Supernova Remnant Studies with *Fermi* LAT

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on behalf of the
***Fermi* LAT collaboration**

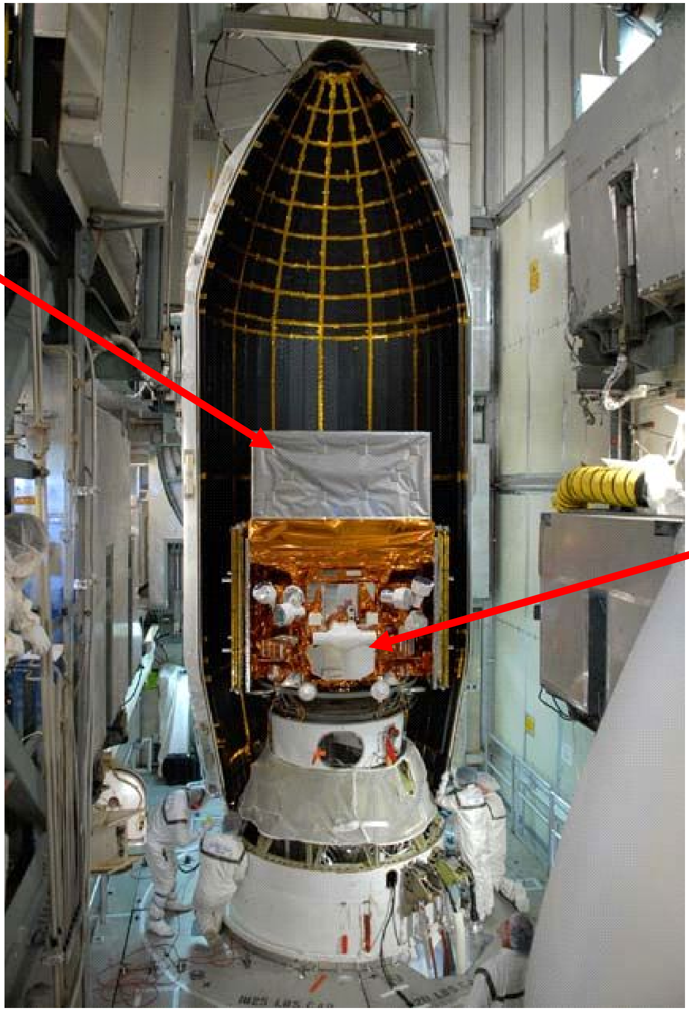
TeVPA 2017
Columbus, OH
August 7, 2017

Fermi Larger Area Telescope (LAT)

Large Area Telescope (LAT) :

- **20 MeV to 2 TeV, including unexplored 10-100 GeV region**
- **2.4 sr field of view scans the entire sky every ~3 hrs**

4 Aug 2017 marks 9 yr of continuous science data!

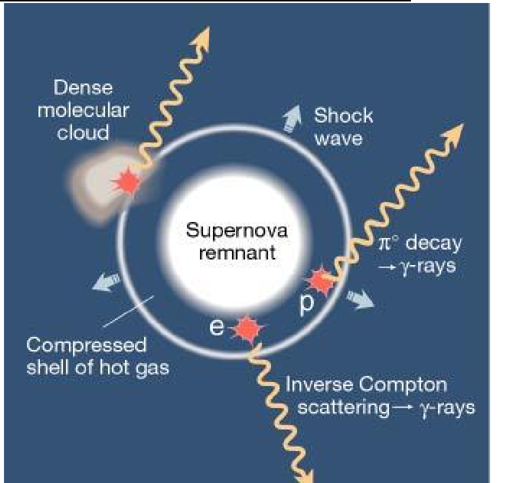


Gamma-ray Burst Monitor (GBM) :

- **8 keV to 40 MeV**
- **Views entire unocculted sky**

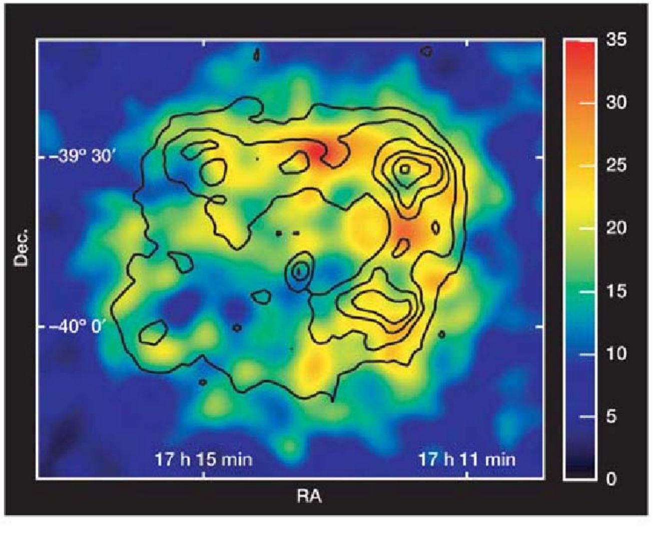
SNR: Sites of Hadronic Acceleration?

- Supernova Remnants: sites of galactic cosmic ray acceleration
  - Non-thermal emission (X-rays)
  - Signs of γ-ray activity
    - EGRET: GeV activity near SNR (3EG J1714-3837)
    - HESS: Recent detection of TeV γ-rays
- Question:
  - Do γ rays originate from hadronic or leptonic processes?
- Measurements in the range of 100MeV-100GeV
  - essential ingredient to resolve the origin (*p* vs *e*+/-)

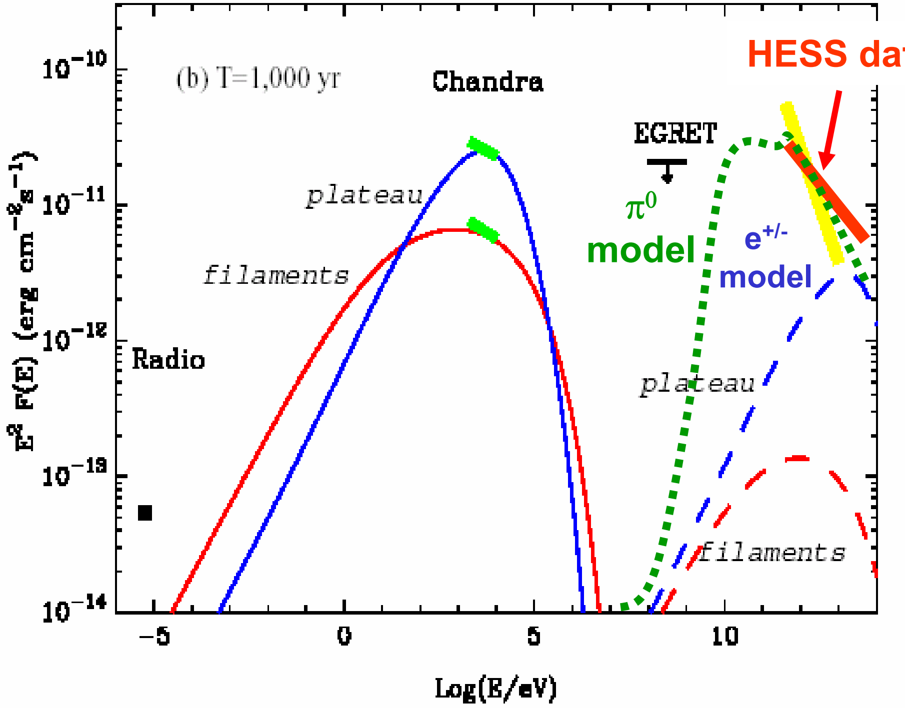


Adapted from Aharonian's talk at the Texas Symposium 2004

Supernova remnant RX J1713.7-3946
HESS 04 (color) + ASCA (contours)



Uchiyama (2003)



E. do Couto e Silva

Has *Fermi* reached its promise? (Re: SNRs)

- ❑ The LAT's excellent spatial and energy resolutions will separate the extended shell emission of an SNR from a compact source (pulsar, tiny plerion) inside it.

- ❑ It will also spectrally resolve electron and nuclei emission.

- ❑ The LAT will resolve >10 remnants, to establish the location of cosmic ray production.

Has *Fermi* reached its promise? (Re: SNRs)

☑ The LAT's excellent spatial and energy resolutions will separate the extended shell emission of an SNR from a compact source (pulsar, tiny plerion) inside it.

- **Systematic searches have cataloged XX SNRs with detectable extension, allowing secure identifications**

☑ It will also spectrally resolve electron and nuclei emission.

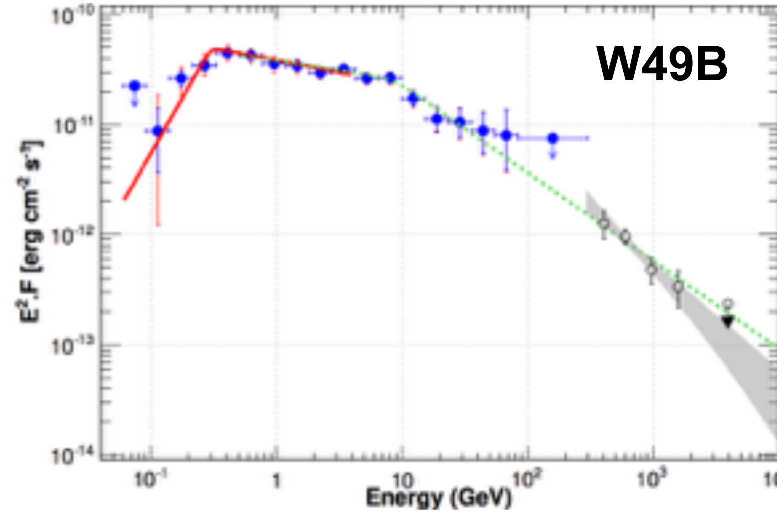
- **Pion cutoff detected in 4 SNRs (with potential for more)**

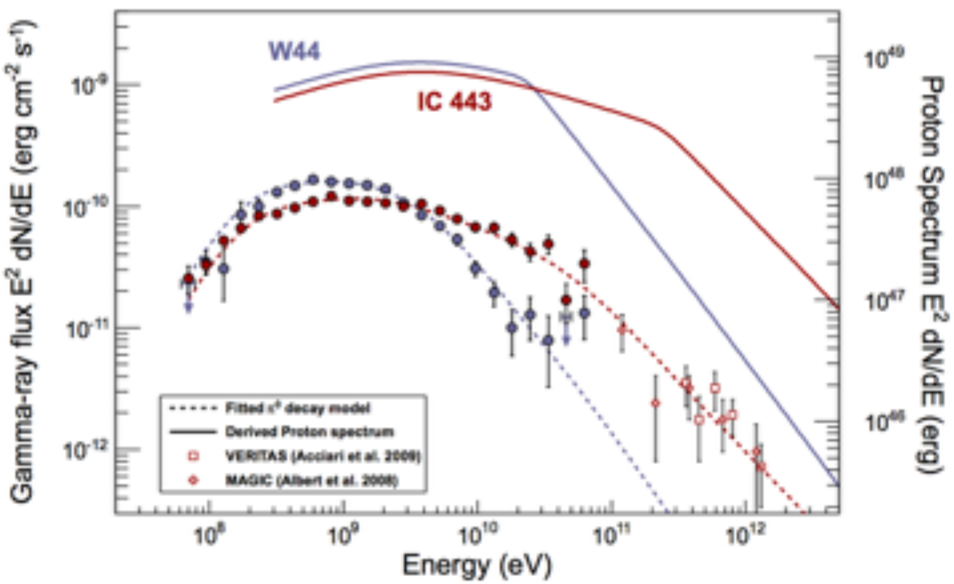
☑ The LAT will resolve >10 remnants, to establish the location of cosmic ray production.

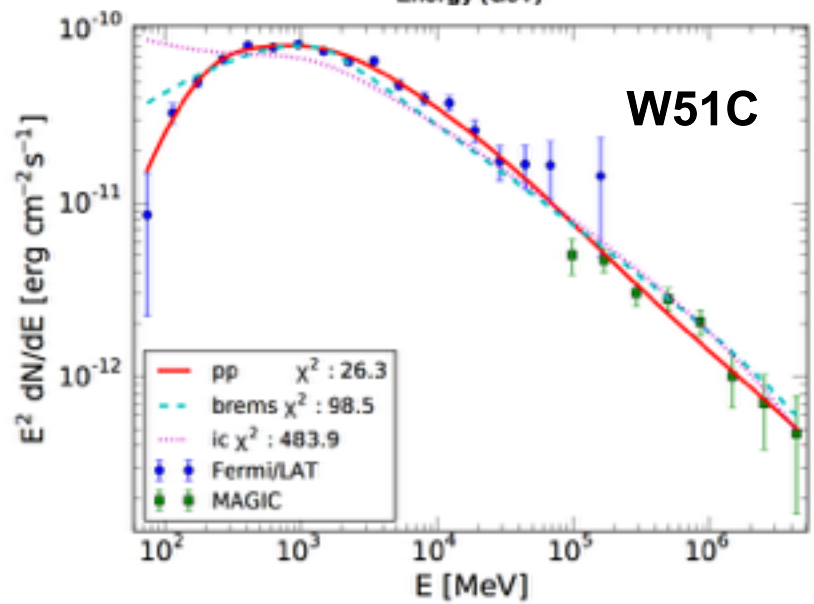
- **Pass 8 data allows spectra-morphological studies of bright SNRs, at a resolution comparable to best TeV telescopes**

Spectrally resolving nuclei emission

- 4 SNR/MCs show π^0-decay spectral cutoff at <300 MeV.
- Spatial correlation between γ-rays and dense MC interaction region
- IC/Bremsstrahlung models require internal break in electron spectrum not seen in radio



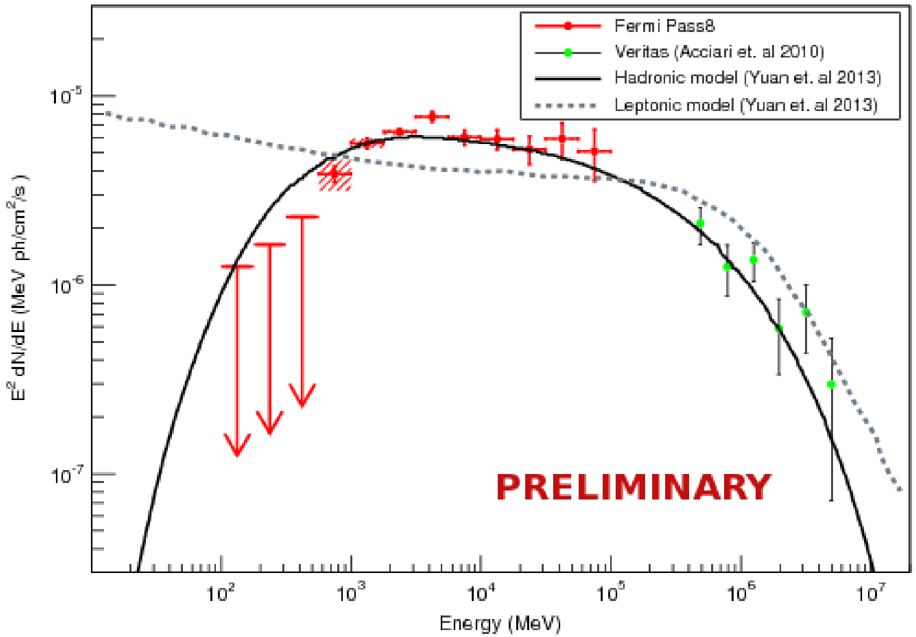




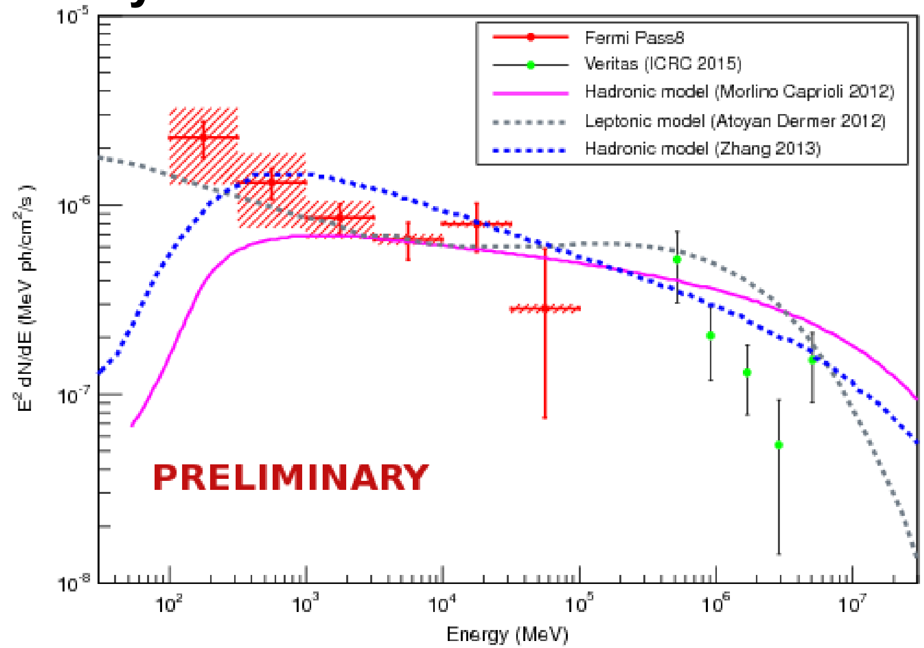
Young SNRs Tycho & Cas A

- **Hard spectrum can be explained by π^0-decay dominated emission…**

Cassiopeia A

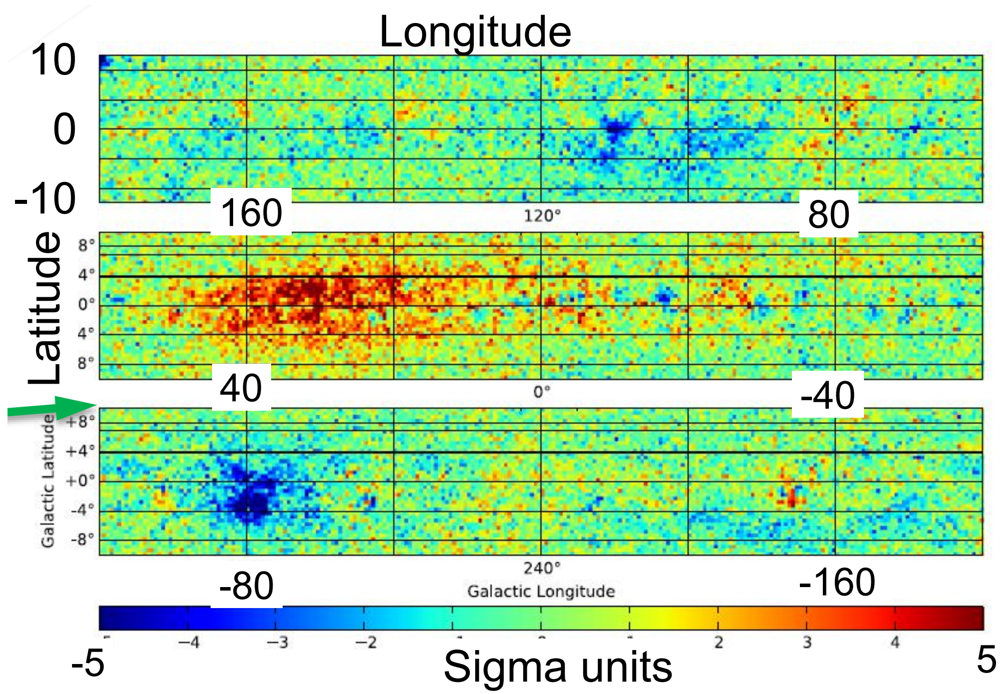


Tycho's SNR LAT collaboration, *in prep.*



Limitations for Low Energy Studies

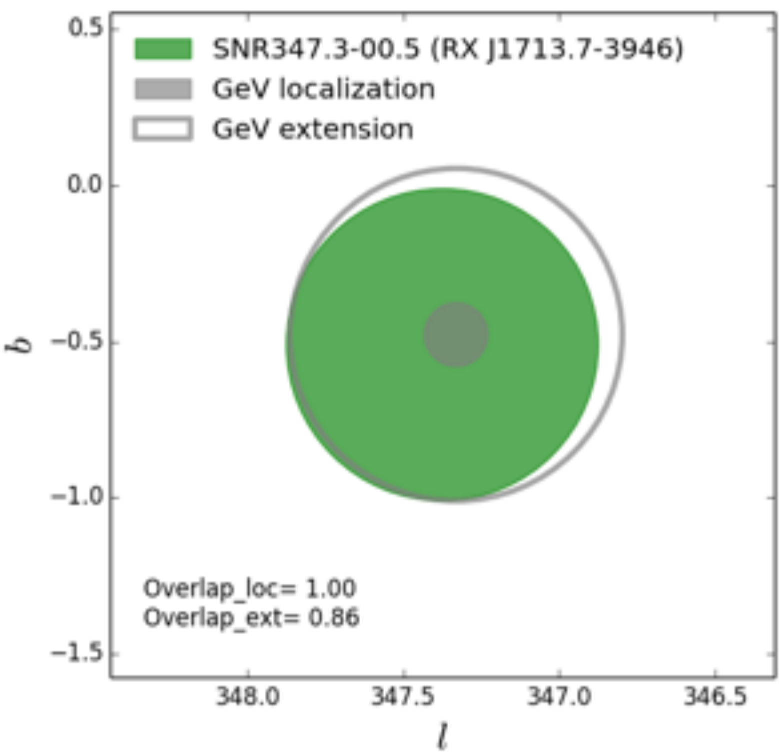
- **Confusion** is strong at low energies (average angular separation of 3FGL sources is 2.2° *outside* the Galactic plane)
- **Galactic interstellar emission** model is *not* perfect (see Acero et al. 2016, ApJS 223, 26)
- Small residuals (2-3%) impact sources at the same level as statistical errors over the whole Galactic plane
- **Low energy spectral studies are limited by diffuse systematics**

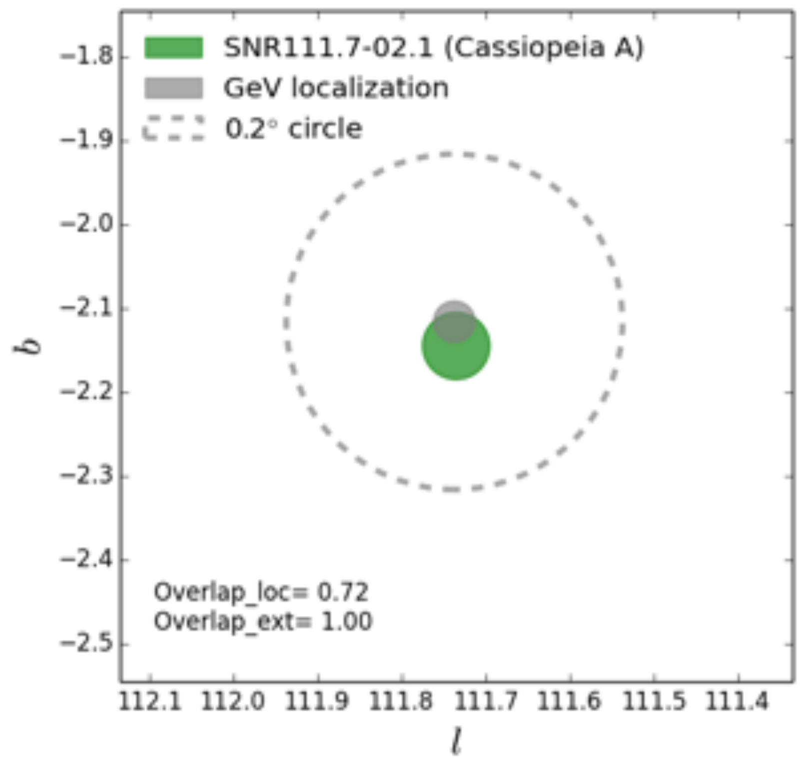


1SC: First SNR Catalog with LAT

https://fermi.gsfc.nasa.gov/ssc/data/access/lat/1st_SNR_catalog/

- Search 279 Galactic SNRs (Green 2009) for 1-100 GeV γ-rays and account for systematics using 3 yr of Pass 7 data
- Use spatial overlap to classify 32 likely GeV SNRs (16 extended)

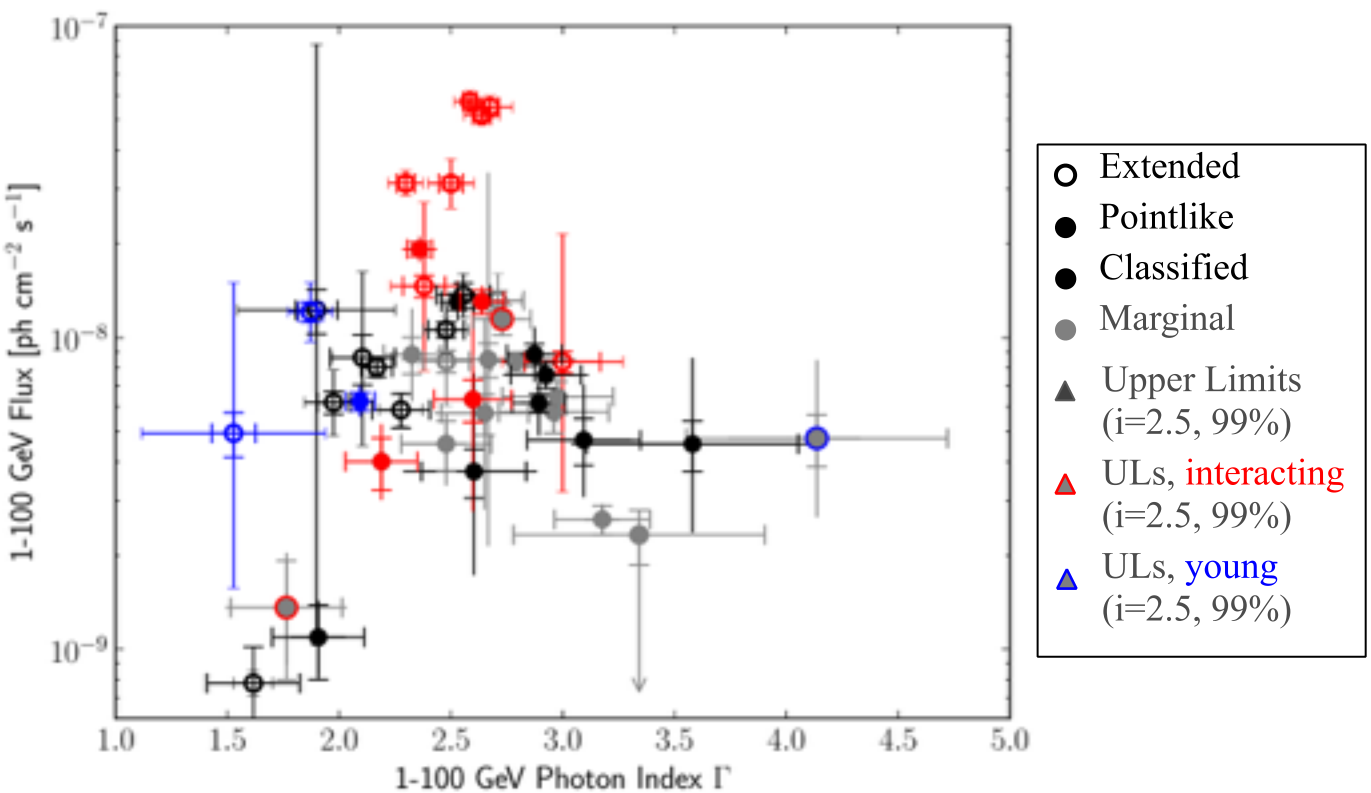




1SC: First SNR Catalog with LAT

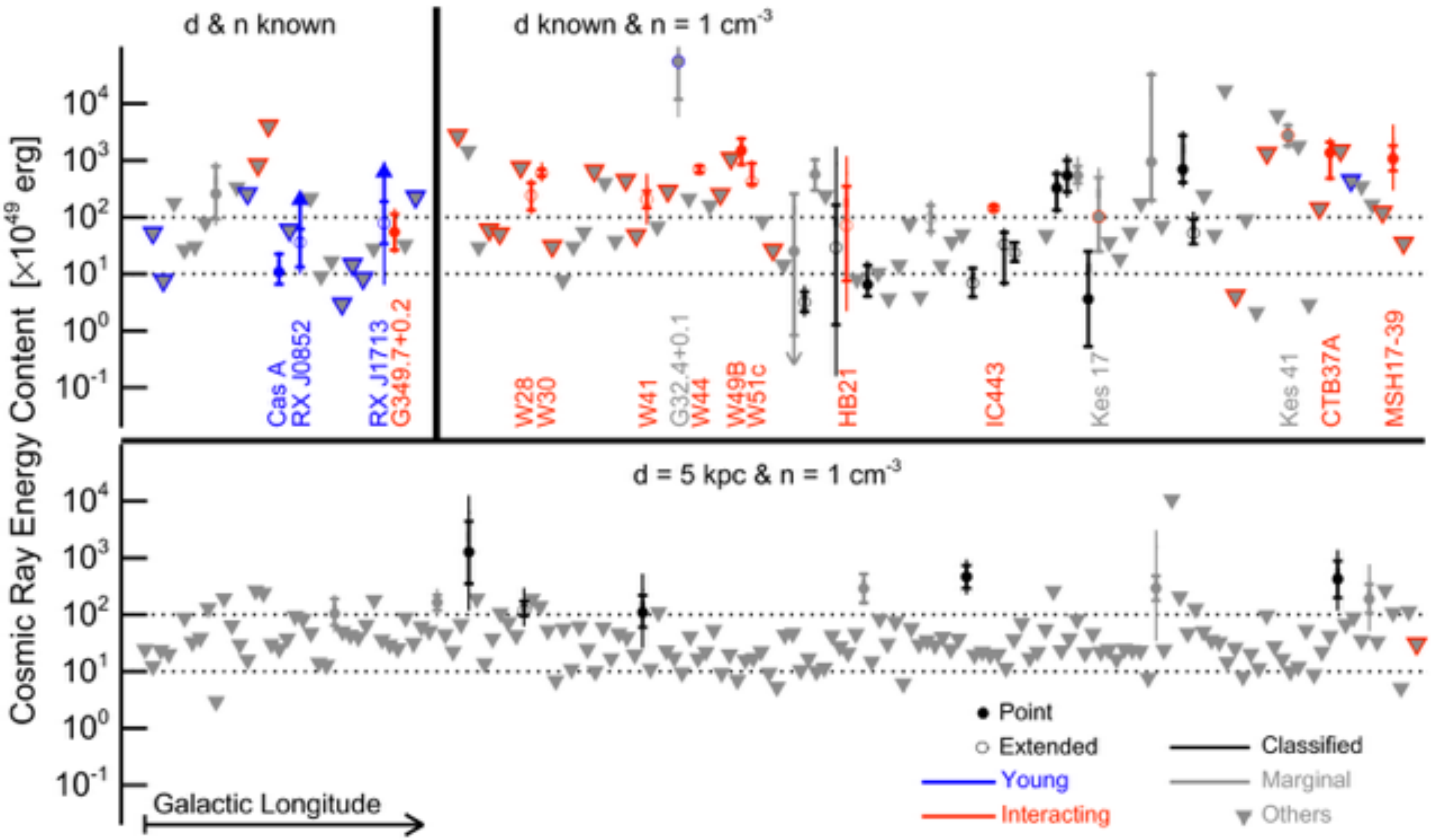
https://fermi.gsfc.nasa.gov/ssc/data/access/lat/1st_SNR_catalog/

- Include multi wavelength information (distance, density, etc.) to explore differing γ-ray SNR types: young TeV shells and evolved interacting SNRs



Energetics under the SNR Paradigm

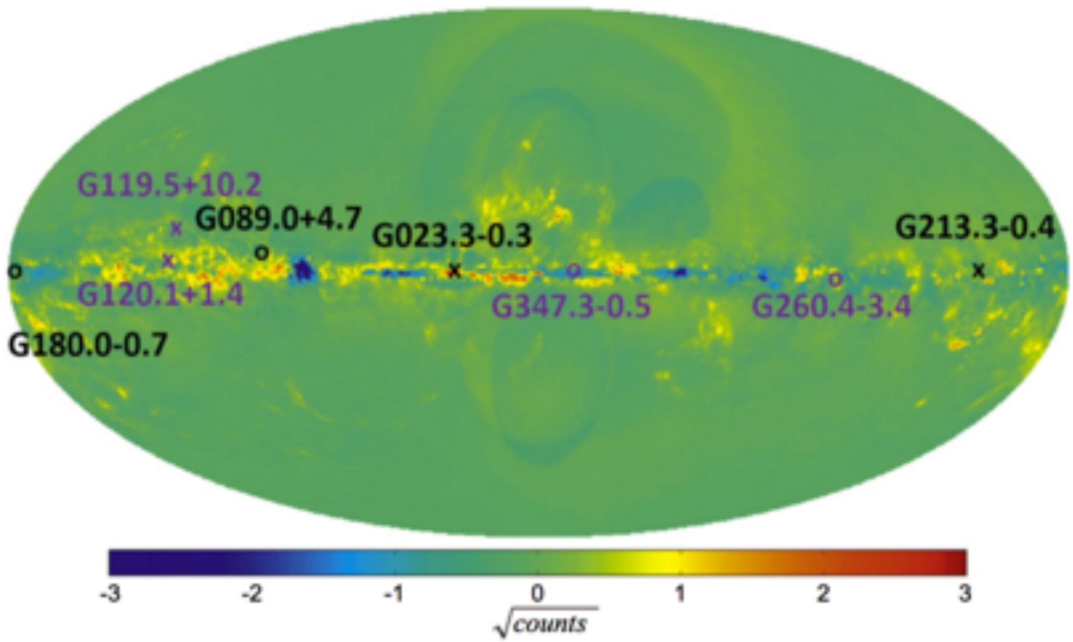
$$\frac{\epsilon_{CR}}{0.1} \times \frac{n}{1\,\mathrm{cm}^{-3}} \approx \frac{F(1-100\,\mathrm{GeV})}{1.5\times10^{-8}\,\mathrm{cm}^2\,\mathrm{s}} \times \left(\frac{d}{1\,\mathrm{kpc}}\right)^2$$



Evaluating Diffuse Systematics

https://fermi.gsfc.nasa.gov/ssc/data/access/lat/1st_SNR_catalog/

- Developed 8 “alternative” Interstellar Emission Models using GALPROP to vary CR source distribution (SNR/Lorimer), halo height (4/10 kpc) and HI spin temperature (150K/optically thin)



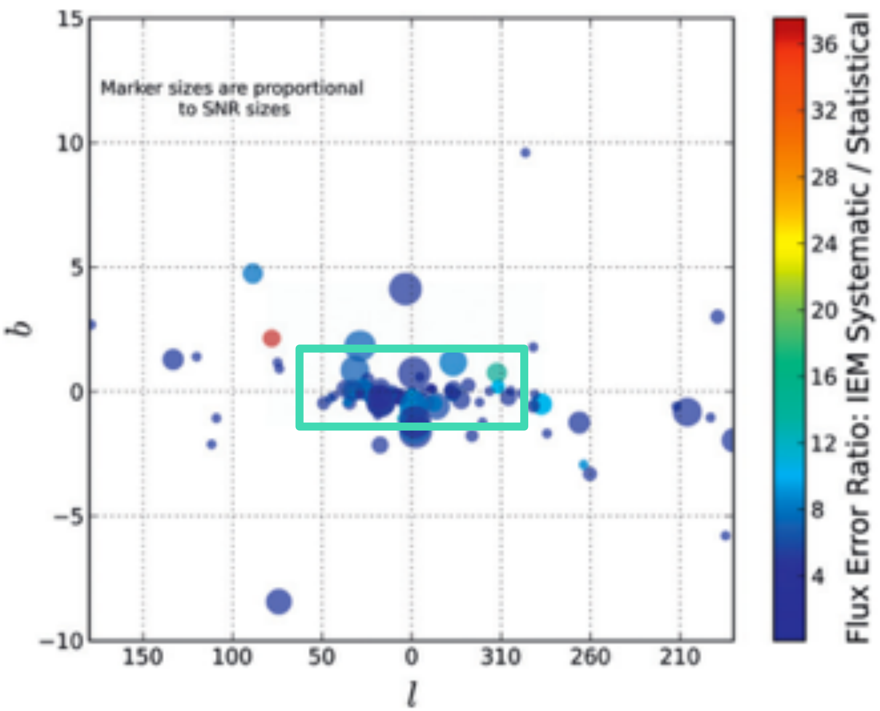
Warning: Models *do not* span the complete systematic uncertainty!

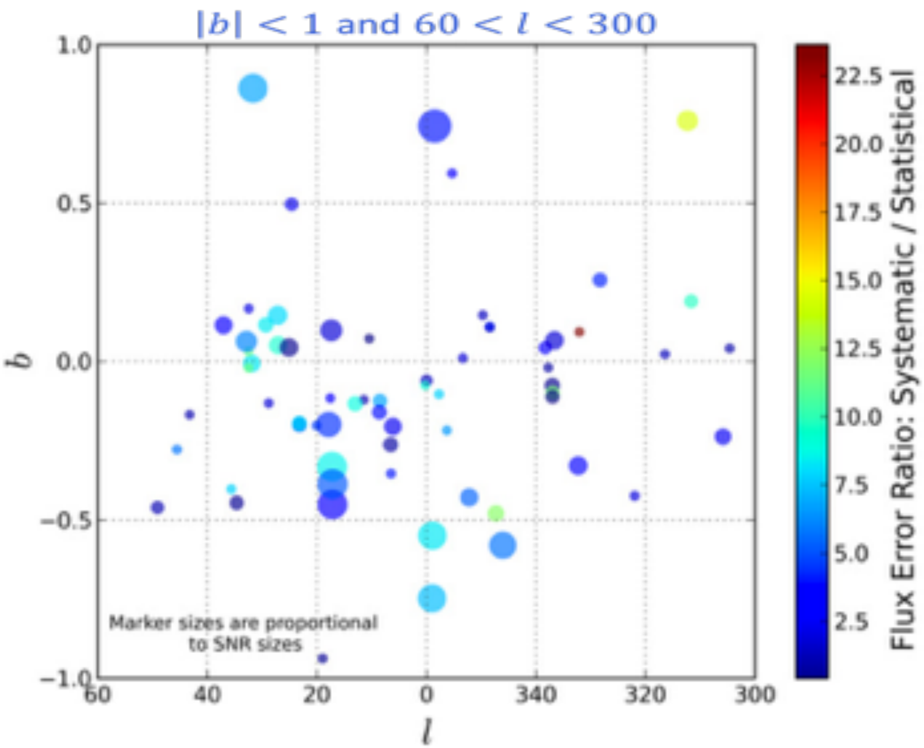
They are **hard**, **soft**, point-like (**x**) and extended (**o**) sources and they are located in regions with different intensities of the IEM.

Evaluating Diffuse Systematics

https://fermi.gsfc.nasa.gov/ssc/data/access/lat/1st_SNR_catalog/

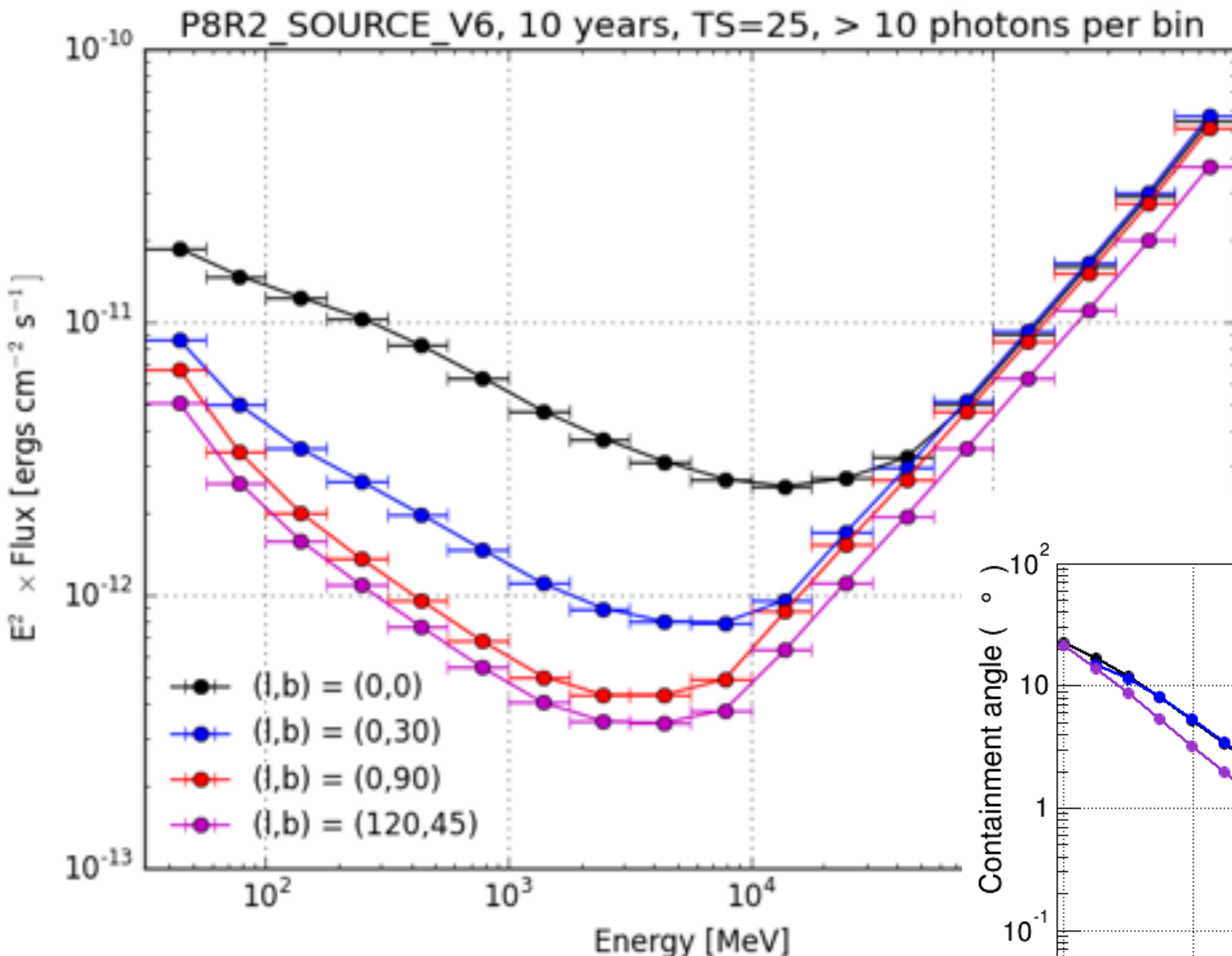
- No particular correlation with the sky position is found for ratio of the alternative IEM systematic and statistical errors on flux



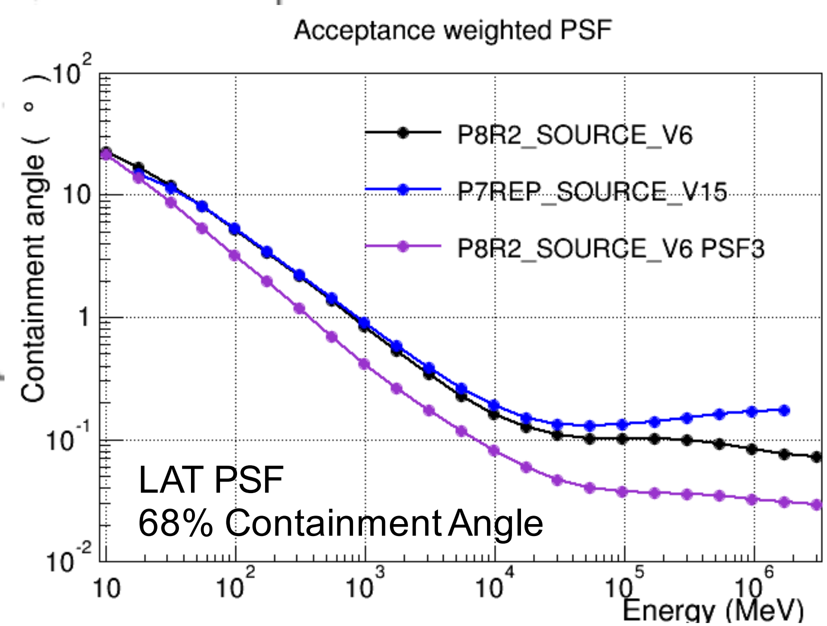


- Need better knowledge of diffuse backgrounds to improve studies of SNRs at ~1 GeV (and lower) energies

SNRs searches with Pass 8 data



High energy searches for extended sources (SNRs, PWNe, etc) are motivated by lower diffuse backgrounds and improved PSF.

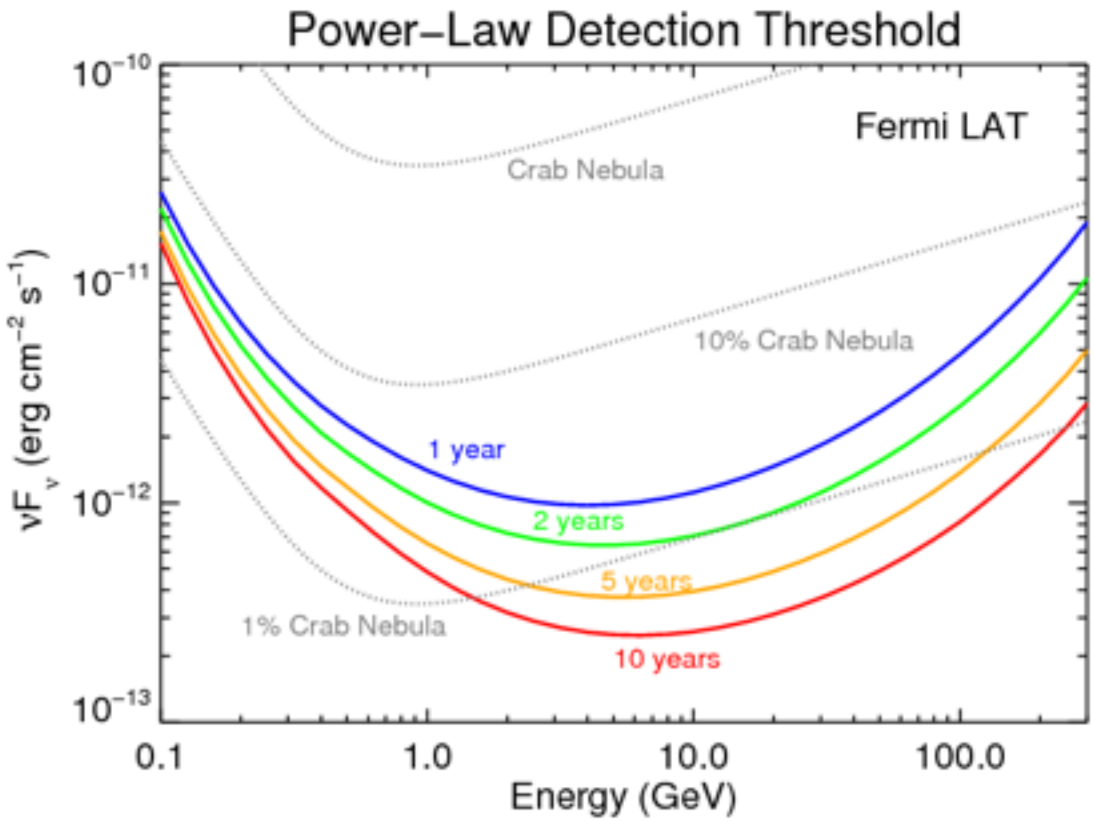


LAT now a "higher-energy" γ-ray telescope

Pass8 data

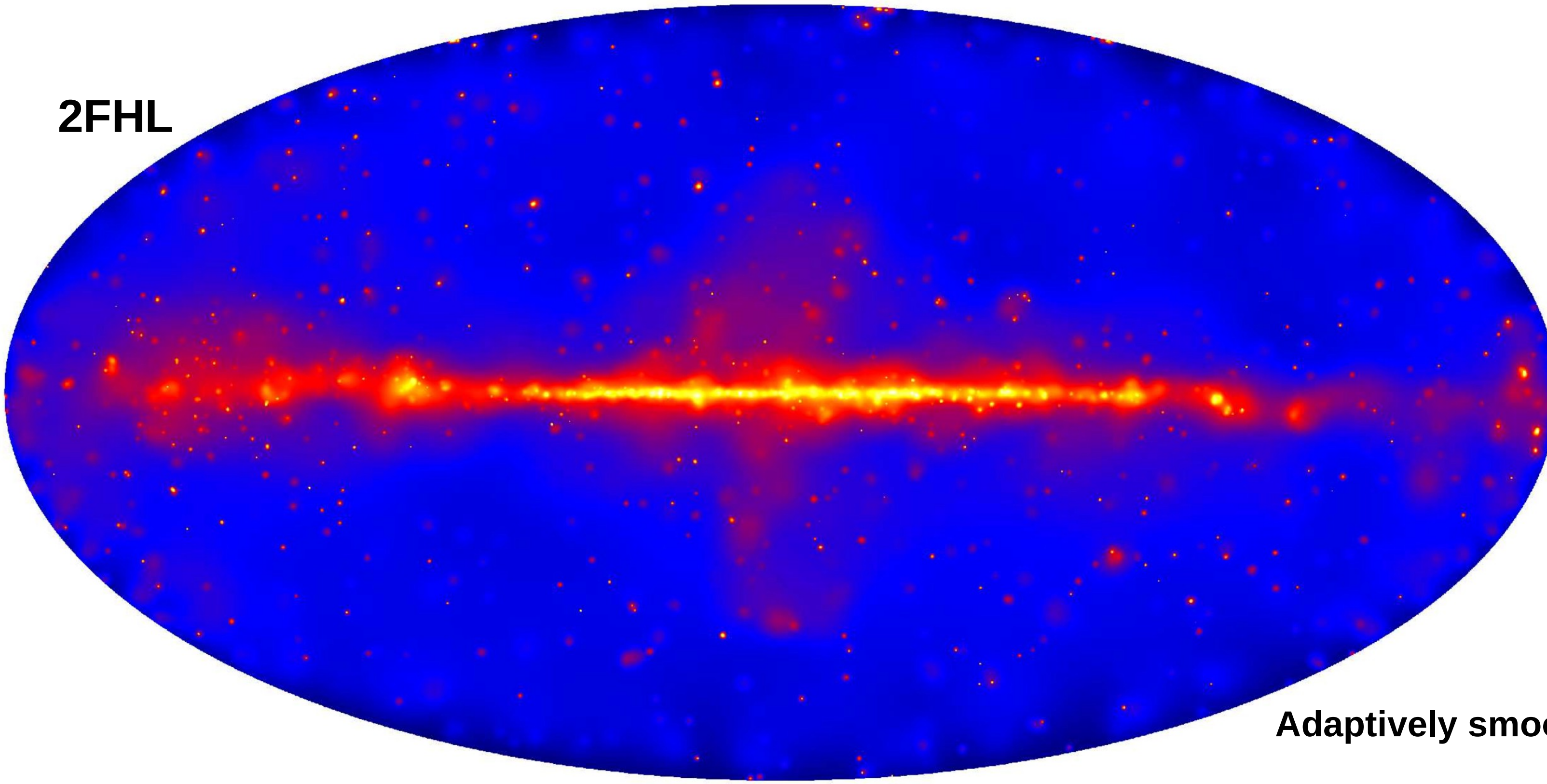
Low energy **spectral studies** limited by:

- Knowledge of **diffuse background** (5% precision)
- **Source density** extrapolated from measured logN-logS

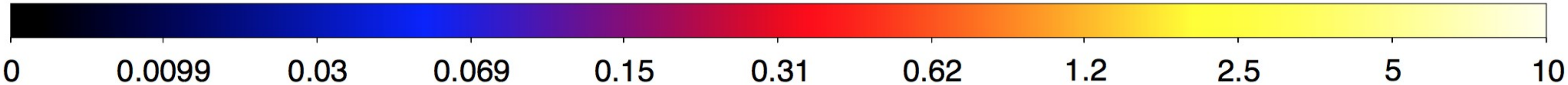


Hard sources limited by count rate (improves **faster than $t^{-1/2}$**)

Fermi's Hard Source Catalogs



360 sources at E>50 GeV in 80 months of *Fermi*-LAT data (~61,000 photons)

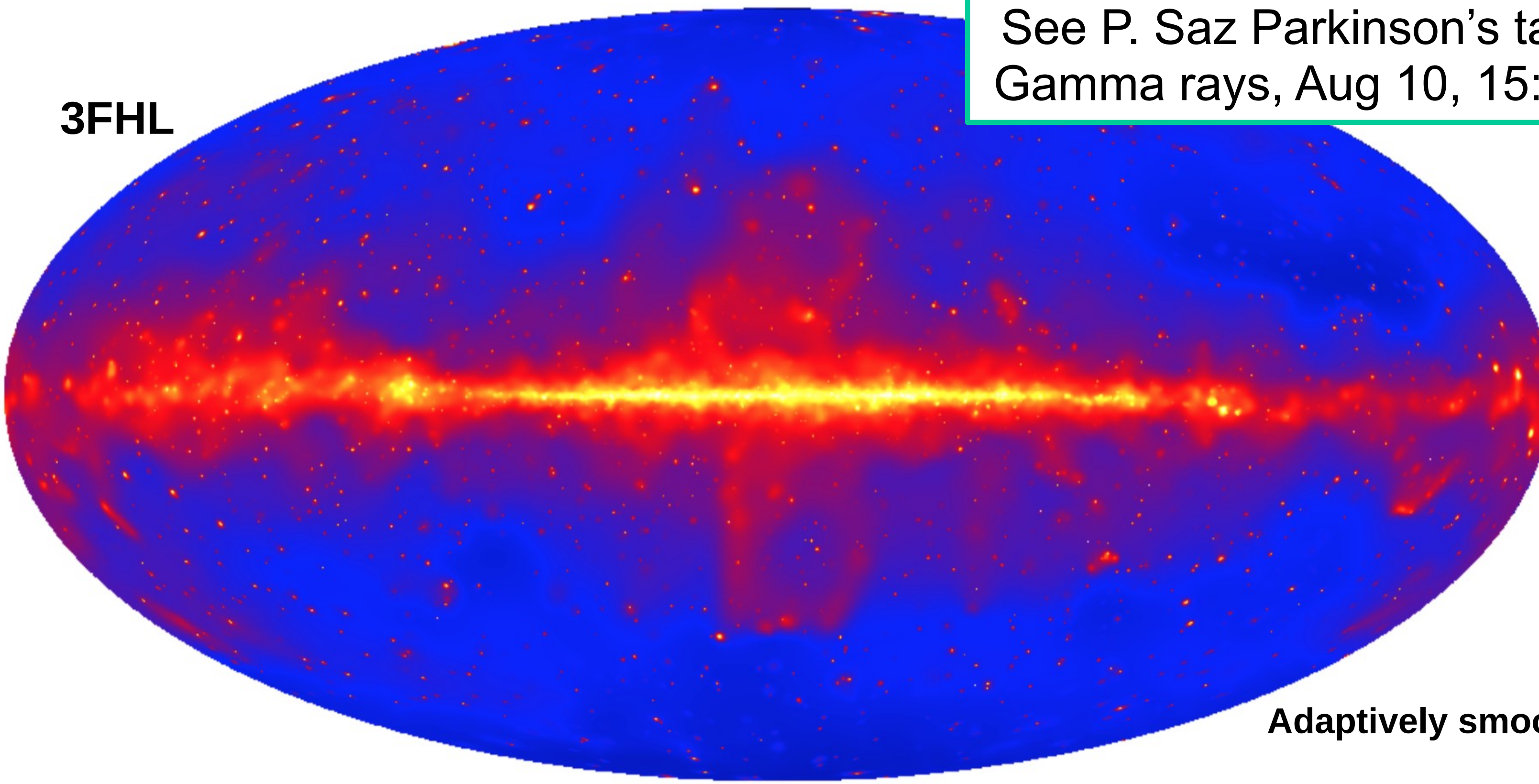


Ackermann et al. (2016)

Fermi's Hard Source Catalogs

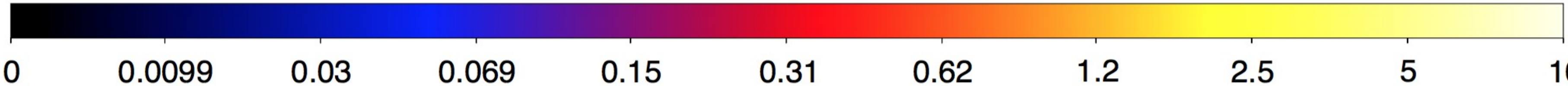
See P. Saz Parkinson's talk
Gamma rays, Aug 10, 15:00

3FHL



Adaptively smoothed

1,556 sources at E>10 GeV in 84 months of *Fermi*-LAT data (~700,000 photons)

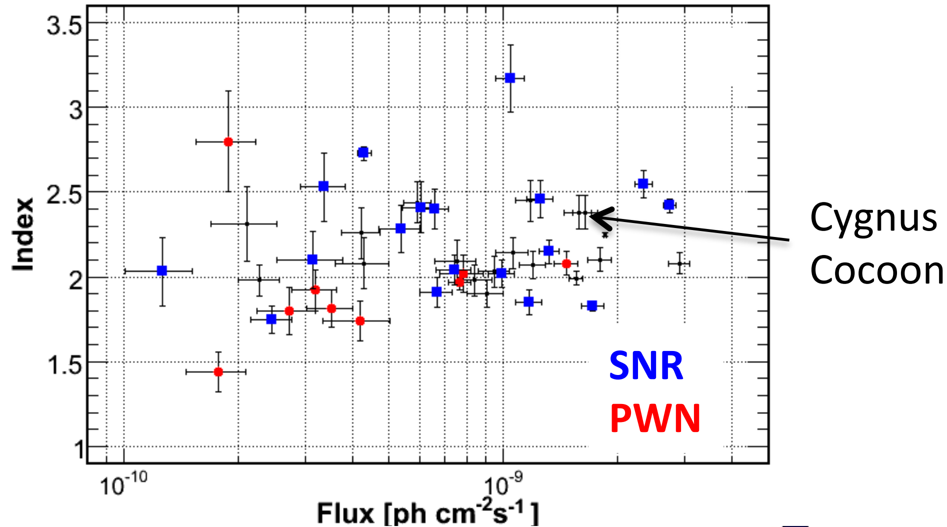


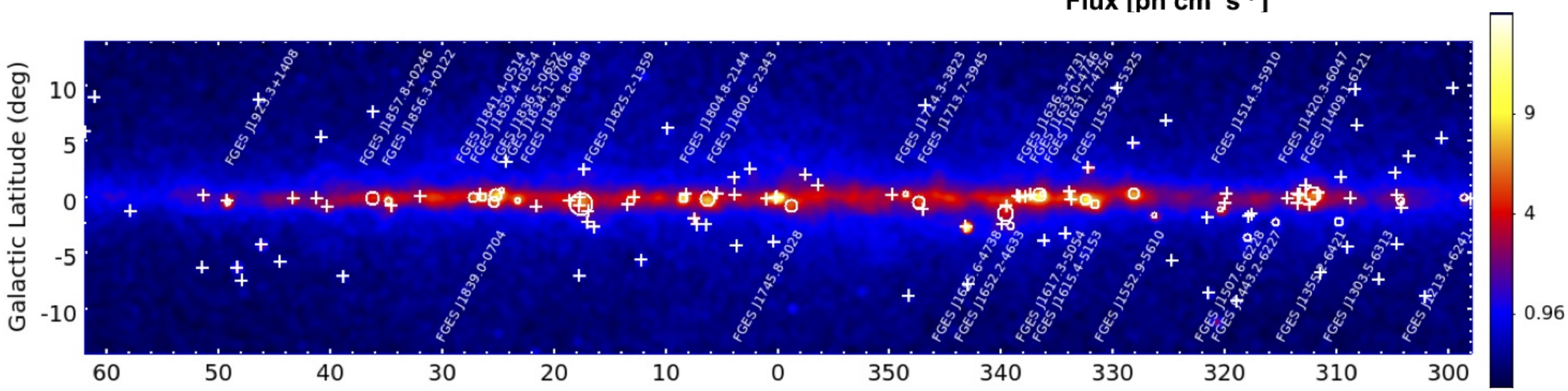
Ajello et al. (2017), submitted to ApJS

Fermi-LAT Galactic Extended Source Catalog

Contact Authors: J. Cohen, M.H. Grondin , E.A. Hays, M. Lemoine-Goumard

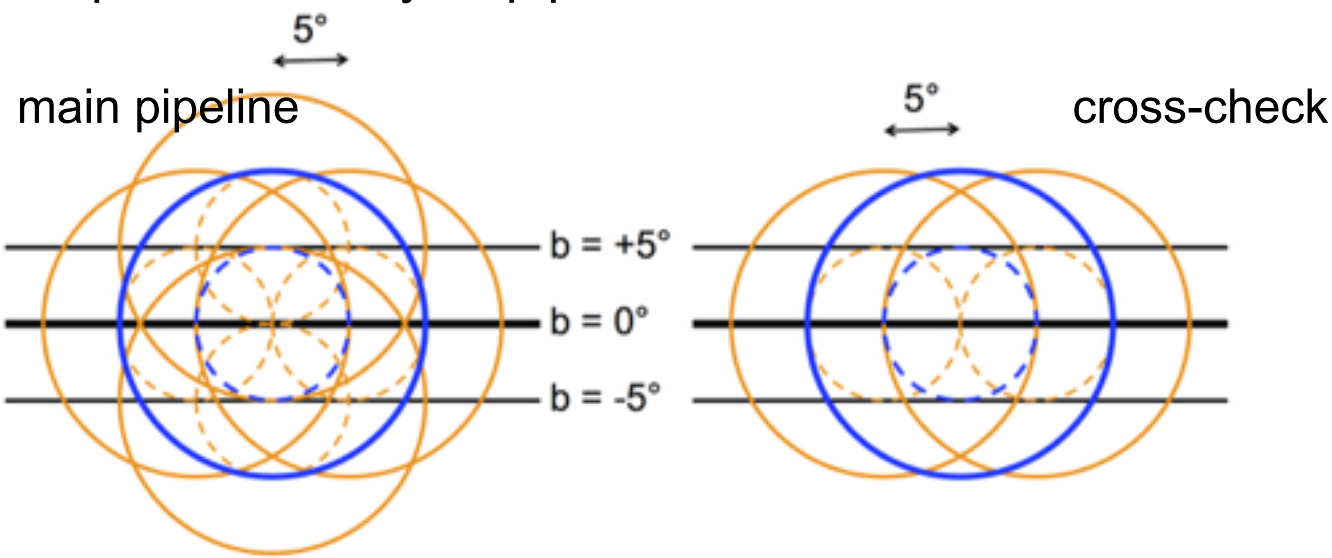
- **FGES** detects 46 extended sources (Ackermann, et al. 2017, ApJ, 843, 2)
  - 16 newly measured GeV extensions
  - 17 previous detections differ in morphology
- Integrated into 3FHL
  - 13 SNR + 17 snr + 9 spp





FGES Analysis Method

- 80 months of Pass 8 data; 10 GeV to 2 TeV energy γ rays
- Scan the Galactic plane (±5°) using overlapping regions and two independent analysis pipelines as a cross-check



- Test candidates for position, extension, alternative hypotheses (2 pt. sources vs 1 ext. source) and spectral curvature
- Extended sources are those with:

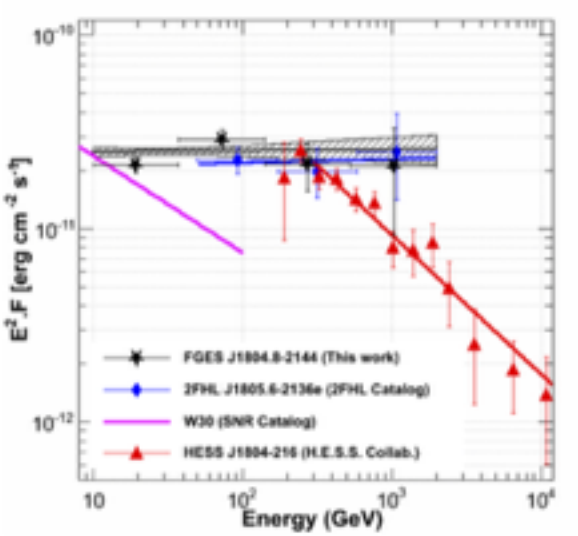
  $TS > 25$; $TS_{ext} > 16$; $TS_{2pts} < TS_{ext}$

$$TS_{2pts} = 2\log(L_{2pts}/L_{ps})$$
$$TS_{ext} = 2\log(L_{ext}/L_{ps})$$

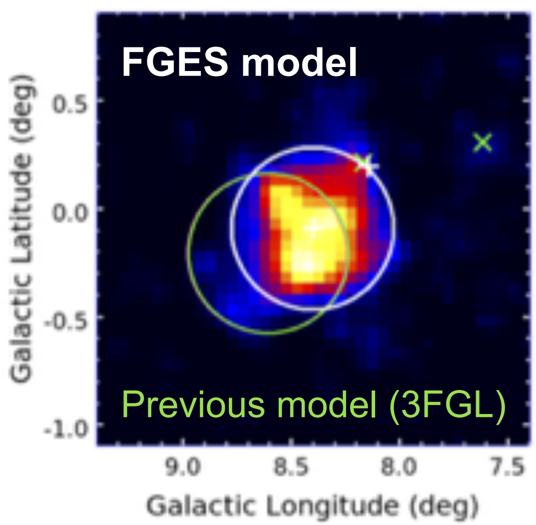
Revealing energy-dependent morphology

- Example: **SNR G8.7-0.1** (**W30** region)
  - Previous lower-energy LAT measurements (Ajello, et al. 2012) match to radio extent while higher-energies correspond to TeV (HESS J1804-216; Aharonian, et al. 2006)
  - Very large for PWN… analog of Vela X?

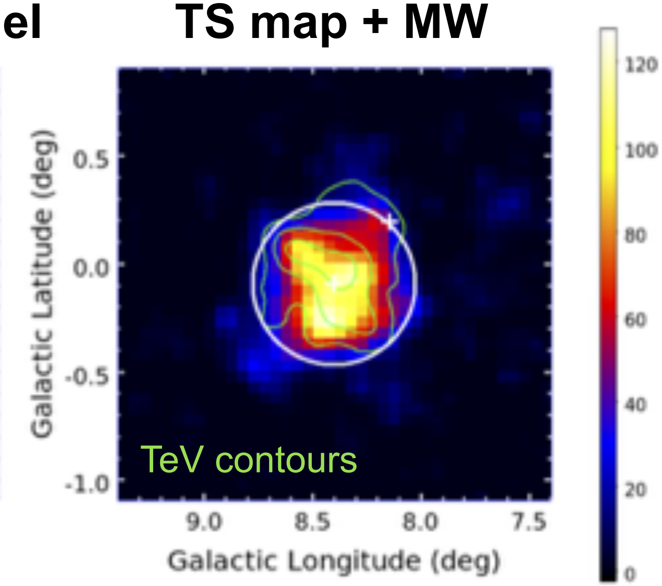
SED



TS Map + Source Model



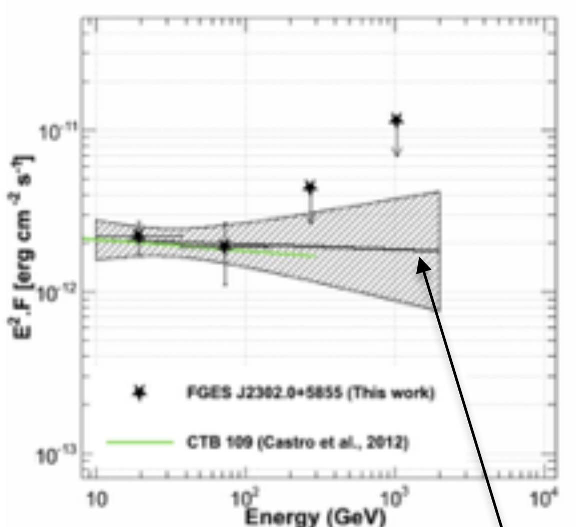
TS map + MW



Motivating new TeV observations

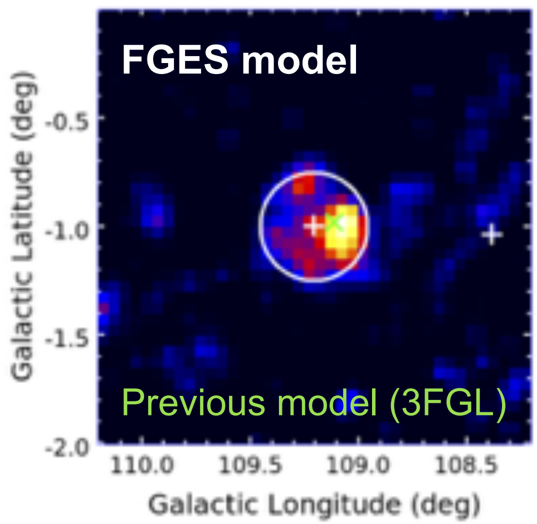
- Example: **CTB 109**
  - Age : 8800 – 14000 yrs; Central magnetar.
  - First detection of GeV extension (pointlike in Castro et al. 2012)
  - Good agreement with X-ray/Radio size: 0.25° ± 0.02°stat

SED



~0.3% Crab at 1 TeV

TS Map + Source Model



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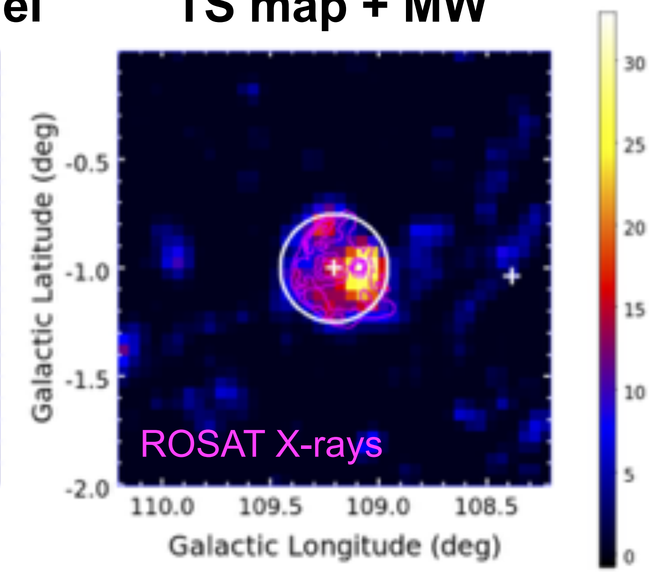
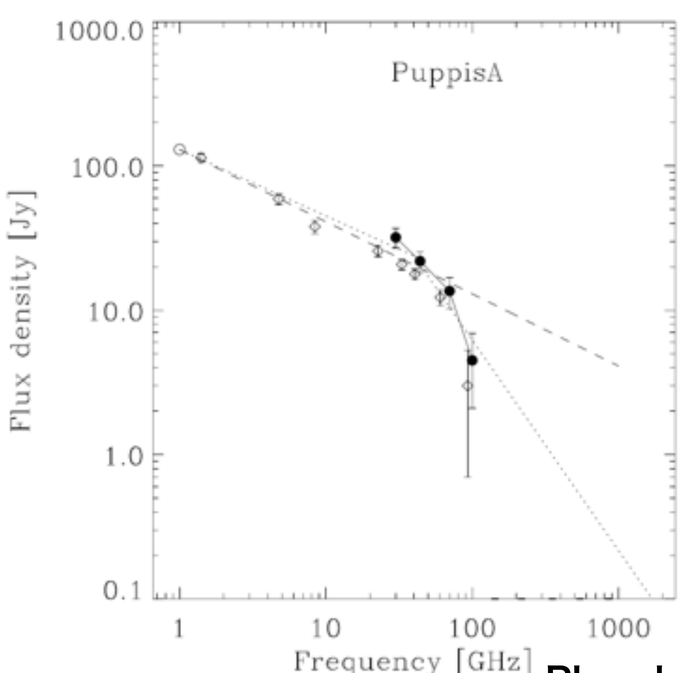
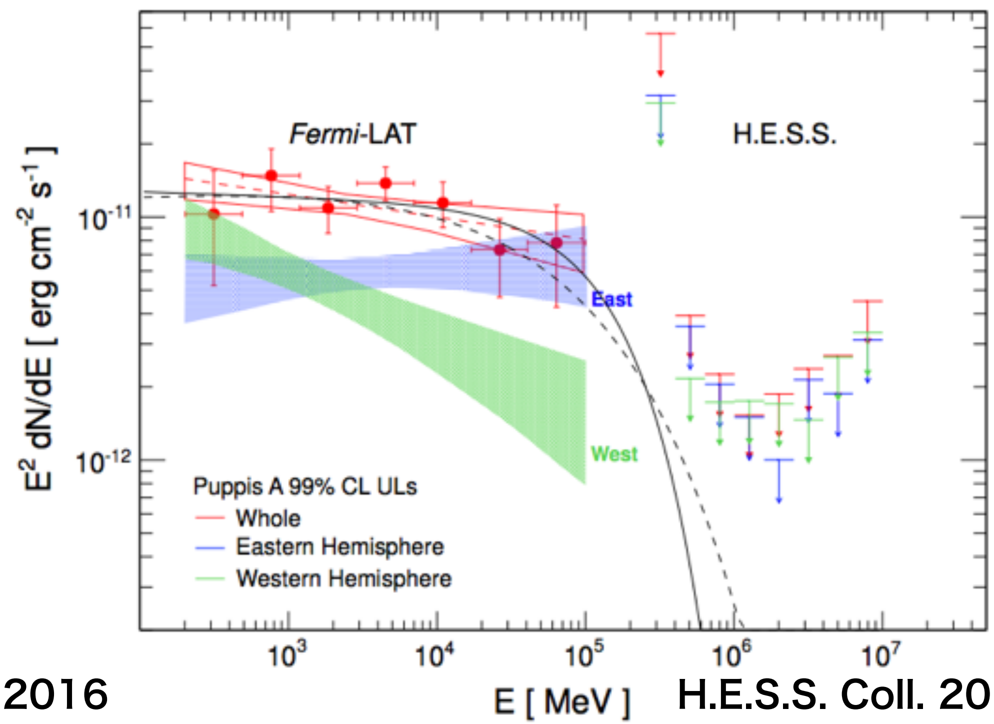


… To find interesting upper limits

- **Puppis A is γ-ray SNR with PL index of 2.1** (Hewitt, et al. 2012)
  - Radio spectrum shows break in e^- synchrotron ~40 GHz
  - HESS observations show high energy TeV cutoff



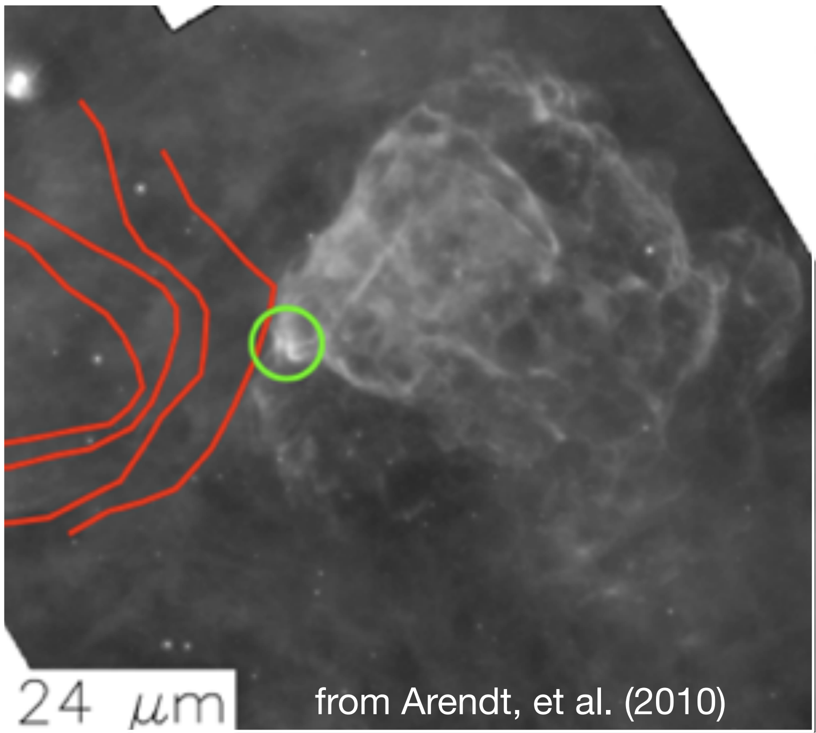
Planck Coll. 2016



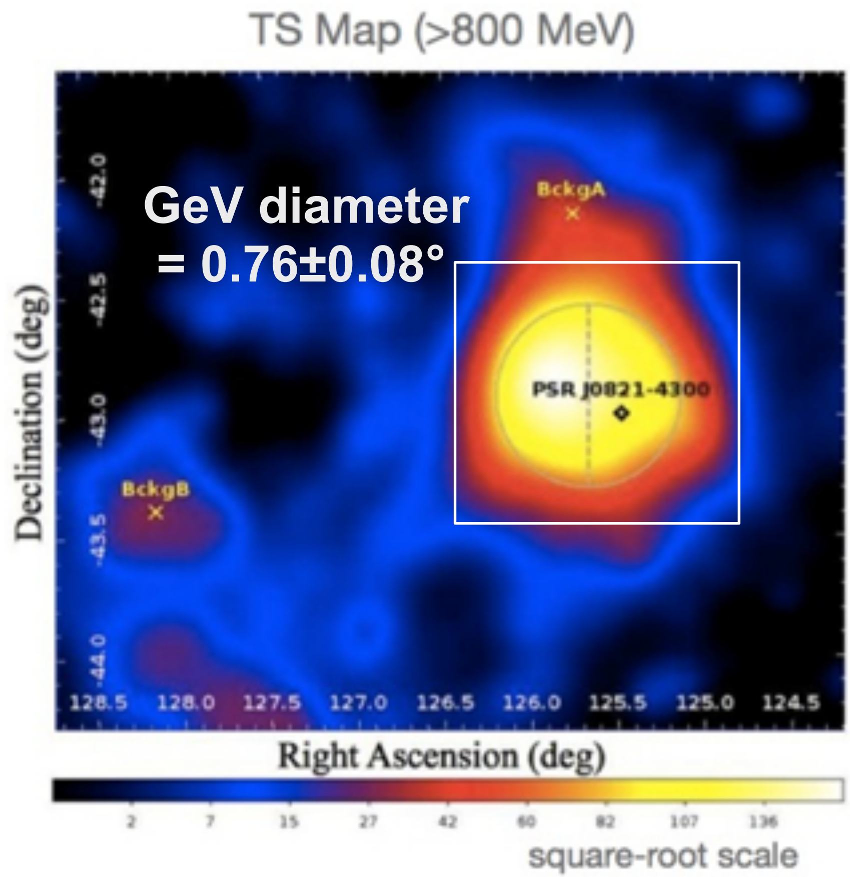
H.E.S.S. Coll. 2015

Puppis A: proto-interacting SNR/MC

- <4,000 yr old SNR with extended GeV γ-rays and interacting with dusty ISM (n~4 cm^{-3}) near a molecular cloud. Not unlike SNR/MCs, but younger with far lower density.



IR emission from shocked dust as Puppis A expands towards a molecular cloud (CO contours). Interaction with a dense clump is indicated.



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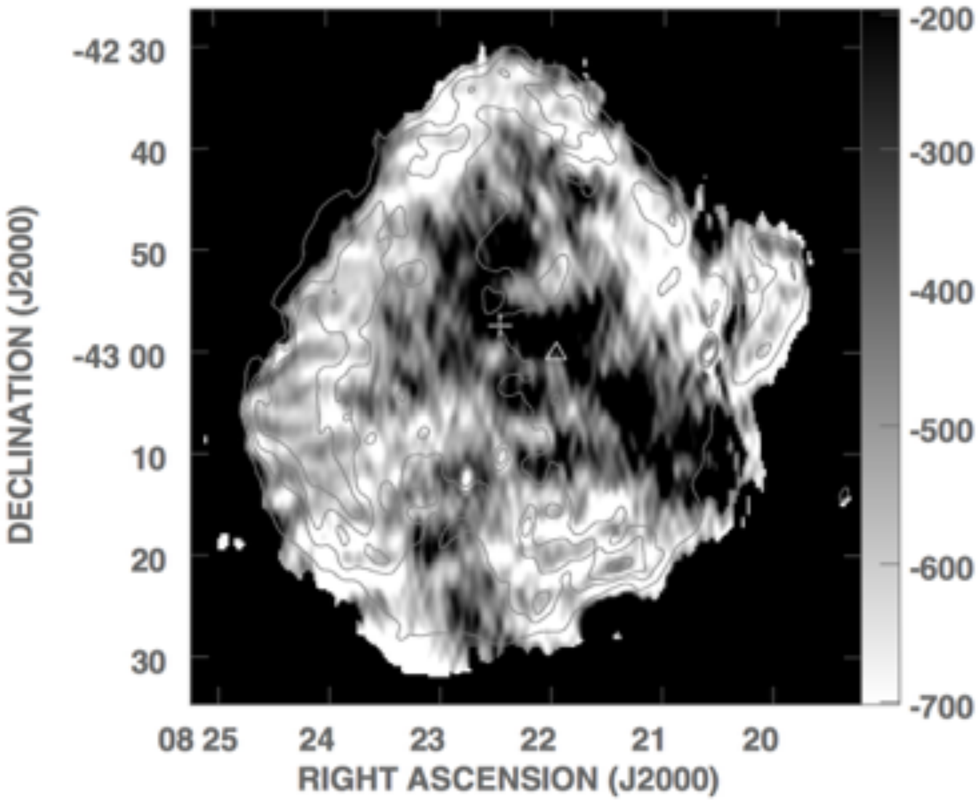
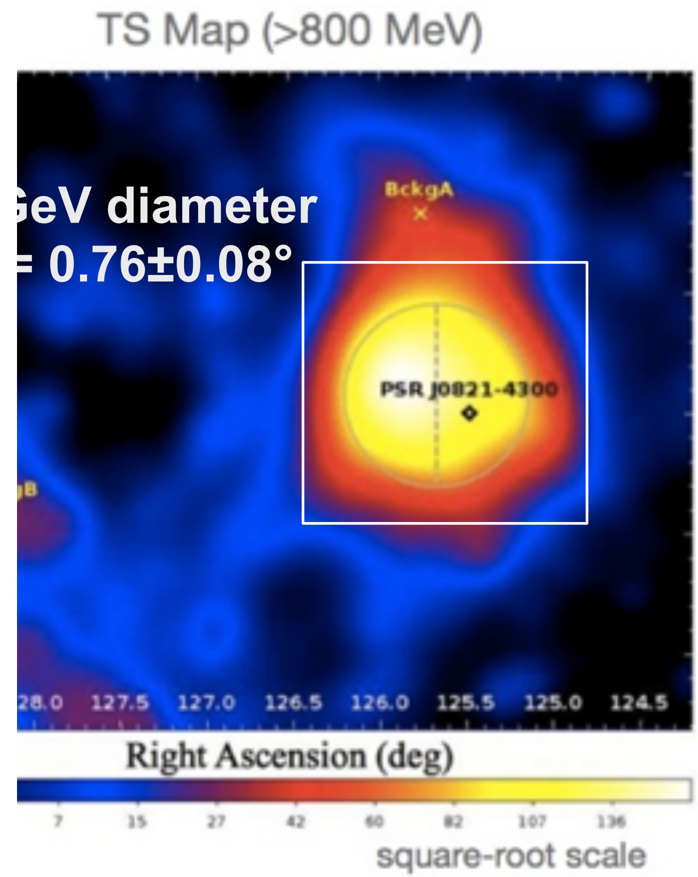


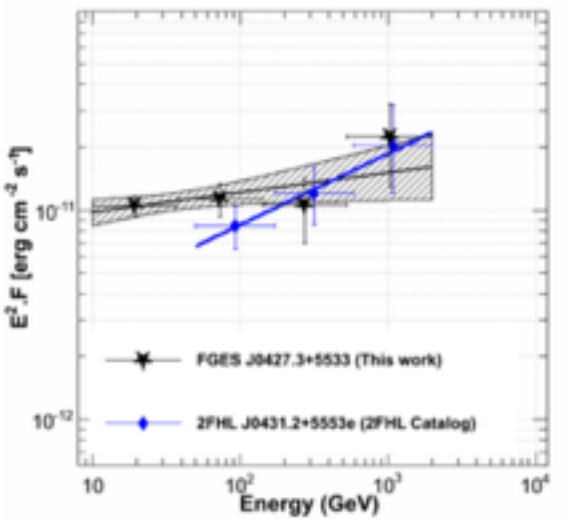
Radio spectral index varies across SNR



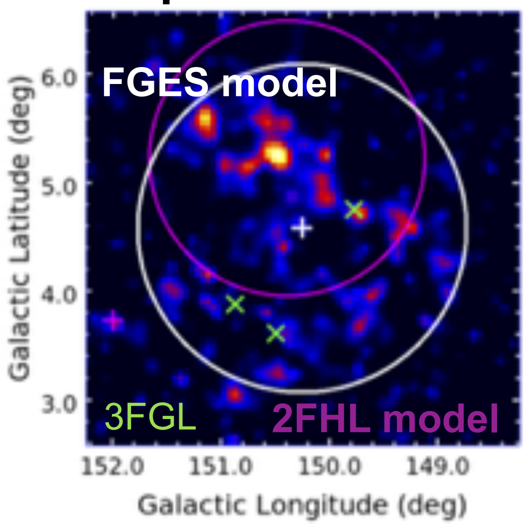
Finding new types of γ-ray SNRs?

- SNR G150.3+4.5 is a high-latitude, large diameter SNR
  - Identified in 2FHL, but only with increased statistics is there agreement with radio size.
  - Large size suggest old, nearby remnant *but* hard spectrum is not seen for other such older SNRs (no energetic PSR to power PWN)

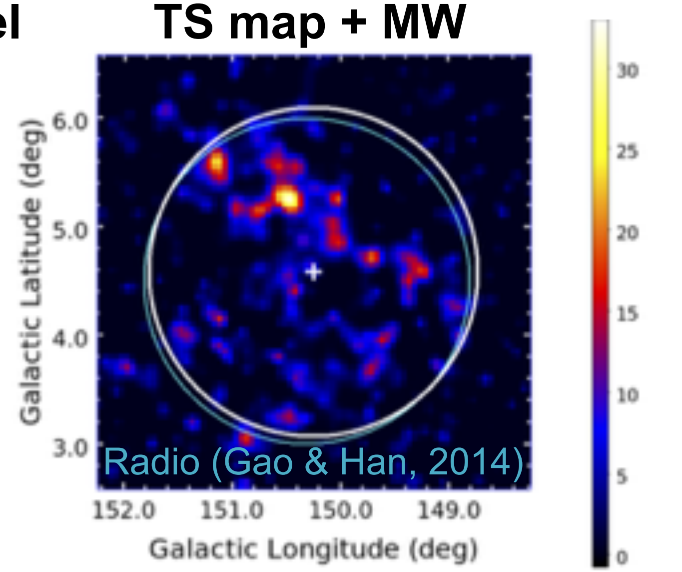
SED



TS Map + Source Model



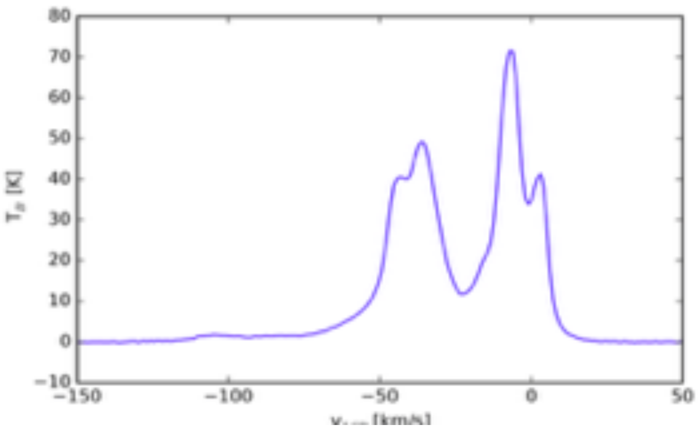
TS map + MW

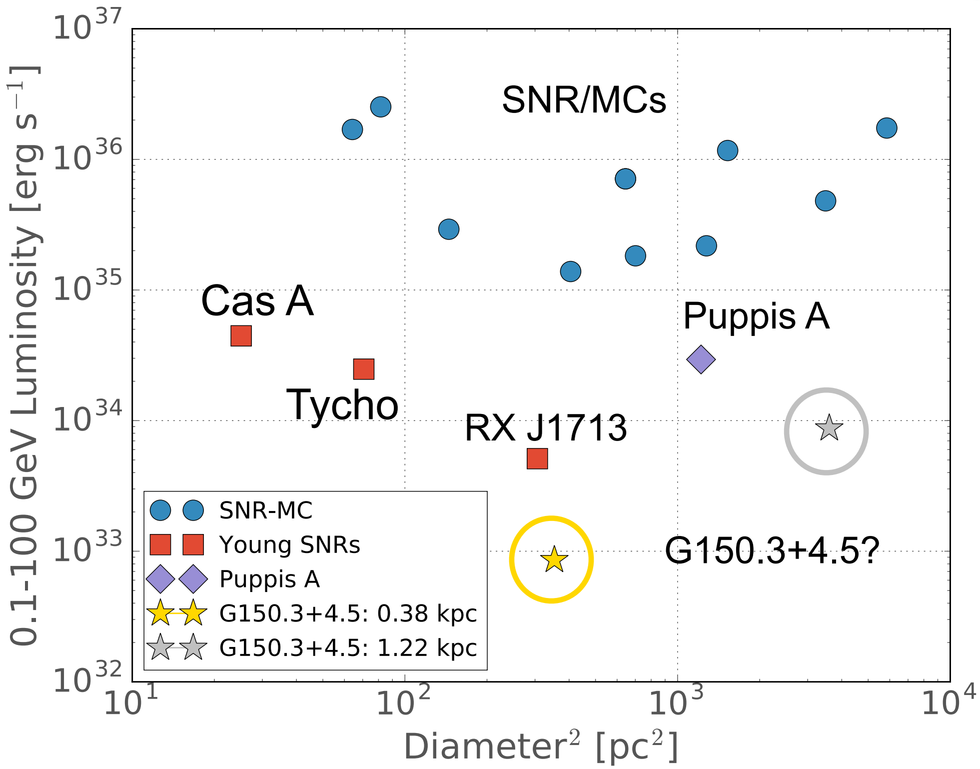


- **Large SNRs (such as G150.3+4.5) are difficult to detect at TeV**

SNR G150.3+4.5: An unusual γ-ray SNR

- HI spectra shows clouds at d = 0.38 to 5.6 kpc (Perseus arm, d = 2 kpc)





- Low γ-ray luminosity similar to shell TeV SNRs?

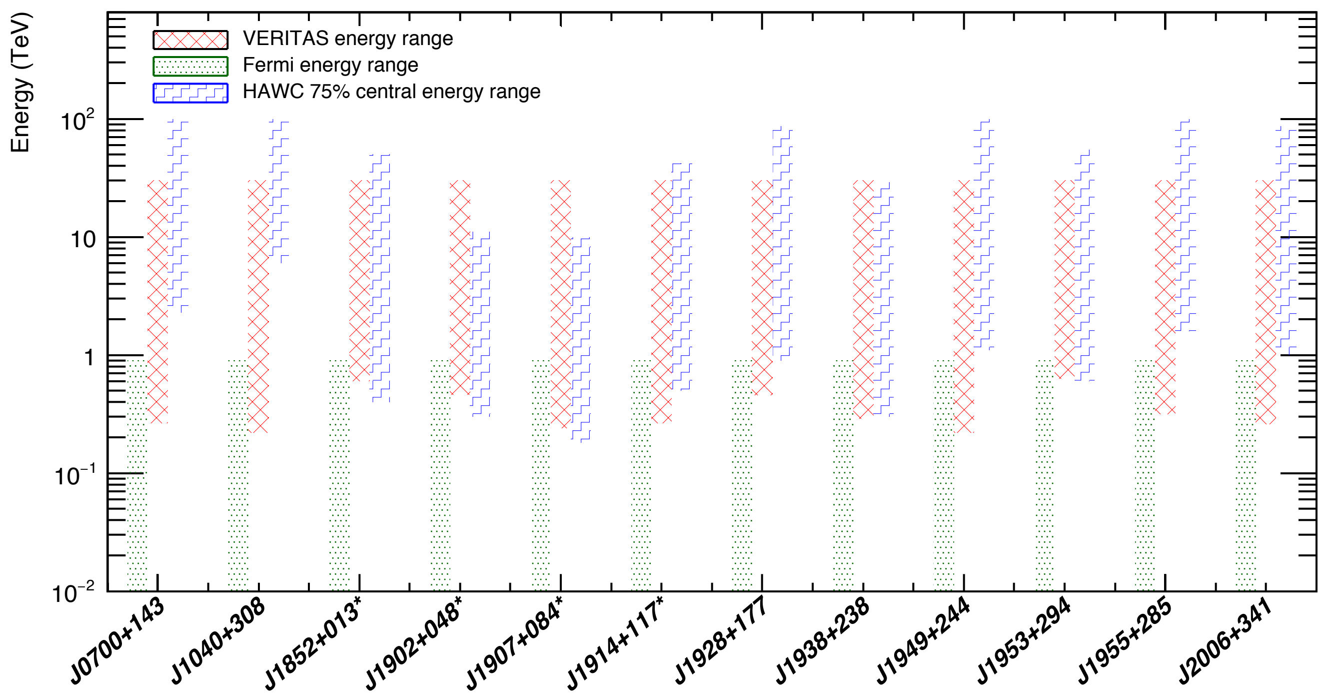
- Similar candidate γ-ray SNR detected by Fermi High-Latitude Extended Source Catalog (FHES) with large angular extent (~3°) and hard spectral index (Γ~1.8)

See M. Meyer's FHES talk Gamma rays: 9 Aug, 14:45

Joint LAT / TeV / HAWC Studies

- HAWC is ideal to find SNRs like G150.3+4.5 (large, hard spectrum)
- 2HWC found 19 sources more than 0.5^{o} away from any known TeV counterpart
  ➡ GeV/TeV follow-up (VERITAS, MAGIC)

See Nahee Park's talk
Galactic, Aug 10, 16:30



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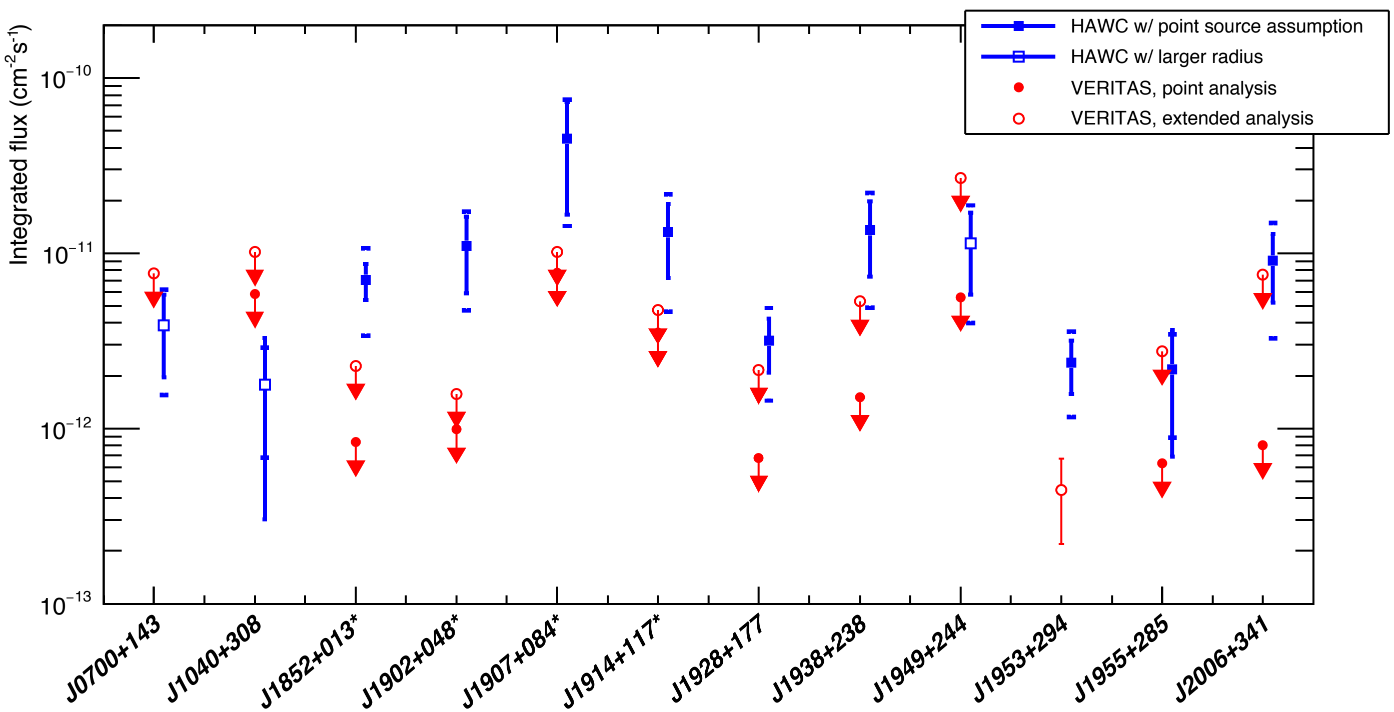

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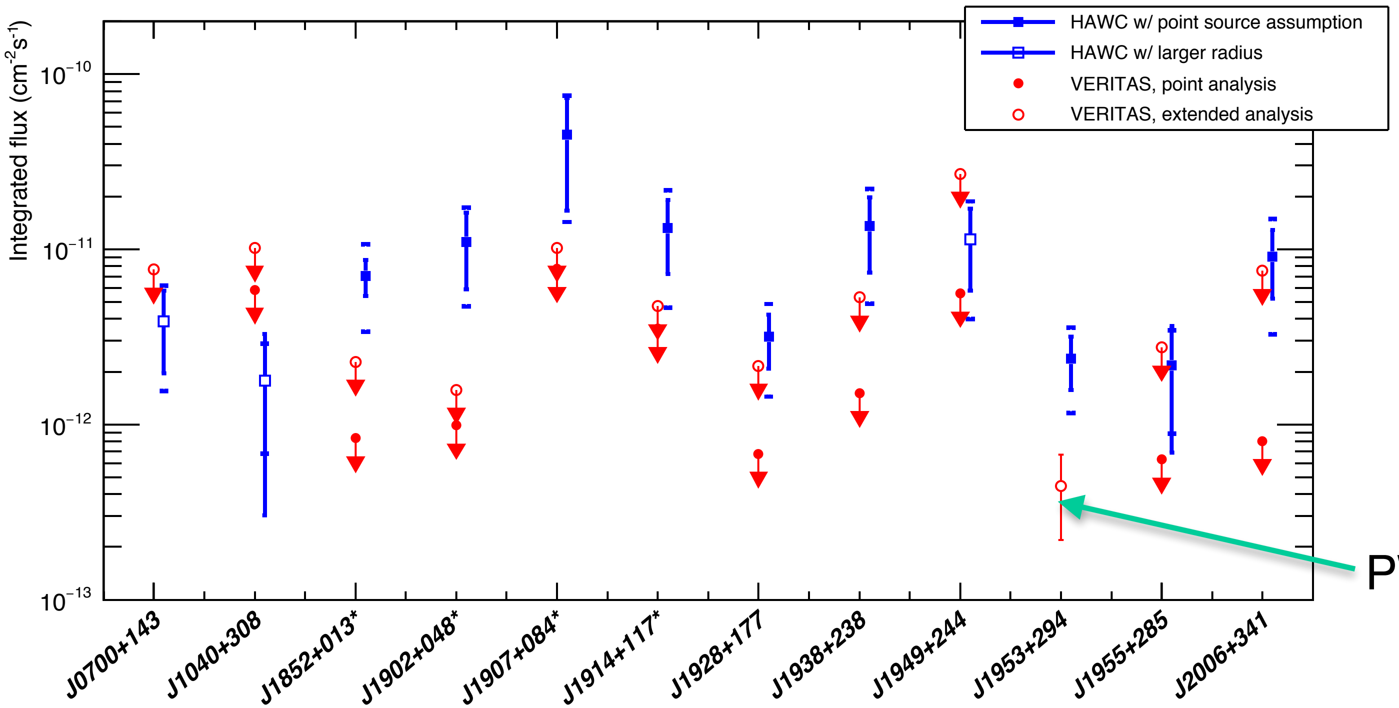
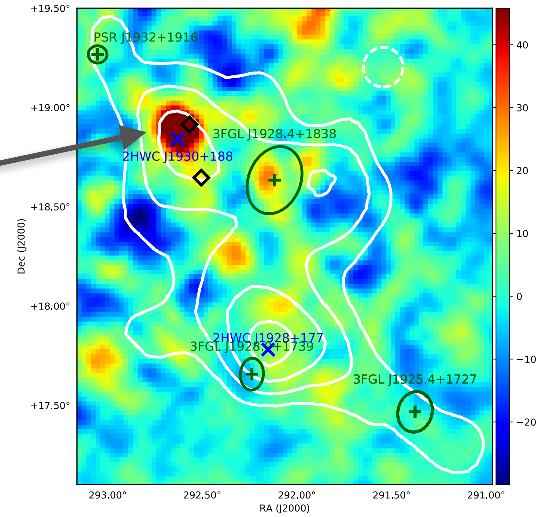
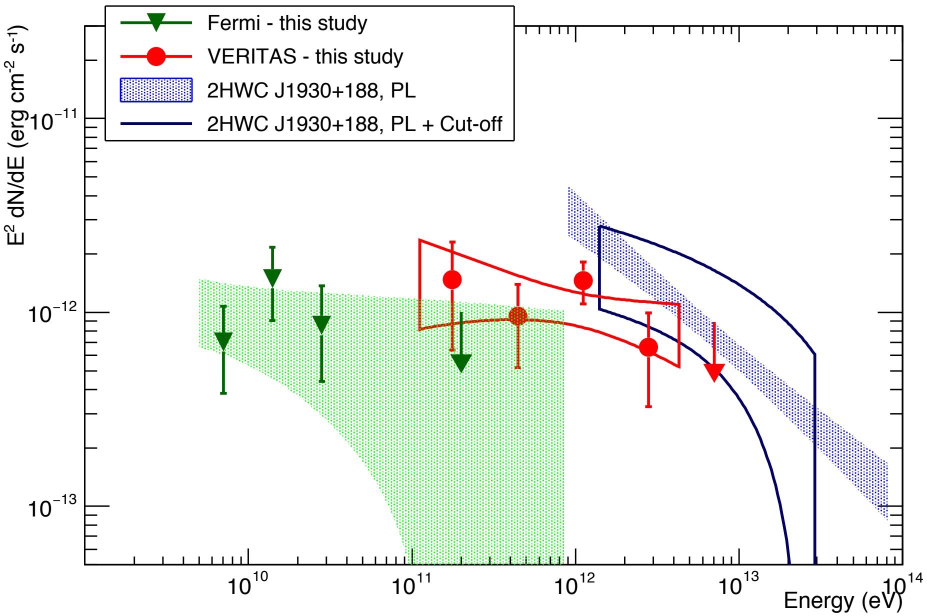


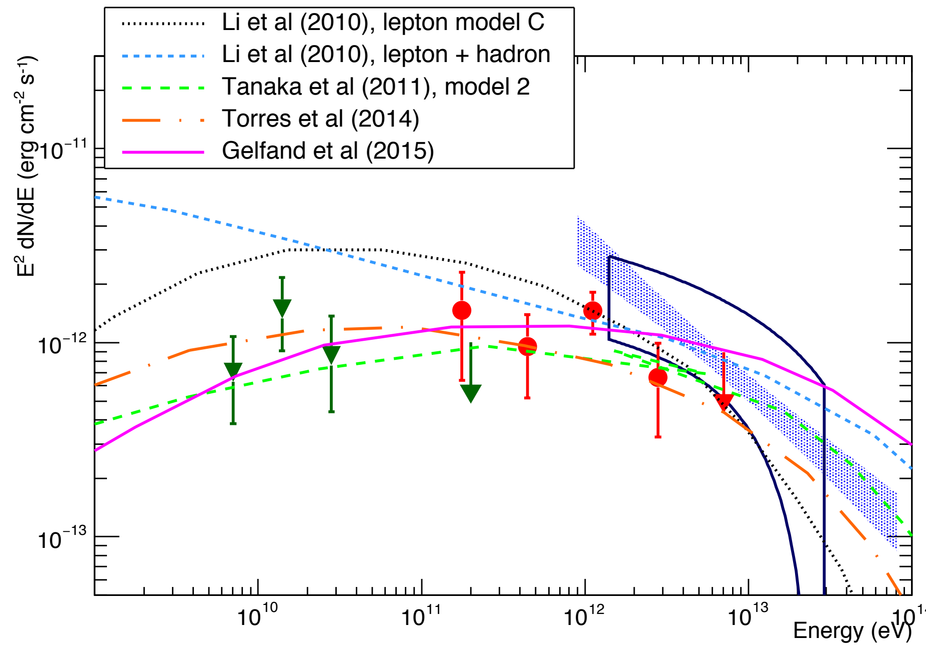
PWN DA 495

New detection of PWN G54.1+0.3

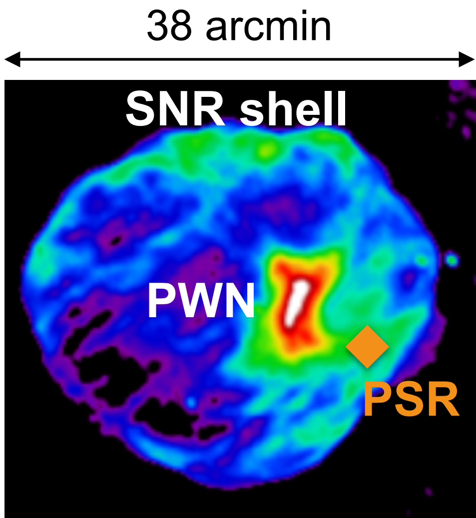
- Not detected by 3FHL, but updated LAT analysis (8.5 yr) detects source matching VERITAS and HAWC TeV sources
- γ ray data well-matched to leptonic models of the PWN.



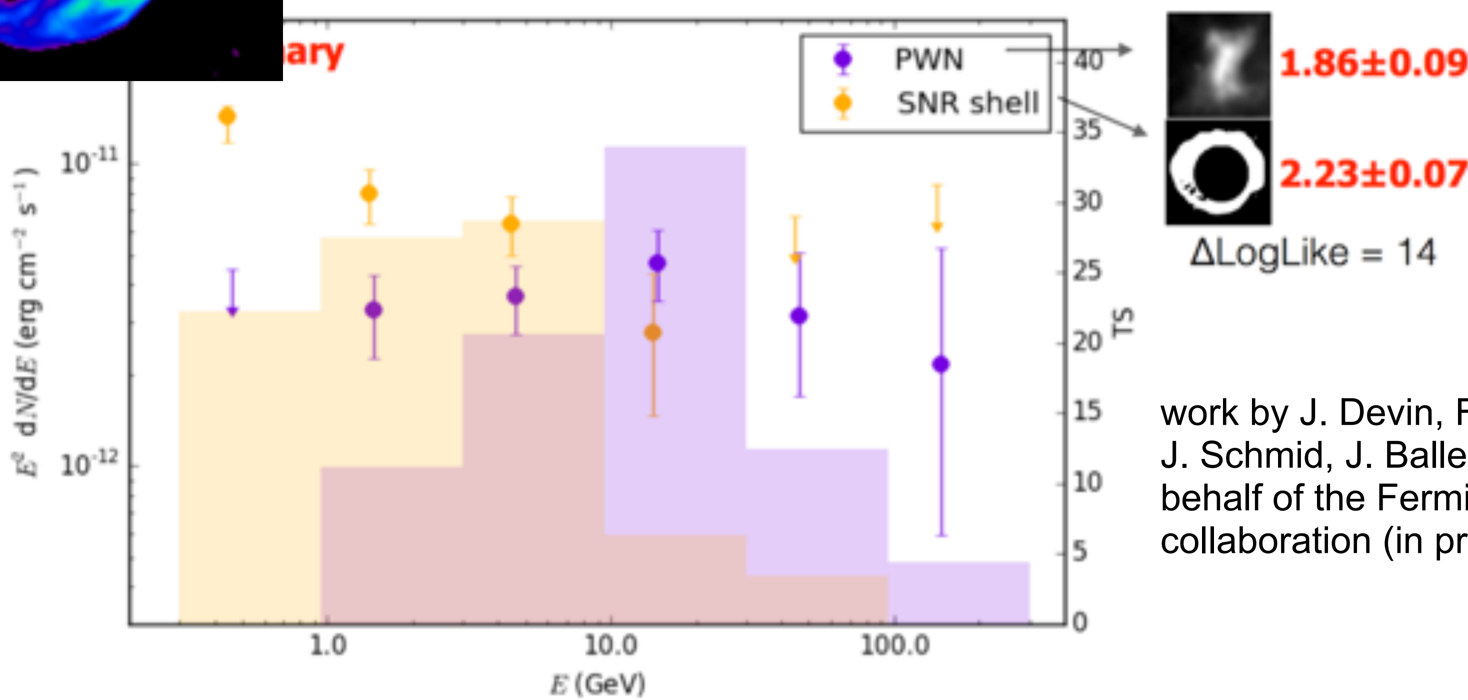




Composite SNR G326.3-1.8



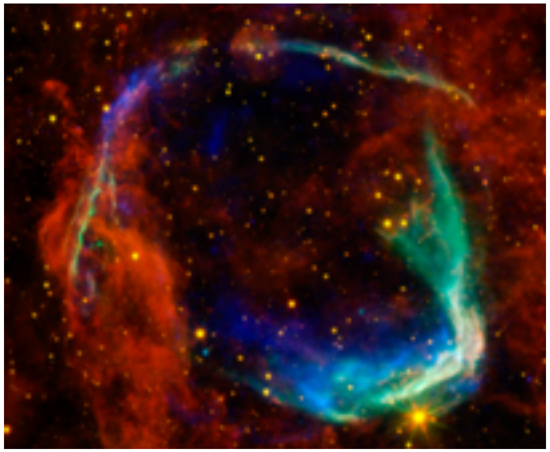
- Sedan phase SNR with energetic PSR+PWN (modeled by Temim, et al. 2013)
- LAT Pass 8 data can spatially separate hard-spectrum PWN from soft-spectrum SNR shell
- Requires spatial resolution, 3-decade energy reach *and* multi-wavelength templates



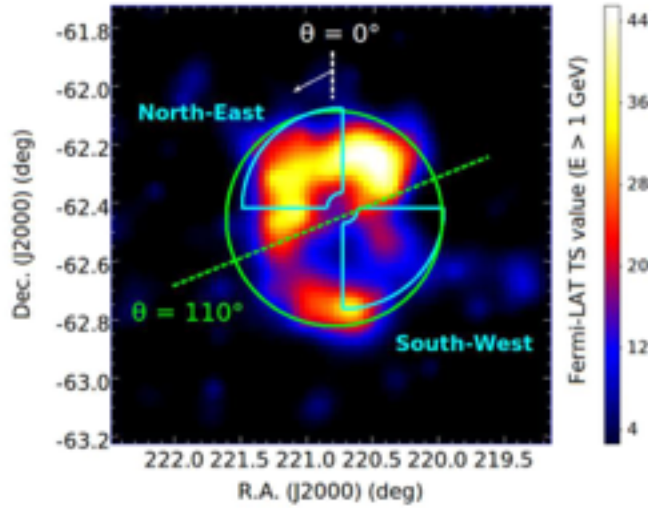
work by J. Devin, F. Acero, J. Schmid, J. Ballet, on behalf of the Fermi LAT collaboration (in prep.)

Young TeV Shell SNR RCW 86

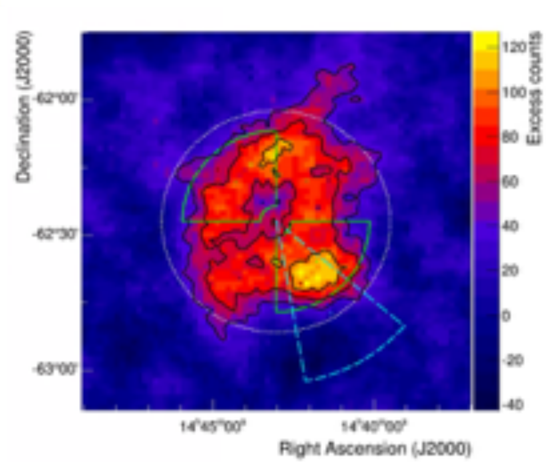
IR + shock + NT X-rays



Fermi LAT significance map

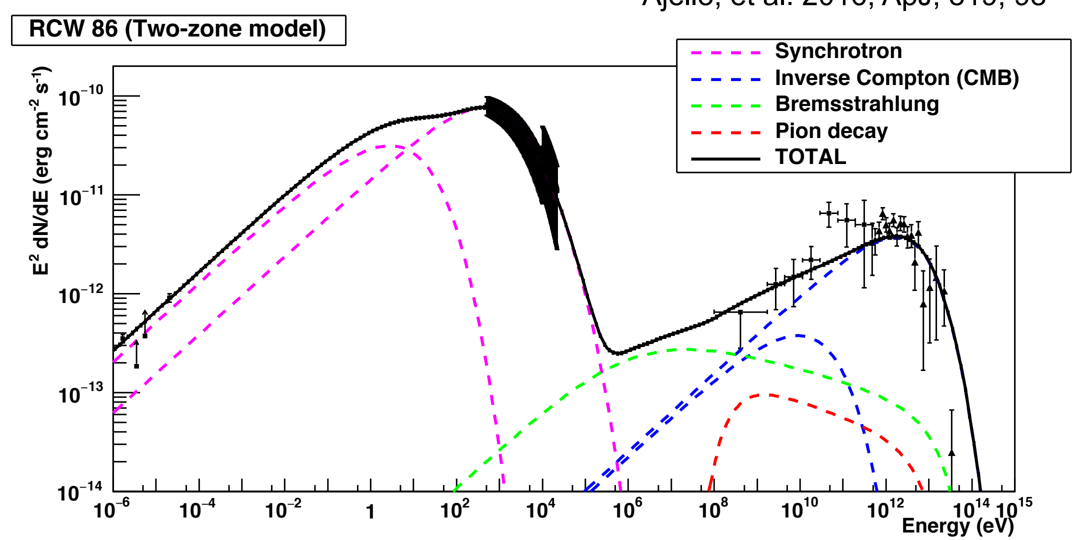


HESS excess counts



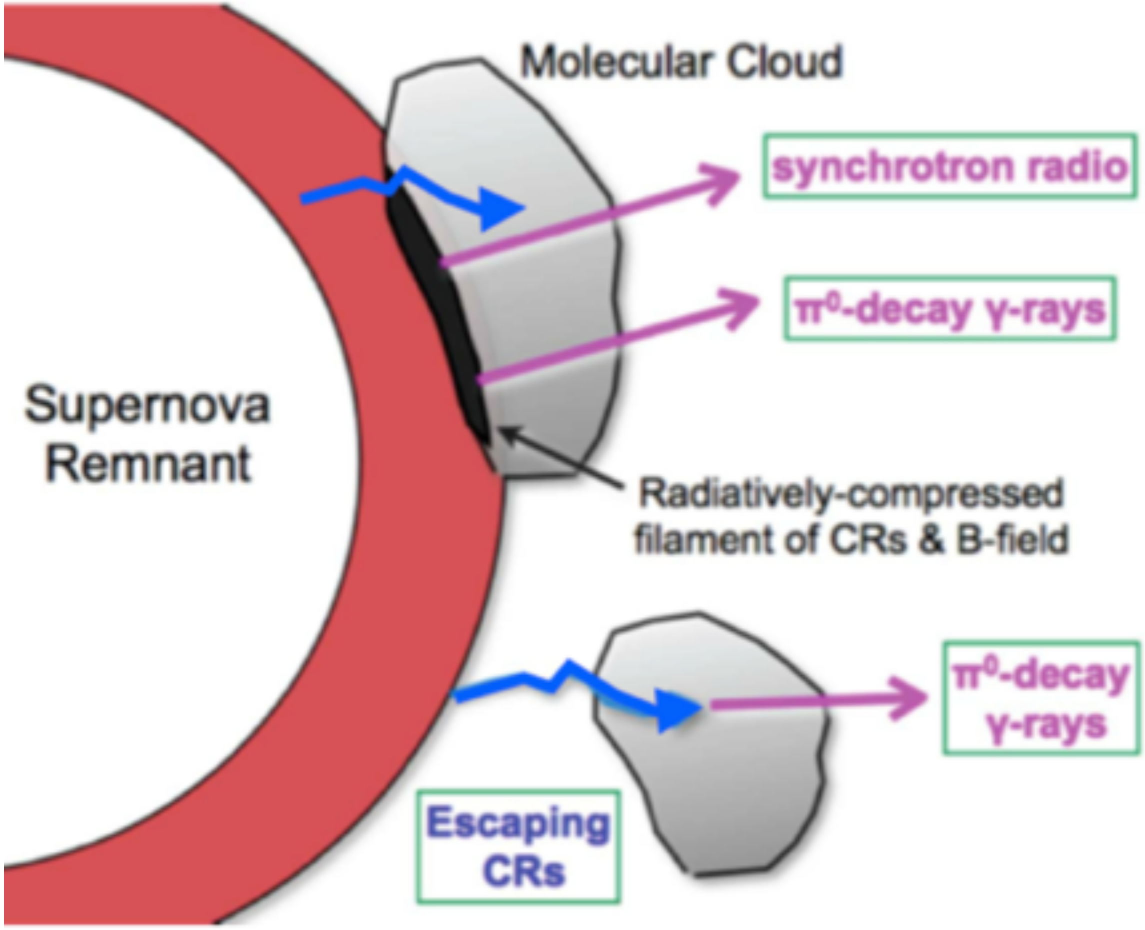
Ajello, et al. 2016, ApJ, 819, 98

- RCW 86 (~1830 yr) is only fit by leptonic models due to hardness of GeV emission
- Two-zone model constrain $W_{CR,p} < 4\text{x}10^{49}$ erg; $n = 1$ cm^{-3}
- SW is TeV bright / GeV faint



Competing models for Interacting SNRs

- Surrounding environment determines CR acceleration efficiency, escape and γ-ray emission interpretation



Two scenarios:

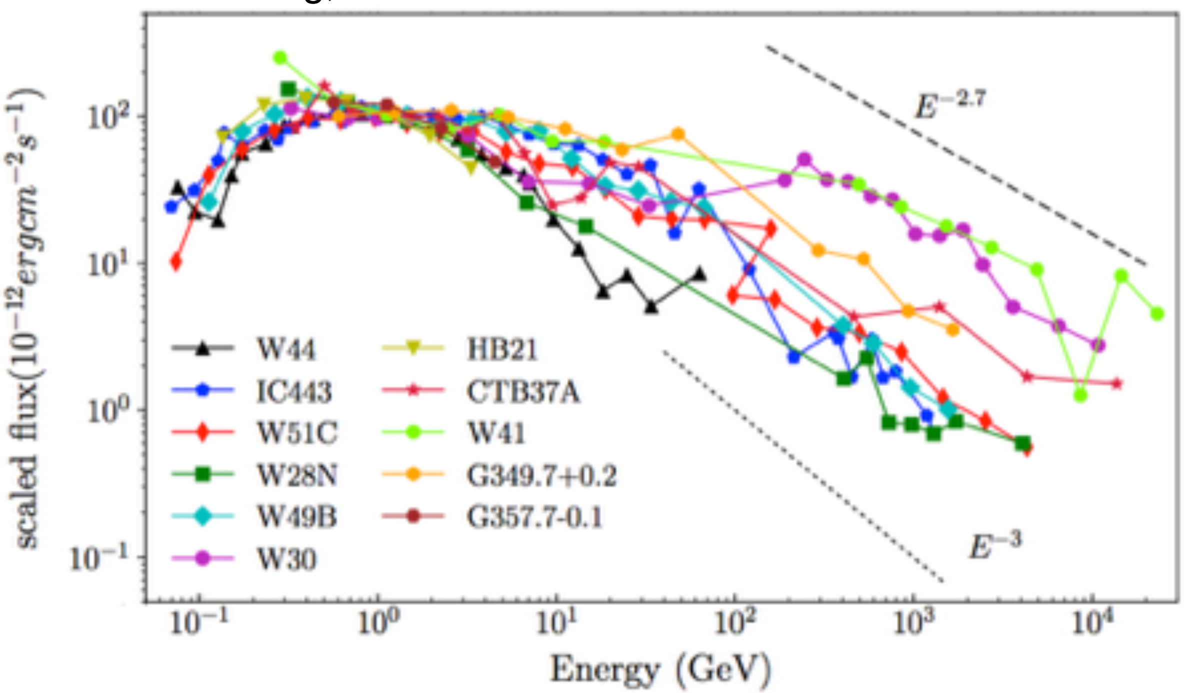
1. Crushed clouds:
CRs + MC compressed
Re-acceleration of GCRs
e.g., Uchiyama+ (2010), Tang & Chevalier (2014)

2. Illuminated clouds:
CRs escape, passively interact with cloud
e.g., Gabici+ (2007), Casanova+ (2010)

Competing models for Interacting SNRs

- Spectra of 11 SNR/MCs show striking similarity… expect more variation if illuminated by escaping CRs?
- Interaction with dense gas leads to acceleration of existing ambient CRs, instead of thermal seed particles in young SNRs

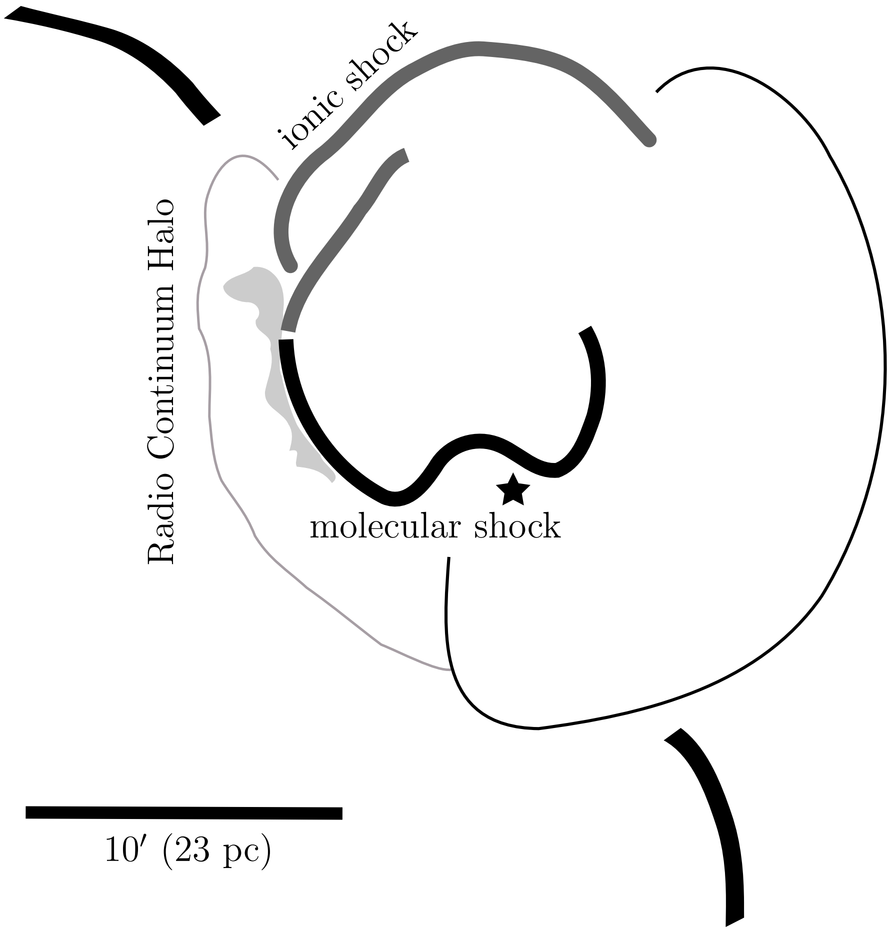
from Tang, arXiv:1707.00958



- TeV-bright SNR/MCs may require reaccel of freshly accelerated CRs, or harder ambient CR spectrum than locally
- Fresh DSA requires ~33% shock energy, while re-accel needs only ~1%(Lee et al. 2015)

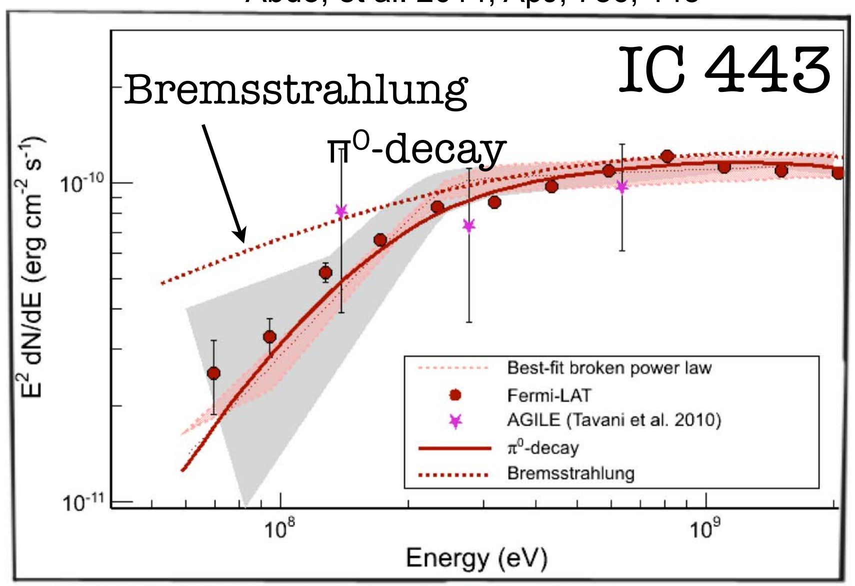
Interacting SNR IC 443 in depth

Schematic of IC 443 from Lee, et al. (2008)



γ-ray spectral turnover matches what is expected from π^0-decay

Abdo, et al. 2014, ApJ, 786, 145



- CR acceleration efficiency 1-4% (uncertainty in mass of clouds)
- *but* VHE shows break ~200 GeV/c

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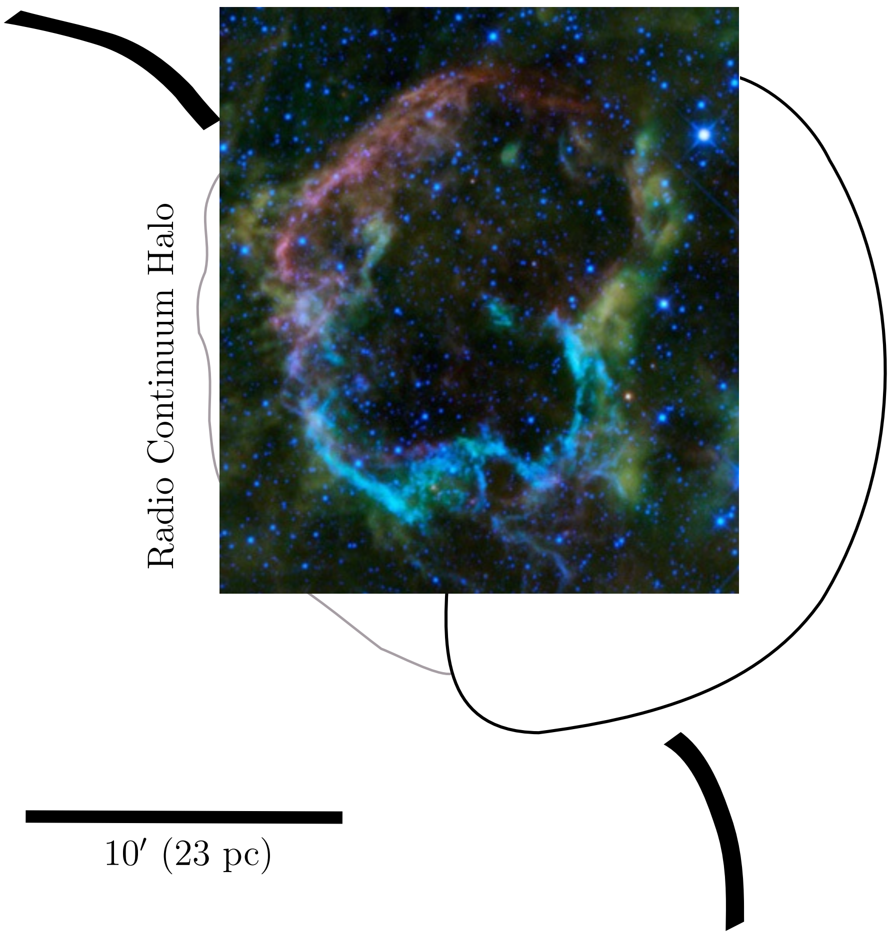

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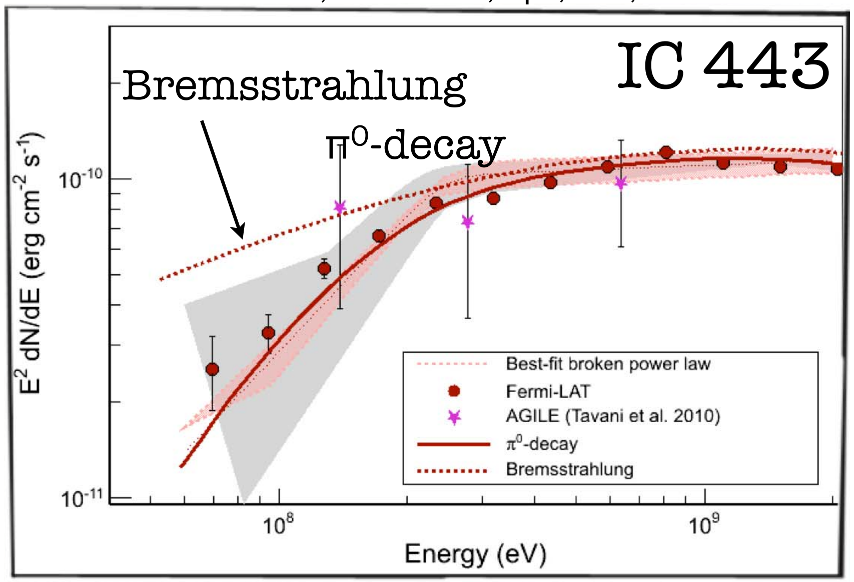
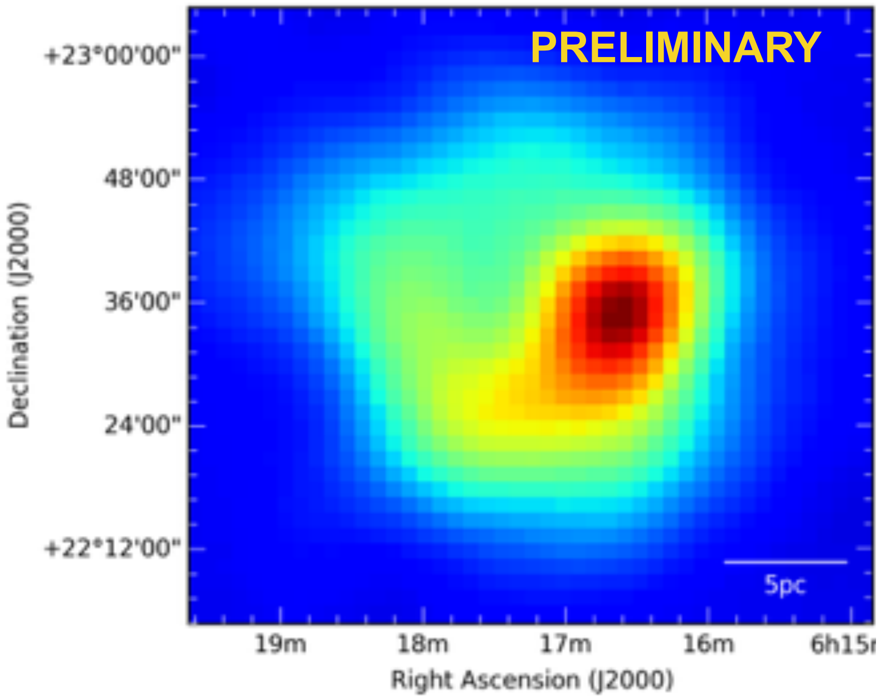


- CR acceleration efficiency 1-4% (uncertainty in mass of clouds)
- *but* VHE shows break ~200 GeV/c

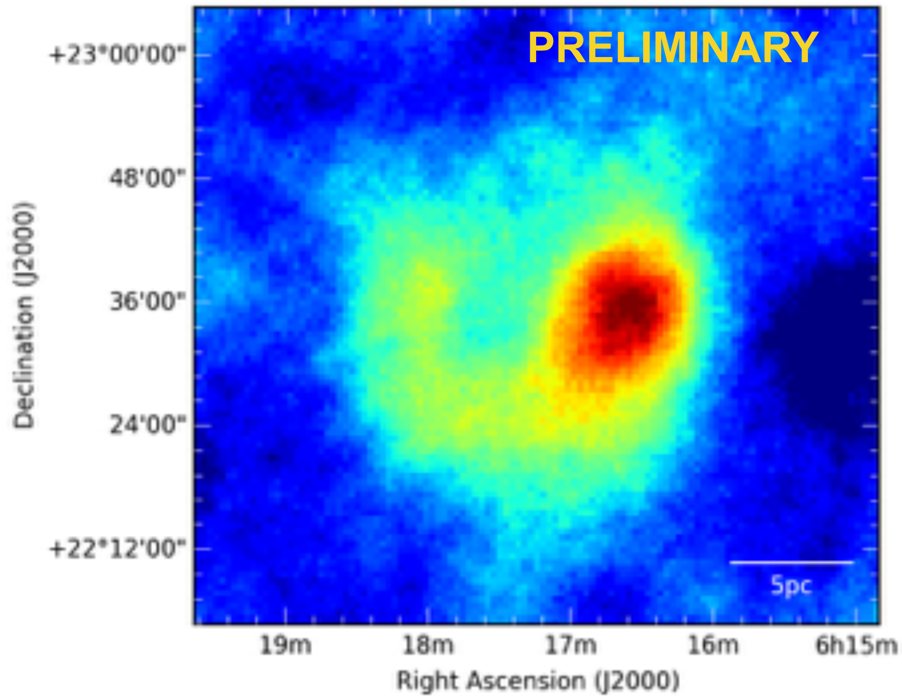
IC 443 Resolved by LAT and VERITAS

7 yr *Fermi* LAT Pass 8 data

178 hr of VERITAS data



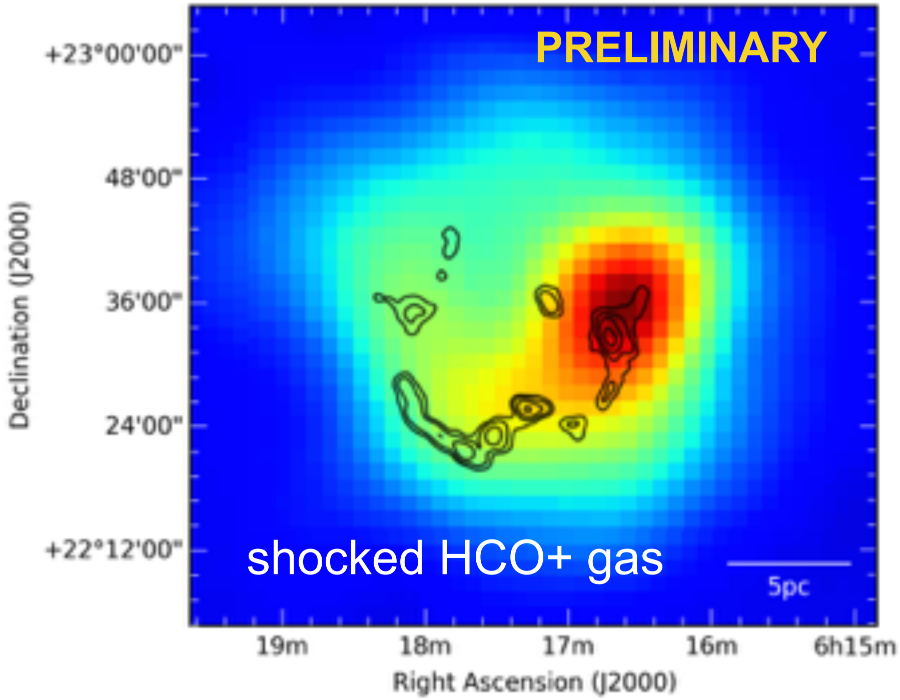
Counts Map >5 GeV (PSF23)



Significance Map

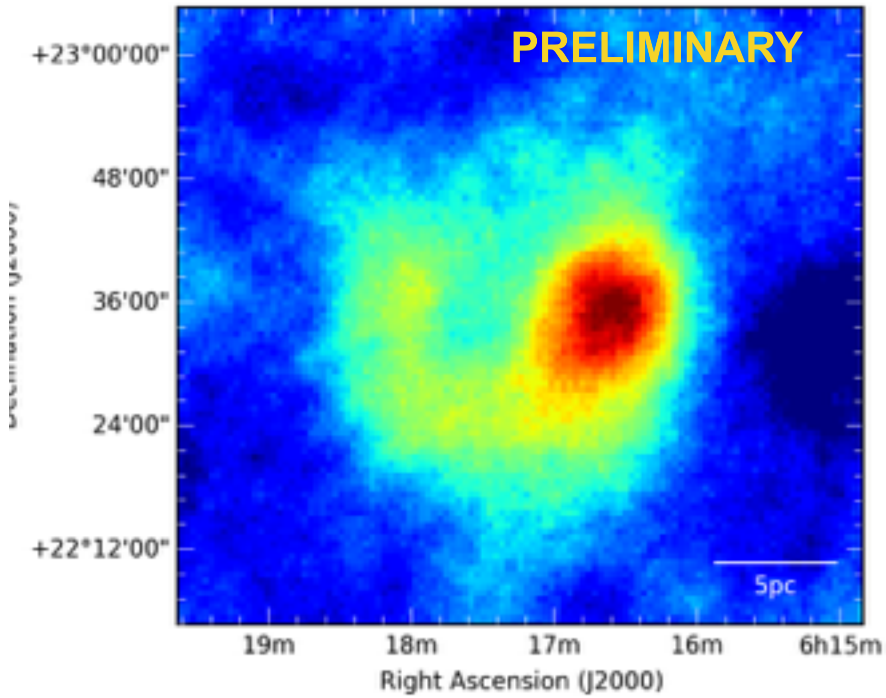
IC 443 Resolved by LAT and VERITAS

7 yr *Fermi* LAT Pass 8 data



Counts Map >5 GeV (PSF23)

178 hr of VERITAS data

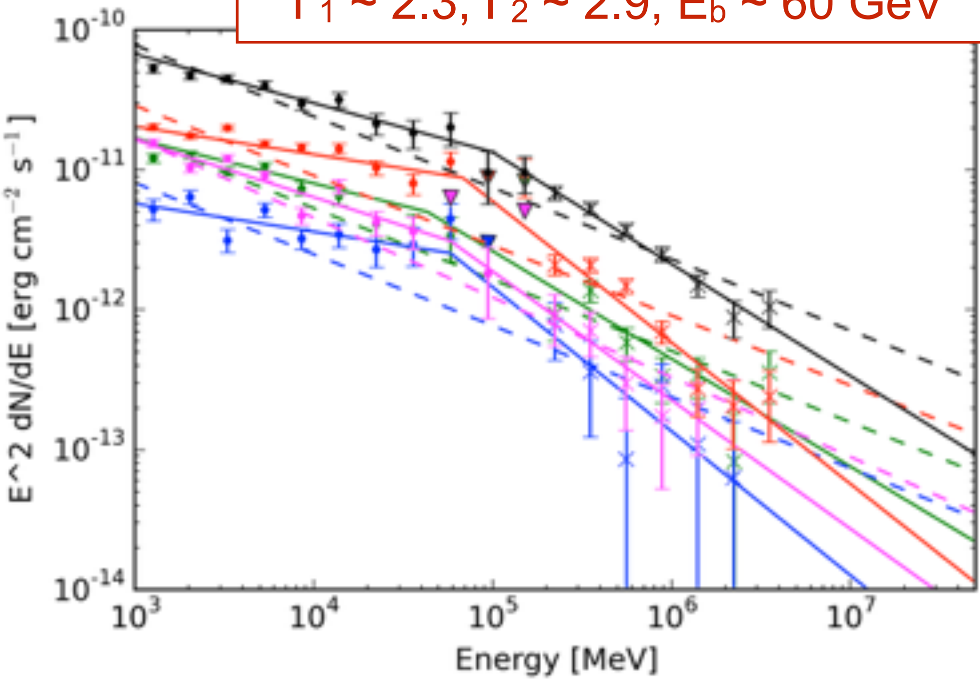


Significance Map

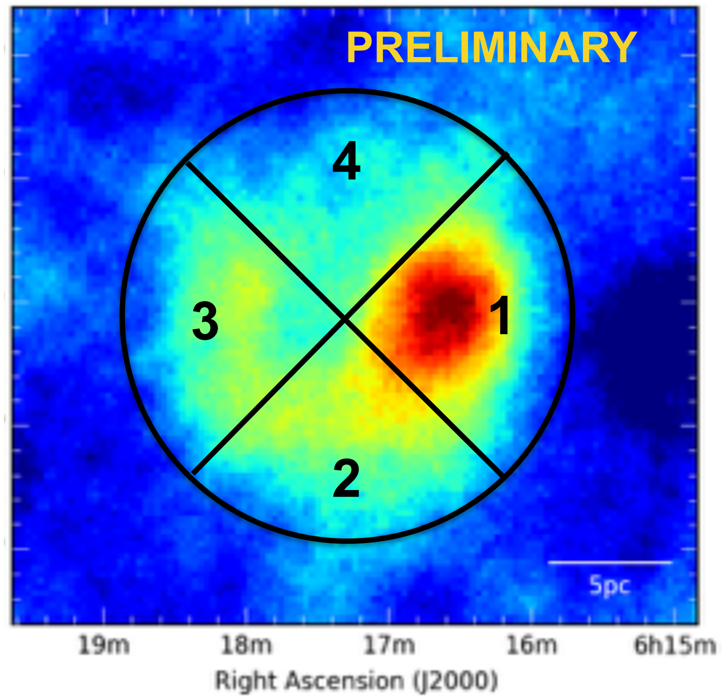
- Excellent correlation observed for GeV, TeV and shocked gas is inconsistent with escaping CR scenario

IC 443 Resolved by LAT and VERITAS

Broken PL fits for all 4 regions:
$\Gamma_1 \sim 2.3$, $\Gamma_2 \sim 2.9$, $E_b \sim 60$ GeV



178 hr of VERITAS data



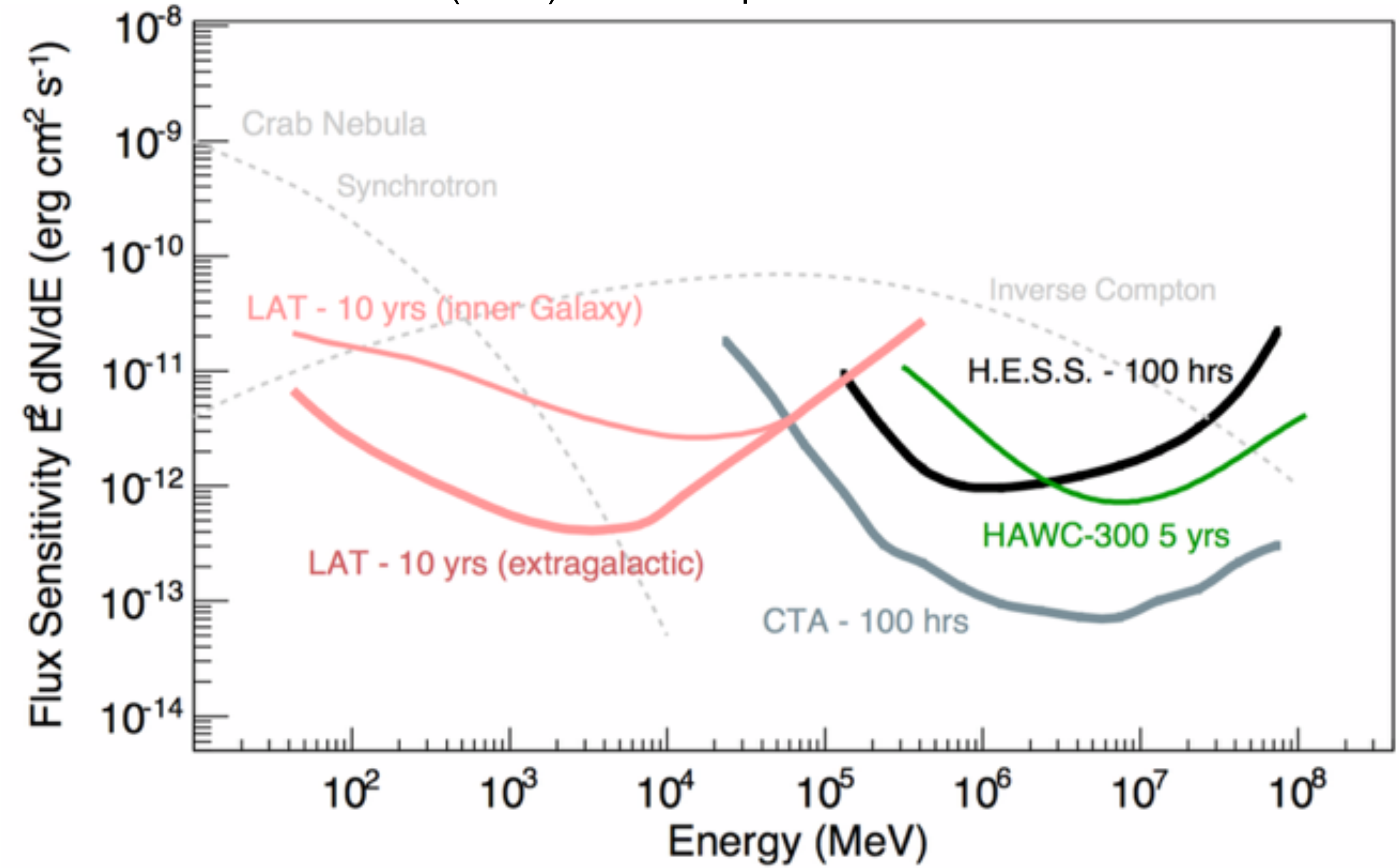
- No clear differences in spectral shape for distinct emission regions (e.g. dense cloud in region 1 vs. fast atomic shock in region 4)
- Observing the same CR spectra across different environments is inconsistent with re-acceleration in "crushed clouds"

Conclusions

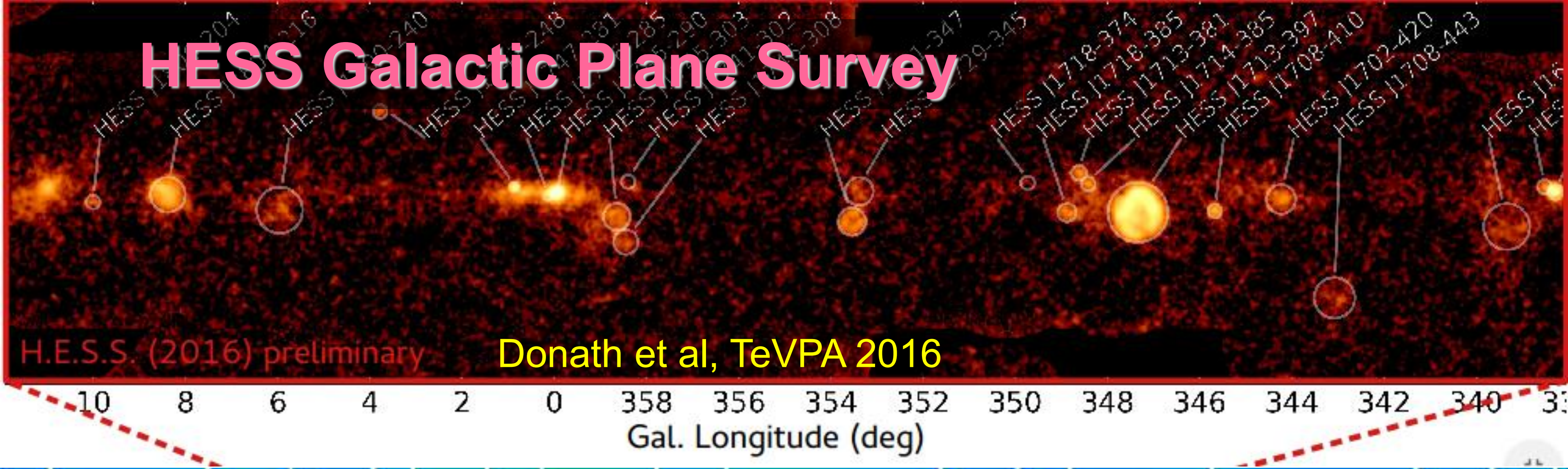
- LAT provides the best γ-ray census of Galactic SNRs
  - New catalog searches: 3FHL, FGES, FHES
- Pass 8 + new diffuse tools will allow low-energy spectral studies for more than just the few brightest SNRs
- Spatially resolved spectral studies at high energies (+TeV obs)
  - Differentiate SNR emission from PWN / PSR.
  - Discriminate b/w *interaction* & *escape* models for SNR-MCs
  - Resolve varying physical conditions in young TeV shells
- *Fermi* LAT continues to identify new targets for TeV telescopes
  - Joint studies with HAWC, HESS, MAGIC, VERITAS… CTA?

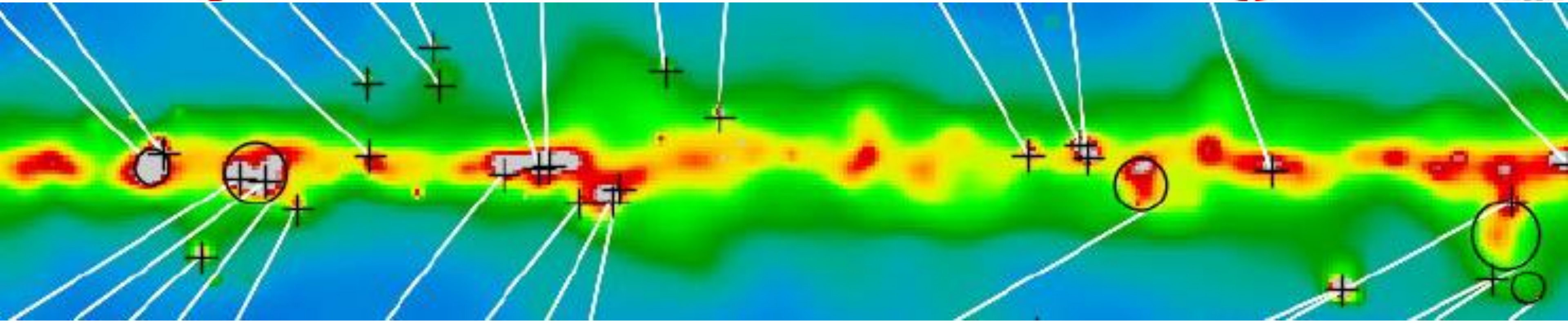
Supernova Remnant Studies in 2018?

From S. Funk (2016) HEAD 15 proc.



HESS Galactic Plane Survey





3FHL (preliminary, > 10 GeV) Dominguez et al, TeVPA 2016

Better resolution and higher stats in HESS Galactic Plane Survey

Most sources **extended**, 60% do not have one obvious MW counterpart

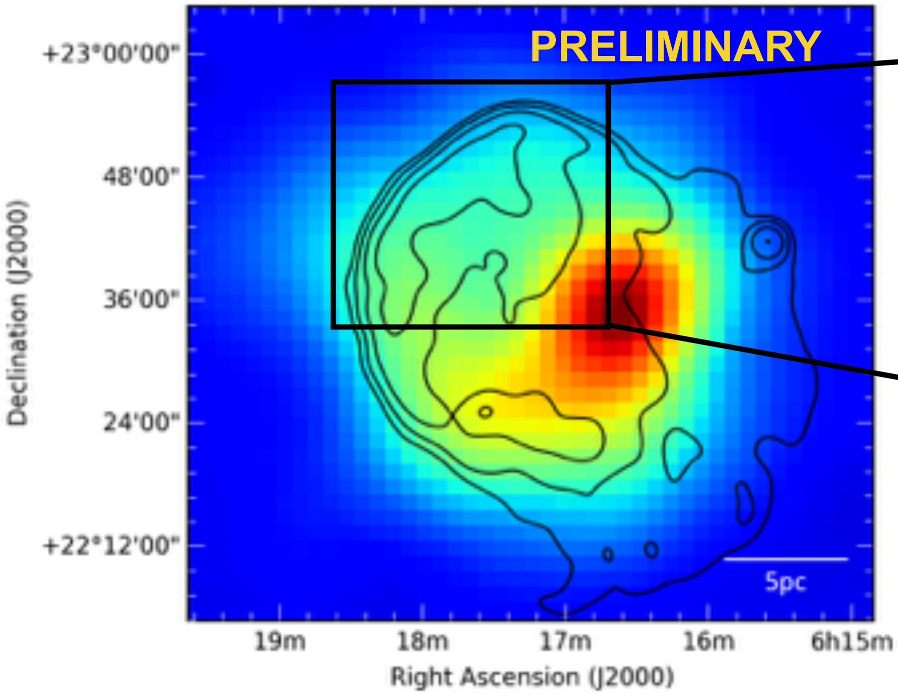
PWN brighter at TeV energies, old SNRs brighter at GeV energies

Resolving the γ-ray morphology of IC 443

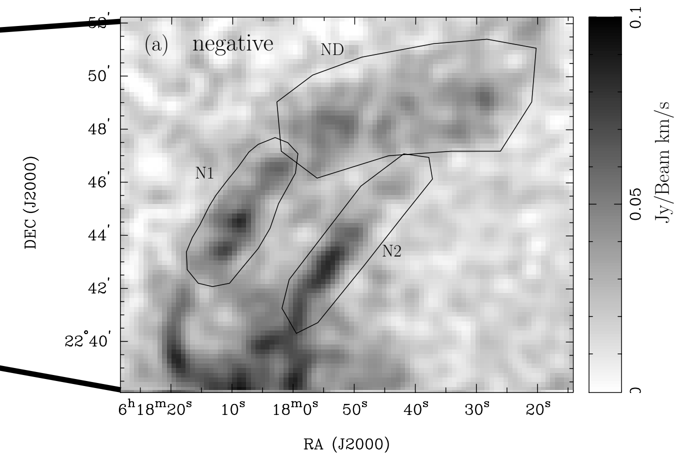
- Multi-wavelength comparison shows the GeV/TeV γ rays match the distributi of *shocked* gas in IC 443

LAT morphology compared to TeV, ~~radio~~, ~~ambient CO~~, shocked HCO+

shocked atomic gas in North?



Counts Map >5 GeV (PSF23)

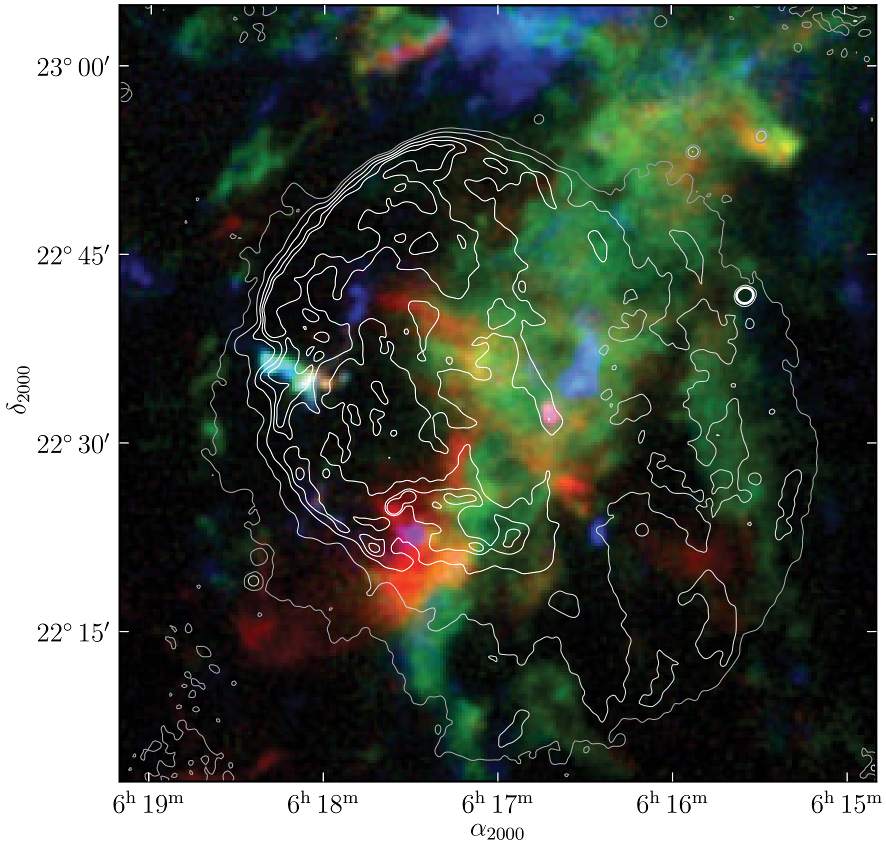


HI absorption → 40±4 M_{sun} (Castelletti, et al. 2011)

H^+ gas has n_e=10-1000 cm^{-3} (Rho, et al. 2001)

Two nearby molecular clouds

- Foreground molecular cloud cuts across SNR.
  RGB image shows v_{LSR} = -2,-4,-6 km/s
  against Radio contours



Figures from Lee+ 2008

- +5 km/s cloud ends at TeV peak

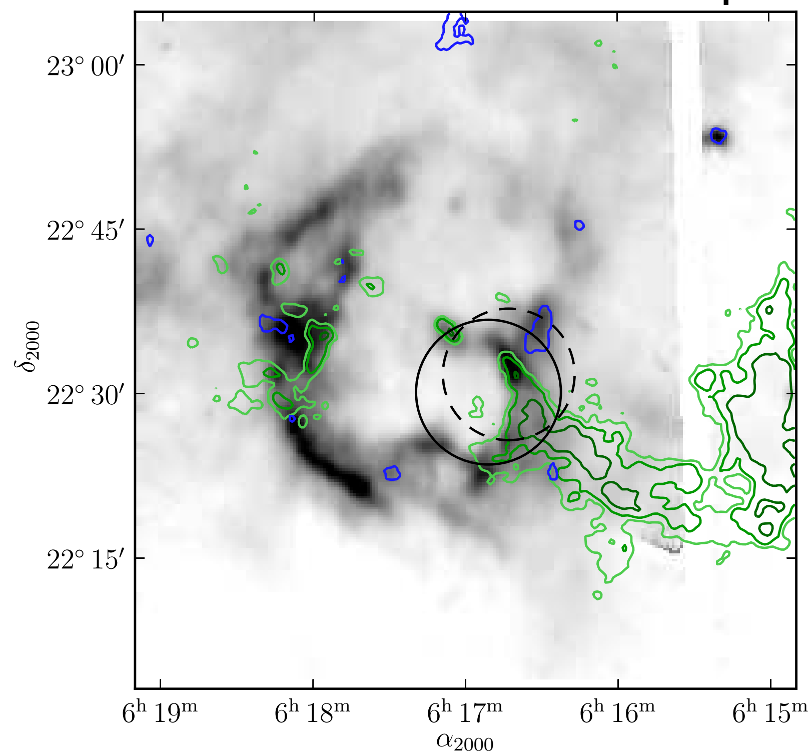
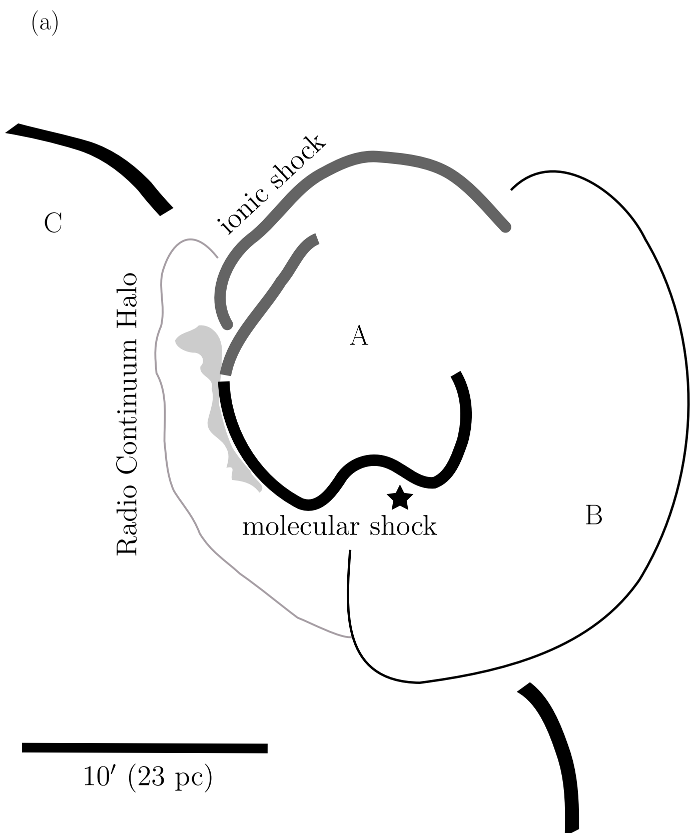
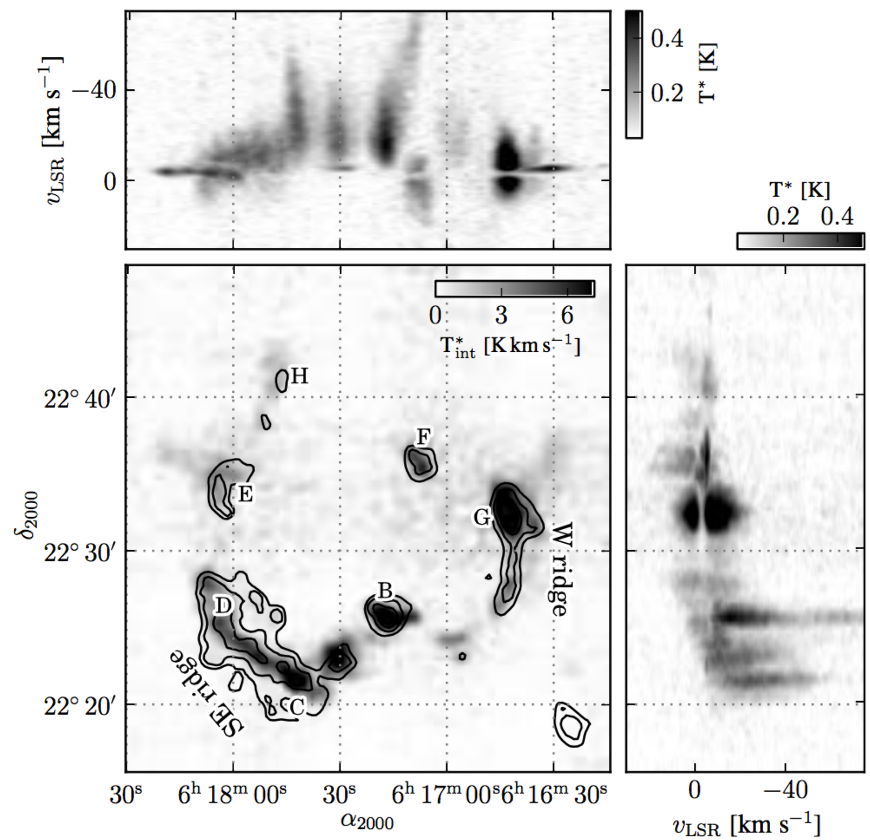


Figure 15. Far-IR 90 μm image taken with the *AKARI* satellite shown in gray scale. The green contours show the distribution of +5 km s^{-1} clouds (the gray scale in Figure 9). The blue contours show locations of SCs. The solid and dashed circles represent the location of γ-ray sources detected by MAGIC and VERITAS, respectively.

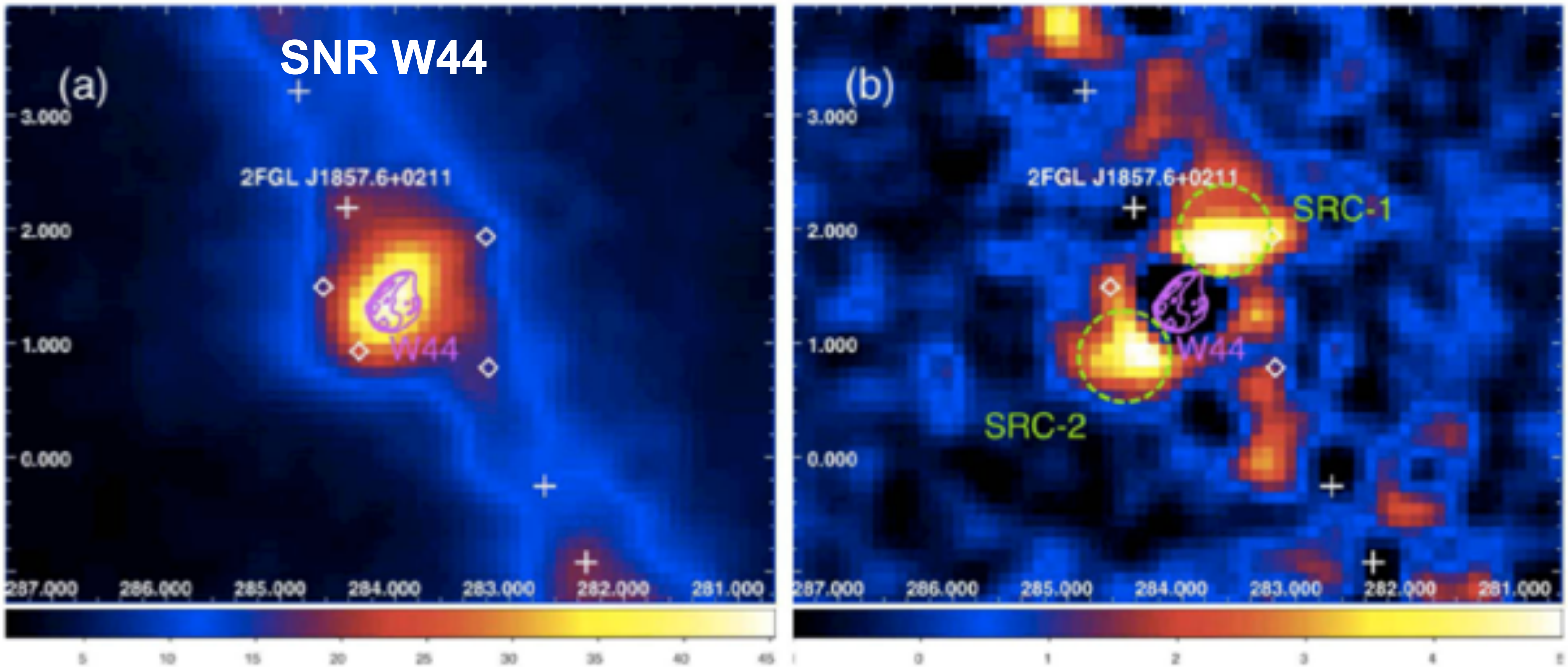
IC 443: SNR interacting with Molecular Clouds

- **Molecular line observations show shock interaction with ~1.1x10^4 M$_{sun}$ along southern ridge (e.g. Lee, et al. 2008)**





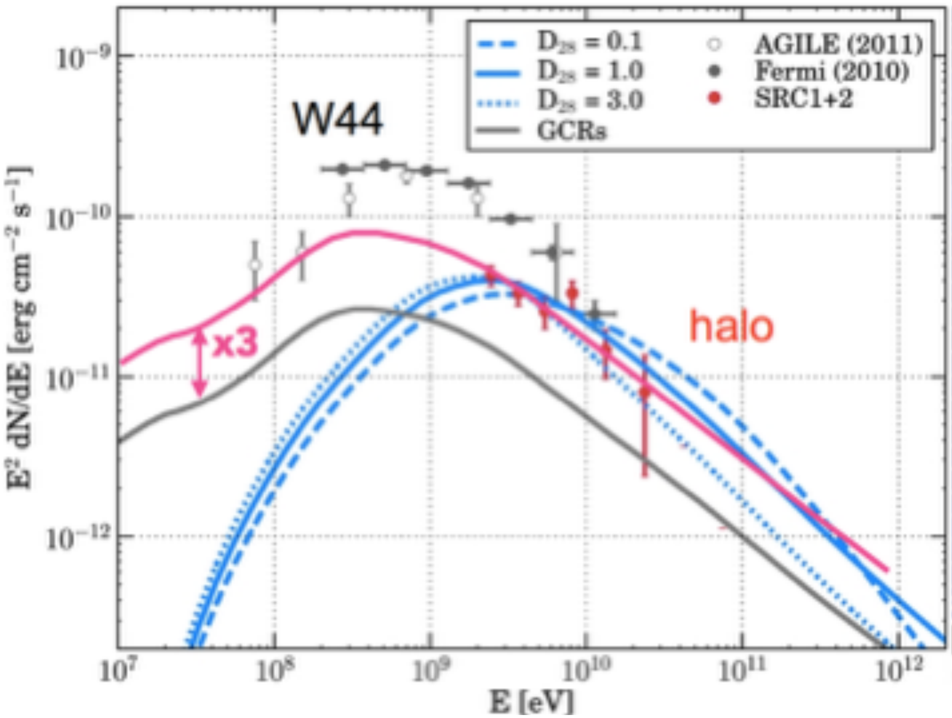
Catching Escaping Cosmic Rays?

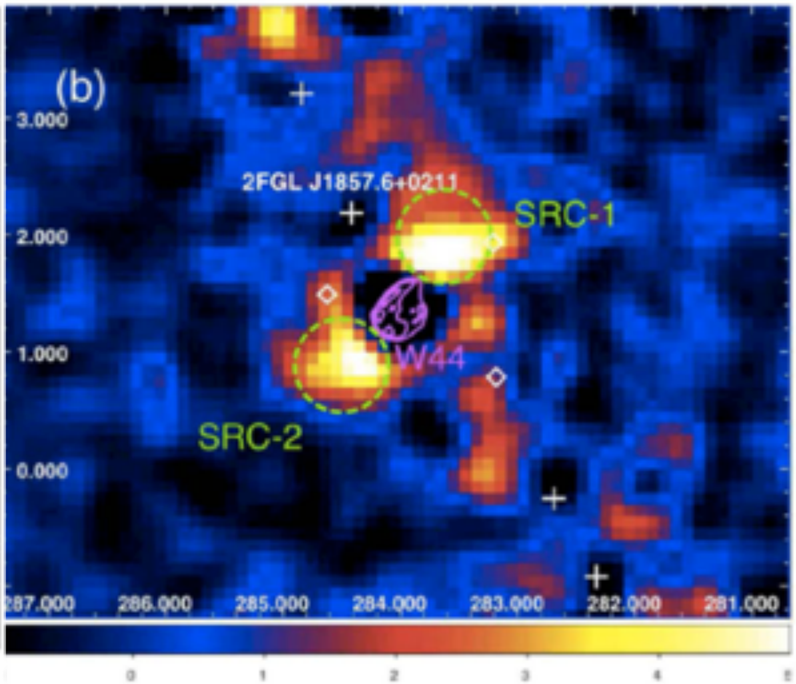


Uchiyama+ 2012, ApJ 749, L35

- Subtracting the SNR (radio model) reveals emission at 2-100 GeV (SRC-1,2) coincident with nearby CO complex

Catching Escaping Cosmic Rays?





Uchiyama+ 2012, ApJ 749, L35

- Subtracting the SNR (radio model) reveals emission at 2-100 GeV (SRC-1,2) coincident with nearby CO complex
- CR diffusion on scales ~100 pc?
  => 3x more W_{CR} in MC than in SNR
- Or uncertainties in Galactic diffuse model?