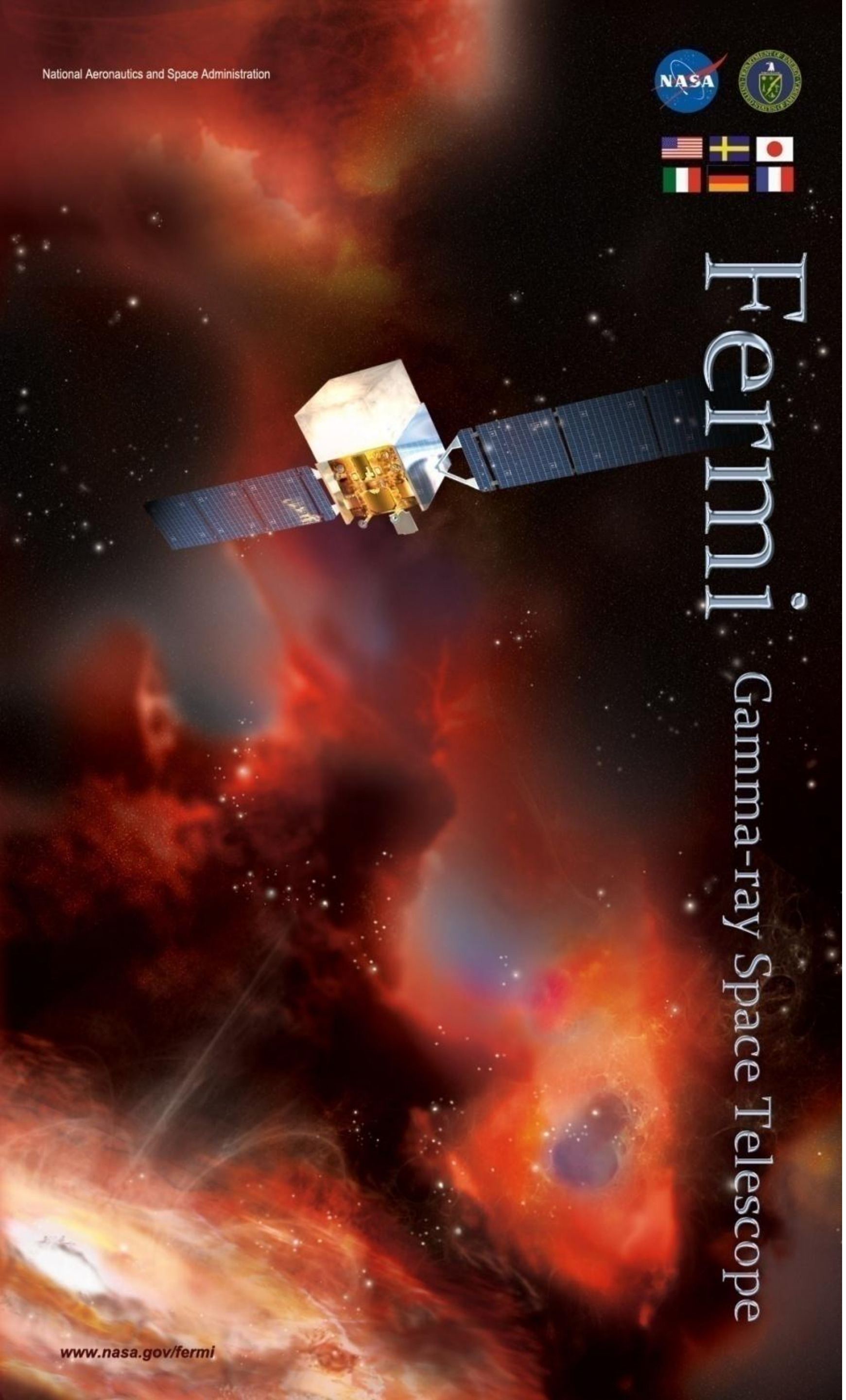

Fermi results on SNRs

Francesco de Palma
INFN Bari

on behalf of the Fermi-LAT Collaboration

11th AGILE Science Workshop

Outline

- SNRs studies and correlation with CRs:
  - Current Fermi-LAT results on SNRs
  - Catalog description and procedure
  - Study of systematic errors related to the interstellar emission modeling
  - Preliminary results and MW correlations
  - Simulation studies
  - Correlation with CR spectra
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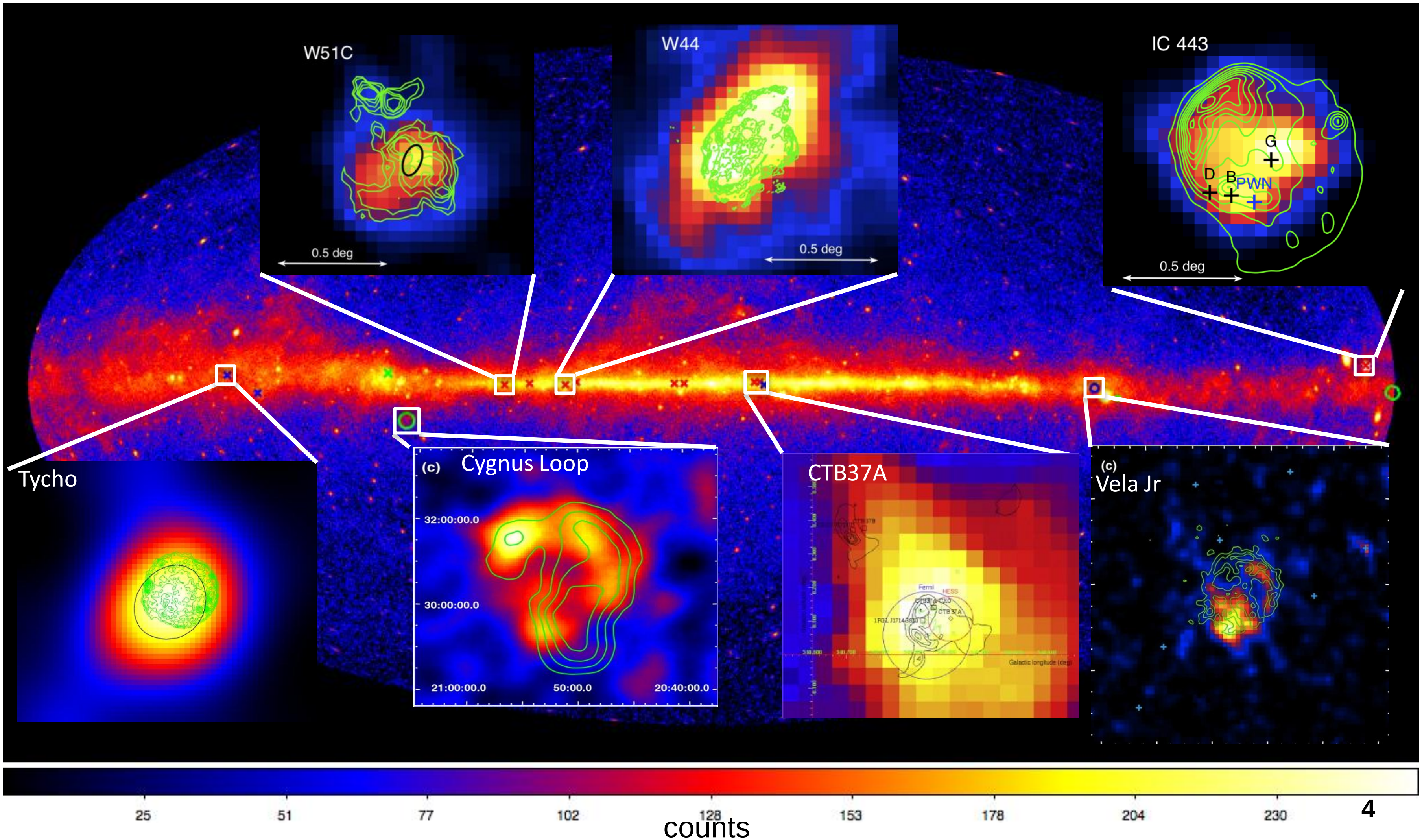
Fermi-Detected SNRs

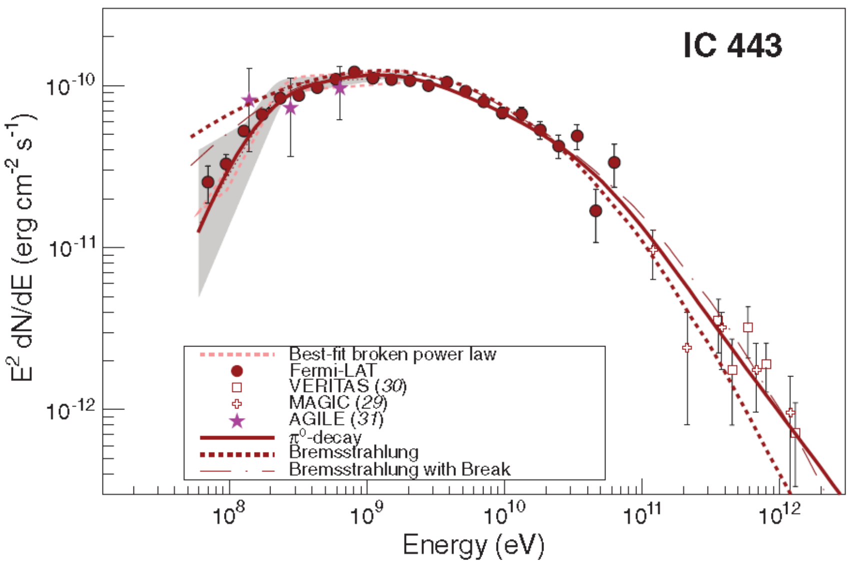
13 identified SNRs: - 9 interacting

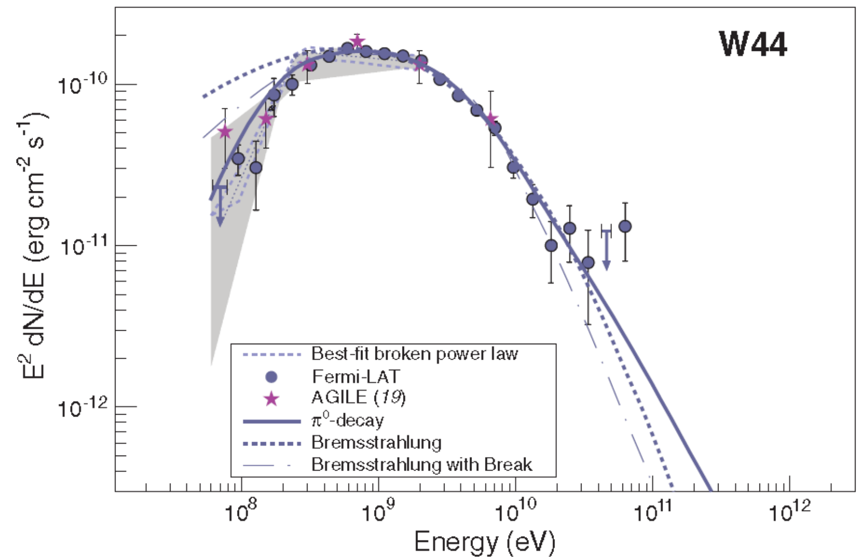
- 4 young SNRs



Detection of the π^0-decay feature in SNRs

IC 443 and W44 are the two brightest SNRs in the Fermi-LAT range





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

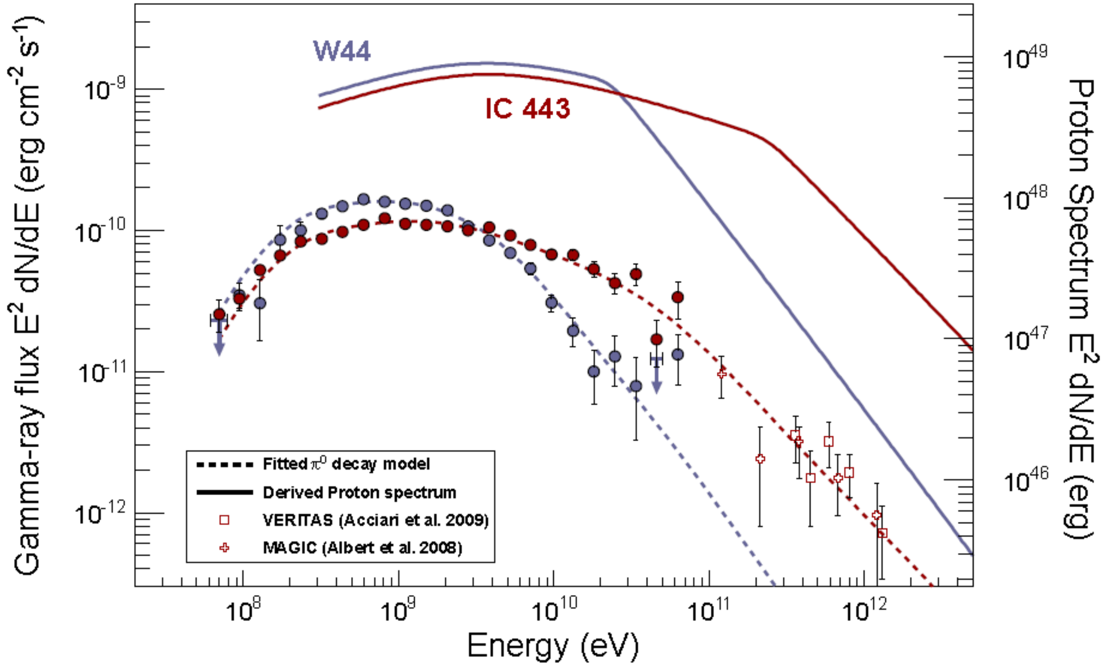
- The low energy break is very significant (~19σ and ~21σ for 60 MeV ≤ E ≤ 2 GeV);
- This gives unambiguous and robust detection of the pion decay spectral feature
- and clear proof that these SNRs accelerate protons.

Detection of the π^0-decay feature in SNRs

$$\frac{dN_p}{dp} \propto p^{-s_1}\left[1+\left(\frac{p}{p_{\rm br}}\right)^{\frac{s_2-s_1}{\beta}}\right]^{-\beta}$$

For IC 443:

- $s_1 = 2.36 \pm 0.02$,
- $s_2 = 3.1 \pm 0.1$,
- $p_{br} = (239 \pm 74)$ GeV/c
- ○ $n = 20\ cm^{-3}$
- ○ $M_{sg} \sim 1 \times 10^3 M_\odot$
- ○ d=1.5 kpc



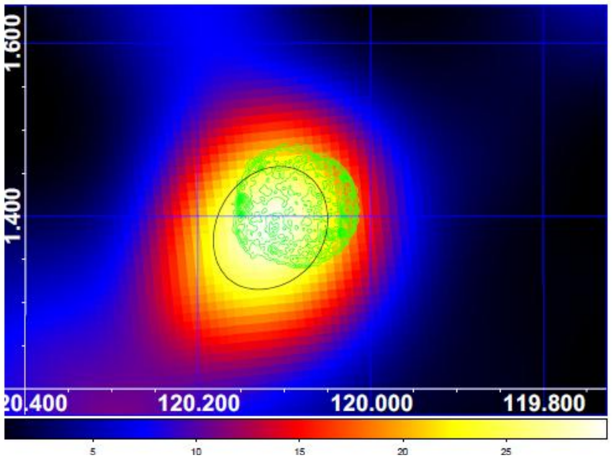
For W44 :

- $s_1 = 2.36 \pm 0.05$,
- $s_2 = 3.5 \pm 0.3$,
- $p_{br} = (22 \pm 8)$ GeV/c
- ○ $n = 100\ cm^{-3}$
- ○ $M_{sg} \sim 5 \times 10^3 M_\odot$
- ○ d=2.9 kpc

The π^0-decay gamma rays are likely emitted through interactions between “crushed cloud” gas and relativistic protons, both of which are highly compressed by radiative shocks driven into molecular clouds that are overtaken by the blast wave of the SNR.

The *Fermi-LAT data allow K_{ep} ~ 0.01 or less*

Tycho

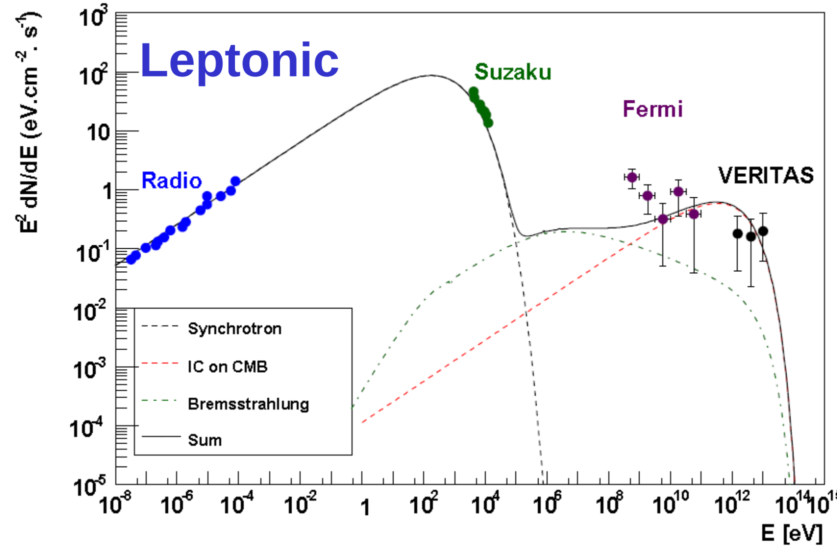


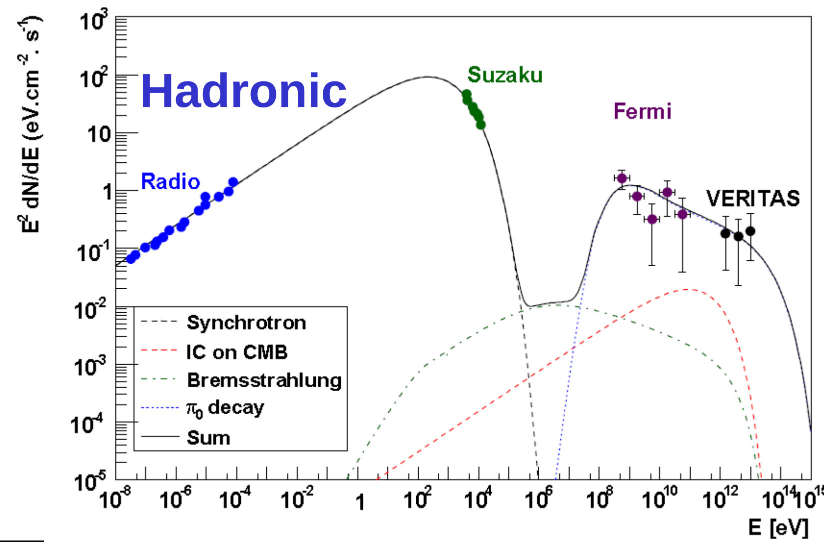
Case	D_{kpc} [kpc]	n_H [cm^{-3}]	E_{SN} [10^{51}erg]	$E_{p,tot}$ [10^{50}erg]	$E_{e,tot}$ erg
Far leptonic	3.50	0.24	2.0	-	1.5×10^{48}
Far hadronic	3.50	0.24	2.0	1.50	6.7×10^{46}
Nearby hadronic	2.78	0.30	1.0	0.61	4.3×10^{46}

Leptonic model not-favoured because:

- IC does not fit the data
  (from X-ray: s_e= 2.2–2.3, $E_{e:max}$=6-7TeV)
- Bremsstrahlung:
  - N_e fixed by IC and TeV obs.
  - n_H ↑ up to 10cm^{-3}
  - B ↓ down to 65μG
- K_{ep}~0.1

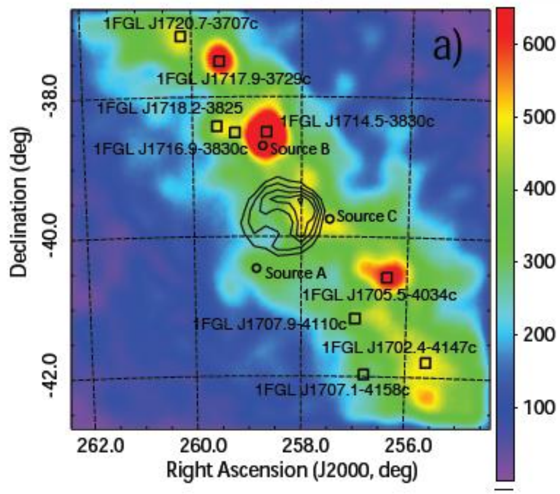
~6-8% of E_{SN} transferred to CRs.



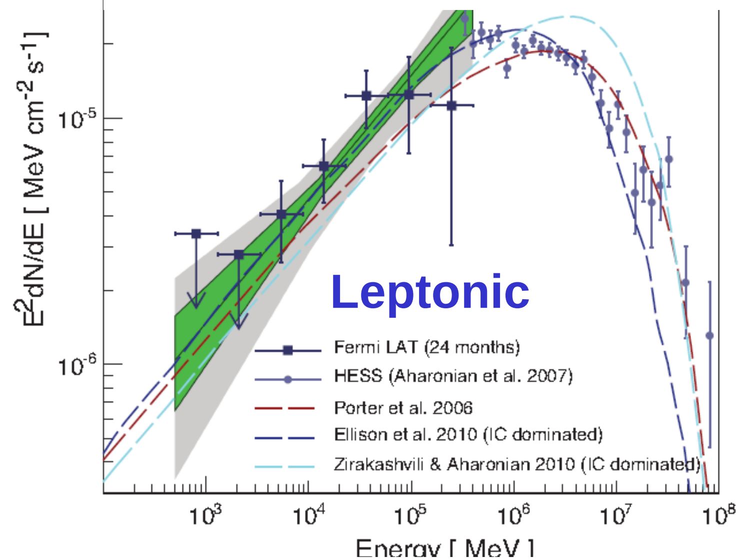


Giordano et al. 2012, ApjL, 744, L2

RXJ1713: a leptonic case



$\Gamma=1.5\pm0.1$ (stat) ±0.1(sys)



lack of thermal X-ray emission

$\rightarrow n_H < 0.2$ cm^{-3}

$\rightarrow$extremely efficient acceleration is needed for hadronic emission

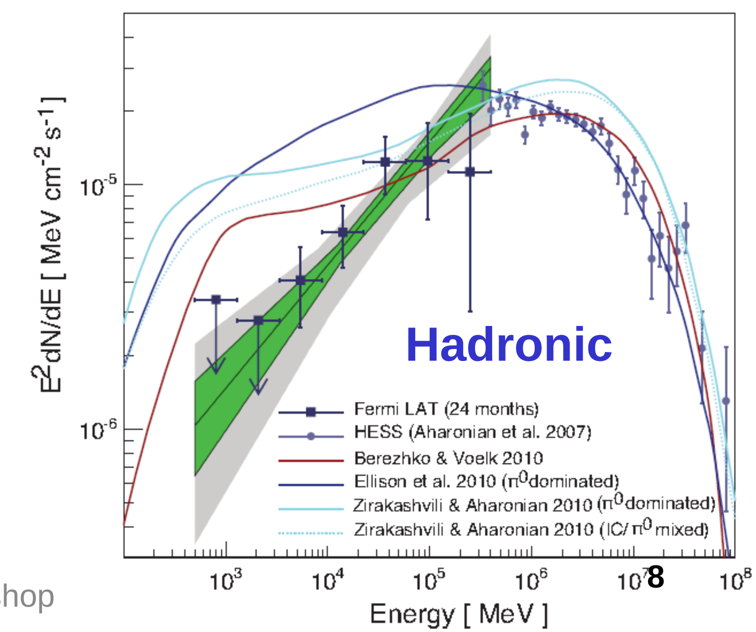
Electron spectra:

PL with $s_e = 2\,\Gamma\text{-}1 = 2.0 \pm 0.2$

$B \simeq 10\ \mu G$

$E_{e;max}$ ~20-40 TeV

$W_p < 0.3\text{x}10^{51}(n_H/0.1\ \text{cm}^{-3})^{-1}$erg

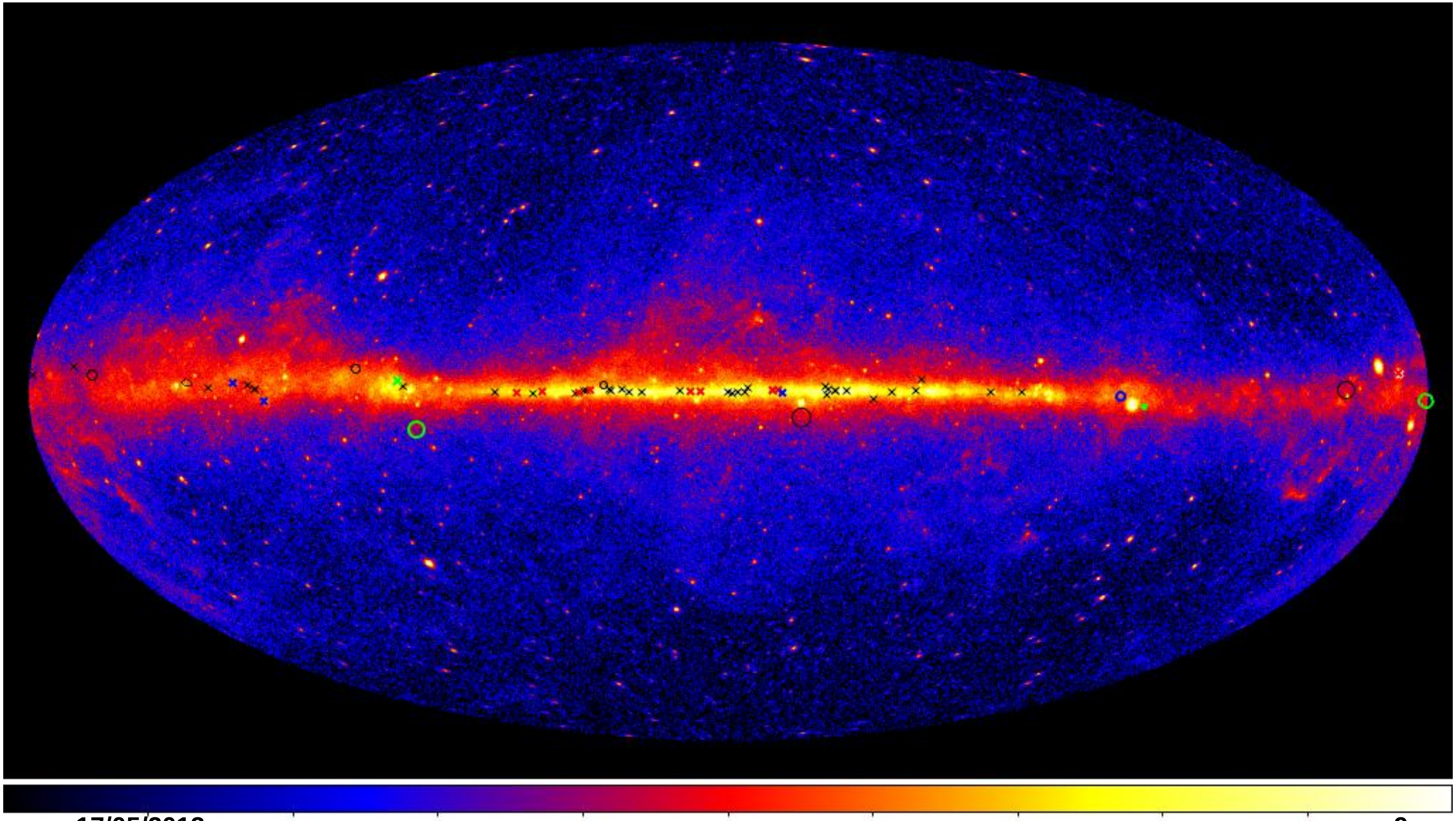


Abdo et al. Apj, 2011, Apj, 734, 28

Fermi-Detected SNRs

13 identified SNRs: - 9 interacting
- 4 young SNRs

+ 43 2FGL candidates,
excluding spatial associations with PSRs, PWN, AGN



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SNR Catalog:

To better understand SNRs in a statistically significant manner within a MW context we:

- characterize the spatial and spectral morphology of all regions containing known SNRs.
- examine multi-wavelength (MW) correlation, including spectrum + morphology for radio, X-ray, and TeV and CO, maser, IR, …
- determine statistically significant SNR classification(s) and perform spectral modeling

On going effort in collaboration with:
F. Acero,T. J. Brandt, F. Giordano, J. Hewitt,
G. Johannesson, L. Tibaldo, and others

Characterize GeV Emission: Analysis Procedure

Data Set:
- 3 years of P7SOURCE_V6 LAT data
- E: 1-100 GeV
- Region Of Interest: 10° around each SNR

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

Starting Model:
- 2FGL

Overlapping sources?
- = None: Add a new extended source
- = 1 source (not PSR): Replace w extended source
- > 1 source: Replace (non-PSR) source closest to radio centroid w extended source. Delete all other (non-PSR) sources.

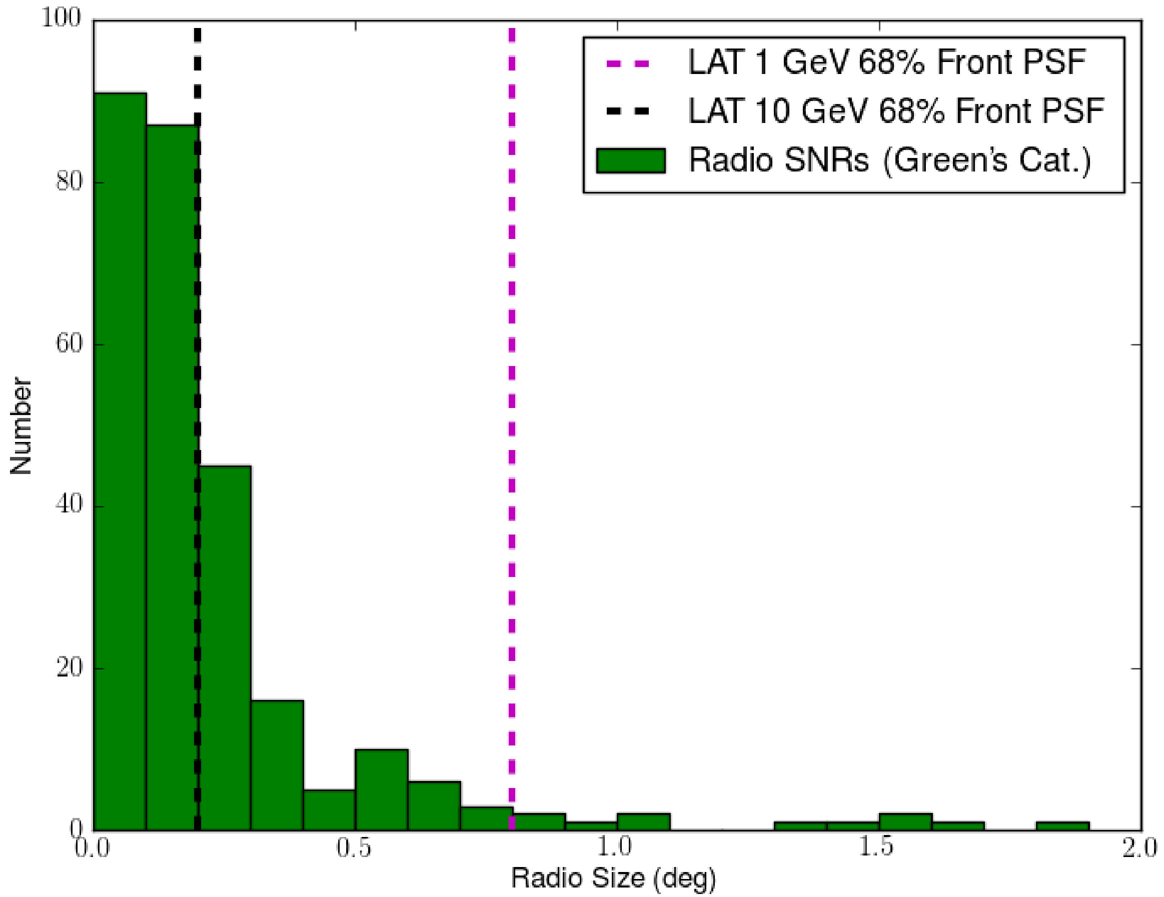
Localize source, fit extension
- Disk extension seed = radio size
- Spectral model: power law
- Normalization of Galactic diffuse and all sources w/in 5° of candidate are free during minimization procedure.

Output:
- Position, extension, significance
- Spectral energy distribution
- Region and residual maps
- Diagnostics

Identifying SNRs via extension:
If a SNR's spatial extension is larger than Fermi's PSF, we can detect its size, helping to positively identify it.

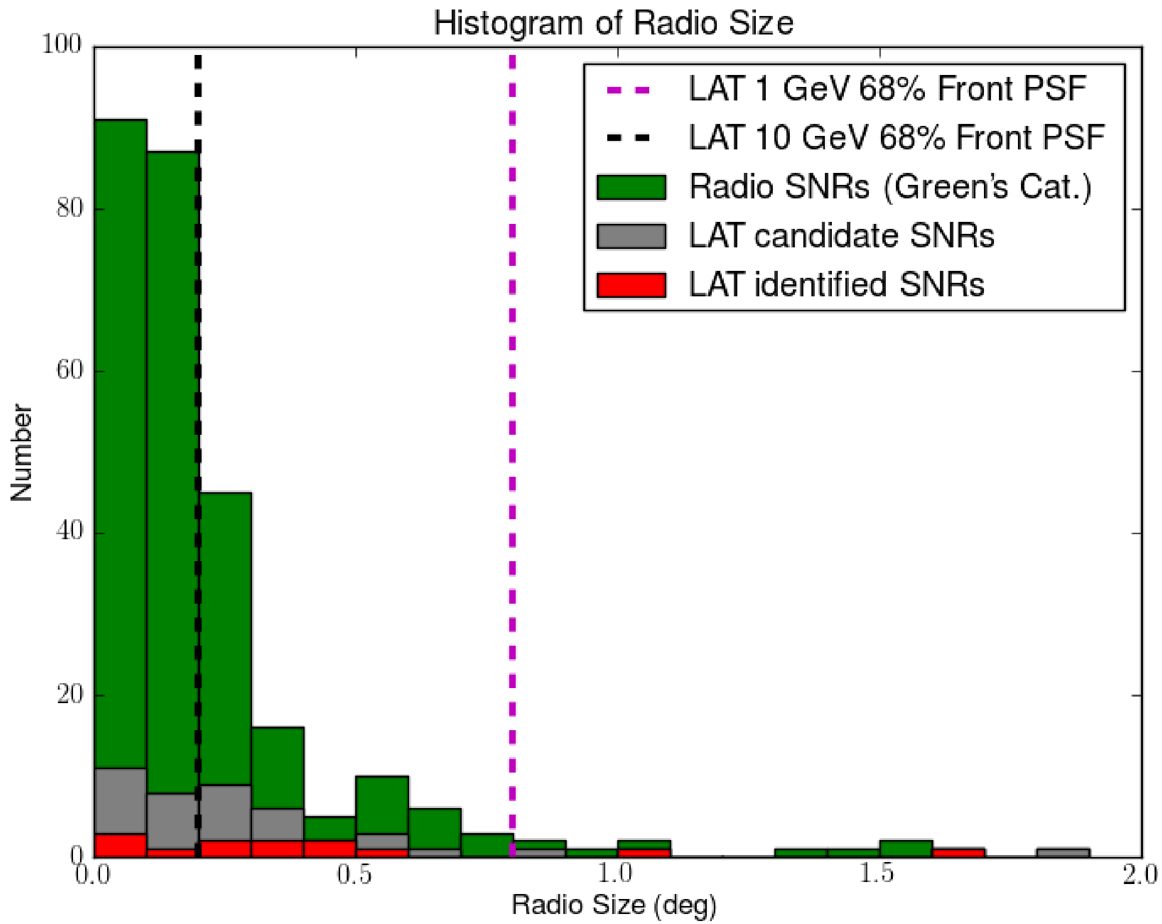
SNR Catalog:

- Fermi-LAT has the ability to spatially resolve a large number of the 279 known SNRs assuming their GeV and radio sizes are similar.



SNR Catalog:

- Fermi-LAT has the ability to spatially resolve a large number of the 279 known SNRs assuming their GeV and radio sizes are similar.
- Spatial extension measured for 15 SNRs, 6 of which are **new candidates**, permitting clear identification.



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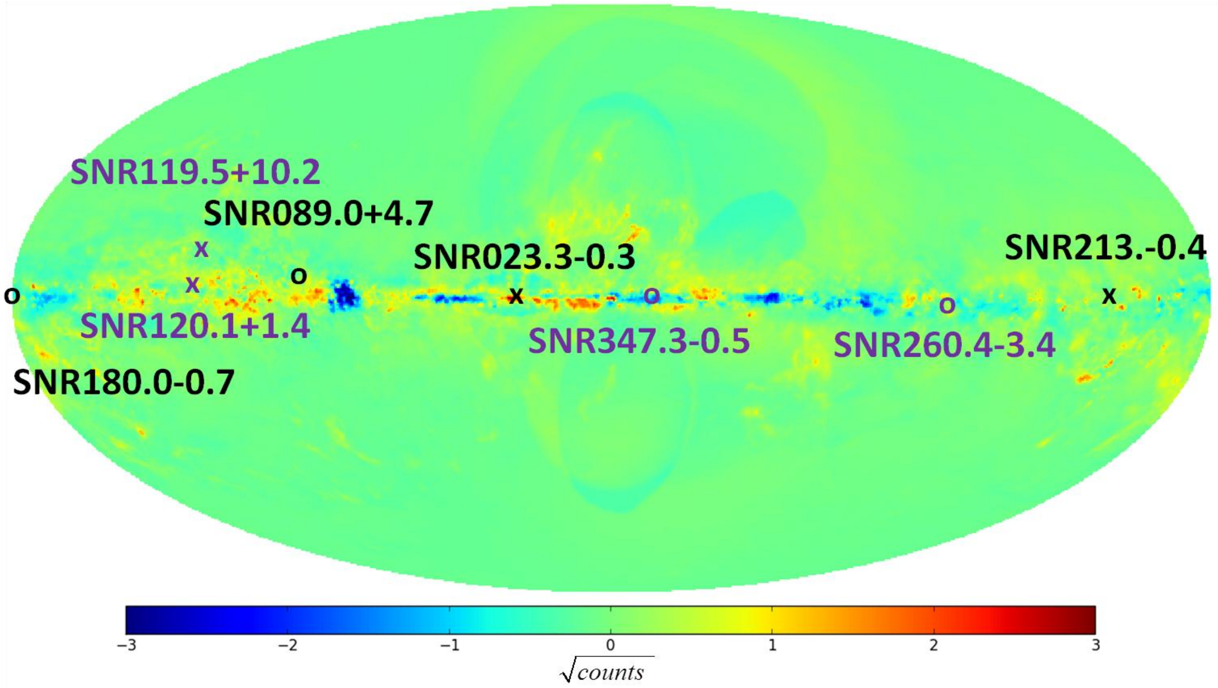
Systematic Error Study

To explore systematic uncertainties related to the choice of the Interstellar Emission Model (IEM), we localized and fit 8 representative candidate SNRs using alternative IEMs.

The eight remnants are a combination of **hard** and **soft** and point-like (**x**) and extended (**o**) sources and they are located in regions with different intensities of the IEM.



See also:
Ackermann et al. , 2012, apj, 750, 3

Alternative IEMs

They are built using GALPROP with input parameters set as:

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

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.

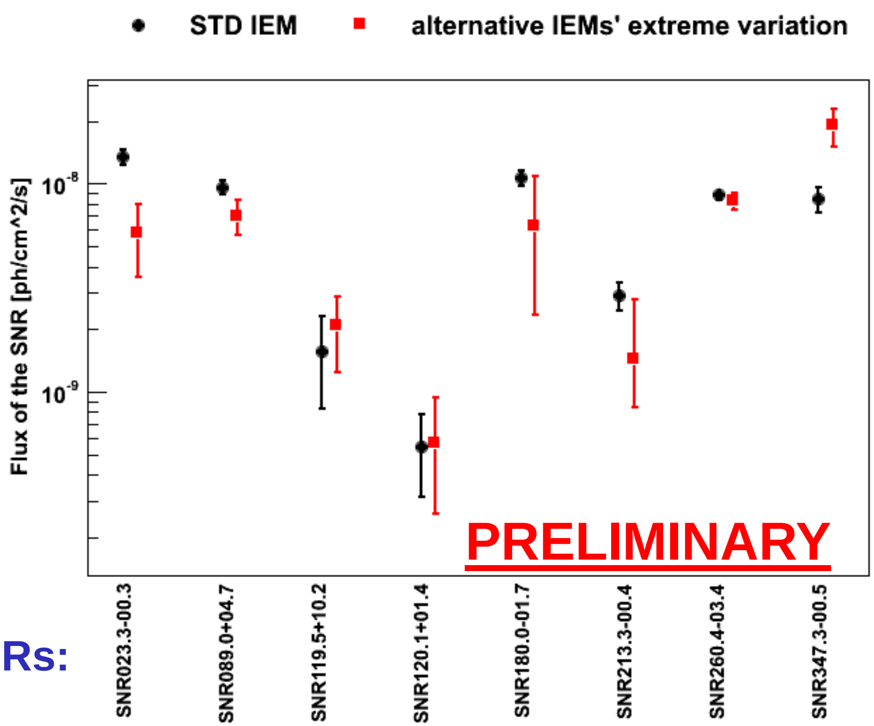
Warning:

- *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.*

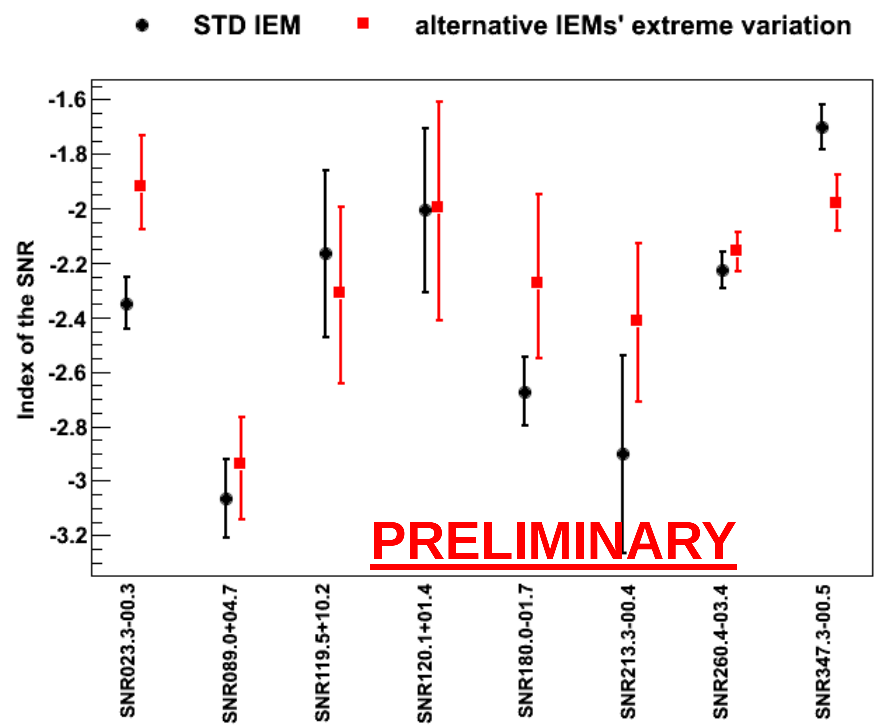
Systematic Error Study

SNR candidates' flux and index averaged over the alternative IEMs' solutions, compared to the standard (STD) model result.

Flux:



Index:

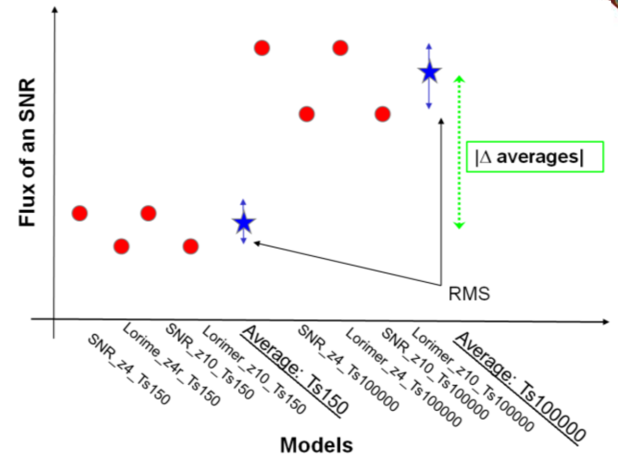


SNRs:

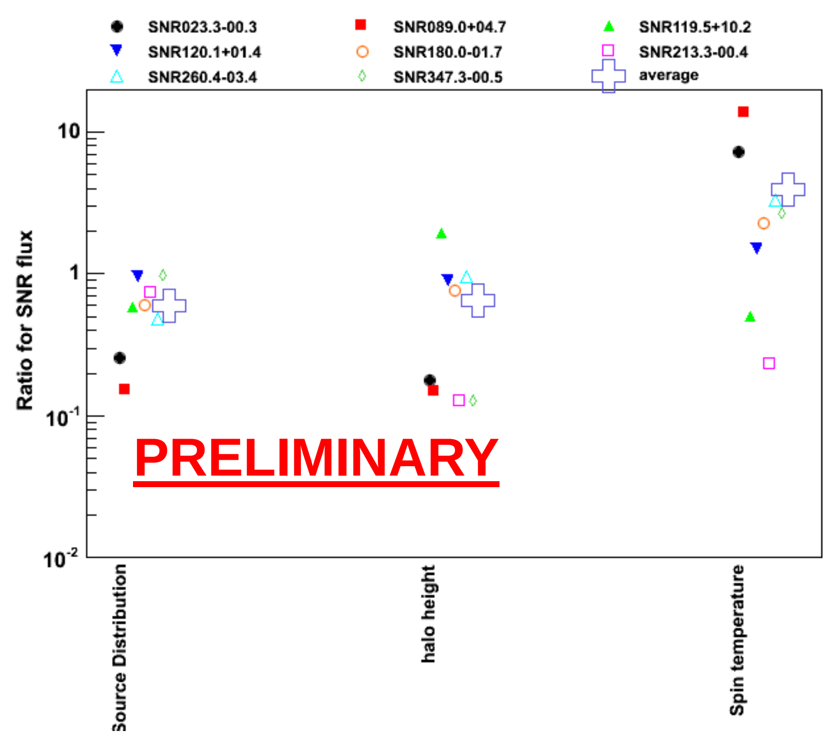
Our automated analysis finds a softer index and a much larger flux for SNR347.3-0.5 (RX J1713) than that obtained in a dedicated analysis. *[Abdo et al. 2010]* Since the best fit radius (0.8º) is larger than the dedicated analysis' (0.55º), the disk encompasses nearby sources that are not in the model. This make it softer than the more accurate analysis.

IEM input parameter comparison

$$\frac{\left|\langle flux\rangle_{Ts150} - \langle flux\rangle_{Ts100000}\right|}{\max(RMS_{Ts150}, RMS_{Ts100000})}$$



A ratio ≥ 1 implies that changing this parameter has a greater effect on the flux than all combinations of the other input parameters.



None of the input parameters has a sufficiently large impact on the fitted source parameter to justify neglecting the others.

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

17/05/2013

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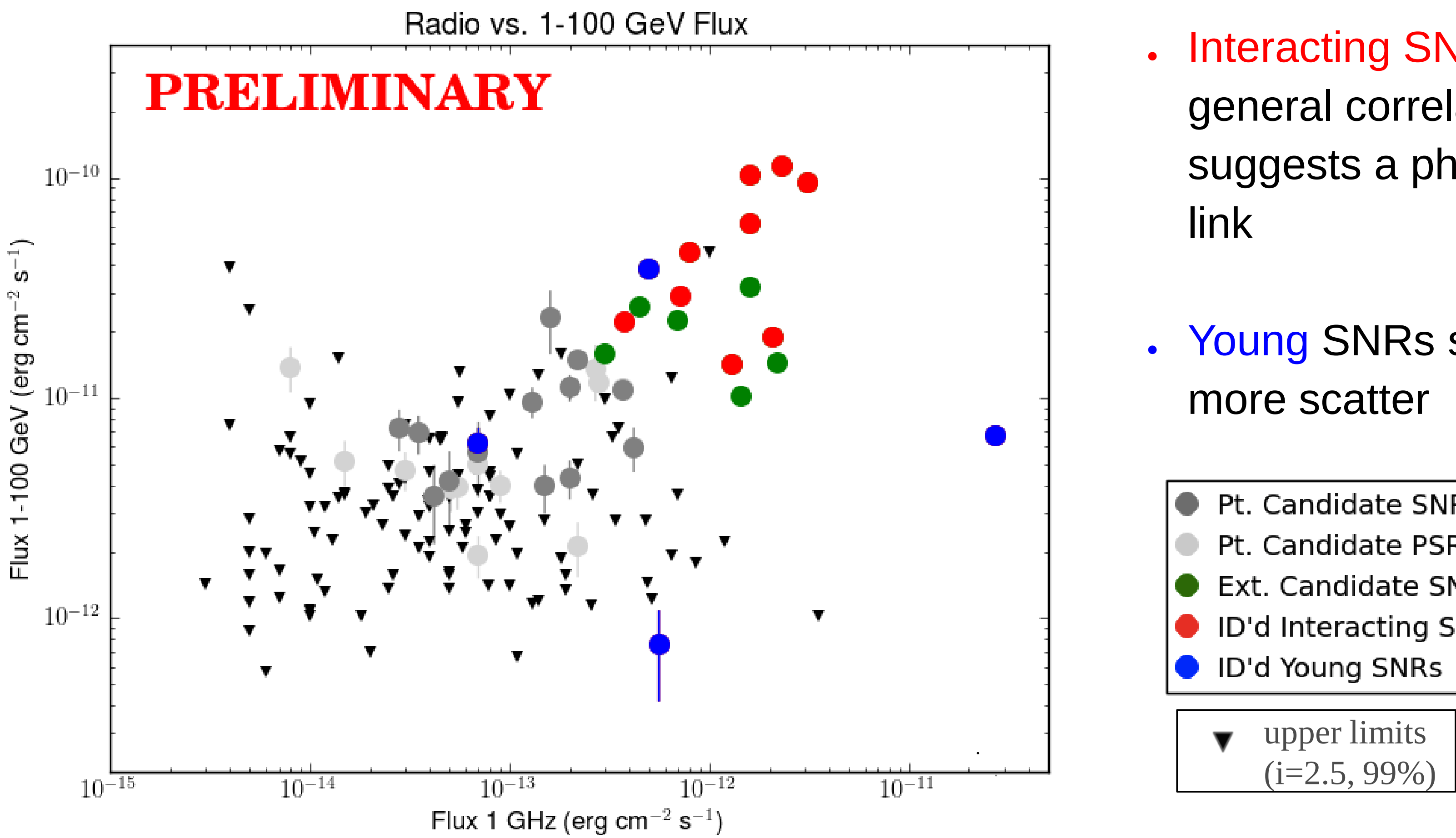
Radio-GeV Correlation?

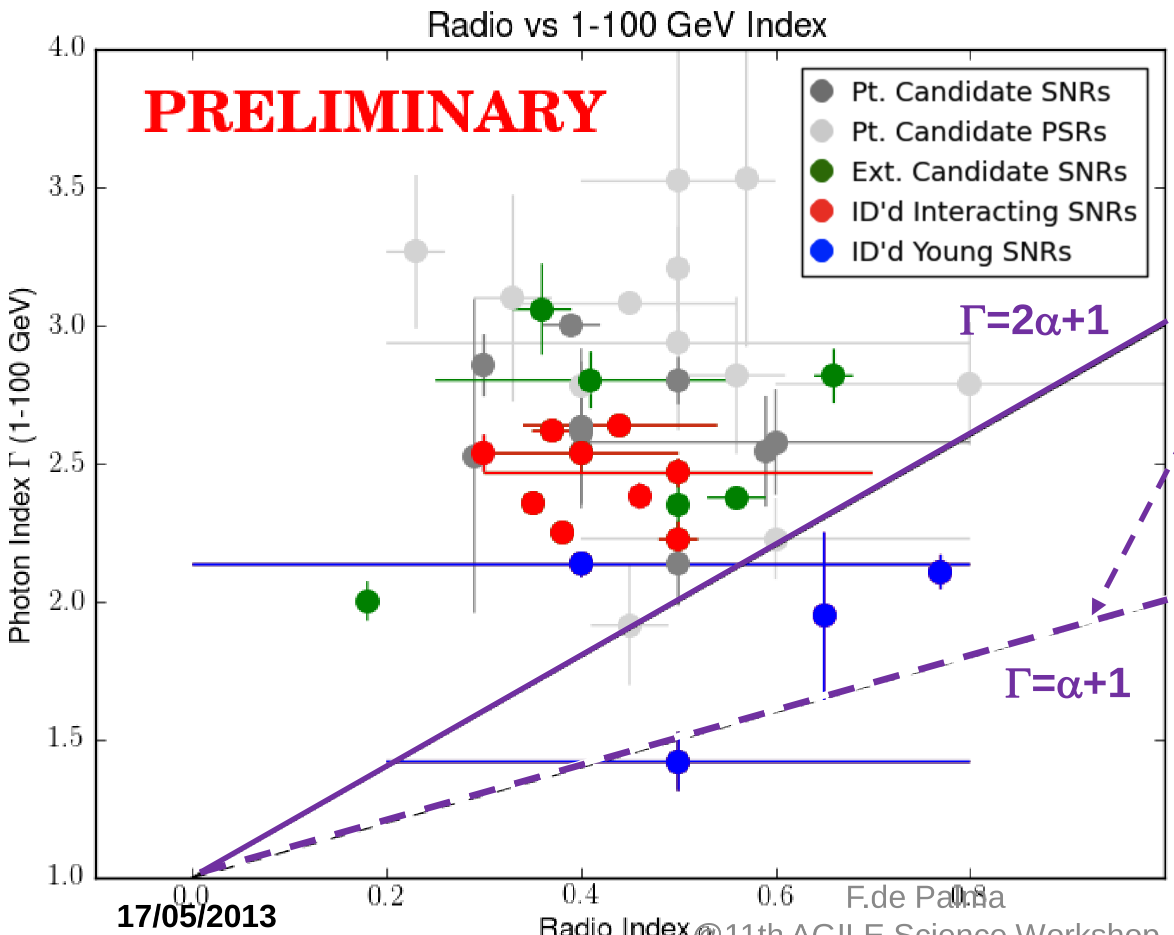
Radio synchrotron emission indicates the presence of relativistic leptons. LAT-detected SNRs tend to be radio-bright:



- Interacting SNRs: general correlation suggests a physical link
- Young SNRs show more scatter

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:

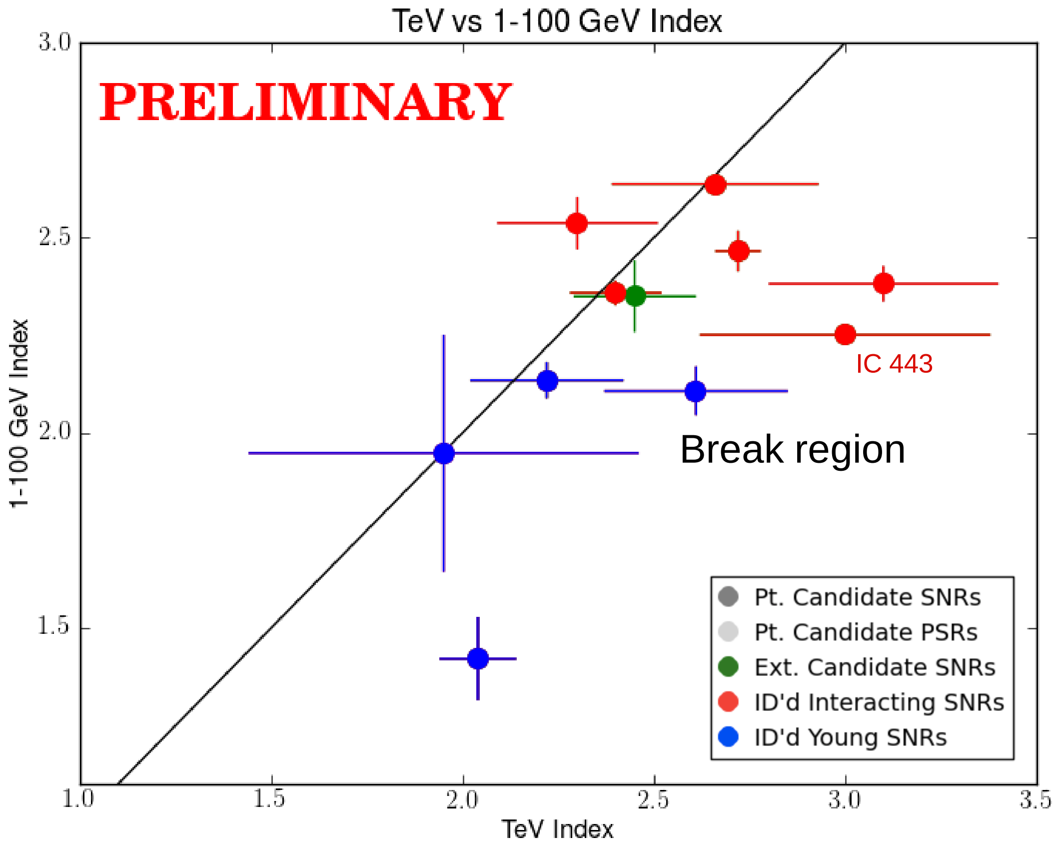


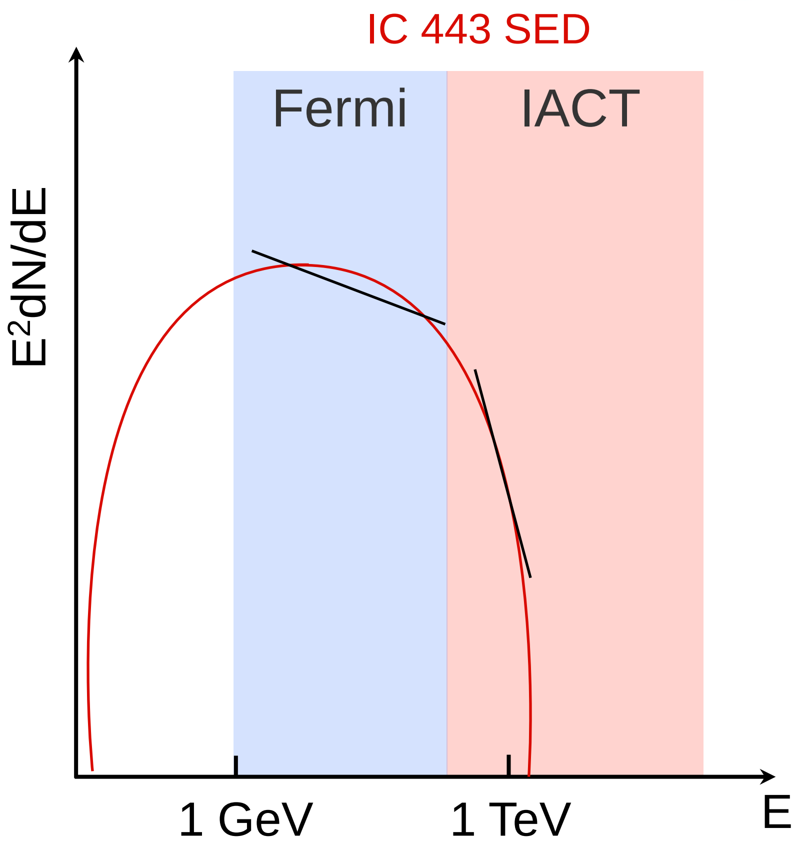
- Young SNRs: seem consistent
- Others, including interacting SNRs: softer than expected
  - π^0 decay or $e^{+/-}$ brem.
  - inverse Compton

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?

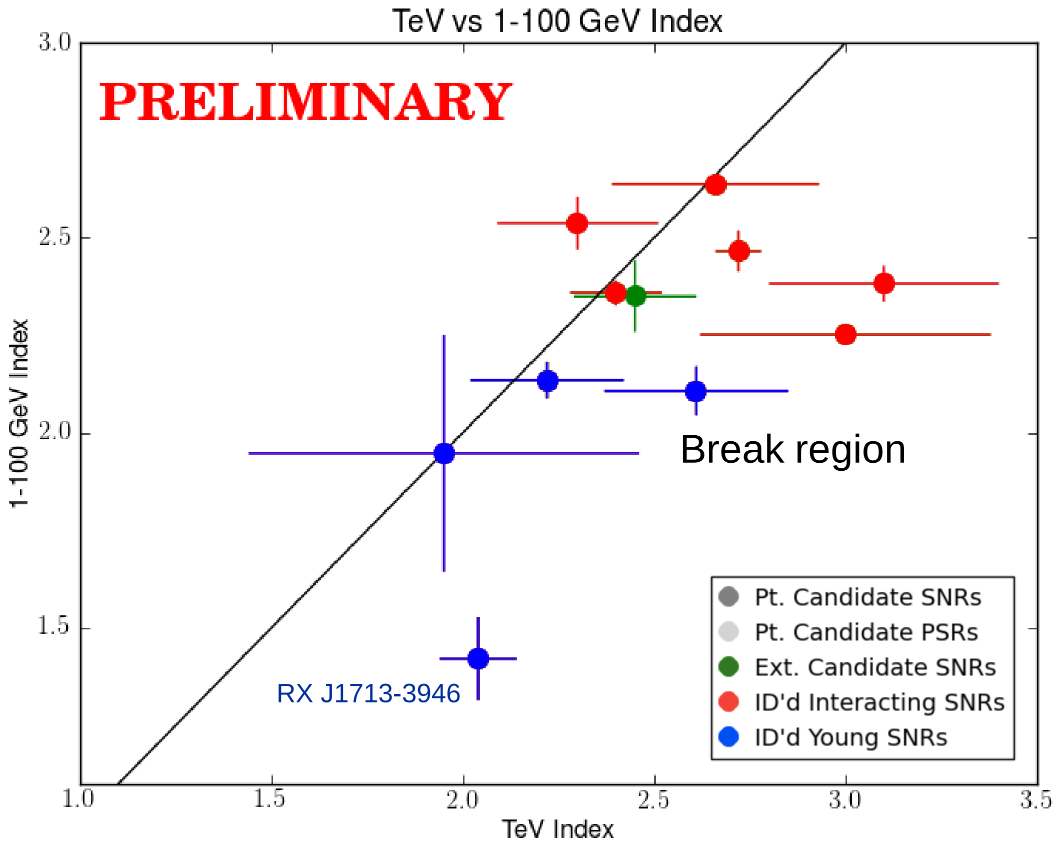
GeV-TeV Index

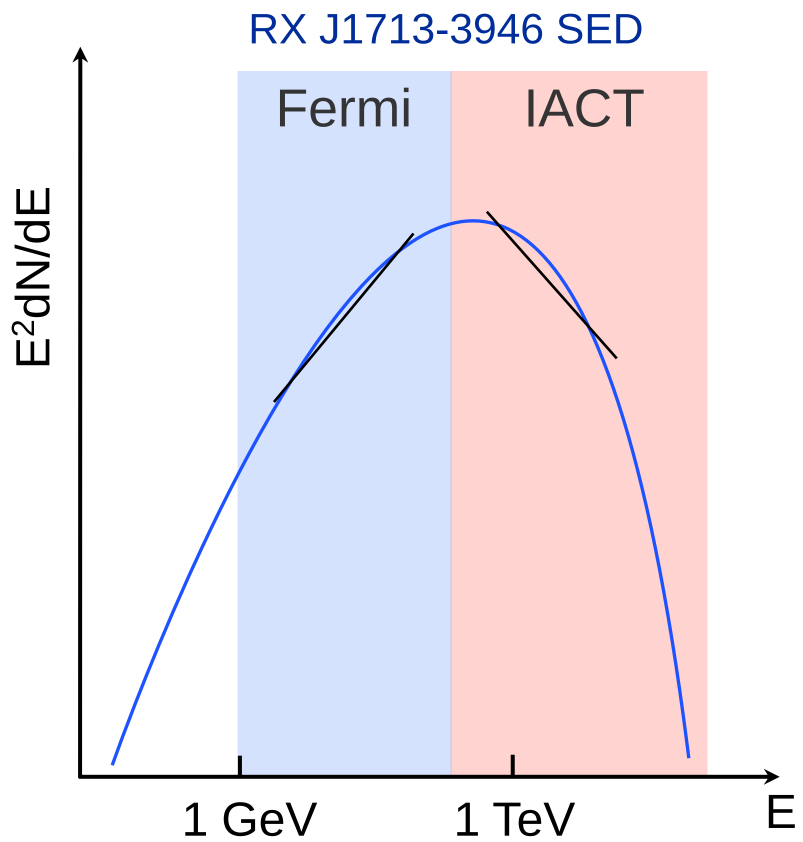




- Indication of break at TeV energies
- Caveat: TeV sources are not uniformly surveyed.

GeV-TeV Index





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

Environment?

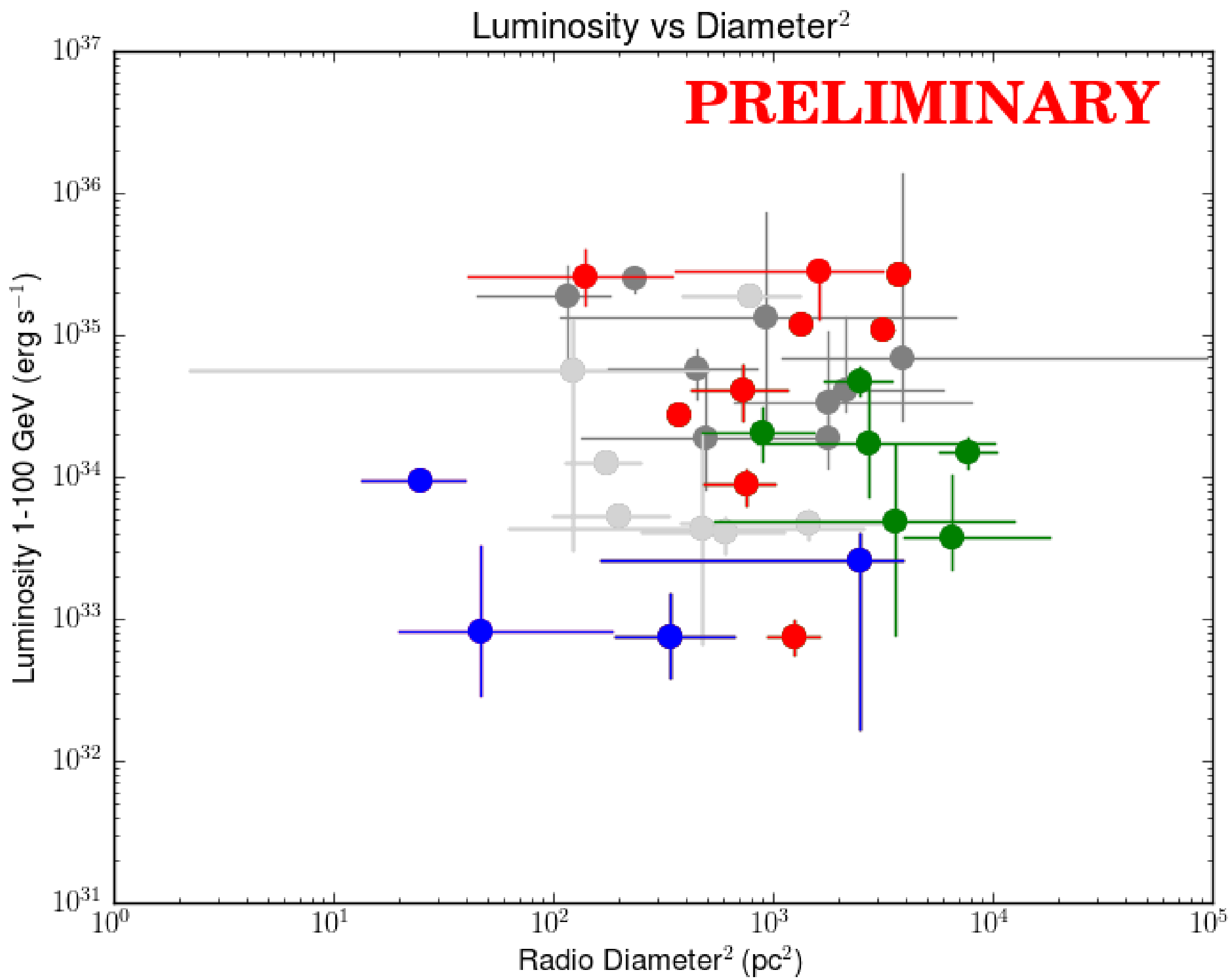
Interacting SNRs tend to be more luminous than young SNRs.

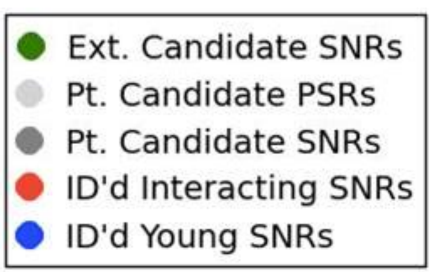
Young SNRs:

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

Interacting SNRs:

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



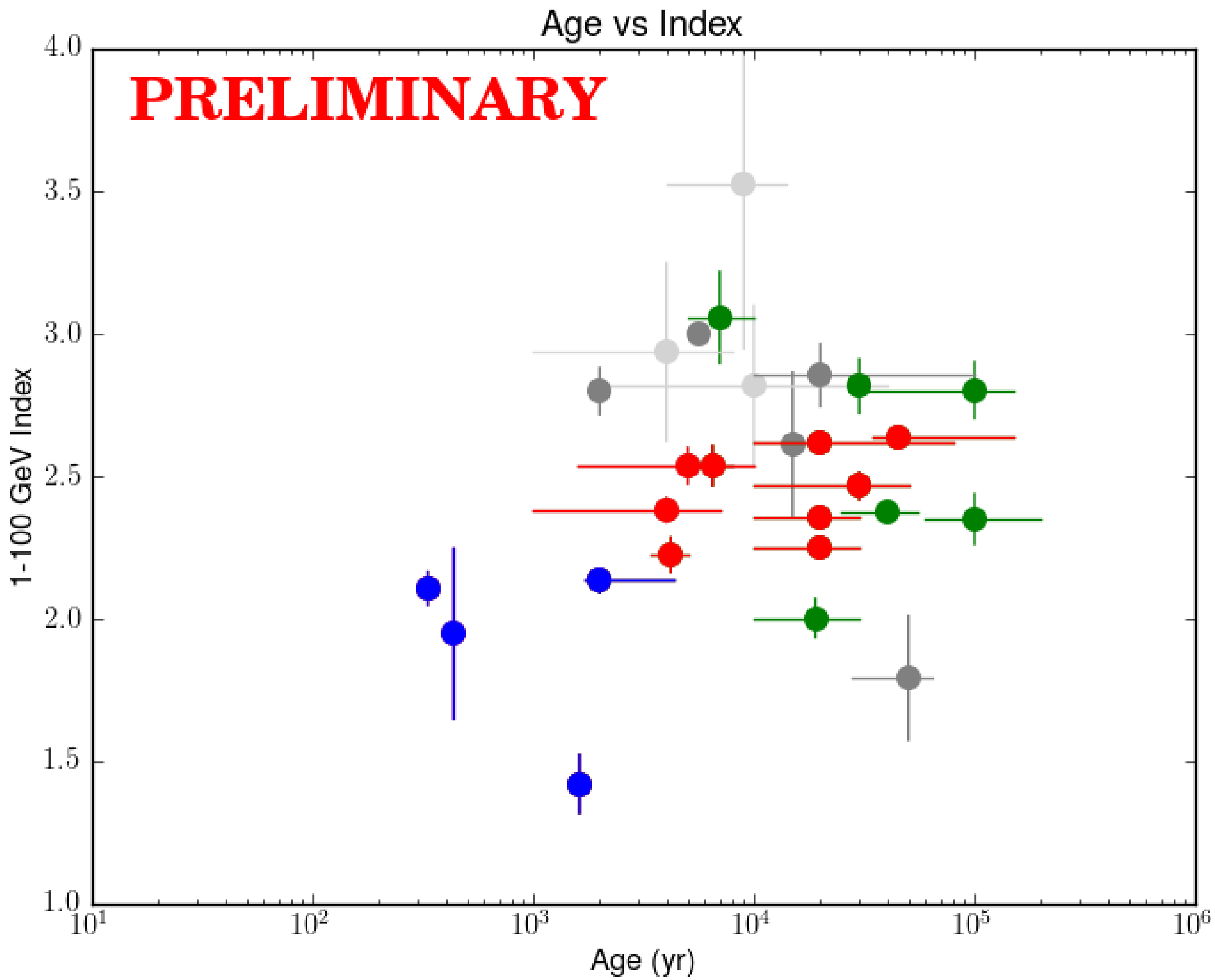


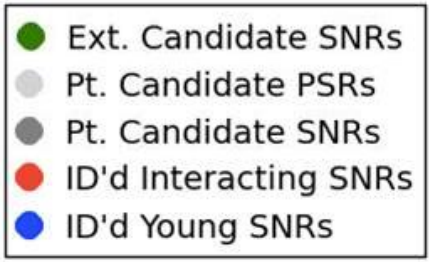
Or Evolution?

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

Due to

- decreasing shock speed allowing greater particle escape?
- decreasing maximum acceleration energy as SNRs age?





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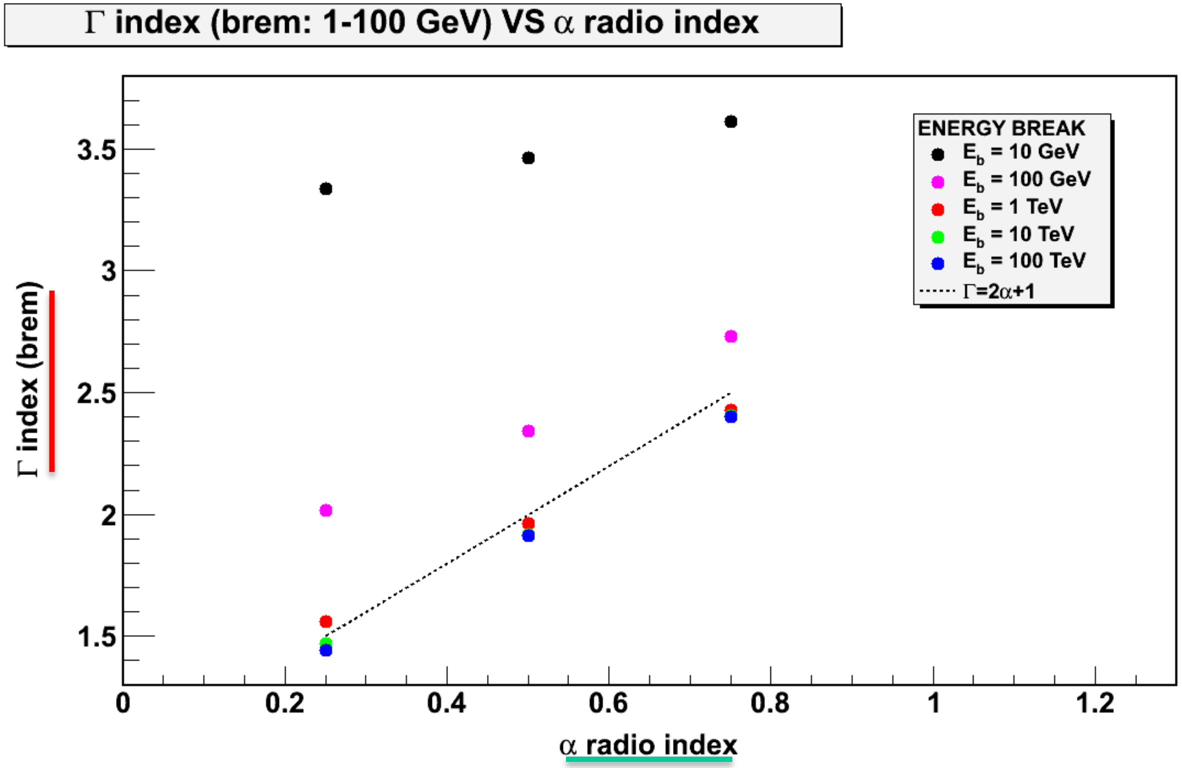
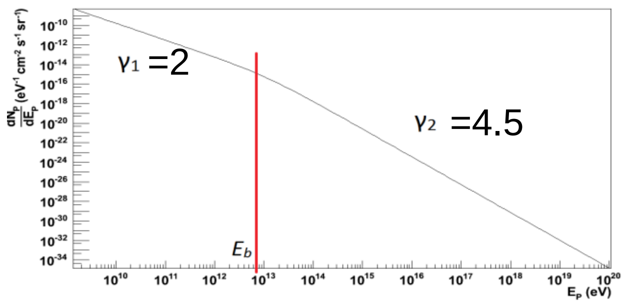
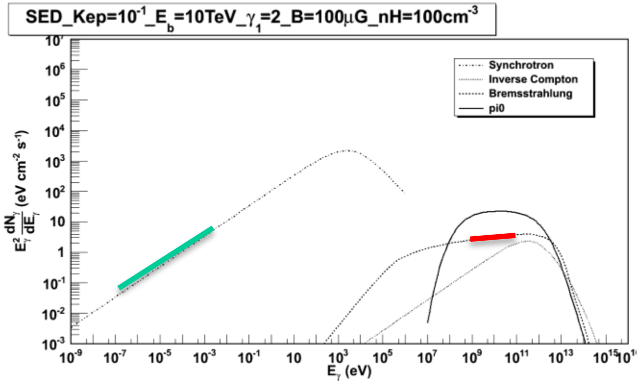
Simulations studies: Bremsstrahlung

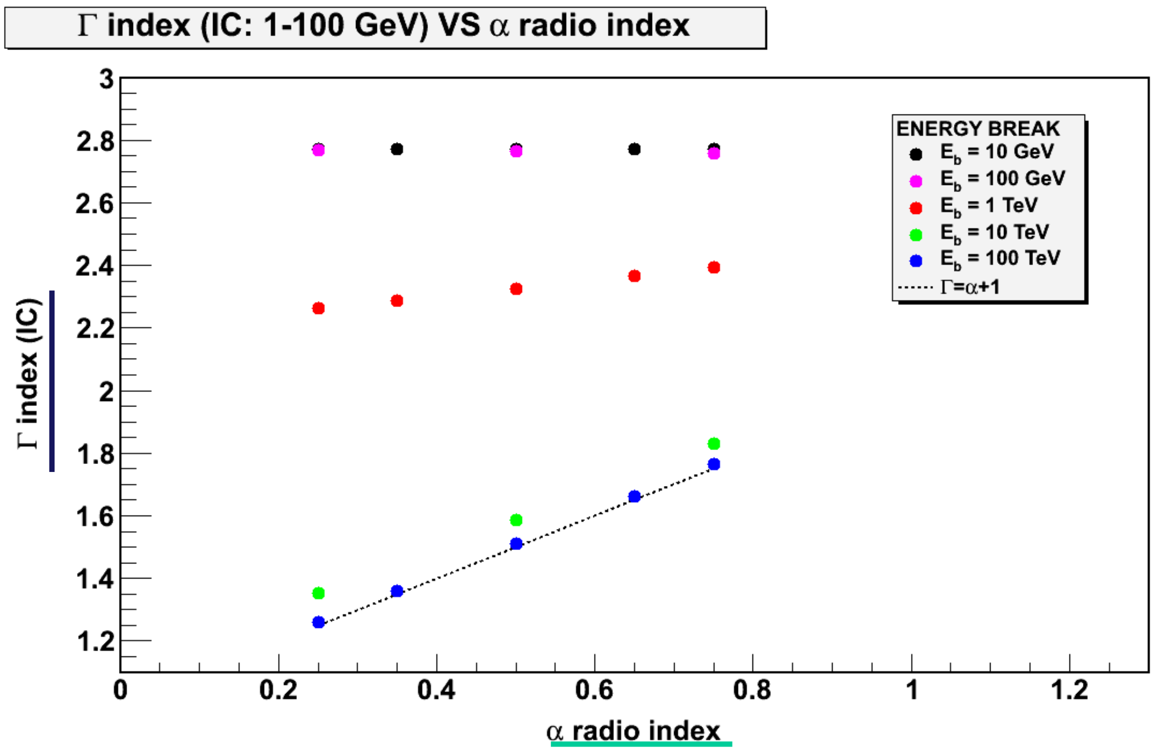


Particle injection

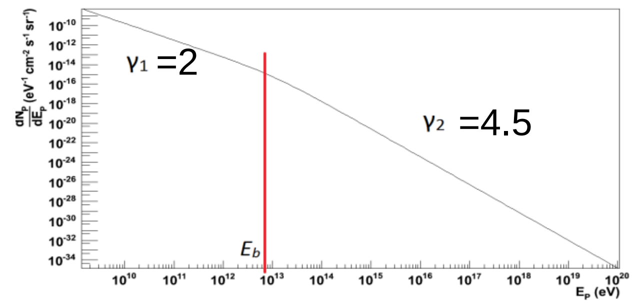


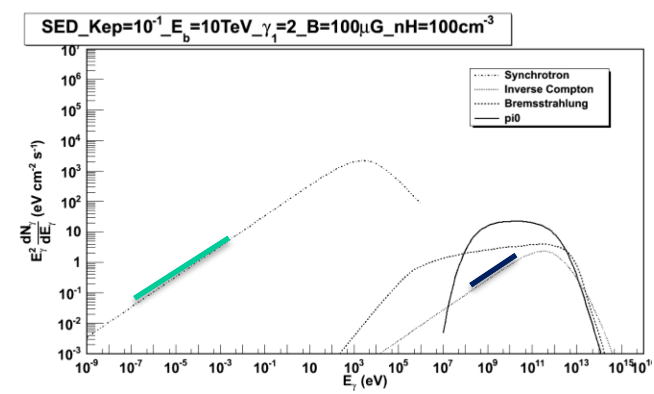


Simulations studies: IC



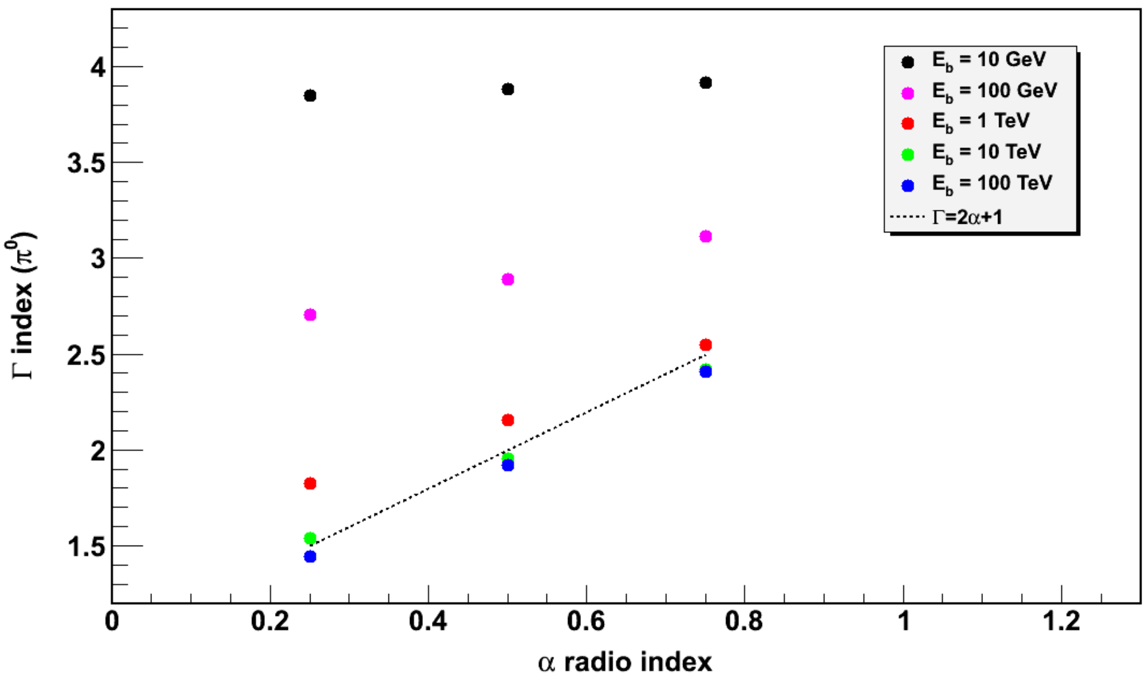
Particle injection



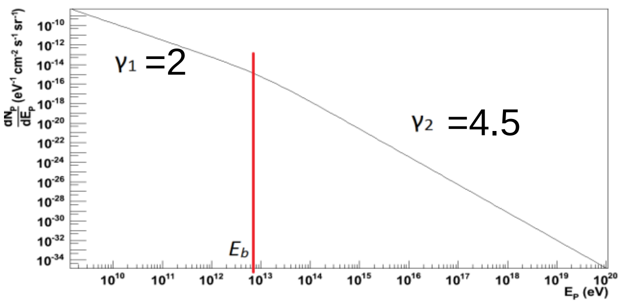


$\pi^0 \to \gamma\gamma$ SEDs

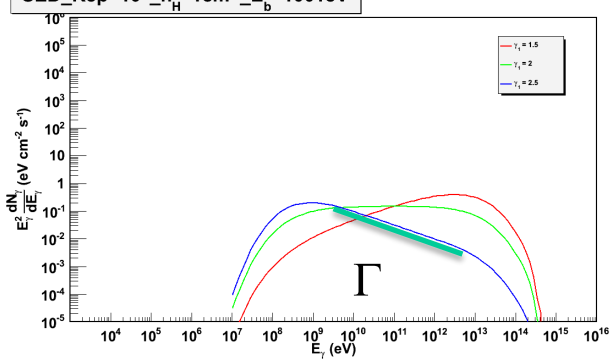
Γ index (π^0: 1-100 GeV) VS α radio index



Particle injection



SED_Kep=10^-1_n_H=1cm^-3_E_b=100TeV



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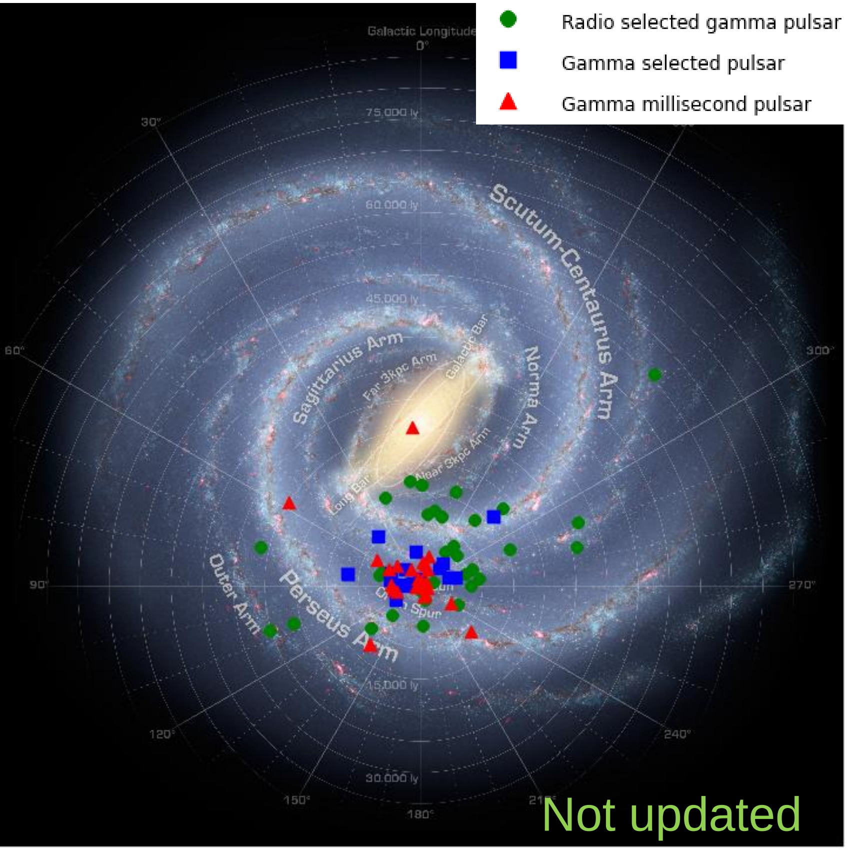
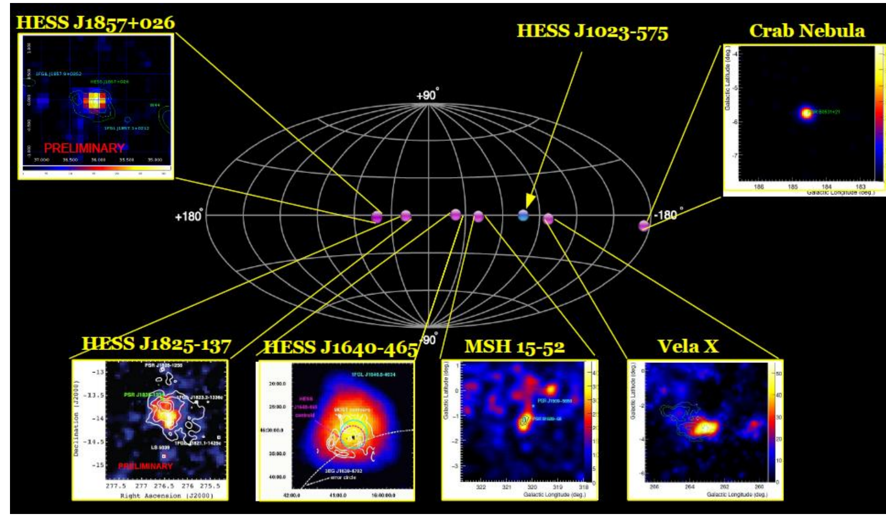
Galactic sources of γ and CR

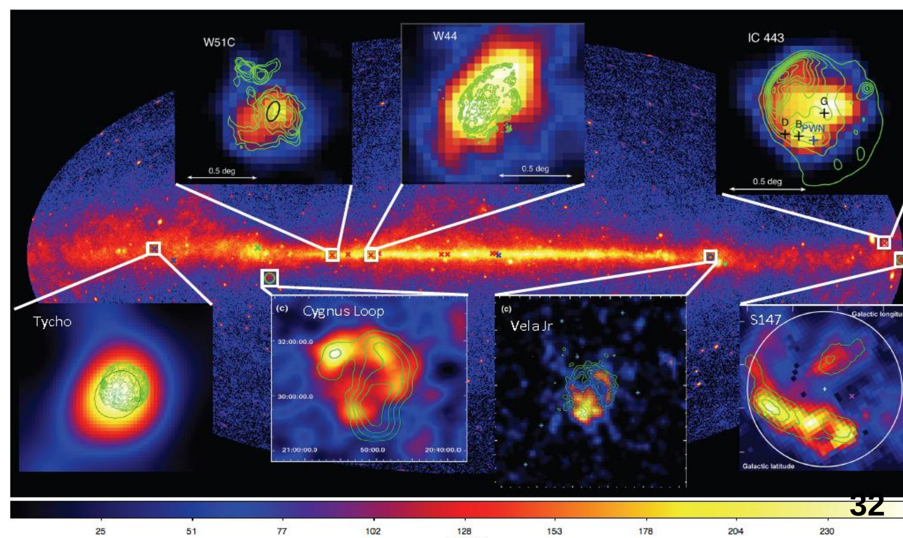
Pulsars map



PWN grouped



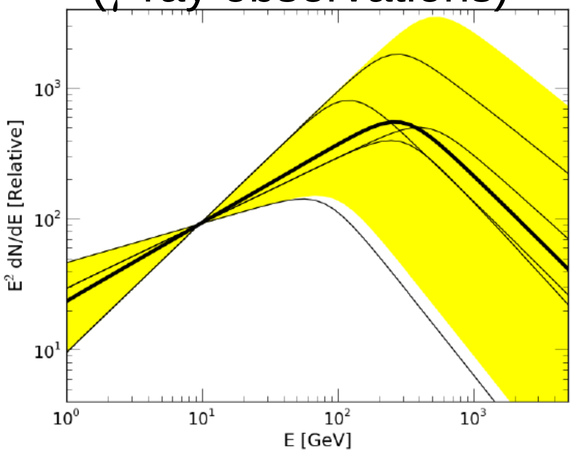
SNRs grouped



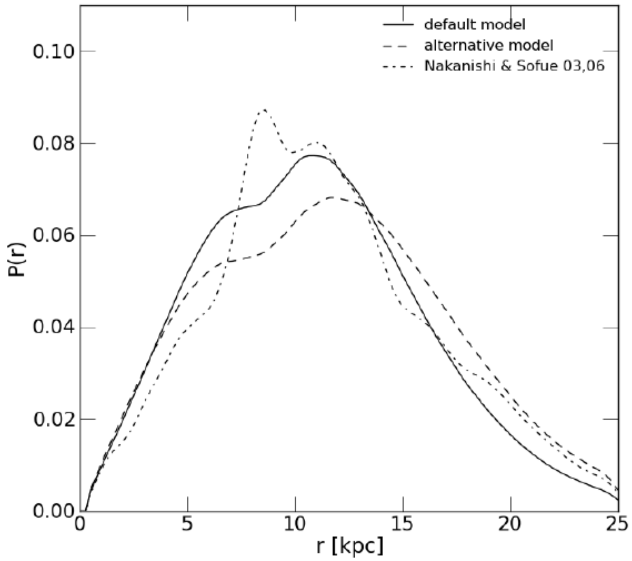
Main Ingredients: Distribution & Injection

All Galactic CRs are assumed to be injected (**in steady-state**) by the ensemble of SNRs and PWNe, or produced through their interactions with the interstellar gas in the Galaxy, or from clouds interacting with SNRs.

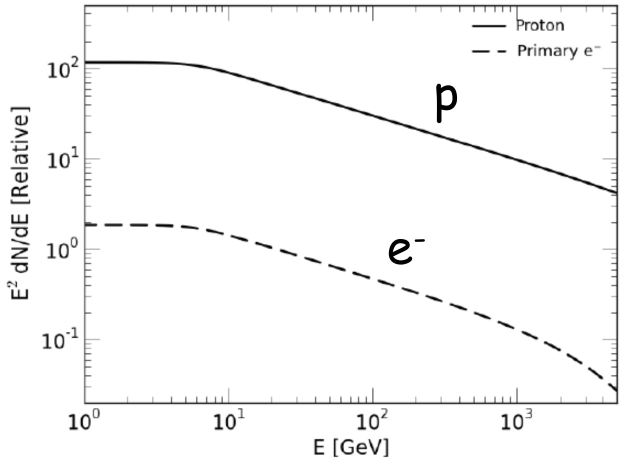
PWN
(γ-ray observations)



Source distributions:
SNRs and PWNe are distributed identically and continuously in the Galaxy

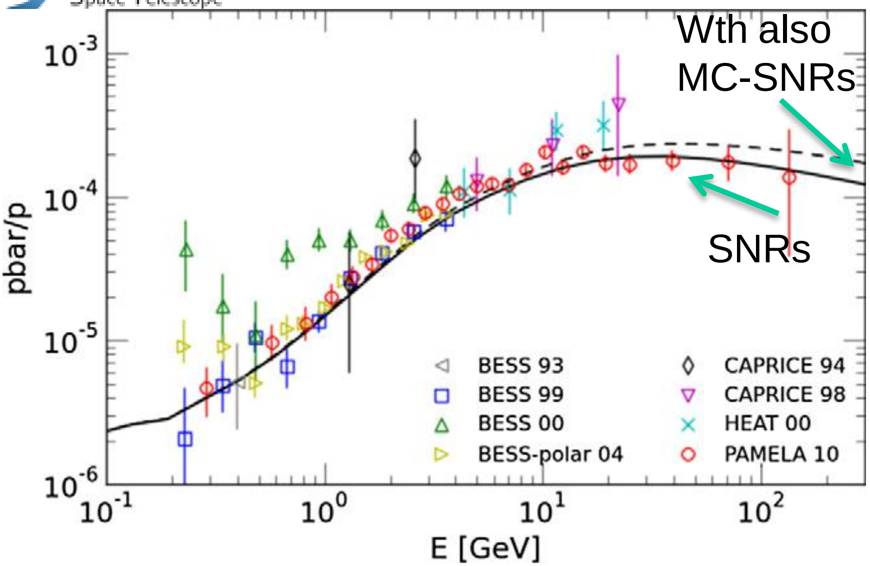


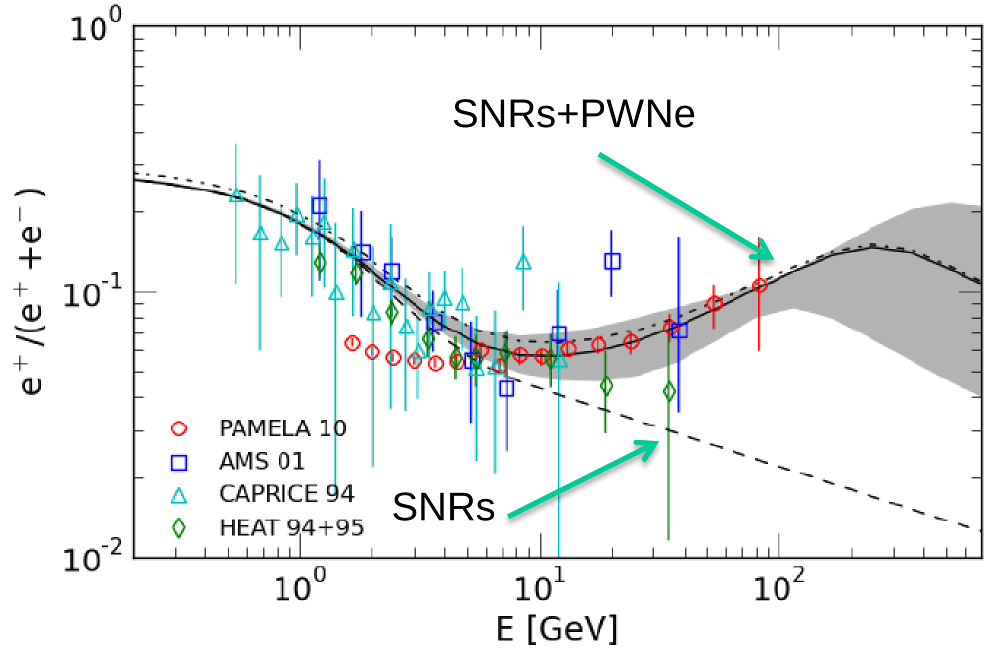
SNRs
constrained by the available observations of CR proton flux at Earth.

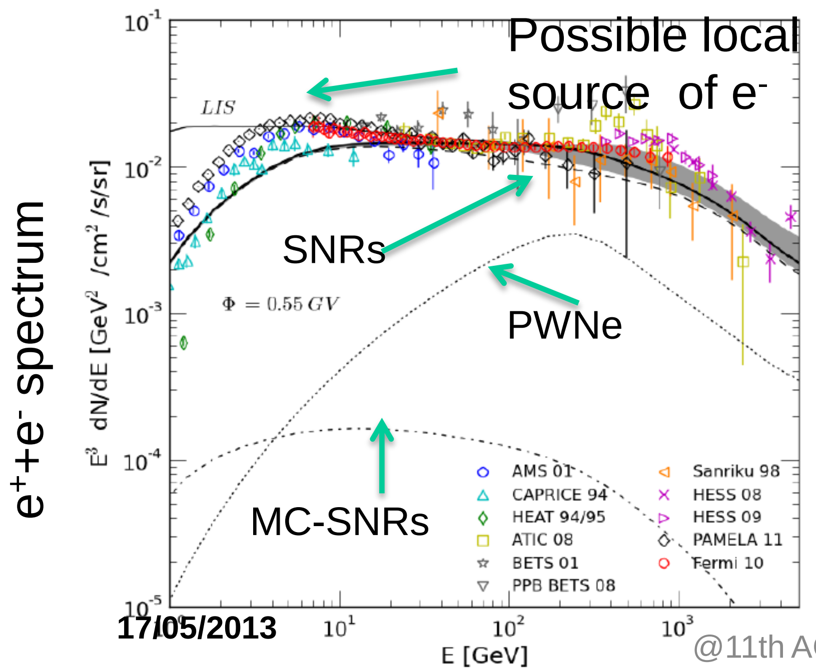


Lee et al. 2011, AP, 35, 211

… to get the “right” observations







The energy dependence of the excess in positron fraction can be mostly explained by the contribution from the Galactic ensemble of PWNe added upon the secondary e^+ produced by SNR interaction.

Conclusions

- Our systematic study has identified a statistically significant population of Galactic SNRs, including:
  - 6 new extended and >25 pointlike SNR candidates,
  - evidence for at least 2 SNRs' classes: young and interacting.
- Combining GeV and MW observations suggests that:
  - some SNRs' emitting particle populations may be linked,
  - simple model assumptions are no longer sufficient, allowing more complex models to be tested.
- Improved observations and modeling will give us greater insight into SNRs, their acceleration mechanisms and their accelerated particles.
- Accurately estimating SNRs' aggregate particle acceleration ability will also allow us to better quantify SNRs' ability to produce the observed CRs.