Fermi-LAT Observations of Supernova Remnants

T. J. Brandt

On behalf of the Fermi-LAT Collaboration

NASA/Goddard Space Flight Center

theresa.j.brandt@nasa.gov

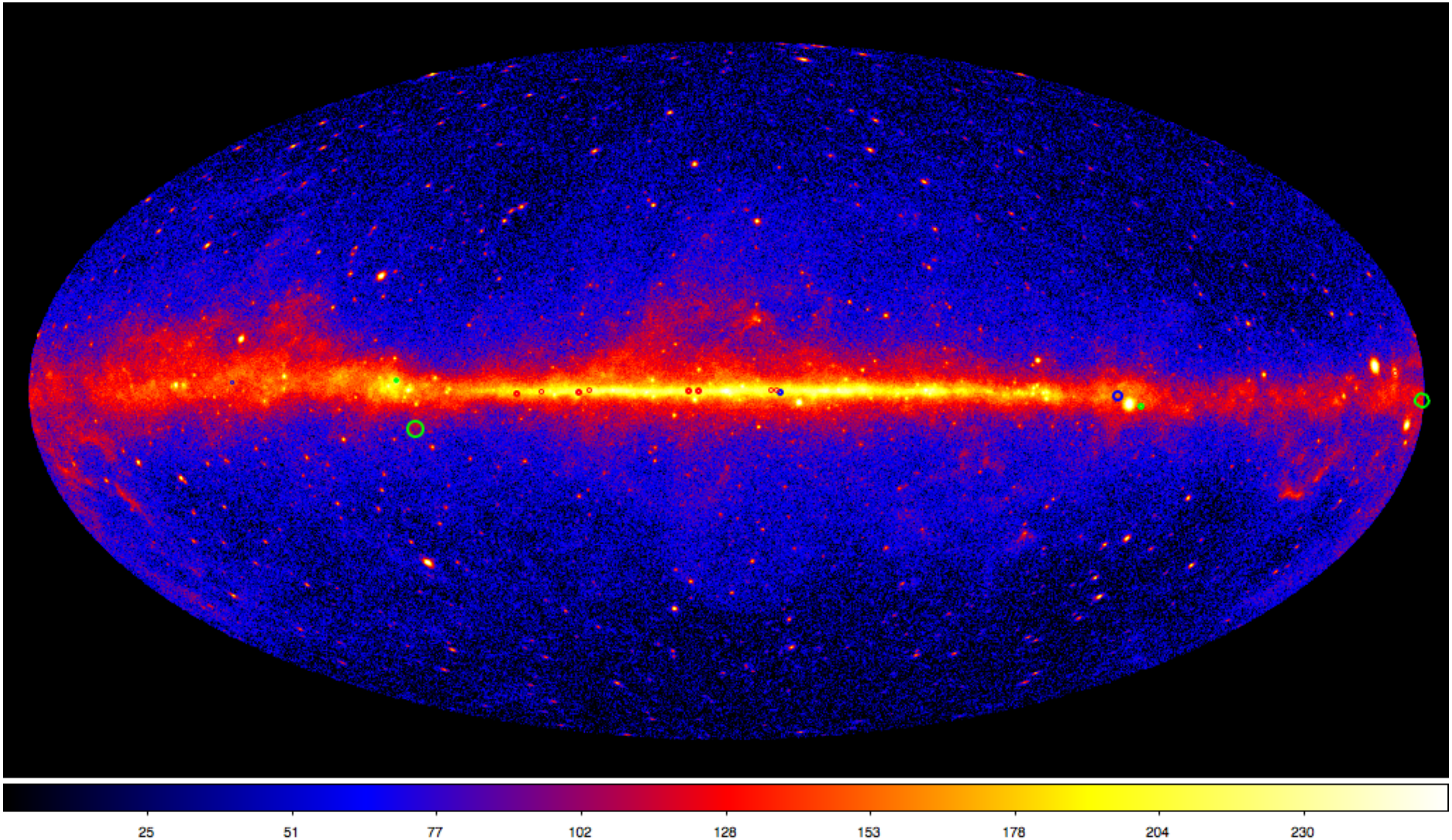
AAS 219: 10 Jan 2012

g-cygni extra?

Fermi-Detected SNRs

16(17) identified SNRs, including

- 9 interacting with Molecular clouds
- 4 young SNRs



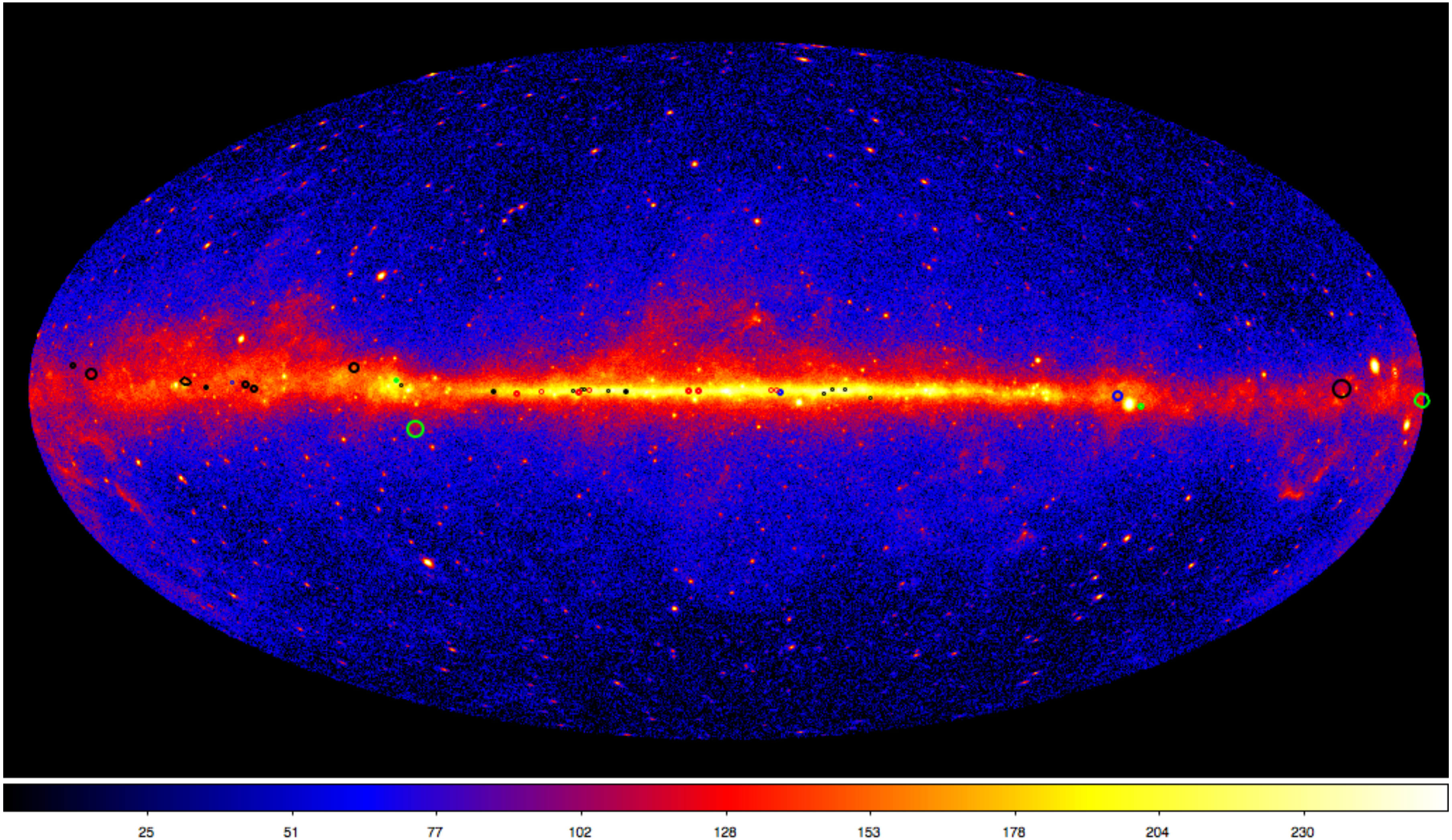
g-cygni extra?

Fermi-Detected SNRs

16(17) identified SNRs, including

- 9 interacting with Molecular clouds
- 4 young SNRs

+ 23 2FGL candidates

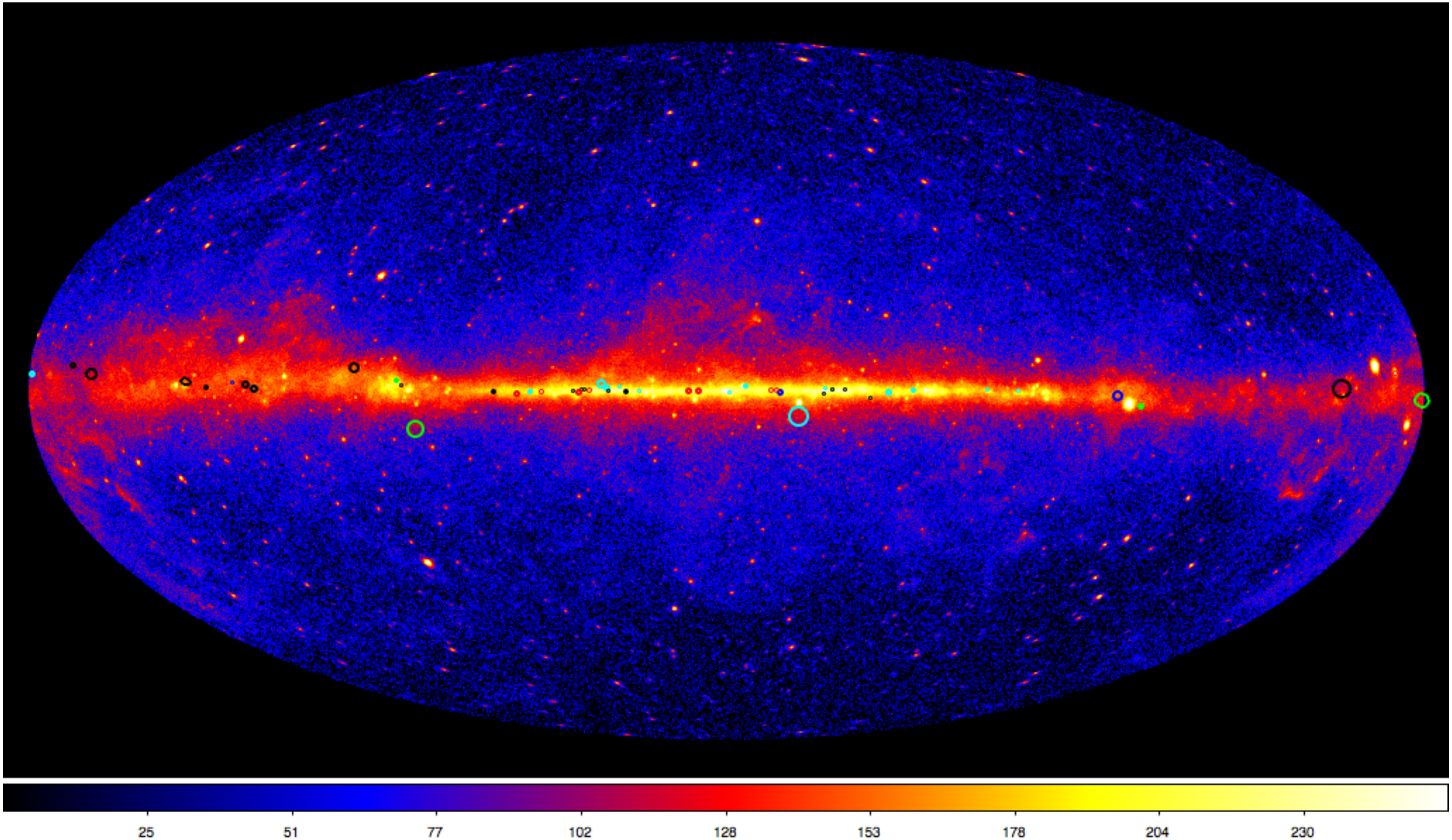


g-cygni extra?

Fermi-Detected SNRs

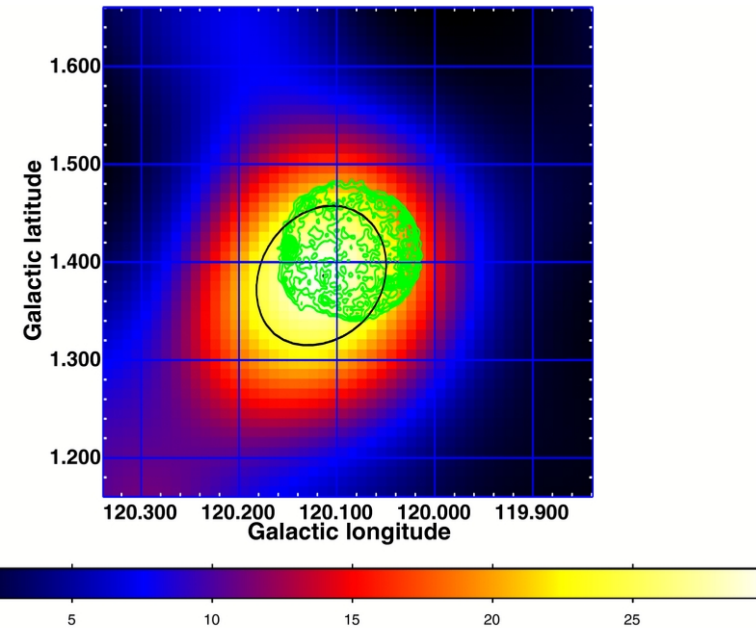
16(17) identified SNRs, including
- 9 interacting with Molecular clouds
- 4 young SNRs

+ 23 2FGL candidates
+ 19 candidates near a PSR,PWN, or AGN



Tycho: a Young SNR

XMM-Newton (4.5-5.8keV)

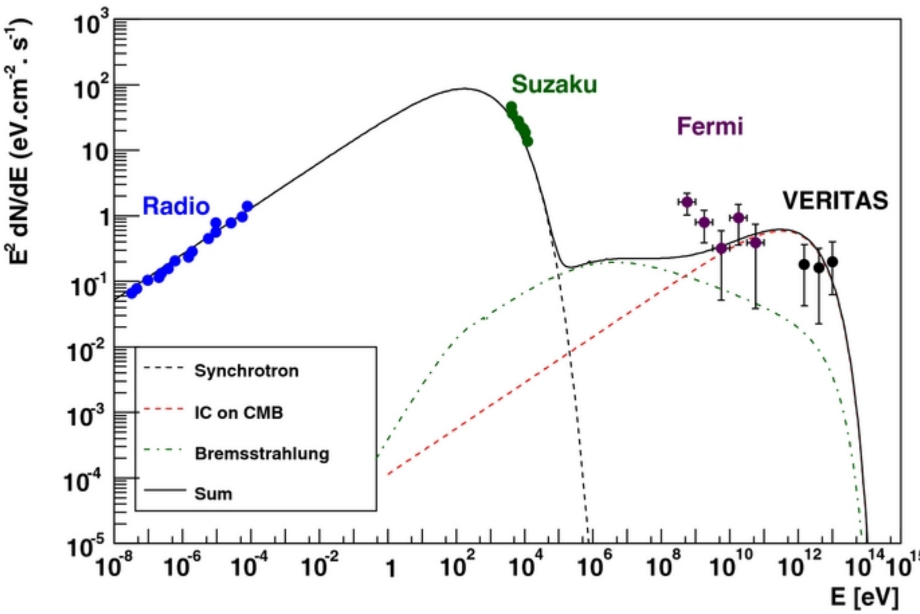


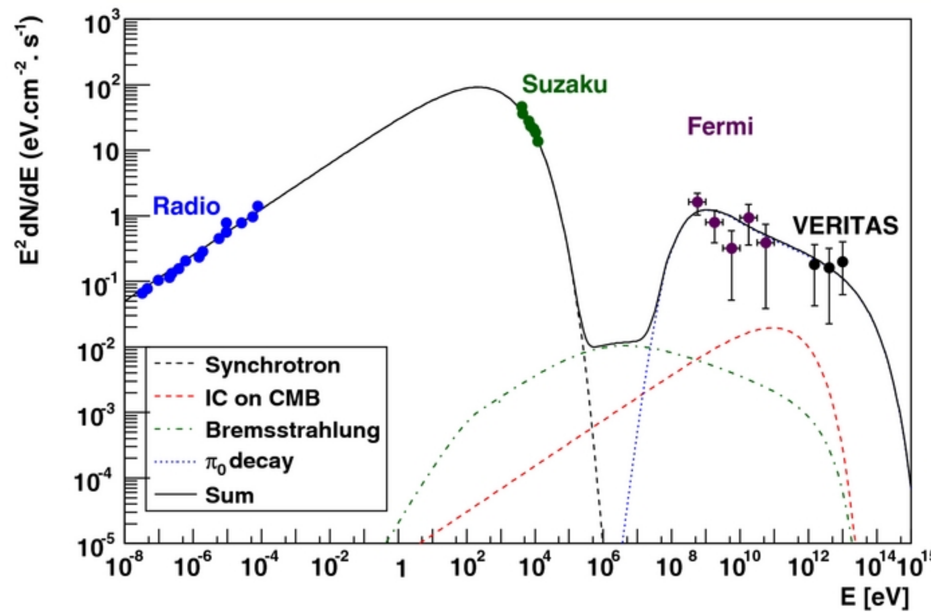
Detection: Fermi-LAT 3yr data shows non-variable emission from a region coincident with the MW SNR.

Spectral study: MW modeling suggests emission is best-fit with π0-decay + minimal IC and brem, making this a hadron-dominated SNR.

Energetics suggest ~10% of the energy goes into CRs.

Black contour: position at 95% confidence





F. Giordano et al. 2012 ApJ 744 L2

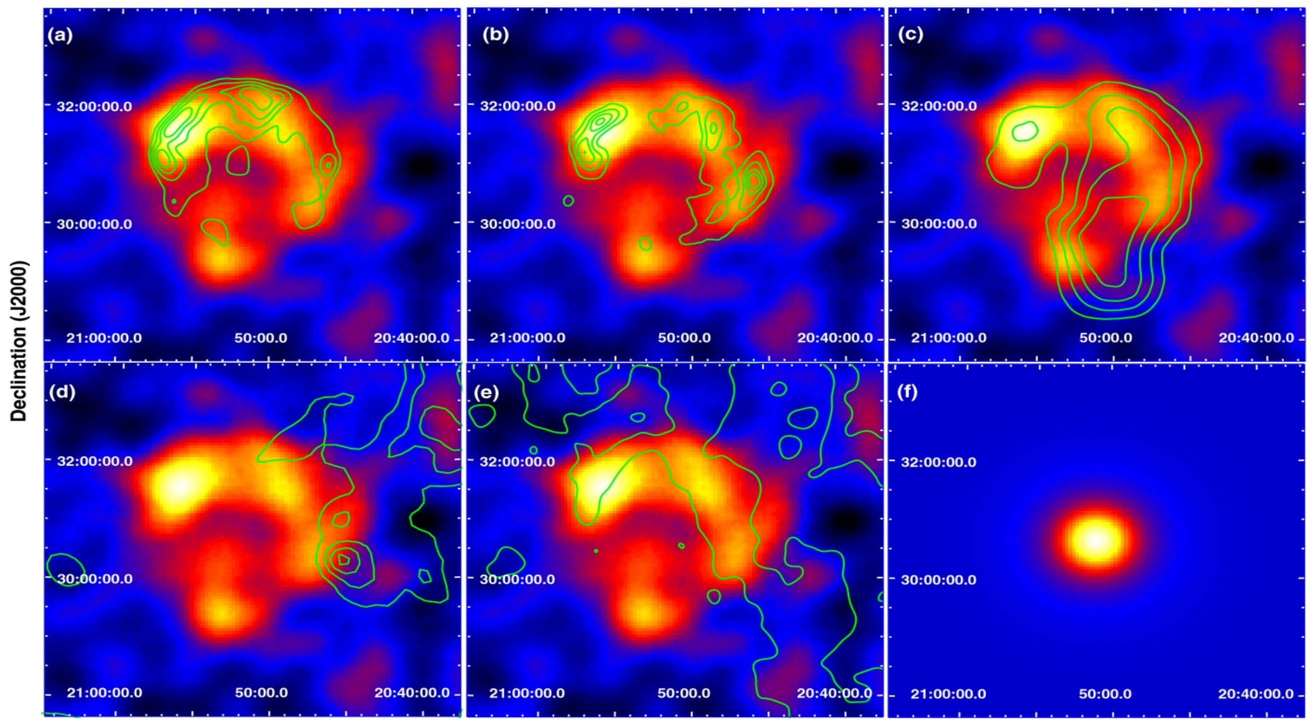
Morphology:

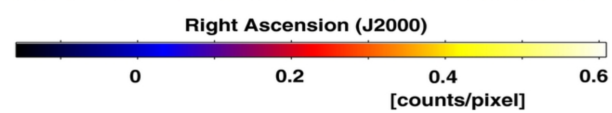
Detection: ~10 of the currently identified SNRs show extended emission.

Morphology: consistent with (some) MW emission improves our understanding of the particle populations and acceleration mechanisms in the source.

Cygnus Loop: shows emission consistent with X-ray, Hα, and (some) radio but not CO or IR.

As the Fermi-LAT data-set increases, we will both ID more SNRs and better understand their emission using their morphology.





LAT count map: 0.5-10 GeV, background subtracted.
Green contours correspond to:

a) 0.1-2keV, cleaned ROSAT **X-ray** emission
b) Hα DSS image (POSS-II F, cleaned)
c) 1420 MHz **radio** continuum emission (Reich 1982)
d) ^{12}**CO** (J = 1 → 0) integrated (-25 km/s ≤ v ≤ 30 km/s) line intensities (Dame et al 2001)
e) 100μ **IR** intensity map (IRAS, Beichman et al 1988)
(f) Effective LAT PSF for photons with a power law index of 2.5

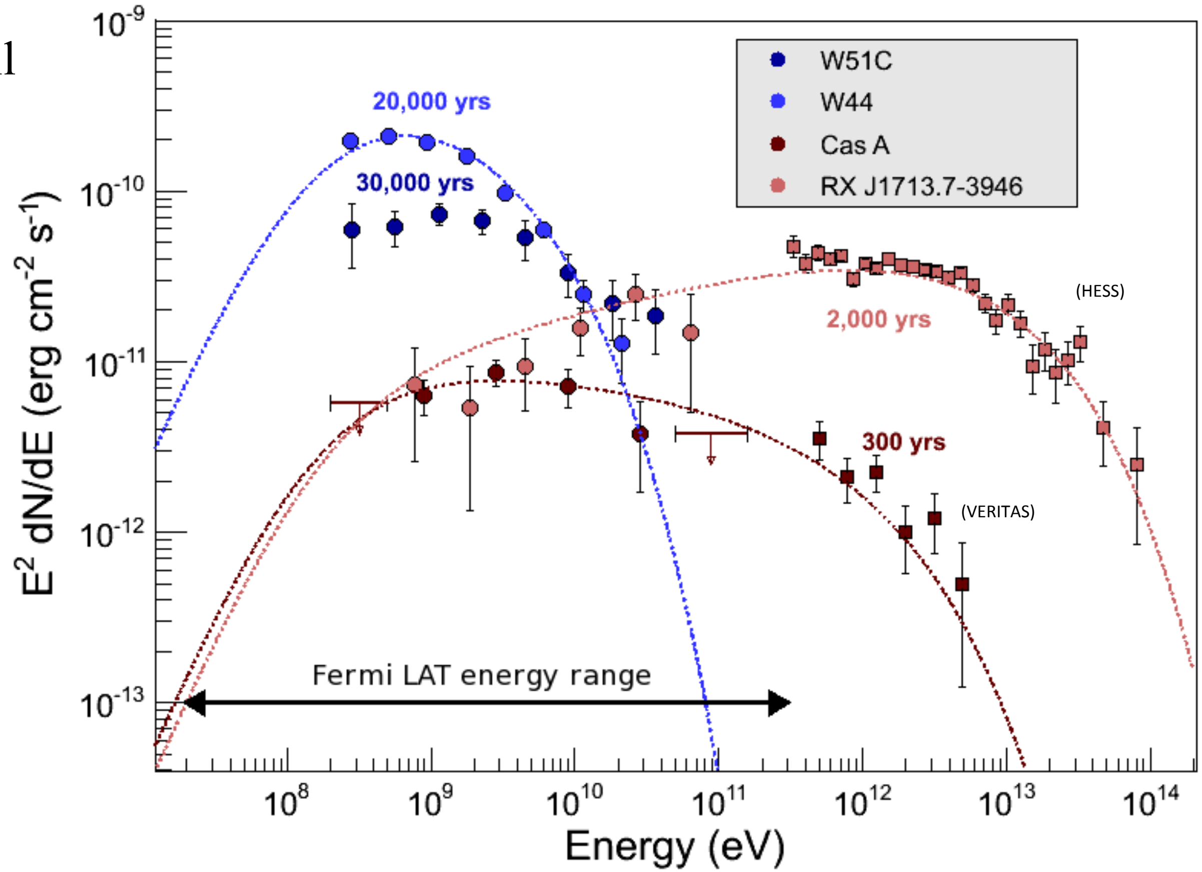
Katagari et al., 2011, ApJ, 741, 44

Multiwavelength SNR Spectra:

Catalog: by combining a uniformly derived understanding of many SNRs particle populations and acceleration mechanisms, we will be able to

- identify classes of γ-ray SNRs
- study their temporal evolution
- understand the role of environment

Cosmic Rays: with an aggregate understanding of SNRs ability to accelerate hadrons, we come substantially closer to evaluating their ability to supply the observed galactic CRs.



Spectral energy distributions for representative SNRs studied with Fermi and ground-based γ-ray observatories. Older SNRs are generally brighter in the GeV band and fainter in the TeV band.

Will be updated
And include reference(s) to poster(s)

Fermi-Detected SNRs:

	Fermi-detected SNRs	Index [1]	Index 2	E_{Break} (GeV)	Age (yrs)	Notes
Young [2]	Casssiopeia A	−2.1 ±0.1	-2.4**	>100	330	[1]
	Tycho	−2.3 ± 0.1			438	[2]
	Vela Jr.	-1.87 ± 0.2	-2.1**		680	[3]
	RX J1713	-1.5 ± 0.1	-2.2**		1600	[4] Lepton-dominated
Middle-aged / Likely hadronic processes	CTB 37A	−2.28 ± 0.1	-2.3 ± 0.3**		1500?	[5]
	W49B	−2.18 ± 0.04 −2.29 ± 0.02	−2.9 ± 0.2	4.8 ± 1.6	1k-4k	[6] PL disfavored at 4.4σ
	Cygnus Loop	-1.83 ± 0.06	-3.23 ± 0.19	2.39 ± 0.26	20k	[7] No clear MC interaction
	IC 443	−1.93 ± 0.03	−2.56 ± 0.11	3.25 ± 0.6	3-4k or 20-30k	[8]
	W44	−2.06 ± 0.1	−3.02 ± 0.22	1.9 ± 0.5	~20k	[9]
	W51C	−1.97 ± 0.08	-2.44 ± 0.09	1.9 ± 0.2	~30k	[10]
	W28 (N) (and G6.5-0.4)	−2.09 ± 0.36	−2.74 ± 0.15	1.0 ± 0.2	35-150k (40k)	[11]

[1] for Power Law or I1 for Broken Power Law
[2] See Giordano, this conference.
**from VHE measurement

… 16 and counting!

including W30, G349.7+0.2, 3C391, W41, …

[1] Abdo et al. 2010 (ApJL 720)
[2] Neumann-Godo 2011, Fermi Symp.
[3] Taka 2011, Fermi Symposium
[4] 2011arXiv1103.5727A
[5] Brandt 2011, Fermi Symposium
[6] Kadagiri H. et al., Submitted to ApJ
[7] Abdo et al., 2010 ApJ 718
[8] Abdo et al., 2010 (ApJ 722)
[9] Abdo, et al. 2010 (AJ 712, 459)
[10] Abdo et al., 2009 (ApJ 706L)
[11] Abdo, et al. 2010 (Sci. 327, 1103)

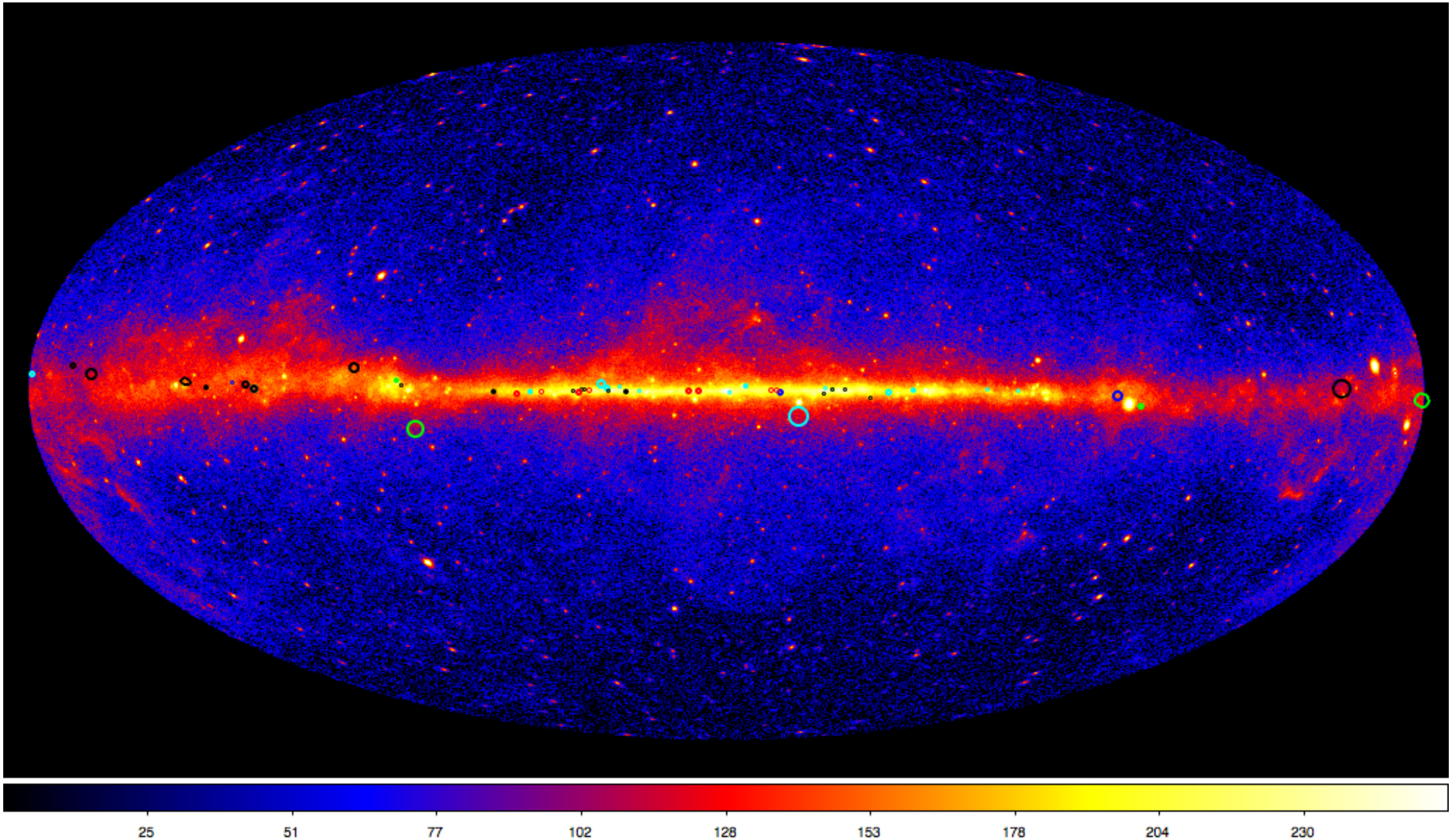
End of slide show

g-cygni extra?

Fermi-Detected SNRs

16(17) identified SNRs, including
- 9 interacting with Molecular clouds
- 4 young SNRs

+ 23 2FGL candidates
+ 19 candidates near a PSR,PWN, or AGN



With only a few years' data, the Fermi Gamma-ray Space Telescope has already provided a wealth of new GeV-detected Supernova Remnants (SNRs). Long held as suspects for galactic cosmic ray (CR) acceleration, emission up to 100 TeV implies that at least some of the SNRs can contribute to the galactic CR population. With well-resolved spectra and morphological studies, Fermi-LAT data allows us to better characterize the SNRs' particle populations and acceleration mechanisms, bringing us closer to quantifying their contribution to the observed galactic cosmic rays. Such clues may bring us substantially closer to solving the 100-year mystery of CR origins. We will review the SNRs detected thus far and discuss their properties, including as they relate to CR acceleration.

- Review
    - SNRs detected:
        - 23 + 4+4+9 (2FGL cand + young + id'd + MC-interacting)
    - their properties: inc part. pops + accel mech => CRs
        - well-resolved spectra
        - + morphological studies
    - => better characterize particle pops and accel mechs
    - => quantify gal CR contribution

Fermi Detection of CTB 37A:

Location & extension consistent with radio & H.E.S.S. data as well as nominal CTB 37A position.

- Detected with 18.6σ

- Radio contours
- H.E.S.S. detection
- Fermi detection
- XMM contours (MOS1: 0.2-10keV)

Location:

- RA = 258.68°± 0.05 ± 0.004
- Dec = -38.54°± 0.04° ± 0.02

Extension:

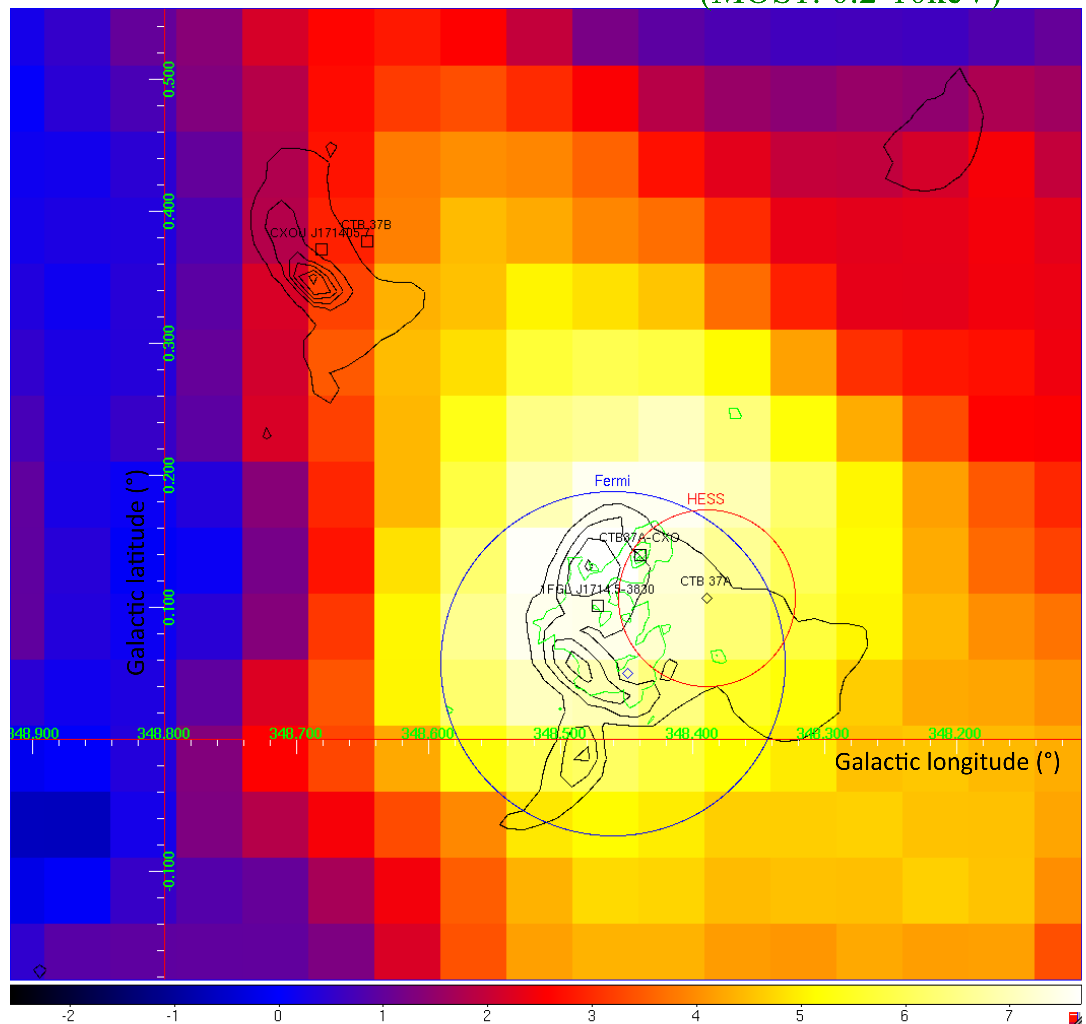
- 0.13° ± 0.02° ± 0.04°
- Significance: ~4.5σ

Position and extension stable for

- 4 of the reasonable diffuse models ~ spanning the parameter space
- high energy events (2-50 GeV)
- "Front" events (inherently better PSF)

Variability: None yet observed

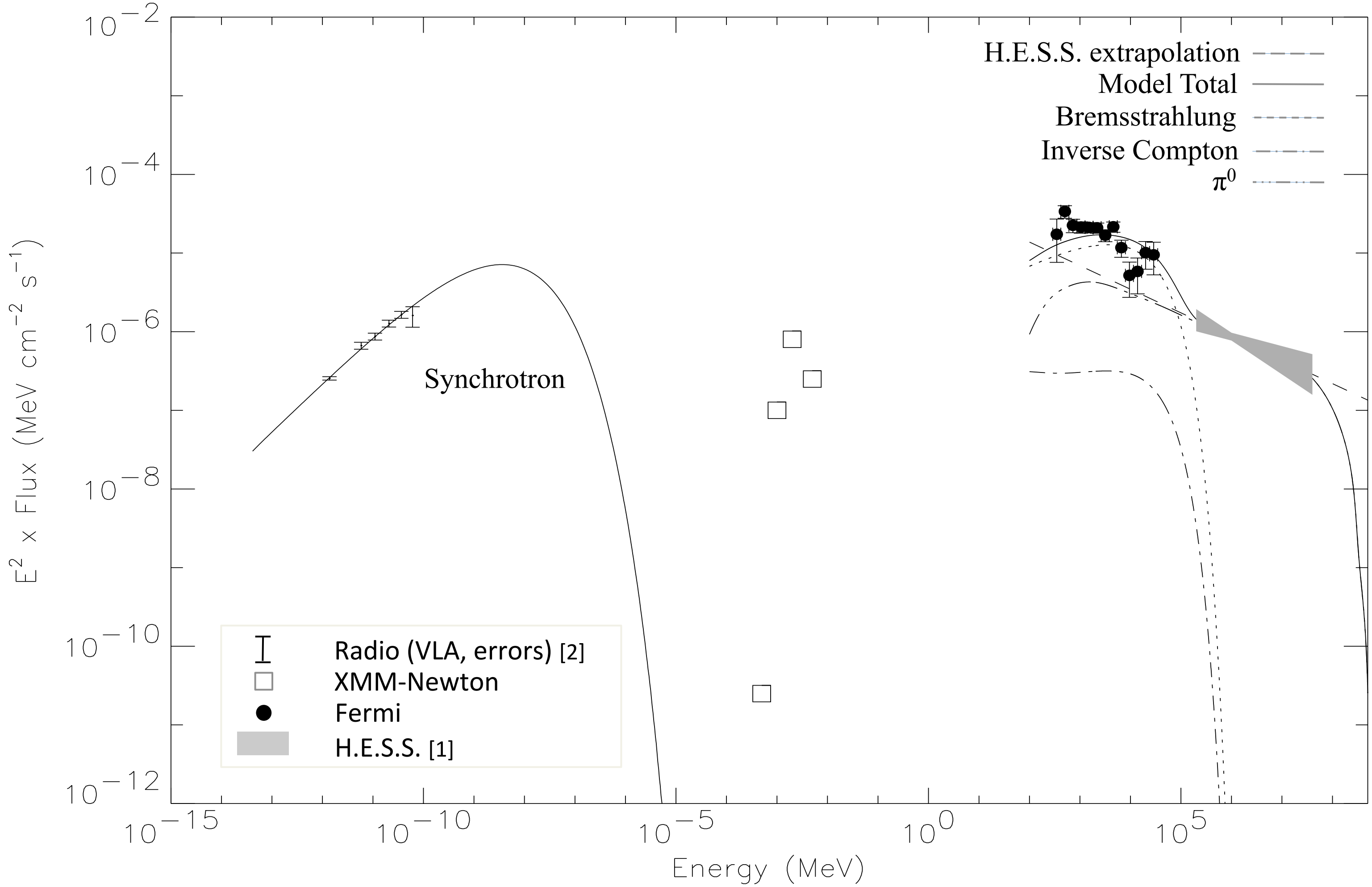
- Light curve: no long-term variability
- Pulsations: none seen in
  - Blind search: < $\sim 3\times10^{-7}$ ph/cm^2/s (pulsed)
  - of possible counterparts (□)



T. J. Brandt

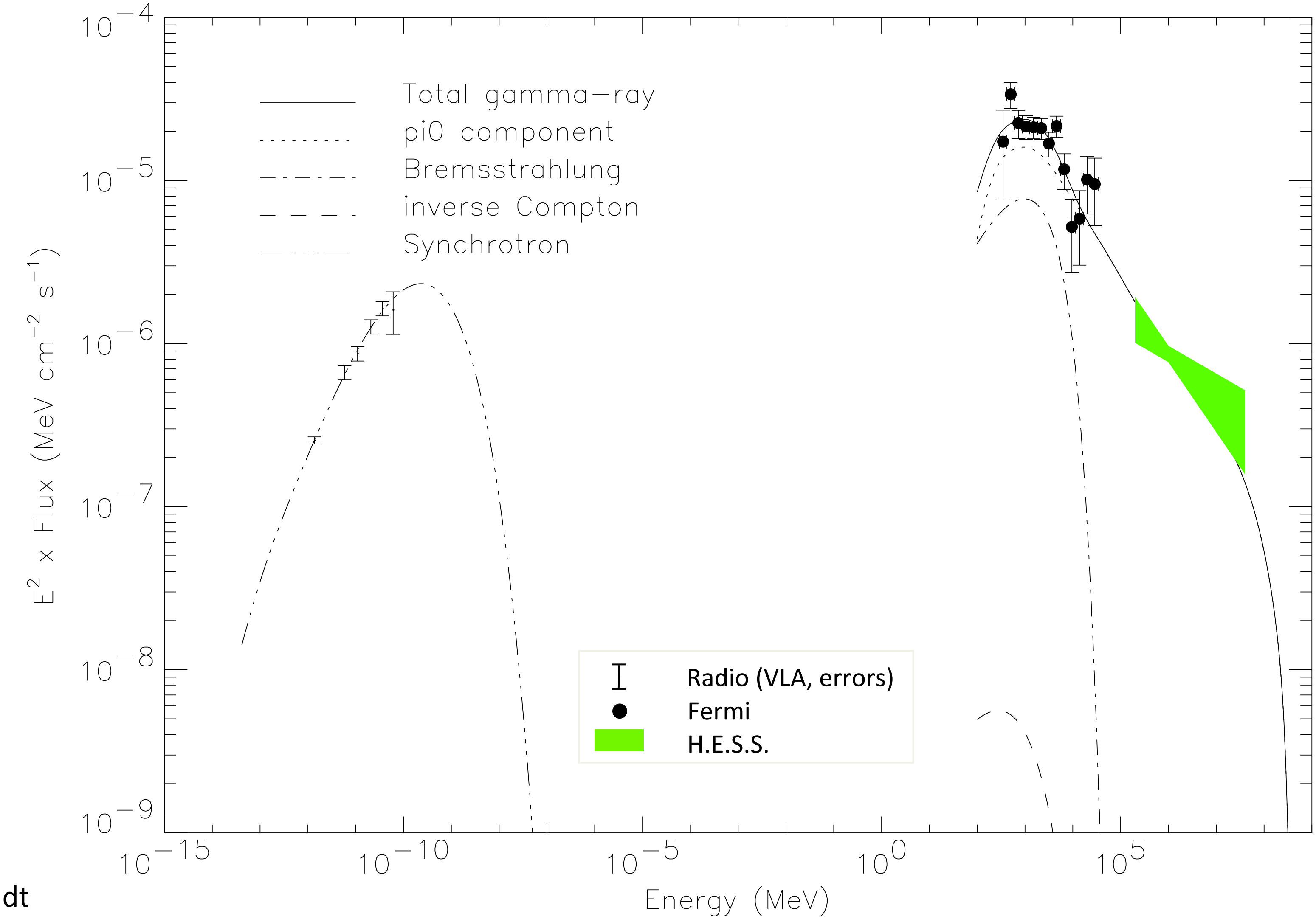
Multiwavelength Spectrum

Fit to a simple model using reasonable values.



Dominant Emission Mechanism

We find within the constraints of our model, the most likely gamma-ray emission scenario to be hadron-dominated, with a non-negligible contribution from bremsstrahlung emission.



T. J. Brandt

Multiwavelength Spectrum: Model

Simultaneously fit both lepton and hadron populations:

- Lepton population:
  - Assume: exponentially cutoff power law:
    - $N_e(E) = N_{0,e} E^{\gamma e} \exp(-E/E_{cut,e})$
  - Fit: $N_{0,e}$, γ_e, $E_{cut,e}$
- Hadron population:
  - Assume: simple power law:
    - $N_p(E) = N_{0,p} E^{\gamma p}$
  - Fit: $N_{0,p}$, γ_p
- Magnetic field:
  - Constrained <1.5mG from OH maser Zeeman splitting observations
  - Fit: magnetic field intensity (B)
- Gas mass:
  - Assume: reasonable $M_H = 6.5 \times 10^4 M_\odot$
  - Consistent with CO measurements
  - Determine: parameters' scaling relations with M_H
- Model emission processes:
  - Synchrotron
  - Bremsstrahlung*
  - inverse Compton
  - Pion decay*
  - *Scaled to solar metallicity
- Minimized χ^2
  - using Powell method, results consistent with other methods
  - $\chi^2 = 16.4$ for 17 dof
- 1σ errors:
  - searched extreme values for which $\Delta\chi^2 = 1$

Multiwavelength Spectrum: Results

- Lepton population:
  - $N_{0,e} = 3.79^{+3.99}_{-1.70}$ e/s/cm^2/GeV/sr
  - $\gamma_e = -1.35^{+0.32}_{-0.23}$
  - $E_{cut,e} = 4.1^{+3.4}_{-1.7}$ GeV
- Hadron population:
  - $N_{0,p} = 163.5^{+60.5}_{-137.7}$ p/s/cm^2/GeV/sr
  - $\gamma_p = -2.5^{+0.04}_{-0.19}$
- Magnetic field:
  - $B = 109^{+56}_{-49}$ μG
  - 1st lower limit
  - Constraining upper limit
- Gas mass:
  - Parameters' scaling relations with M_H
  - $N_{0,p}$ has slope ~1, as expected for π^0 emissivity scaling with gas mass
  - All other parameters showed no significant variation with gas mass beyond the errors.

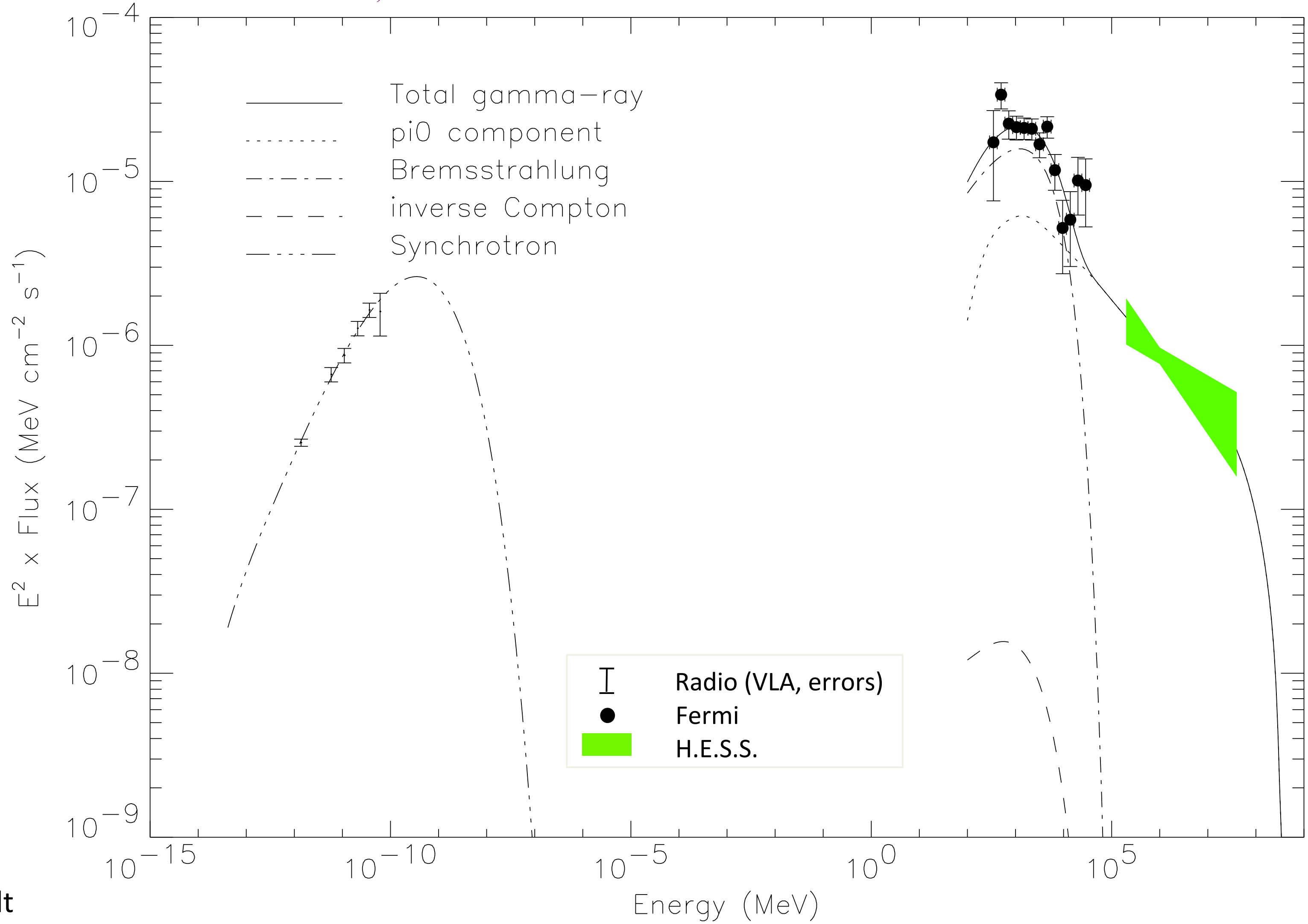
- Particle type:
  - ✓ Hadrons
- Spectral index
  - ✓ 1σ, consistent with γ ~ 2.1 from direct detection
- Proton Cutoff Energy
  - $E_{p,max} \sim 10^{14}$eV
  - ✓ consistent with direct detection $E_{max} \sim 10^{15}$eV for all CR accelerators

Multiwavelength Spectrum: Results

- Lepton population:
  - $N_{0,e} = 3.79^{+3.99}_{-1.70}$ e/s/cm^2/GeV/sr
  - $\gamma_e = -1.35^{+0.32}_{-0.23}$
  - $E_{cut,e} = 4.1^{+3.4}_{-1.7}$ GeV
- Hadron population:
  - $N_{0,p} = 163.5^{+60.5}_{-137.7}$ p/s/cm^2/GeV/sr
  - $\gamma_p = -2.5^{+0.04}_{-0.19}$
- Magnetic field:
  - $B = 109^{+56}_{-49}$ μG
  - 1st lower limit
  - Constraining upper limit
- Gas mass:
  - Parameters' scaling relations with M_H
  - $N_{0,p}$ has slope ~1, as expected for π^0 emissivity scaling with gas mass
  - All other parameters showed no significant variation with gas mass beyond the errors.
- Energetics:
  - Total, steady-state energy:
  - hadrons = $5.1^{+1.3}_{-3.6} \times 10^{49}$ ergs
  - leptons = $2.7^{+4.0}_{-1.4} \times 10^{48}$ ergs
  - $E_{cut,e} = 4.1^{+3.4}_{-1.7}$ GeV
- Find typical conversion efficiency: ~5%
  - $\eta \sim (1.5\text{-}6.4) x (M/M_H)^{-1} x (d/10.3\text{kpc})^5 x (E_{SN}/10^{51}\text{erg})$ %
  - Consistent with HESS result when scaled to their mass and distance

Allowed Lepton Scenario

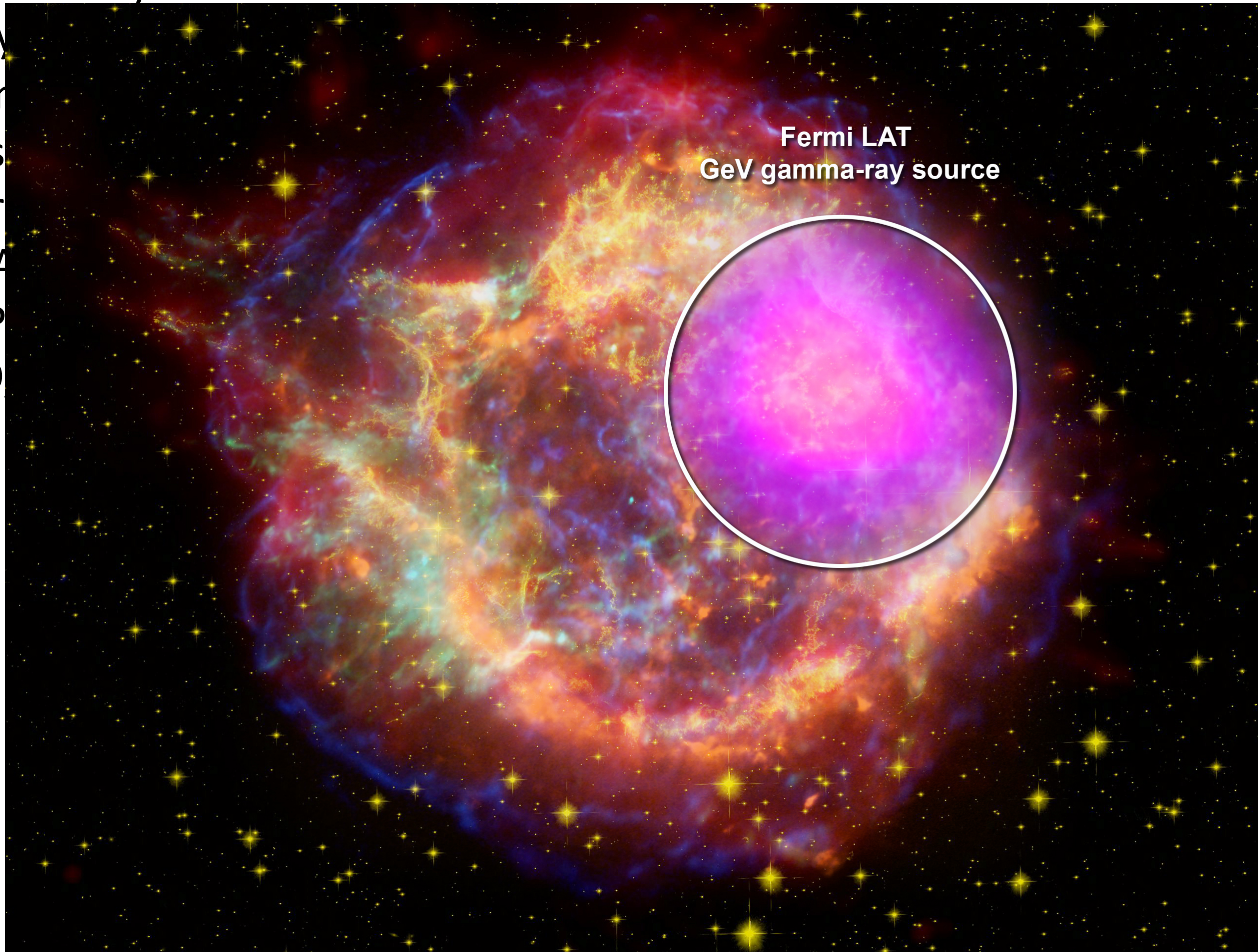
- at 1σ:
  - Lepton population:
    - $N_{0,e}$ = 6.39 e/s/cm²/GeV/sr
    - γ_e = -1.49
    - $E_{cut,e}$ = 7.0 GeV
  - Hadron population:
    - $N_{0,p}$ = 42.6 p/s/cm²/GeV/sr
    - γ_p = -2.35
  - Magnetic field: B = 67 μG



T. J. Brandt

http://www.nasa.gov/mission_pages/GLAST/news/cosmic-rays-source.html

This composite shows the Cassiopeia A supernova remnant across the spectrum: Gamma rays (magenta) from NASA's Fermi Gamma-ray Space Telescope; X-rays (blue, green) from NASA's Chandra X-ray Observatory; visible light (y
Hubble Space Telescope; in
NASA's Spitzer Space Teles
(orange) from the Very Lar
Socorro, N.M. Credit: NASA
Collaboration, CXC/SAO/JP
O. Krause et al., and NRAO



Fermi Gamma-ray Space Telescope

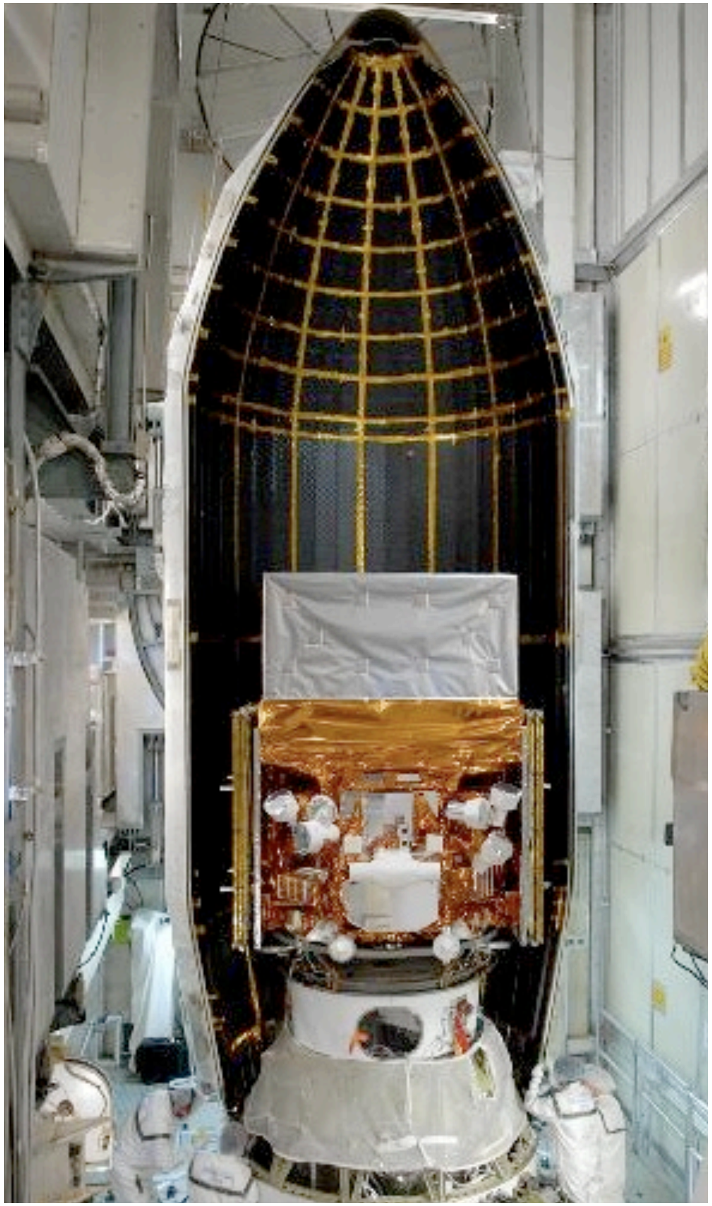
Photon Detector

Launched: 11 June 2008 on a Delta II rocket

Photon Energy and Direction

from 2 main (science) subsystems:

- GBM: GLAST Burst Monitor
  - 12 NaI detectors: 8 keV – 1 MeV
  - 2 BGO detectors: 0.15 – 30 MeV
  - nearly full sky coverage at all times
- LAT: Large Area Telescope
  - Tracker: 4x4 array of towers, each with 18 planes of Si-strip detectors interleaved with W converting foils
  - Calorimeter - E: 8 layers of 12 CsI(Tl) crystals oriented orthogonally
  - ACD - CR veto: tiled plastic scintillator



Fermi Collaboration

Fermi Gamma-ray Space Telescope

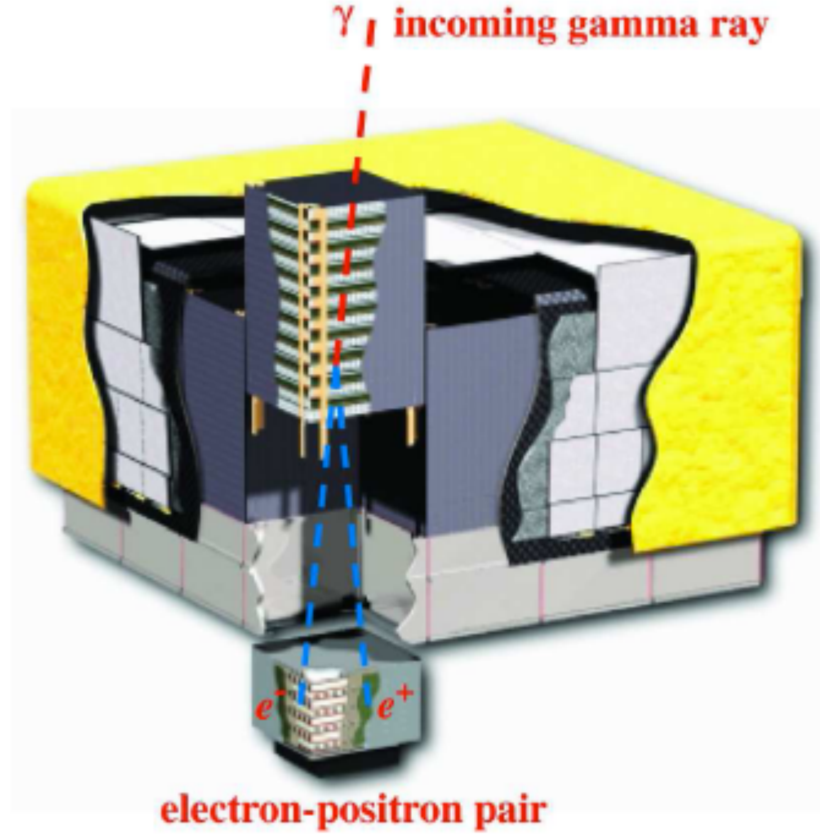
Photon Detector

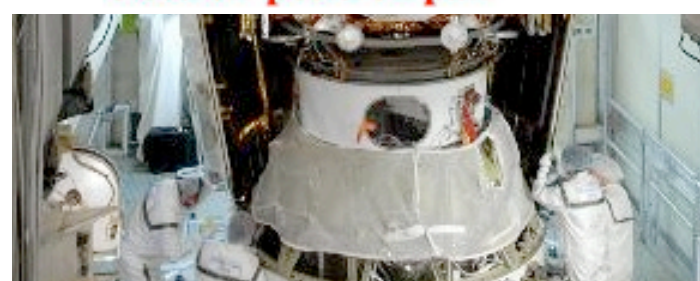
Launched: 11 June 2008 on a Delta II rocket

Photon Energy and Direction

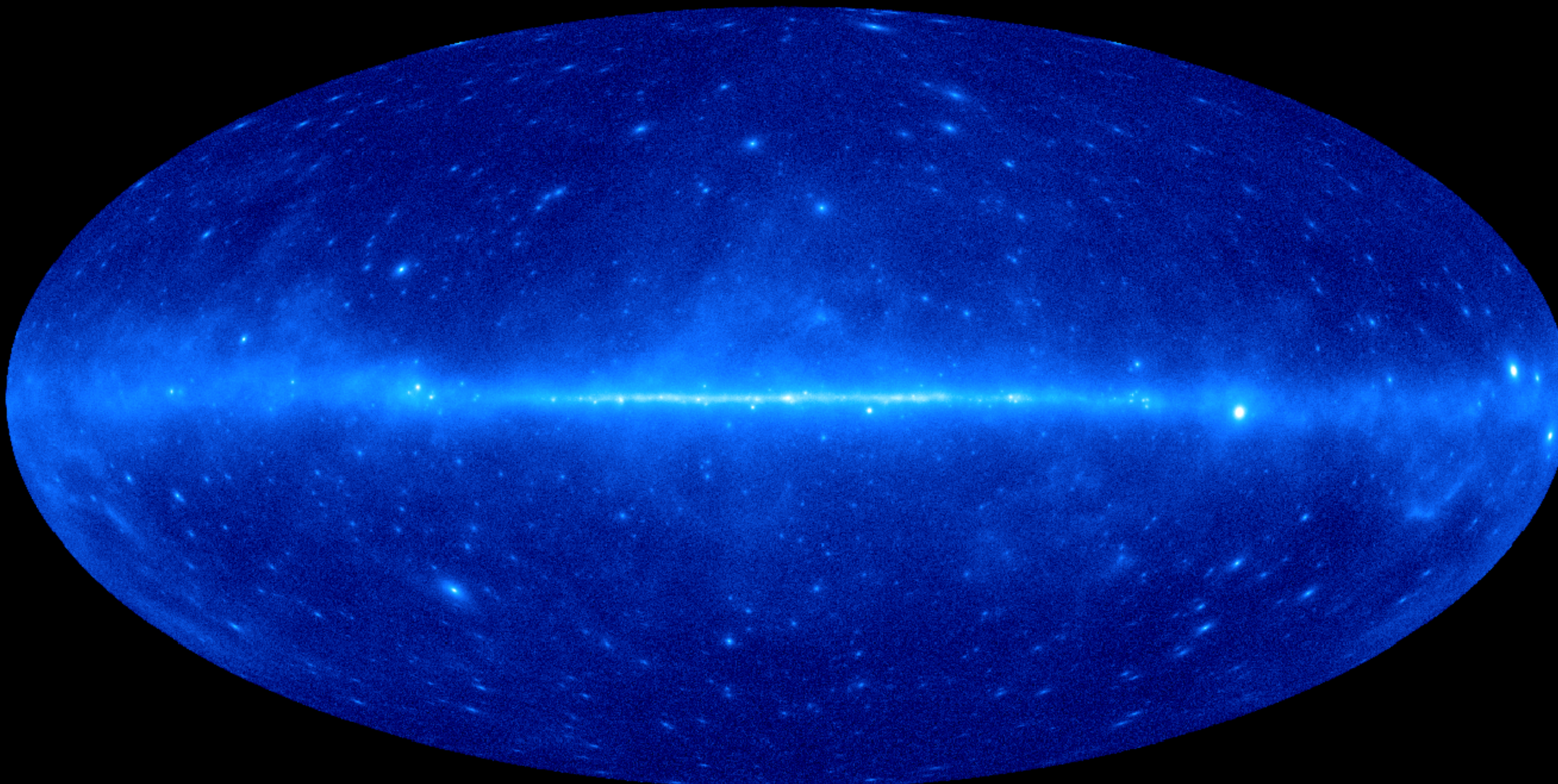
from 2 main (science) subsystems:

- GBM: GLAST Burst Monitor
  - 12 NaI detectors: 8 keV – 1 MeV
  - 2 BGO detectors: 0.15 – 30 MeV
  - nearly full sky coverage at all times
- LAT: Large Area Telescope
  - Tracker: 4x4 array of towers, each with 18 planes of Si-strip detectors interleaved with W converting foils
  - Calorimeter - E: 8 layers of 12 CsI(Tl) crystals oriented orthogonally
  - ACD - CR veto: tiled plastic scintillator



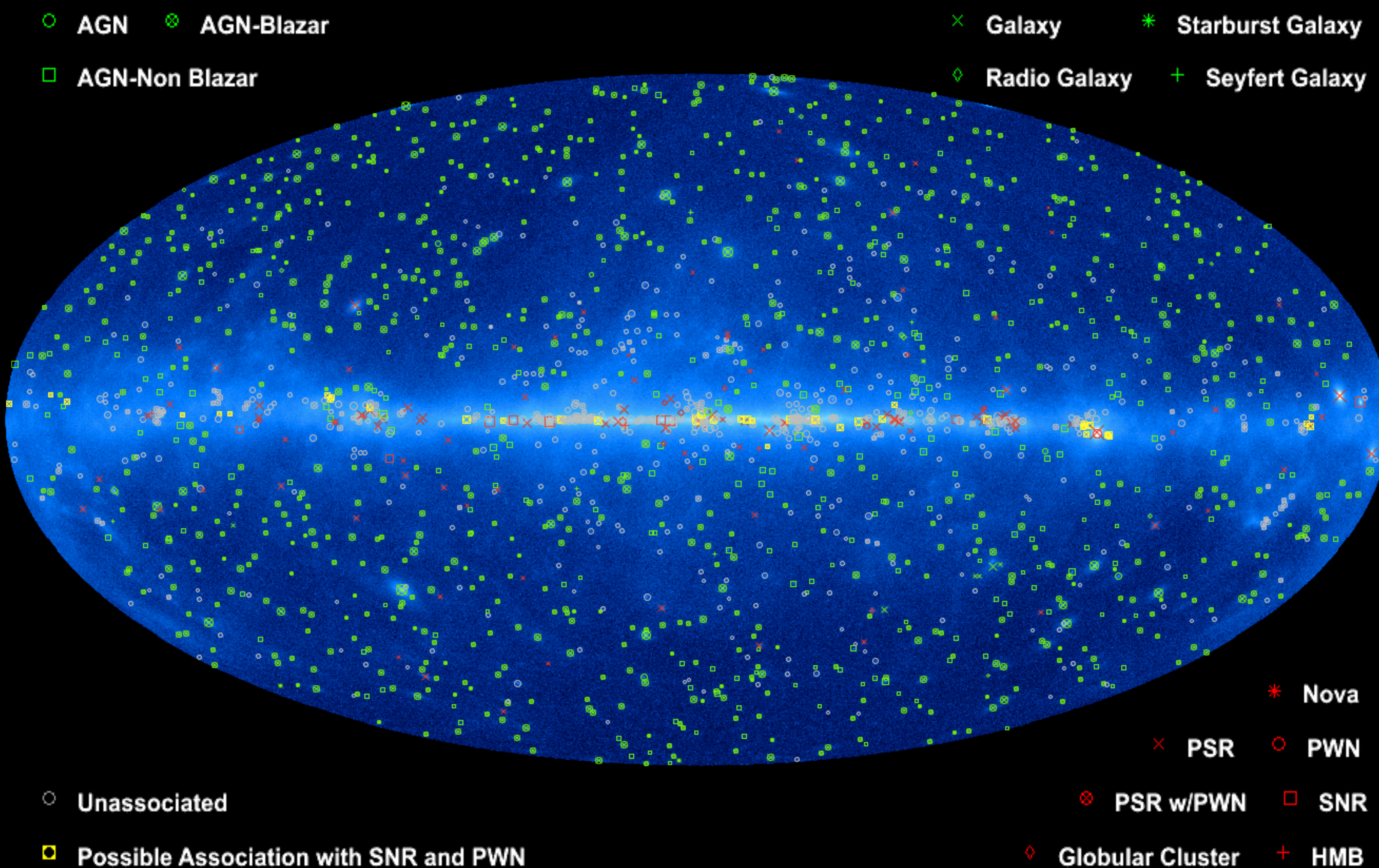


Fermi Large Area Telescope 2FGL catalog



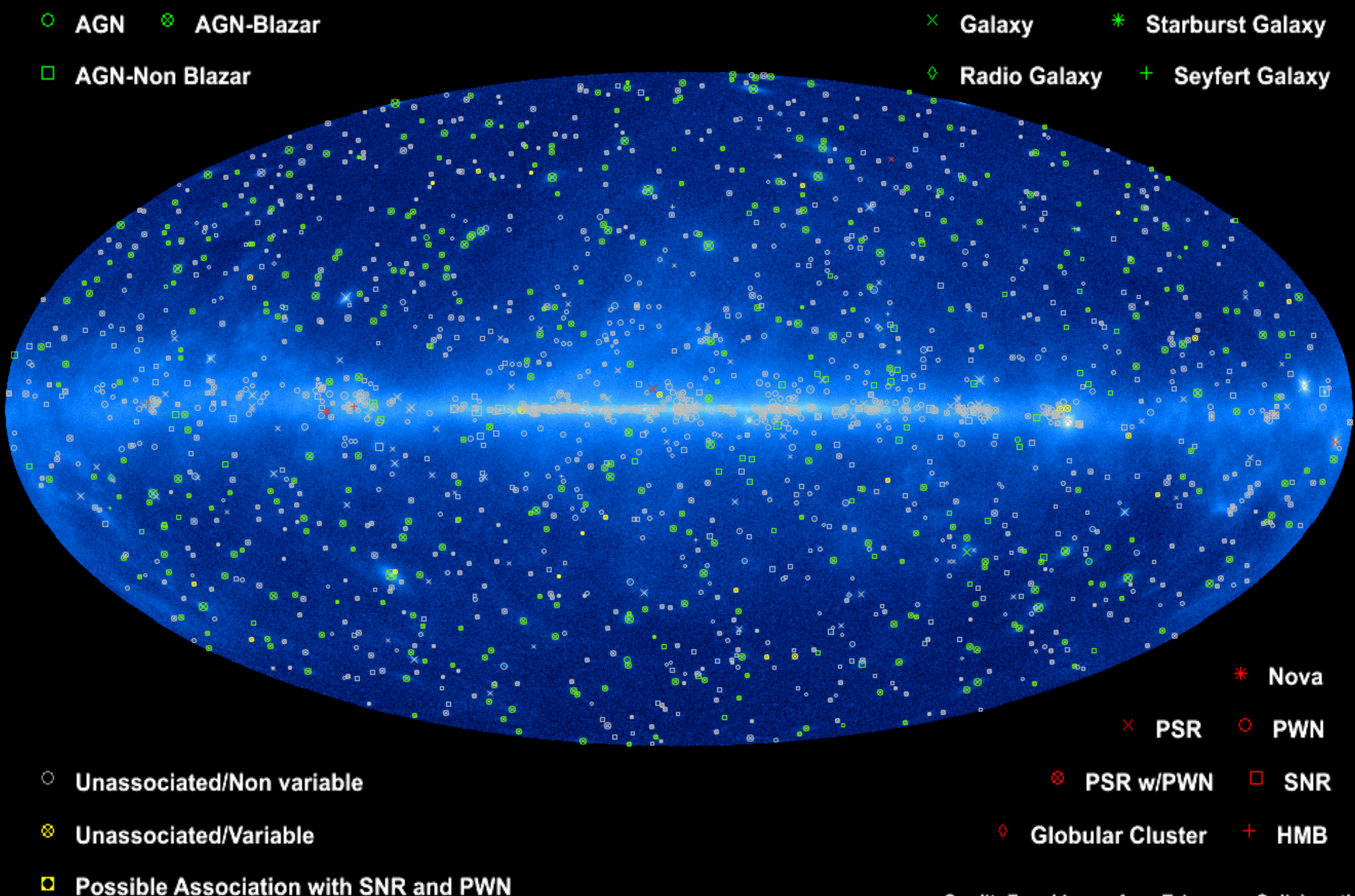
Credit: Fermi Large Area Telescope Collaboration

Fermi Large Area Telescope 2FGL catalog



Credit: Fermi Large Area Telescope Collaboration

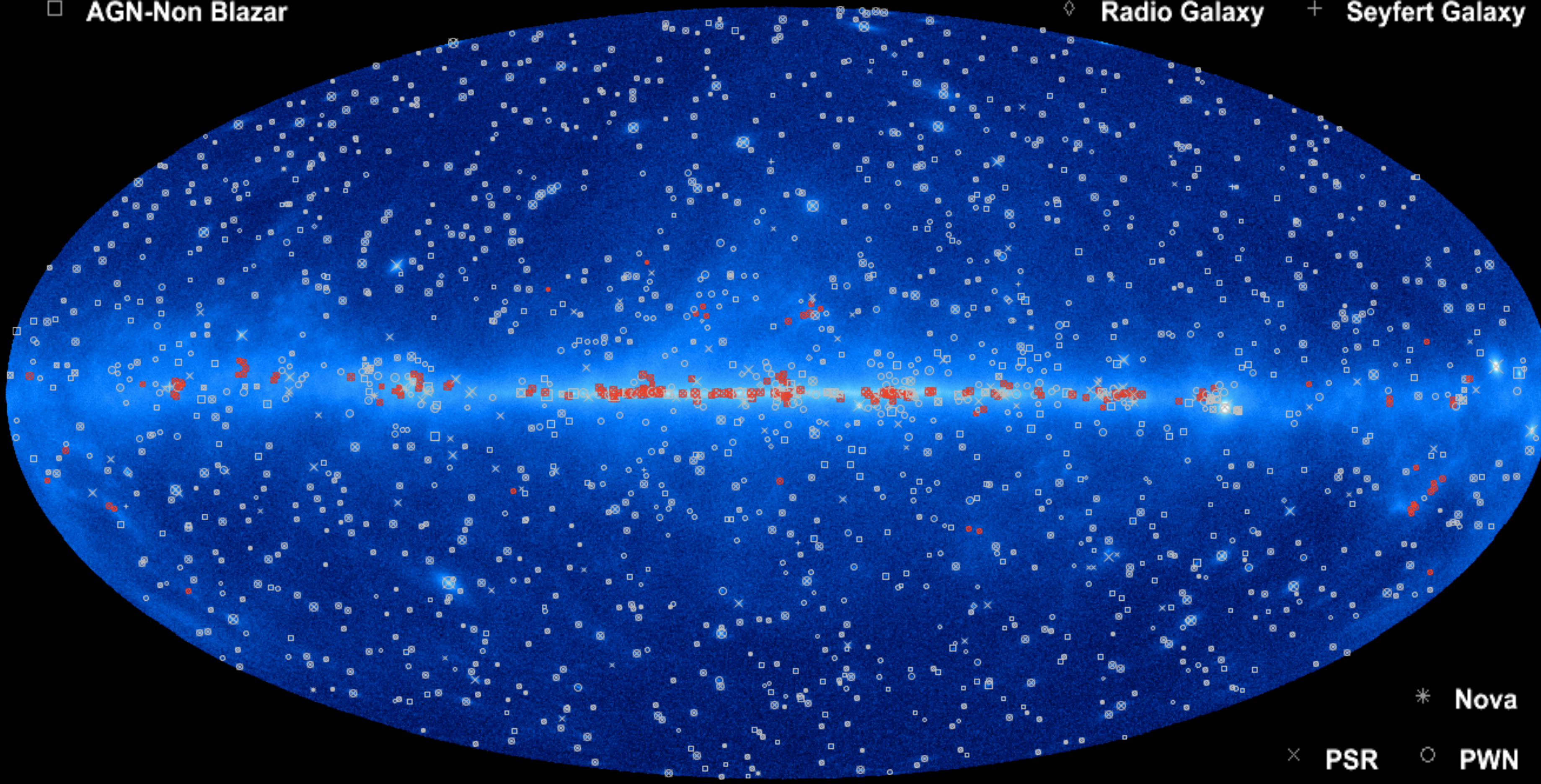
Fermi Large Area Telescope 2FGL catalog



Credit: Fermi Large Area Telescope Collaboration

Fermi Large Area Telescope 2FGL catalog

AGN
AGN-Blazar
AGN-Non Blazar
Galaxy
Starburst Galaxy
Radio Galaxy
Seyfert Galaxy



Nova
PSR
PWN
PSR w/PWN
SNR
Globular Cluster
HMB

Unassociated
Possible Association with SNR and PWN
Possible confusion with Galactic diffuse emission

Credit: Fermi Large Area Telescope Collaboration