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On the Origin of the Cosmic Radiation

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A theory of the origin of cosmic radiation is proposed according to which cosmic rays are originated and accelerated primarily in the interstellar space of the galaxy by collisions against moving magmetic fields. One of the features of the theory is that it yields naturally an inverse power law for the spectral distribution of the cosmic rays. The chief difficulty is that it fails to explain in a straightforward way the heavy nuclei observed in the primary radiation.

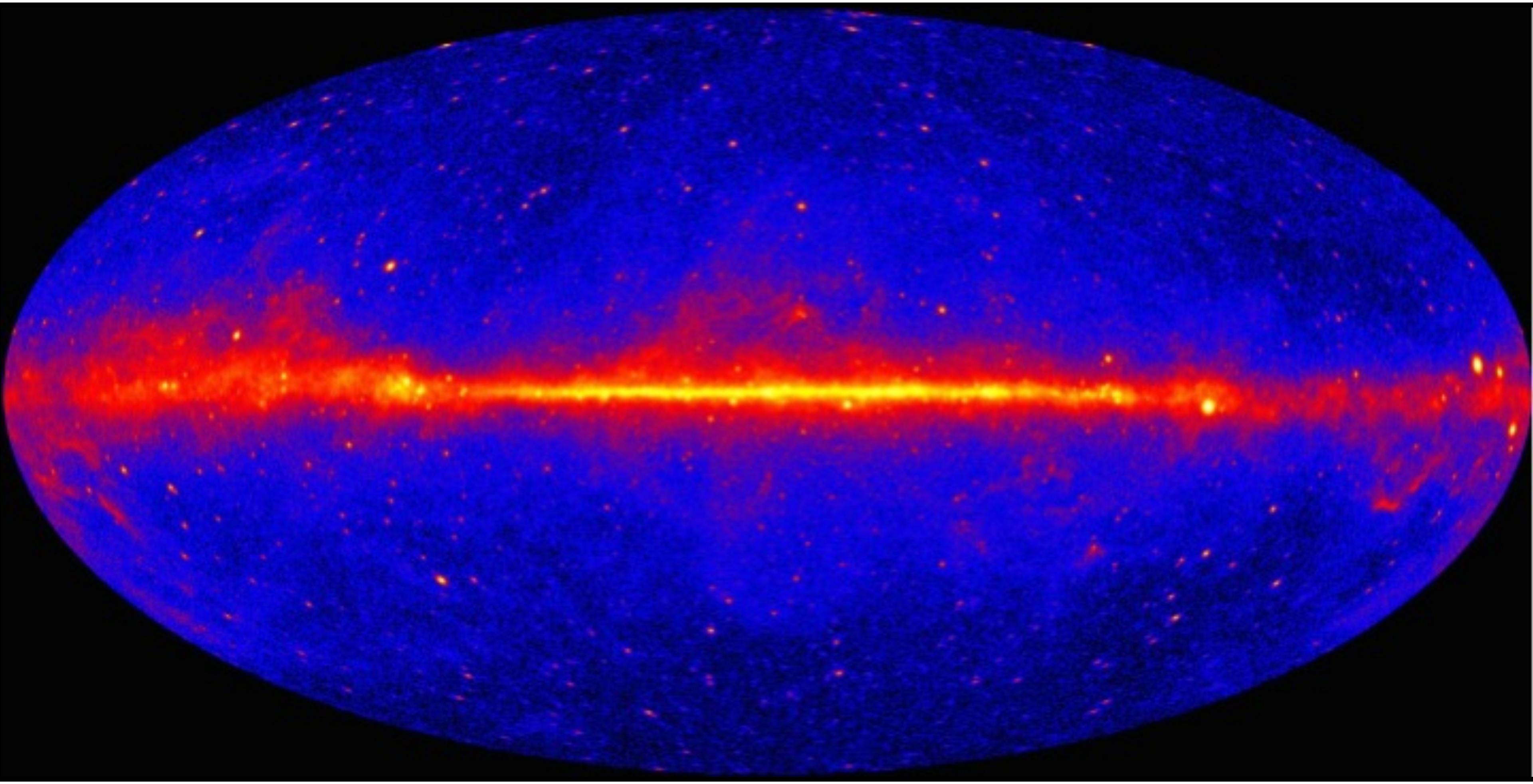
I. INTRODUCTION

IN recent discussions on the origin of the cosmic radiation E. Teller[1] has advocated the view that cosmic rays are of solar origin and are kept relatively near the sun by the action of magnetic fields. These views are amplified by Alfvén, Richtmyer, and Teller.[2] The argument against the conventional view that cosmic radiation may extend at least to all the galactic space is the very large

where H is the intensity of the magnetic field and ρ is the density of the interstellar matter.

One finds according to the present theory that a particle that is projected into the interstellar medium with energy above a certain injection threshold gains energy by collisions against the moving irregularities of the interstellar magnetic field. The rate of gain is very slow but appears capable of building up the energy to the maximum

Galactic Cosmic γ-Rays



All-sky Fermi >1 GeV map using 60 months of data (credit: NASA GSFC)

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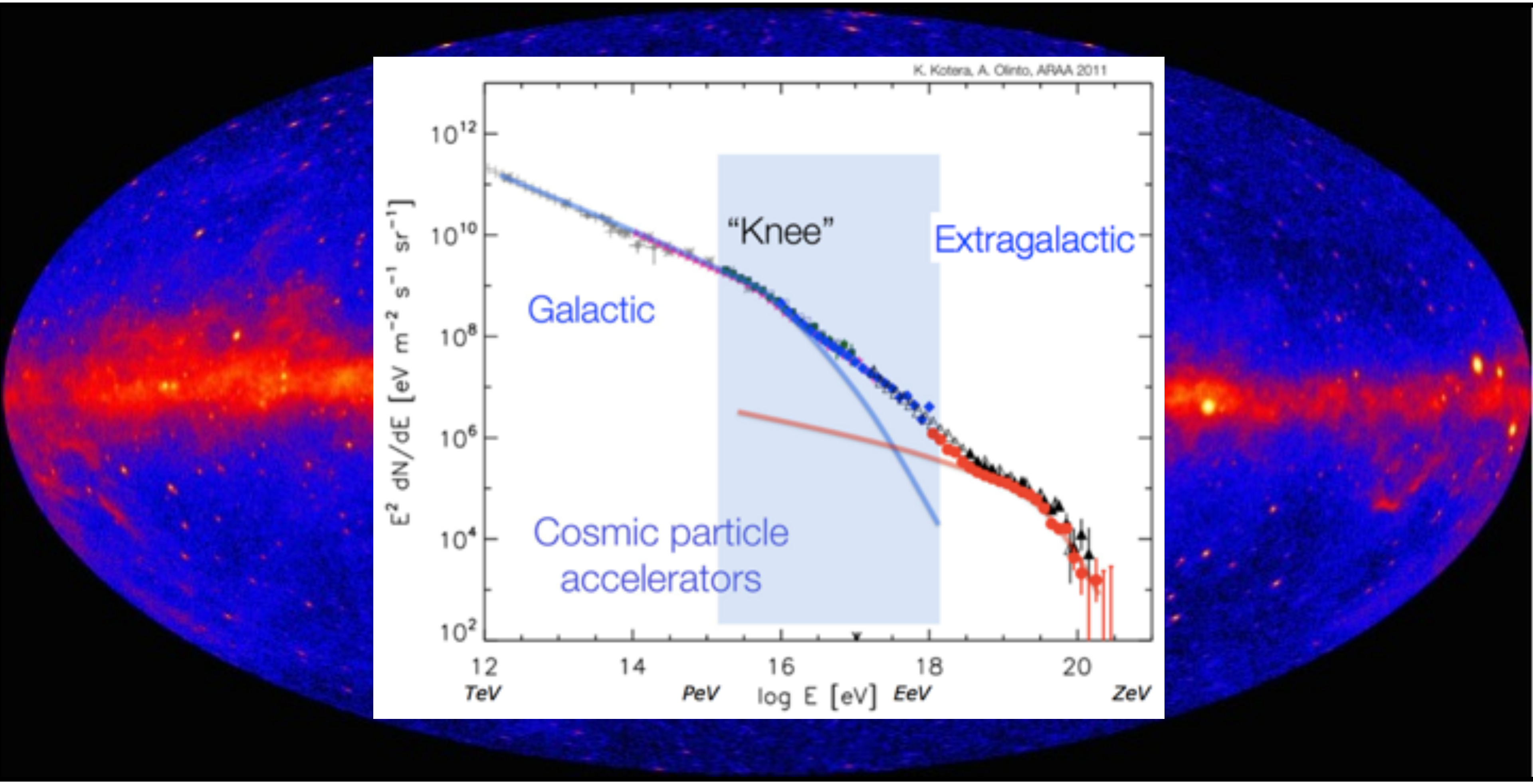
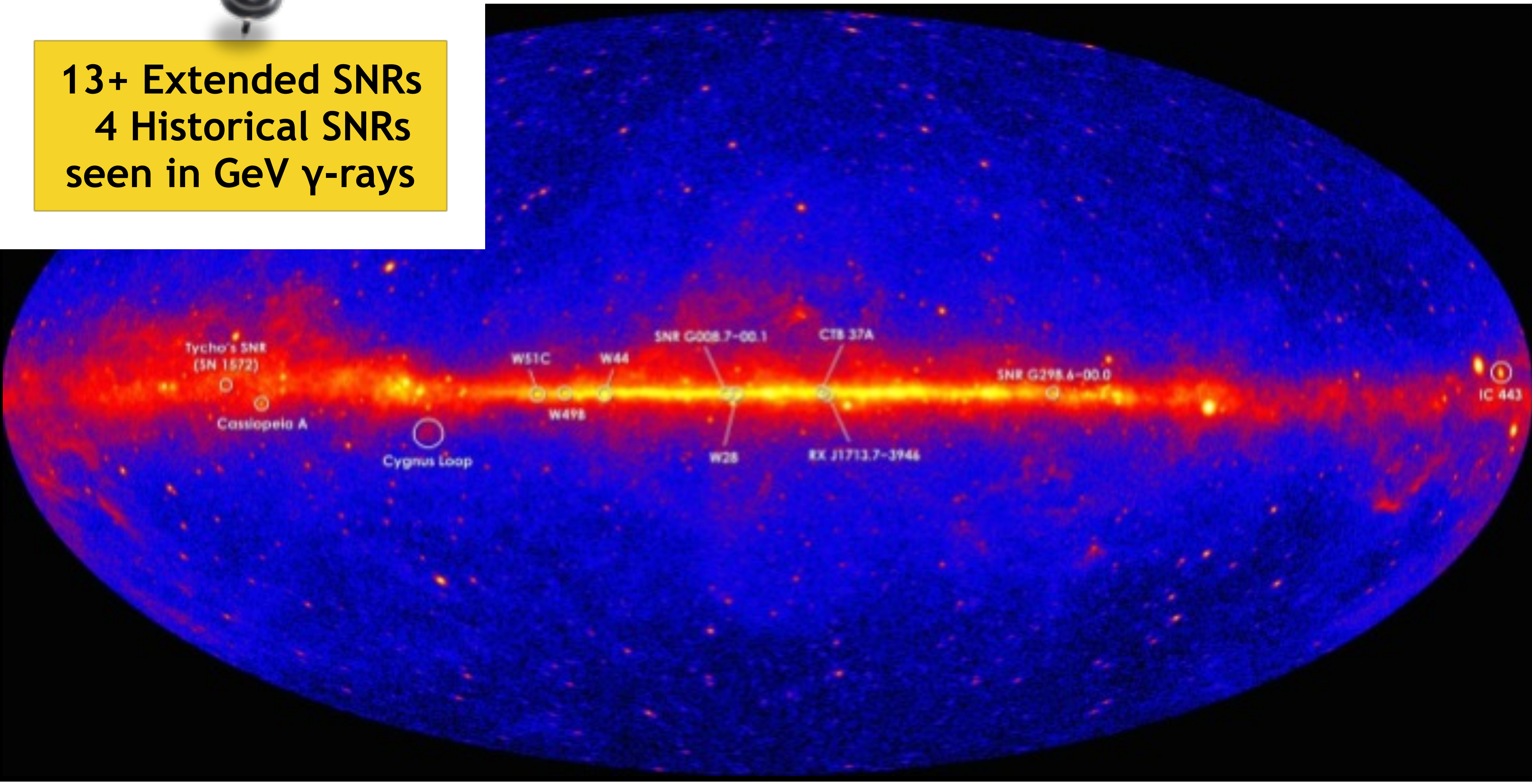


All-sky Fermi >1 GeV map using 60 months of data (credit: NASA GSFC)

Galactic Cosmic γ-Ray Sources?

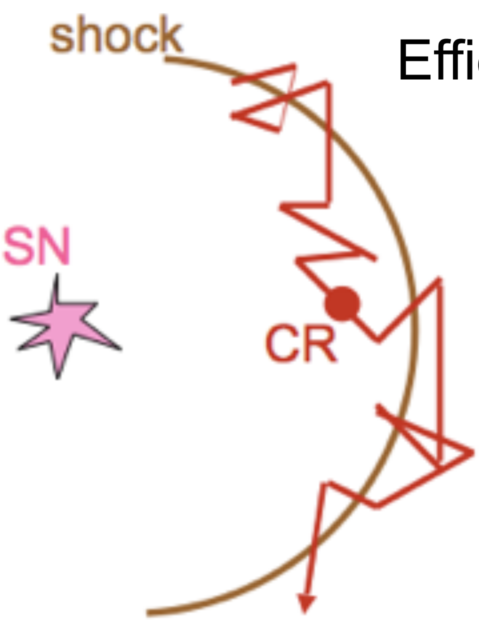
13+ Extended SNRs
4 Historical SNRs
seen in GeV γ-rays



Supernova remnants identified in the Galactic cosmic-ray “sea”

SNR Paradigm for CR Origins

- (Non-linear) Diffusive Shock Acceleration in SNRs
  + Features: PL index, thin X-ray rims, ~PeV "knee" CRs
  - Difficulties: Injection? B-field amplification? Escape?
- Must also produce observed CR abundances, anisotropy



Efficient DSA transforms ~10% E_{SN} into CR population

Krymsky (1976, 1977), Bell (1978) …

$$N_{CR} \propto p^{-\gamma} \qquad \gamma = \frac{\sigma+2}{\sigma-1}$$

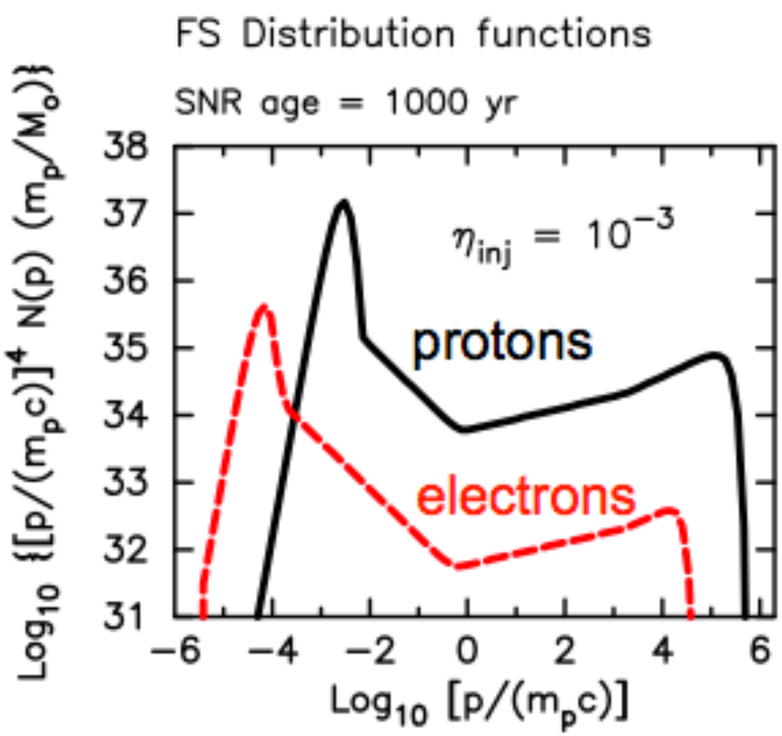
$$\sigma = 4 \qquad \gamma = 2$$

What change does CR spectrum undergo from source to detection?

Simulated SNR Spectrum

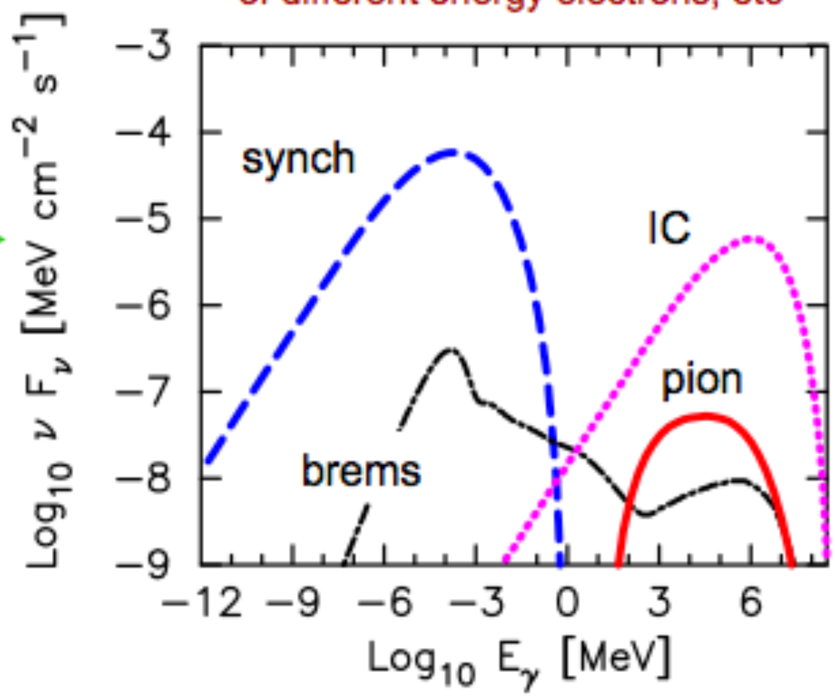
- Simulations by Ellison et al. (2009) assuming non-linear DSA

Accelerated Particles



Observed γ-Rays

Must consider B-field, diffusion lengths of different energy electrons, etc



Fermi detects the "pion bump"

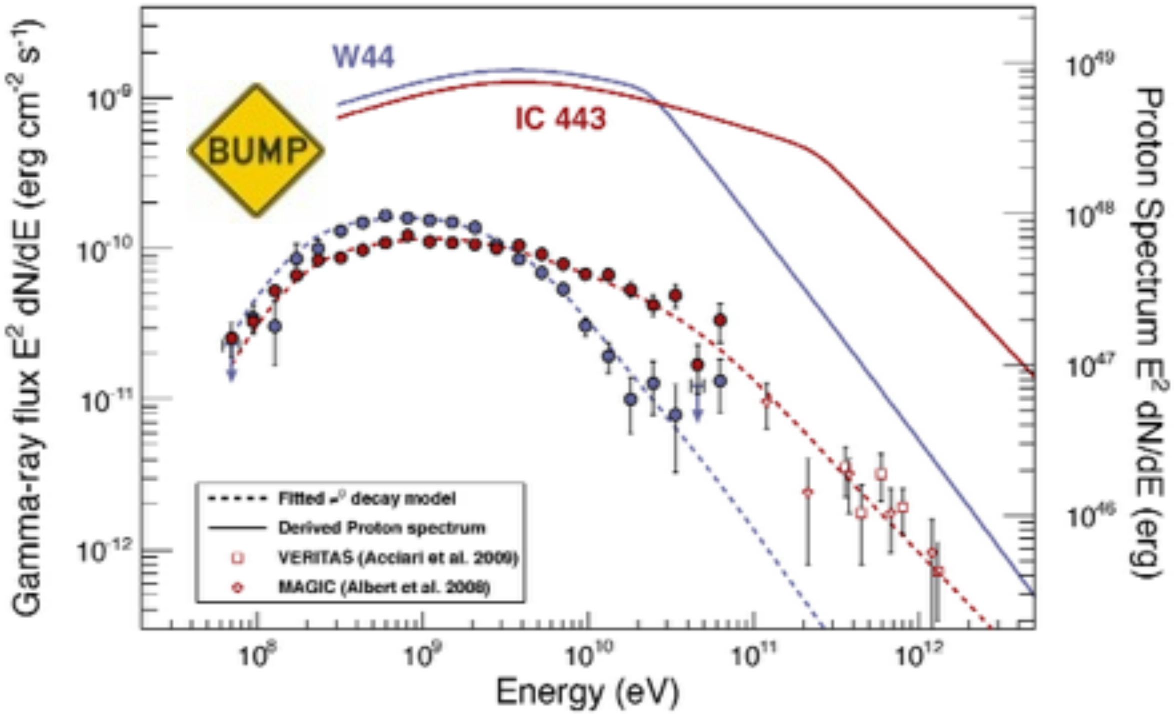
AGILE, *Fermi* provide important support for the SNR paradigm

γ-rays from SNRs IC 443 & W44 are *hadronic!*

(Ackermann+ 2013, *Science* 339, 807)

Proton spectra modeled with smooth broken power-law in momenta:

$$\frac{dN_p}{dp} \propto p^{-s_1}\left[1+\left(\frac{p}{p_{br}}\right)^{\frac{s_2-s_1}{\beta}}\right]^{-\beta}$$



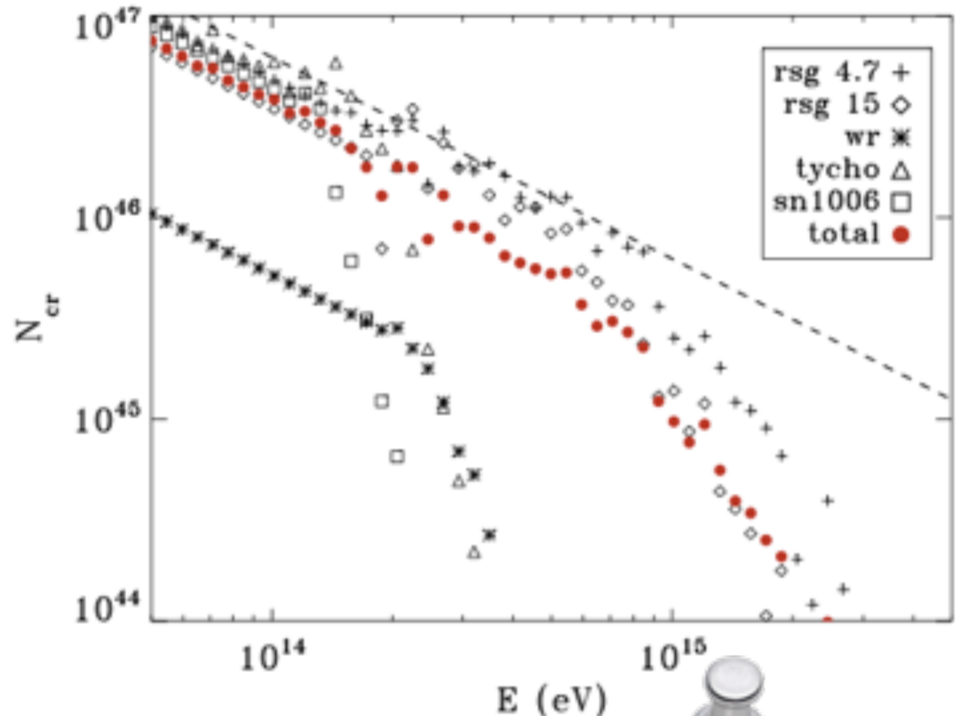
- CR content ~1-4 x10^{51} erg (depending on gas density)
- Proton spectra softens above ~10 GeV ($s_{2,p}$~3)
- Radio electrons harder than protons ($s_{1,e}$~1.7, $s_{1,p}$~2.2)

Seeking young, active accelerators

- Which SNRs are capable of accelerating PeV protons?

  e.g Schure & Bell (2013)

  - Assume escaping CRs trigger B-amplification
  - E_{max} set by confining B
  - Expect variations in CR yield with SN type!
  - RSG SNe dominate PeV?

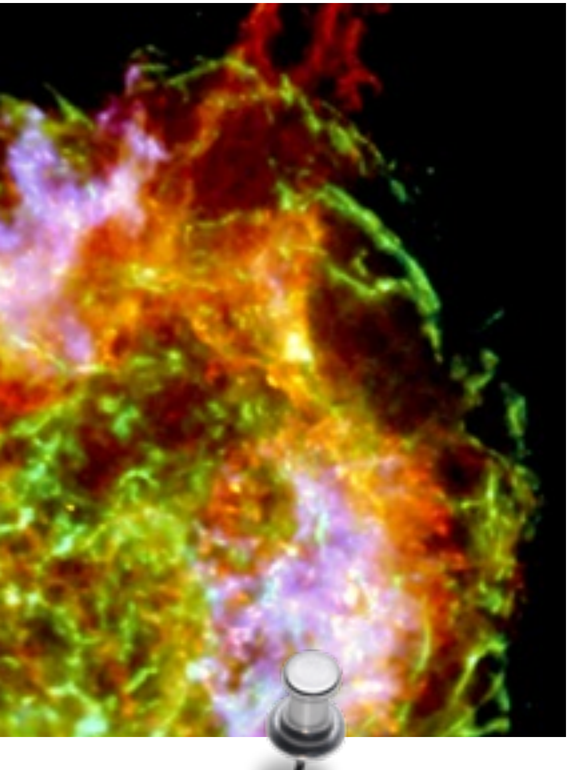


- *When can we observe these accelerators?* Prediction: When they begin to interact with dense CSM…

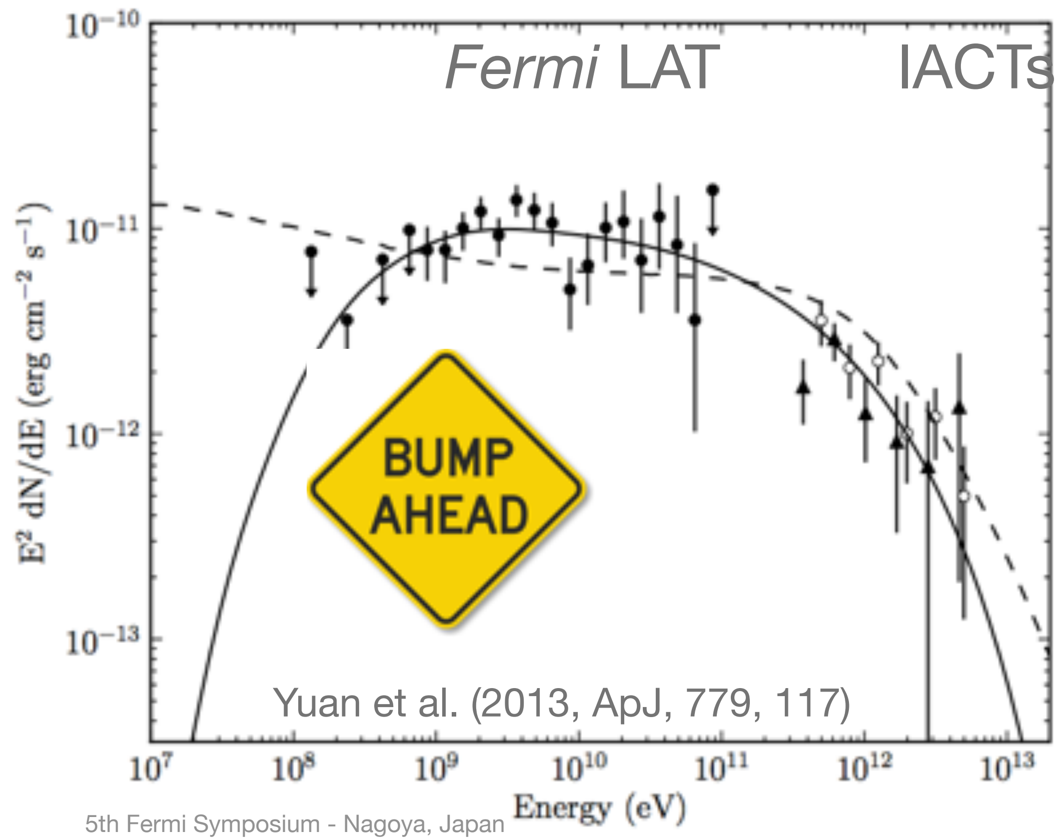
Dense CSM SNe
Poster 10.01
A. Franckowiak

Cas A: Young Galactic Accelerator

Cas A in X-rays (Chandra)



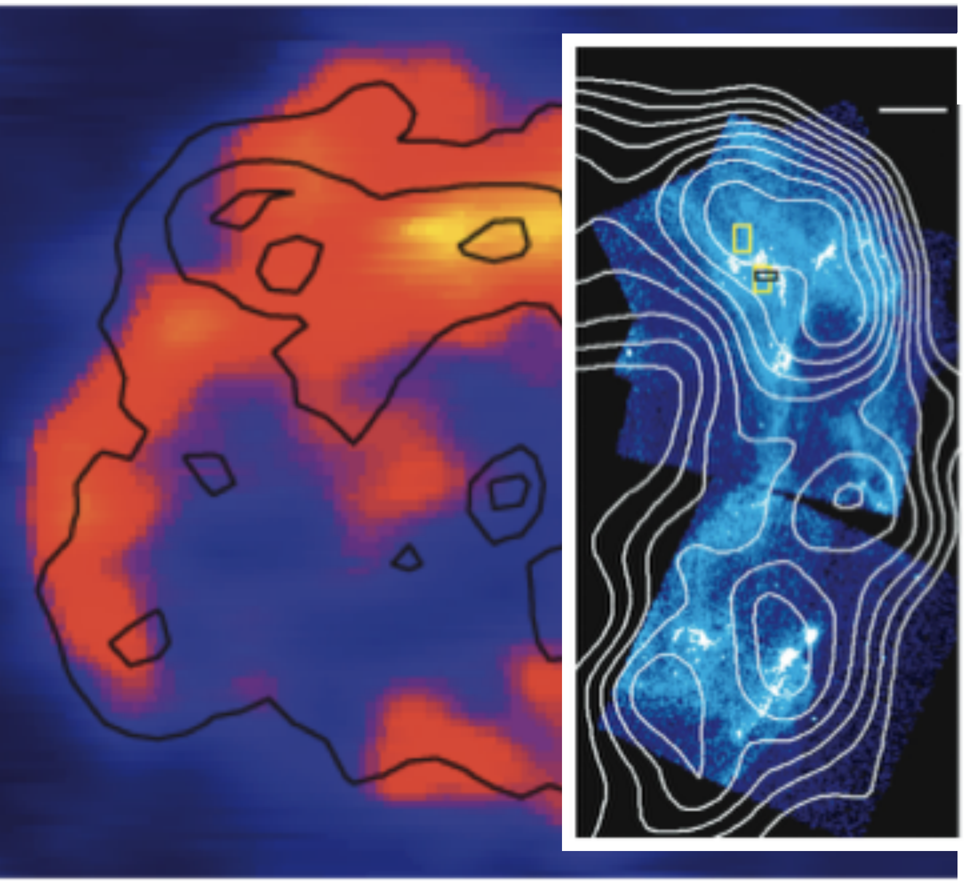
- SN ~1680, Type IIb
- X-ray rims indicate B~200 μG, $E_{max,e}$~50 TeV
- Hadronic accelerator with index Γ_{GeV} ~2.2 $W_{CR,p}$~$4x10^{49}$ erg, $E_{max,p}$~10 TeV (escaped?)



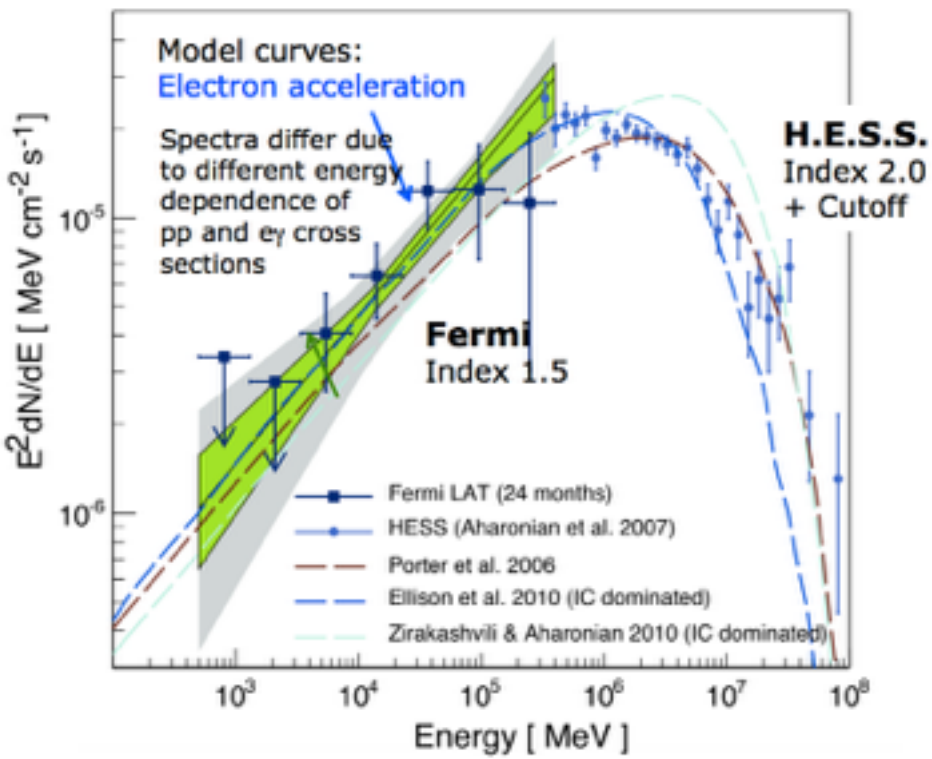
See also Tycho F. Giordano in 1 hour…

TeV Shell-type SNR RX J1713.7-3946

- Can 1000+ yr SNRs still reach PeV energies? (5 such TeV SNRs)
- Yearly X-ray variability indicates B ~1 mG and PeV electrons

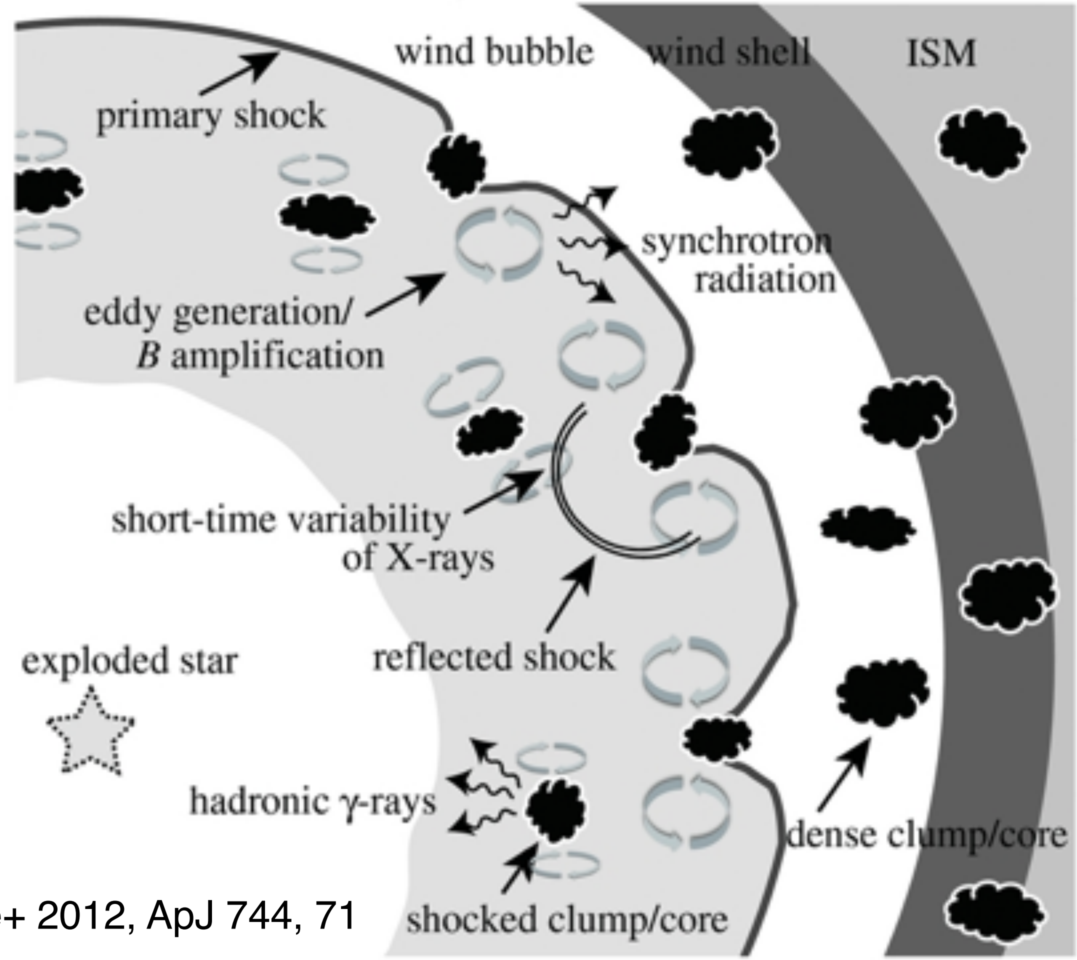


- GeV spectra confirms IC models



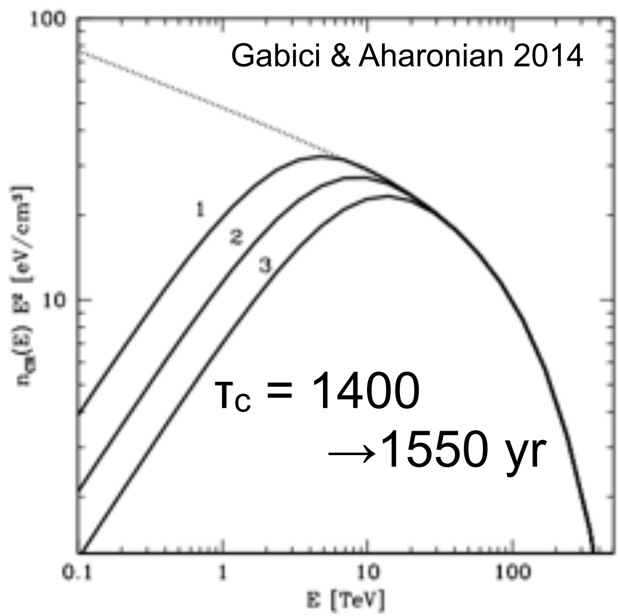
TeV Shell-type SNR RX J1713.7-3946

- Or is hard GeV spectrum due to energy-dependent penetration of CR protons in dense molecular clumps?



Inoue+ 2012, ApJ 744, 71

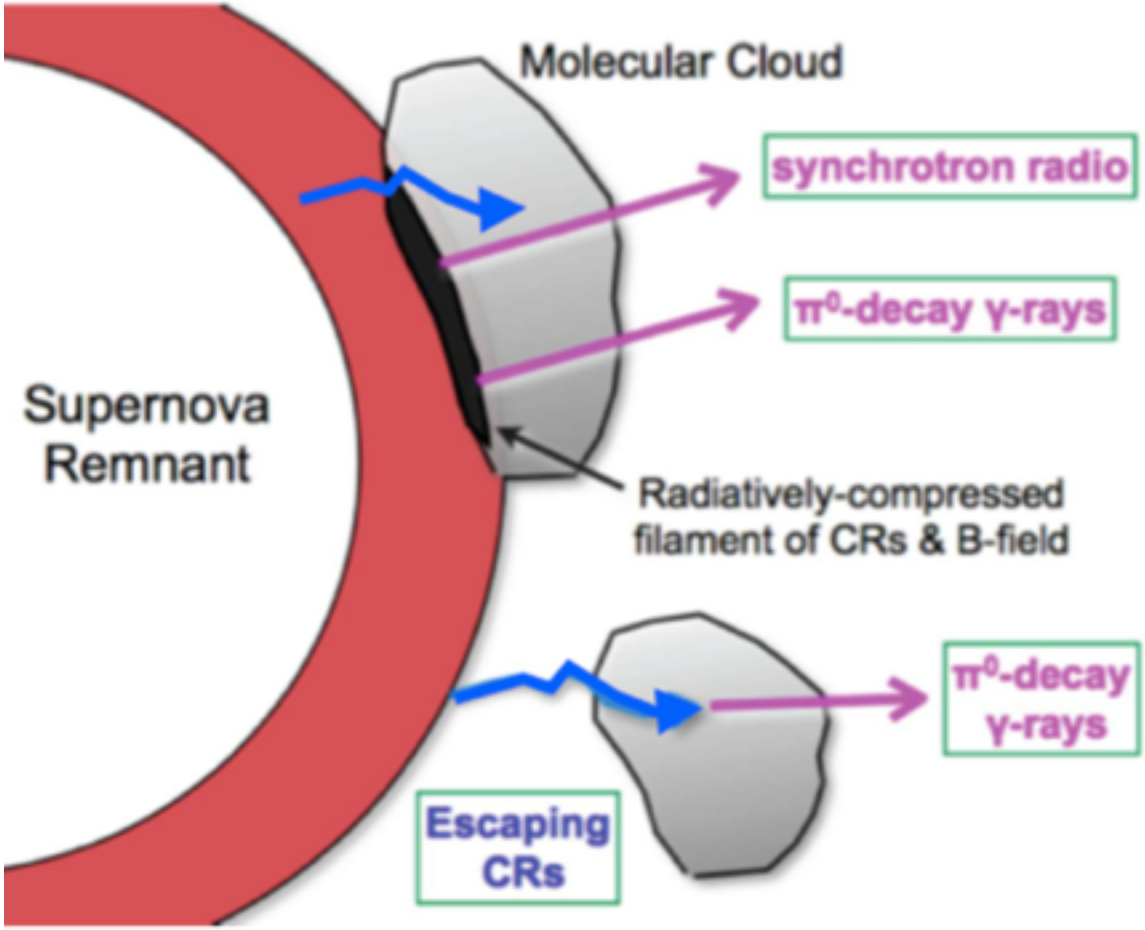
- Protons in shell slowly enter shocked clump



- Evidence from X-rays surrounding CO? (Sano+ 2013; 2014)

SNRs Interacting with the ISM

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

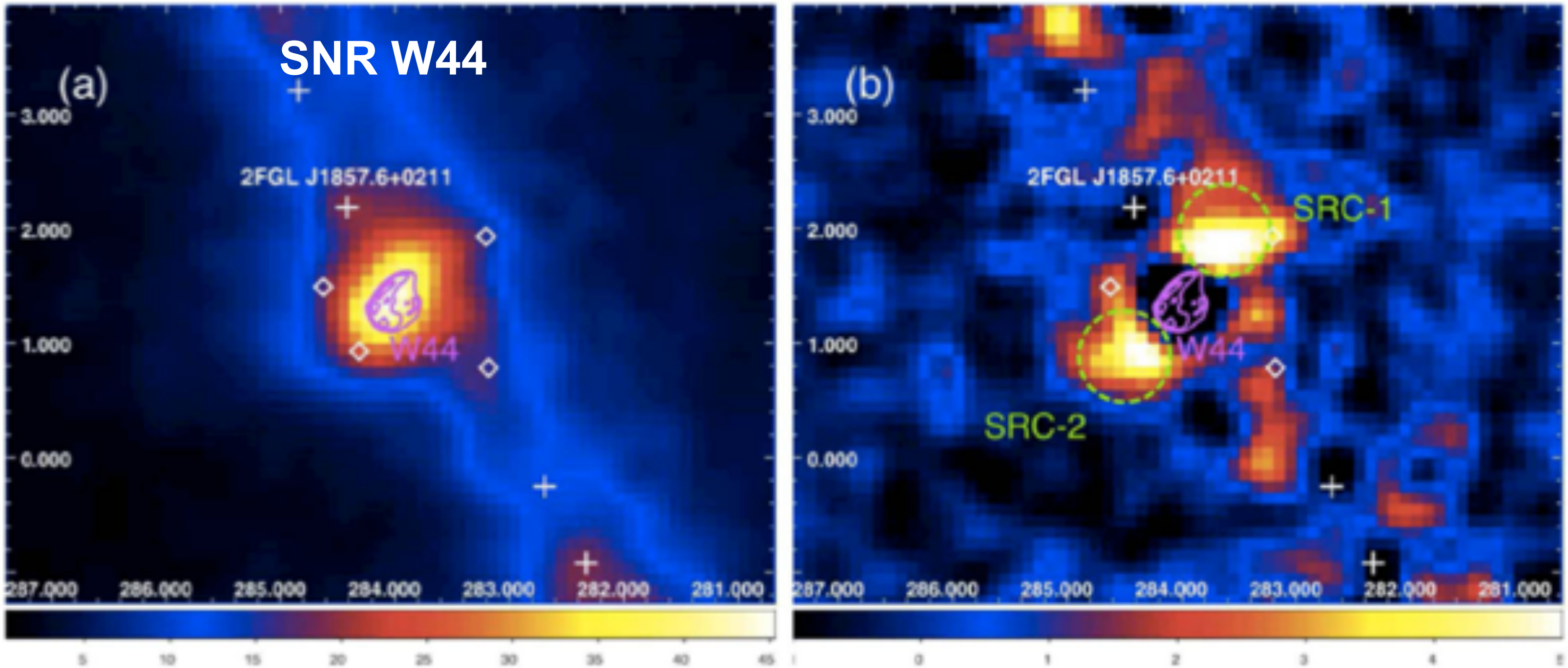


Two scenarios:

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)

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

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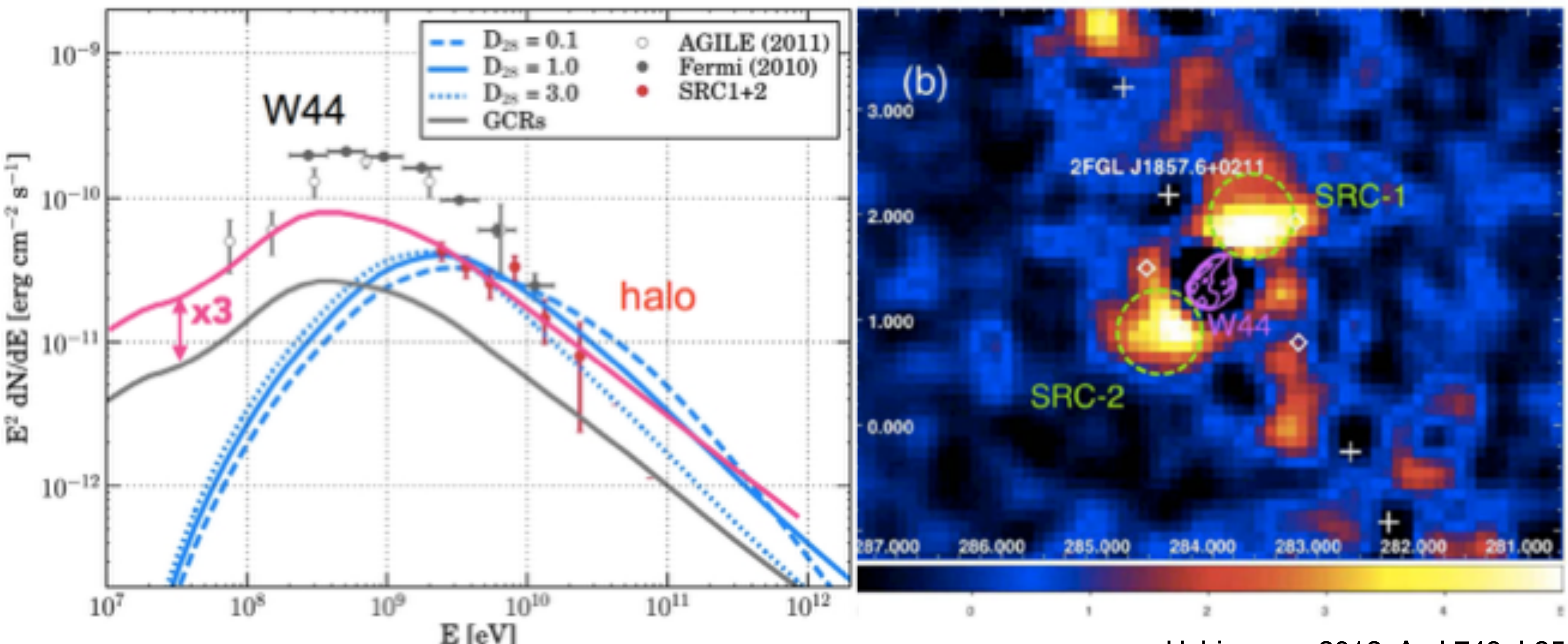


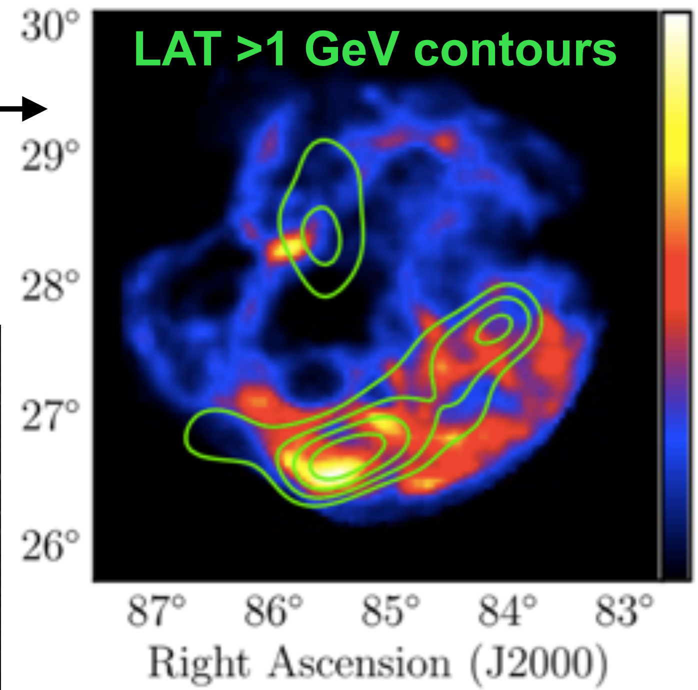
Uchiyama+ 2012, ApJ 749, L35

- 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?

W28: Poster 5.04
Y. Hanabata

GeV Shell-type SNR S147

- Shell SNR (age ~3x10^4 yr) with radiative Hα filaments →
- γ-rays dominated by π^0-decay in filaments (n_H~250 cm^{-3})

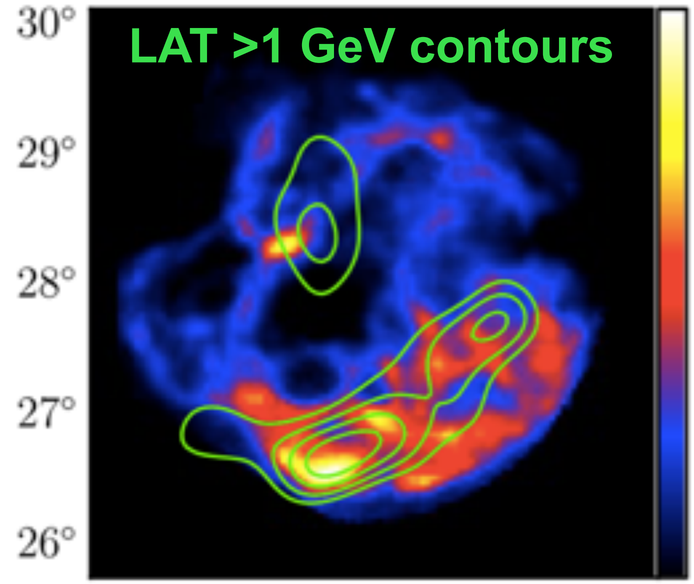


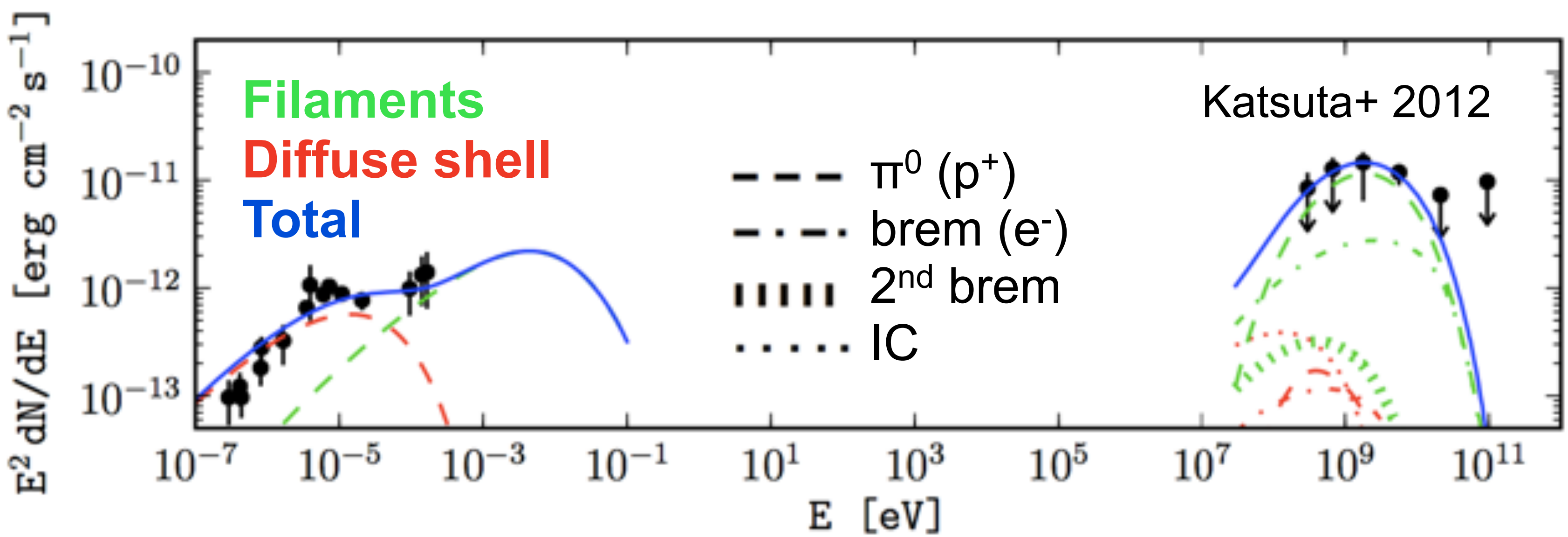
Katsuta+ 2012

Radiative SNRs
Poster 5.01 Asvarov
& 5.07 Reichardt

GeV Shell-type SNR S147

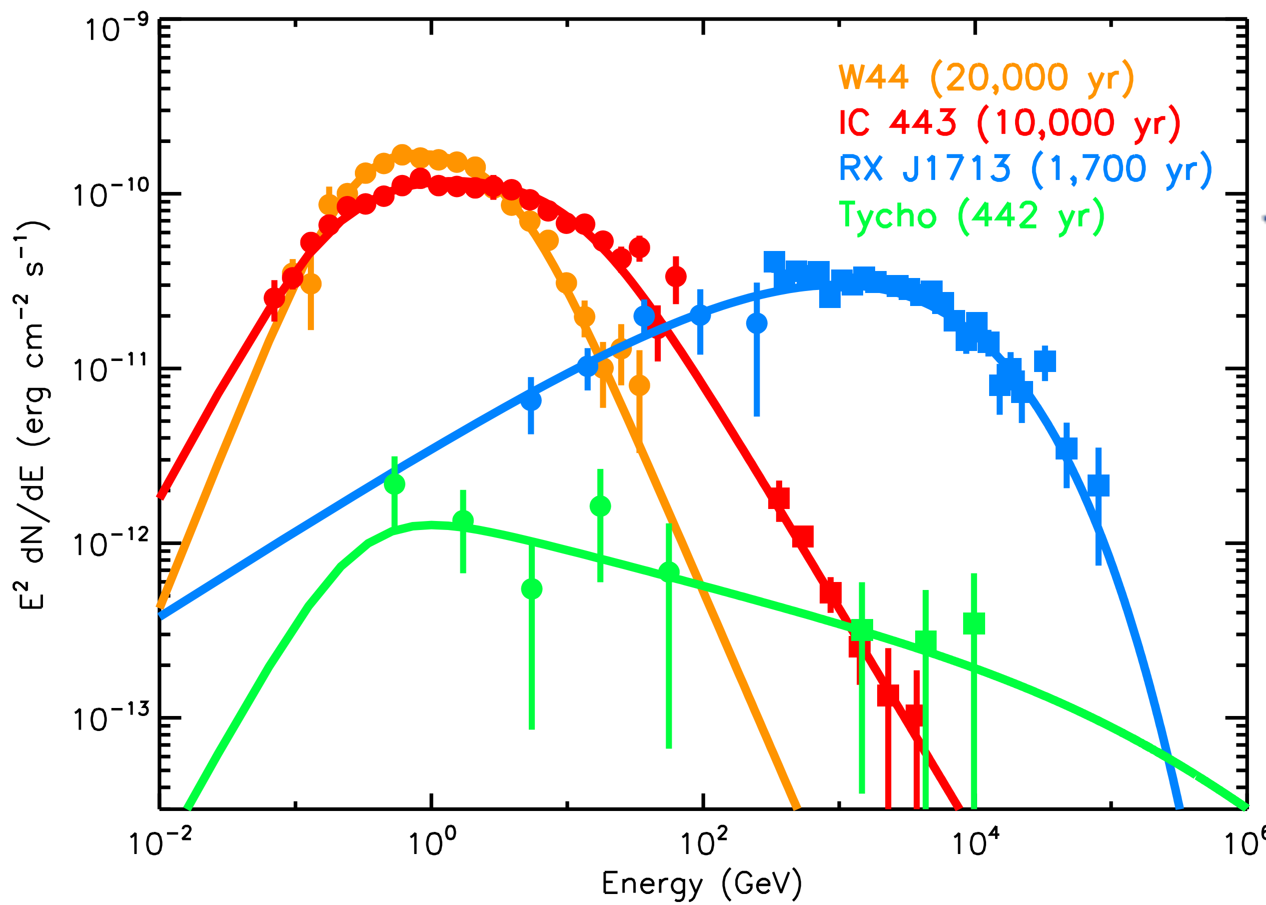
- Shell SNR (age ~3x10^4 yr) with radiative Hα filaments
- γ-rays dominated by π^0-decay in filaments (n_H~250 cm^{-3})
- No new CRs required!
  Adiabatic compression and re-acceleration of swept-up GCRs is sufficient to explain GeV emission



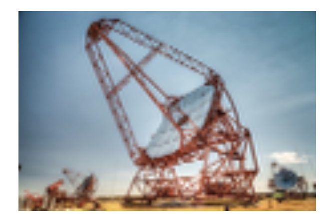


Evolving Accelerators?

denser
target



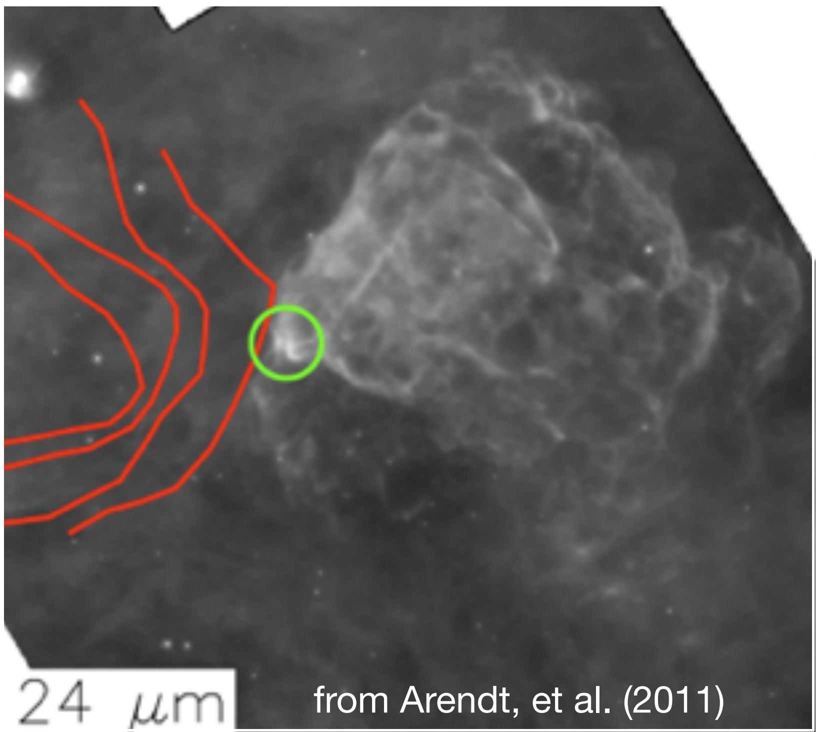
+



old young

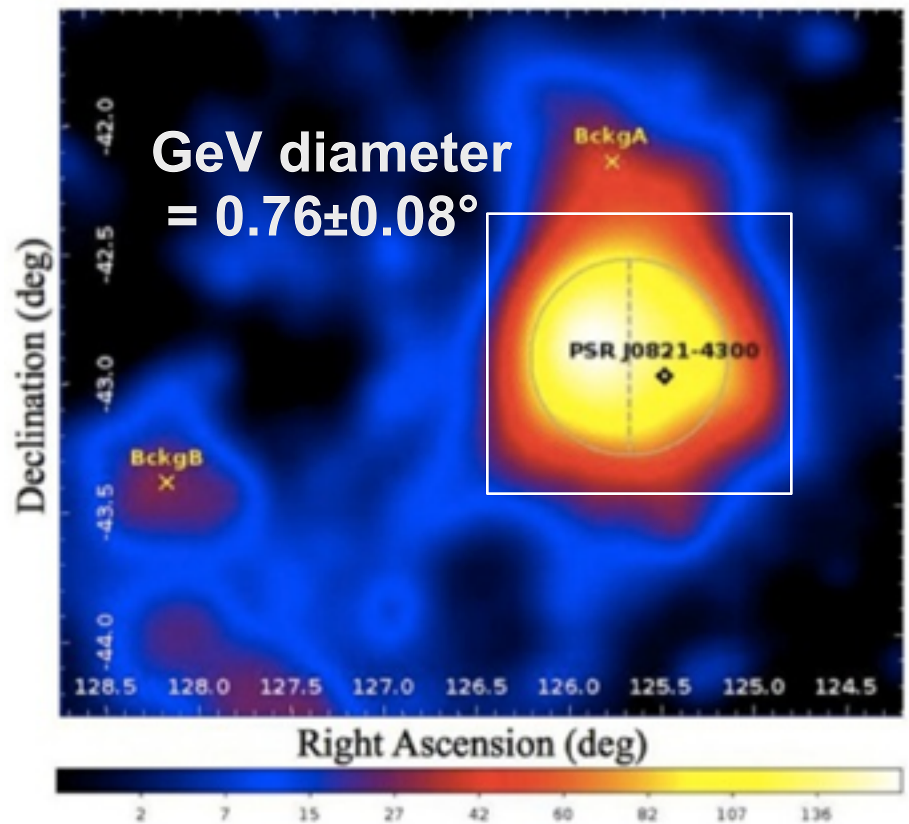
Puppis A: proto-Interacting SNR

4,000 yr SNR with extended GeV γ-rays and interacting with dusty ISM (n~4 cm^{-3}) near a molecular cloud



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

TS Map (>800 MeV)



Hewitt, et al. (2012)

Puppis A: proto-Interacting SNR

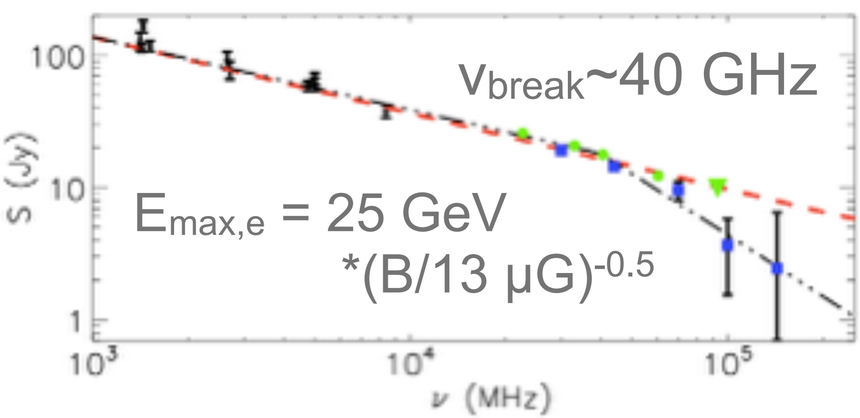
One-zone SED modeling:

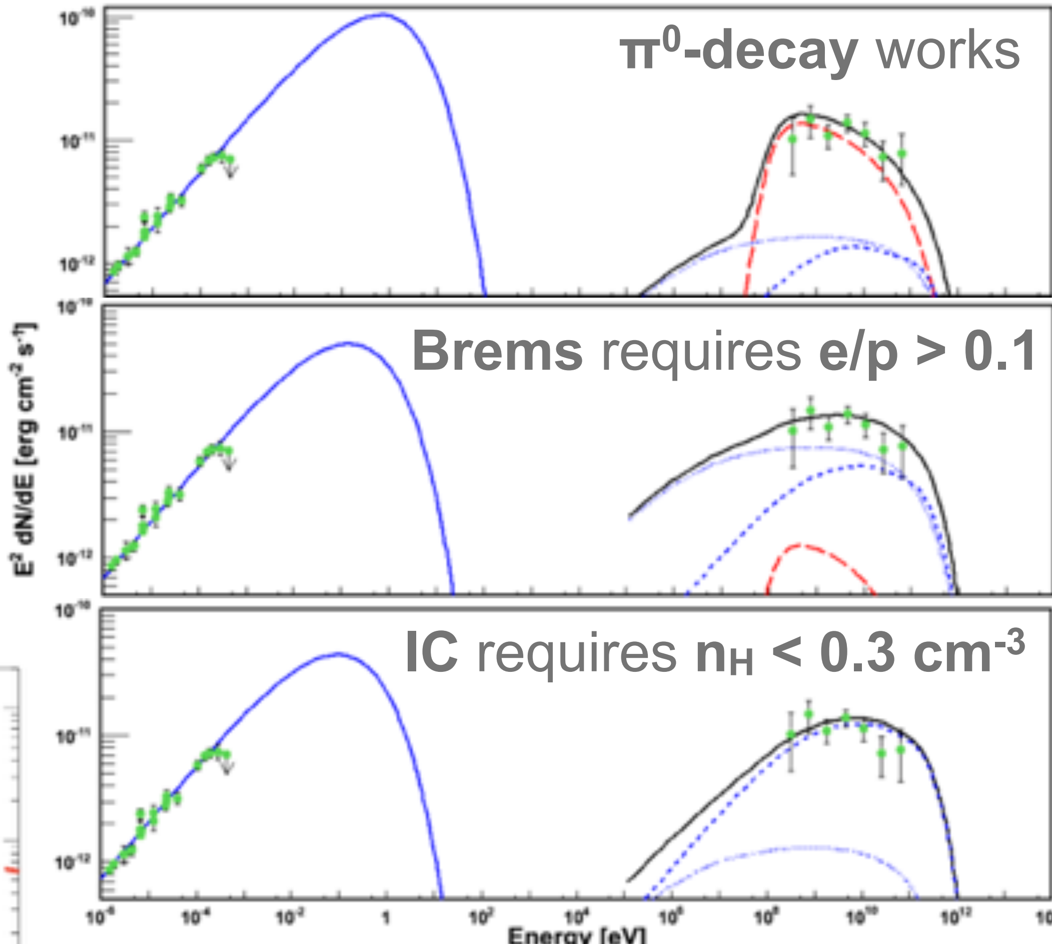
- All mechanisms are viable, with W_{CR}~(1-5)x10^{49} erg, but **π^0-decay** is most reasonable

Looks like a CR accelerator

$W_{CR,p}$ = 4x10^{49} erg
Proton Index = 2.1
Cutoff at TeV γ-rays?

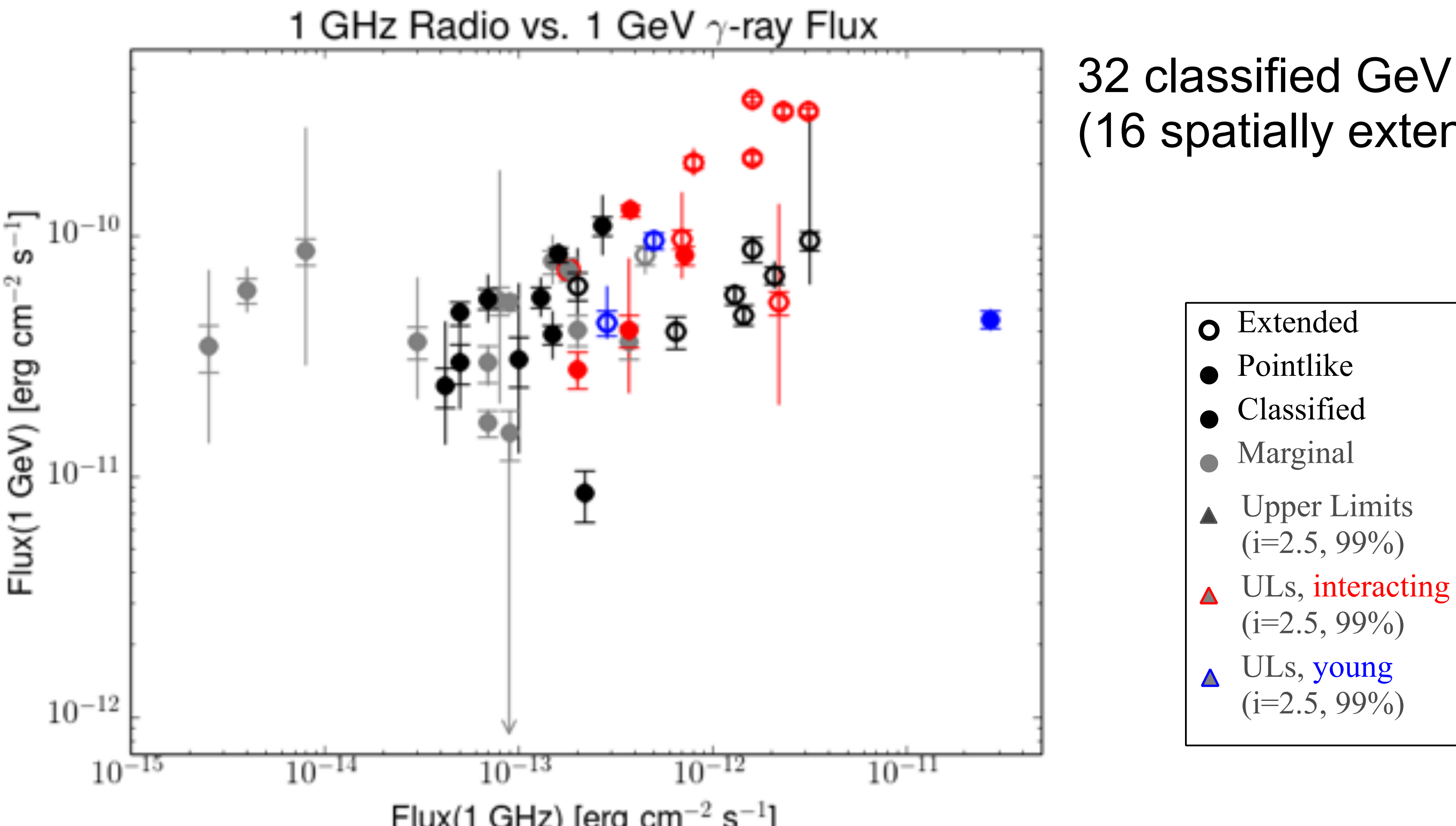
Planck confirms **radio break**





Cataloging SNRs with *Fermi* LAT

- Search 279 Galactic SNRs (Green 2009) for 1-100 GeV γ-rays and account for systematics (including Interstellar Emission Model)



32 classified GeV SNRs (16 spatially extended)

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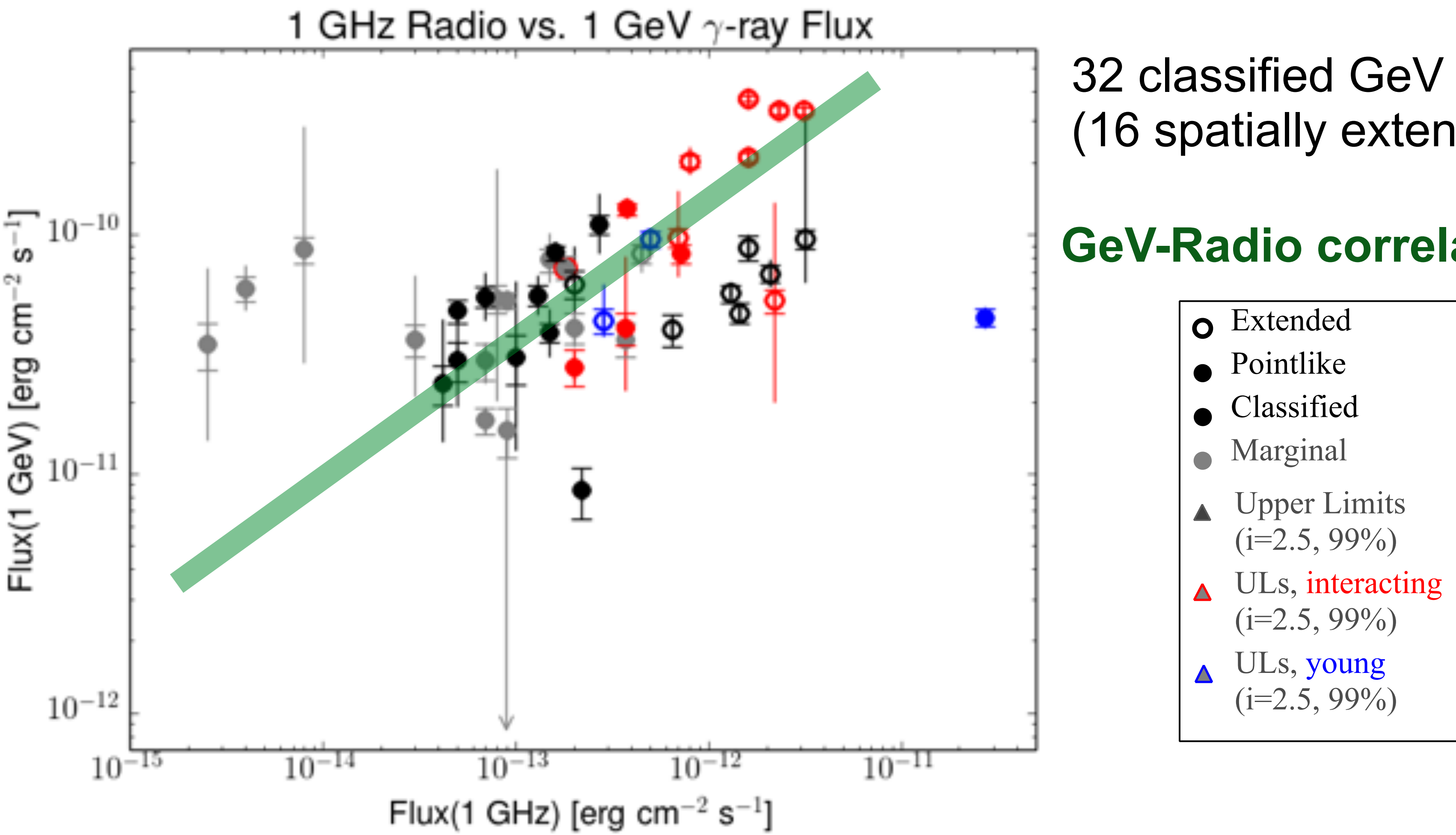

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GeV-Radio correlation?

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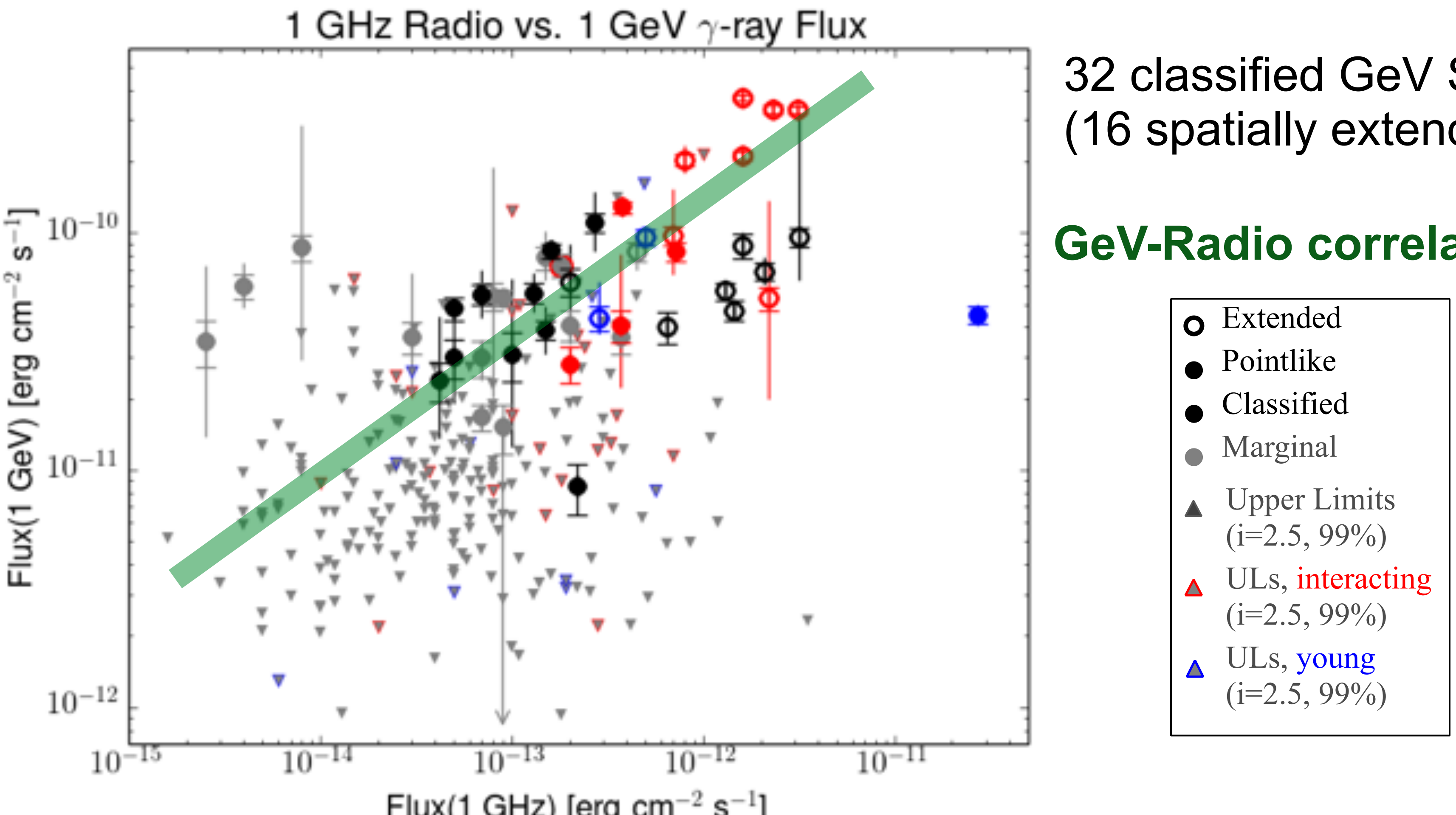

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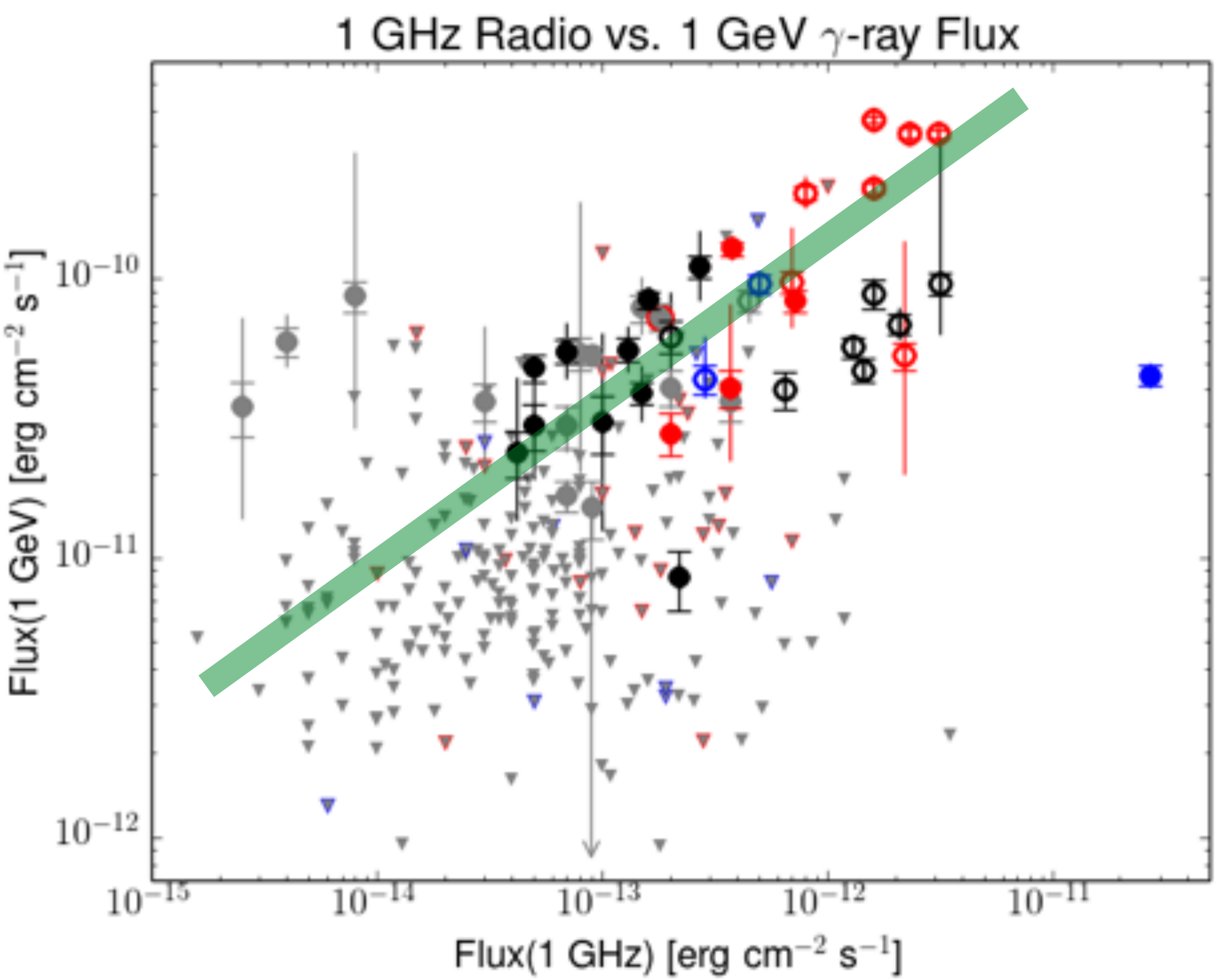

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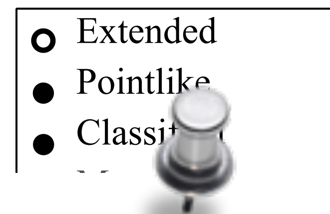
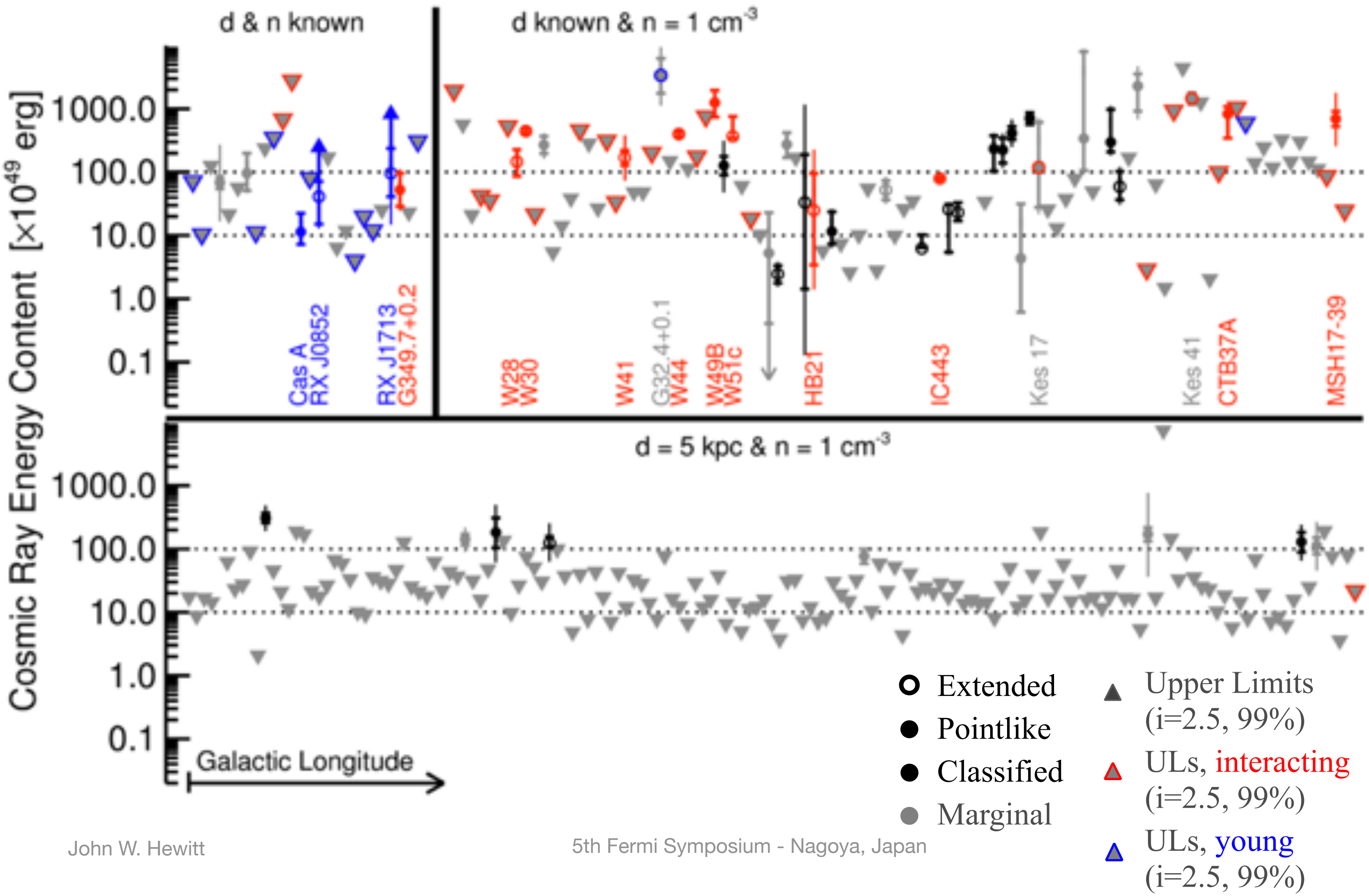


<u>Fermi SNR Catalog</u>
Wed, 2:15p 9A
T.J. Brandt
Wed, 5:00p 10B
F. de Palma

Energetics under the SNR Paradigm

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



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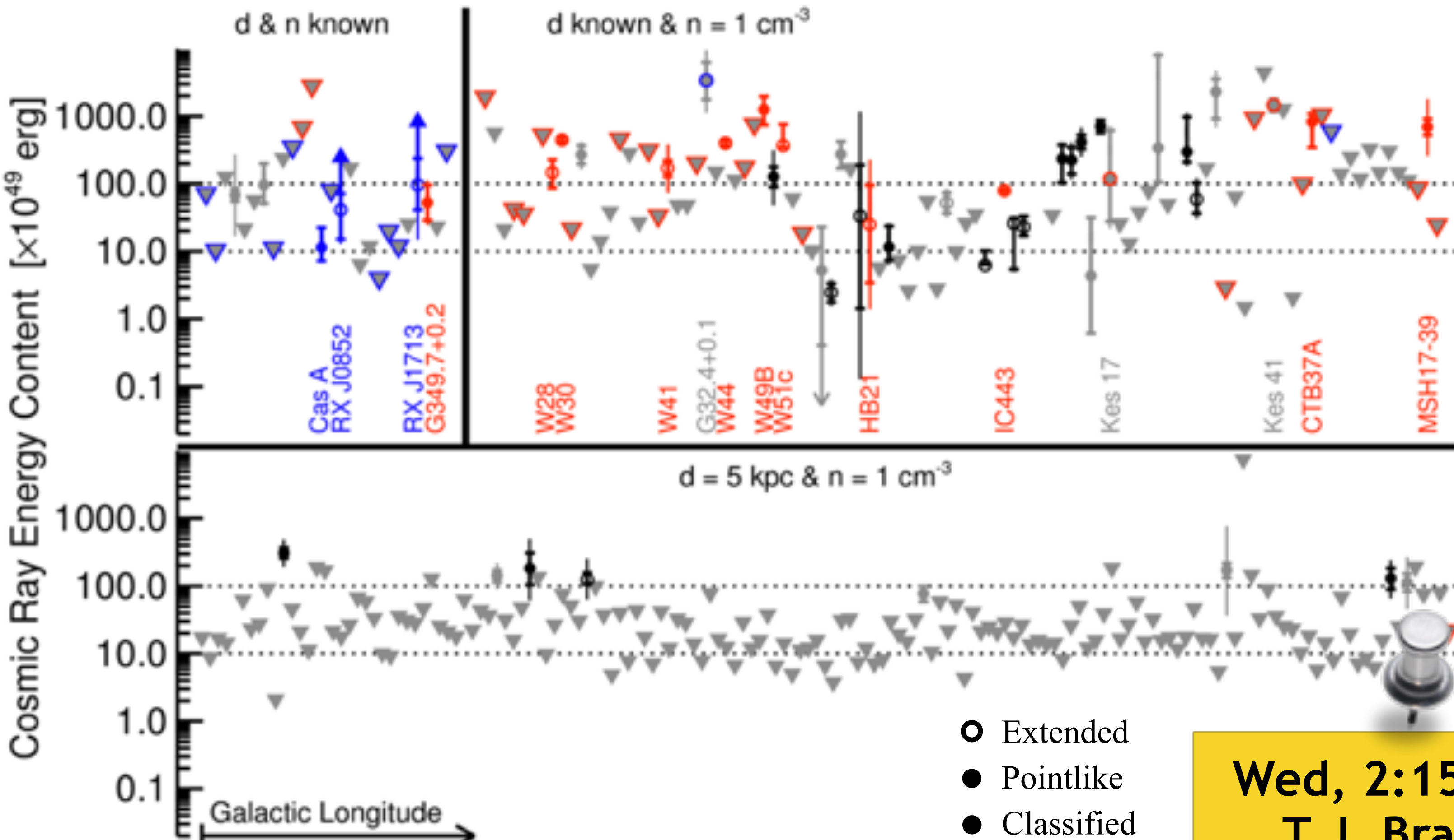
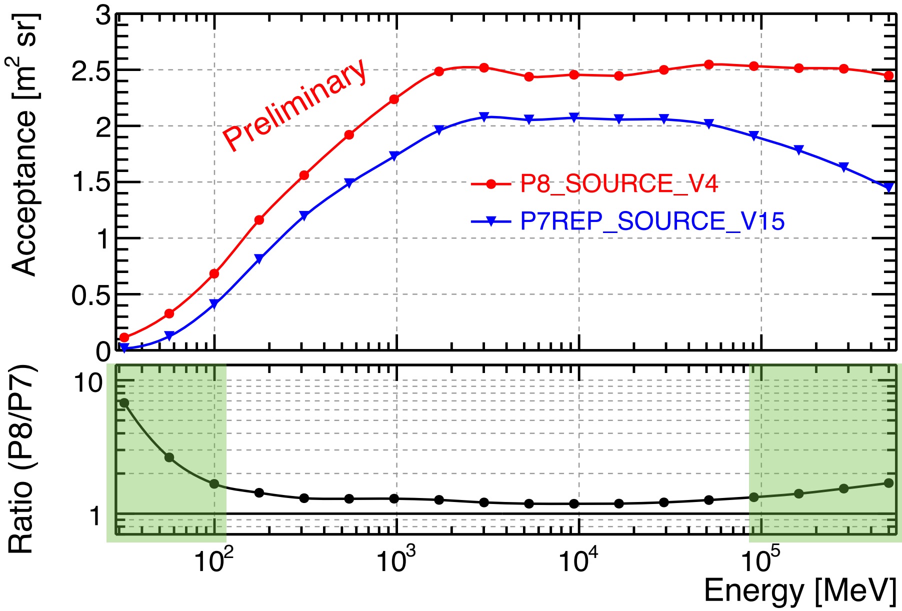
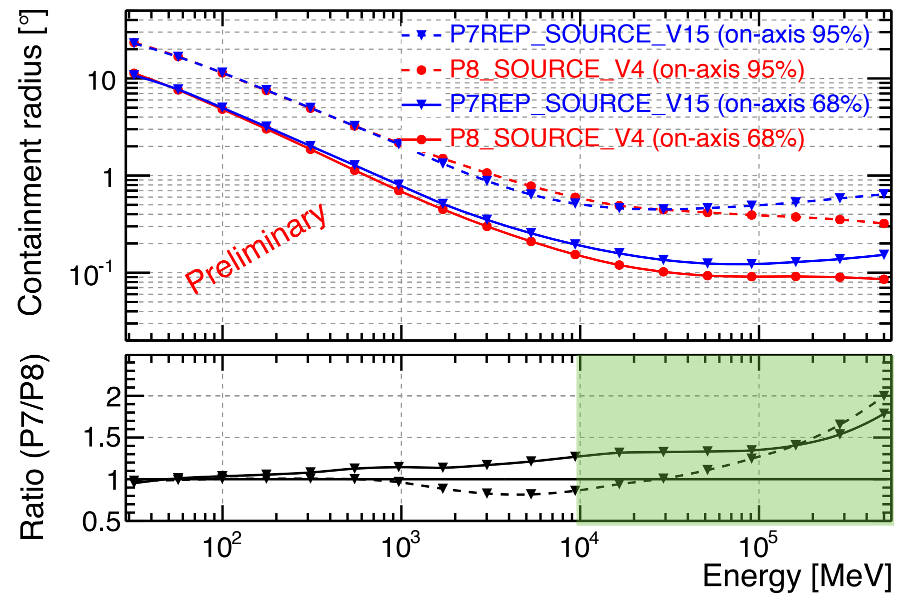


Wed, 2:15p 9A
T.J. Brandt

(i=2.5, 99%)

Pass 8 benefits SNR studies

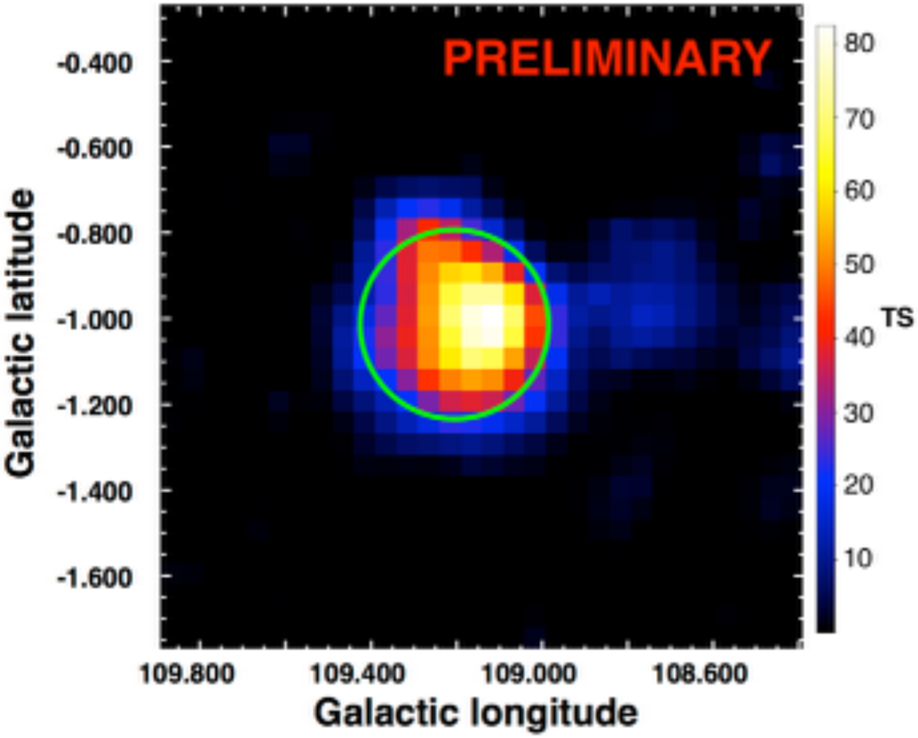


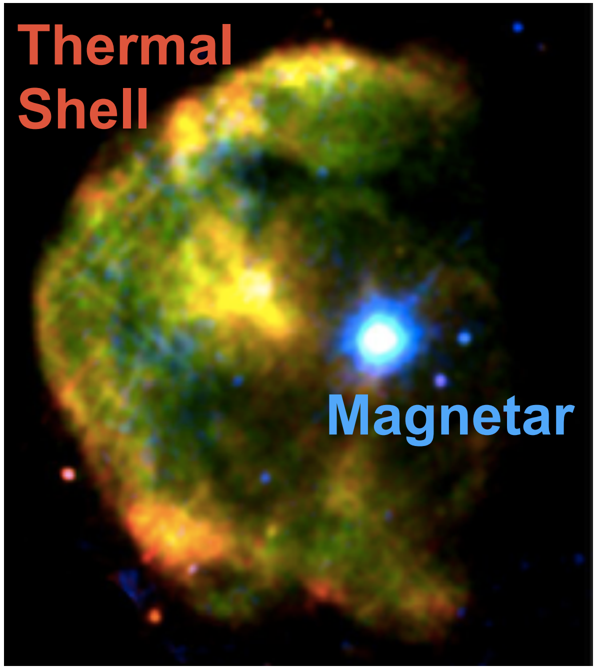


- **Improved low-energy acceptance:**
  - π^0-decay bump in more (and fainter) SNRs
- **Improved spatial resolution:**
  - Identify more γ-ray SNRs through extension
  - Resolve acceleration regions & track escape
- More GeV candidates + seeds for TeV observations

CTB 109: A Newly Identified SNR

- LAT γ-ray source: SNR or Magnetar 1E 2259+586?
- Pass 8 data reveals an **extended GeV SNR** (TS=110, TS_{ext}=20) matching the radio size (**D = 0.44±0.04°**)





- Hadronic or leptonic accelerator? Γ_{GeV}=1.8

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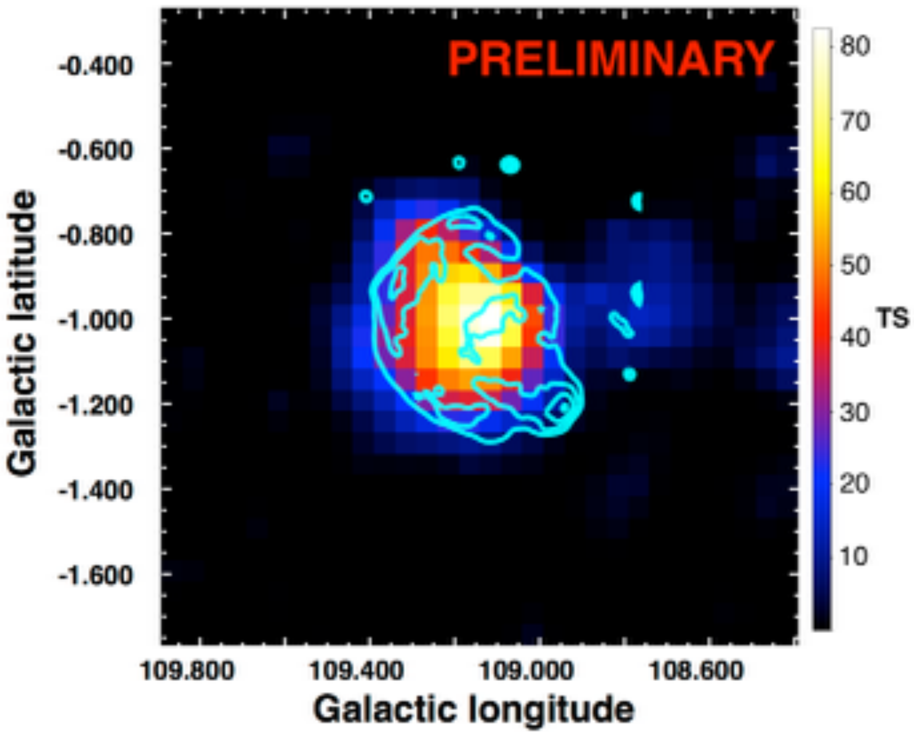
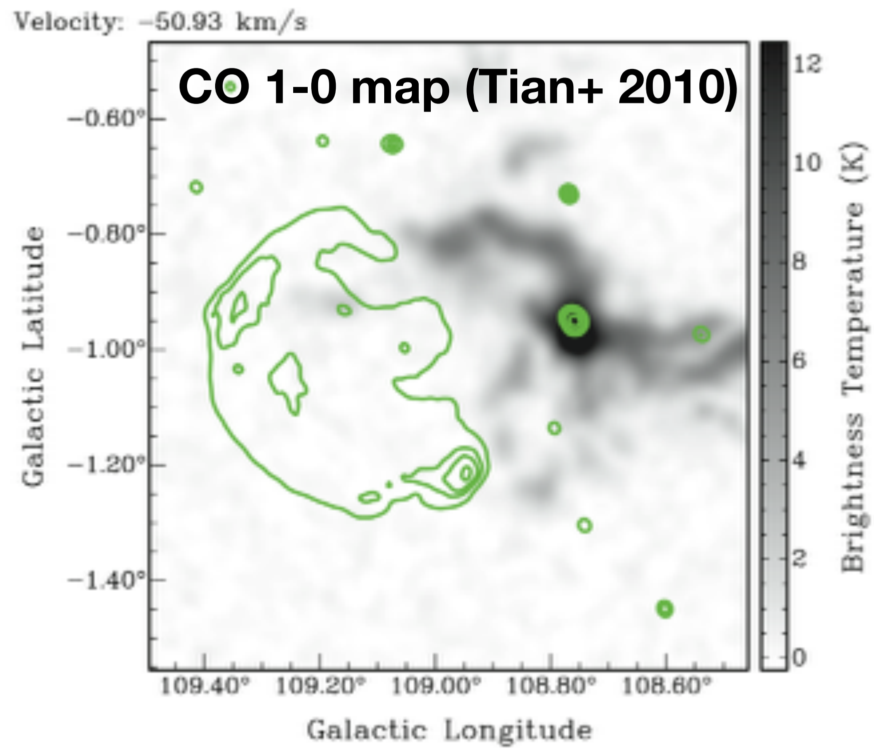


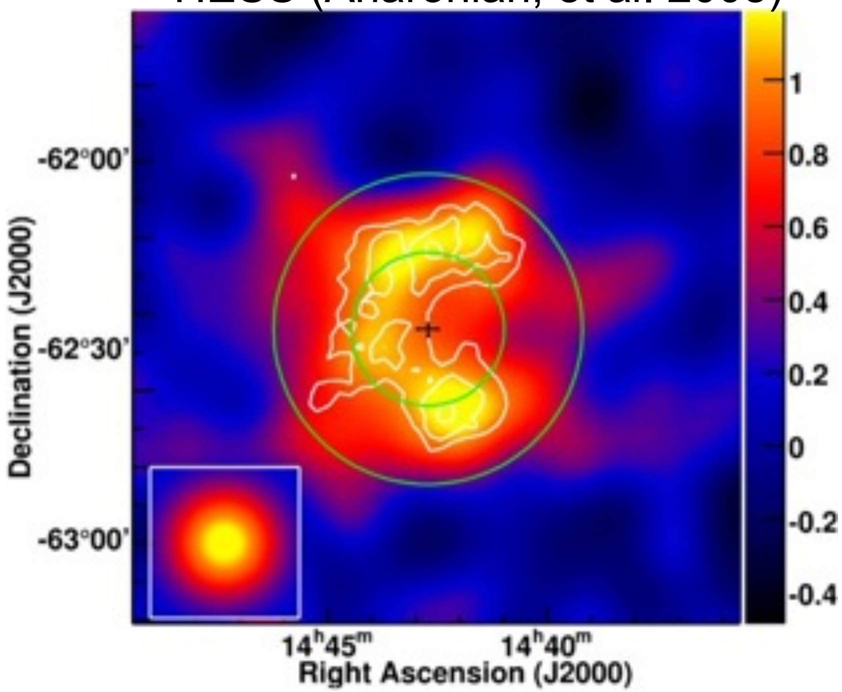


- Hadronic or leptonic accelerator? Γ_{GeV}=1.8

TeV shell-type SNR as seen by Fermi

- RCW 86: TeV shell-type SNR detected by HESS (D = 0.82°)

HESS (Aharonian, et al. 2008)



Type Ia (SN 185) with a pre-SN cavity

<u>Still a young accelerator?</u>

- CR acceleration efficiency ~20% from Balmer lines (Morlino+ 2014)
- Agrees with multi-zone SED models (Lemoine-Goumard+ 2012)
- LAT detection 5.1σ (Yuan+ 2014) $\Gamma_{GeV} = 1.4 \pm 0.2$

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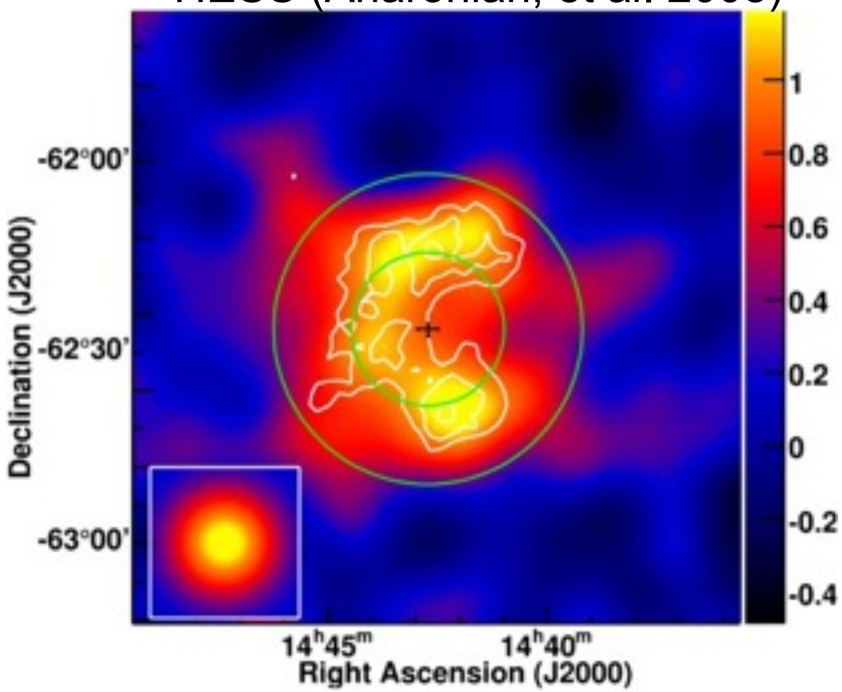
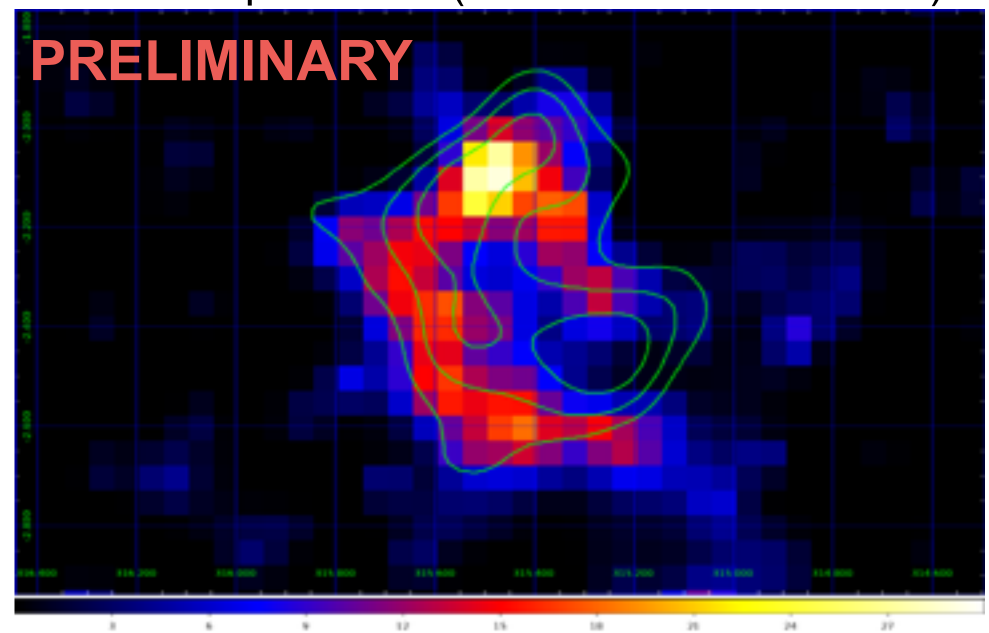


TS Map >1 GeV (69 months Pass 8 data)



- Pass 8 reveals extended emission
  Diameter = 0.7±0.06°

Poster 5.03
M. Caragiulo

Yes. SNRs accelerate CRs, but…

- **Confirming the SNR paradigm requires much more:**
  - **Identifying and understanding active accelerators**
  - **Effect of SNR interaction with ISM on CRs**
  - **γ rays + Multiwavelength + Direct detection**

- **γ-ray SNRs require increasingly sophisticated models:**
  - **Particle spectra during acceleration and escape**
  - **Spatial morphology of SNRs**
  - **Differences in electron and proton acceleration**
  - **CR Diffusion in complex environments**

- ***Fermi* has much more to say about SNRs and CR origins!**
  Pass 8 results: CTB 109, RCW 86, Tycho… and more to come