Searching for MSPs in Fermi-LAT Unassociated Sources

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for the
Fermi-LAT Collaboration

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In the beginning there was...

- **CGRO - EGRET/COMPTEL/OSSE**
  - **Young pulsars**
    - **Detected: 6**
    - **Speculated: at least 4**
  - **MSPs:**
    - **Detected-ish: 1**
      - **J0218+4232 - Kuiper et al. - marginal detection**
    - **Speculated: 1**
      - **J0030+0451 - Harding et al.**
- **Plus more positionally coincident but undetected.**

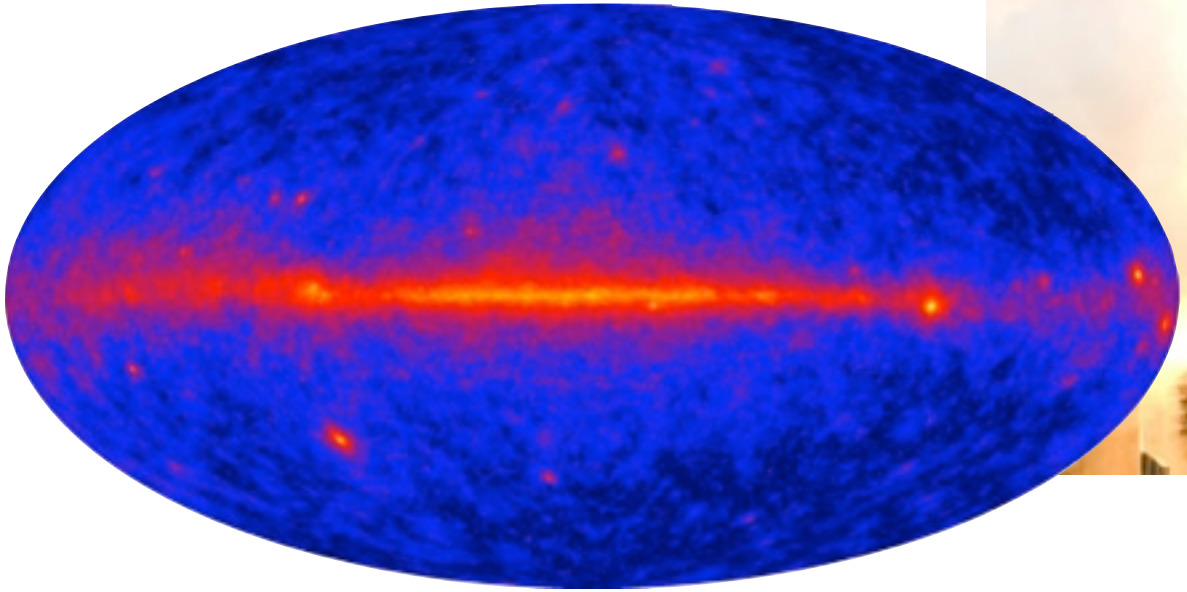
And then....

Fermi Launches!

- **June 11, 2008**

  Still called GLAST

- **LAT first light image**
  - **June 30 - July 3**



Credit: NASA/DOE/ International LAT Team

Credit: NASA/Jerry Cannon, Robert Murray

Rapid confirmation

- **Confirmation of most CGRO pulsars provided confidence in the LAT data**
  - **First pulsar catalog - 6 months of data**
    - **All CGRO detections confirmed**
      - **Except B1509-58, which came later**
      - **Includes the MSP PSR J0218+4232**
    - **Two speculated pulsars confirmed**
      - **CTA 1 pulsar first LAT blind search pulsar (16 Oct 2008)**
      - **MSP PSR J0030+0451**

- **But the pulsar search consortium (PSC) was not sitting still...**

Race for discovery!

- **Unassociated sources targeted for follow-up by the PSC**
  - **MSP candidates were:**
    - **|b| > 10 deg**
    - **non-variable**
    - **no association with an AGN or pulsar**

LAT Data	# sources	Candidates to PSC	MSPs found
3 months	205 (>10σ)	16	9
6 months	740 (>5σ)	189	9
9 months	1136	(368) 65	1
1FGL*	1471	420 (185)	23

* Abdo, A. A. et al. 2010, ApJS, 188, 405

Total = 42 MSPs

Searching for MSPs post-1FGL

- **After 1FGL, the LAT team made major changes to catalog analysis to remove spurious detections**
  - **Revised Galactic diffuse model**
  - **Changed Galactic model pixel size and registration**
  - **Added extended sources**

- **Result: 2-year catalog** had "only" 1873 sources**
  - **575 unassociated**
    - **205 with 1FGL associations**
    - **370 completely new sources**

Too many sources!!!
Must filter source list!

- **Mission accomplished!**
  - **~100 of the 1FGL unassociated sources were "not confirmed" in the 2FGL**
  - **Much cleaner sample for follow-up**

** Nolan, P. L. et al. 2012, ApJS, 199, 31

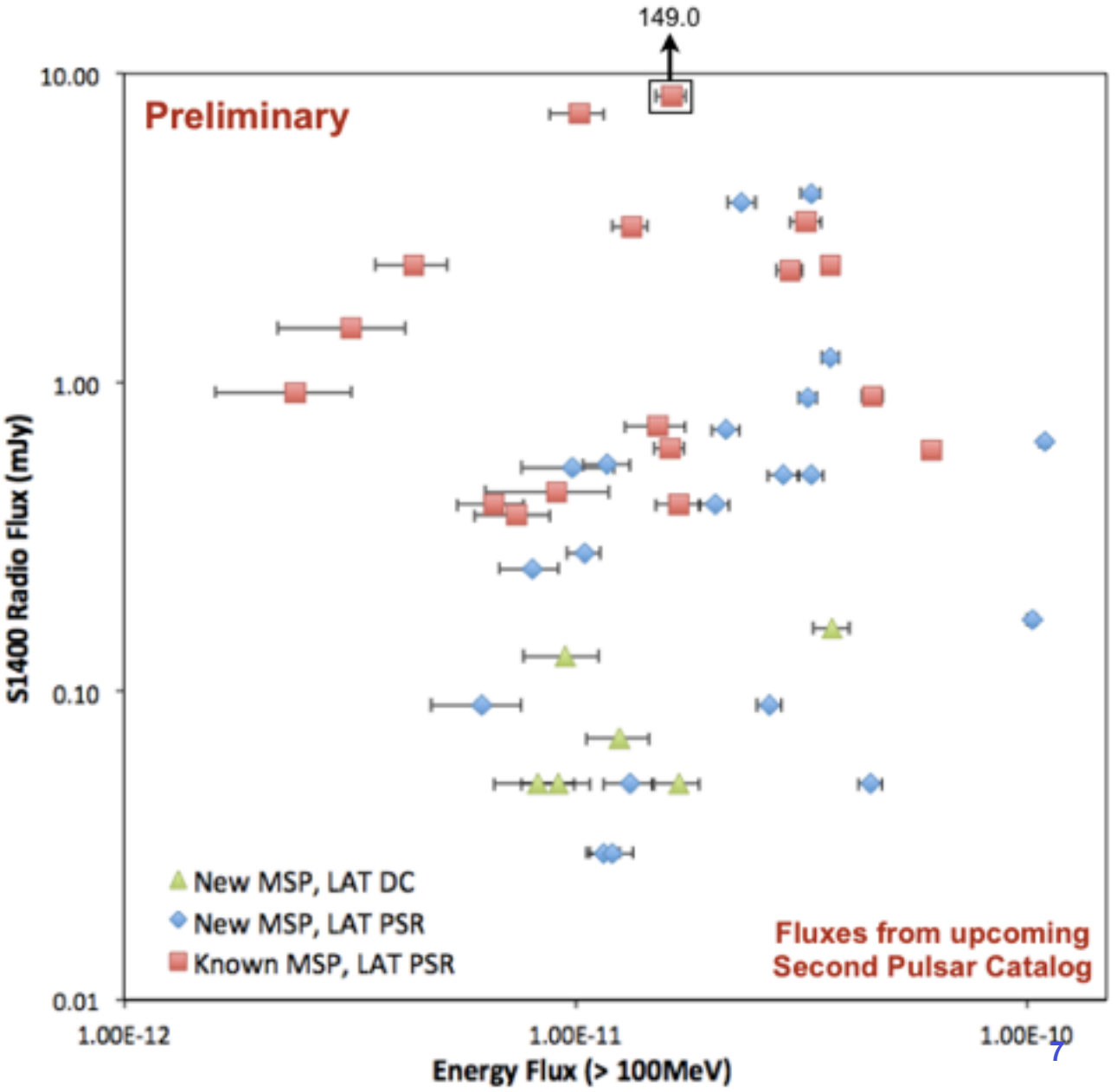
Is there a correlation we could leverage?

Should we only look at bright LAT sources?

Only faint ones?

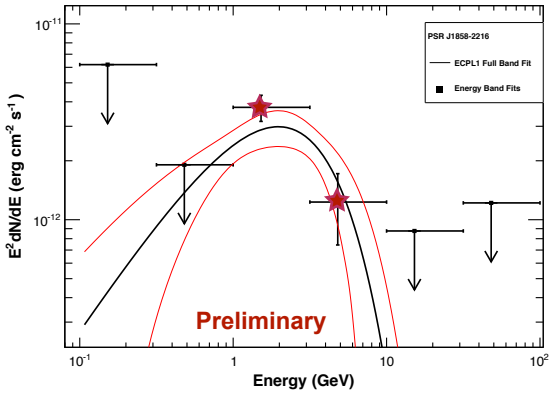
↓

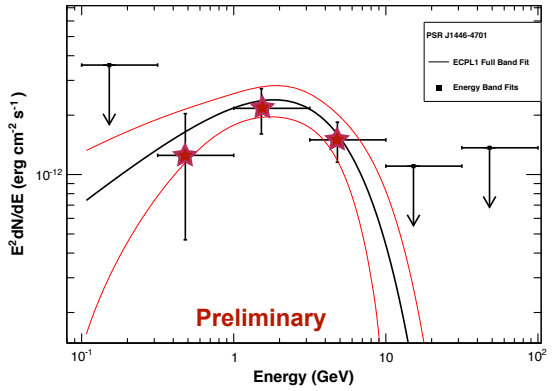
No obvious correlation between radio and gamma-ray fluxes



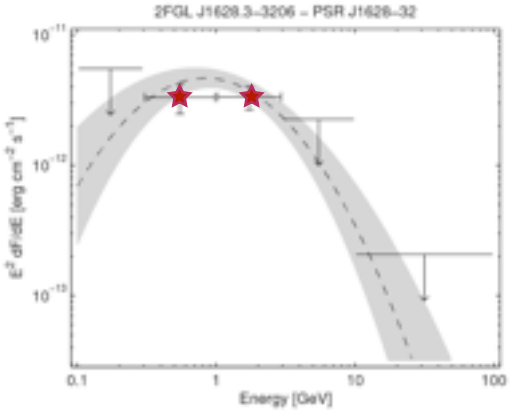
What about spectral shape?

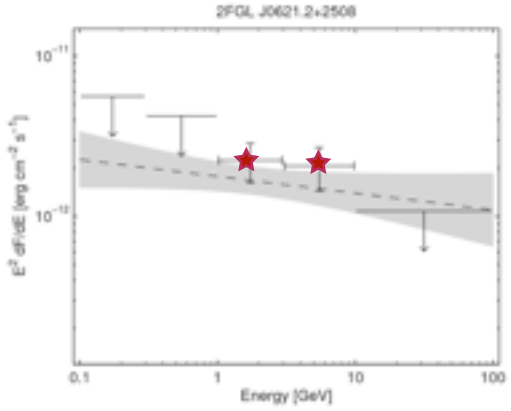
- **Catalog spectra for faint LAT pulsars are not obviously curved**



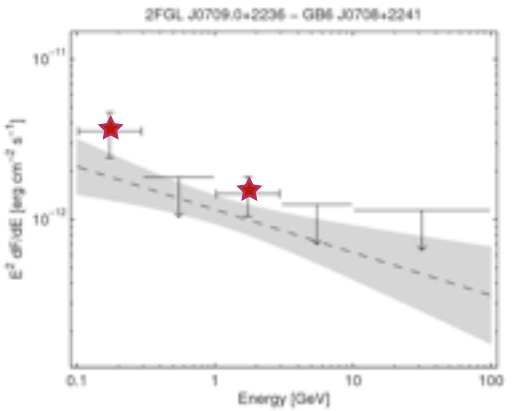


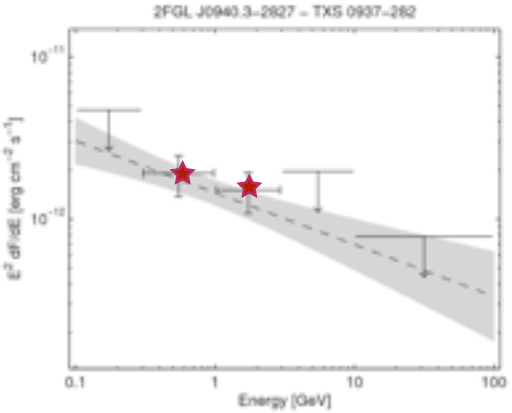
New MSPs with LAT pulsations (from upcoming 2PC)





Radio MSPs from LAT positions (from 2FGL)





AGN of "uncertain type" (from 2FGL)

Smarter source selection

- **Use gamma-ray properties of known pulsars to find pulsars**
  - **Machine learning techniques*****
    - **Classification Trees**
    - **Logistic Regression**
  - **Output the probability of being a LAT pulsar**
    - **~100 2FGL sources likely to be pulsars!**

- **Provided optimized lists to radio pulsar searchers from recent data on several occasions**
  - **Pulsar probabilities from machine learning**
  - **Graded spectra by eye**
  - **Weighted combinations**

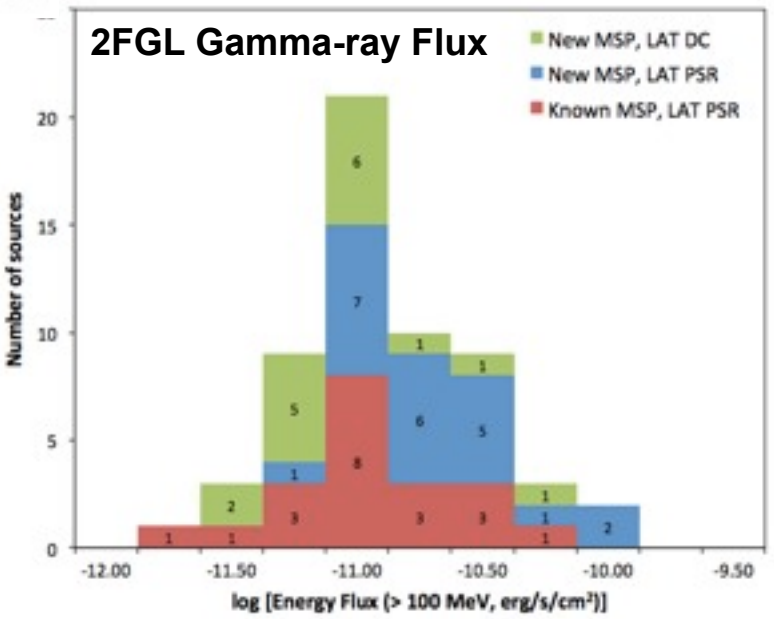
*** Ackermann, M. et al. 2012, ApJ, 753, 83

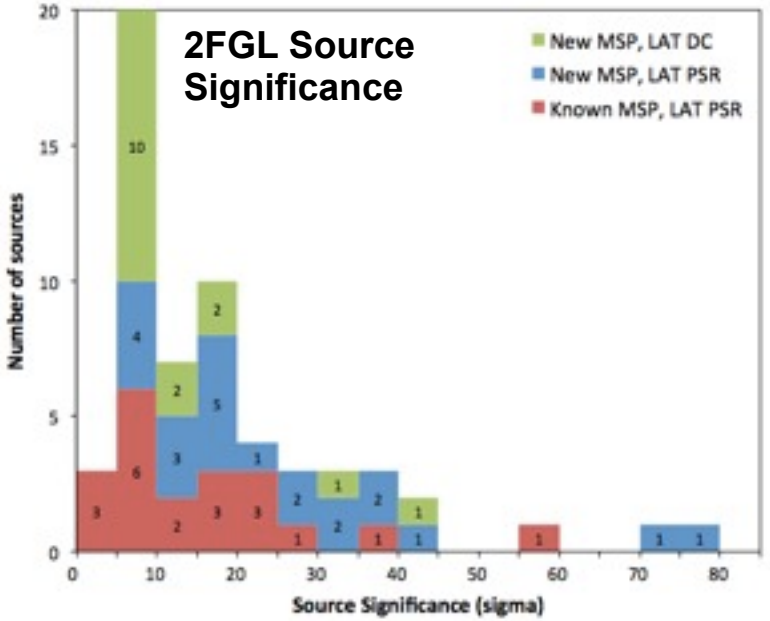
Results of "optimized" source lists

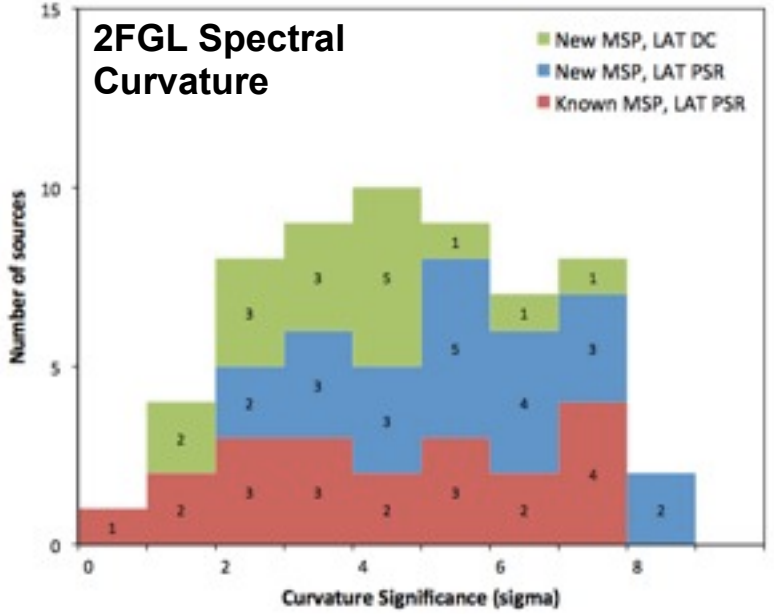
- Total of three MSPs discovered from later lists
- While machine learning is good for population analysis,
  - Not so good for pinpointing specific sources for follow up
- Requires signal on the individual source level to be able to draw conclusions on a specific source
  - Not possible for faint LAT sources

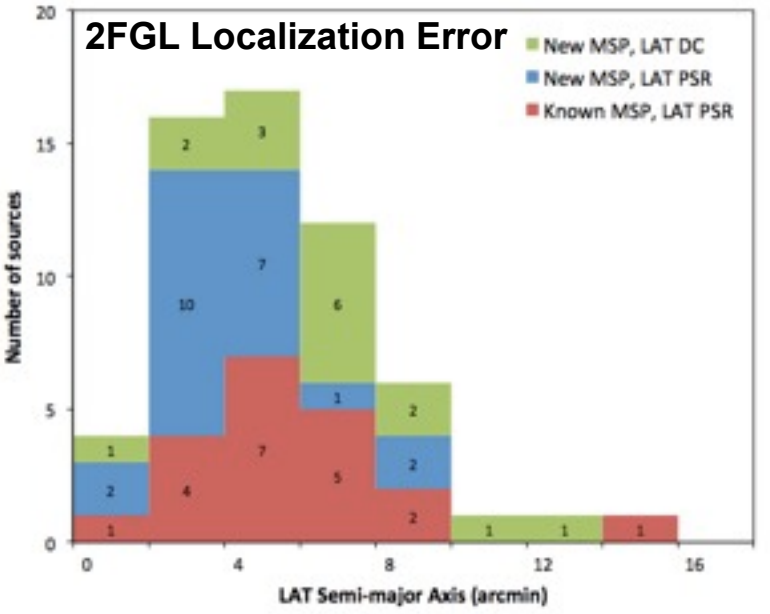
Have we just run out of MSPs in LAT?

Gamma-ray properties of the MSPs









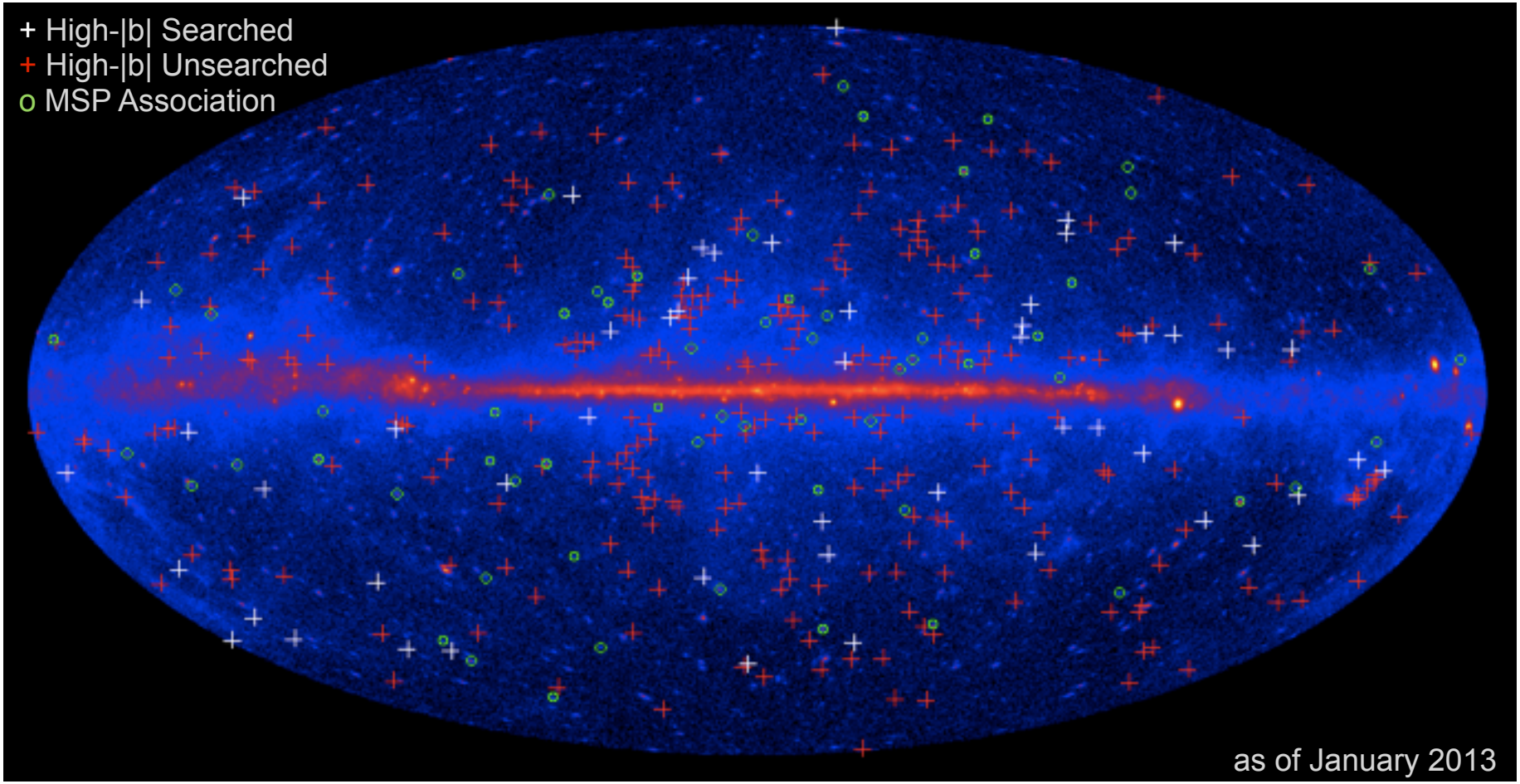
What have we learned from this?

- LAT positions can do a great job of pointing to MSPs
- Radio MSPs don't care about the source's gamma-ray flux
- Radio beams are big ➙ better LAT localizations less important
- Faint gamma-ray MSPs don't necessarily have any obvious "signatures"

So where should we search?

Search everywhere!

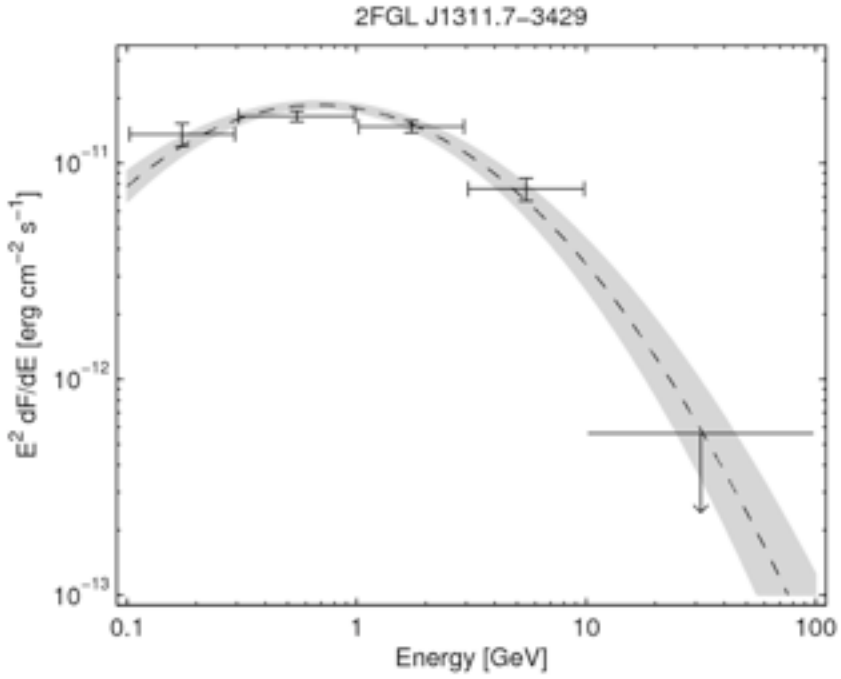
- **Still 306 non-varying unassociated sources above |b|=5**

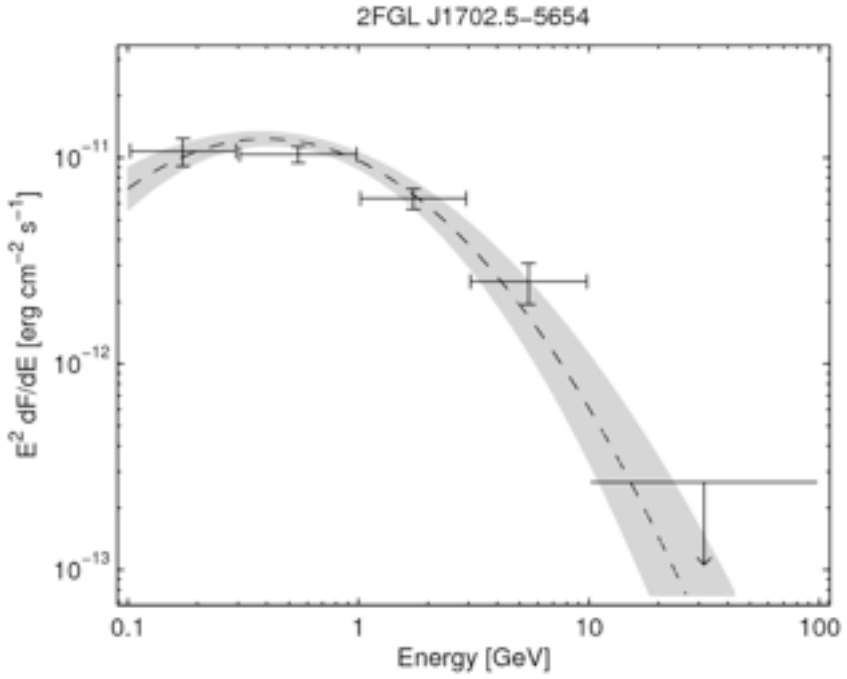


Those persnickety bright Unassocs

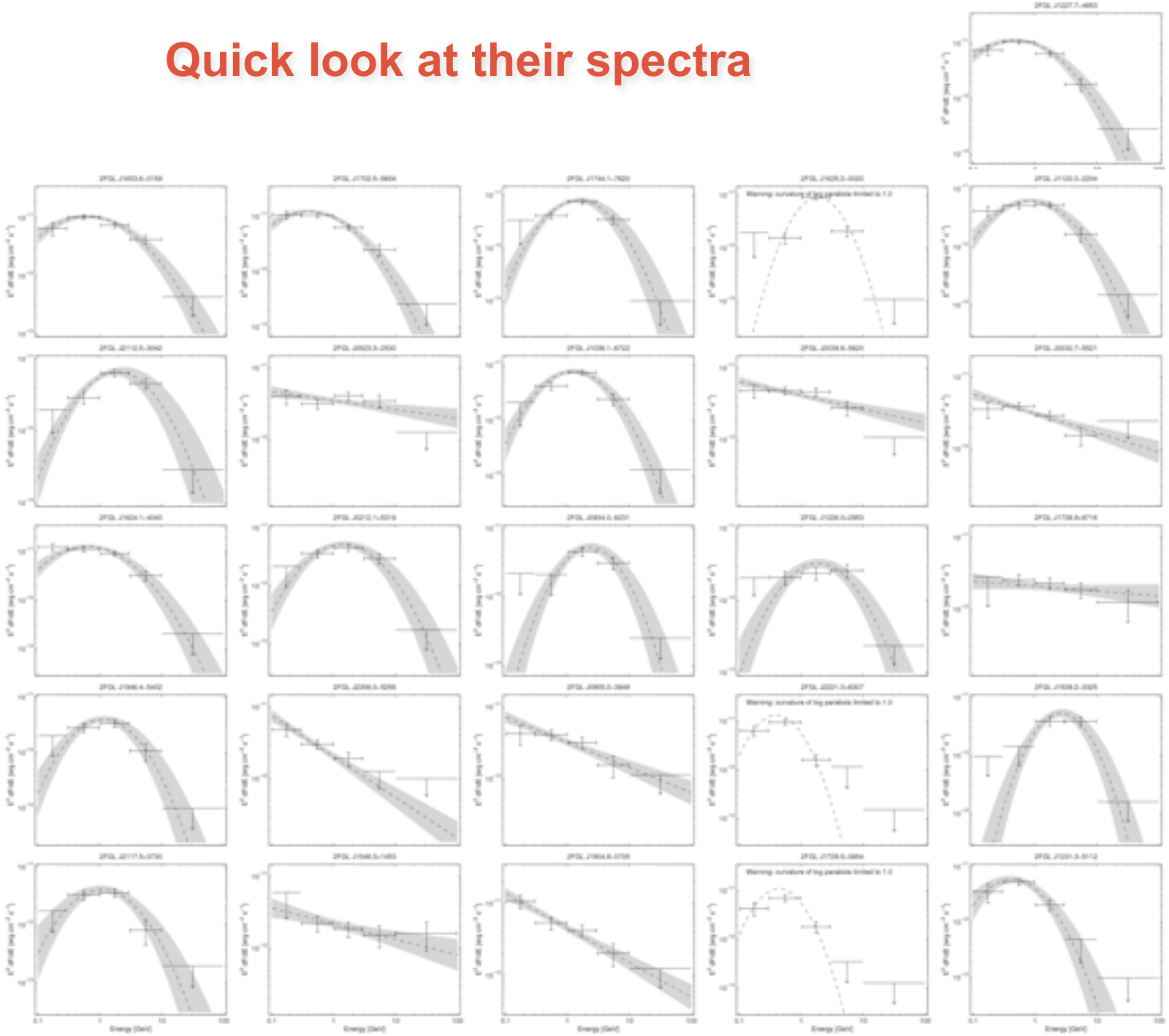
- **27 high-|b| unassociated sources remain that have:**
  - **No gamma-ray variability**
  - **High significance in LAT (6 above 20σ, 27 above 10σ)**
  - **Many have curved spectra**

- **May be black widow systems like J1311-3430**





Quick look at their spectra



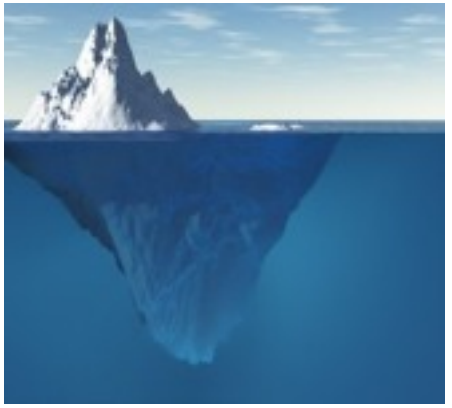
Conclusions

- **45 MSPs have been discovered in follow-up observations of *Fermi*-LAT unassociated sources**
  - **42 from positions using only the first year of LAT data**
  - **Increase of nearly 75% in Galactic plane MSPs!**
  - **At least 26 currently have detected gamma-ray pulsations**

- **Reviving the discovery rate may require searching <u>all</u> unassociated source positions**

- **Many of the remaining bright unassocs are pulsars**

- **Hopefully these discoveries are just...**



<u>Thanks</u>!