Fermi-LAT highlights on Supernova Remnants

Leonardo Di Venere
Francesco de Palma

for the *Fermi*-LAT collaboration

University and INFN of Bari

Cosmic Ray Origin -
beyond the standard models
San Vito di Cadore
20th September 2016

Outline

- **Cosmic Rays and Supernova remnants**

- ***Fermi*-LAT detection of SNRs**
  - **Young SNRs**
  - **'Pion bump' observation**
  - **Morphology studies**

- **The first *Fermi*-LAT SNR Catalog**
  - **Analysis method and results**
  - **Multi-wavelength correlation (radio, TeV)**
  - **Constraining CR acceleration**

SNRs as sources of CRs

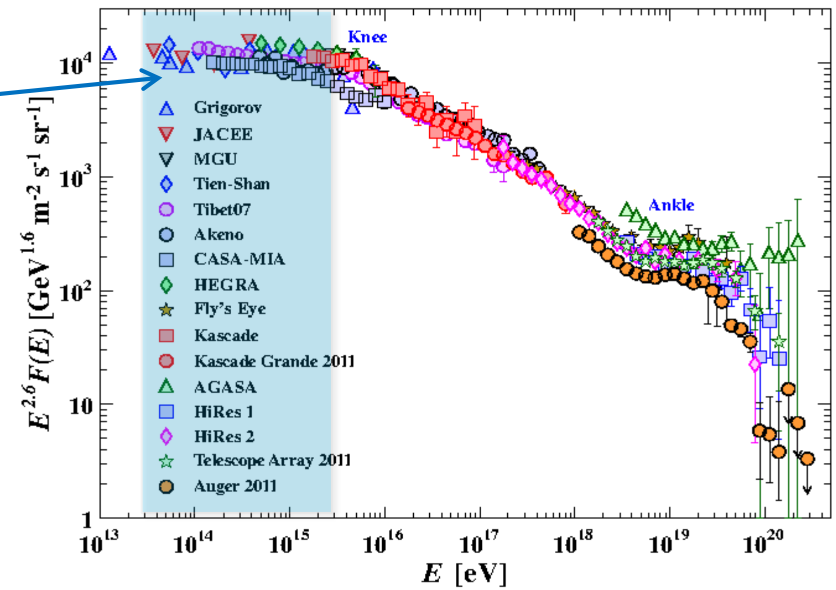
Galactic Cosmic ray spectrum

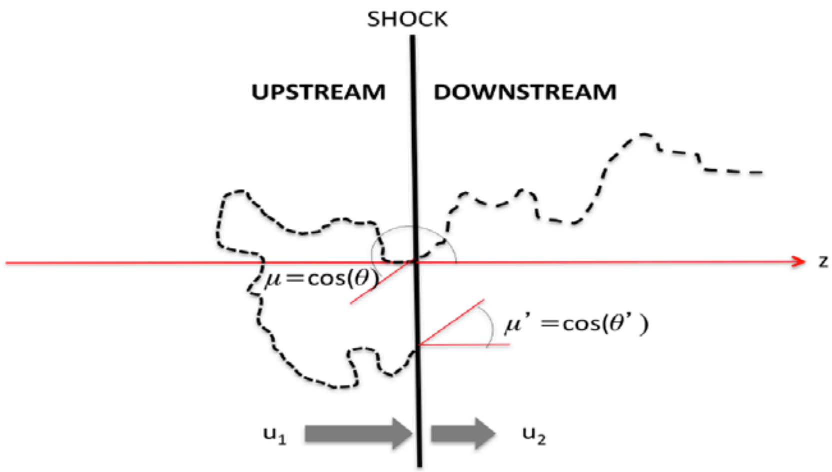
$$N(E) \propto E^{-2.7}$$

up to the 'knee': ≈10^{15} eV

From CR diffusion:

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

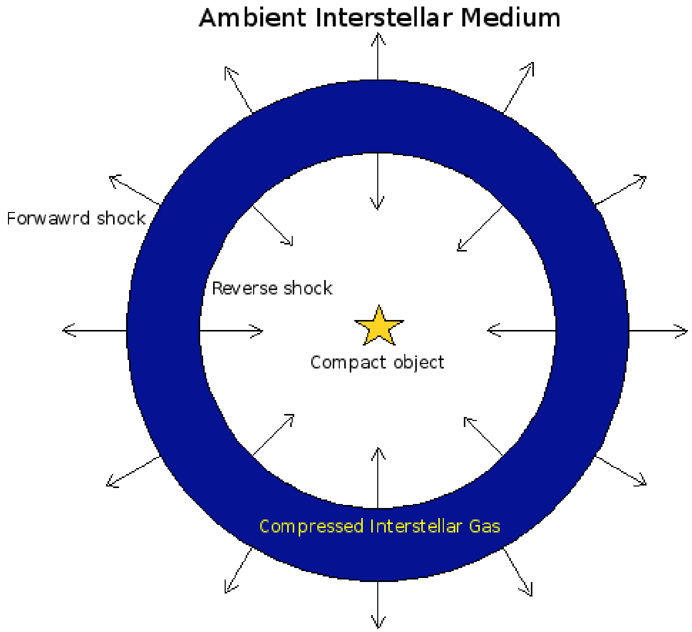


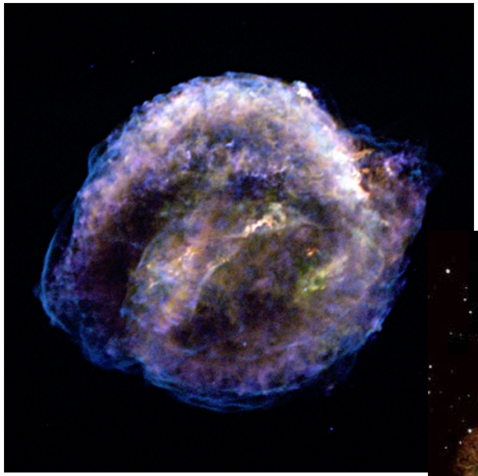


Diffusive Shock Acceleration

- Predicts $N(E) \propto E^{-q}$, with $q = 2$
- The required acceleration efficiency is not so small ⟶ dynamical reaction of accelerated particles on the shock ⟶ NLDSA
- Magnetic field amplification

Supernova Remnants





Kepler SNR

Crab Nebula

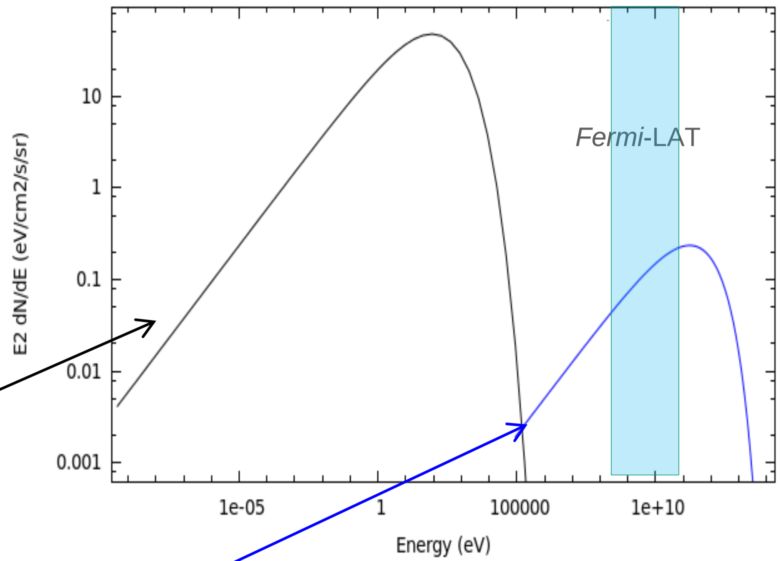
Energetics of SNRs

- 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 $\varepsilon \leq 10\%$

Spectral energy distribution (SED) of SNRs



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

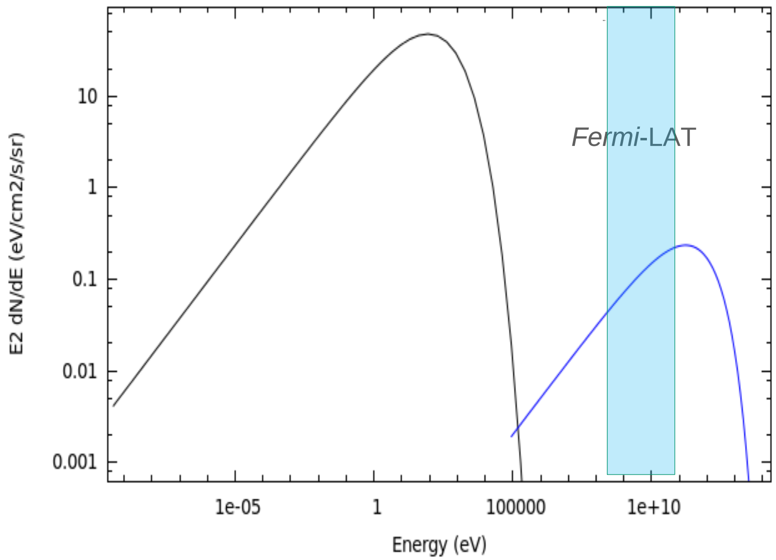
Radio to X-ray range
- Synchrotron peak

Three competitor processes for GeV-TeV energy range
- Inverse Compton
- Bremsstrahlung
- Pion decay

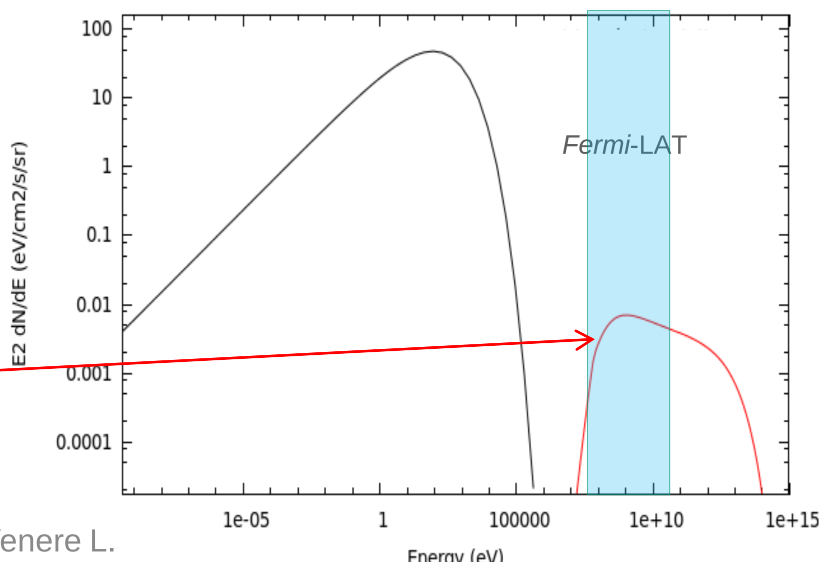
Spectral energy distribution (SED) of SNRs

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

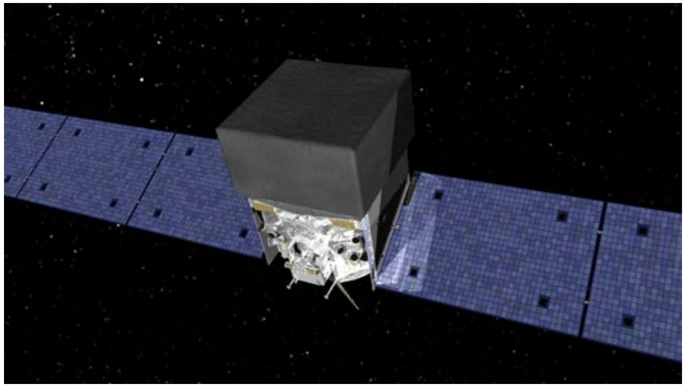
Radio to X-ray range
- <u>Synchrotron peak</u>

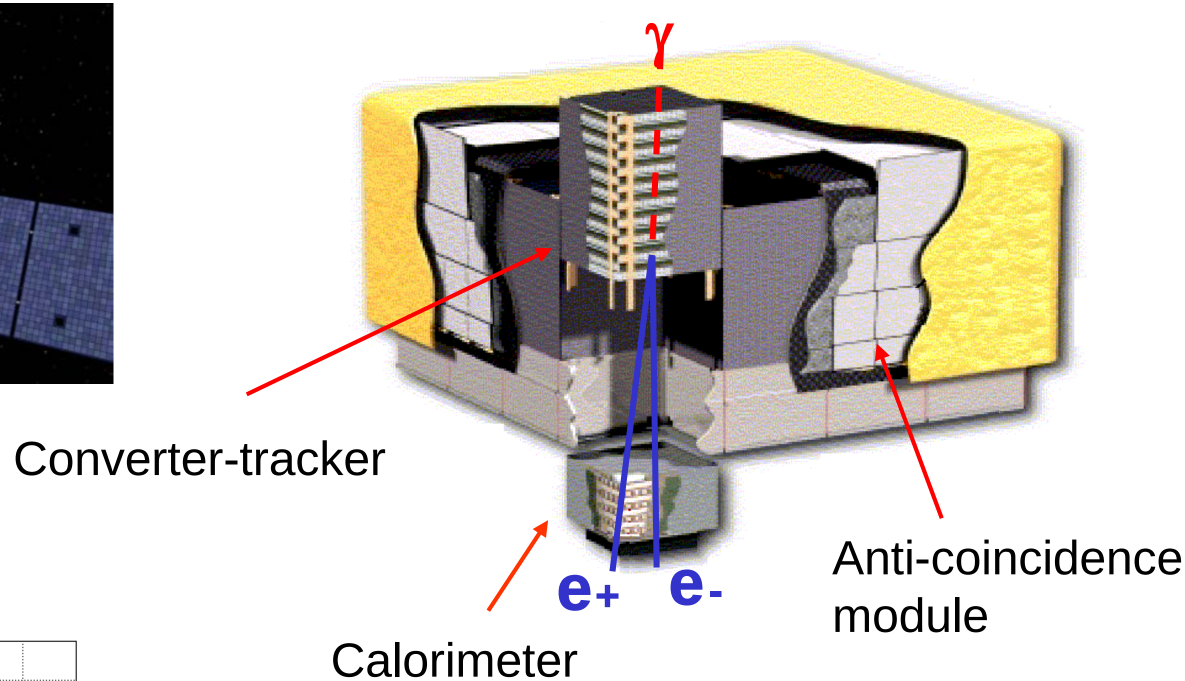


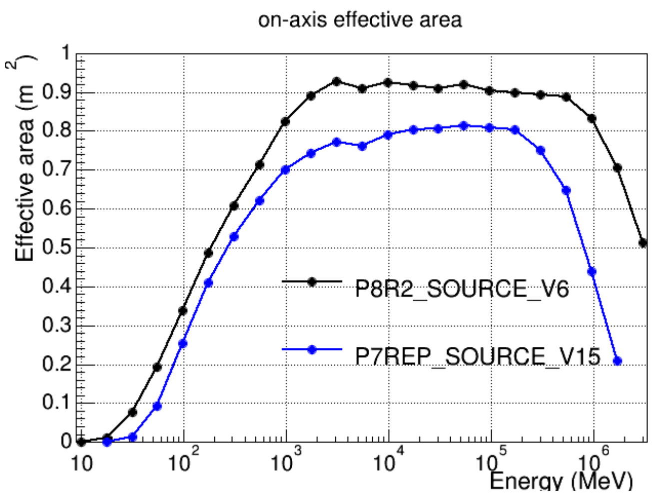
Three competitor processes for GeV-TeV energy range
- <u>Inverse Compton</u>
- <u>Bremsstrahlung</u>
- <u>Pion decay</u>



The *Fermi*-LAT experiment



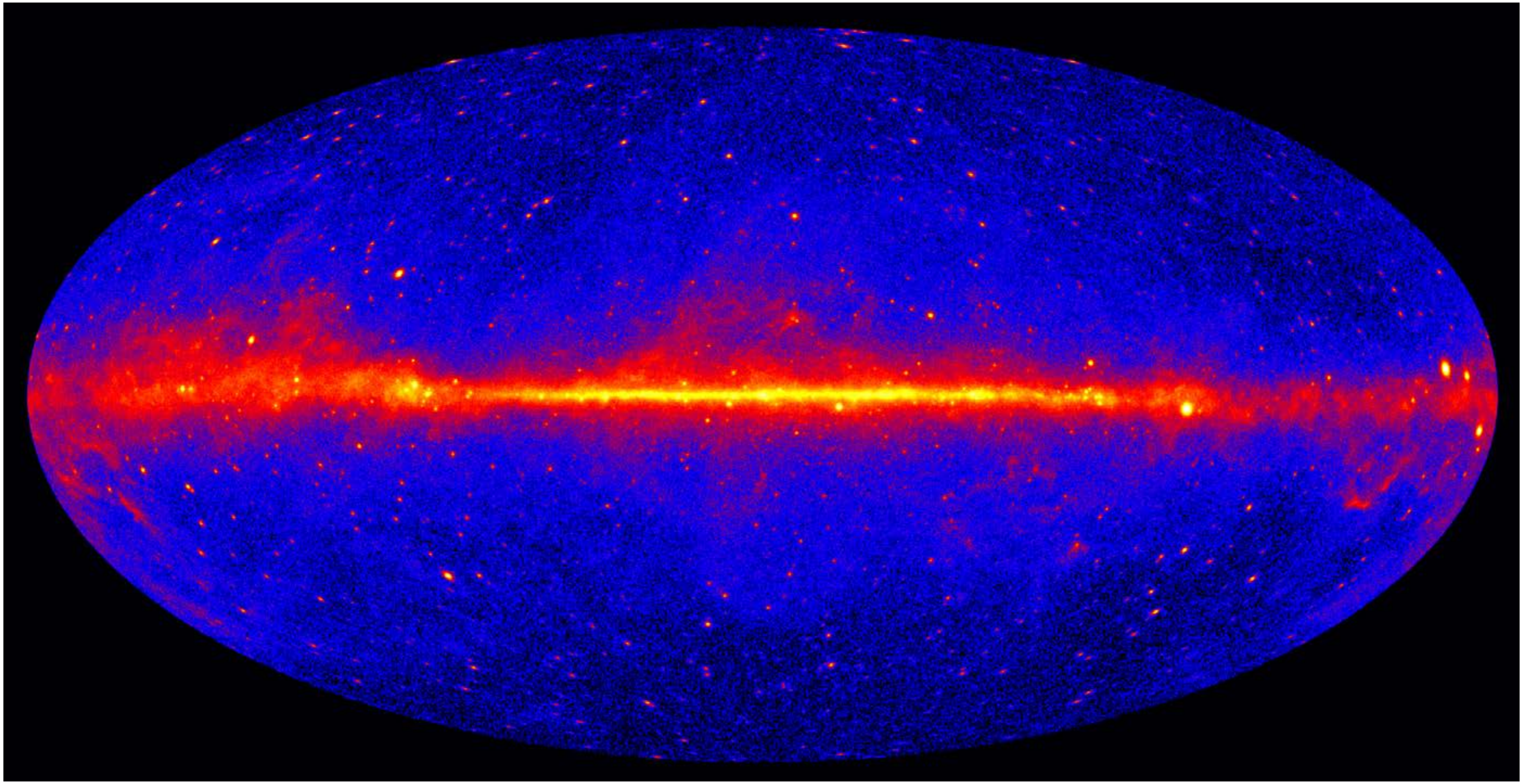




Pass 8 data release:

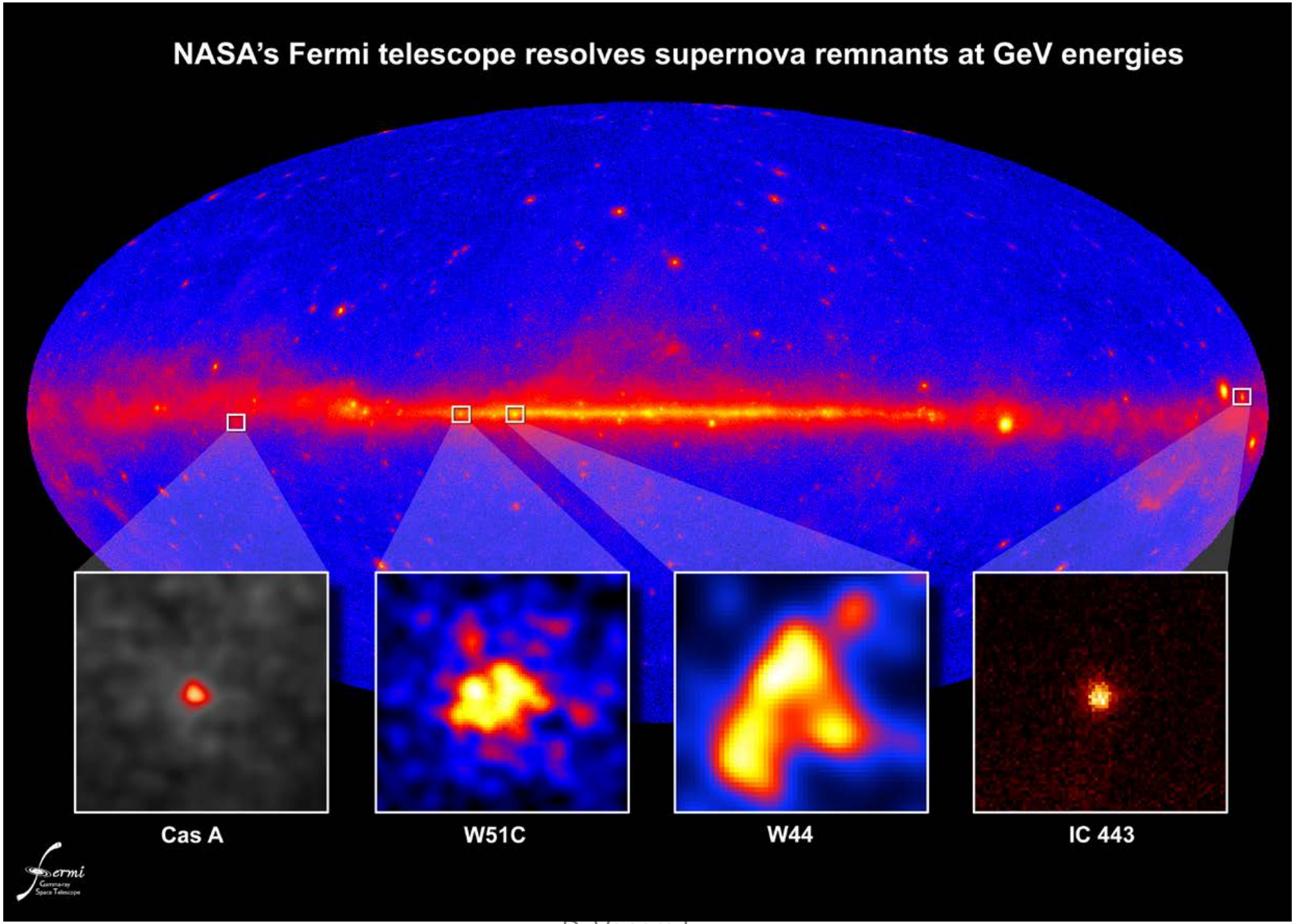
- Increased effective area
- Better Point Spread Function (PSF)
- Introduction of PSF and EDISP subclasses

Gamma-ray sky



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

Supernova Remnants



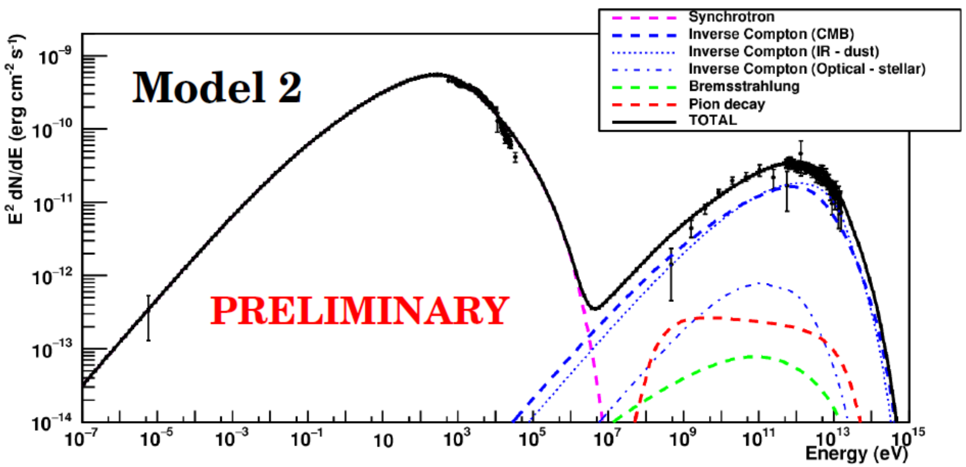
Young SNRs

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

→ Ideal targets to test the acceleration theory and look for 'Pevatrons'

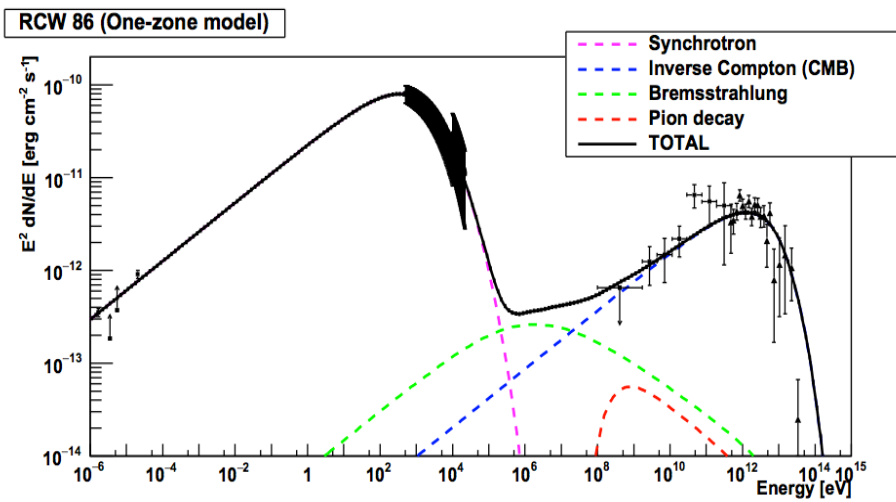
Leptonic scenario

RX J1713.7-3946



B. Condon et al. @ Gamma 2016

RCW 86

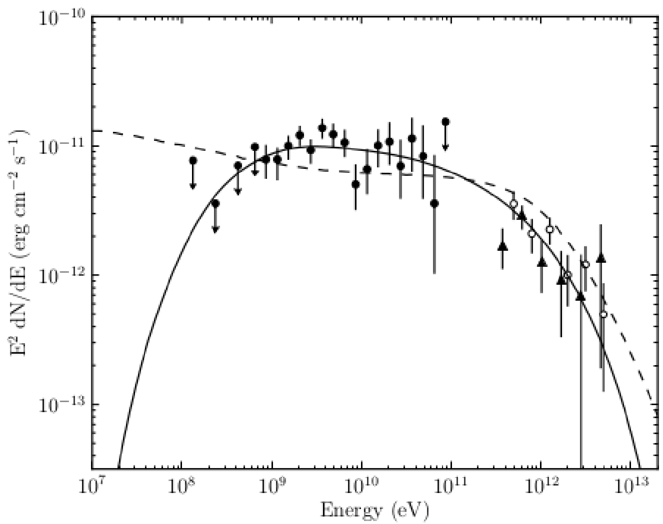


M. Ajello et al., ApJ 819 (2016) 98

γ-ray emission dominated by Inverse Compton

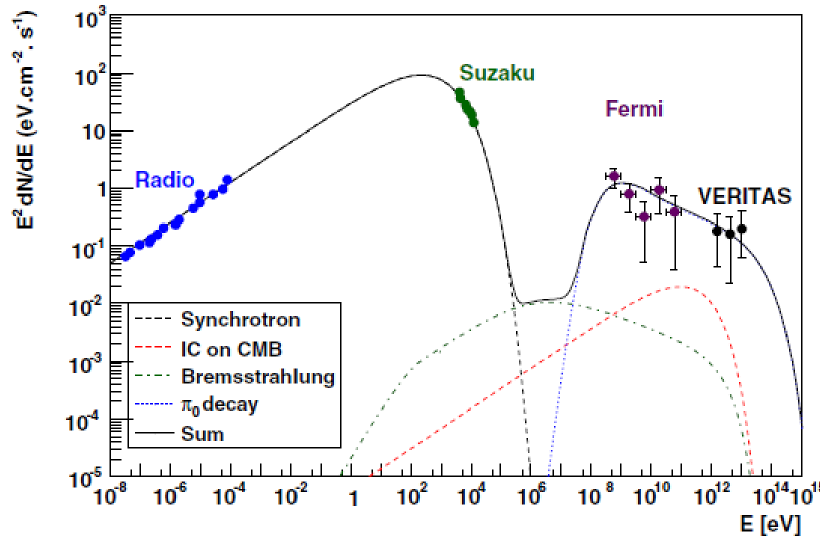
Hadronic scenario

Cassiopeia A



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

Tycho



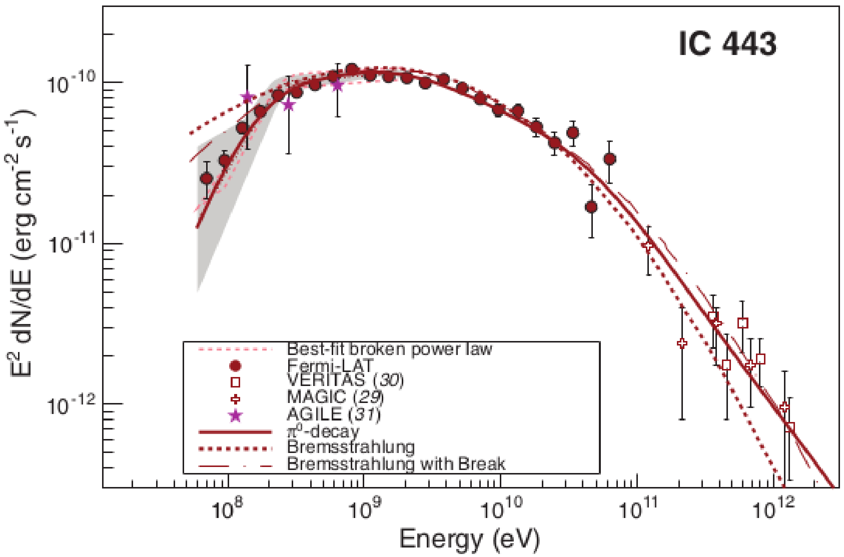
F. Giordano et al., ApJL 744 (2012) L2

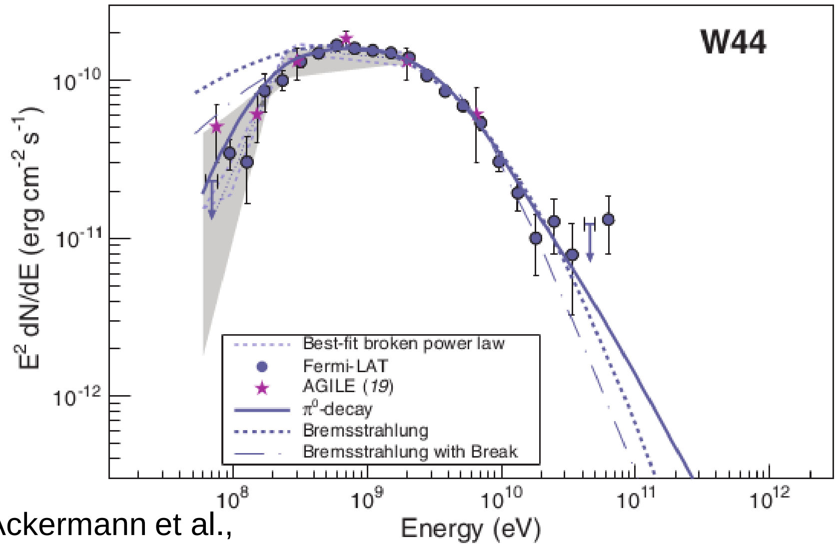
γ-ray emission dominated by pion decay

Presence of accelerated protons

‘Pion bump’ in SNRs

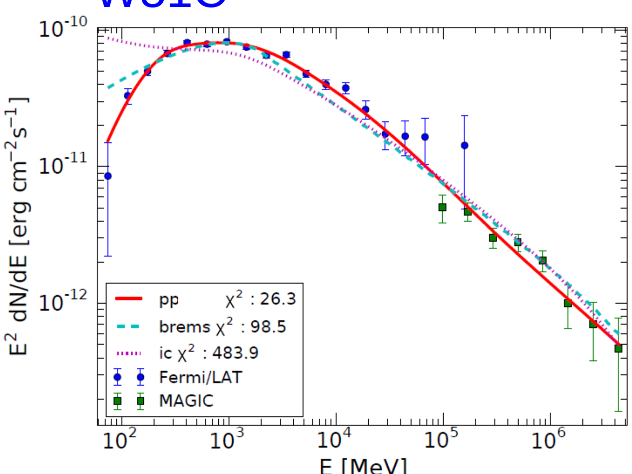
IC443 and W44





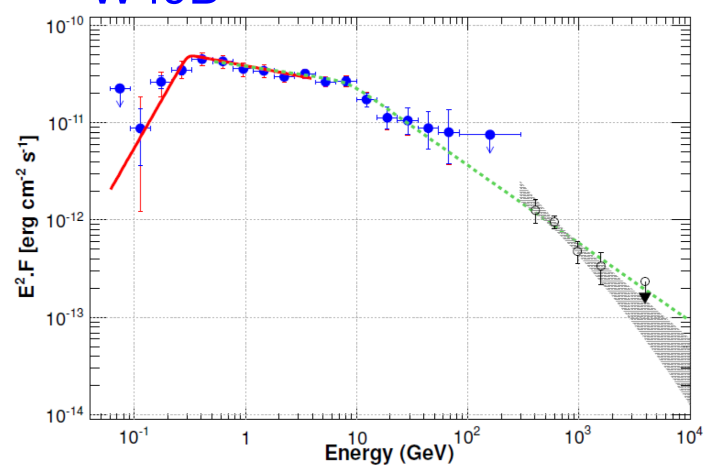
M. Ackermann et al., Science 339 (2013), 807.

W51C



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

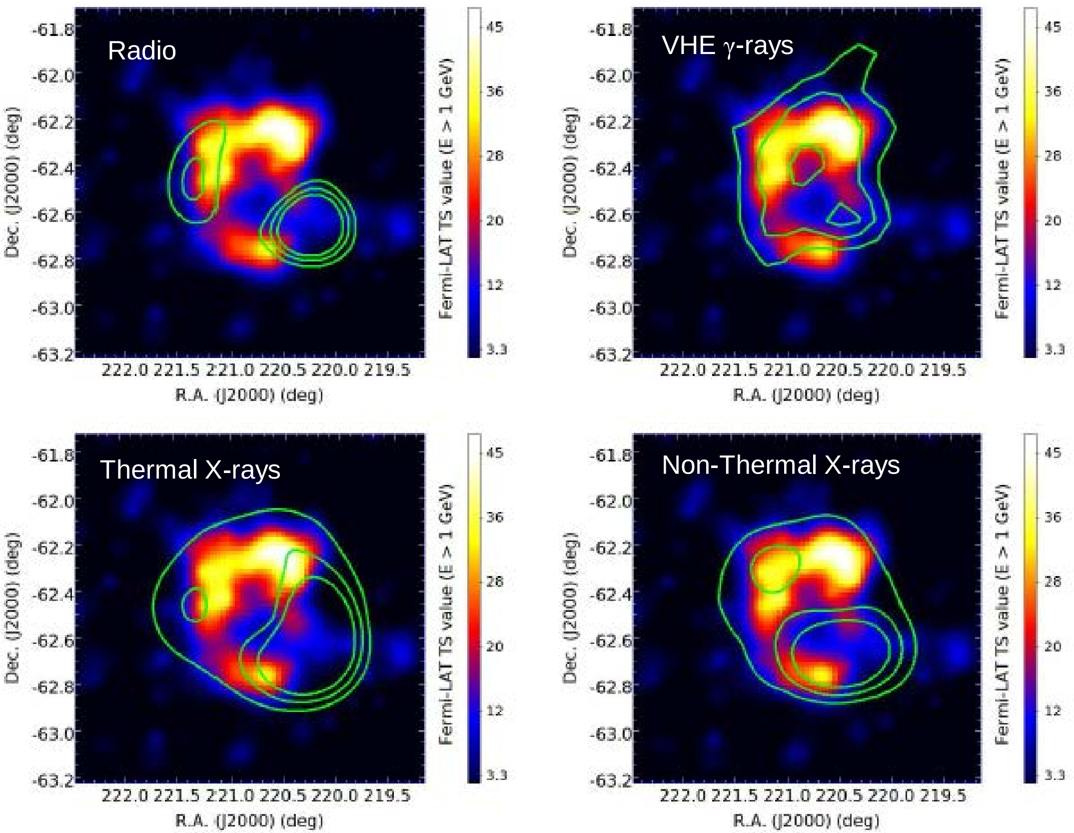
W49B



HESS + Fermi-LAT Accepted for publication in A&A

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))

Multi-zone analysis ongoing

RX J1713.7-3946
Preliminary results in
Condon et al @ Gamma 2016

IC 443
Preliminary results in
Hewitt @ Fermi Symposium 2015

1st Supernova Remnant Catalog

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

Data Set
- 3 years of P7SOURCE_V6 LAT data
- Remove variable sources (FAVA catalog)
- E: 1-100 GeV
- 10° around each SNR

SNRs
- 274 (Green's Catalog 2009) +5

Background model
- Add source method.
- 2nd *Fermi*-LAT source Catalog
- 2nd *Fermi*-LAT pulsar Catalog
- Standard IEM.

Systematic Error evaluation
- Alternative interstellar emission models (IEMs)
- Effective area

Hypotheses Tested
- Spectral models: Power Law or Log Parabola
- Extension: Point, disk and disk removing some nearby sources.

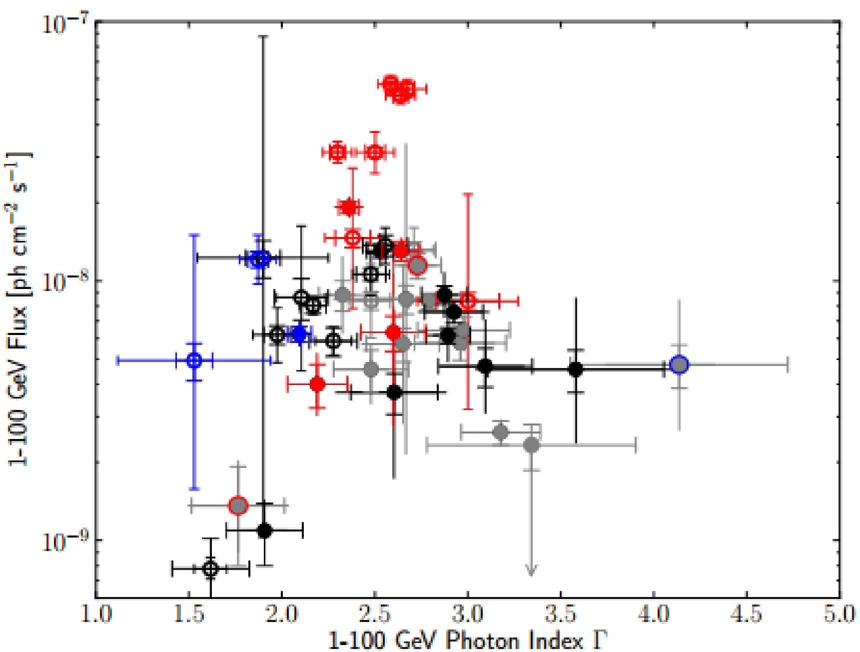
Fit
- Localization and extension
- Spectral parameters (SNRs and background sources)

Output
- Source significance
- Best position, extension, and spectral model
- Or flux upper limits at radio position

Classification
- Spatial coincidence
- Mock Catalog

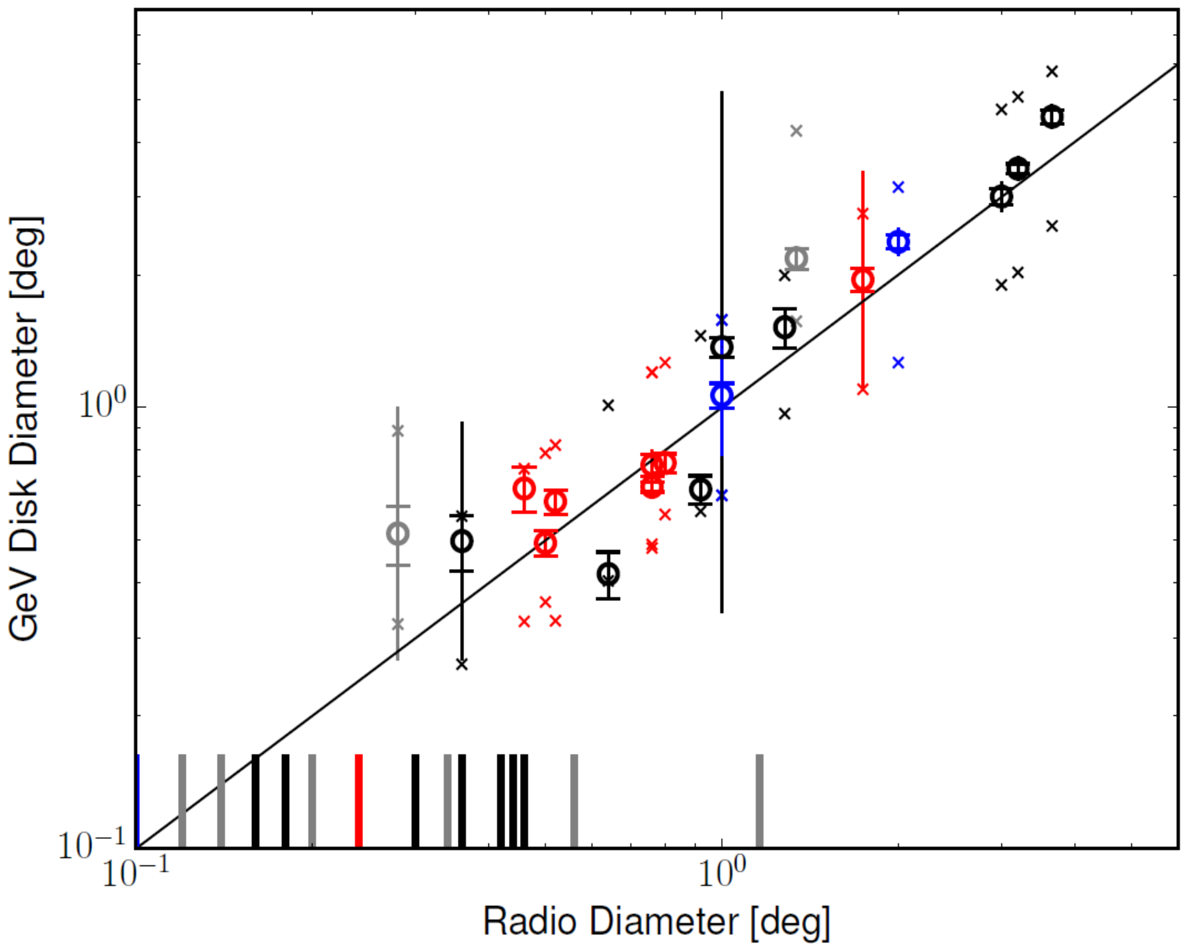
SNR Catalog results

- 36 SNR candidates with spatial association with radio counterparts
  - 17 extended sources: 4 new
  - 13 point-like sources: 10 new
  - 2 are flagged for IEMs systematics
  - 4 identified as other sources (Crab, binary, and PWN/PSR)
  - 14 marginally classified



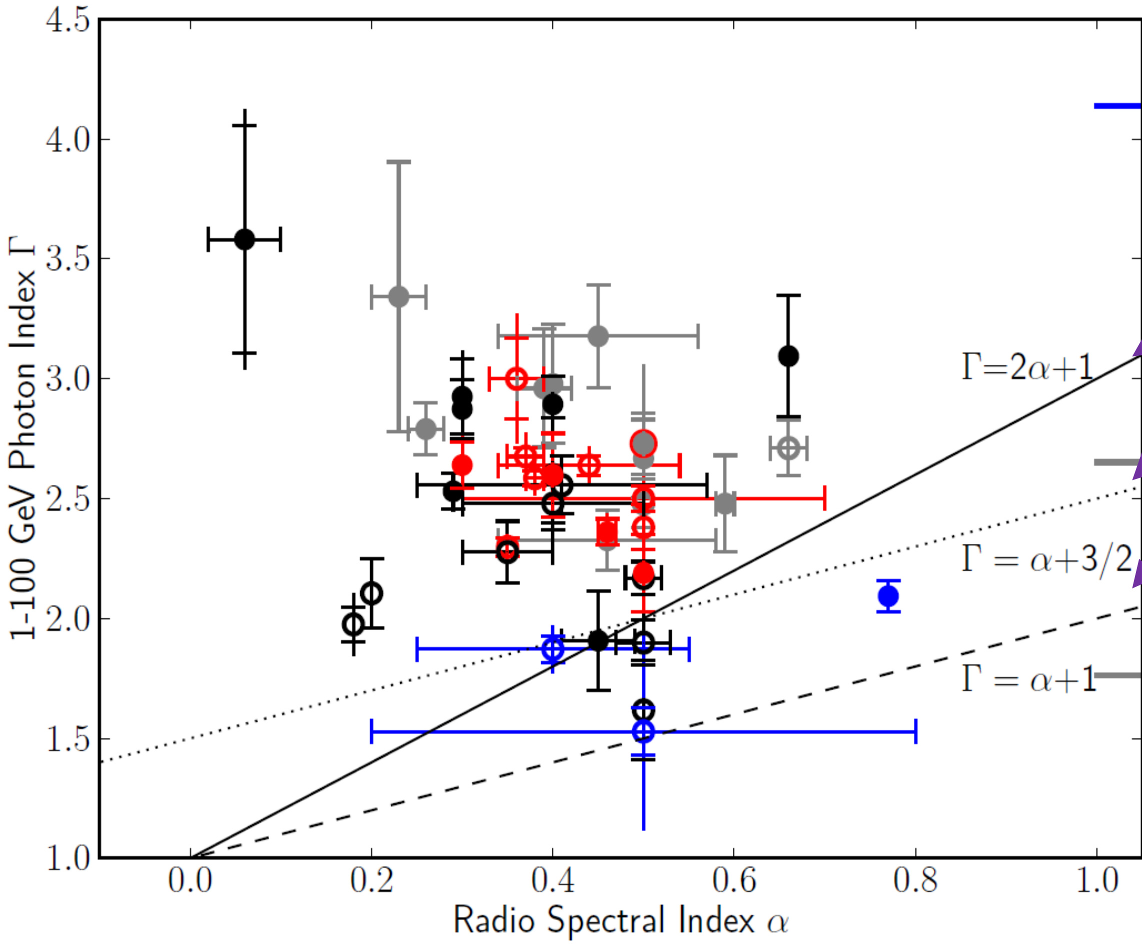
- Interacting SNRs (density ≥ 100 cm^{-3})
- Young SNRs (non-thermal X-ray emission)
- Classified candidates
- Marginal candidates
- Point-like sources
- Extended sources

Radio-GeV Diameter



- Interacting SNRs
- Young SNRs
- Classified candidates
- Marginal candidates
- X Min and max extension of the source needed to remain in the same class.

Radio-GeV Index

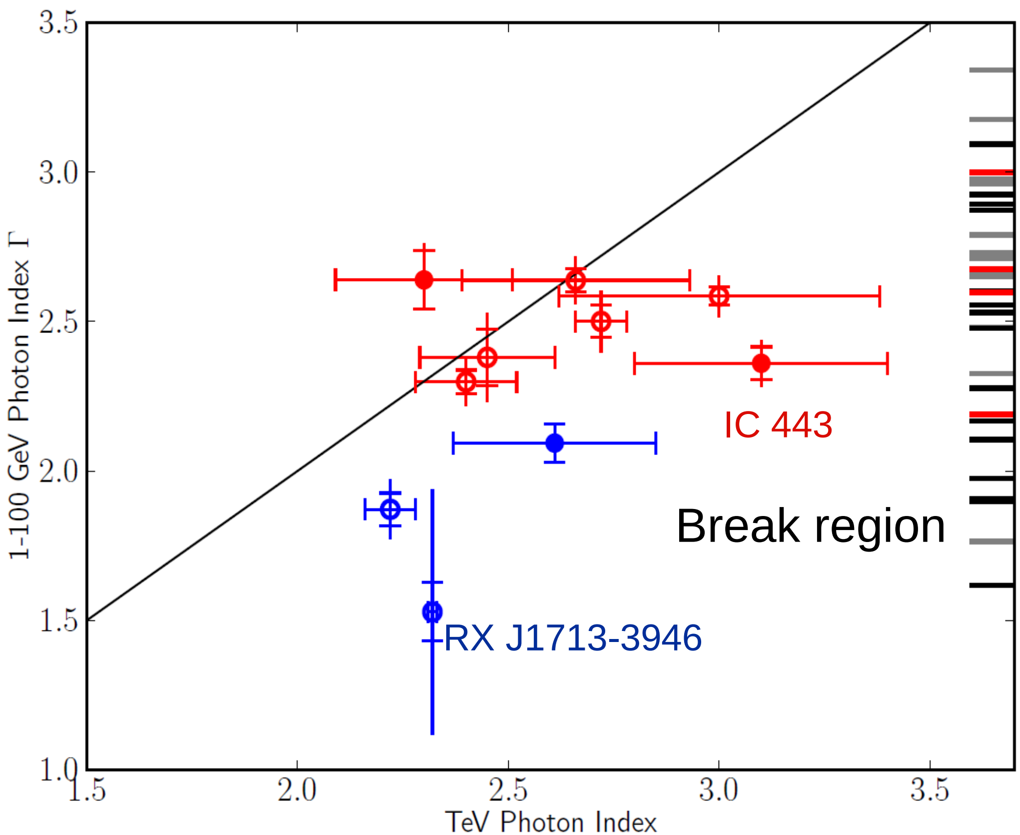


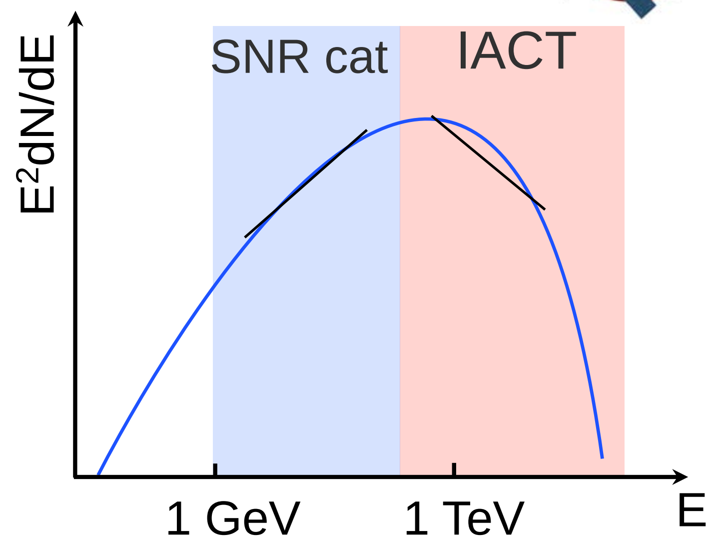
- Young SNRs: seem consistent
- Others, including interacting SNRs: softer than expected
  - π^0 decay or $e^{+/-}$ brem.
  - Inverse Compton w cooling
  - inverse Compton w/o cooling

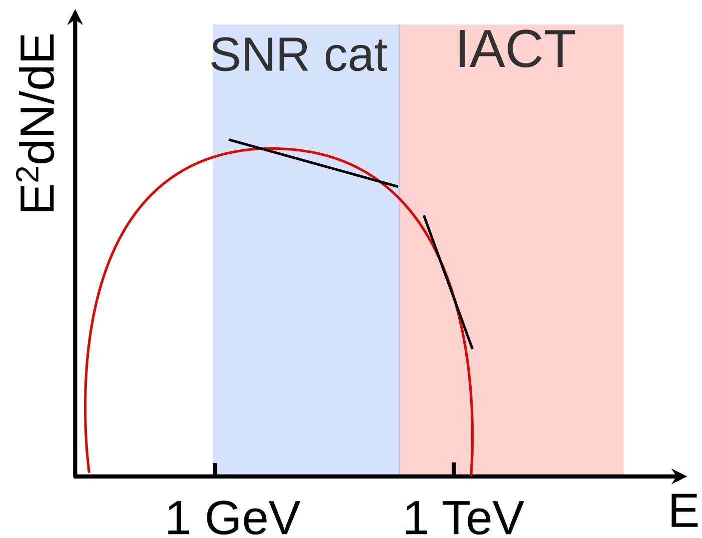
- Emitting particle populations may not follow a power law: breaks?
- Multiple emission zones?

Pass 8 can help!

GeV-TeV Index







- Indication of break at TeV energies
- Caveat: TeV sources are not uniformly surveyed.

Environment?

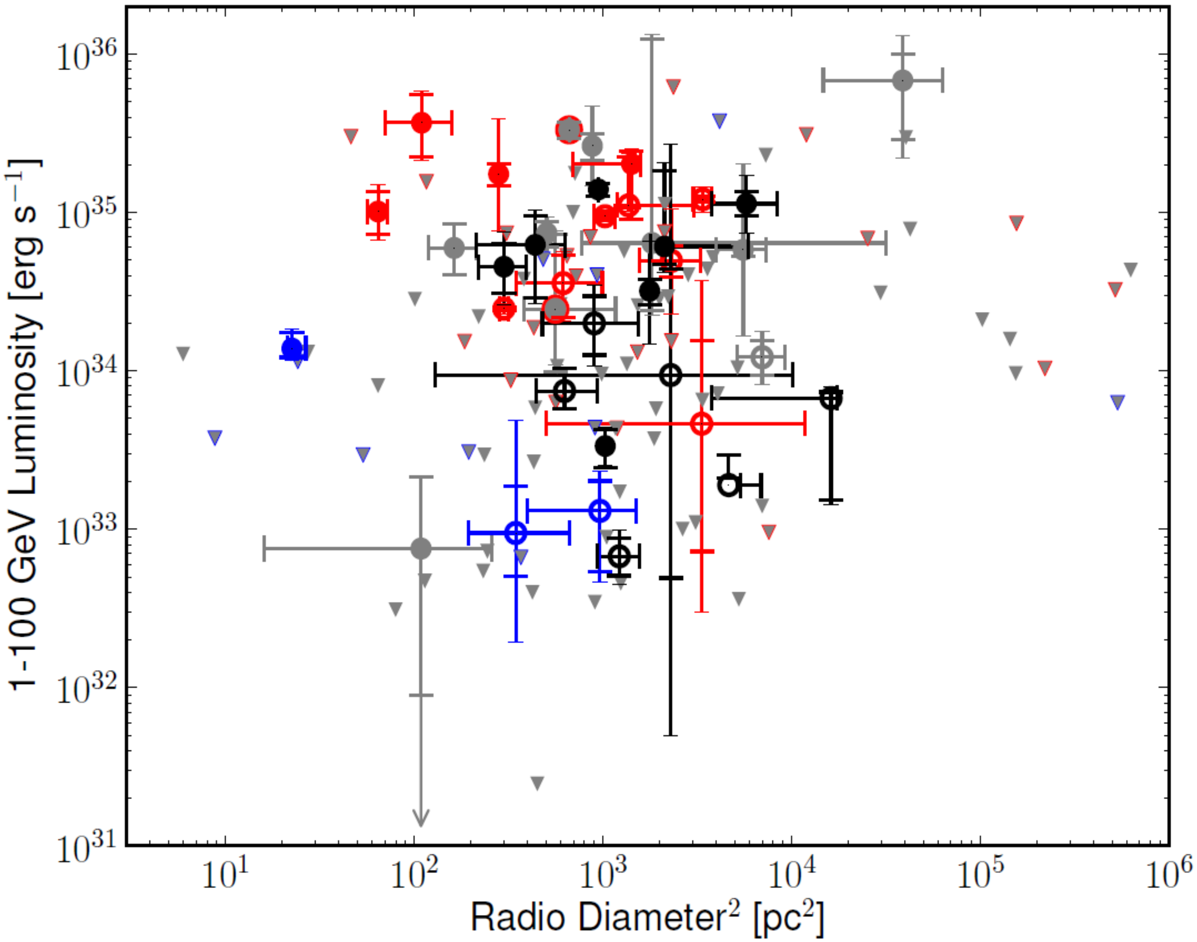
No clear trend though both axes are proportional to distance^2. Some separation between classes, diminishing as we find more, fainter candidates.

Young SNRs:

- Low $L_\gamma \rightarrow$ evolving into low density medium?

Interacting SNRs:

- Higher $L_\gamma \rightarrow$ encountering higher densities?



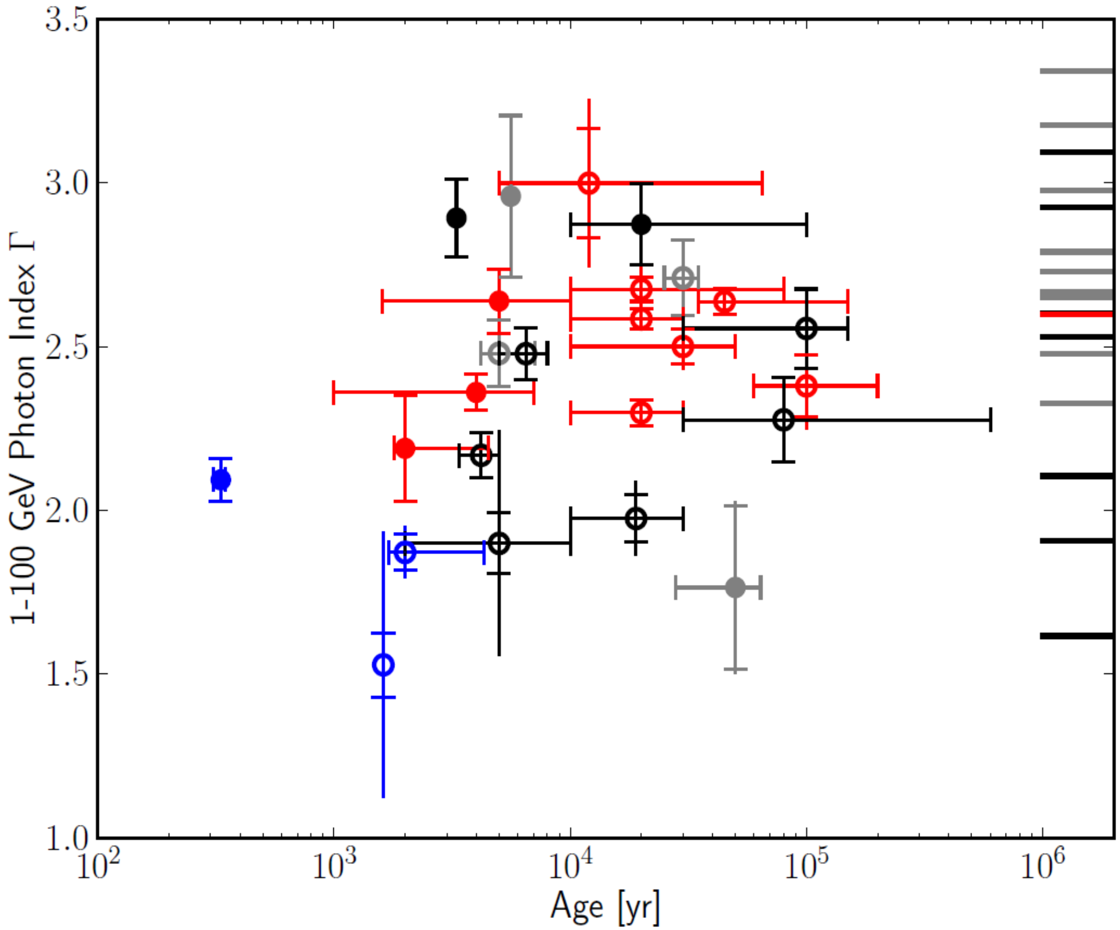
Or Evolution?

Young SNRs tend to be harder than older, interacting SNRs.

GeV index evolves with time: apparent increase for older remnants

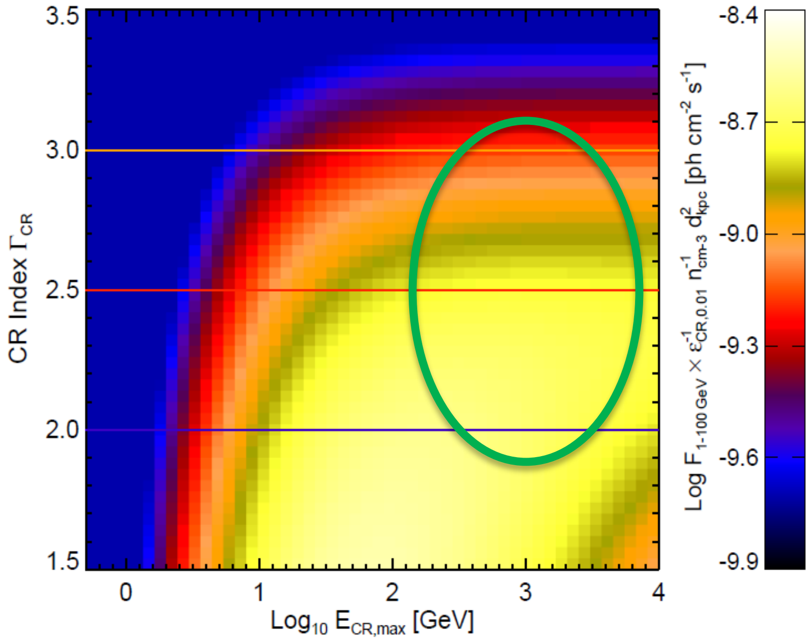
May be due to a combination of:

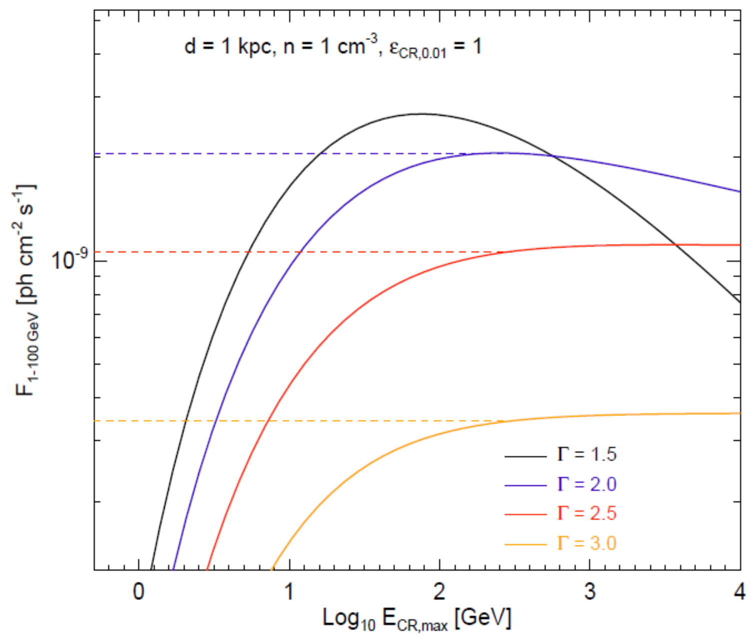
- decreasing shock speed allowing greater particle escape?
- decreasing maximum acceleration energy with SNR age?



Constraining CR emission

Assume that the whole gamma ray emission arises from the interaction of CR with the ISM.



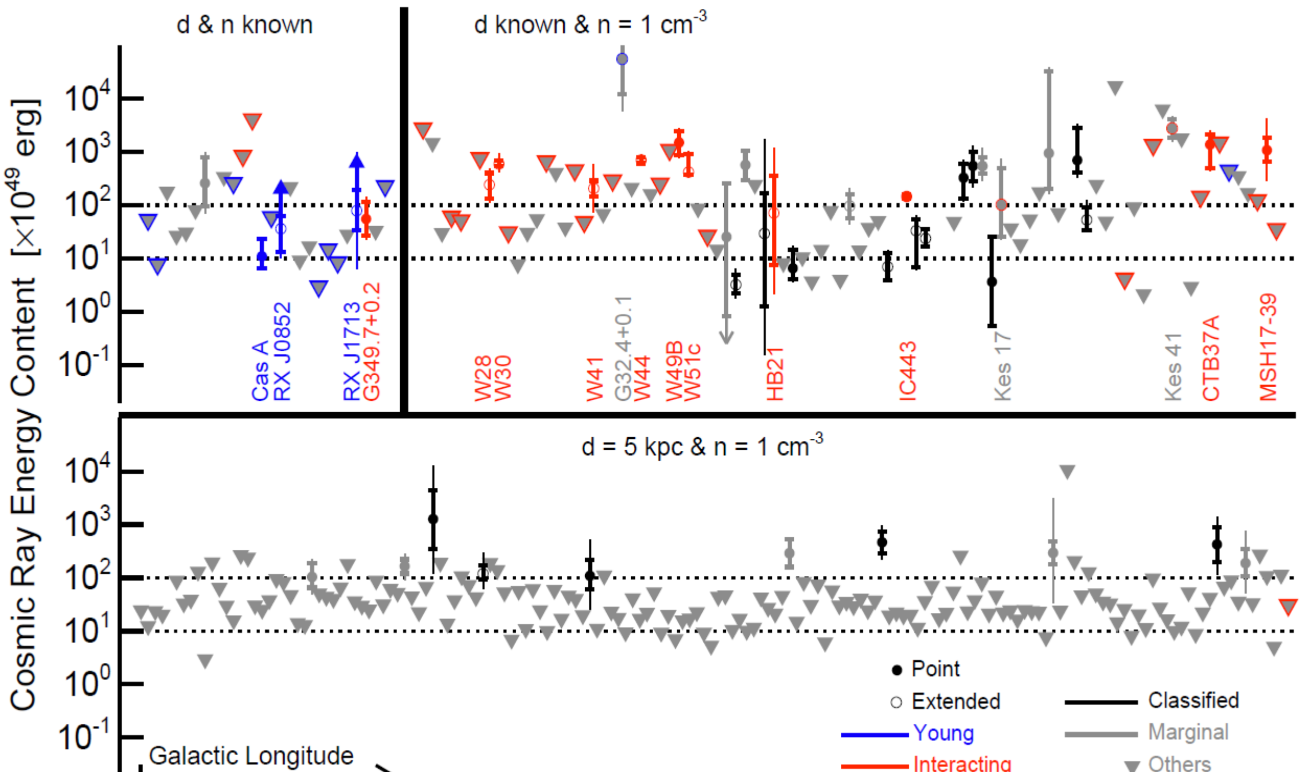


$$F(1-100\,\mathrm{GeV}) \approx f(\Gamma_{\mathrm{CR}}) \times \frac{\epsilon_{\mathrm{CR}}}{0.01} \times \frac{E_{\mathrm{SN}}}{10^{51}\,\mathrm{erg}} \times \frac{n}{1\,\mathrm{cm}^{-3}} \times \left(\frac{d}{1\,\mathrm{kpc}}\right)^{-2} \times 10^{-9}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$$

Constraining CRs from detections and ULs

The estimates and upper limits on the CR energy content span more than three orders of magnitude, from a few 10^{49} erg to several 10^{52} erg.

- SNRs above the $\epsilon_{CR} = 1$ ($E_{CR} = E_{SN} = 10^{51}$ erg) → higher density than derived from X-ray or assumed → interacting SNRs are in dense environment.
- Young SNRs $\epsilon_{CR} \sim 0.1$ → IC processes may contribute to their measured luminosity.



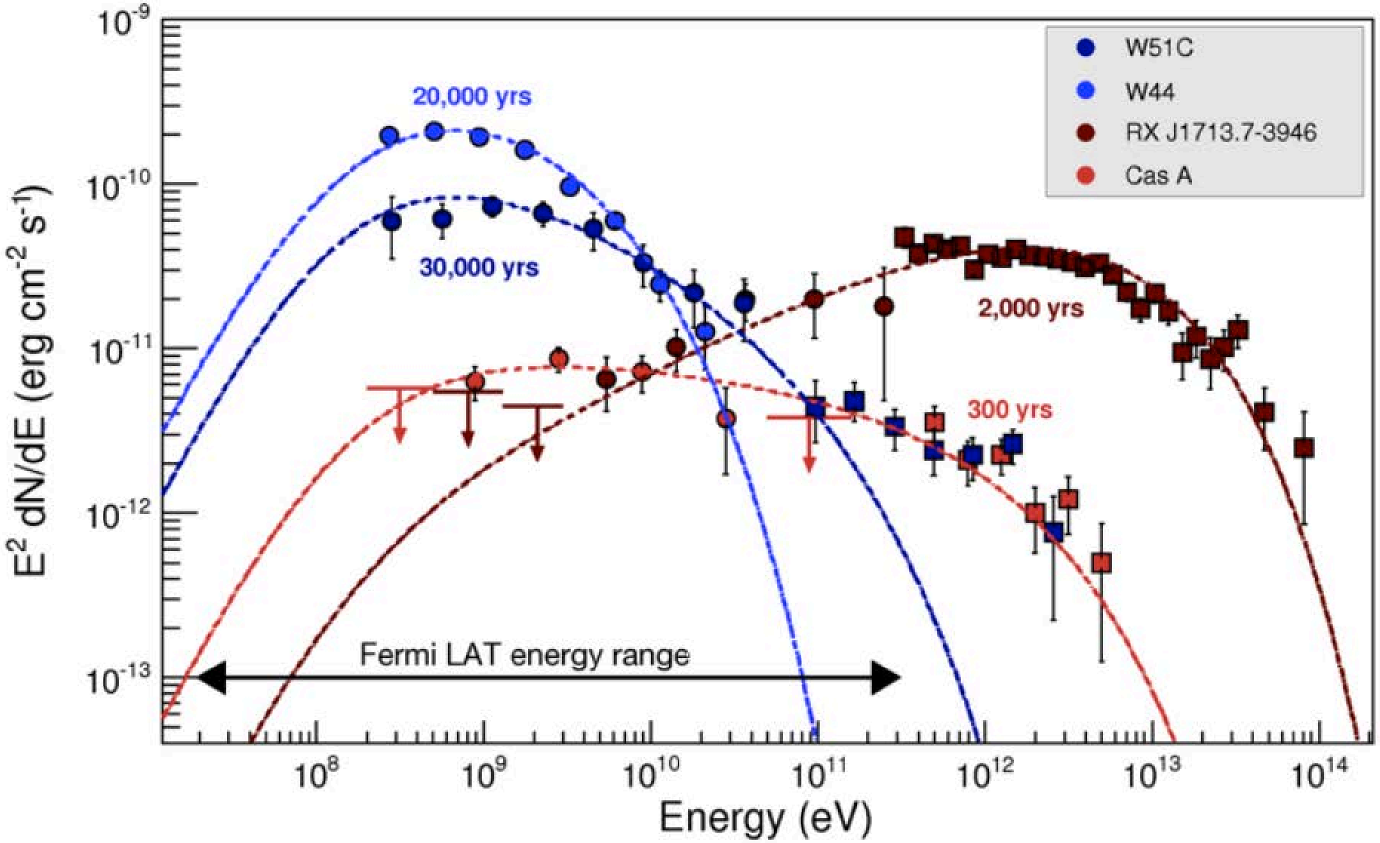
Conclusions

- 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 evidence of accelerated CRs in SNRs
- Young SNRs are very interesting targets to test the acceleration theory
- Pass 8 improvements are allowing spatial extension studies, to compare γ-ray emissions with other wavelengths
- The first SNR catalog suggested possible correlations from MW observations:
  - changes in spectral slope at or near TeV energies (sample limited)
  - a softening and brightening in the GeV range with age
  - simple model assumptions are no longer sufficient

Stay tuned!

Backup

Comparing Gamma-Ray SNRs



- Young SNRs have hard spectra, extend to ~ 10^{13-15} 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

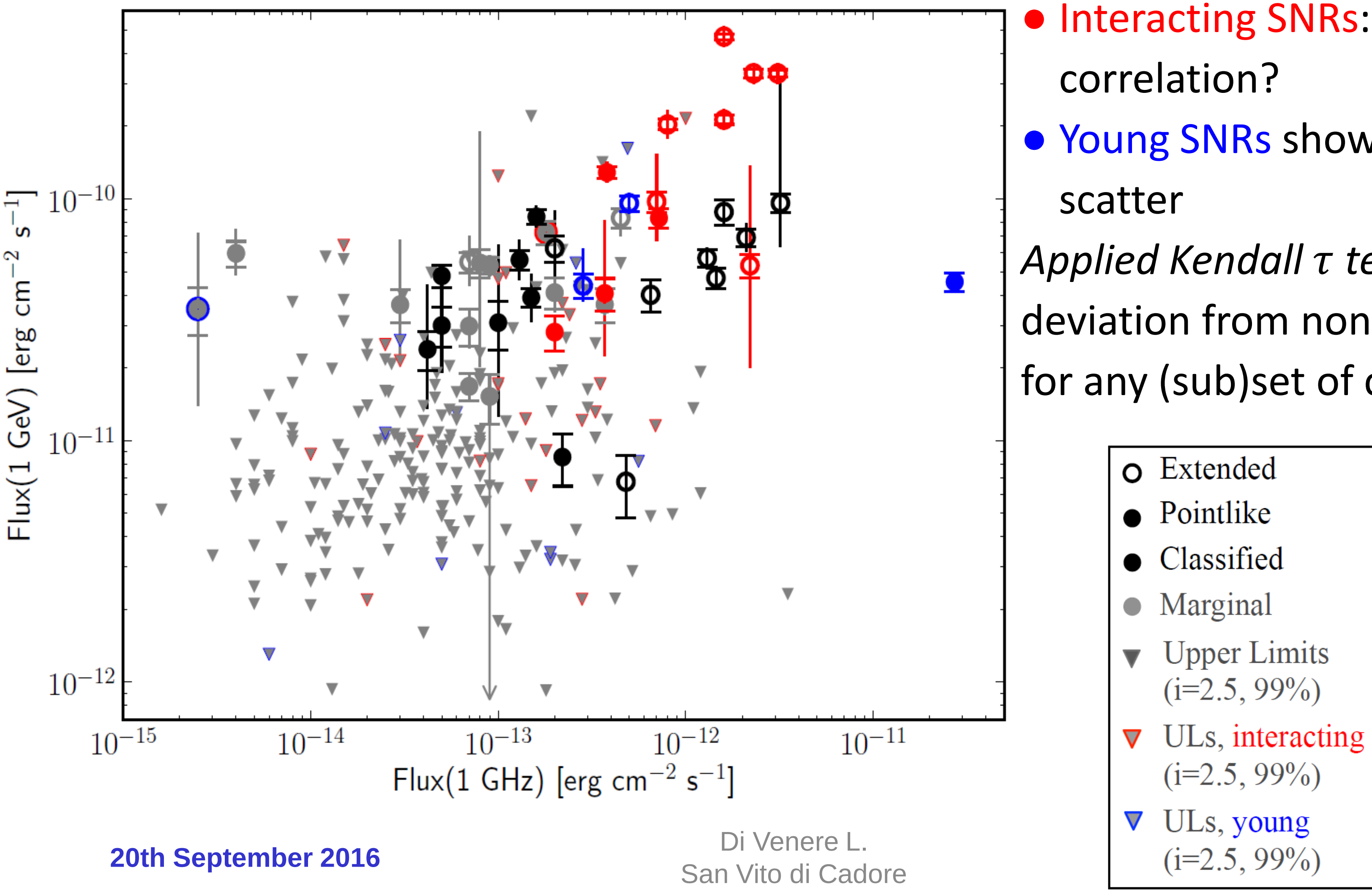
- Young Age (440 yr), Distance 3.5 Kpc
- SN Type Ia explosion

Cas A

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

Radio-GeV Flux

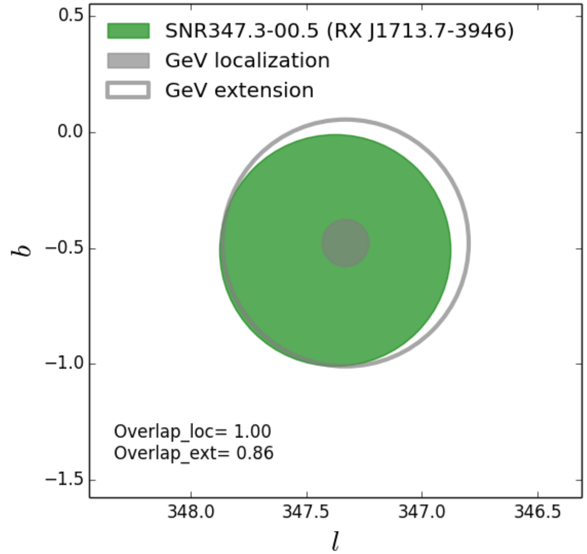
LAT-detected SNRs tend to be radio-bright:

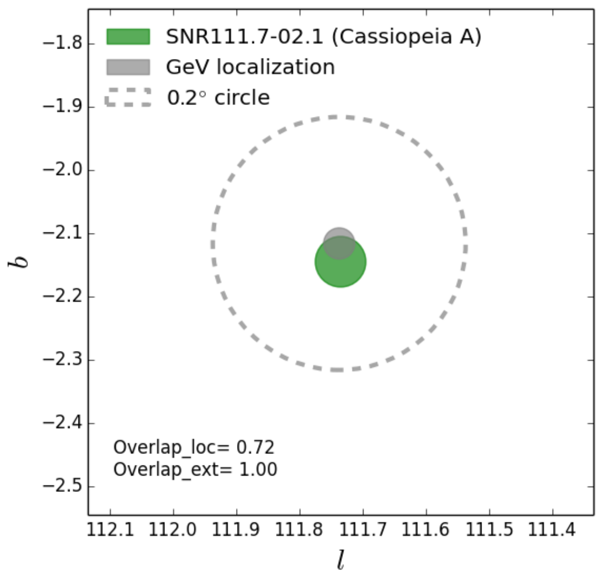


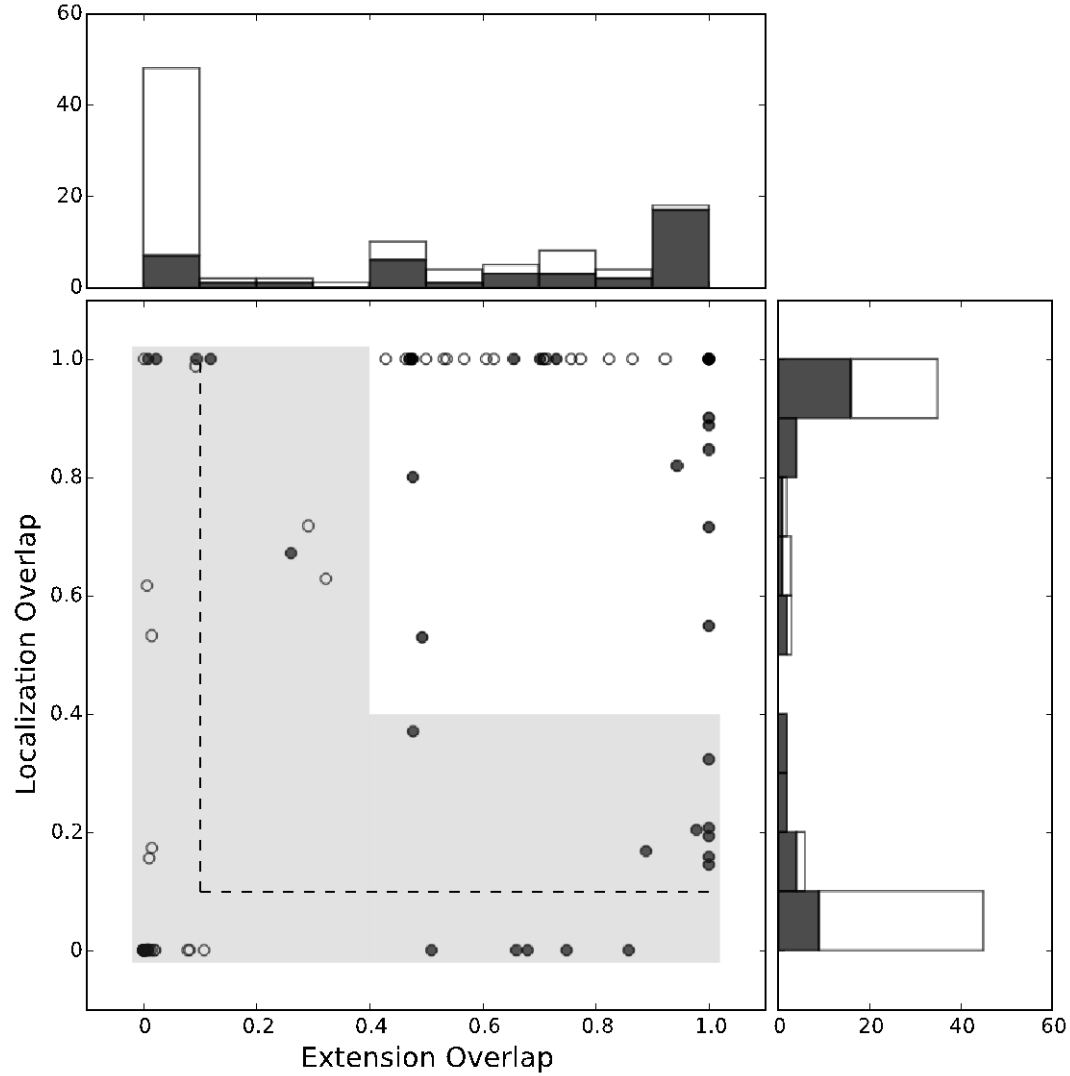
- Interacting SNRs: general correlation?
- Young SNRs show more scatter

Applied Kendall τ test: no deviation from non-correlation for any (sub)set of candidates.

Spatial coincidence

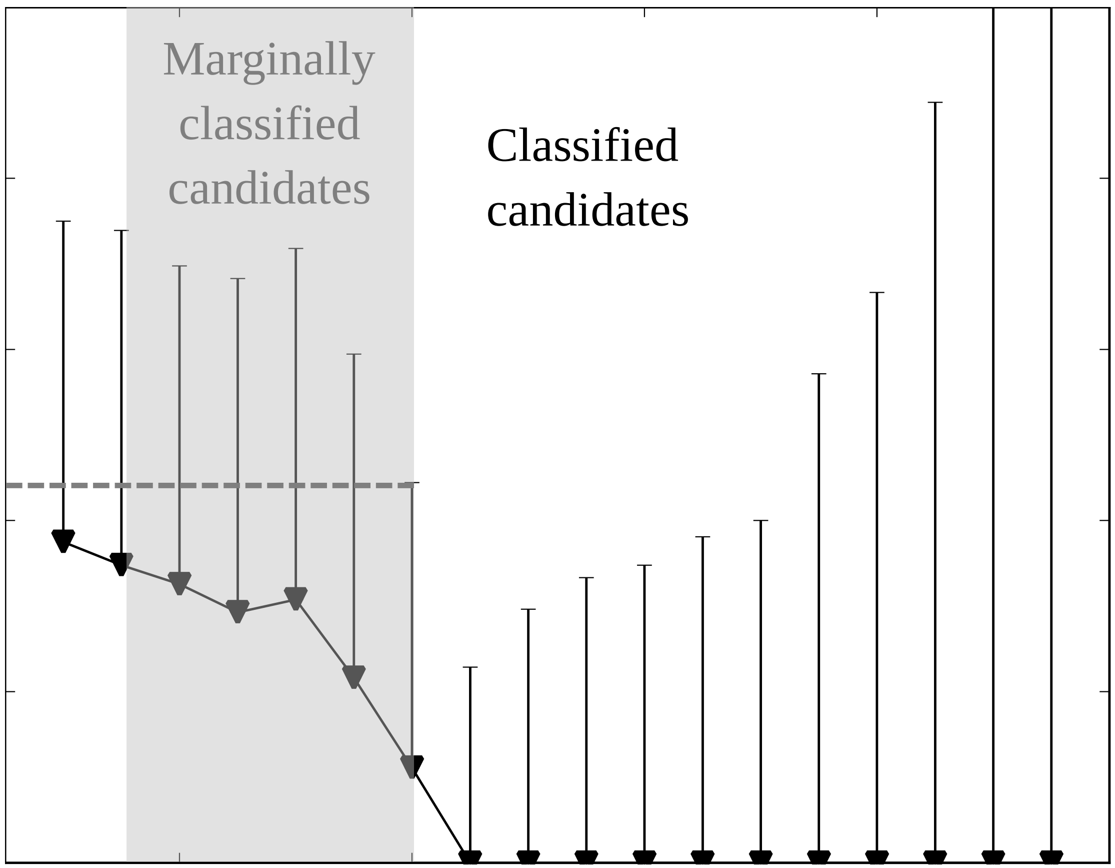






Mock catalog: Chance Coincidence Study

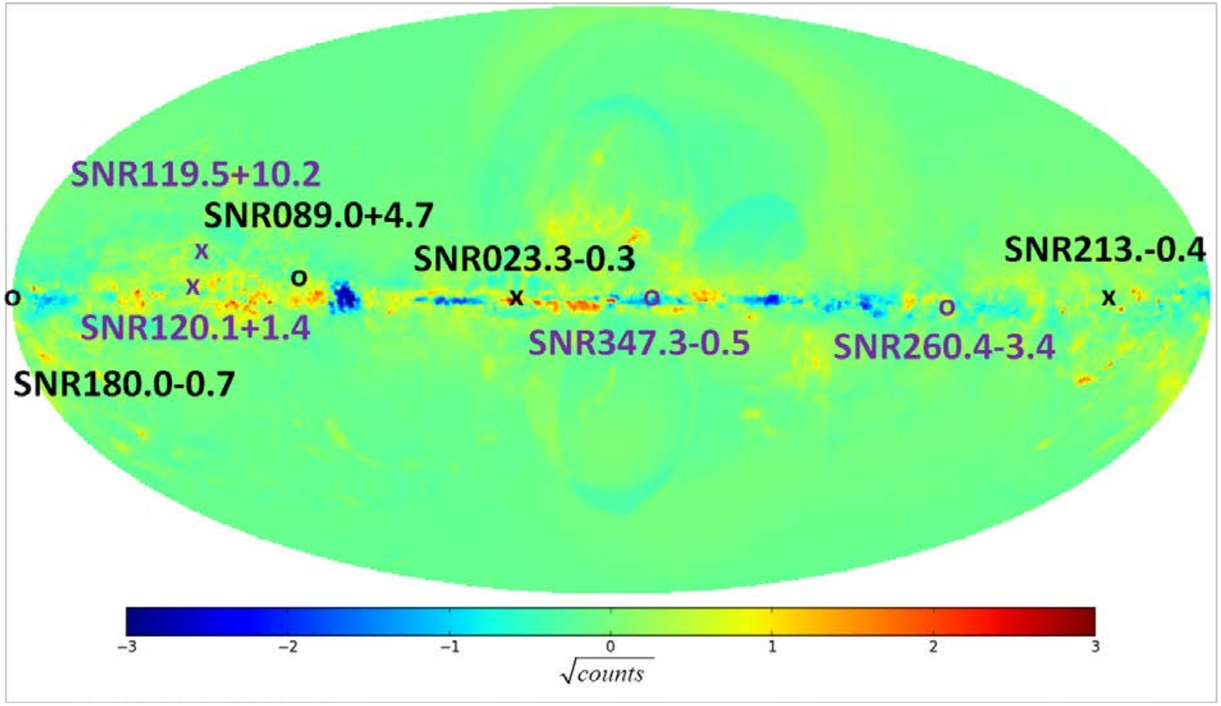
Use measure of chance coincidence in mock catalog to estimate false alarm rate and error.
Set thresholds to 0.4: $< 22\%$ false-positive rate.



Systematic Error Study

To evaluate the systematic uncertainties related to the choice of the Interstellar Emission Model (IEM), we used 8 alternative IEM and for each of them and each candidate we perform an independent fit and localization.

We developed this method using 8 representative candidate SNRs.
They are **hard**, **soft**, point-like (**x**) and extended (**o**) sources and they are located in regions with different intensities of the IEM.



For the description of the models see:
Ackermann et al. , 2012, *Apj*, 750, 3

Alternative IEMs

They are built using GALPROP with input parameters set as:

- CR source distribution =[SNR and Lorimer],
- Halo height = [4 kpc and 10 kpc],
- HI spin temperature =[150K and optically thin]

and then fit to the data.

The HI and CO emission split into 4 Galactocentric rings and the inverse Compton emission are fit simultaneously with the source of interest.

Warning:

- *these 8 models do not span the complete uncertainty of the systematics.*
- *the method for creating this model differs from that used to create the official Fermi-LAT interstellar emission model, so these 8 models do not bracket the official model.*

F. de Palma et al., *Fermi* Symposium 2012 proceedings
arXiv:1304.1395

Definition of weighted systematic error for the IEM analysis

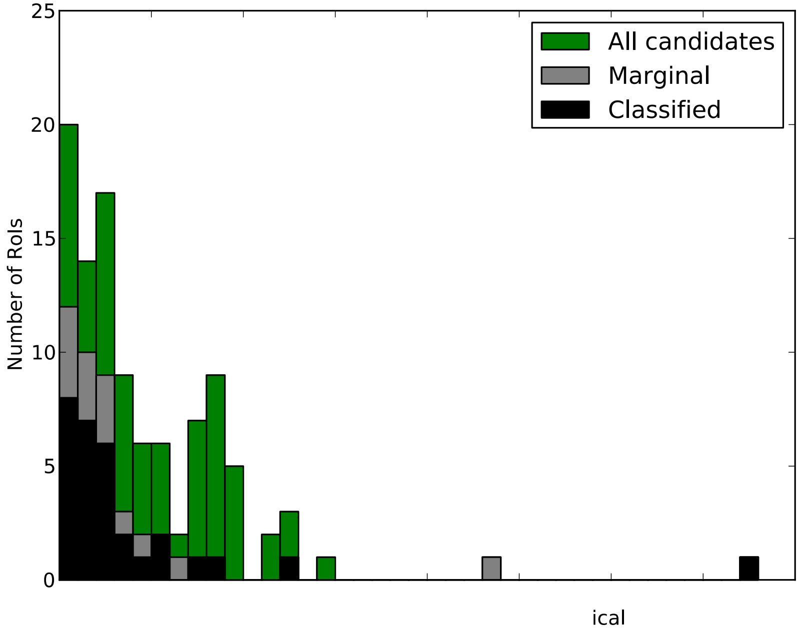
For each parameter (e.g. Flux, Index,..) obtained with the STD IEM P_{STD} we evaluate using the parameter P_i obtained with the alternative IEM the weighted systematic error:

$$E_{sys,w} = \sqrt{\frac{1}{\sum_i^M \omega_i} \sum_i^M \omega_i \, (P_i - P_{STD})^2}.$$

The weight is:

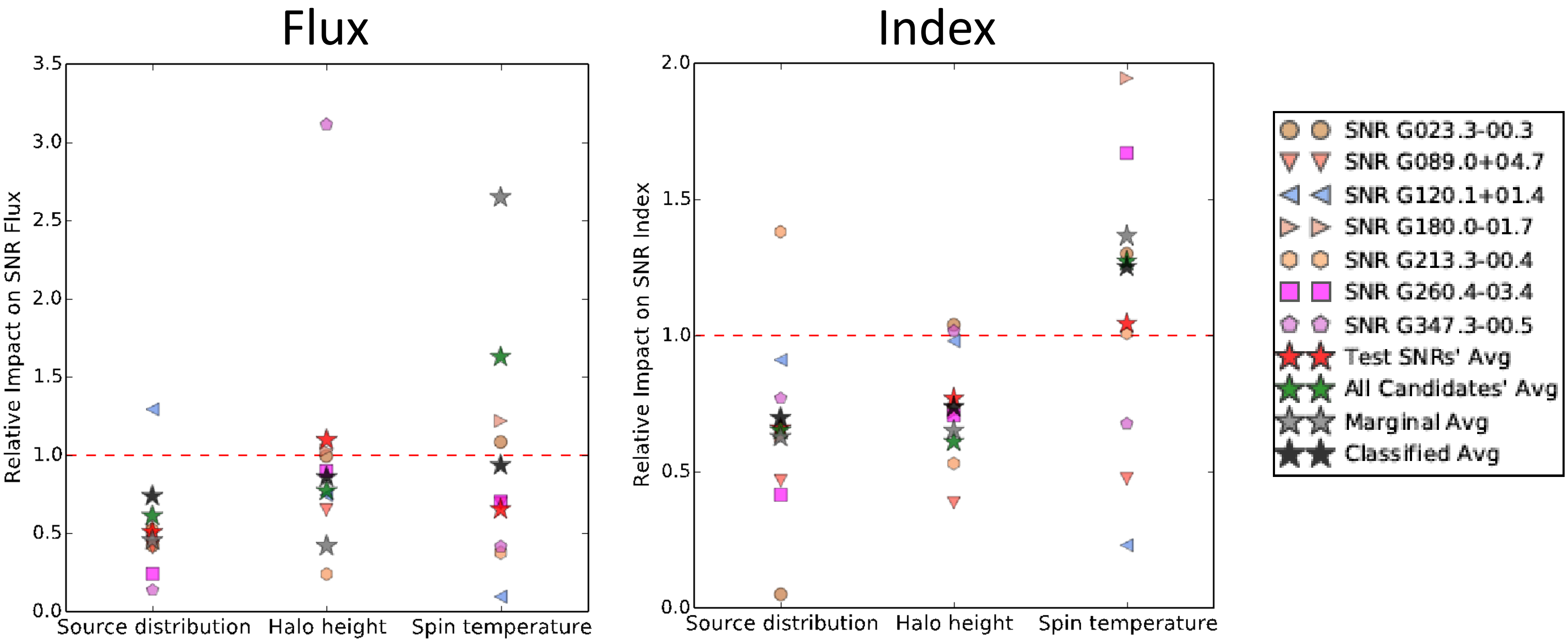
$$\omega_i = \frac{1}{\sigma_i^2},$$

where σ_i is P_i statistical error.



Systematic Uncertainties from IEM

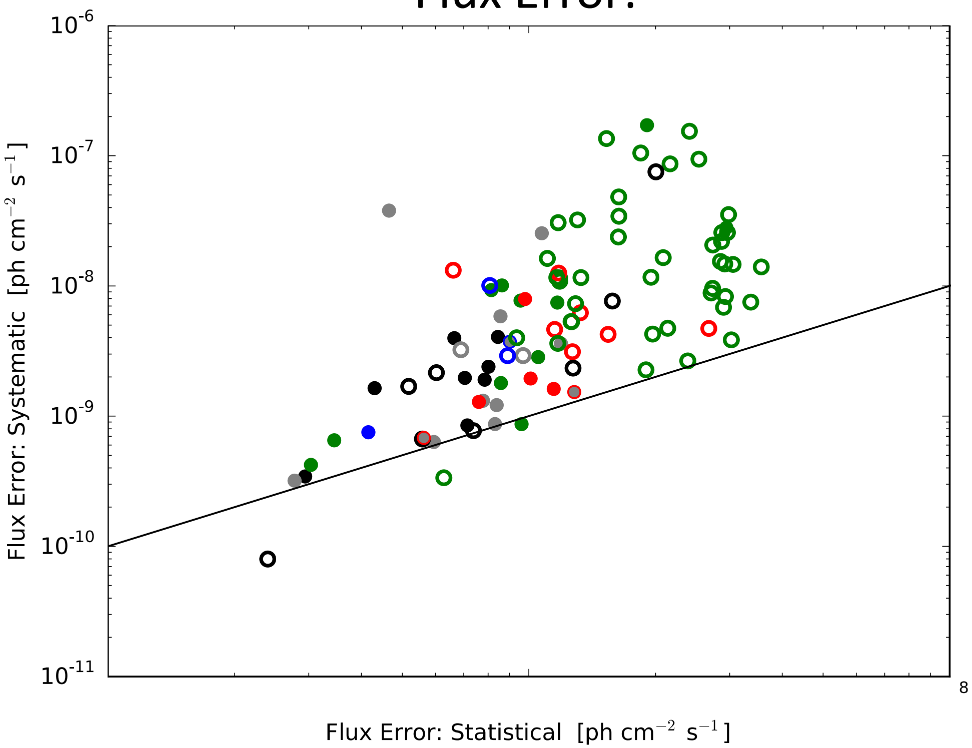
$$R \equiv \frac{|<P_i> - <P_j>|}{\max(\sigma_{P_i}, \sigma_{P_j})}.$$



Systematic Errors

We estimate the systematic errors using the alternative IEMs and the effective area bracketing IRFs, summing the independent errors in quadrature.

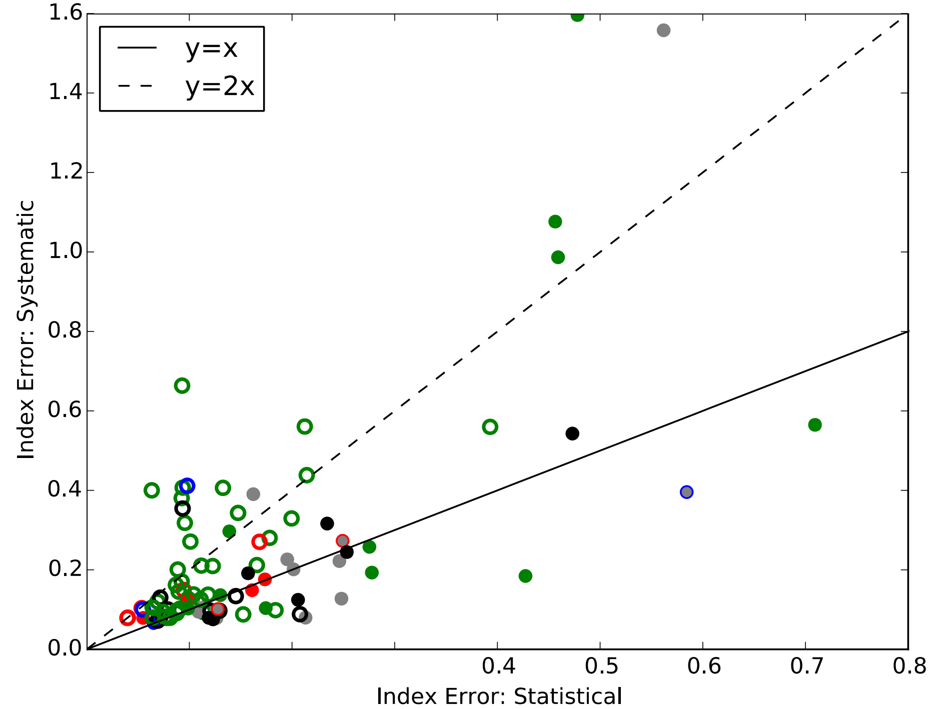
Flux Error:



Interacting
Young

Extended
Pointlike
Classified
Marginal
All other

Index Error:



Background sources

Added background sources compared to the number of 2FGL sources in 3°.