Fermi-LAT observations of Supernova Remnants

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for the Fermi-LAT collaboration

University and INFN of Bari

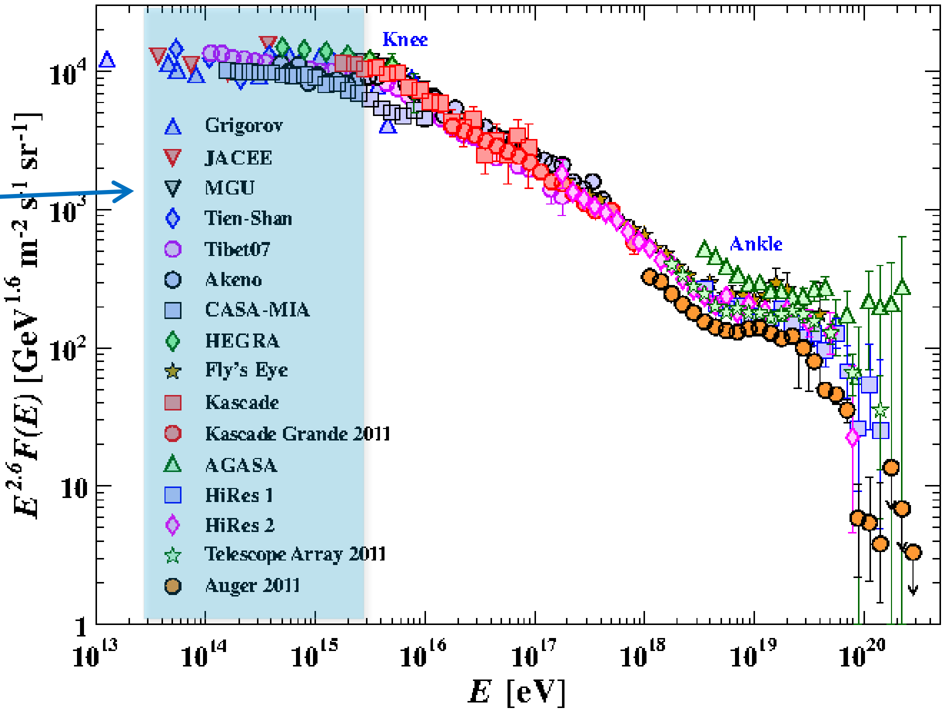
CRIS

Ischia, 4th July 2016

SNRs as sources of CRs

Galactic Cosmic ray spectrum

$$N(E) \propto E^{-2.7}$$



up to the 'knee': 10^{15} eV

Maximum energy of acceleration of GCRs ?

From CR diffusion:

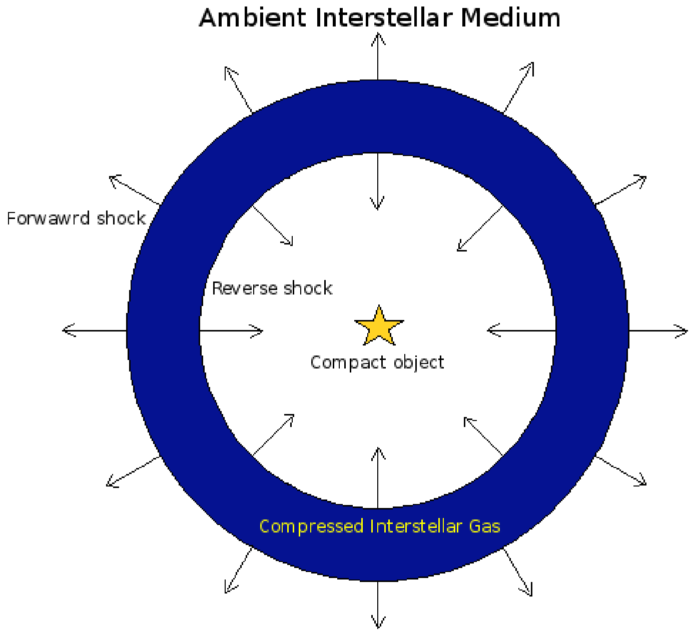
$$N(E) = Q_{inj}(E)\tau_{esc}(E)$$

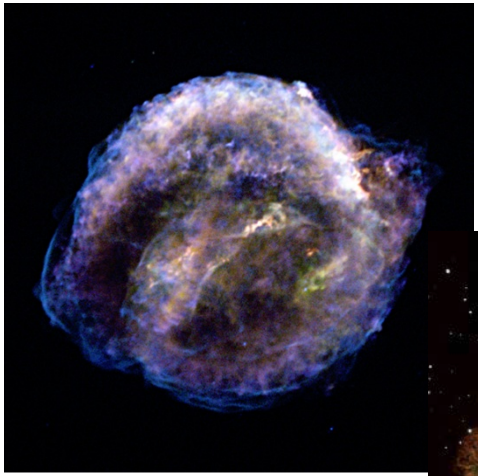
$$\tau_{esc}(E) \propto E^{-0.6\div -0.3}$$

$$Q_{inj}(E) \propto E^{-2.1\div -2.4}$$

from B/C ratio measurements

Supernova Remnants





Kepler SNR

Crab Nebula

Energetics of SNRs

- SN explosion energy E_{SN}~10^{51} erg
- Rate of explosion in the Galaxy R_{SN}~3 SN/century
- Confinement time of cosmic rays τ_e~10 Myr
- Cosmic-ray energy density ρ_{CR}~1 eV cm^{-3}

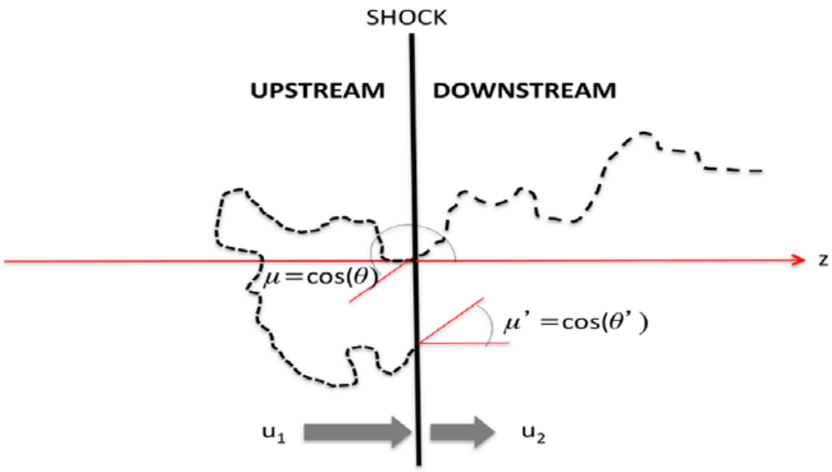
$$\rho_{CR} = R_{SN}\, E_{SN}\, \tau_e\, \epsilon$$

Acceleration efficiency required $\varepsilon \lesssim 10\%$

Non-linear diffusive shock acceleration theory

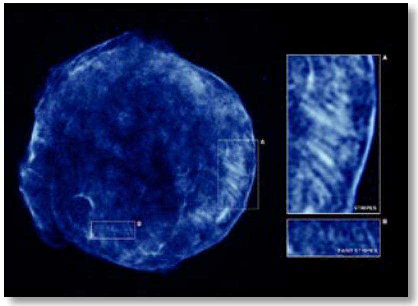
Diffusive Shock Acceleration

- Conservation of mass, momentum and energy
- Predicts an accelerated particle distribution $\propto E^{-q}$, with $q = 2$ in case of strong SNR shocks
- The required acceleration efficiency is not so small ⟶ dynamical reaction of accelerated particles on the shock.

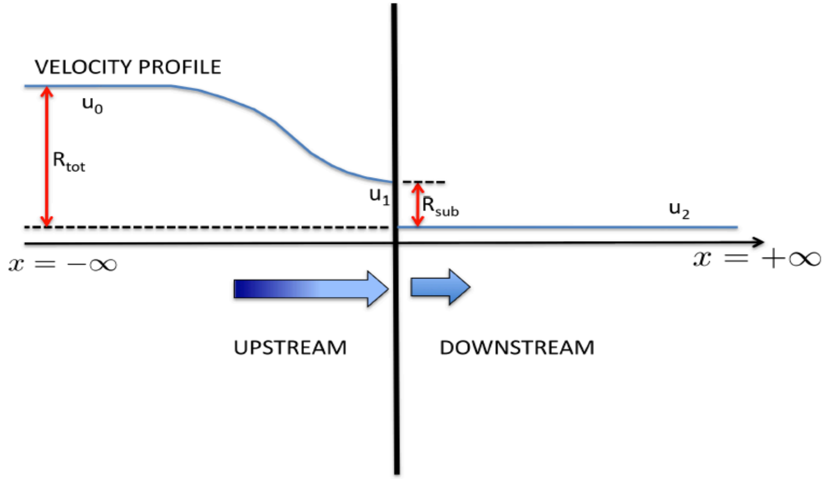


Non linear Diffusive Shock Acceleration

- Generalization of conservation equations with the introduction of CR contribution
- Predicts softer accelerated particle distribution: $q = 2.1 - 2.4$
- Magnetic field amplification: most important evidence of NLDSA



Credit: NASA/CXC/ Rutgers/K.Eriksen et al.

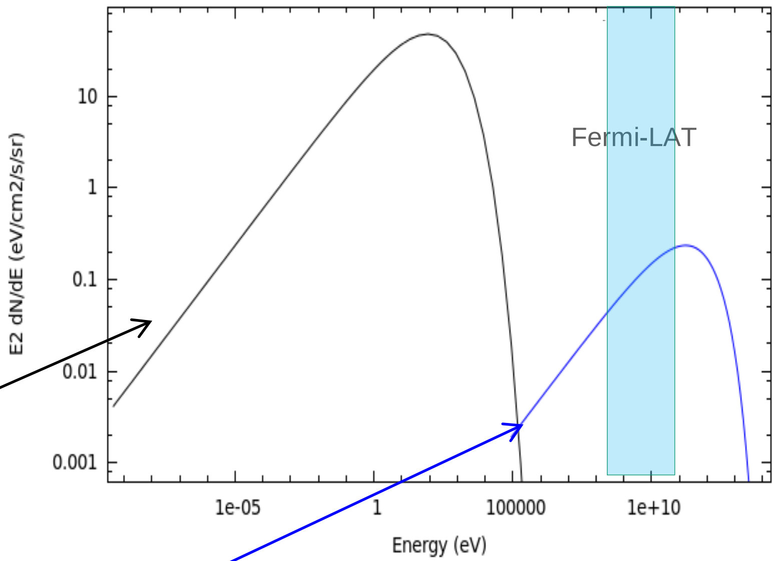


Blasi, P.: 2013, Astron. Astrophys. Rev. 21, 70

Spectral energy distribution (SED) of SNRs

<u>Thought to be cosmic ray sources:</u>

γ-ray flux originates from the interaction of <u>accelerated particles</u> with the SNR environment:
SNR paradigm for Cosmic Rays



Radio to X-ray range

- <u>Synchrotron peak</u>

Three competitor processes for GeV-TeV energy range

- <u>Inverse Compton</u>
- <u>Bremsstrahlung</u>
- <u>Pion decay</u>

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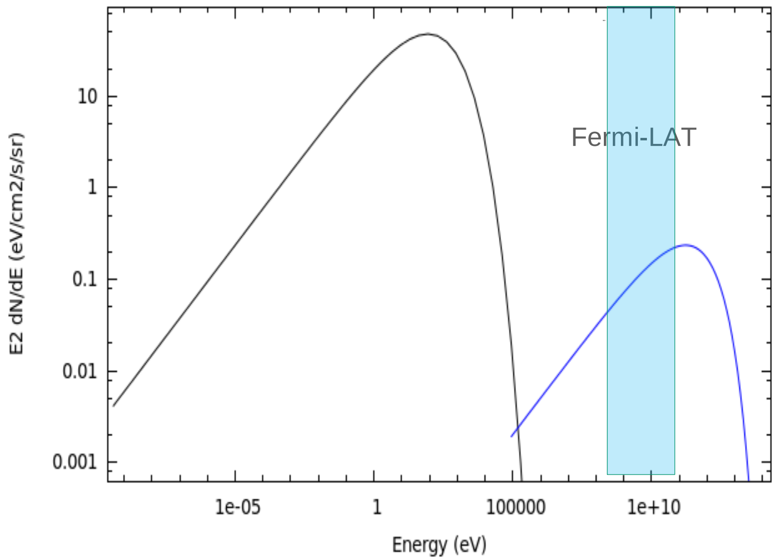

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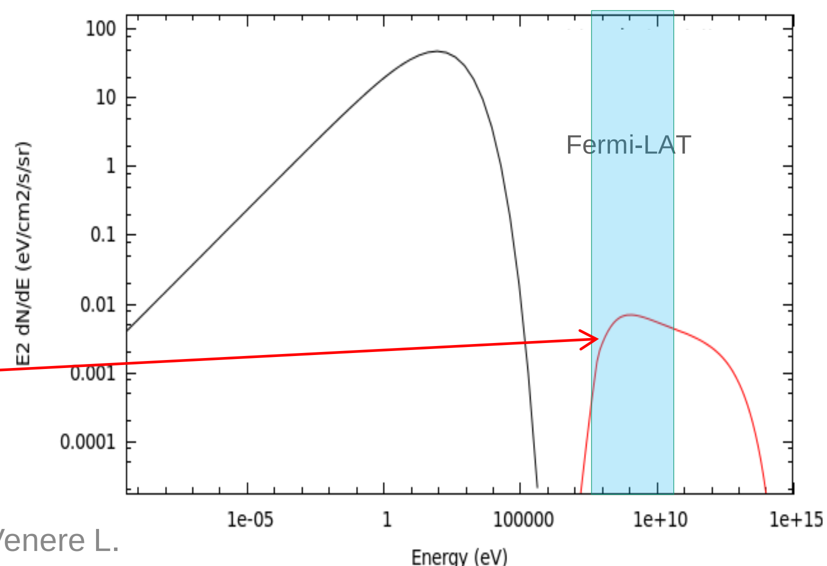
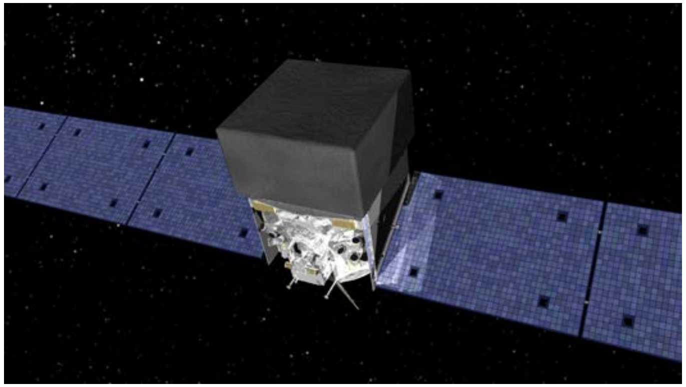
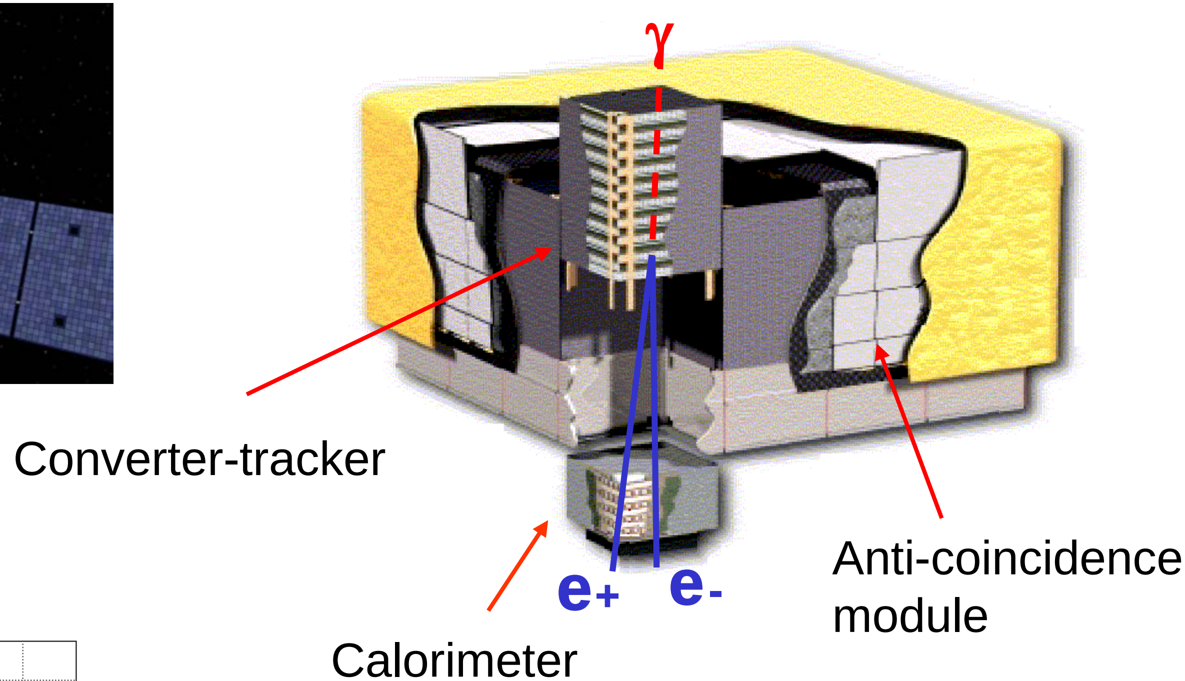
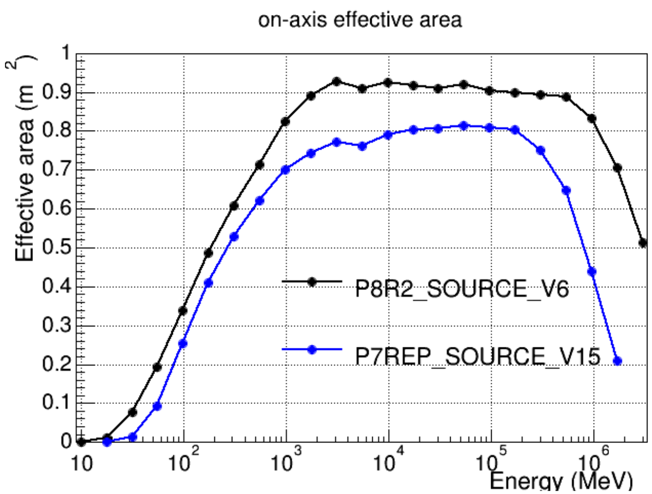


The Fermi-LAT experiment



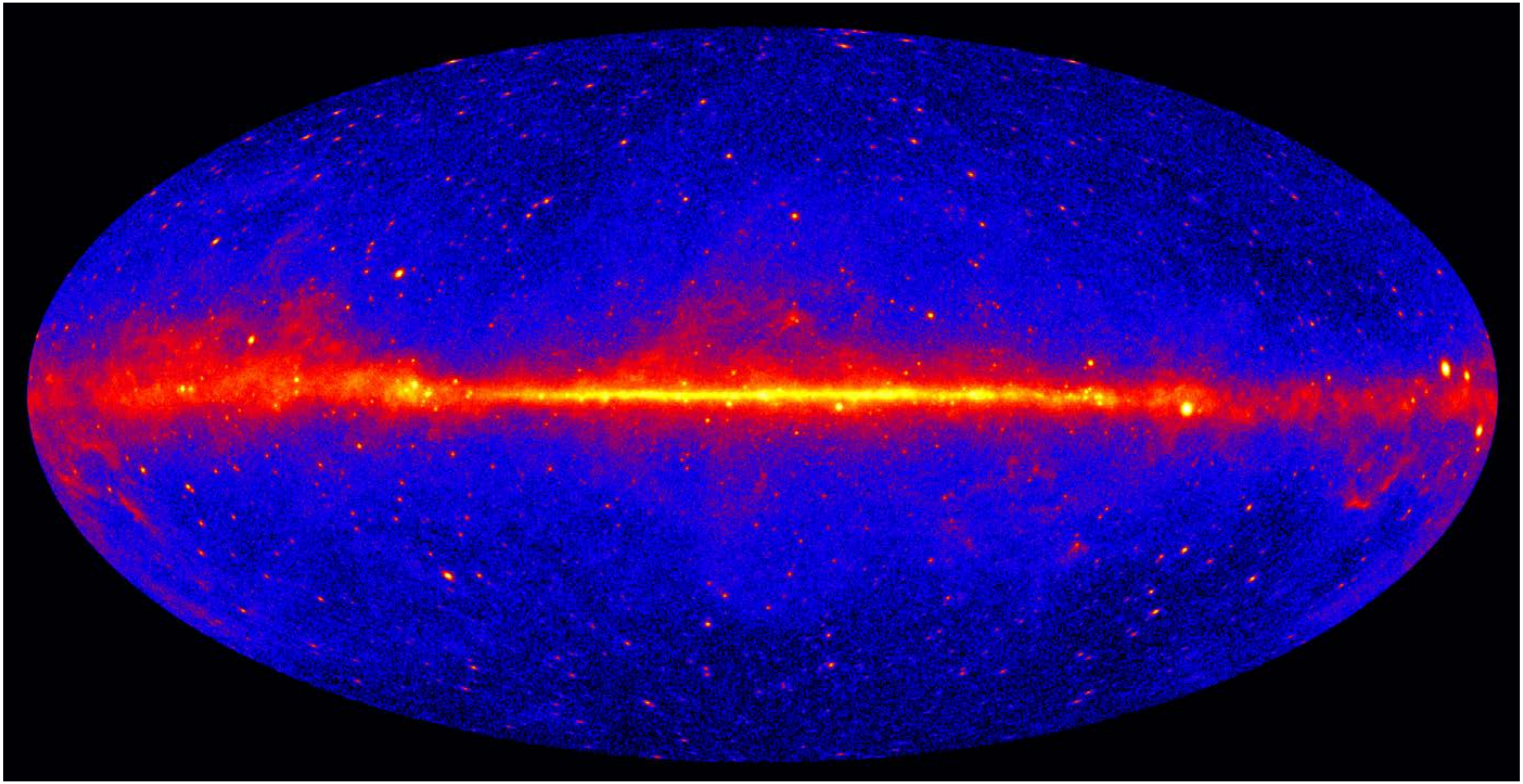




Pass 8 data release:

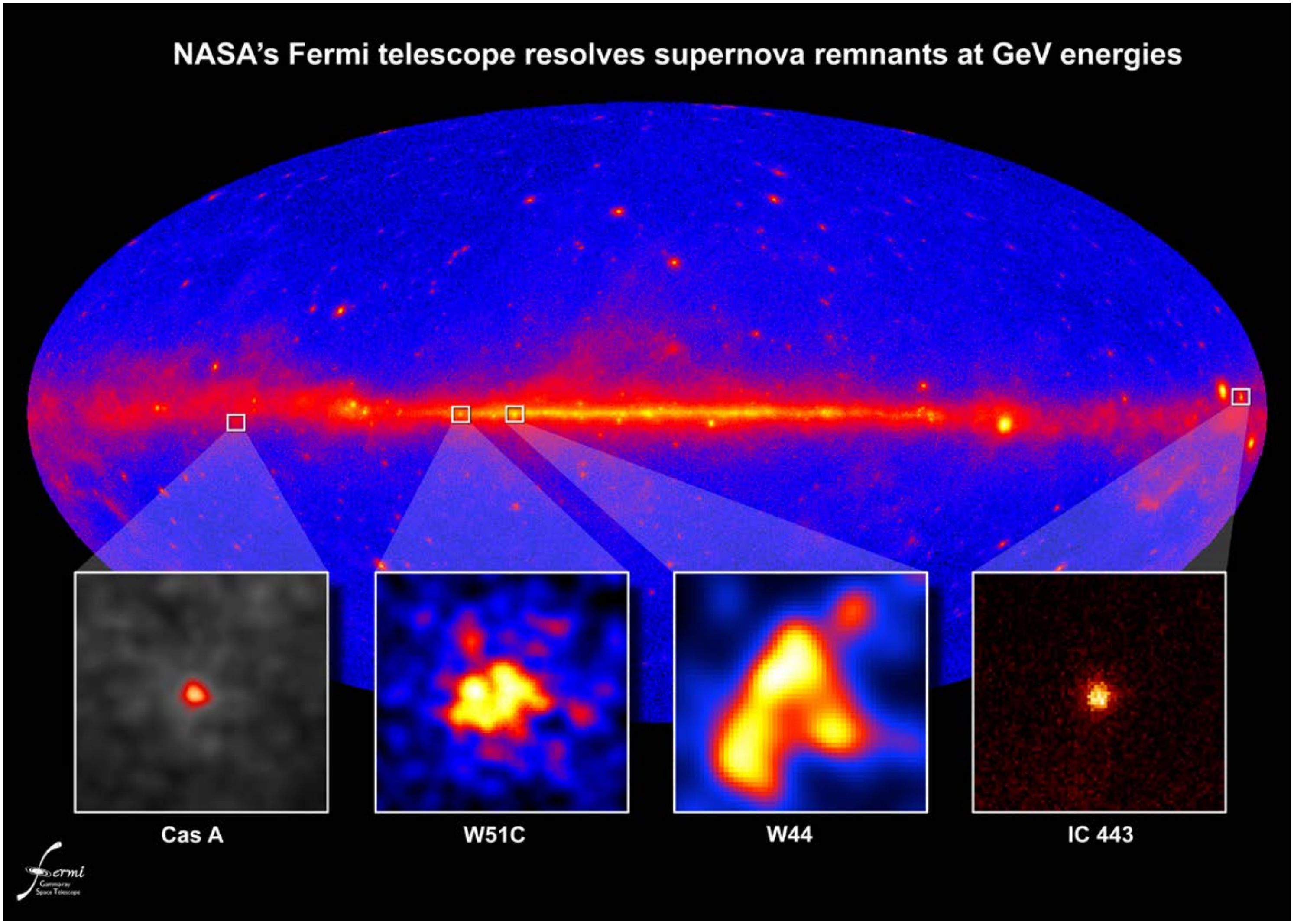
- Increased effective area
- Better Point Spread Function (PSF)
- Introduction of PSF and EDISP subclasses

Gamma-ray sky



Gamma-ray sky obtained with 5 years of Fermi-LAT data with E>1GeV

Supernova Remnants



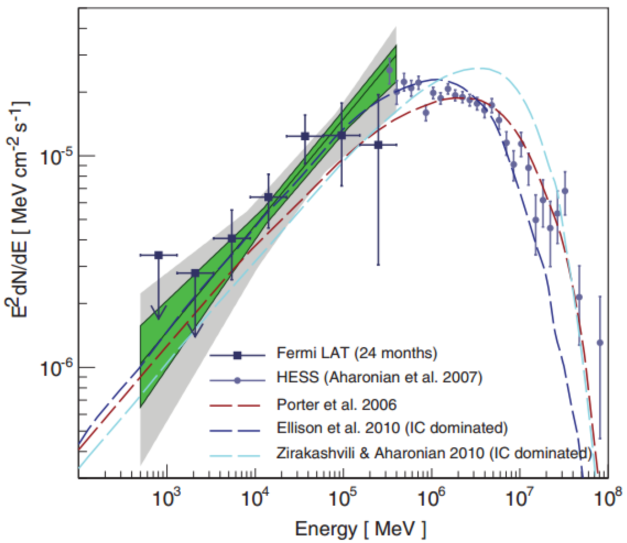
Young SNRs

- Approx. Few thousands years old
- Simple environments
- Small energy losses

→ <u>Ideal targets to test the acceleration theory and look for 'Pevatrons'</u>

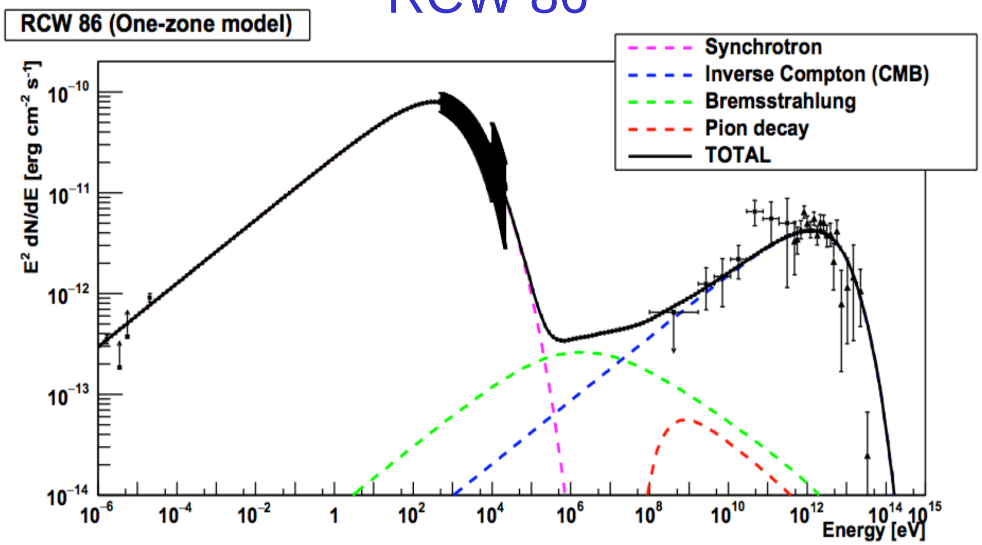
<u>Leptonic scenario</u>

RX J1713.7-3946



A. A. Abdo et al., ApJ 734 (2010), 28

RCW 86

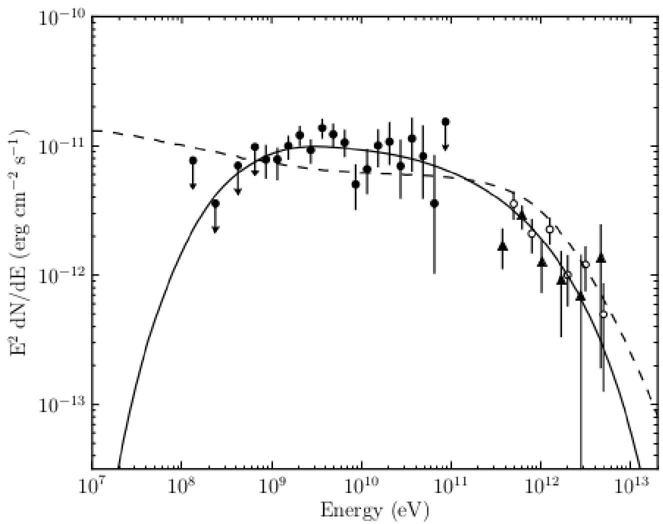


M. Ajello et al., ApJ 819 (2016) 98

γ-ray emission dominated by Inverse Compton or Bremsstrahlung emission

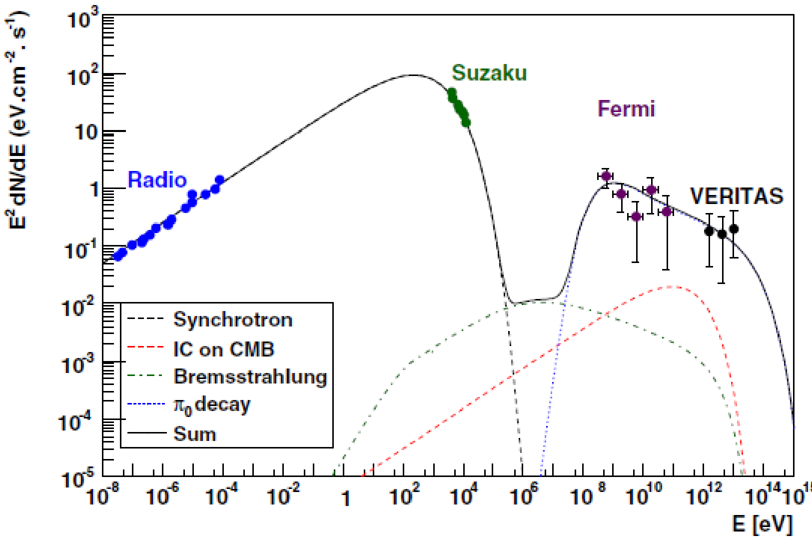
Hadronic scenario

Cassiopeia A



Y. Yuan et al., ApJ 779 (2013), 117.

Tycho



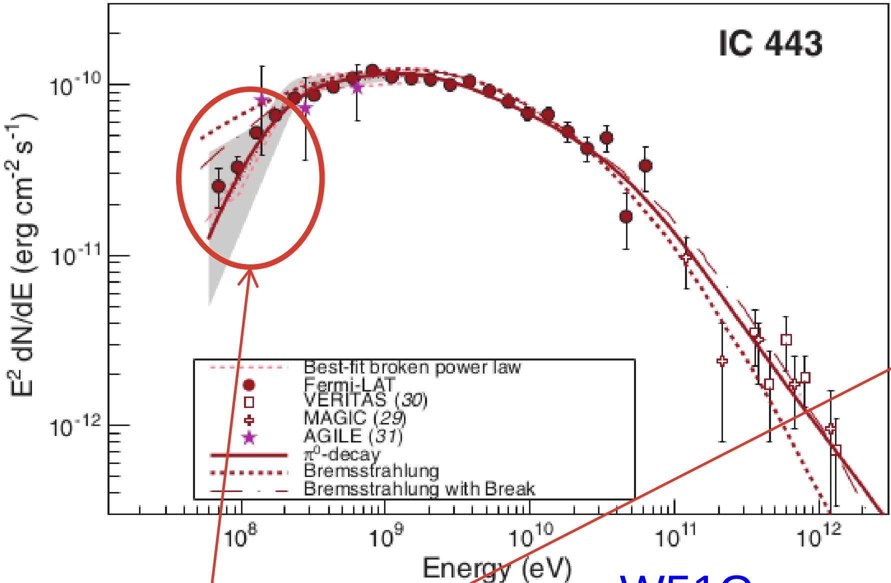
F. Giordano et al., ApJL 744 (2012) L2

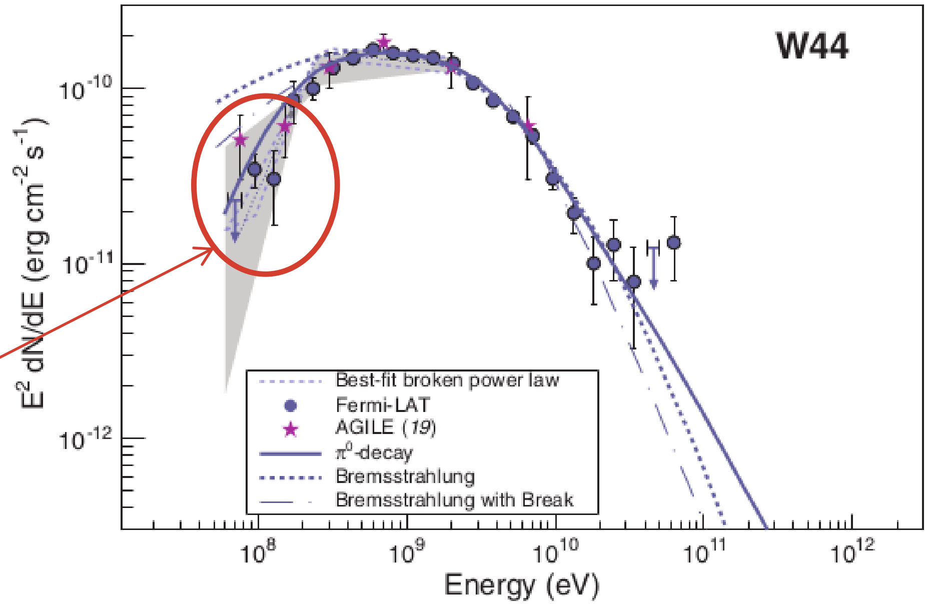
γ-ray emission dominated by pion decay

Presence of accelerated protons!

‘Pion bump’ in SNRs

IC443 and W44

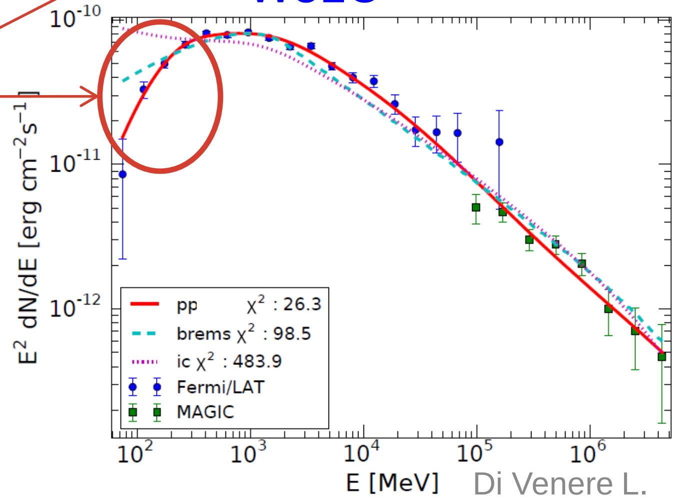




M. Ackermann et al., Science 339 (2013), 807.

W51C

‘π^0 cutoff’



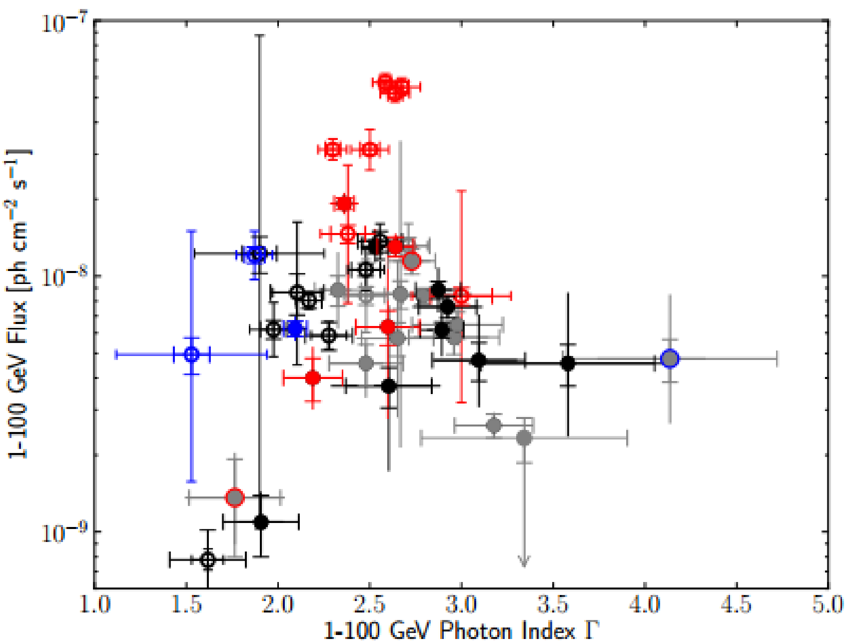
T. Jogler and S. Funk, ApJ 816 (2016), 100

Observed also by AGILE

Giuliani, Cardillo, Tavani et al., ApJL 742 (2011)2, L30

1st Supernova Remnant Catalog

- **Search of known SNRs in 3 years of Fermi-LAT data**
- **36 SNR candidates with spatial association with radio counterparts**
  - **17 extended sources: 4 new**
  - **13 point-like sources: 10 new**



- **Interacting SNRs**
- **Young SNRs**

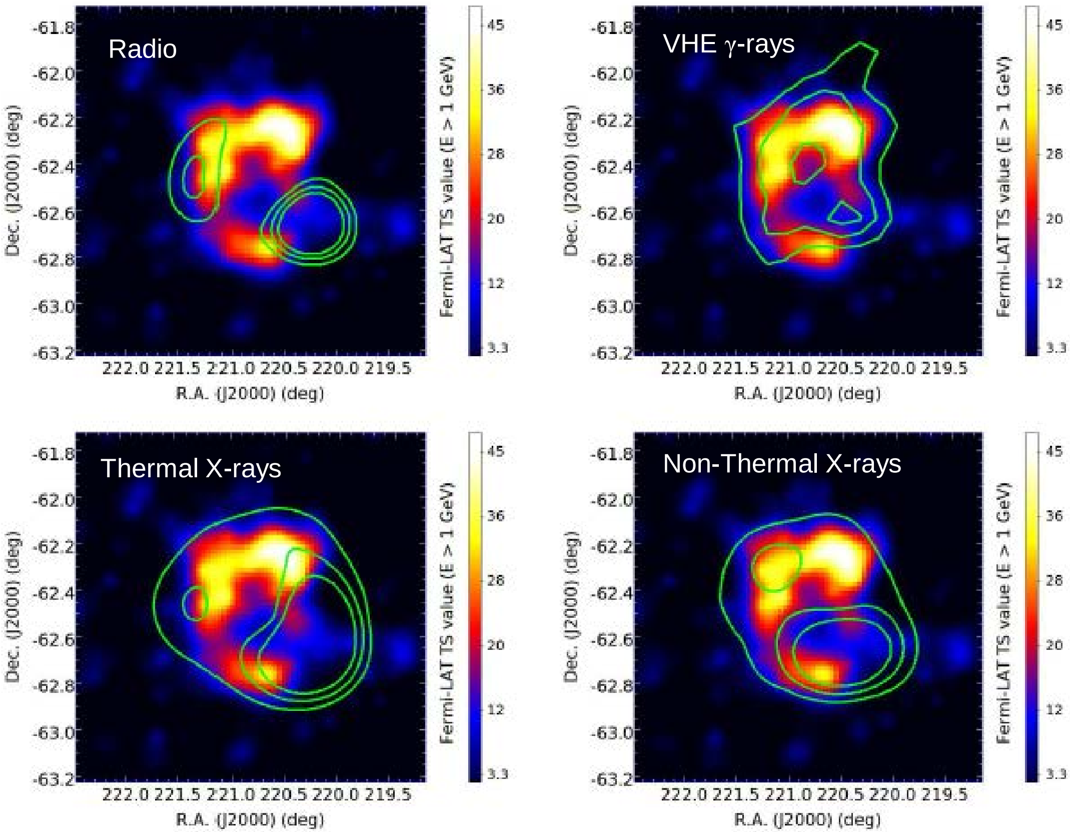
- **Classified candidates**
- **Marginal candidates**

- **Point-like sources**
- **Extended sources**

F. Acero et al., Astroph. Journ. Suppl. Series , 224 (2016), 8

Morphology studies with Pass 8

RCW 86

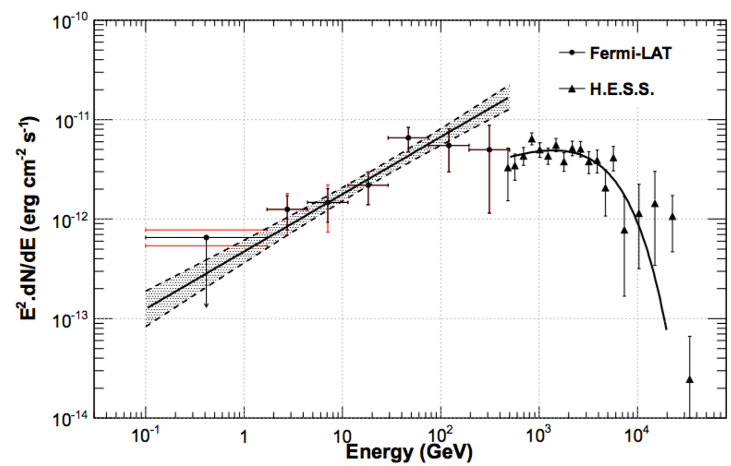


M. Ajello et al., ApJ 819 (2016) 98

Detected as extended with Pass8: **radius ~ 0.37° ±0.02**.

Best morphological photon distribution: **H.E.S.S. template**

(A. Abramowski et al., arXiv:1601.04461 (2016))

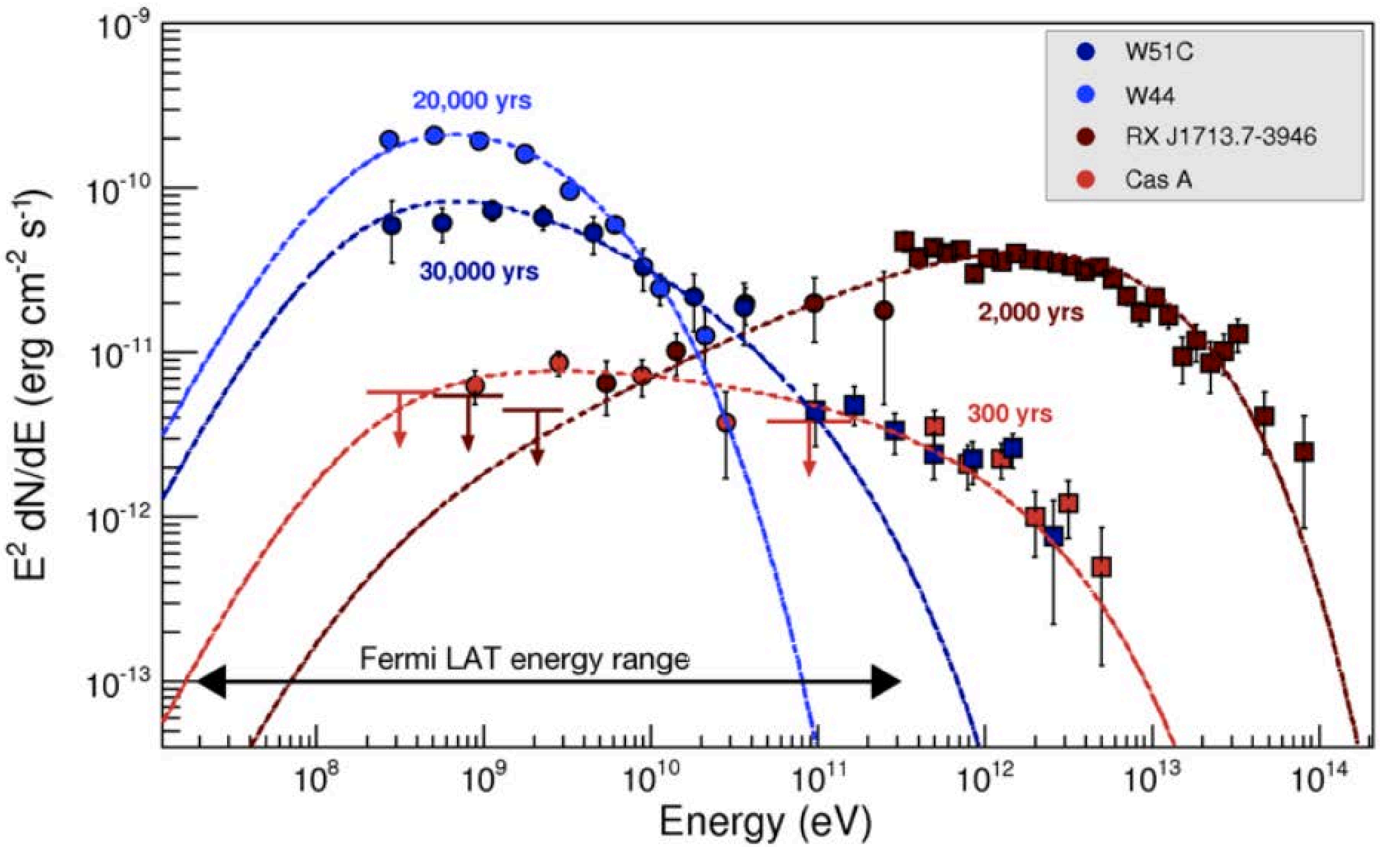


Conclusions

- SNRs are the best candidates to be CR acceleration sites
- NLDSA predictions are compatible with CR observations
- Fermi-LAT is providing key information to find direct evidence of CR acceleration in SNRs: <u>many cases already found</u>
- Young SNRs are very interesting targets to look for pion decay signals and to test the maximum energy of acceleration
- Pass 8 improvements are allowing spatial extension studies, to compare γ-ray emissions with other wavelengths

Backup

Comparing Gamma-Ray SNRs



- Young SNRs have hard spectra, extend to ~ $10^{13\text{-}15}$ eV
- Older SNRs are brighter (due to high density target) but show a clear break in their spectrum at ~ few GeV

Middle age SNRs

IC 433

- Middle age (3000-30000 yr), Mixed morphology SNR, Distance 1.5 Kpc
- Interactions with Molecular Cloud

W 44

- Middle age (~20000 yr), Mixed morphology SNR, Distance 3 Kpc
- Interactions with Molecular Cloud

W 51C

- Middle age (~30000 yr), Distance 5.5 Kpc
- Interactions with Molecular Cloud

In this kind of SNRs the **acceleration process** is **not very efficient** anymore, as suggested by the steep spectrum at high energies.

SNRs interacting with MCs are useful to investigate **CR propagation around sources and escape** from them.

Young SNRs

They are at the **initial stage of their evolution**, they are evolving in much simpler (and in most cases **low density**) **environments**.

A multi-wavelength observation might give very detailed **information about the shock** generated by the SN explosion and **CRs acceleration** in SNRs.

RX J1713.7-3946

- Young Age (2000 yr), Distance 1 Kpc
- SN Type II/Ib explosion

RCW 86

- Young Age (1800 yr), Distance 2.5 Kpc
- SN Type Ia explosion

Tycho

- Young Age (440 yr), Distance 3.5 Kpc
- SN Type Ia explosion

Cas A

- Young Age (340 yr), Distance 3.4 Kpc
- SN Type IIb explosion