The First Fermi-LAT SNR Catalog: Multiwavelength Context and Cosmic Ray Energetics

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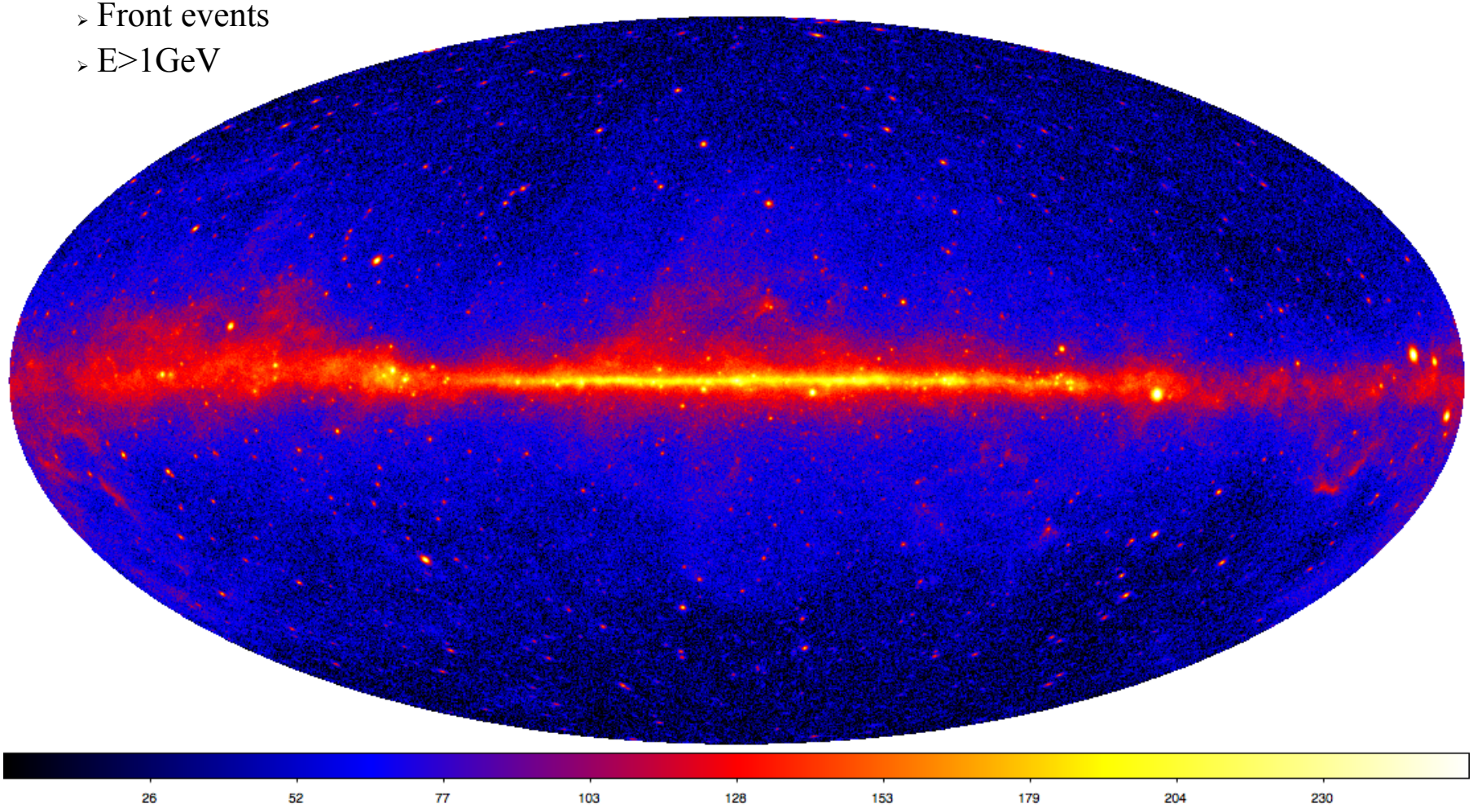
Buénerd

Fermi Detected γ–ray Emission

Data:

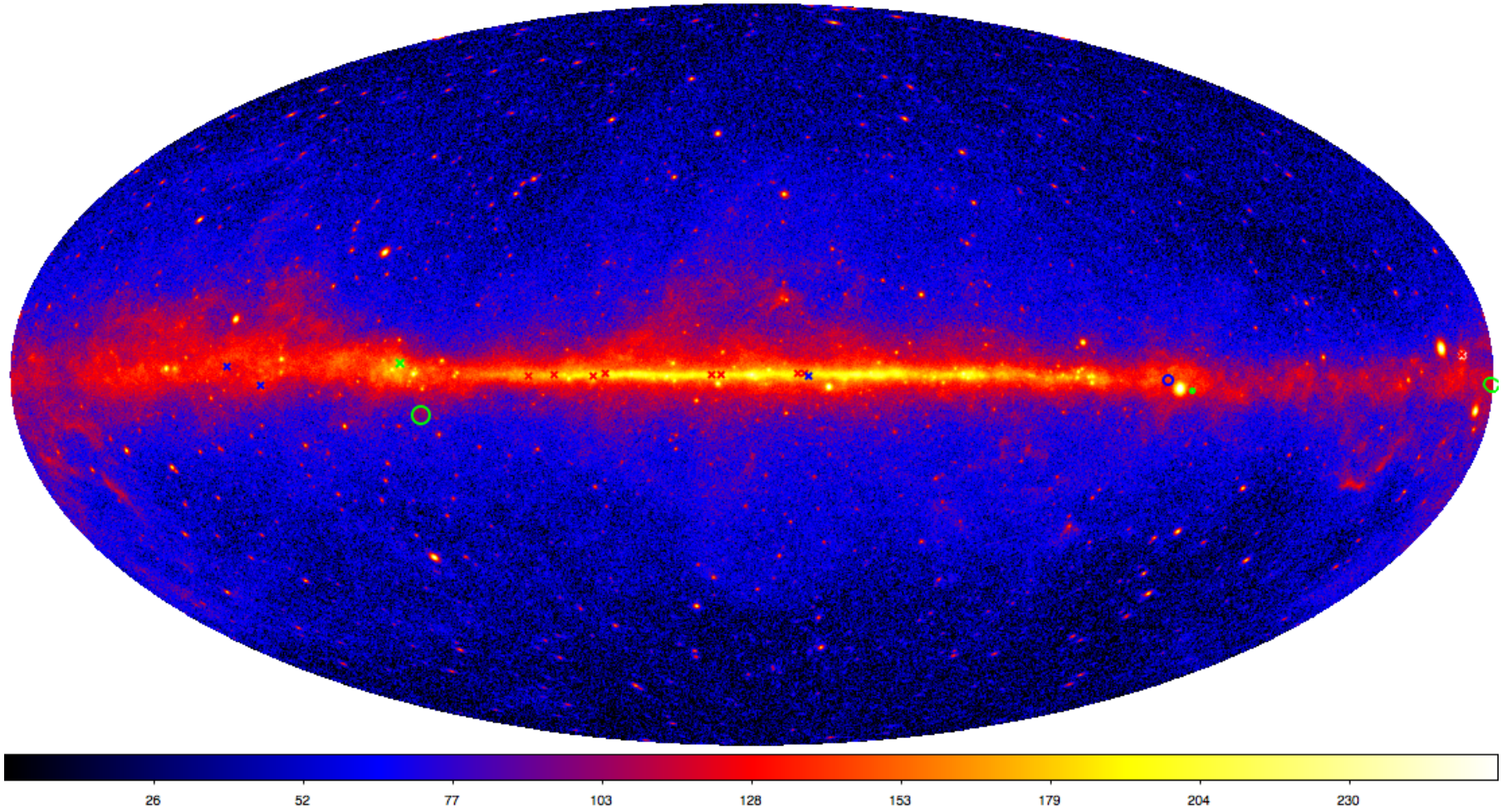
- 4yrs' exposure
- P7v6
- Front events
- E>1GeV



Fermi-Detected γ–ray SNRs

13 identified SNRs, including

- 9 interacting
- 4 young SNRs



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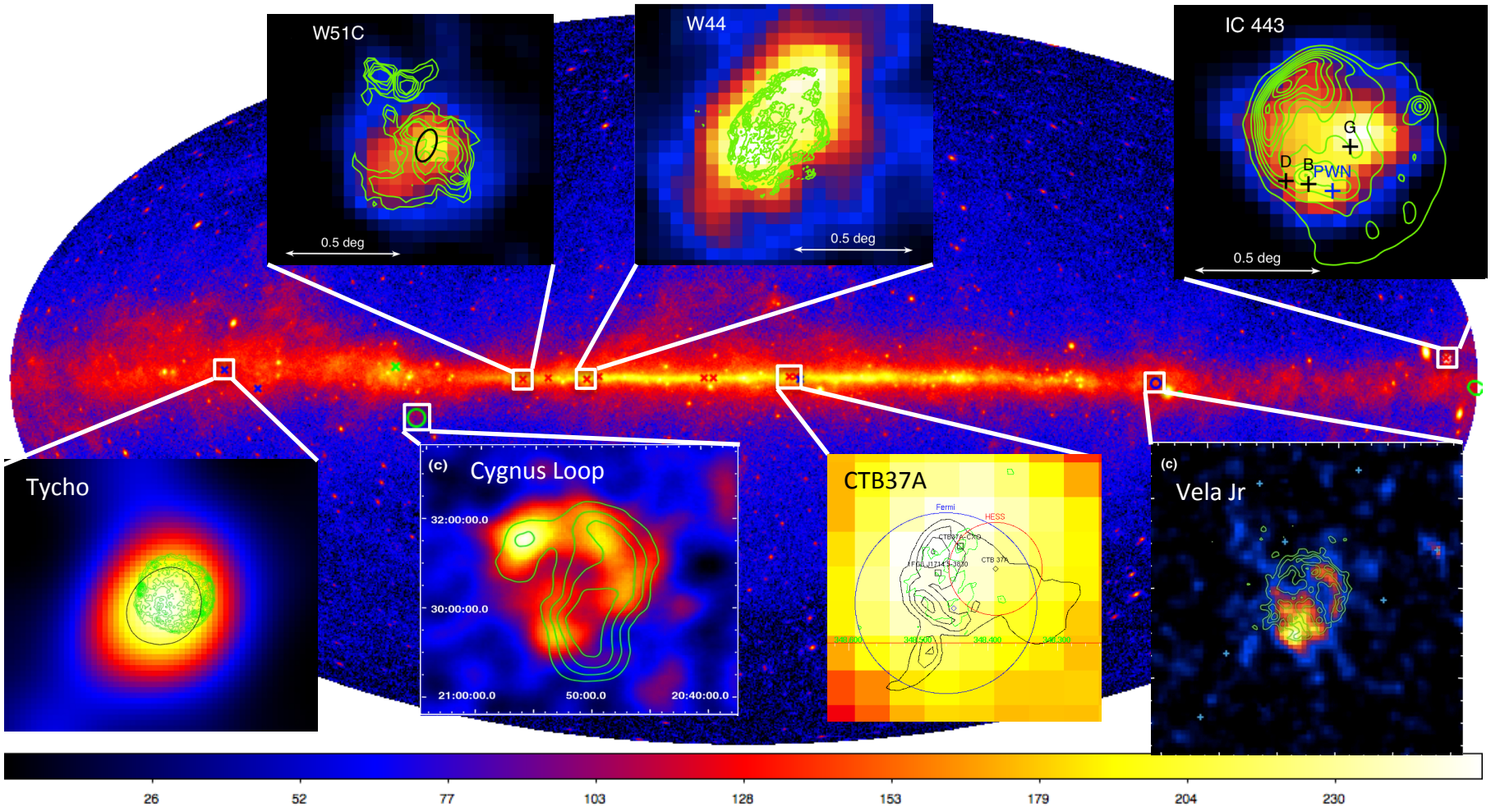
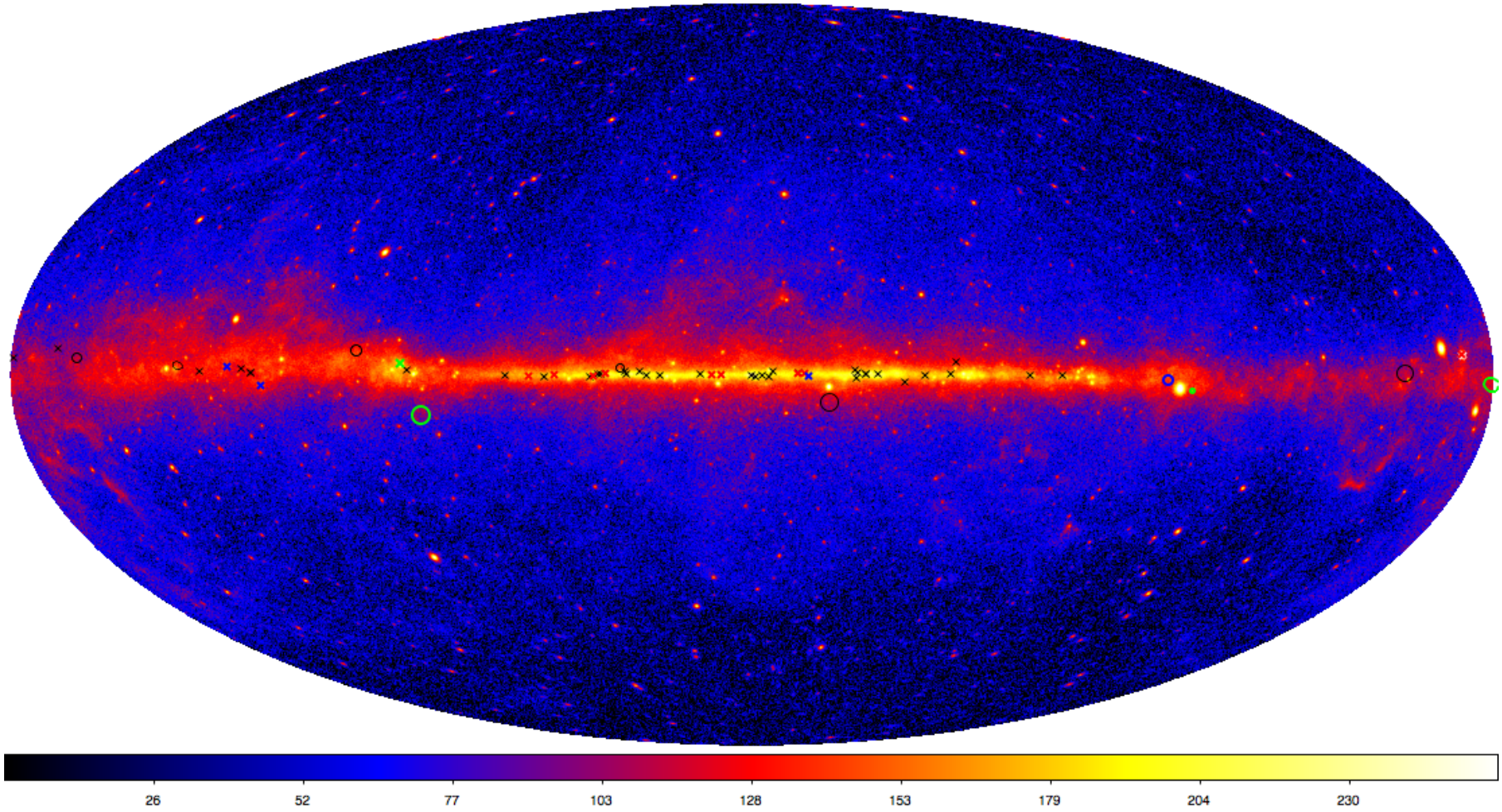


Fermi-Detected SNRs

13 identified SNRs, including
- 9 interacting
- 4 young SNRs

+ 43 2FGL candidates,
excluding identified PSRs,
PWN, & AGN



SNR Catalog:

To better understand SNRs in a statistically significant manner, within a MW context.

- Systematically characterize GeV emission in regions containing SNRs,
- Determine the characteristics of the population of GeV SNRs
- Examine multiwavelength (MW) correlation(s),
- Constrain known SNRs' contribution(s) to the Galactic CR population

With particular efforts from:

F. Acero, J. Ballet (CEA-Saclay/France)
J. Cohen, J. W. Hewitt (NASA/Goddard)
F. de Palma (INFN/Bari), G. Johannesson (U. Iceland)
M. Renaud (LUPM), L. Tibaldo (SLAC),
B. Wells (UCSC)

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)
- 279 SNRs

Starting Model:
- 2FGL

Improve starting model: AddSources

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.

Characterize systematic error from the interstellar emission model

See F. de Palma's talk in 10B / 5p!

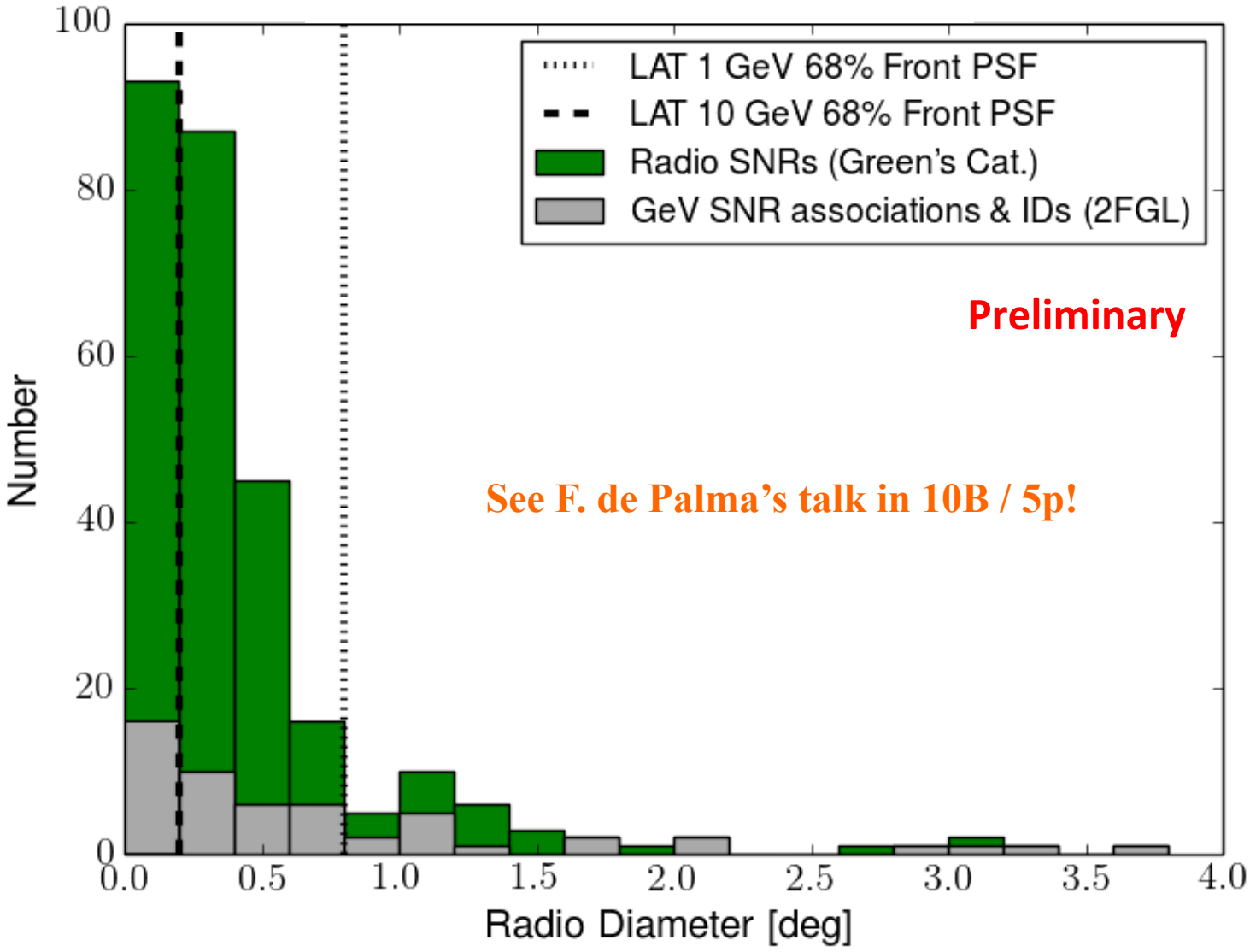
Output:
- Position, extension, significance
- Spectral energy distribution
- Region and residual maps
- Diagnostics

Identify candidates as likely SNRs by spatial coincidence.

T. J. Brandt

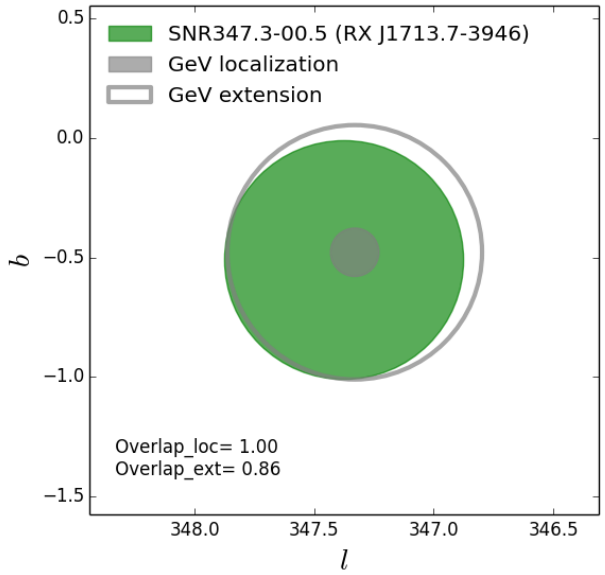
SNR Catalog:

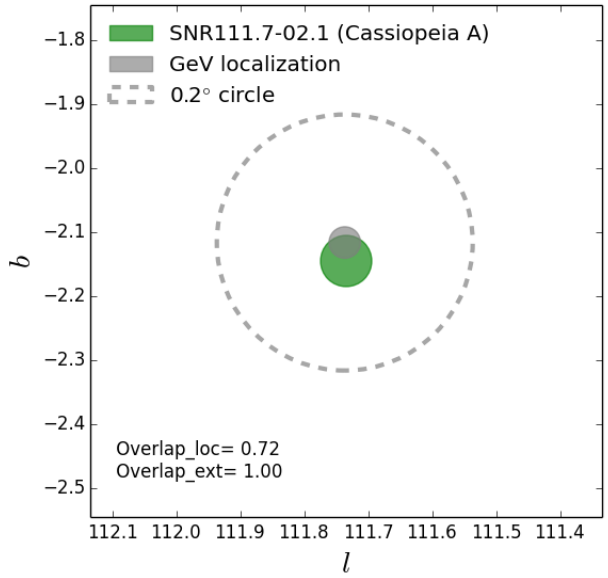
- Fermi-LAT has the ability to spatially resolve a large number of the 279 known SNRs.

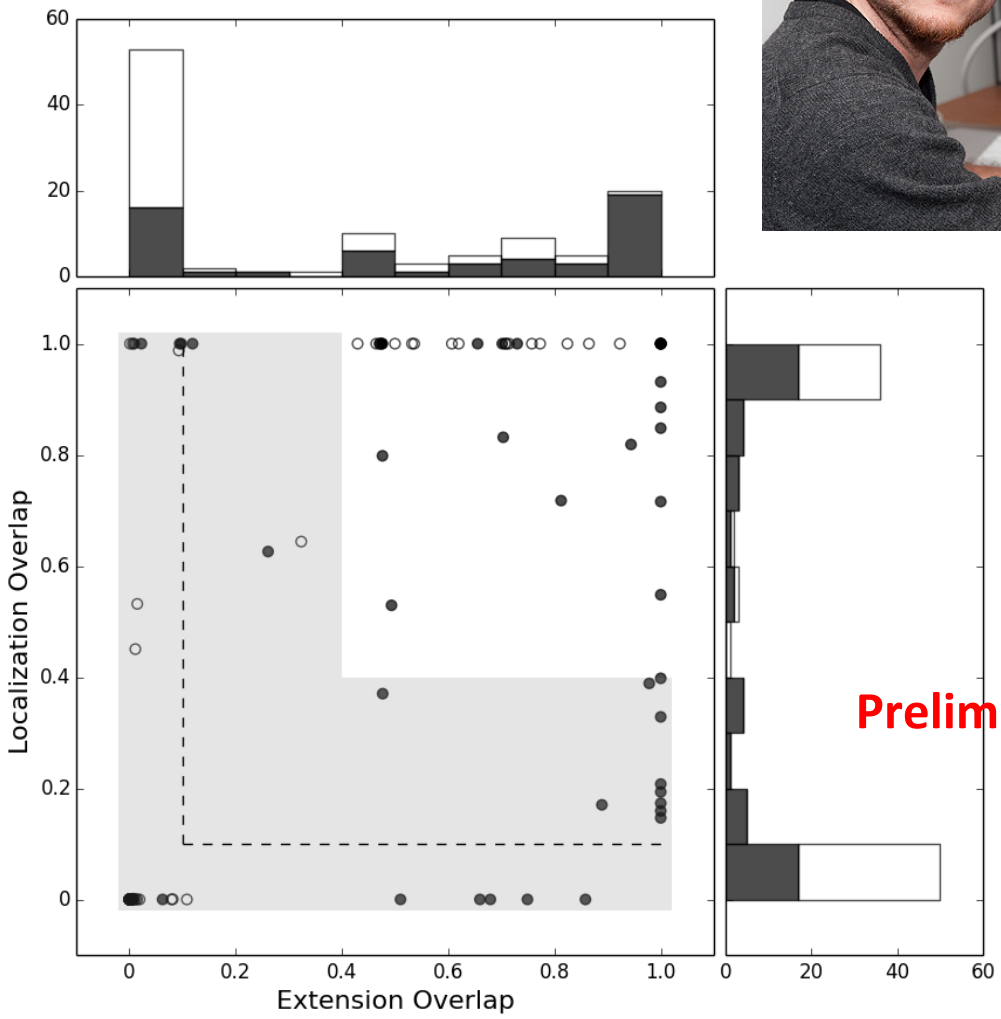


Classification

Quantify spatial overlap:



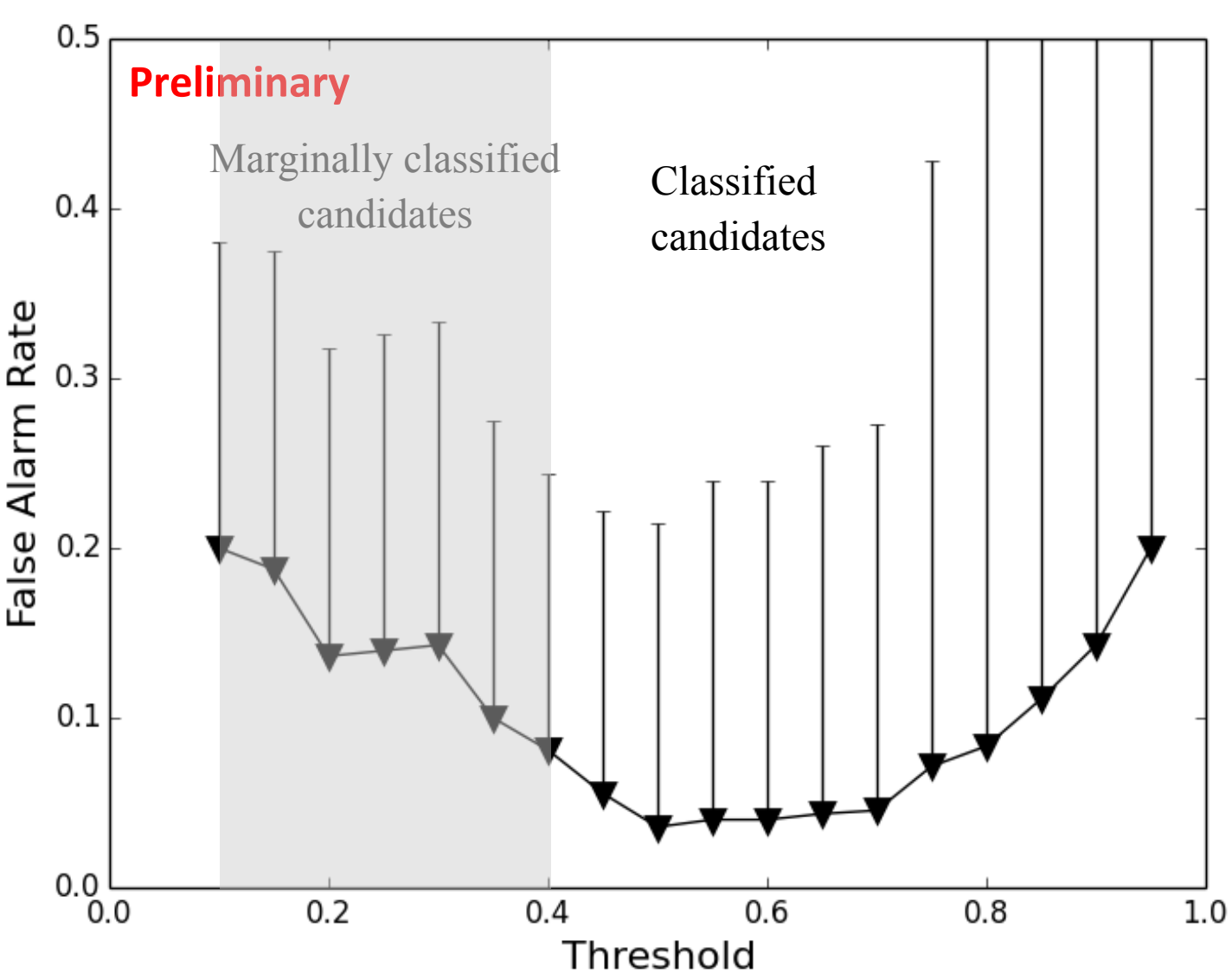




Preliminary

Classification

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



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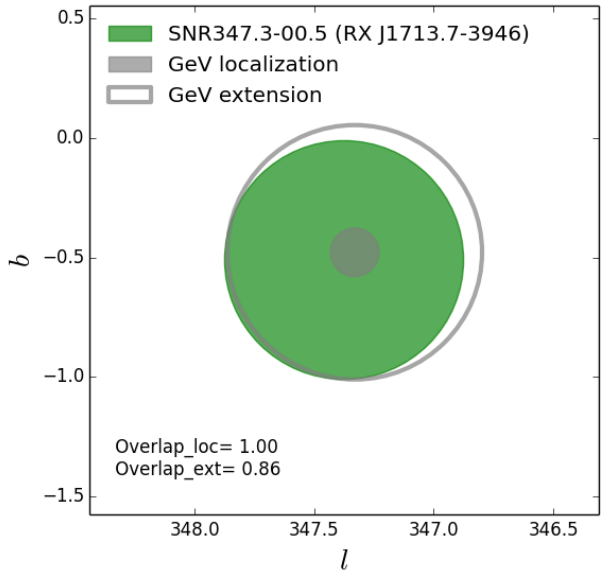
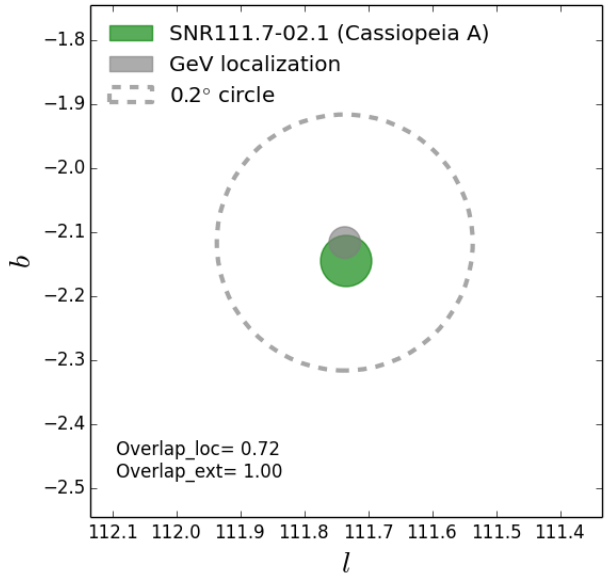
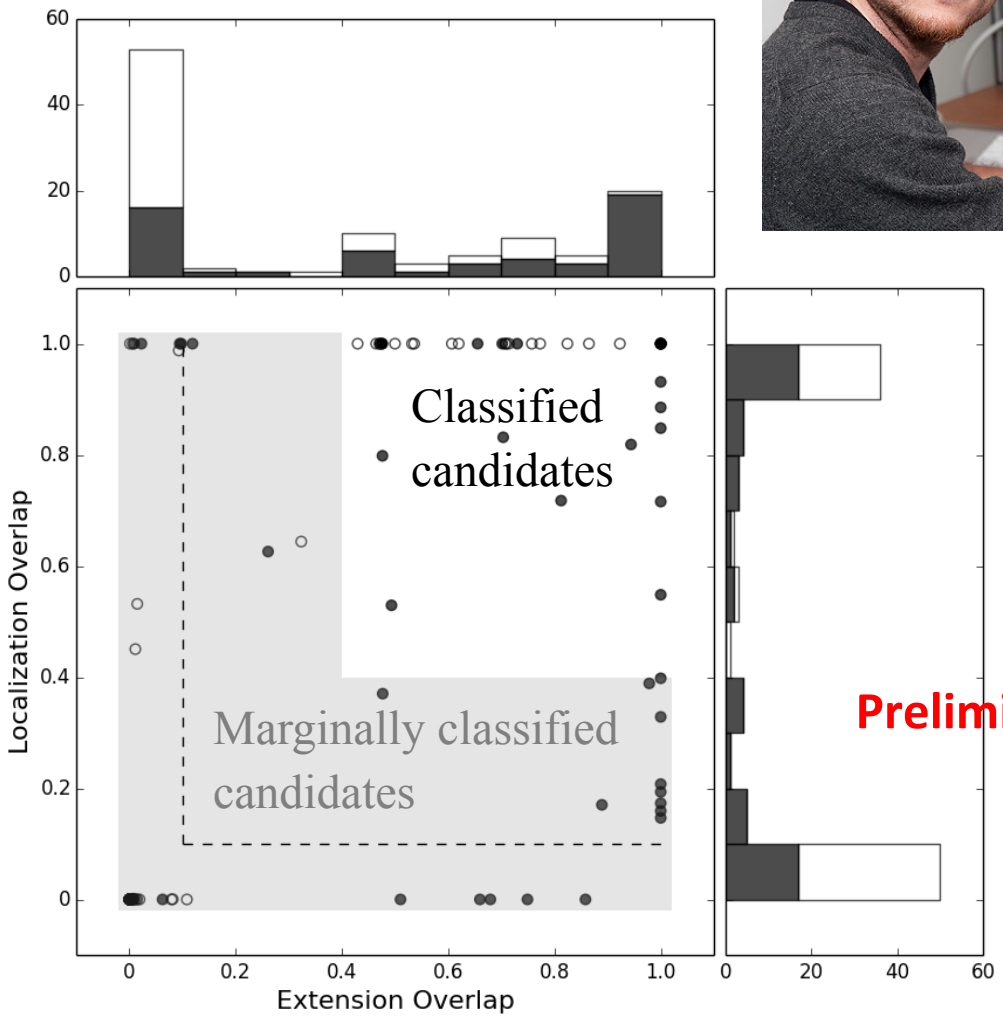






Preliminary

See F. de Palma's talk in 10B / 5p!

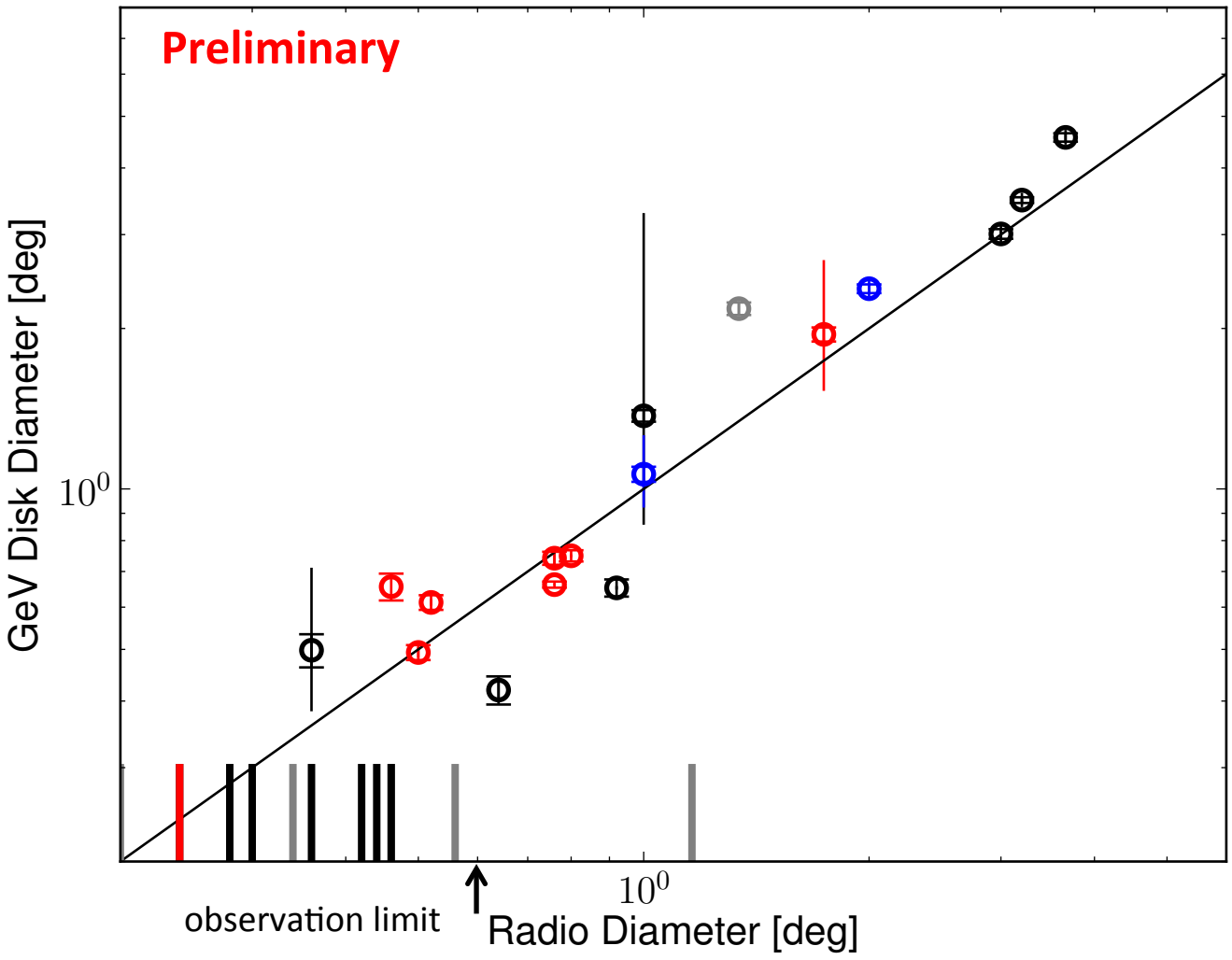
SNR Catalog: Results!

Characterized 279 regions containing known radio SNRs:

- 109 candidates have significant GeV emission:
- 4 identified as other sources (Crab, binary, and PWN/PSR)
- 32 candidates pass classification threshold:
  (location and extension overlap fractions ≥0.4)
  - 16 extended: 3 new!
  - 16 pointlike hypothesis preferred: 7 new!
  - 2 have logP spectra (in 1-100GeV energy range)
- 242 flux upper limits at radio position and extension
  - for those which are significant but don't pass classification: both candidate parameters and radio SNR UL reported

GeV v Radio Radius

Classified GeV candidates tend to correlate with their radio size:



- Interacting SNRs: density≥100cm^{-3}
- Young SNRs: evidence of non-thermal X-ray emission

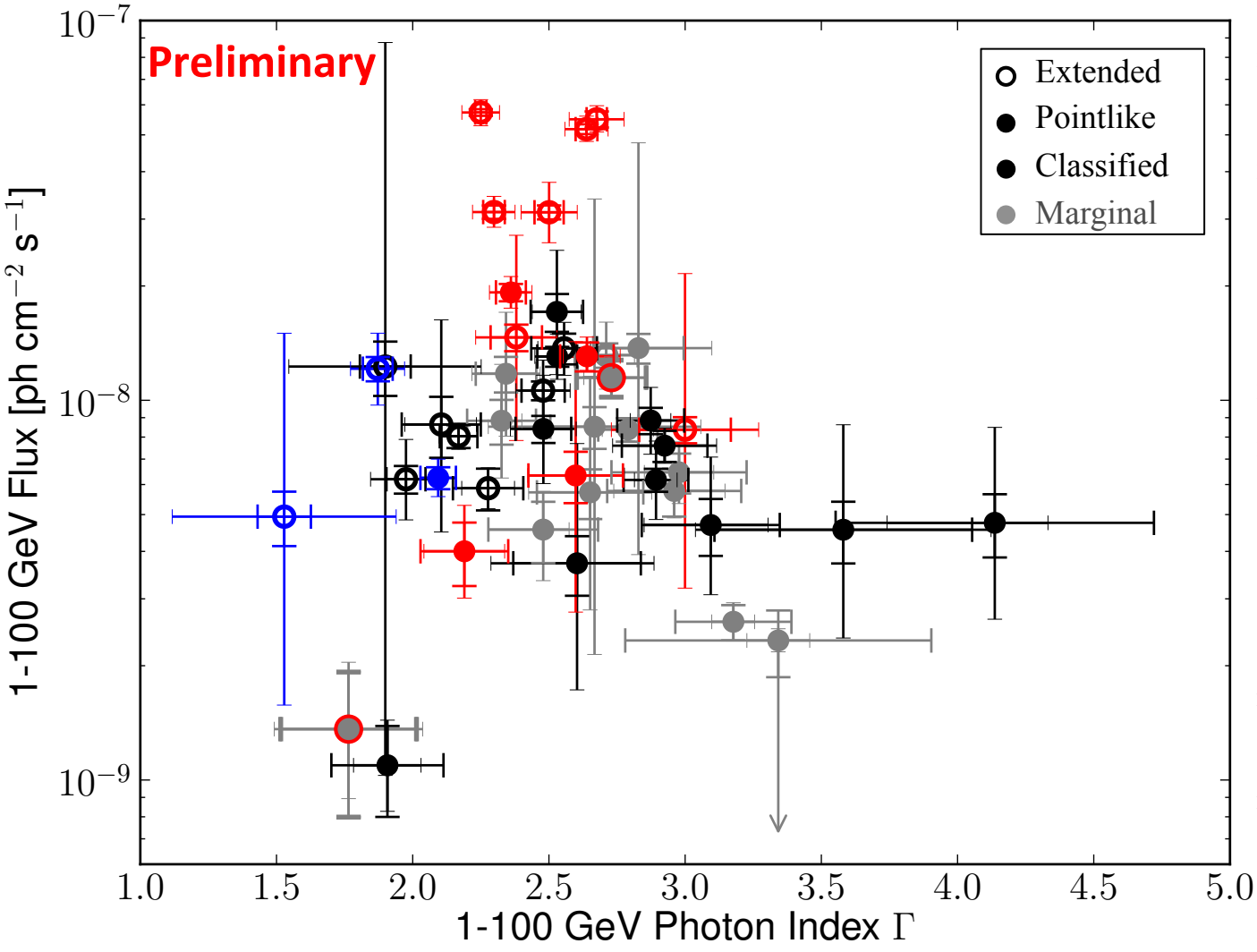
- Classified candidates
- Marginal candidates: 0.1 ≤ classification thresholds (location and extension overlap) < 0.4

- Capped error bars: Statistical
- Uncapped: Systematic

Error estimate details: F. de Palma 10B / 5p!

GeV Flux v Index

Candidates span 2 orders of magnitude in flux and from 1.5 – 5.0 in index, despite examining only 1-100GeV energy range.



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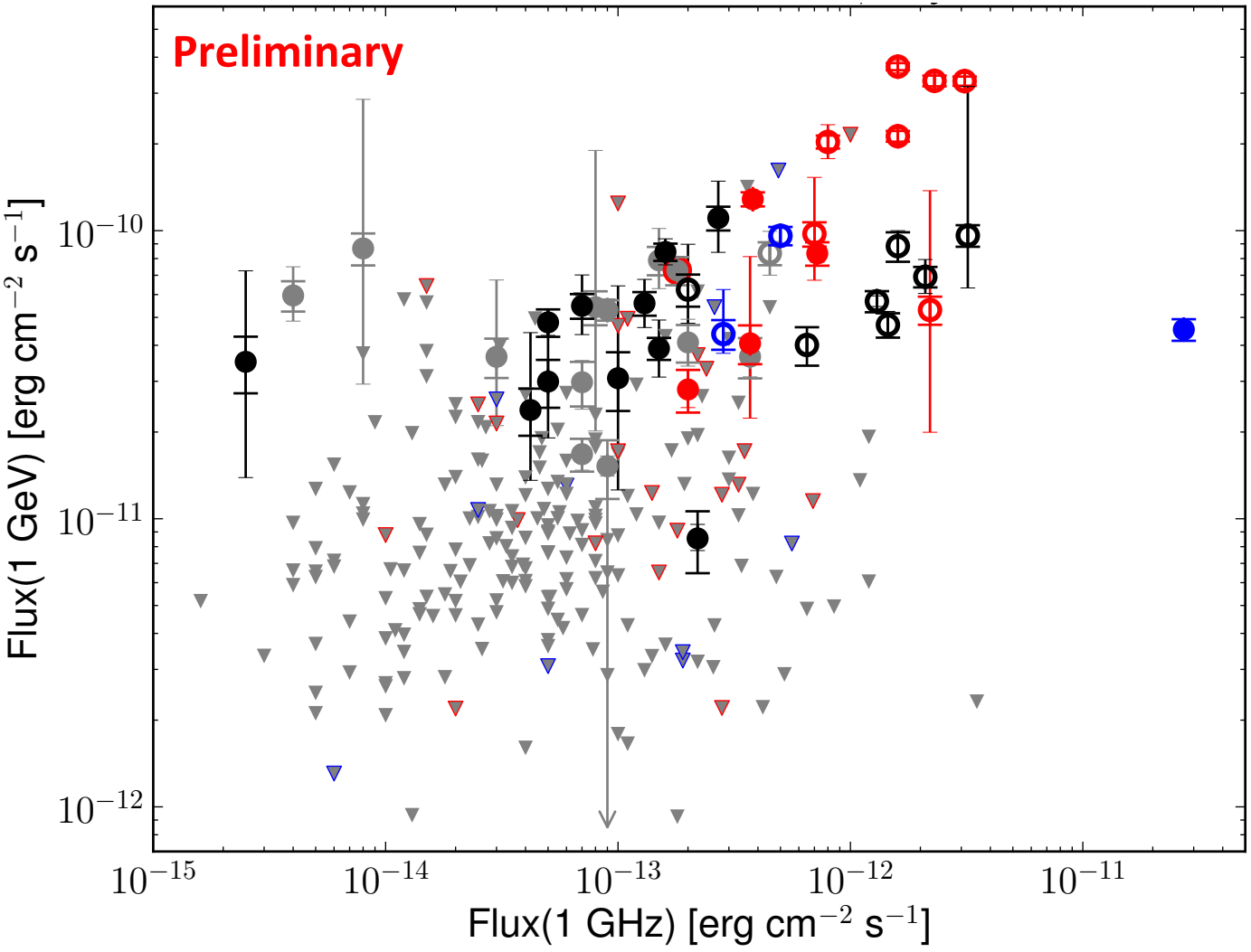
Radio-GeV Correlation?

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

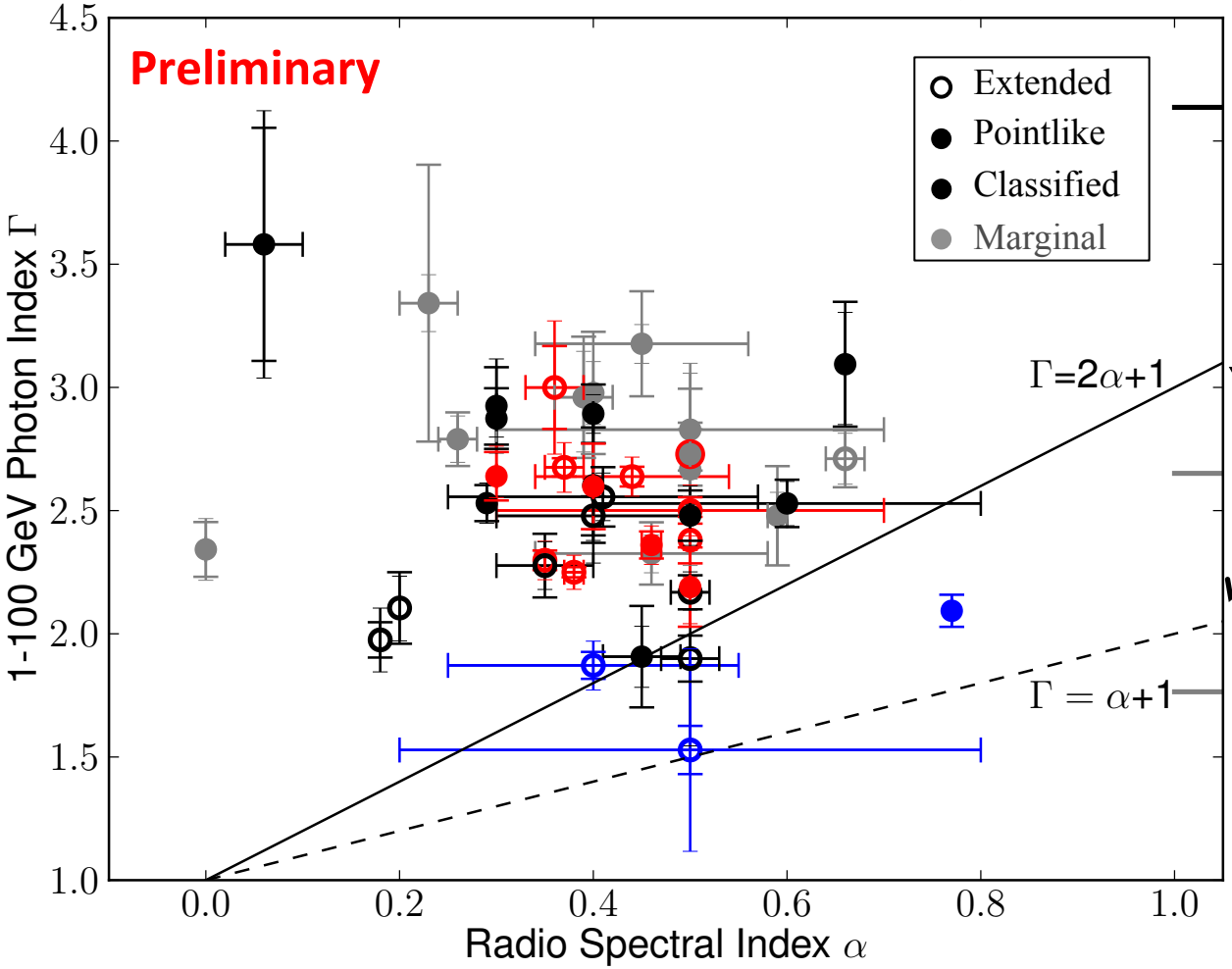


- Interacting SNRs: general correlation suggests a physical link
- Young SNRs show more scatter

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:



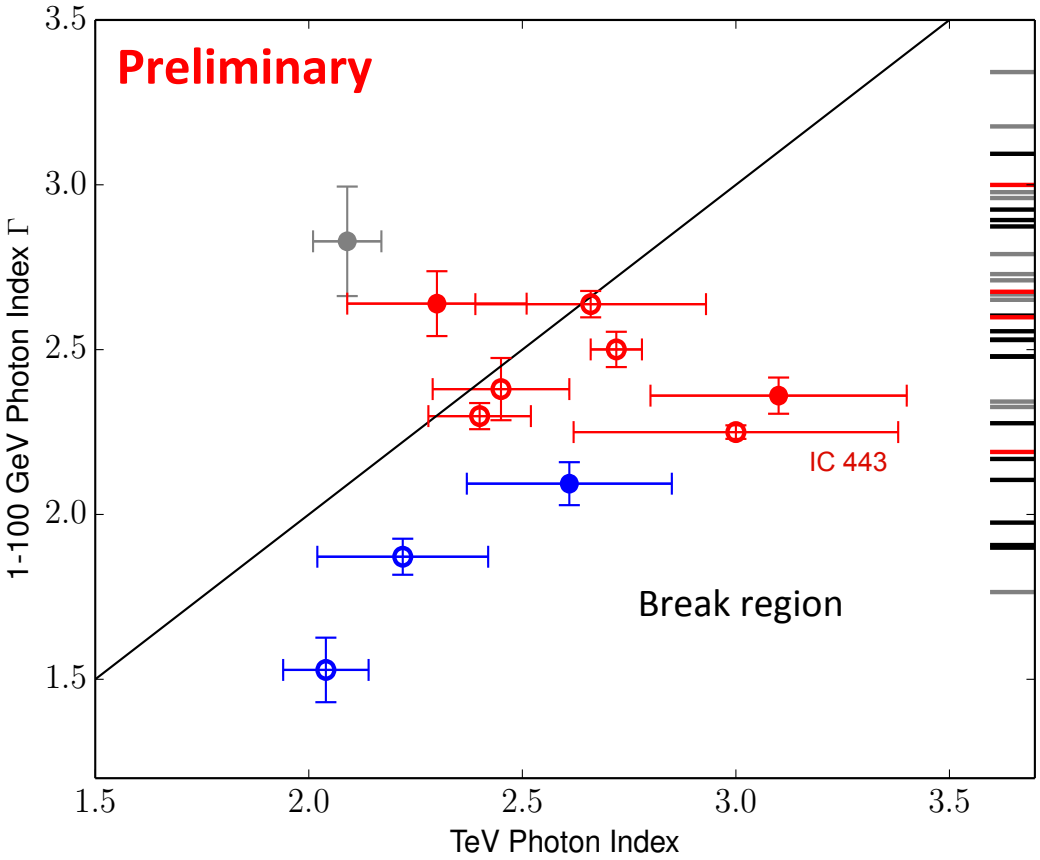
- Young SNRs: seem consistent
- Others, including interacting SNRs: softer than expected

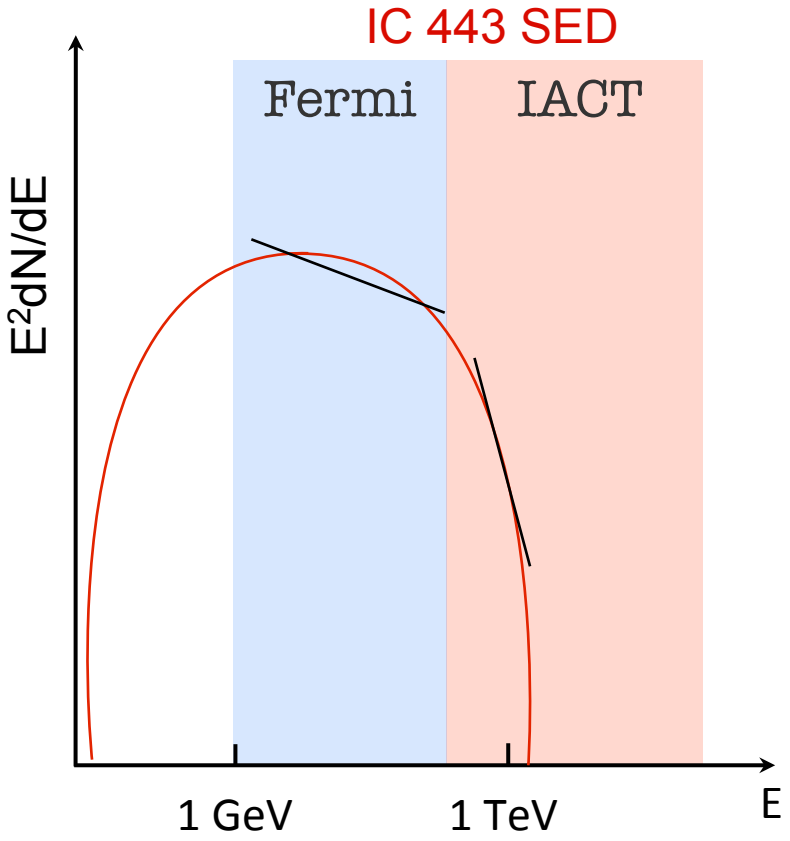
GeV-Radio slope correlation for:
- π^0 decay or $e^{+/-}$ bremmstrahlung
- inverse Compton

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

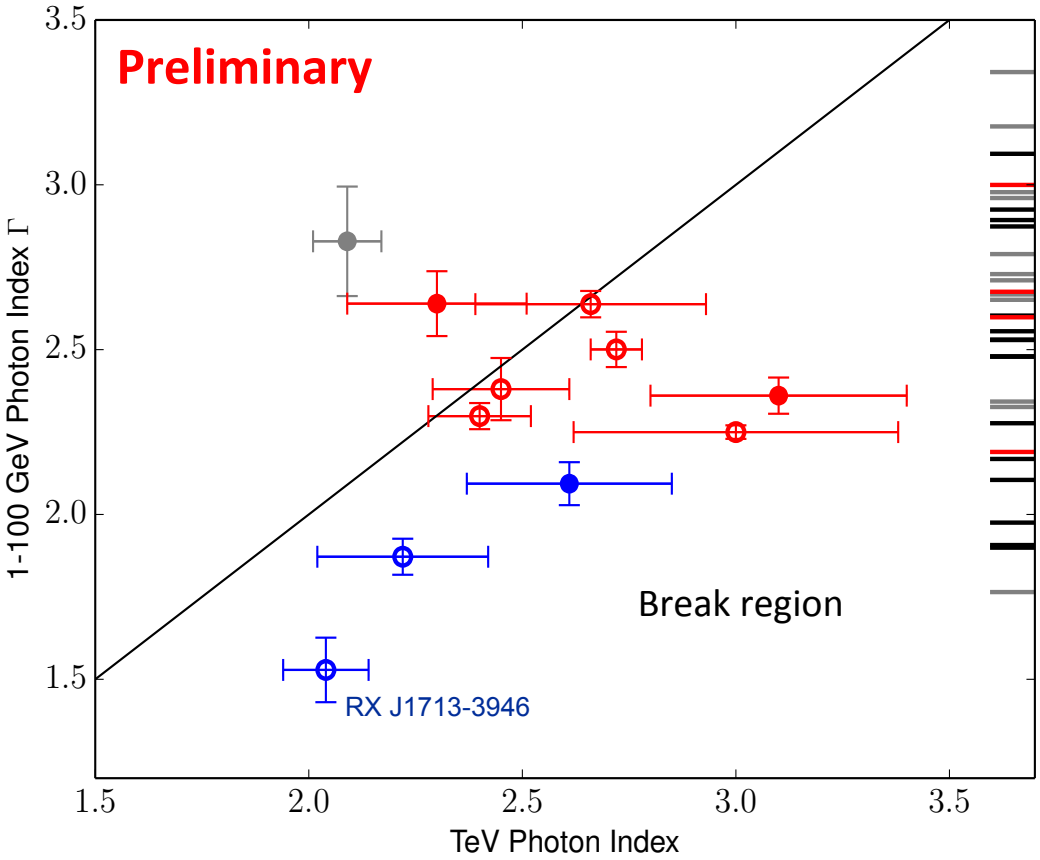


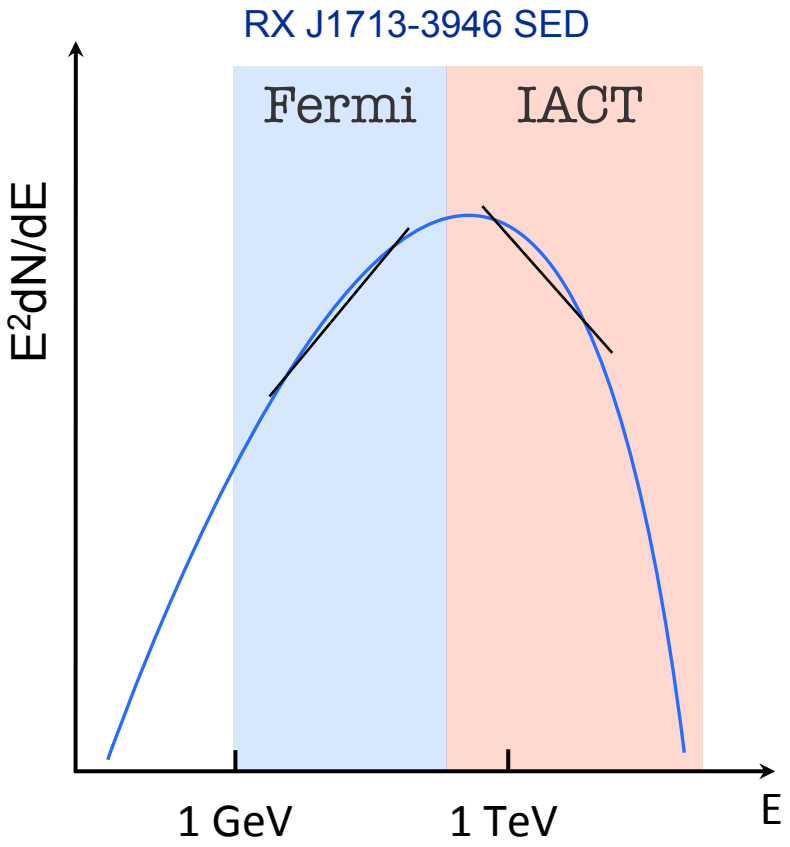


- Extended
- Pointlike
- Classified
- Marginal

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

GeV-TeV Index





- Extended
- Pointlike
- Classified
- Marginal

- Indication of break between GeV and TeV
- Caveat: TeV sources are not uniformly surveyed.

Age v GeV Index

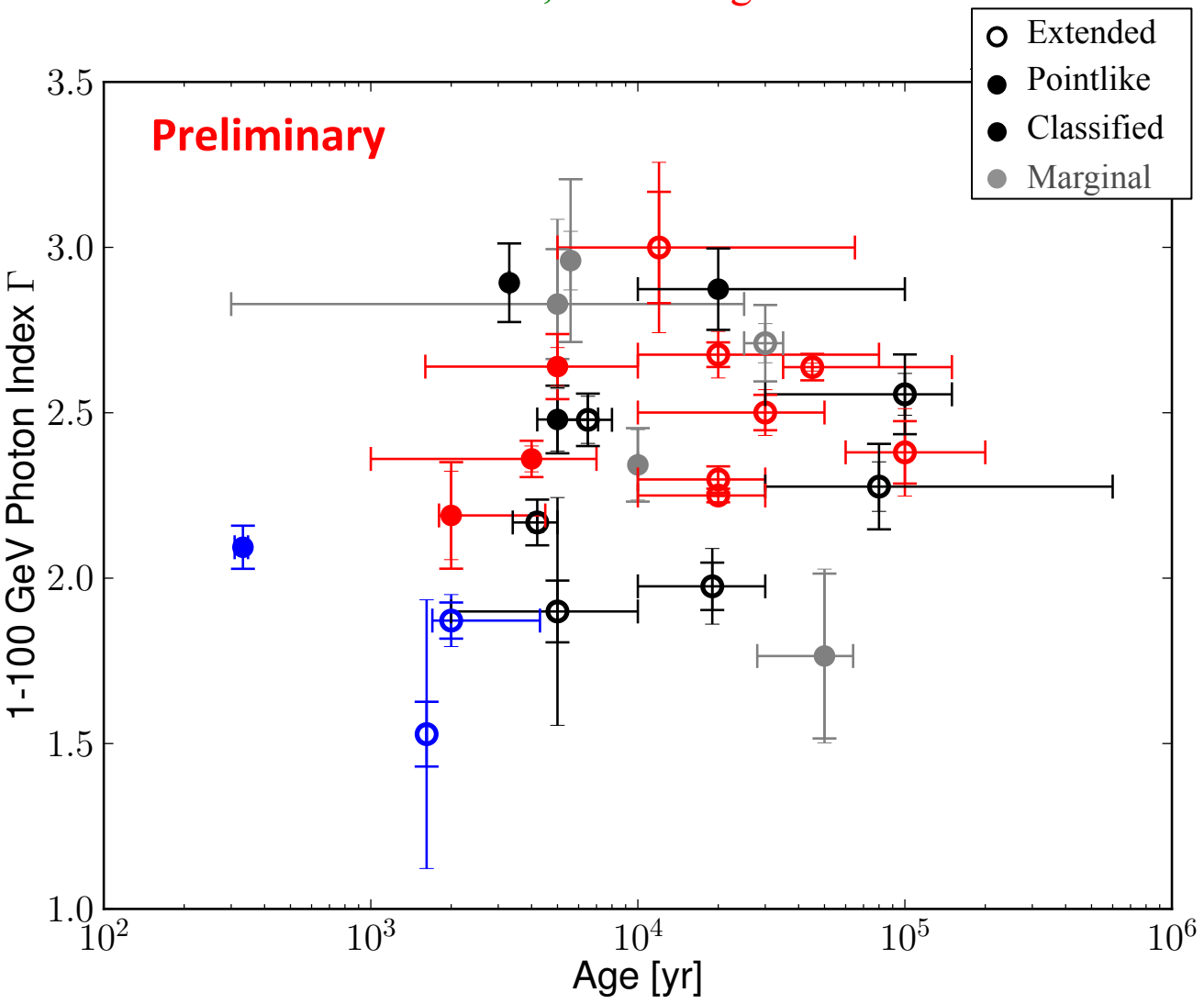
Young SNRs tend to be harder than older, interacting SNRs.

GeV index evolves w 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

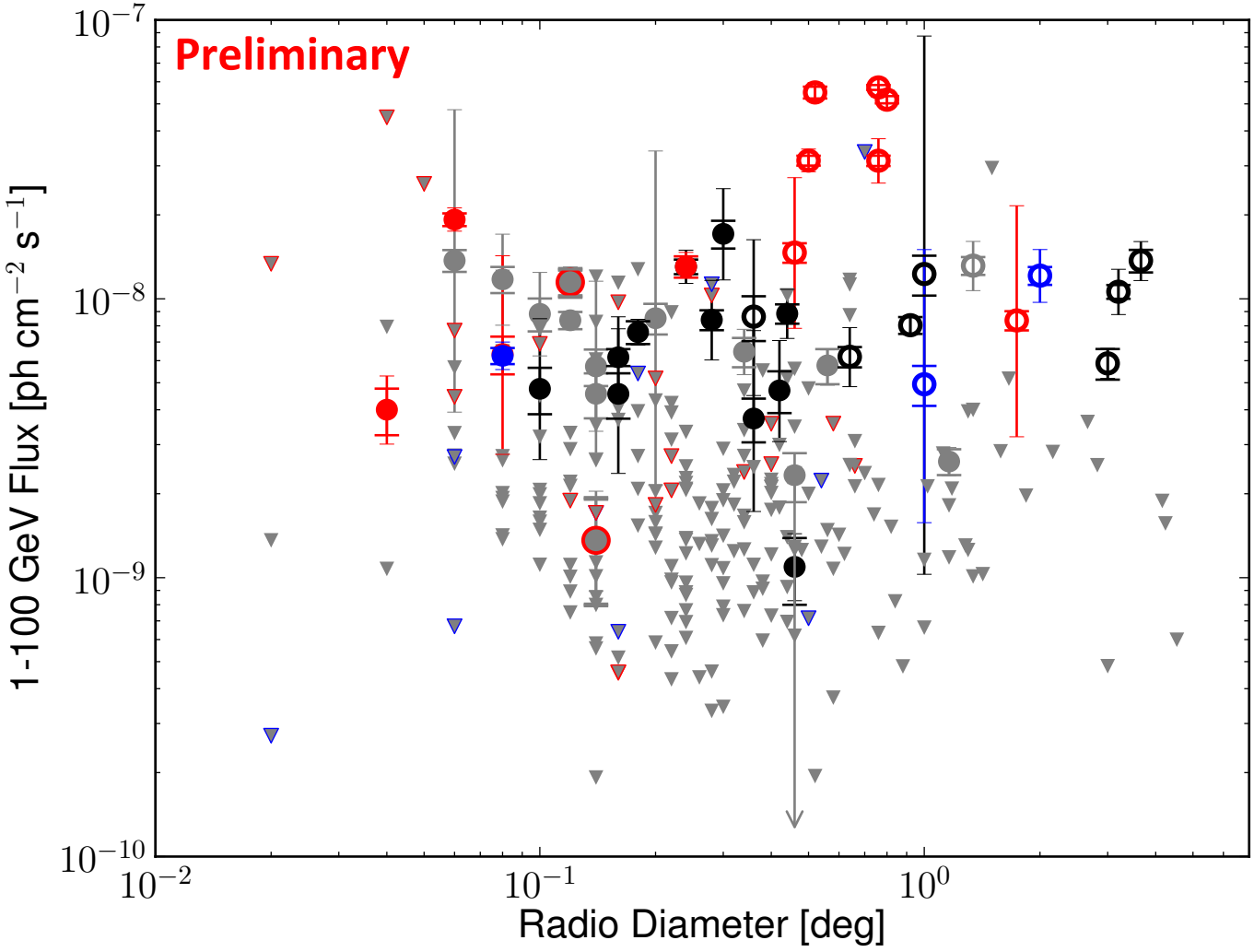


Flux v Radio Size

No clear correlation nor separation between classes:

Candidates tend to:

- span the range of known sizes
- fill in regions w previously fewer known sources =>
- ability to make more statistically robust population statements!



Constraining CR Acceleration

We can relate our SNR flux measurements to the energy imparted to CRs:

$$F(1-100\,\mathrm{GeV}) \approx 10^{-8}\,\frac{\varepsilon_{\mathrm{CR}}}{0.1} \times \frac{E_{\mathrm{SN}}}{10^{51}\mathrm{ergs}} \times \frac{n}{1\,\mathrm{cm}^{-3}} \times \left(\frac{d}{1\,\mathrm{kpc}}\right)^{-2} \mathrm{cm}^{-2}\mathrm{s}^{-1}$$

where we assume

- all emission is hadronic in origin,
- $E_{CRmax} > \approx 200$GeV, and
- $\Gamma_{CR} \approx 2.5$

ε_{CR} is the content in particles accelerated up to the observation time relative to the SN explosion energy which, under the assumption that energy losses & escape are negligible, is the hadron efficiency.

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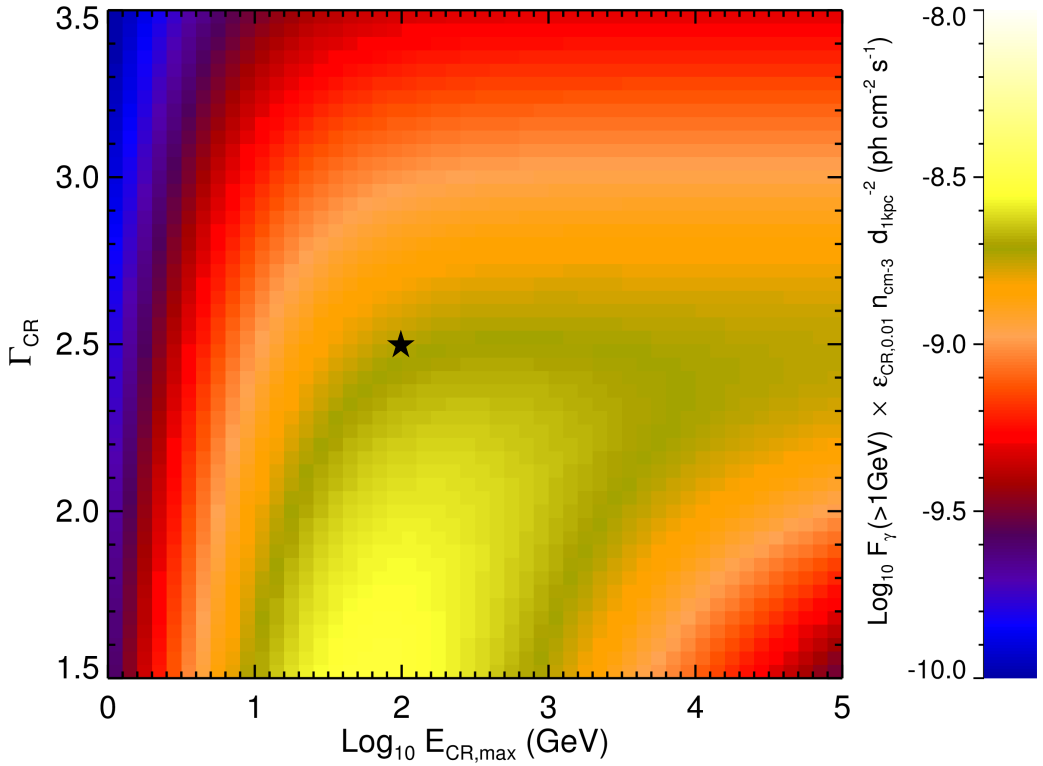
We can also allow E_{CRmax} and Γ_{CR} to vary:



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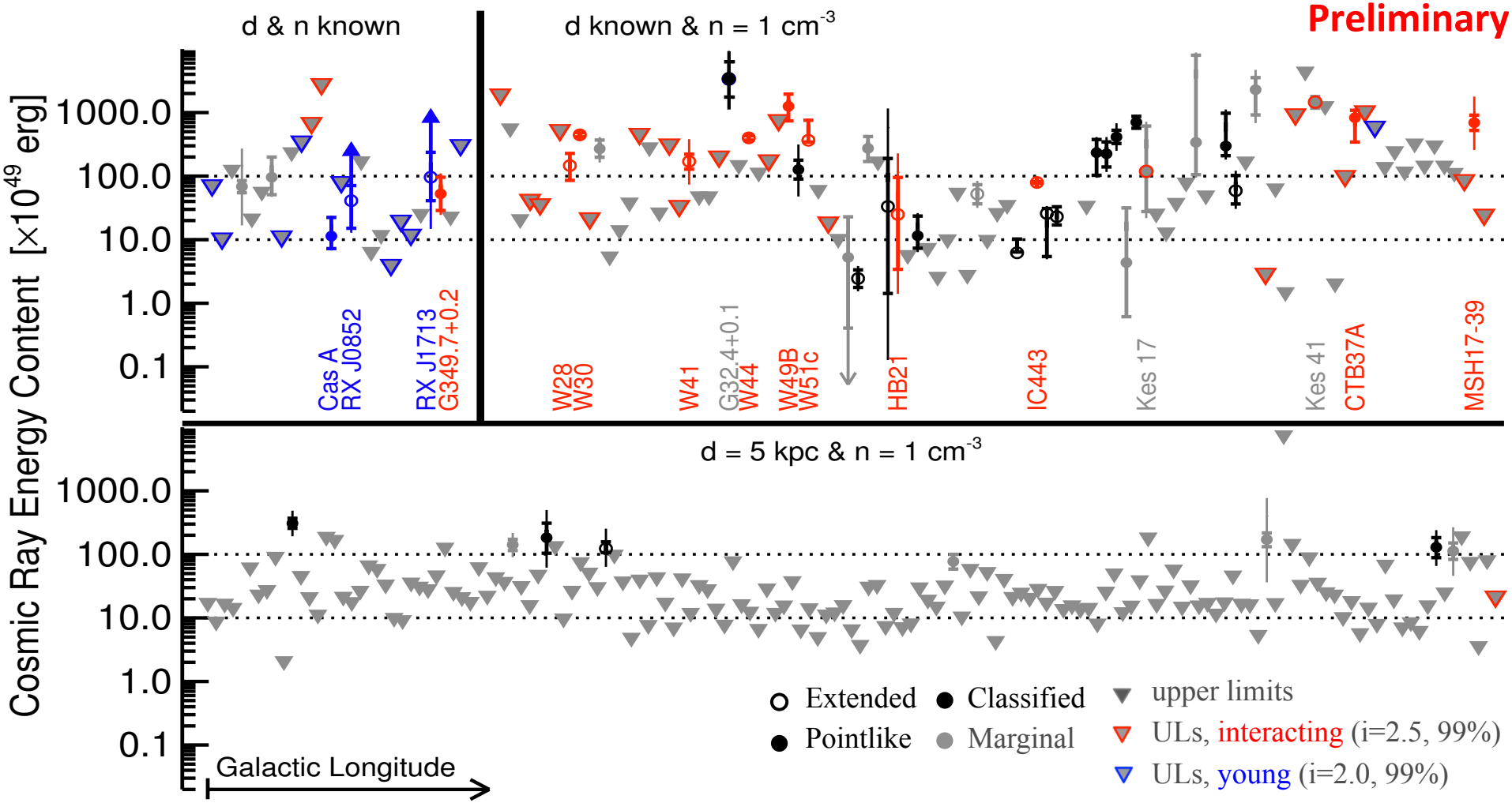
Solving for the energetics,

$$\varepsilon_{\mathrm{CR}} \times 10^{49}\,\mathrm{erg} \approx \frac{F(1-100\,\mathrm{GeV})}{1.5\times10^{-7}\,\mathrm{cm}^2\mathrm{s}}\left(\frac{d}{1\,\mathrm{kpc}}\right)^{2}\left(\frac{n}{1\,\mathrm{cm}^{-3}}\right)^{-1}$$

Constraining CR Acceleration

Relating SNR flux measurements to the energy imparted to CRs:



Fermi-LAT has the ability to probe population-wide, the CR-relevant phase space!

"Efficiency"

- ~ 10-100% for all candidates
- ~1000% suggests emission may also be leptonic and/or d, n estimate may be inaccurate


Conclusions

Conclusions

- SNR Catalog systematically confronts and solves challenges faced by analyses of Galactic Plane sources:
  - Uniquely addressed with: AddSrcs, aIEM, classification & mock catalog
- GeV SNR population characteristics:
  - Candidate distribution to flux completeness of 10^{-8} ph $cm^{-2}s^{-1}$ with a characteristic index of 2.5 & range (4, 1.5)
  - Data are challenging model assumptions!
  - Index appears to soften with age: possible separation between young & interacting SNRs
- MW correlations:
  - TeV-GeV index shows evidence of breaks for many sources; sample limited
  - Quantifying radio-GeV correlation within constraints of incomplete, non-uniform distances
- Constraining CR contribution:
  - Ability to constrain known SNRs' aggregate contribution to CRs
  - Measured efficiencies average ~ 10% => possible to create bulk

Measuring a statistically significant population of GeV SNRs within a MW context permits us to assess the class's ability to supply CRs observed by direct detection experiments.