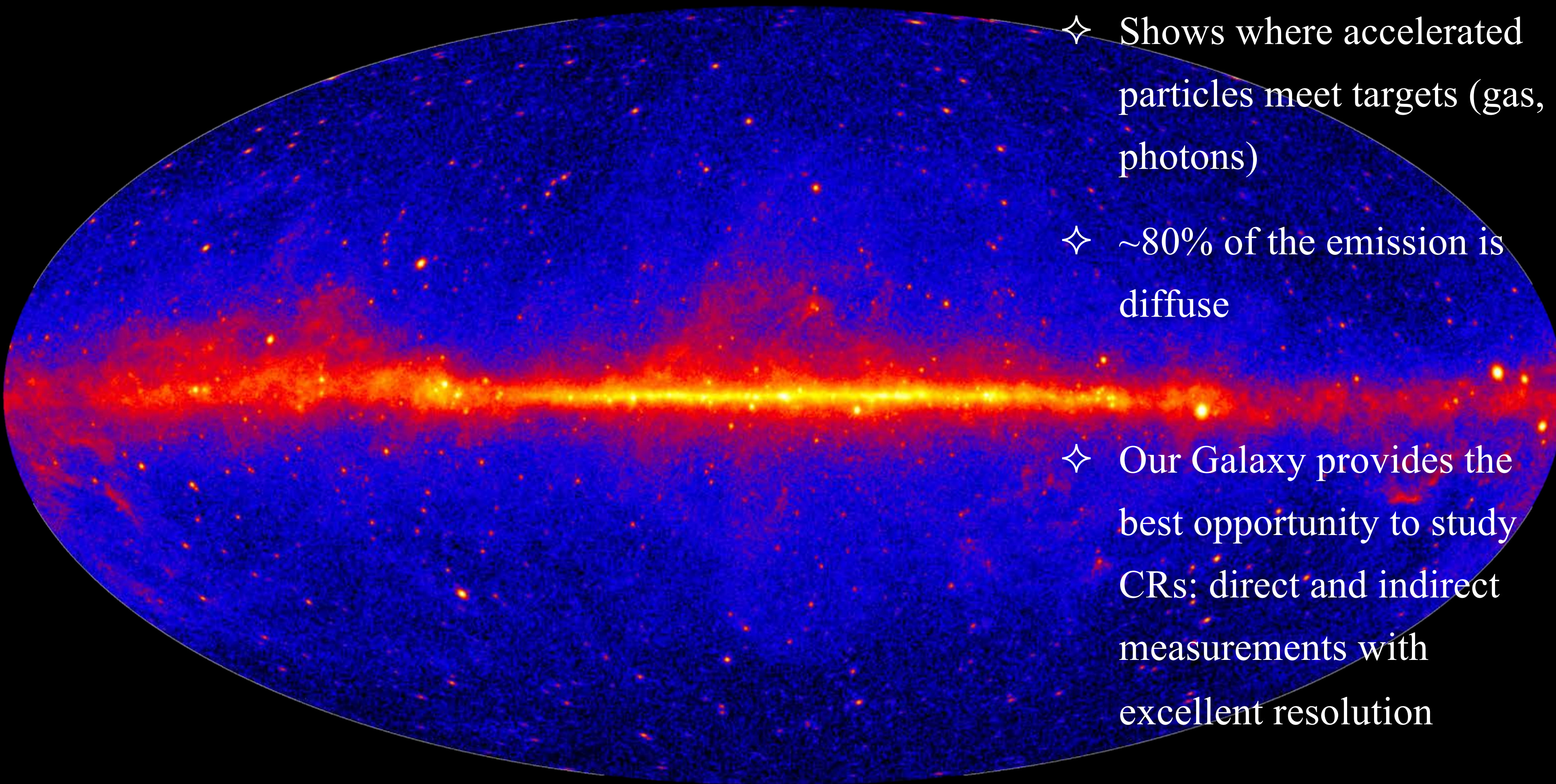


Production of high energy γ-rays



- *pp –> π^0(2γ)+X* – production and decay of neutral pions π^0 and Kaons K^0
- Inverse Compton Scattering
- Bremsstrahlung
- Synchrotron emission

Fermi-LAT skymap >1 GeV, 48 months



- ✧ Shows where accelerated particles meet targets (gas, photons)
- ✧ ~80% of the emission is diffuse
- ✧ Our Galaxy provides the best opportunity to study CRs: direct and indirect measurements with excellent resolution

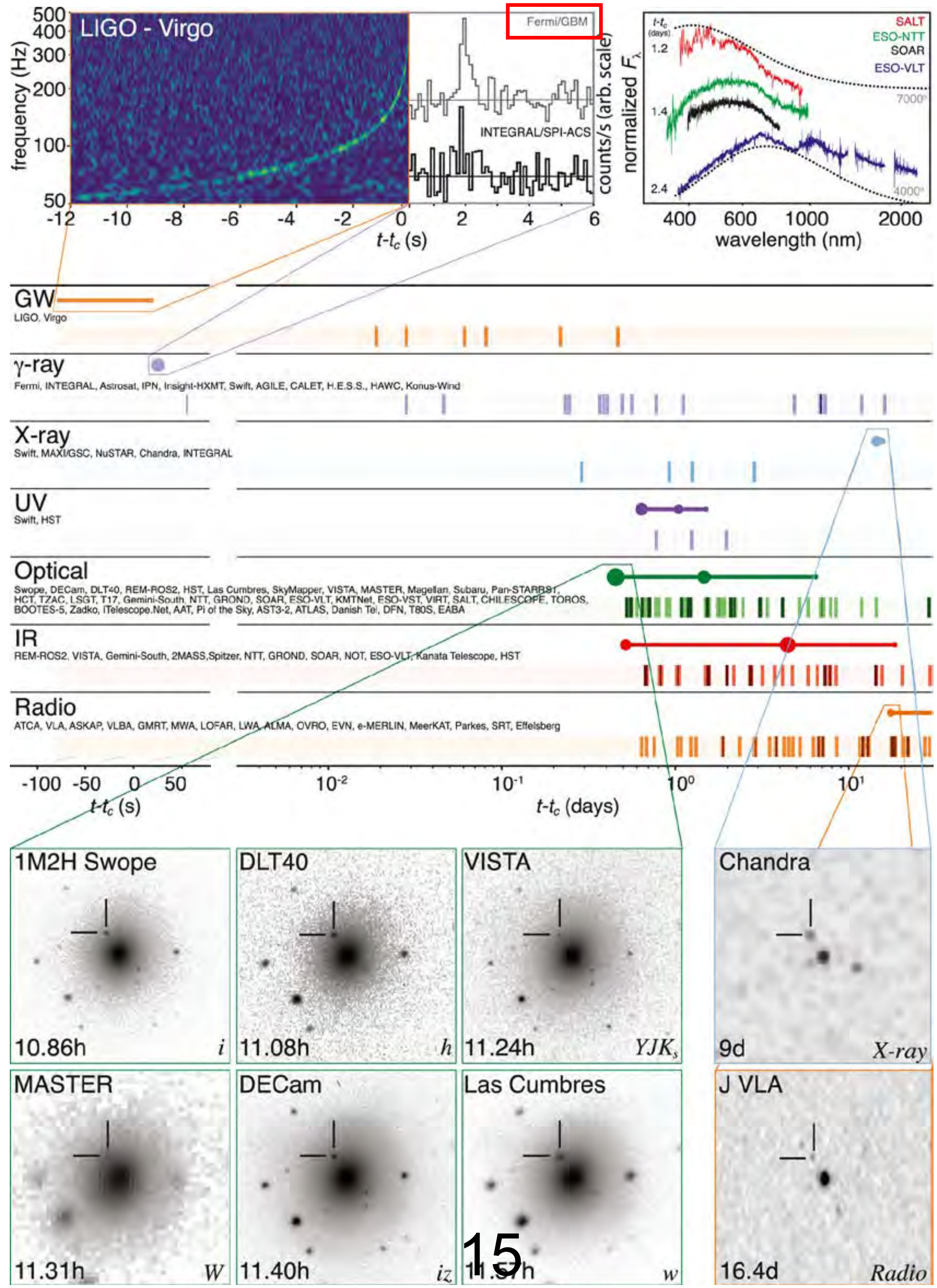
4-year sky map, >1 GeV, front converting (best psf) (4.52M events)

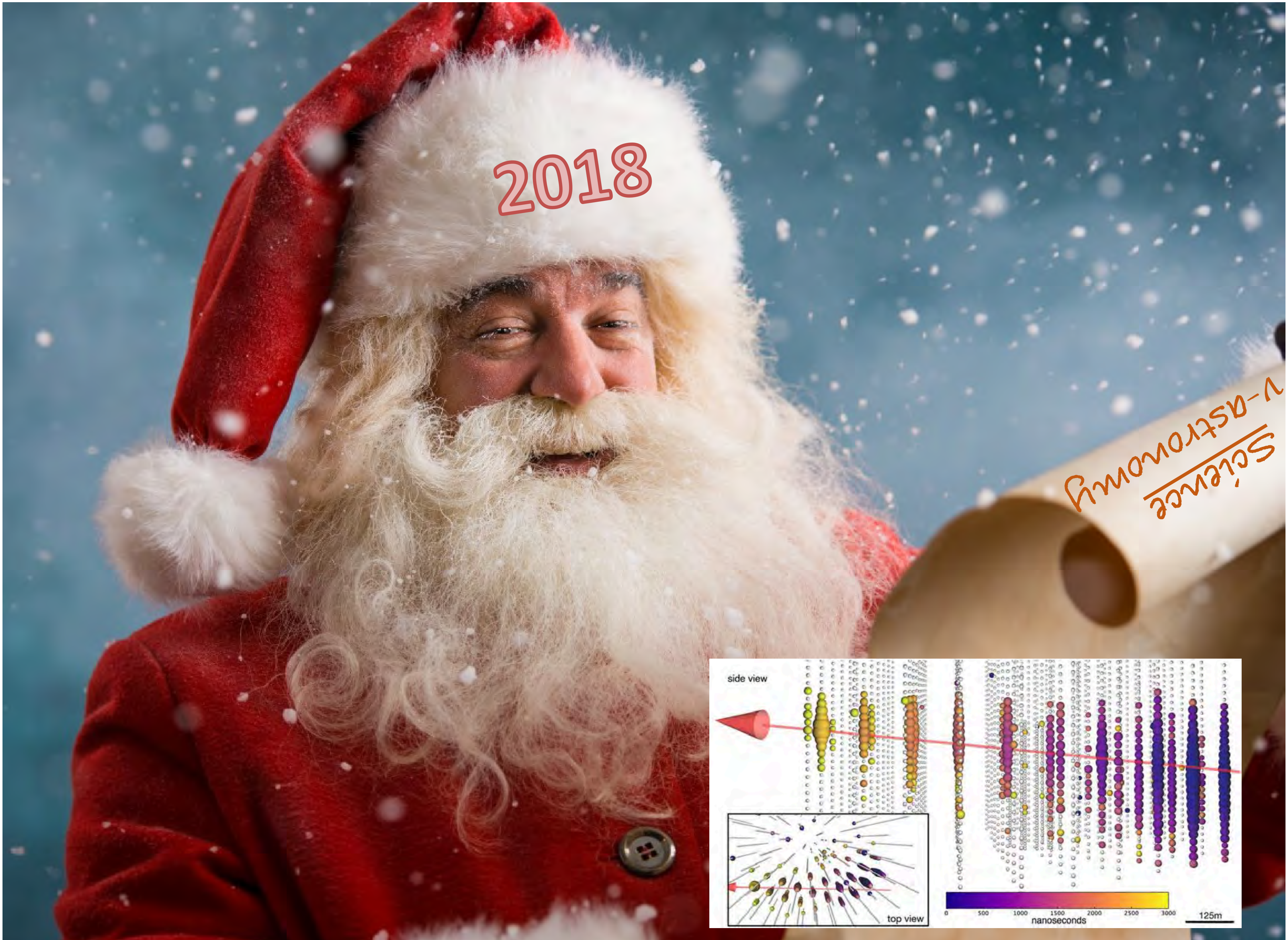
- ✧ LAT: ~275B triggers, 225M Source class events
- ✧ GBM: >1000 GRBs


2017
First Cosmic Event Observed
in Gravitational Waves and Light
Colliding Neutron Stars Mark New Beginning of Discoveries
G-Waves
LIGO

Multi-wavelength light curve - GW170817

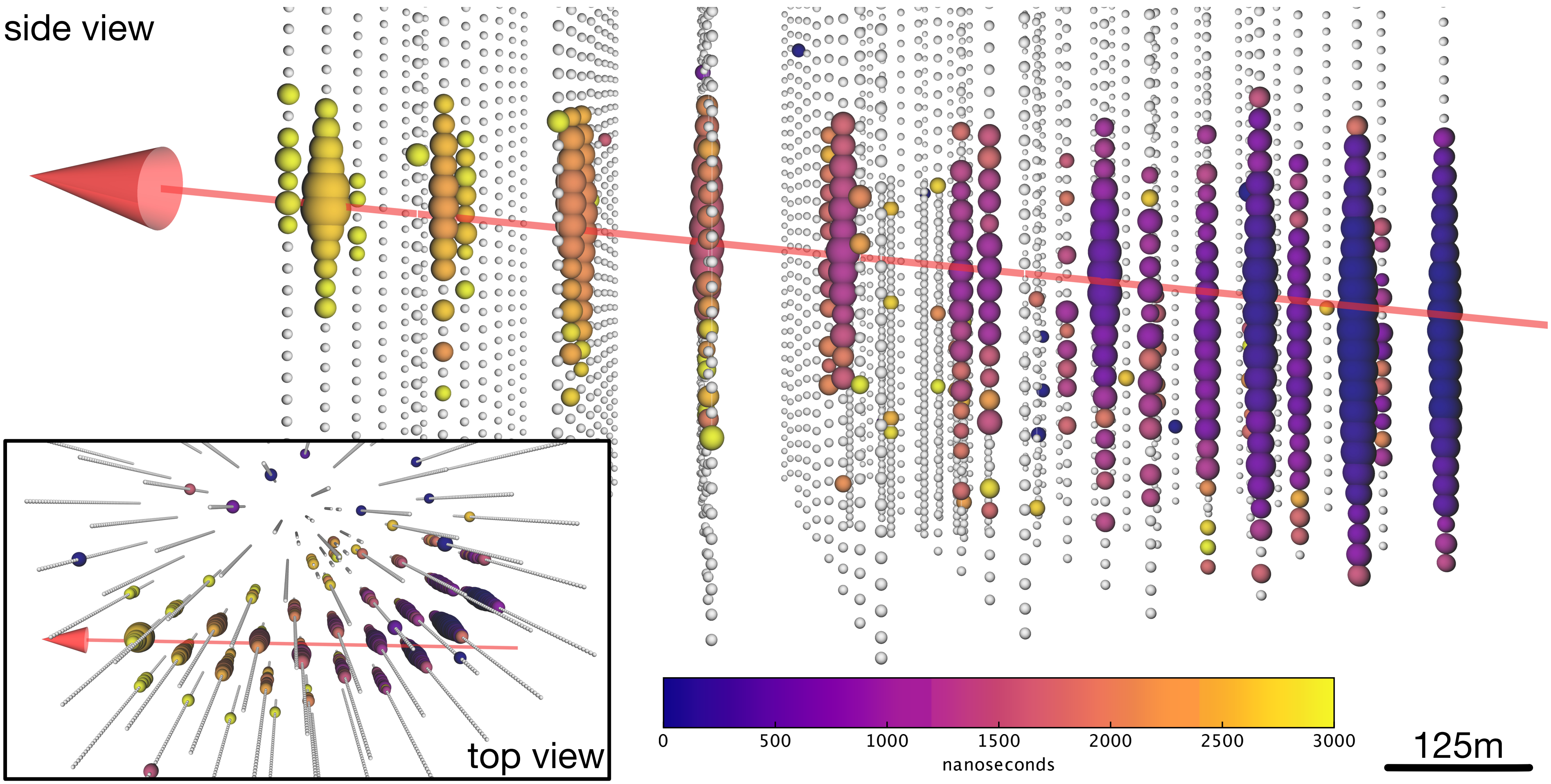
- Timeline of the discovery of GW170817, GRB 170817A, SSS17a/AT 2017gfo, and the follow-up observations
- Fermi GBM: 90% of the burst fluence is accumulated in the energy range of 50–300 keV
- GRB 170817A is the closest sGRB with measured redshift
- Unfortunately, Fermi-LAT was off line entering the SAA




2018
Science
ν-astronomy
side view
top view
0 500 1000 1500 2000 2500 3000
nanoseconds
125m

IC-170922A – a 290 TeV Neutrino

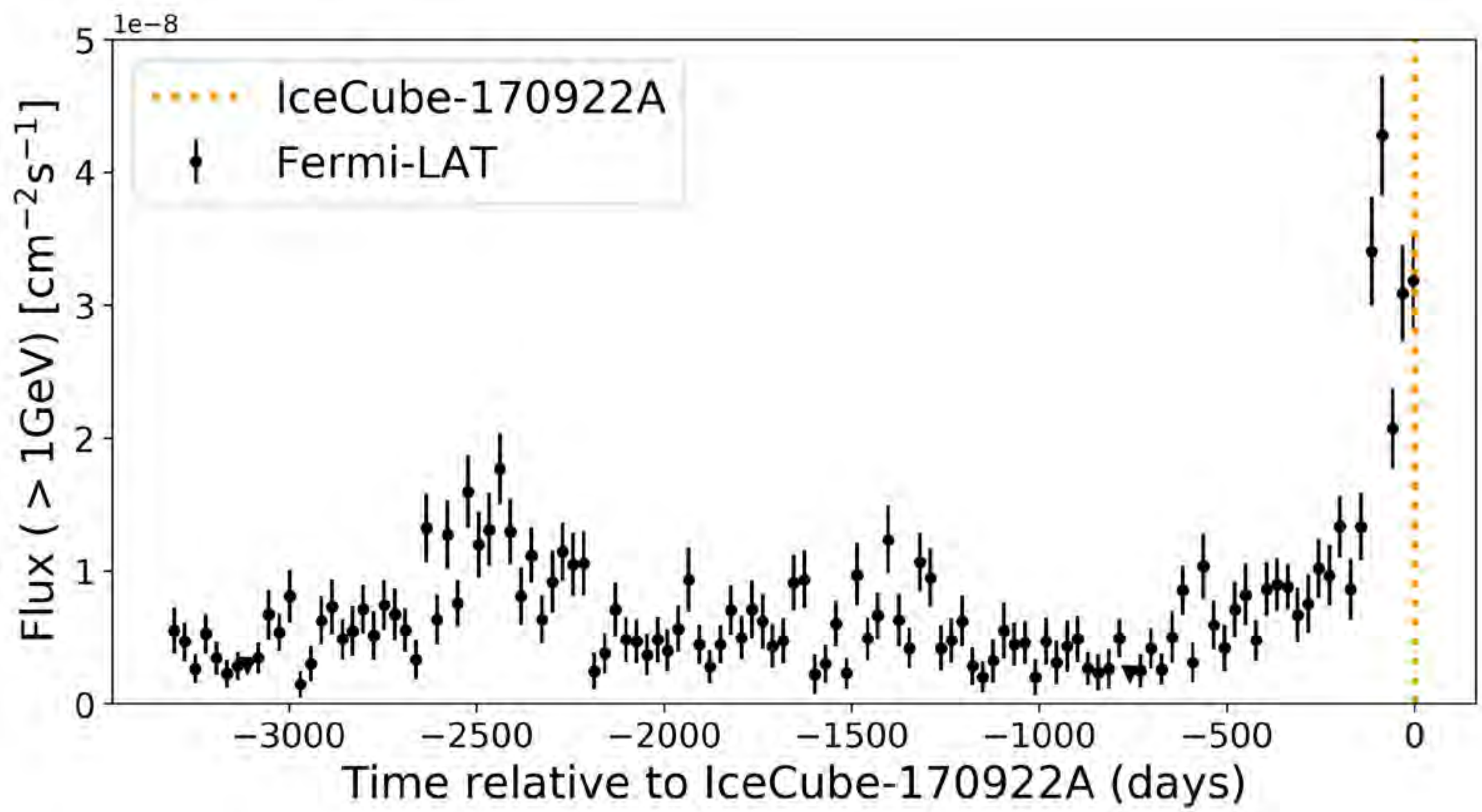
Science 12 Jul 2018



Signalness: 56.5%

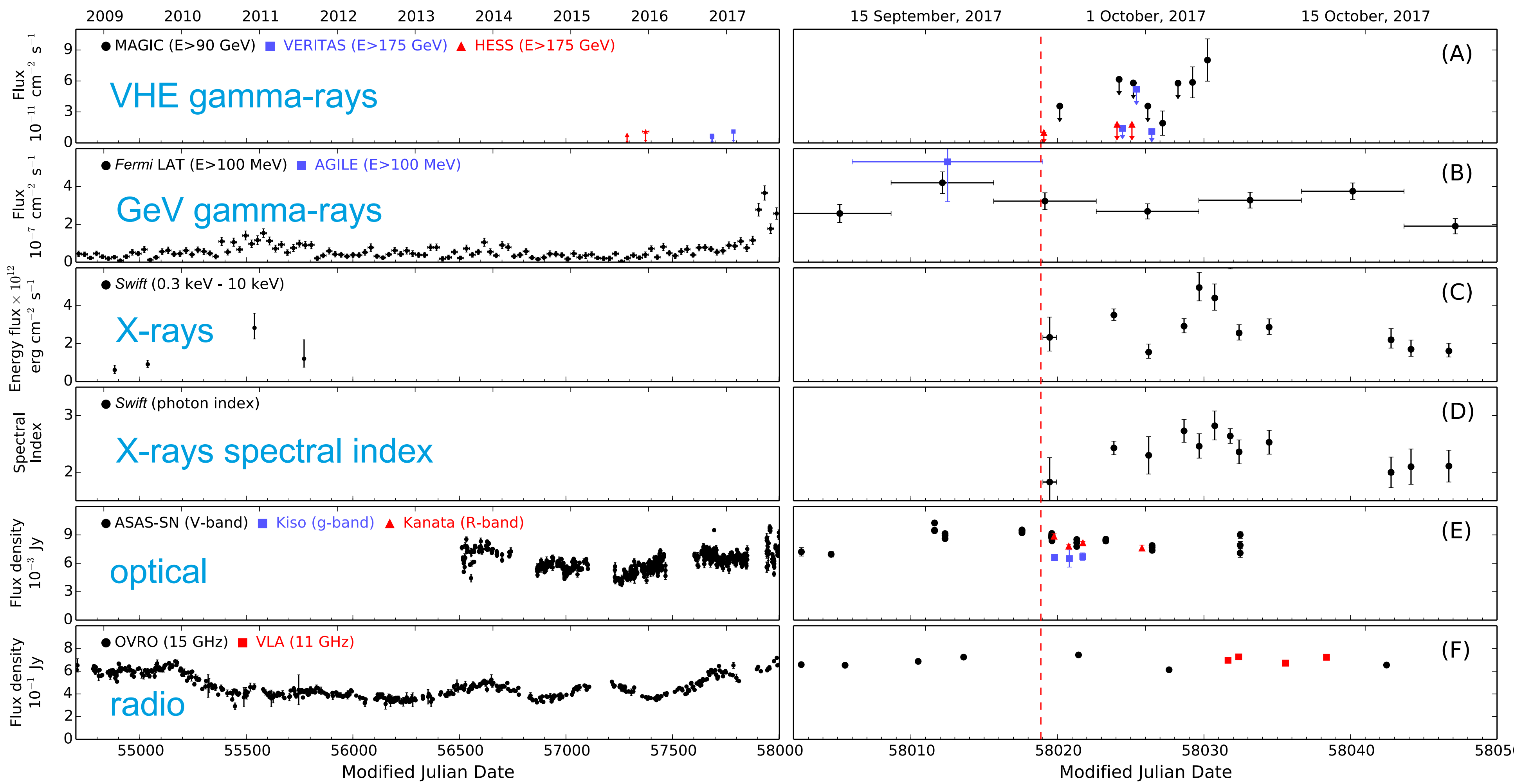
IceCube, Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S, INTEGRAL, Kapteyn, Kanata, Kiso, Liverpool, Subaru, Swift, VERITAS, VLA, Science 2018

Fermi-LAT finds Flaring Blazar: TXS 0506+056



Key result to claim the identification of the 1st true astrophysical ν source!

The Multi-Messenger Light Curve

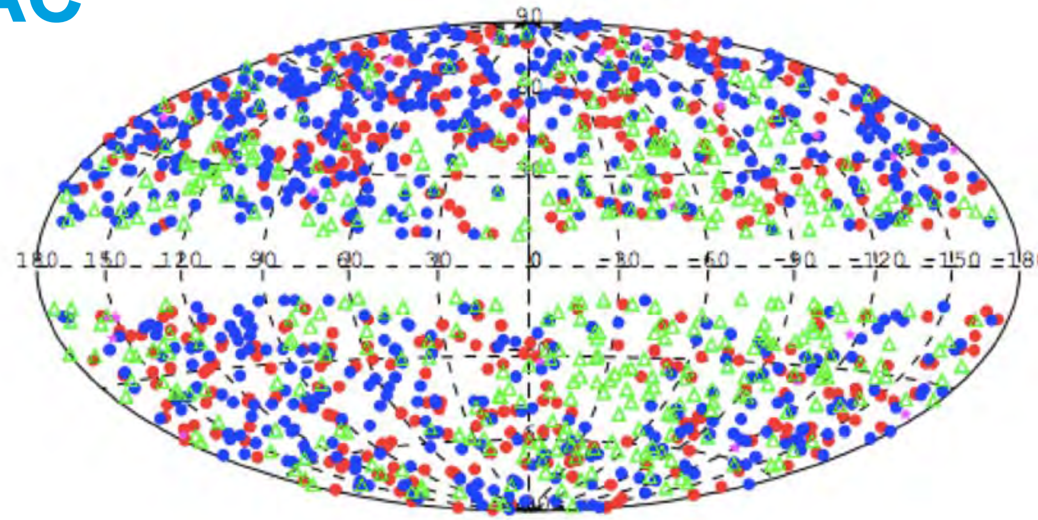


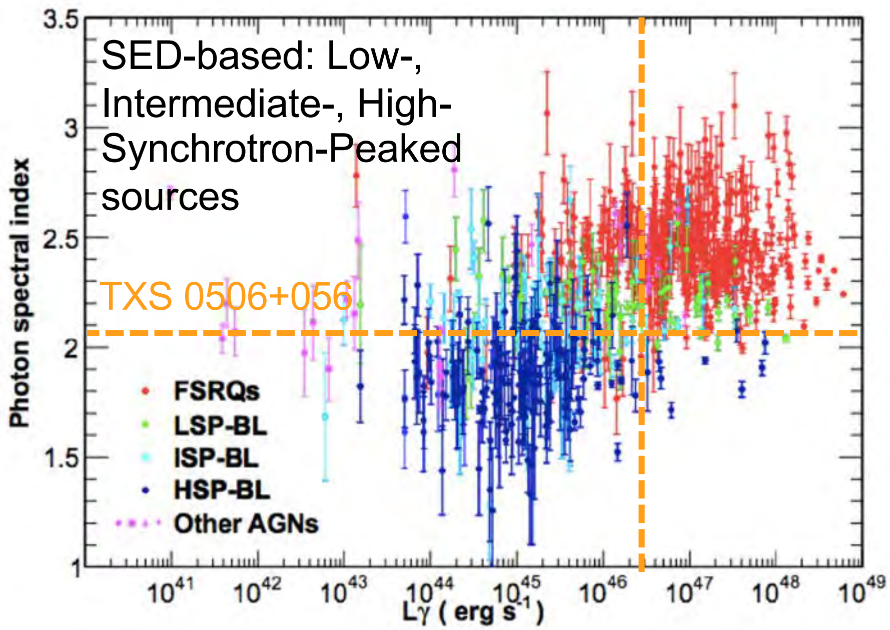
IceCube, Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S, INTEGRAL, Kapteyn, Kanata, Kiso, Liverpool, Subaru, Swift, VERITAS, VLA, Science 2018

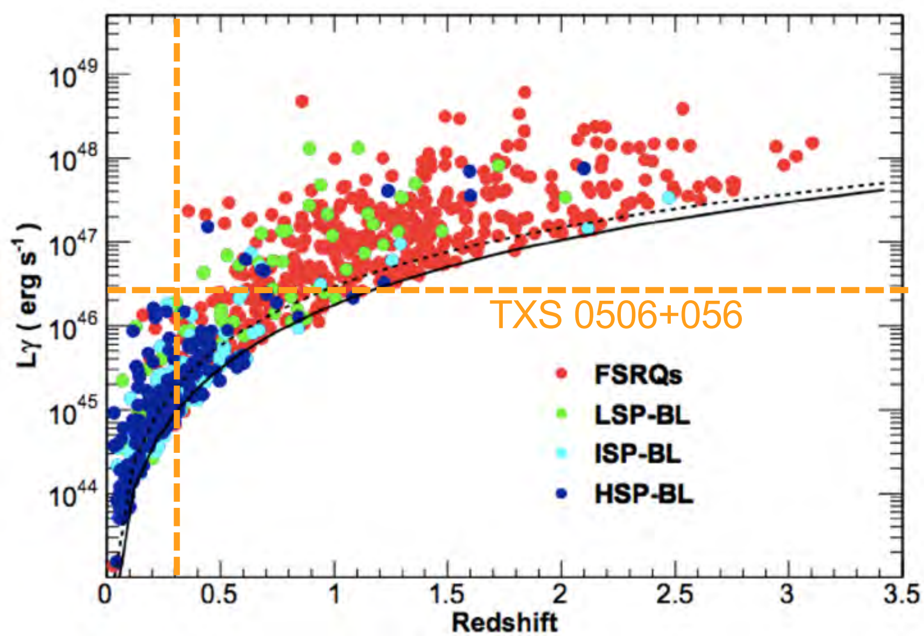
TXS 0506+056 in 3LAC

Among 50 brightest blazars (3%) in 3LAC ISP

Redshift 0.3365±0.0010 (S. Paiano et al. 2018)





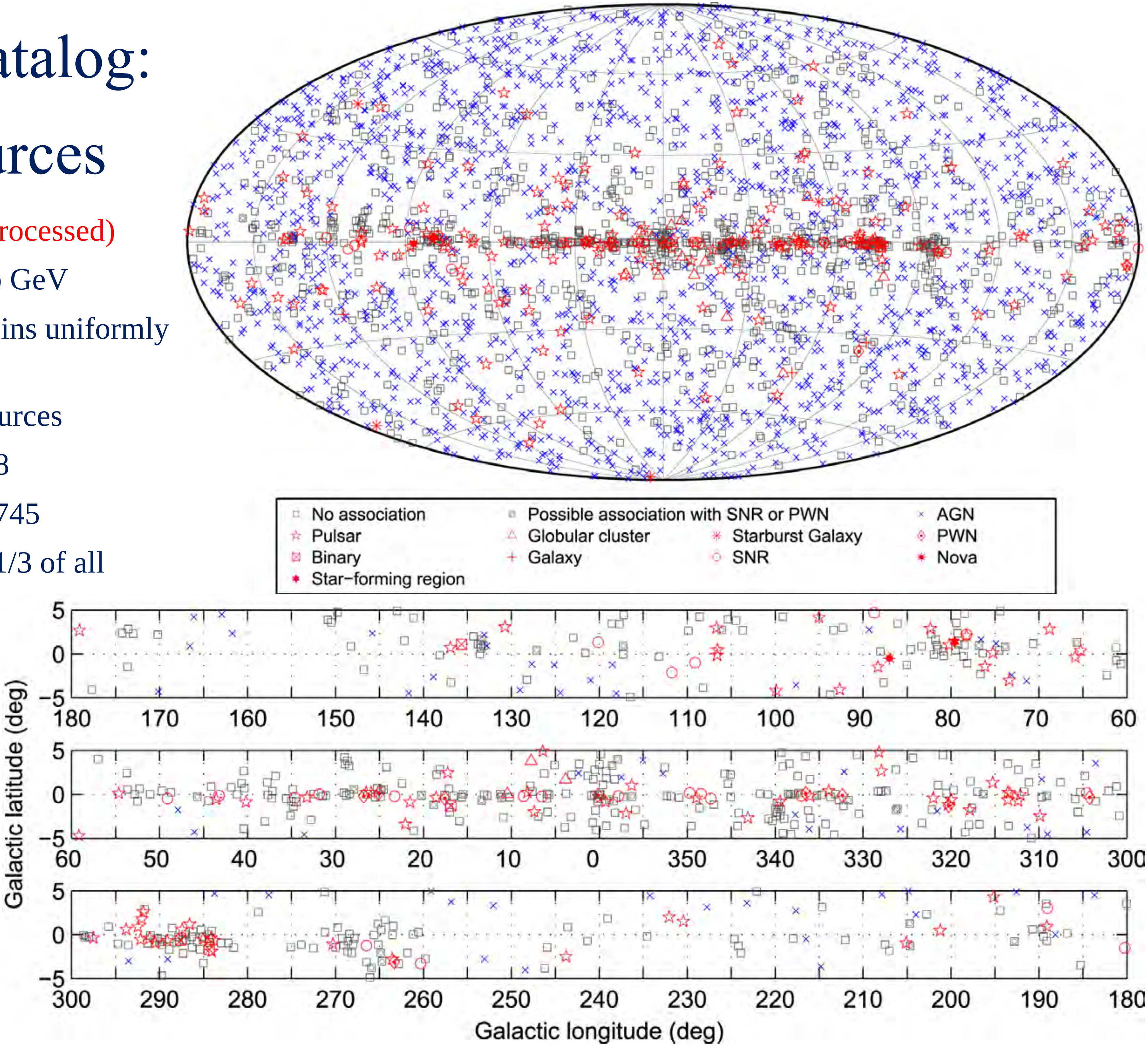


Fermi-LAT Collaboration, ApJ 810 (2015)


2019
?
?
?
?
?

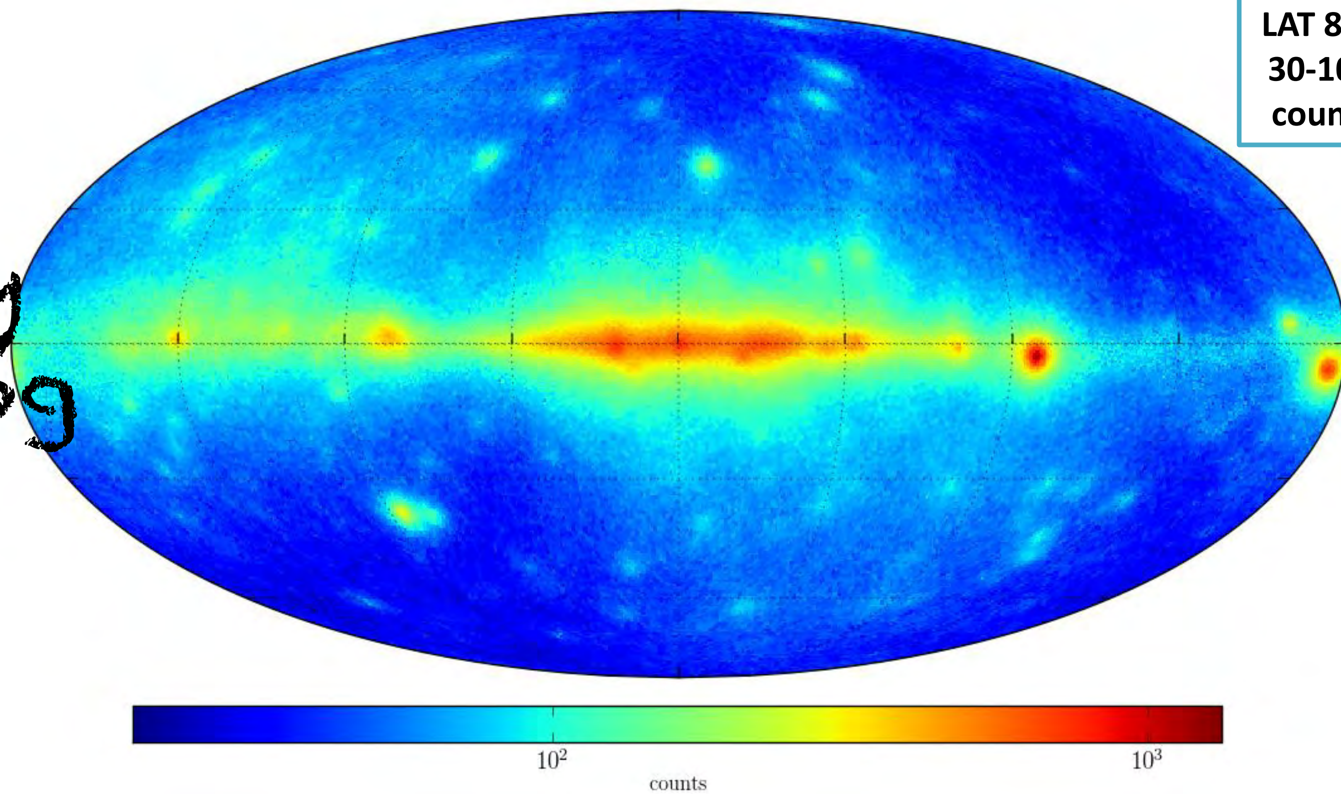
3FGL Catalog: 3033 sources

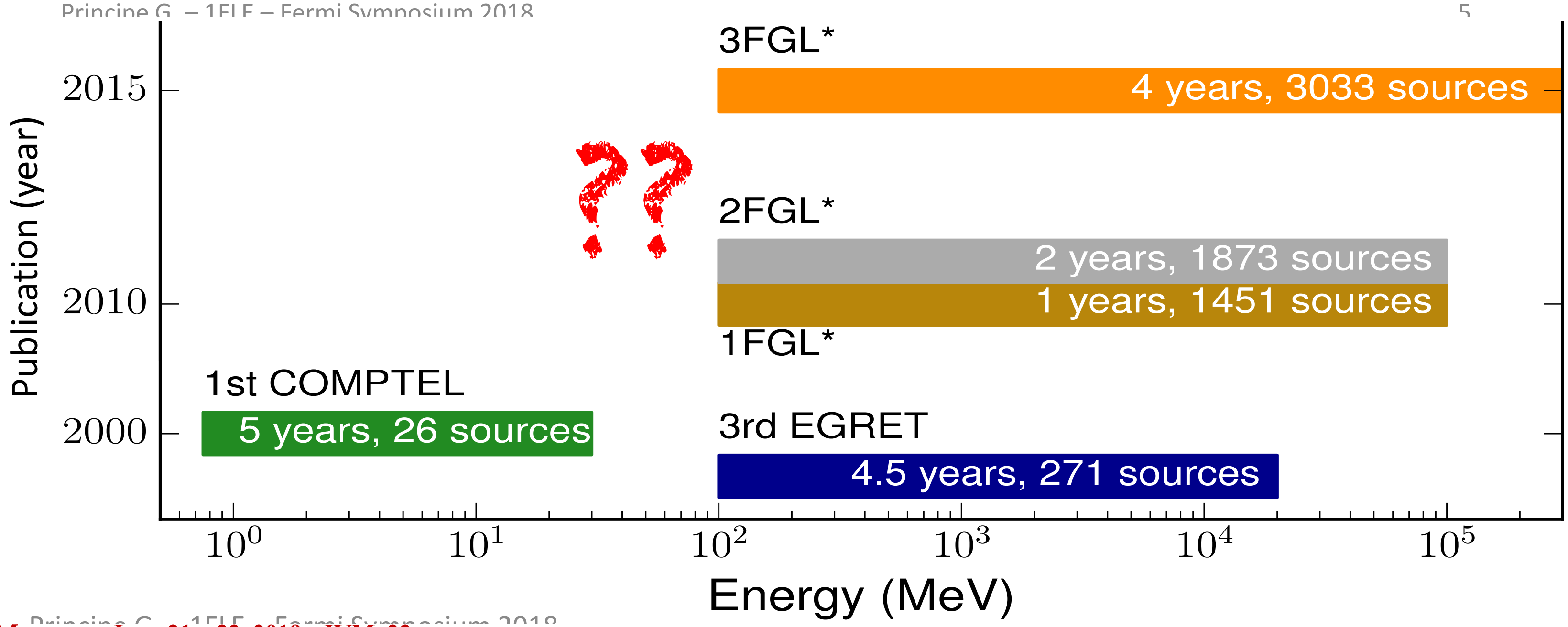
- 4 years (P7 reprocessed)
- 0.1 – 100 (300) GeV
- 5 (14) energy bins uniformly spaced in log E
- 20 extended sources
- Identified – 238
- Associated – 1745
- Unidentified ~1/3 of all sources



Fermi Low-Energy Catalog

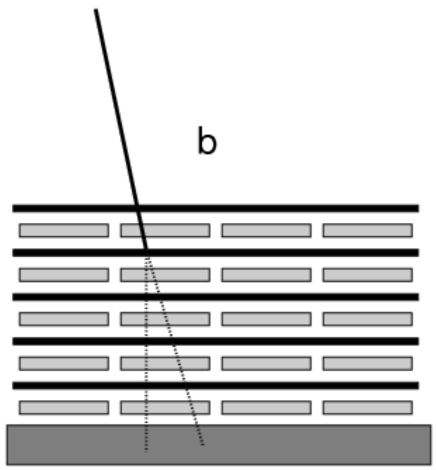
LAT 8.7 years
30-100 MeV
counts map

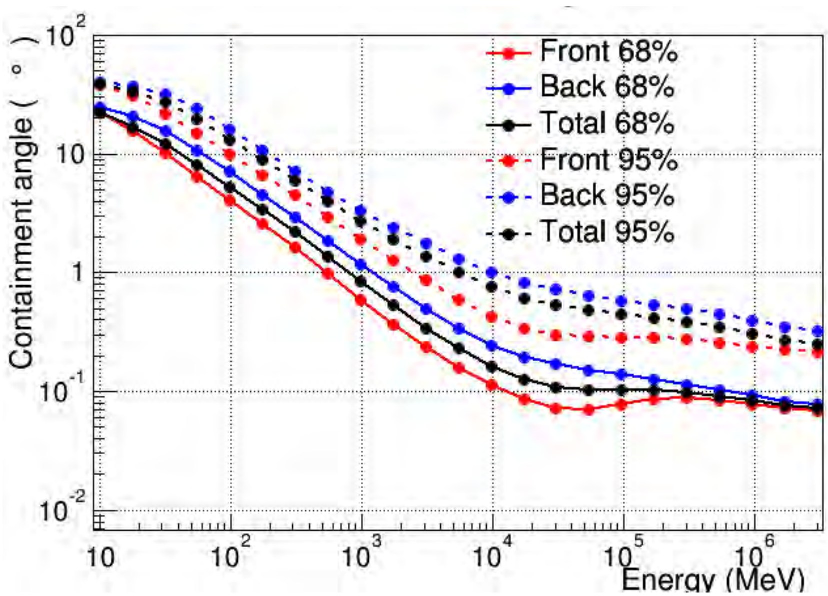




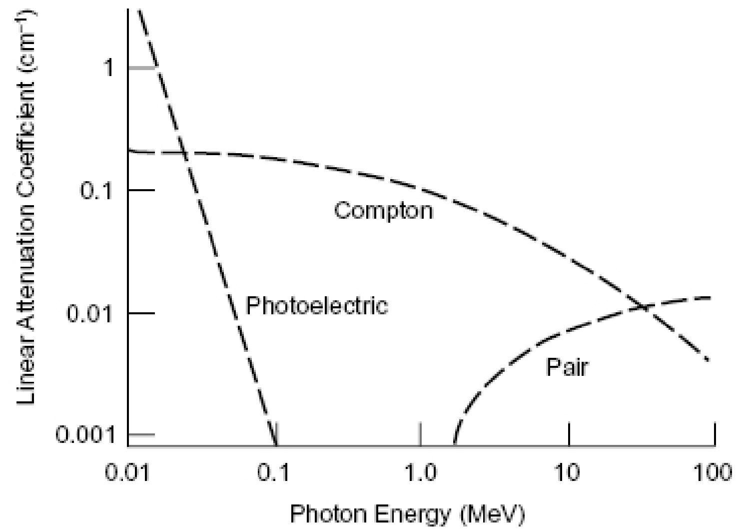
Why are there no Catalogs in the 30-100 MeV band?

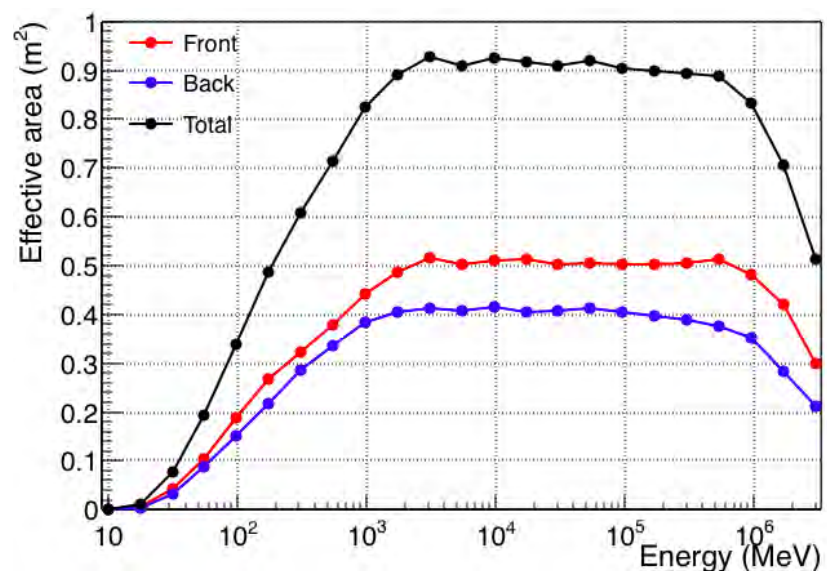
1) Angular resolution gets worse





2) Effective area gets smaller

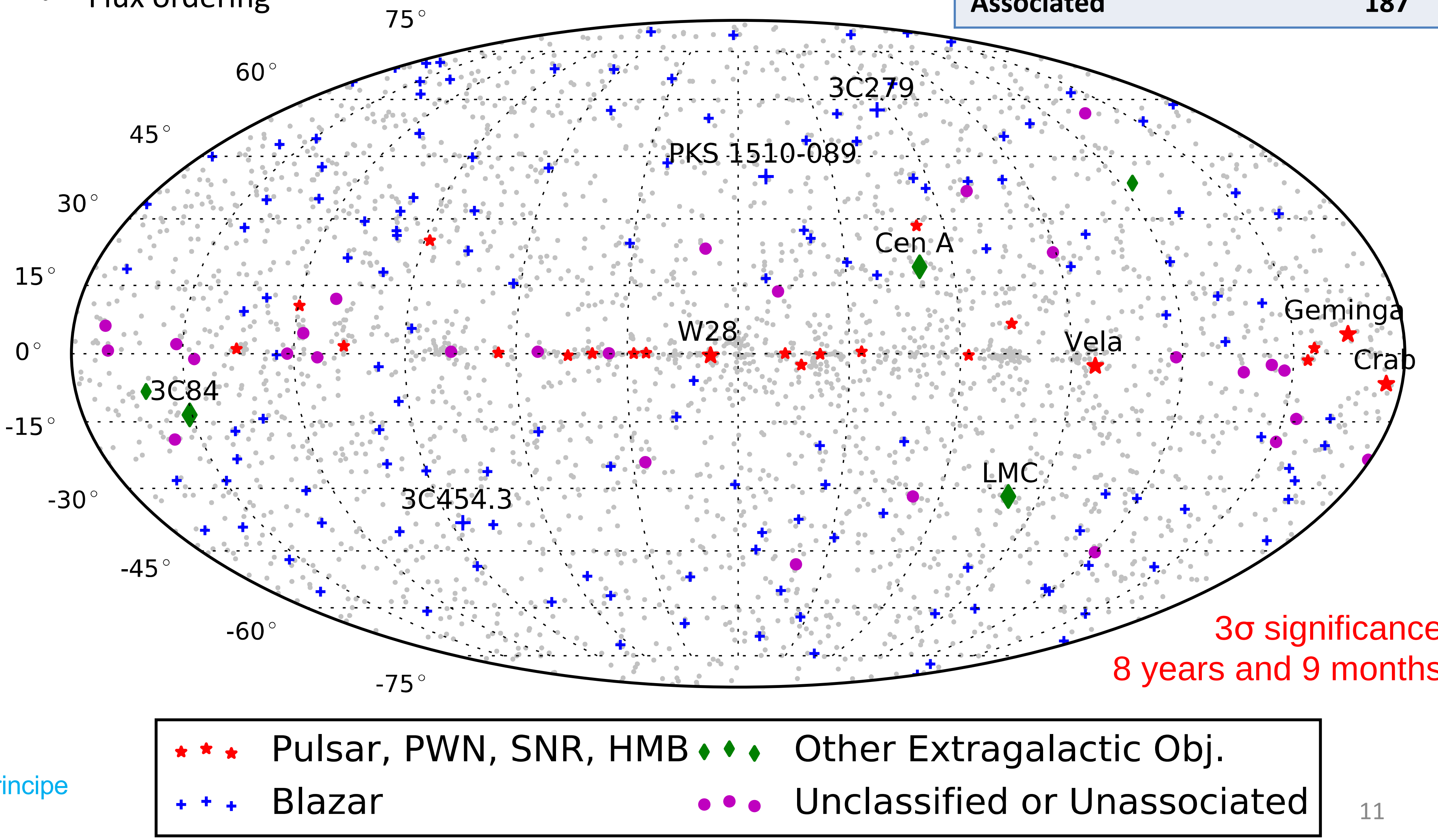




Fermi-LAT sources below 100 MeV

Association:
- Based on a positional coincidence
- Tolerance radius 1°.5
- Flux ordering

Results	PS (counts)
3FGL (grey points)	3034
PGWave 30-100 MeV	198
Associated	**187**

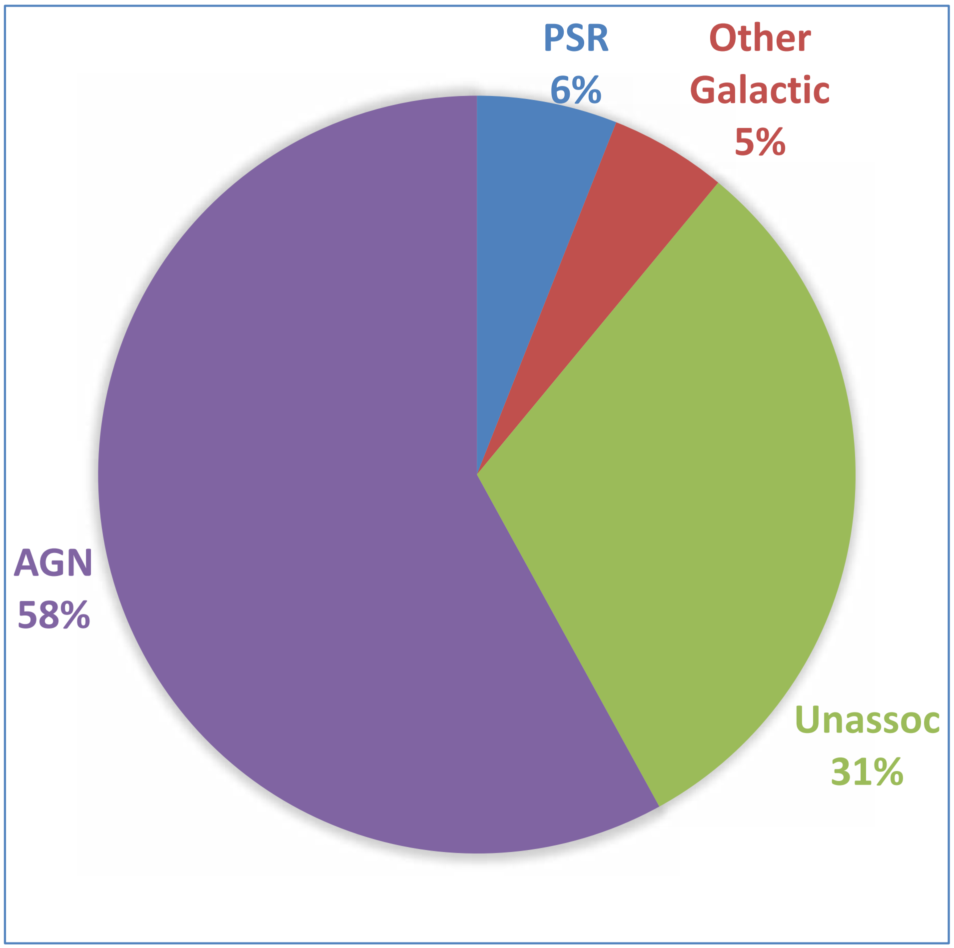


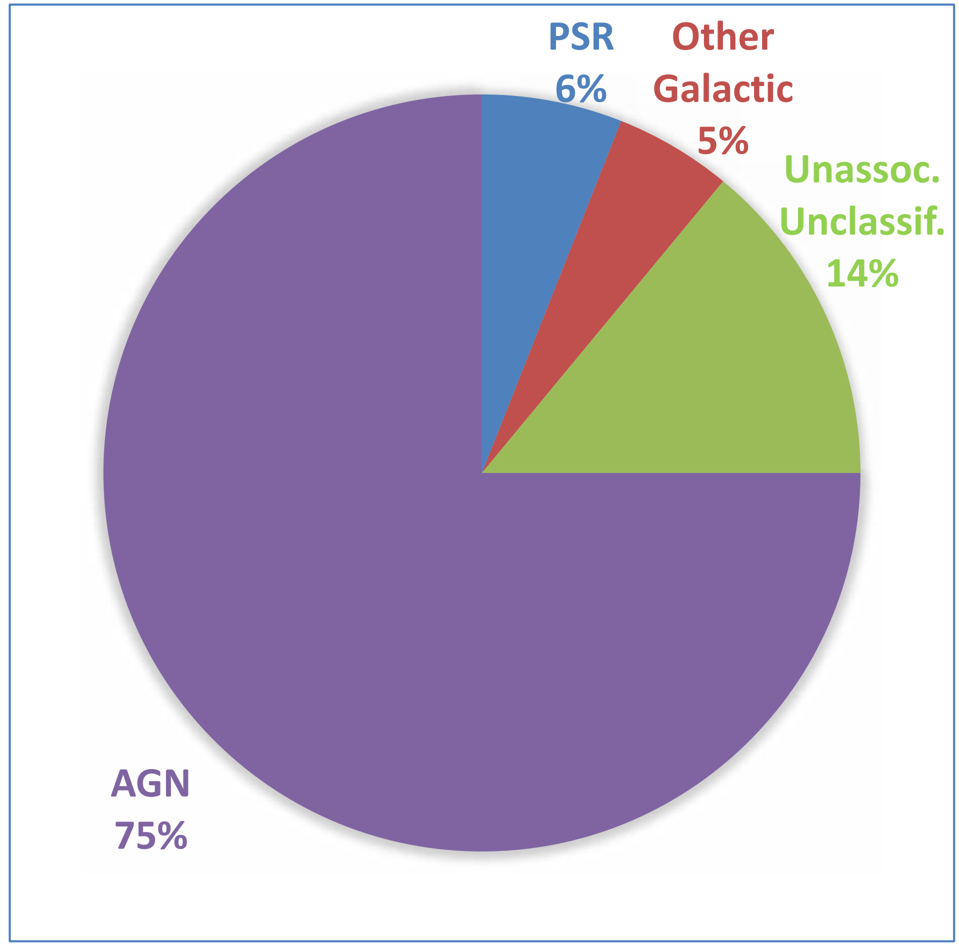
G.Principe

1FLE and 3FGL Catalog comparison

3FGL
(3033 sources)

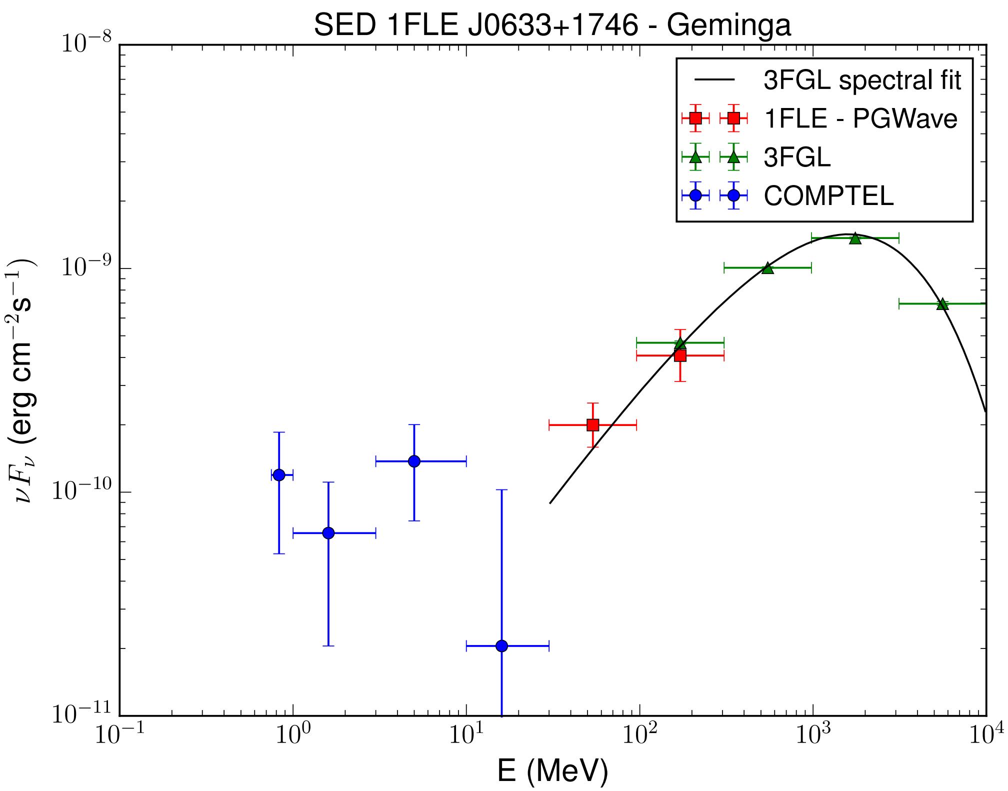
1FLE
(198 sources)

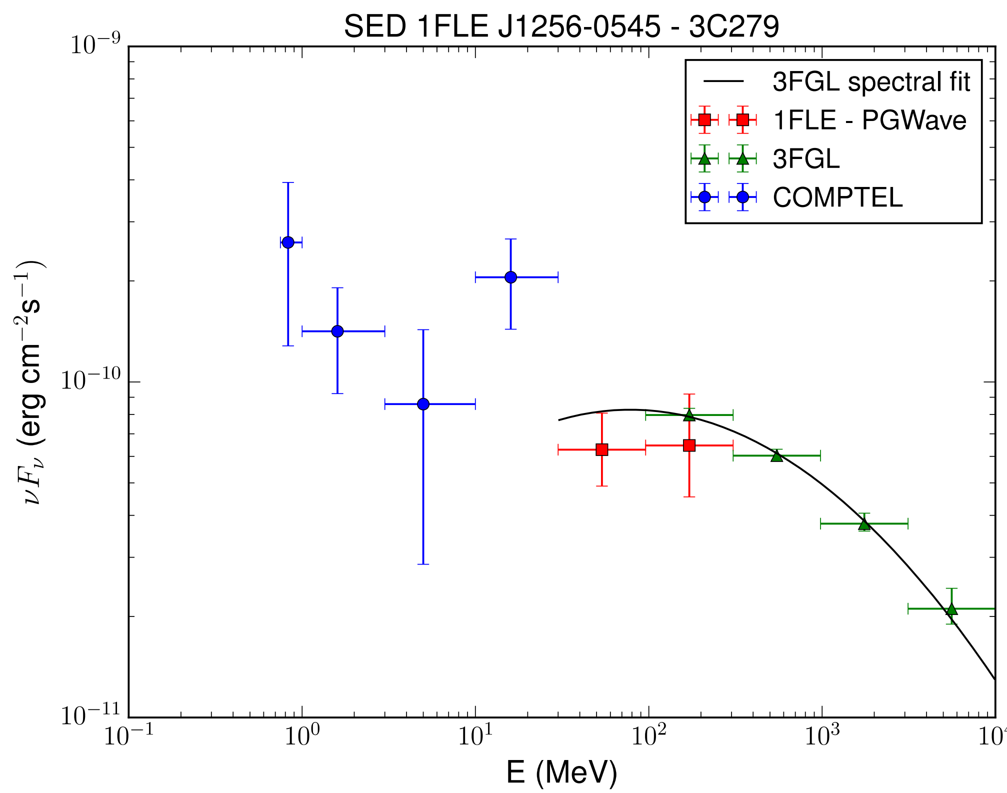




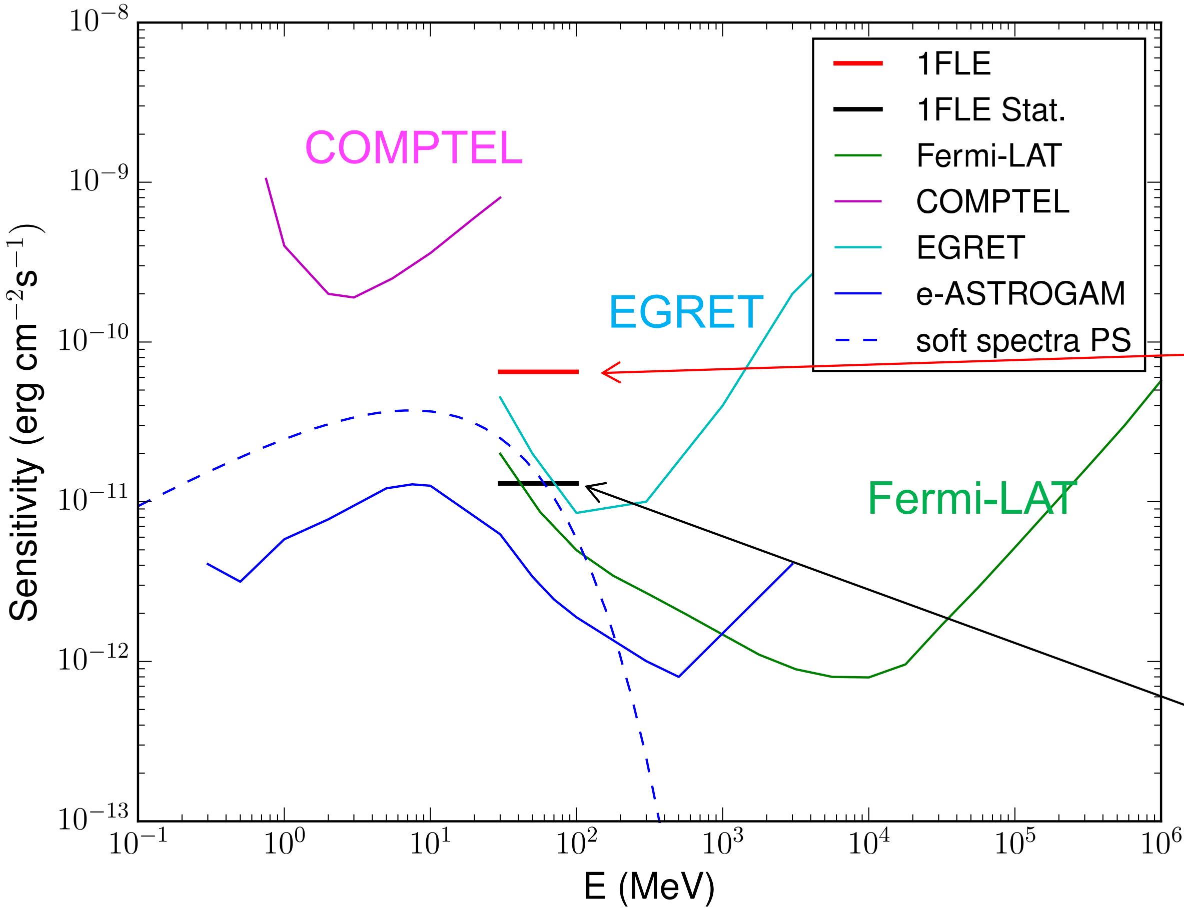
Spectral Energy Distributions

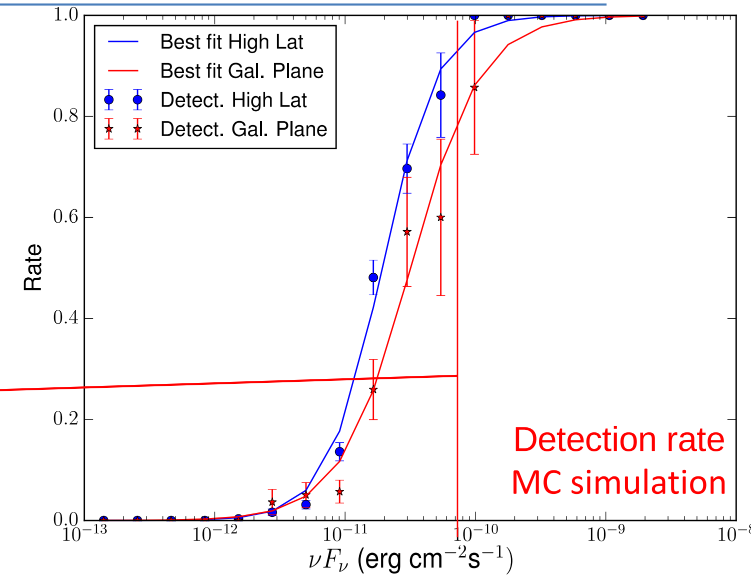
Two examples of SED.

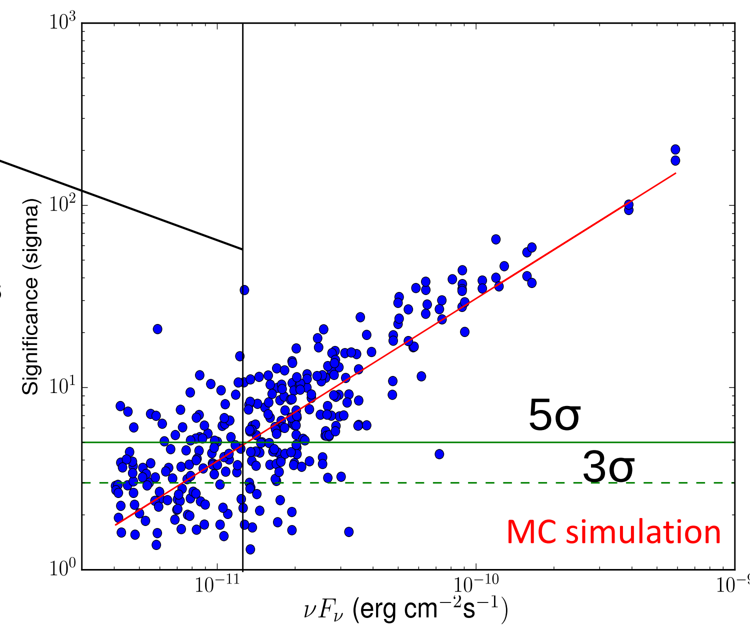




1FLE Sensitivity



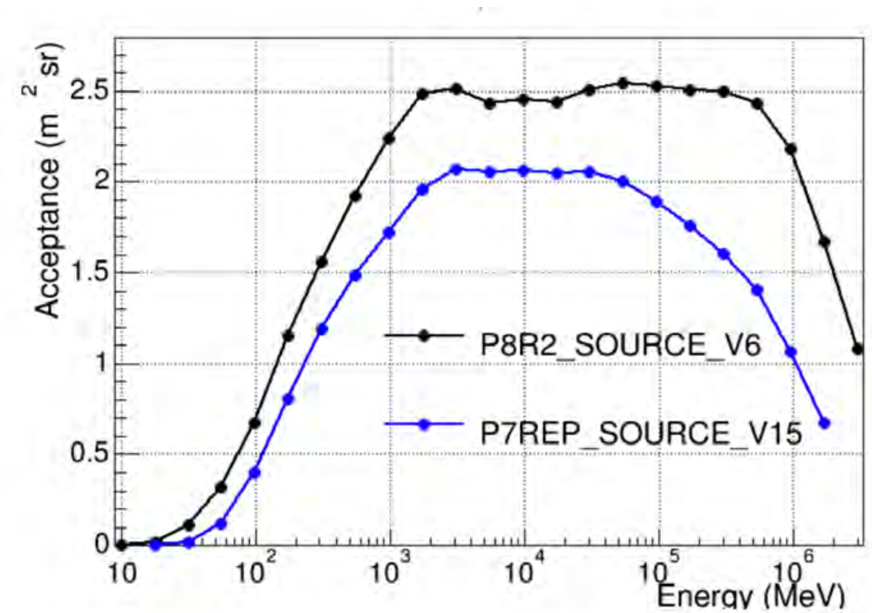




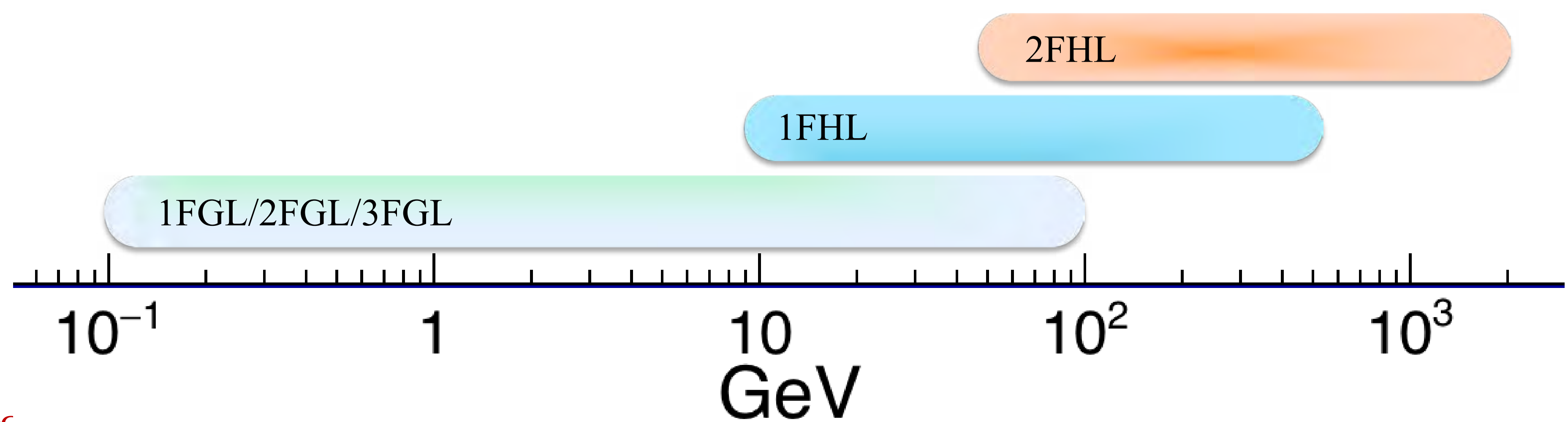
In red, the 1FLE total sensitivity (95% detection efficiency at |b| > 10°), while in black the **1FLE statistical sensitivity** determined as the flux corresponding to the 5σ significance of PGWave.

Fermi-LAT Catalogs

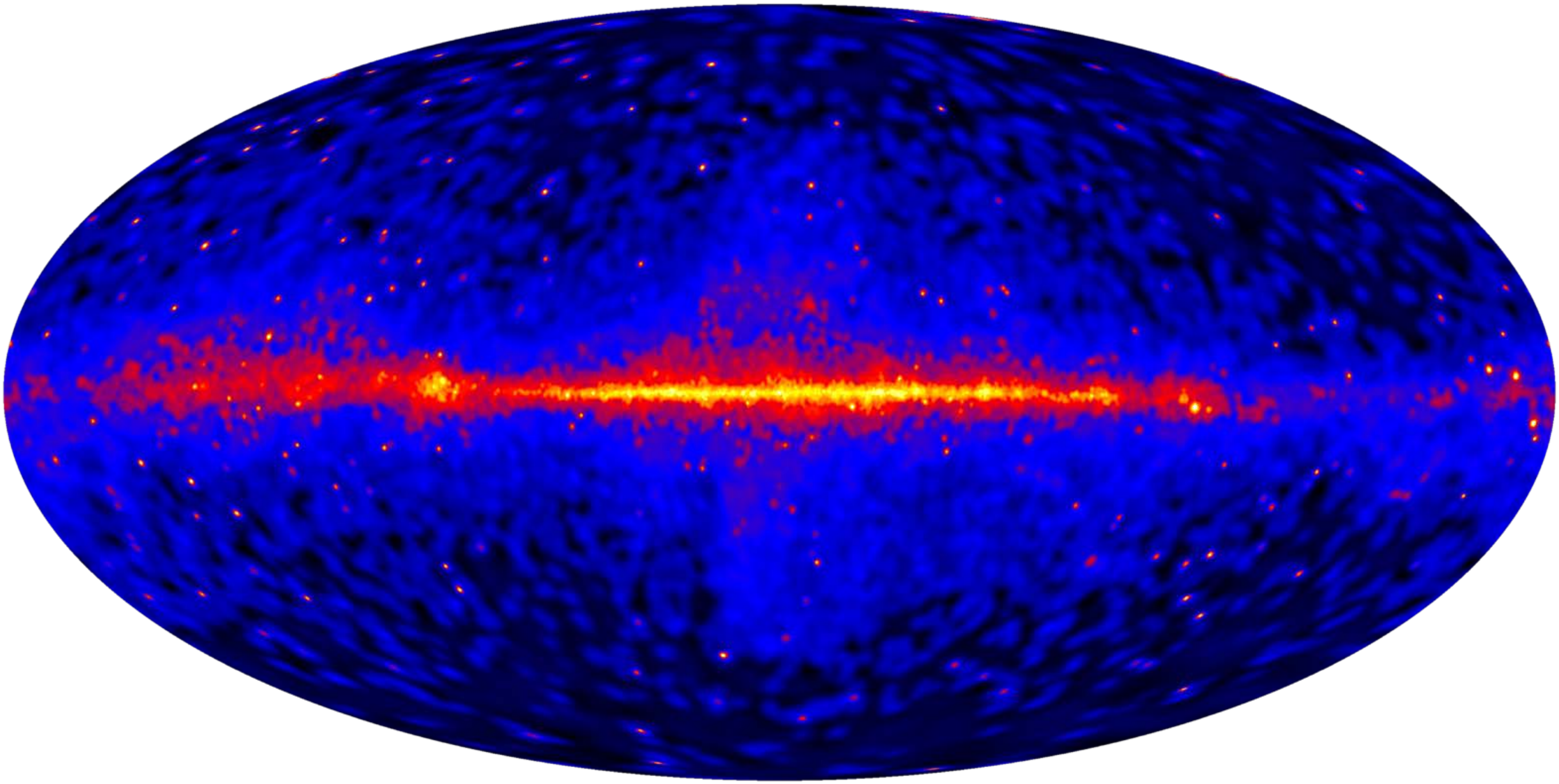
*n*FGL Catalogs detect and characterize sources in the ~0.1-100 GeV energy range
*n*FHL Catalogs explore the higher-energy sky



Why 2FHL ? Improvement delivered by Pass 8 enables study of the EBL, EGB, Galactic plane, etc, and connects well to the TeV world



1FHL: Fermi-LAT skymap >10 GeV



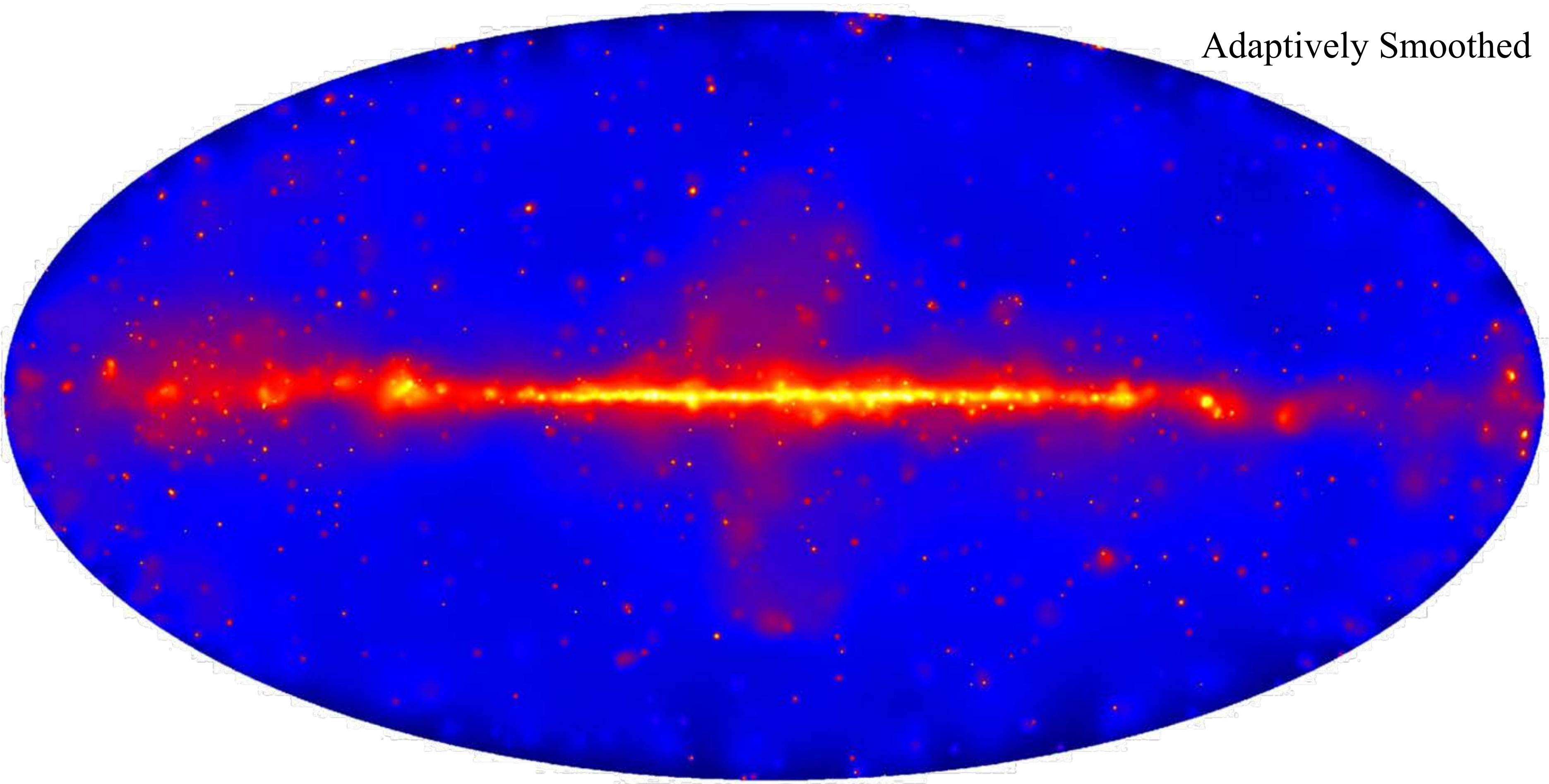
✧ Less diffuse emission

✧ Fewer but more powerful sources at high energies

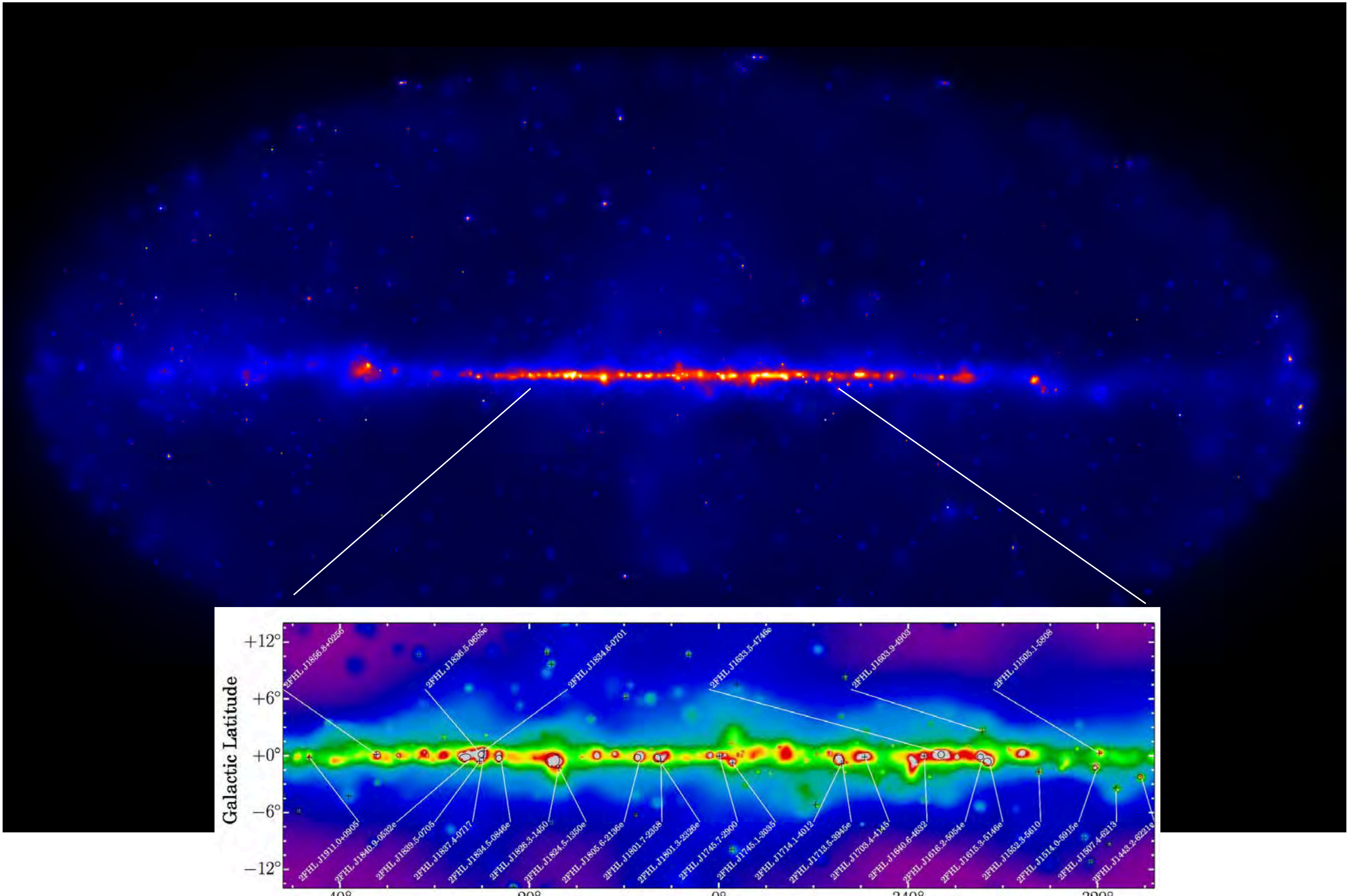
Count Map:
80 months of P8 data (50 GeV – 2 TeV)

61,000 photons E > 50 GeV
22,100 photons E > 100 GeV
2,000 photons E > 500 GeV

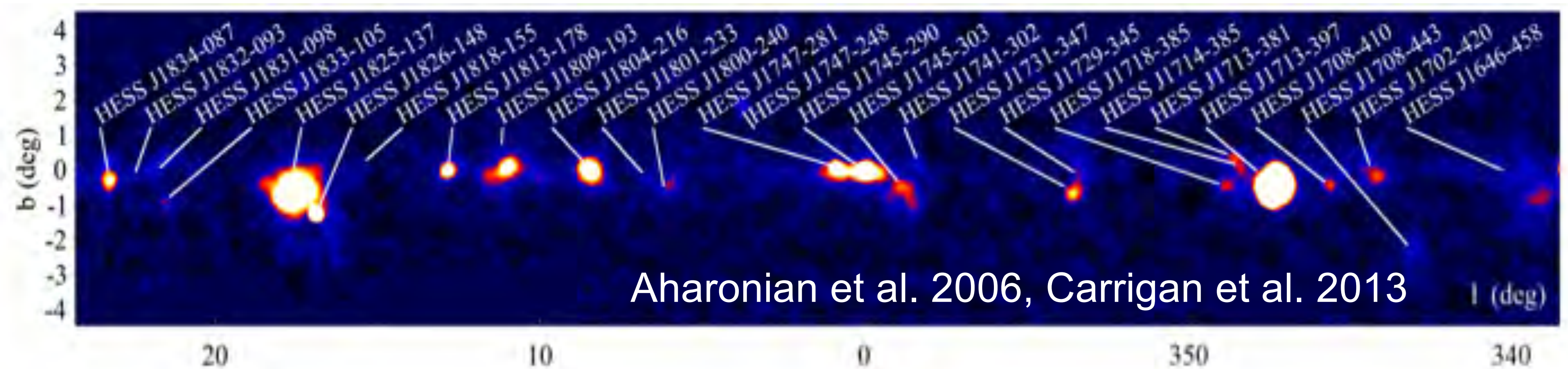
~1.5 photon every deg^2



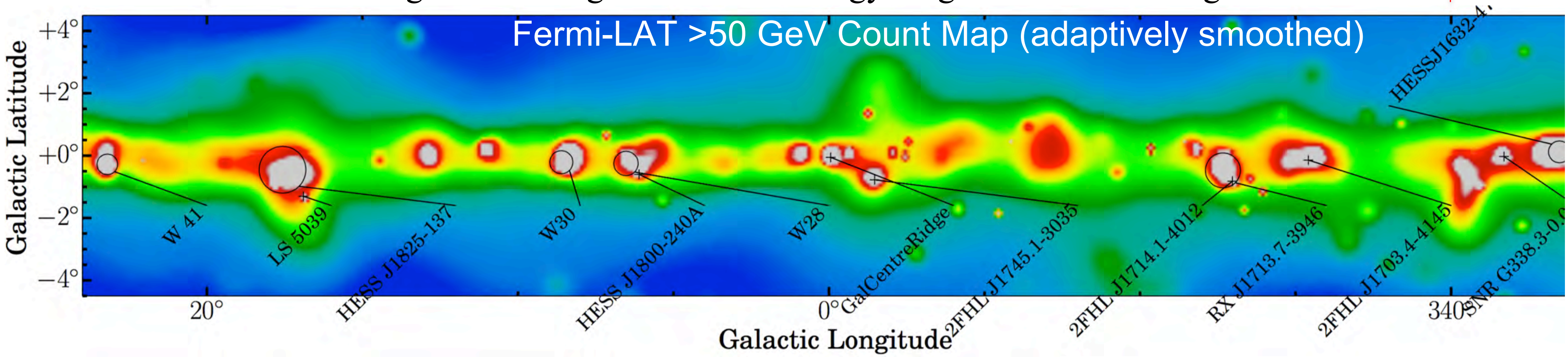
2FHL: "TeVatron map" – Fermi Sky >50 GeV



Comparison with HESS Galactic Plane survey



- ✧ H.E.S.S. detects 69 sources reaching a sensitivity of ~2% of the >1 TeV Crab Nebula flux
- ✧ LAT detects 36 sources (in 2FHL) in the same region reaching an average sensitivity of 3-4% of the Crab Nebula flux
- ✧ The sorce brightness change in the LAT energy range vs. H.E.S.S. range

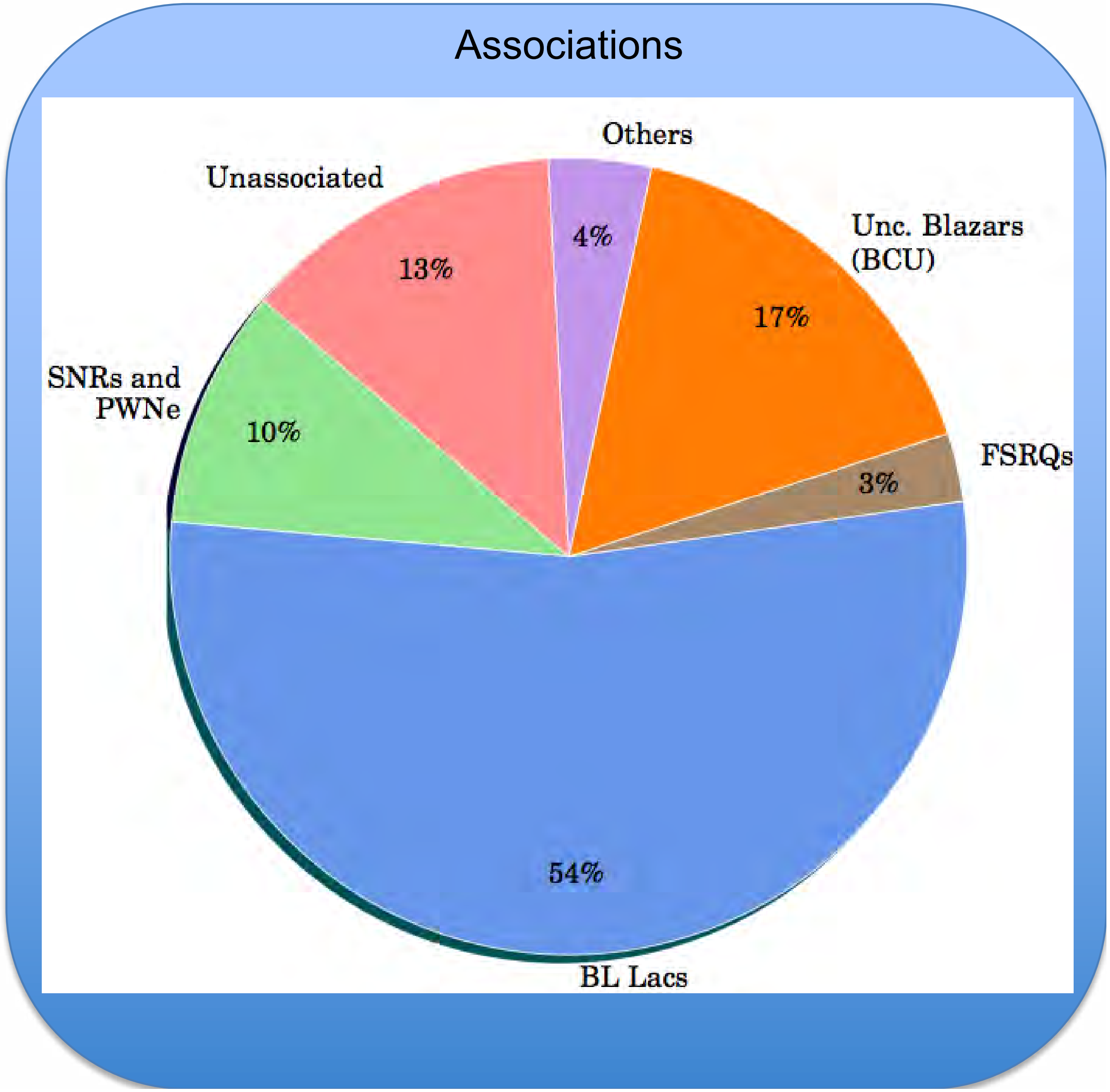


Total: 103 sources at |b|<10°

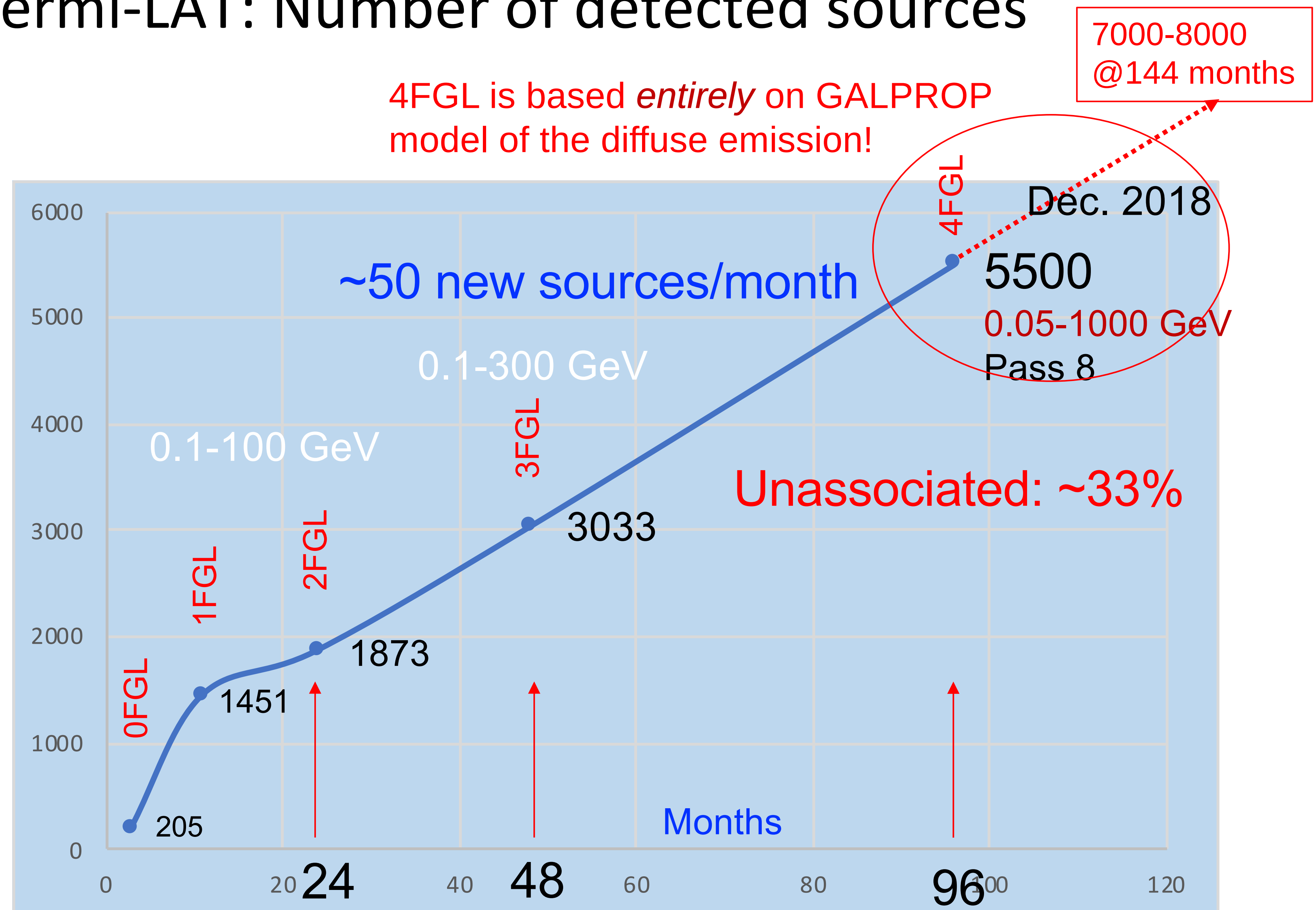
2FHL details

Median localization accuracy is 1.7’ (68%)!

- Detections (>50 GeV)
  - 360 sources:
    - 75% blazars, 11% Galactic sources, 14% unassociated
  - 78 detected by IACTs (TeVCat)
  - 230 detected in 1FHL
  - 303 detected in 3FGL
  - 57 brand new sources (not 1FHL/3FGL)
- Sensitivity is increasing with time, so expect more in 3FHL!

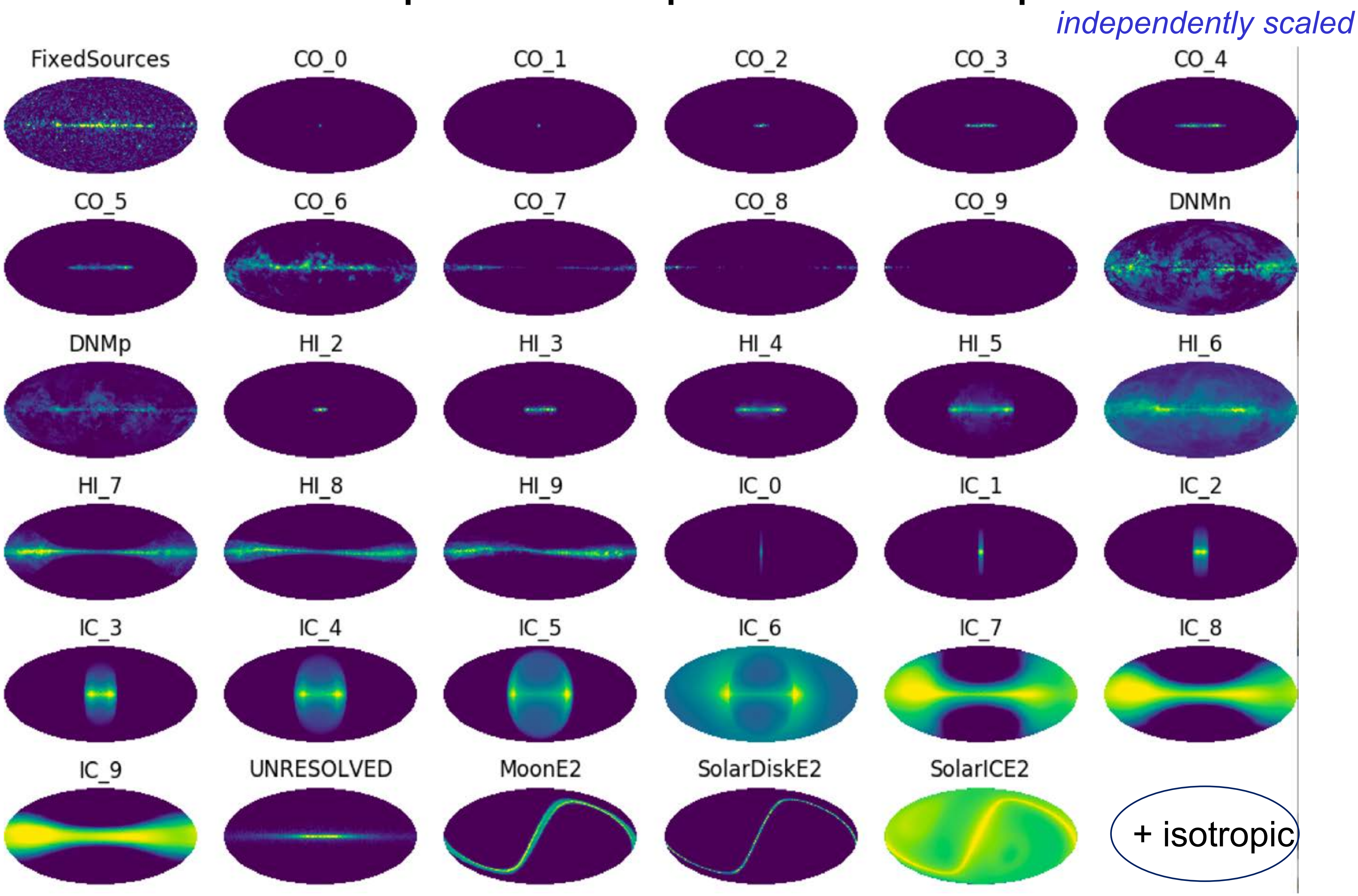


Fermi-LAT: Number of detected sources



Example Templates – 36 (one energy band)

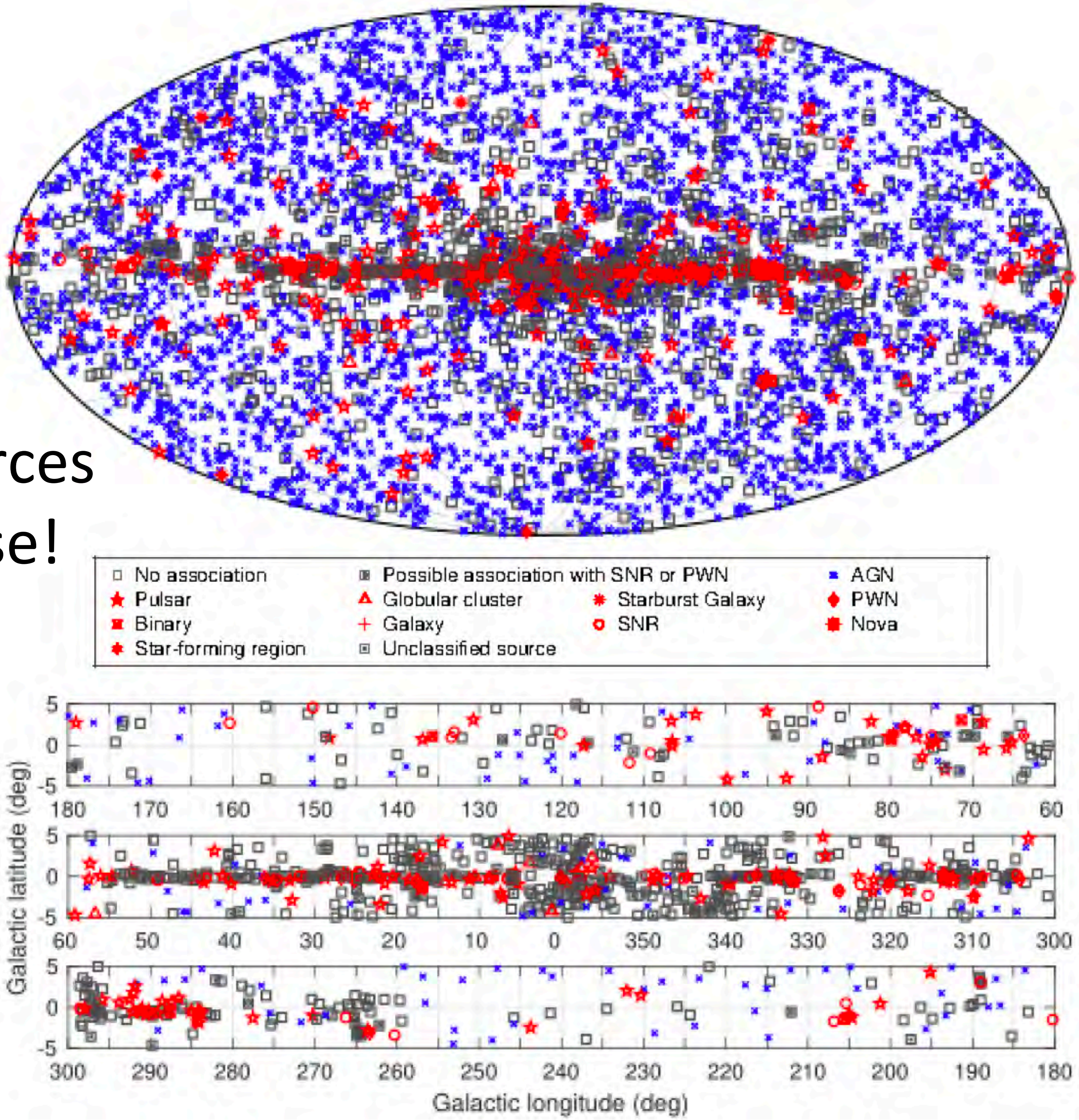
- **These have been processed into predicted counts maps**



GALPROP + Moon + Solar disk + Solar IC + fixed sources + unresolved sources + isotropic

S.Digel

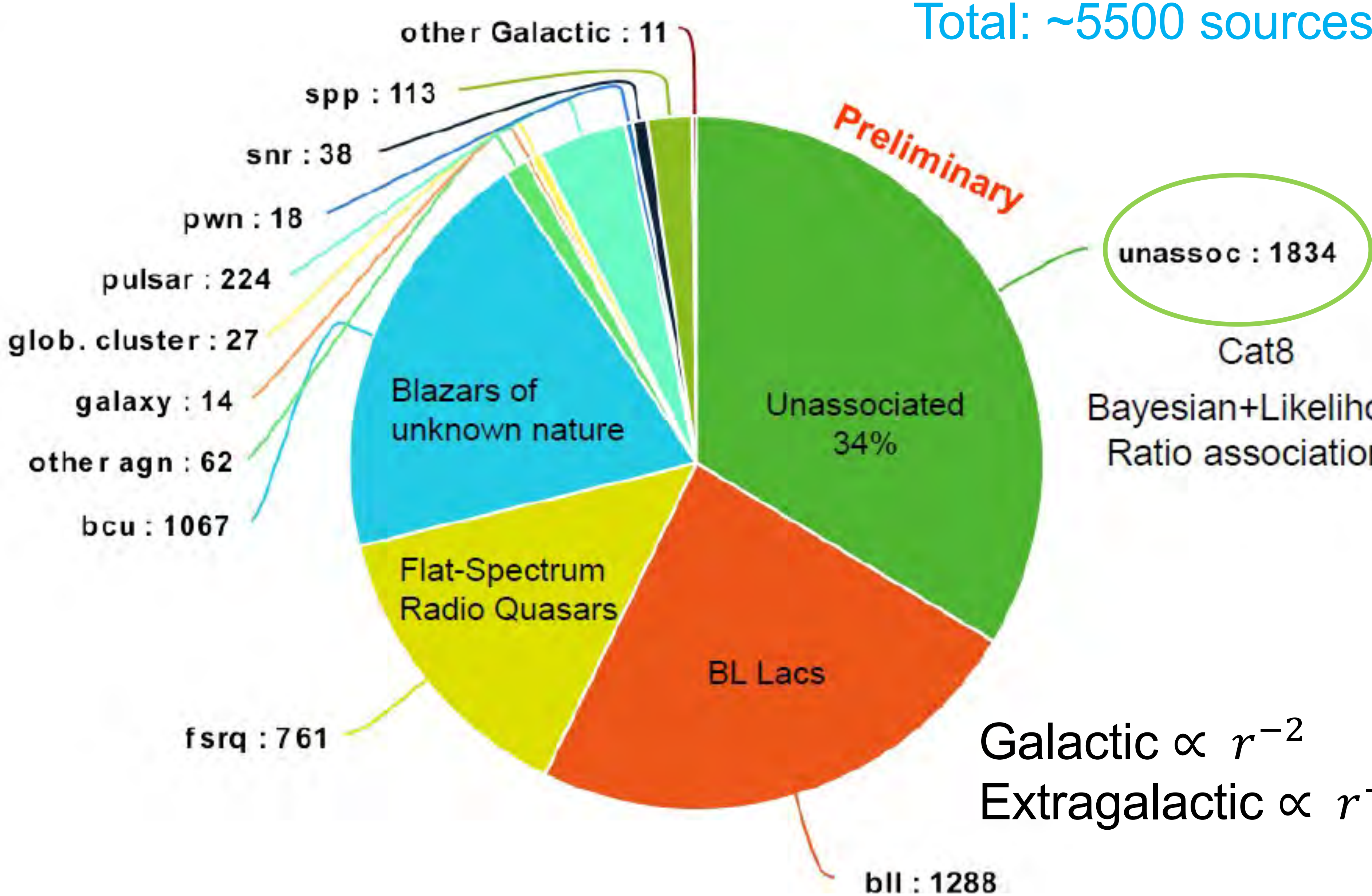
4FGL



5500 sources
Very dense!

FL8Y (4FGL) association summary

Total: ~5500 sources



Cat8

Bayesian+Likelihood Ratio associations

Galactic $\propto r^{-2}$

Extragalactic $\propto r^{-3}$

B.Lott

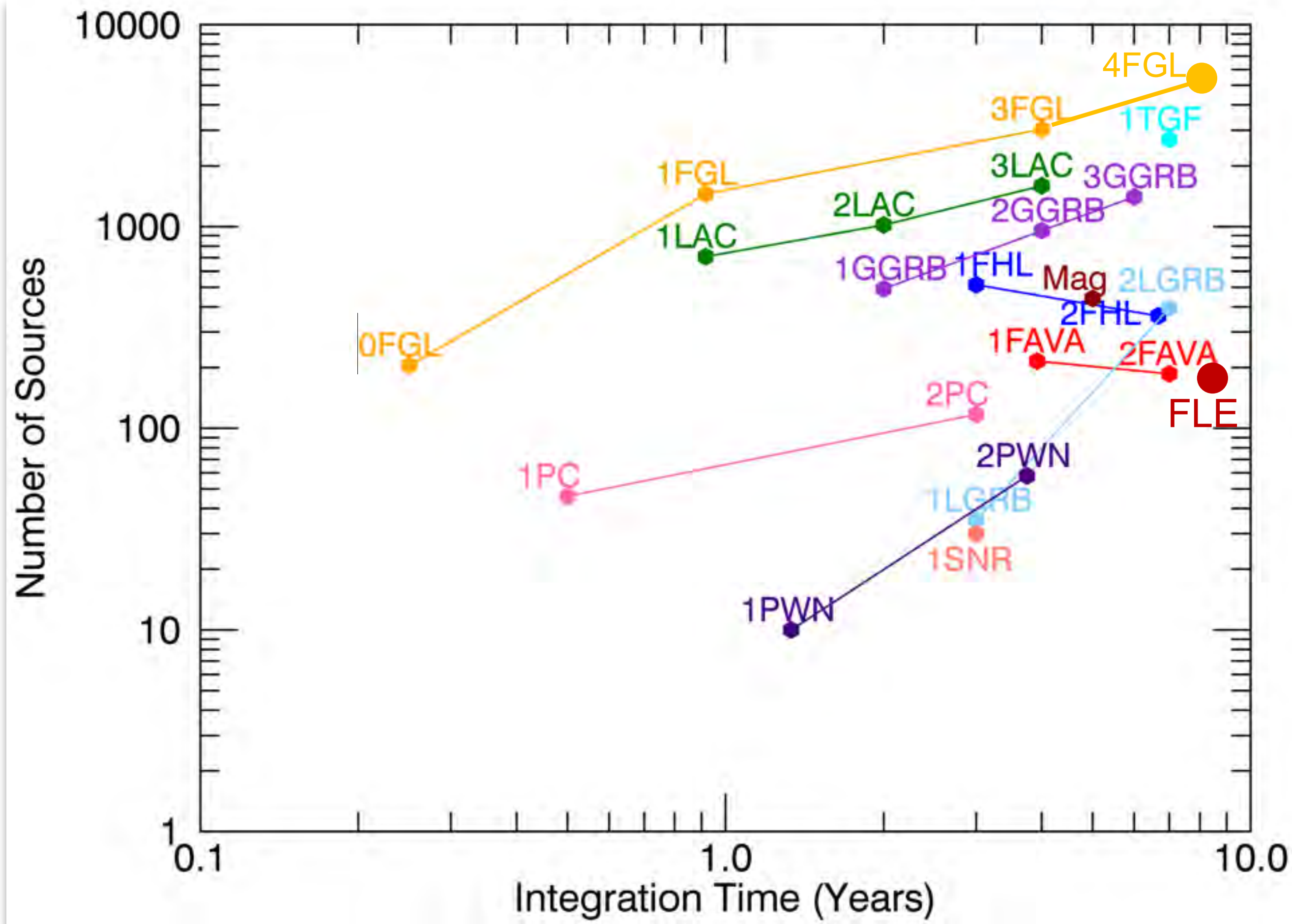
What are LAT catalogs good for?

- 3FGL: 838 citations (NASA ADS)
- Reference for studies of:
  - individual sources
  - source populations
  - multi-wavelength analyses
- Source samples to investigate
  - Extragalactic Background Light
  - Extragalactic Diffuse Gamma-ray Background
- Exploration of new classes: stars, galaxy clusters…
- Nature of unassociated sources via follow-up observations
- Classification of unassociated sources
- Optimization of future observatories: LHAASO, CTA, SKA…

Fermi Status: Catalogs

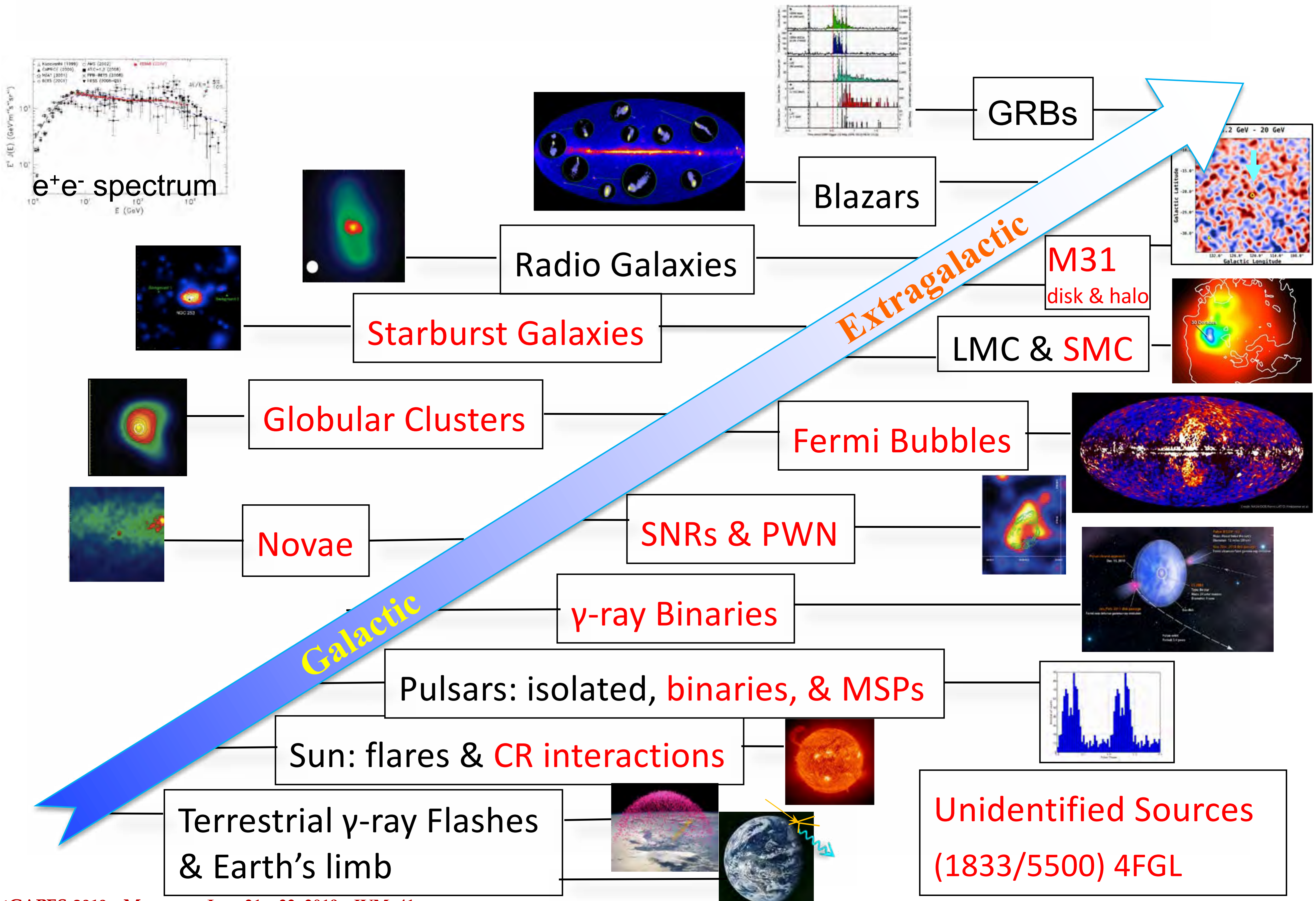
Fermi Catalogs

- **LAT**
  - **FGL (General)**
  - **FHL (High-energy)**
  - **LAC (AGN)**
  - **PC (Pulsars)**
  - **LGRB (GRBs)**
  - **FAVA (Flaring sources)**
  - **SNR (supernova remnants)**
  - **Solar flares (upcoming)**
- **GBM**
  - **GGRB (GRBs)**
  - **Mag (Magnetar bursts)**
  - **TGF**



\+ LAT: FLE (Low energy)

Fermi Highlights and Discoveries (GeV range)



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FERMI-LAT OBSERVATIONS OF γ-RAY EMISSION TOWARDS THE OUTER HALO OF M31

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GALPROP-based foreground model

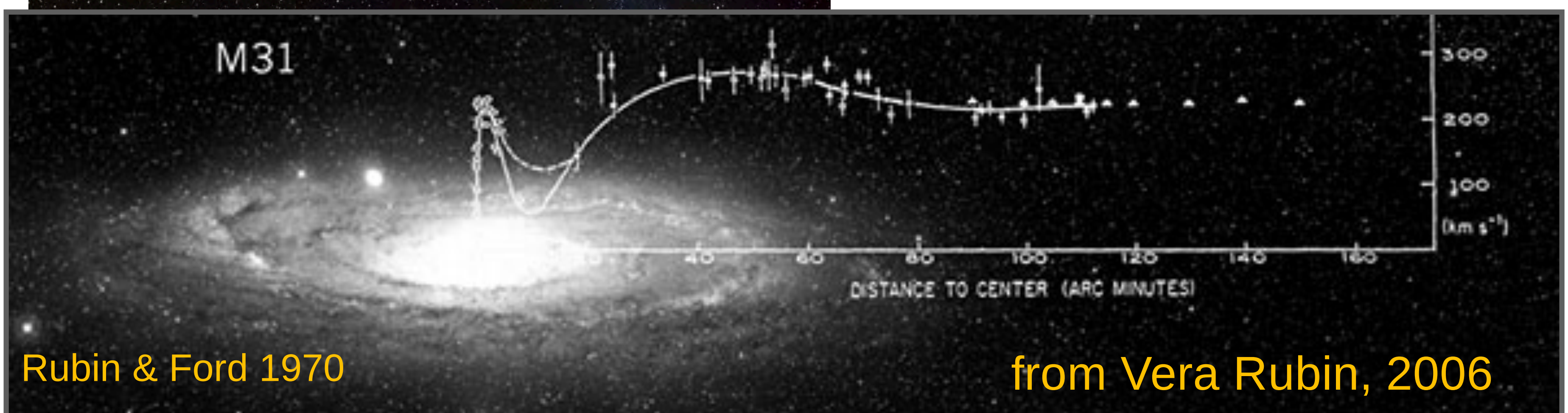
ABSTRACT

The Andromeda Galaxy is the closest spiral galaxy to us and has been the subject of numerous studies. It harbors a massive dark matter (DM) halo which may span up to ~600 kpc across and comprises ~90% of the galaxy's total mass. This halo size translates into a large diameter of 42° on the sky for an M31–Milky Way (MW) distance of 785 kpc, but its presumably low surface brightness makes it challenging to detect with γ-ray telescopes. Using 7.6 years of *Fermi* Large Area Telescope (*Fermi*–LAT) observations, we make a detailed study of the γ-ray emission between 1–100 GeV towards M31's outer halo, with a total field radius of 60° centered at M31, and perform an in-depth analysis of the systematic uncertainties related to the observations. We use the cosmic ray (CR) propagation code GALPROP to construct specialized interstellar emission models (IEMs) to characterize the foreground γ-ray emission from the MW, including a self-consistent determination of the isotropic component. We find evidence for an extended excess that appears to be distinct from the conventional MW foreground, having a total radial extension upwards of ~120–200 kpc from the center of M31. We discuss plausible interpretations of the excess emission but emphasize that uncertainties in the MW foreground, and in particular, modeling of the H I-related components, have not been fully explored and may impact the results.

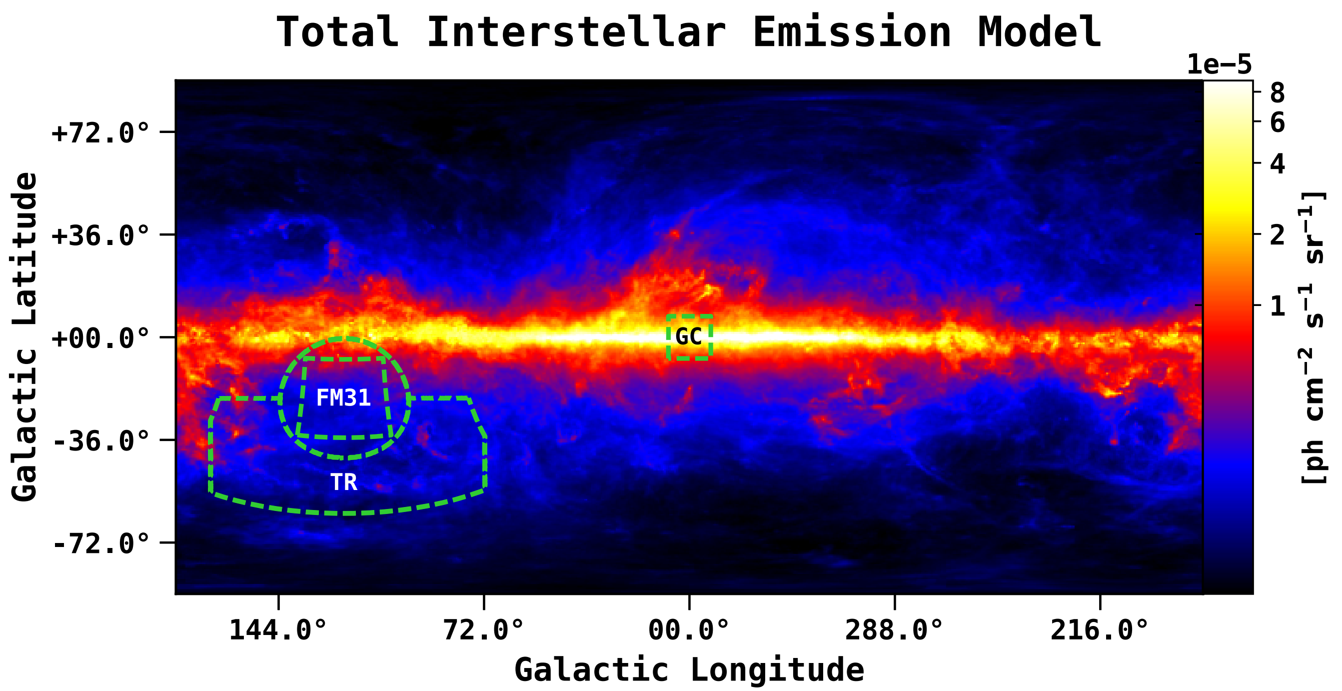
We find evidence for an extended excess that appears to be distinct from the conventional MW foreground, having a total radial extension upwards of ~120-200 kpc from the center of M31…

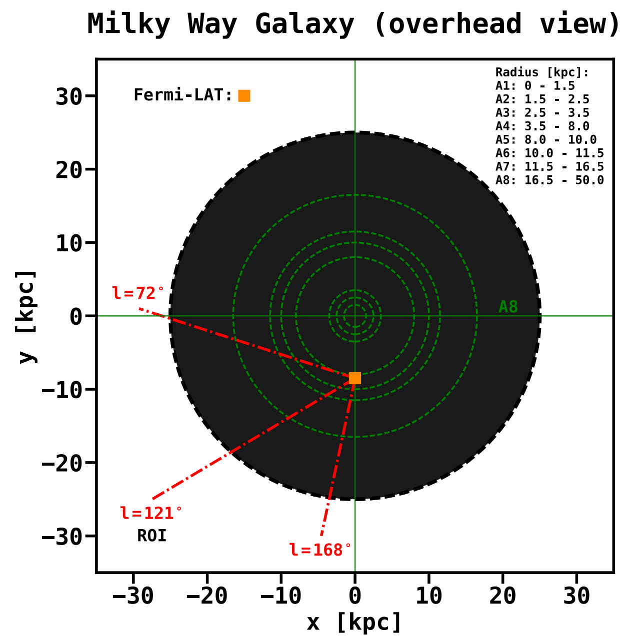
Andromeda galaxy M31 – a closest spiral

- Similar to the Milky Way at 778 kpc
- Provides an external view on our own Galaxy
- Large size on the sky 3°×1° – easy to resolve
- The rotation curve remains constant over large distances – large content of DM
- Virial radius ~300 kpc



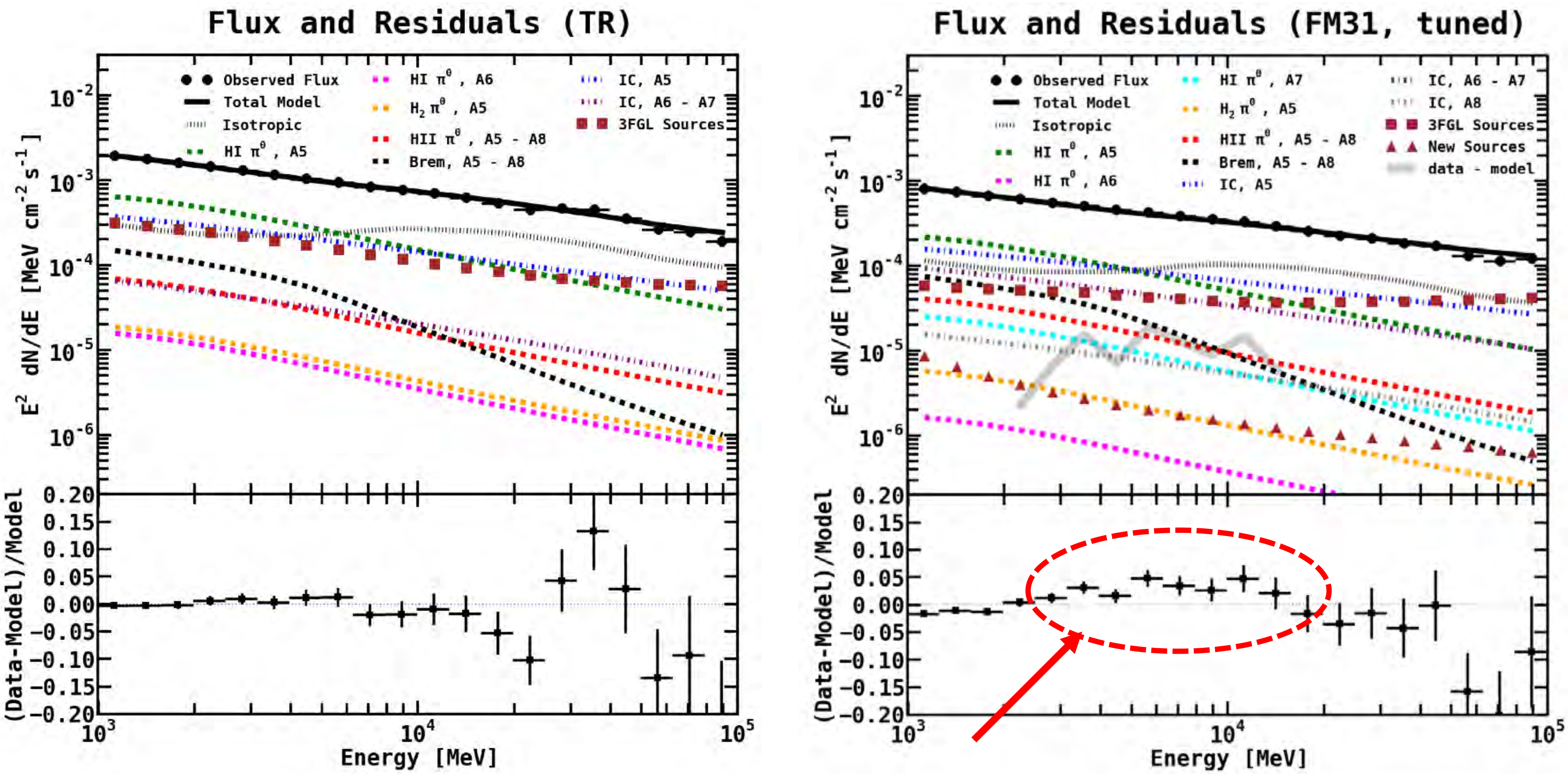
Test region and M31 field





- The interstellar emission model for the MW (1-100 GeV):
  π^0-decay + (anisotropic) inverse Compton + Bremsstrahlung
- "Square" region is M31 field
- "TR" labels the test region
- Schematic of the eight concentric circles which define the annuli (A1-A8) in the MW foreground model. Only A5-A8 contribute to the Galactic foreground emission for the field used in this analysis.

Spectral fits in TR and FM31

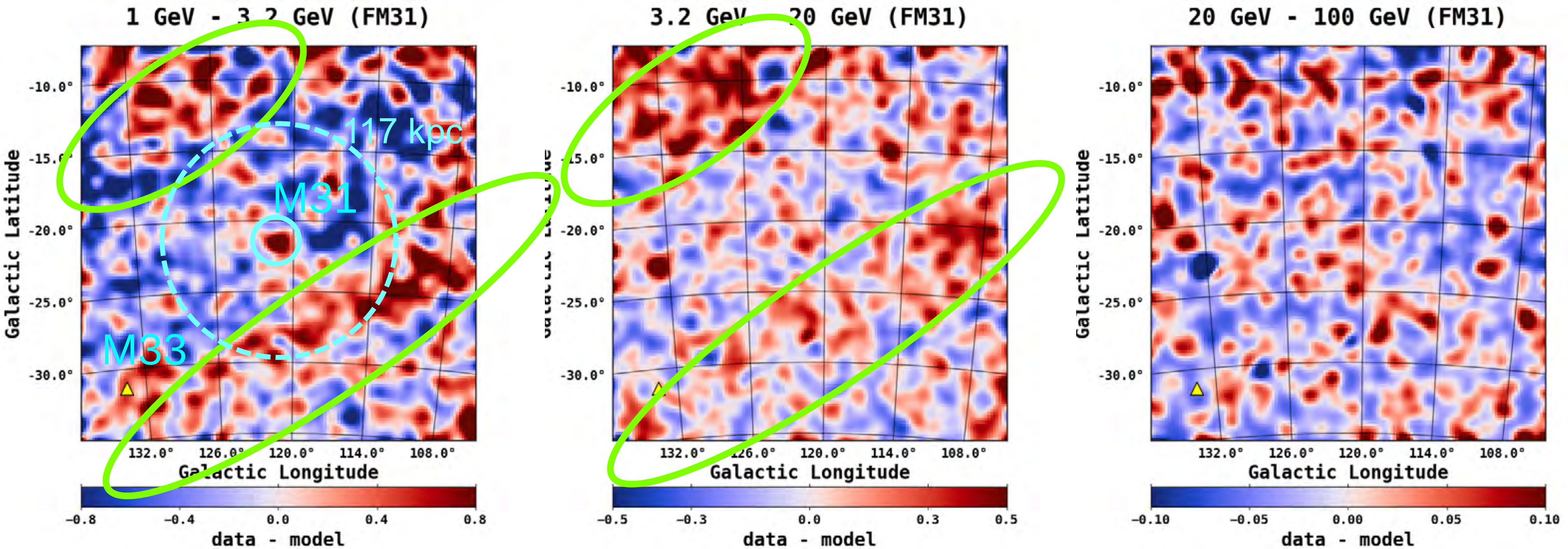


✧ Flux and fractional count residuals for the fit in the TR and FM31

✧ The fractional residuals (FM31) show an excess between 3-20 GeV reaching a level of 4%

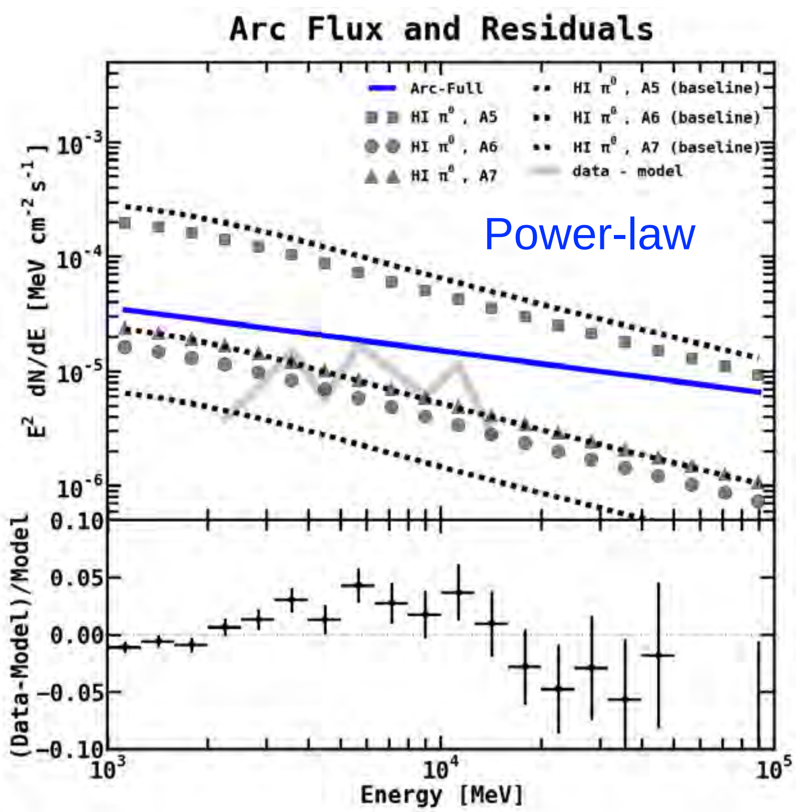
✧ Residuals at HE is due to the spectral approximation of the 3FGL sources

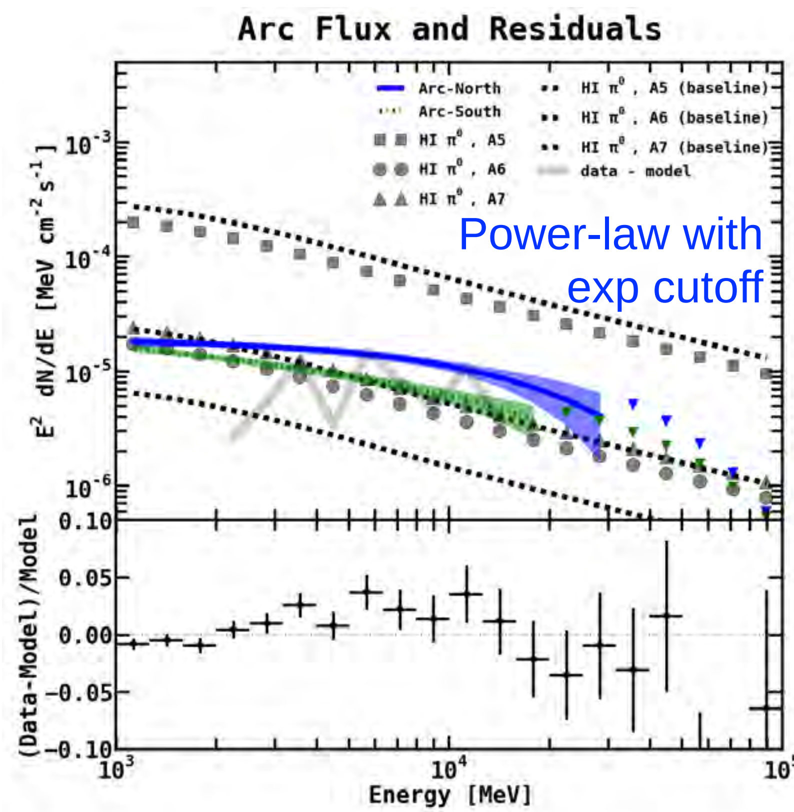
FM31: Spatial residuals



- Spatial count residuals (data – model) resulting from the baseline fit in FM31 for three different energy bands. Smoothed using 1° Gaussian kernel. The pixel size is 0.2°×0.2°
- The "arc" structure is clearly seen in the 1st and 2nd pixels
- M33 is in the bottom left angle
- Dashed circle – "spherical halo" of 117 kpc radius (8.5°)

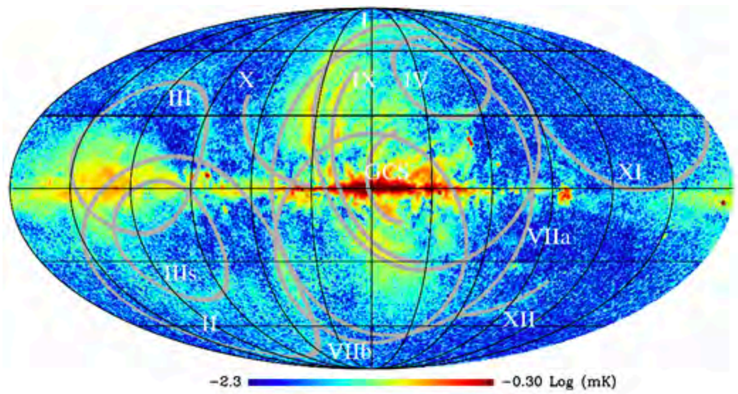
Arc flux and residuals

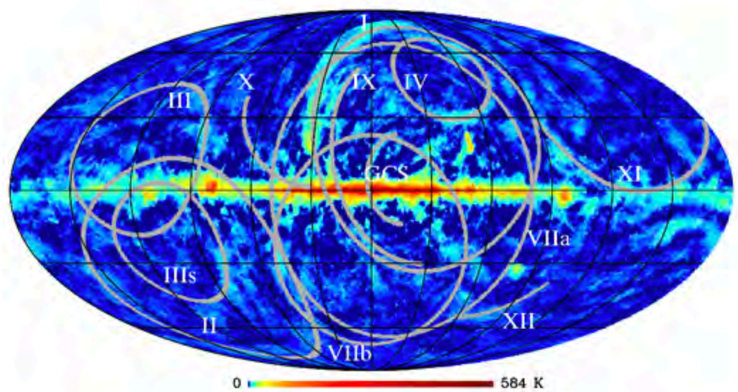


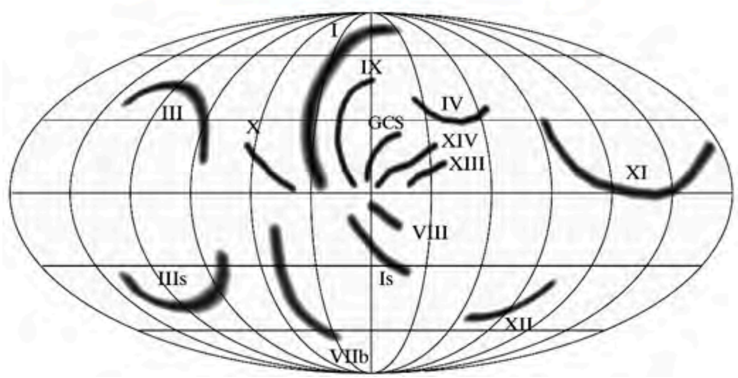


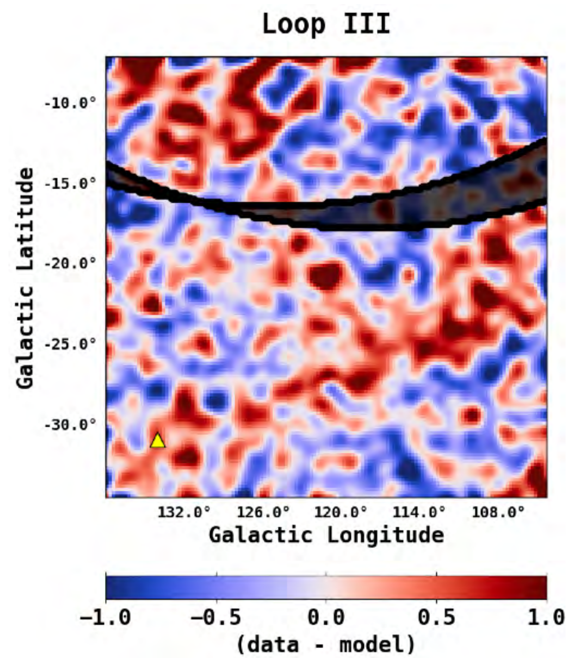
- Simultaneous fit of the arc template with other components
- Power-law (left) and power-law with exponential cutoff (right) spectral fits are unable to flatten the residuals in the range 3-20 GeV
- The right panel shows a separate fit of two parts of the arc (North and South)
- The index of the arc emission has a value ~2.0-2.4, notably flatter than other components

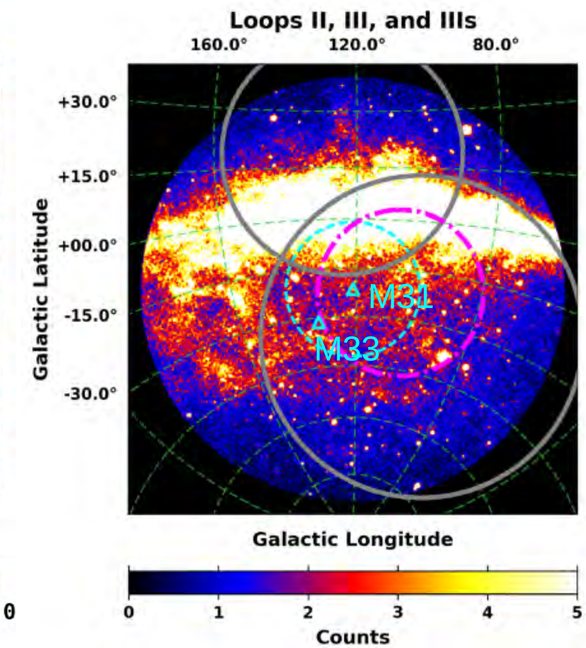
What is the arc? Loops, loops, loops…





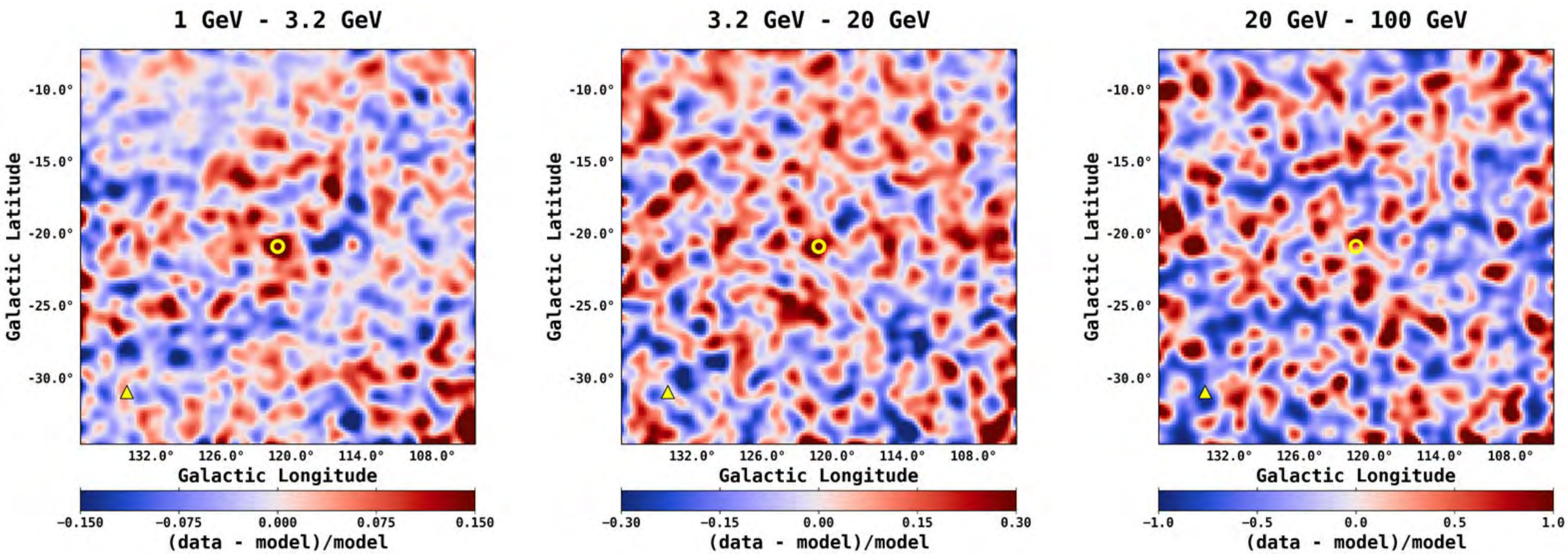






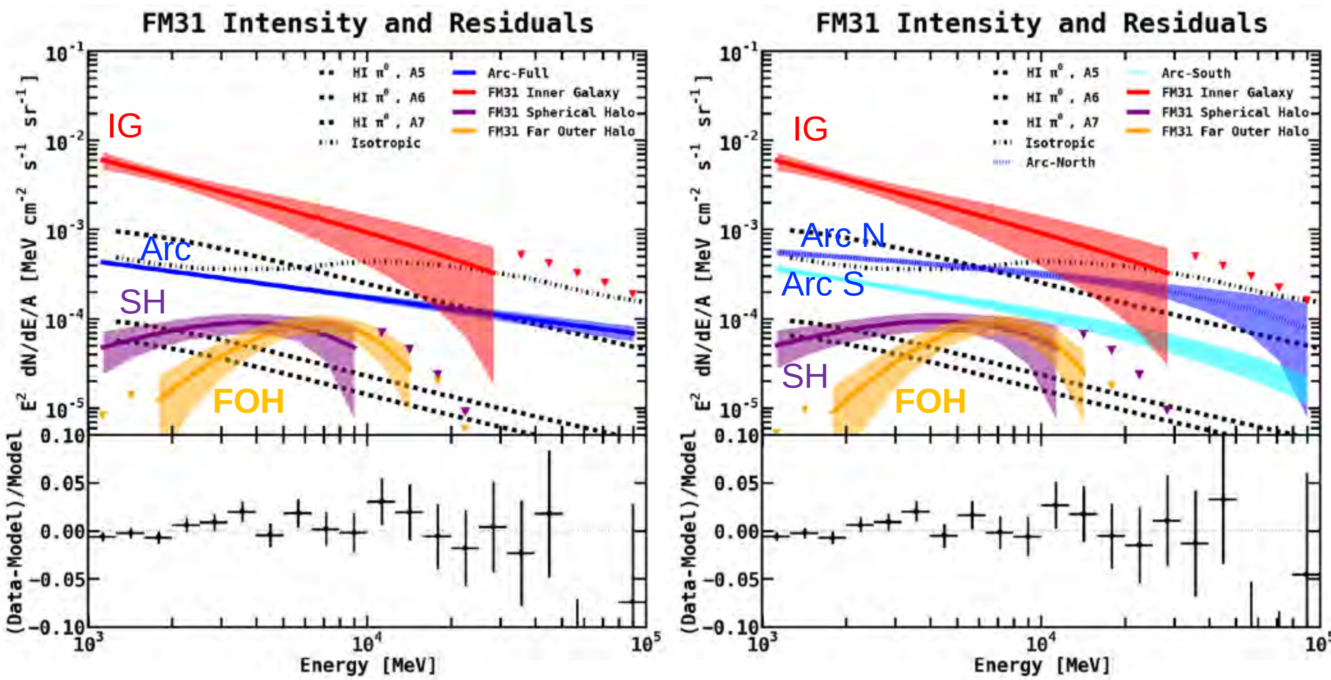
- ✧ There are ~17 so-called Loops found on the sky in radio and polarized radio emission
- ✧ Loops or Spurs are large structures covering a significant part of the sky – their origin is unknown
- ✧ A part of the shell of Loop III seems to be associated with the north part of the arc, and Loops II and IIIs are covering the entire ROI
- ✧ The Arc could be a part of the old Loop III or other Loops; hard spectrum perhaps indicates particle acceleration

2D residuals after the Arc fit



✧ Subtraction of the Arc flattens the 2D residuals, which show no obvious residual structure

Adding M31 components: all-component fit

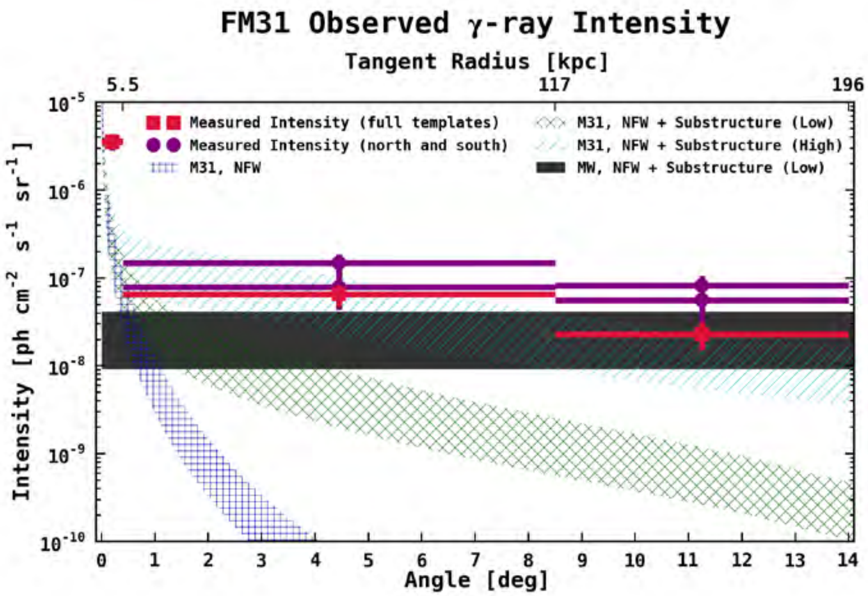


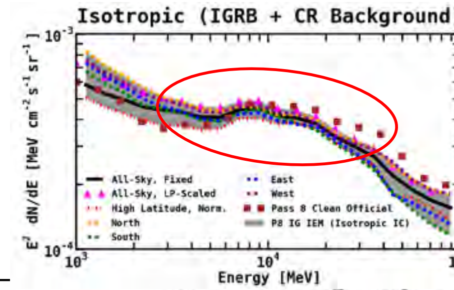
- ✧ Inner Galaxy (IG):
  - ✦ $0^{\circ} < r \leq 0.4^{\circ}$ (5.5 kpc)
- ✧ Spherical Halo (SH):
  - ✦ $0.4^{\circ} < r \leq 8.5^{\circ}$ (117 kpc)
- ✧ Far Outer Halo (FOH):
  - ✦ $r > 8.5^{\circ}$ ($\sim$200 kpc)

M31-related geometry: Uniform intensity templates centered at M31

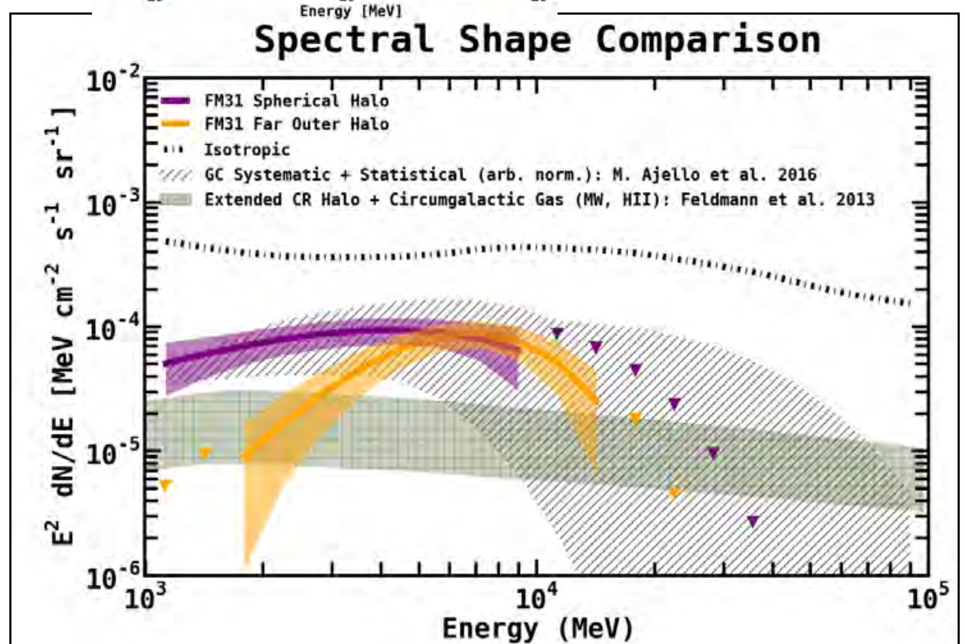
- ✧ Three spherically symmetric templates centered at M31 are added to the model: inner galaxy (IG), spherical halo (SH), and far outer halo (FOH).
- ✧ Templates are given PLEXP spectral models and fit simultaneously with other components of the IEM, including the arc template. Two fit variations are performed, amounting to two different variations in the arc template: full arc with PL, arc north and south with PLEXP
- ✧ IG, SH, and FOH are detected at the significance levels of 7σ, 7σ, and 5σ, respectively. Results for the two fit variations are similar
- ✧ Spectral shapes (SH, FOH) are noticeably different from other components

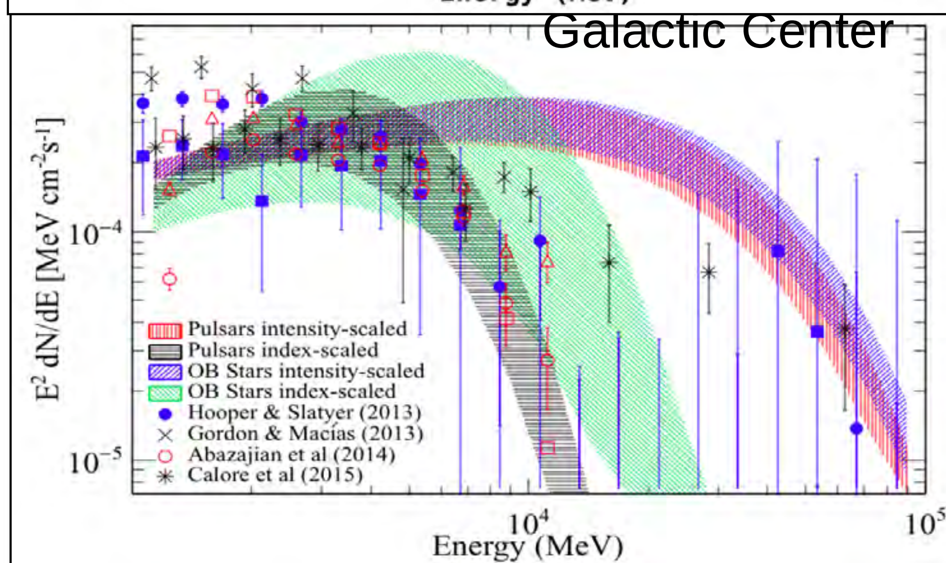
Spectrum of the excess and interpretation





Spectrum of isotropic γ-ray background





- Spectral shape is not resembling other CR-related components
- FM31: properties of the extended (DM?) halo remain highly uncertain
- Consistent with DM interpretation of the Galactic center excess (requires a large boost factor)
- Decaying DM looks more natural
- Interestingly, isotropic component has a “bump” in the same energy range

THANKS!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