Fermi Gamma-ray Space Telescope

Galactic GeV Gamma-ray Sources Observed by Fermi

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On behalf of the Fermi-LAT Collaboration

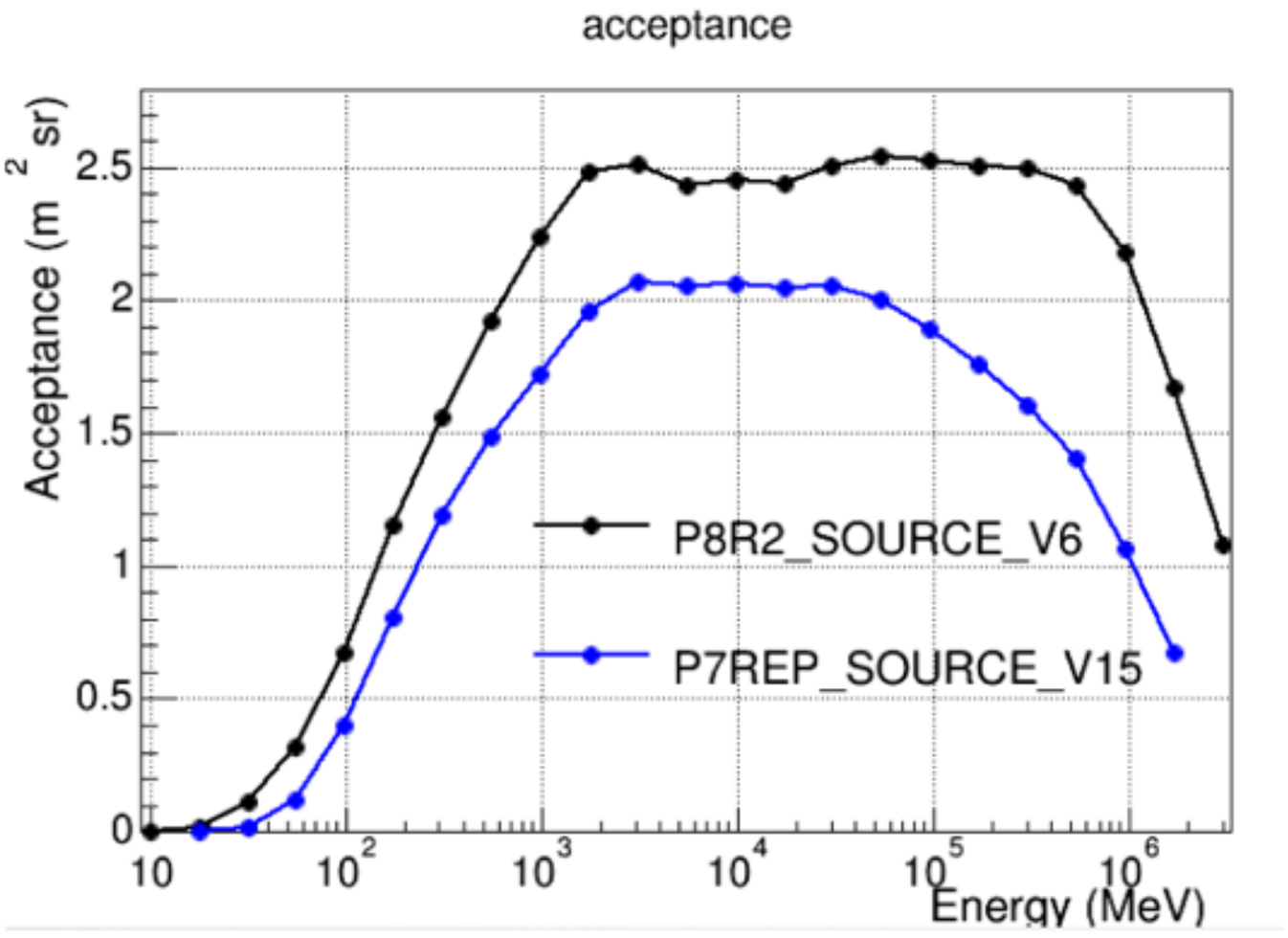
Jan 13, 2016, CTA Conference @Kashiwa, ICRR

Outline

- Status of Fermi-LAT Gamma-ray Analysis
- Catalog Sources
- Nova/Pulsars
- SNR/Diffuse Gamma-rays
- GeV excess at the Galactic Center
- Summary

Status of Fermi-LAT Gamma-ray Analysis

- Launched in 2008 and steady operation for ~7.5 years
- Update the instrumental response function from Pass 7 to Pass 8



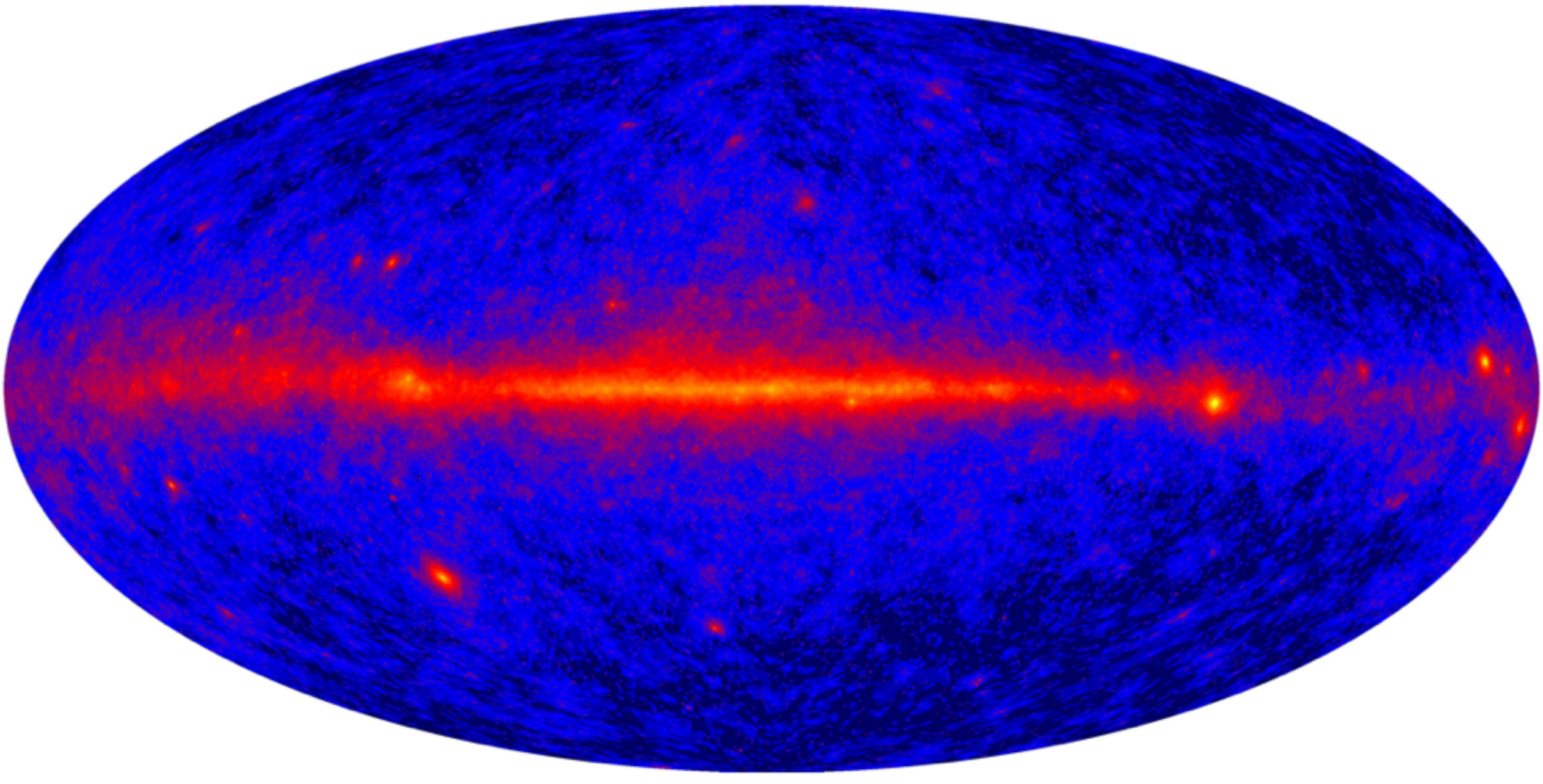
http://www.slac.stanford.edu/exp/glast/groups/canda/lat_Performance.htm

- Substantial improvement in the capability
  - Acceptance is ~2 times larger at very low (< 100 MeV) and very high (> 100 GeV) energies
  - 40% increase in point-source sensitivity

- Direct impact on the LAT science performance
- Pass 8 data publicly available as of June 2015

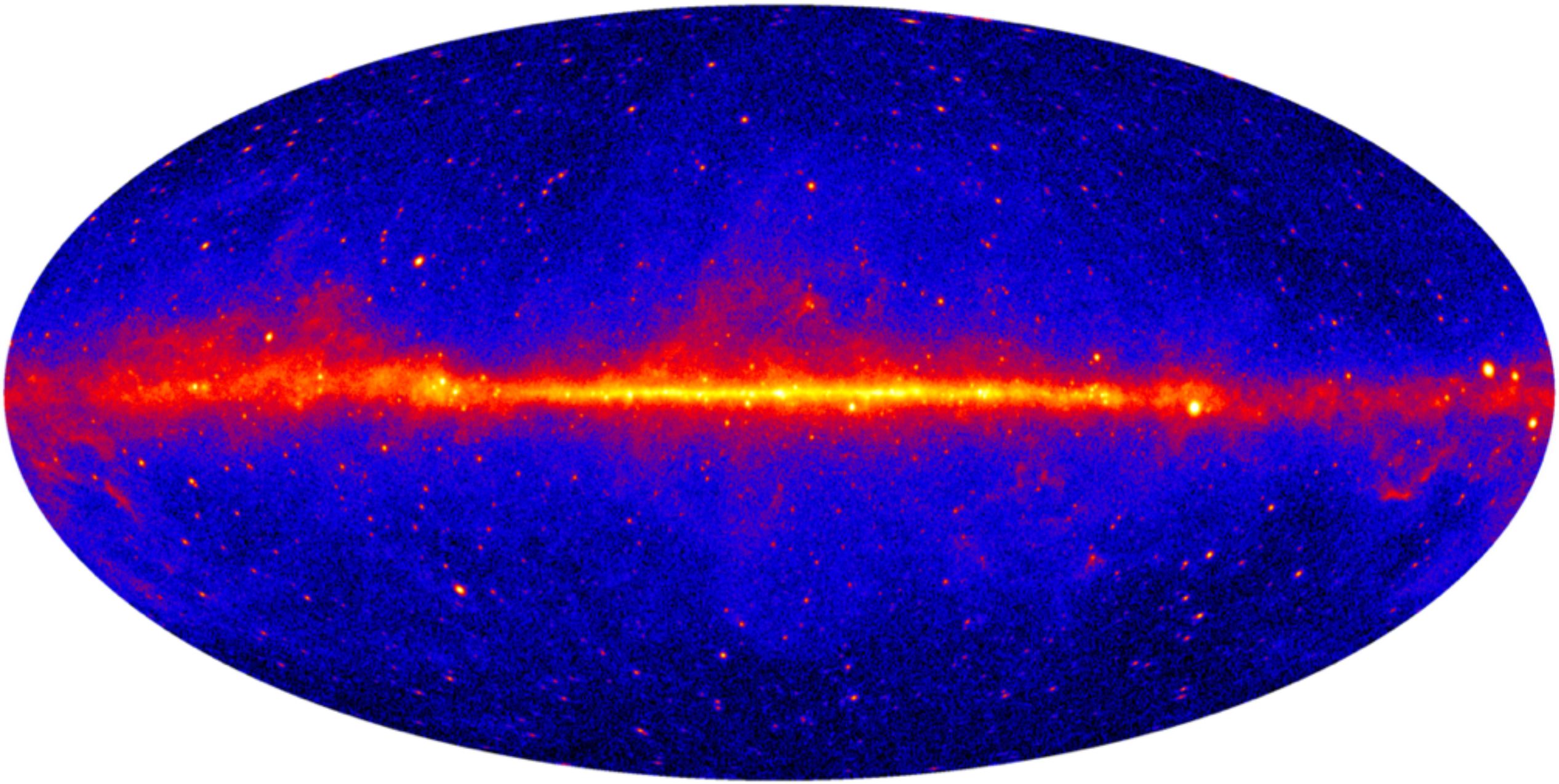
The First LAT All-sky Map

E > 100 MeV, Duration: a few days



The 3FGL All-sky Map

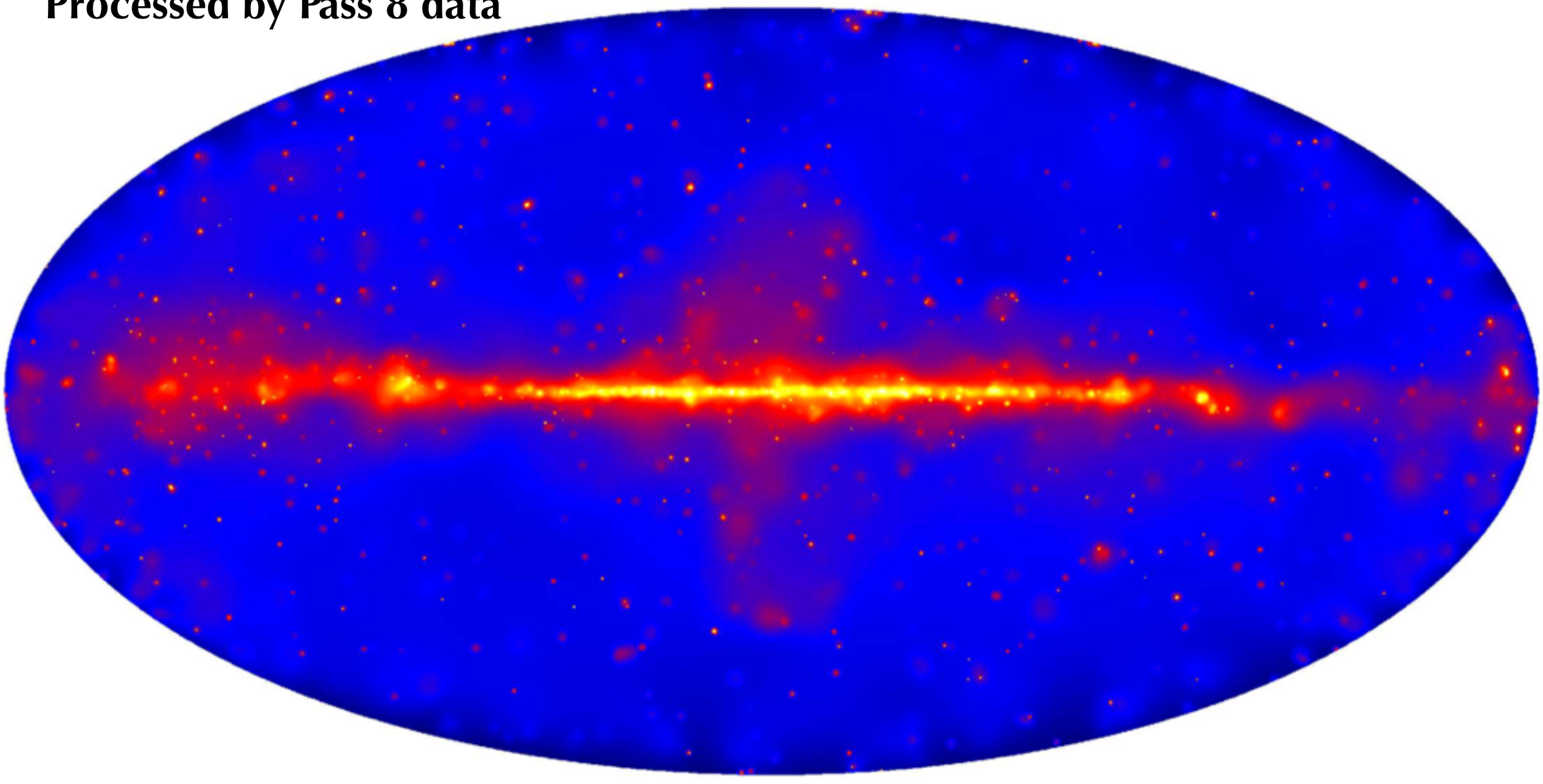
E > 1 GeV, Duration: 48 months



The 2FHL All-sky map

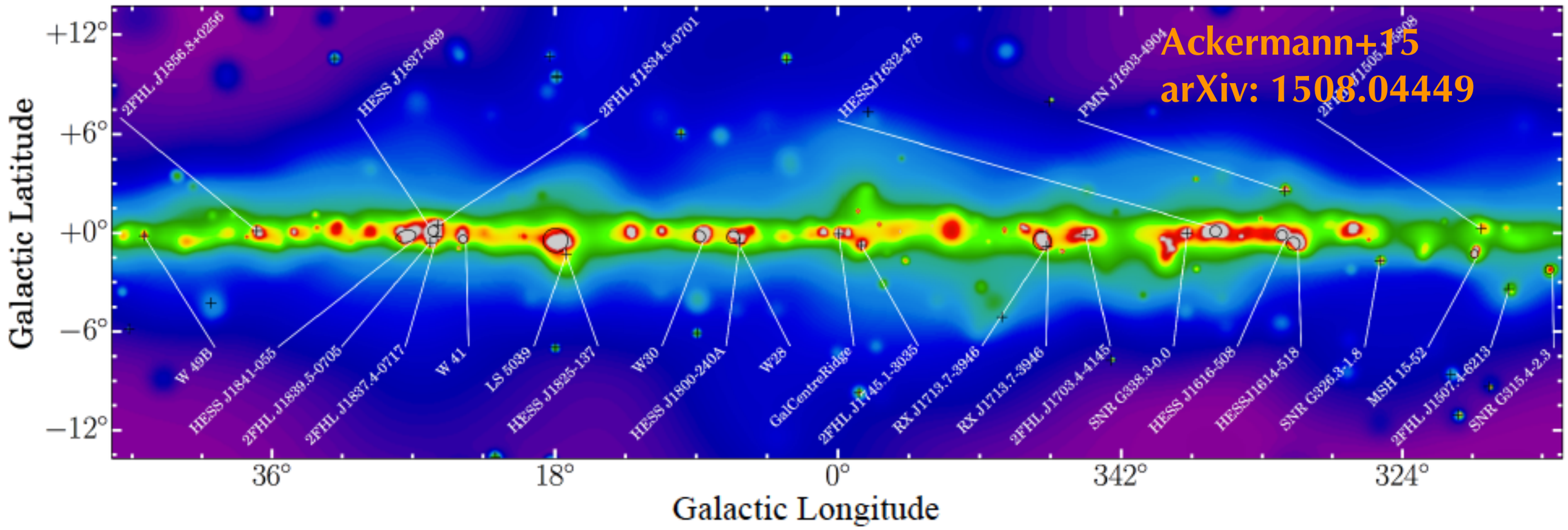
50 GeV < E < 2 TeV, Duration: 80 months

Processed by Pass 8 data



smoothed with a Gaussian kernel minimizing S/N

Galactic Sources



- 39 Galactic objects, 13 unassociated and 9 Dark Accelerator (|b|<10°)
  - PWNe/SNRs represent 87% of the Galactic population
  - Hard spectra: median photon-index ~2
- 5 new extended sources are found (TS>75)
- Count map with E > 50 GeV matches to the H.E.S.S. Galactic plane survey

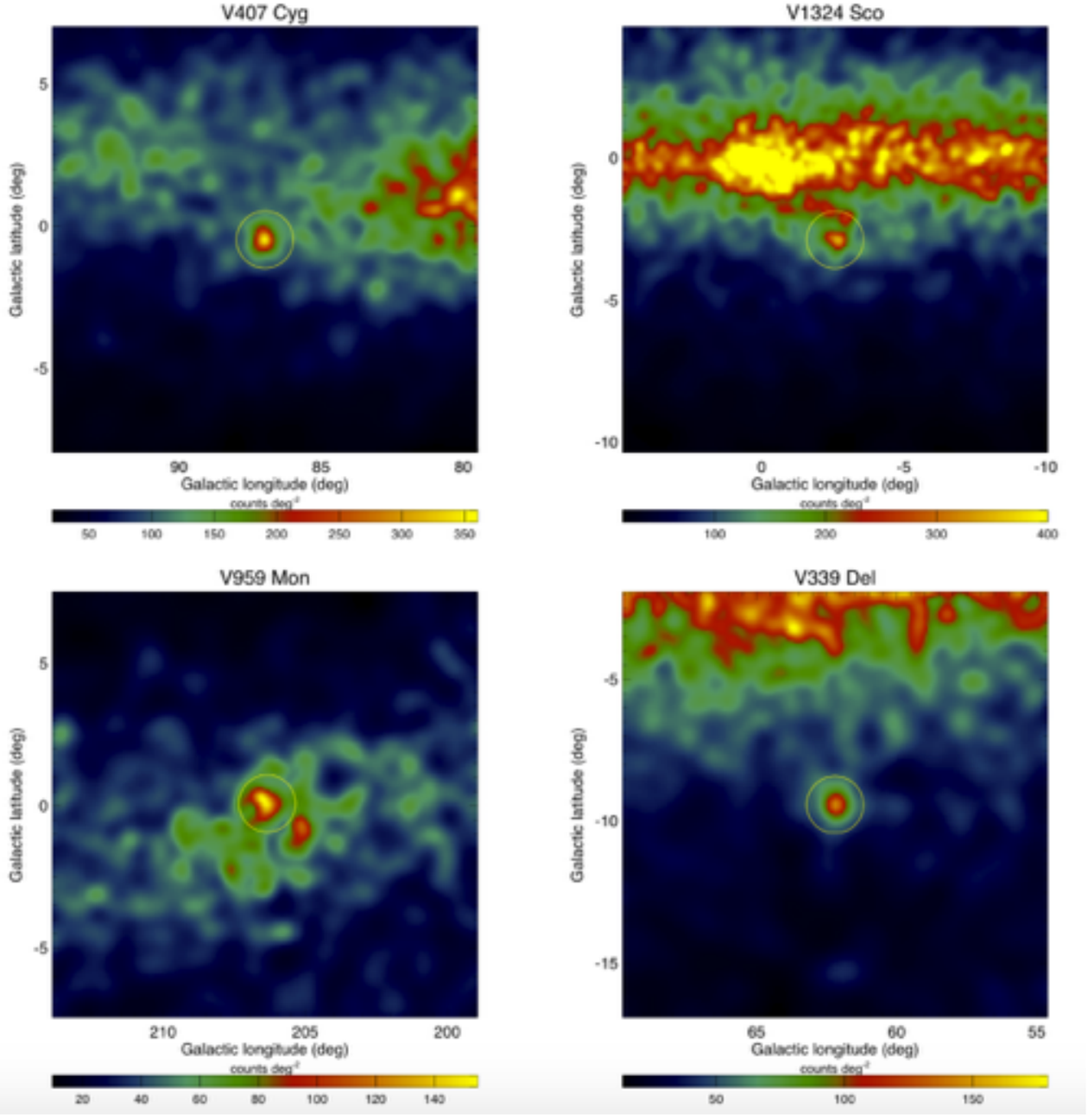
Gamma-ray Novae/Pulsars

Gamma-rays from Nova

- **Resulting from thermonuclear explosions on the surface of WD**

Fermi-LAT > 100 MeV Detection

Ackermann+14 arXiv: 1408.0735



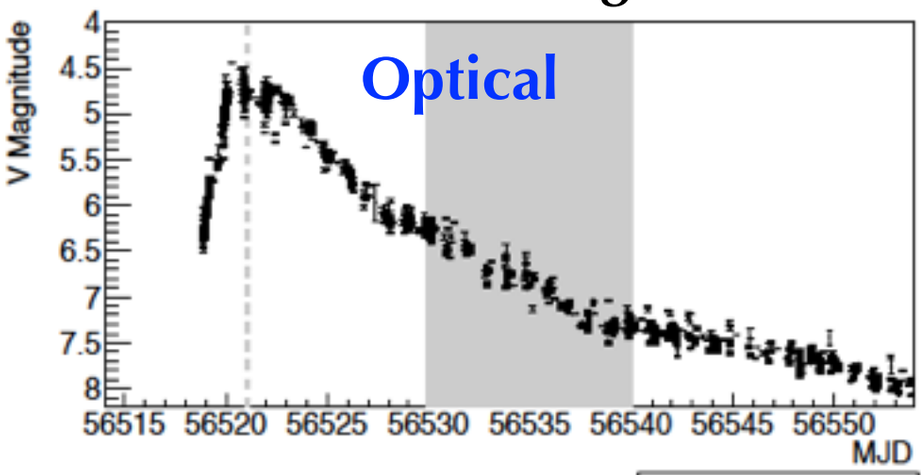
- **Compact cataclysmic variable:**
  - **Classical novae**
  - **WD + Main sequence**
  - **Roche lobe overflow**

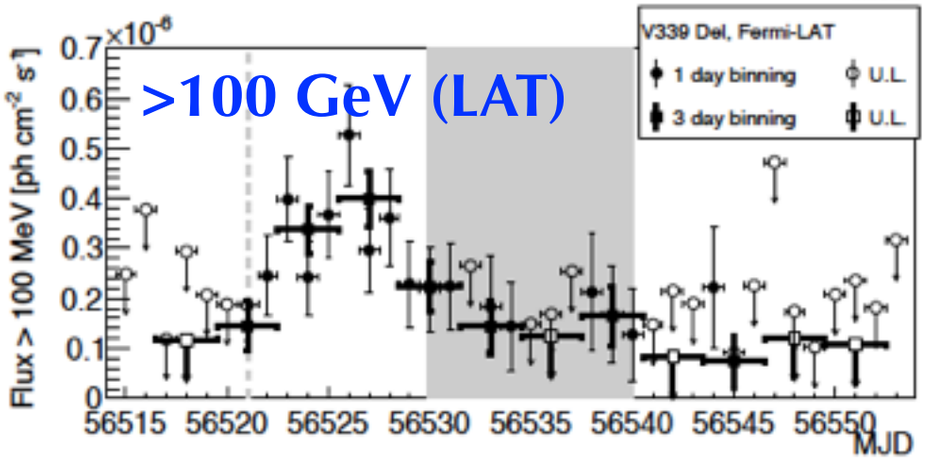
- **Symbiotic system:**
  - **Symbiotic/Recurrent novae**
  - **Massive WD + Red Giant**
  - **Outburst due to accretion from a red giant wind**
  - **V407 Cyg**

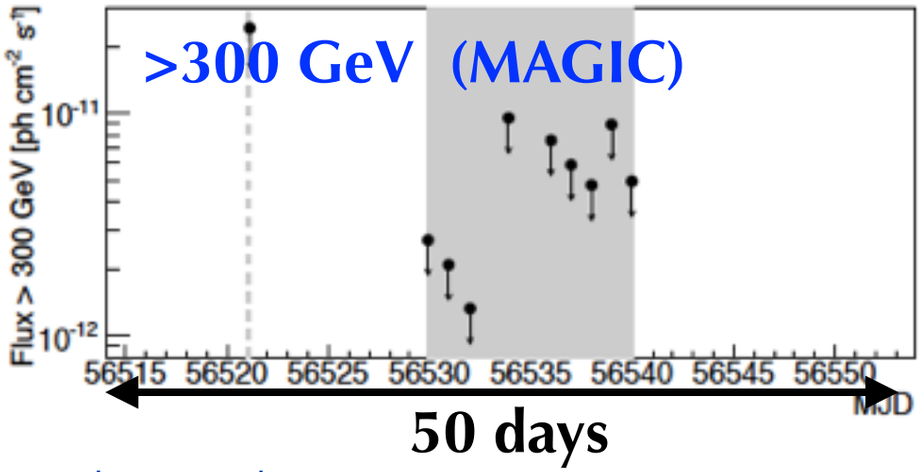
V339 Delphini

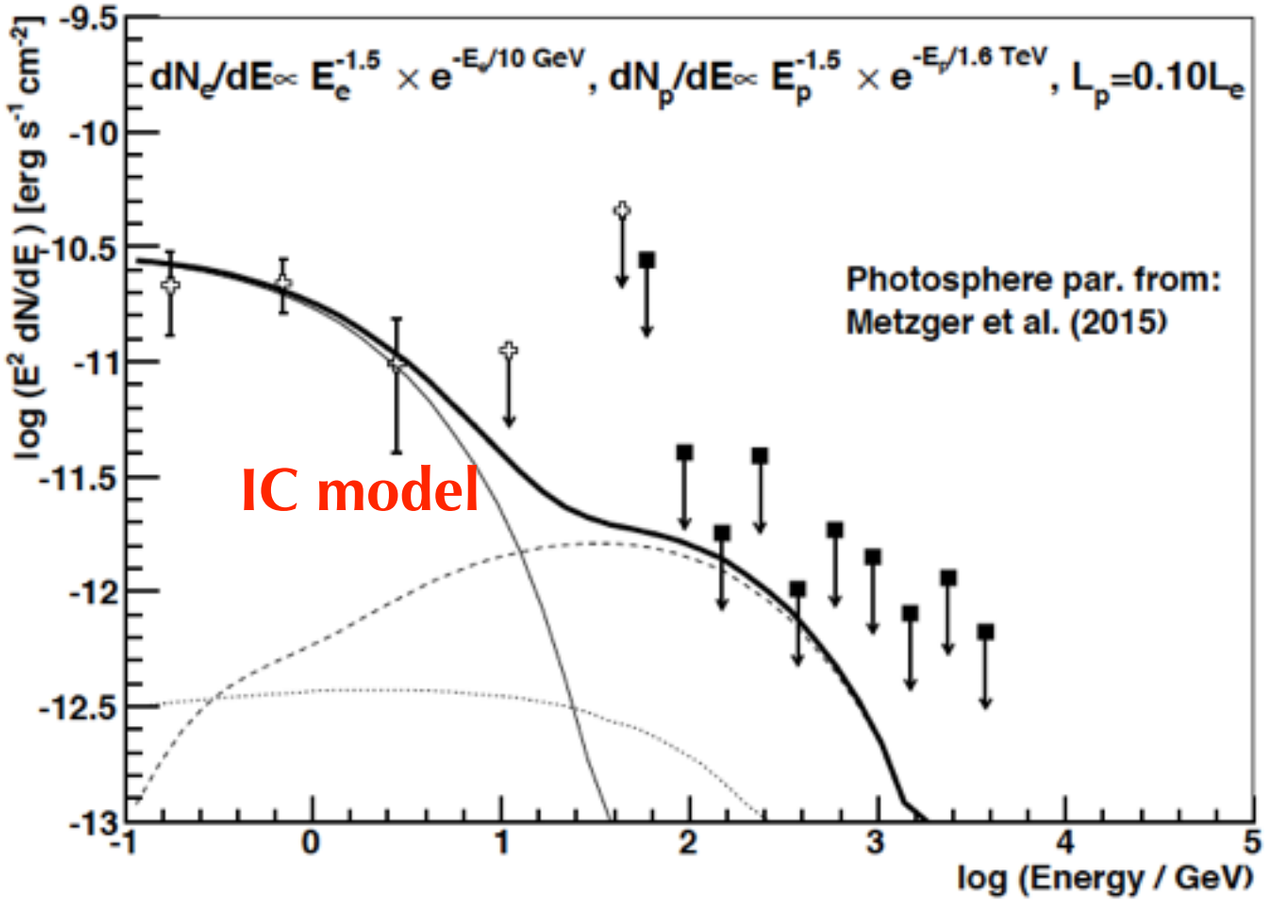
Ahnen+15

August 2013



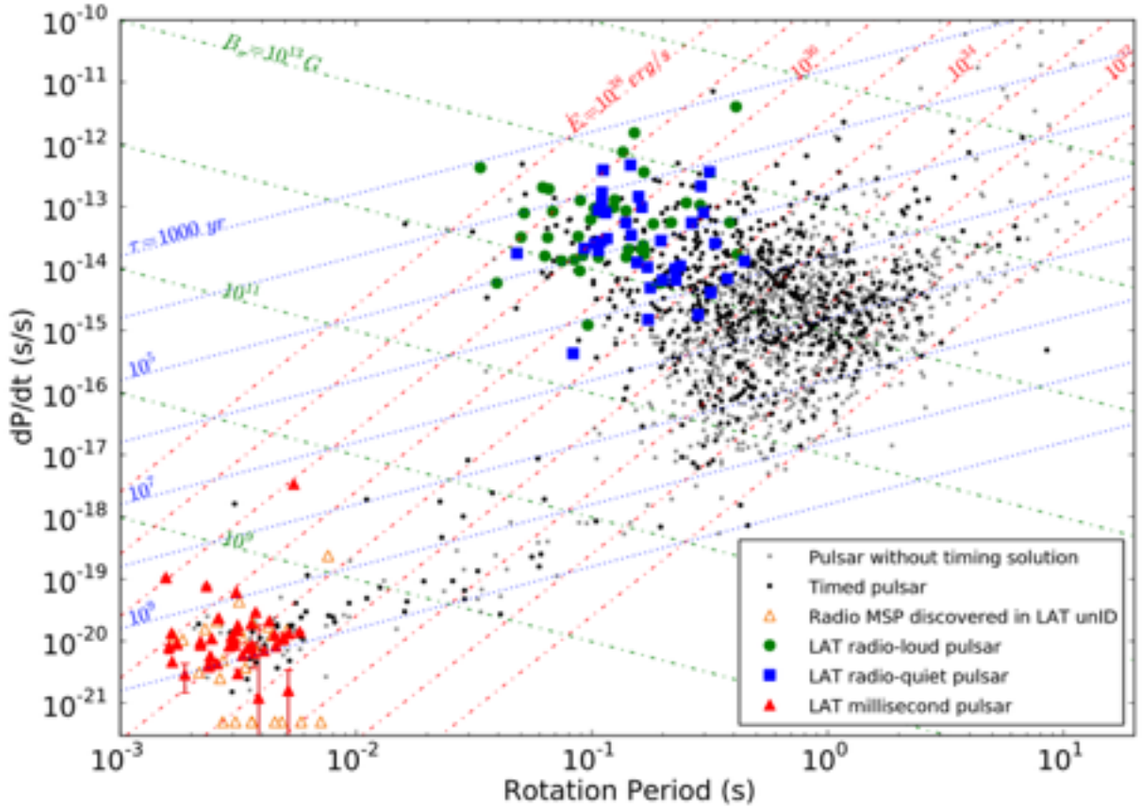




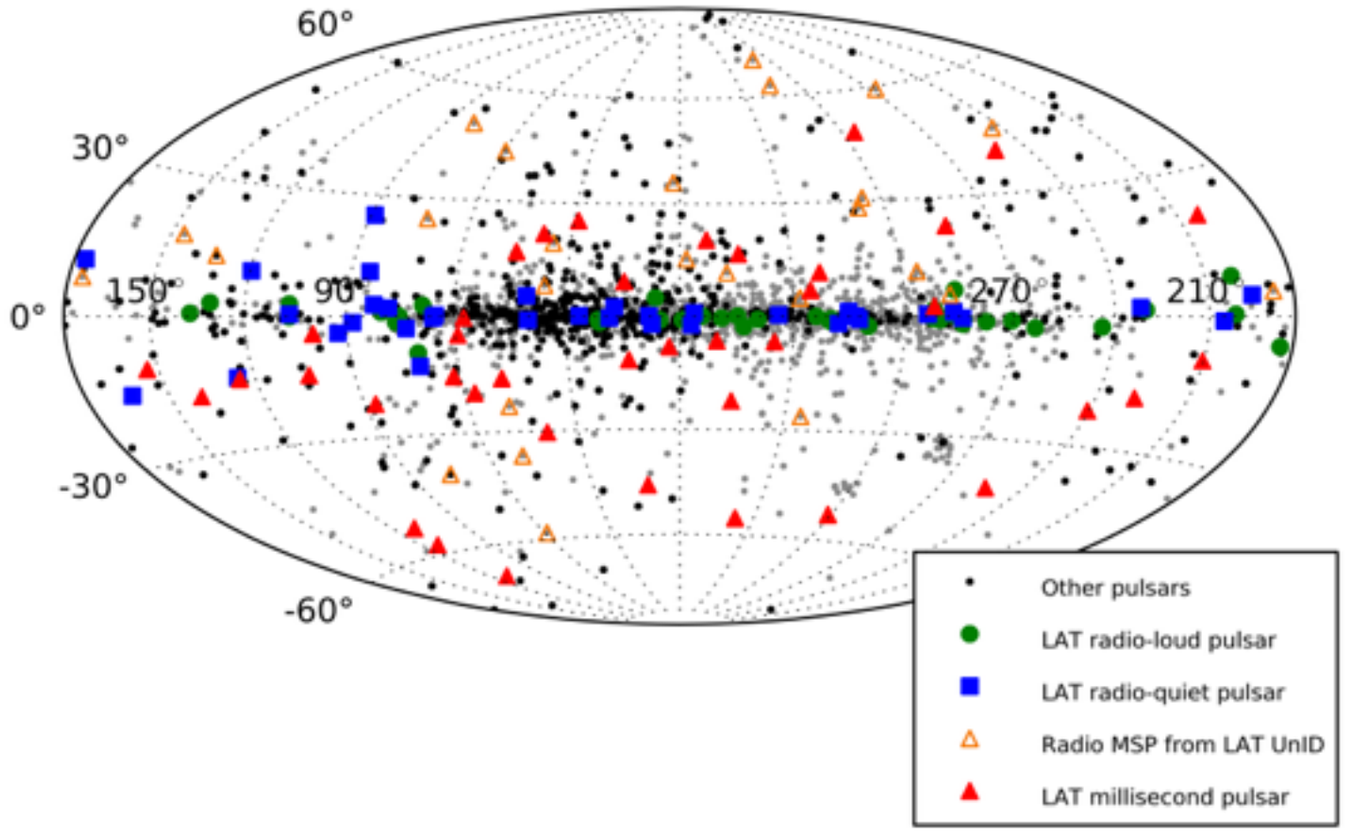


- **IC model of thermal photons from the photosphere by the electrons accelerated in the nova shock**
- **Combined the GeV and TeV results limit the ratio of proton to electron luminosities to Lp < 0.15 Le**

LAT-discovered Pulsar



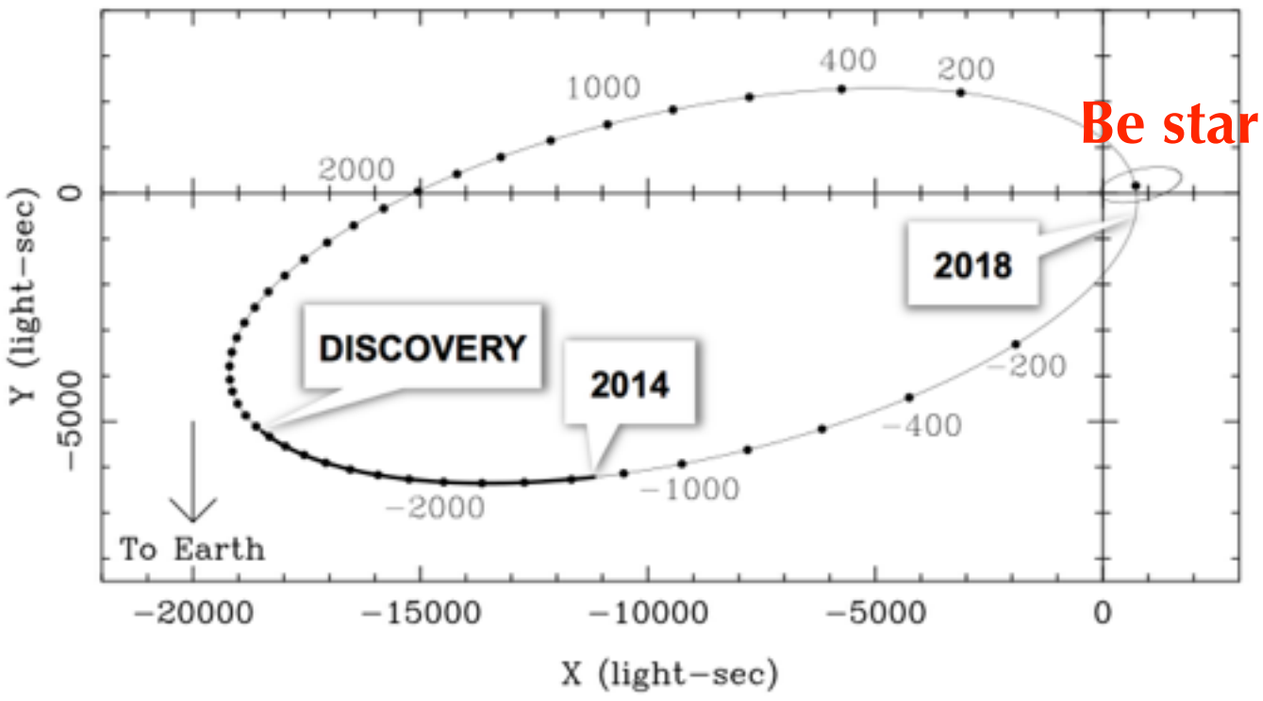
Abdo+13 arXiv: 1501.02003



- **117 pulsars were identified by 2013 (2nd Pulsar Catalog, Pass 7)**
  - **millisecond pulsars(40), young radio-loud(42), young radio-quiet(35)**

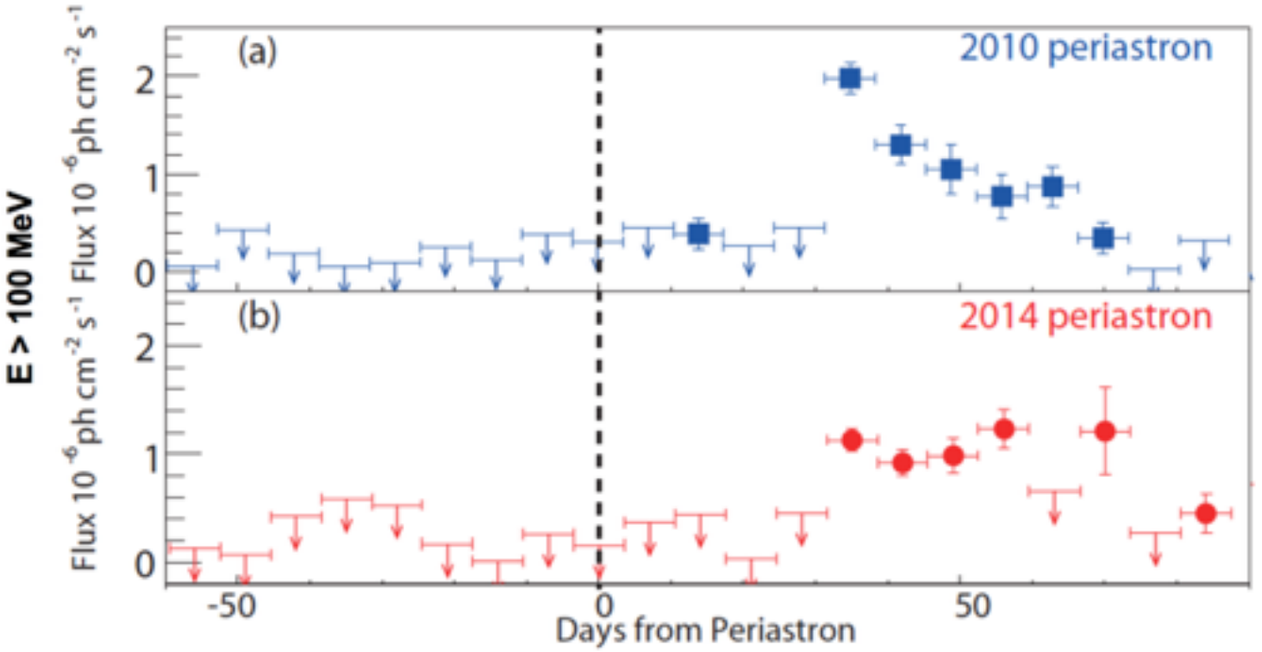
- **160 pulsars are detected by 2014 (Pass 8)**
  - **growing fraction of MSP: 18%(2009) —> 43%(2014)**

Pulsar Binary System



PSR J2032+4217 (Lyne+15)

- Gamma-ray and radio-emitting pulsar
- Timing models of binary motions fit the data well —> NS around a Be star with periastron every 25 years
- Expected flaring activity near periastron in 2018



PSR B1259-63 (Caliandro+15)

- In orbit around a Be Star with periastron every 3.4 years
- Flare activity (>50% pulsar's rotational energy loss) in both 2010 and 2014, but with somewhat different characteristics

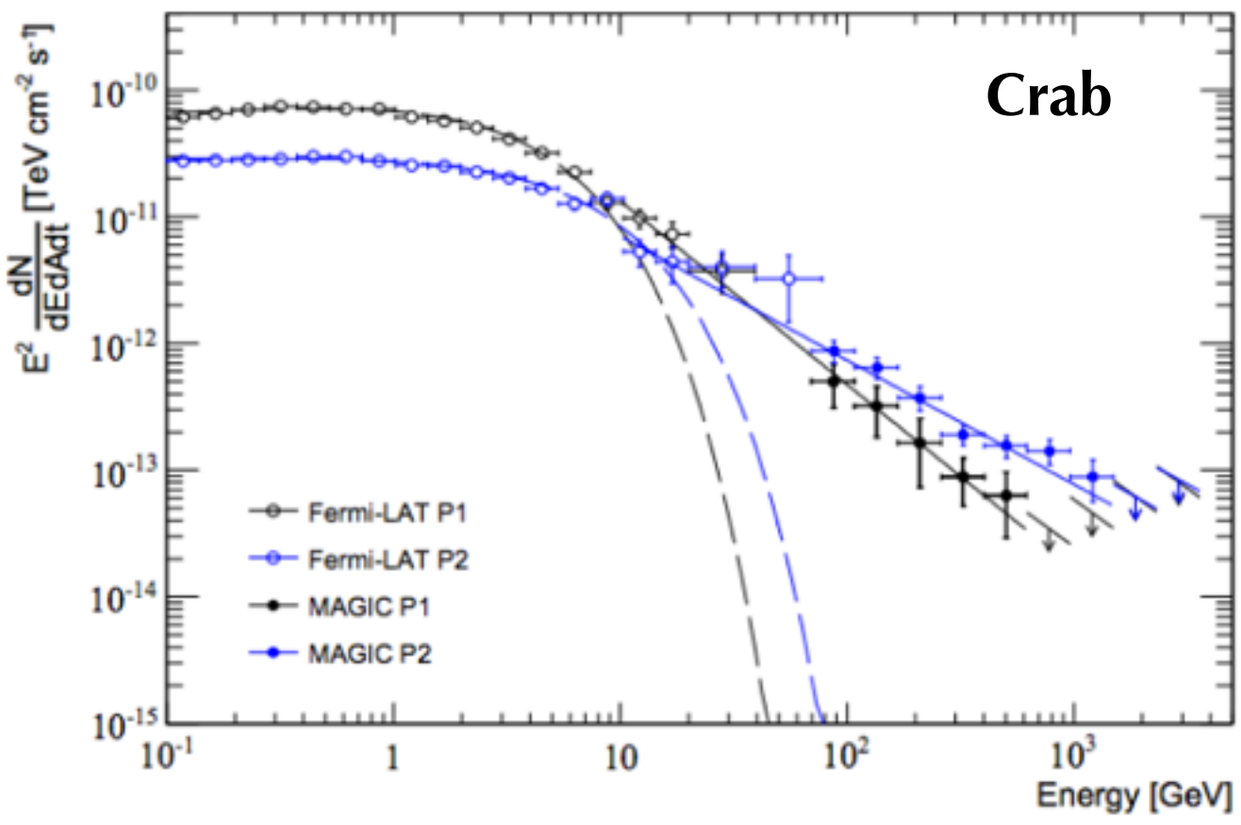
VHE Pulsar

Ackermann+15 arXiv: 1305.4385

Table 11. *Fermi*-LAT γ-ray pulsars detected above 25 GeV

PSR	E_{max}	$E_{max}^{detected}$	$\Phi_{\gamma_{max}}$	Notes
J0007+7303#	28	788	0.64	
J0534+2200†#	26	784	0.33	Crab
J0614–3329	63	63.6	0.68	
J0633+1746#	33	52.7	0.05	Geminga
J0835–4510†#	37	752	0.28	Vela
J1028–5819	27	386	0.49	
J1048–5832	35	201	0.28	
J1413–6205	29	331	0.28	
J1809–2332	26	159	0.07	
J1836+5925	26	97.9	0.05	
J1954+2836	62	95.7	0.57	
J2021+3651#	26	113	0.64	
J2229+6114#	31	169	0.17	

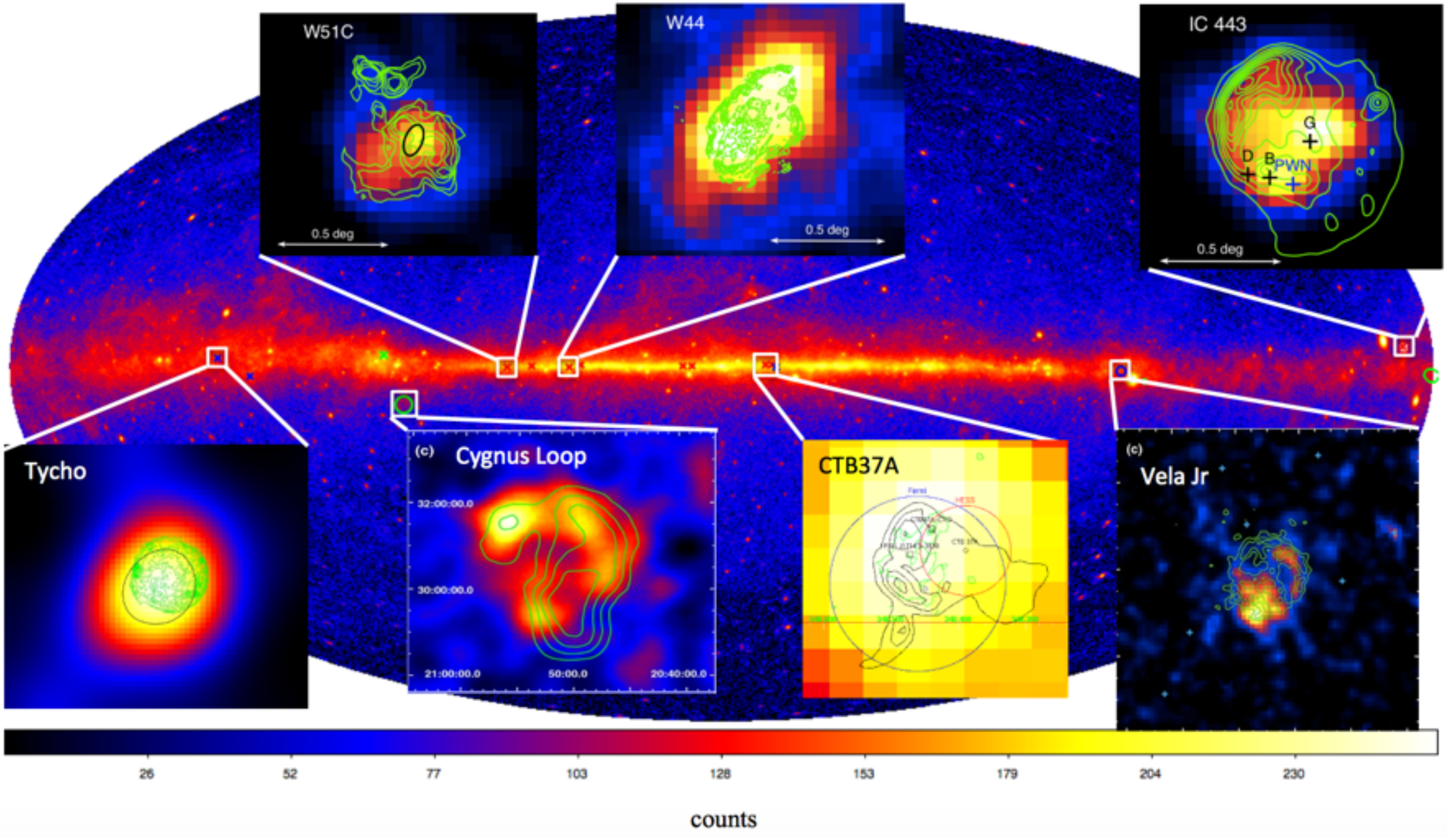
Ansoldi+15, Saito+15



- 12 LAT pulsars were shown to emit pulsations at > 25 GeV
  - Very high energy gamma-rays (> 100 GeV) from Crab, Vela Pulsars (PWN)
    - Does not follow a model of PL with exponential cut-off
    - PL with break around 5 GeV
  - J0614-3329: candidates of the next very high energy pulsar

SNR/Diffuse Gamma-rays

SNRs Observed by Fermi-LAT

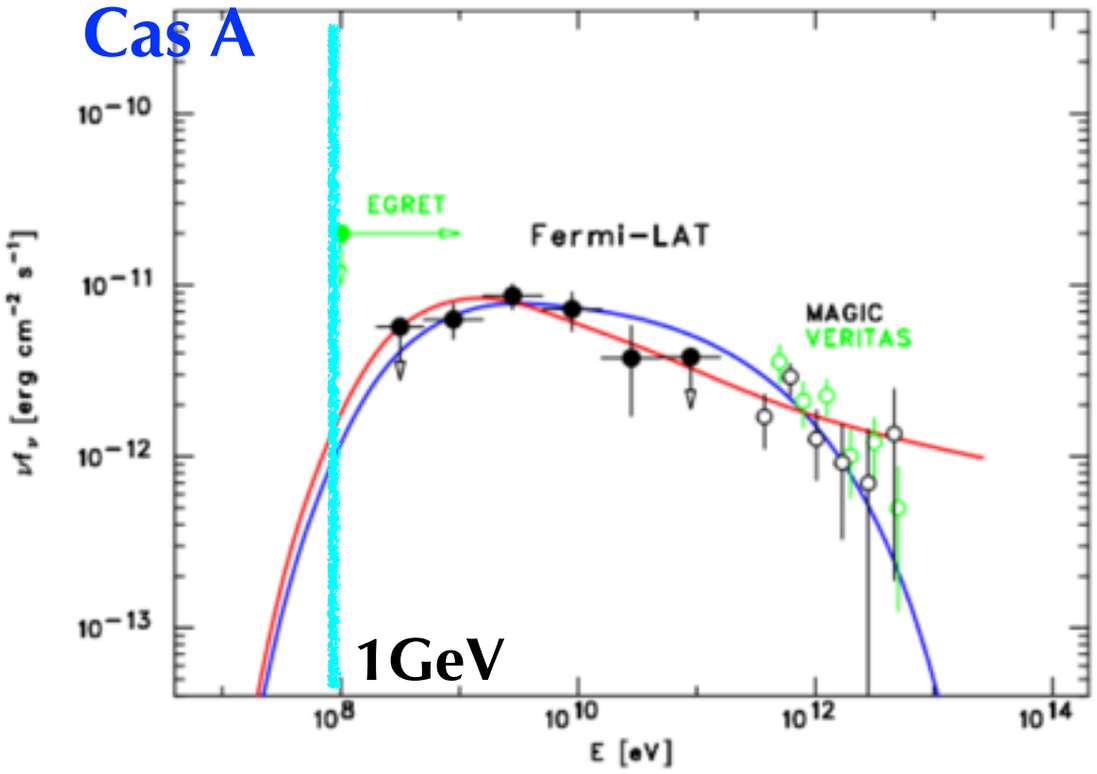


- **SNRs with GeV gamma-rays**
  - **13 identified SNRs: 9 interacting, 4 young SNRs (by 2014)**

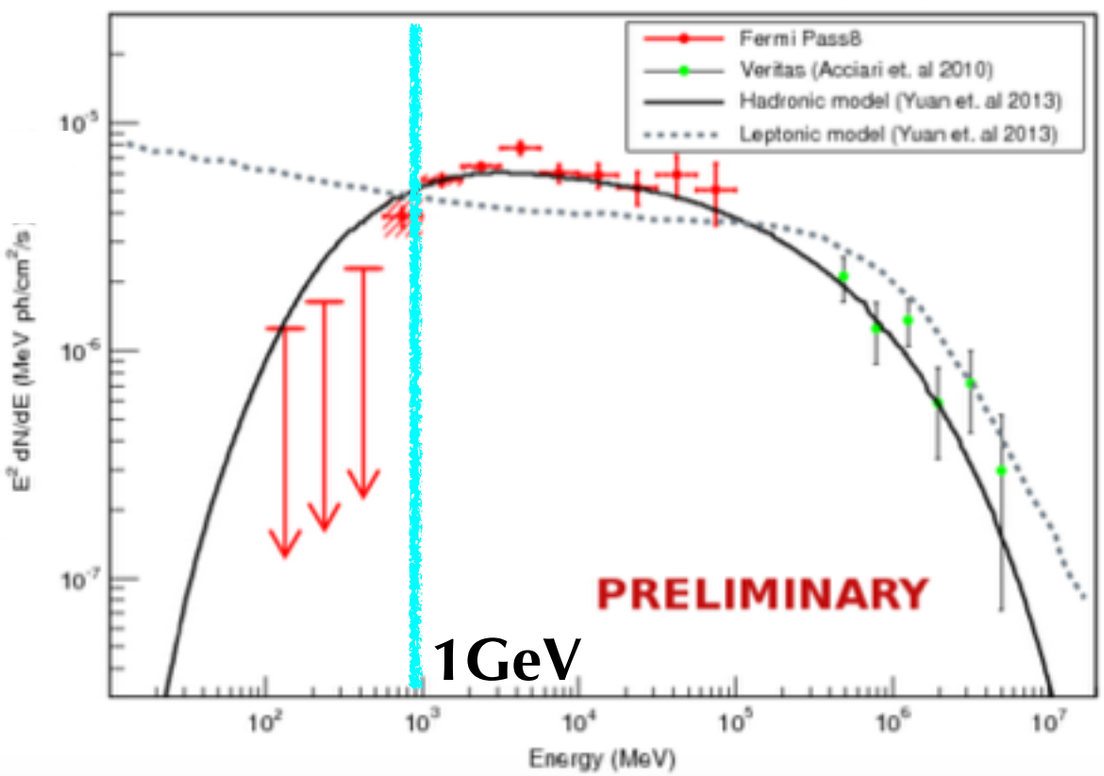
Individual Studies of SNR

Abdo+10 arXiv: 1001.1419

Cas A



DiVenere et al. 6th Fermi Symposium



- **Young SNRs** (DiVenere et al. 6th Fermi Symposium)
  - **Cas A: hadronic model favored thanks to the increased sensitivity**
  - **Tycho: no clear evidence that is dominated by hadronic gamma-rays**
- **Middle aged SNRs** (Acero et al. 6th Fermi Symposium)
  - **G326.3-18: different spectral signatures b/w SNR and PWN components**
- **TeV SNRs RXJ1713.7-3946, RCW86, SN1006 etc** (Acero+15 arXiv: 1506.02307)
  - **Photon index (Γ<1.8) in 0.1 < E < 100 GeV**
  - **Bulk emission produced by accelerated electrons (synchrotron, IC)**

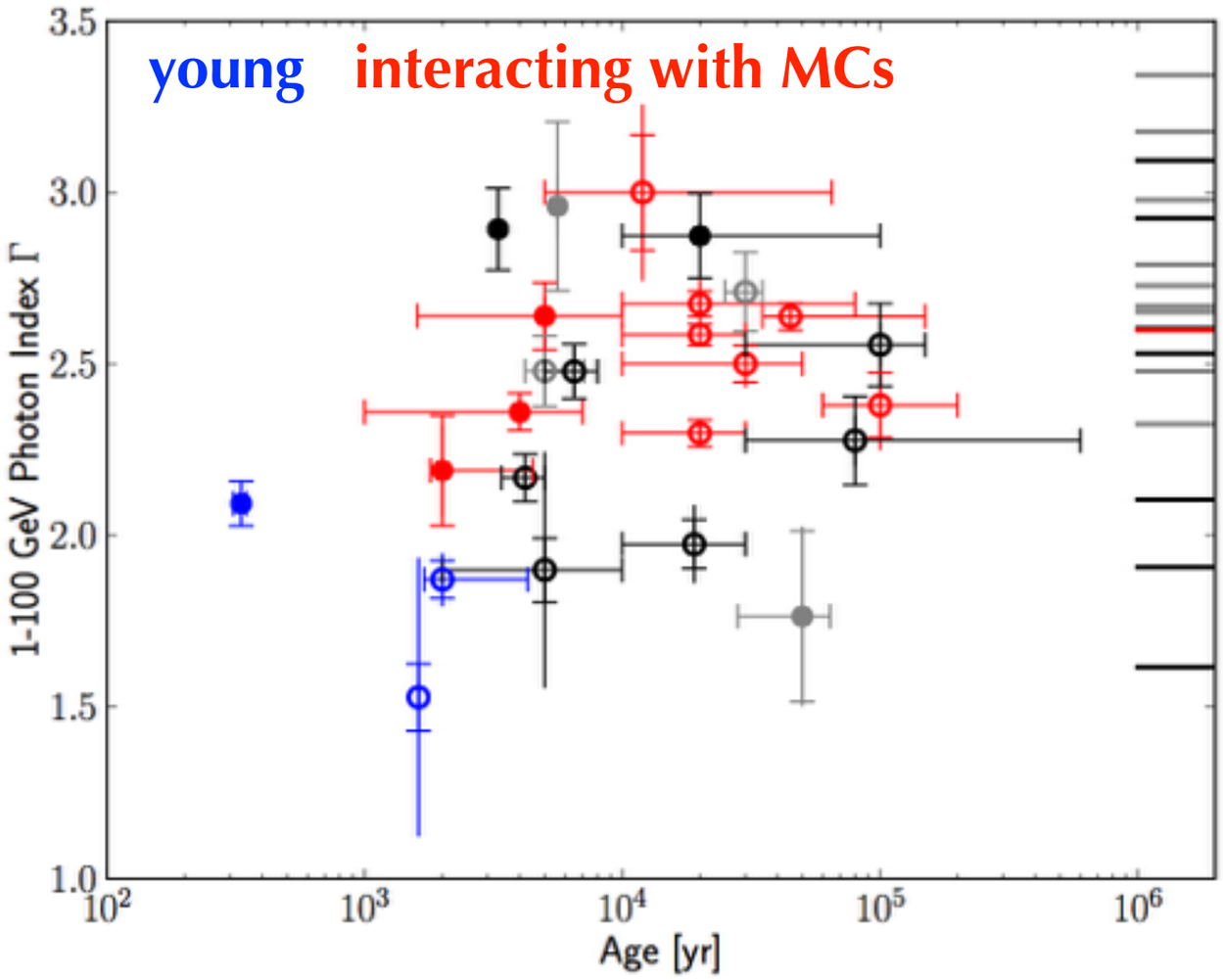
SNR Systematic Study

- Spatially overlap of sources detected at GeV energies with SNRs known from radio survey

- 30 sources and 14 marginal candidates (with a false identification < 22%)

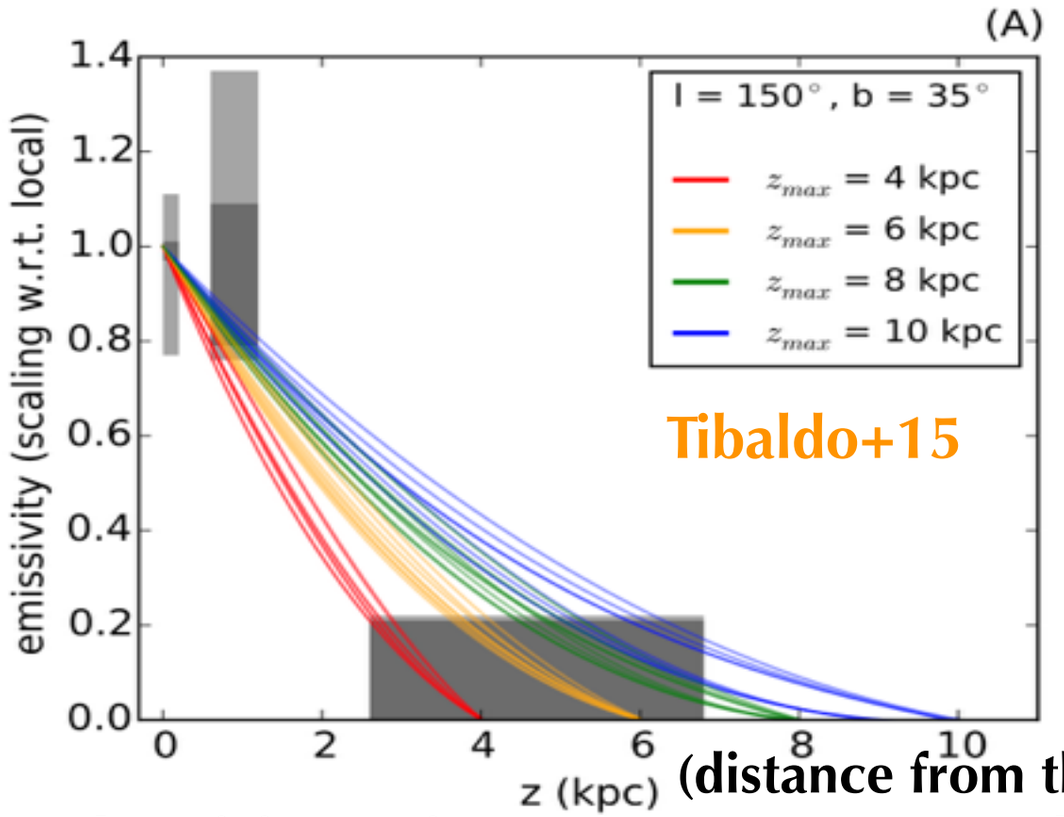
- 4 new extended SNR Candidates

Acero+15 arXiv: 1511.06778



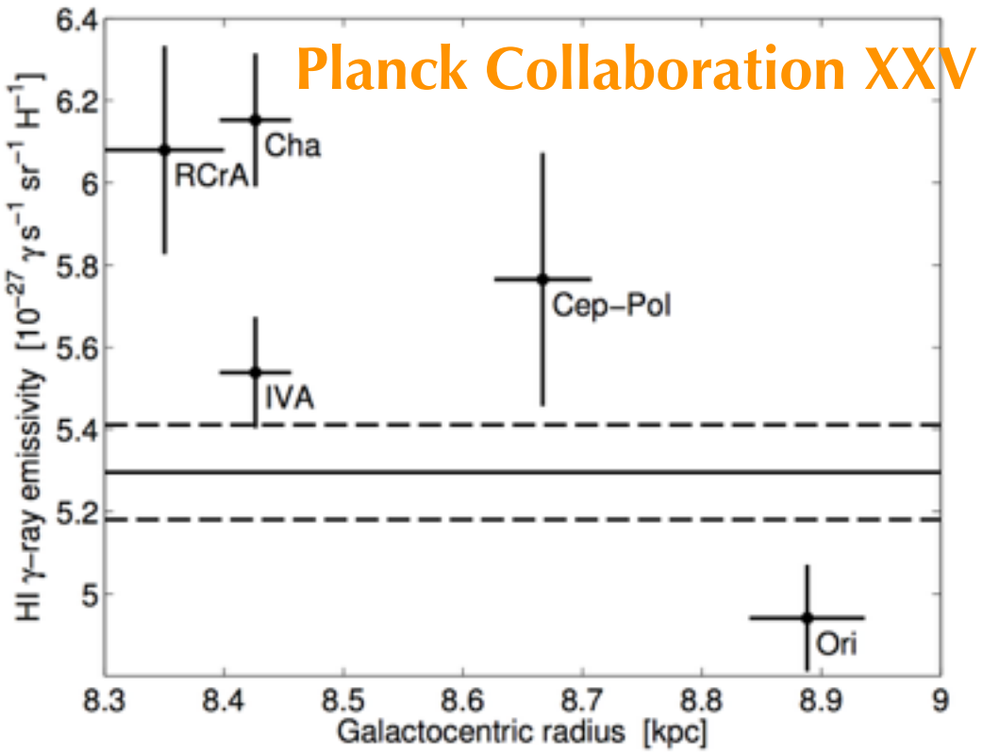
- Constrain SNRs' aggregate, contribution to the study of Galactic CRs
  - Support changes in spectral slope in TeV range, and a softening and brightening in GeV range with SNR age
  - With GeV and MW data, the candidates and upper limits are within expectations if SNRs provide the majority of Galactic CRs

ISM/CR



Tibaldo+15

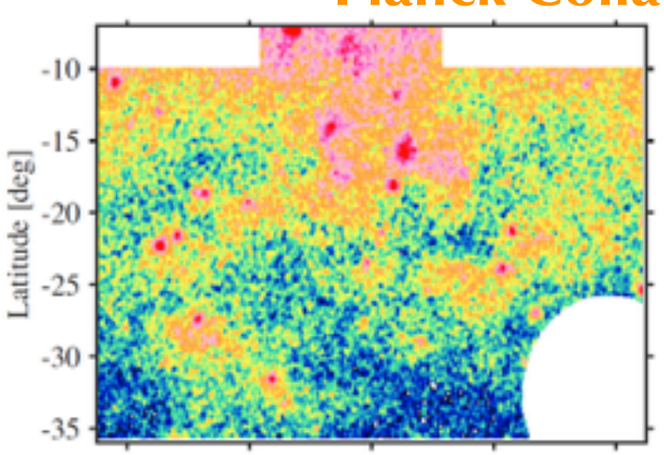
(distance from the disk)



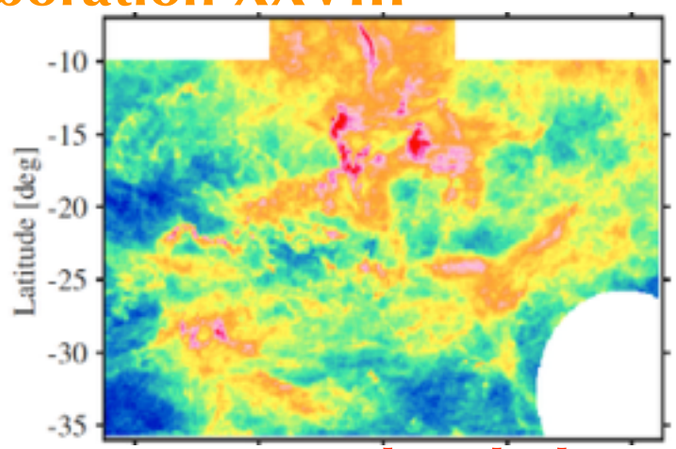
Planck Collaboration XXVIII

- CR densities using gamma-rays produced by CR interactions with ISM
  - High and intermediate-velocity clouds: decease CR density with the altitude
  - Nearby MCs: do not expect CR gradient in small distance range

Planck Collaboration XXVIII



gamma-rays

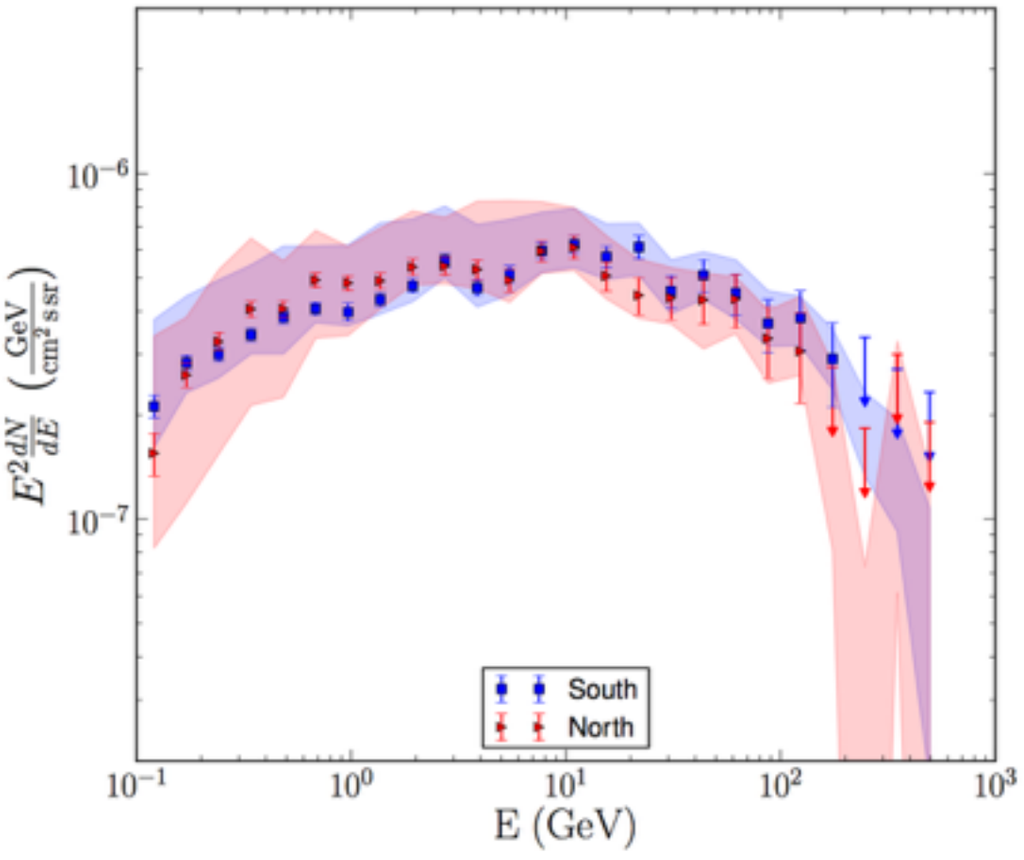


Planck dust

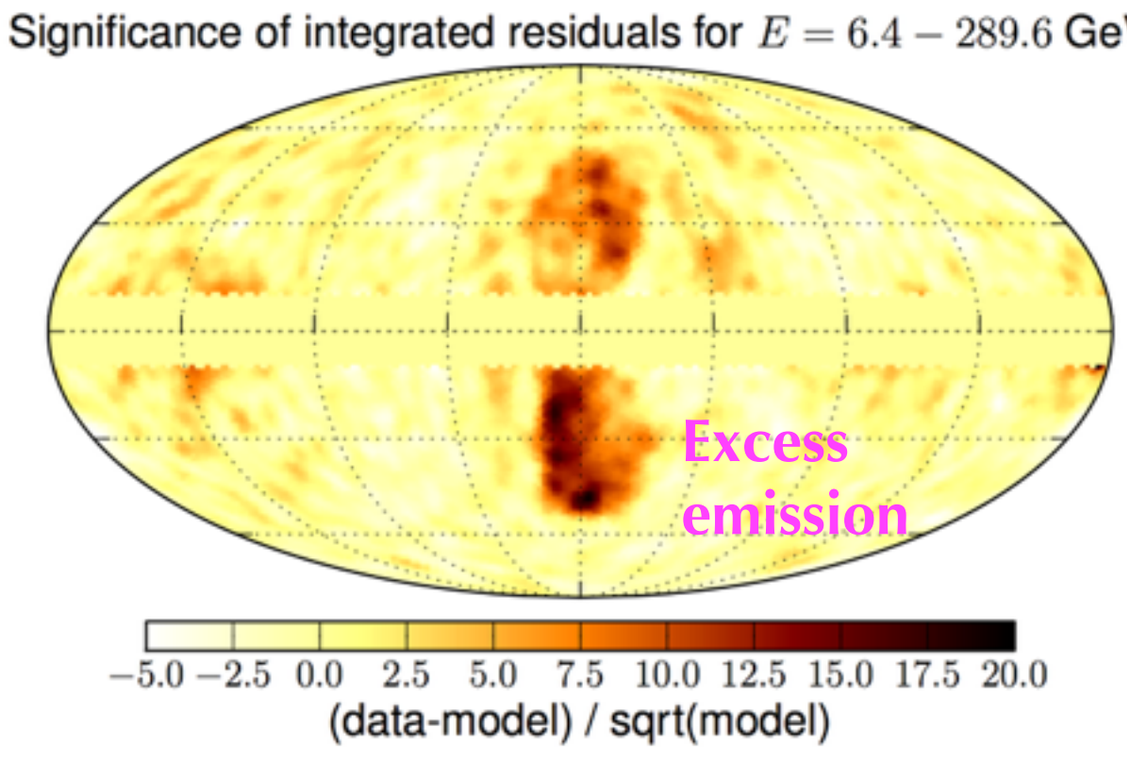
- Correlations with thermal dust emission in nearby MCs
  - Study of DNMs, CO-to-H_2 conversion factor and dust properties

Fermi Bubble

- Data analysis : ~50 months, 100 MeV- 500 GeV
  - Evaluate systematic uncertainty due to the diffuse emission model
- Spectrum modeled by log parabola or PL with an exponential cut-off
  - Exclude a simple PL model



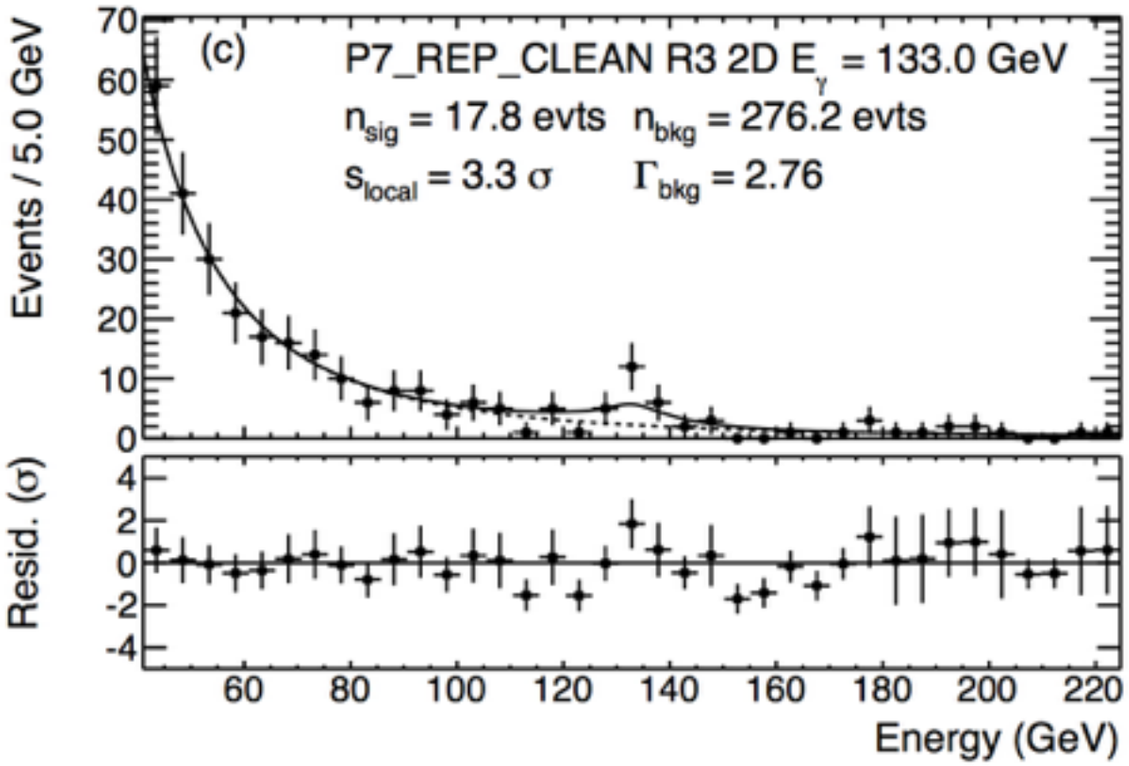
Ackermann+14 arXiv: 1407.7905



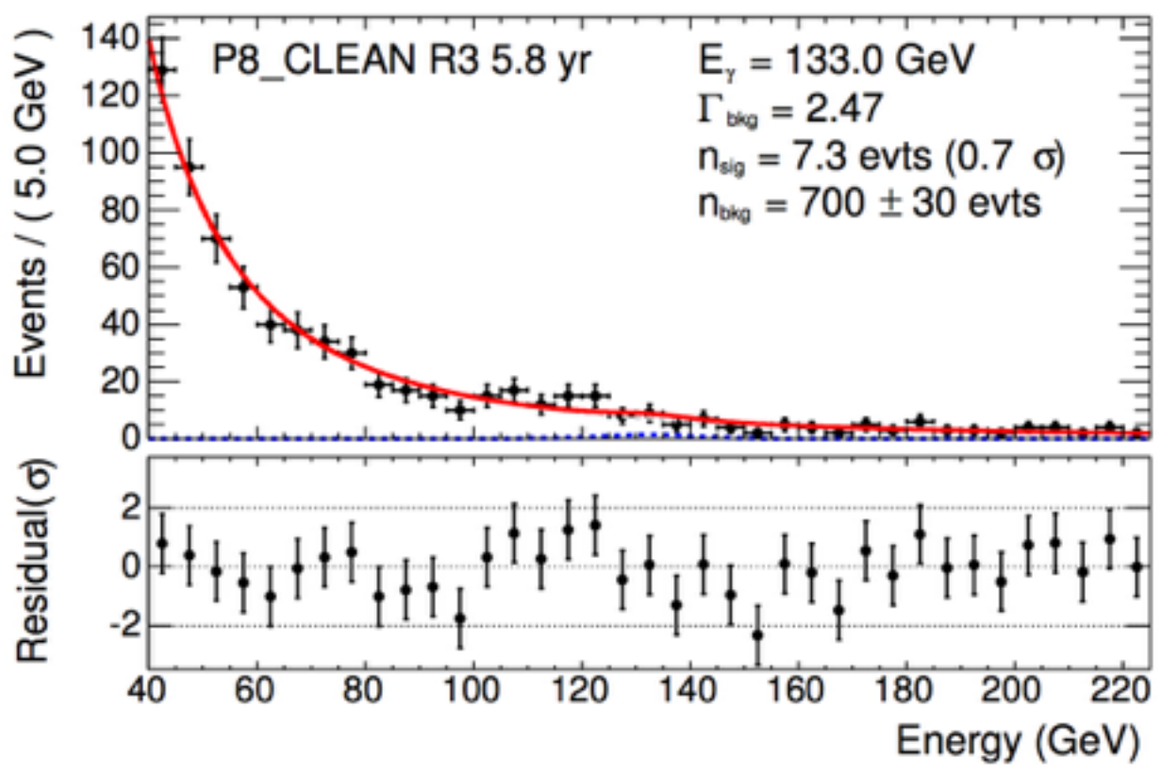
- Both leptonic and hadronic scenarios describe the spectrum well
  - hadronic model including IC emission from secondary leptons
- Leptonic model can explain microwave haze for B~8μG

GeV Excess Line

Ackermann+13 arXiv: 1305.5597



Ackermann+15 arXiv: 1506.00013

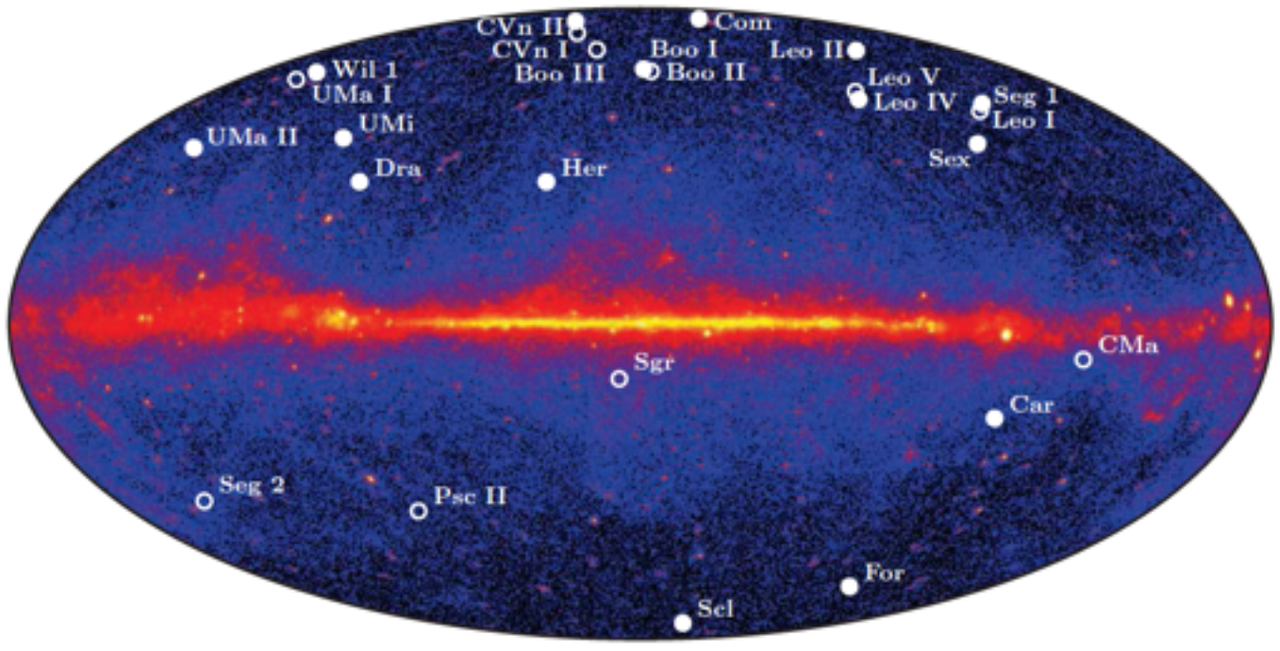


- **Tentative emission line from the Galactic center was reported at ~133 GeV in the first 3.7 year data (Pass 7)**

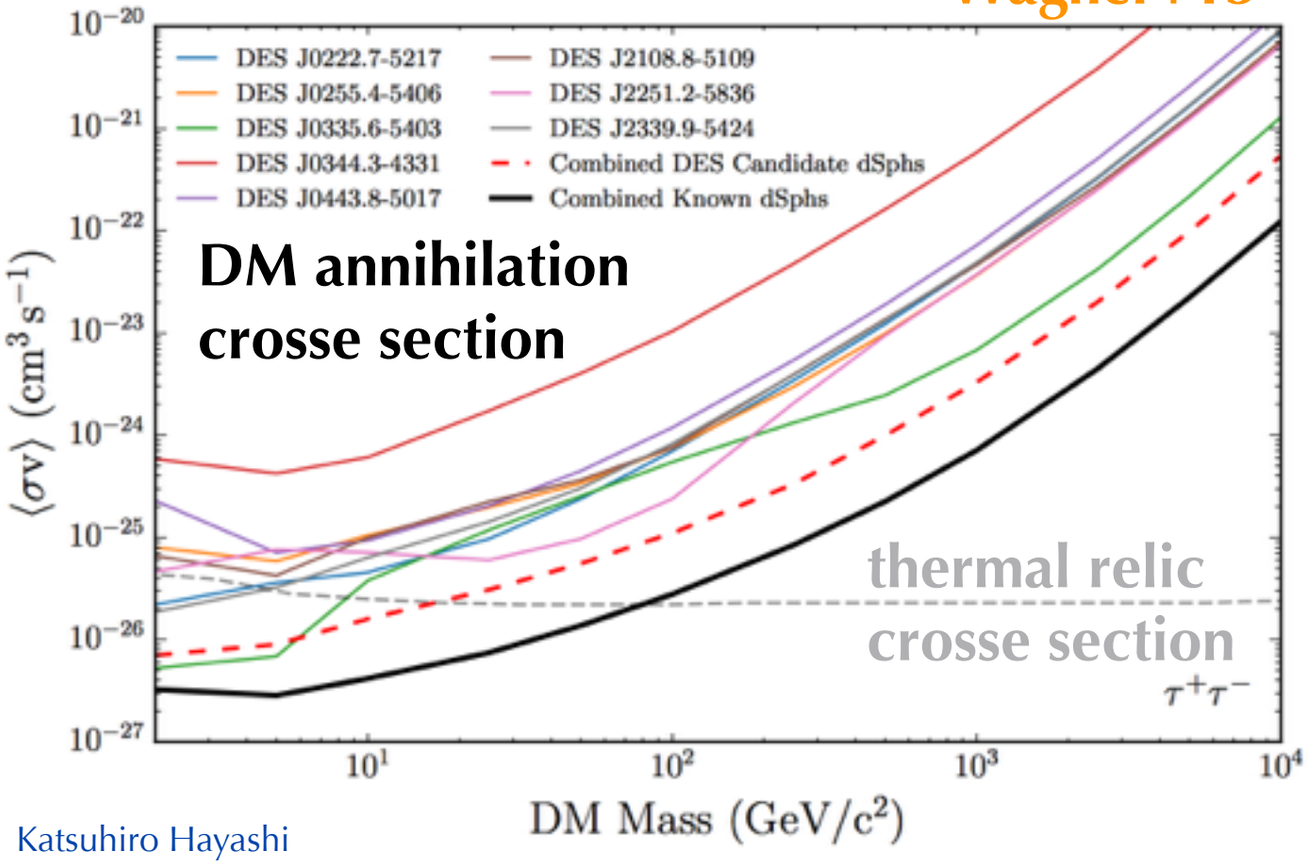
- **The excess has further decreased in the 5.8 year data (Pass 8)**
  - **The feature is still marginally significant for Earth limb data**
  - **More stacked data and sophisticated background models are needed**

DM Search (dSphs)

Ackermann+14 arXiv: 1310.0828



Wagner+15



- Dwarf spheroidal satellite galaxies (dSphs) are excellent targets for the indirect detection of dark matter
- New 8 dSphs candidates are found by DES
- No significant gamma-ray
- Upper limits on DM annihilation cross section from a combined analysis
- These constraints lie below the canonical thermal relic cross section for DM of mass < 100 GeV

Excess at Galactic Center

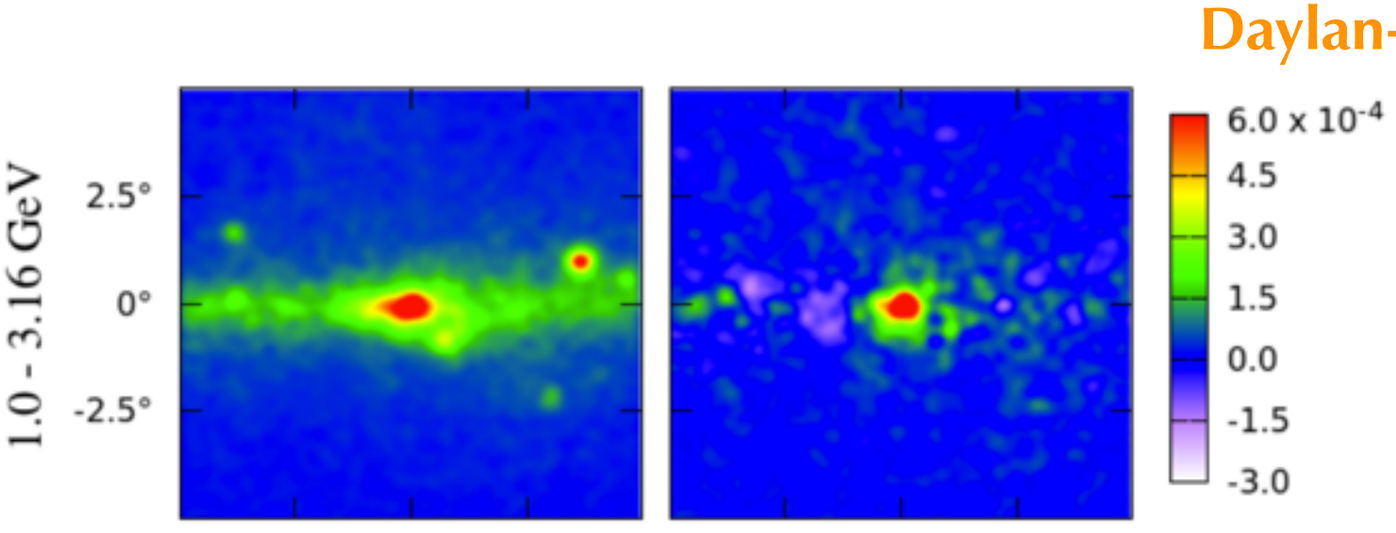
Excess at the Galactic Center

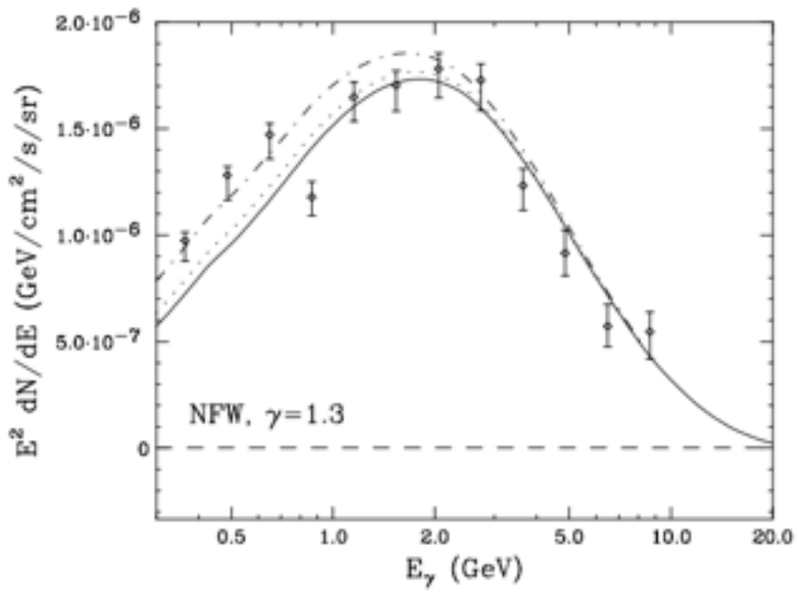
- **GeV gamma-ray excess at the Galactic Center is claimed in many papers**

Goodenough & Hooper+09, Vital & Morselli 09, Boyarsky+11, Abazjian & Kaplinghat 12, Abazajian+14, Daylan+14, Huang+15, Carlson+15, Ajello+15, Zhou+14, Calore+15…

- **Extended diffuse emission above**
  - **Galactic diffuse emission model**
  - **gamma-ray emission at Sgr A***
  - **other 2FGL sources**
- **Radial profile $F_\gamma \propto r^{-(2.2\text{-}2.6)}$**

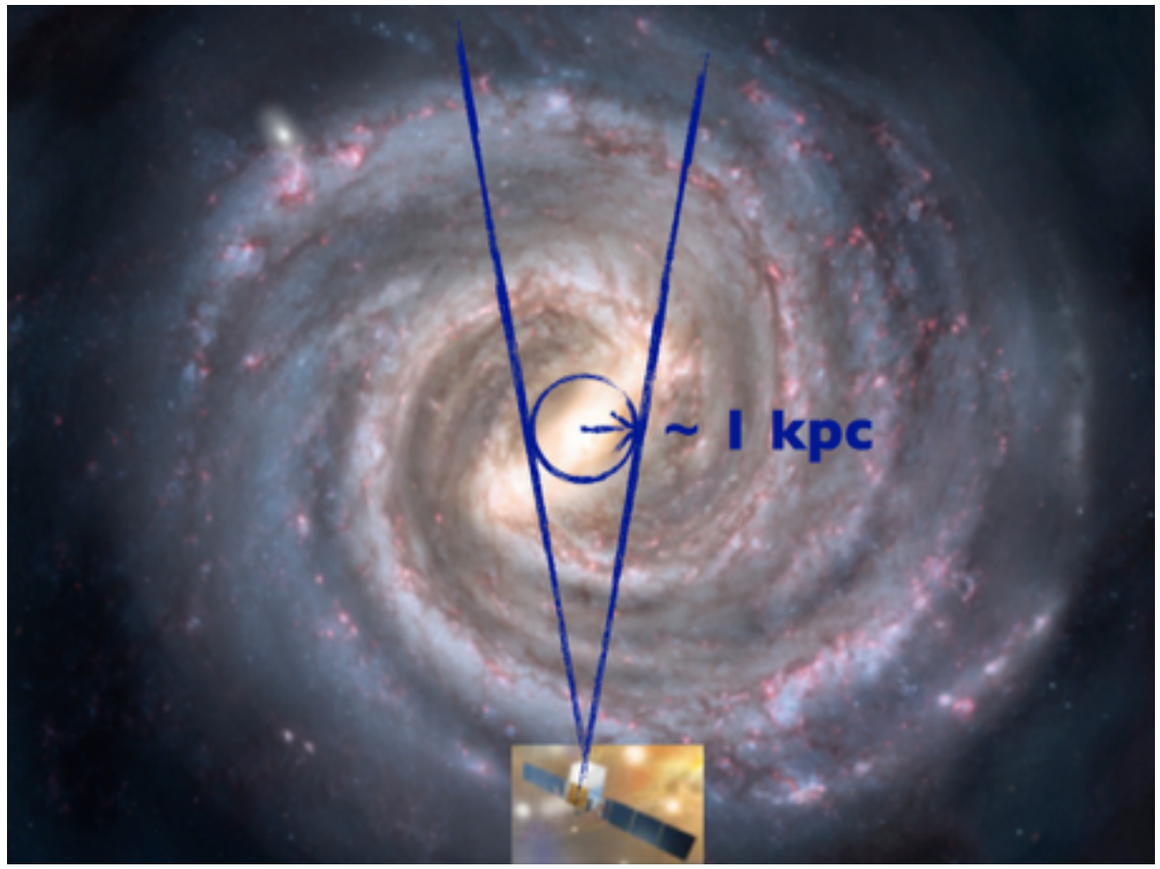
Daylan+14

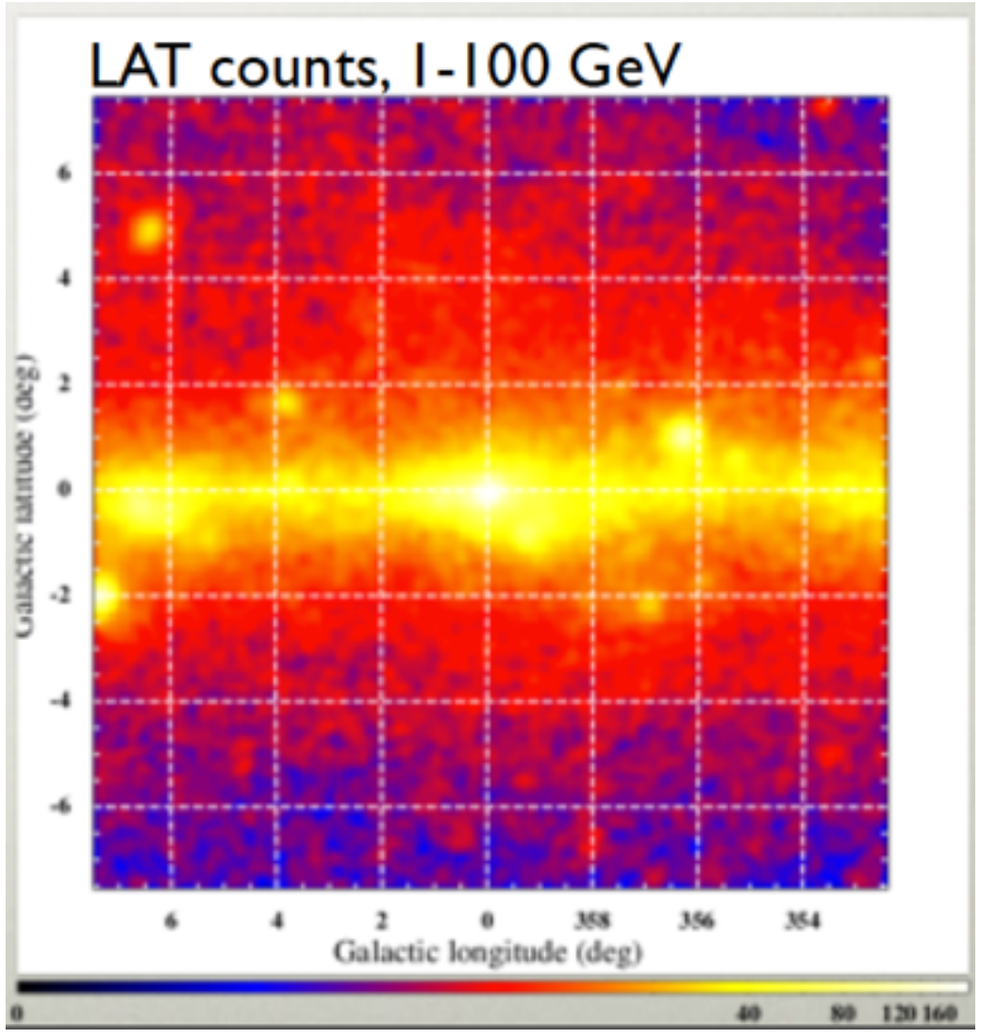




- **Caveats for using the Galactic diffuse emission model**
  <u>Model is optimized for reproducing all sky diffuse emission and not tuned for the analysis of specific region like the Galactic center</u>

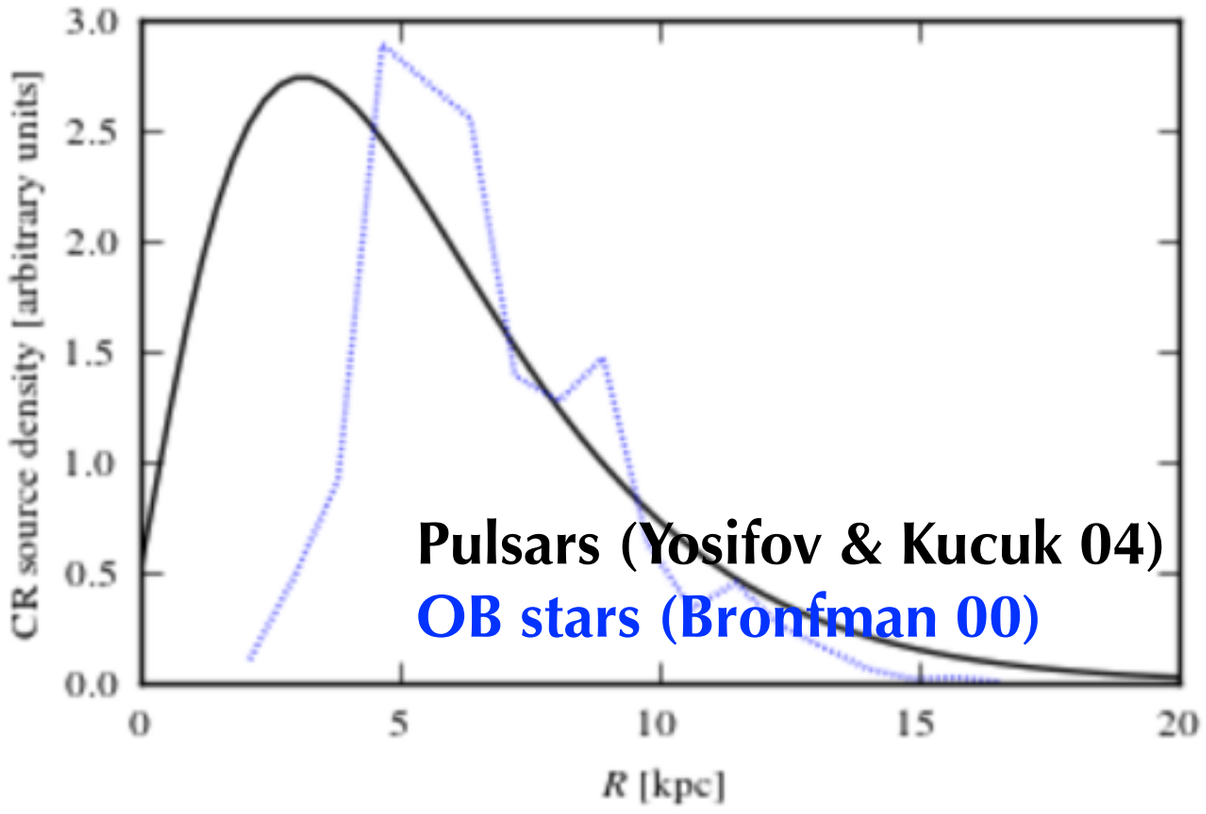
Detailed Analysis by LAT Team
(Ajello+15 arXiv: 1511.02938)





- **Focus on a 15°x15° region around the Galactic Center**
- **1 — 100 GeV data taken during 62 months**
- **<u>Constructed specialized interstellar emission models (IEMs)</u>**
  - **Separation of emission from the inner ~1 kpc about the GC from the fore- and background emission**

Modeling the Interstellar Emission

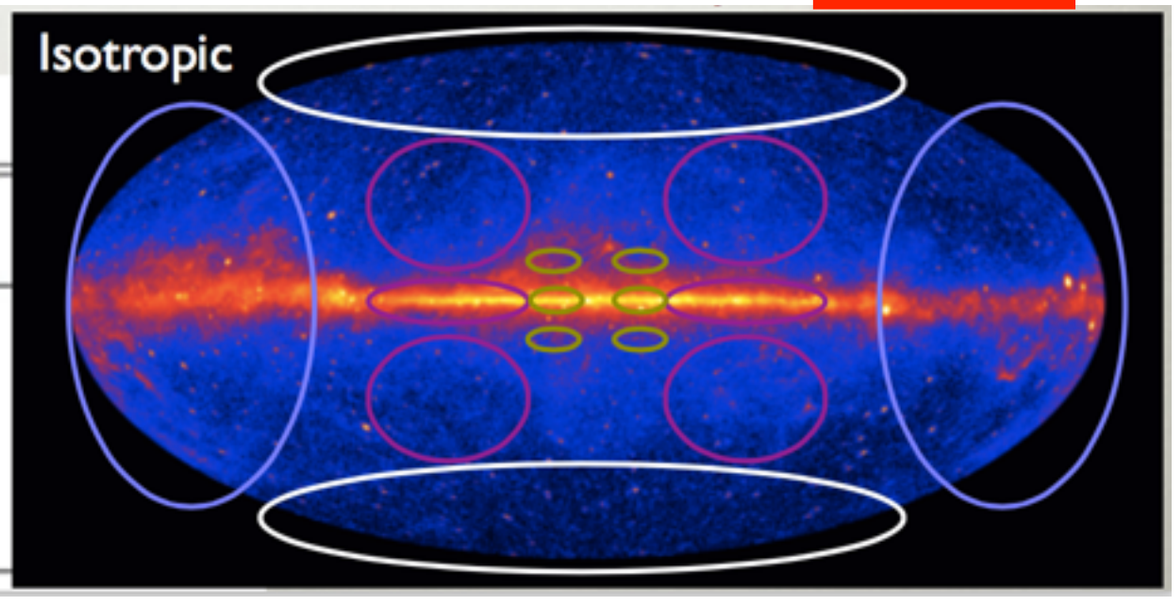


- **Construct IEM with a combination of templates from model GALPROP (Ackermann+12 arXiv: 1202.4039)**
  - **Two models of CR source distribution**
- **<u>Determine intensity for π^0 and IC contributions in galactocentric rings</u>**
  - **intensity scaled Pulsars/OBstars**
  - **intensity & index scaled model Pulsars/OBstars**

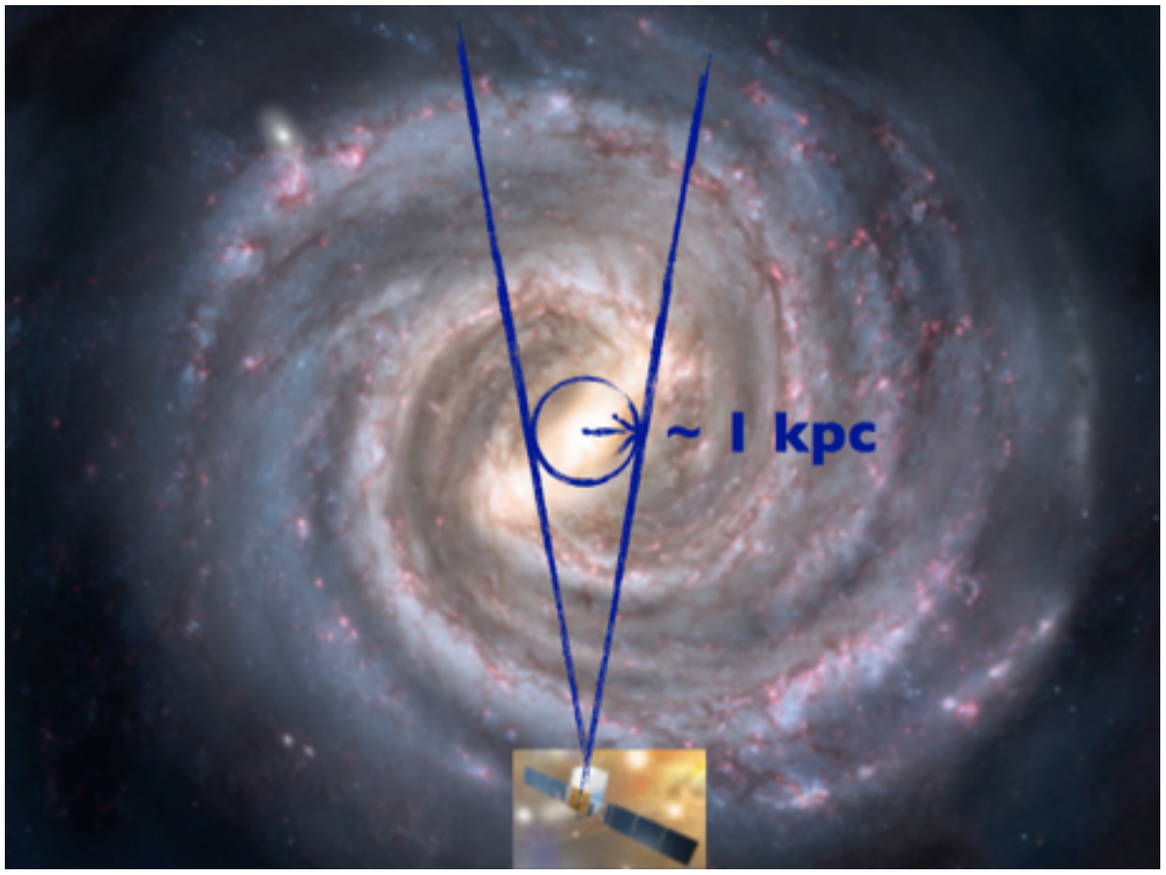
4 IEMs

Galactocentric ring boundaries.

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



Modeling the 15°x15° ROI



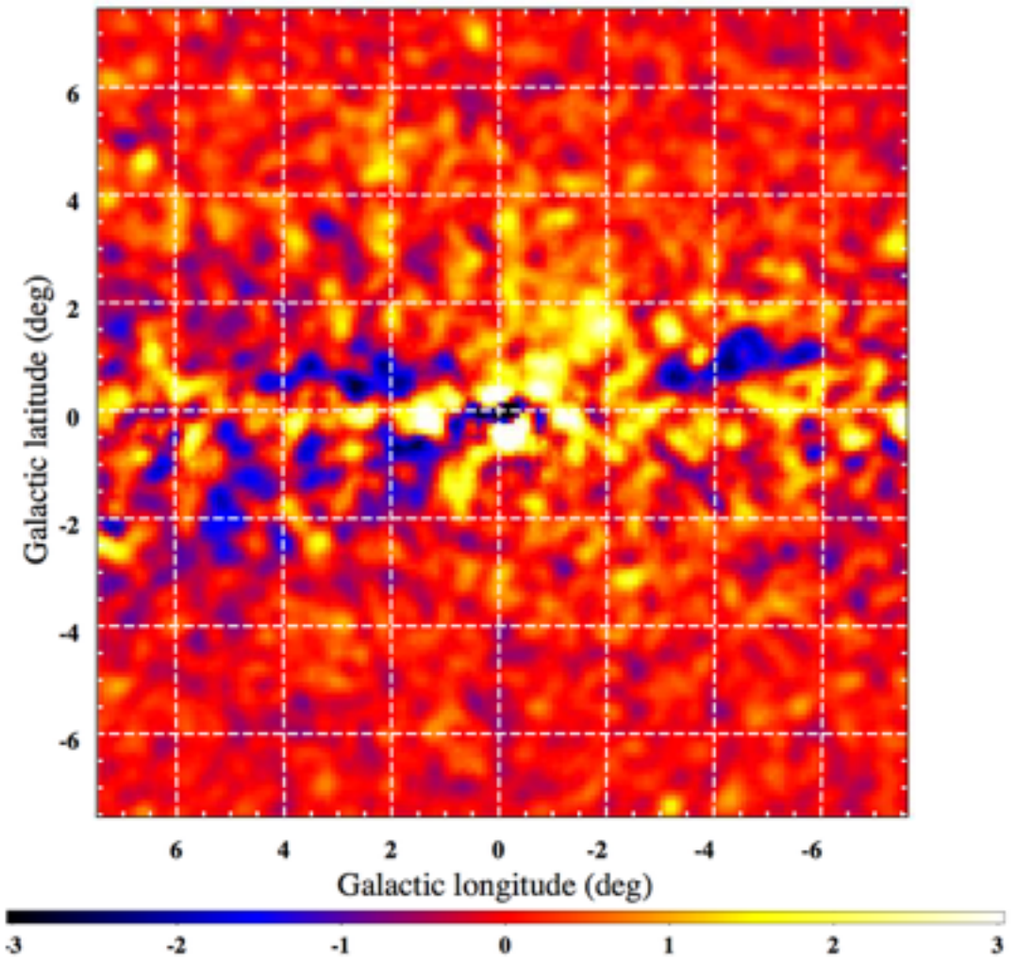
- Model the emission from 15°x15° ROI

- Point source model in ROI is self-consistently constructed
  - Identify point source candidates by "PGWave" (Damiani +97)
  - Find and characterize the point sources near the GC for each IEM

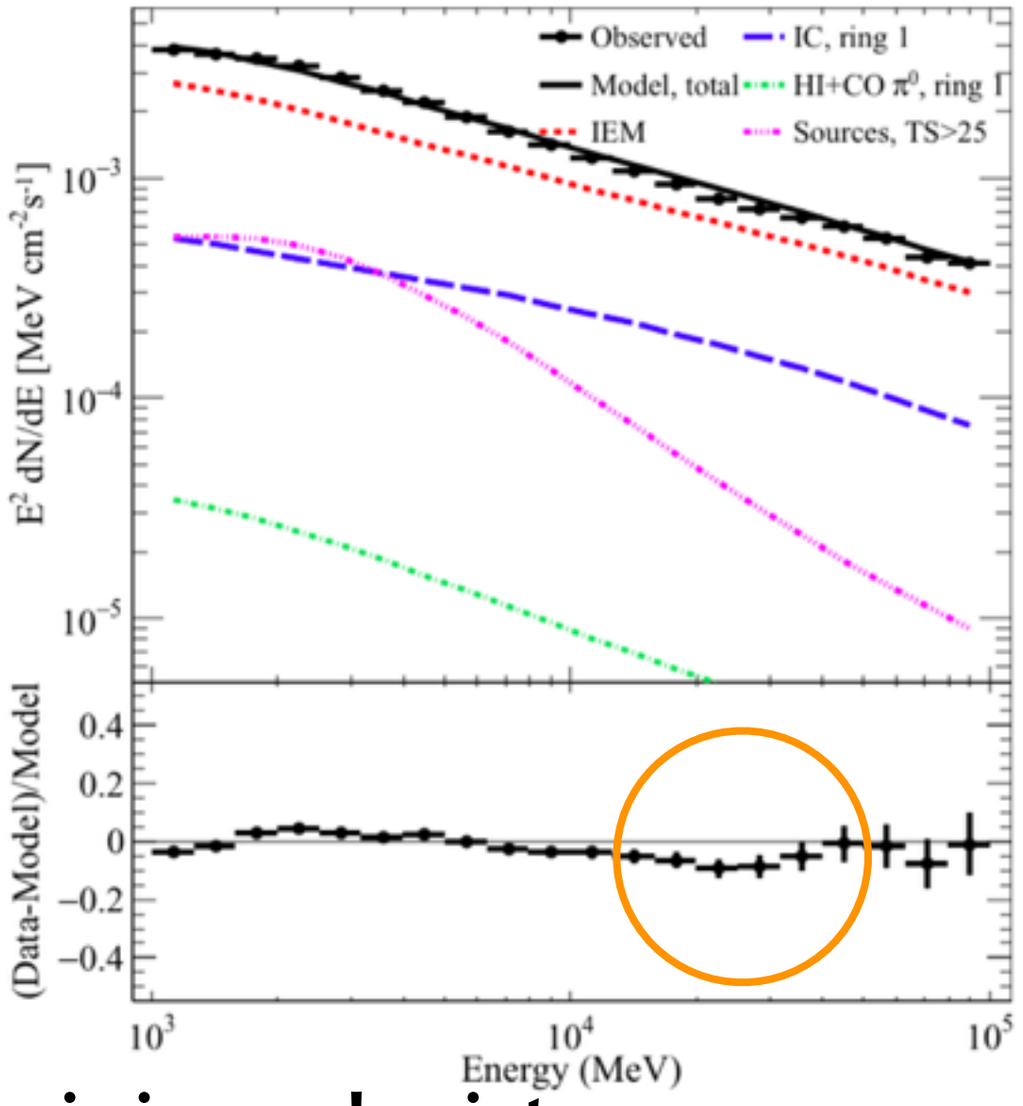
- Source-seeds and IEMs are combined in a maximum Likelihood fit
  - Intensities for HI/H_2 (π^0) and IC are determined by fitting data concurrently with point source candidates

- Bremsstrahlung and HII (π^0) emissions are fixed to GALPROP prediction

Fitting Results (Pulsars index-scaled)

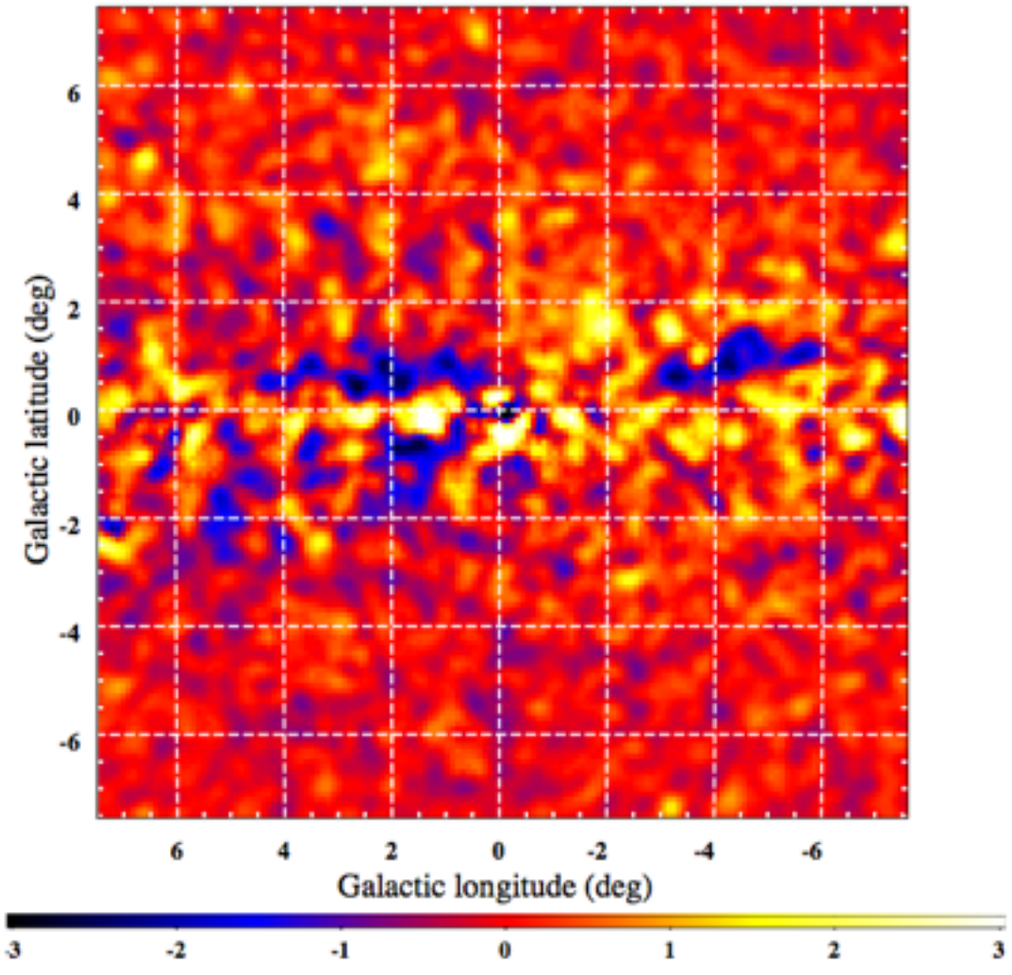


Residual Map(1.6–10 GeV)

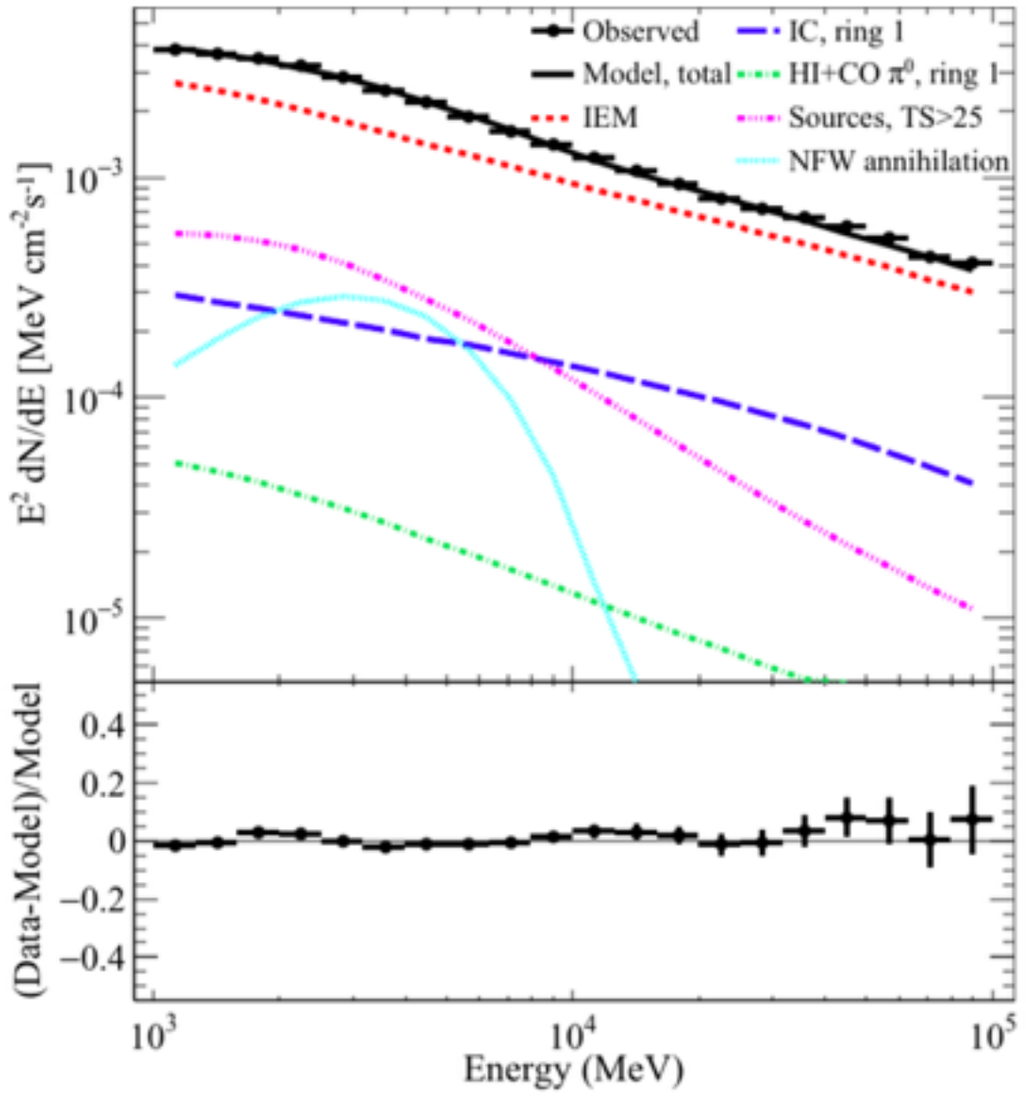


- Residuals map in which interstellar emission and point-source contributions are subtracted
  - Some general peaks are seen around the Galactic center
- IC contribution is dominant
  - strongly enhanced compared to previous studies

Fitting with Additional Component

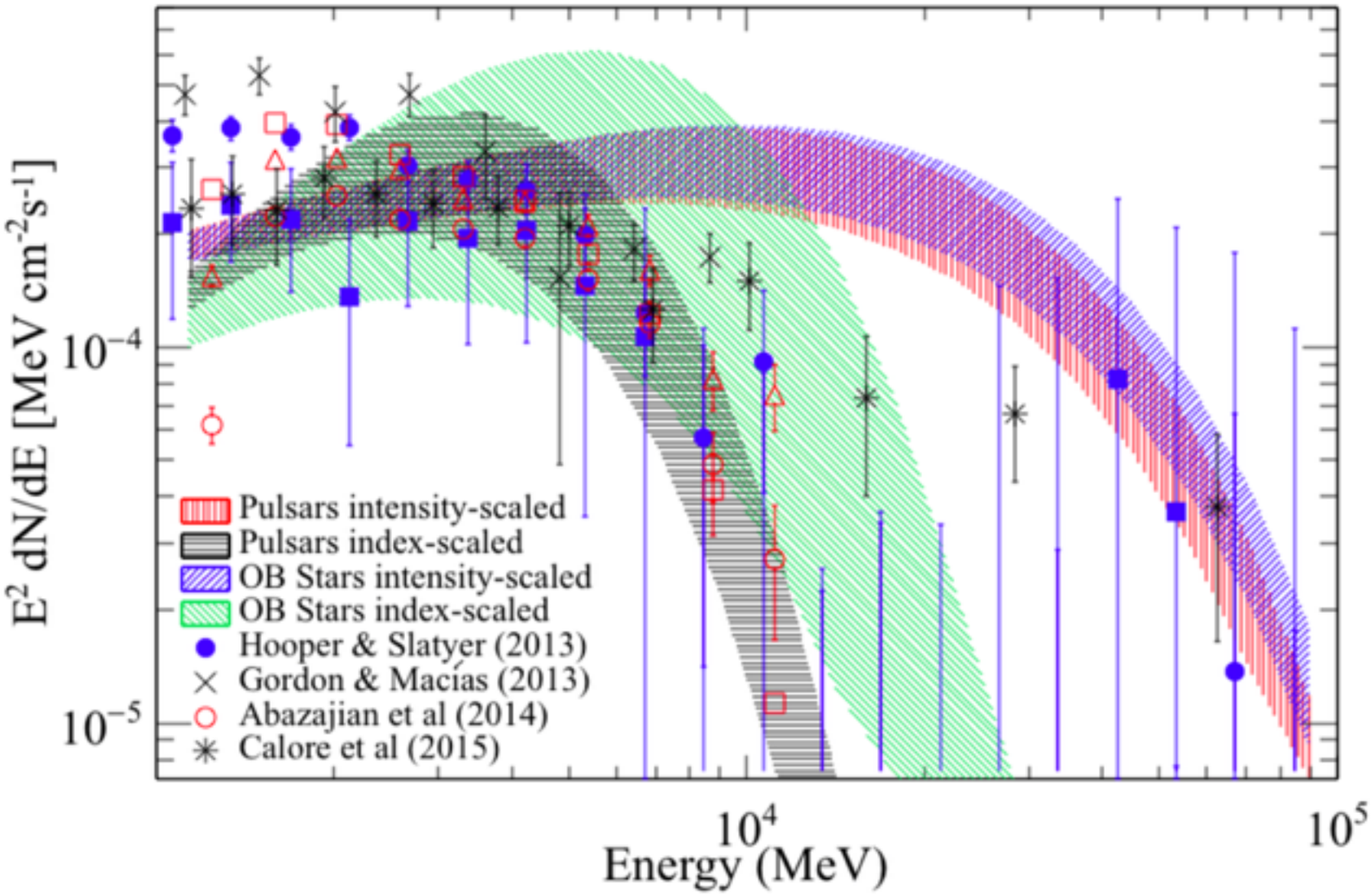


Residual Map(1.6–10 GeV)



- Test the possibility of additional components in the Galactic center
  - Centrally peaked template model (2D gaussian, NFW, unresolved sources)
- Overall improvement for all the spectral models up to ~30 GeV
  - IC is ~2-3x smaller, HI ring is ~2-5x larger
- Still has extended positive residuals on the Galactic plane

Spectrum Additional Component (NFW)



- Differential fluxes in the ROI of the additional component (NFW model)
  - Spectra are modeled with an exponential cut-off power-law with fit uncertainties for the normalization and spectral-index
- Different spectral shapes depending on the IEMs
  - Interpretation for residuals is difficult

Possible Interpretations

- **DM annihilation** (Hooper & Goodenough 09; Vitail & Moselli 09)
  - Typical DM annihilation spectra, cross-section

- **Star formation in central molecular zone** (Carlson +15)
  - IC emission from electrons accelerated by star formation

- **Leptonic outburst from the SMBH** (Petrovich +13)
  - Multiple bursts with varying injection indices could do the trick

- **Millisecond gamma-ray pulsar** (O'Leary +15; Bartels+15)
  - MSP in globular clusters, spilled out into the bulge by tidal disruption

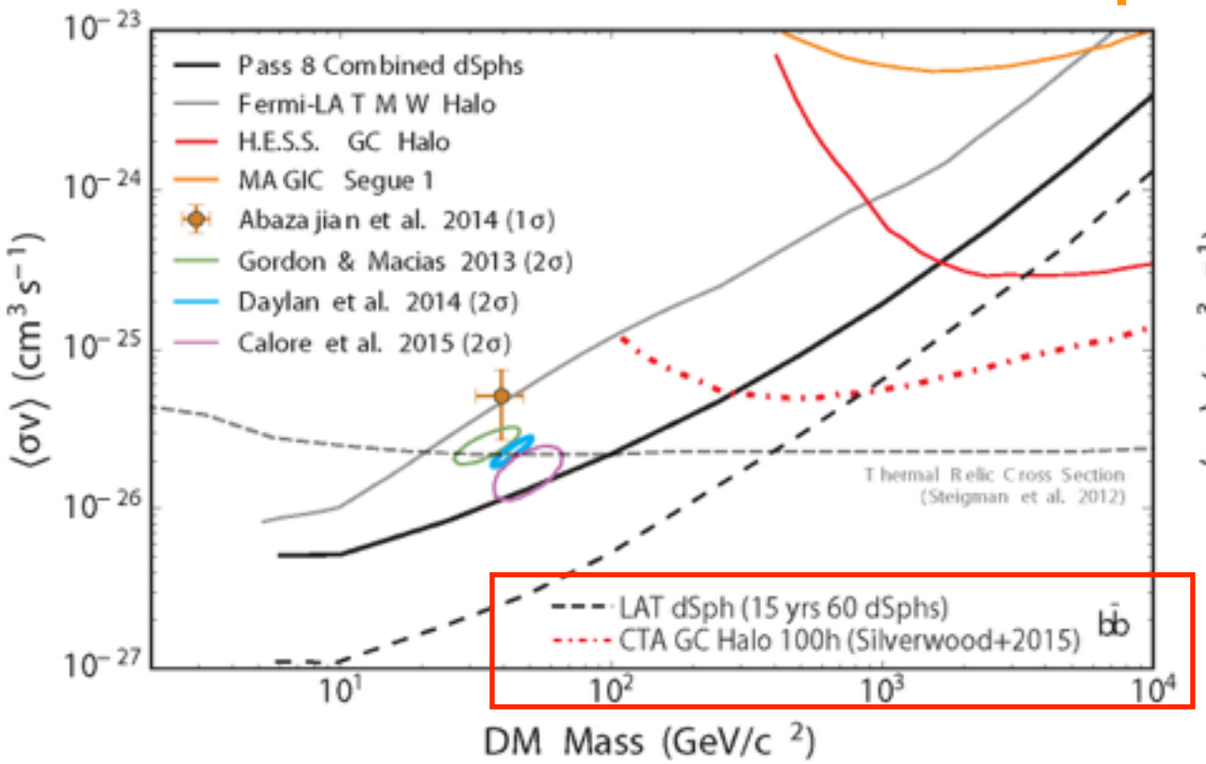
- **Unresolved point sources** (Lee+15)
  - By using Wavelet analysis, 5-10% of the flux can be accounted for by a population of unresolved point sources, which can absorb the excess

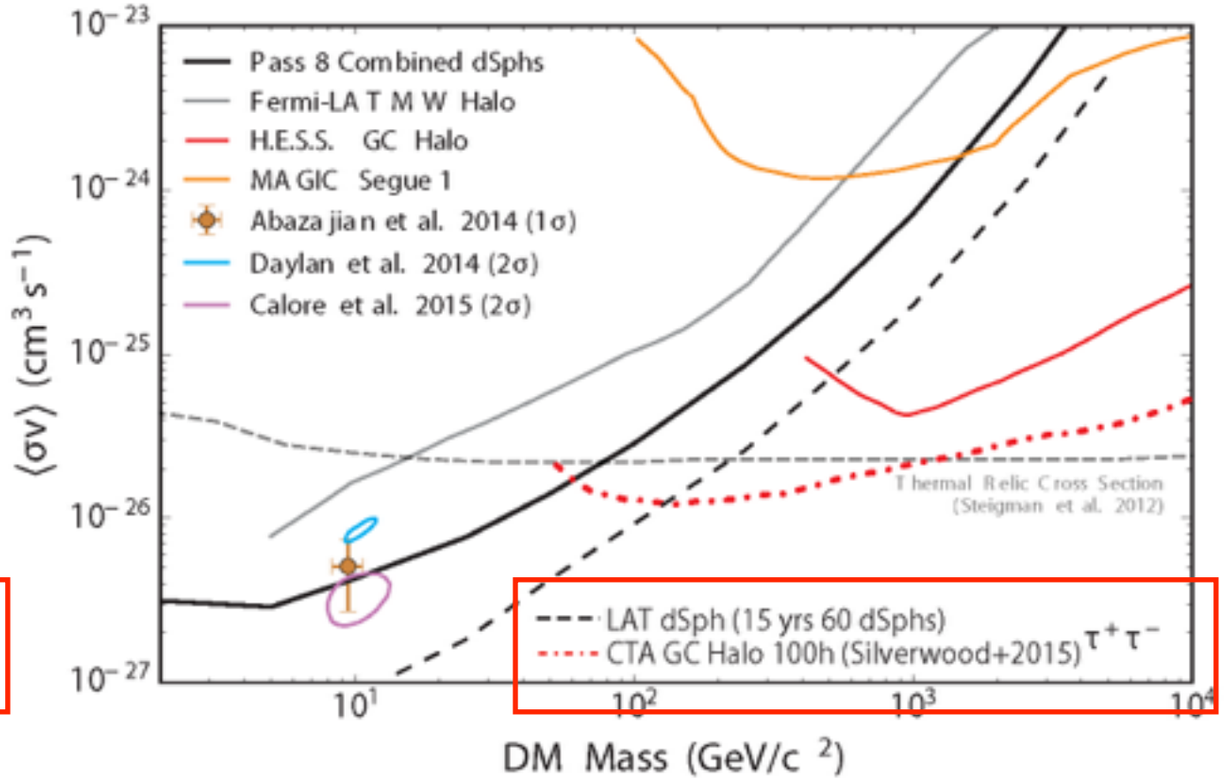
Future Prospectivity

- More stacked data can reduce systematic uncertainties in the diffuse emission model, and define better source populations.
  → Resolve the interpretation of the inner Galaxy GeV excess
- Thermal relic cross section for WIMP masses in 200—400 GeV by observations of dSphs → hint of DM origin from the Galactic Center
- CTA necessary to probe WIMP models ~1 TeV

Ackermann+15 arXiv: 1503.02641

DM annihilation crosse section **expected sensitivities of LAT and CTA are overlaid**





Summary

- **Fermi-LAT yields significant progress on the study of Galactic GeV gamma-ray sources (substantial improvement of the response function)**
  - **Update of catalog sources (3FGL, 2FHL, pulsar, SNR)**
  - **Gamma-rays from binary systems (nova, pulsar)**
  - **SNR study (individual and systematic studies)**
  - **Diffuse gamma-rays (ISM/CR, Fermi Bubble)**
  - **Dark Matter search (GeV line, dSphs)**
  - **Excess at the Galactic Center**
    - **Detailed analysis subtracting fore/backgrounds emissions**
    - **Residuals are robust but the cause is still unclear**
- **More stacked Fermi-LAT data and CTA results are expected to be advanced for further study of Galactic GeV gamma-ray sources**