Astrophysics with Fermi-LAT

Fermi is 8!

Some highlights from *Fermi* Large Area Telescope

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For the *Fermi* LAT Collaboration

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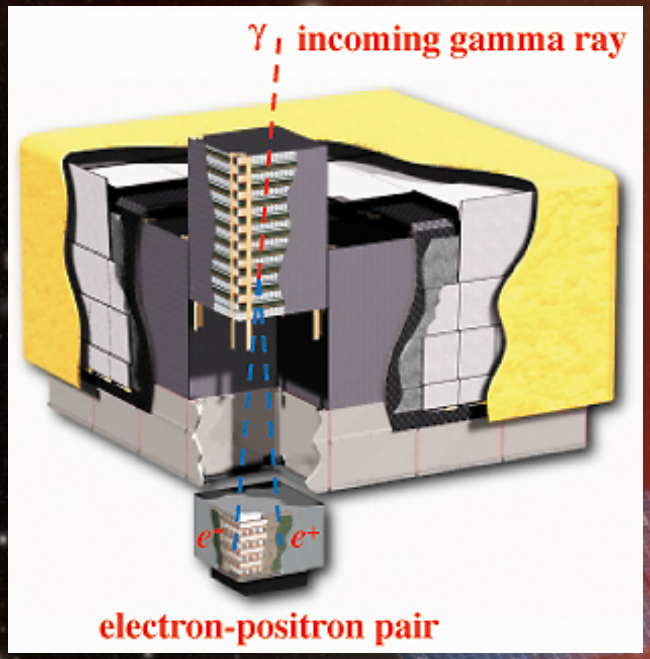
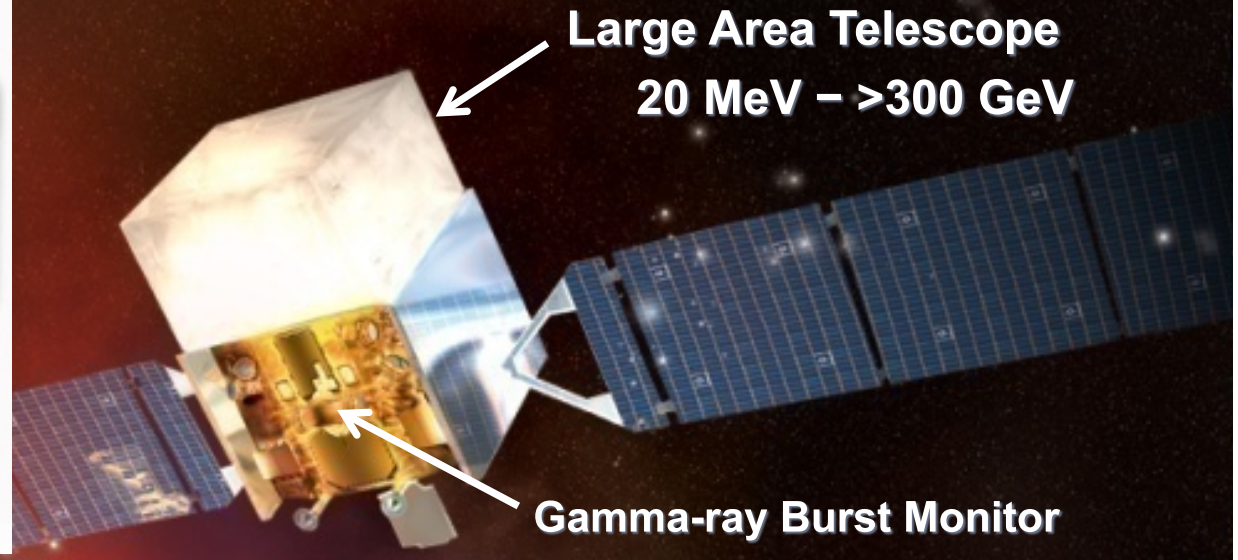
June 11, 2008
12:05 pm (EDT)

Fermi Gamma-ray Space Telescope

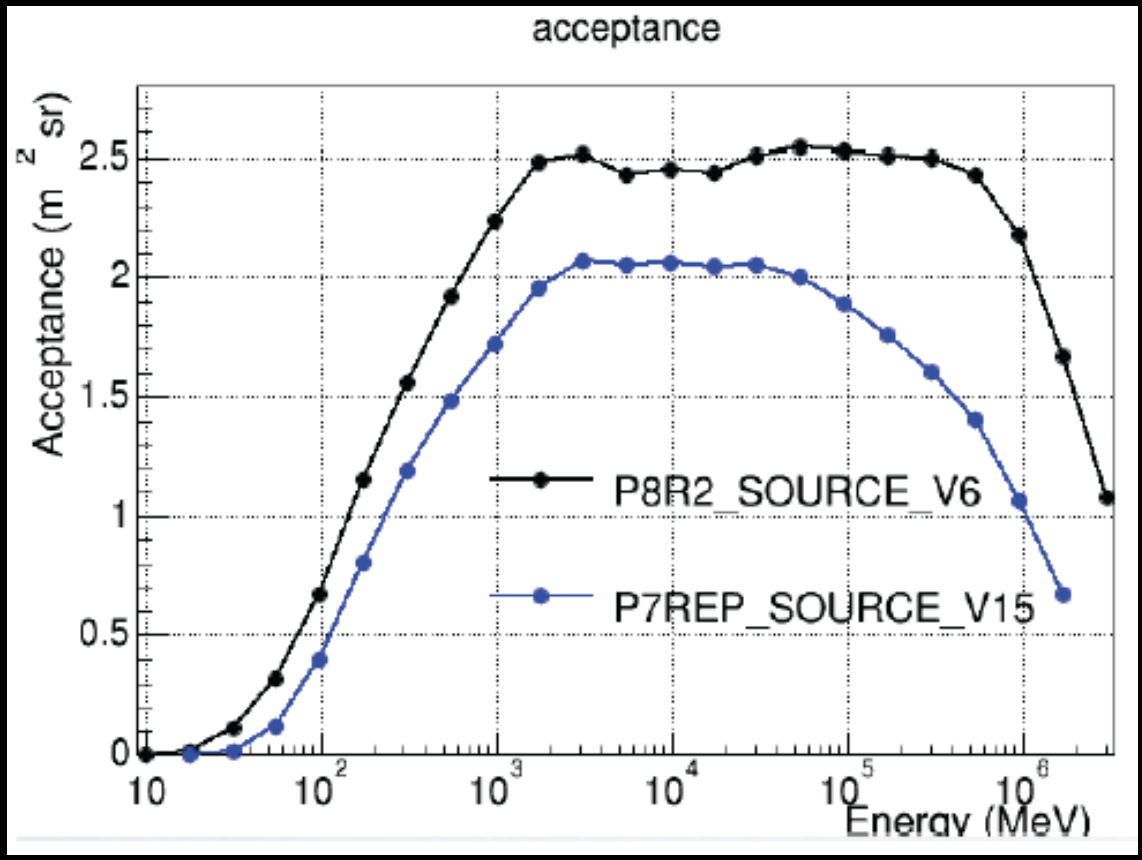




- The LAT is a unique resource providing
  - *Broad energy coverage, overlap with ACTs*
  - *Large FoV: all-sky coverage every 3 hours – transients*
- Observatory is operating smoothly
  - *Instruments and spacecraft operate as designed, no degradation in science performance since launch*
- Observation Modes
  - *Dec 2013 – Dec 2014 in Galactic Center biased survey mode*
  - *Currently in 50° rock sky survey*

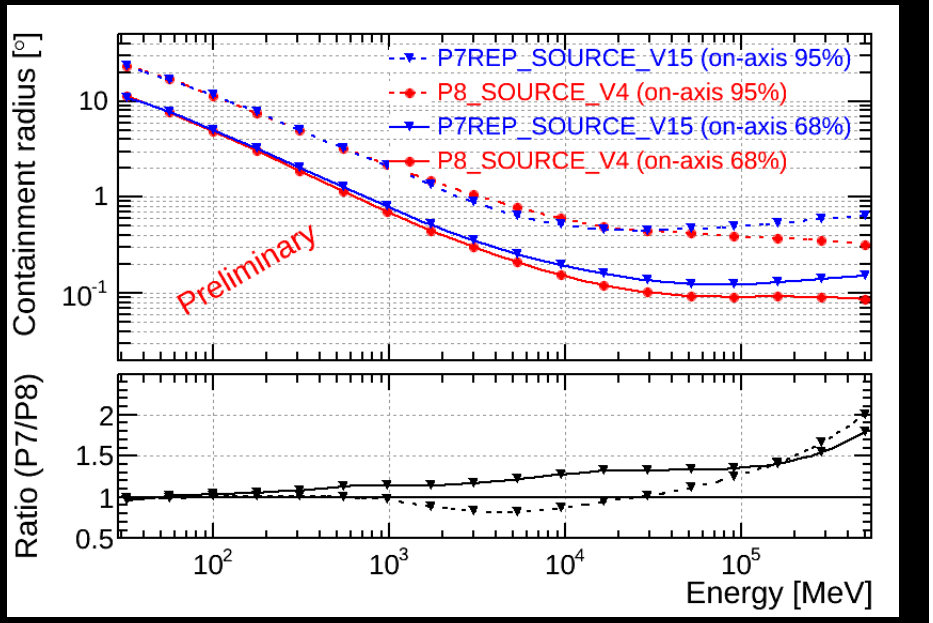
Pass 8 is here!

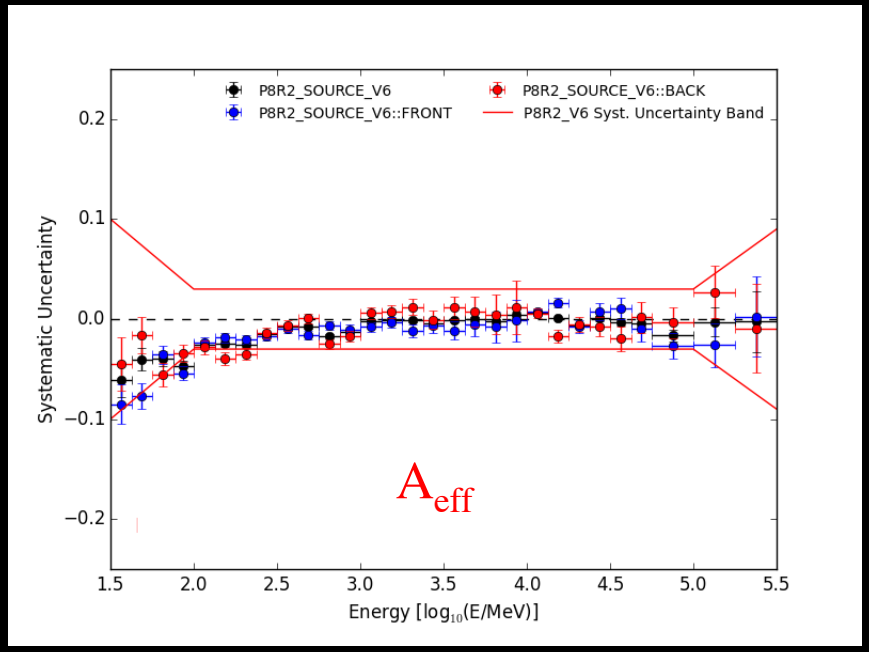
- Provided a substantial improvement in the capabilities of the LAT
  - 40% increase in point-source sensitivity
  - Up to ×2 gain in acceptance at very low (<100 MeV) and very high (>100 GeV) energies
- Updates: data and software releases
  - In-flight IRFs
  - Cal-only event class
  - New Science Tool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

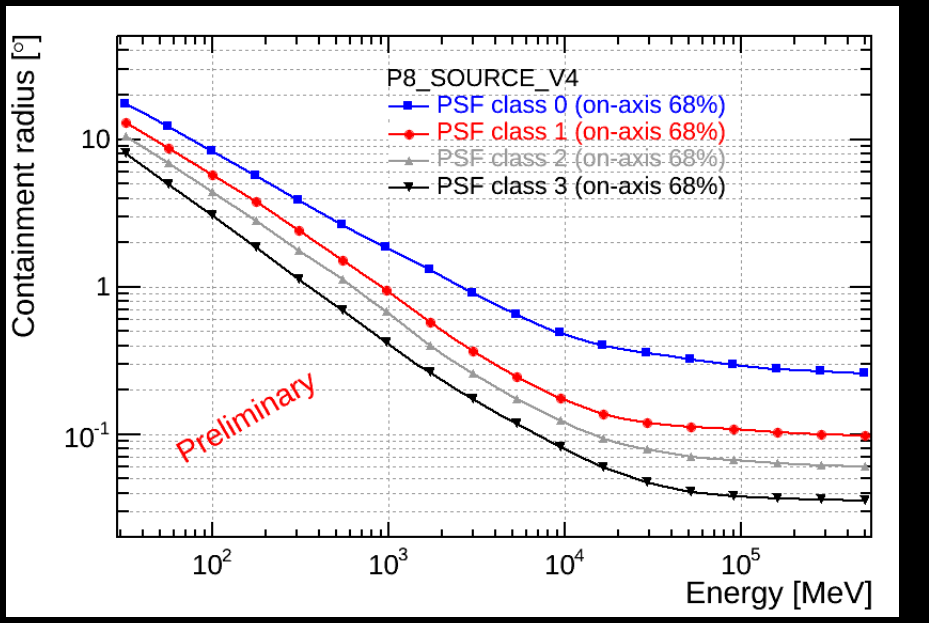


Pass 8 Performance

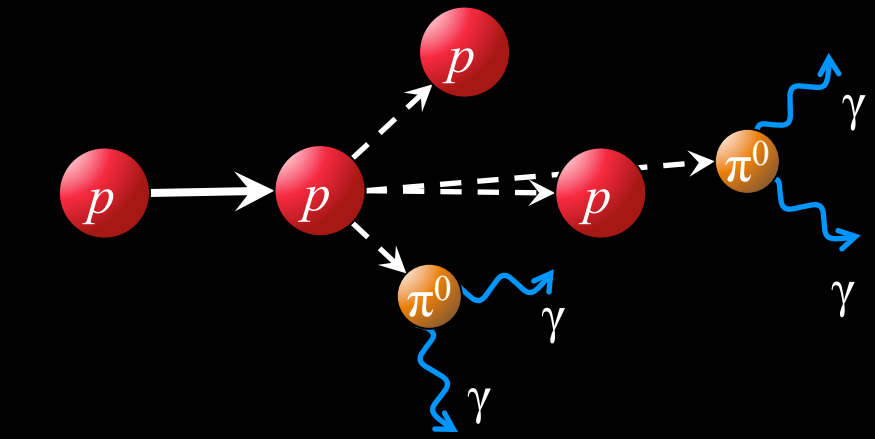
- Significant improvement in the angular resolution
- Additional event selection classes
- On-axis 68% containment (class 3)
  - 3° at 100 MeV
  - 0.4° at 1 GeV
  - 0.07° (~4.2') at 10 GeV
  - 0.035° (~2.1') at >100 GeV
- Cf. HESS 2 angular resolution is ~0.05° at best
- Significant reduction in the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



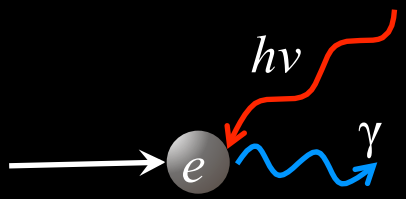




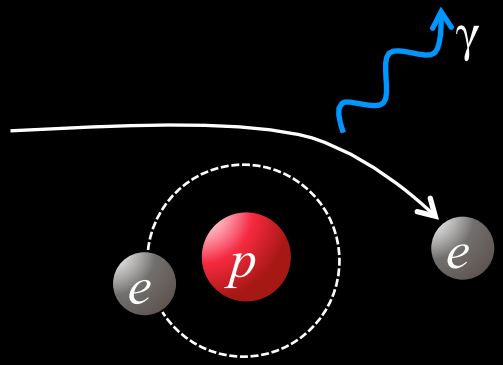
High energy gamma-ray emission processes



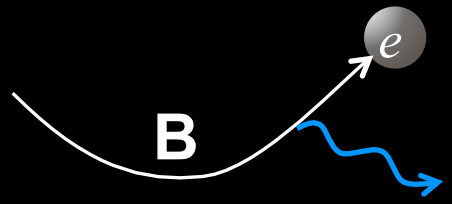
✧ $pp \rightarrow \pi^0(2\gamma)+X$ – neutral pion production and decay



✧ Inverse Compton scattering

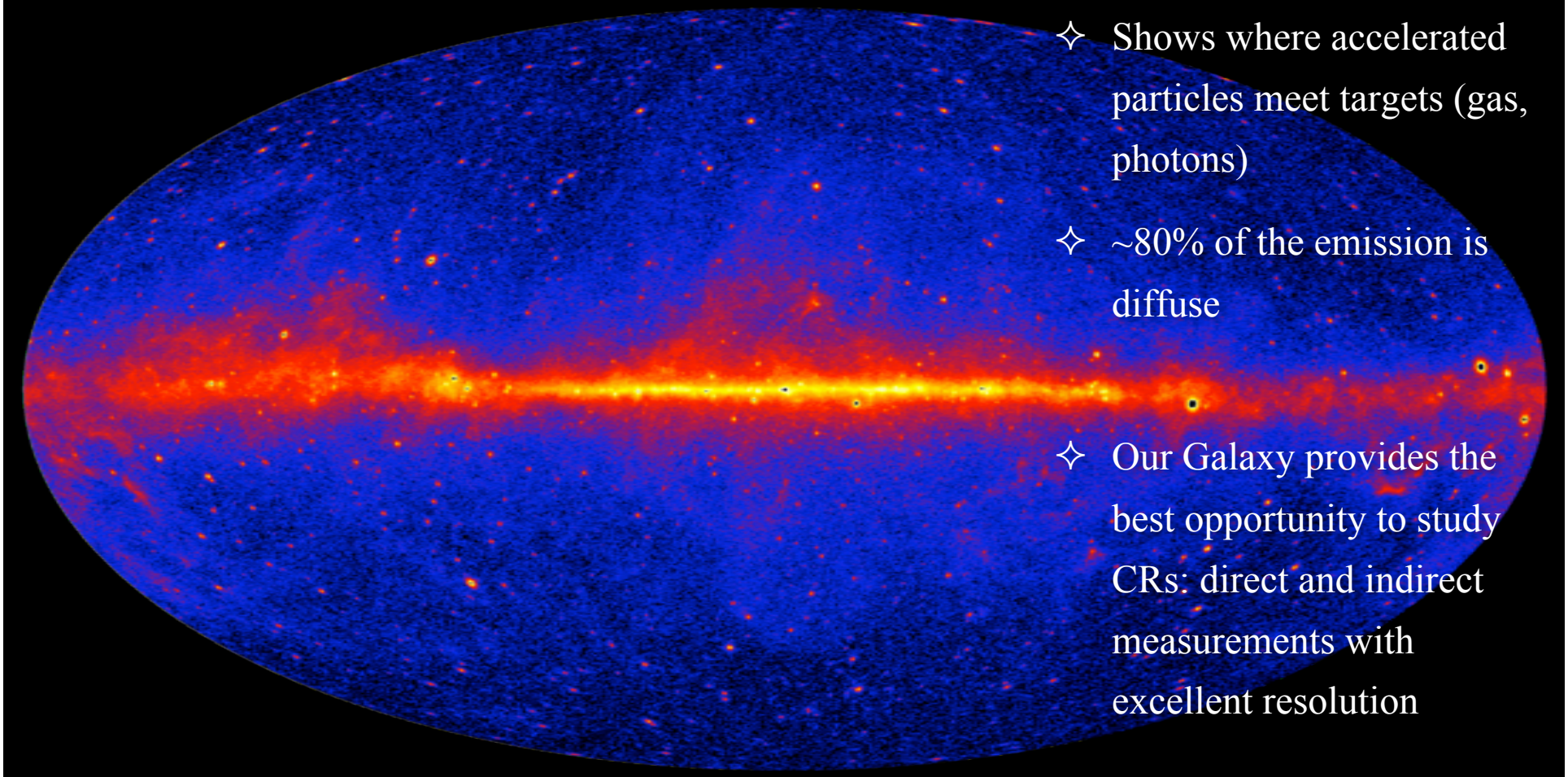


✧ Bremsstrahlung



✧ Curvature (or synchrotron) radiation

Fermi-LAT skymap >1 GeV, 48 months



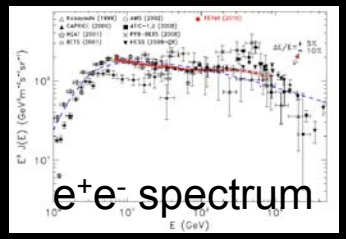
- Shows where accelerated particles meet targets (gas, photons)
- ~80% of the emission is diffuse
- Our Galaxy provides the best opportunity to study CRs: direct and indirect measurements with excellent resolution

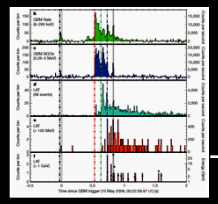
4-year sky map, >1 GeV, front converting (best psf) (4.52M events)

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

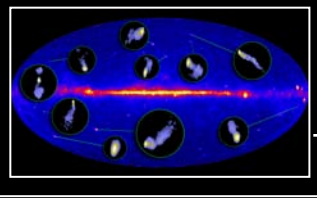
•In 8 years LAT collected ~2 PetaBytes of data!

Fermi Highlights and Discoveries (GeV range)

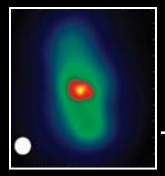




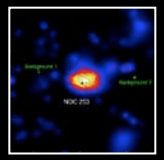
GRBs



Blazars

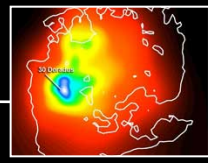


Radio Galaxies

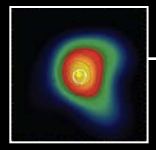


Starburst Galaxies

LMC & SMC

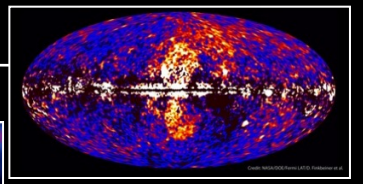


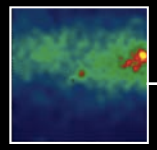
Extragalactic



Globular Clusters

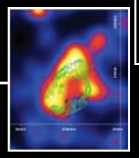
Fermi Bubbles

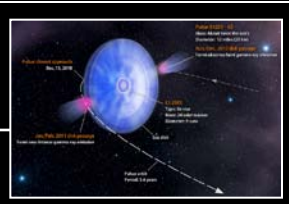




Novae

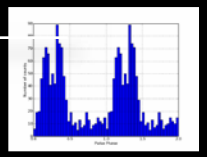
SNRs & PWN





γ-ray Binaries

Pulsars: isolated, binaries, & MSPs



Galactic

Sun: flares & CR interactions

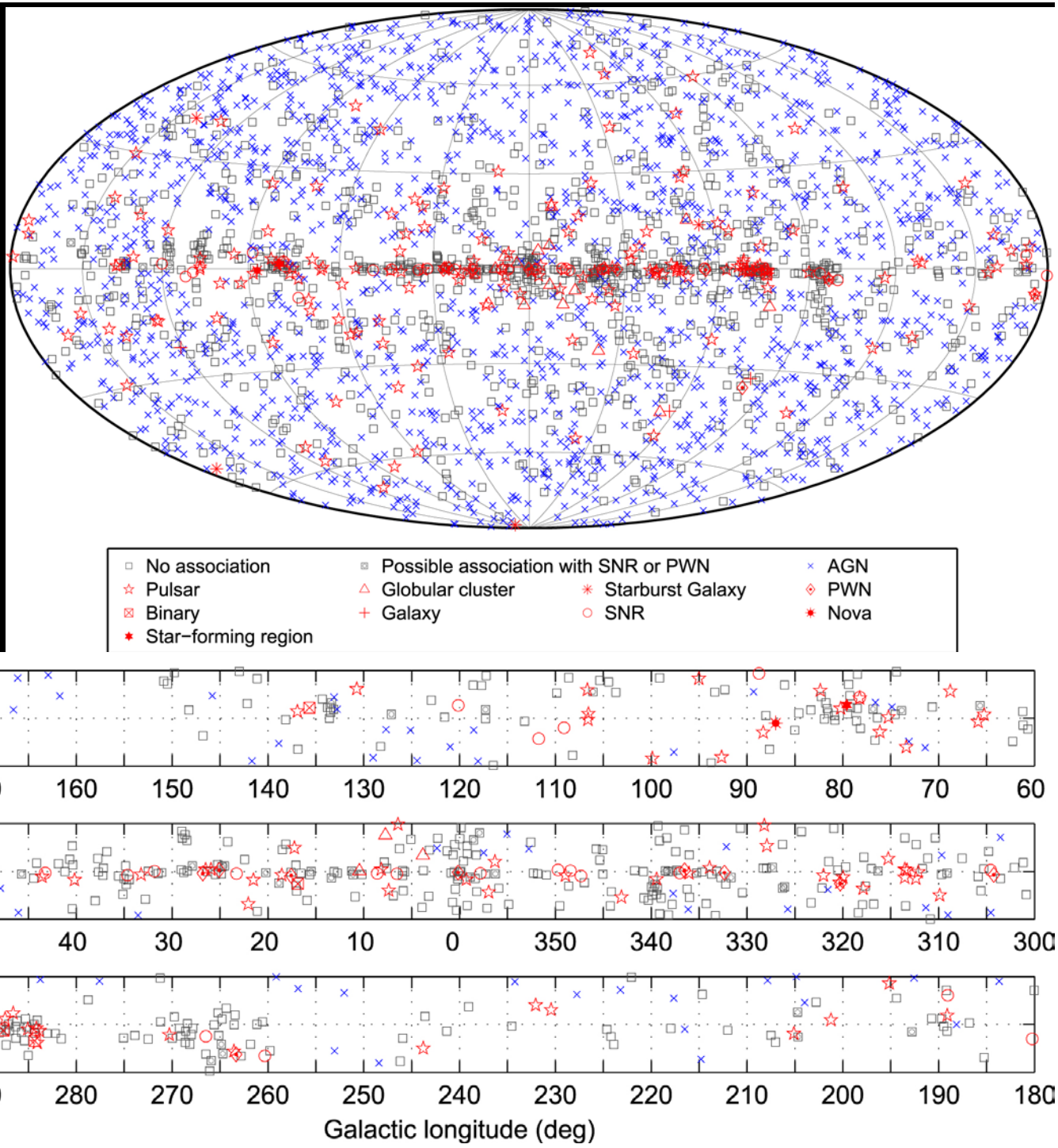
Terrestrial γ-ray Flashes
& Earth's limb

Unidentified Sources
(1010/3033) 3FGL

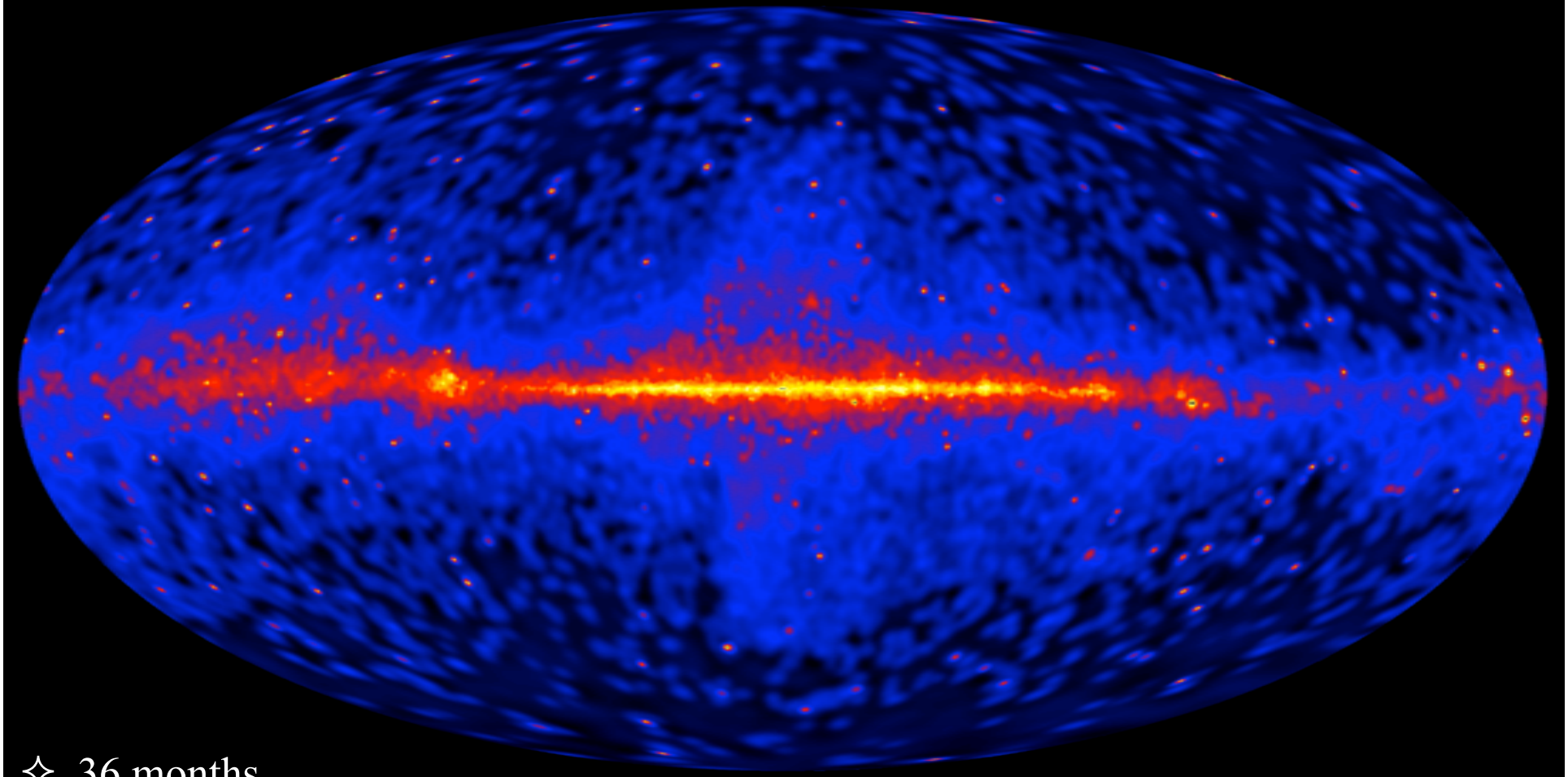
3FGLC atalog: 3033 sources

- ✧ 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

4FGL Catalog – in progress



1FHL: Fermi-LAT skymap >10 GeV

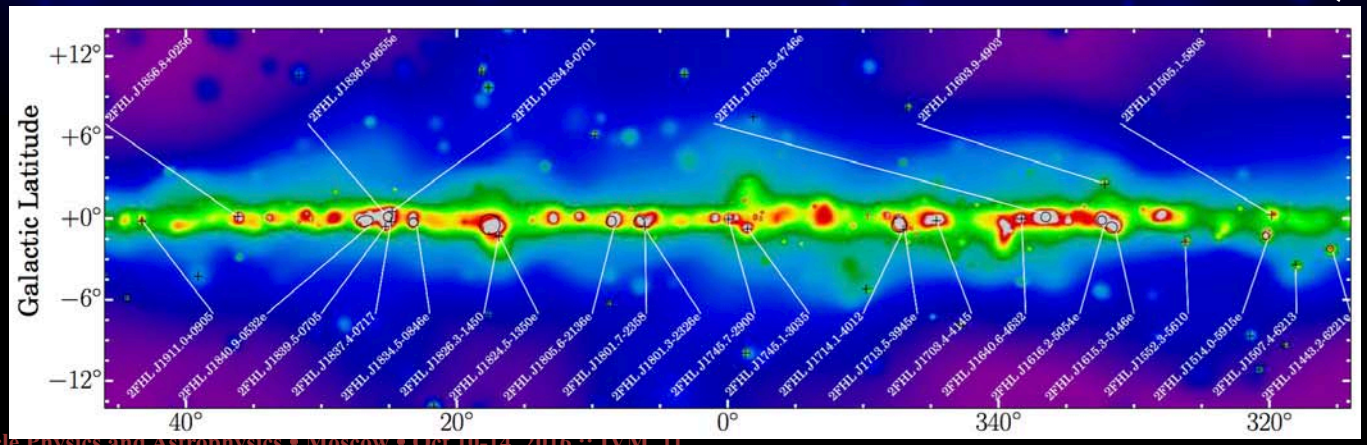


- 36 months
- Less diffuse emission
- Fewer (514 sources) but more powerful sources at high energies

2FHL:“TeVatron map” – Fermi Sky 50 GeV–2 TeV

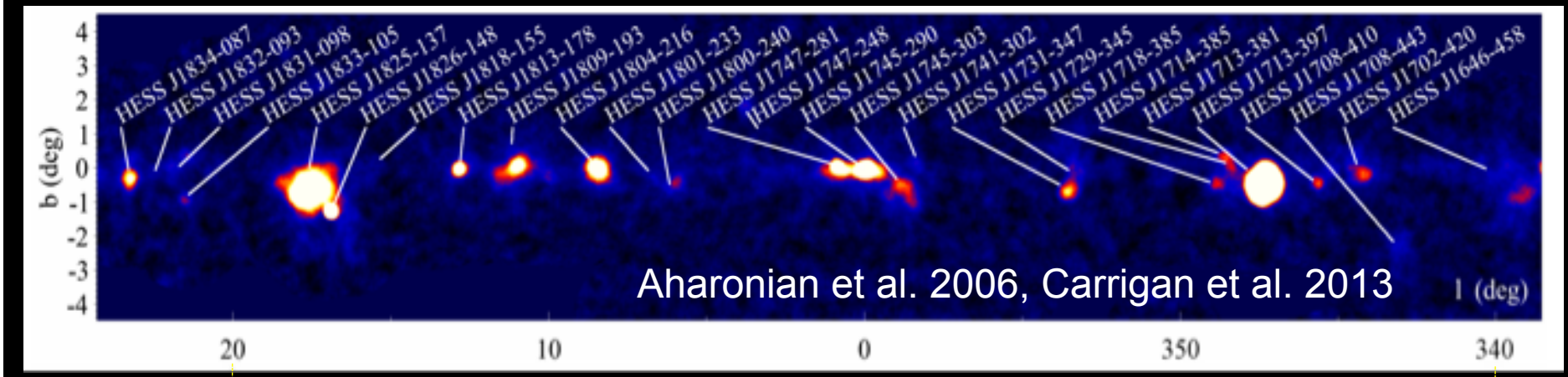
- ✧ 360 sources
- ✧ 80 months

61,000 photons E > 50 GeV
22,100 photons E > 100 GeV
2,000 photons E > 500 GeV
~1.5 phot/deg^2

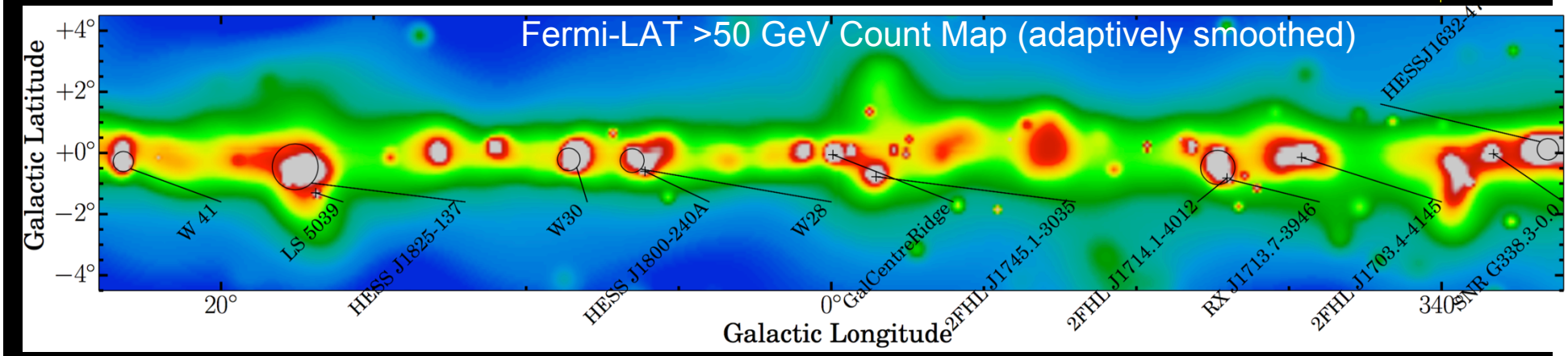


Comparison with HESS Galactic Plane survey

Significance Map

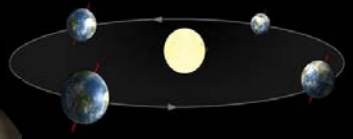


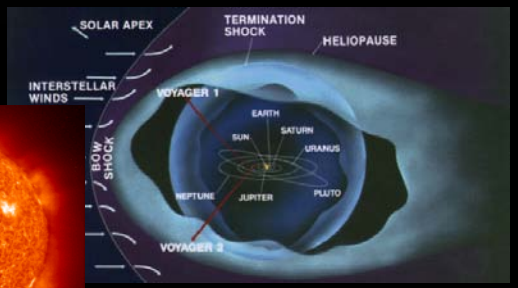
- ✧ H.E.S.S. detects 69 sources reaching a sensitivity of ~2% of the >1 TeV Crab Nebula flux
- ✧ LAT detects 36 sources (in 2FHL) in the same region reaching an average sensitivity of 3-4% of the Crab Nebula flux

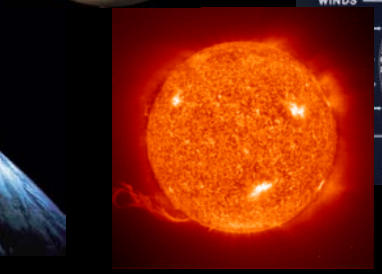


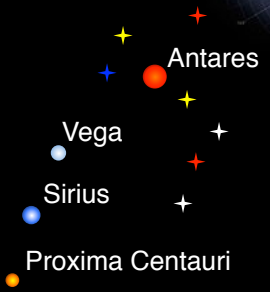
Total: 103 sources at |b|<10°

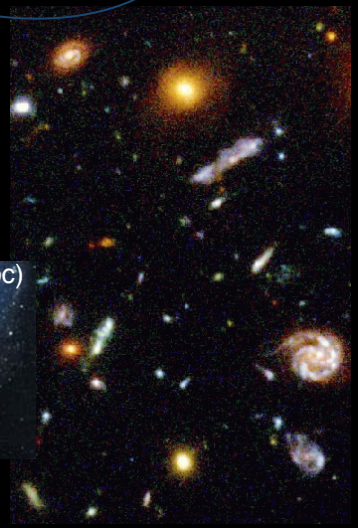
Cosmic Scales





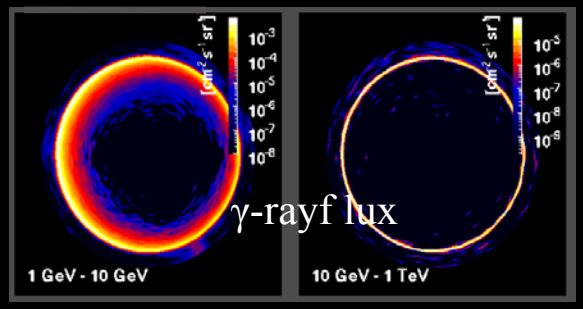




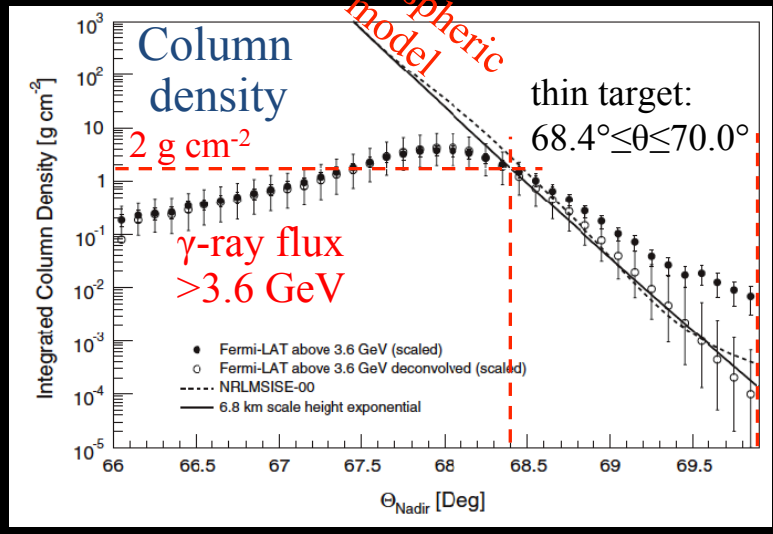


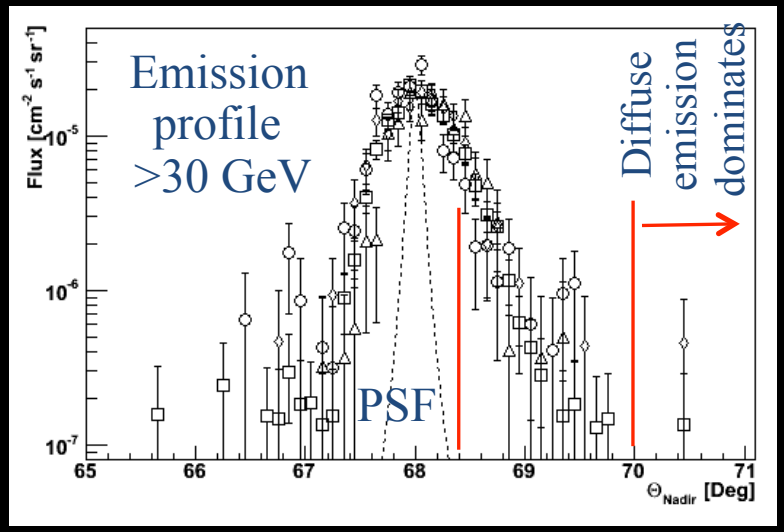
parsec	10^{-10}	10^{-9}	10^{-8}	10^{-7}	10^{-6}	10^{-5}	10^{-4}	10^{-3}	10^{-2}	10^{-1}	10^{0}	10^{1}	10^{2}	10^{3}	10^{4}	10^{5}	10^{6}	10^{7}	10^{8}	10^{9}	10^{10}
	3 000 km	30 000 km	300 000 km	3×10^{6} km	3×10^{7} km	2 AU	20 AU	200 AU	2 000 AU	0.1 pc	1 pc	10 pc	100 pc	1 kpc	10 kpc	100 kpc	1 Mpc	10 Mpc	100 Mpc	1 Gpc	10 Gpc

Fermi-LAT observations of the Earth's limb



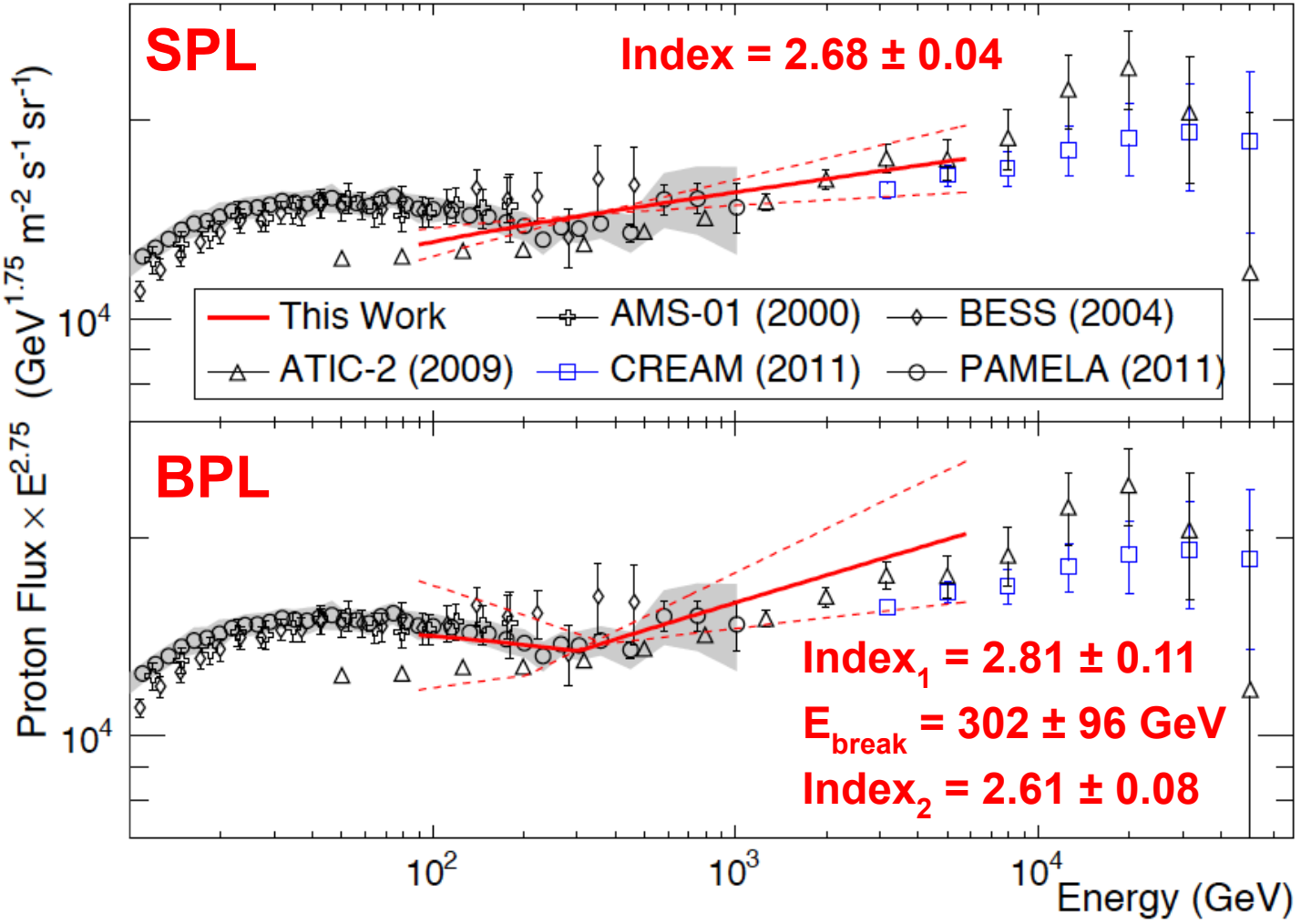
γ-rayf lux





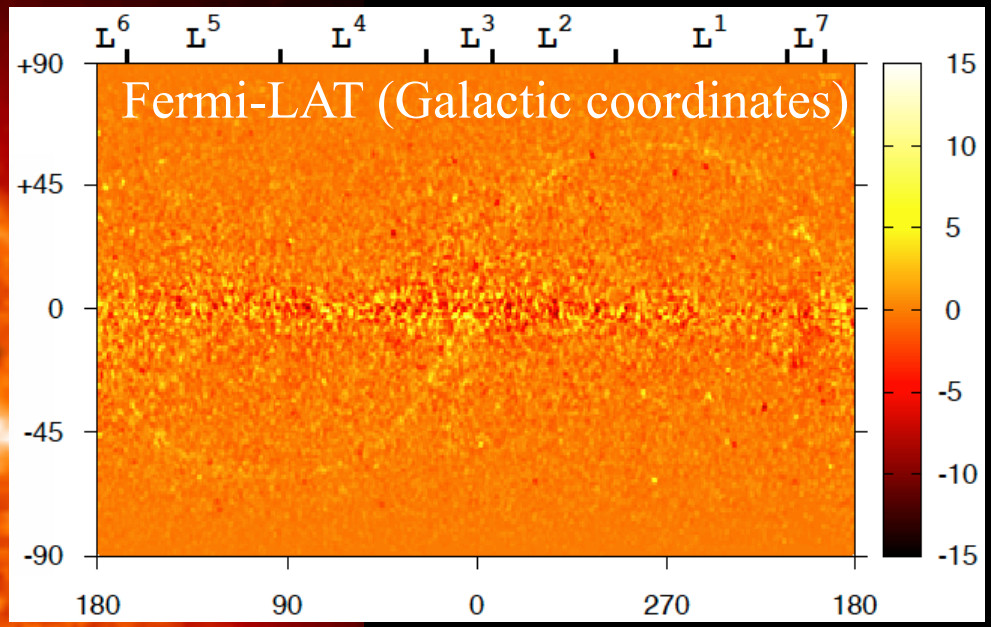
- Due to its proximity, the Earth is the brightest γ-ray source on the sky
- The emission is produced by the CR cascades in the atmosphere
- Most energetic γ-rays are produced by CRs hitting the top of the atmosphere at tangential directions (thin target)

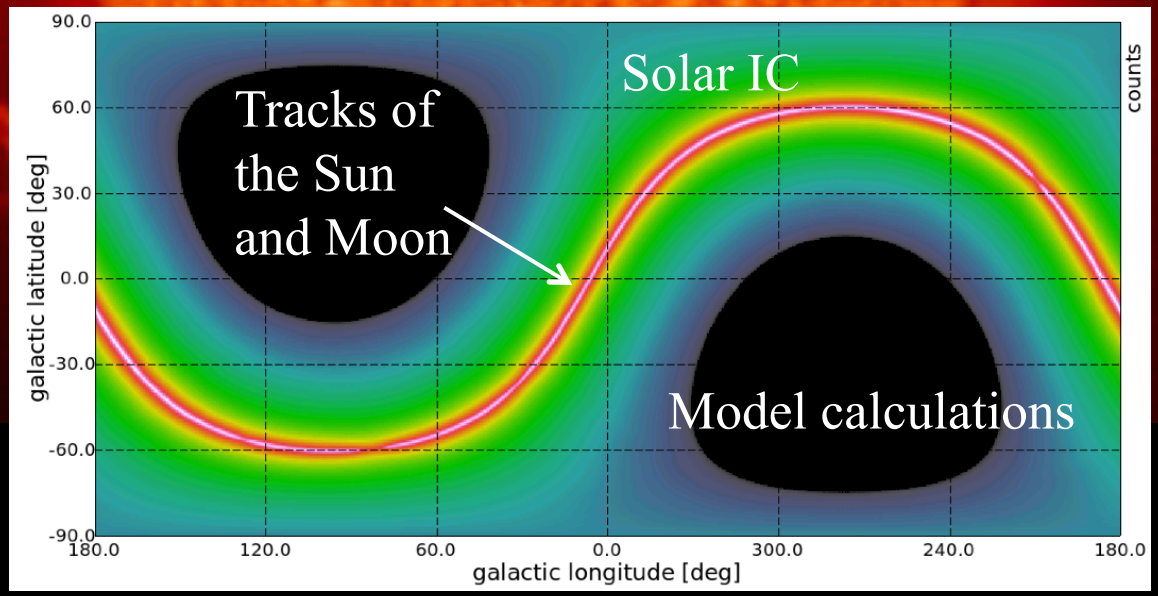
Inferred CR Proton Spectrum from *pp* Model by Kachelrieß & Ostapchenko (2012)



Solar system

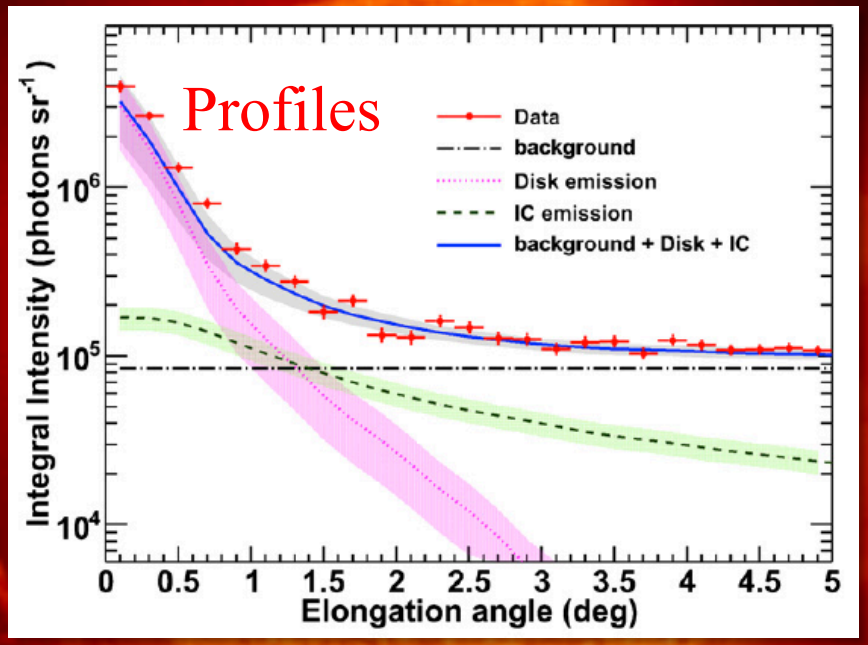
- Raw data sliced by 2 months interval, background removed; ➔ the solar track is clearly visible

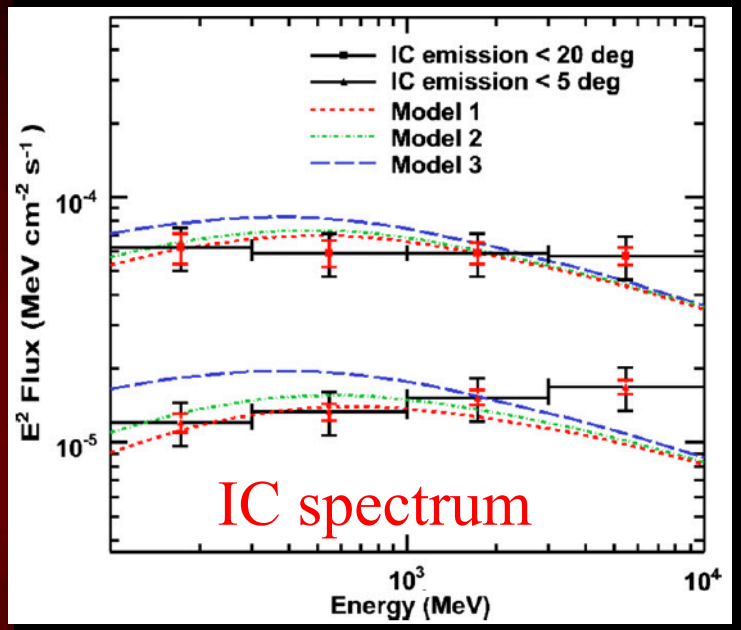


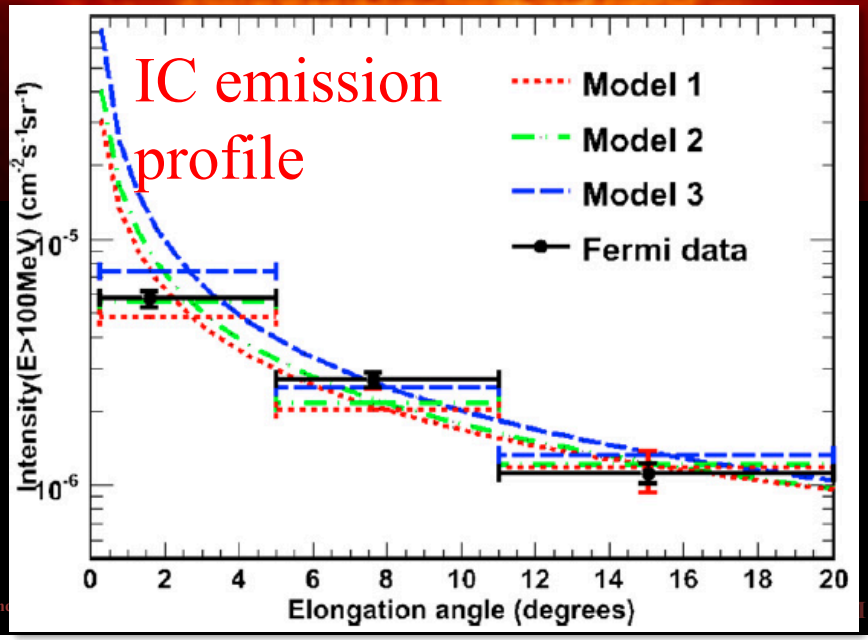


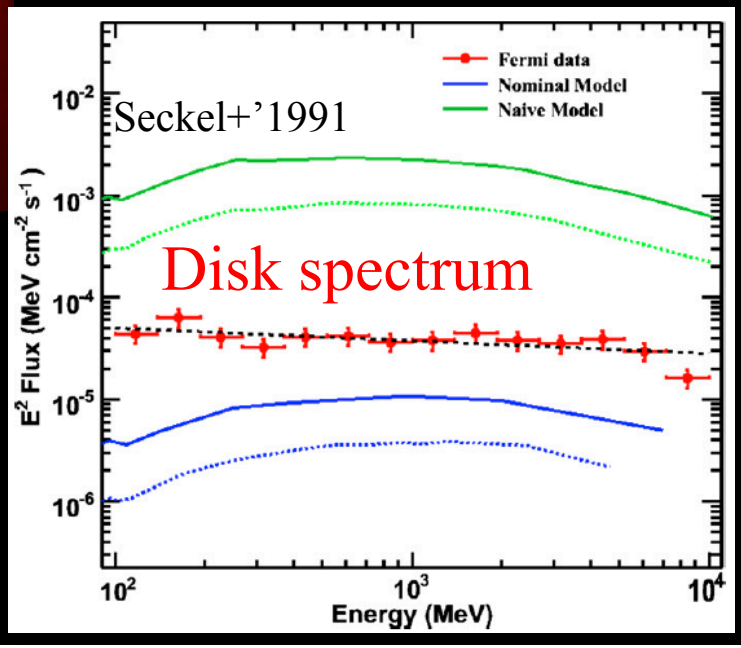
- Averaged over one year, the ecliptic is seen as a bright stripe on the sky, but the emission comes from all directions

Fermi-LAT observations of the Sun (Abdo+'2011)



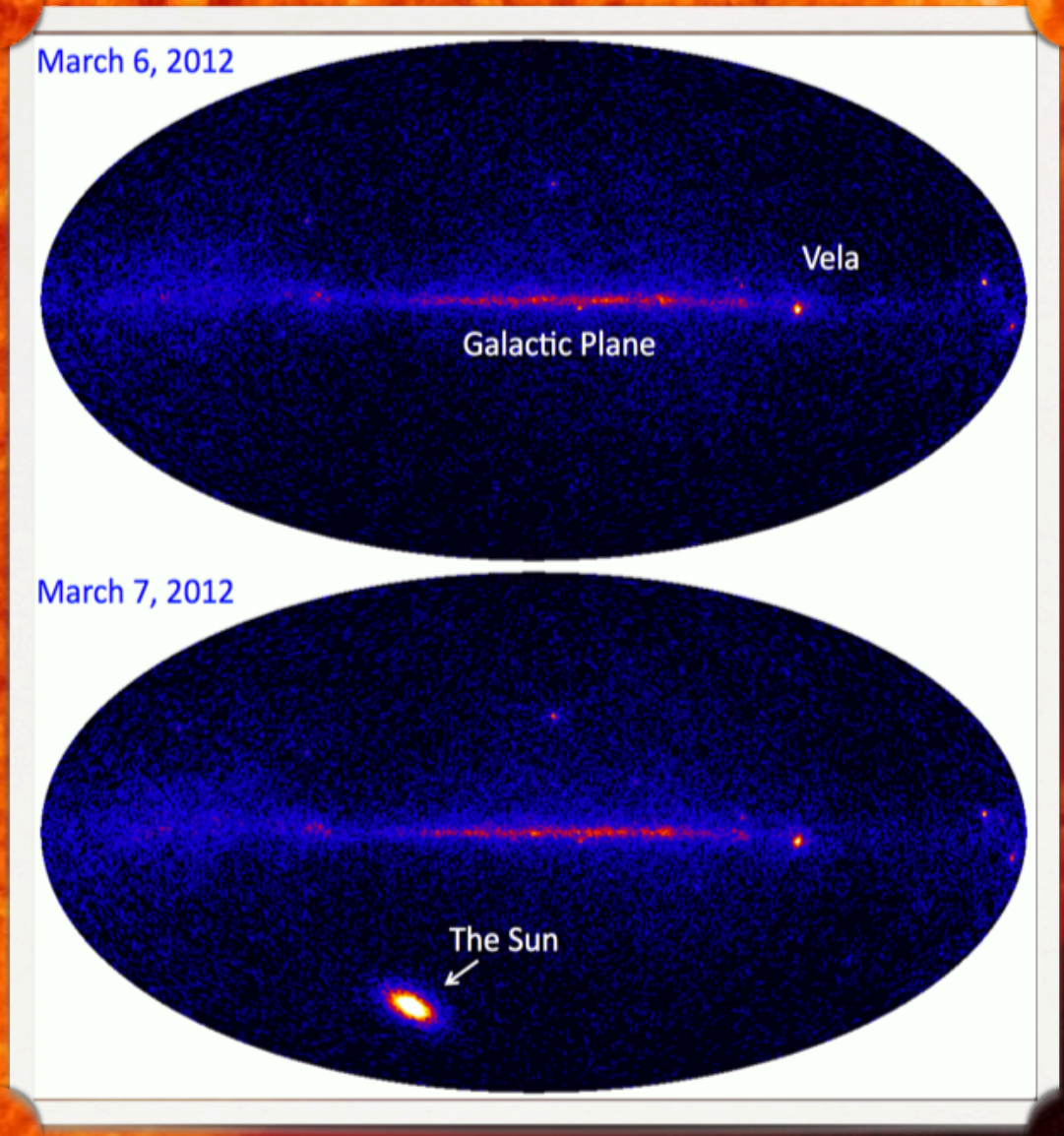






New analysis is in progress

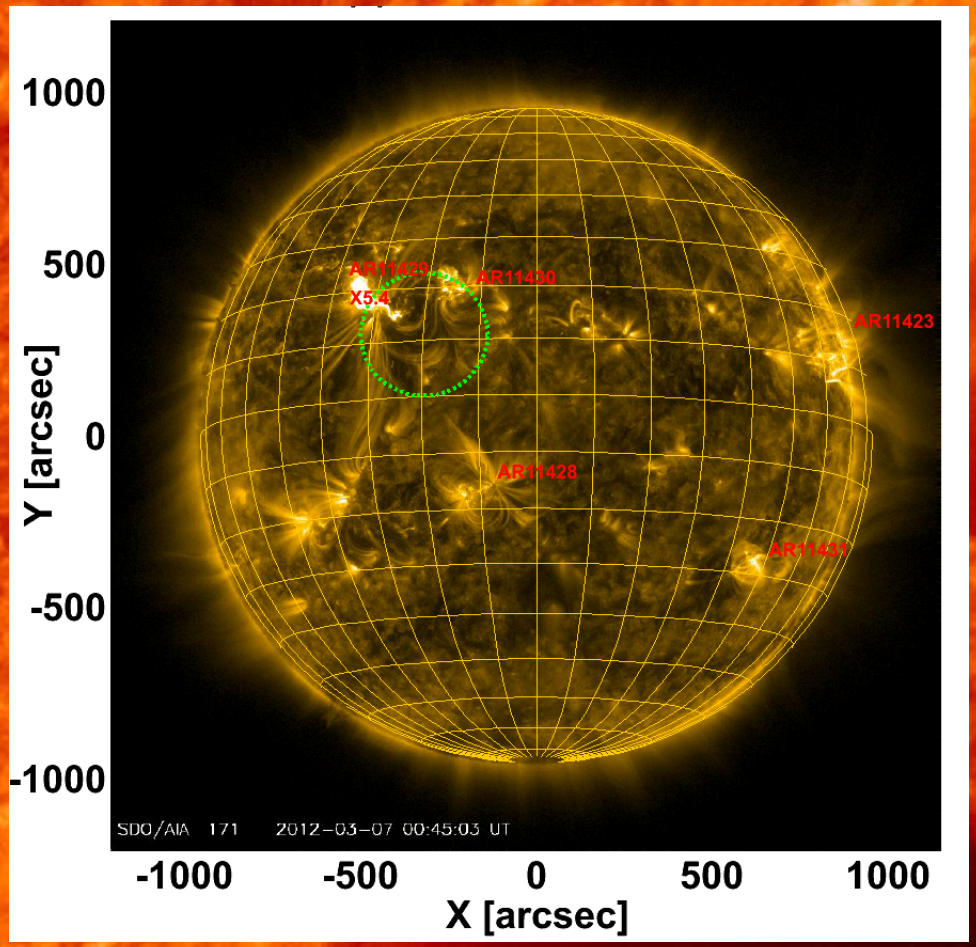
Solar Flares



The March 7, 2012, X5.4 solar flare was the second most intense in 5 years. Fermi observed gamma-ray flux at >100 MeV:

- 1,000 times brighter than the steady Sun's
- 100 times brighter than the Vela pulsar's
- 50 times brighter than the Crab "*superflare*" of April 2011
- Highest-energy photon (4 GeV) ever detected from a solar flare!
- The high-energy emission lasted about 20 hours – the longest ever seen from a solar flare.

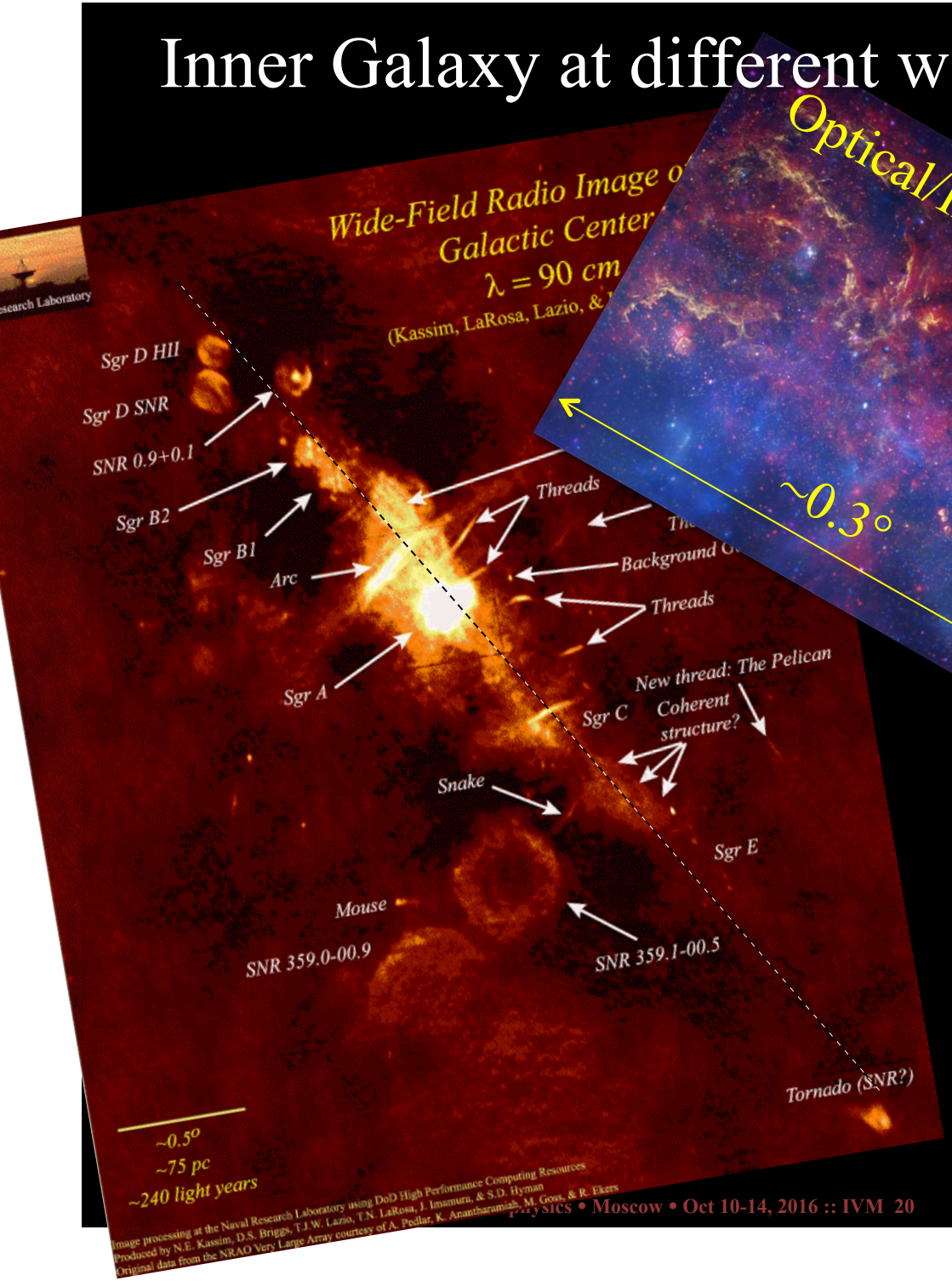
Localization of Solar Flares

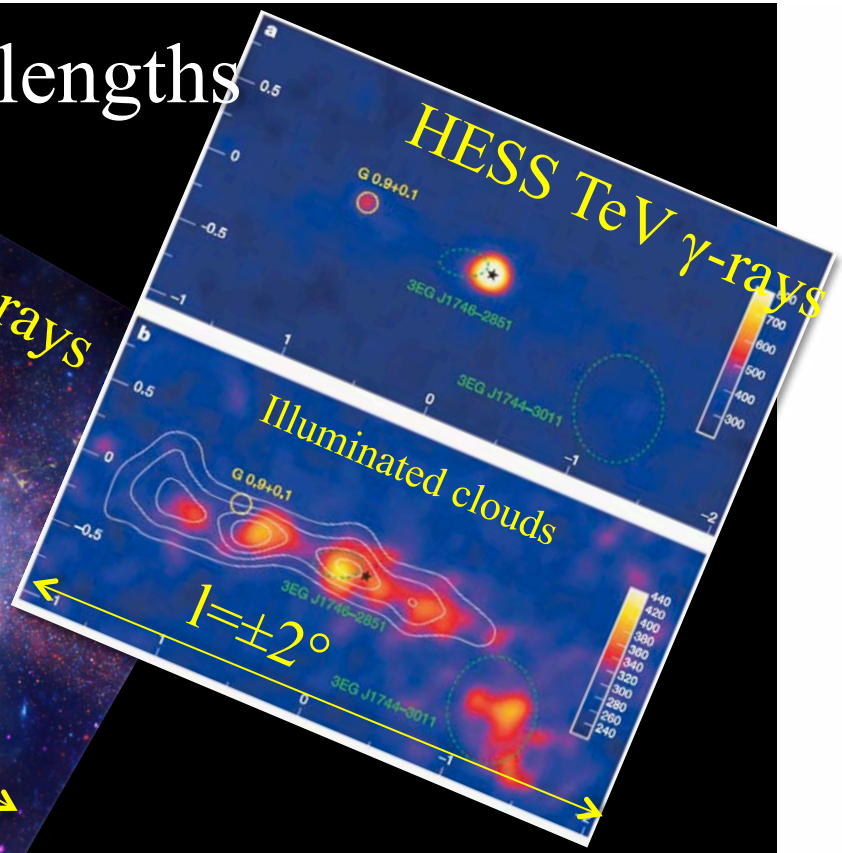


- For the first time >100 MeV emission was localized on the solar disk thanks to the LAT's improved angular resolution (green circle)
- Location consistent with region of flare, even at later times
- This suggests some local acceleration or trapping phenomenon

N.Omodei

Inner Galaxy at different wavelengths





- Harbors a SMBH ~4×10^6 $M_\odot$
- Flaring activity of SMBH: large flare ~100 years ago, and faint flares
- Huge over-density of dark matter
- 1000s of stars in the innermost parsec
- Large concentration of binary systems and compact objects

S. Murgia ICRC 2015 (ApJ 819 [2016] 44A)

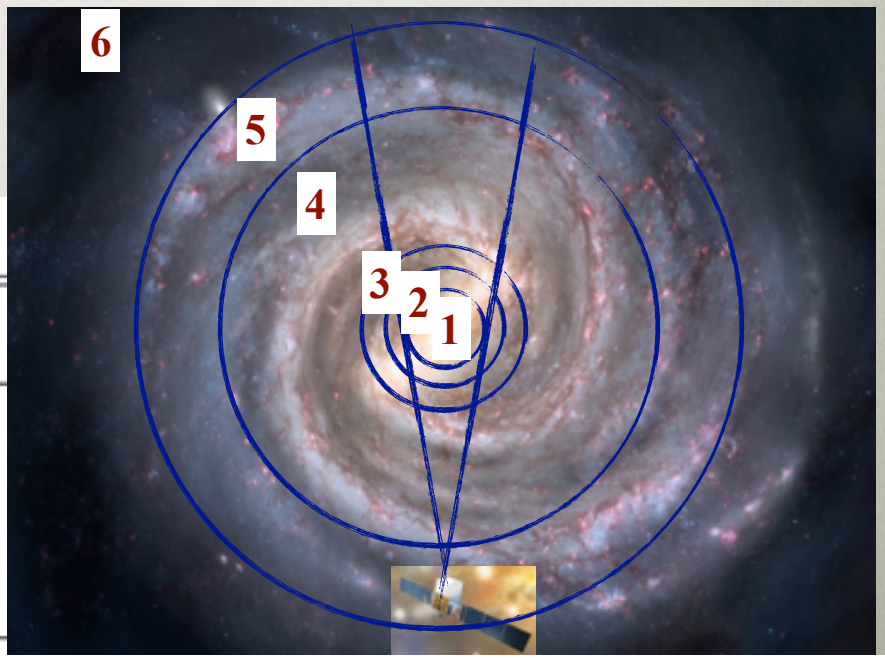
Fermi-LAT Study of the Inner Galaxy

Scaling Procedure

- Determine intensity for π^0 (from HI and H_2 gas) and IC contributions in galactocentric rings,
  - IC component divided in rings (dev. version of GALPROP), same boundaries as the gas: these additional degrees of freedom can compensate for uncertainies in the GALPROP model of the electron spectrum or ISRF used to calculate the IC templates
- Isotropic and Loop I (*Wolleben, 2007, ApJ 664*) emissions also fitted to the data
- Different sky regions are employed based on where the components that are fitted dominate. Point source locations and spectra taken from the preliminary 3FGL.

Galactocentric ring boundaries.

Ring #	$R_{\rm min}$ [kpc]	$R_{\rm max}$ [kpc]	Longitude Range (Full)
1	0	1.5	$-10^\circ \leq l \leq 10^\circ$
2	1.5	2.5	$-17^\circ \leq l \leq 17^\circ$
3	2.5	3.5	$-24^\circ \leq l \leq 24^\circ$
4	3.5	8.0	$-70^\circ \leq l \leq 70^\circ$
5	8.0	10.0	$-180 \leq l \leq 180^\circ$
6	10.0	50.0	$-180 \leq l \leq 180^\circ$



Sources in the inner Galaxy

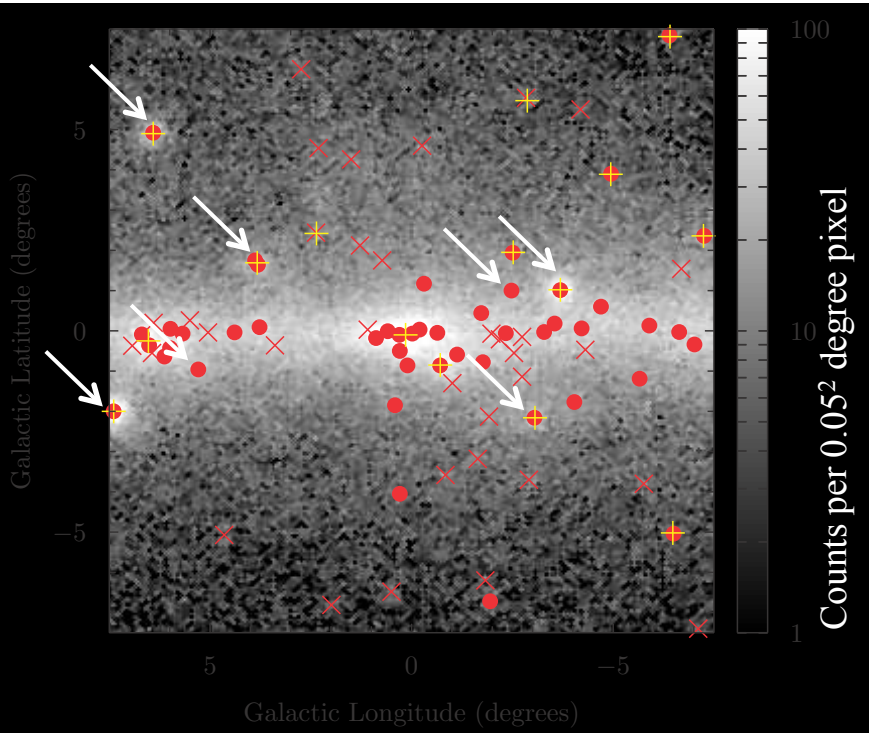
- Fixing the background model allows the sources to be detected
- The sources' position and spectra depend on the background model
- The brightest sources (TS≥25) are not very much model-dependent

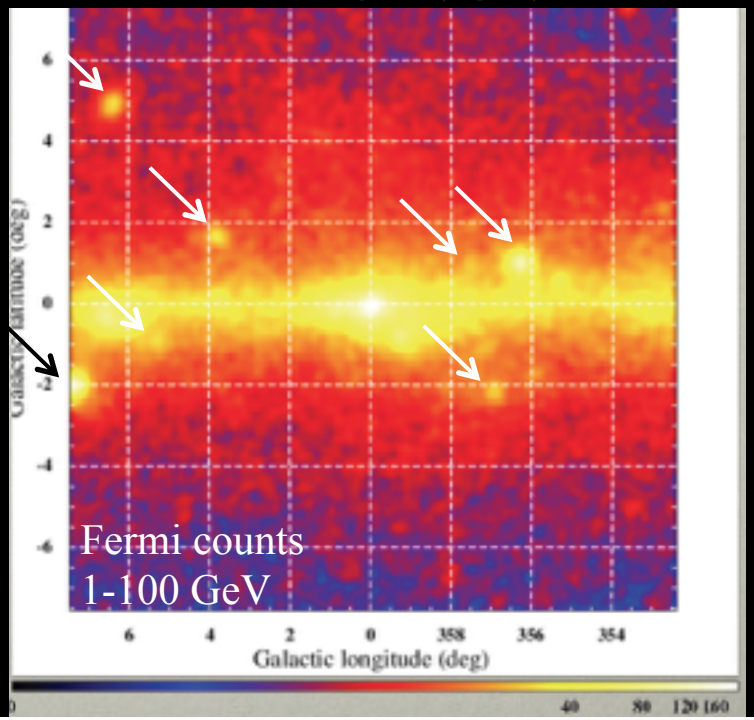
● – 1FIG sources TS≥25

× – 1FIG source candidates TS≤25

\+ – 3FGL sources with multi-wavelengths associations

(1FIG = 1st Fermi Inner Galaxy Catalog)



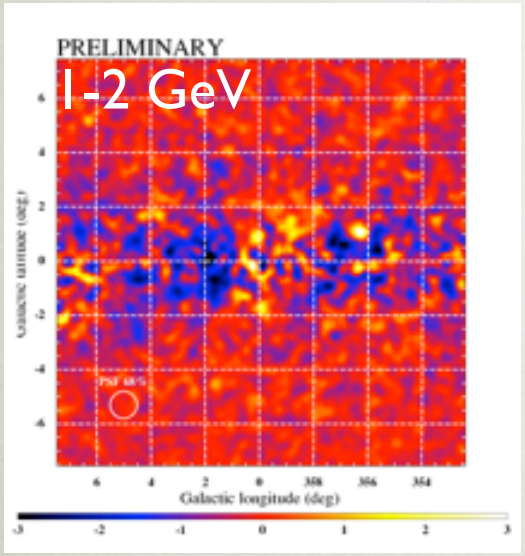


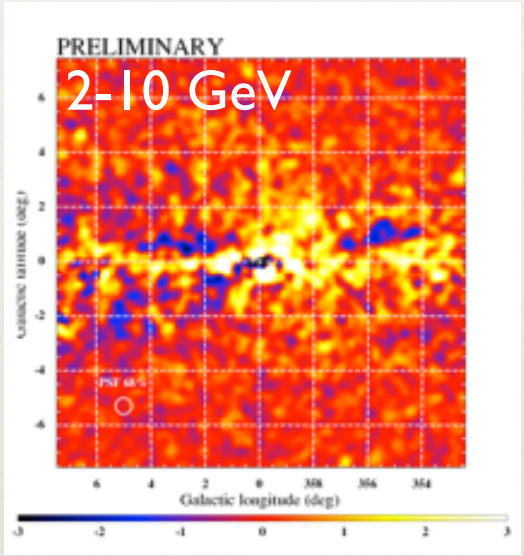
Point sources removed

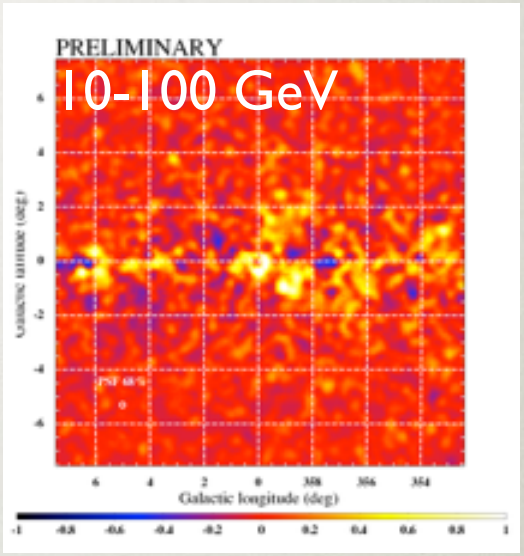
Results - Residual Maps

DATA-MODEL

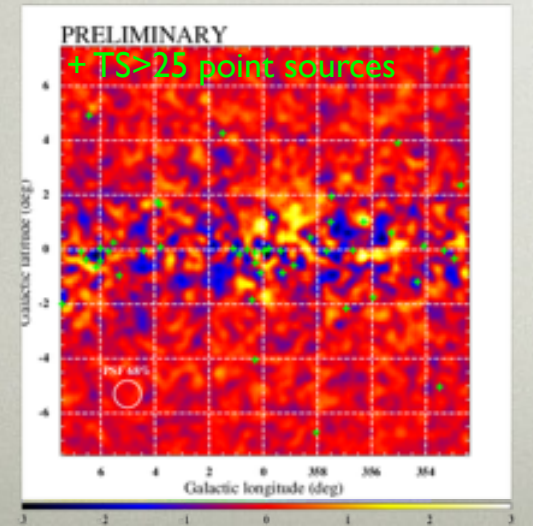
Pulsars, tuned-intensity

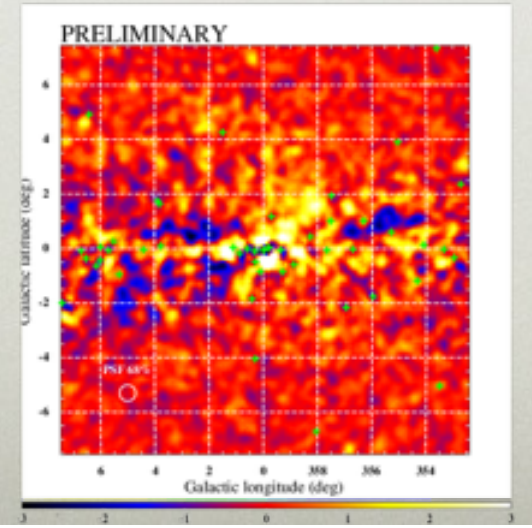


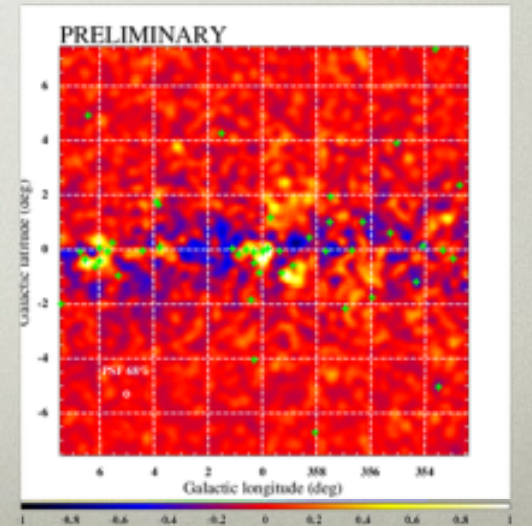




Pulsars, tuned-index





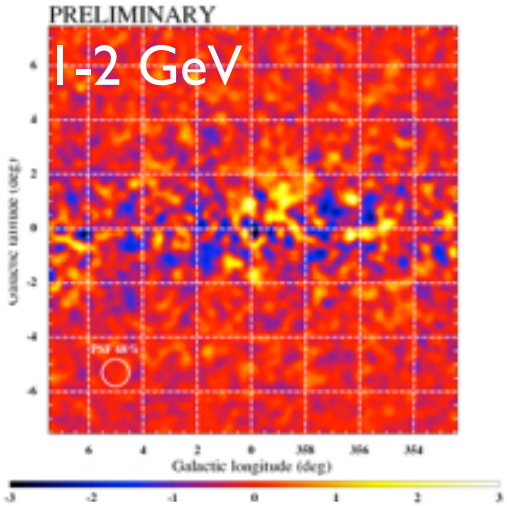


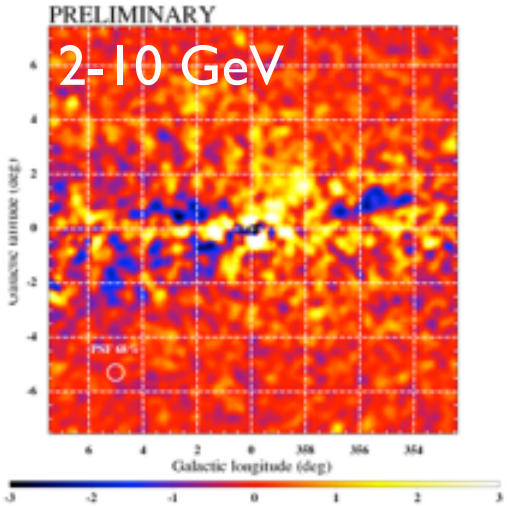
Counts in 0.1°x0.1° pixels, 0.3° radius gaussian smoothing

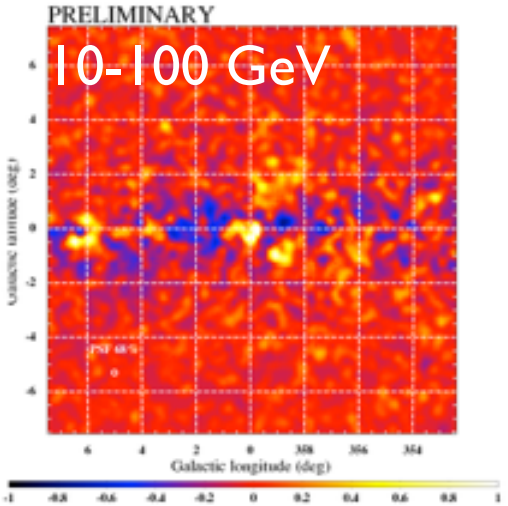
Results - Dark Matter

DATA-MODEL (Pulsars, index scaled)

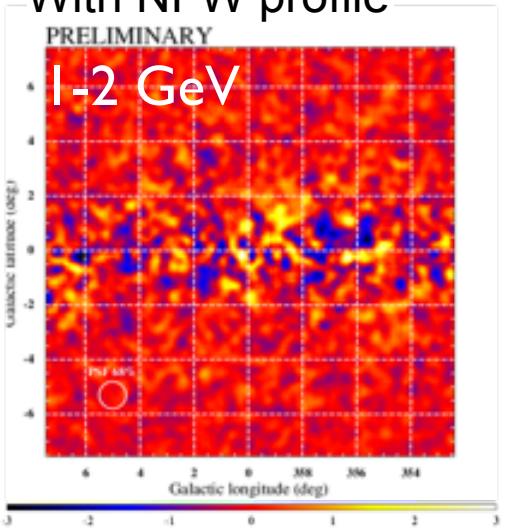
Without DM:

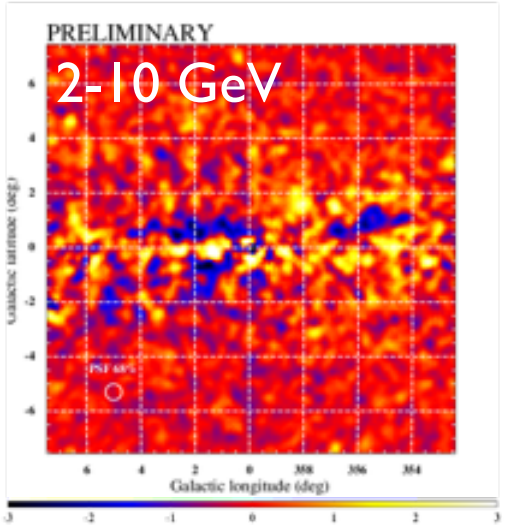


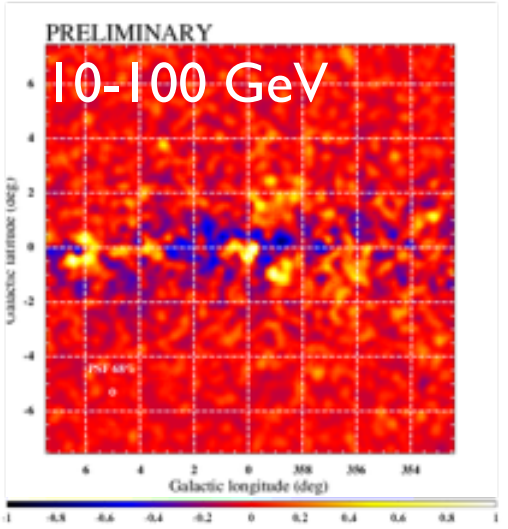




With NFW profile





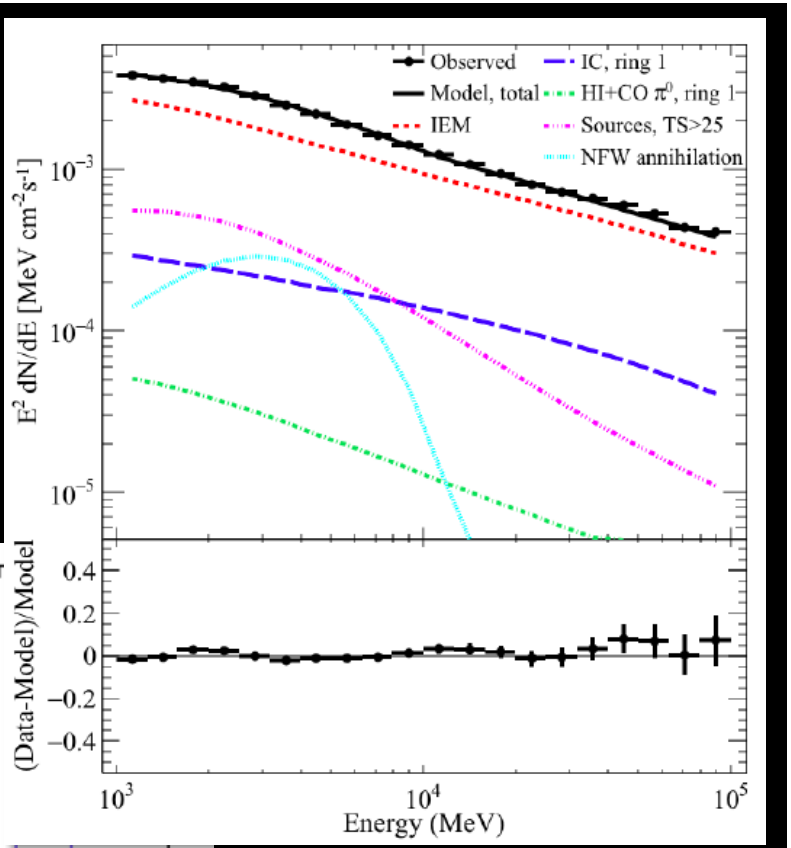


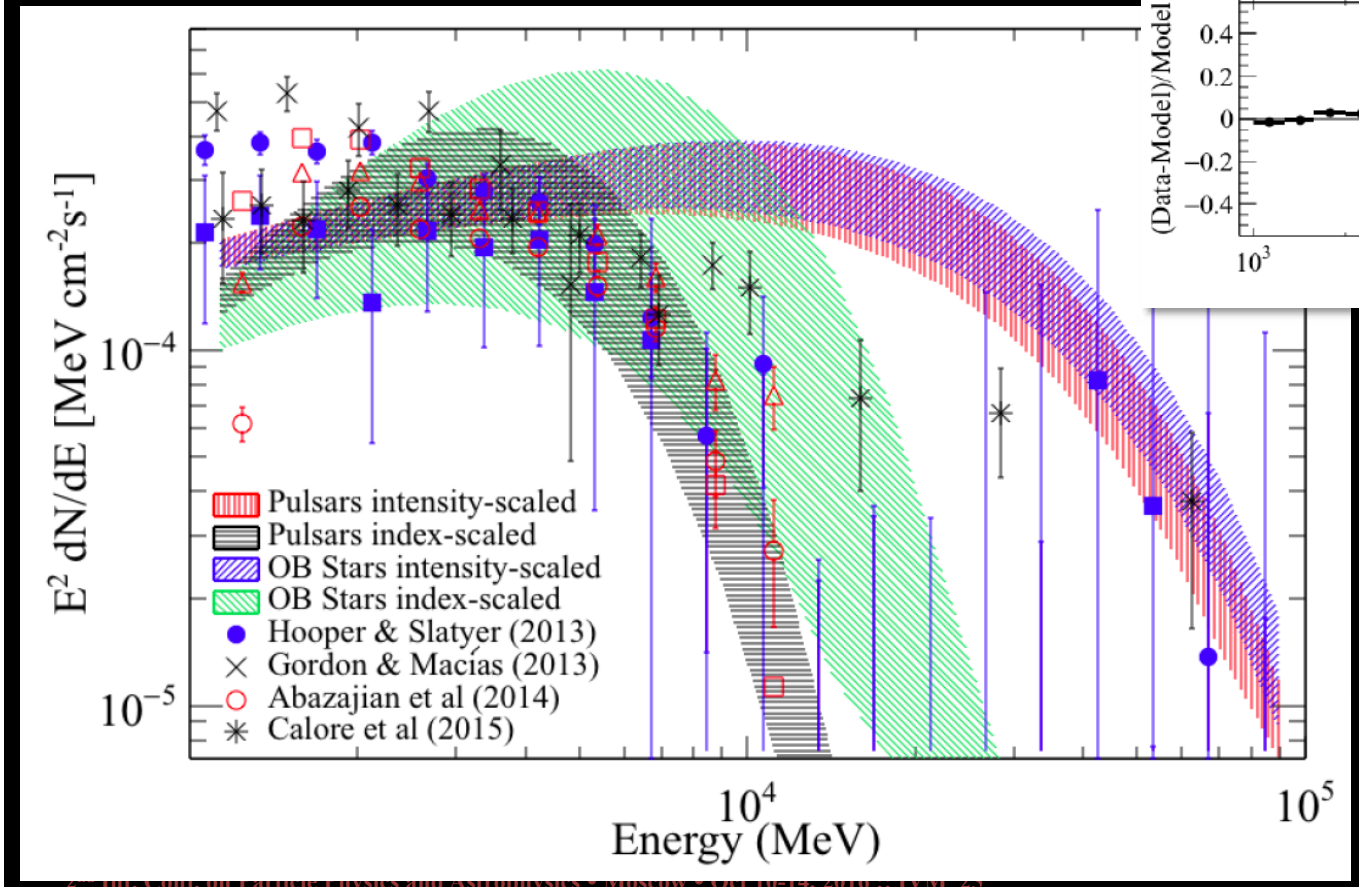
Counts in 0.1°x0.1° pixels, 0.3° radius gaussian smoothing

NFW component in different background models

- NFW = Navarro-Frenk-White
- NFW – is a peaked profile predicted in DM simulations

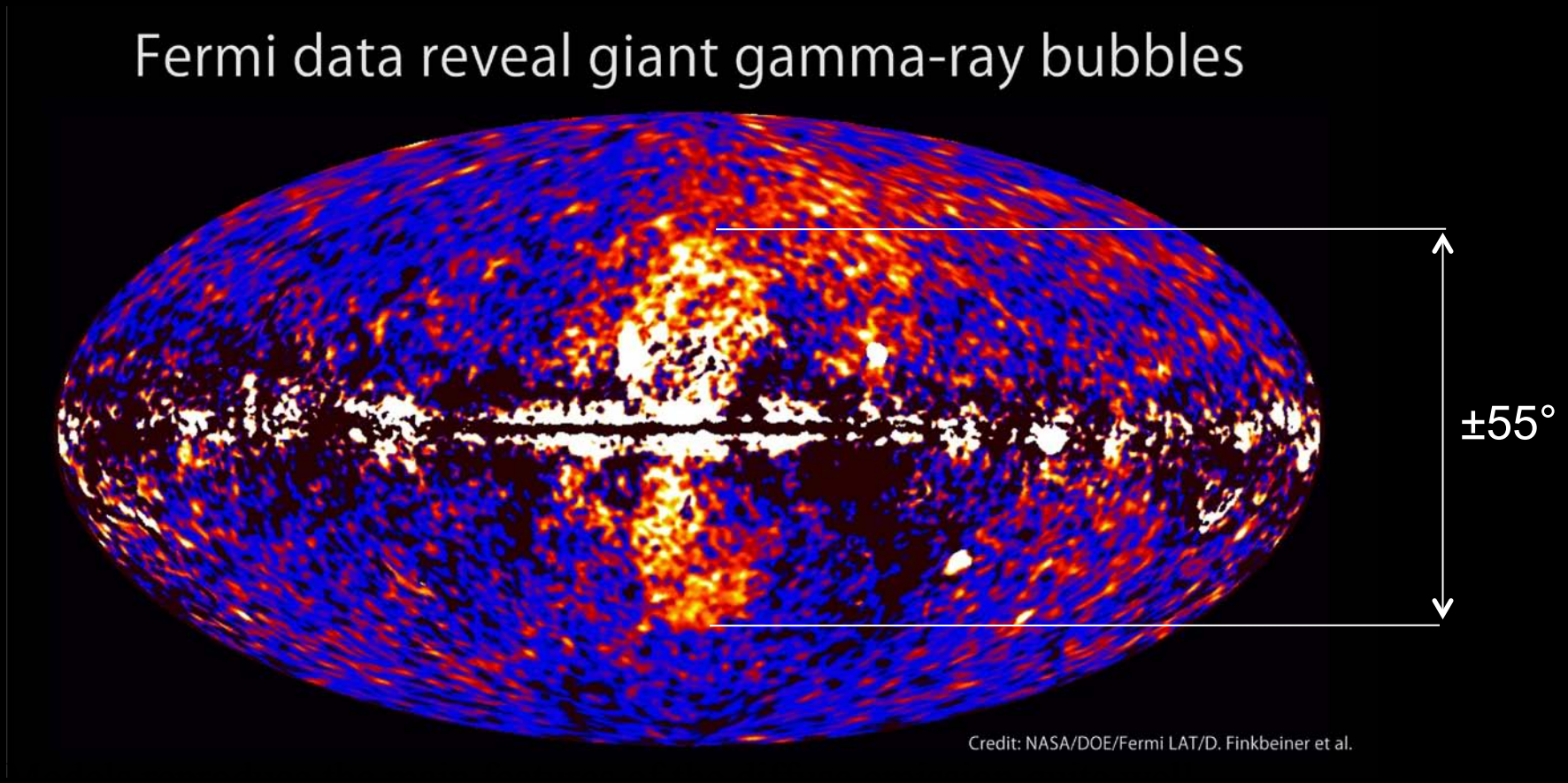
$$\rho(r) = \frac{\rho_0}{\frac{r}{R_s}\left(1 + \frac{r}{R_s}\right)^2}$$





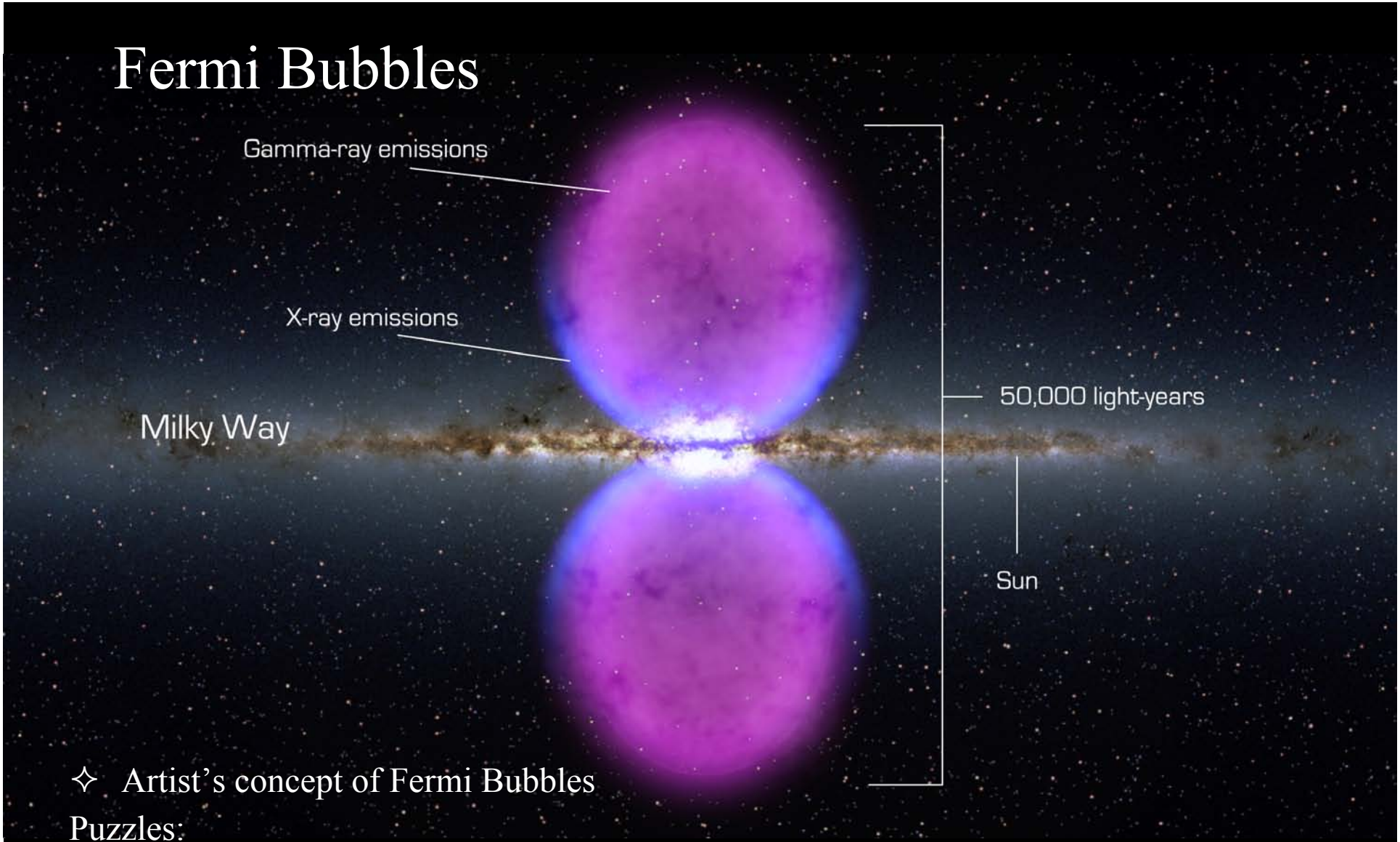
- Components of the emission observed in the inner 15°×15° (one of the models)
- Spectrum of the NFW component in different models

NASA press release



- Discrepancies between the physical model and high-resolution data (residuals) are the gold mines of new phenomena!

Fermi Bubbles

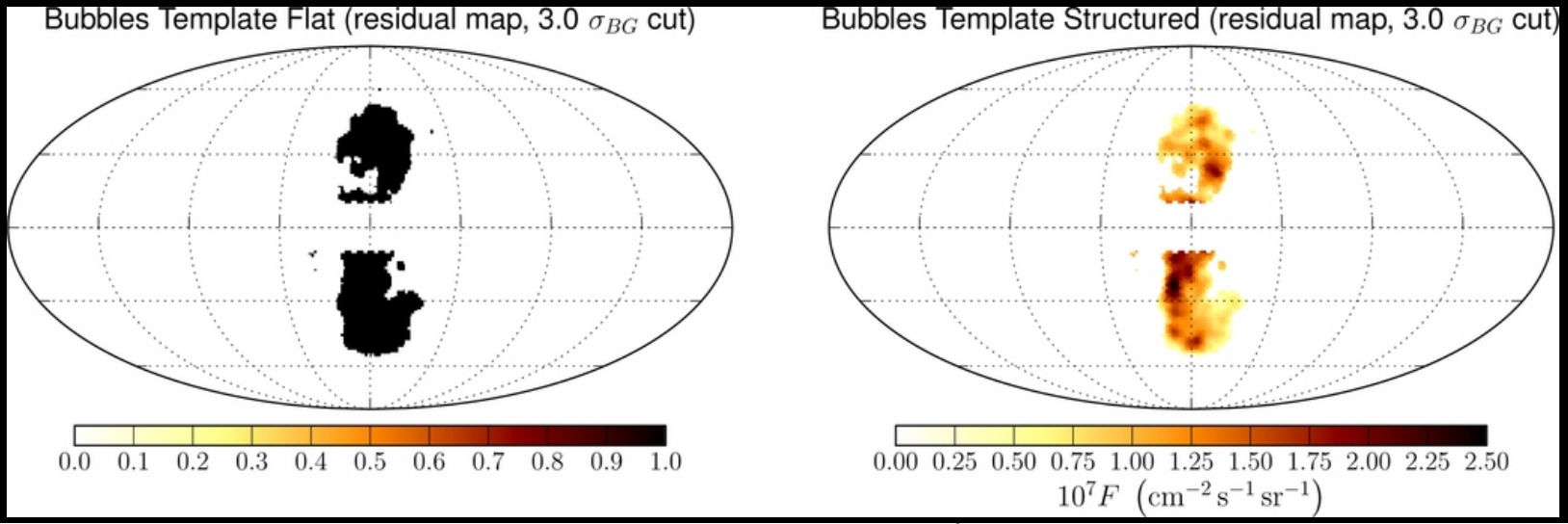


- Artist's concept of Fermi Bubbles

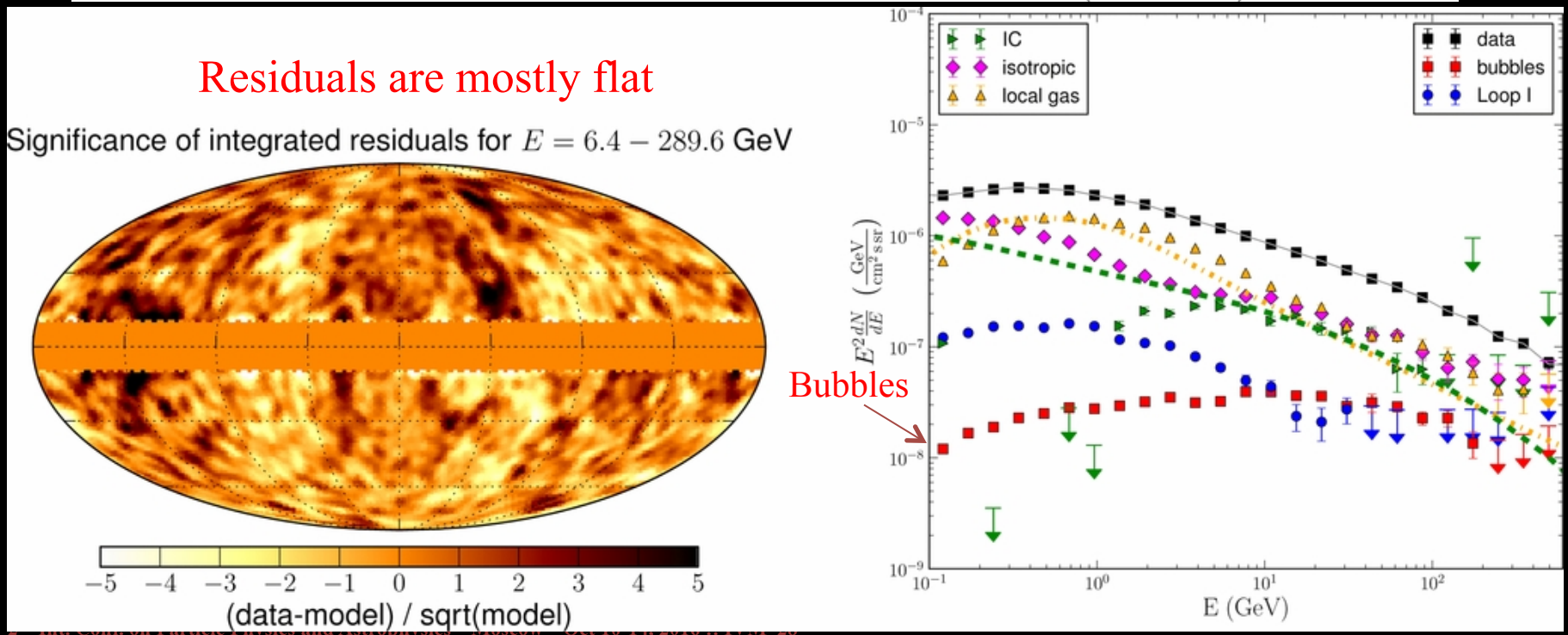
Puzzles:

- The spectrum is "flat" (ongoing acceleration!)
- The spectrum is uniform over these huge structures! (what is the mechanism?)

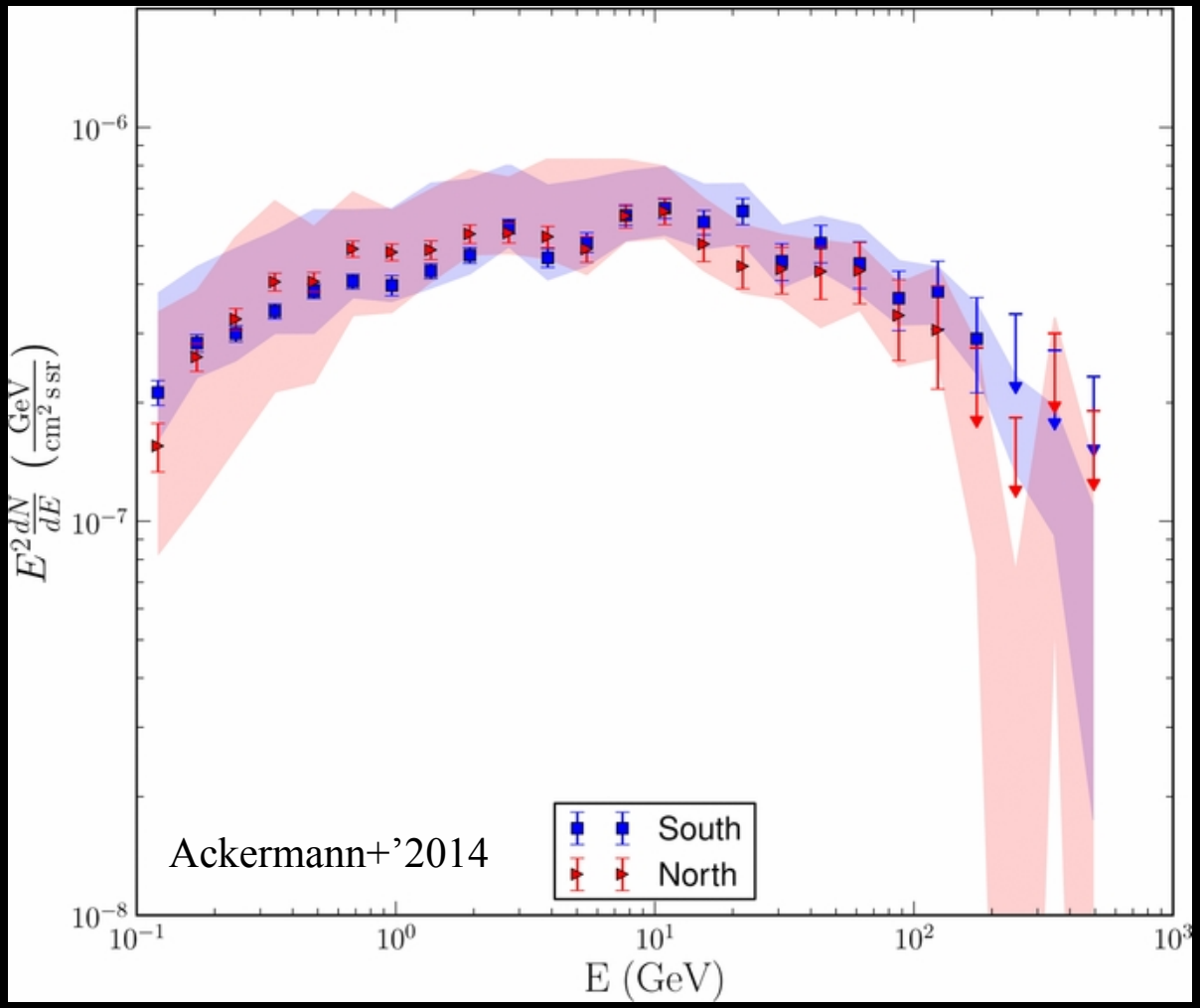
Fitting the Bubbles



Residuals are mostly flat

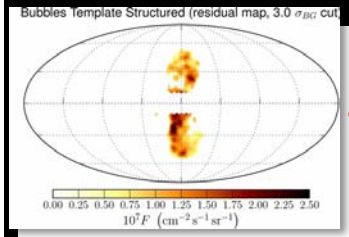


Spectrum of the Bubbles

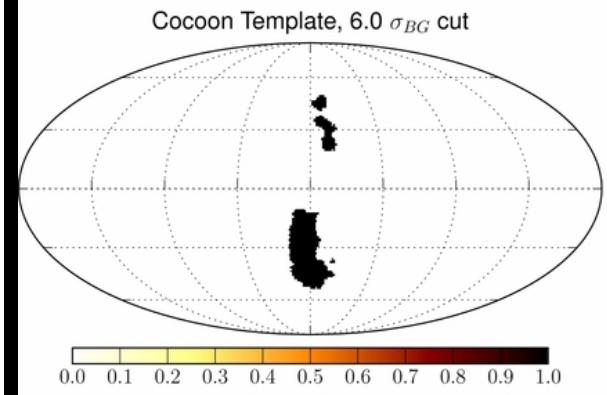


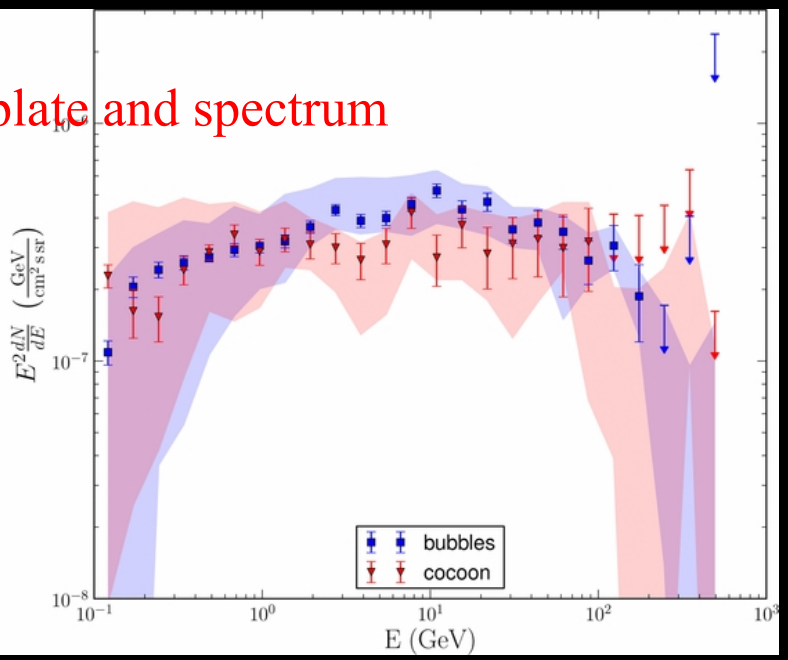
- The North and South lobes have very similar spectra
- The spectrum is very flat which testifies that the particle acceleration is ongoing
- Power-law with an exponential cutoff: index 1.9±0.2, cutoff energy 110±50 GeV

Substructures and longitude strips



"Cocoon" template and spectrum



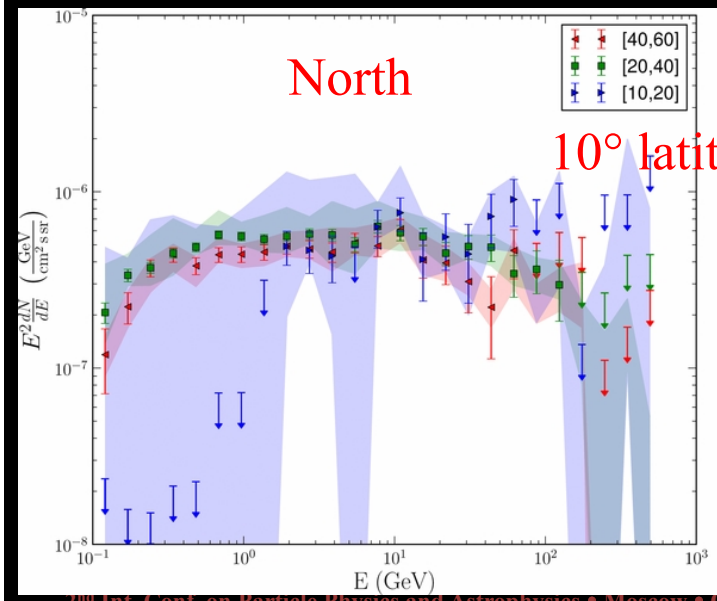


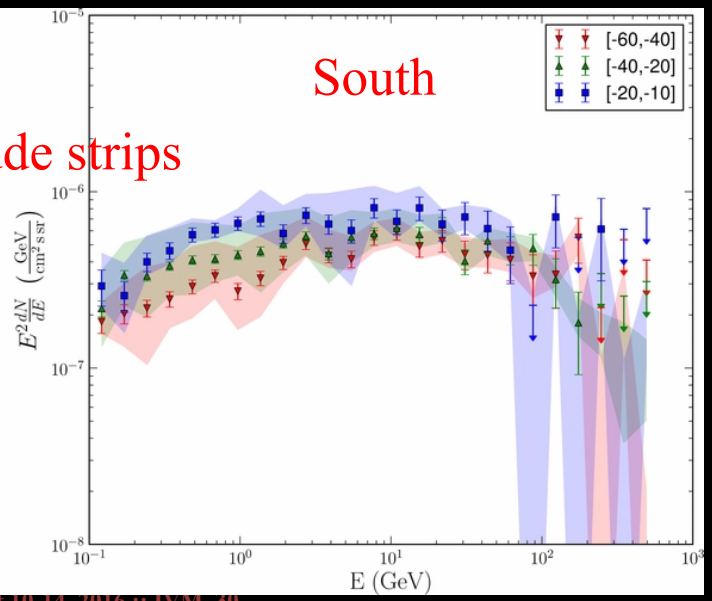
- The lobes are uniform
- The spectrum of the "cocoon" is pretty much the same as the spectrum of the whole lobes
- No spectral variations with the Galactic longitude

North

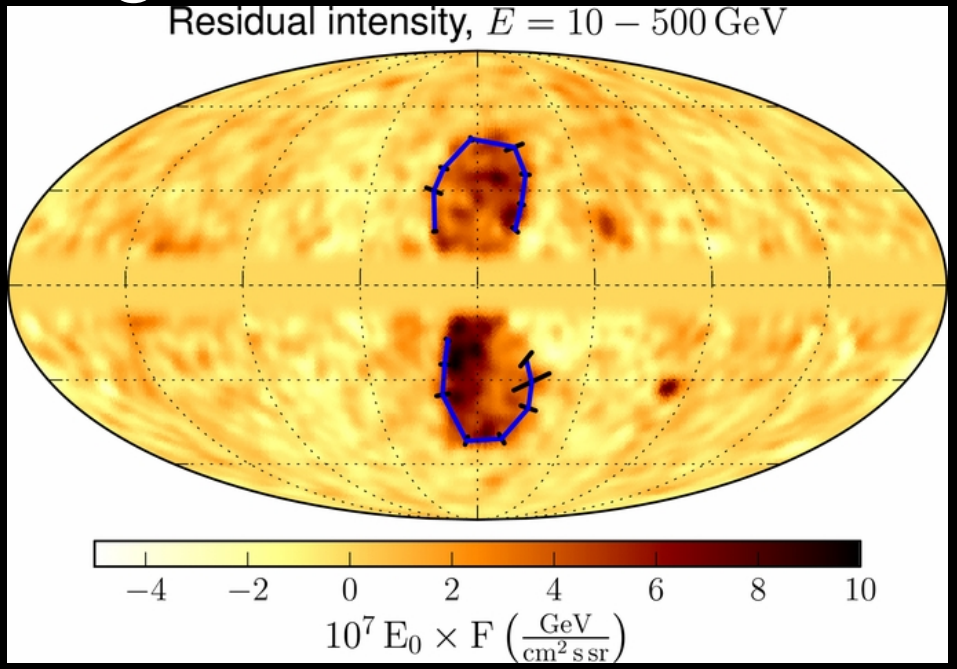
South

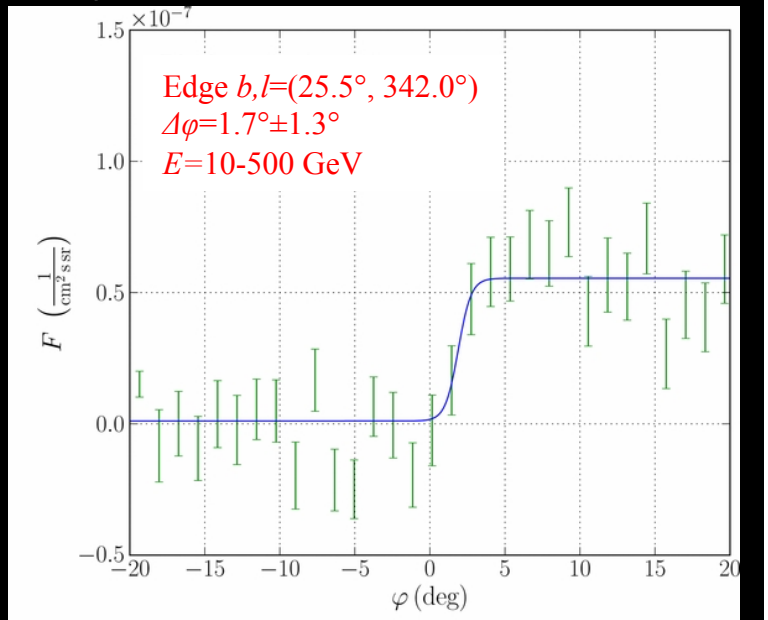
10° latitude strips

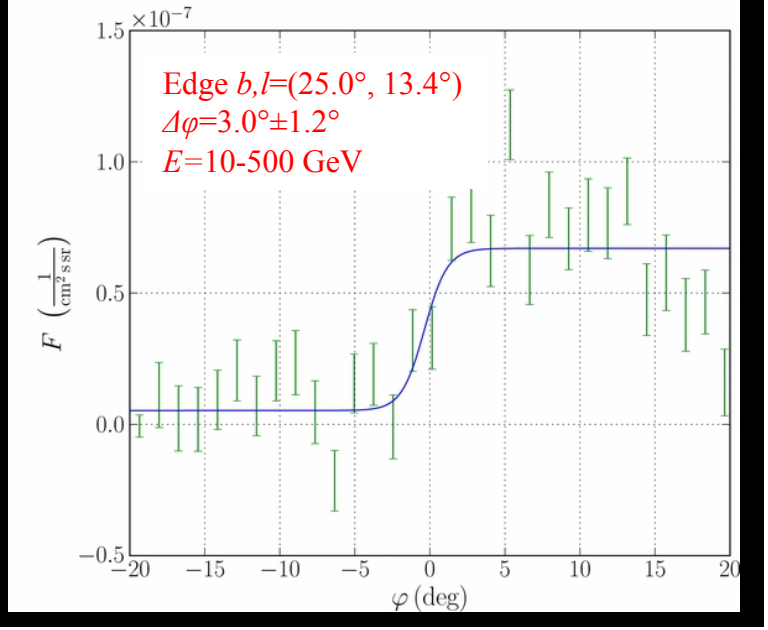




Edges: the width of the boundary





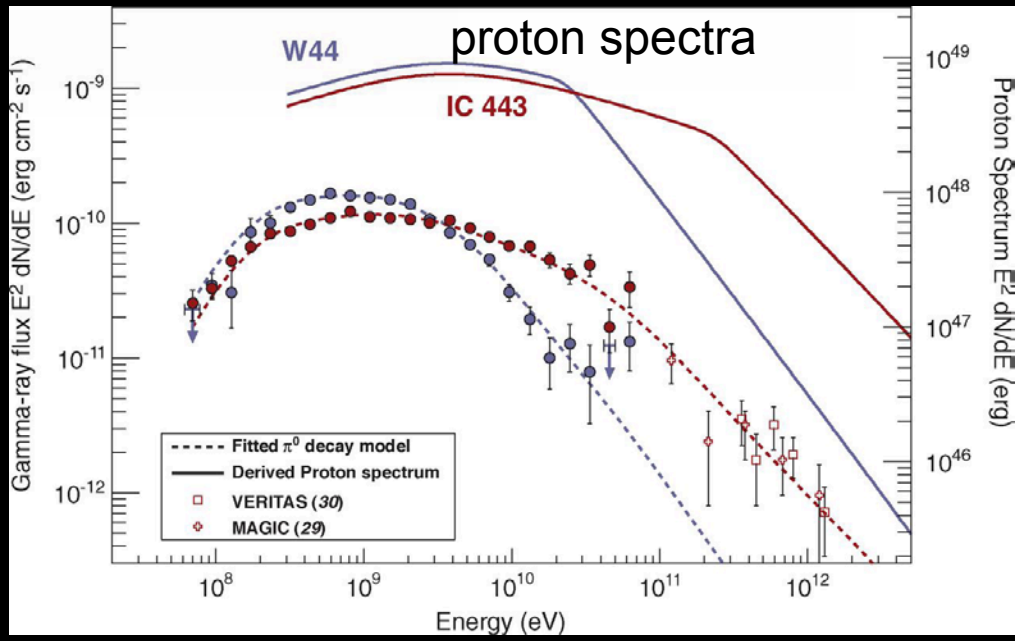


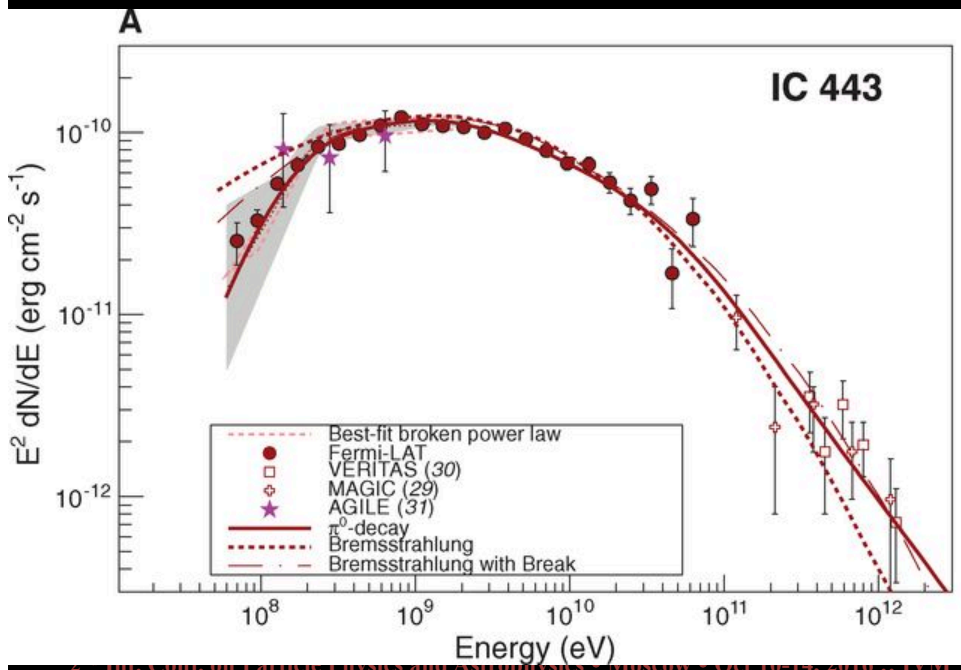
- Three energy ranges (68% PSF):
  - 1–3 GeV (0.5°)
  - 3–10 GeV (0.25°)
  - 10–500 GeV (0.12°)

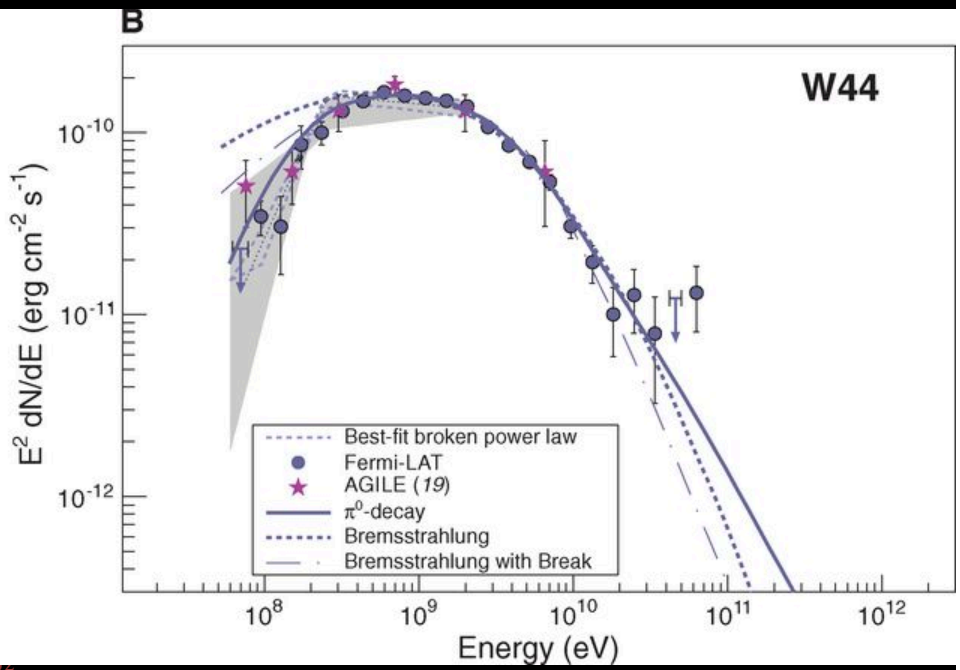
- The edges of the Bubbles are well defined
- The width is <6°, about $3.4°_{-2.6}^{+3.7}$ in average

Fermi-LAT spectra of IC443 & W44: π^0 decay γ-rays

- Low-energy cut off at half the π^0 mass
- Clear evidence for SNR as hadronic acceleration sites

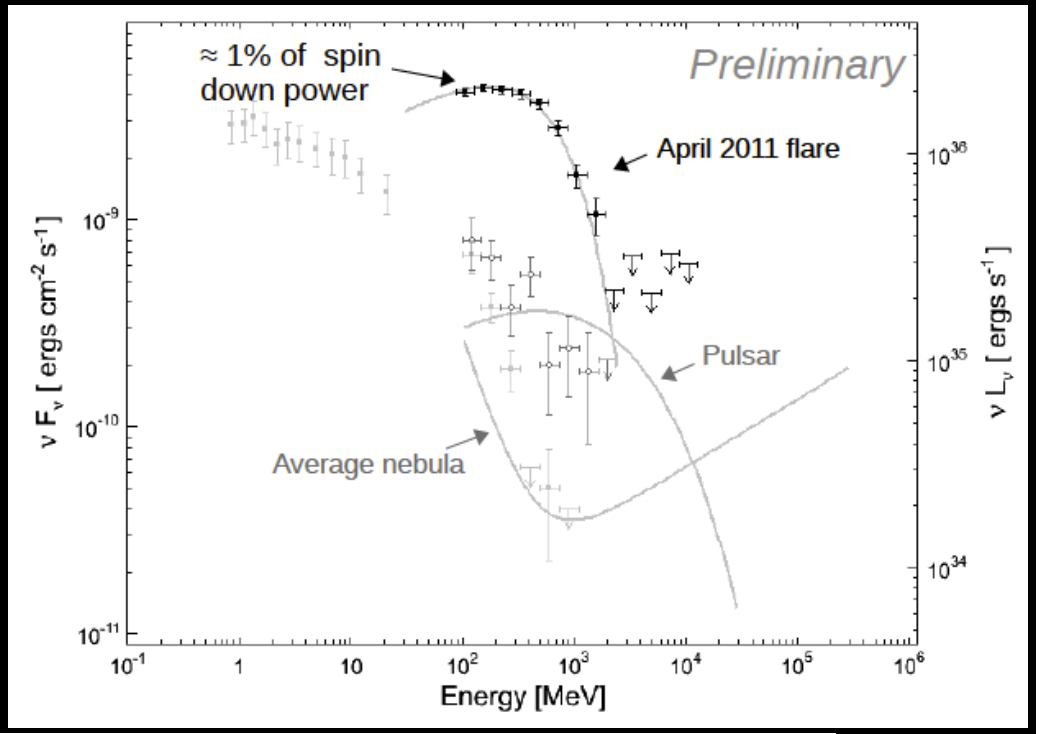




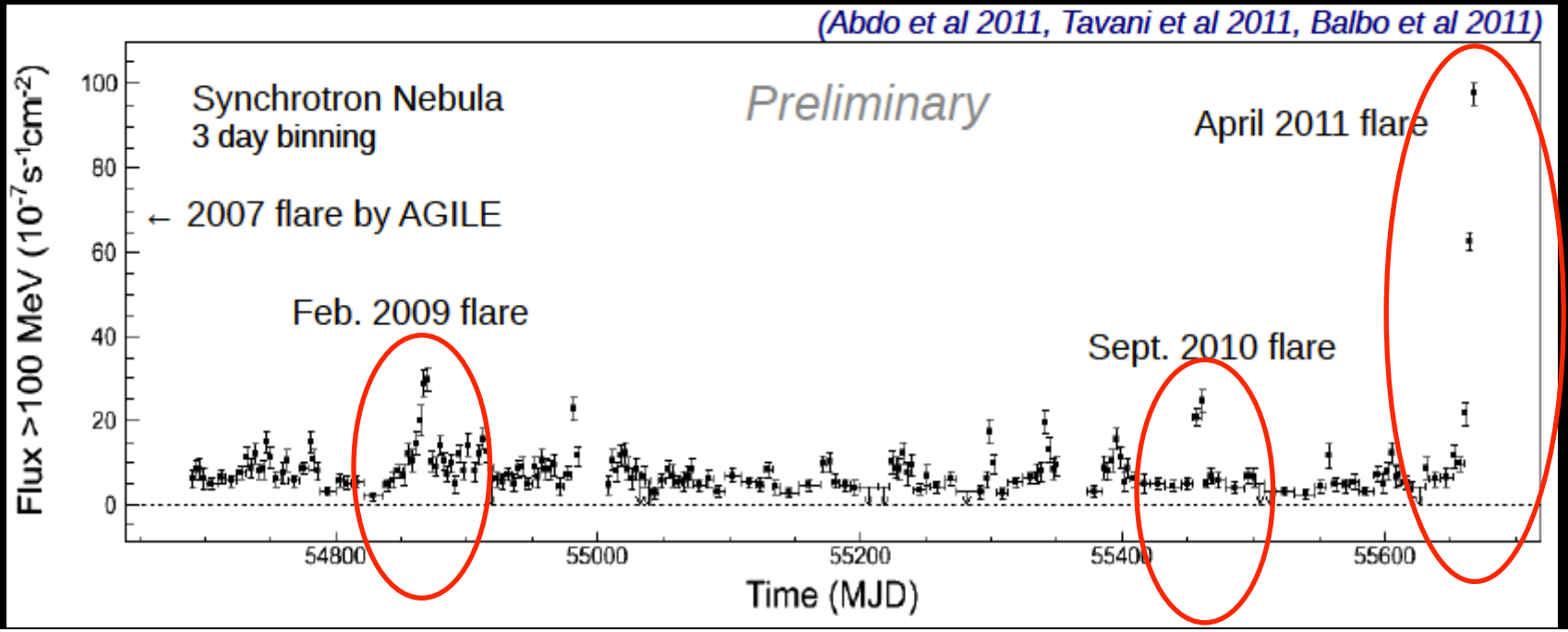


Crab: Recent flares of the synchrotron component

- Average flux ~6×10^{-7} phot/cm^2/sec above 100 MeV
- Two flares with flux increase by a factor of ~5 (years: 2009, 2010)
- A flare with flux increase by a factor of ~30 (year: 2011)
- Compact emission region <0.0004 pc ~ 80 AU – diameter of the Pluto's orbit!
- No change in the pulsed emission

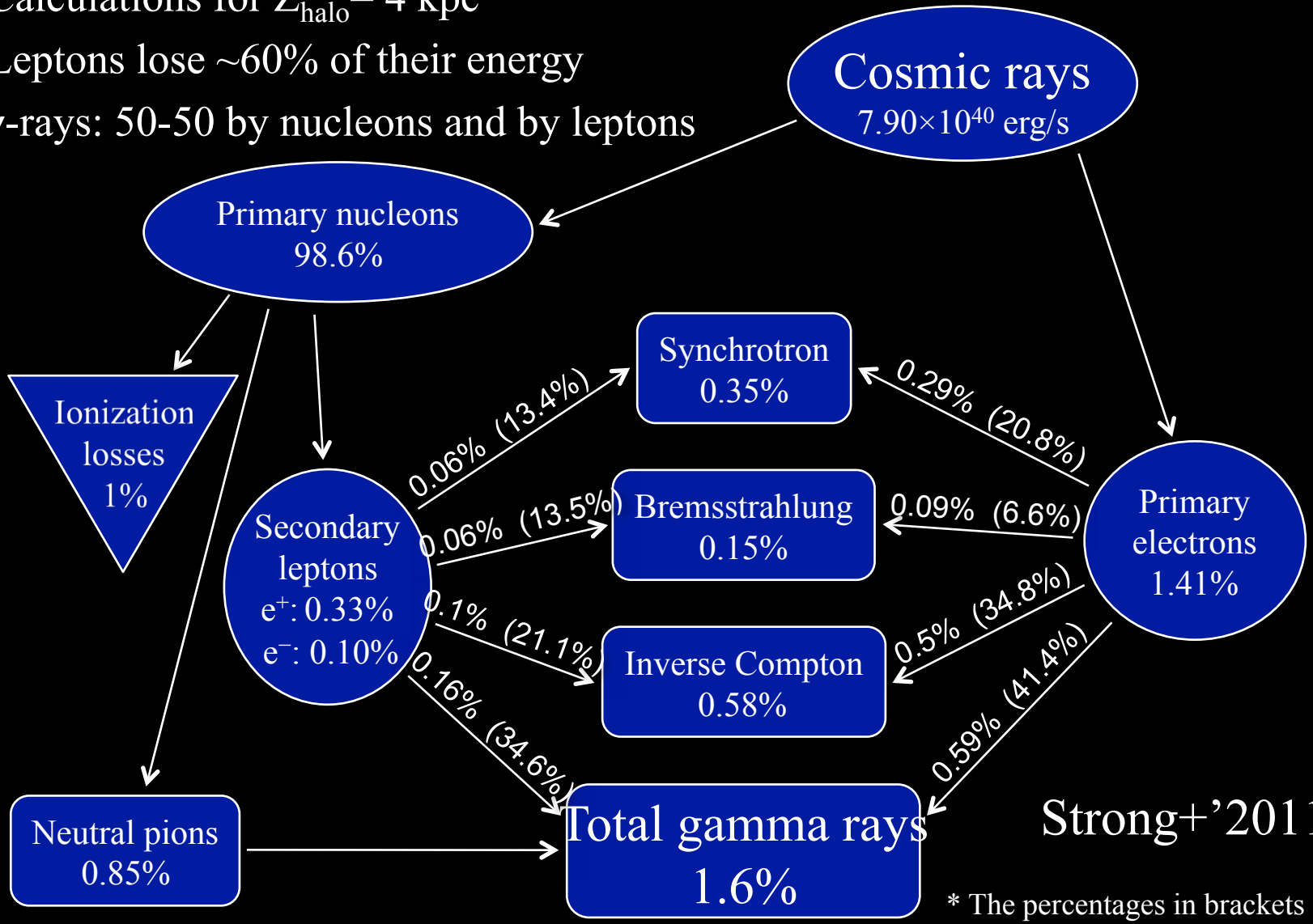


(Abdo et al 2011, Tavani et al 2011, Balbo et al 2011)



Milky Way as an electron calorimeter

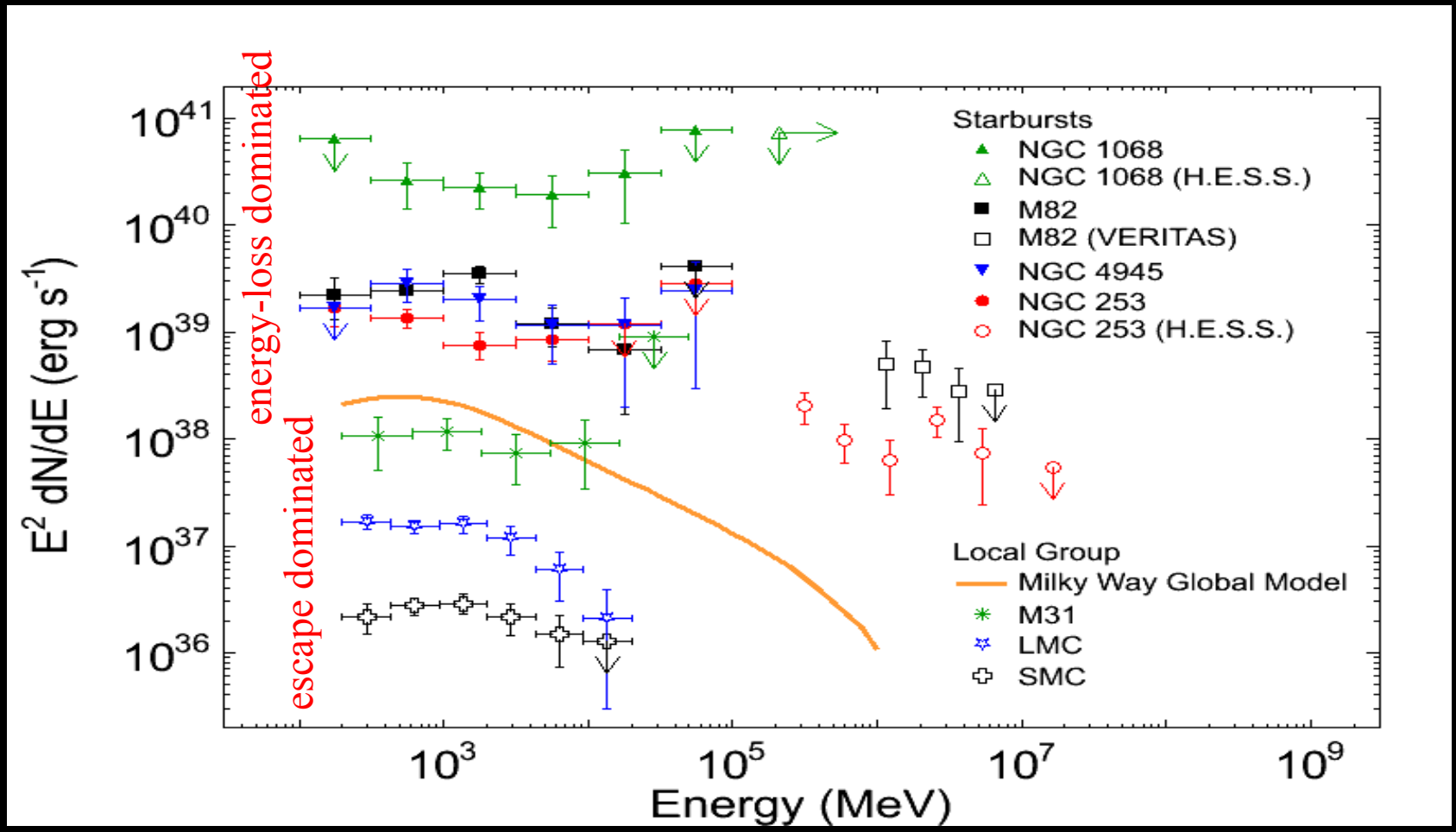
- Calculations for Z_{halo}= 4 kpc
- Leptons lose ~60% of their energy
- γ-rays: 50-50 by nucleons and by leptons



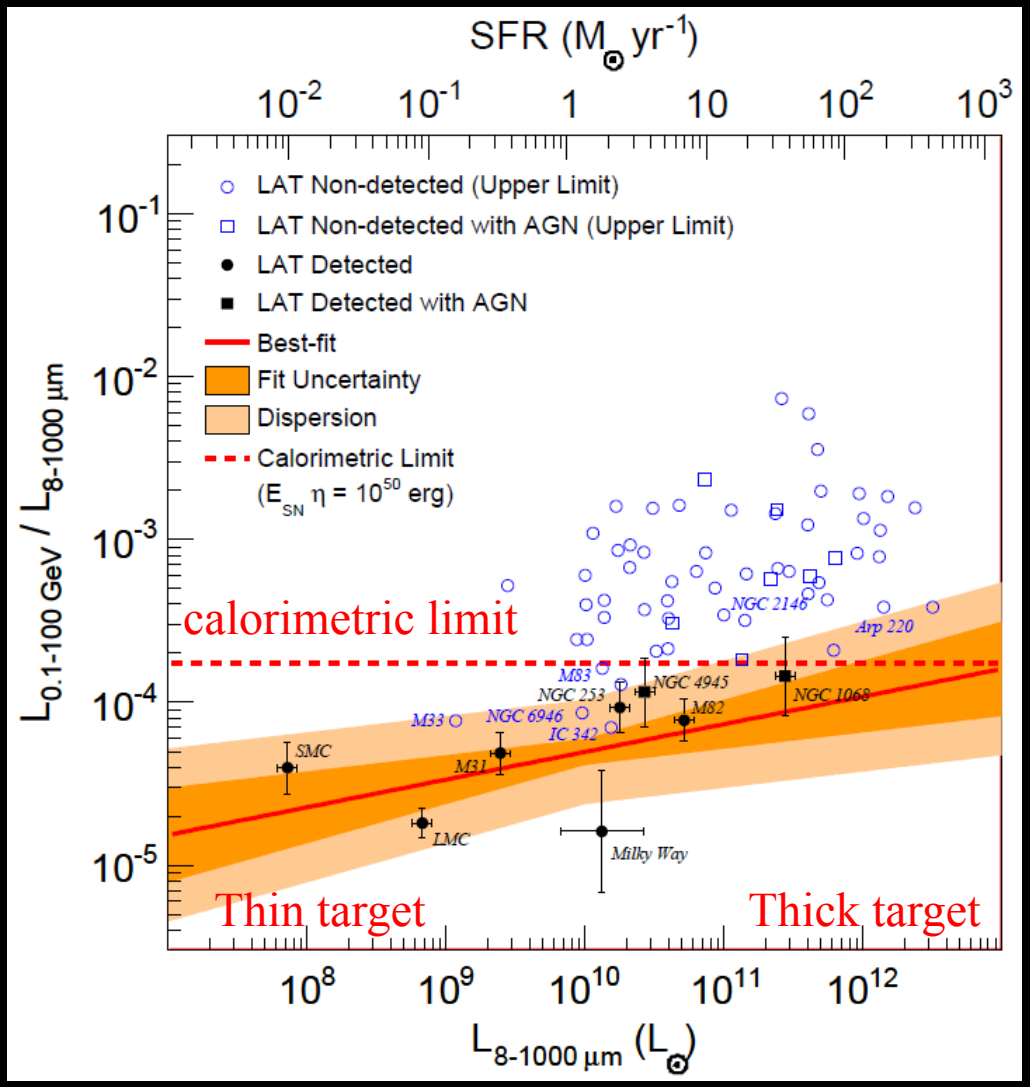
Strong+'2011

* The percentages in brackets show the values relative to the luminosity of their respective lepton populations

Starforming Galaxies

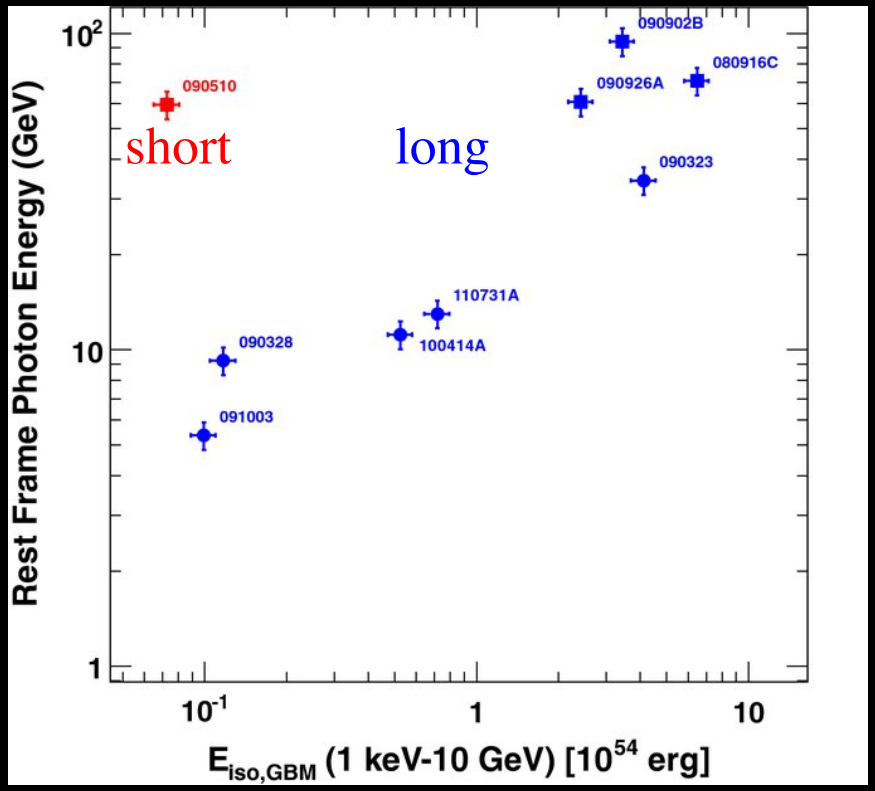


Cosmic Rays as a Universal Phenomenon

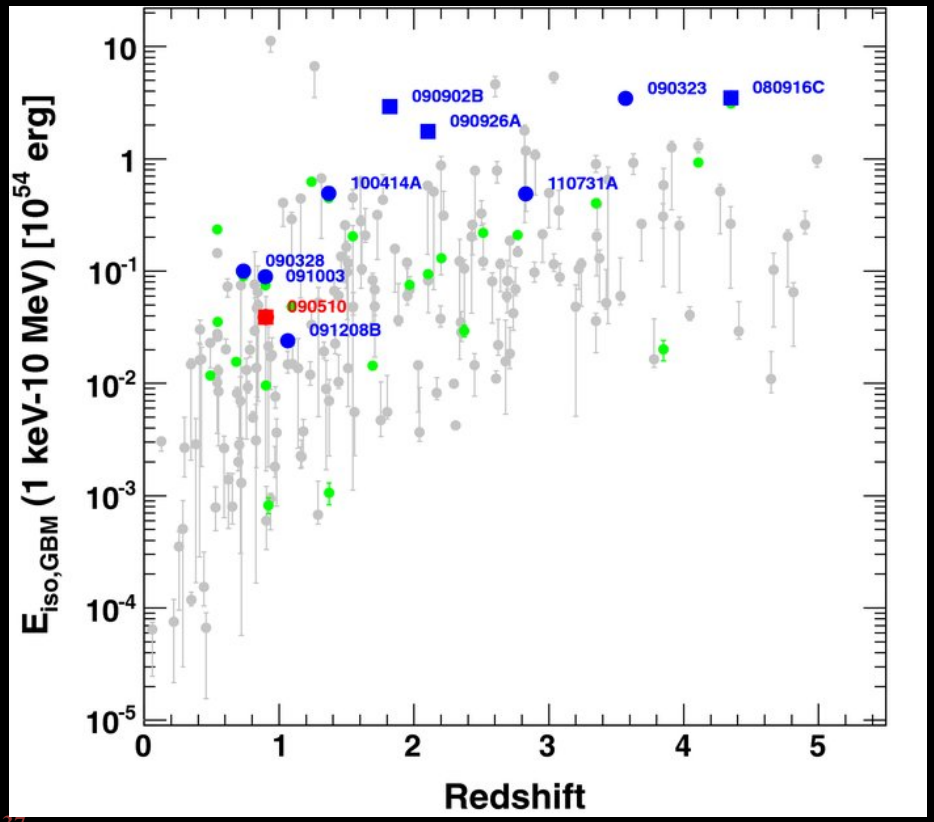


- γ-ray luminosity vs. IR luminosity for normal galaxies detected with Fermi-LAT
- The γ-ray luminosity scales linearly (index ~1.1) with the total emission of hot stars reprocessed by dust – a tracer of star formation
- The ratio approaches the calorimetric limit in star-burst galaxies
- An evidence of the SNR-CR connection in normal star-forming galaxies

1st Fermi catalog of gamma-ray bursts (2008-11)



- Pass 6
- 35 GRBs (E>20 MeV) out of 733 GRBs detected by the GBM
- Fermi-LAT GRBs in the brighter site



The highest energy photons come at random time during the burst and afterglow

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What's next?

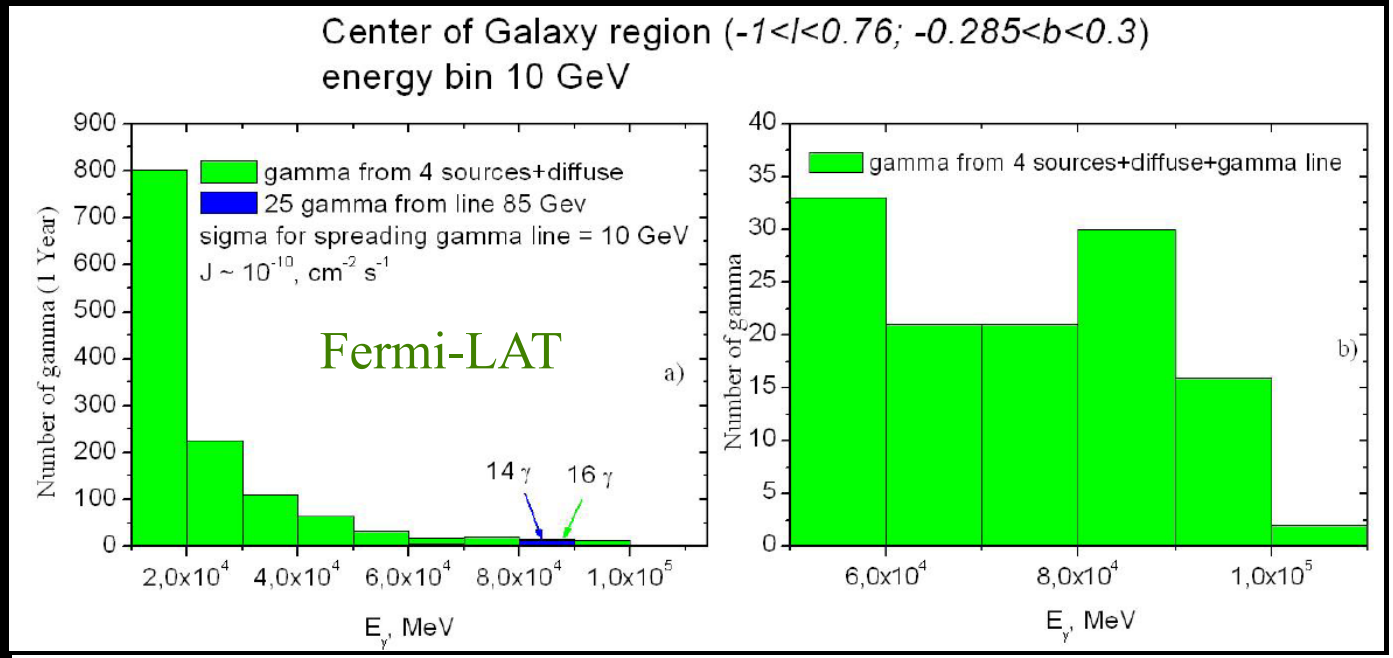
Table 2. Comparison of parameters for the current, future space- and ground-based instruments.

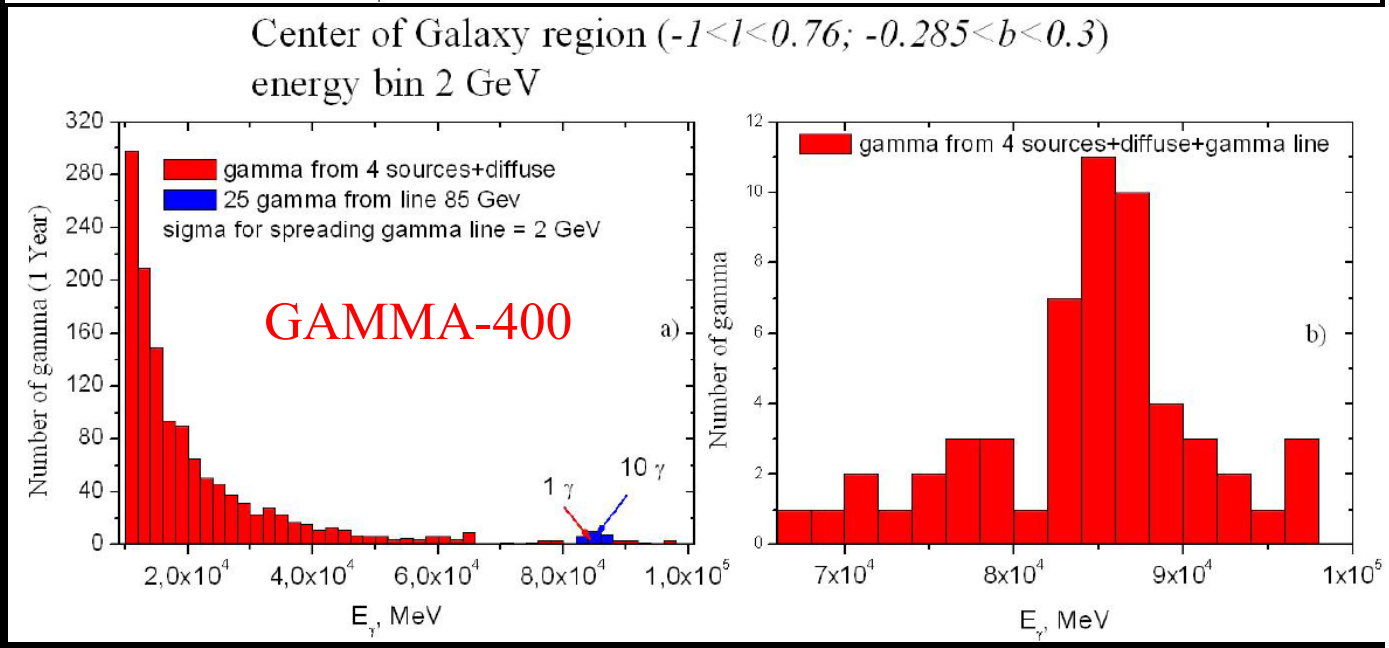
	SPACE-BASED GAMMA-RAY INSTRUMENTS				GROUND-BASED GAMMA-RAY INSTRUMENTS			
	Fermi-LAT	**DAMPE**	**CALET**	**GAMMA-400**	**H.E.S.S.**	**MAGIC**	**VERITAS**	**CTA**
Particles	γ, e	e, nuclei, γ	e, nuclei, γ	γ, e, nuclei	γ	γ	γ	γ
Operation period	2008-	2015	2015	~2023	2012-	2009-	2007-	~2020
Energy range, GeV	0.02-300	5-10000	10-10000	**0.02-10000**	> 30	> 50	> 100	> 20
Angular resolution (E_γ > 100 GeV)	0.1°	0.1°	0.1°	**~0.01°**	0.07°	0.07° (E_γ = 300 GeV)	0.1°	0.1° (E_γ = 100 GeV) 0.03° (E_γ = 10 TeV)
Energy resolution (E_γ > 100 GeV)	10%	1.5%	2%	**~1%**	15%	20% (E_γ = 100 GeV) 15% (E_γ = 1 TeV)	15%	20% (E_γ = 100 GeV) 5% (E_γ = 10 TeV)

Topchiev+'16

Lines in gamma-rays?

- Better energy resolution of GAMMA-400 (smaller bins)
- More sensitive to potential gamma-ray lines





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Thank you!