New SNR Candidates in the First Fermi-LAT SNR Catalog

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Purpose:

To better understand SNRs in a statistically significant manner, within a MW context we:
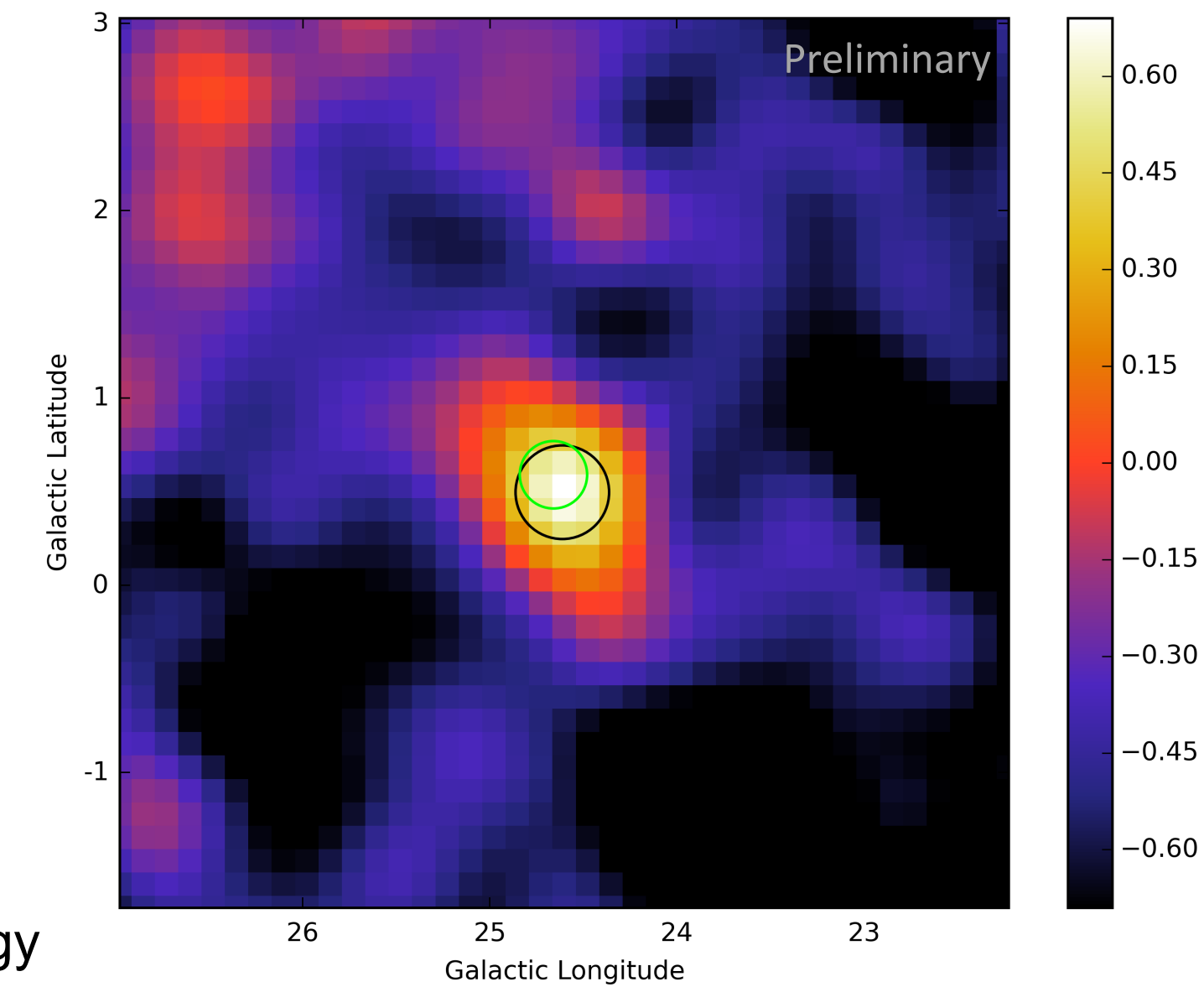
▹ Systematically characterize GeV emission in regions containing SNRs,
▹ Determine the characteristics of the population of GeV SNRs
▹ Examine multiwavelength (MW) correlation(s),
▹ Constrain known SNRs' contribution(s) to the Galactic CR population

Results:

Characterized 279 regions containing known radio SNRs:

▹ 102 candidates have significant GeV emission:
  ▹ **30 candidates pass classification threshold & are likely SNRs**: (location and extension overlap fractions ≥0.4)
  ▹ 17 **extended: 4 new!**
  ▹ 13 point hypothesis preferred: 10 new!
  ▹ 2 have logP spectra (in 1-100GeV energy range)

▹ 4 identified as not SNRs (Crab, binary, and PWN/PSR)
▹ 2 candidates were demoted from classified to marginally classified due to their behavior under the systematic errors
▹ 245 flux upper limits at radio position and extension
  ▹ All marginally classified and other candidates
  ▹ for those which are significant but don't pass classification, both candidate parameters and radio SNR UL reported

We explore here some of the interesting characteristics of the SNR candidates and touch on the remaining >50 interesting GeV sources within 3° of a known radio remnant.
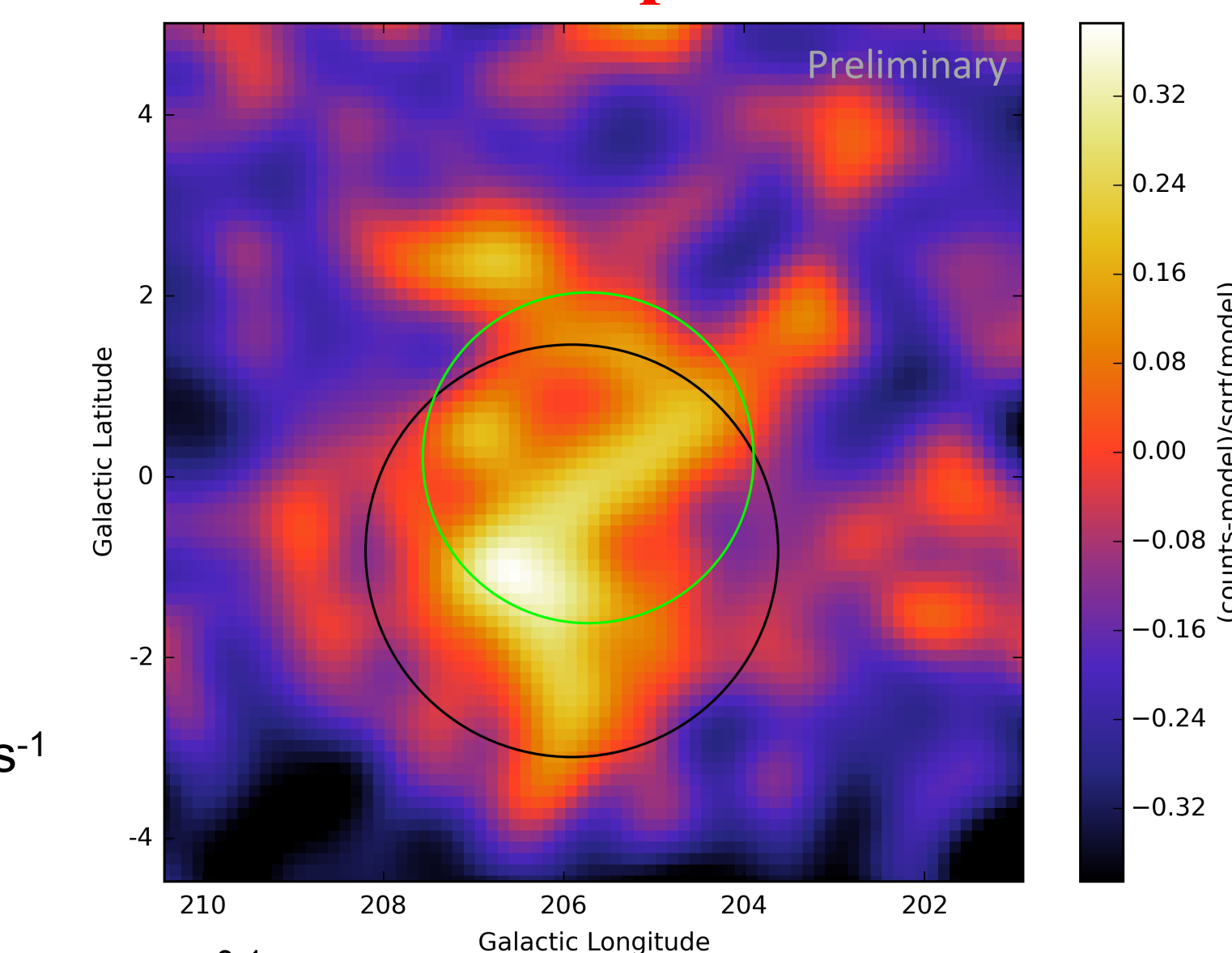
Characterizing GeV Emission:

Data Set:
▹ 3 years of P7SOURCE_V6 LAT data
▹ E: 1-100 GeV
▹ Removed variable sources[2]
▹ Region Of Interest: 10° around each SNR

SNRs:
▹ 274 Green's Catalog (09)
▹ + 5 newer SNRs

Starting Model:
▹ 2nd Fermi-LAT Source Catalog (Nolan+12)
▹ 2nd Fermi-LAT Pulsar Catalog (Abdo+13)
▹ Standard Interstellar Emission Model (IEM)

Improve starting model: AddSources

[2]FAVA (Ackermann+13)

Analysis Procedure

Hypotheses Tested:
▹ Spectral models:
  ▹ Power Law
  ▹ Log Parabola
▹ Extension:
  ▹ Point, extended
  ▹ Effect of nearby sources on extended hypothesis

Fit:
▹ Localization and extension
▹ Spectral parameters for candidate & nearby background sources

Characterize the systematic error from the IEM and effective area

Output:
▹ Significance
▹ Position, extension, and spectral model
▹ Or flux upper limit at radio position
▹ Diagnostics

Classify candidates as likely SNRs via spatial coincidence.

Classification

Quantify spatial overlap:

Preliminary

- Extended (○)
- Pointlike (●)
- Classified (●)
- Marginal (●)

GeV and radio SNR's extension consistent?

Radio v GeV Diameter

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

Preliminary

▹ **Interacting SNRs:** density≥100cm⁻³
▹ **Young SNRs:** evidence of non-thermal X-ray emission
▹ 'x' shows limit on GeV size imposed by classification
▹ Capped error bars: Statistical
▹ Uncapped: Systematic

New Extended Likely SNRs:

SNR 24.7+0.6

▹ GeV Fast Facts:
  ▹ TS = 89
  ▹ TS_{ext} = 25
  ▹ radius = 0.25° ± 0.04$^{+0.21}_{-0.12}$
  ▹ Localization overlap = 1.00
  ▹ Extension overlap = 0.47
  ▹ Best fit spectrum: **Power Law**
  ▹ Flux [E:1-100GeV] = 8.63±1.58$^{+7.65}_{-4.13}$ x 10⁻⁹ ph cm⁻² s⁻¹
  ▹ Index = 2.10 ± 1.5 $^{+0.13}_{-0.13}$

Preliminary

▹ "Crab-like" composite radio morphology
▹ Little MW coverage, no compact object yet identified to power the putative central nebula.
▹ Previous GeV counterparts in 1FGL, 2FGL, and 1FHL.
▹ GeV emission slightly offset towards southern massive star-forming region; no clear evidence of interaction yet found.
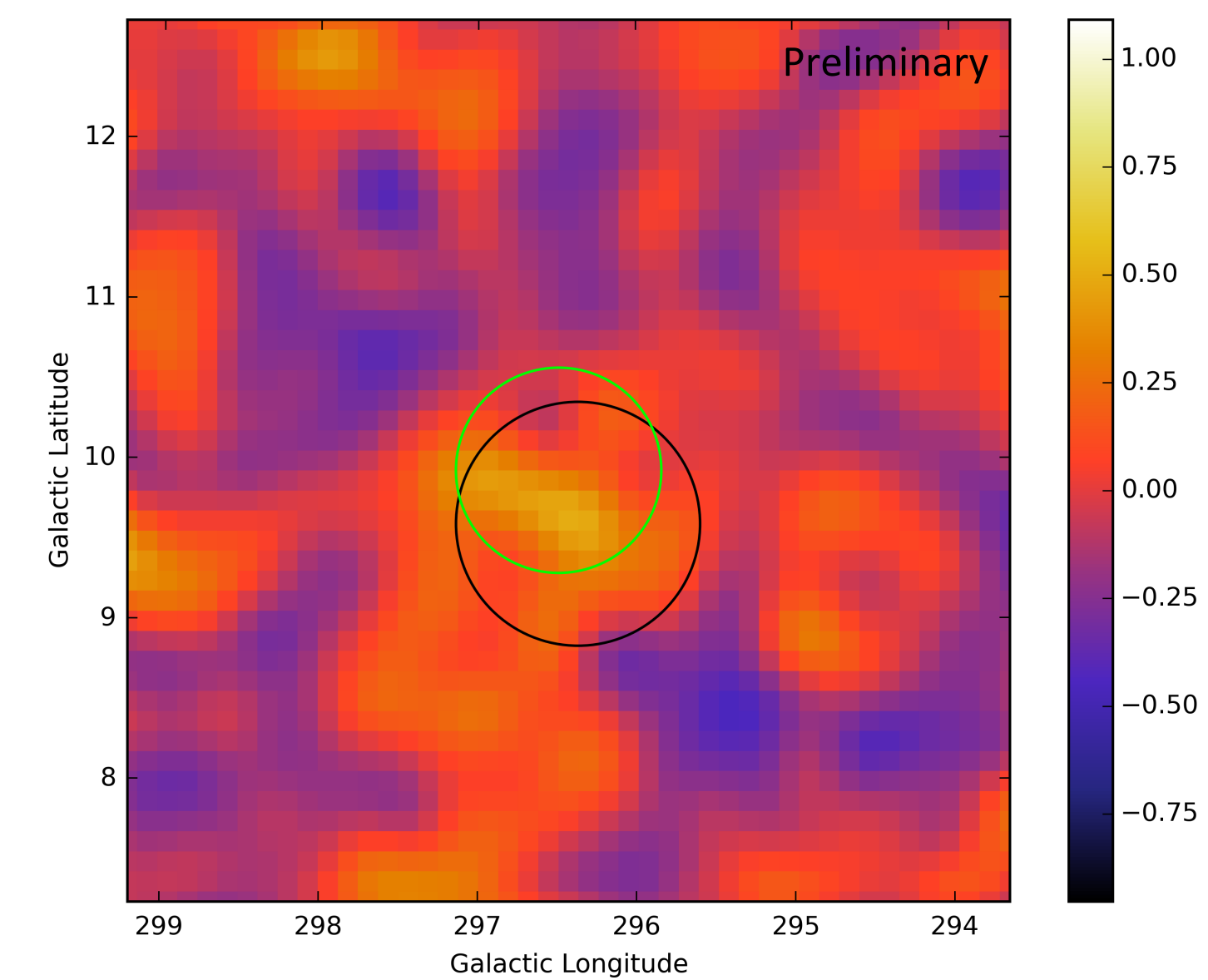▹ Galactic plane is particularly bright in this region => detailed study underway! (Katsuta+, in prep)

SNR 296.5+10.0: PKS 1209-51/52

▹ GeV Fast Facts:
  ▹ TS = 27
  ▹ TS_{ext} = 21
  ▹ radius = 0.76° ± 0.08 *
  ▹ Localization overlap = 1.00
  ▹ Extension overlap = 0.57
  ▹ Best fit spectrum: **Power Law**
  ▹ Flux [E:1-100GeV] = 0.78±0.24$^{+0.08}_{-0.07}$ x 10⁻⁹ ph cm⁻² s⁻¹
  ▹ Index = 1.62 ± 0.21 $^{+0.09}_{-0.09}$

Preliminary

▹ Bilateral shell SNR detected in radio, optical, and X-rays
▹ 424ms pulsar detected with Chandra X-rays (Zavlin+00) and not radio or γ-ray
▹ Kinematic distance from HI absorption: 2.1$^{+1.8}_{-0.9}$ kpc (Giacani+00)
▹ Araya (2013) found that an extended disk improved the likelihood for E: 0.2-100GeV, but not sufficiently to claim extension
▹ *Significance of extension falls below threshold for all alternative IEMs => Caution! Complex region requiring detailed study.

SNR 205.5+0.5: Monoceros Loop

▹ GeV Fast Facts:
  ▹ TS = 130
  ▹ TS_{ext} = 89
  ▹ radius = 2.28° ± 0.08$^{+0.15}_{-0.14}$
  ▹ Localization overlap = 1.00
  ▹ Extension overlap = 0.54
  ▹ Best fit spectrum: **Power Law**
  ▹ Flux [E:1-100GeV] = 13.7±1.27$^{+2.34}_{-2.08}$ x 10⁻⁹ ph cm⁻² s⁻¹
  ▹ Index = 2.56 ± 1.2 $^{+0.10}_{-0.10}$

Preliminary

▹ Kinematic distance from HI absorption: 1.5$^{+0.1}_{-0.7}$ kpc (Odegard 86, Fesen+85, Xiao&Zhu 12)
▹ GeV emission is slightly larger than the radio and is offset toward Rosette nebula, a massive molecular cloud with star formation.
▹ Recent study of neutral Hydrogen gas suggests possible interaction between Monoceros and the Rosette Nebula. (Xiao&Zhu 12)
▹ Detailed study of GeV morphology underway! (Katagiri+, in prep)

SNR 326.3-1.8: MSH 15-56

▹ GeV Fast Facts:
  ▹ TS = 341
  ▹ TS_{ext} = 19
  ▹ radius = 0.21° ± 0.03 $^{+0.02}_{-0.02}$
  ▹ Localization overlap = 1.00
  ▹ Extension overlap = 0.43
  ▹ Best fit spectrum: **Power Law**
  ▹ Flux [E:1-100GeV] = 6.20±0.52$^{+1.69}_{-1.35}$ x 10⁻⁹ ph cm⁻² s⁻¹
  ▹ Index = 1.98 ± 0.07 $^{+0.13}_{-0.13}$

Preliminary

▹ Composite SNR w a Pulsar Wind Nebula (PWN) at the SW rim of the radio shell
▹ X-ray studies suggest remnant is ~10kyr and expanding at 860kms⁻¹ (Yatsu+13)
▹ Distance from extinction estimate in optical/X-rays: 4.1$^{+0.7}_{-0.7}$ kpc (Rosado+96, Kassim+93)
▹ Temim (2013) found a similarly hard PL source.
▹ Their evolutionary modeling including radio, X-ray, and TeV suggested a PWN origin for the γ-ray emission, but they could not rule out the possibility of SNR emission.
▹ Further detailed study of the GeV morphology will help clarify this question! => Acero+ S.13!
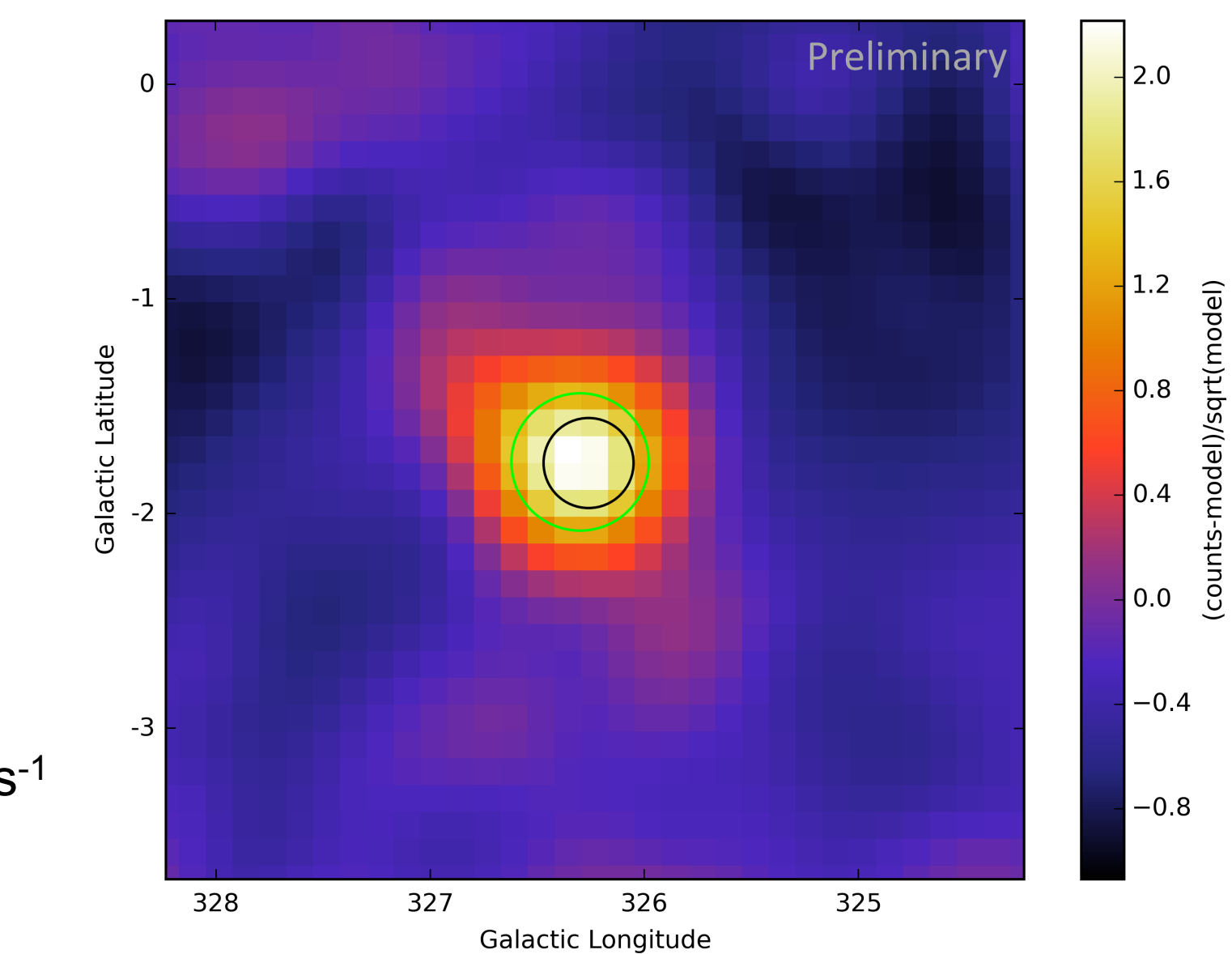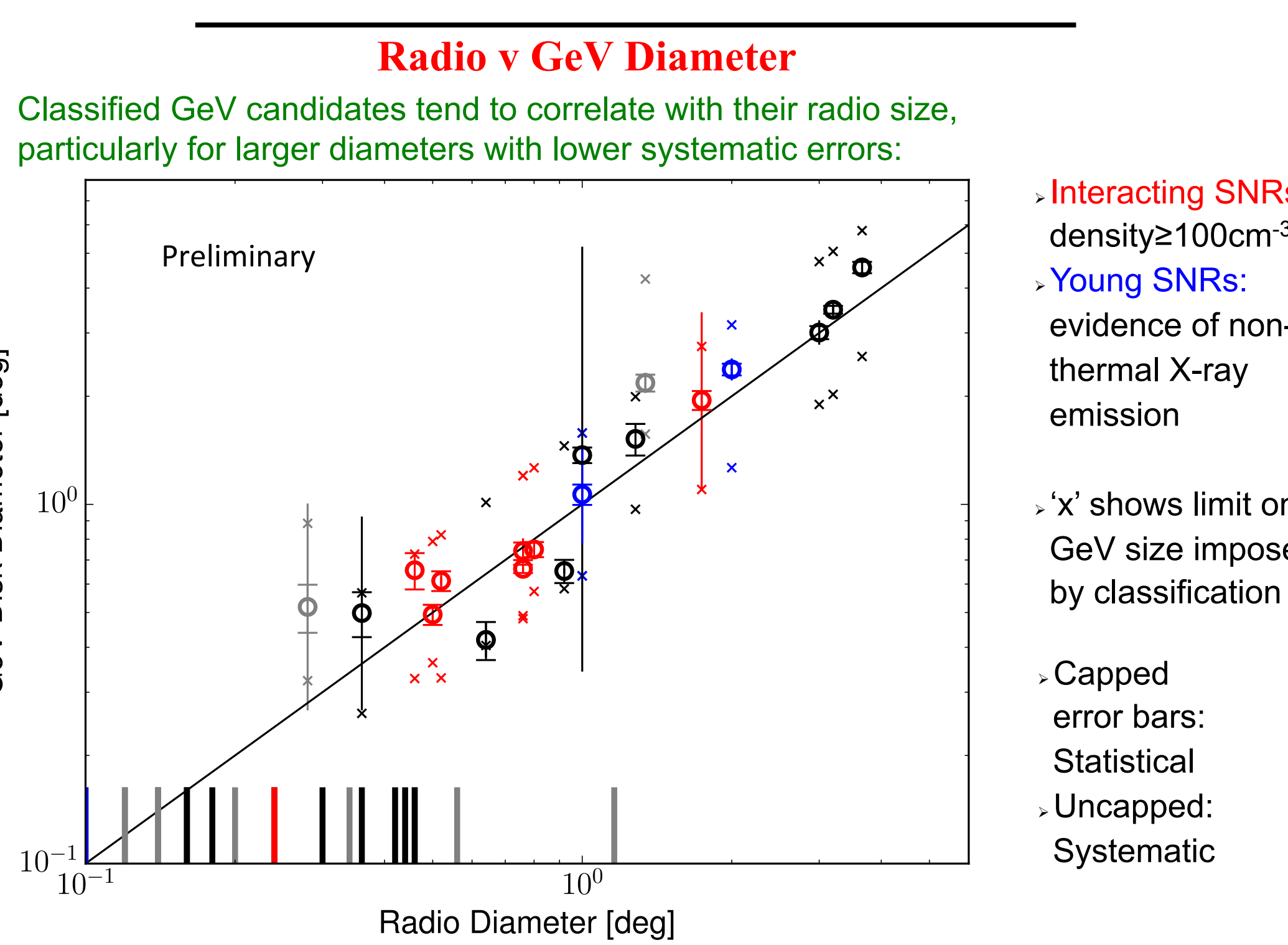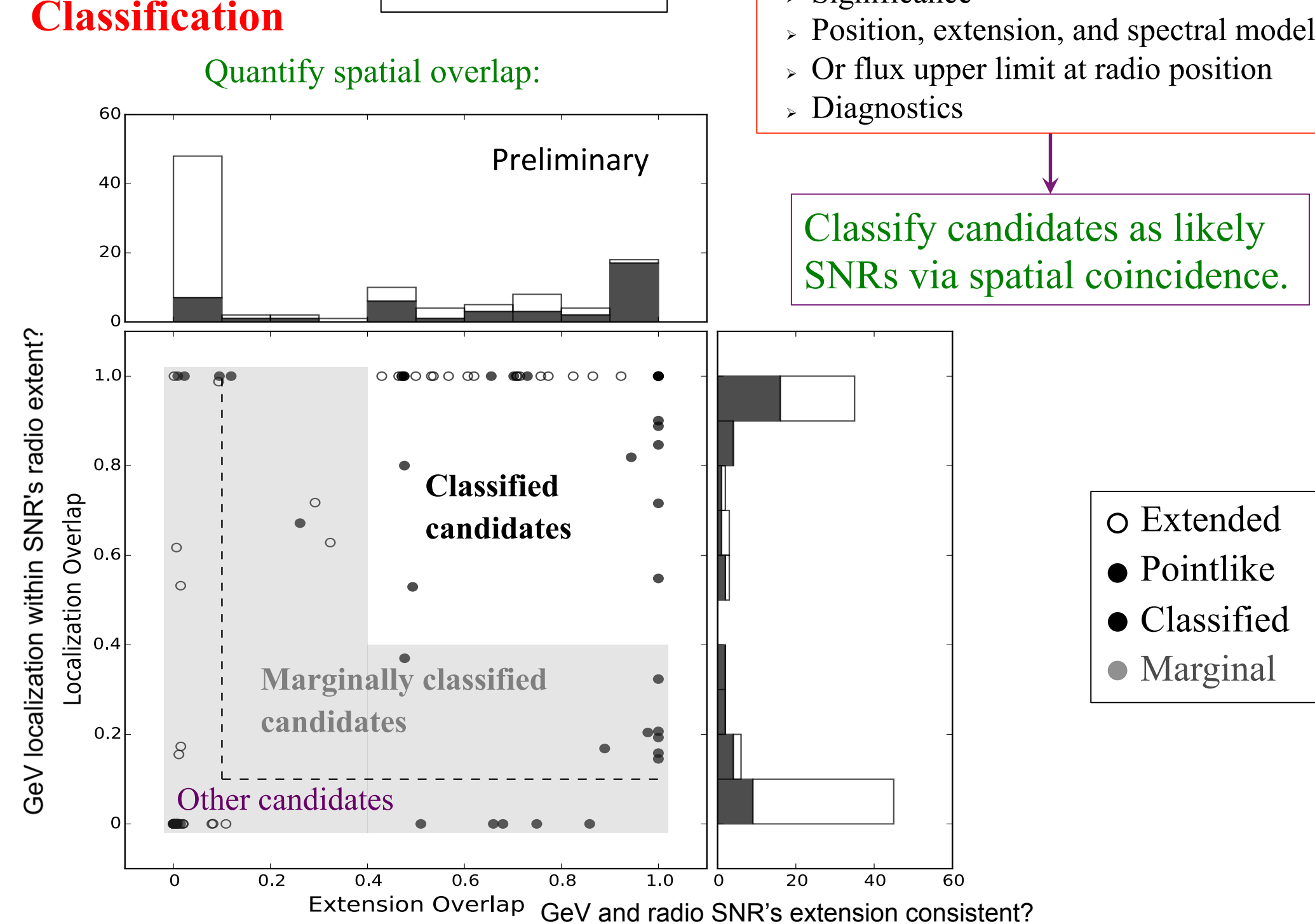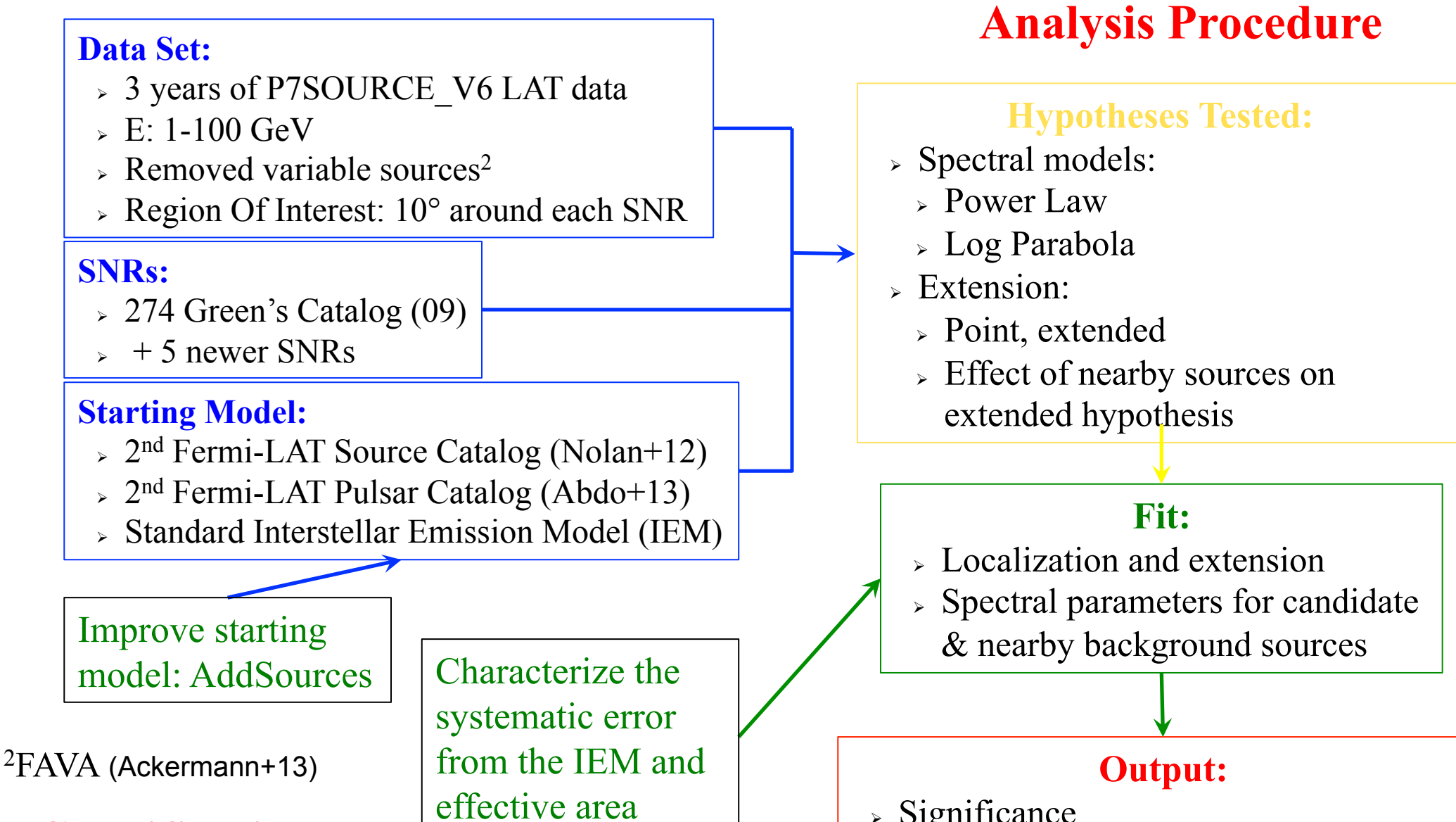
GeV Candidates' Power Law Spectra:

▹ Best fit flux and index for all 102 candidates, show as a function of their spatial classification.
▹ Systematic and statistical errors (not shown for clarity), roughly span the range of the population.
▹ **Red** lines indicated MW evidence of **interaction** with dense regions.
▹ **Young SNRs** are shown with **blue** lines.
▹ The diversity of spectra are evident in spite of covering only 2 decades in energy.
▹ This is particularly true for the **"other" candidates** which lie within 3° of an SNR and may in some cases be evidence of interaction between accelerated particles (eg cosmic rays) and nearby dense material (eg molecular clouds).
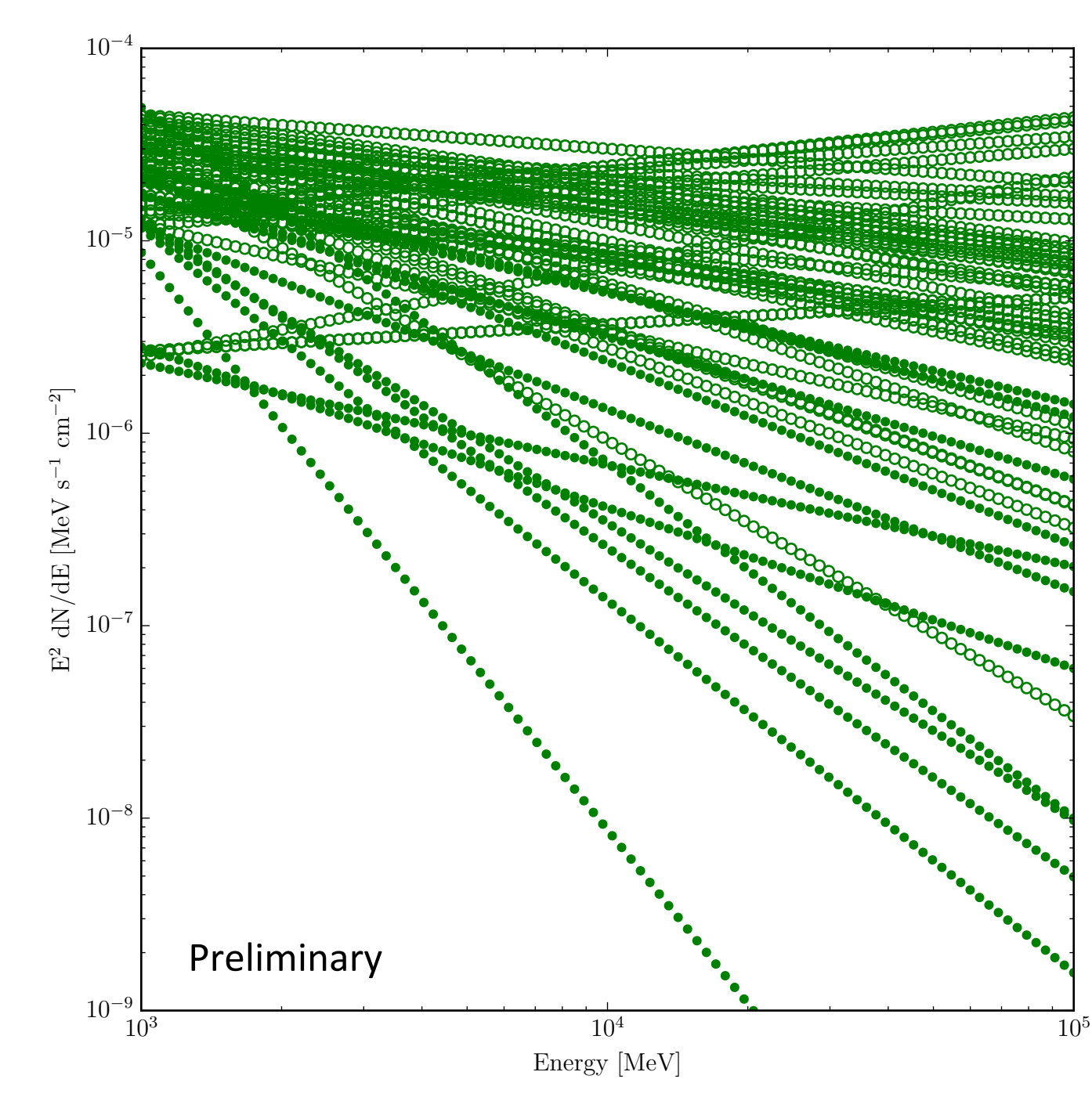
Classified as likely SNRs:

- Extended (○)
- Pointlike (●)

Preliminary
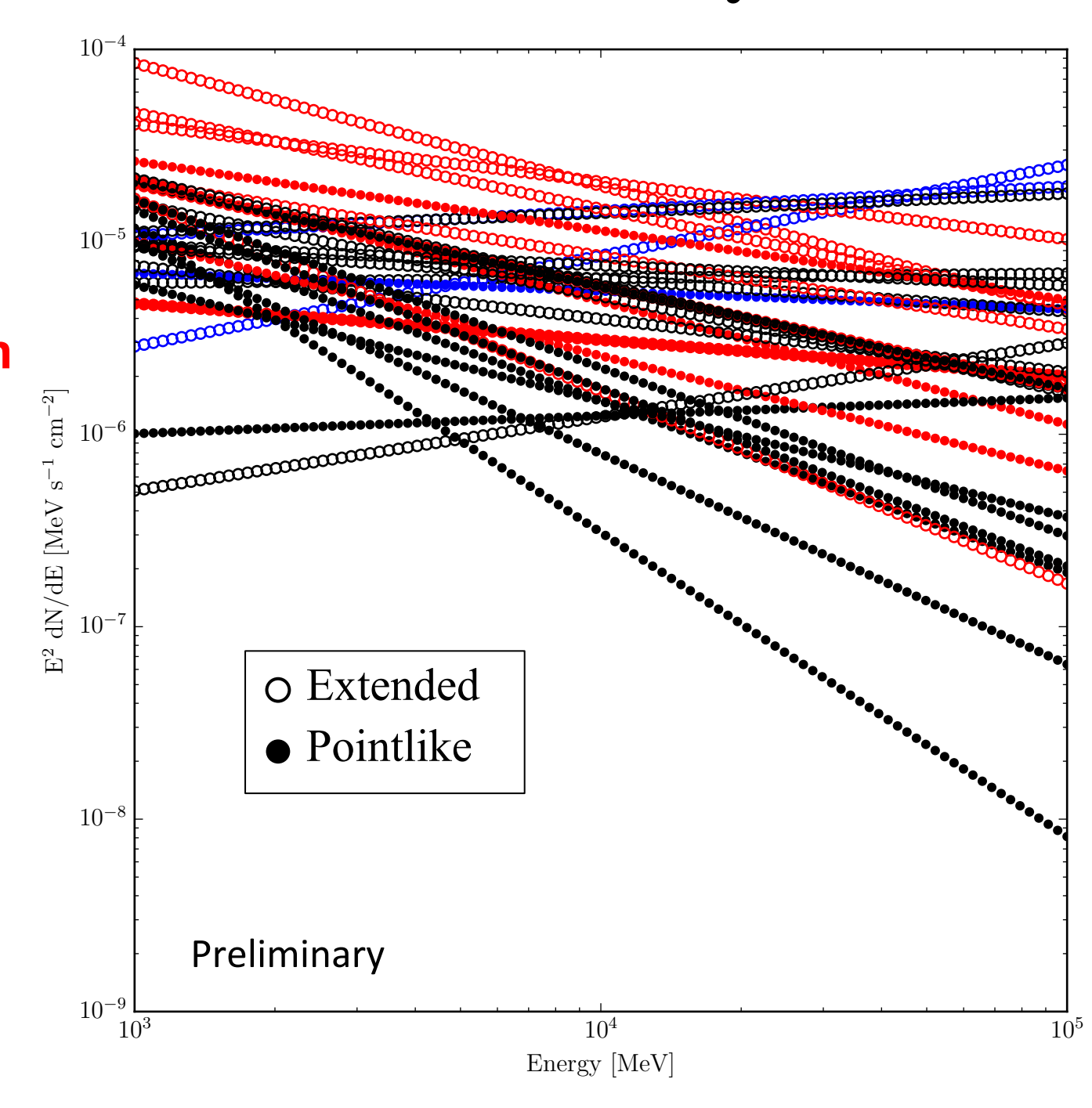
Marginally Classified as SNRs:

Preliminary
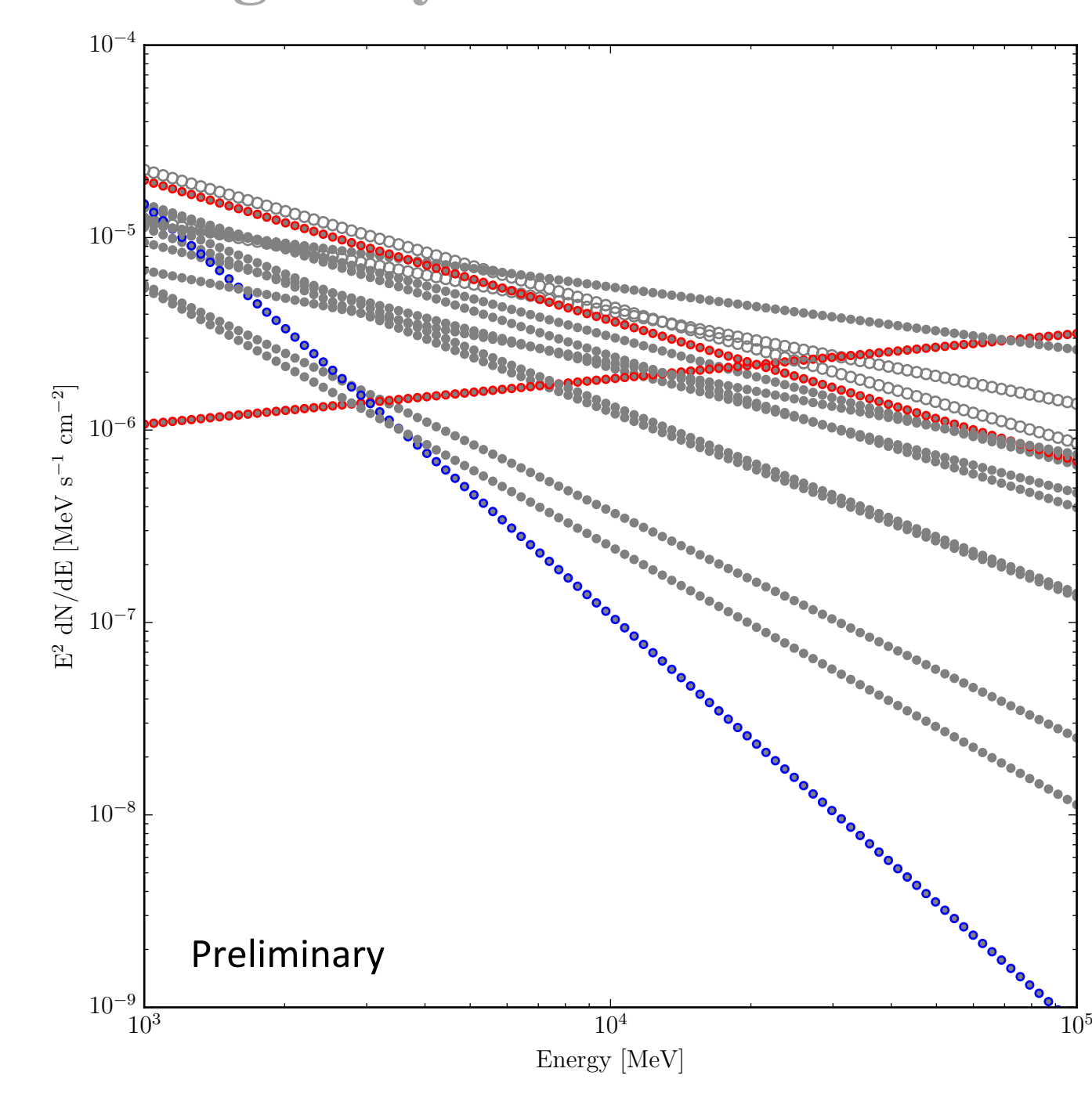
Other Candidates Near SNRs:

Preliminary

Conclusions

▹ The SNR Catalog systematically confronts and solves challenges faced by Fermi-LAT analyses of Galactic Plane sources:
  ▹ Uniquely addressed with: AddSrcs, aIEM, classification & mock catalog

▹ 4 New Extended SNR Candidates:
  ▹ The SNR Catalog's systematic region description is key for discovering and classifying new extended SNR candidates which significantly contribute to our understanding of these energetic objects.
  ▹ For a wide range of sizes, fluxes, and indexes, candidates' localization overlap =1.0; extension overlap ~0.5.
  ▹ The Galactic interstellar emission can have a large impact on extended sources, particularly in bright and/or complex regions.

▹ GeV SNR population characteristics:
  ▹ Candidate distribution to flux completeness of 10⁻⁸ ph cm⁻²s⁻¹ with a characteristic index of 2.5 & range (1.5, 4).
  ▹ Candidates have a diverse range of characteristics regardless of class, interaction evidence, or relative youth.
  ▹ Data are challenging model assumptions!

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

▹ **All data will be publically available in electronic format from the Fermi Science Support Center:** http://fermi.gsfc.nasa.gov/ssc/data/access/lat/1st_SNR_catalog/