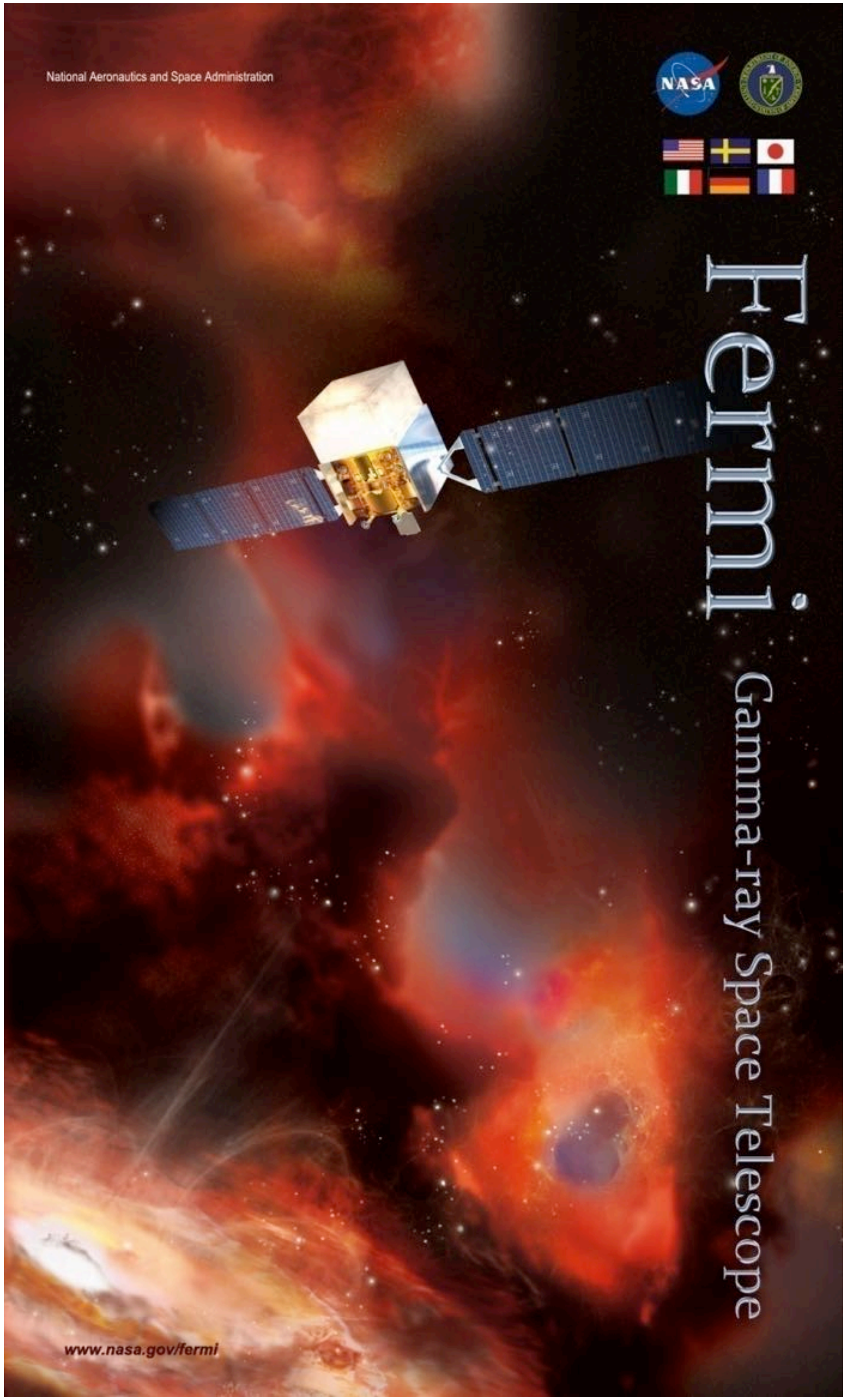


Supernova Remnants with *Fermi* Large Area Telescope

Caragiulo M.

Di Venere L.

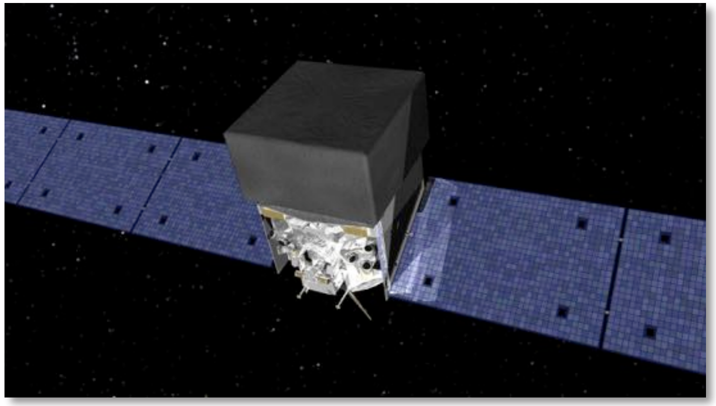
on behalf of the Fermi-LAT collaboration

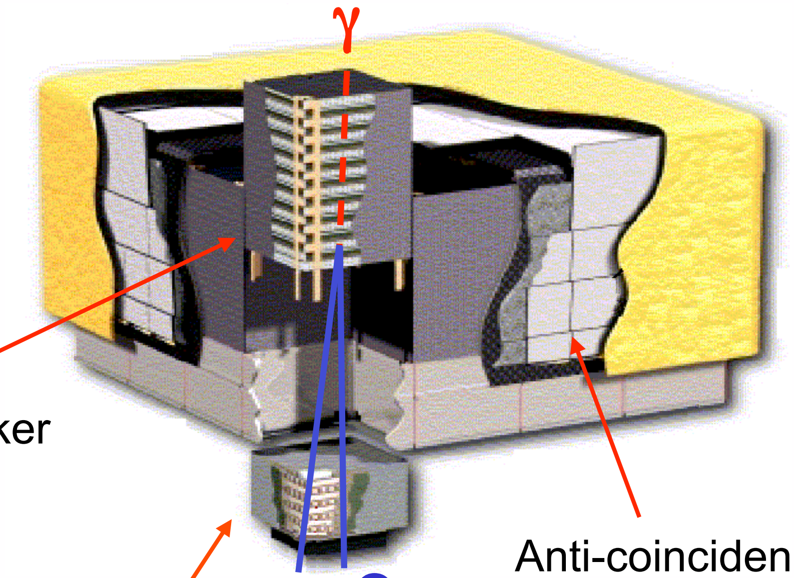
University and INFN of Bari

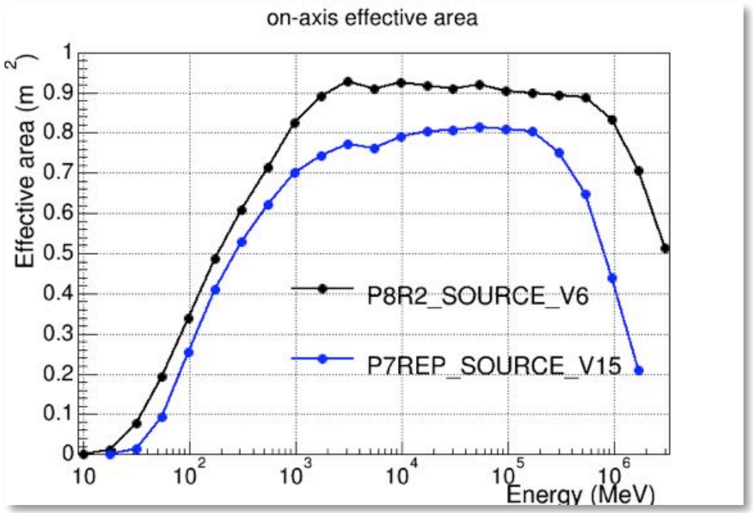
6th Roma International Conference on AstroParticle Physics

Frascati, 23rd June 2016

THE FERMI-LAT EXPERIMENT

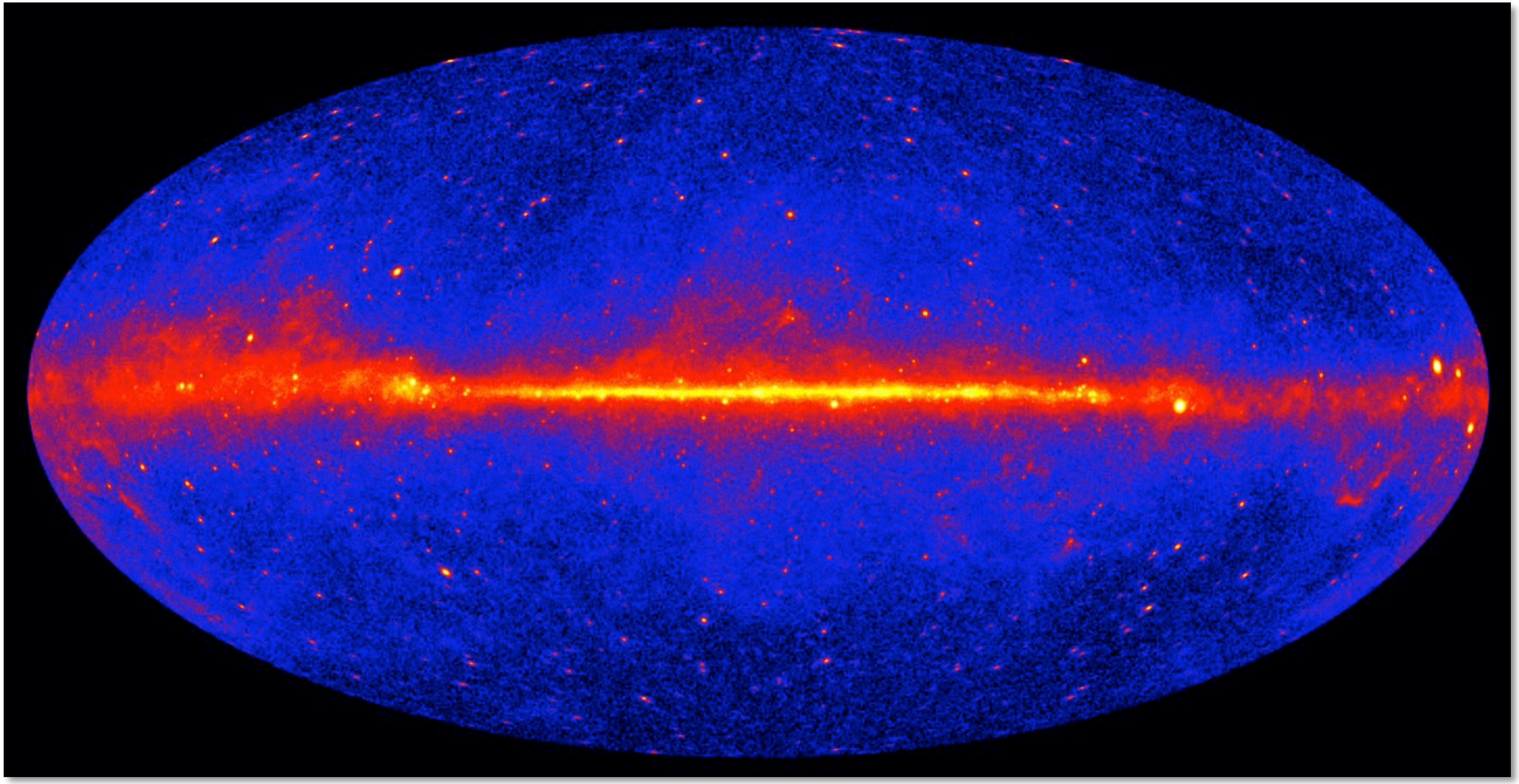






Pass 8 data release:
- Increased effective area
- Better Point Spread Function (PSF)
- Introduction of PSF and EDISP subclasses

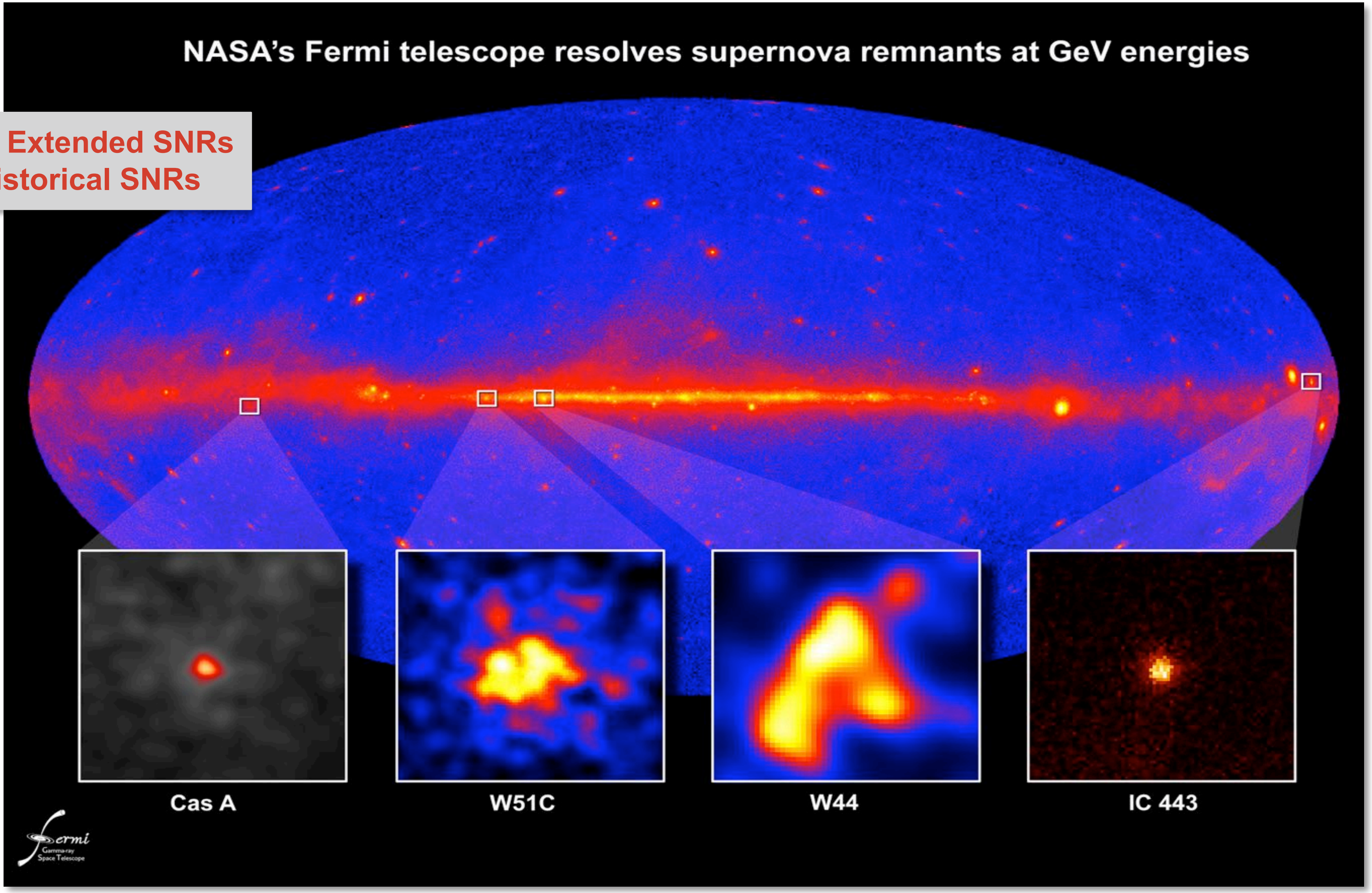
GAMMA-RAY SKY



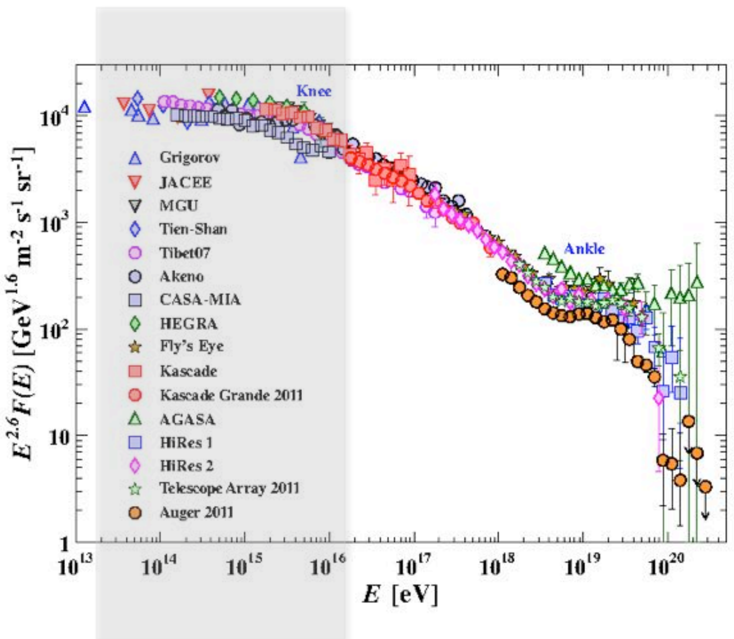
Gamma-ray sky obtained with 5 years of Fermi-LAT data with E>1GeV

SUPERNOVA REMNANTS

- 13+ Extended SNRs
- 4 Historical SNRs



SNRs as sources of CRs



Galactic Cosmic ray spectrum:

$$F(E) \propto E^{-2.75}$$

$$F(E) = Q_{inj}(E)\tau_{esc}(E) \propto E^{-(q+\delta)}$$

$\delta \sim 0.3 \div 0.6$ (From B/C ratio measurements)

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

- SN explosion energy $E_{SN} \sim 10^{51}$ erg
- Rate of explosion in the Galaxy $R_{SN} \sim 3$ SN/century
- Confinement time of CRs $\tau_{esc} \sim 10$ Myr
- CR energy density $\rho_{CR} \sim 1$ eV cm^{-3}

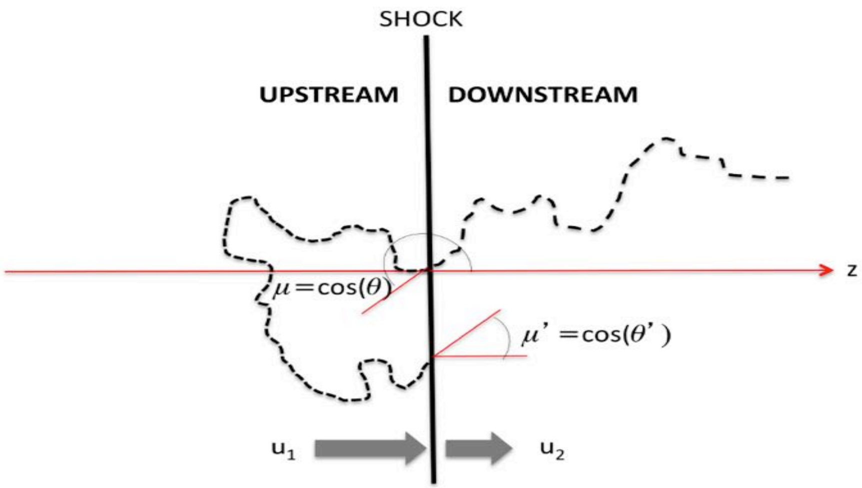
$$\rho_{CR} = R_{SN} E_{SN} \tau_{esc} \varepsilon$$

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

NON-LINEAR DIFFUSIVE SHOCK ACCELERATION THEORY

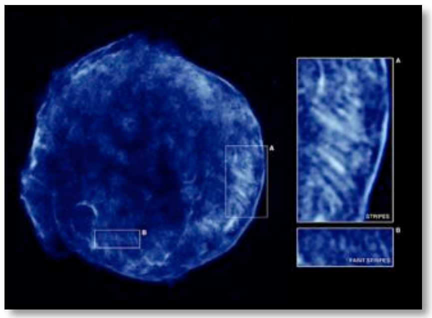
Diffusive Shock Acceleration

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

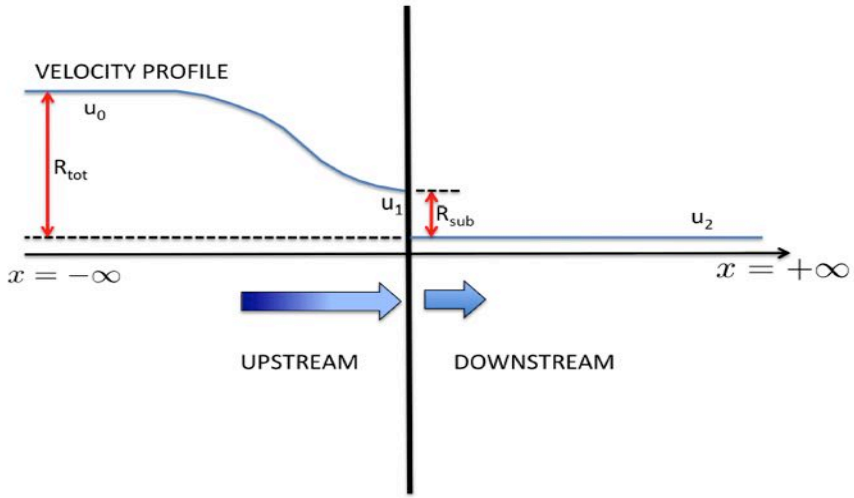


Non-Linear Diffusive Shock Acceleration

- ❑ Generalization of conservation equations with the introduction of CR contribution;
- ❑ Predicts softer accelerated particle distribution: $\mathbf{q} = \mathbf{2.1 \div 2.4}$;
- ❑ **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 of SNRs

Thought to be cosmic ray sources:

γ-ray flux originates from the interaction of accelerated particles with the SNR environment:

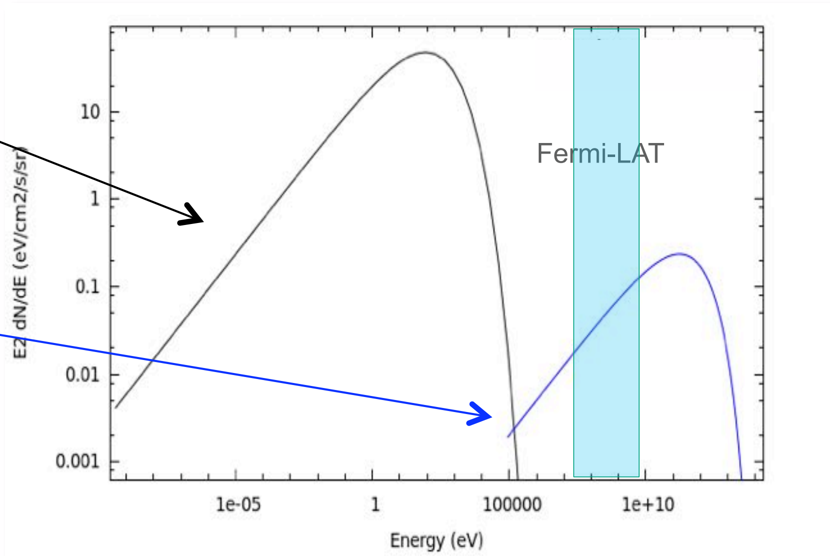
SNR paradigm for CRs

Radio to X-ray range:

- **Synchrotron radiation**

Three competitor processes for MeV-TeV energy range

- **Inverse Compton scattering**
- Bremsstrahlung radiation
- Hadronic interaction



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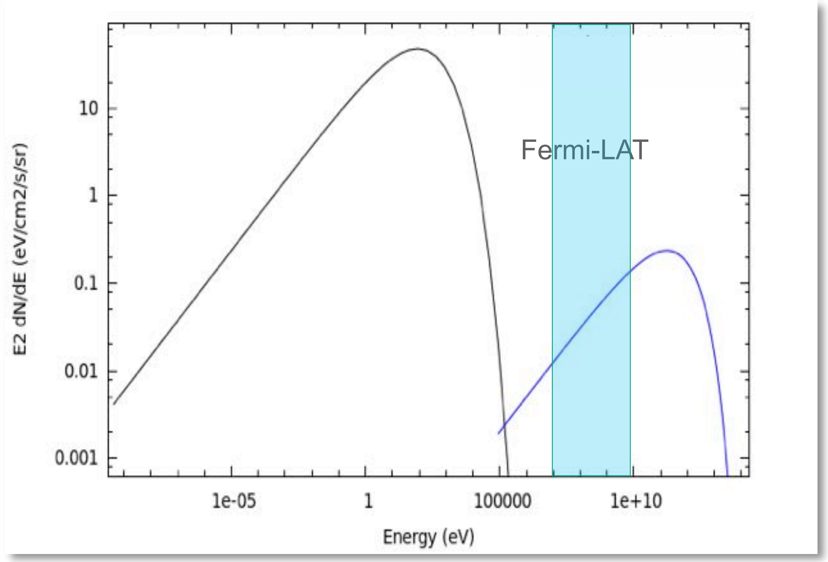

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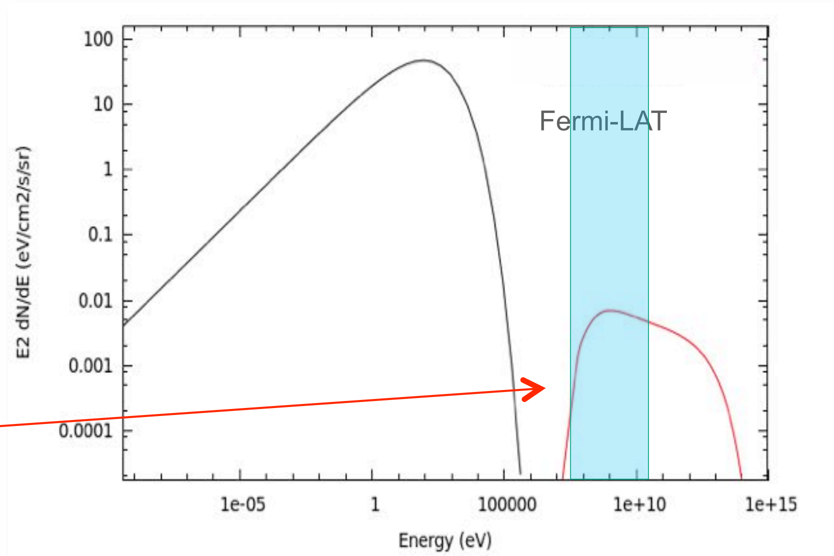
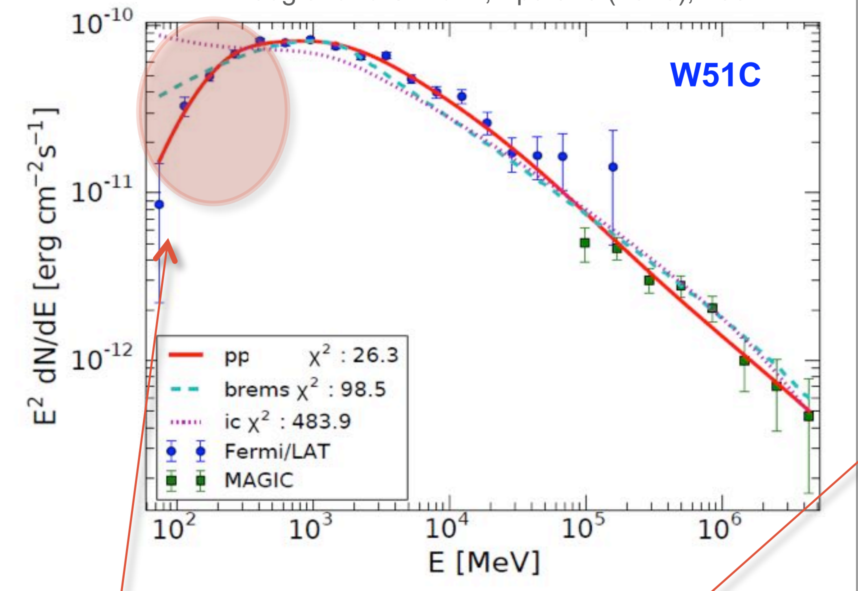
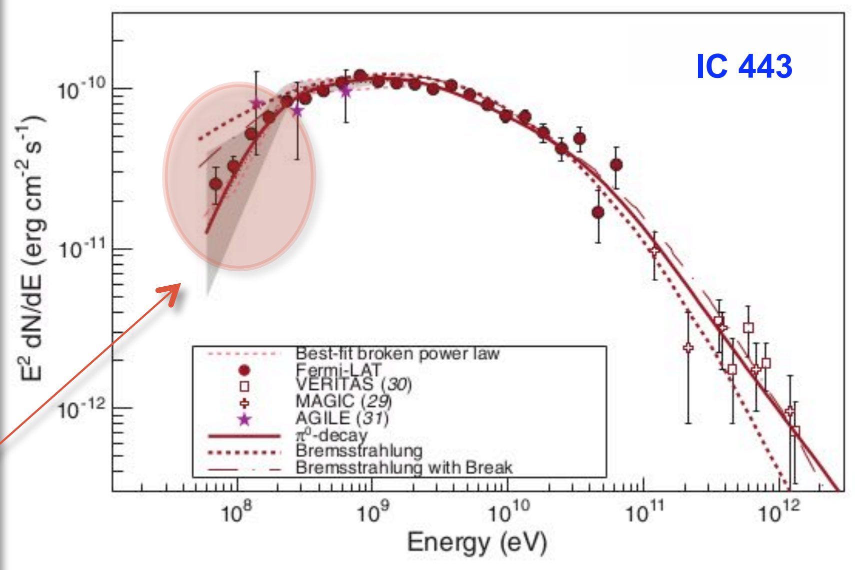


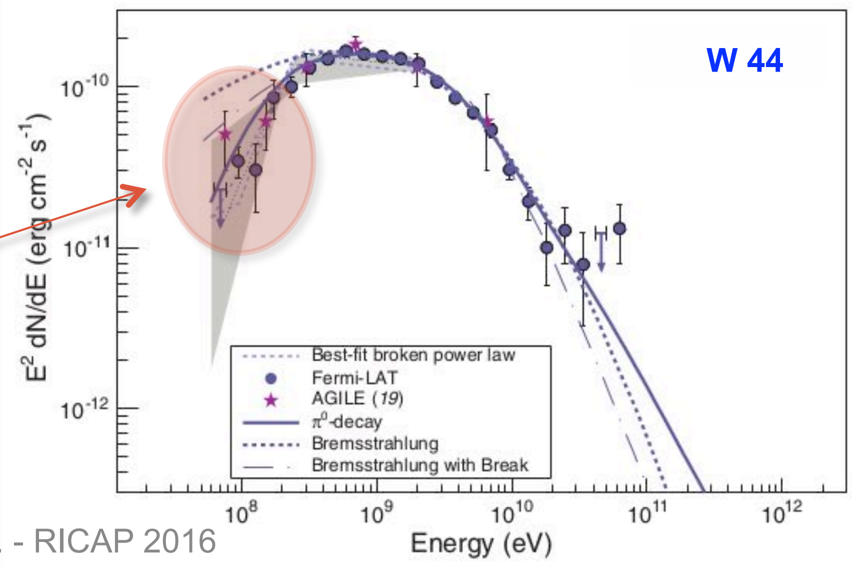
‘PION BUMP’ IN SNRS

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



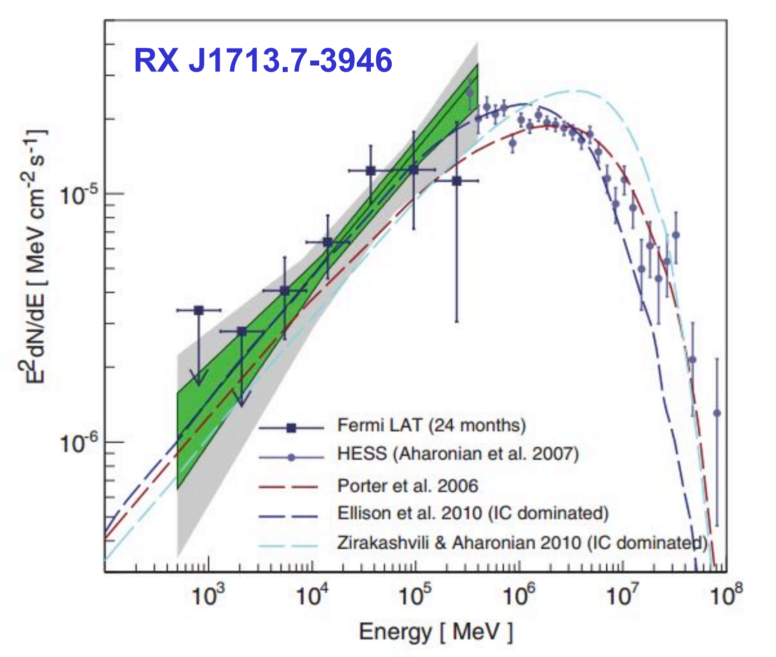
M. Ackermann et al., Science 339 (2013), 807



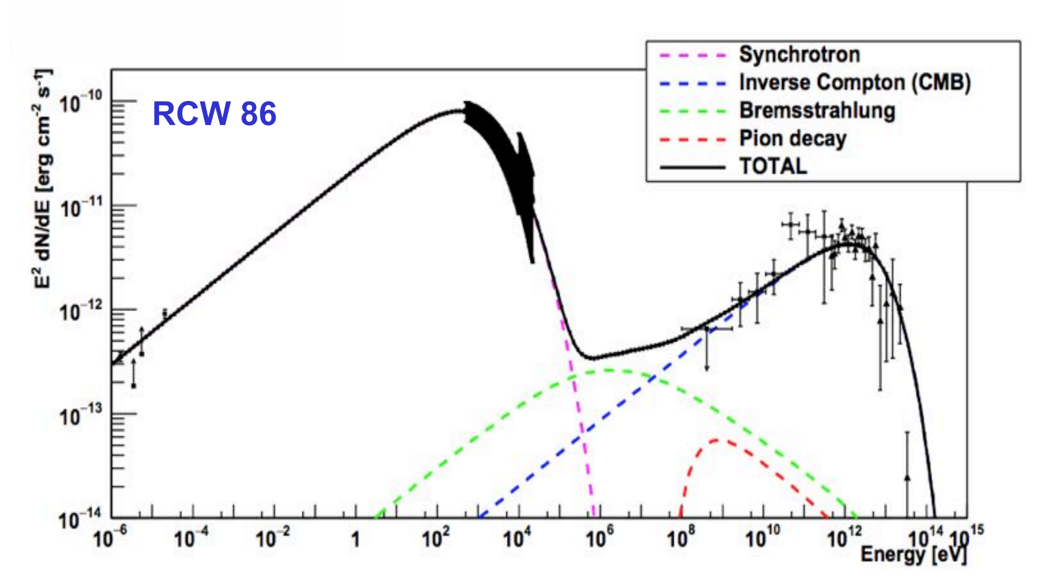


π^0–decay cut-off
‘smoking gun’ for
accelerated protons

Leptonic Scenario



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

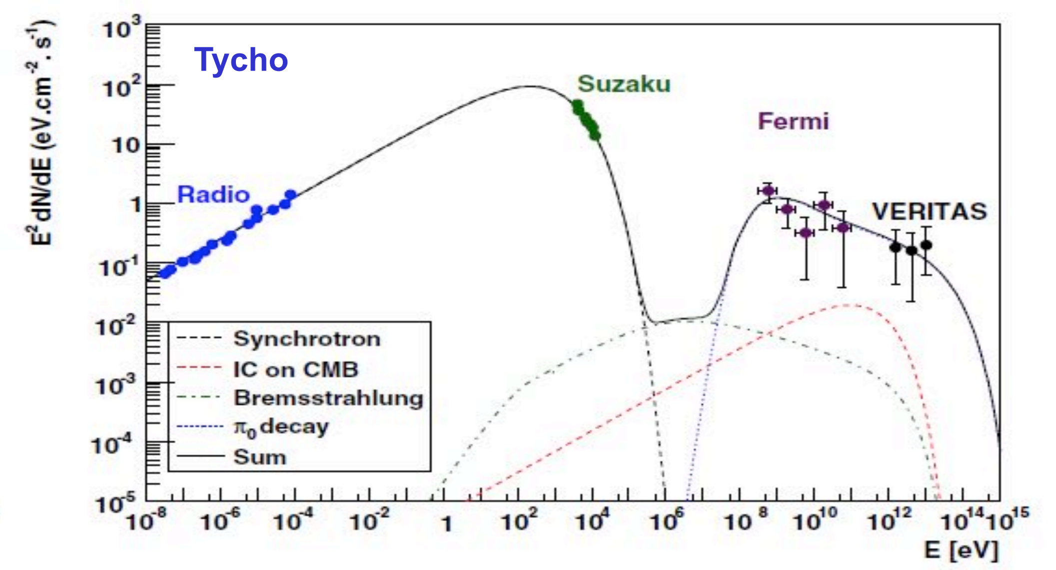


M. Ajello et al., ApJ 819 (2016) 98

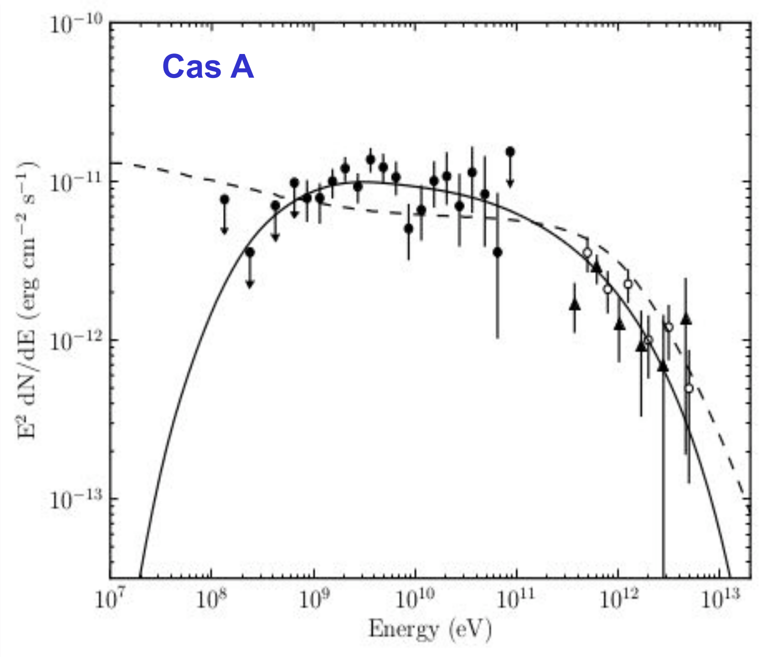
The γ-rays emission is due to the **IC scattering** of high energy leptons **on** local photon fields, namely only Cosmic Microwave Background (**CMB**).

The **absence of γ-rays from π^0-decay** does not rule out the possibility of an efficiently accelerated of CRs in this remnant, but **might be due to a low gas density** around the source.

Hadronic Scenario



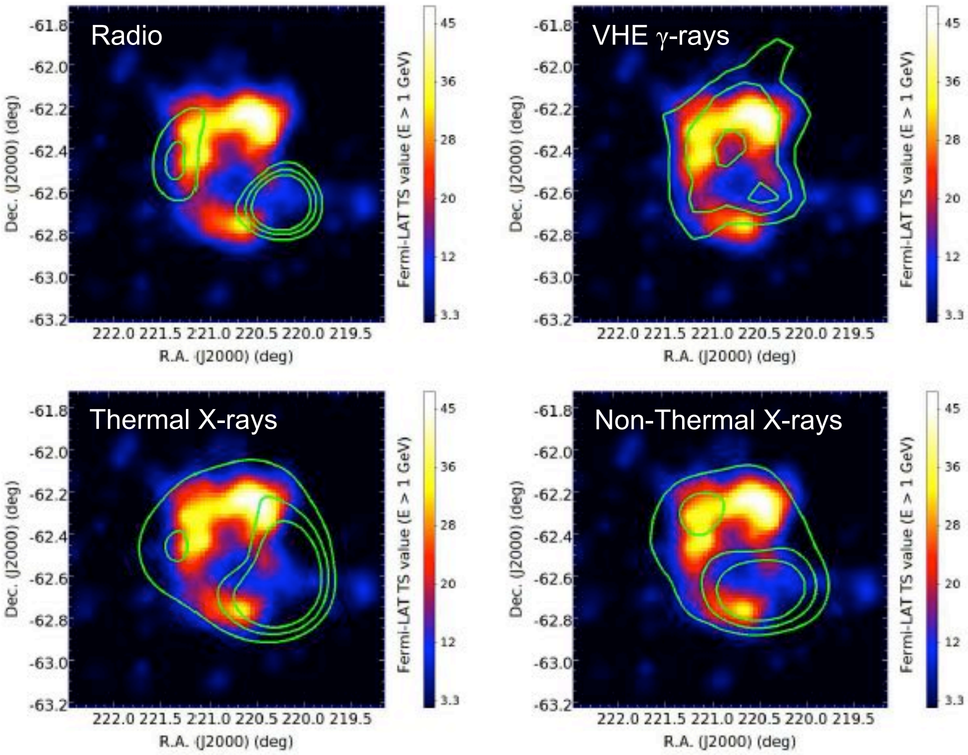
F. Giordano et al., ApJL 744 (2012) L2



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

The γ-rays spectrum seems to be compatible only with the **π^0-decay** produced in nuclear collisions between relativistic nuclei and the background gas.

Furthermore, multiwavelength modeling of **Tycho** SED (G. Morlino and D. Caprioli, Astron. Astrophys. (2012) 538, A81) infer a **maximum proton energy** around **500 TeV**, which is very **close to the *knee*** of the CR spectrum.



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

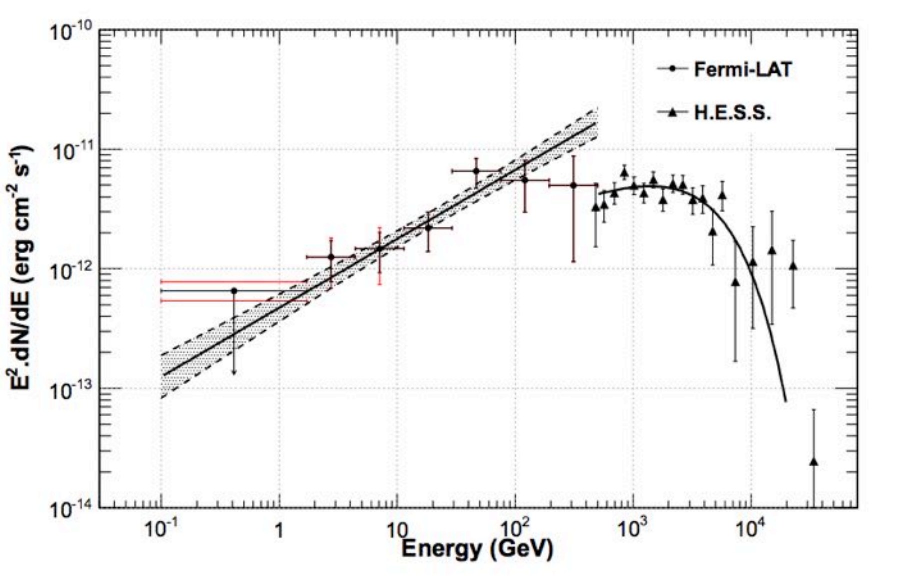
Leptonic interpretation:
constrain on the nearby gas density and the total energy injected in protons.

RCW 86

New SNR detected as extended: **radius ~ 0.37°±0.02**.

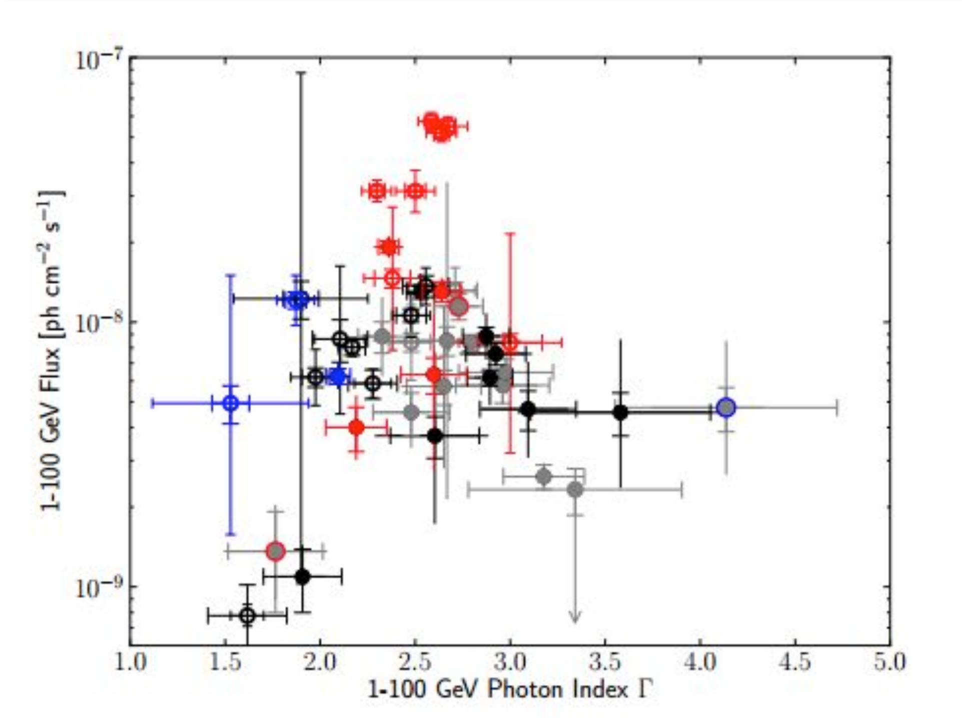
Best morphological photon distribution: **H.E.S.S. template**

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



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**



F. Acero et al., arXiv:1511.06778

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

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

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

MORE DETAILS IN F. DE PALMA'S TALK!

CONCLUSIONS

• **SNRs** are the most plausible candidates for **CR acceleration sites**;

• **NLDSA theory** predicts a spectrum for acceleration particles **spectrum steeper than E^{-2}**, compatible with the CR spectrum measured at Earth;

• ***Fermi*-LAT** is providing an unprecedented wealth of **detections and observations of γ-ray bright SNRs**, giving information on physical processes involving both accelerated leptons and hadrons;

• A **direct evidence of** γ-ray spectrum due to the **π^0-decay** has been found in three middle aged SNRs interacting with molecular clouds: **IC 443, W 44 and W 51C**.

• Thanks to the improvement of effective area, the point spread function and the energy resolution, **PASS 8** is a powerful tool to **identify and study extended SNRs**: for example **RCW 86**.

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

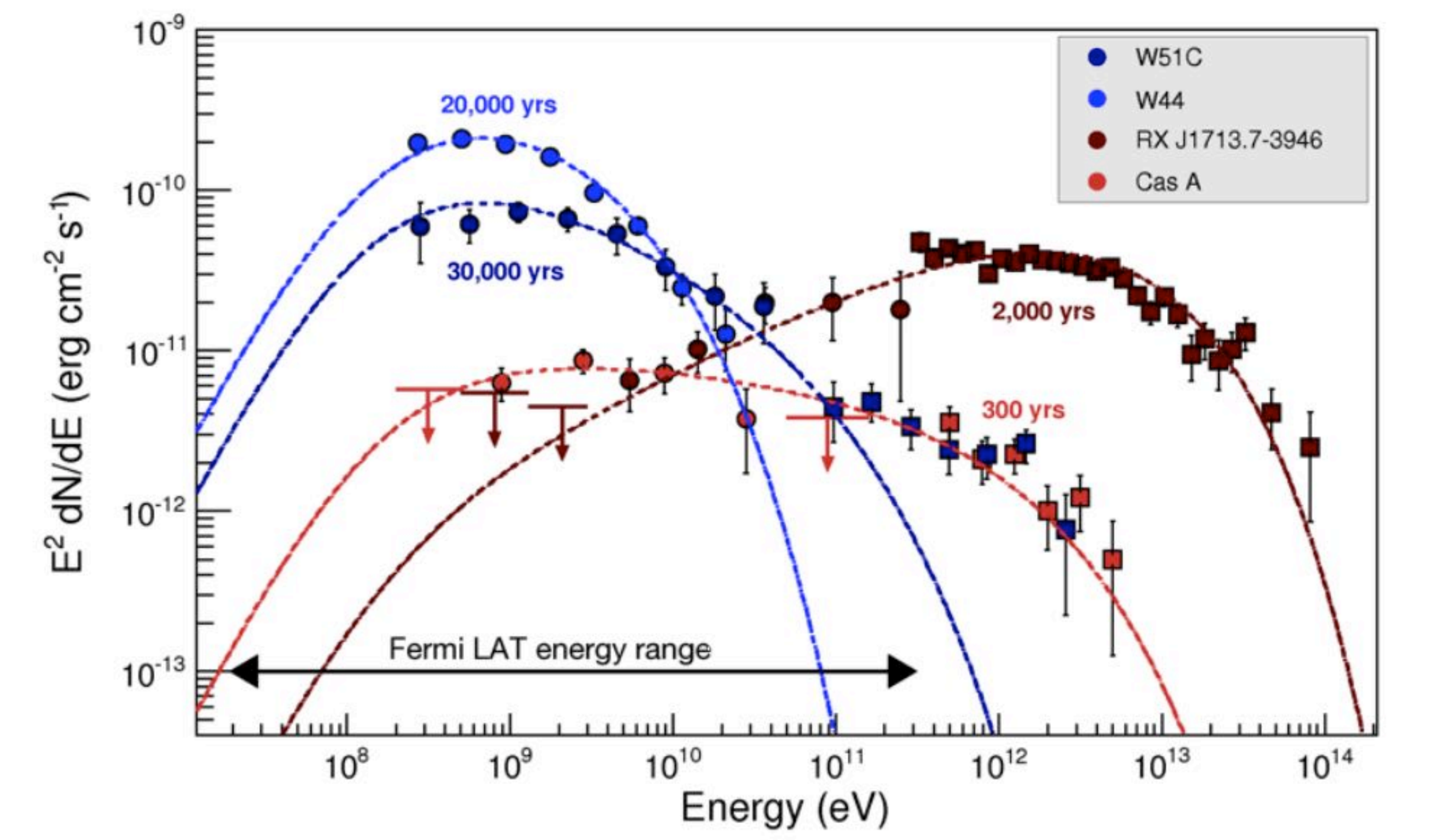
Tycho

- 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

COMPARING GAMMA-RAY SNRS



✓ Young SNRs have hard spectra, extend to ~ $10^{13\text{-}15}$ eV

✓ Older SNRs are brighter (due to large target) but show a clear break in their spectrum at ~ few GeV