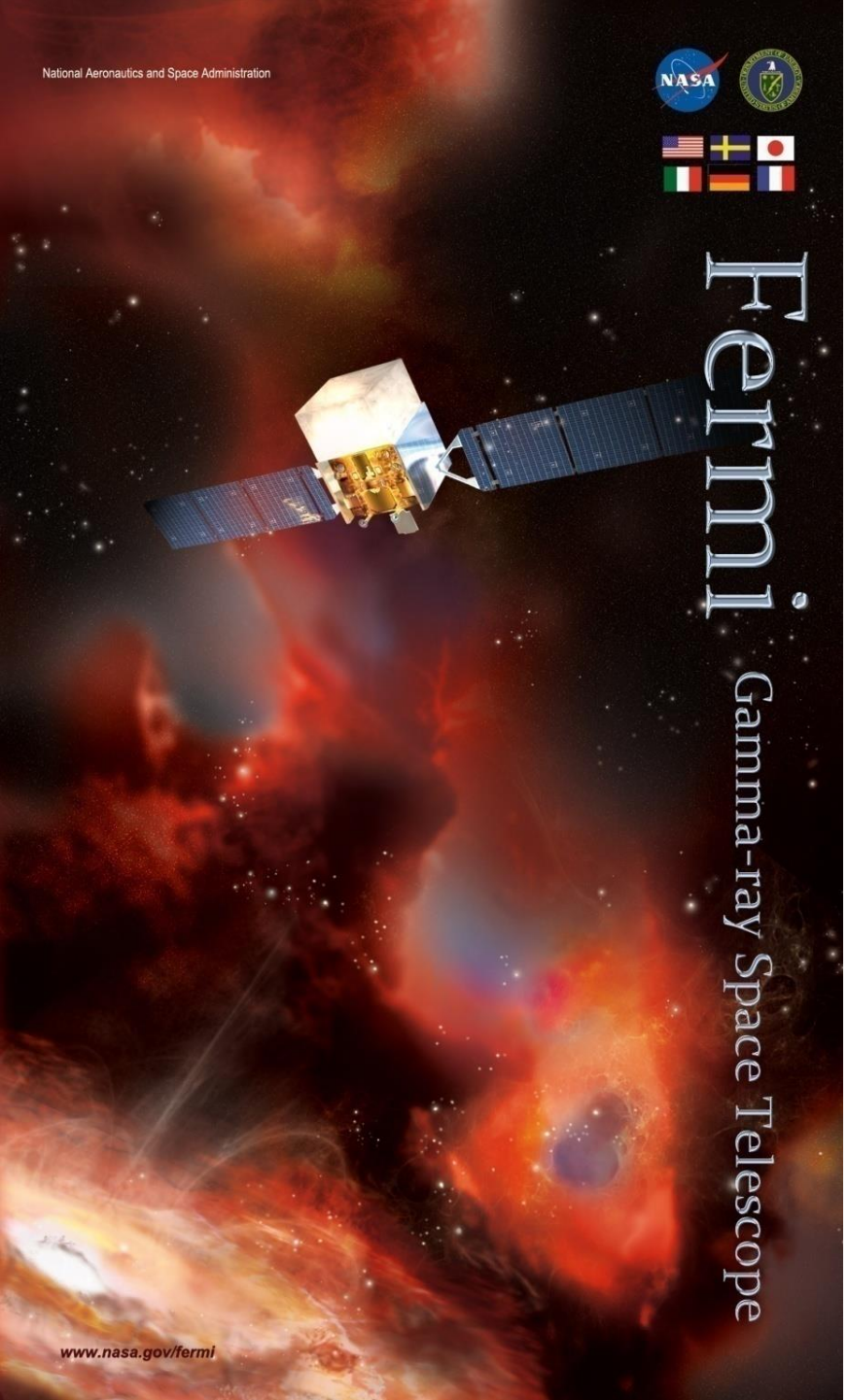


Observations of Galactic cosmic ray accelerators in the gamma ray sky with Fermi-LAT

F. de Palma

(INFN Bari and Università Telematica Pegaso),

M. Caragiulo and L. Di Venere

on behalf of the

Fermi LAT Collaboration

SciNeGHE 2016

Outline

- Galactic sources
  - Pulsar Wind Nebulae
  - Binaries
  - Novae
- LAT SNR observations
  - SNRs with hadronic emission
  - Young SNRs
- SNR Catalog:
  - Results
  - Multiwavelength correlations
  - Constraining Cosmic Ray (CR) acceleration
- Conclusions

What does Fermi see of our Galaxy?

Galactic sources:

- **PWNe**
- **Novae**
- **Binary systems**
- **SNRs**
- Pulsars

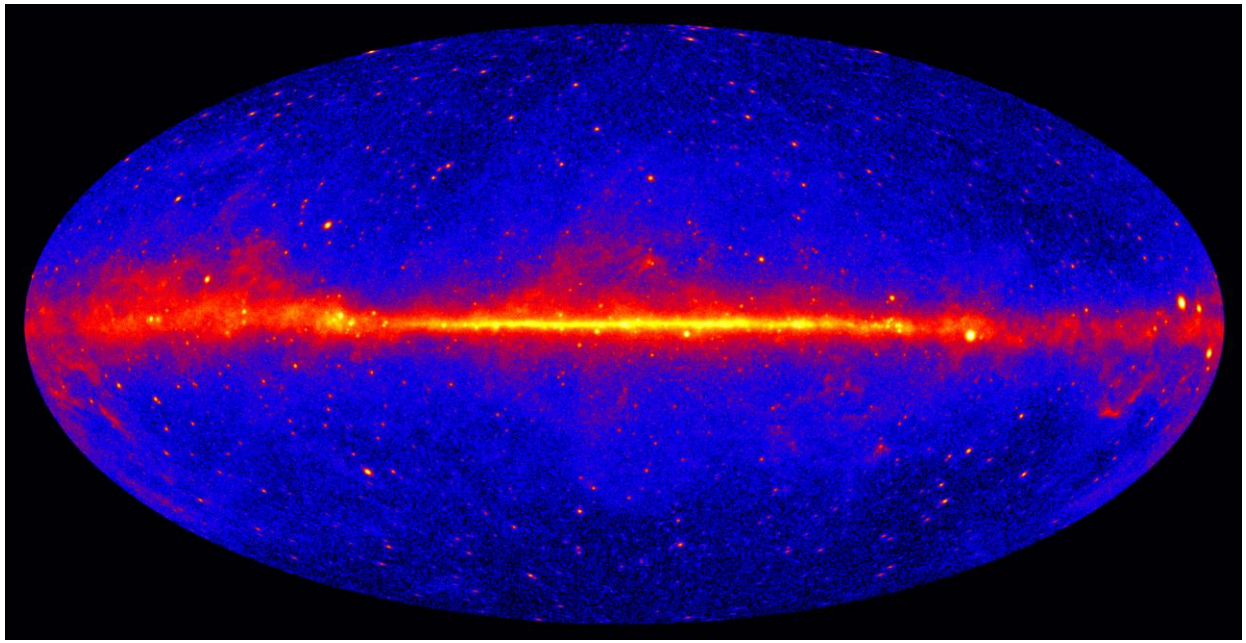
(See P. Parkinson talk)

- Galactic center and interstellar emission

(see E. Orlando talk)

- Solar System

(See R. Desiante talk)



3FGL Catalog: 3033 sources

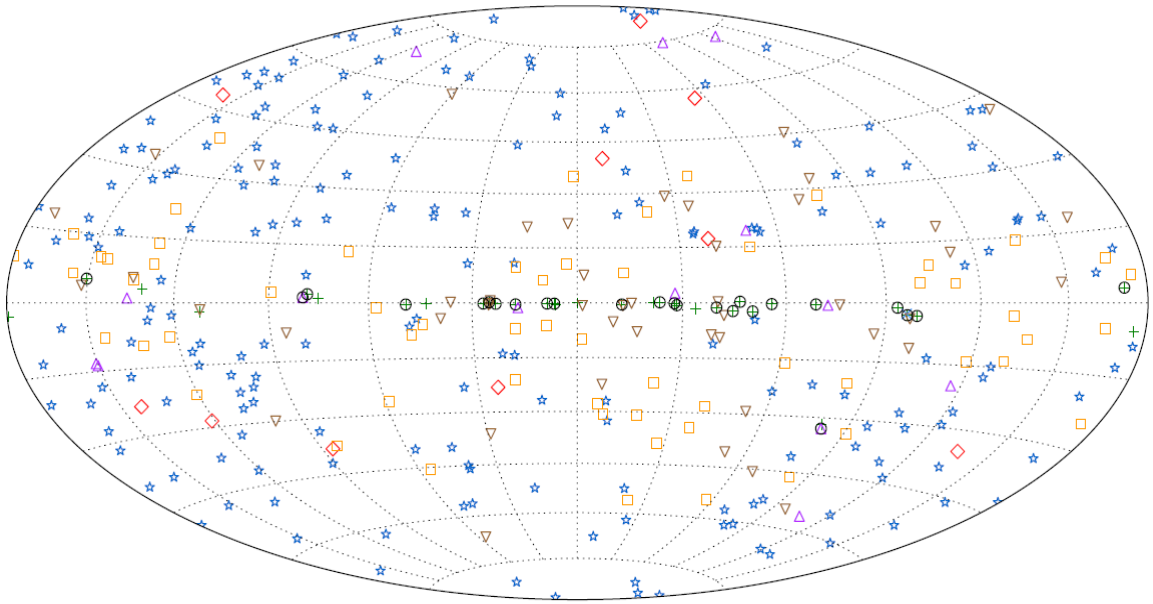
6% are PSR and 5% other Galactic sources

See J. Ballet talk

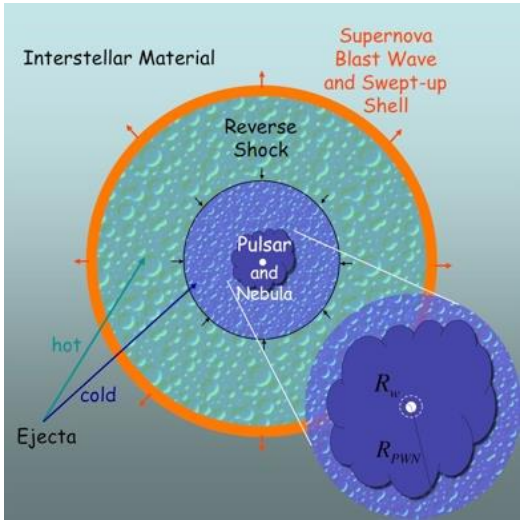
Gamma-ray sky above 50 GeV

- 38 Galactic sources above 50 GeV in 2FHL (Ackermann+ 2016):

Pulsar	psr	1
Pulsar wind nebula	pwn	14
Supernova remnant	snr	16
Supernova remnant/Pulsar wind nebula	spp	4
High-mass binary	hmb	2
Binary	bin	1
Star-forming region	sfr	1

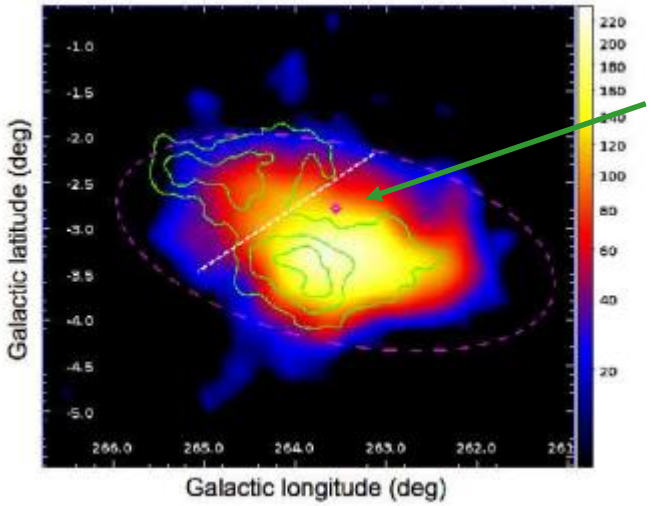


Pulsar Wind Nebulae



- Energy is carried away in a magnetized wind of charged particles.
- PWNe contain both the relic accelerated particles from the pulsar and particles accelerated within the termination shock.

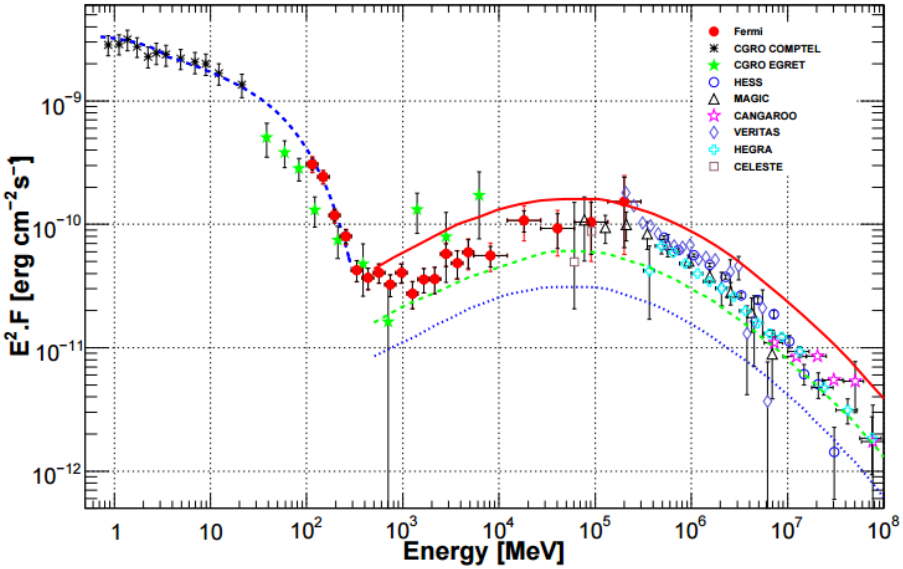
Vela X



Vela PSR

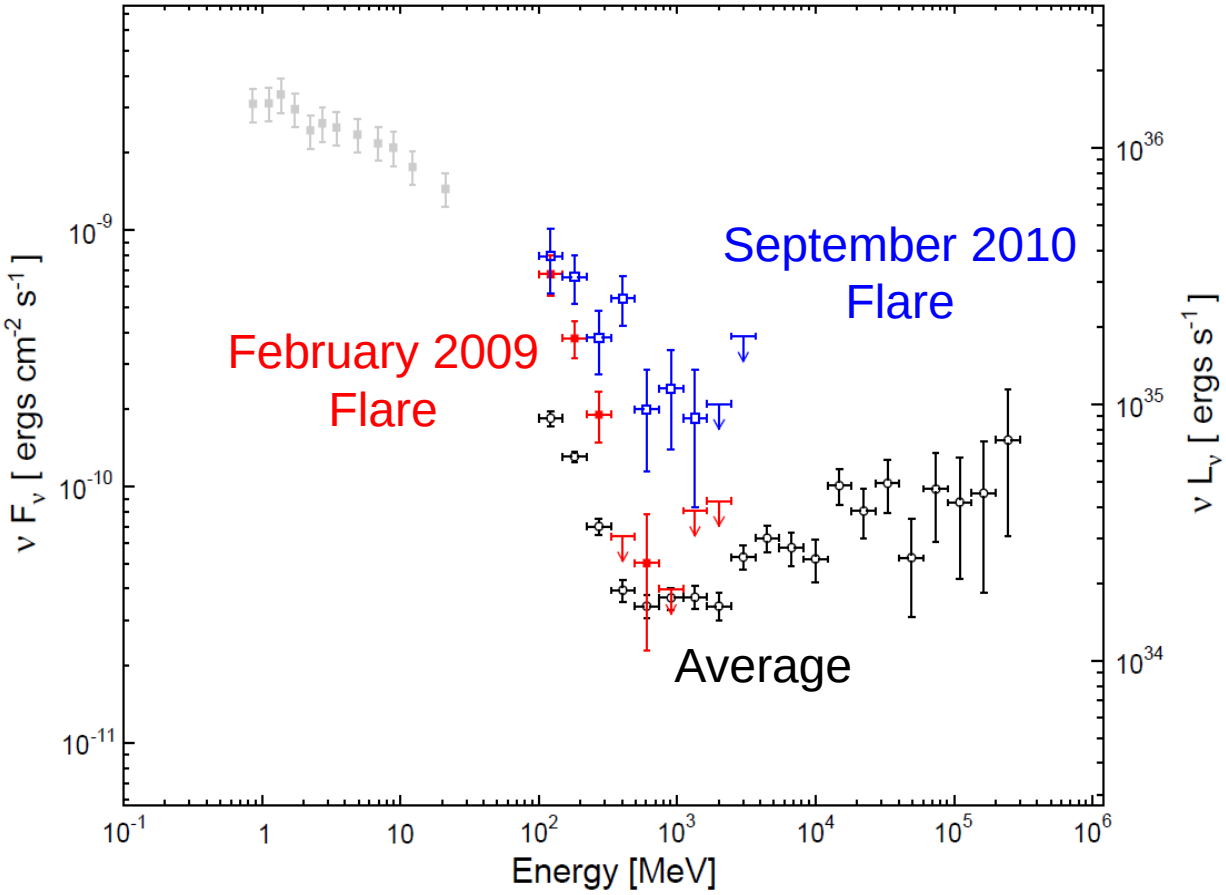
Grondin+ ApJ 2013

Crab



Abdo+ ApJ 2010

Crab not a standard candle

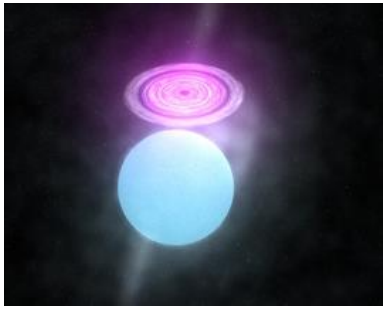


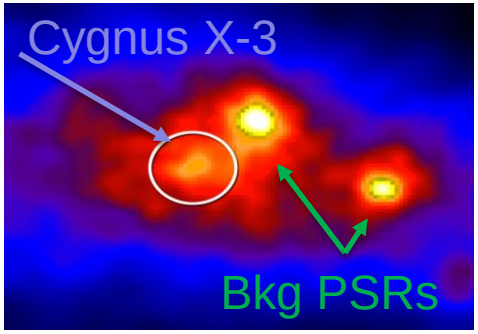
Abdo+ Science 2011, Buehler+ ApJ 2012 (2011 flare) Mayer+ ApJ 2013 (2013 flare)
Also detected by Agile: Tavani+ Science 2011

Binary systems with γ-ray variability

Microquasars: Cygnus X-3

- BH or NS in binary systems with relativistic jets
- Identified by:
  - Location;
  - modulation of the γ-ray flux at the orbital period of the binary system;
  - γ-ray variability correlated with the radio emission.

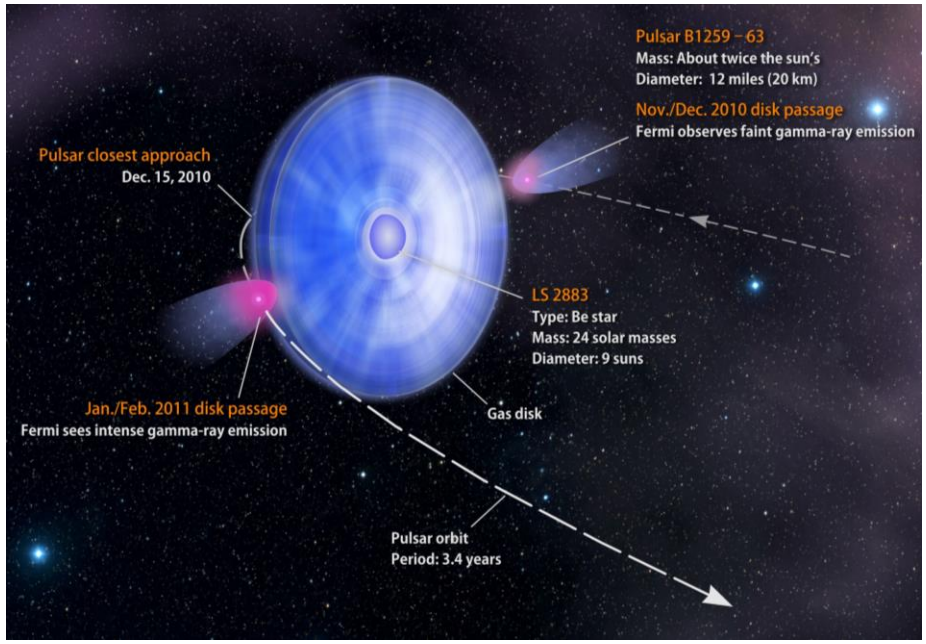




Corbel+ MNRAS 2012, Abdo+ Science 2009.
Also detected by Agile: Tavani+ Nature 2009

Pulsar Binaries: PSR B1259-63

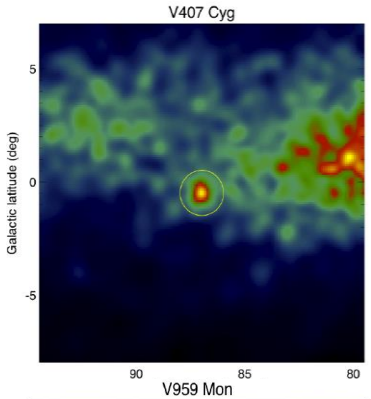
- Emission due to the interaction of the relativistic PSR wind and the photon field of the massive star.
- Periodicity: 3.4 years

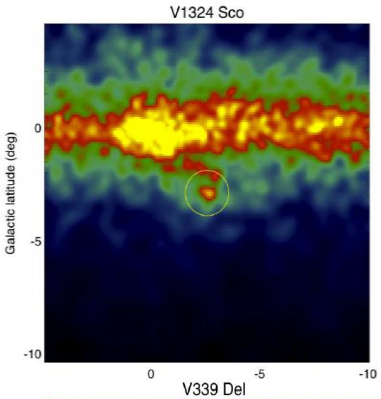


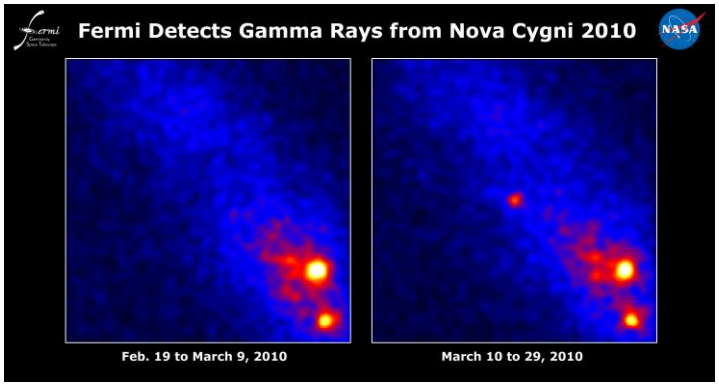
Abdo+ Apj 2011.

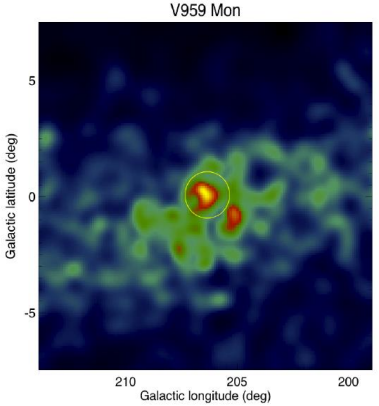
γ-ray Novae

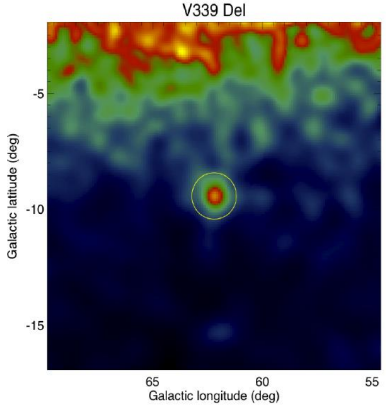
- 6 Novae detected up to now (ongoing researches on new candidates)
- Soft spectrum transient γ-ray sources detected over 2–7 week.
- Unexpected high-energy particle acceleration processes linked to the mass ejection from thermonuclear explosions.

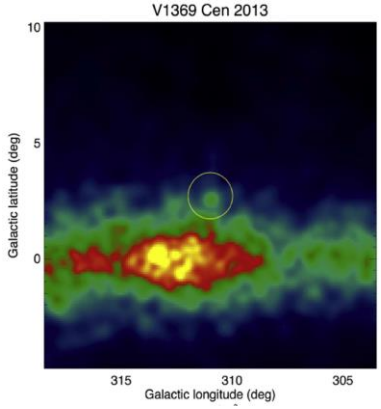


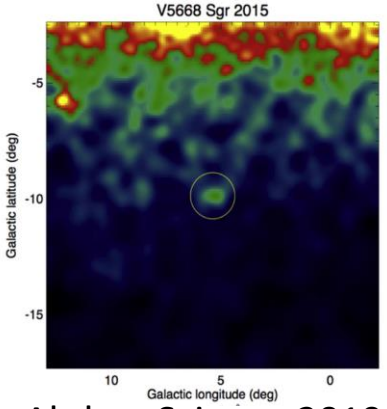






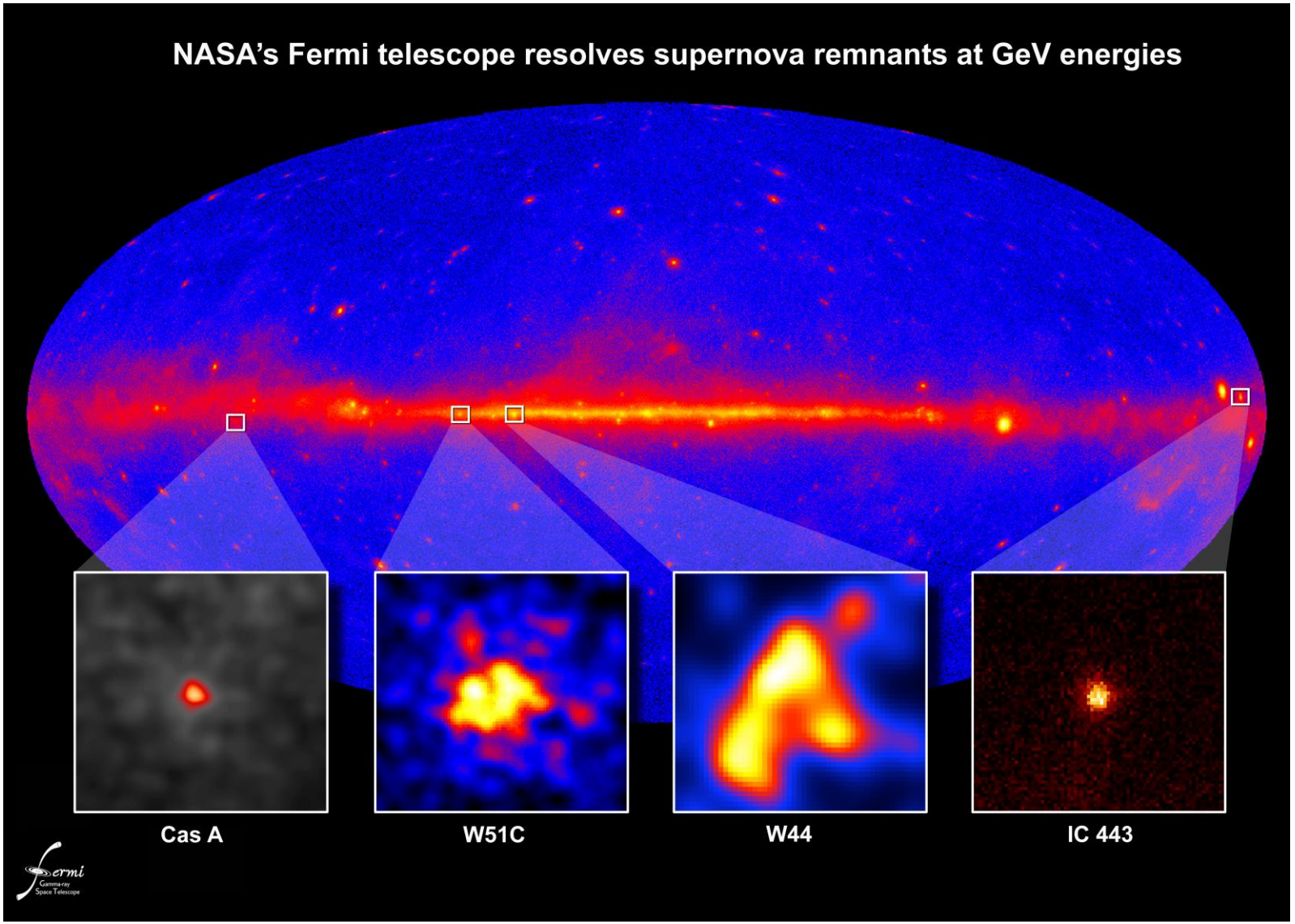




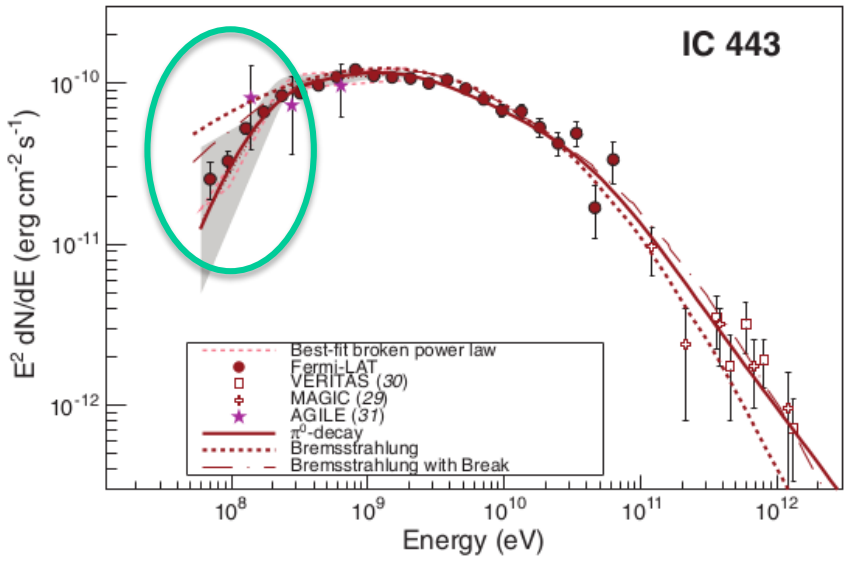


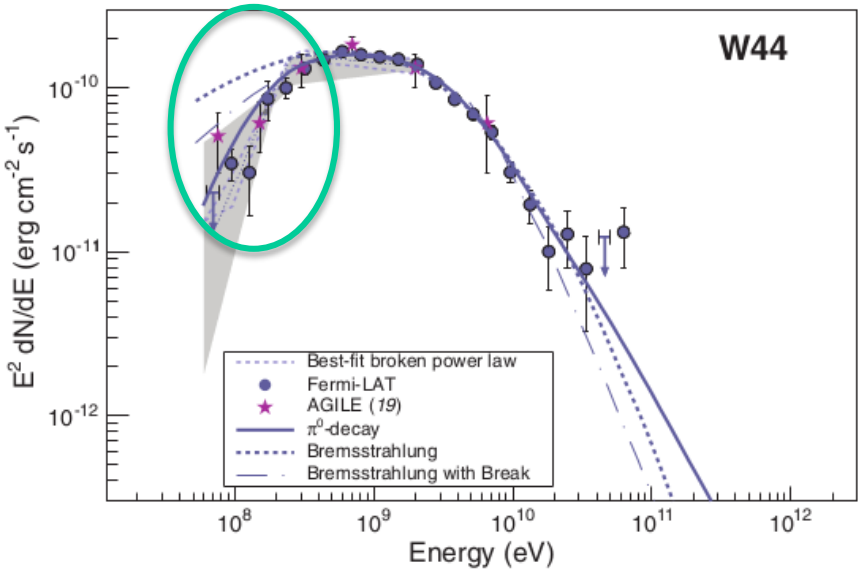
Abdo+ Science 2010
Ackermann+ Science 2014
Cheung+ Apj 2016

Supernova Remnants

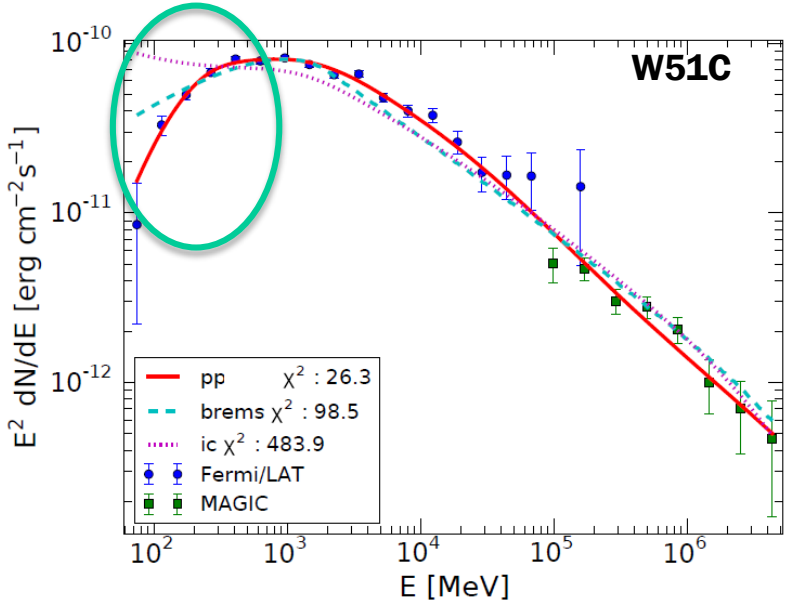


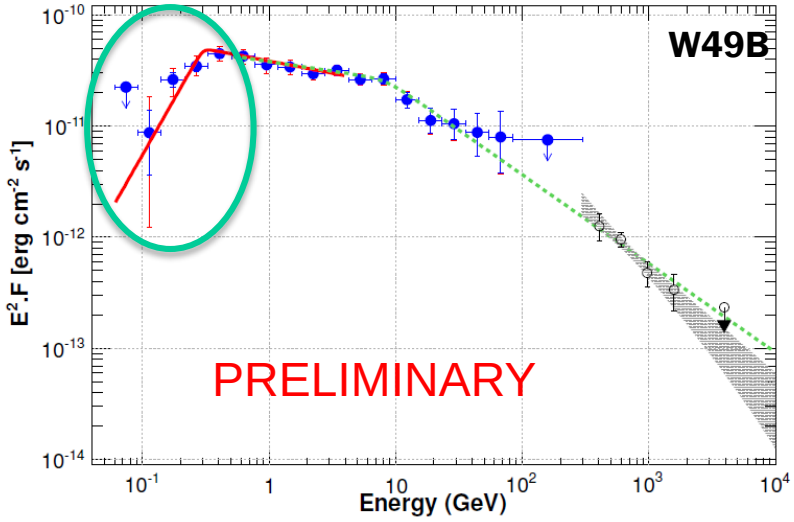
SNRs with hadronic emission





M. Ackermann+ 2013 (detected also by AGILE: Giuliani+ 2011)





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

T. Jogler and S. Funk, ApJ 2016

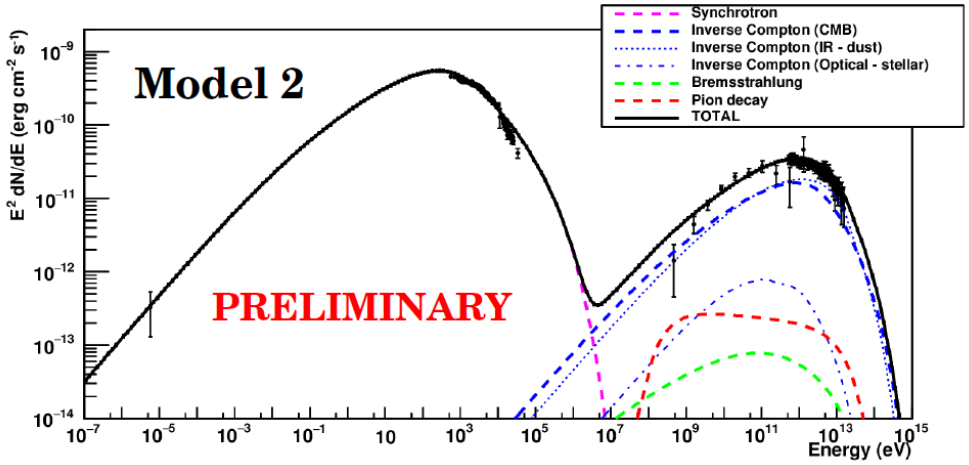
Young SNRs

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

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

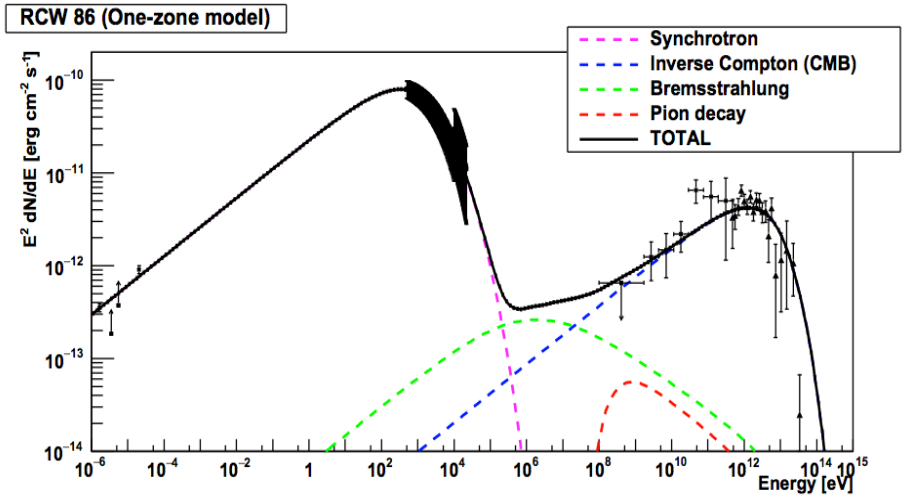
Leptonic scenario

RX J1713.7-3946



B. Condon+ @ Gamma 2016

RCW 86



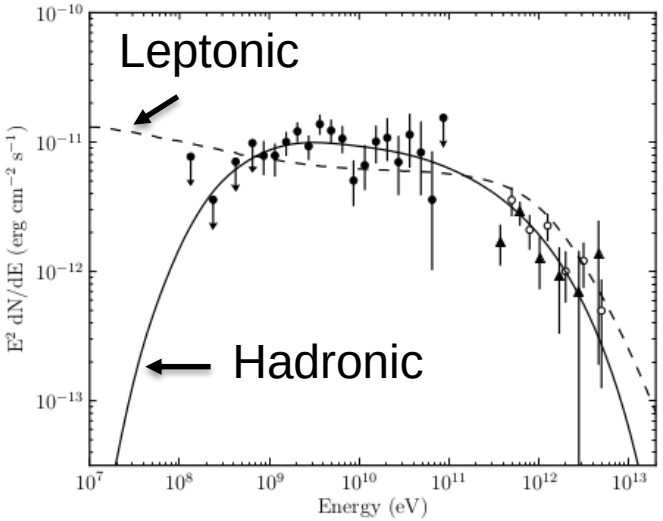
M. Ajello+ ApJ 2016

γ-ray emission dominated by Inverse Compton

Young SNRs

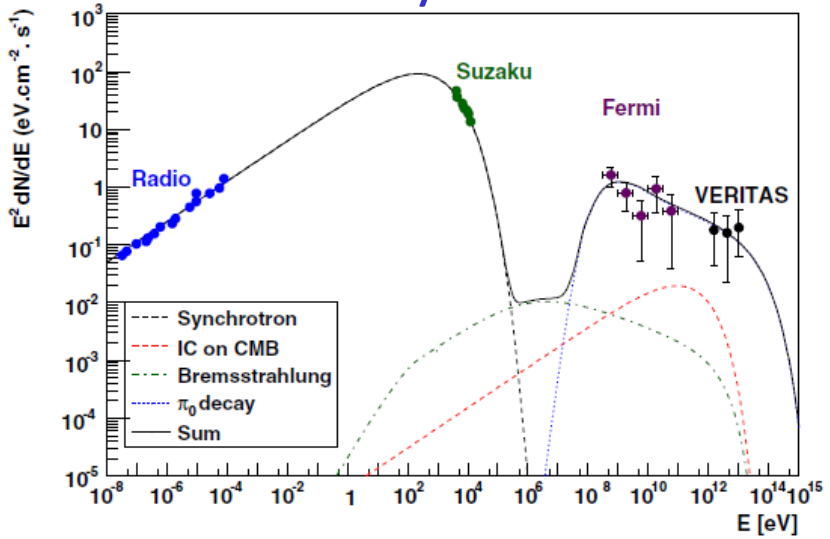
Hadronic scenario

Cassiopeia A



Y. Yuan+ ApJ 2013

Tycho



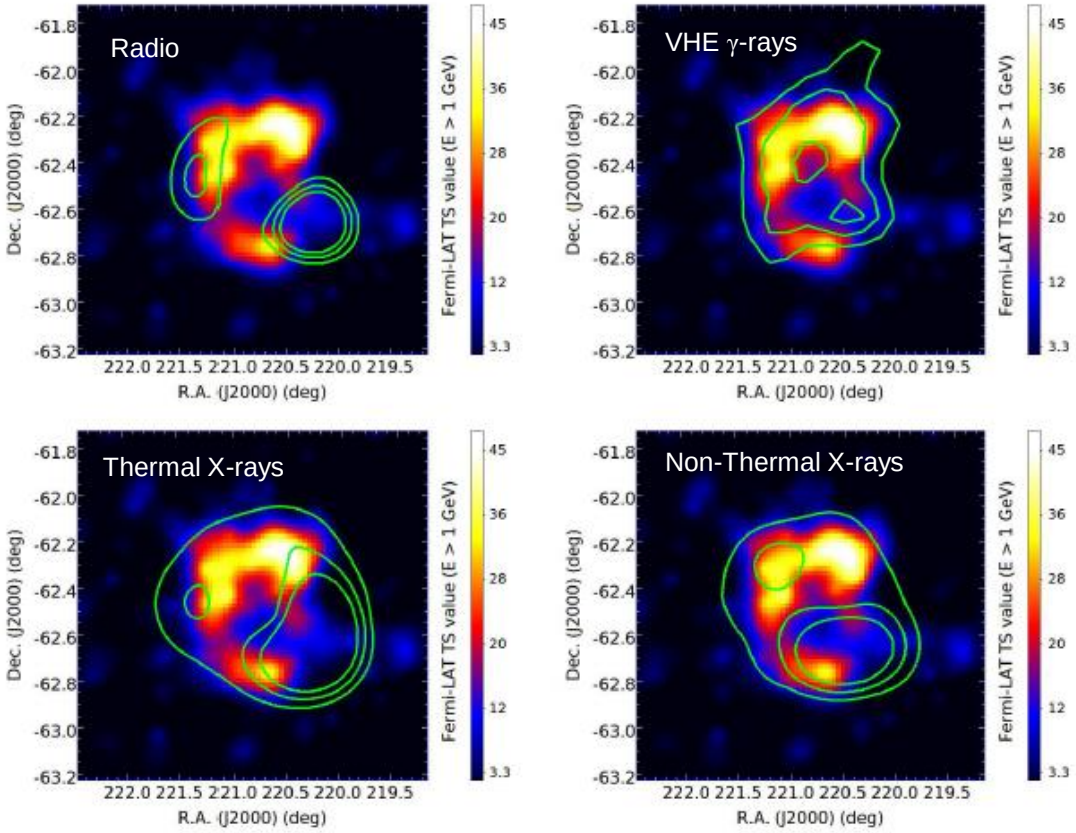
F. Giordano+ ApJL 2012

γ-ray emission dominated by pion decay

Presence of accelerated protons

Morphology studies with Pass 8

RCW 86



M. Ajello+ ApJ 2016

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

Best morphological photon distribution: **H.E.S.S. template**
(A. Abramowski+,
accepted for publication by A&A)

Multi-zone analysis ongoing

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

IC 443
Preliminary results in
Hewitt+ @ Fermi Symposium 2015

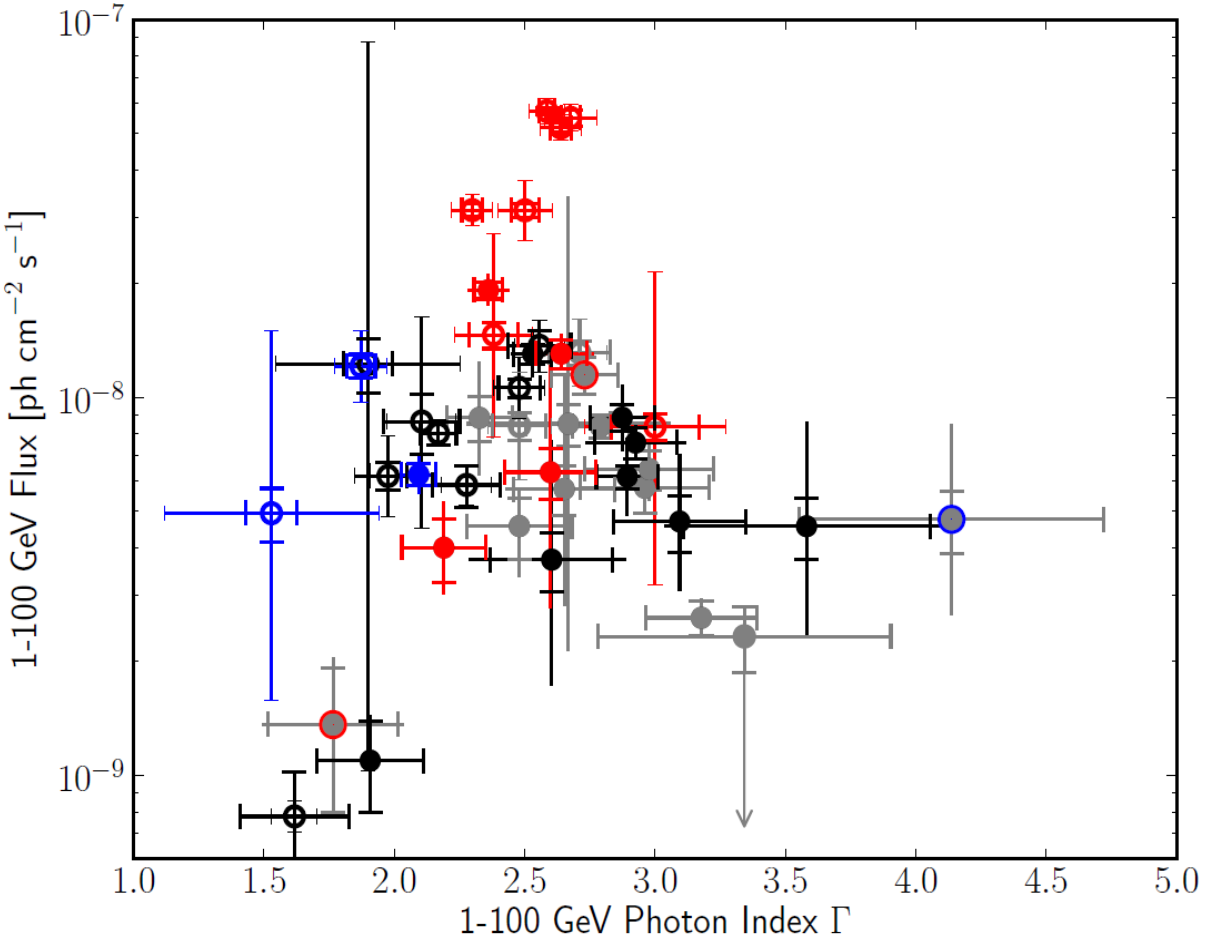
SNR catalog results

Characterized 279 regions containing known radio SNRs:

- 102 candidates have significant GeV emission:
  - 36 candidates classified through spatial association with radio data:
    - 17 extended: 4 new!
      - 2 show spectral curvature
    - 13 point-like hypothesis preferred: 10 new!
    - 2 are flagged for IEMs systematics
    - 4 identified as other sources (Crab, binary, and PWN/PSR)
  - 14 marginally classified candidates
- For the 245 candidates that don't have a significant GeV emission or that fail classification, we report their ULs.
- All the detected sources were tested for effects related to the choice of IEMs.

GeV Flux Vs. Index

Indexes of the candidate sources are distributed in the large range between 1.5 and 5, while fluxes are in a two orders of magnitude interval.

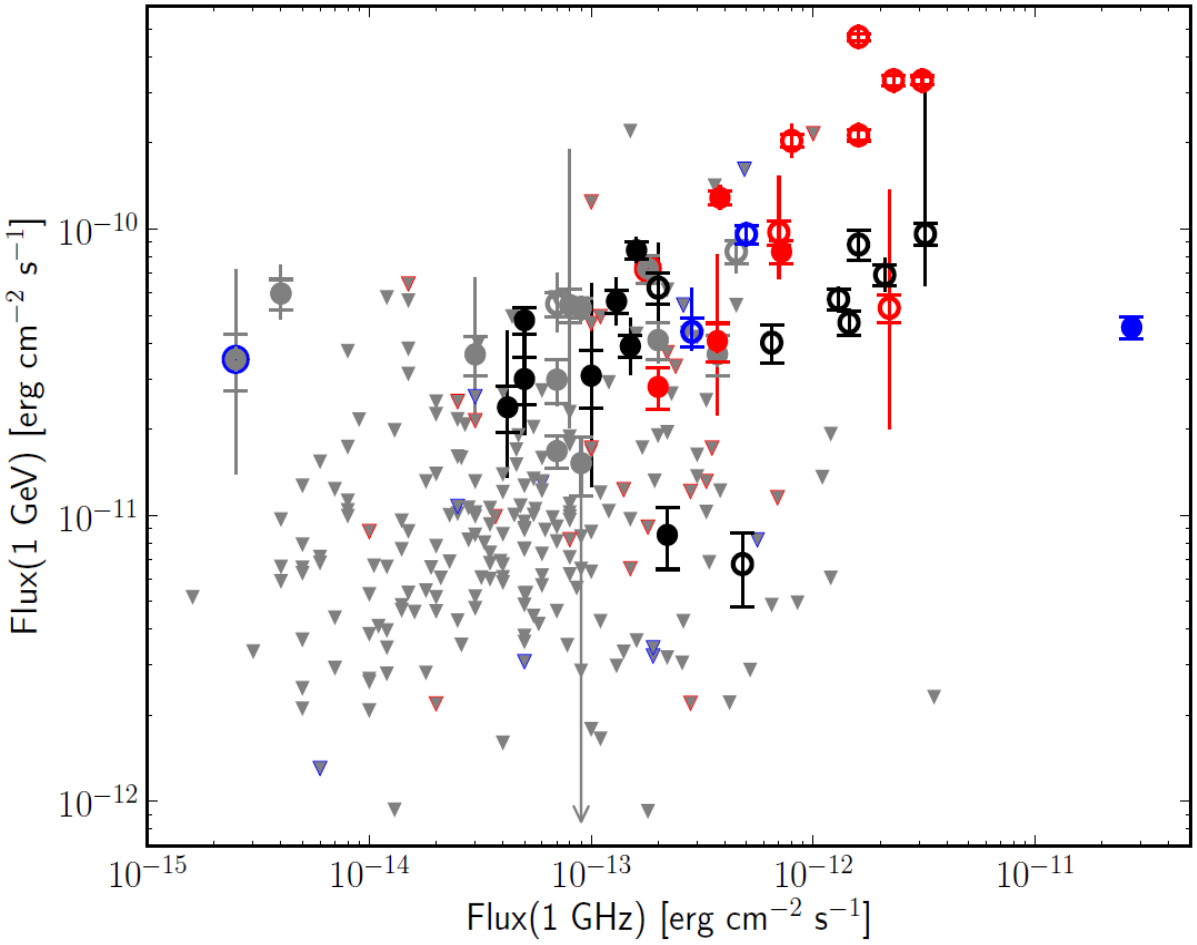


- Interacting SNRs density $\geq$ 100 cm^{-3}
- Young SNRs show evidence of non-thermal X-ray emission
- Classified candidates
- Marginal candidates
- Pointlike sources
- Extended sources

- Capped error bars: statistical errors
- Uncapped: systematic uncertainties.

Radio-GeV Flux

LAT-detected SNRs tend to be radio-bright:



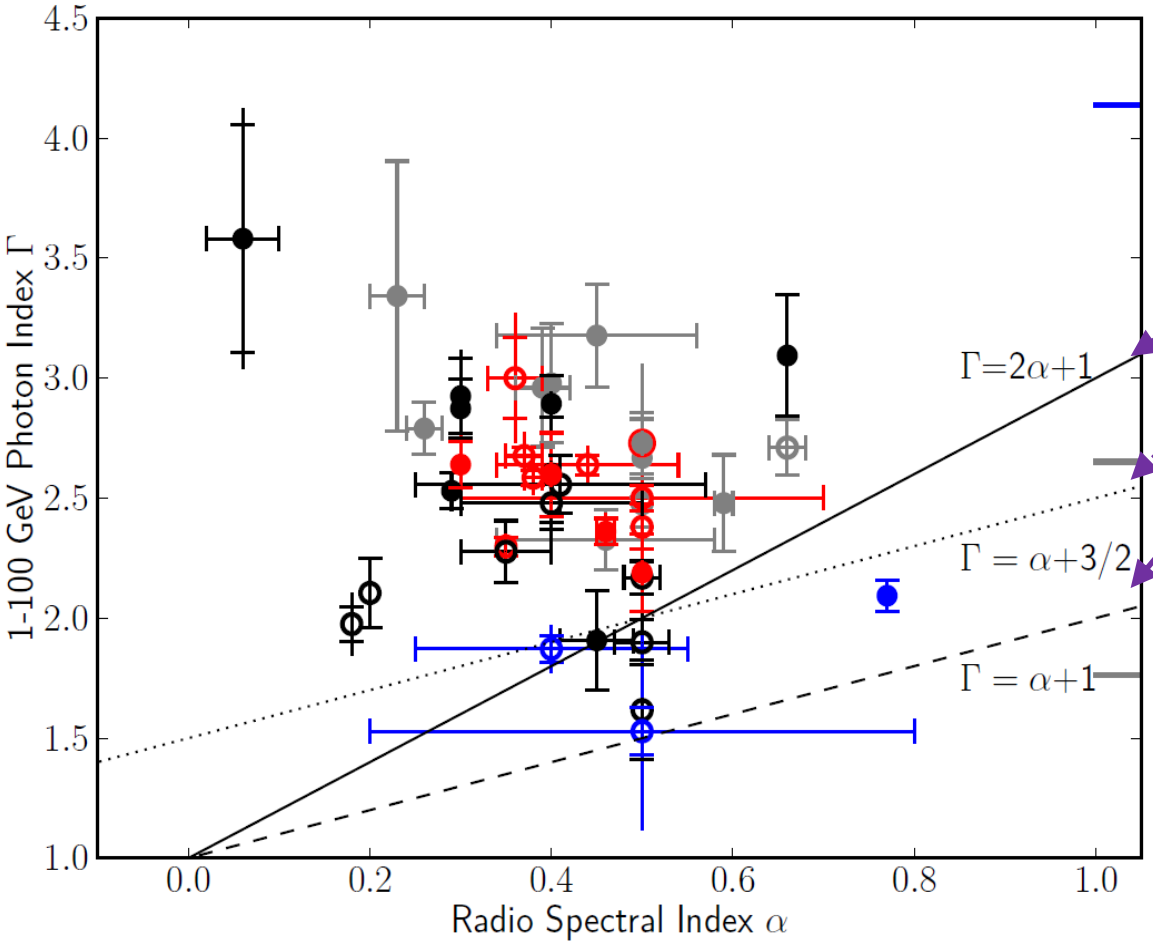
- Interacting SNRs: general correlation?
- Young SNRs show more scatter

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

- Extended
- Pointlike
- Classified
- Marginal
- Upper Limits (i=2.5, 99%)
- ULs, interacting (i=2.5, 99%)
- ULs, young (i=2.5, 99%)

Radio-GeV Index

If radio and GeV emission arise from the same particle population(s), under simple assumptions, the GeV and radio indices should be correlated:



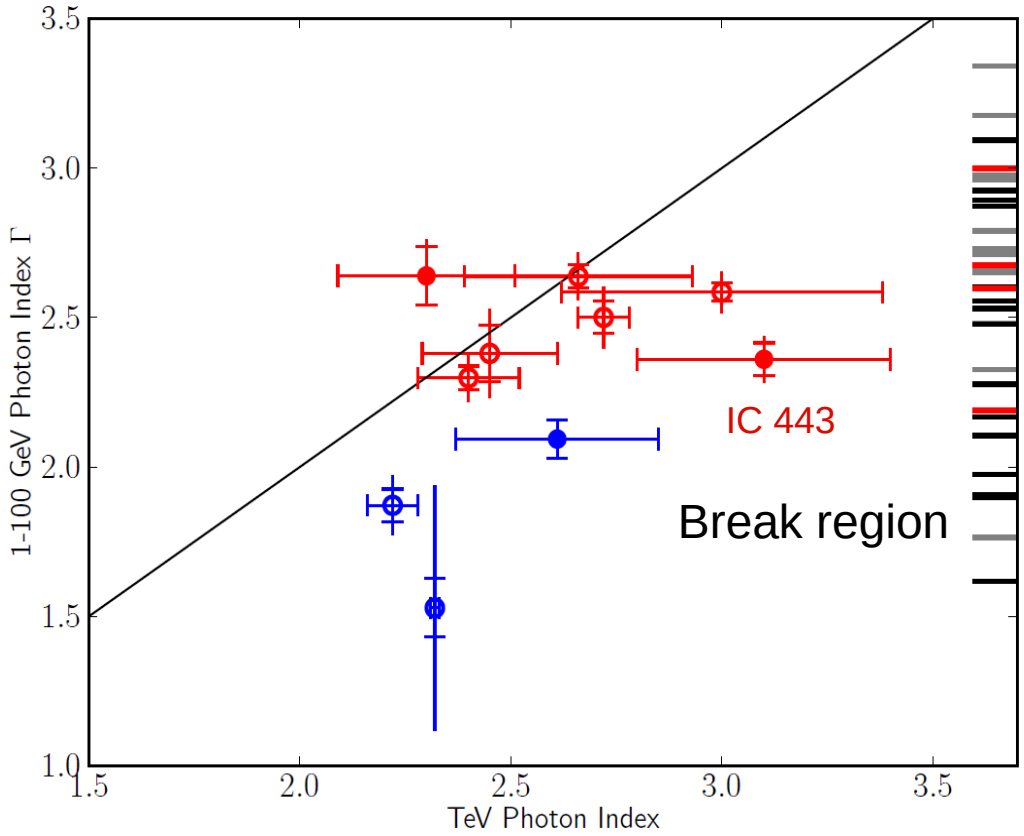
- Young SNRs: seem consistent
- Others, including interacting SNRs: softer than expected

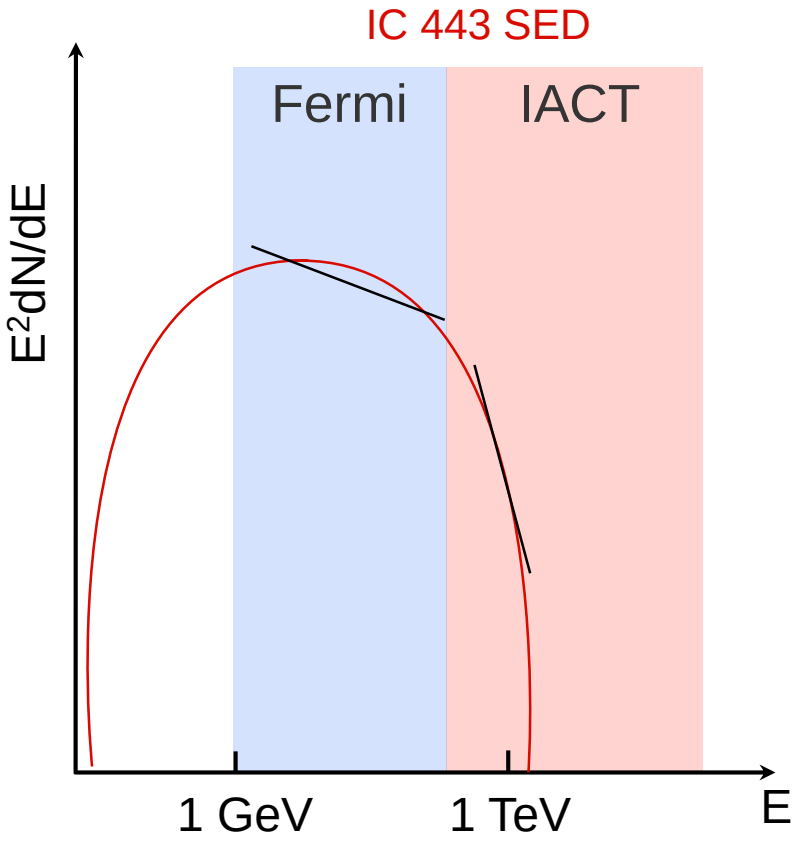
- π^0 decay or $e^{+/-}$ brem.
- Inverse Compton w cooling
- inverse Compton w/o cooling

<u>Data now challenge model assumptions!</u>

- Underlying particle populations may have different indices.
- Emitting particle populations may not follow a power law: breaks?
- Multiple emission zones?

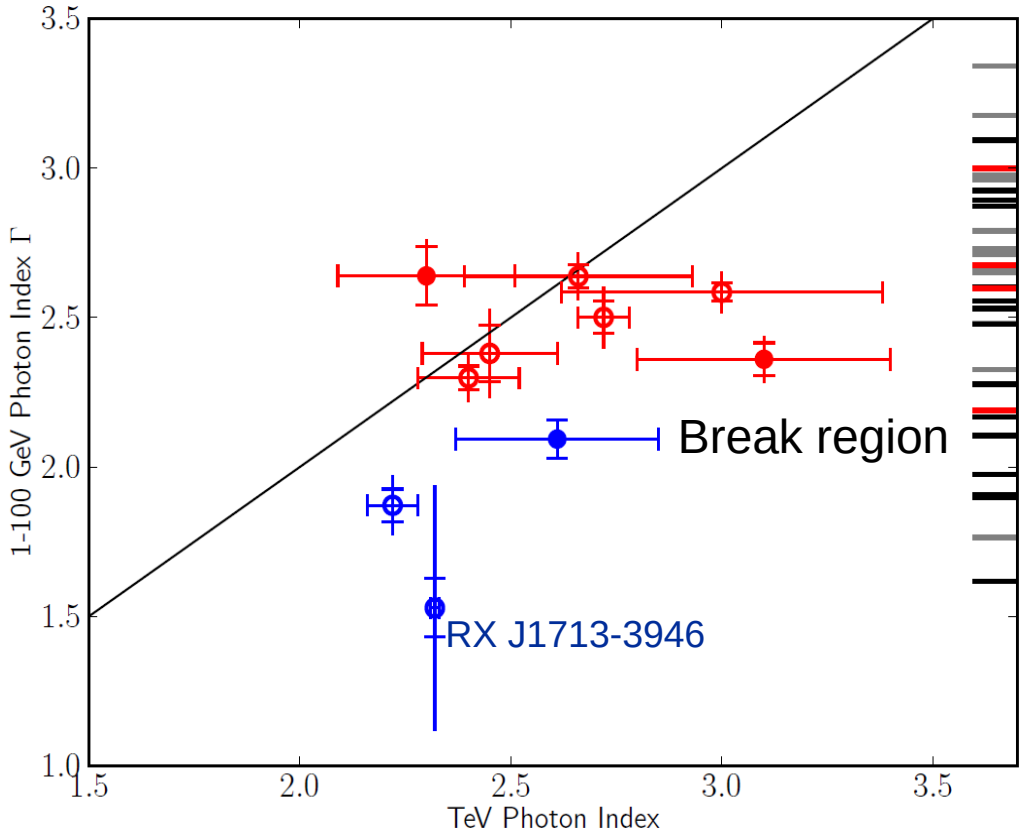
GeV-TeV Index

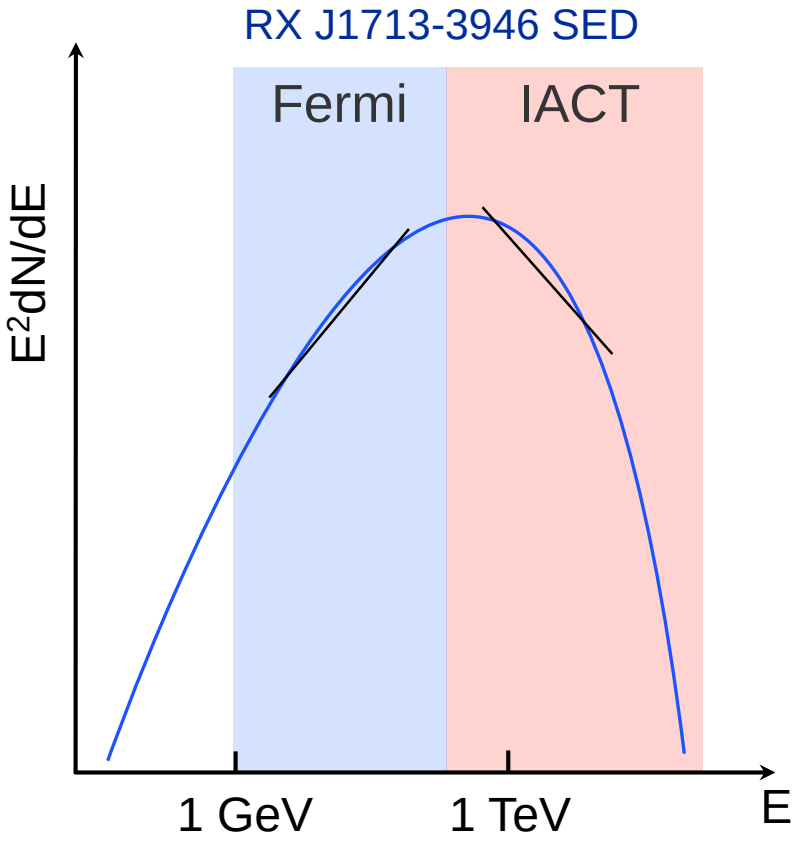




- Indication of break at TeV energies
- Caveat: TeV sources are not uniformly surveyed.

GeV-TeV Index



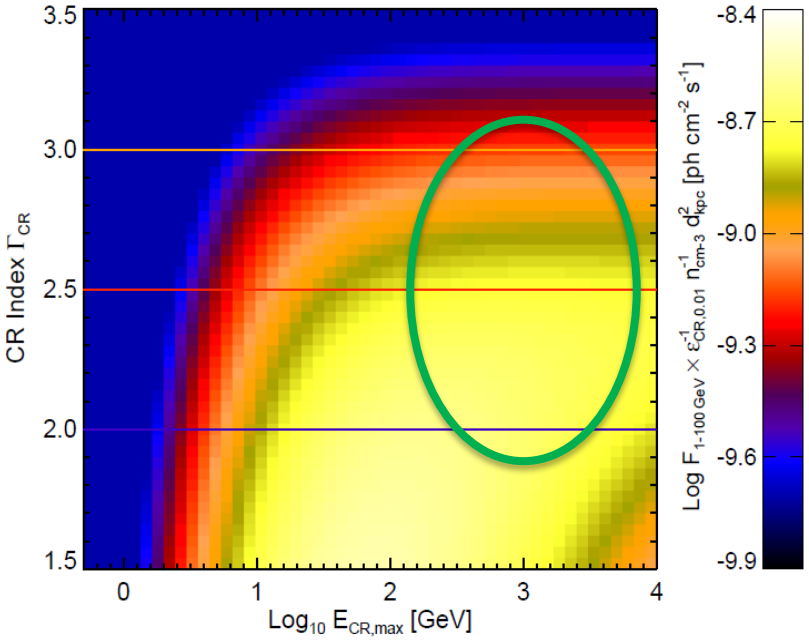


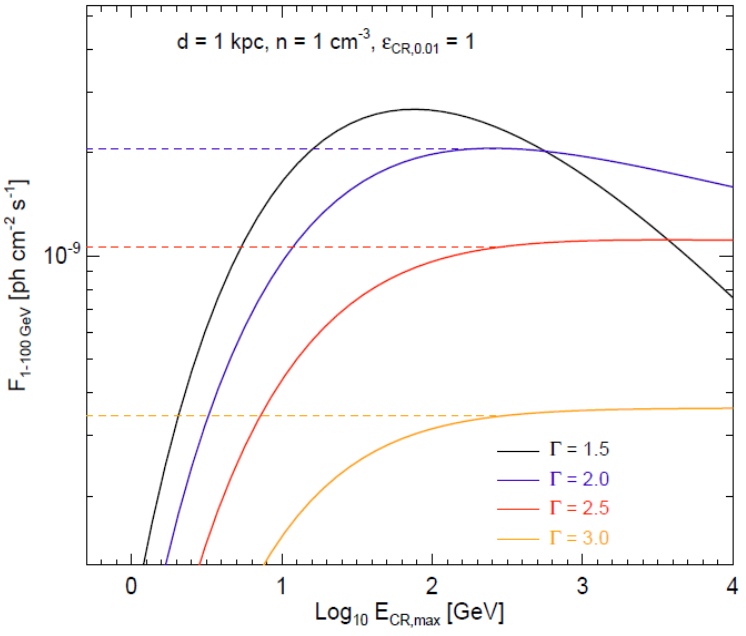
- Indication of break at TeV energies
- Caveat: TeV sources are not uniformly surveyed.

Constraining CR emission

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

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

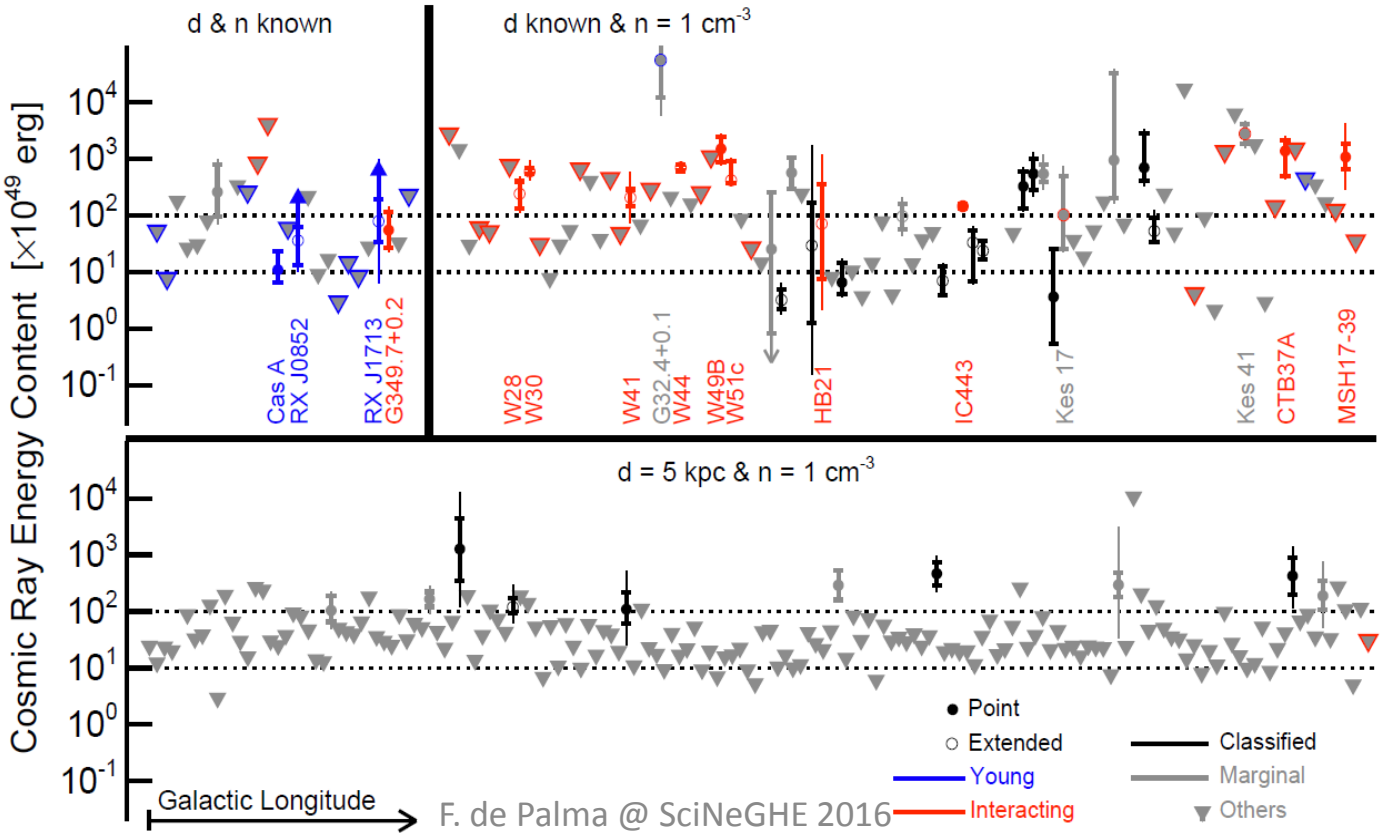




Constraining CRs from detections and ULs

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

- Fermi has proved to be extremely successful in studying galactic sources, both steady and variable.
- Pass 8 is allowing detailed studies of the morphology of extended sources, better identifying emitting regions.
- Multiwavelength analysis allows to study the emission mechanism.
- In the SNR catalog we have identified a statistically significant population of Galactic SNRs, including:
  - 17 **(4 new)** extended and 13 **(10 new)** pointlike SNR candidates
  - Candidate distribution to flux completeness of $10^{-8}\ ph\ cm^{-2}s^{-1}$ with a characteristic index of 2.5 and range [1.5, 4]
  - Candidates SNRs and ULs are generally within expectations if SNRs provide the majority of Galactic CRs.