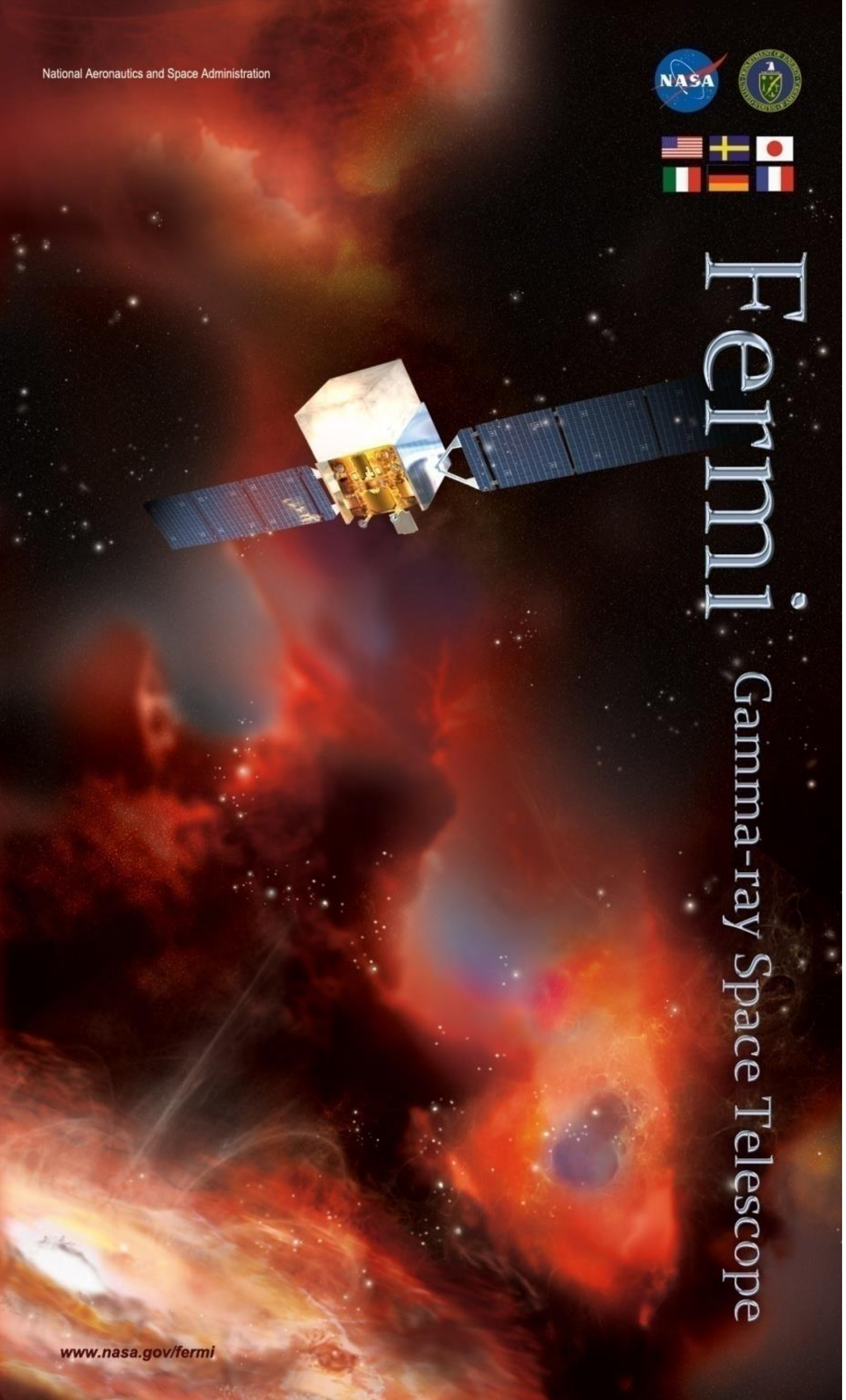

The First Fermi-LAT SNR Catalog and Cosmic Ray Implications

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on behalf of the

Fermi LAT Collaboration

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Outline

- SNR Catalog:
  - analysis method
  - results
- Multiwavelength correlations: GeV, Radio, and TeV
- Population studies: age versus environment
- Constraining Cosmic Ray (CR) acceleration

Characterize GeV Emission: Analysis Procedure

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)

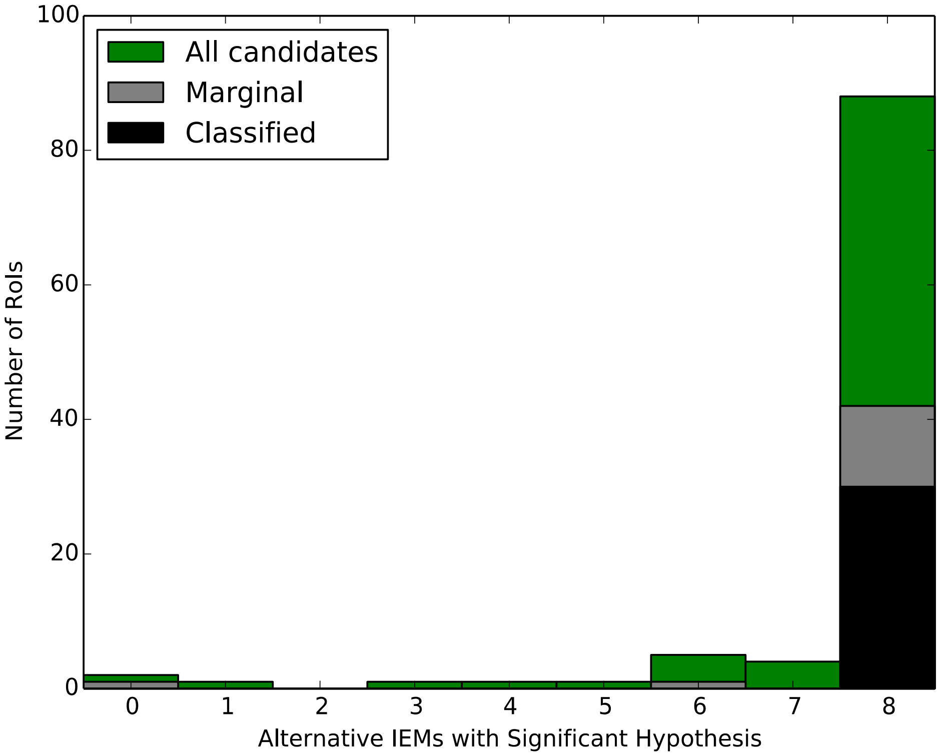
Output
- Source significance
- Best position, extension, and spectral model
- Or flux upper limits at radio position

Classification
- Spatial coincidence
- Mock Catalog

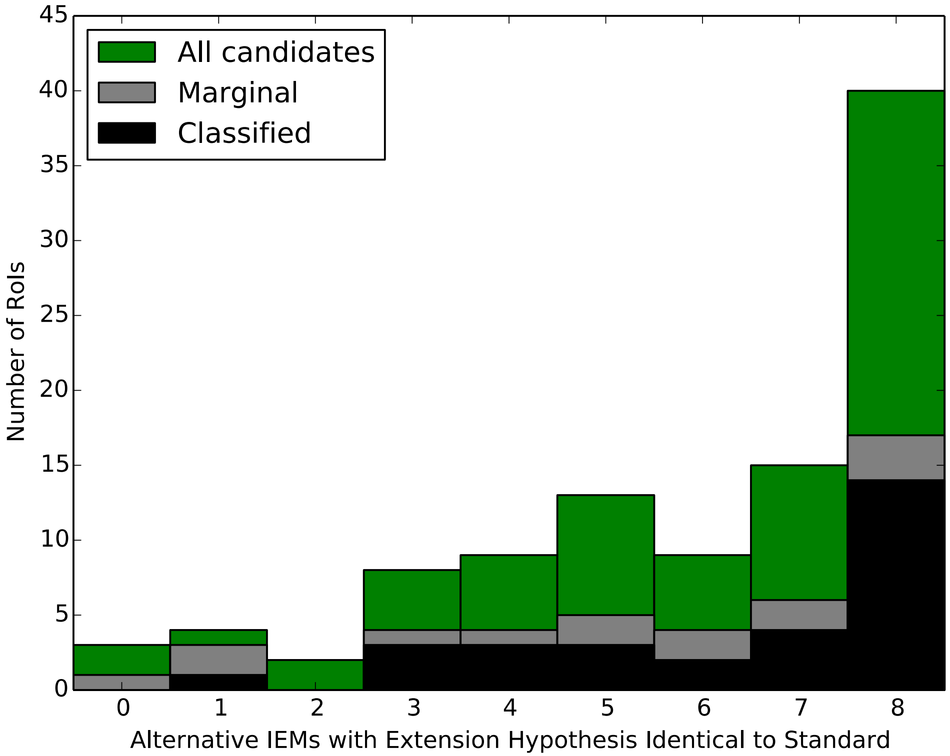
Systematic Errors with alternative IEMs

To understand the quality of our analysis using the most accurate methods to date, we refit for all quantities, including extension and best final hypothesis with eight alternative IEMs (**Ackermann et al. , 2012, *Apj*, 750, 3)**:

Significant Source:



Extension Hypothesis:



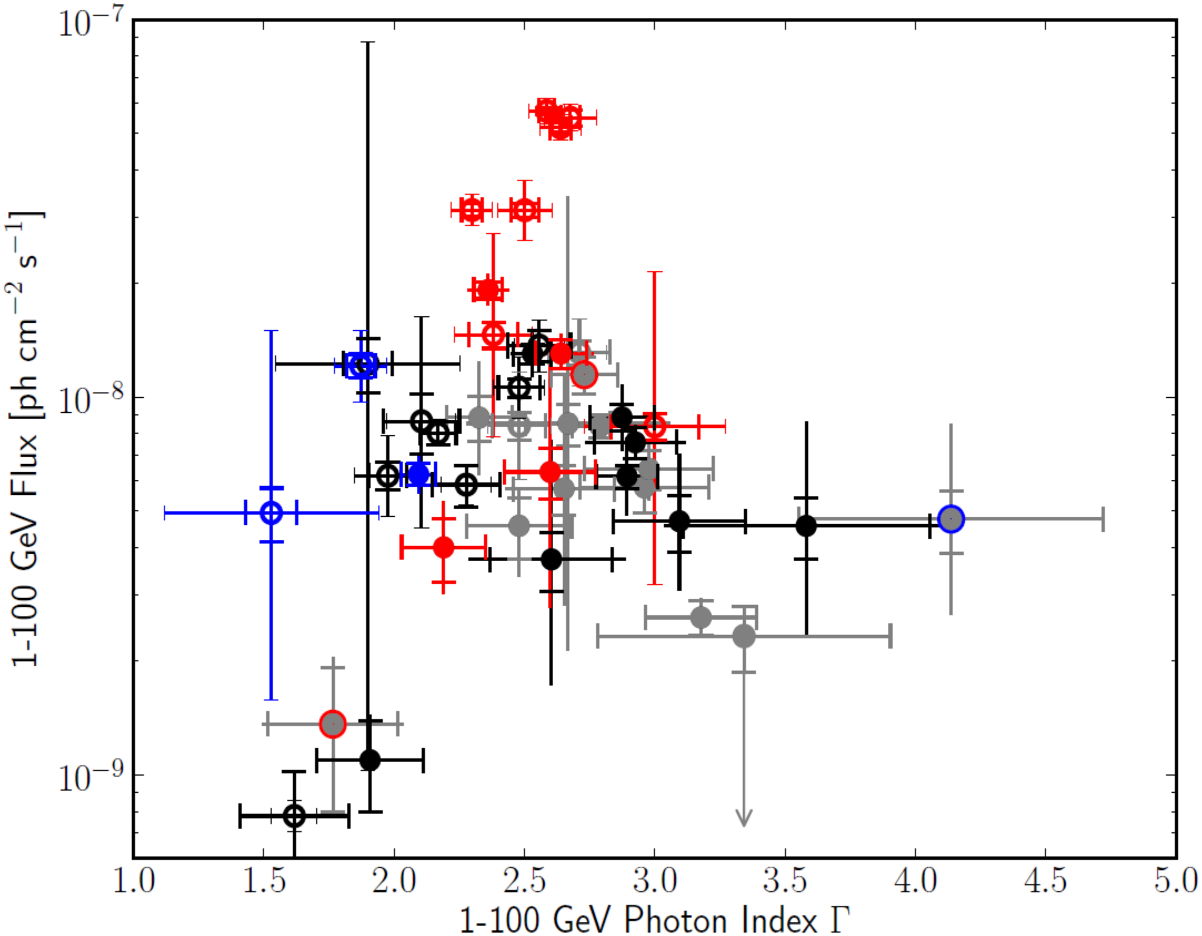
SNR catalog results

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.

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.

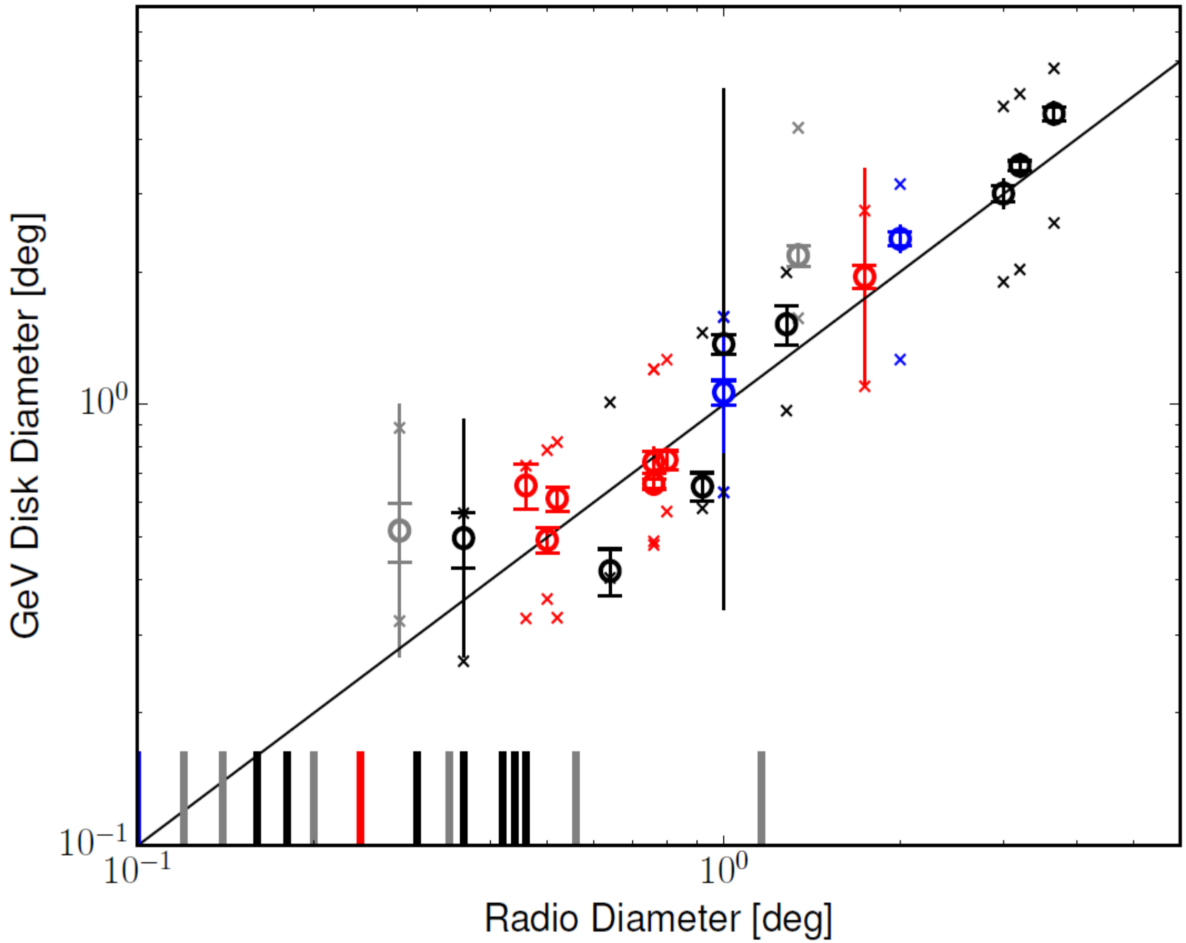


- Interacting SNRs density $\geq$ $100\ cm^{-3}$
- Young SNRs show evidence of non-thermal X-ray emission
- Classified candidates
- Marginal candidates
- Pointlike sources
- Extended sources

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

Radio-GeV Diameter

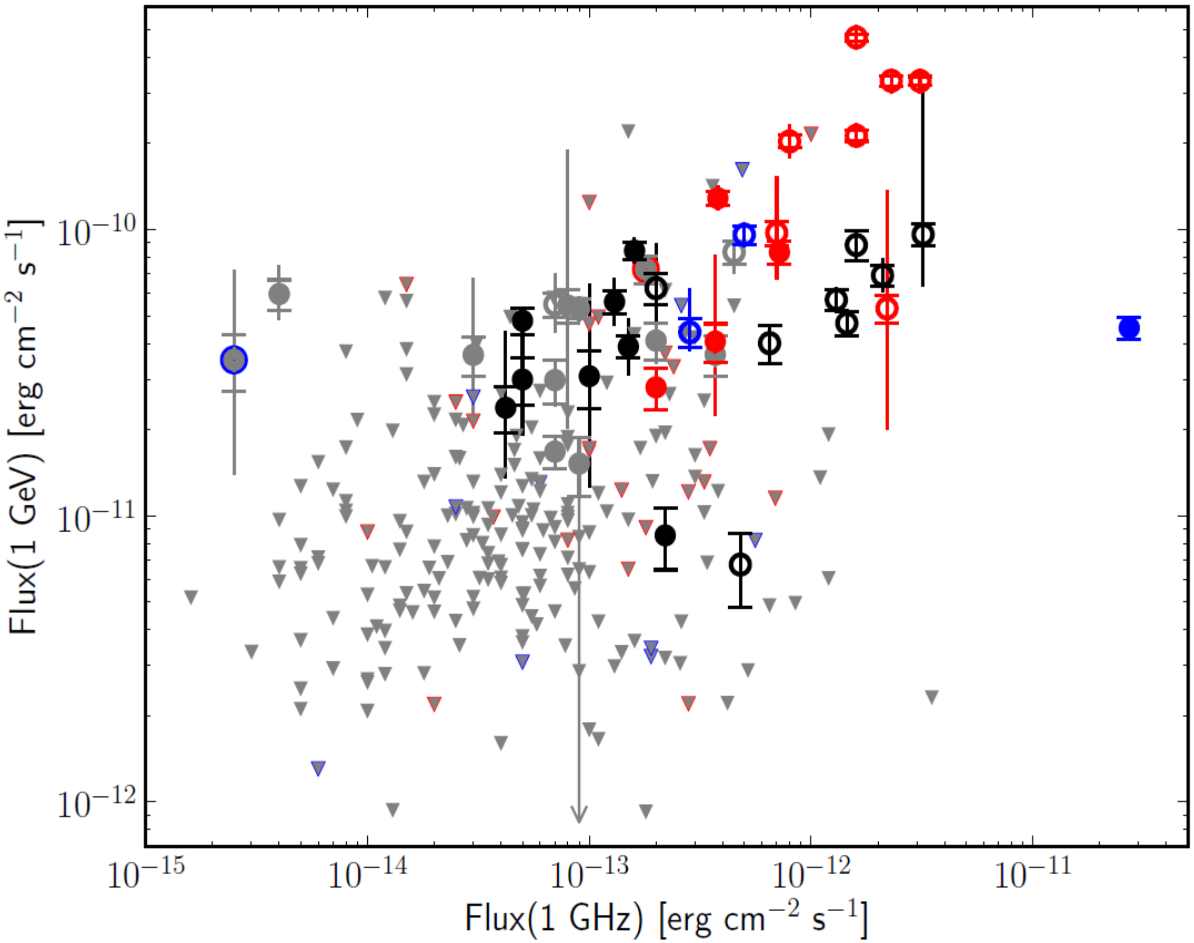
Classified GeV candidates tend to correlate with their radio size, particularly for larger diameters with lower systematic errors:



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

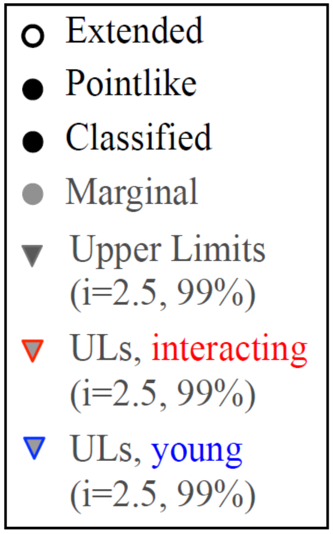
Radio-GeV Flux

LAT-detected SNRs tend to be radio-bright:



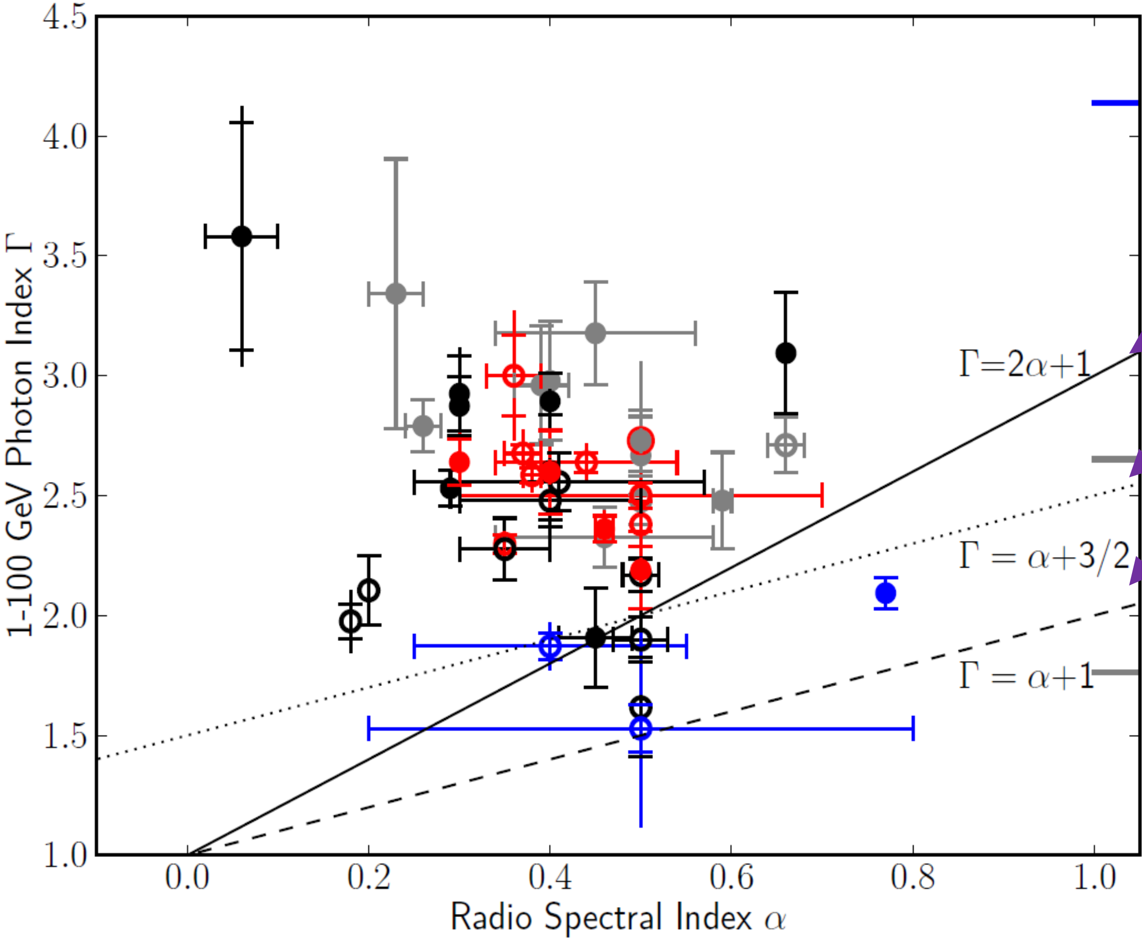
- Interacting SNRs: general correlation?
- Young SNRs show more scatter

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:



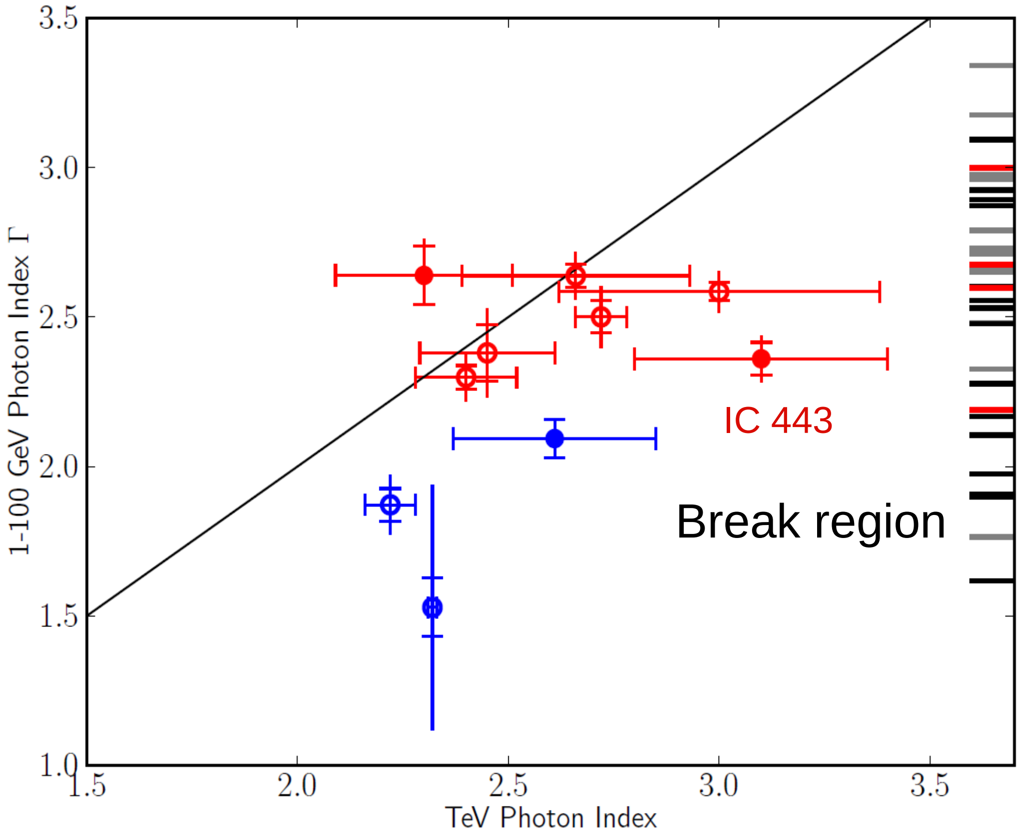
- Young SNRs: seem consistent
- Others, including interacting SNRs: softer than expected

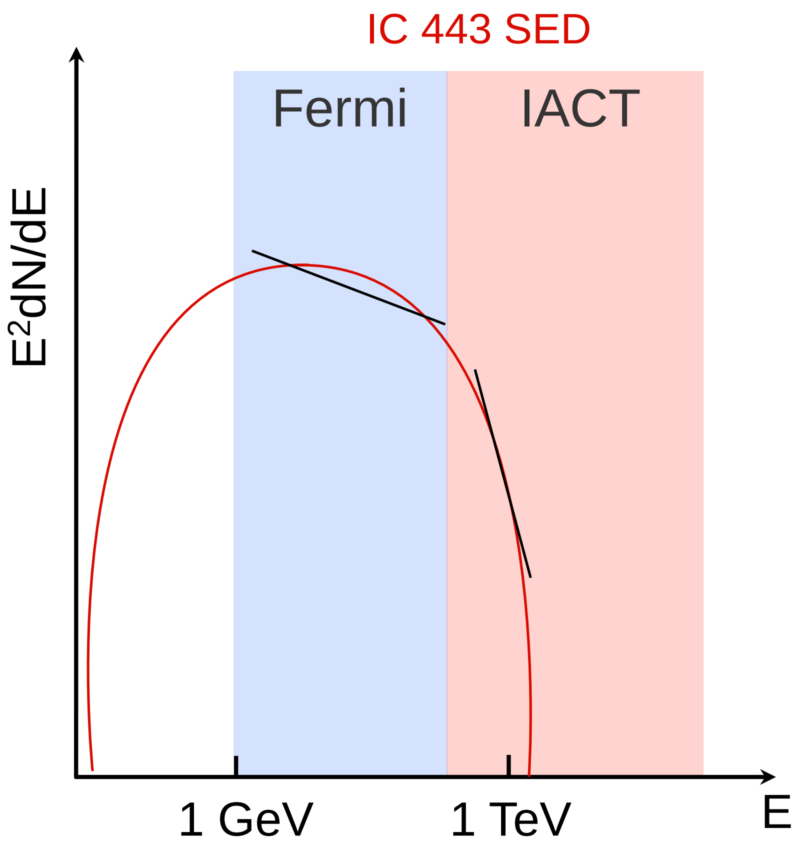
- π^0 decay or $e^{+/-}$ brem.
- Inverse Compton w cooling
- inverse Compton w/o cooling

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?

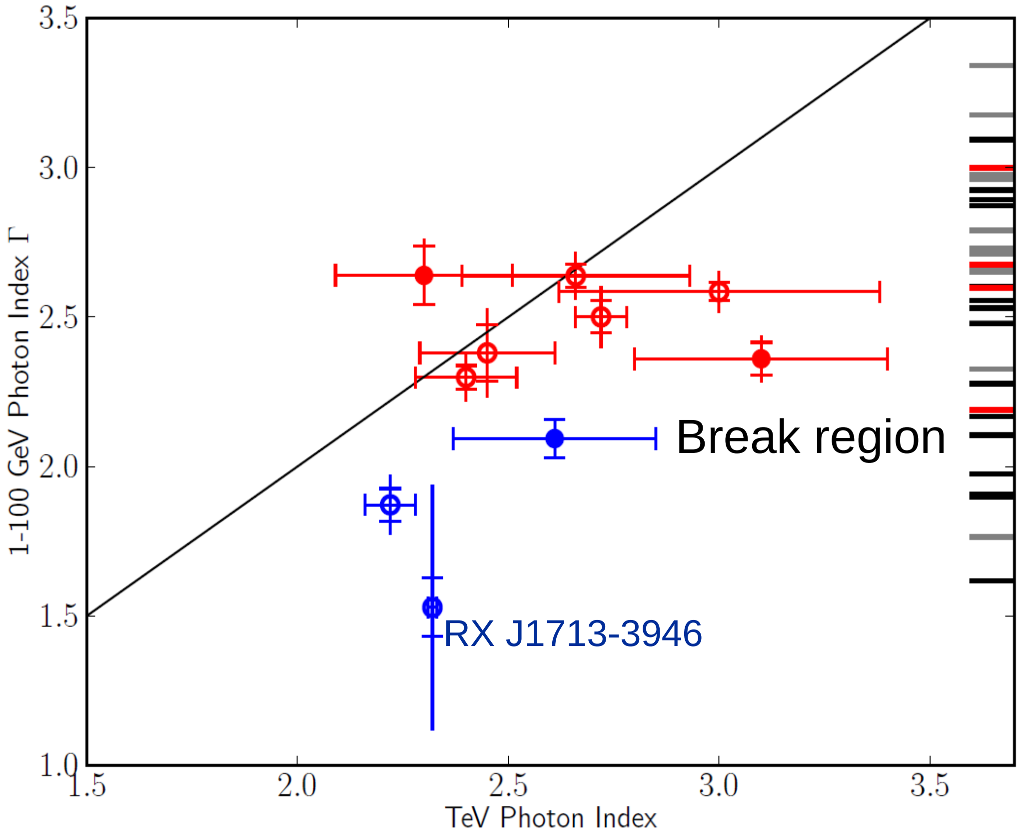
GeV-TeV Index

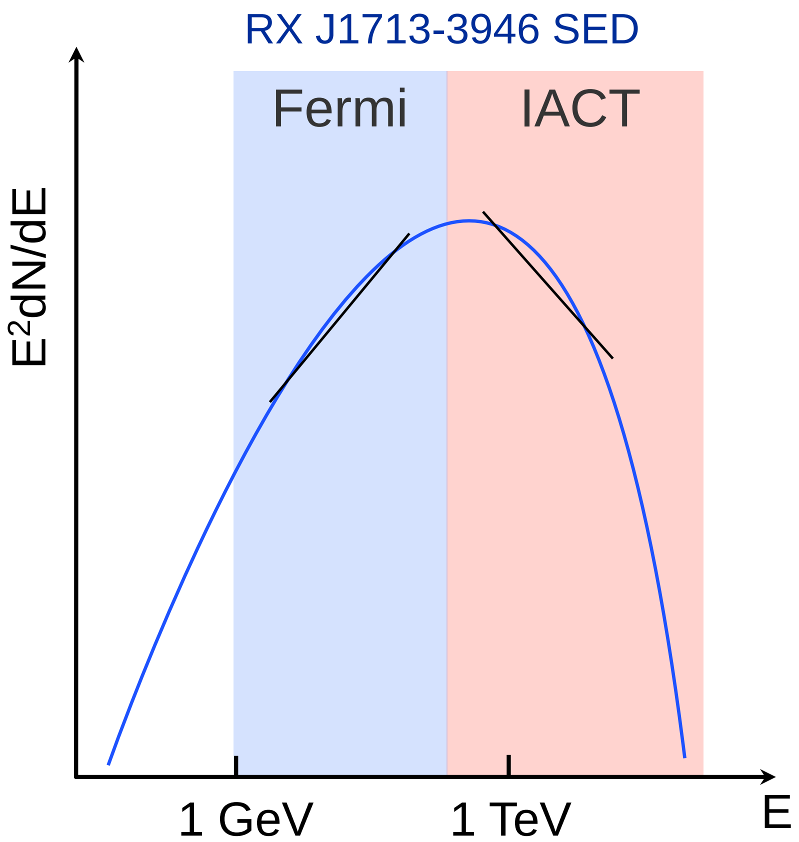




- Indication of break at TeV energies
- Caveat: TeV sources are not uniformly surveyed.

GeV-TeV Index





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

Environment?

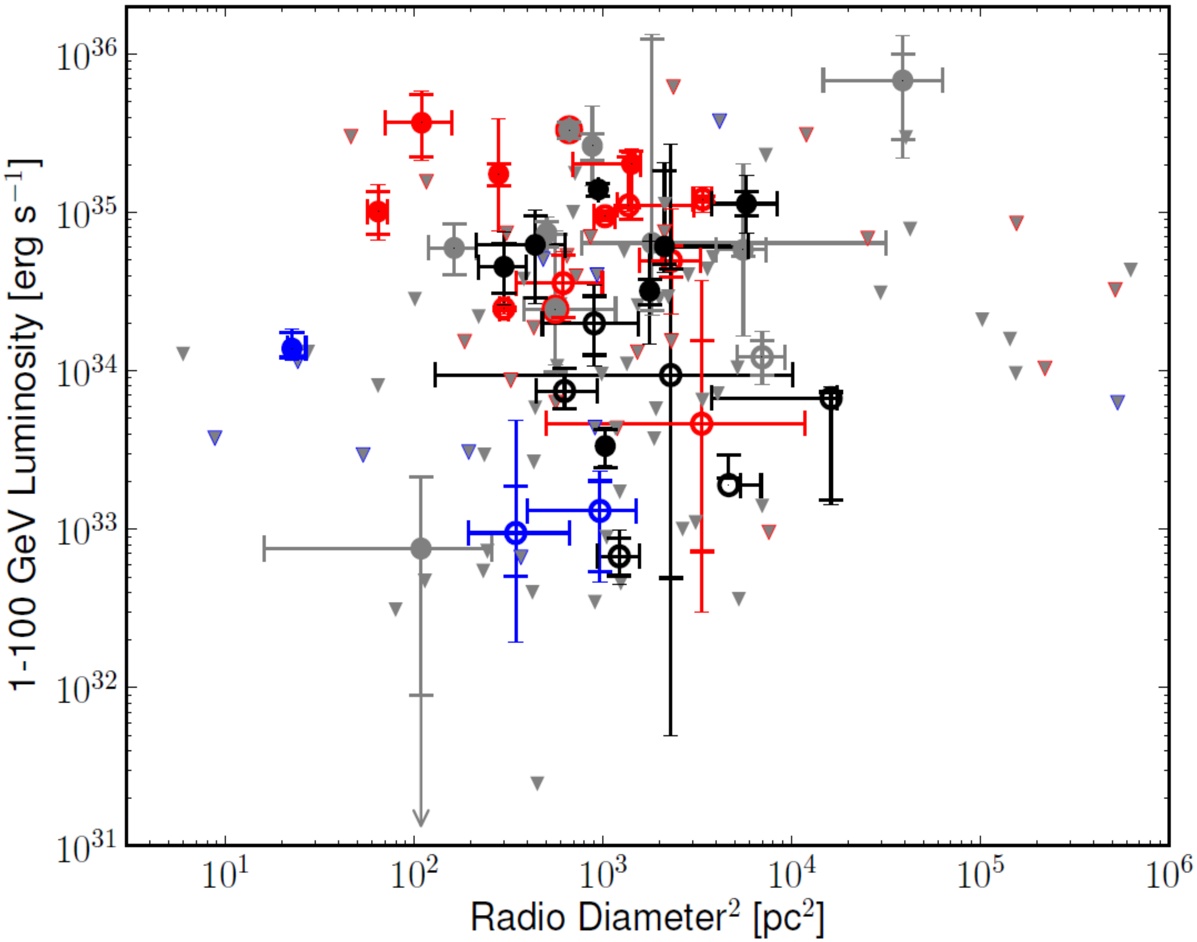
No clear trend though both axes are proportional to distance². Some separation between classes, diminishing as we find more, fainter candidates.

Young SNRs:

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

Interacting SNRs:

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



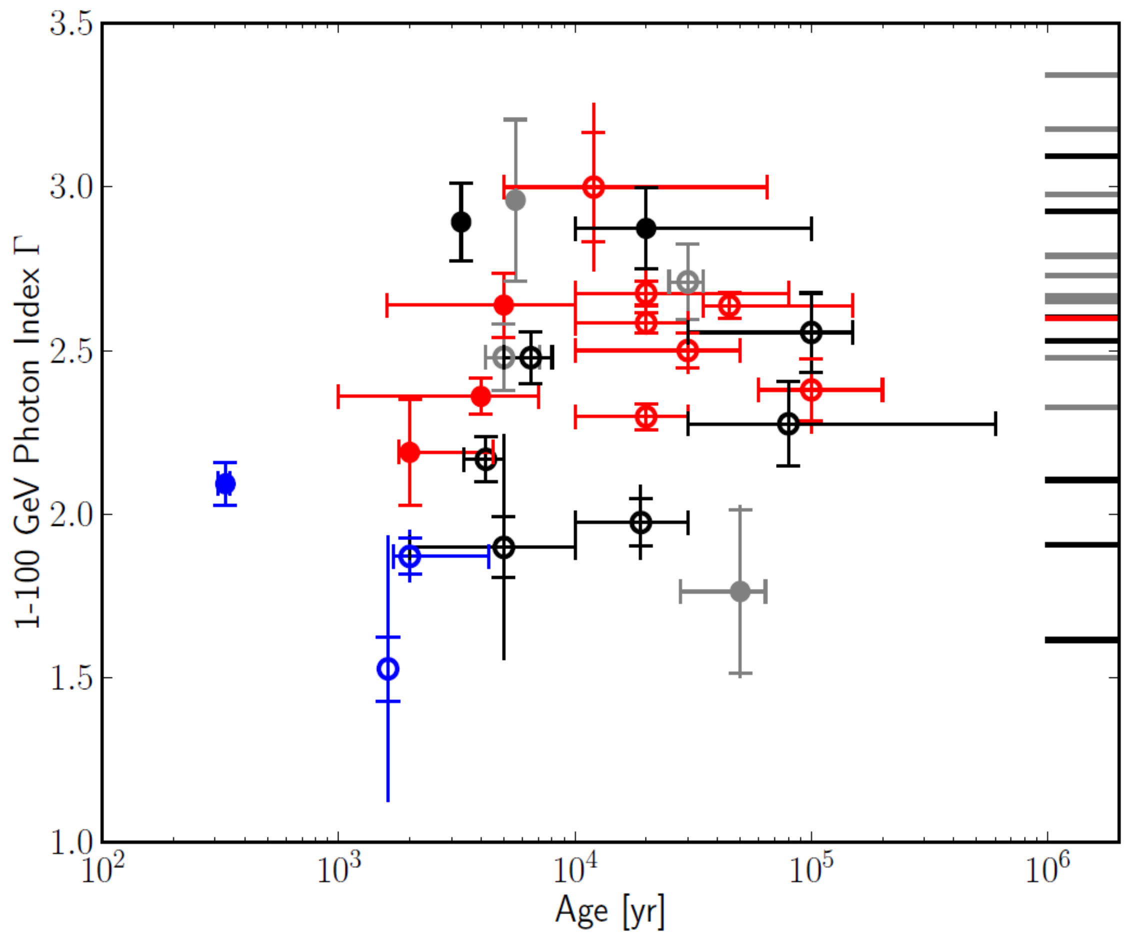
Or Evolution?

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:

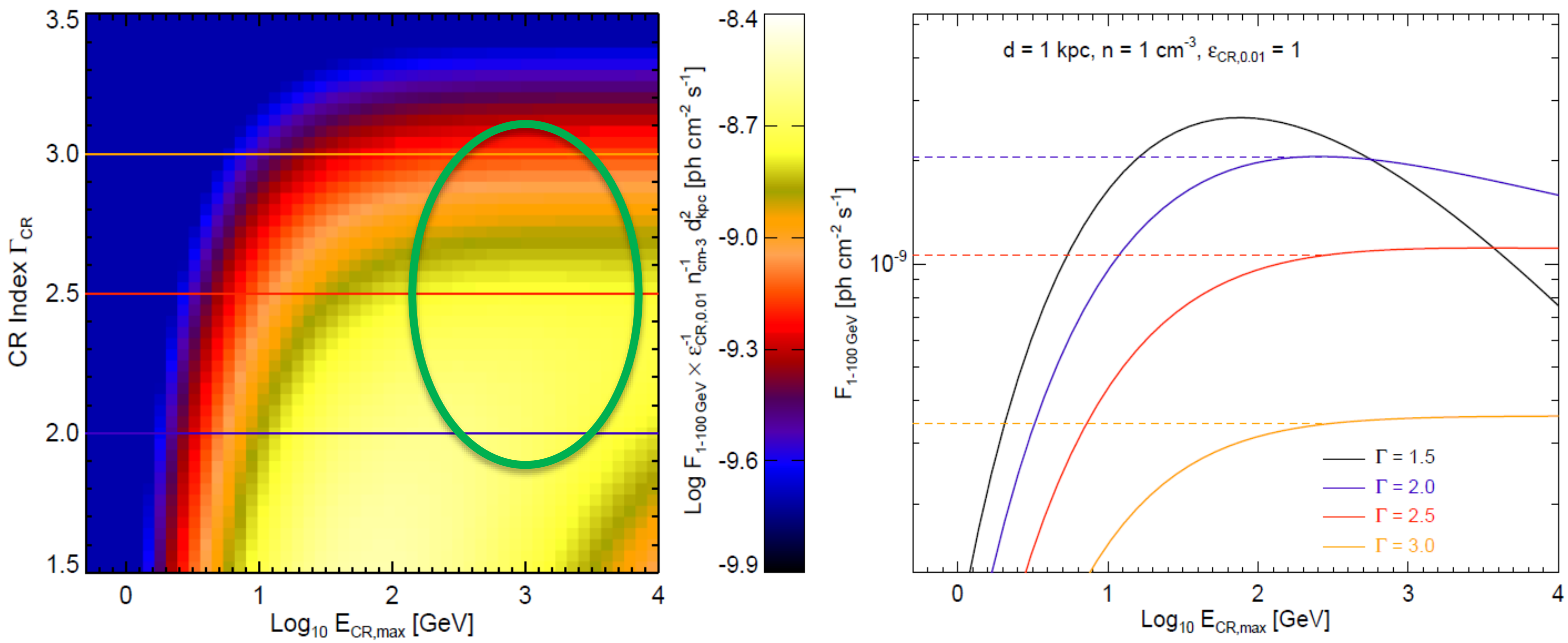
- decreasing shock speed allowing greater particle escape?
- decreasing maximum acceleration energy as SNRs age?



Constraining CR emission

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

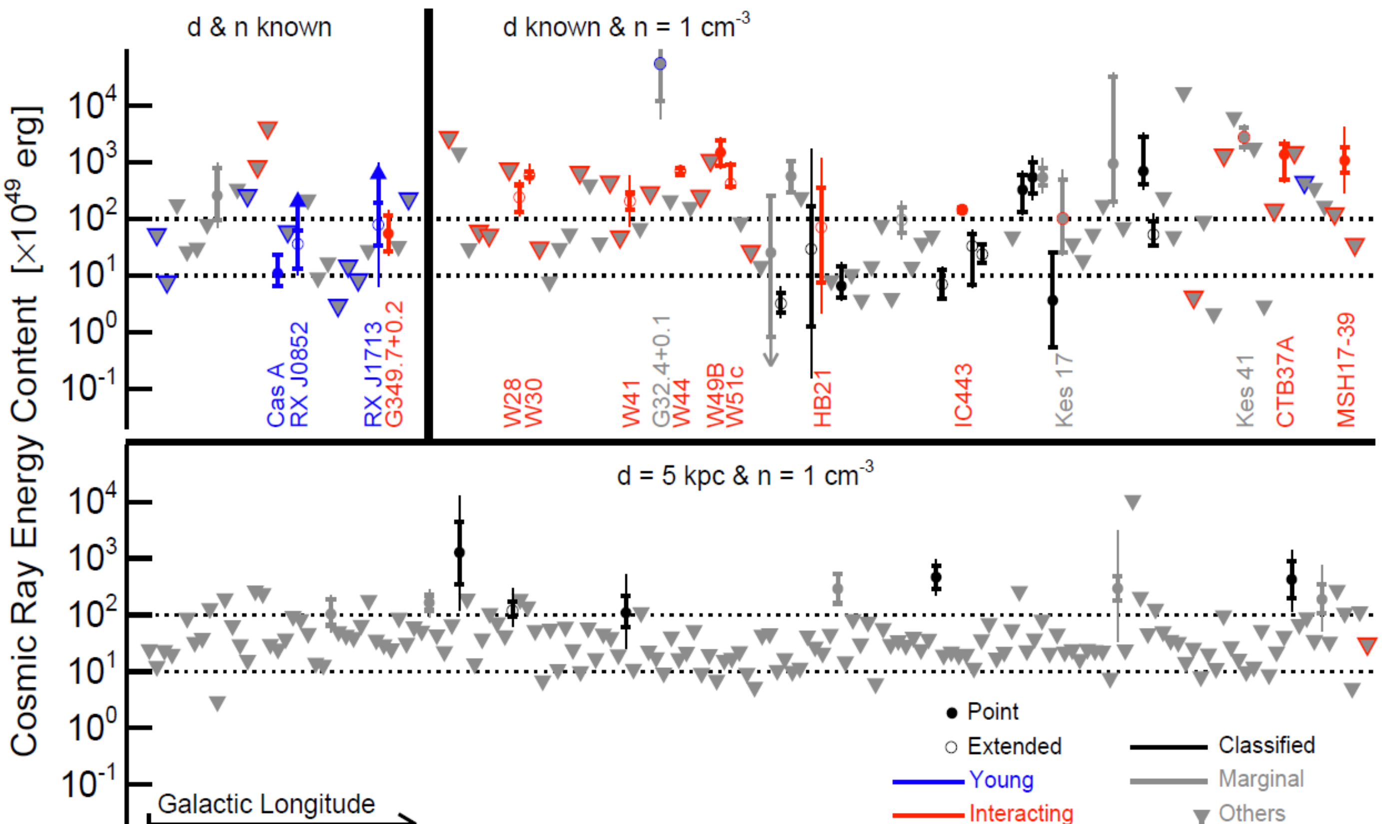
$$F(1-100\,\mathrm{GeV}) \approx f(\Gamma_{\rm CR}) \times \frac{\epsilon_{\rm CR}}{0.01} \times \frac{E_{\rm SN}}{10^{51}\,\mathrm{erg}} \times \frac{n}{1\,\mathrm{cm}^{-3}} \times \left(\frac{d}{1\,\mathrm{kpc}}\right)^{-2} \times 10^{-9}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$$



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



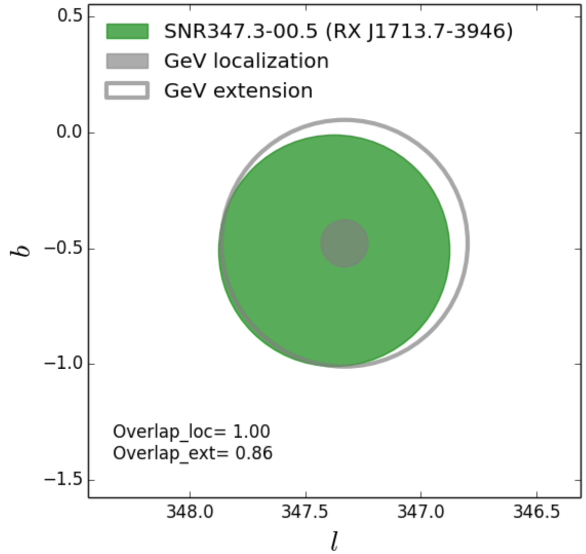
Conclusions

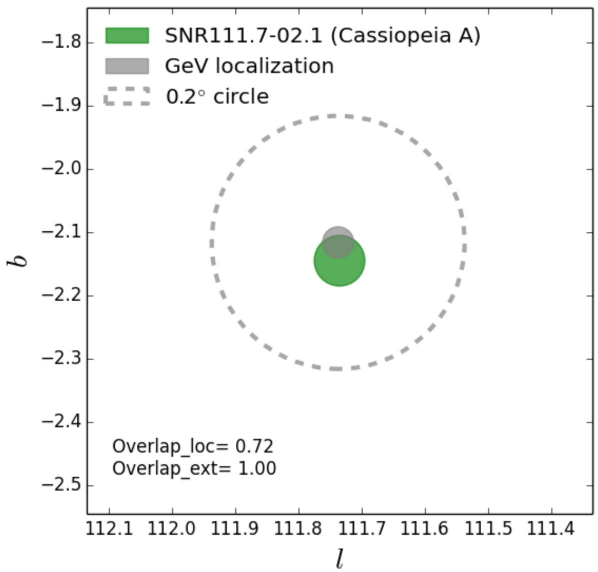
Published as Acero et al. 2016 APJS Volume 224, Issue 1, article id. 8

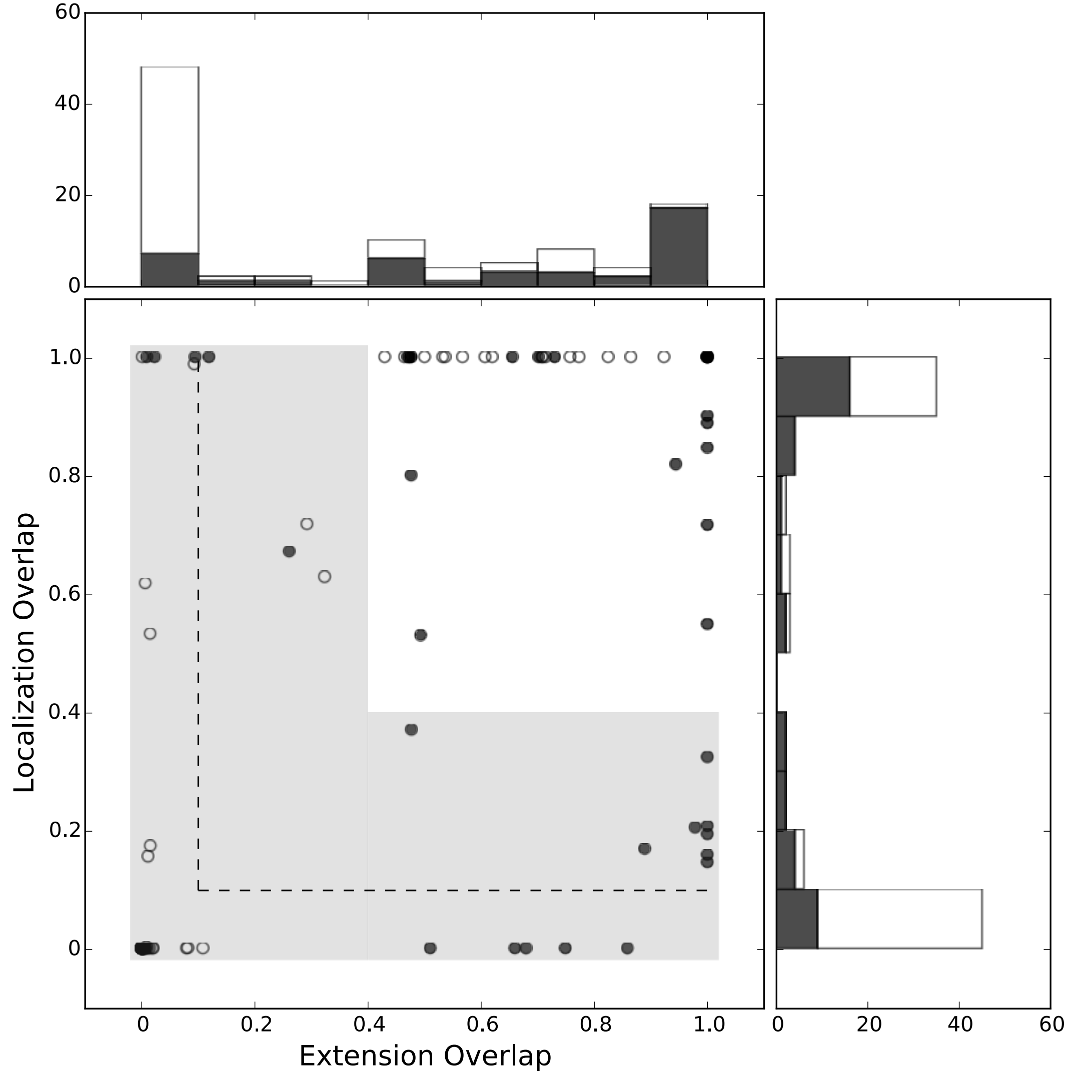
- We have identified a statistically significant population of Galactic SNRs, including
  - 17 **(4 new)** extended and 13 **(10 new)** pointlike SNR candidates
  - Candidate distribution to flux completeness of $10^{-8}\ ph\ cm^{-2} s^{-1}$ with a characteristic index of 2.5 and range [1.5, 4]
- Candidates SNRs and ULs are generally within expectations if SNRs provide the majority of Galactic CRs.
- Combining GeV and MW observations suggests that:
  - there may be changes in spectral slope at or near TeV energies **(sample limited)** and a softening and brightening in the GeV range with age
  - simple model assumptions are no longer sufficient.
- New Pass 8 *Fermi* joint studies with MW observatories (in particular TeV) will shed new light on some SNRs with unprecedented details. Stay tuned!

backup

Spatial coincidence

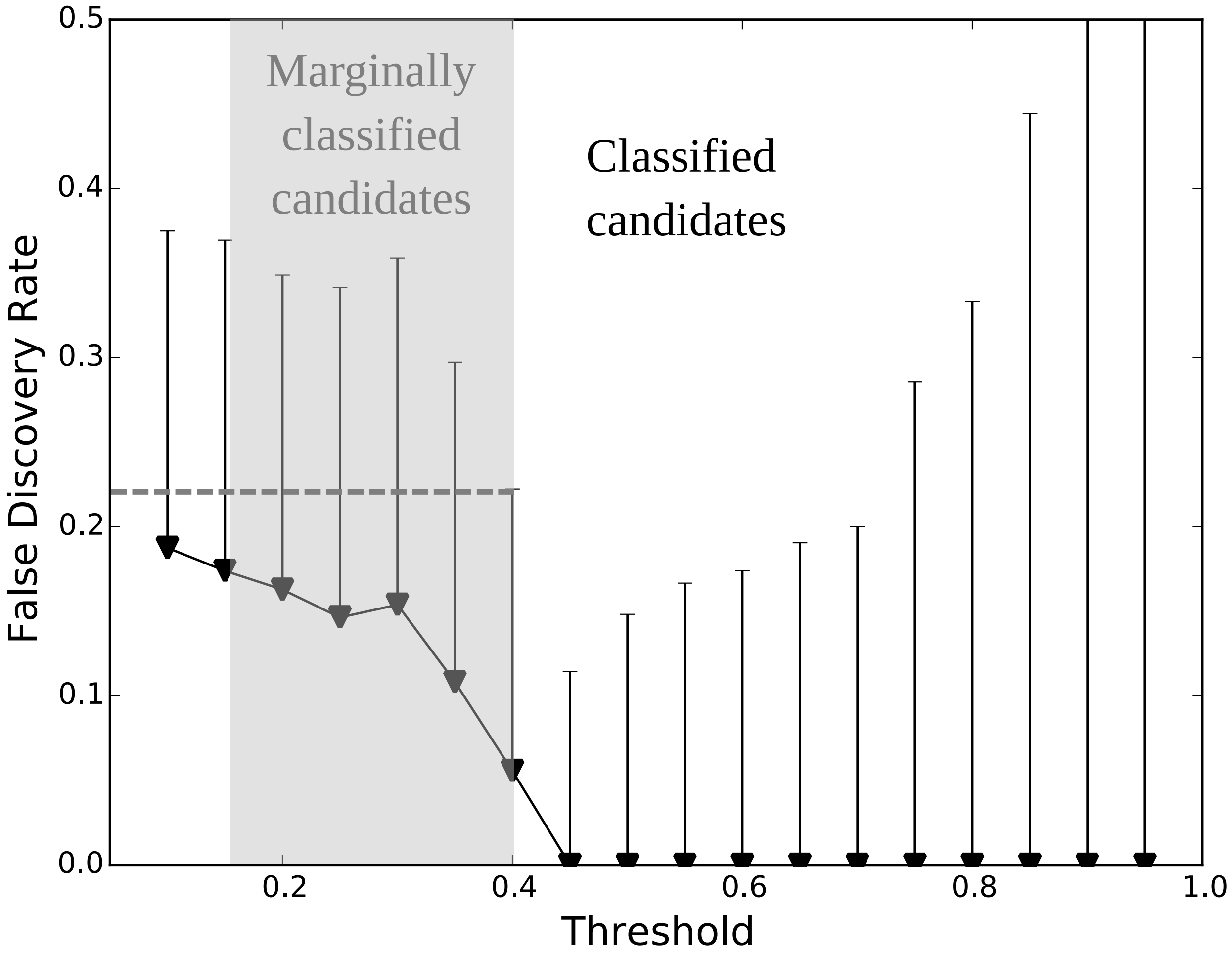






Mock catalog: Chance Coincidence Study

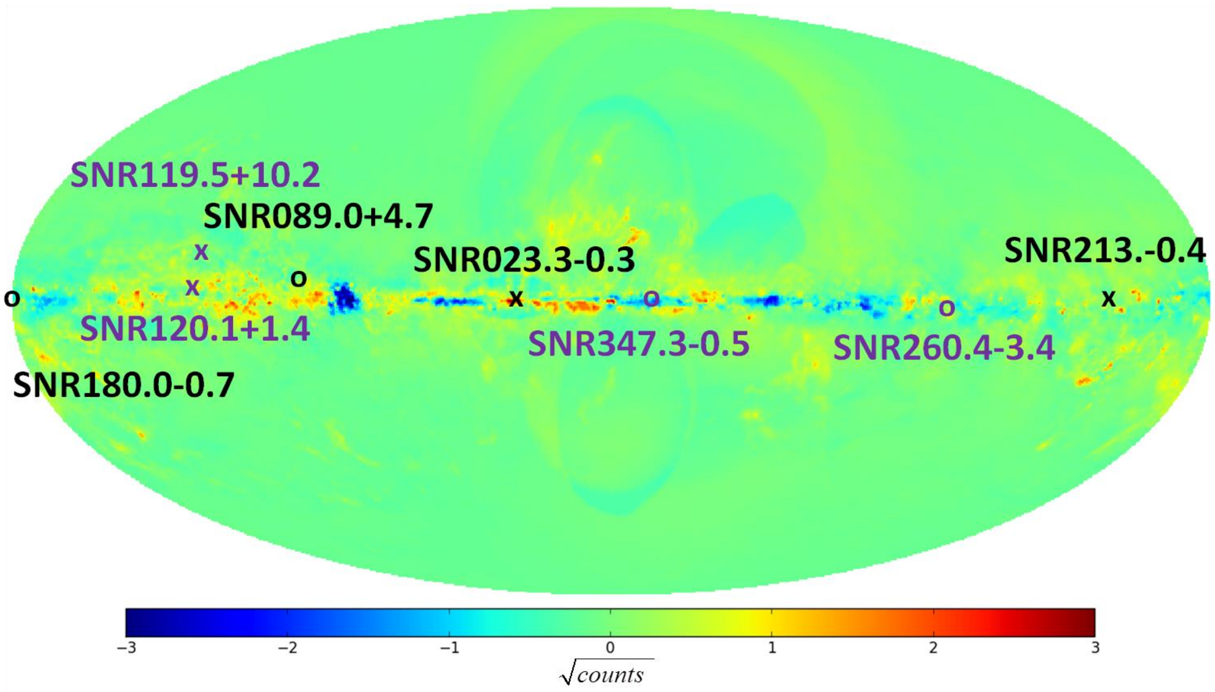
Use measure of chance coincidence in mock catalog to estimate false alarm rate and error.
Set thresholds to 0.4: $< 22\%$ false-positive rate.



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

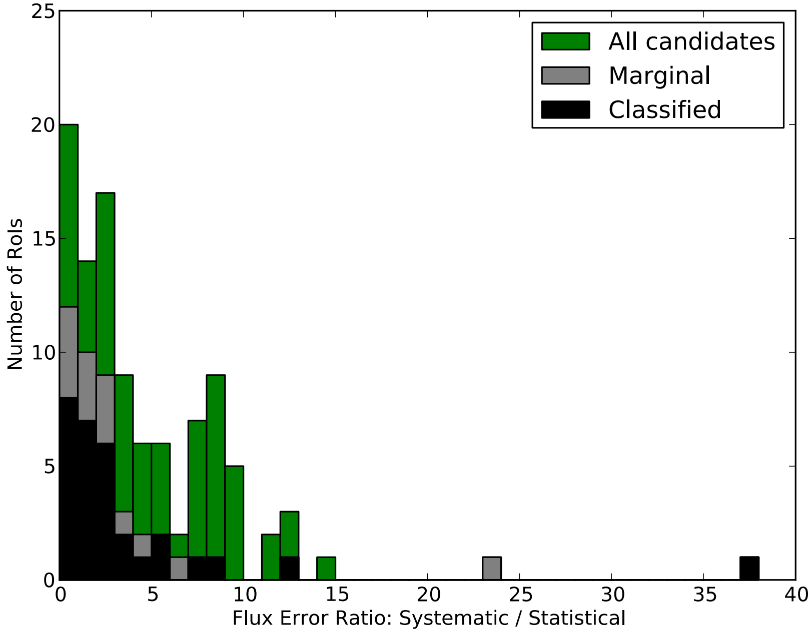
For each parameter (e.g. Flux, Index,..) obtained with the STD IEM P_{STD} we evaluate using the parameter P_i obtained with the alternative IEM the weighted systematic error:

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

The weight is:

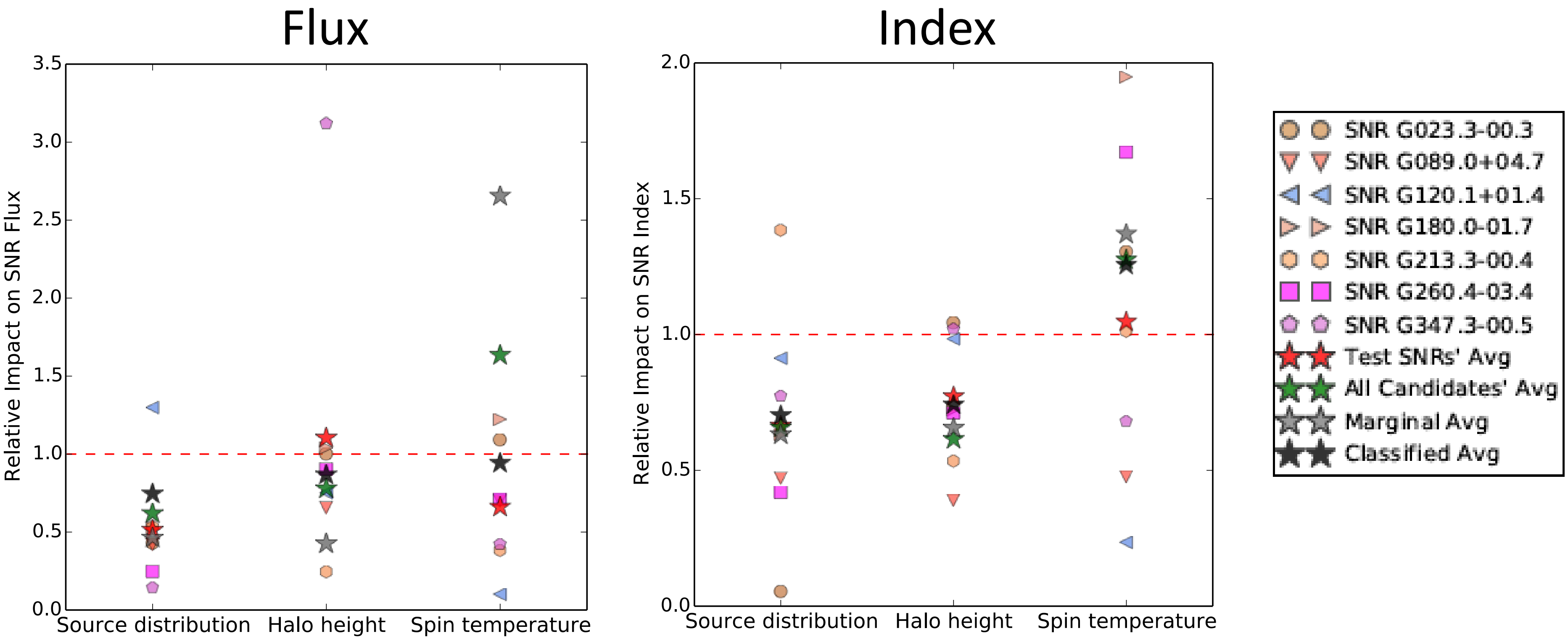
$$\omega_i = \frac{1}{\sigma_i^2},$$

where σ_i is P_i statistical error.



Systematic Uncertainties from IEM

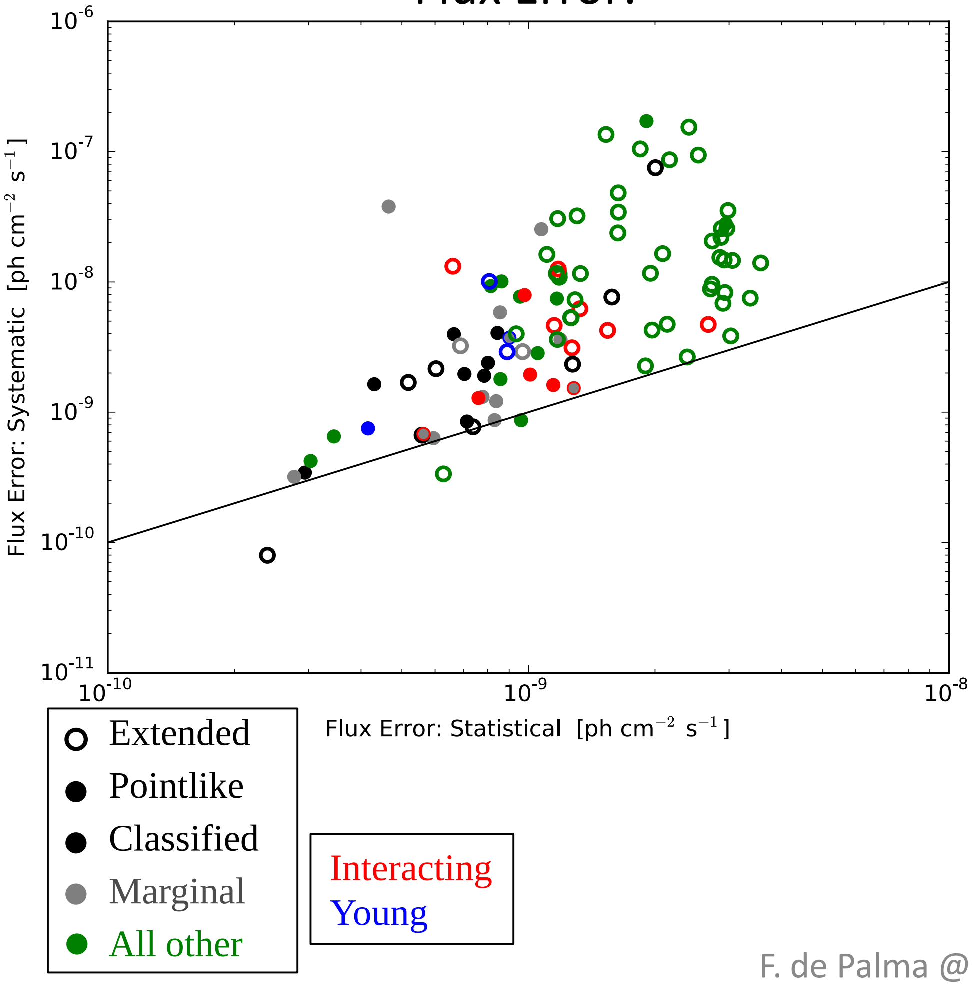
$$R \equiv \frac{| < P_i > - < P_j > |}{\max(\sigma_{P_i}, \sigma_{P_j})}.$$



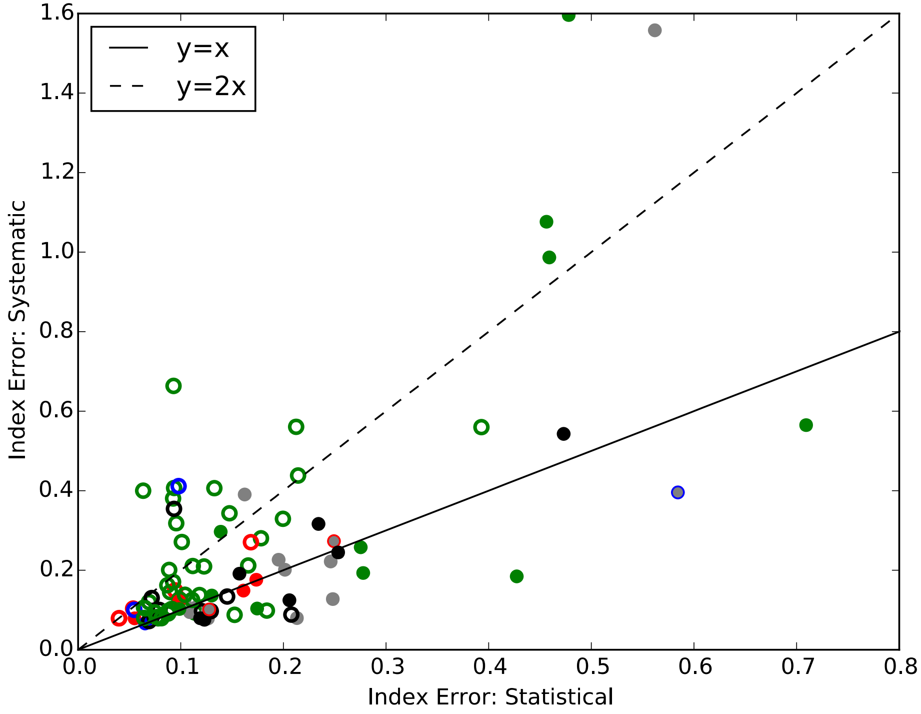
Systematic Errors

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

Flux Error:



Index Error:



Background sources

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