Fermi Gamma-ray Space Telescope

Characterizing the Population of Gamma-Ray Pulsars in the Galactic Bulge

Eric Charles

On behalf of the Fermi-LAT Collaboration

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Garmisch-Partenkirchen, Germany

Characterizing the Population of Gamma-Ray Pulsars in the Galactic Bulge

- LAT-team paper (arXiv:1705.00009) tests the pulsar interpretation of the GC excess. This involves:

1. Identifying candidate pulsar sources:

   Deriving spectral selection criteria for γ-ray pulsar-like sources using identified pulsars and blazars

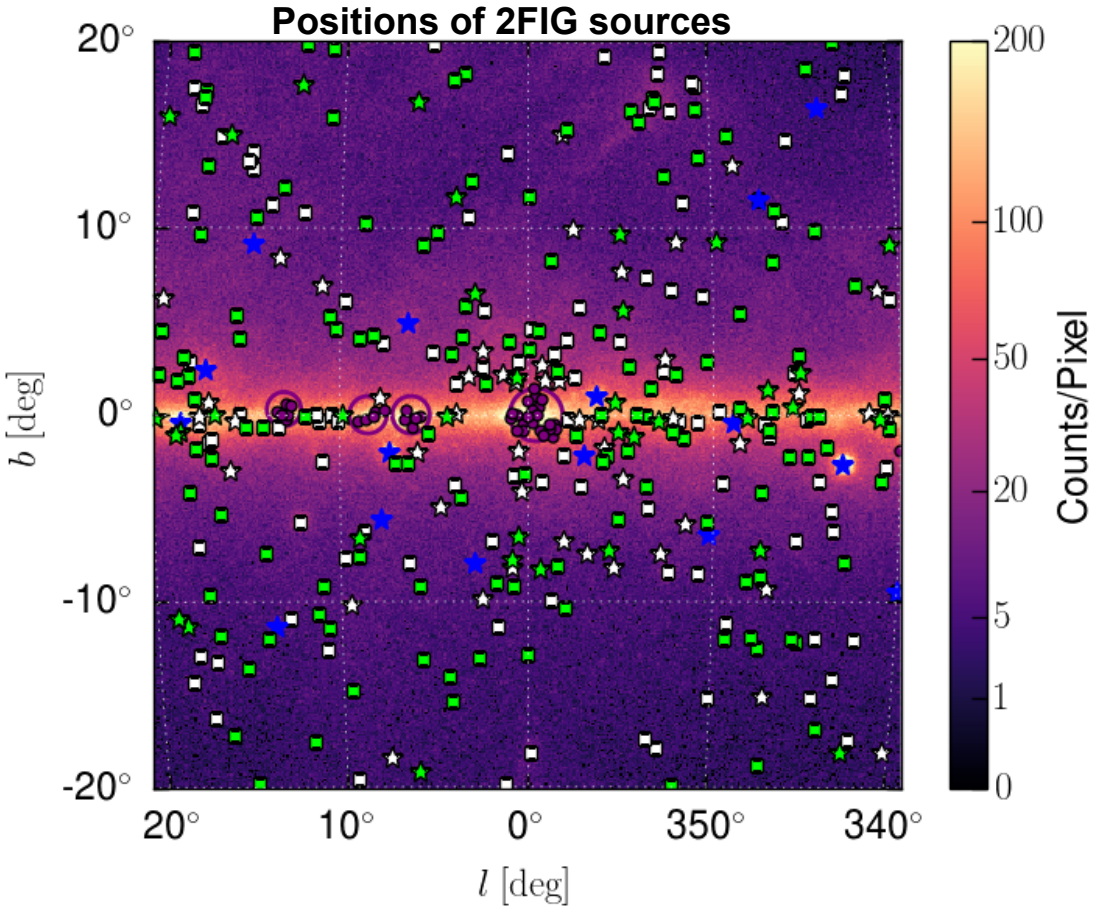
   Finding point sources in the inner 40° x 40° of the Galaxy (2FIG) using two different models of Galactic diffuse emission

   Applying selection criteria to 2FIG source list

2. Using simulations to estimate the efficiency of the pulsar selection criteria
3. Constraining the γ-ray pulsar luminosity function from known pulsars
4. Combining 1-3 in a maximum likelihood analysis to extract luminosity function and morphology of the Galactic bulge pulsar population

Results in arXiv:1705.00009 affected by error in integration of source distribution

The 2FIG Source List



3FGL Sources
New Sources
Known PSR
Clusters

★ PSR Cand.
■ Non-Cand.

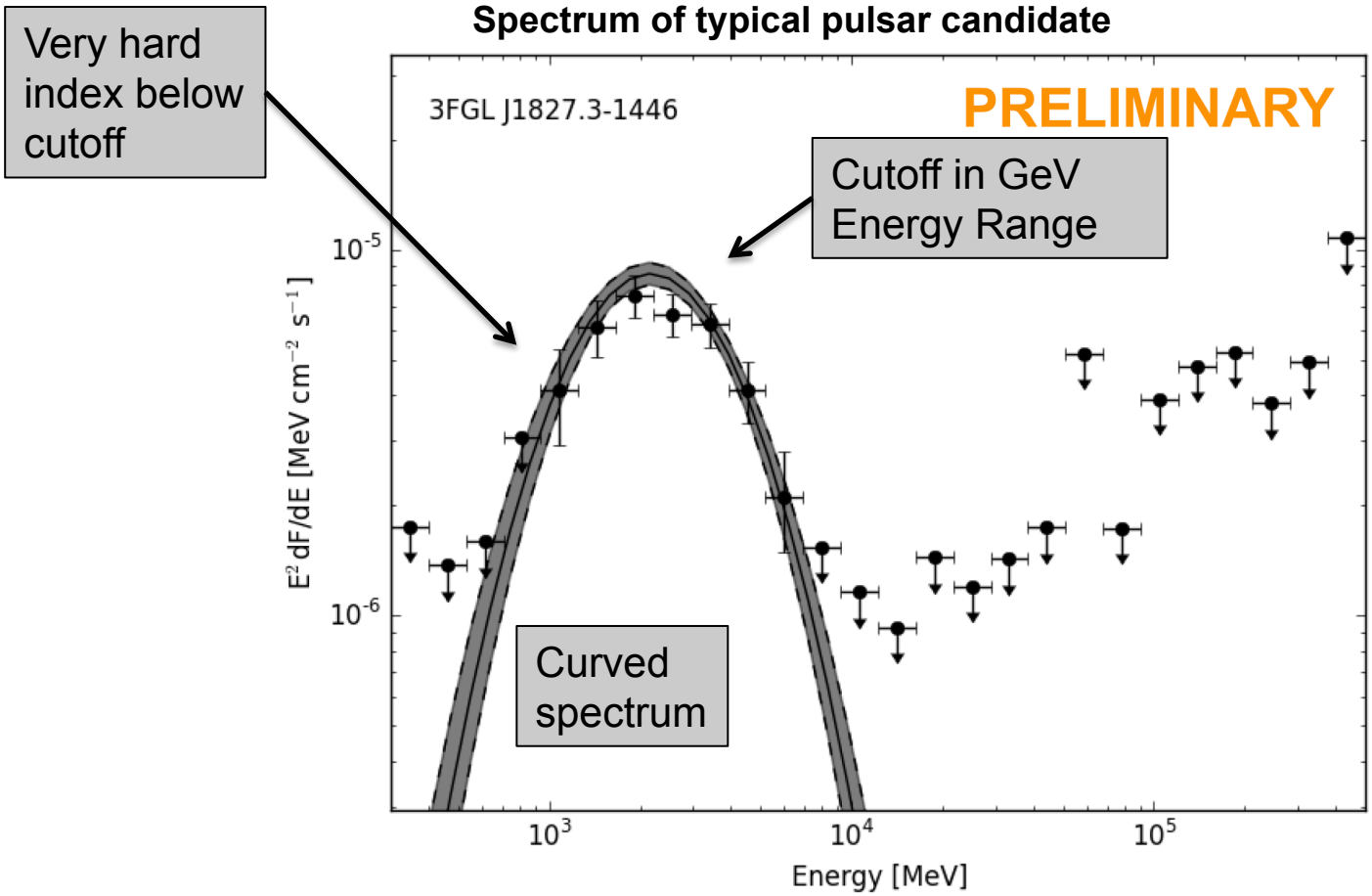
Off. IEM 374 srcs
Alt. IEM 385 srcs

Merged: 290

Minimal spanning tree algorithm used to identify clusters of sources that are likely related to diffuse emission or spatially extended sources and removed from consideration

- Primary result is a catalog of sources in the inner 40° x 40° region of the Galaxy
- Complete analysis pipeline was performed using two different interstellar emission models (IEMs), the “Official” one (“Off.”, i.e., the publicly released one) and an “Alternate” model (“Alt.” from Ackermann et al, 2017)

Typical Pulsar Candidate Spectrum



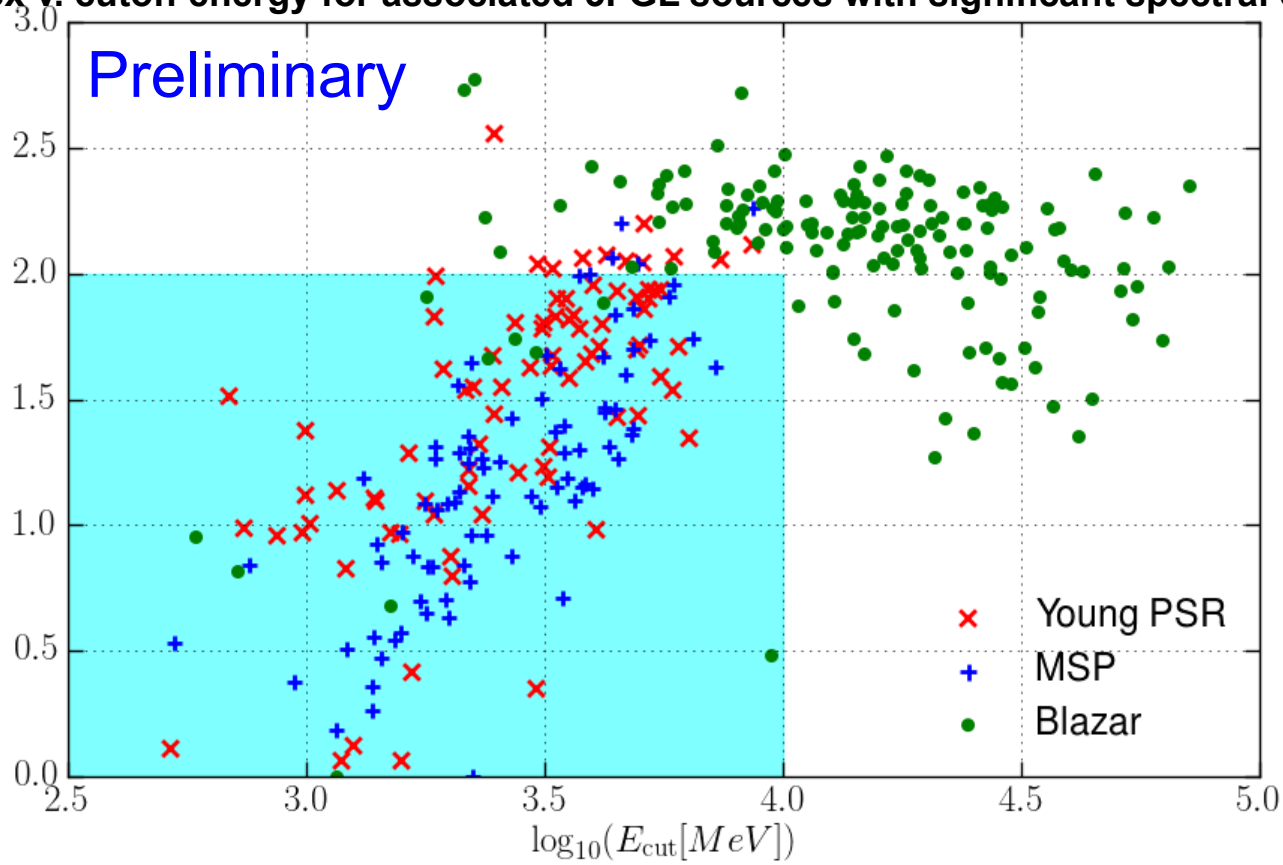
- It is important to note that detecting e.g., spectral curvature, requires more photons than simply detecting a source
- This source has since been confirmed as a pulsar by “Einstein@Home”
  - https://einsteinathome.org/gammaraypulsar/FGRP1_discoveries.html

Pulsar Selection Criteria

Spectral index v. cutoff energy for associated 3FGL sources with significant spectral curvature

Figure includes sources with $TS_{curv} > 9$ preselection.

E_{cut} and Γ are taken from fit to Exponentially-cutoff powerlaw

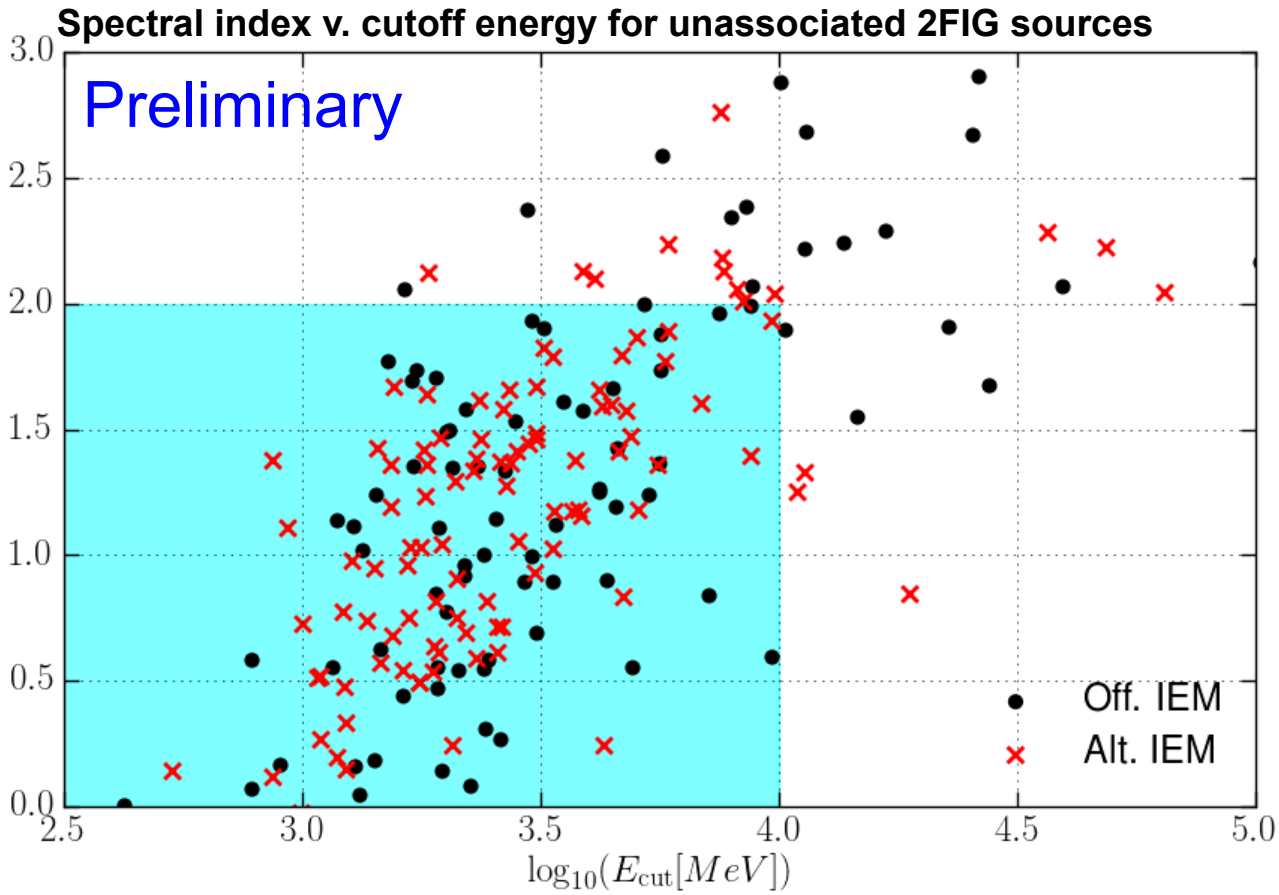


- We used samples of known γ-ray pulsars and blazars to derive spectral selection criteria for pulsars: $TS_{curv} > 9$ & $\Gamma < 2$ & $E_{cut} < 10$ GeV
- Efficient for bright pulsars with minimal blazar contamination

Pulsar Selection Results

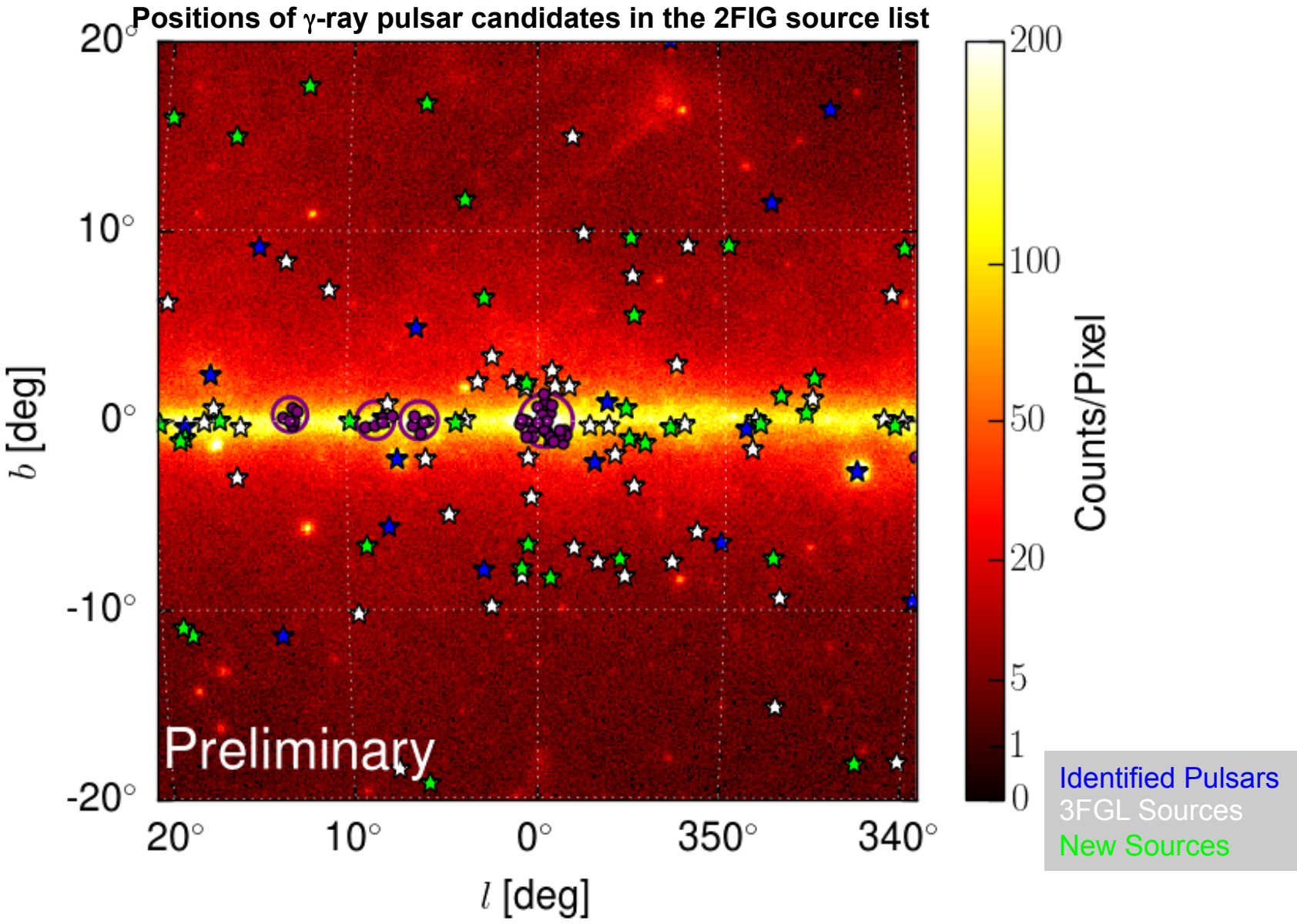
Figure includes sources with $TS_{curv} > 9$ preselection.

E_{cut} and Γ are taken from fit to Exponentially-cutoff powerlaw



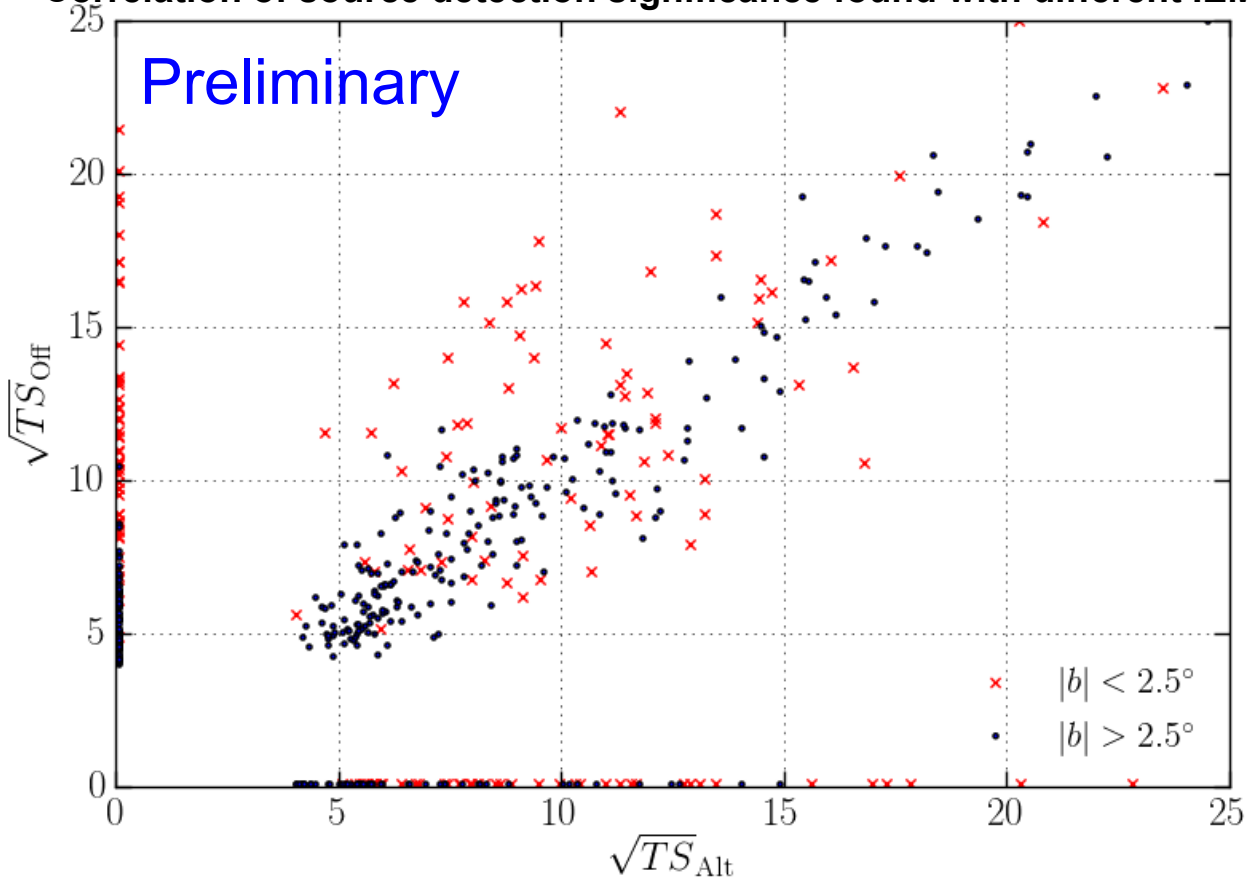
- We applied these criteria to the unassociated 2FIG sources to derive a list of PSR candidates

Pulsar Candidates in the Galactic Bulge



Effect of IEM on Source Detection Significance

Correlation of source detection significance found with different IEMs



- Away from the Galactic plane (|b| > 2.5°) we observe good correlation between the source detection significance seen with the two IEMs
- Along the Galactic plane the correlation is poor (rms ~ 5σ)

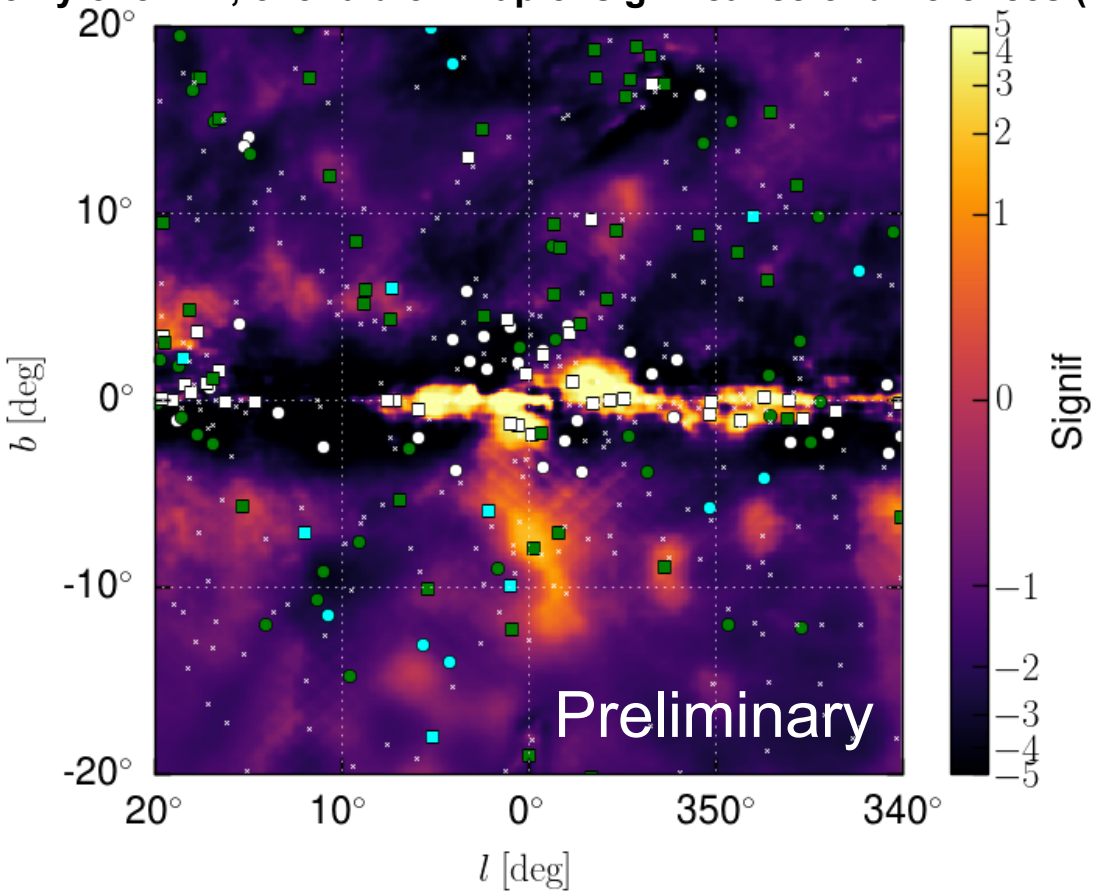
Unmatched Sources Along the Plane

Sources found in only one IEM, overlaid on map of significance of differences (Off-Alt) between IEMs

Large markers show sources found only with one IEM

TS 16-25 w/ other Model
TS < 49

■Off. and not Alt.
O Alt. and not Off.



- Most sources found with only one IEM are either low-significance or found at sub-threshold significance with the other IEM (cyan and green markers)
- Sources found with high-significance with only one IEM (large white markers) occur in regions where the two IEMs differ significantly (color scale)

Robustness of 2FIG Source List

- Study of how much source detection and spectral parameter estimation are biased by errors in the IEMs
  - Away from the Galactic plane (|b| > 2.5°) , on average the effect is roughly similar in magnitude to the statistical uncertainties
  - Along the Galactic plane (|b| > 2.5°) the effect can be several times the statistical uncertainties
    - Large enough to create spurious sources or significantly degrade sensitivity for real sources
- Aside: (see my talk from Thursday at the Fermi Symposium)
  - Likelihood de-weighting scheme has been implemented and performs as expected, reduces source detection significance and narrows scaled residual distribution
  - Some additional tuning of weighting scheme is still warranted

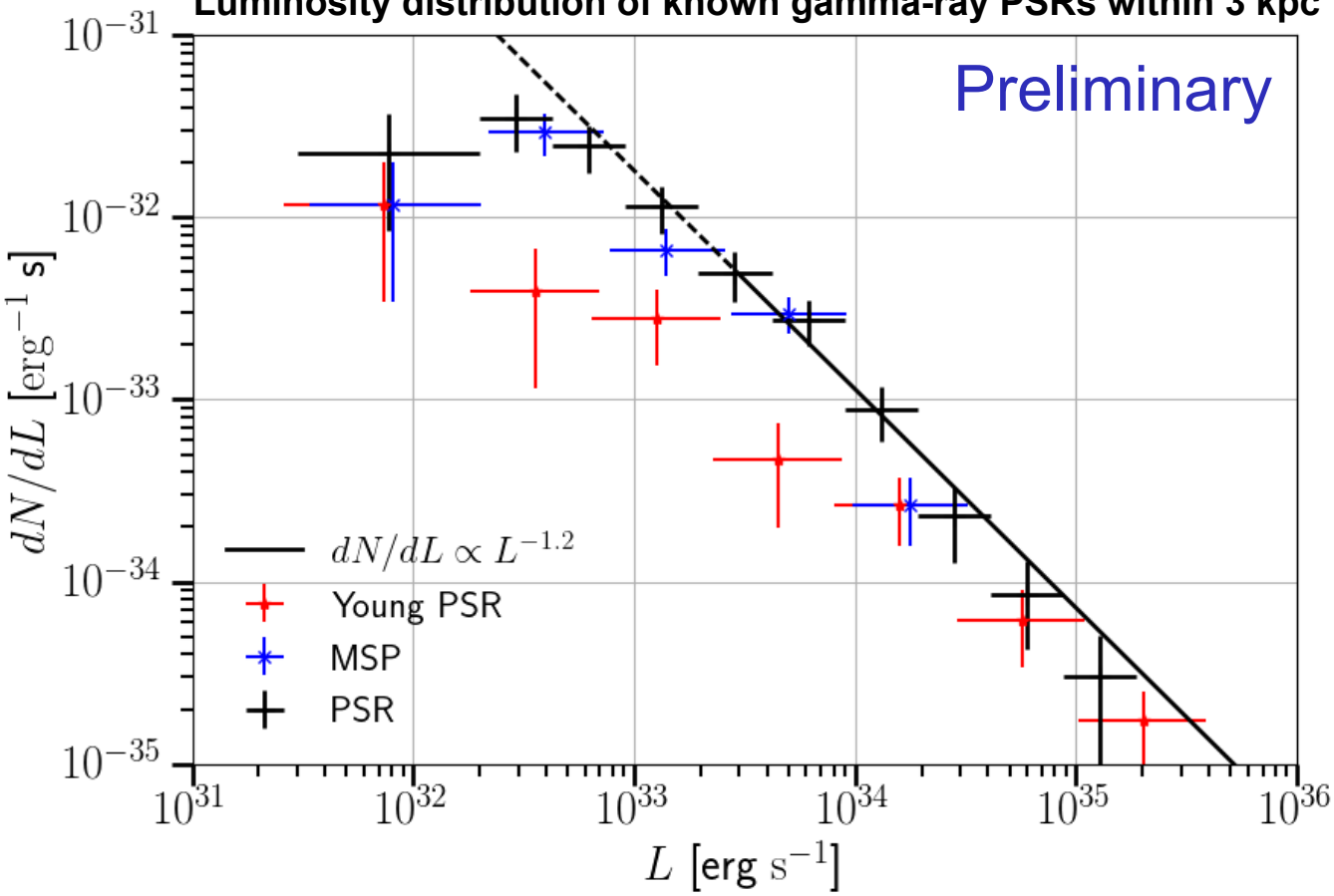
Constraining the PSR dN/dL Distribution

Caveat:
The best-fit line in this figure is incorrect

The fitting procedure was incorrectly calculating the number of expected detections

The true slope is steeper than $L^{-1.2}$

Luminosity distribution of known gamma-ray PSRs within 3 kpc



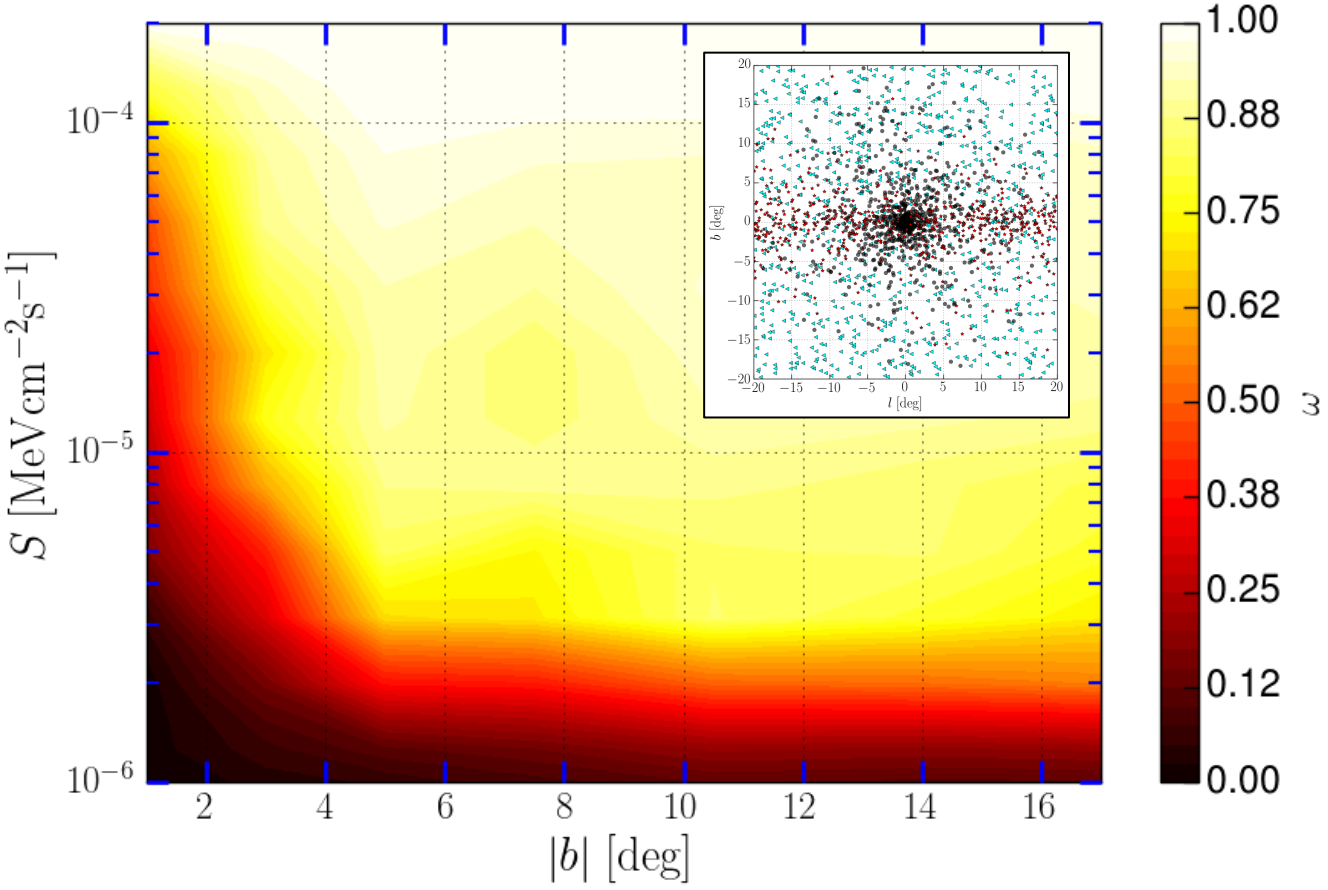
- Analysis of nearby (d < 3kpc) identified gamma-ray pulsars used to constrain the slope of the dN/dL distribution.

Efficiency of PSR Selection Criteria

Efficiency of PSR selection criteria v. Galactic latitude and energy flux, (Inset, simulated sources)

Caveat:
This plot show integral efficiency across wide bins

This efficiency depends on the model details and may change somewhat when we perform simulations with softer dN/dL



- We simulate pulsars (disk and bulge components) across 40° x 40° region around GC and extract the detection efficiency as a function of l,b, and integrated energy flux (S) from 300 MeV to 500 GeV

Likelihood Analysis of Source Counting

- We performed a binned likelihood analysis of number of γ-ray pulsar candidates selected by our analysis:

Number of candidates observed in each bin of l,b, and energy flux (S)

$$\log(\mathcal{L}) = \sum_{i,j,k} N^{\mathrm{obs}}_{i,j,k} \log\left(N^{\mathrm{model}}_{i,j,k}(\lambda)\right) + N^{\mathrm{model}}_{i,j,k}(\lambda)$$

Number of candidates expected to be observed in each bin of l,b,S, for a model with parameters λ, and given the detection efficiency as a function of l,b,S

Results of Likelihood Analysis

- The results of the original Ajello et al. (2017) likelihood analysis strongly favored the existence of a Galactic bulge PSR population:
  - TS ~ 30 to 60, depending on the scenario tested
  - Flat dN/dS distribution, α ~ 1.3
- Bartels et al. (2017) attempted to reproduce these results using 2FIG lists and efficiency tables and found a steeper luminosity function and only marginal evidence for the bulge population (**https://github.com/bsafdi/GCE-2FIG/**)
  - TS ~ 8 to 9, depending on the scenario tested
  - Steep dN/dS distribution, α ~ 2.1
- Comparison of analysis codes identified error in out results
- Preliminary updated analysis gives results consistent with Bartels et al.
  - Both groups are working together to correct and update the result
  - Bartels et al. study uses efficiency tables from Ajello et al., see caveats (slides 11,12).

Summary

- We constructed the 2FIG list of sources in a 40°x40° region around the GC using two different IEMs and found ~500 sources (290 found using both IEMs)
  - We developed PSR selection criteria based on the significance of the spectral curvature, spectral index and cutoff energy
  - With those criteria we found 135 PSR candidates, or which 66 were selected when using both IEMs
- We have investigated the systematic uncertainties associated with the IEMs
  - Away from the Galactic plane ($|b| > 2.5°$) they are similar in magnitude to the statistical uncertainties
  - Along the Galactic plane ($|b| < 2.5$) they are dominant and cause significant scatter in the detection sensitivity and clustered groups of spurious sources
- We extracted the PSR selection efficiencies as functions of b,l,S and used these to perform a maximum likelihood analysis of the PSR population
  - Thanks to comparison with Bartels et al. (2017 https://github.com/bsafdi/GCE-2FIG/), we identified an error in the integration of number of expected candidates
  - We are working with that group to correct and update the maximum likelihood analysis

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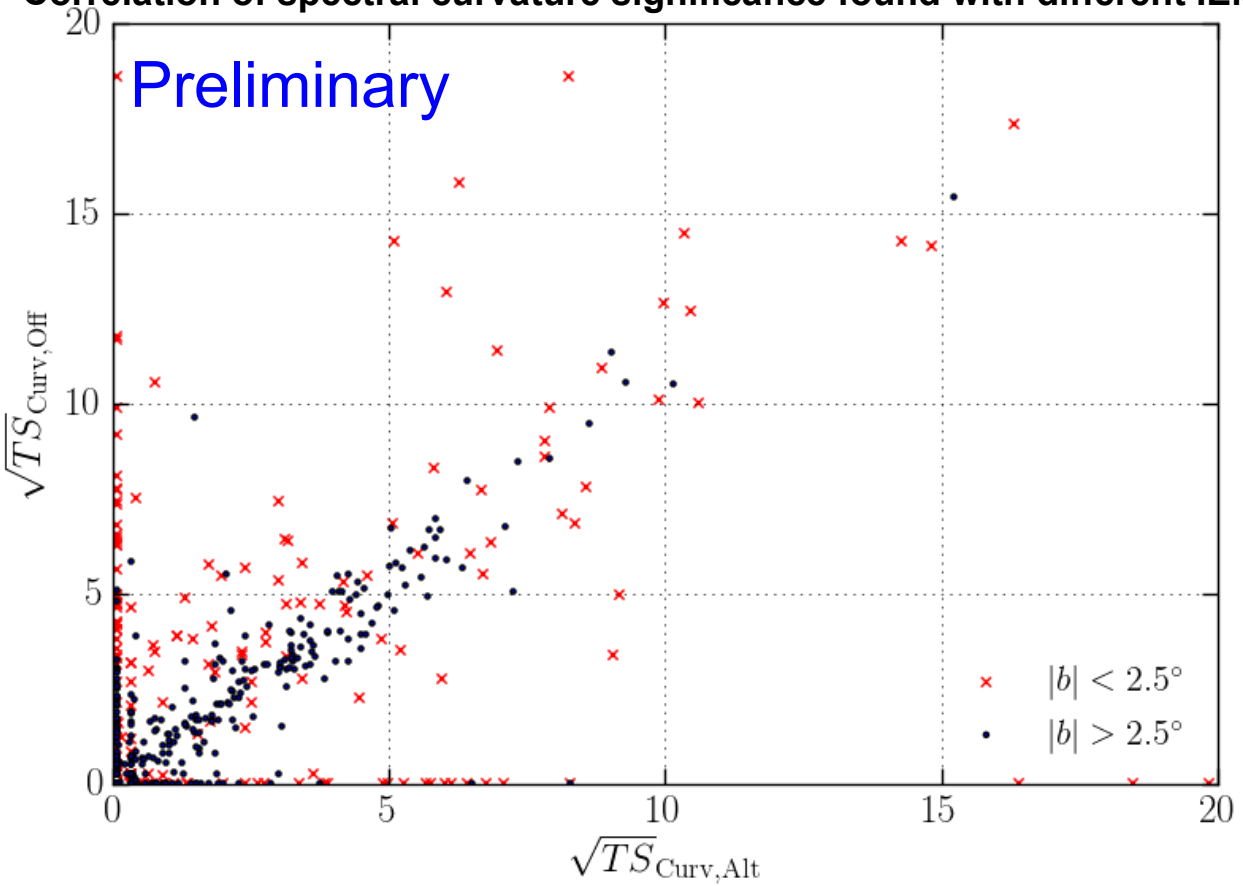
Thank You

EXTRA SLIDES

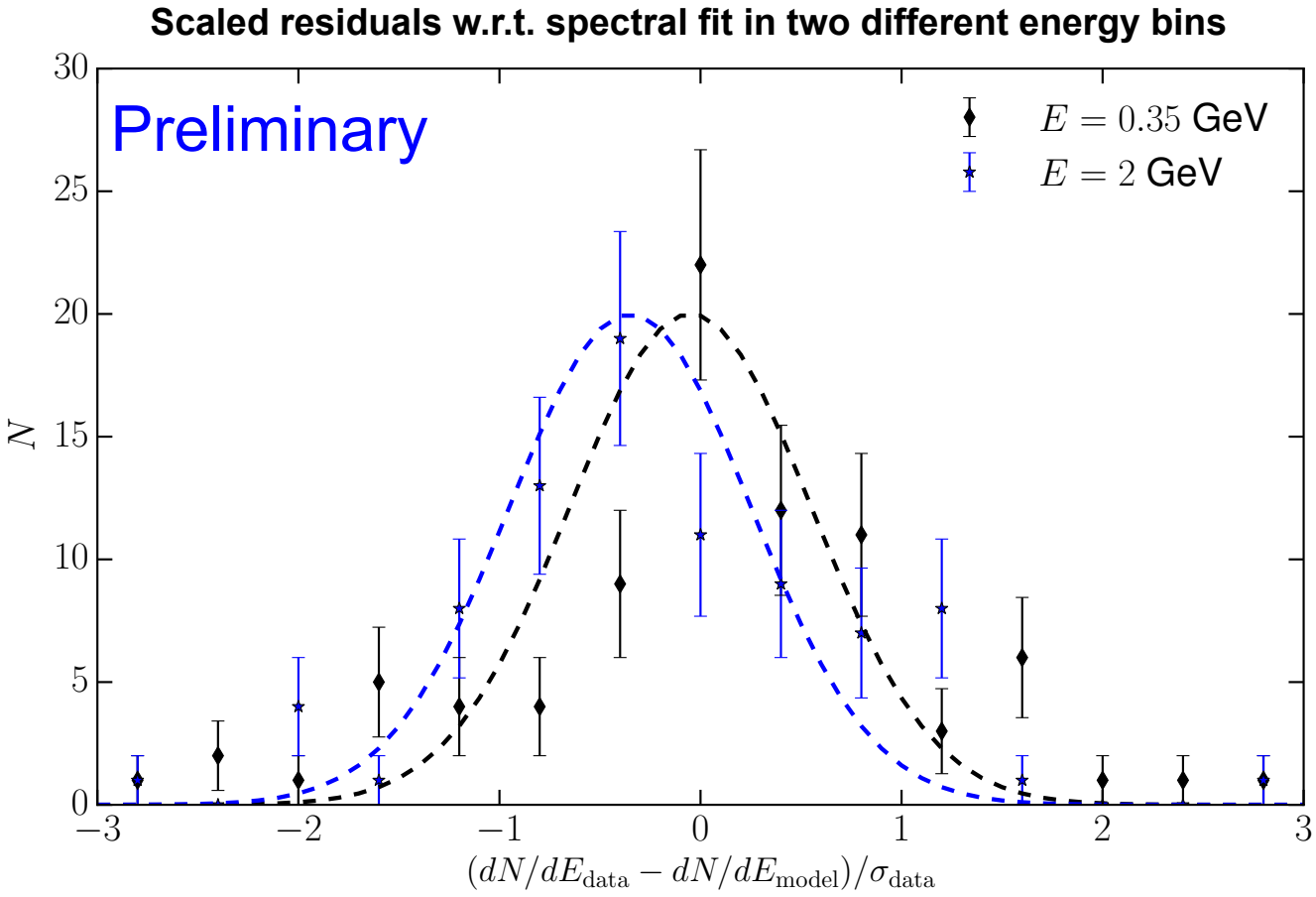
Effect of IEM on Spectral Curvature Significance

Correlation of spectral curvature significance found with different IEMs



- Away from the Galactic plane (|b| > 2.5°) we observe good correlation between the spectral curvature significance seen with the two IEMs
- Again, along the galactic plane the correlation is poor

Test for Spectral Biases



- The flux value in individual energy bins agrees reasonable well with the broadband spectral models
- No evidence of strong biases, but a few outliers, both positive and negative