SEXTEN CENTER FOR ASTROPHYSICS

cta cherenkov telescope array

fermi Gamma-ray Space Telescope

Galactic Science: from *Fermi*-LAT to CTA

F. de Palma

(INFN Bari and Università Telematica Pegaso),

on behalf of the

***Fermi*-LAT and CTA Collaborations**

Gamma Ray Astrophysics with CTA

Sexten 2017

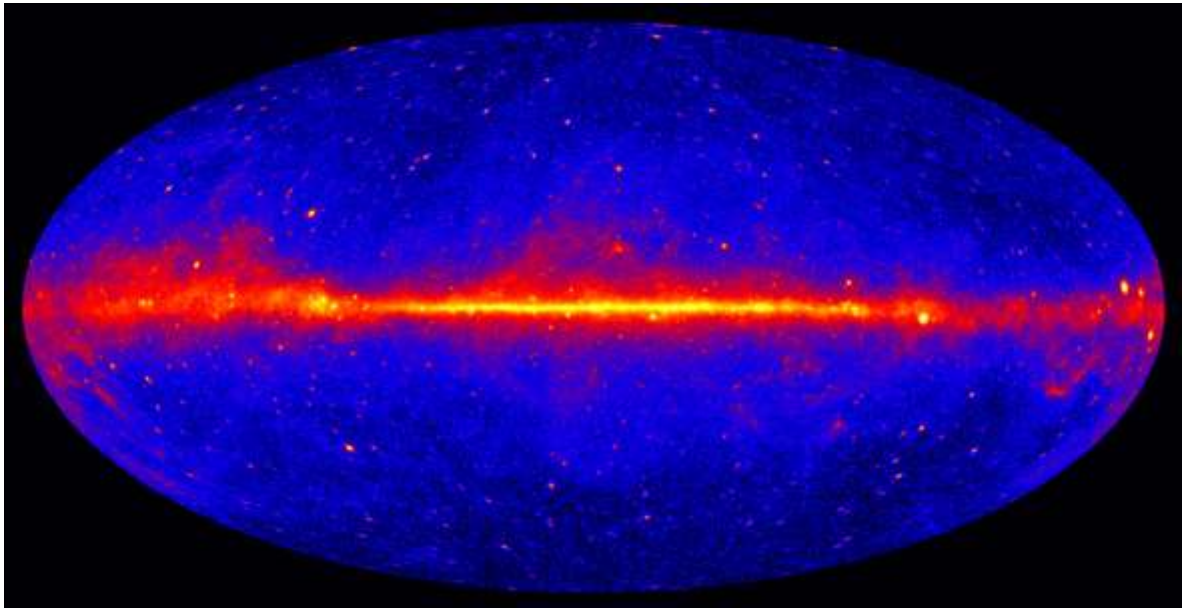
Outline

- Overview of Galactic sources
  - Pulsars
  - Pulsar Wind Nebulae
  - Binaries
  - Novae
- LAT SNR observations
- Catalogs
- Prospect for CTA Galactic science
- Conclusions

What does Fermi see of our Galaxy?

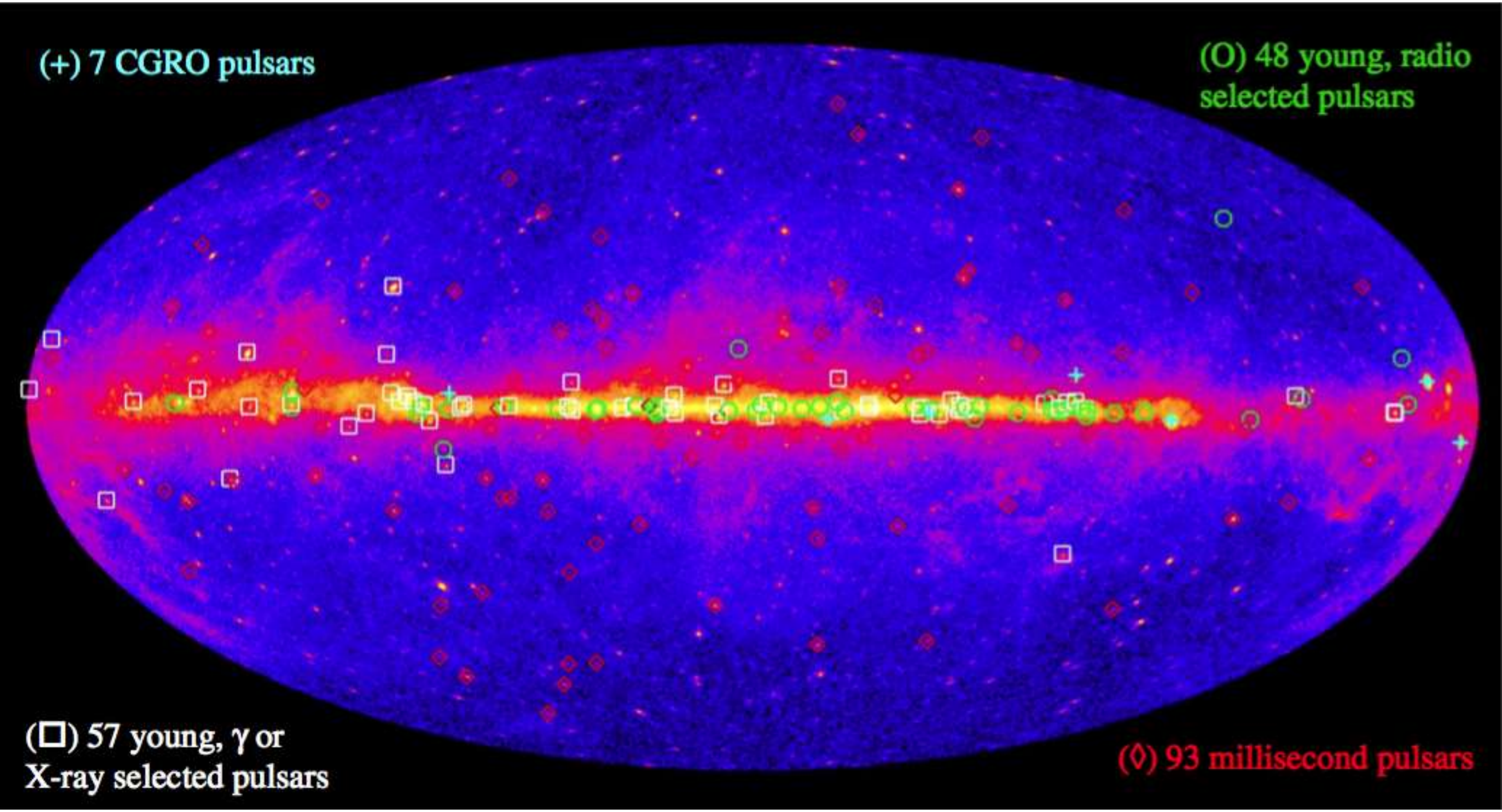
Galactic sources:

- **Pulsars**
- **PWNe**
- **Novae**
- **Binary systems**
- **SNRs**
- Galactic center and interstellar emission
- Solar System



3FGL Catalog: 3033 sources
6% are PSR and 5% other Galactic sources

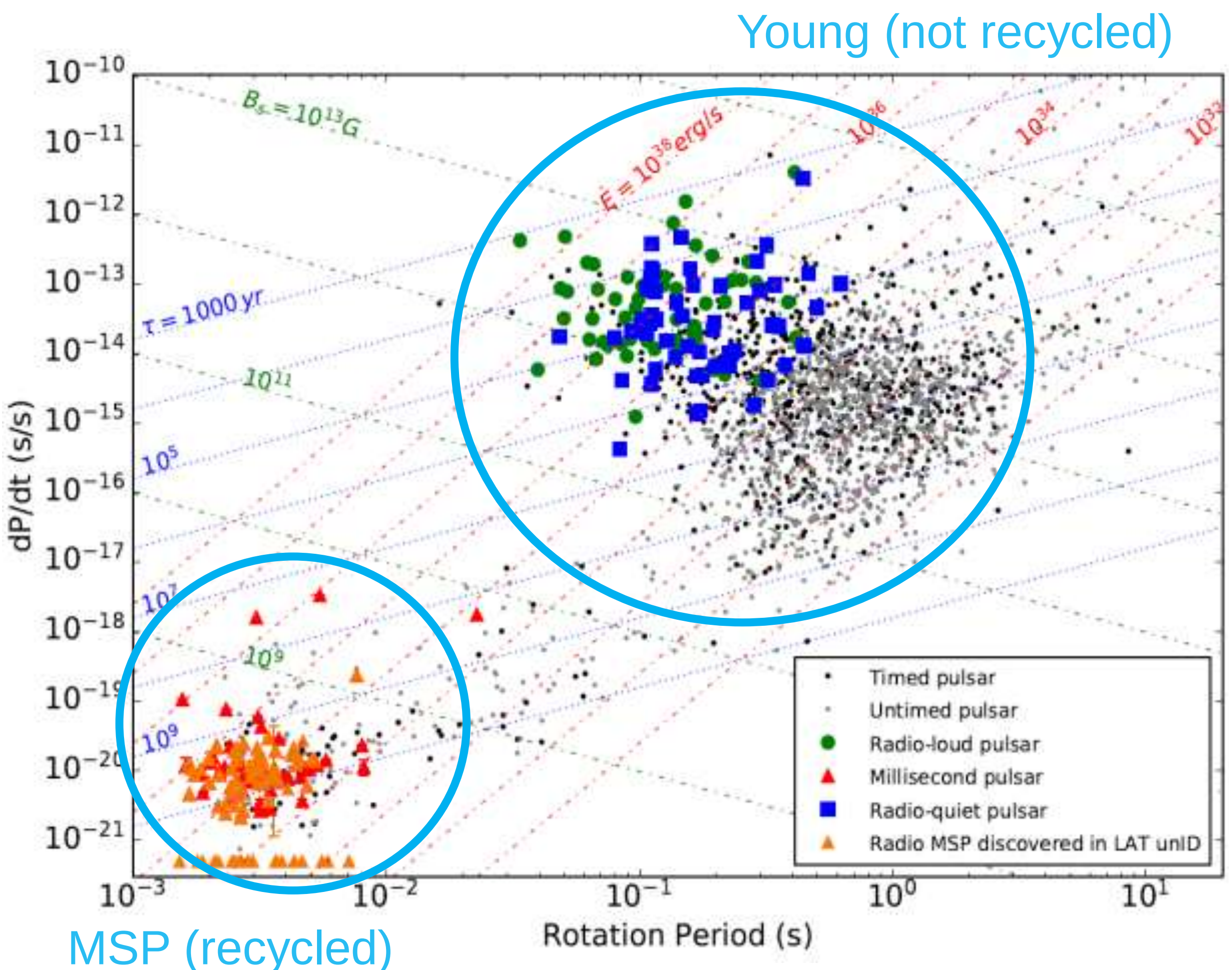
Now up to 205 γ-ray pulsars!



Current public gamma-ray pulsar list: http://tinyurl.com/fermipulsars

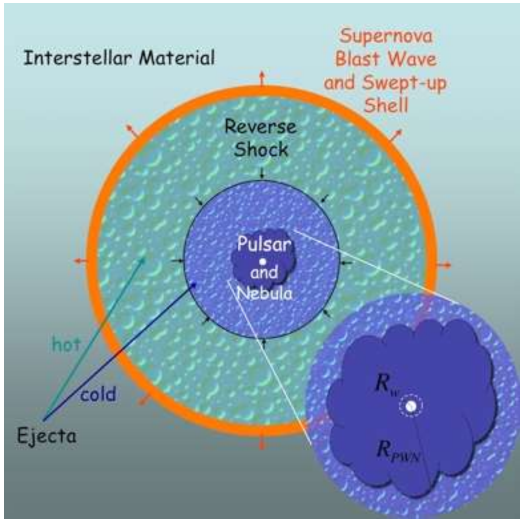
Credit: T. Johnson

Pulsar classes



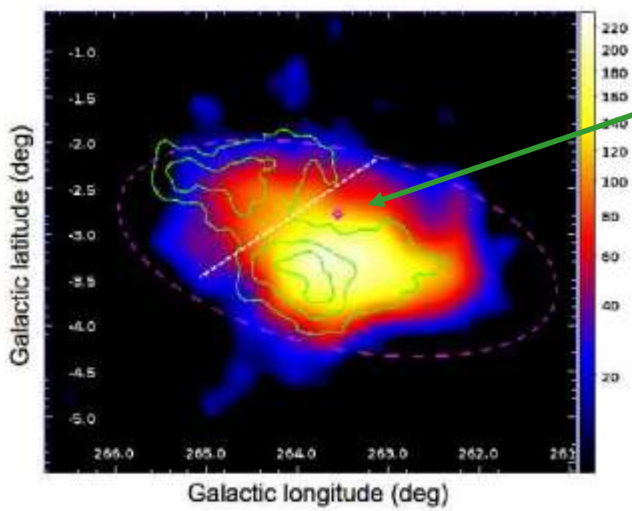
https://arxiv.org/abs/1706.03592

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.

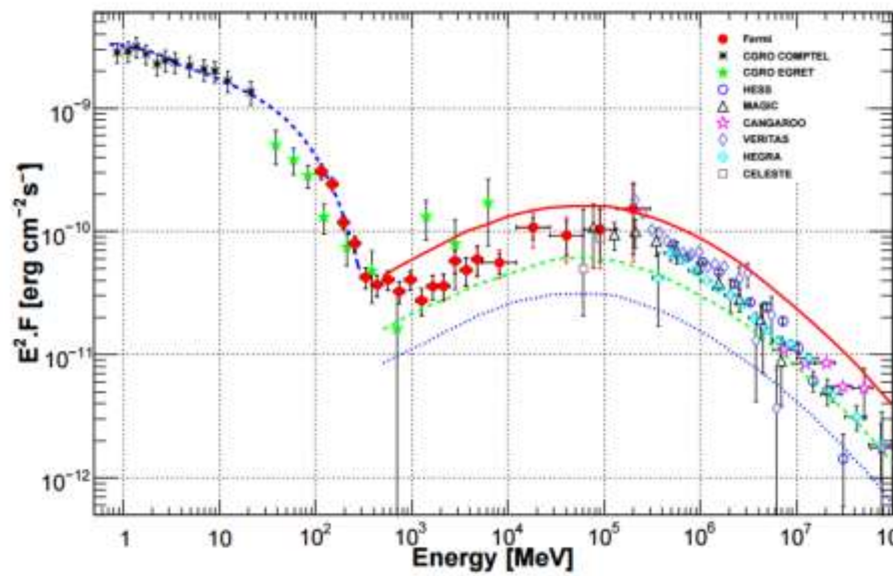
Vela X



Vela PSR

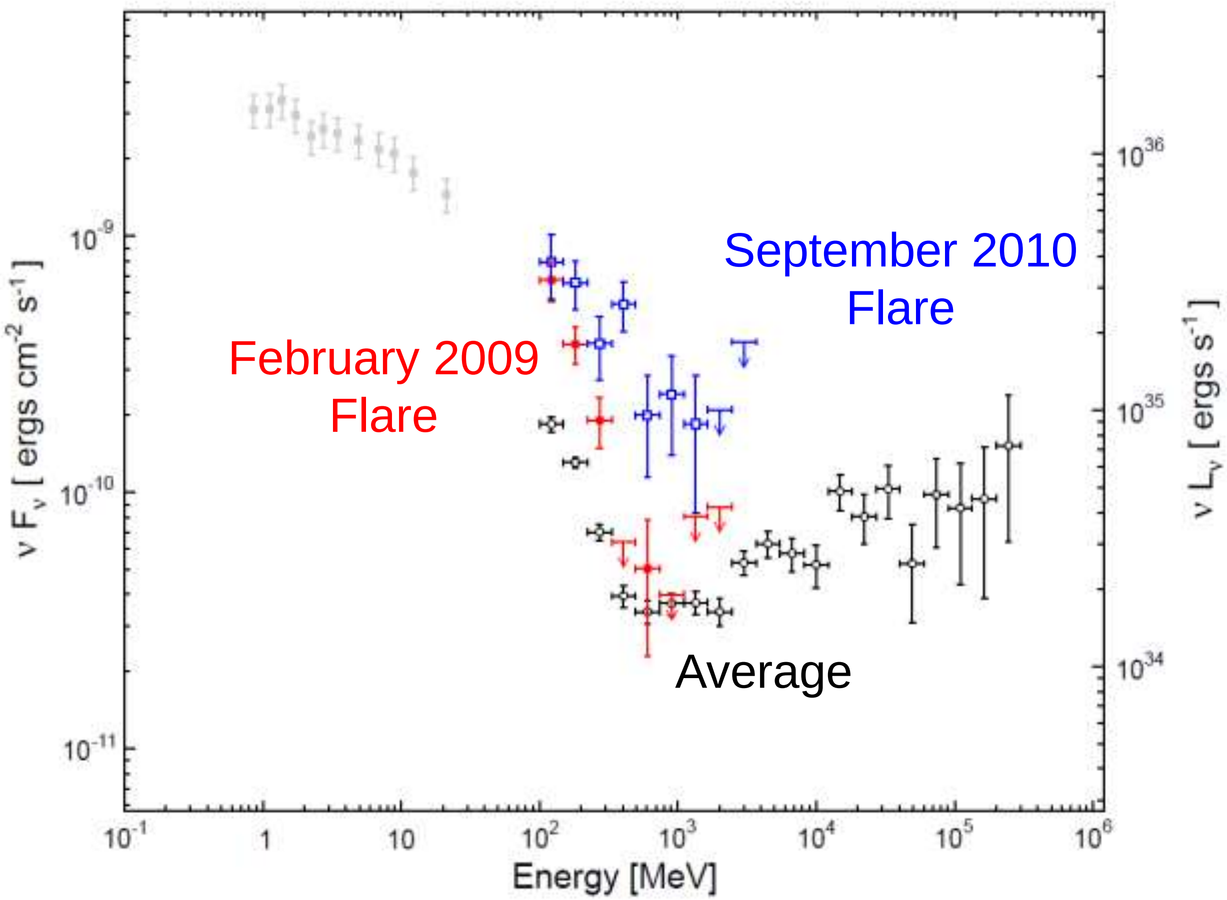
Grondin+ ApJ 2013

Crab



Abdo+ ApJ 2010

Crab not a standard candle

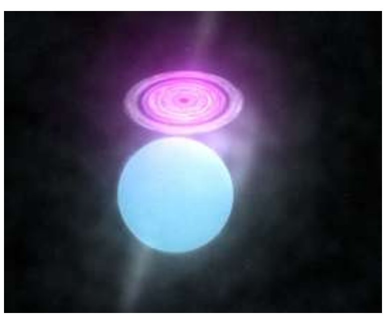


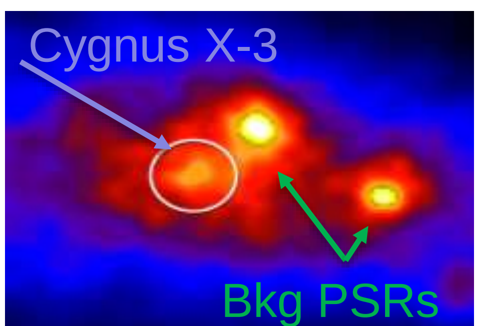
Abdo+ Science 2011, Buehler+ ApJ 2012 (2011 flare) Mayer+ ApJ 2013 (2013 flare)
Also detected by Agile: Tavani+ Science 2011

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.

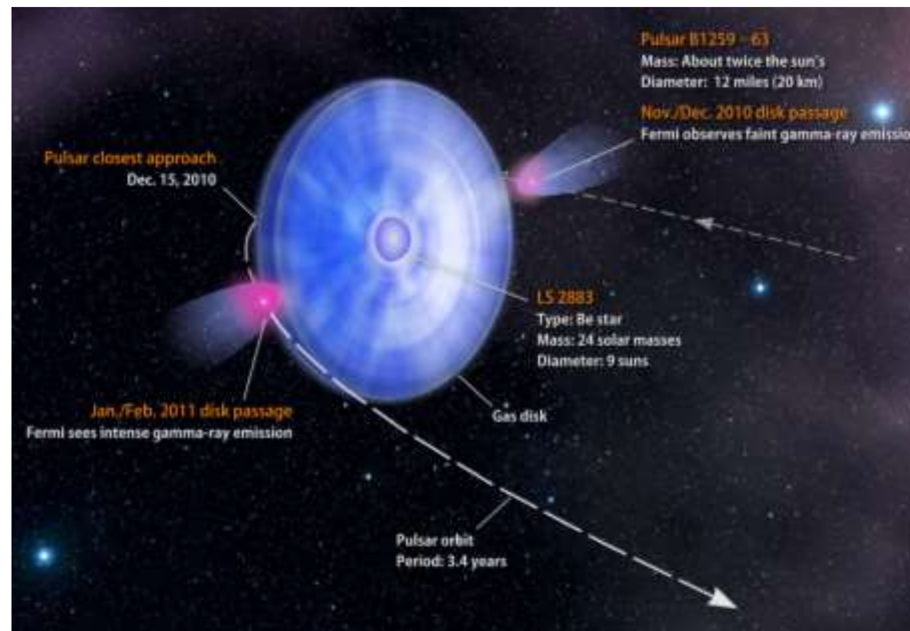




Corbel+ MNRAS 2012, Abdo+ Science 2009.
Also detected by Agile: Tavani+ Nature 2009

Pulsar Binaries: PSR B1259-63

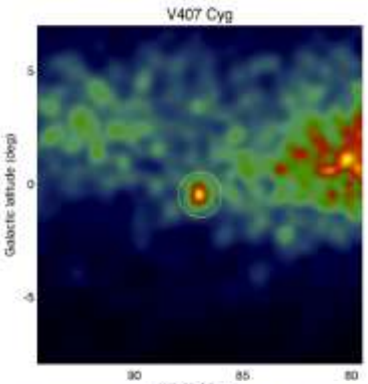
- Emission due to the interaction of the relativistic PSR wind and the photon field of the massive star.
- Periodicity: 3.4 years

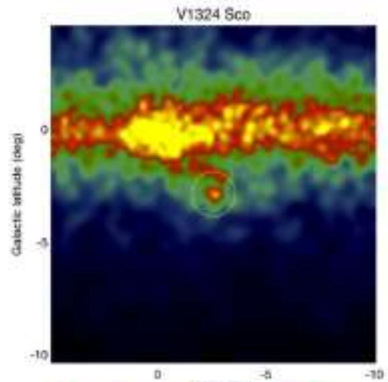


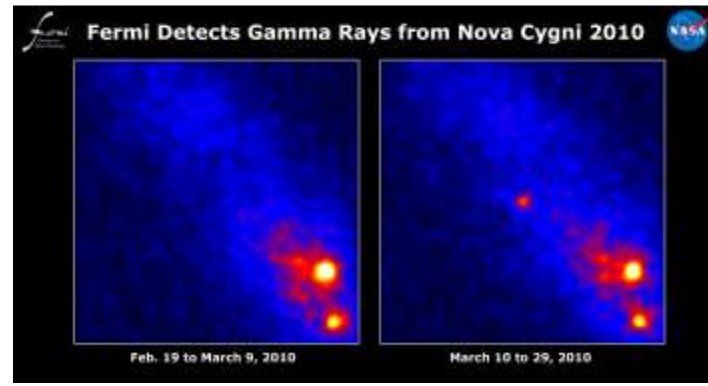
Abdo+ Apj 2011.

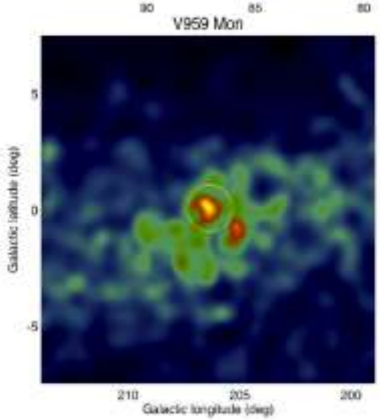
γ-ray Novae

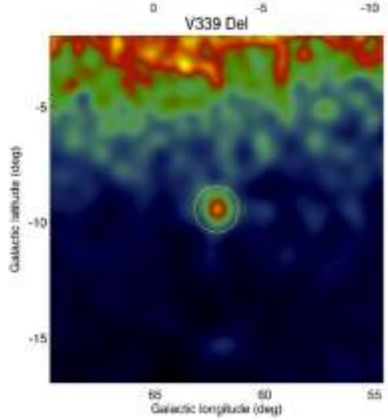
- 6 Novae detected up to now (ongoing researches on new candidates)
- Soft spectrum transient γ-ray sources detected over 2–7 weeks.
- Unexpected high-energy particle acceleration processes linked to the mass ejection from thermonuclear explosions.

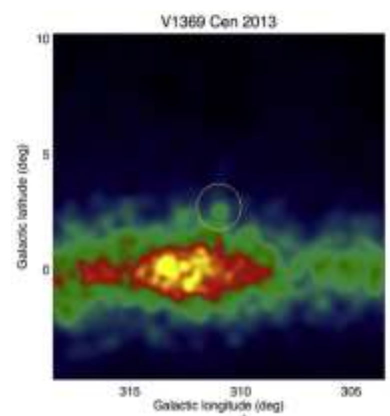


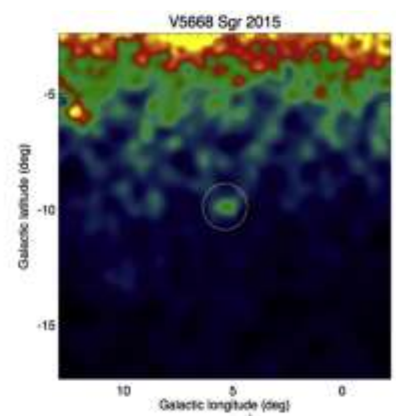






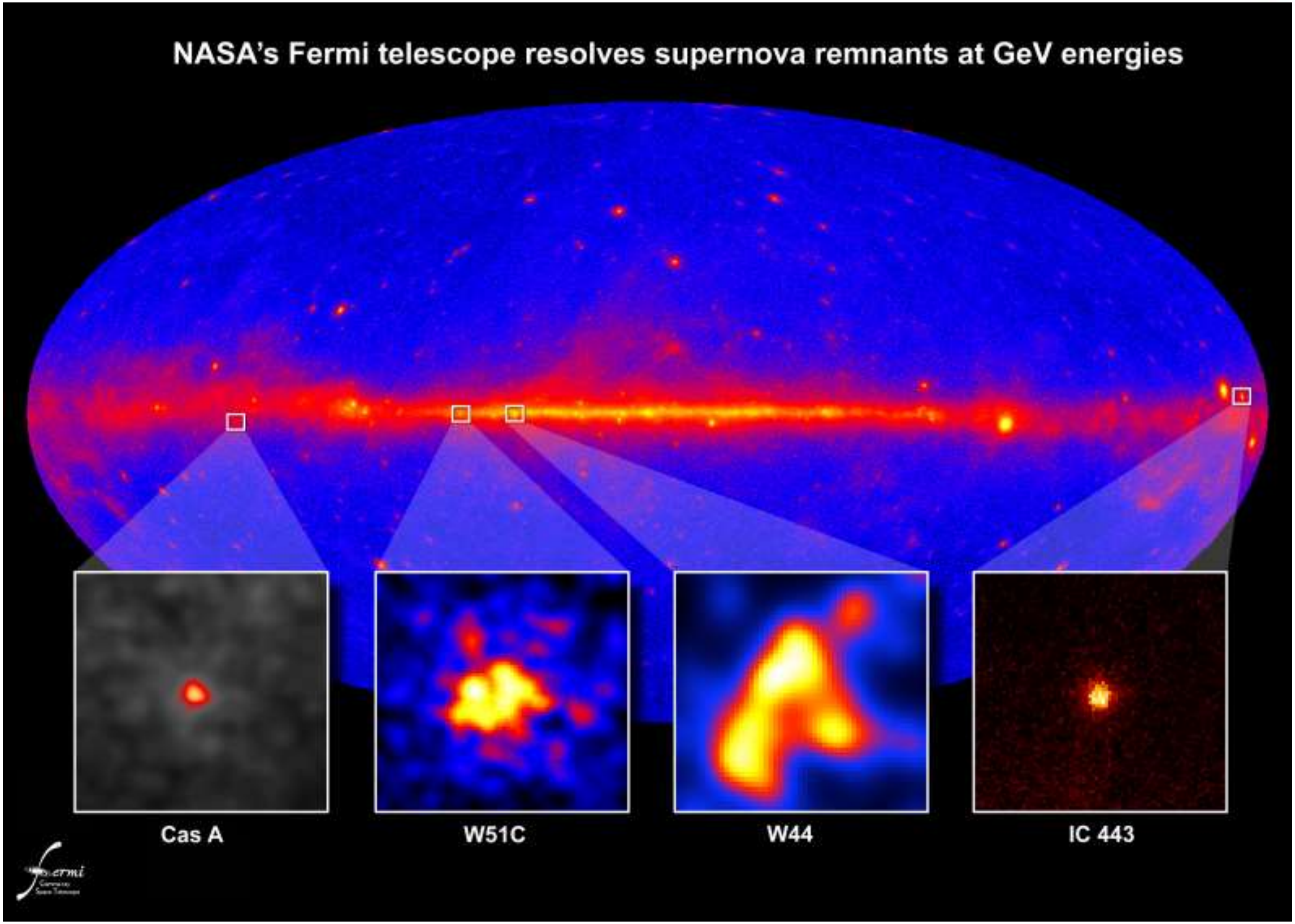




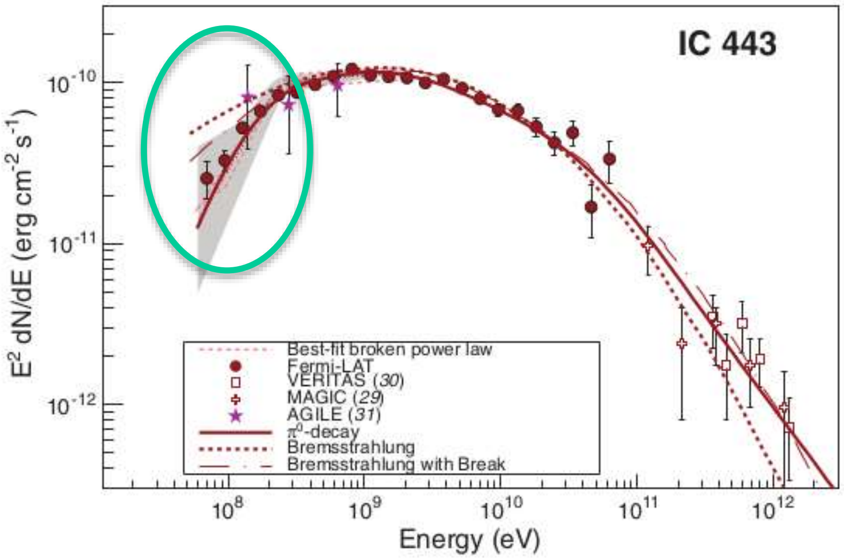


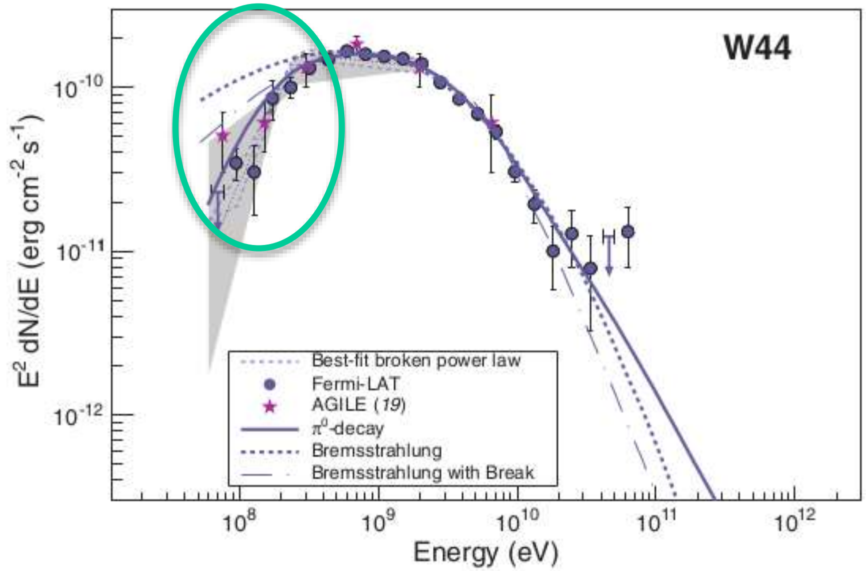
Abdo+ Science 2010
Ackermann+ Science 2014
Cheung+ Apj 2016

Supernova Remnants

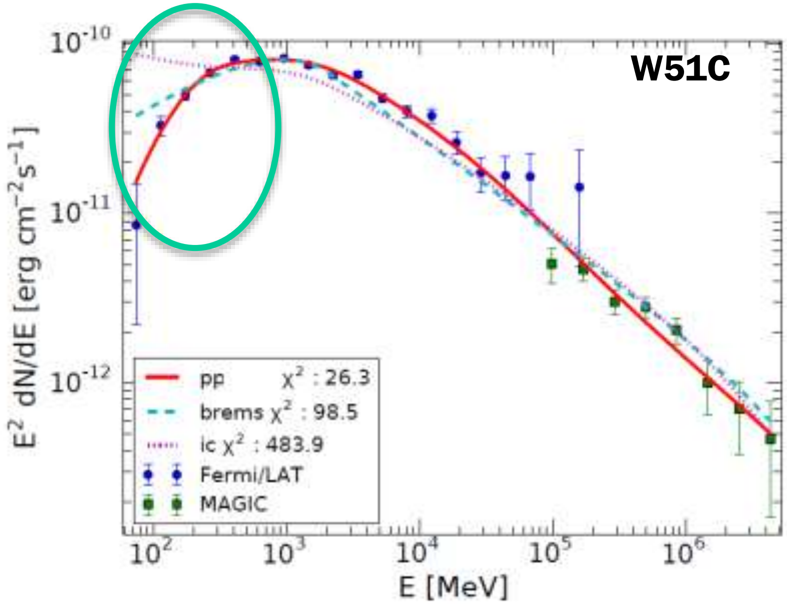


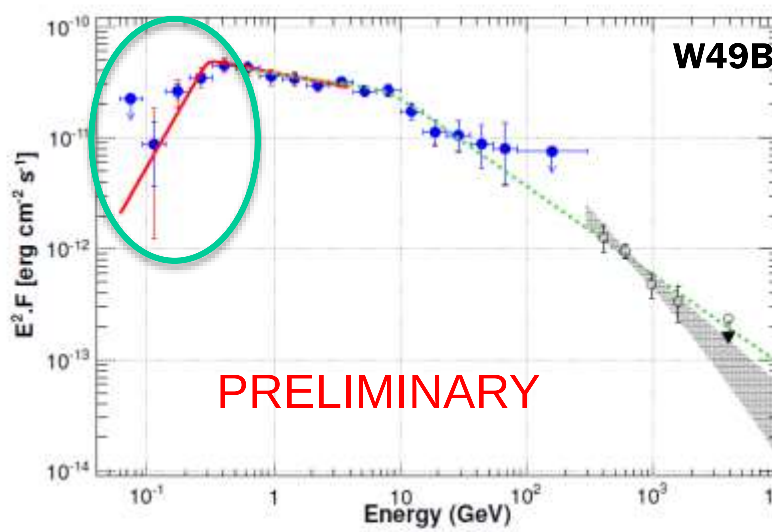
SNRs with hadronic emission





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

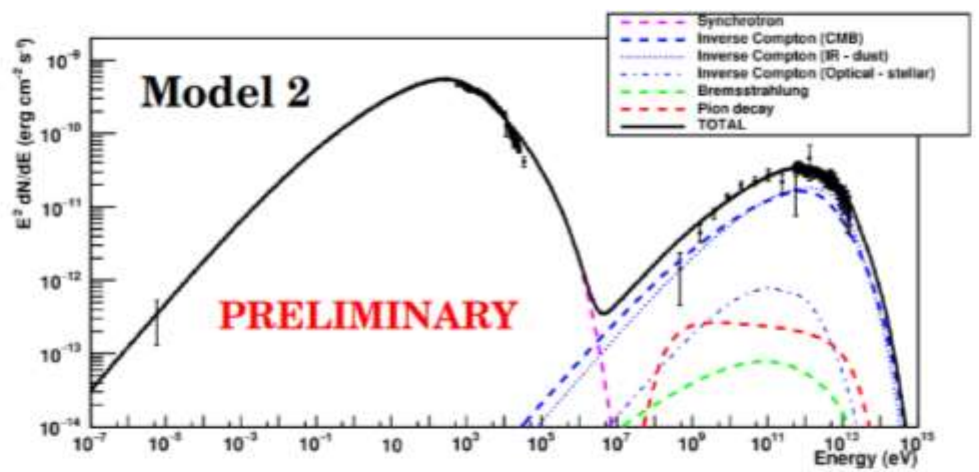
Young SNRs

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

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

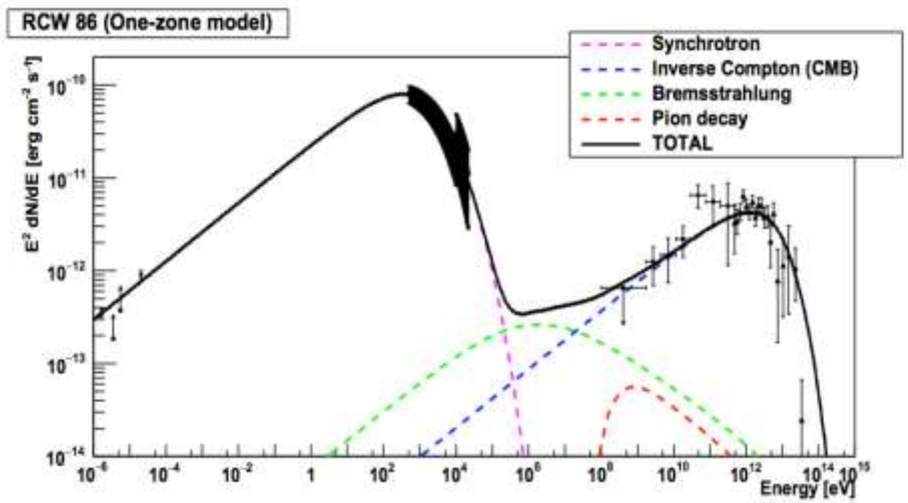
<u>Leptonic scenario</u>

RX J1713.7-3946



B. Condon+ @ Gamma 2016

RCW 86

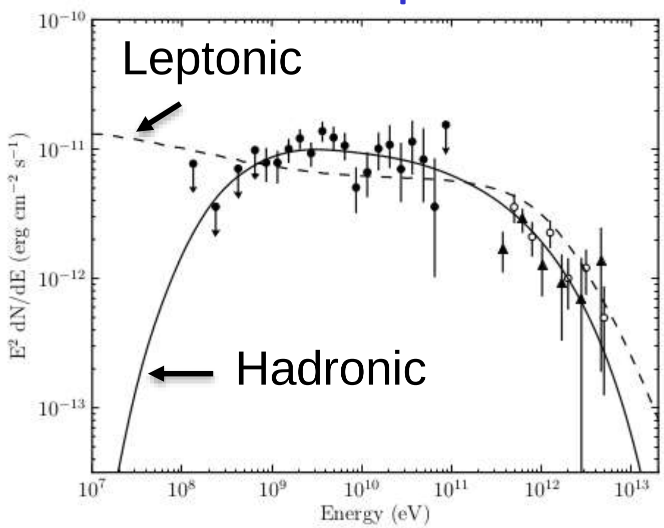


M. Ajello+ ApJ 2016

γ-ray emission dominated by Inverse Compton

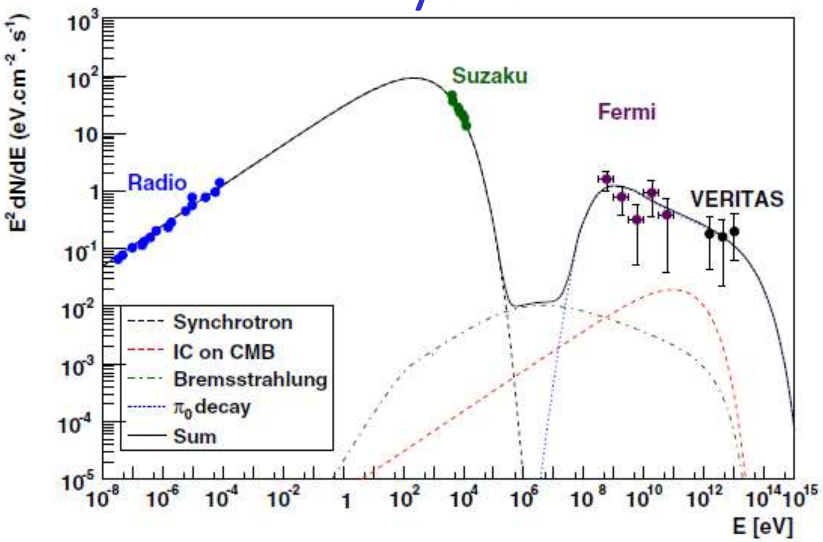
Hadronic scenario

Cassiopeia A



Y. Yuan+ ApJ 2013
Also in: M. L. Ahnen+ 2017 Submitted

Tycho



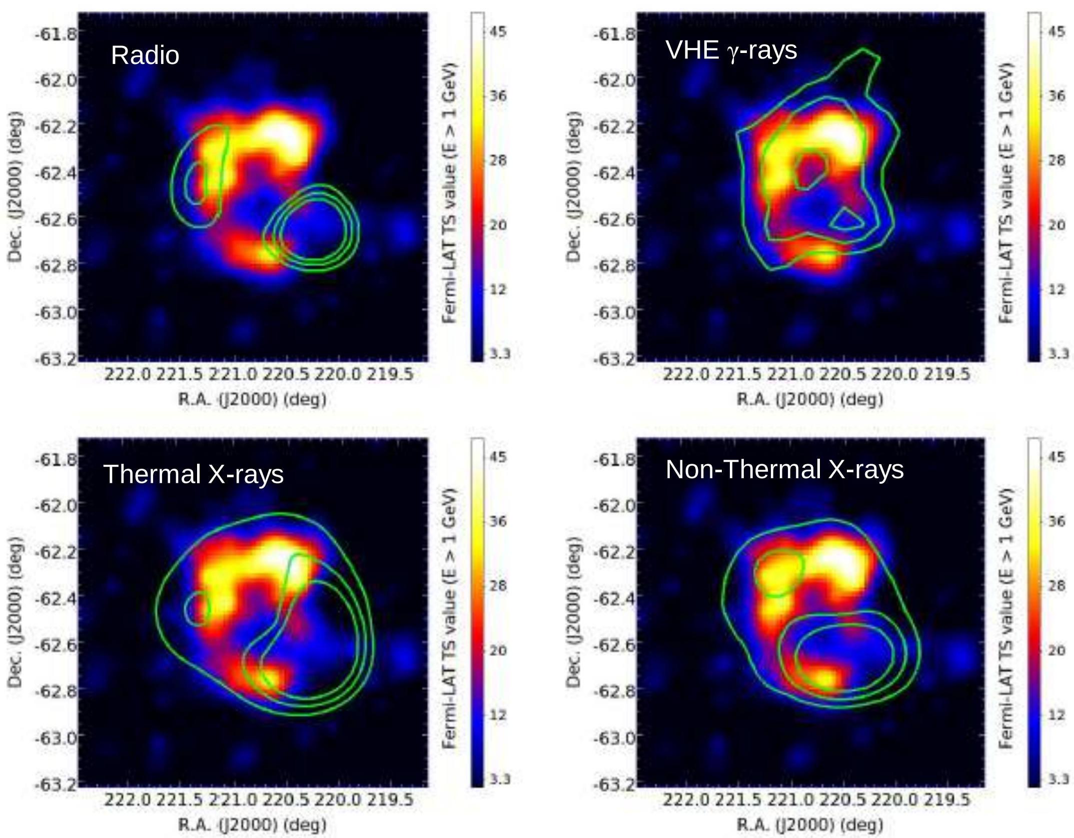
F. Giordano+ ApJL 2012
Also in: S. Archambault 2017 Accepted by ApJ

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°

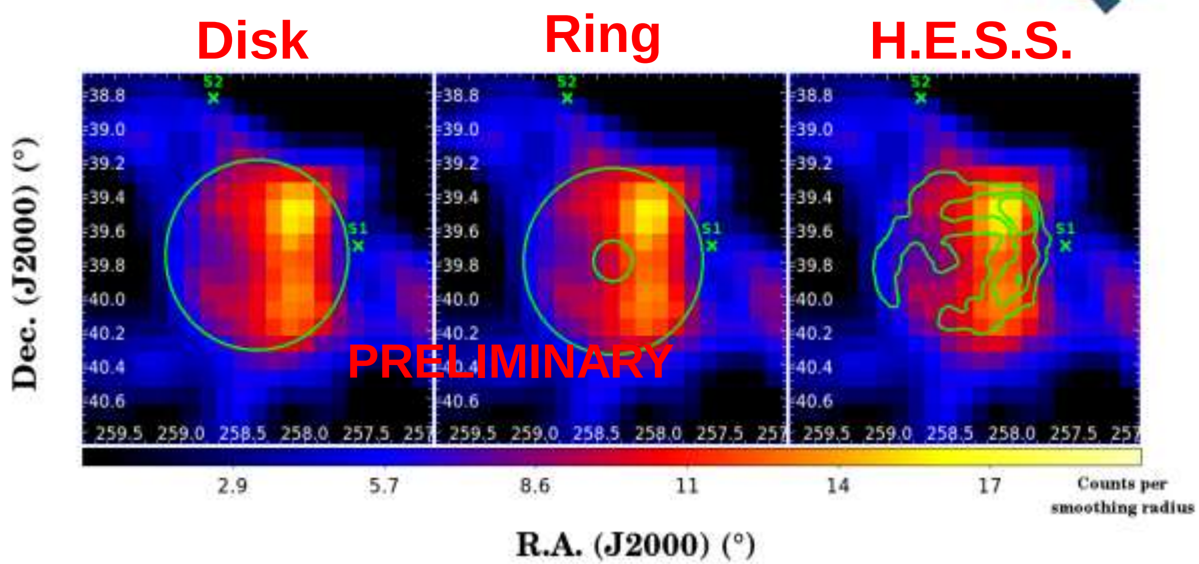
Best morphological photon distribution: **H.E.S.S. template**
(A. Abramowski+,
accepted for publication by A&A)

Multi-zone analysis ongoing

IC 443

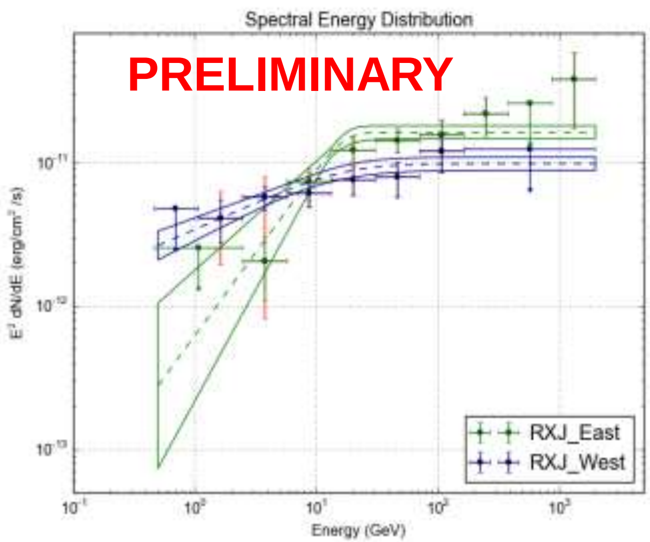
Preliminary results in
Hewitt+ @ Fermi Symposium 2015

RX J1713.7-3946 with Pass 8



- Improved spatial correlation with TeV template (*Aharonian + 2006)*

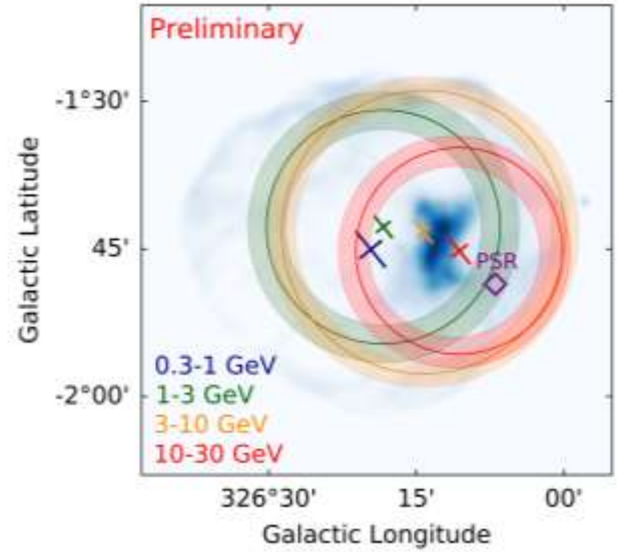
- 3.5 σ significance of improvement using a split template



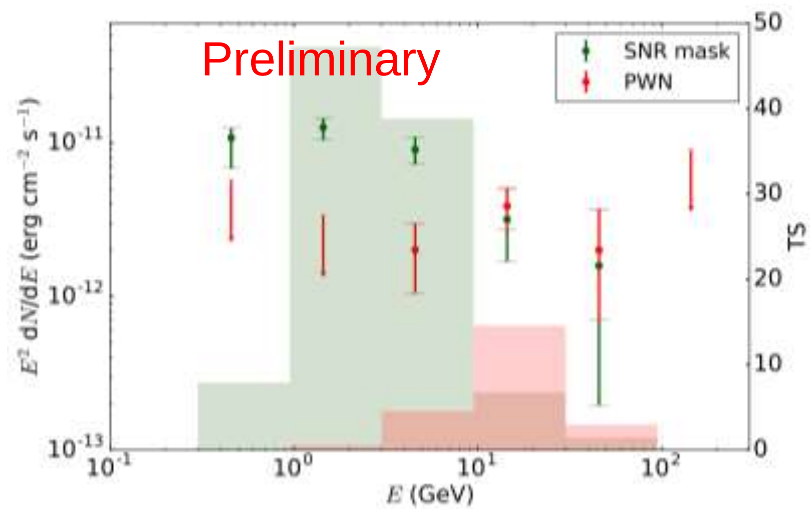
Condon, B+ @ Gamma 2016

G326.3-1.8

- Energy dependent morphology
  - Clear trend toward the PWN at higher energies



- Harder and softer spectrum for the PWN and the SNR respectively



Devin, J+ @ SF2A 2017

3FHL identification & association

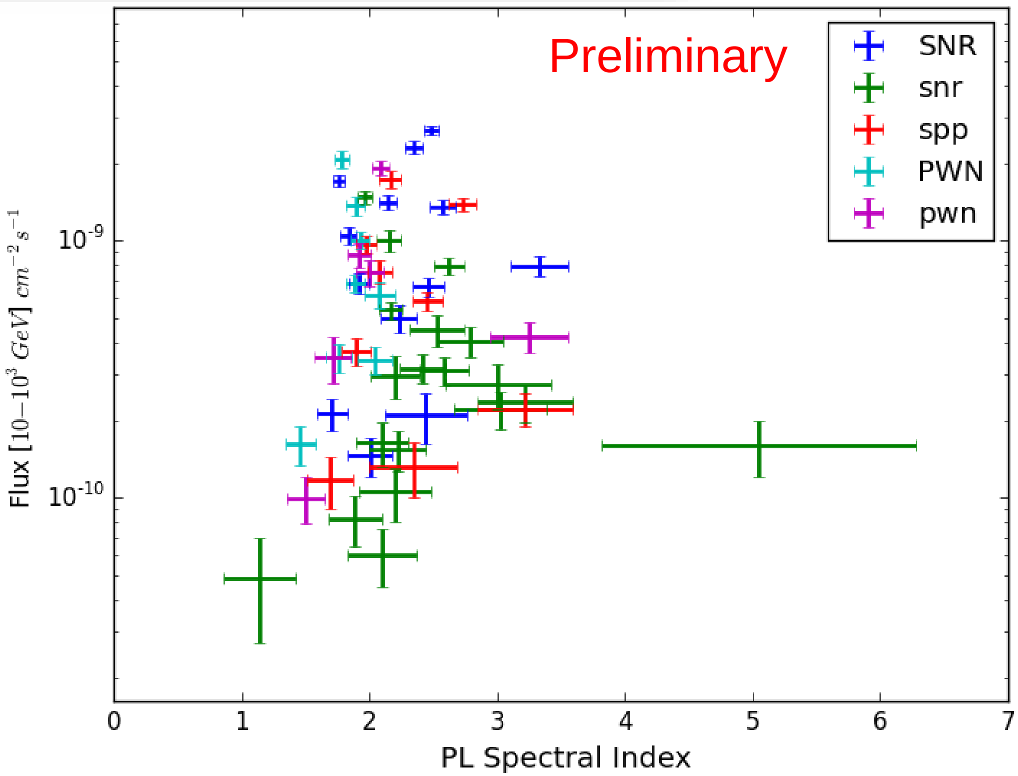
Description	Identified Designator	Identified Number	Associated Designator	Associated Number
Pulsar	PSR	58	psr	7
Pulsar Wind Nebula	PWN	8	pwn	6
Supernova remnant	SNR	13	snr	19
Supernova remnant / Pulsar wind nebula	...	...	spp	9
High-mass binary	HMB	3	hmb	1
Binary	BIN	1	...	...

Data:

- Pass 8,
- 7 Years,
- 10-10^3 GeV
- 1556 objects (8% Galactic)

Preliminary version: Arxiv:1702.00664

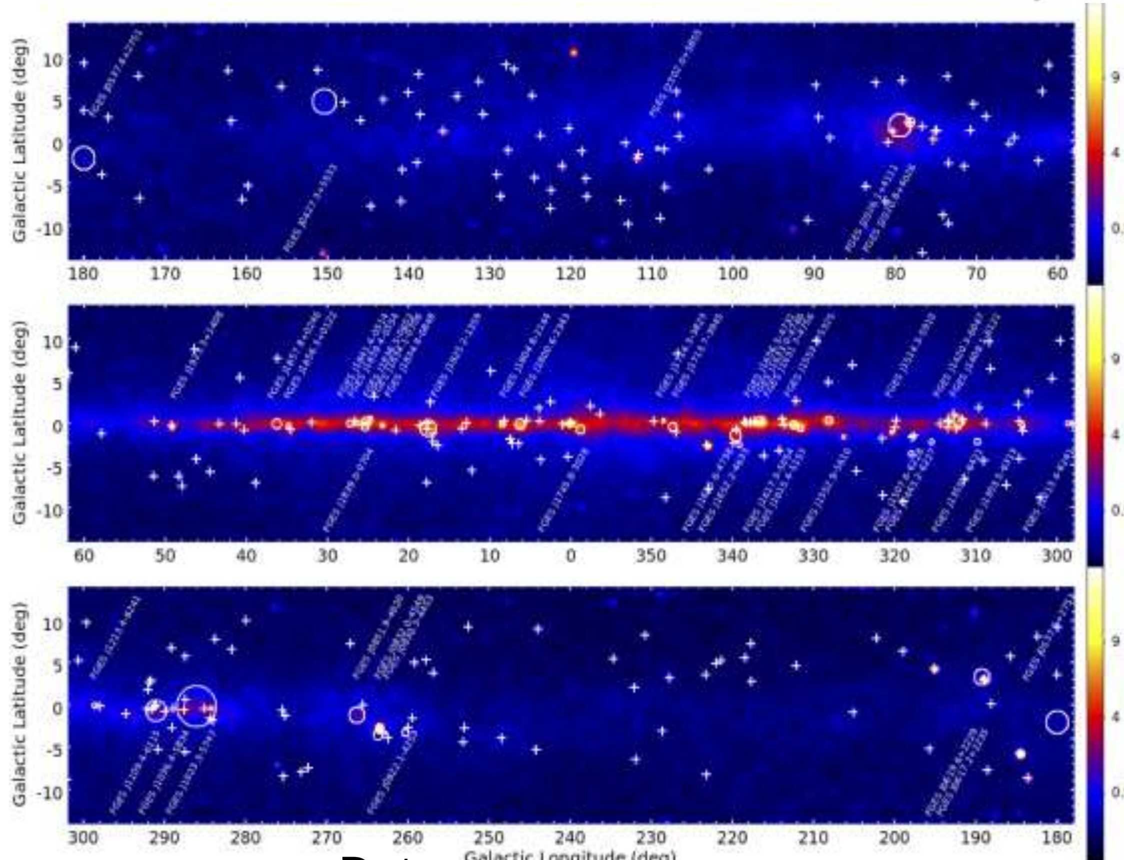
Fits on the FSSC webpage: gll_psch_v11.fit



FGES

- Study of extended sources in the Galactic plane
- Detected 46 extended sources:
  - 16 are new
  - 13 agree with previous publications
  - 17 have a different morphology.
  - Only 4 known LAT extended sources were not detected since they don't have emission above 10 GeV

Preliminary version:
Arxiv:1702.00476



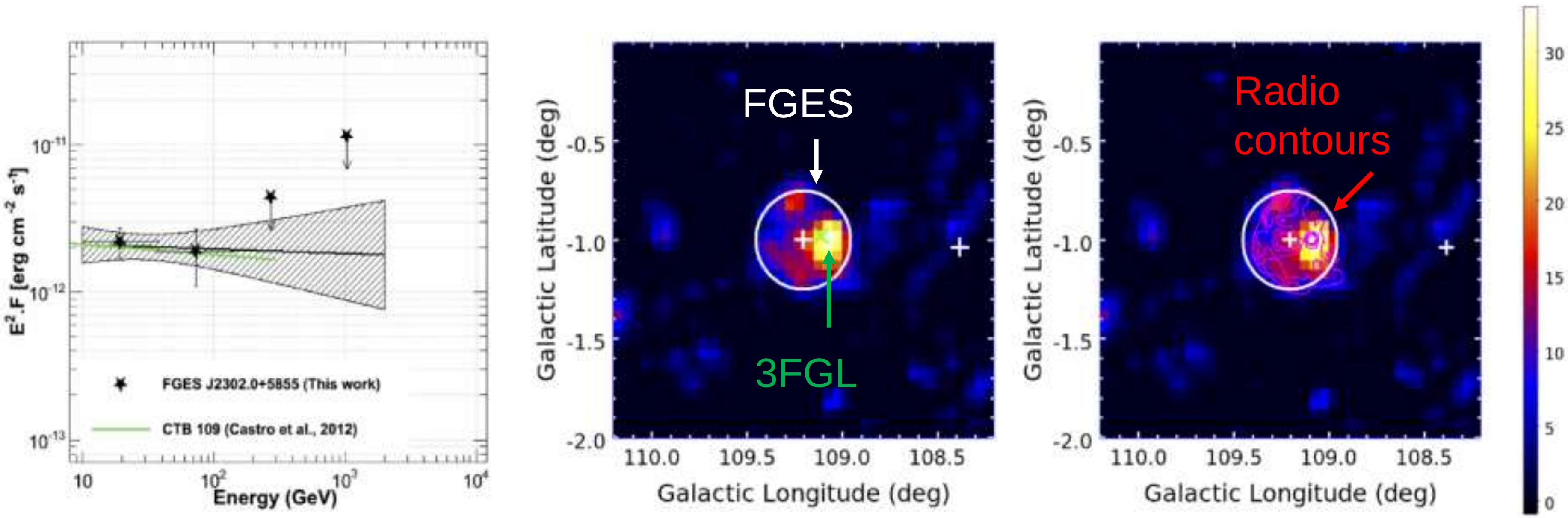
Data:

- Pass 8,
- 6 Years,
- 10 GeV - 2 TeV

Sources modeled as flat disk

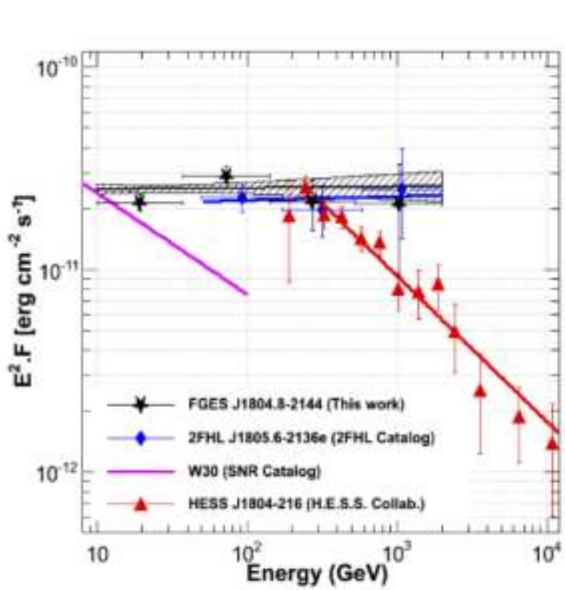
New extended sources in FGES: CTB109

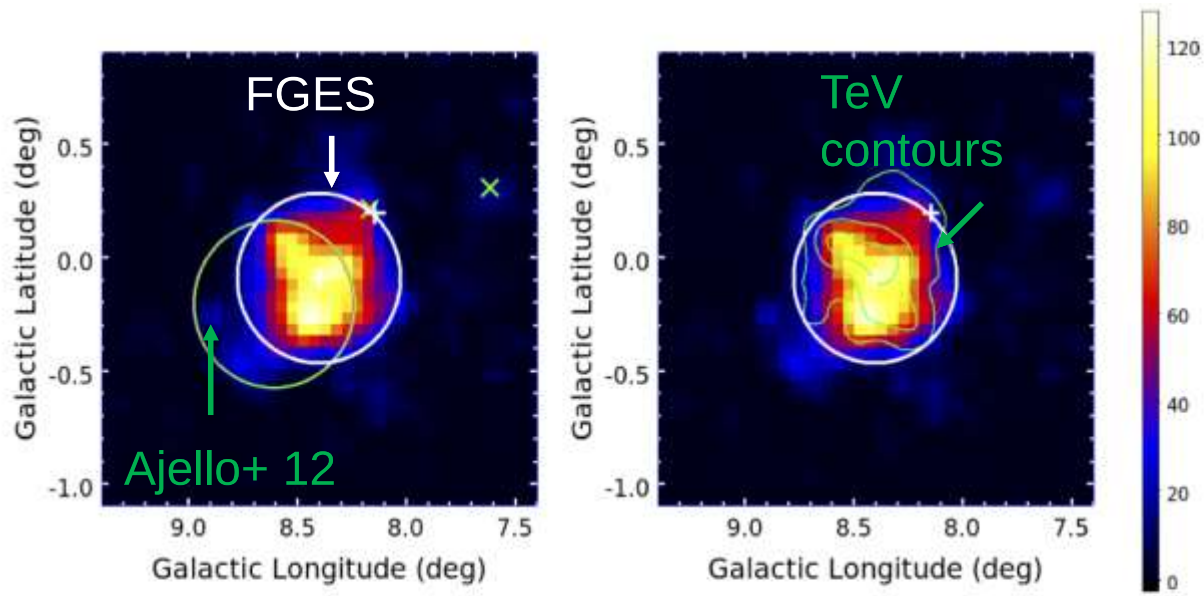
- First detection of gamma-ray extension (point source in Castro+ 2012)
- Good agreement with x-ray/radio size
- Rules out giant molecular cloud west of remnant
- Good candidate for TeV observation



Energy dependence: W30 region

- Previous analysis starting at 2 GeV (Ajello+ 2012) correspond to radio structure while at above 10 GeV (FGES) it seems to correspond to TeV contours (HESS J1804-216, Aharonian+2006)
- Origin of the GeV TeV emission:
  - PWN, but it is unusually large spatial extent for a PWN, or
  - interaction of escaping CR with nearby MC





SNR catalog results

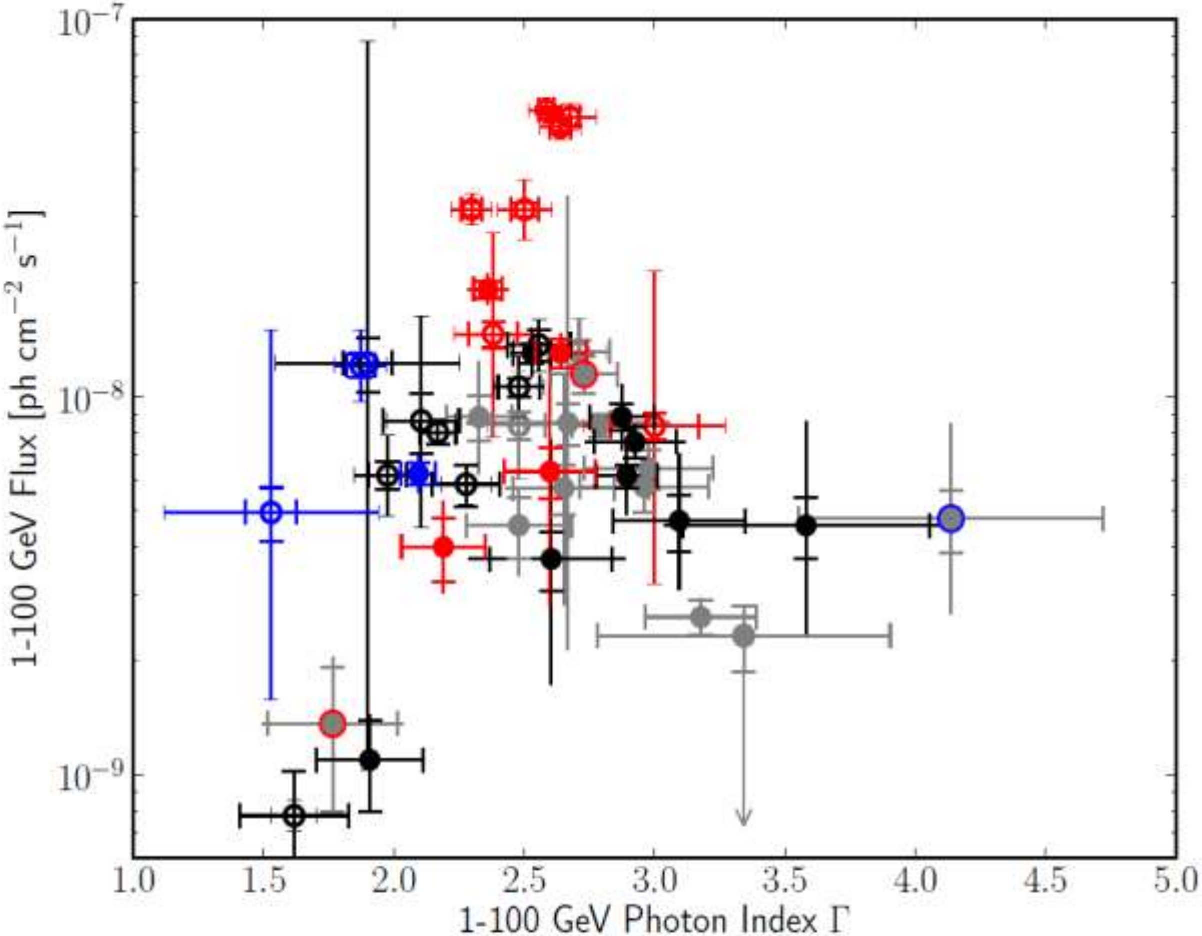
Characterized 279 regions containing known radio SNRs:

- 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.

Acero+ 2016 APJS

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.

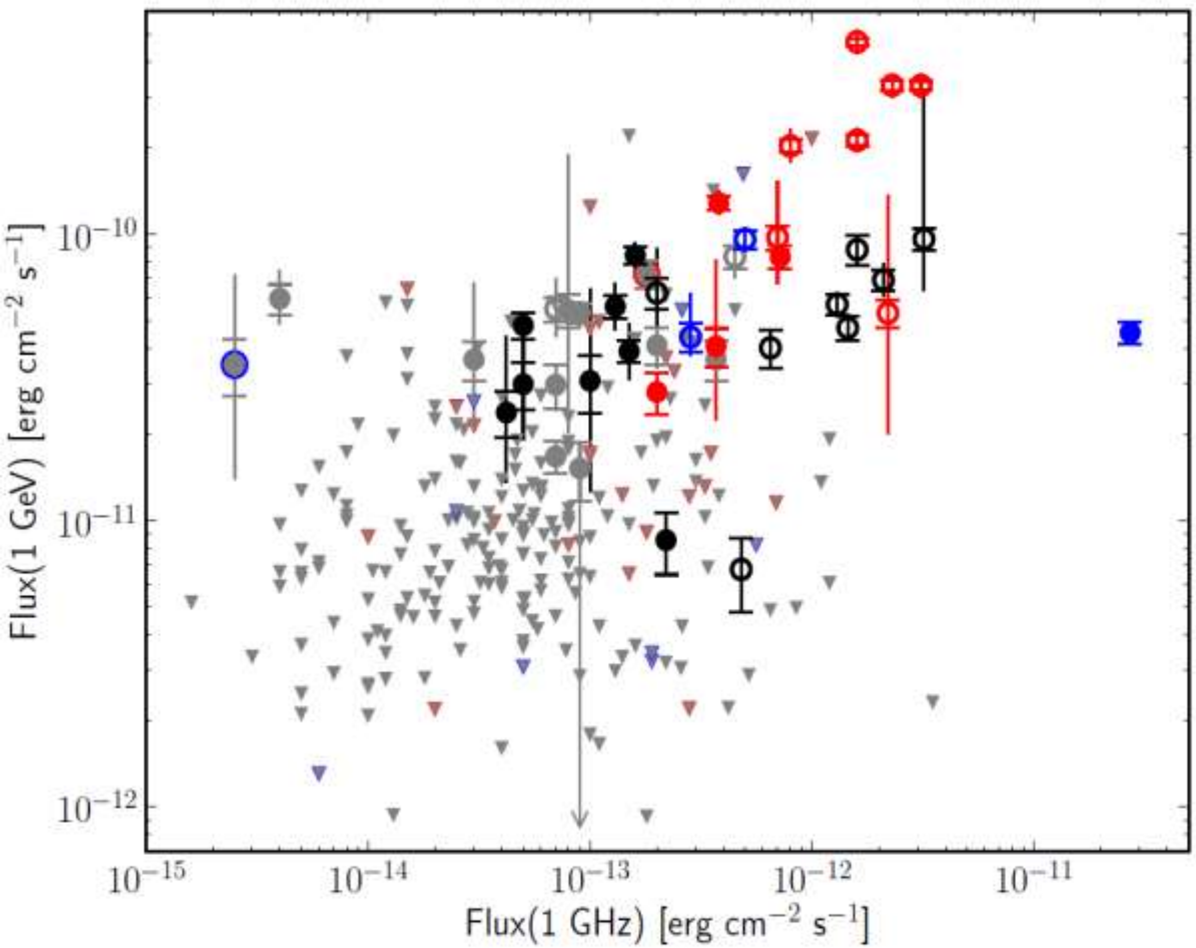


- Interacting SNRs density $\geq\ 100\ cm^{-3}$
- Young SNRs show evidence of non-thermal X-ray emission
- Classified candidates
- Marginal candidates
- Pointlike sources
- Extended sources

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

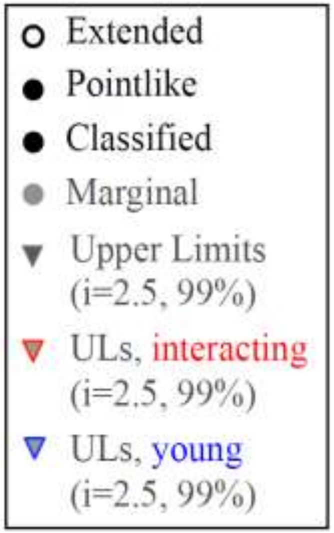
Radio-GeV Flux

LAT-detected SNRs tend to be radio-bright:



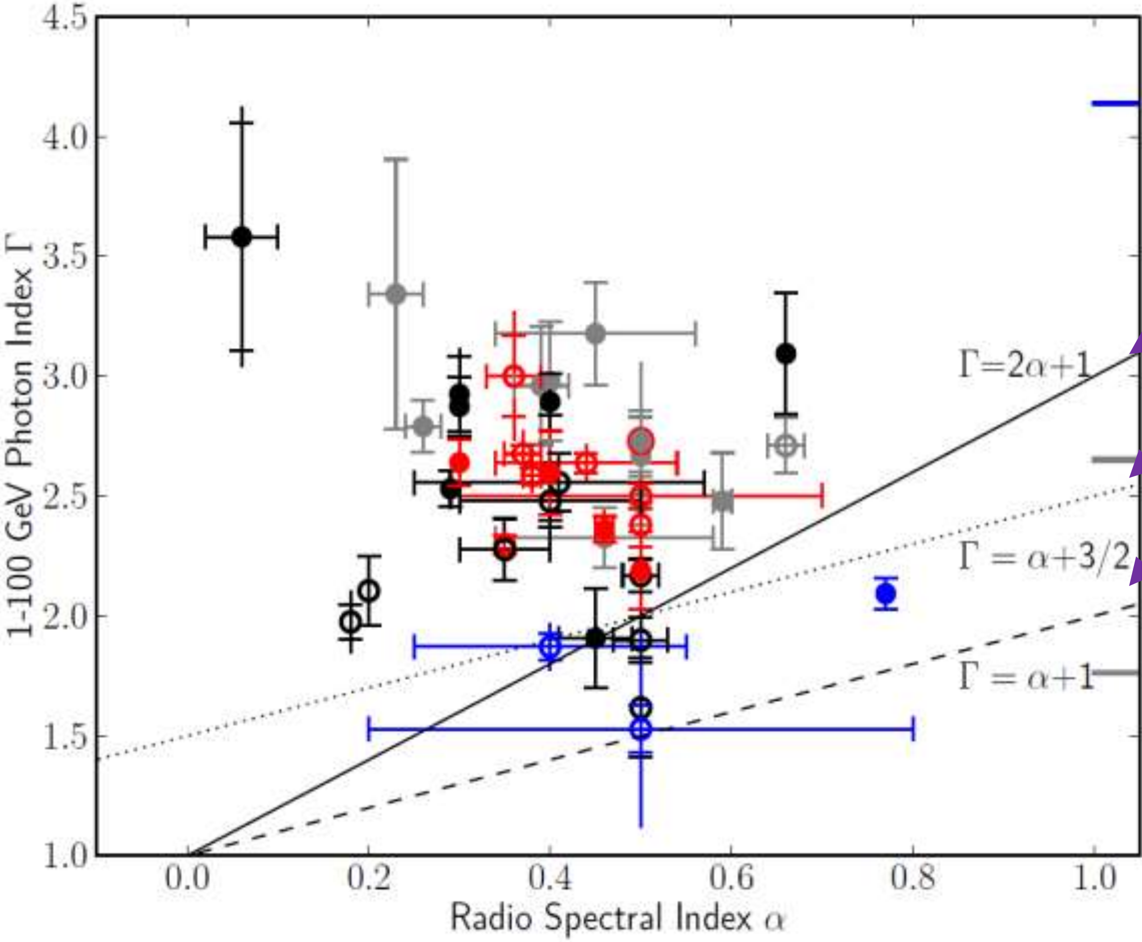
- Interacting SNRs: general correlation?
- Young SNRs show more scatter

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



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:



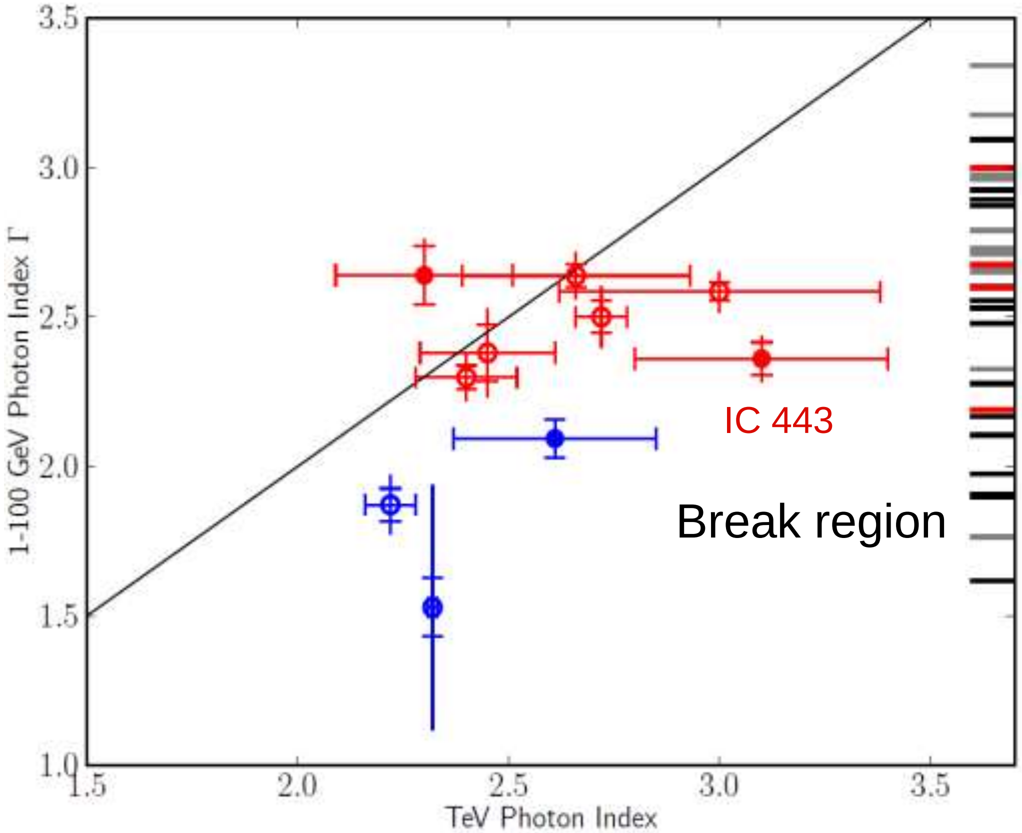
- Young SNRs: seem consistent
- Others, including interacting SNRs: softer than expected

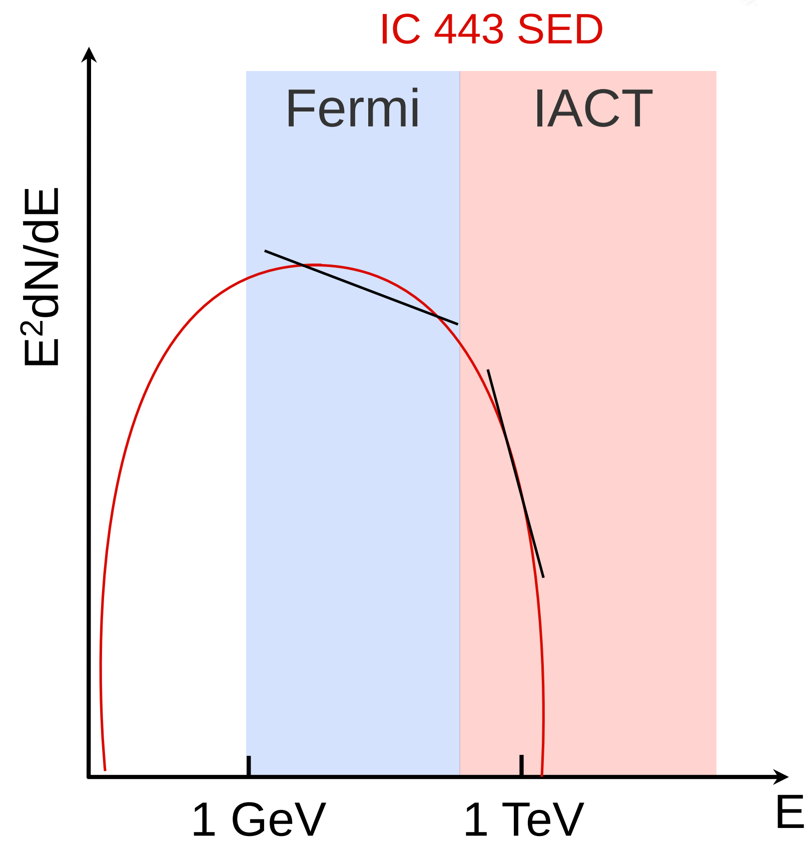
- π^0 decay or $e^{+/-}$ brem.
- Inverse Compton w cooling
- inverse Compton w/o cooling

Data now challenge model assumptions!

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

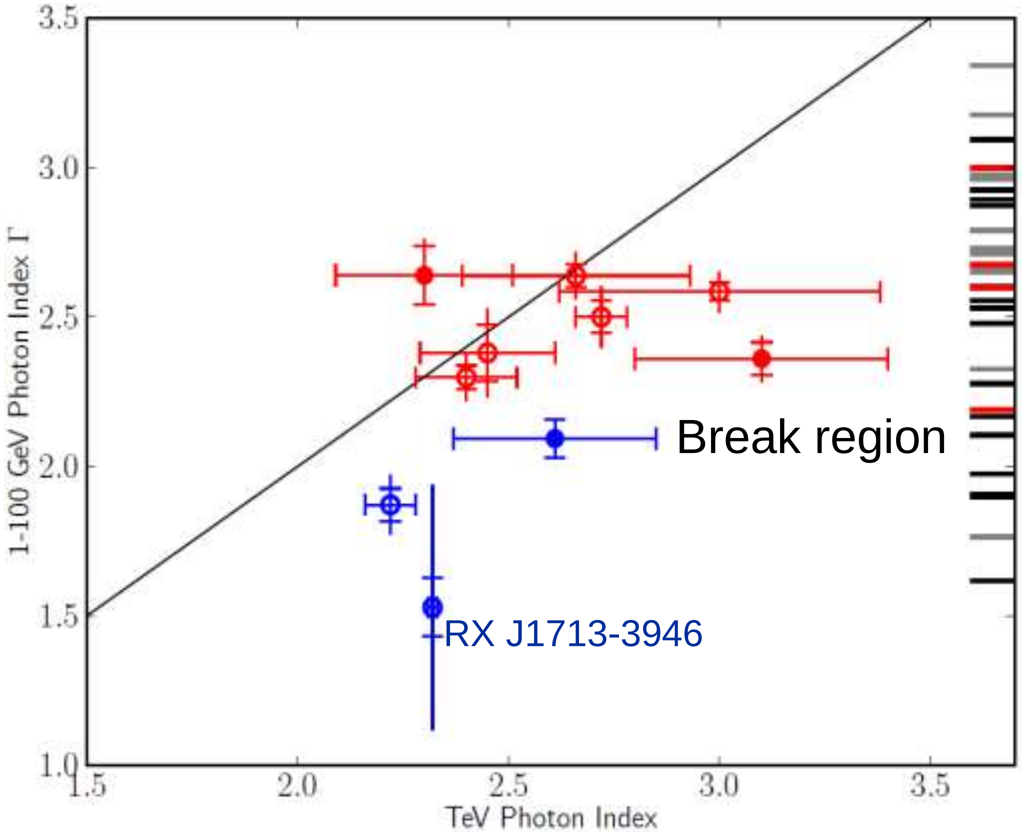
GeV-TeV Index

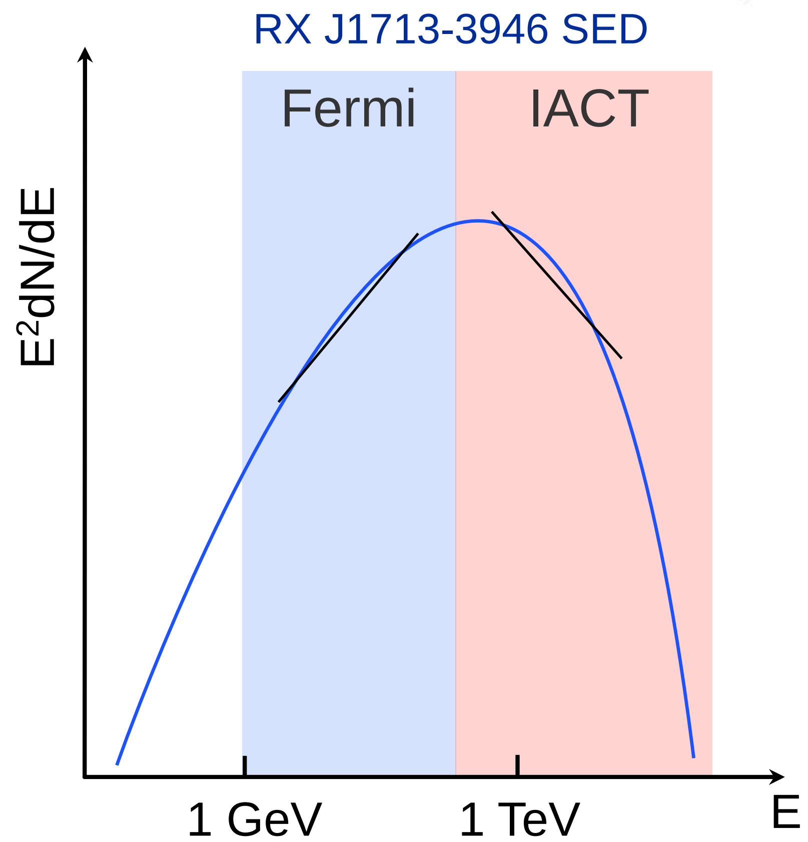




- Indication of break at TeV energies
- Caveat: TeV sources are not uniformly surveyed.

GeV-TeV Index



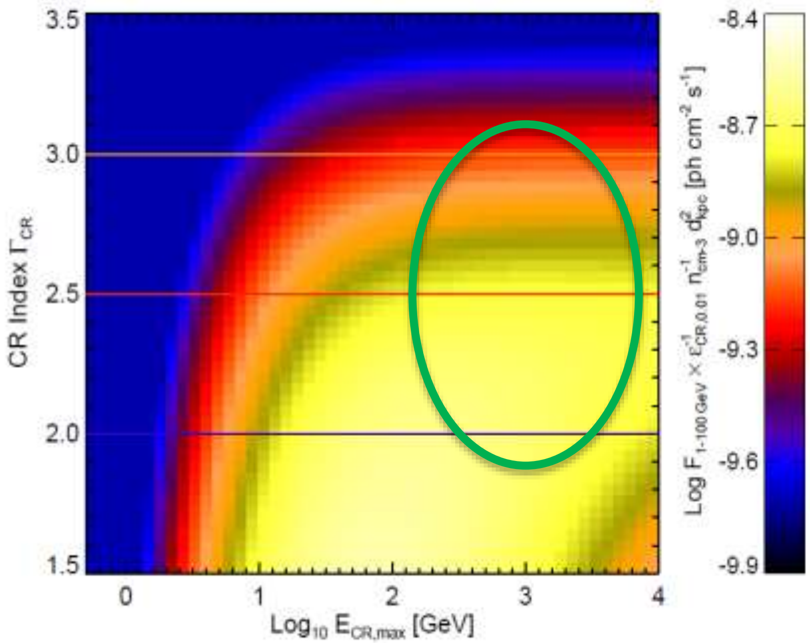


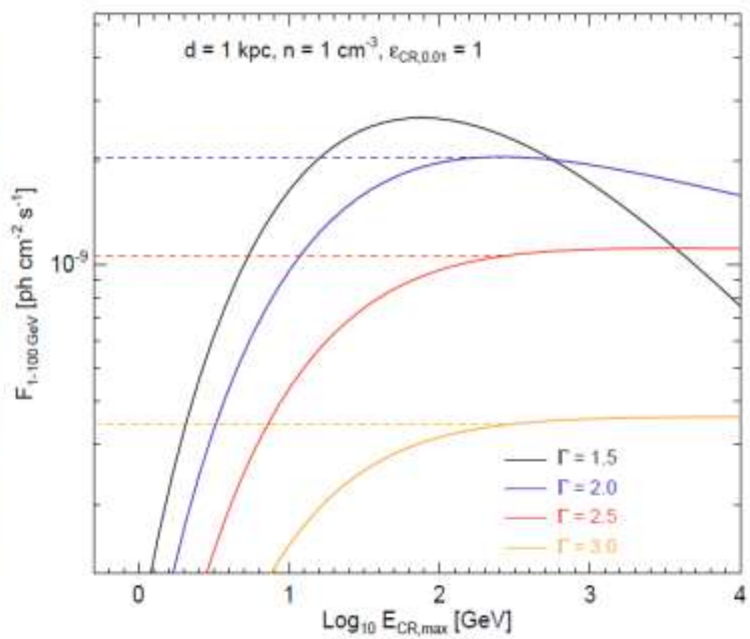
- Indication of break at TeV energies
- Caveat: TeV sources are not uniformly surveyed.

Constraining CR emission

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

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

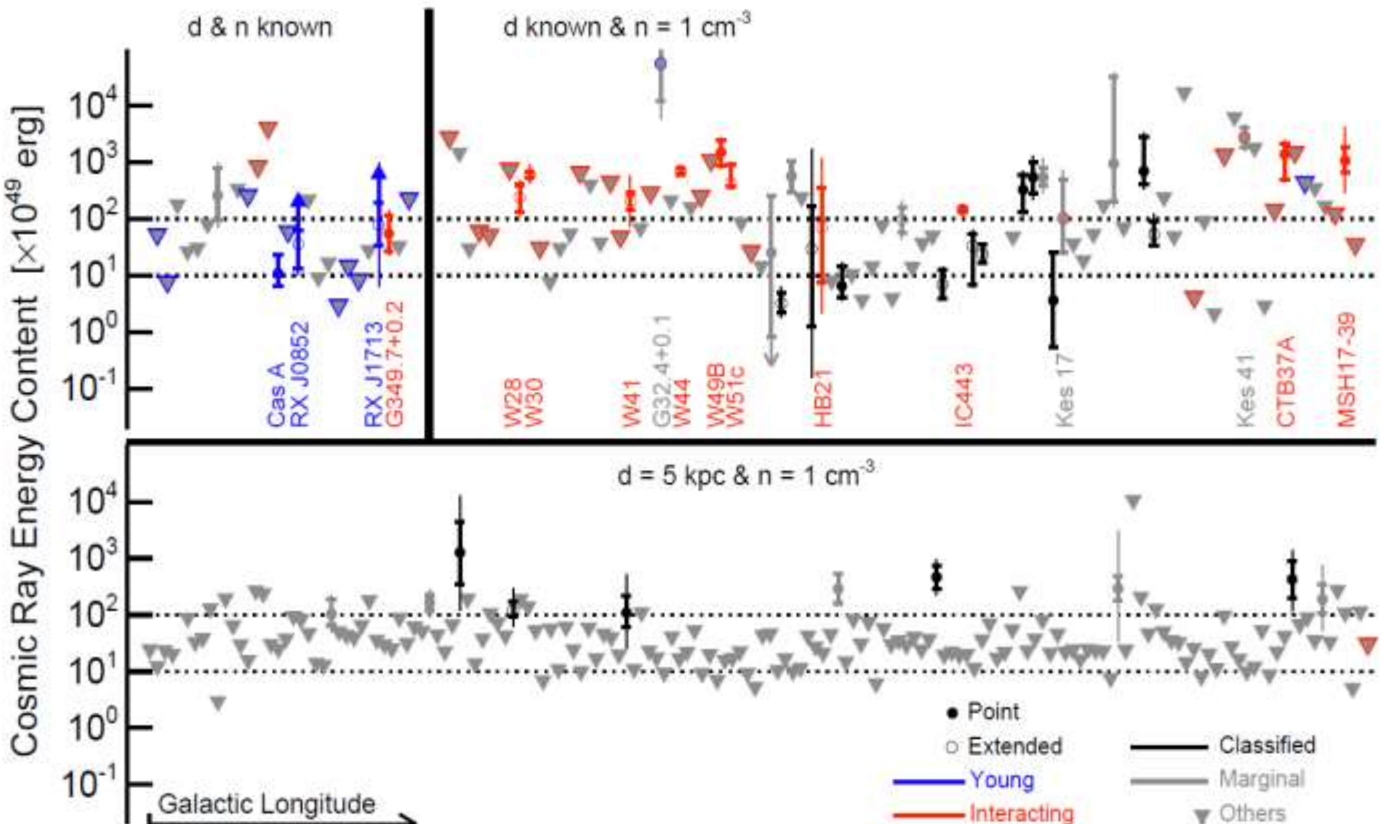




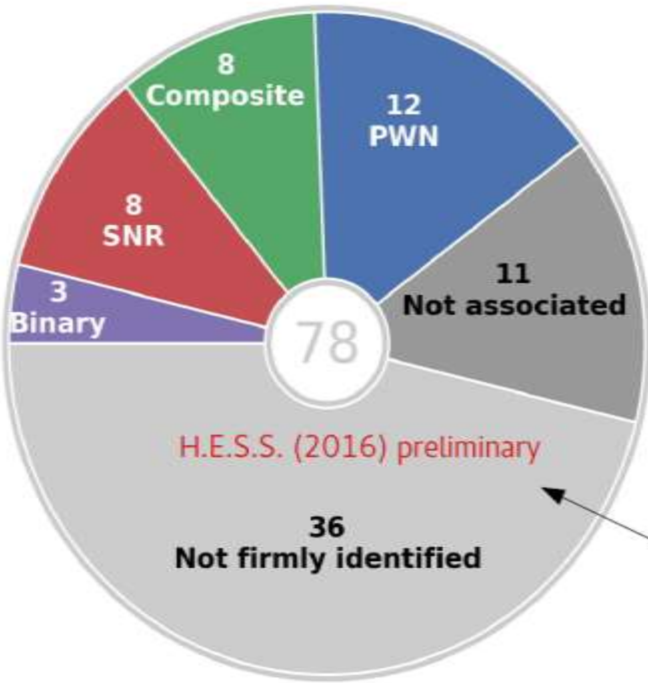
Constraining CRs from detections and ULs

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.



H.E.S.S. source classification in the Galactic Plane survey



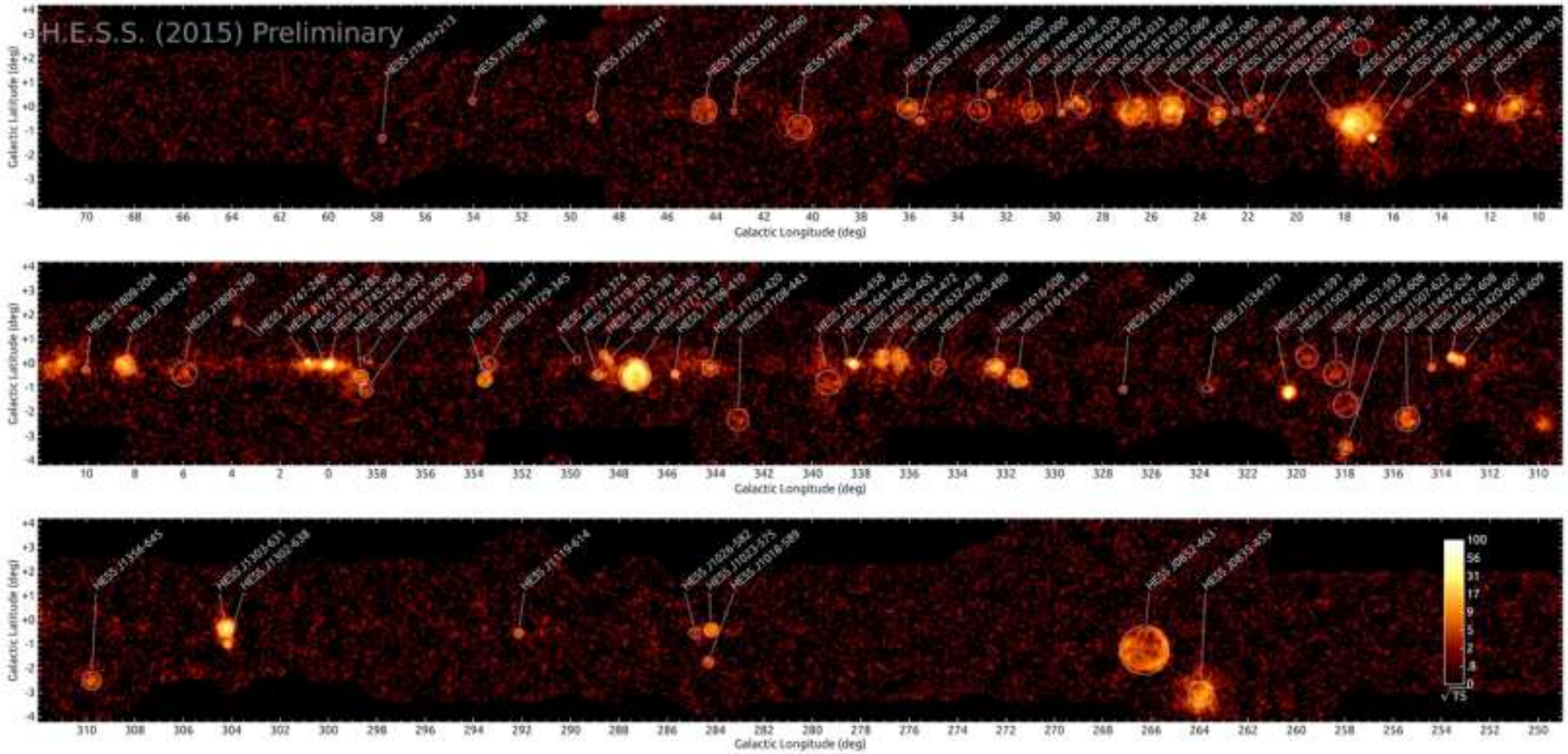
See C. Van Eldik talk!

MWL counterparts:
- Pulsars (ATNF)
- PWN (SNRcat)
- SNRs (SNRcat)

Sources with **multiple associations**

Donath A.+, TeVPa 2016

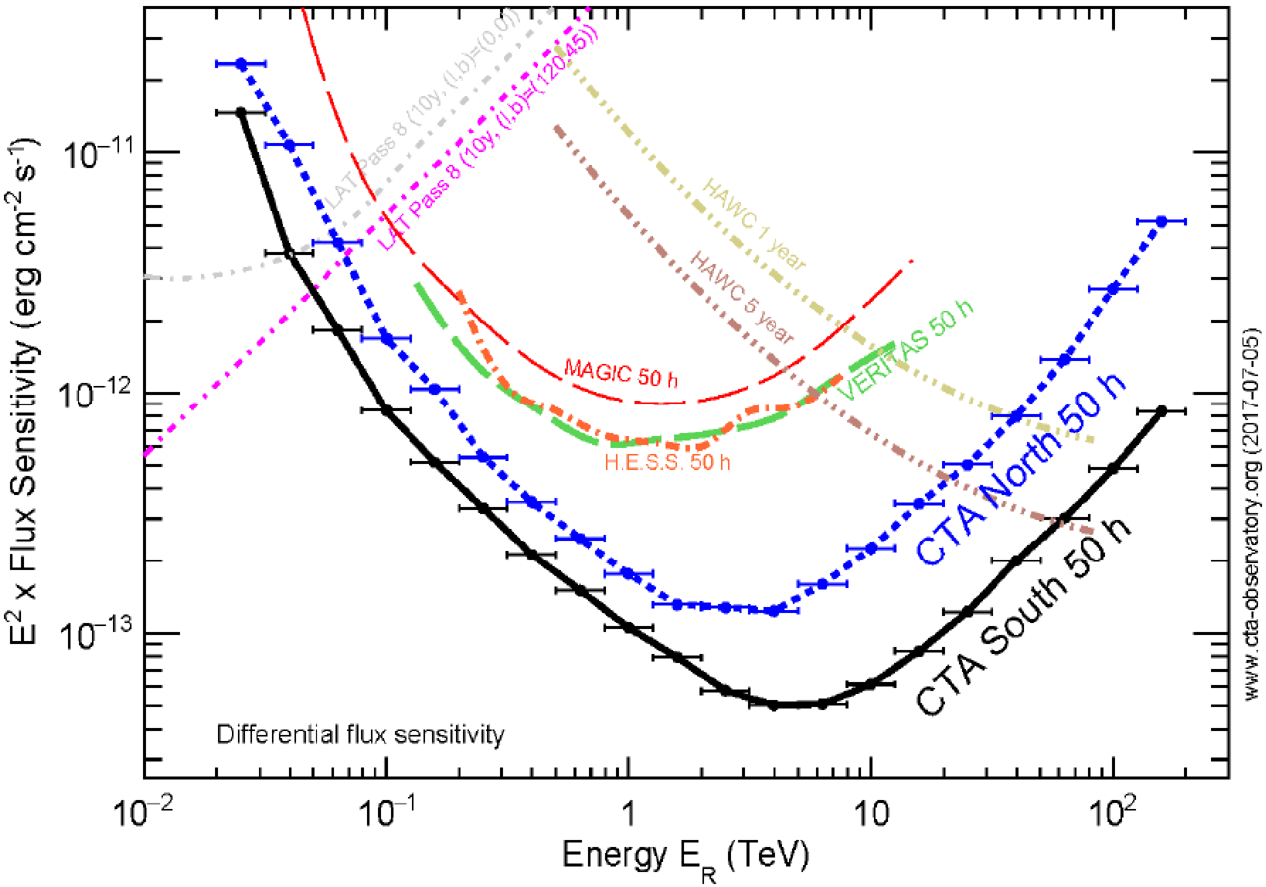
H.E.S.S GPS



Very High Energy (VHE – 0.2-100 TeV) γ-ray image of the inner part of the Milky Way (l=65°-250°, |b|<3.5°) from the latest H.E.S.S. Galactic Plane Survey (HGPS).

Deil et al. 2015, **talk at the 34th ICRC**

CTA flux sensitivity



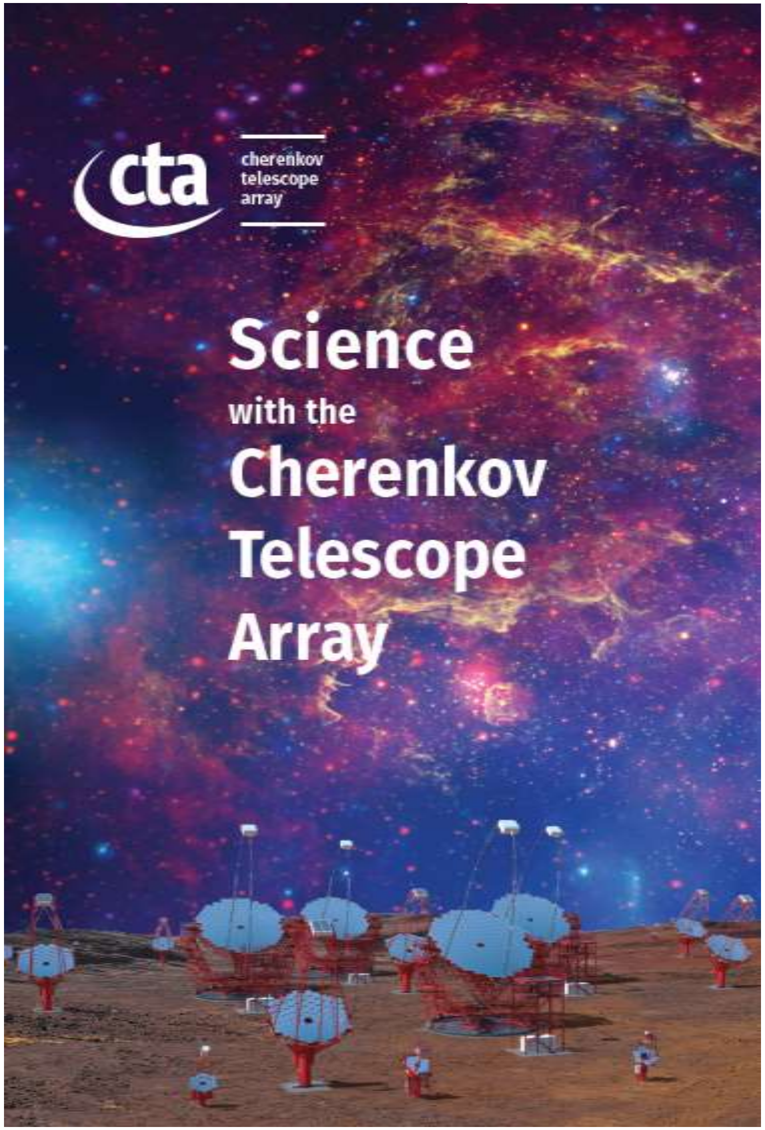
Major sensitivity improvement & wider energy range

Science with CTA

- total dark time available for all CTA observations will be 1100–1300 h/year at each site.
- open, proposal-driven observatory
- for first 10 years 40% of the time is devoted to **key science programs (KSP)** run by the CTA consortium

The plot and tables in the next slides are from:
The CTA Consortium, Science with the Cherenkov Telescope Array, to be submitted soon.

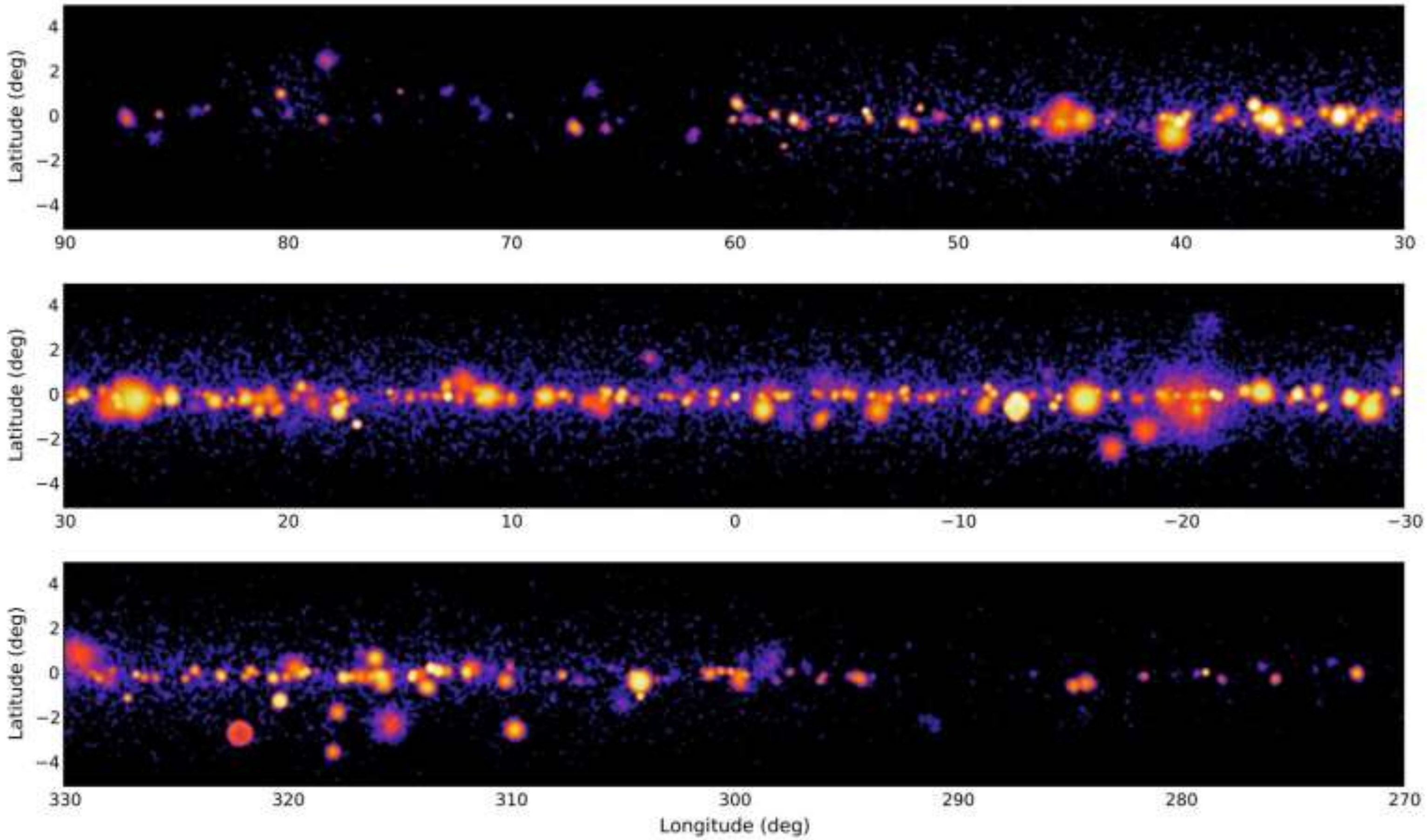
See A.Giuliani talk!



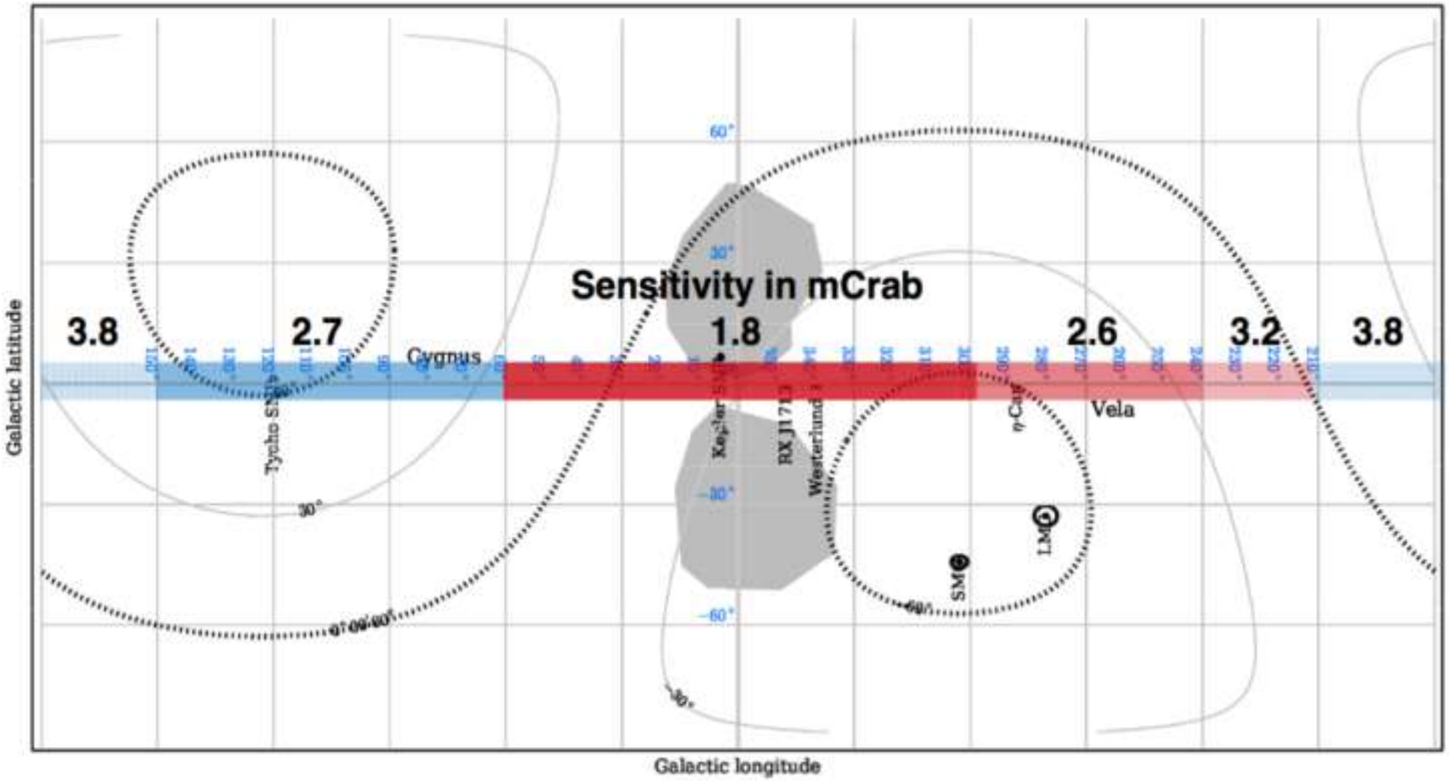
Key Science Projects (KSP)

Theme		Question	Galactic Plane Survey	Cosmic Ray PeVatrons
Understanding the Origin and Role of Relativistic Cosmic Particles	1.1	What are the sites of high-energy particle acceleration in the universe?	✔✔	✔
	1.2	What are the mechanisms for cosmic particle acceleration?	✔	✔✔
	1.3	What role do accelerated particles play in feedback on star formation and galaxy evolution?		
Probing Extreme Environments	2.1	What physical processes are at work close to neutron stars and black holes?	✔	✔✔
	2.2	What are the characteristics of relativistic jets, winds and explosions?	✔	✔✔
	2.3	How intense are radiation fields and magnetic fields in cosmic voids, and how do these evolve over cosmic time?		

Simulated GPS

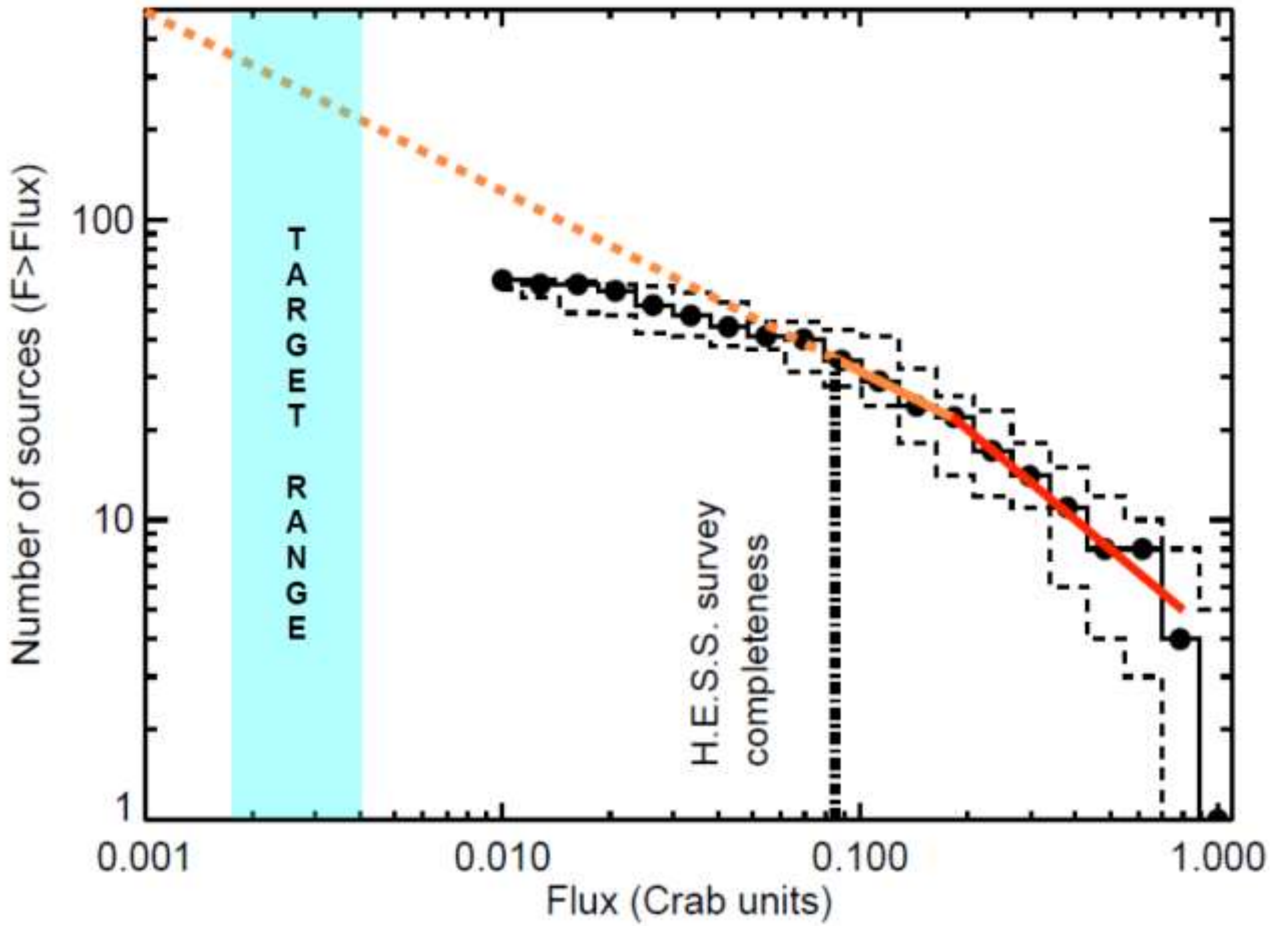


10 y Sensitivity of the GPS



A total of 1020 and 600 hours for CTA-South and CTA-North, respectively.

Estimated number of target sources

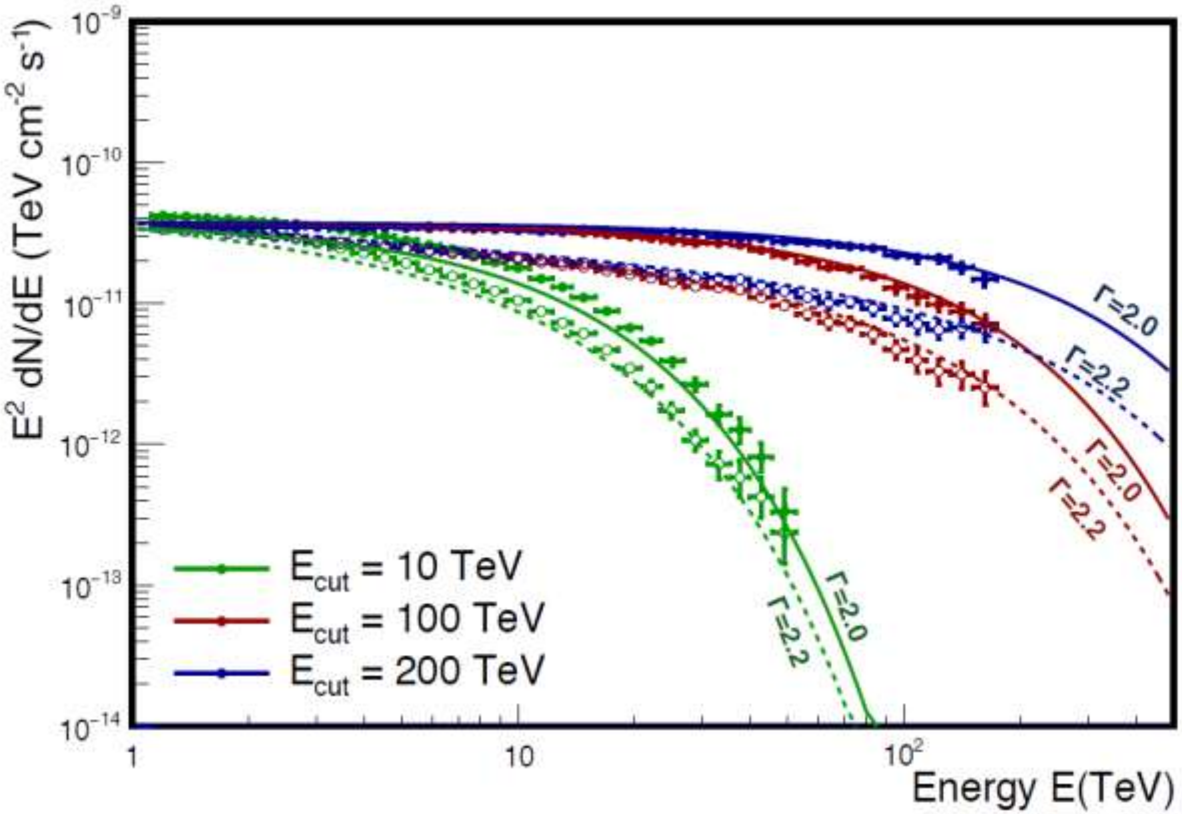


From 1st approx. estimation ~ 100 new SNRs, hundreds of PWN, handful of binaries and few pulsars.

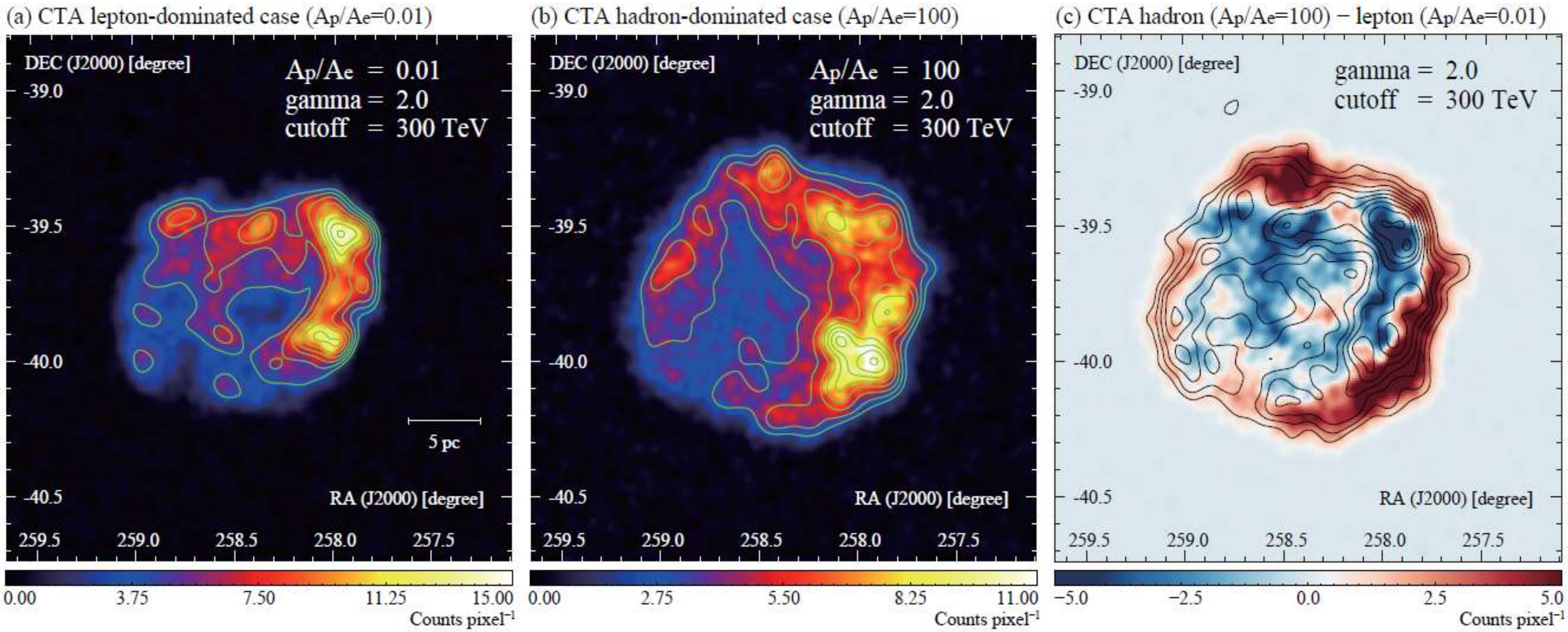
From R. Zanin ICRC2017

Pevatron KSP

Target	Type	Exposure (h)	Array	Year	Configuration
RX J1713.7–3946	SNR	50	S	$1-3$	Full array
PeVatrons	Unknown	5×50	S	>3	MSTs + SSTs



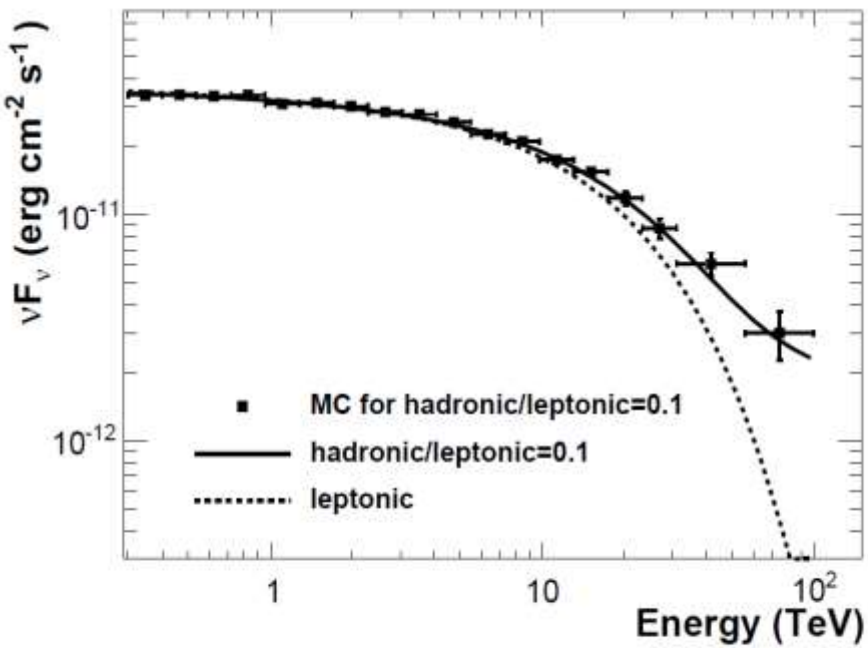
Morphology studies for RX J 1713



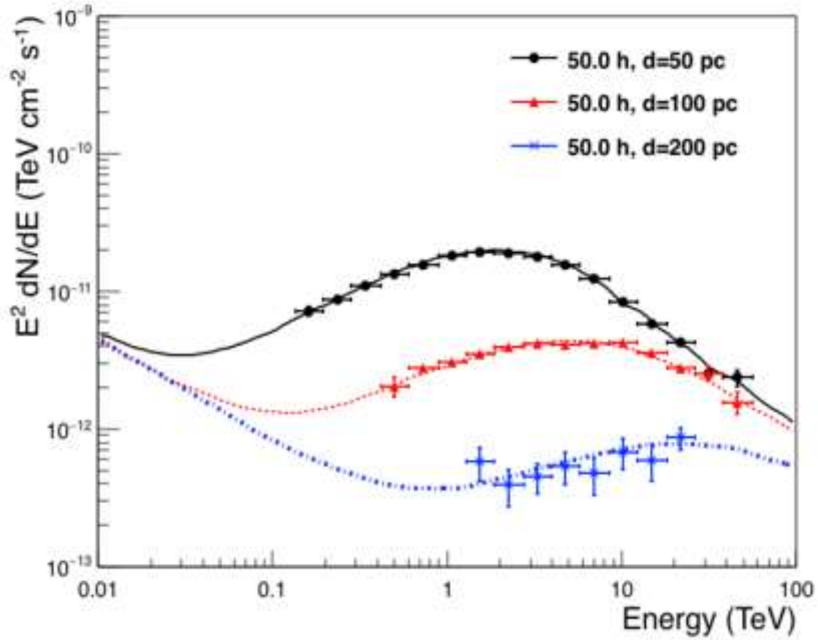
Simulated morphologies for different emission mechanisms with 50h of observation.

Spectral studies

SNR RXJ1713.7-3946



Molecular cloud illuminated by cosmic rays coming from a nearby SNR at different distances



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
- CTA observations of the Galactic plane will strongly improve our understanding of the Galactic high energy emission.
  - A strong increase of detected sources is expected
  - Spatial resolved spectroscopy will be possible given CTA high spatial and spectra resolution.