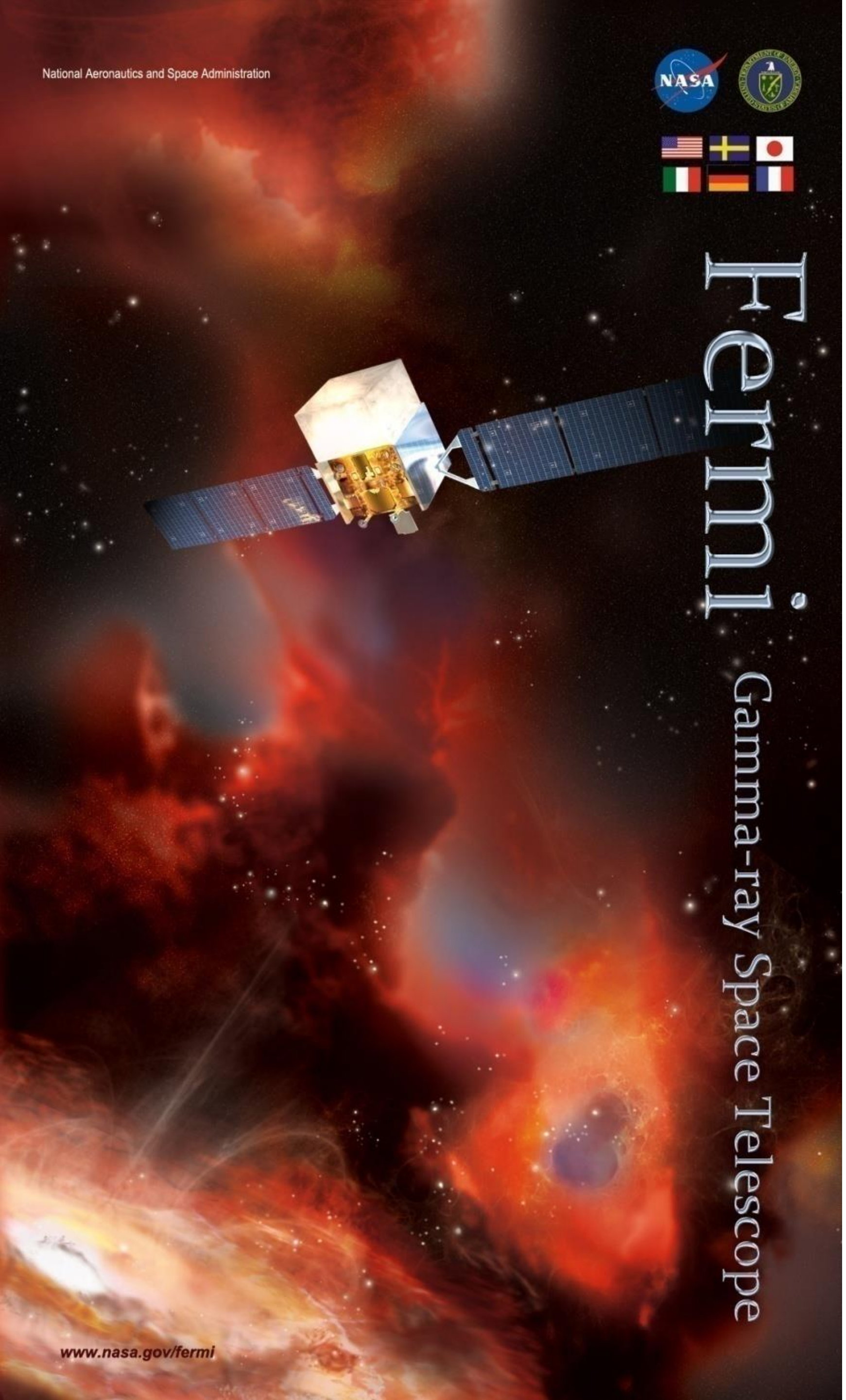

Systematically Characterizing Regions of the First Fermi-LAT SNR Catalog

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on behalf of the Fermi-LAT Collaboration

*INFN Bari and
Università Telematica Pegaso

Fifth Fermi Symposium
Nagoya, Japan

SNR Catalog:

To better understand SNRs candidate regions in a systematic way we need to:

- characterize the spatial and spectral morphology of all regions containing known SNRs (274 from the Green's Catalog + 5 new sources).
- Evaluate the spatial coincidence of our results with radio SNRs.
- Estimate the systematic errors that can affect our measures.

Characterize GeV Emission: Analysis Procedure

Data Set
- 3 years of P7SOURCE_V6 LAT data
- FAVA flares removed
- E: 1-100 GeV
- 10° around each SNR

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

Background model
- *Add source method* (J. Cohen)
- STD IEM

Tested Hypotheses
- Spectral models: Power Law or Log Parabola
- Extension: Point or disk and effect of nearby sources

Fit
- Localization and extension
- Spectral parameters (SNRs and bkg sources).

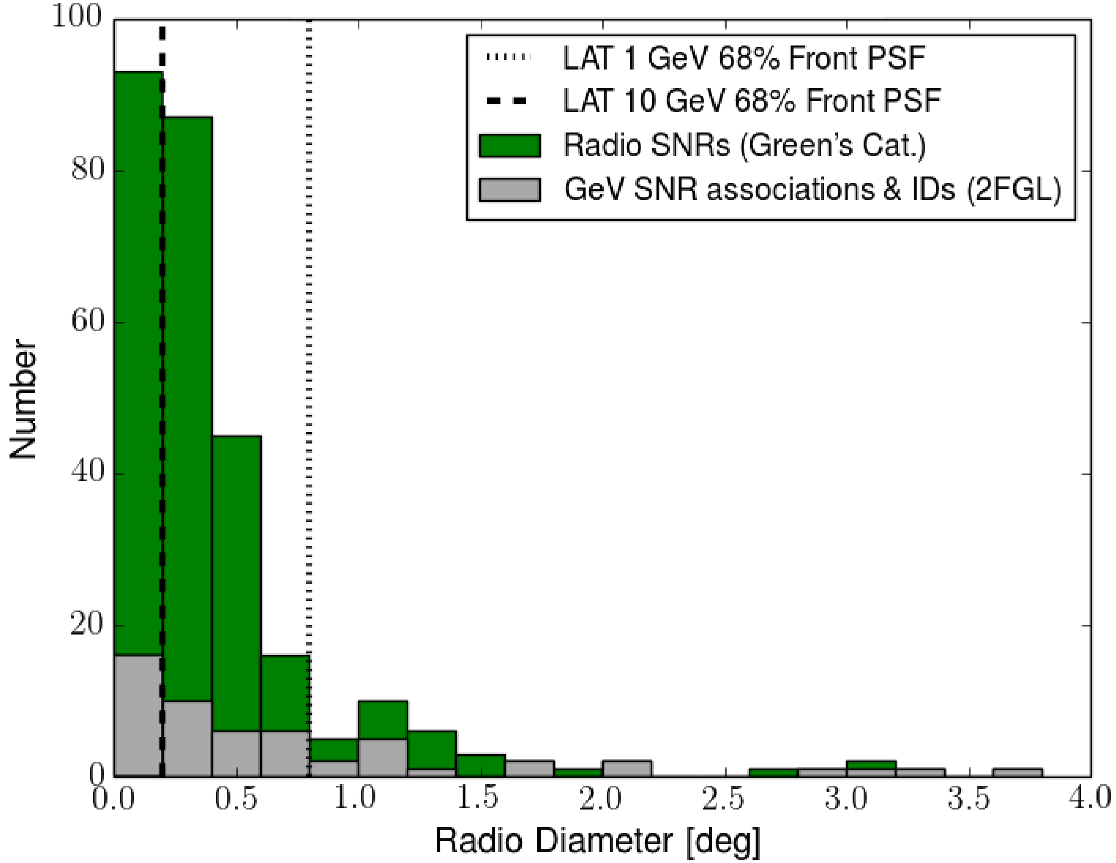
Systematic Error evaluation
- Alternative IEM
- Effective area.

Output
- Best extension and spectral model
- Position, size and significance
- Upper limits if not detected

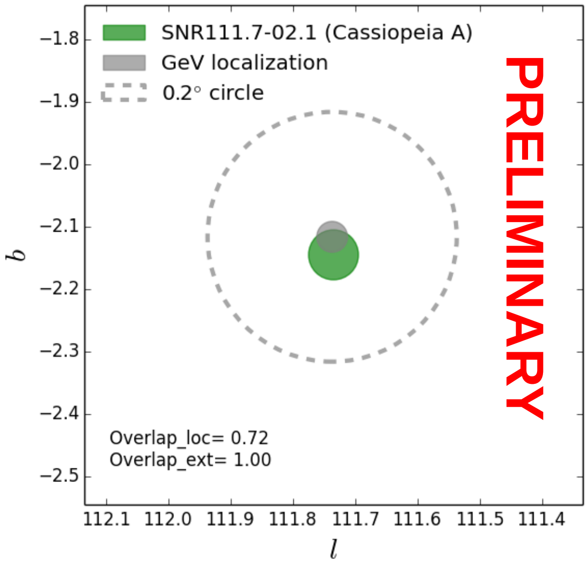
Classification
- Spatial coincidence (F. Acero)
- Mock Catalog (B. Wells)

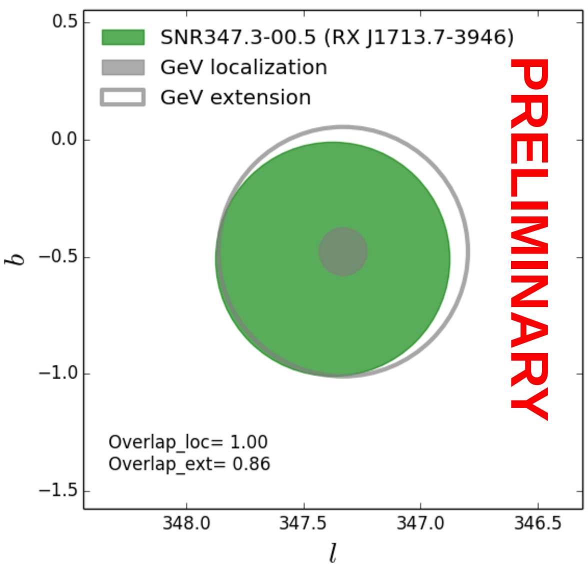
SNR Catalog

- Fermi-LAT has the ability to spatially resolve a large number of the 279 known SNRs assuming their GeV and radio sizes are similar.
- The LAT 10 GeV 68% PSF is roughly equivalent to the limit at which bright sources can have detectable extensions.

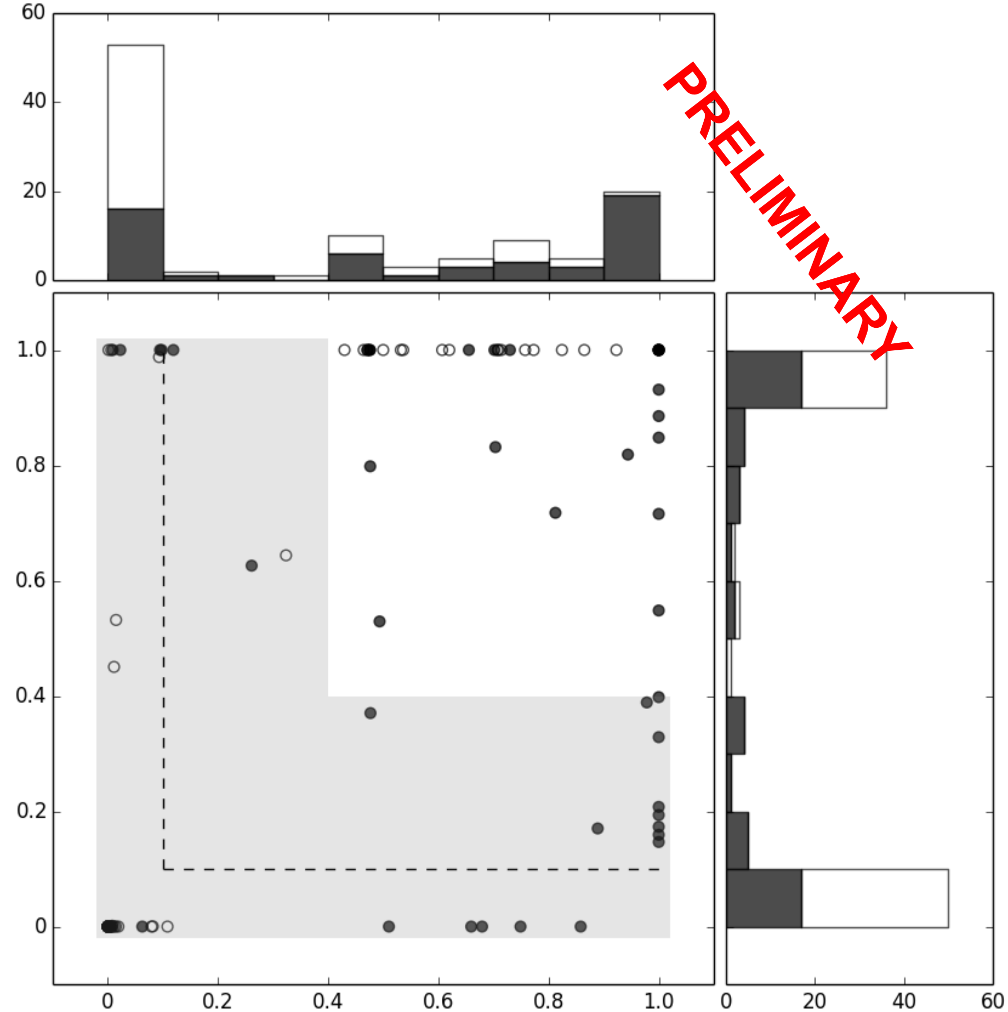


Spatial coincidence





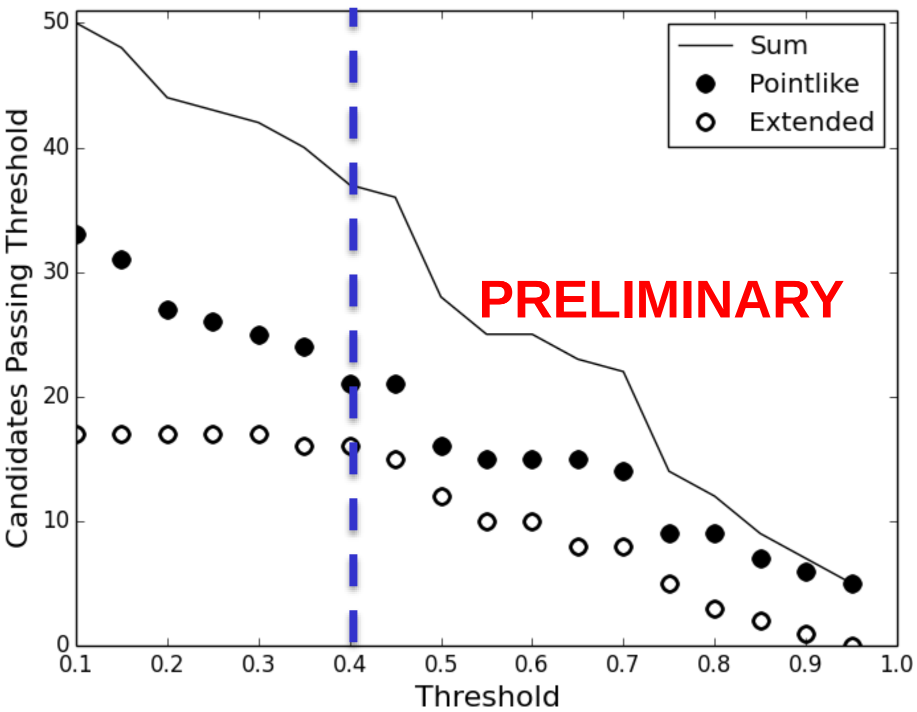
$$\text{Overlap}_{\text{loc}} = \frac{\overline{Radio \cap GeV_{\text{loc}}}}{\min(\overline{Radio}, \overline{GeV_{\text{loc}}})}$$



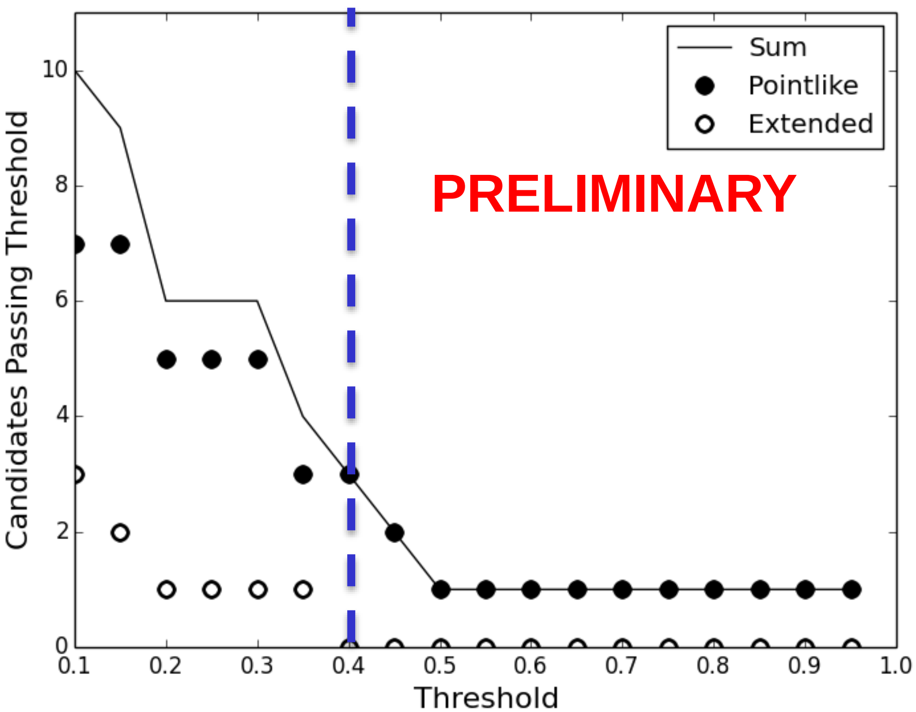
$$\text{Overlap}_{\text{ext}} = \frac{\overline{Radio \cap GeV_{\text{ext}}}}{\max(\overline{Radio}, \overline{GeV}_{\text{ext}})}.$$

Mock catalog: Chance Coincidence Study

LAT SNR Catalog

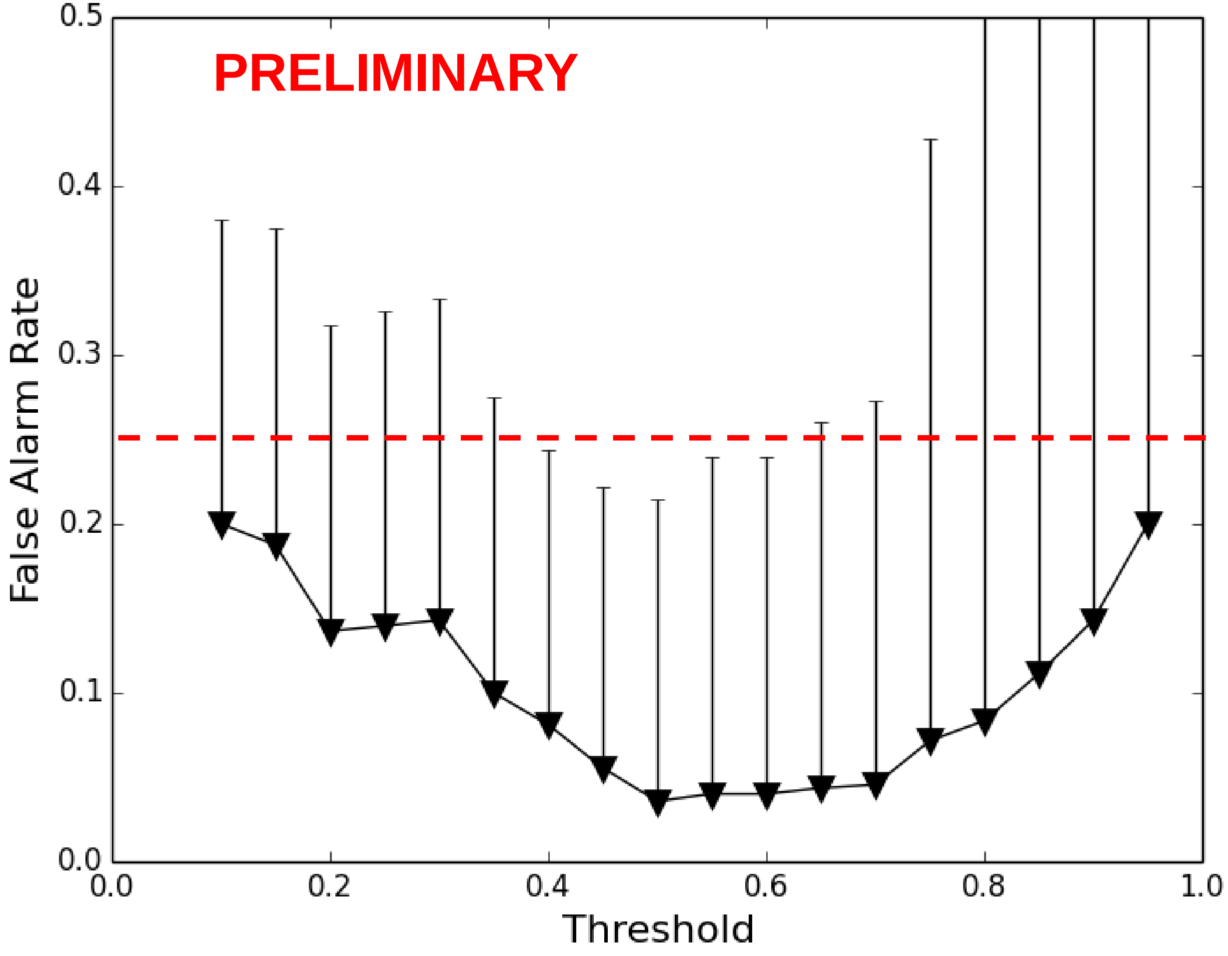


Mock Catalog

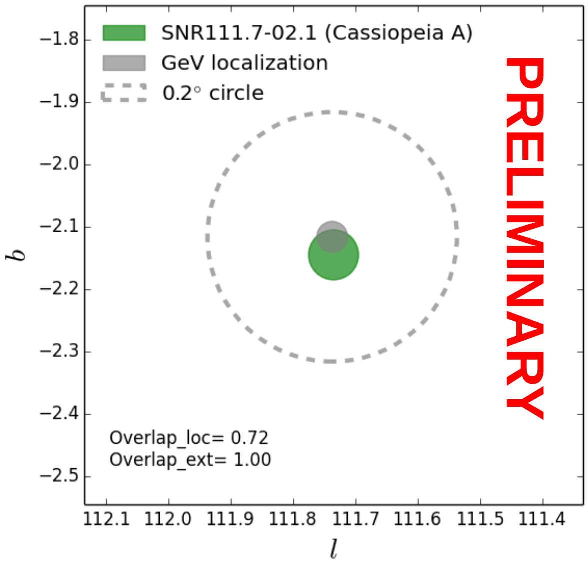


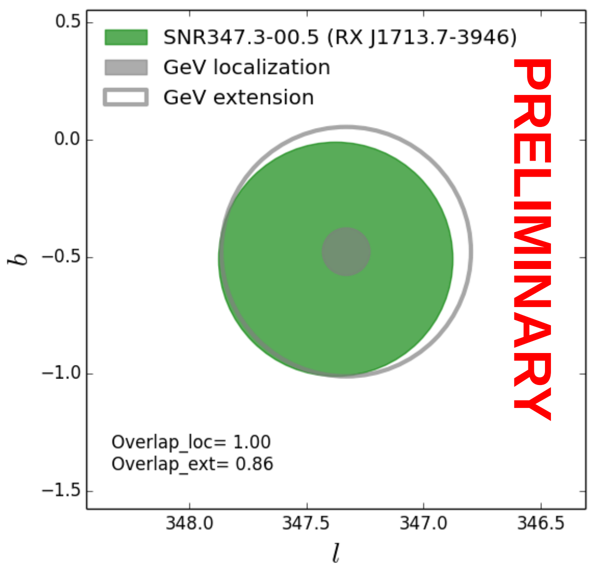
Mock catalog: Chance Coincidence Study

Use measure of chance coincidence in mock catalog to estimate false alarm rate and error. Set thresholds to 0.4: $< 25\%$ false-positive rate.

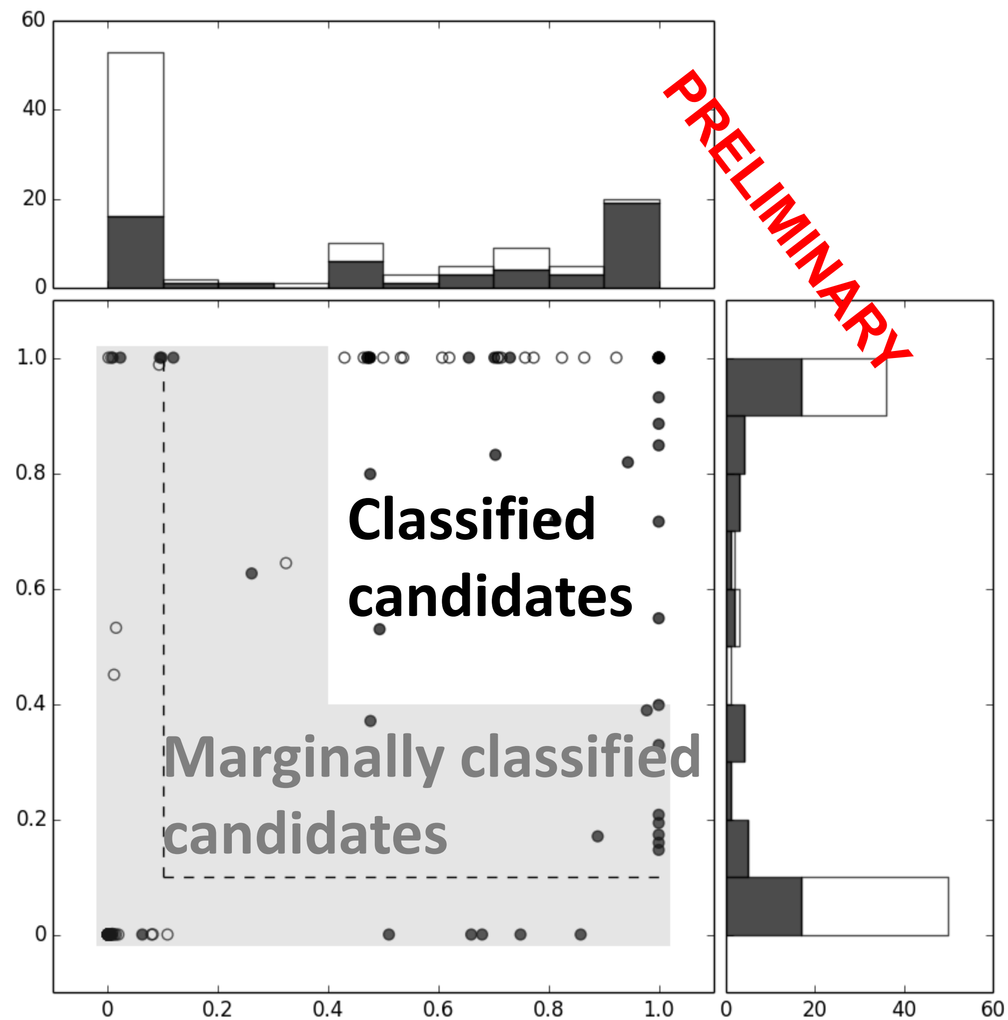


Spatial coincidence





$$\mathrm{Overlap_{loc}} = \frac{\overline{Radio \cap GeV_{\mathrm{loc}}}}{\min(\overline{Radio}, \overline{GeV_{\mathrm{loc}}})}$$

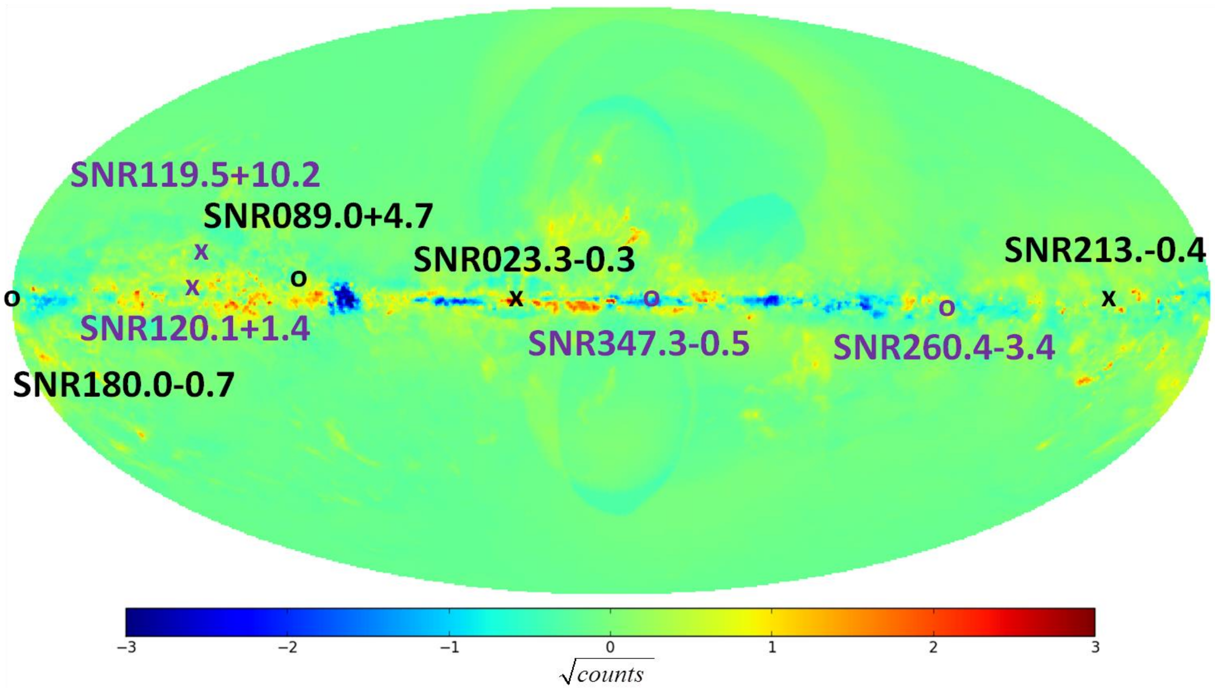


$$\mathrm{Overlap_{ext}} = \frac{\overline{Radio \cap GeV_{\mathrm{ext}}}}{\max(\overline{Radio}, \overline{GeV_{\mathrm{ext}}})}.$$

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.

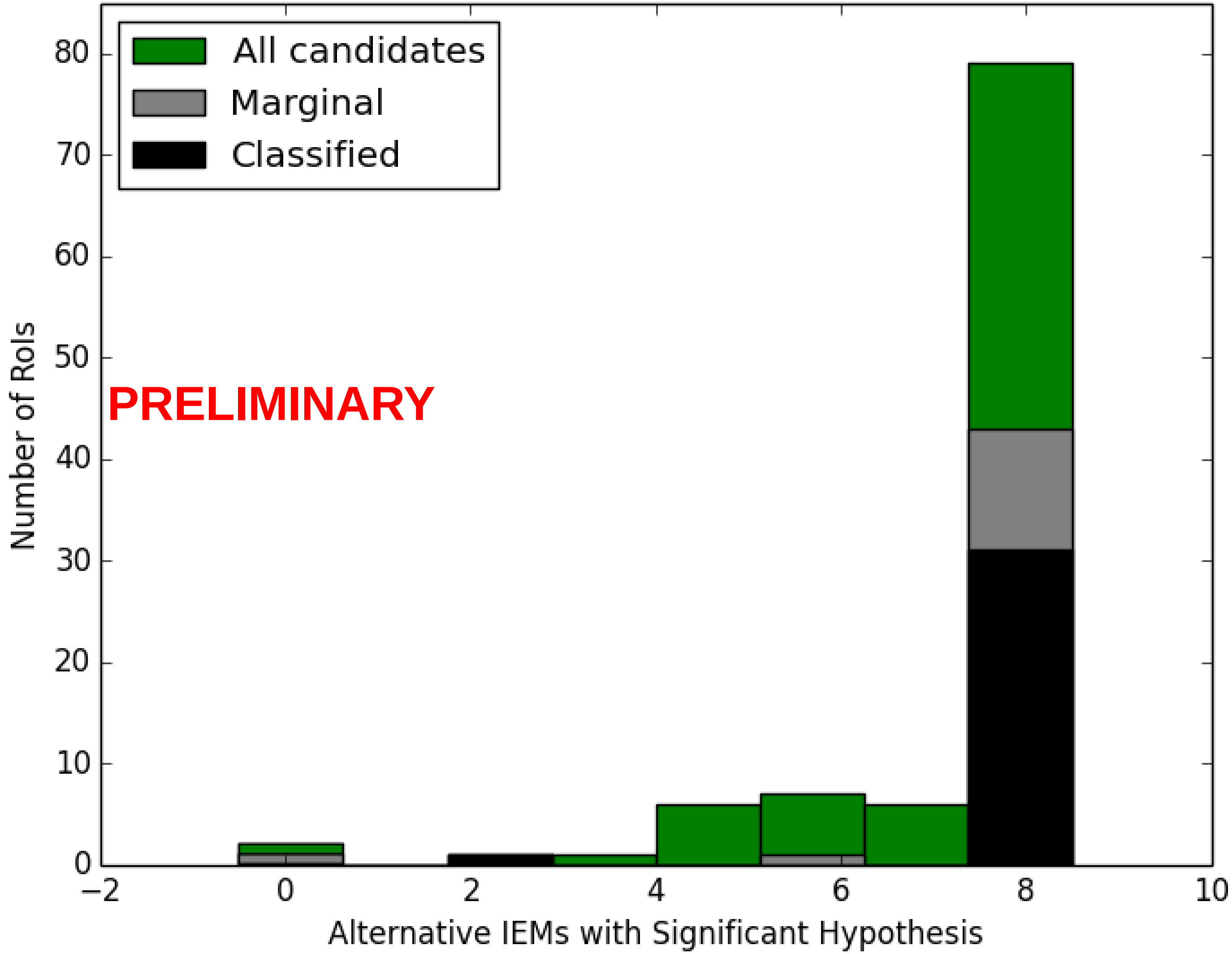
The HI and CO emission split into 4 Galactocentric rings and the inverse Compton emission are fit simultaneously with the source of interest.

Warning:

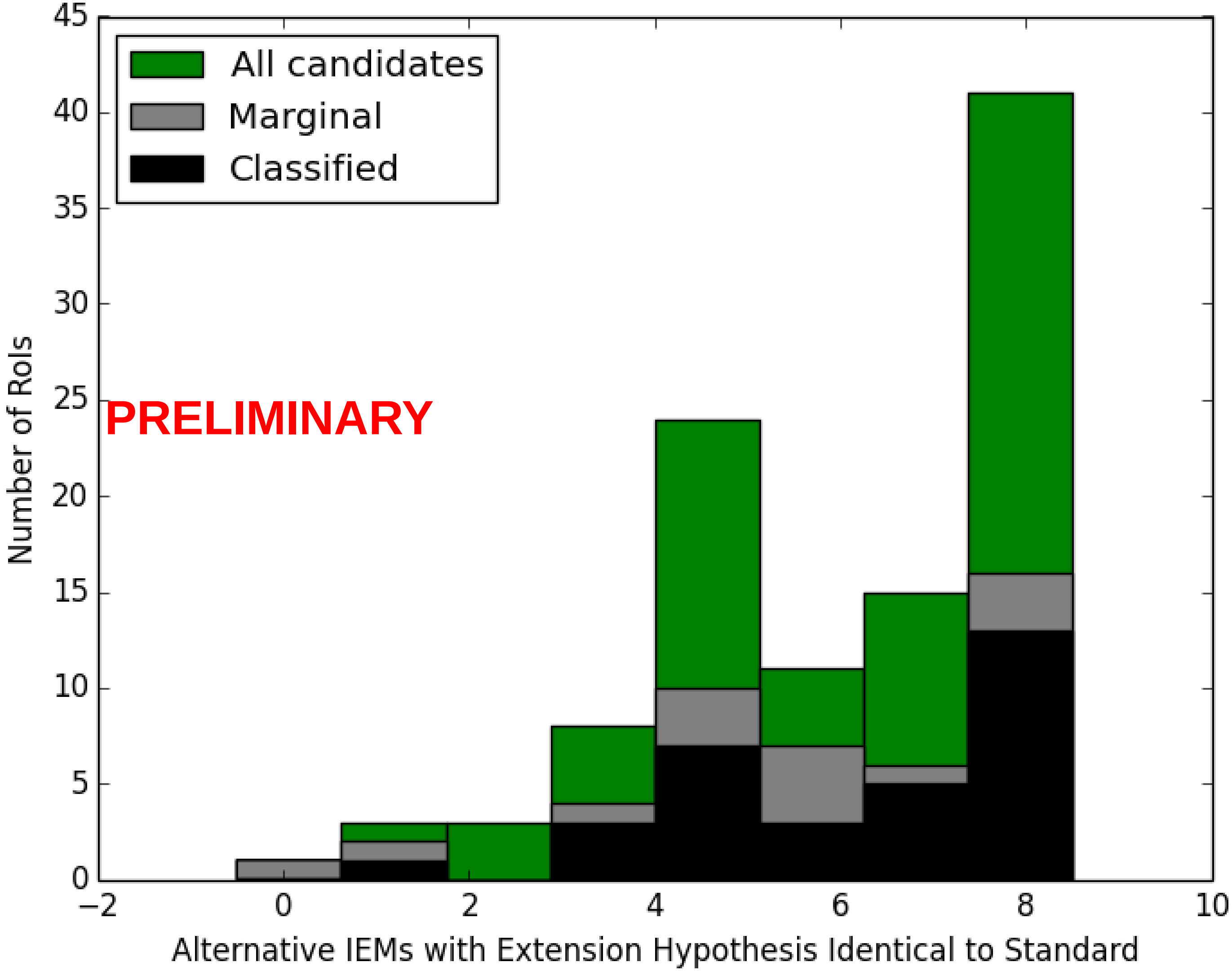
- *these 8 models do not span the complete uncertainty of the systematics.*
- *the method for creating this model differs from that used to create the official Fermi-LAT interstellar emission model, so these* ***8 models do not bracket the official model****.*

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

Candidates' significance with alternative IEMs



Candidates' best extension hypothesis with alternative IEMs



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:

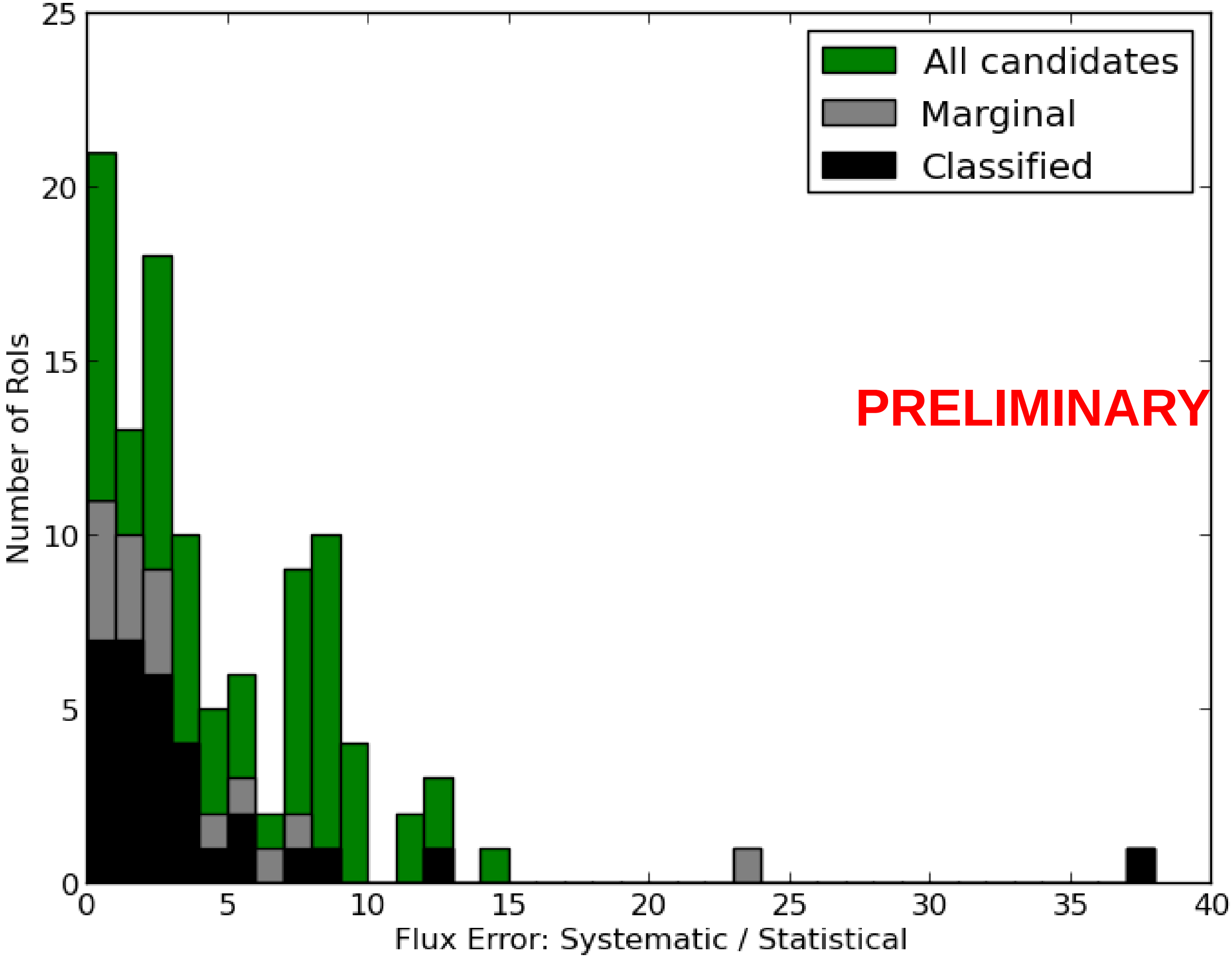
$$E_{sys,w} = \sqrt{\frac{1}{\sum_i^M \omega_i} \sum_i^M \omega_i \,(P_i - P_{STD})^2}.$$

The weight is:

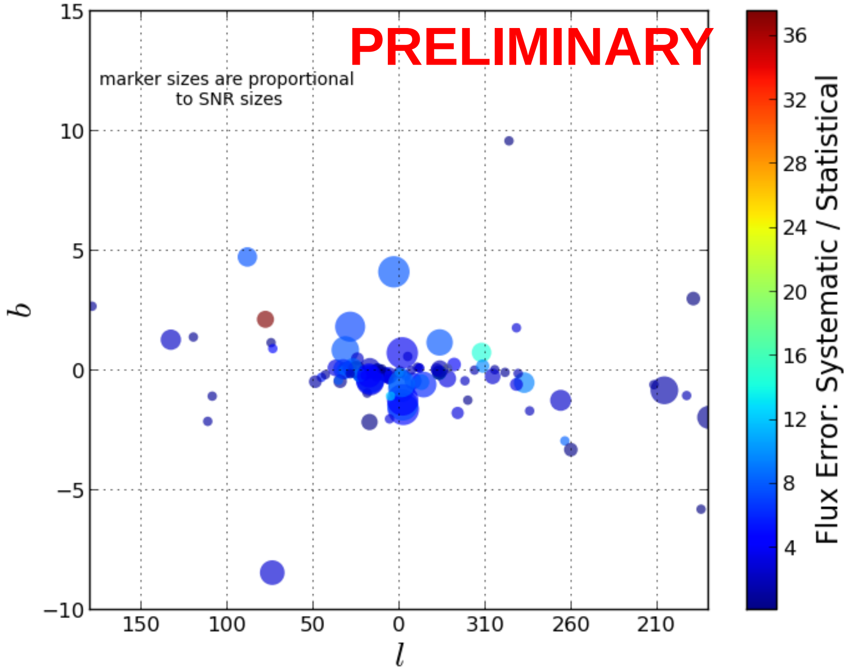
$$\omega_i = \frac{1}{\sigma_i^2},$$

where σ_i is P_i statistical error.

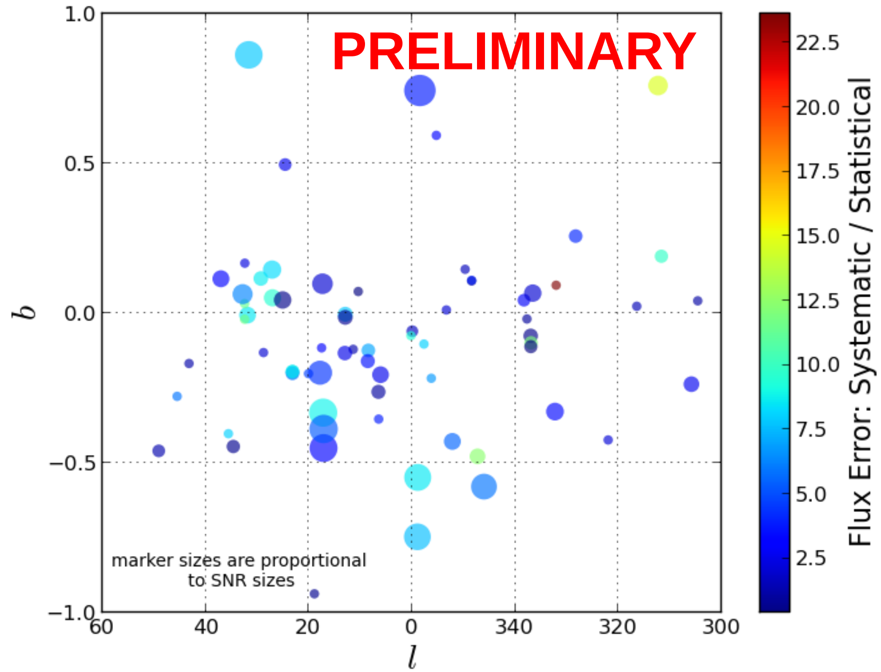
Flux Error: Systematic for IEMs/Statistical



Skymap with error ratio for flux



$|b| < 1$ and $60 < l < 300$

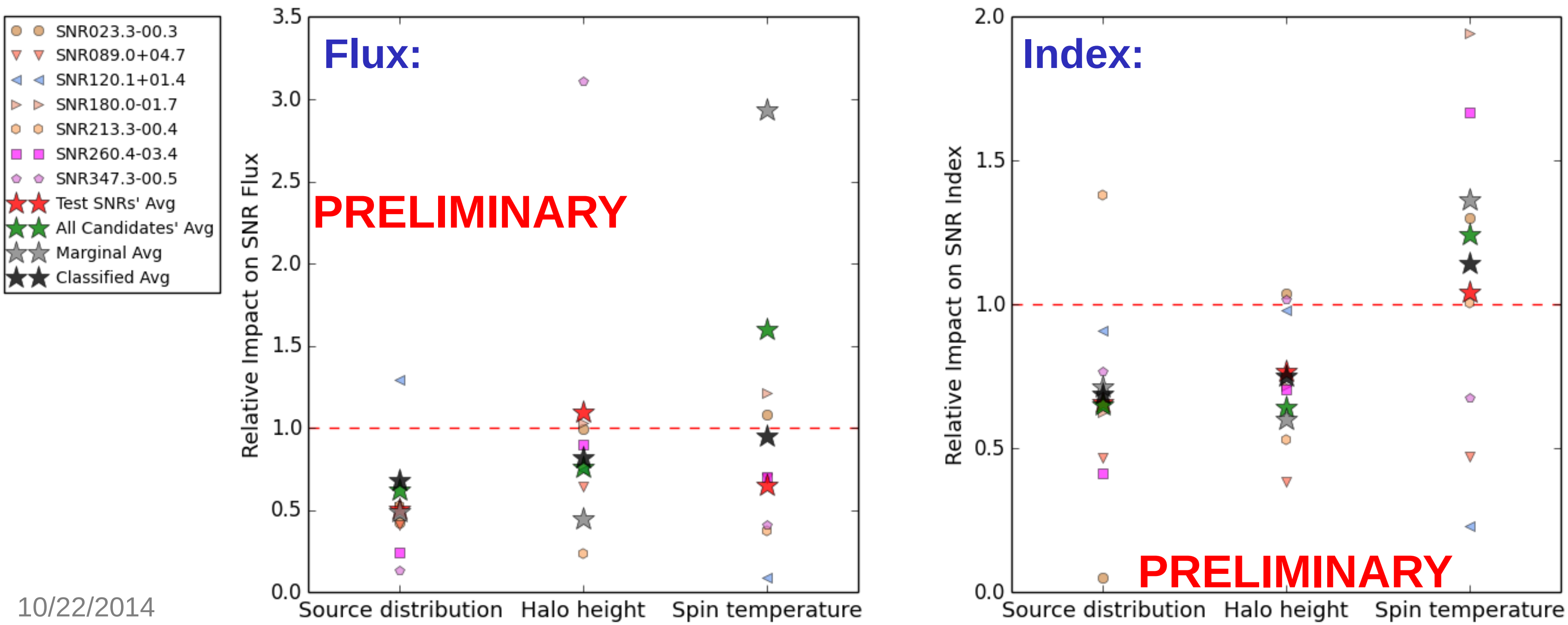


No particular correlation with the sky position is found.

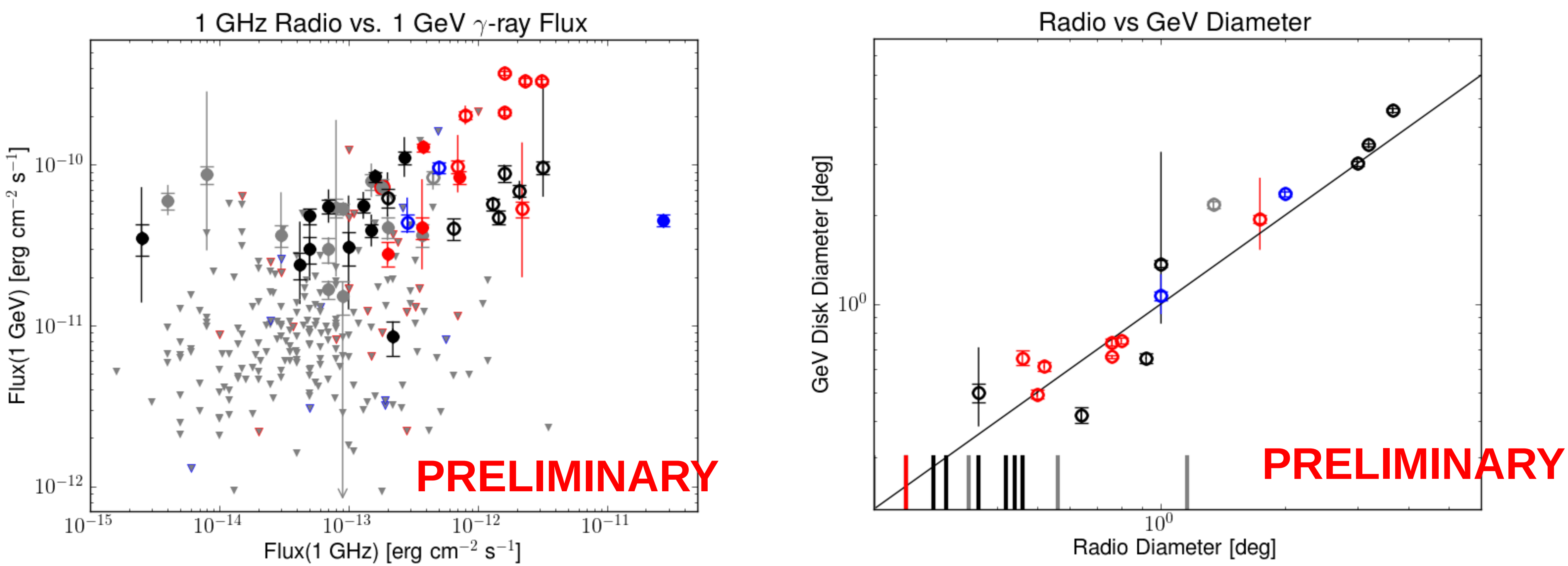
Alternative IEM parameter effects

For a fitted parameter P_l (flux and PL index) and a GALPROP input parameter set $\{i, j\}$ (CR source distribution, CR propagation halo height and HI spin temperature) we evaluated the ratio:

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



Systematic errors in Radio vs GeV plots



- Systematic error is the sum in quadrature of systematic error for the IEMs and for the effective area.
- 1 SNRs have been considered marginally associated just for large systematics.
- The systematic error for the IEMs for the flux is symmetric in log space.

SNR catalog results

Characterized 279 regions containing known radio SNRs:

- 109 candidates have significant GeV emission:
  - 37 candidates classified through spatial association with radio data:
    - 16 extended: 3 new!
    - 16 point-like hypothesis preferred: 7 new!
    - 1 are flagged for IEMs systematics
    - 4 identified as other sources (Crab, binary, and PWN/PSR)
  - 72 candidates not classified, we report the candidate parameters and the upper limits (UL)
- 170 candidates don't have a significant GeV emission, we report their Uls.

Several results of the SNR catalog were presented by Jack (Monday afternoon plenary) and Terri (today Galactic splinter).

Conclusions

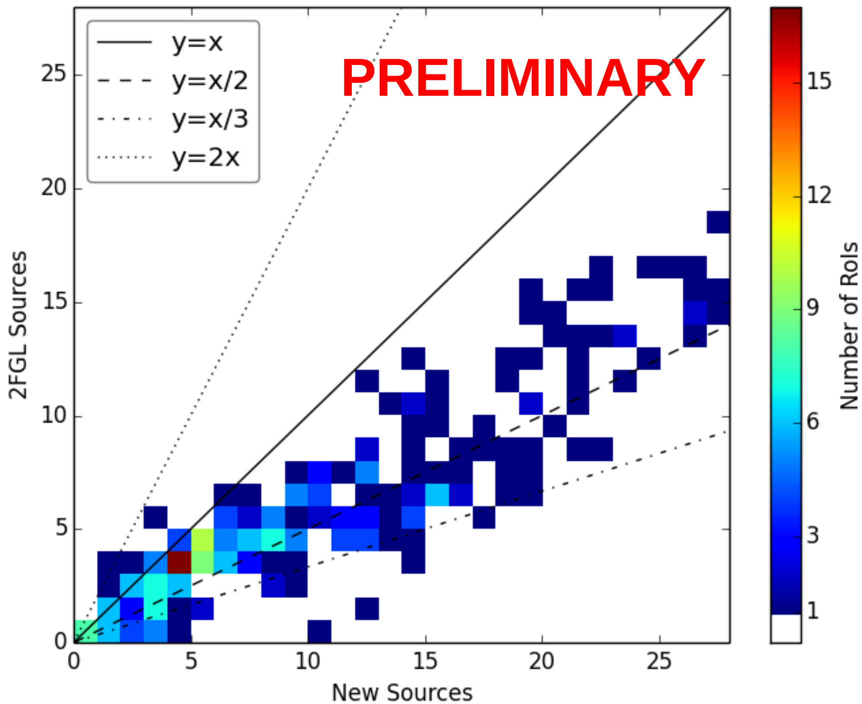
To better understand SNRs candidate regions in a systematic way we:

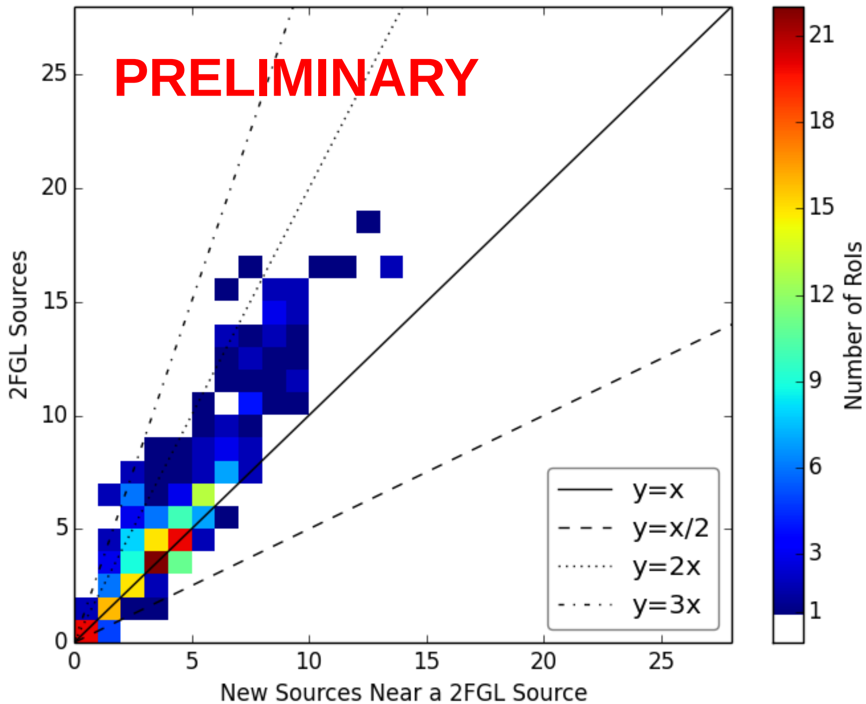
- characterized the spatial and spectral morphology of all regions containing known SNRs.
- evaluated the spatial coincidence of our results with radio SNRs, using also a mock catalog for estimate the false positive rate.
- Evaluated the systematic errors on all the significant sources for IEMs and effective area.

Backup

Background sources

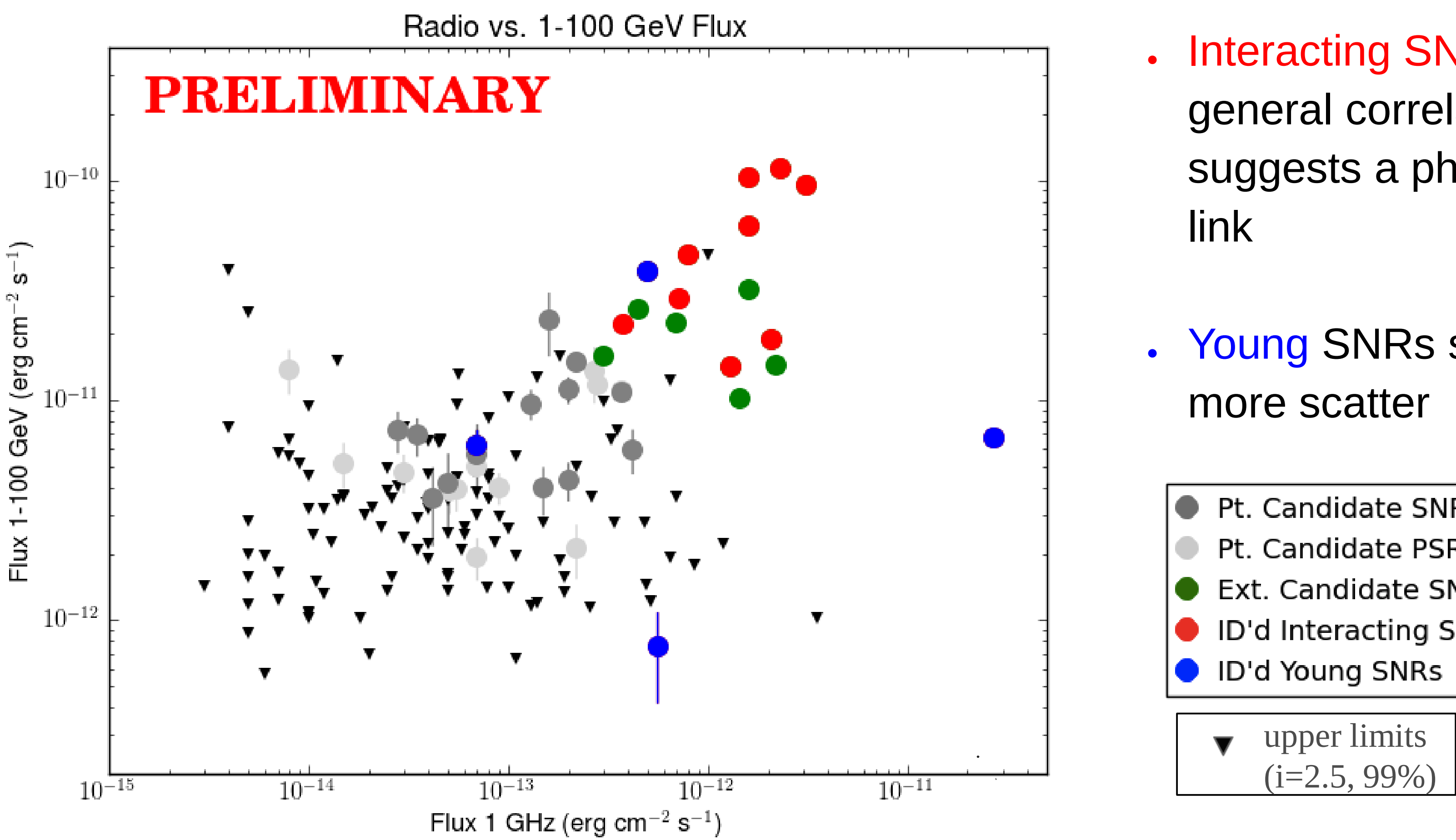
Added background sources compared to the number of 2FGL sources in 3°.





Radio-GeV Correlation?

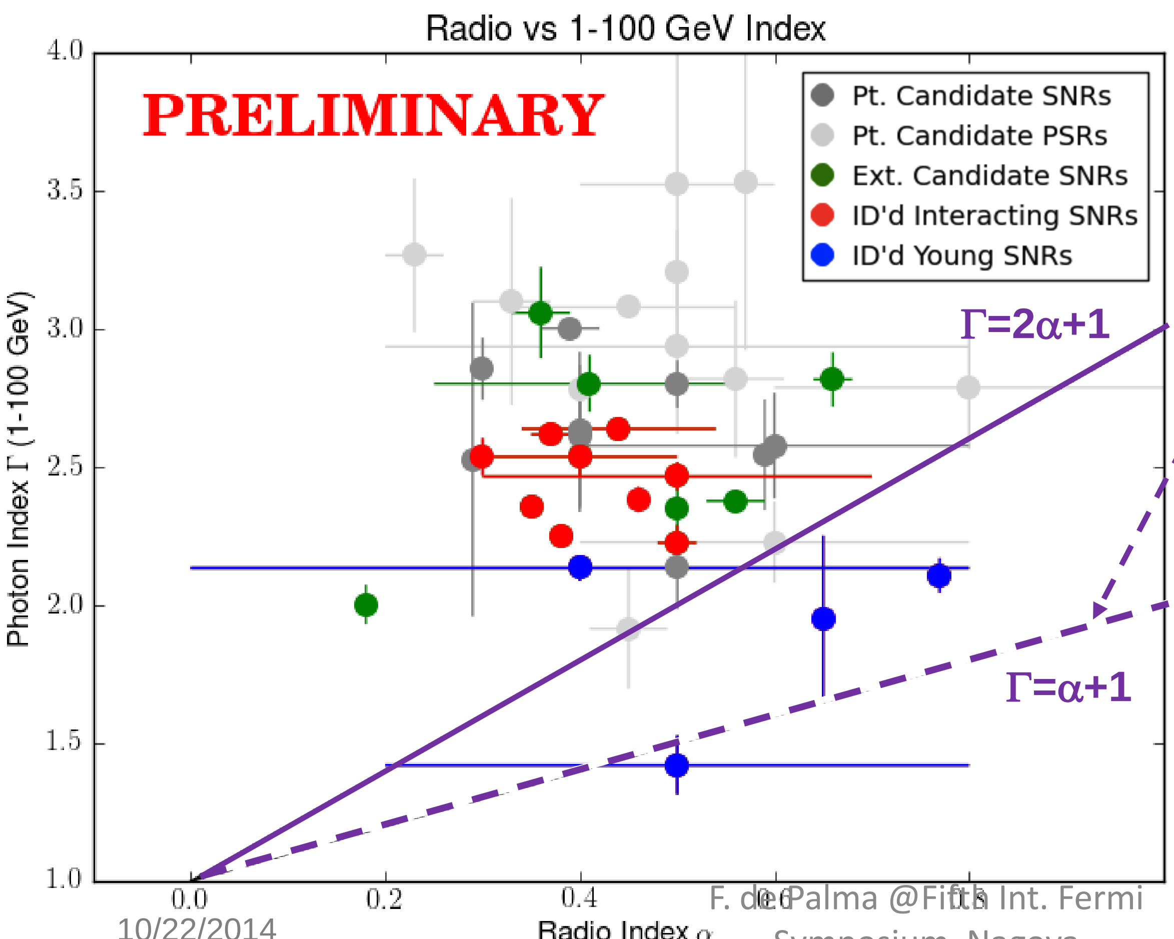
Radio synchrotron emission indicates the presence of relativistic leptons.
LAT-detected SNRs tend to be radio-bright:



- 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:



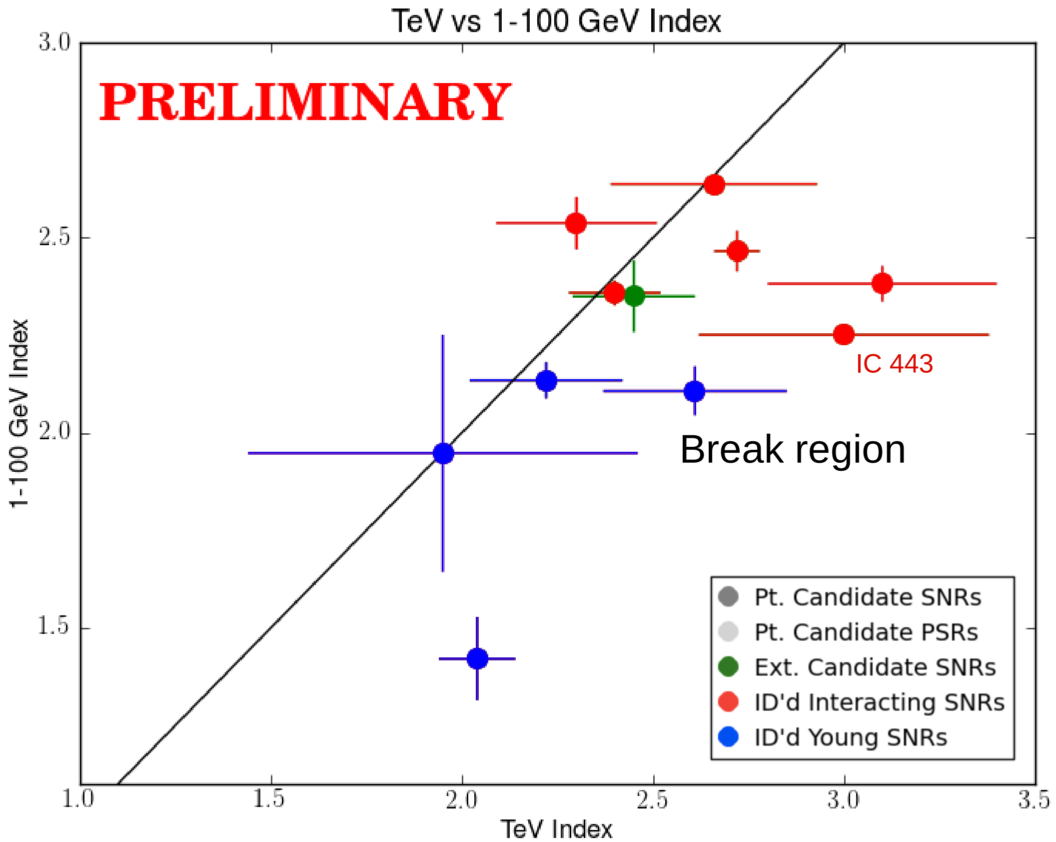
- Young SNRs: seem consistent
- Others, including interacting SNRs: softer than expected

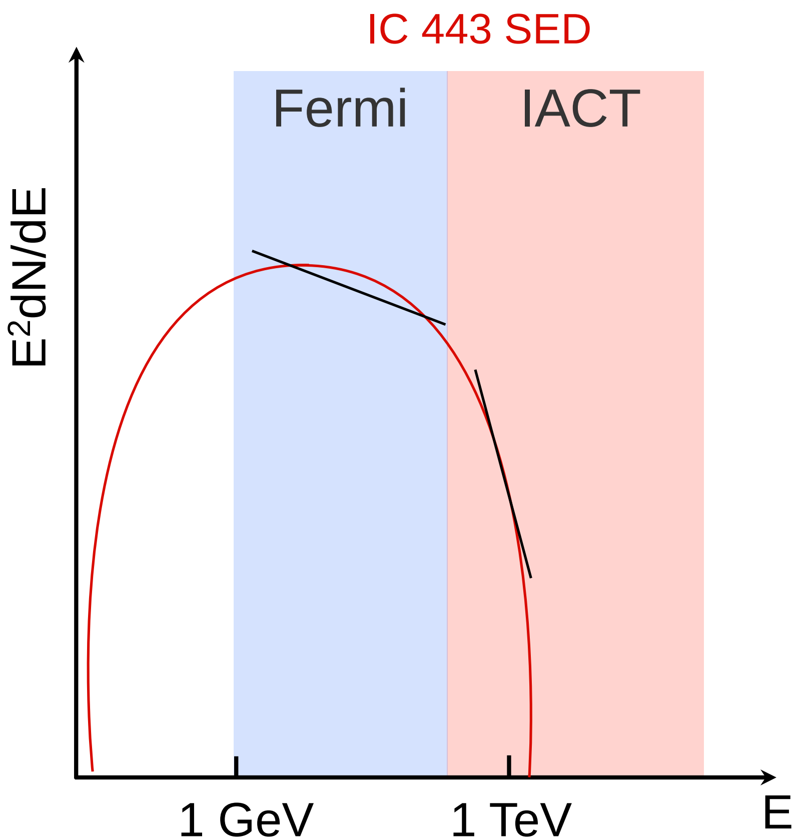
▪ *π^0 decay or $e^{+/-}$ brem.*
▪ *inverse Compton*

<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?

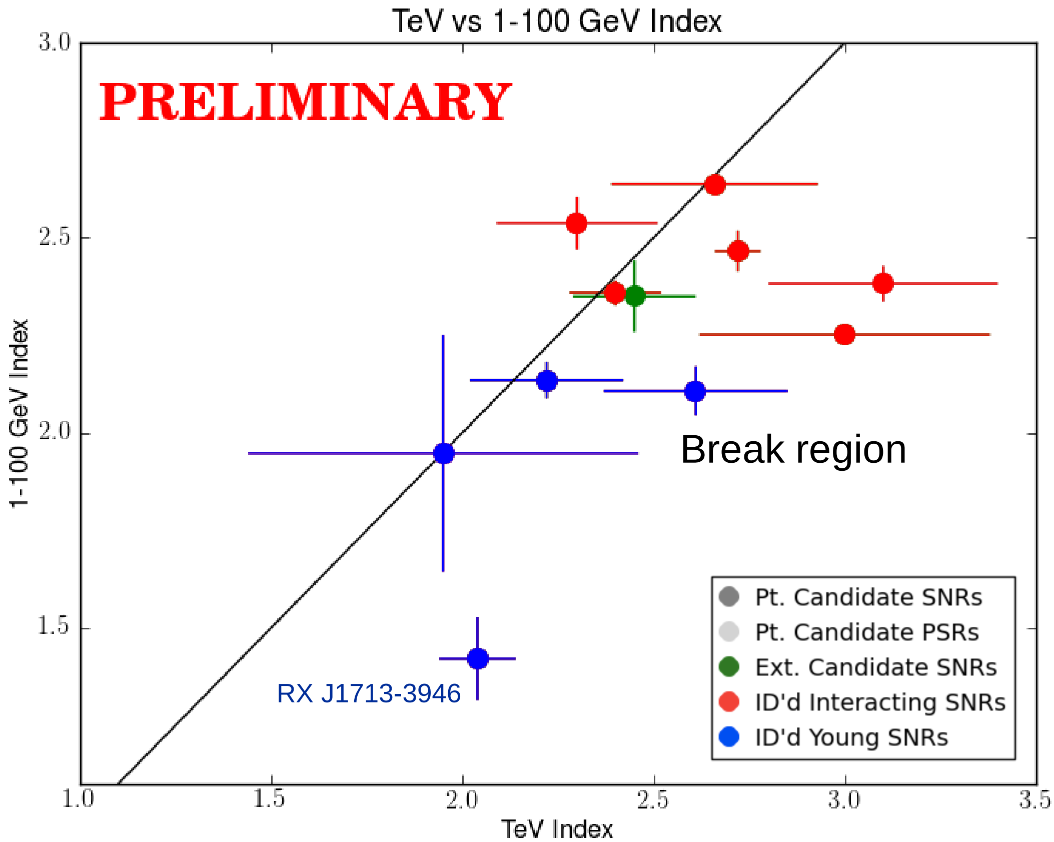
GeV-TeV Index

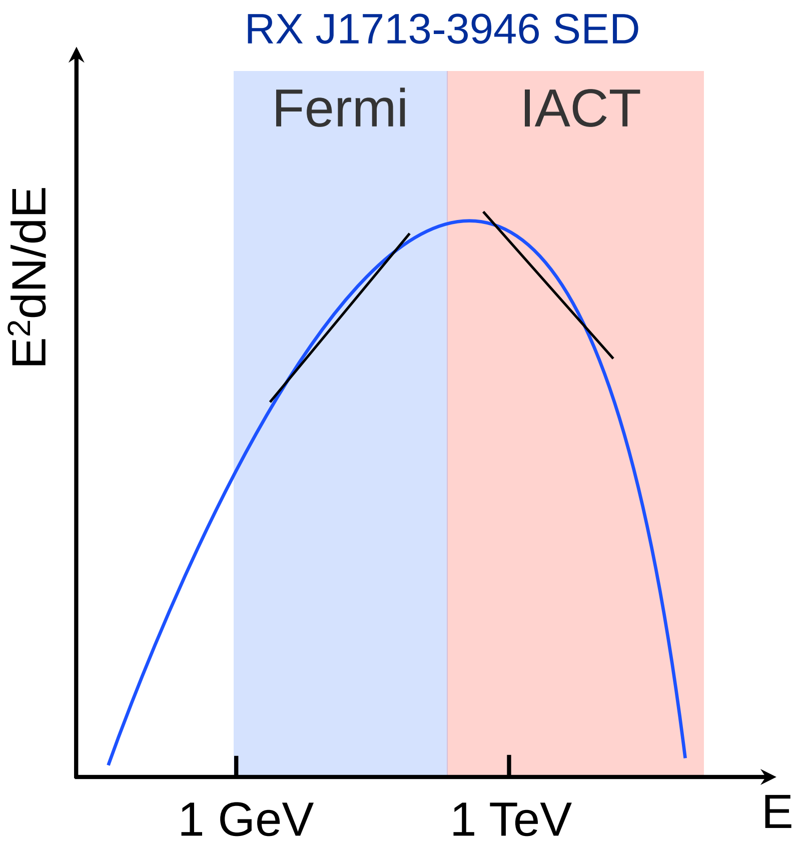




- Indication of break at TeV energies
- Caveat: TeV sources are not uniformly surveyed.

GeV-TeV Index





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

Environment?

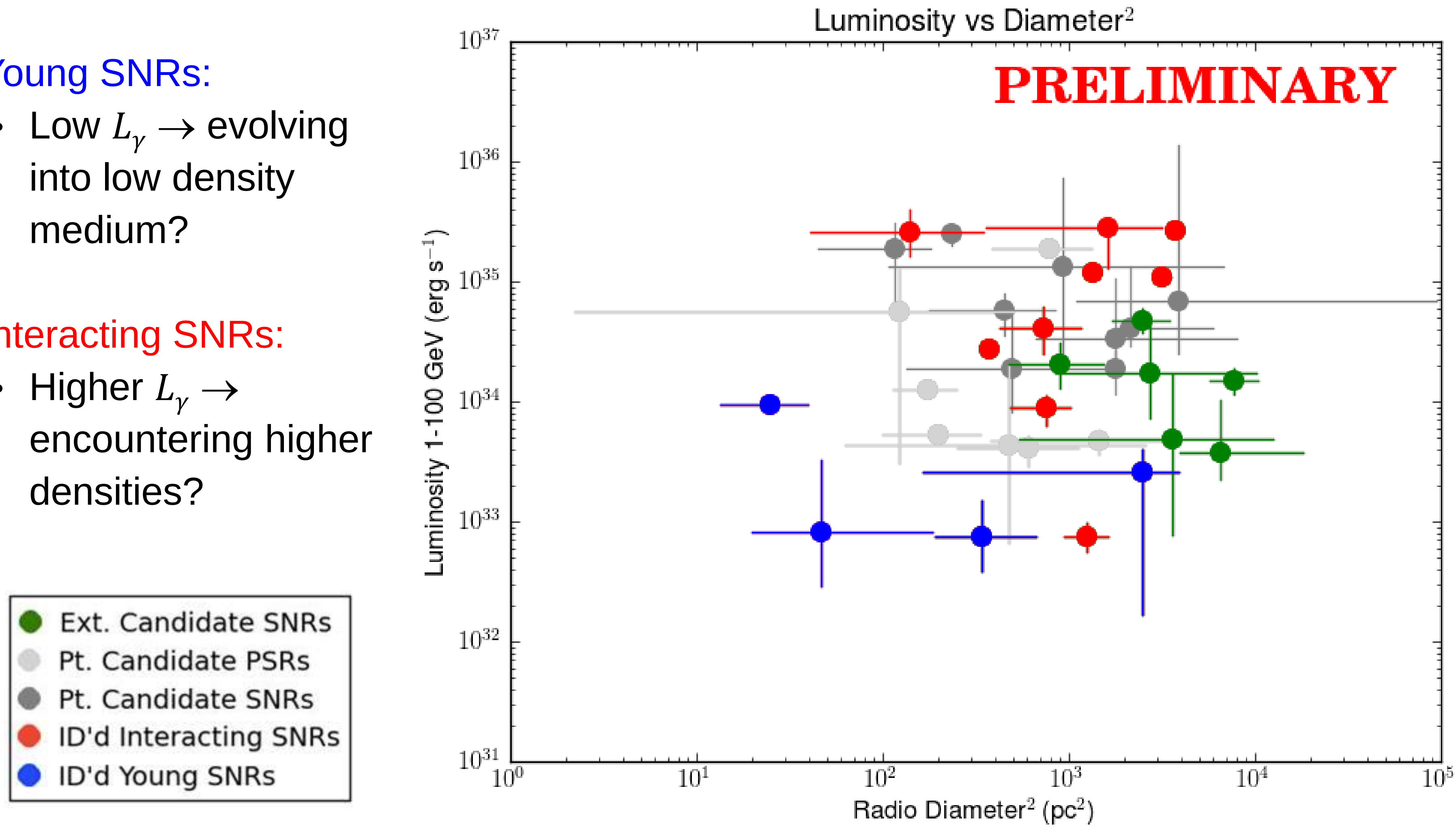
Interacting SNRs tend to be more luminous than young SNRs.

Young SNRs:

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

Interacting SNRs:

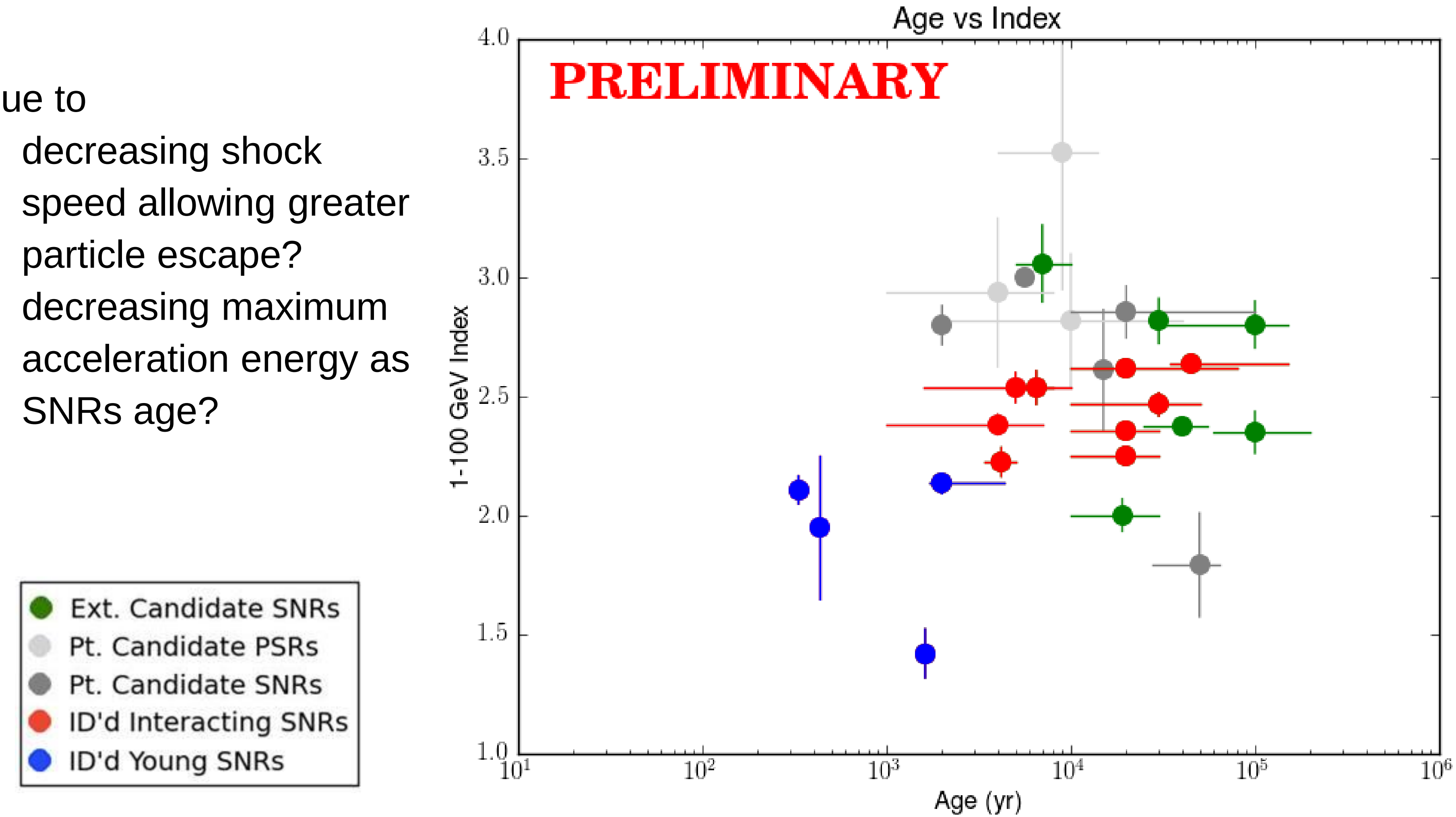
- Higher $L_\gamma \rightarrow$ encountering higher densities?



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?

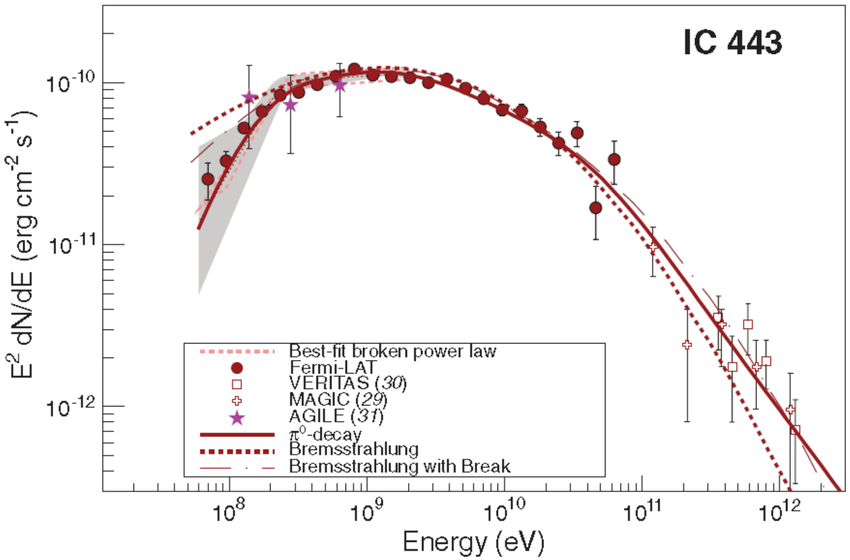


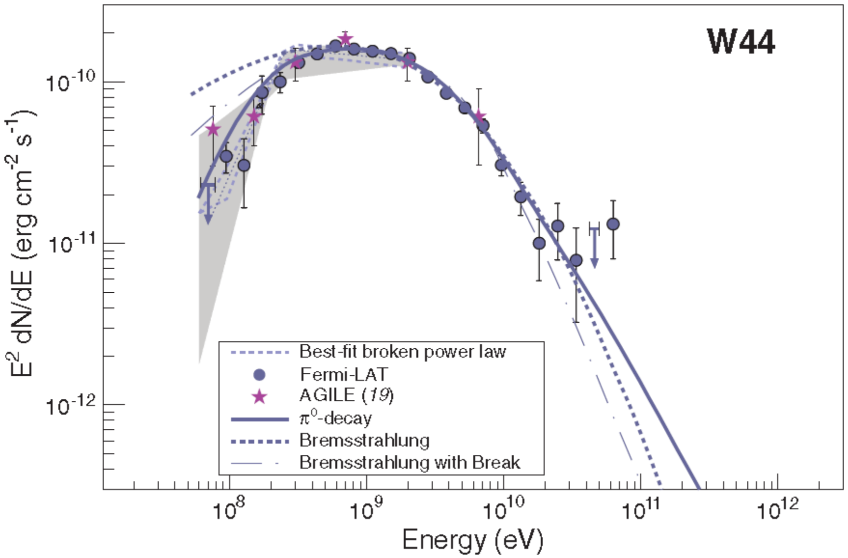
Conclusions

- The π^0 signature was observed for two SNR. For several others we can infer the emission model from MW analysis.
- In the catalog we have 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. This will also allow us to better quantify SNRs' ability to produce the observed CRs.

Detection of the π^0-decay feature in SNRs

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



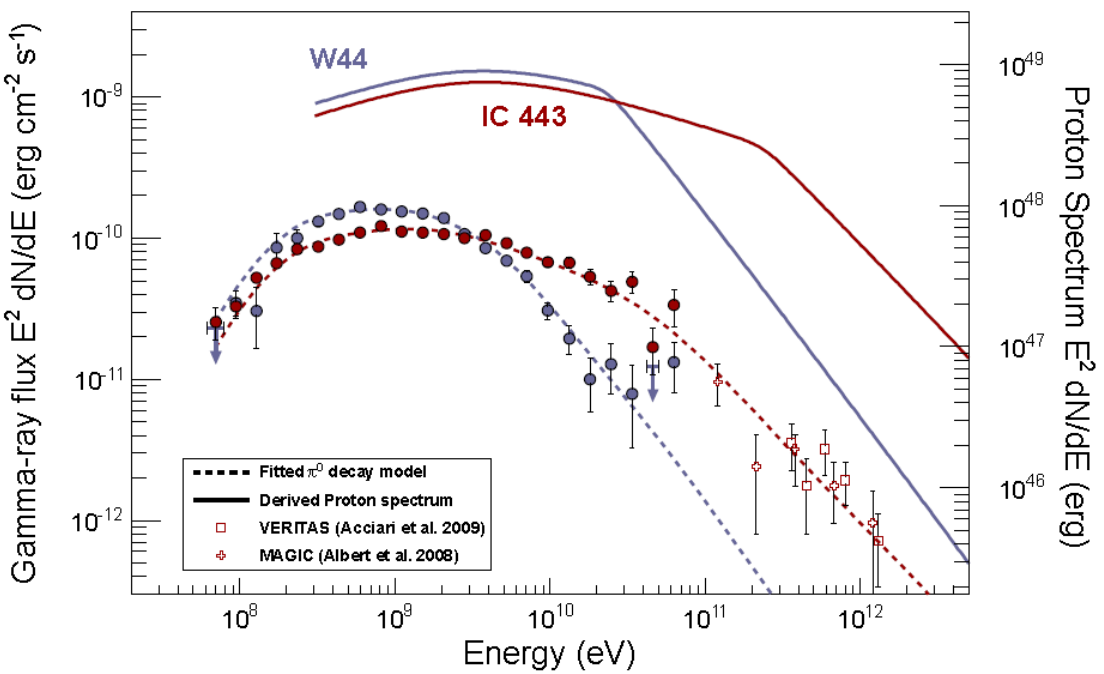


M. Ackermann et al. 2013, *Science*, 339, 807

- The low energy break is very significant
  ($\sim 19\sigma$ and $\sim 21\sigma$ for 60 MeV ≤ E ≤ 2 GeV);
- This gives unambiguous and robust detection of the π^0 decay spectral feature and a 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 :

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

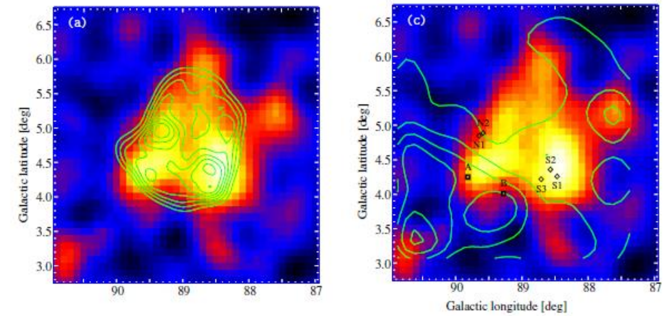
The π^0-decay gamma rays are likely emitted through interactions between “crushed cloud” gas and relativistic protons, both of which are highly compressed by radiative shocks driven into molecular clouds that are overtaken by the blast wave of the SNR.

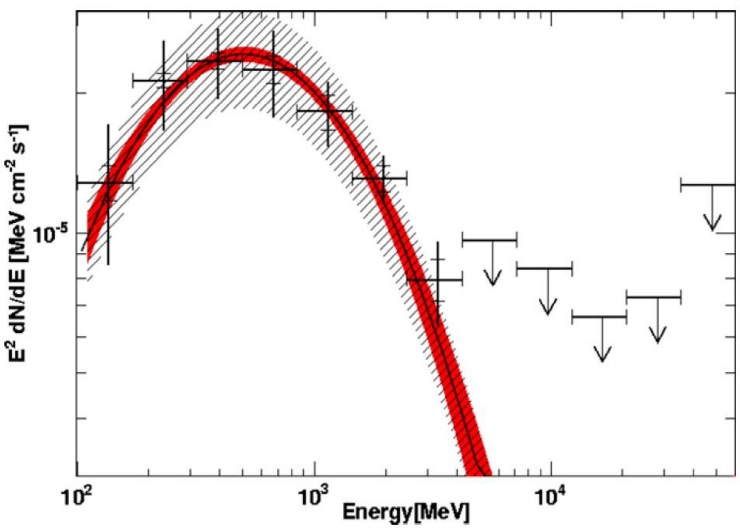
The Fermi-LAT data allow an electron to proton ratio $(K_{ep}) \sim$ *0.01 or smaller.*

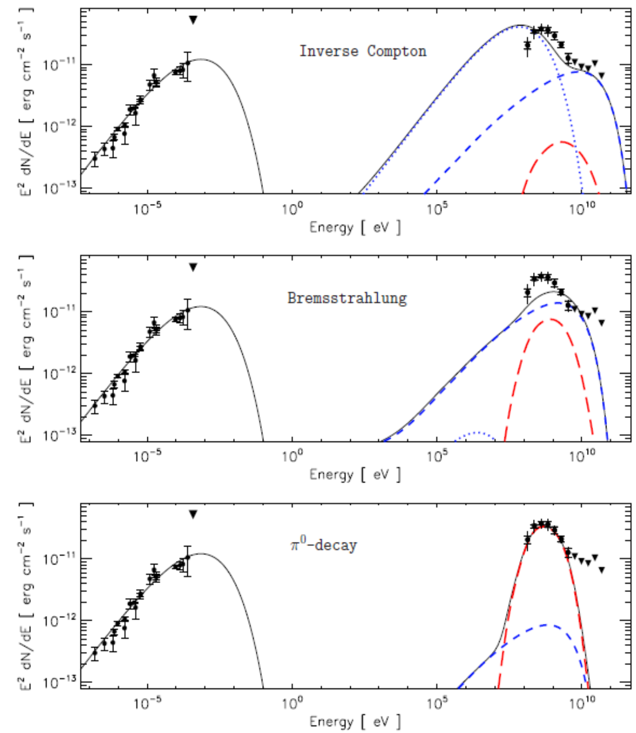
HB 21

A mixed morfology middle aged SNR.

The LAT emission is well modeled by a uniform disk with a radius of $1.19° \pm 0.06°$.
The γ-ray spectrum shows clear evidence of curvature suggesting a cutoff or break in the underlying particle population at an energy of a few GeV.



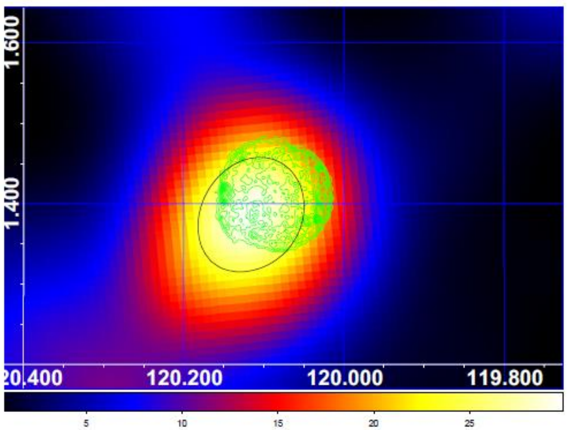




Single population lepton emission is disfavored.
Low γ-ray emission may be explained by small amount of material encountered.

G. Pivato et al. 2013, *Apj*, 779 ,179

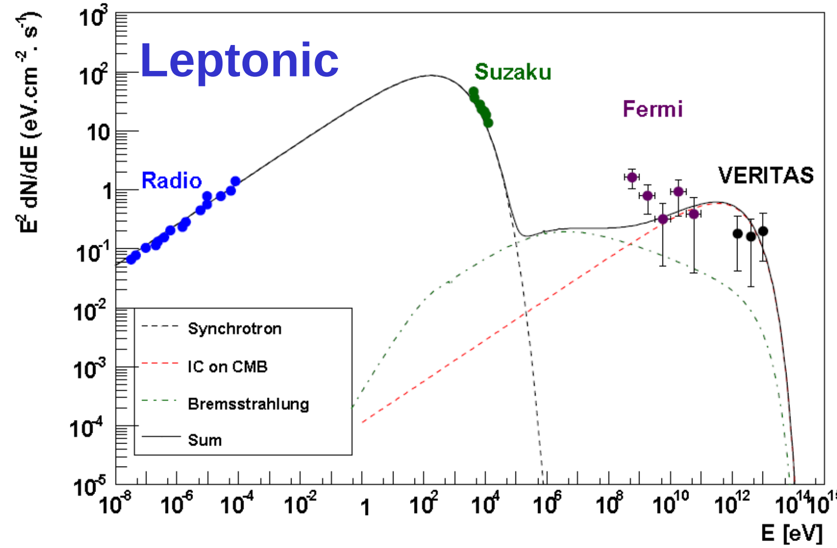
Tycho

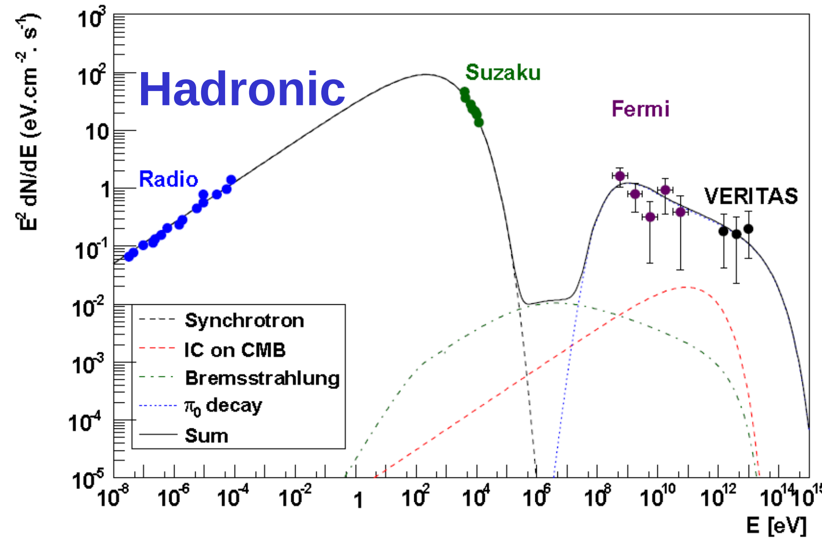


Case	D_{kpc} [kpc]	n_H [cm^{-3}]	E_{SN} [10^{51}erg]	$E_{p,tot}$ [10^{50}erg]	$E_{e,tot}$ erg
Far leptonic	3.50	0.24	2.0	-	1.5×10^{48}
Far hadronic	3.50	0.24	2.0	1.50	6.7×10^{46}
Nearby hadronic	2.78	0.30	1.0	0.61	4.3×10^{46}

Leptonic 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.
  - $n_H \uparrow$ up to $10\ cm^{-3}$
  - $B \downarrow$ down to $65\ \mu G$
  - $K_{ep} \sim 0.1$
- 6-8% of E_{SN} transferred to cosmic rays (CRs)

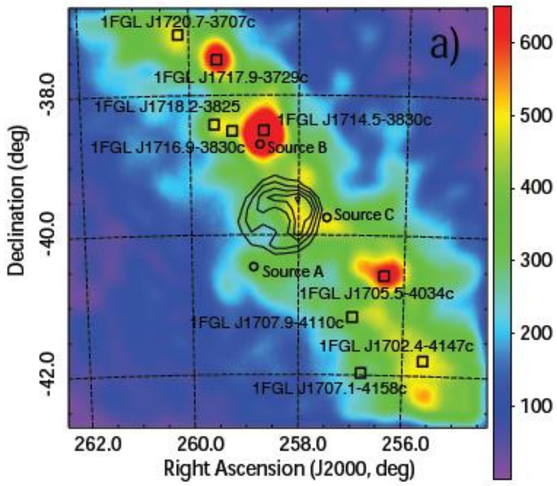




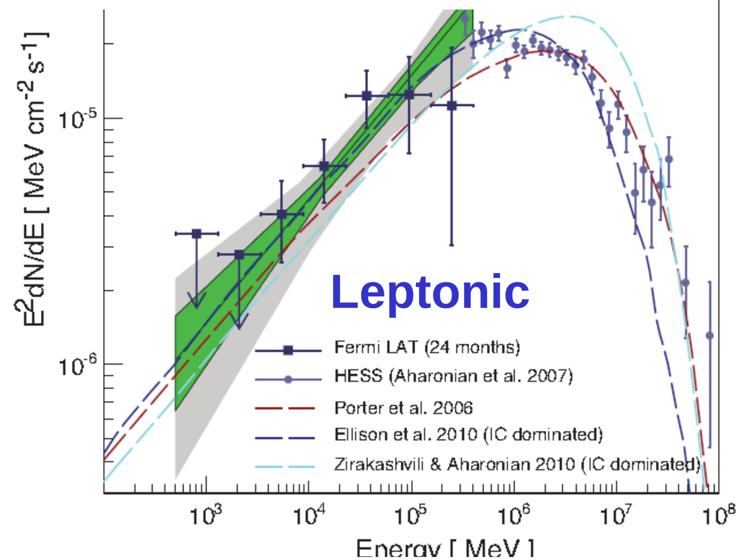
Giordano et al. 2012, *ApjL*, 744, L2

RXJ1713: a leptonic case

Uniform disk with radius $0.55° \pm 0.04°$



$\Gamma = 1.5 \pm 0.1$ (stat)± 0.1(sys)



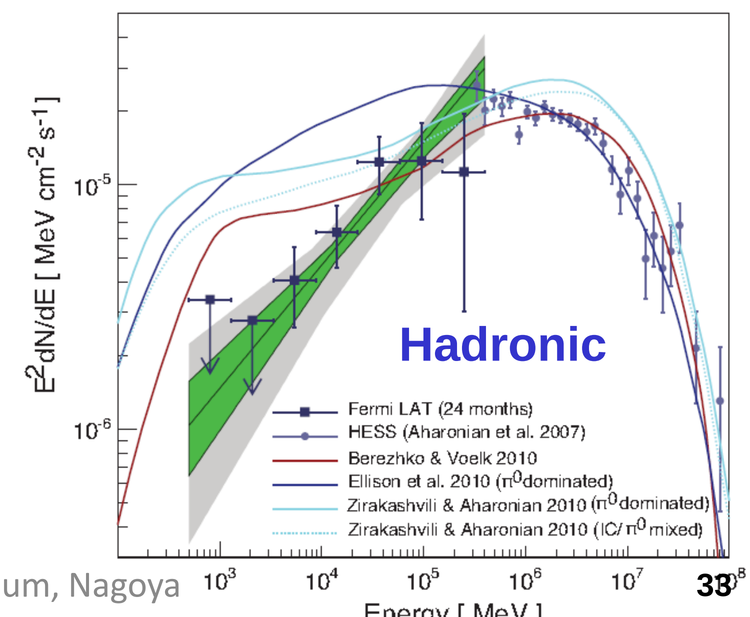
Lack of thermal X-ray emission

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

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

Electron spectra:

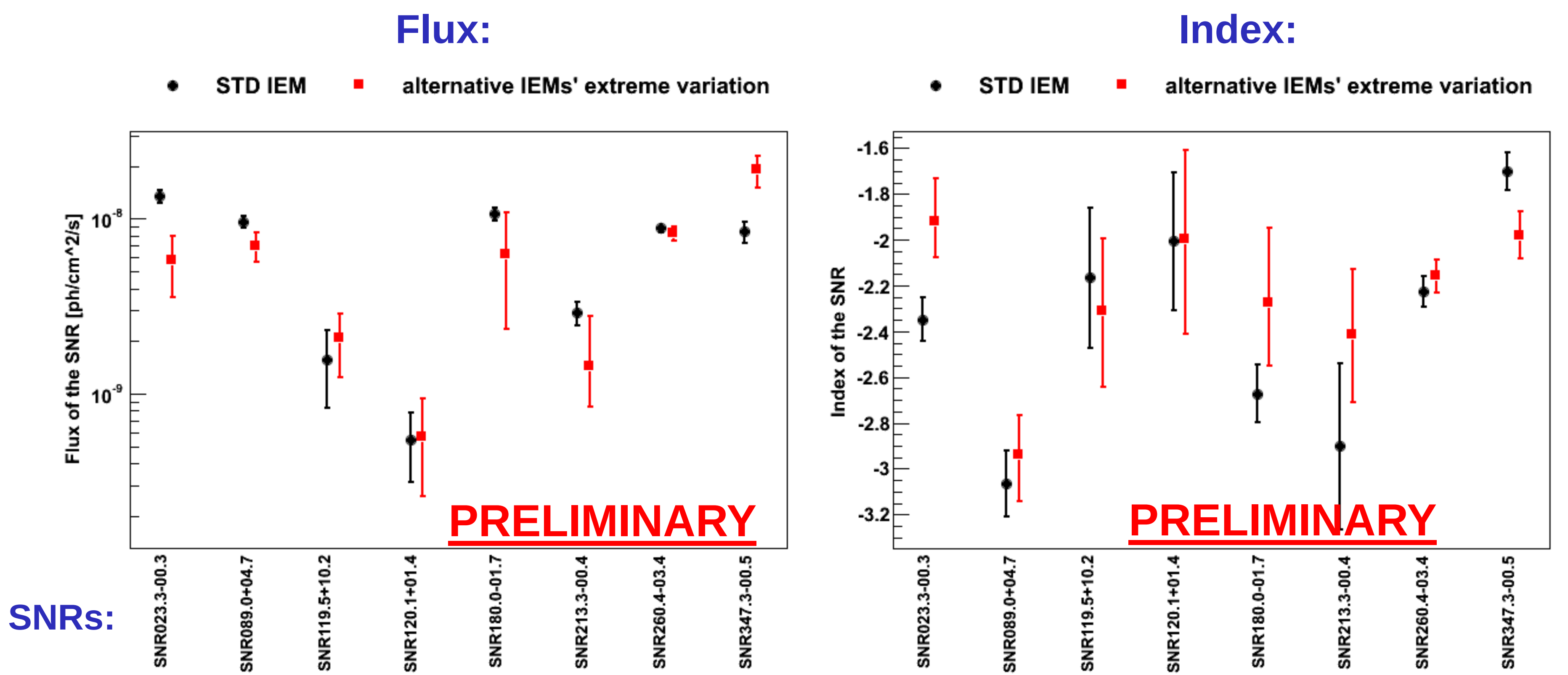
- PL with $s_e = 2\Gamma - 1 = 2.0 \pm 0.2$
- $B \simeq 10\ \mu G$
- $E_{e\ max} \sim 20 - 40\ TeV$
- ○ $W_p' < 0.3 \times 10^{51} (n_H/0.1 cm^{-3})^{-1} erg$



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

Systematic Error Study

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



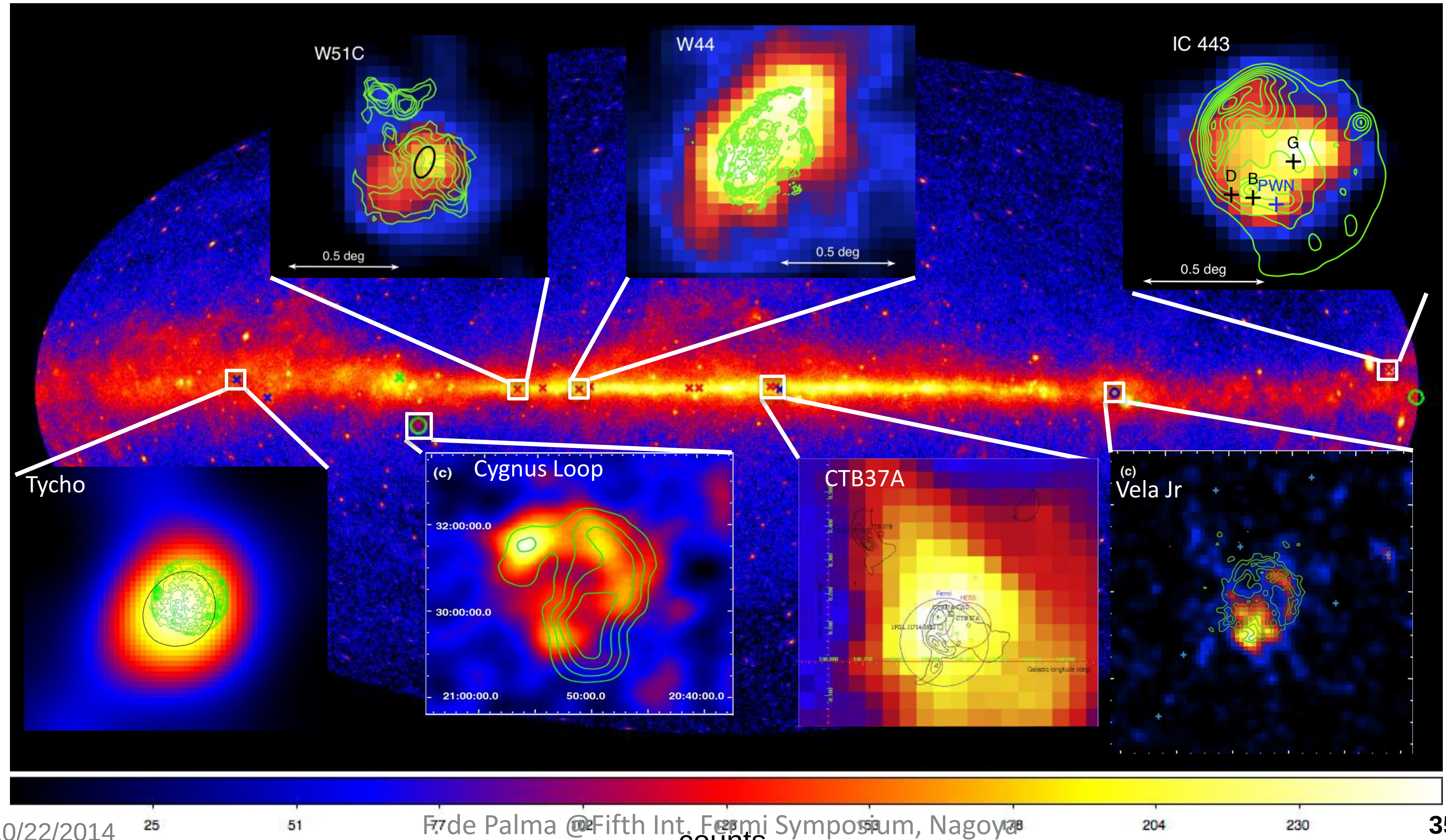
Our automated analysis finds a softer index and a much larger flux for SNR347.3-0.5 (RX J1713) than that obtained in a dedicated analysis. *[Abdo et al. 2010]* Since the best fit radius (0.8º) is larger than the dedicated analysis' (0.55º), the disk encompasses nearby sources that are not in the model.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

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

Fermi-Detected SNRs

13 identified SNRs: - 9 interacting

- 4 young SNRs



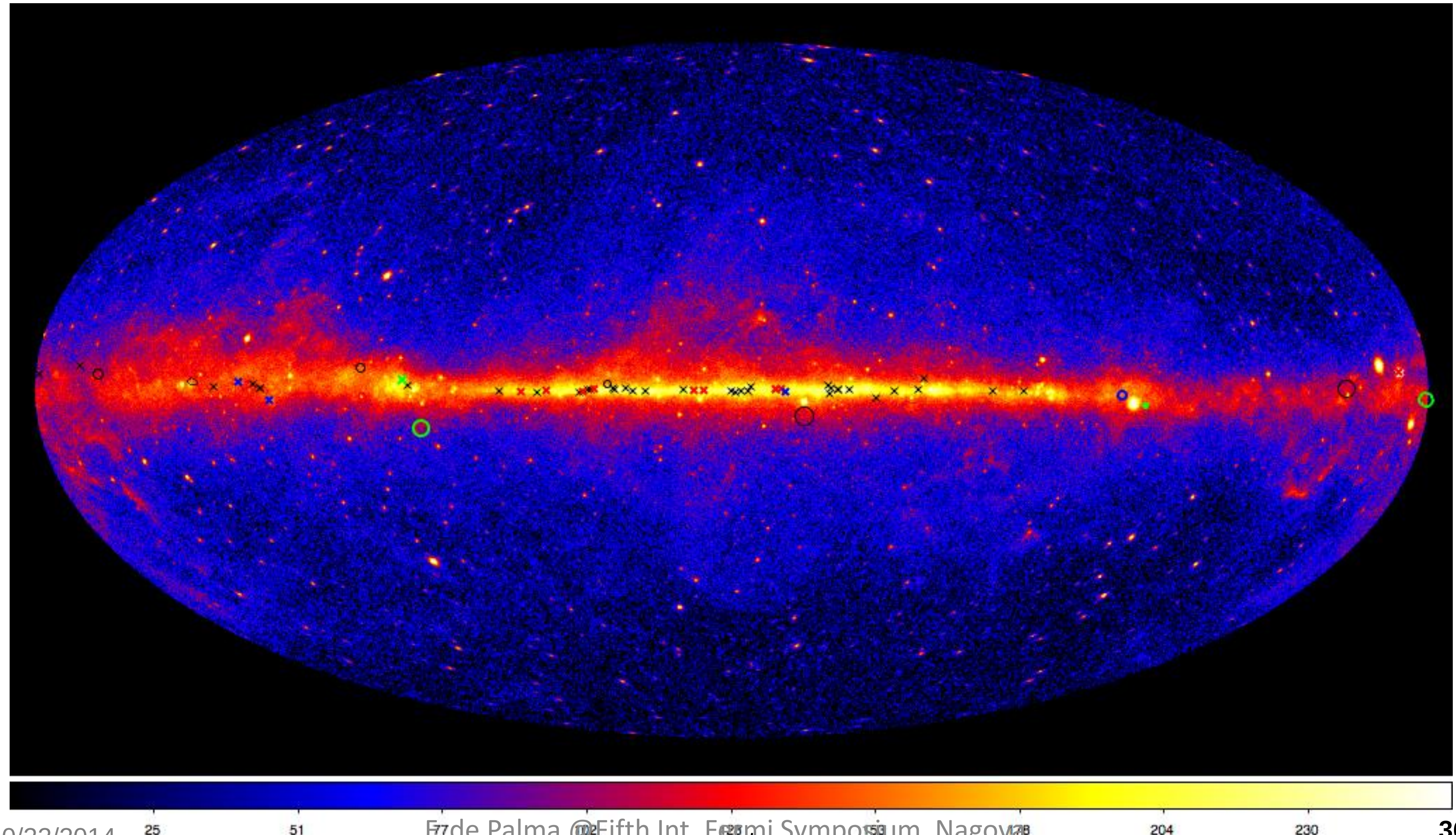
Fermi-Detected SNRs

13 identified SNRs: - 9 interacting

- 4 young SNRs

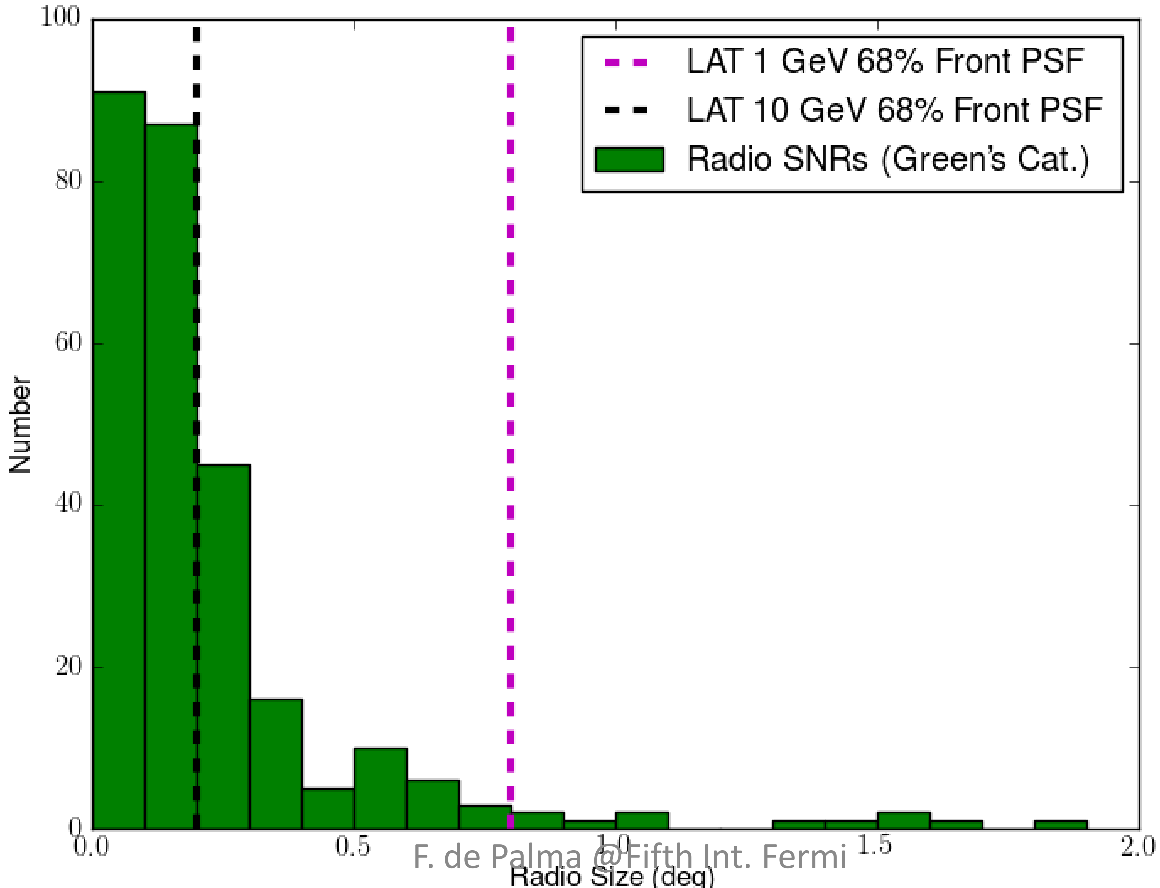
+ 43 2FGL candidates,

excluding spatial associations with PSRs, PWN, AGN



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:

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 (274 from the Green's Catalog + 5 new sources).
- 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.
- place upper limits on GeV emission from all SNRs.