



The Fermi-LAT Collaboration acknowledges support for LAT development, operation and data analysis from NASA and DOE (United States), CEA/Irfu and IN2P3/CNRS (France), ASI and INFN (Italy), MEXT, KEK, and JAXA (Japan), and the K.A.-Wallenberg Foundation, the Swedish Research Council and the National Space Board (Sweden). Science analysis support in the operations phase from INAF (Italy) and CNES (France) is also gratefully acknowledged. This work performed in part under DOE Contract DE-AC02-76SF00515. Fermi work at NRL is supported by NASA.

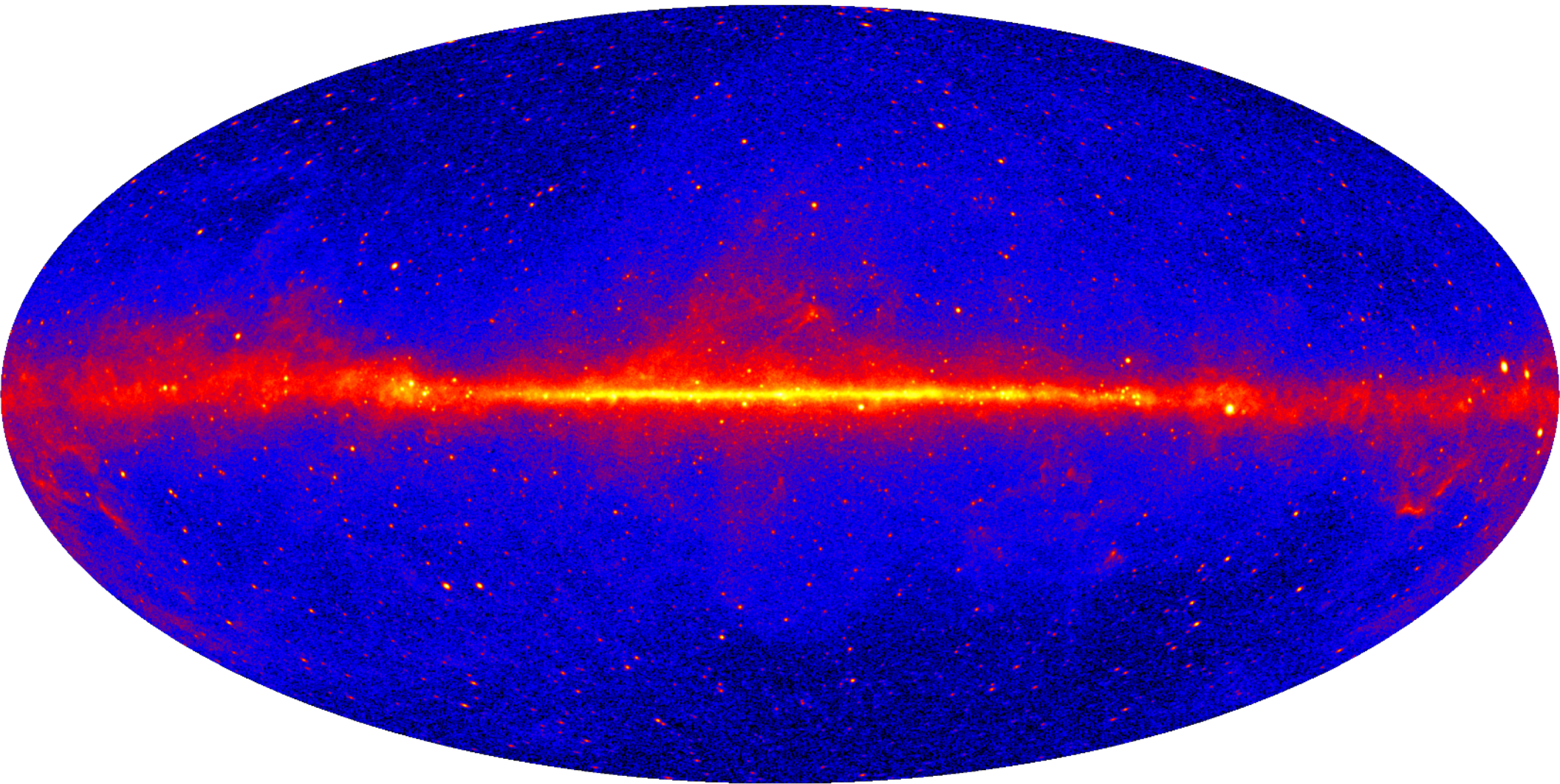
Following the Treasure Map: An update on the Fermi Pulsar Search Consortium (PSC)

**Paul Ray (U.S. Naval Research Laboratory),
on behalf of the Fermi Pulsar Search Consortium**
8th Fermi Symposium, October 15–19, 2018

Fermi Pulsar Search Consortium

- Officially formed with MOU in December 2008, a few months after the start of LAT survey operations in August 2008.
- Goal is to coordinate sharing of LAT information with a broad group of radio astronomers with access to the largest telescopes in the world to:
 - Search for radio pulsations from LAT blind-search pulsars
 - Search for radio pulsars powering LAT gamma-ray sources
- Within the first year, it became clear that the high-latitude unassociated LAT sources were an extremely good source of MSPs.
 - First discovery PSR J2214+3000 on September 30, 2009
- New telescopes have been added:
 - GMRT with several discoveries in early 2011
 - LOFAR in 2016
 - LAT with blind search MSP discoveries (with radio help in 2012, alone in 2016)
 - FAST (via separate MOU) in 2018
- New (old) techniques brought to bear:
 - Steep spectrum radio sources from GMRT and VLA (Frail et al. starting in 2016)
 - Headed back to low latitudes (Deneva et al. in 2017)
- **90th MSP** found by targeting LAT sources in May, 2018

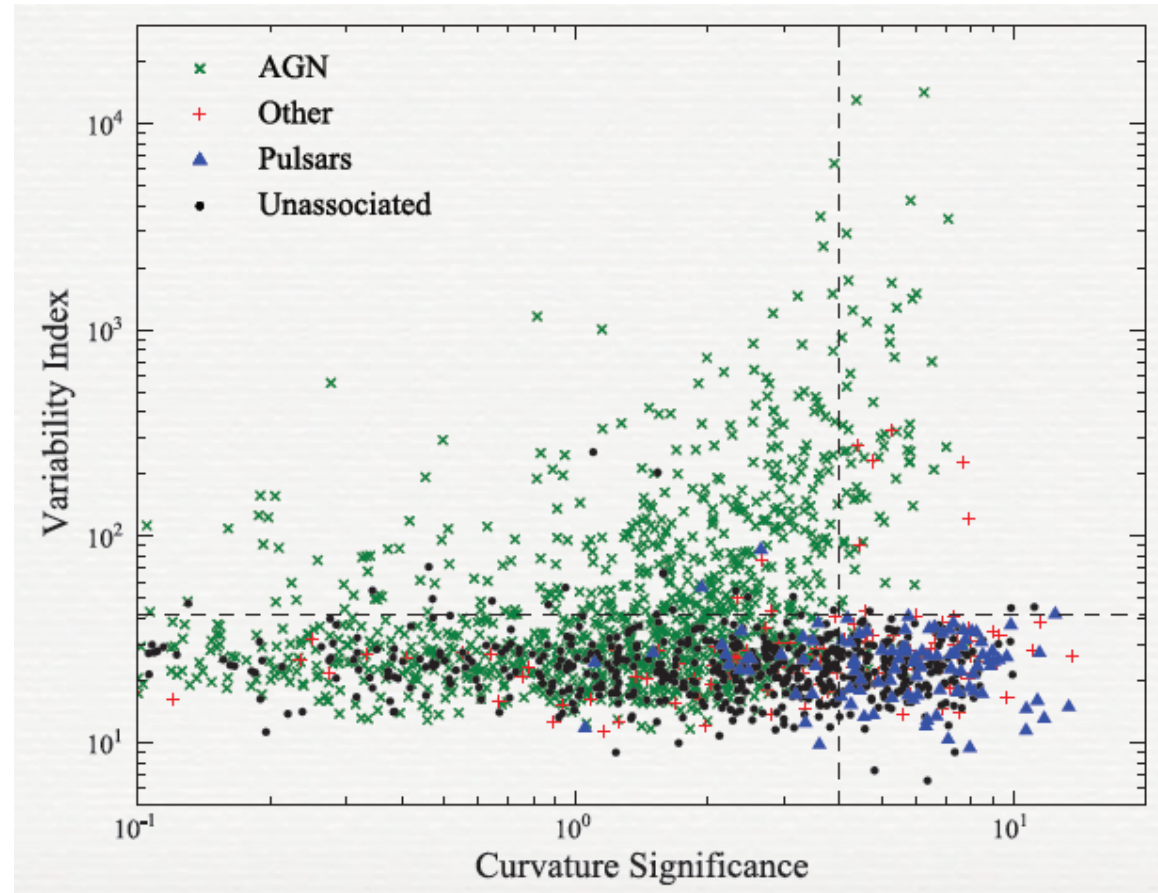
The Treasure Map



10 years, $E > 1$ GeV sky map

Ranking LAT Sources

- In 3FGL, out of 3033 sources, 1010 unassociated with plausible counterparts at other wavelengths
- 4FGL has 5500 sources, still with 1/3 unassociated
- Best targets are sources with low variability and “pulsar-like” spectra
- Used multiple techniques for ranking sources
- More details on ranking of “pulsar-likeness”:
 - Ackermann et al., ApJ 753, 83 (2012)
 - Lee et al., MNRAS 424, 2832 (2012)
 - Saz Parkinson et al. ApJ 820, 8 (2016)
- In the end, human eye/brain ranking seems to work best



Steep Spectrum Sources

- Recently, Dale Frail revived an older technique: looking for steep spectrum radio point sources that are likely pulsars (Frail et al. 2018, MNRAS 475, 942; Frail et al. 2016, MNRAS 461, 1062)
- Made use of GMRT sky survey (TGRSS ADR1) to find steep spectrum sources, followed up with interferometric observations to confirm compactness
- Generated 16 candidates
- This both directs attention to LAT unassociated sources for radio searches and provides precise positions to see gamma-ray blind searches. Both have been successful!
- So far, **6 millisecond pulsars** and 1 normal pulsar (likely line of sight coincidence) have been found in searches of these candidates!

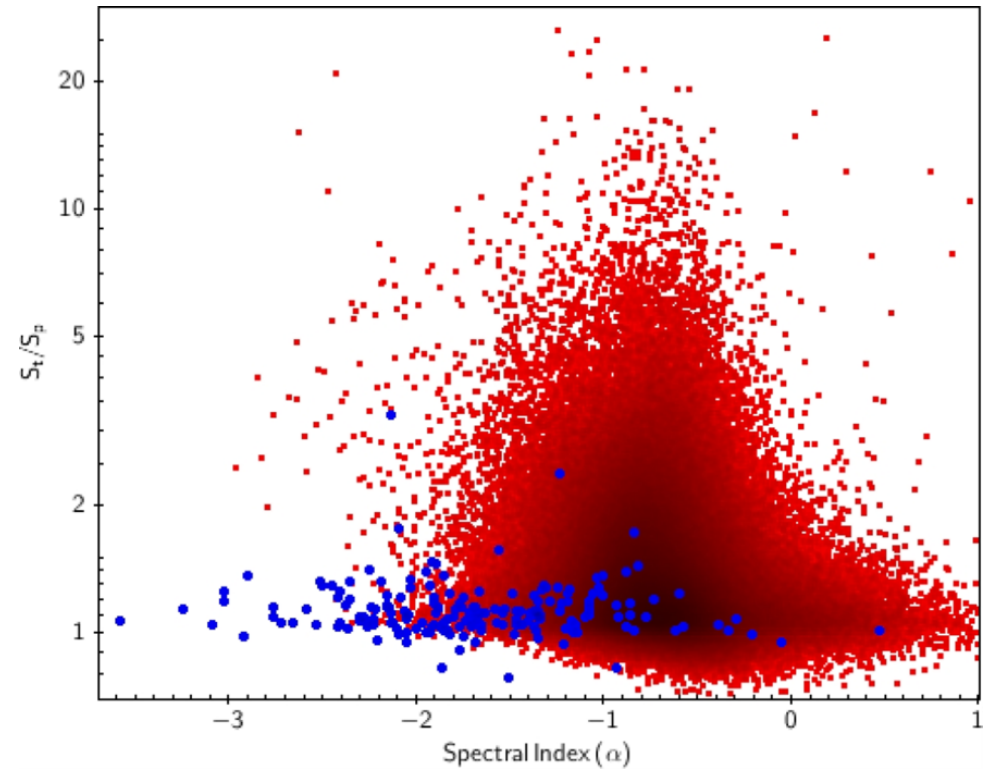
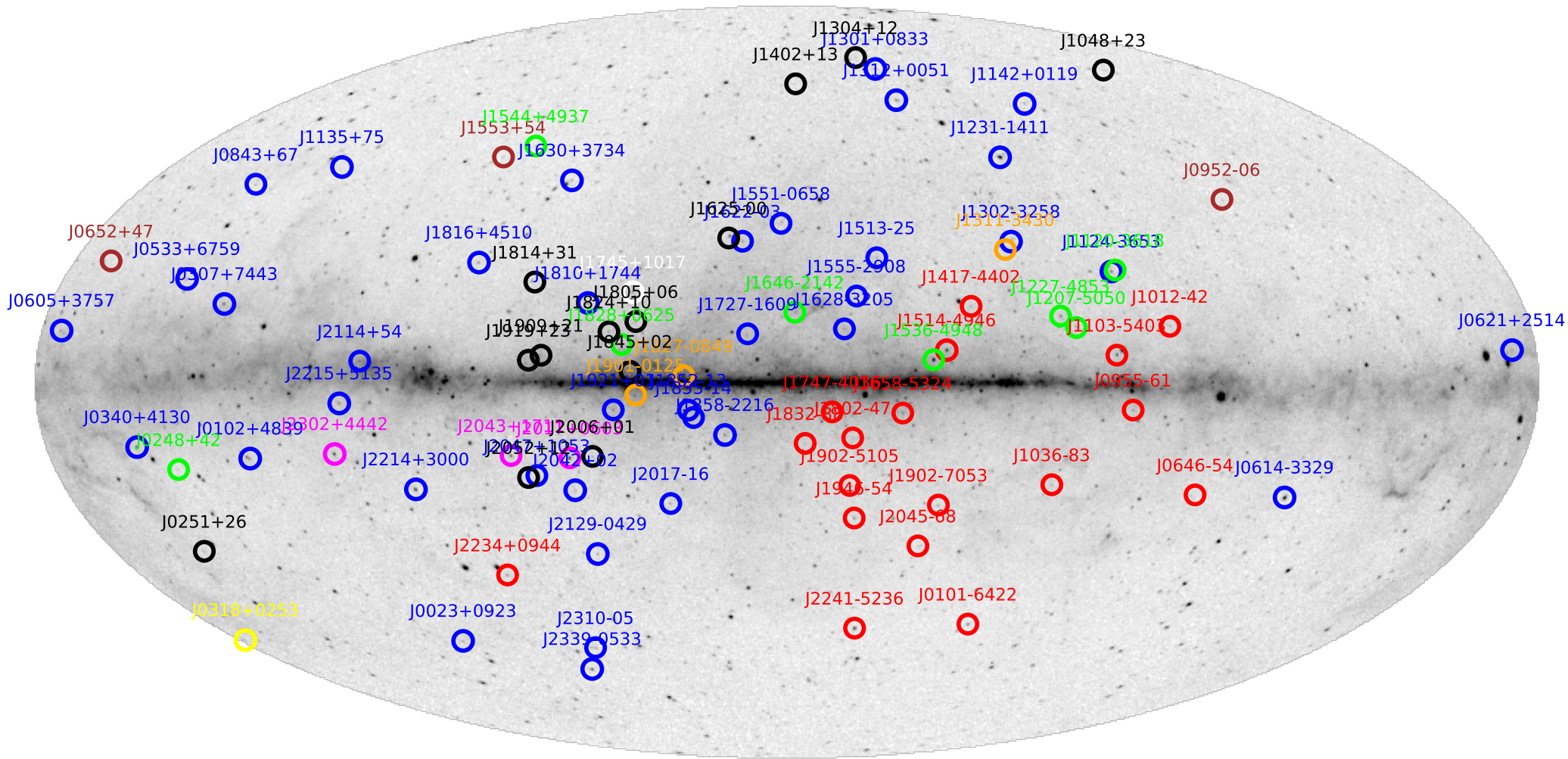


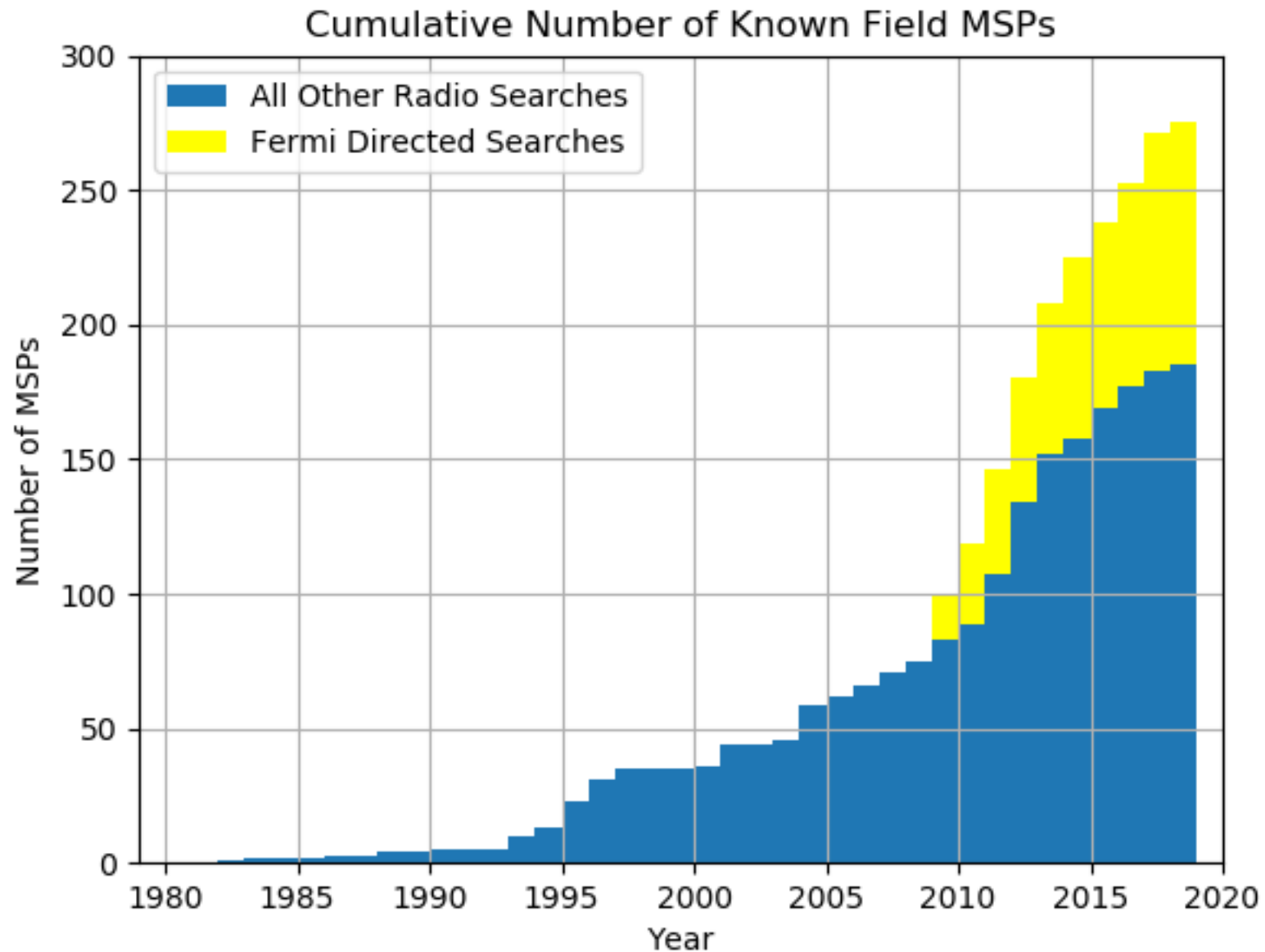
Figure 1. The distribution of spectral indices versus compactness for background radio sources (red squares) and known pulsars (blue circles). Spectral indices are two-point values computed from the TGSS ADR1 and NVSS catalogues at 150 MHz and 1.4 GHz, respectively (Intema et al. 2017).

PSC Sky Map

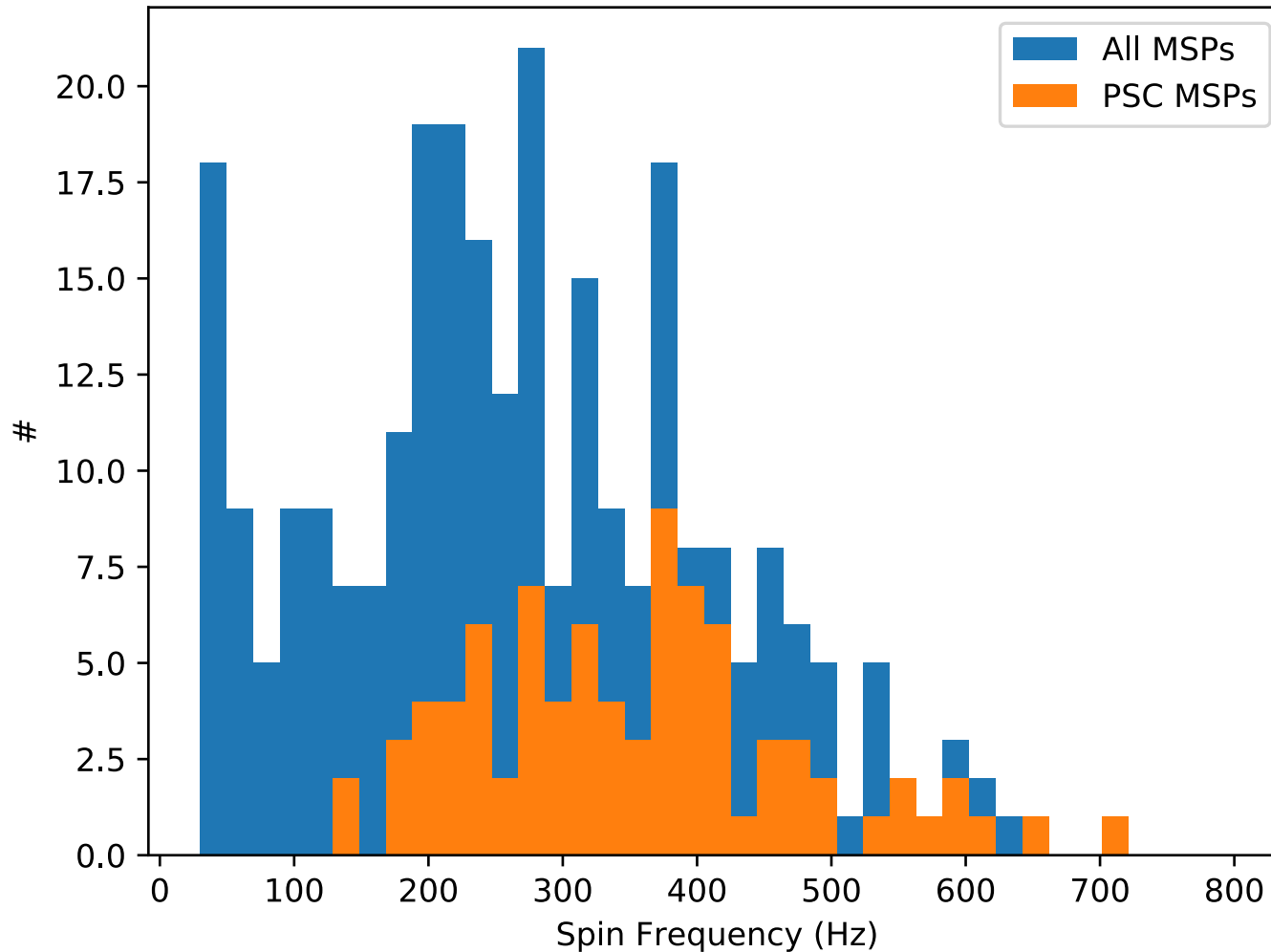


GBT, Arecibo, Parkes, Nançay, GMRT, LOFAR, Effelsberg, LAT, FAST

PSC Contributes to Total MSPs



Preference for Fast MSPs



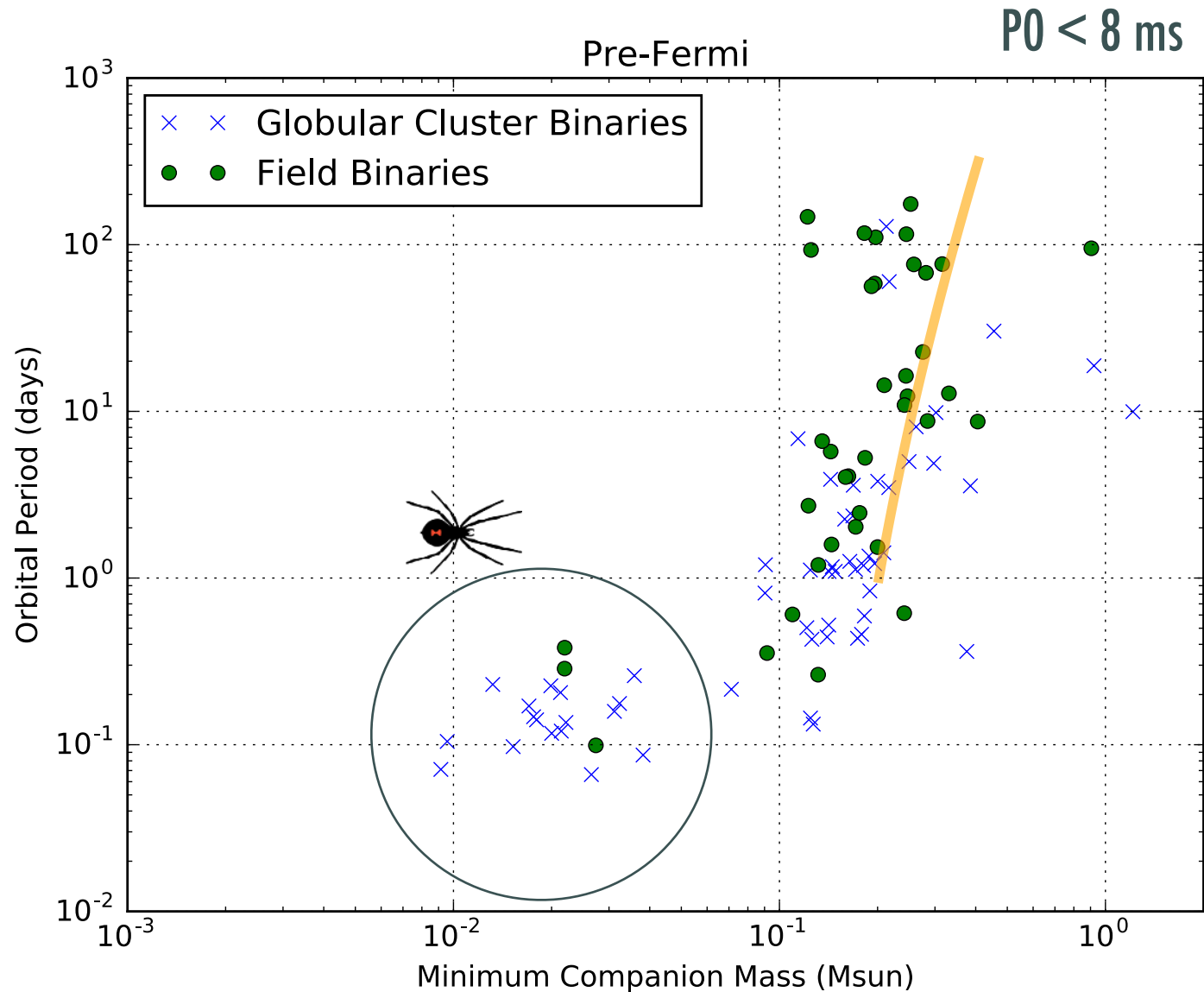
Finding the fastest, most energetic MSPs, including the current record holder in the Galactic field (707 Hz, Bassa et al. 2017)

Catching Spiders

- At least **19** new “Black Widow” systems (only 3–4 previously known outside of globular clusters) found in these searches
- Plus, **7–9** new “Redbacks” that are eclipsing but with a more massive companion ($\sim 0.2 M_{\text{sun}}$).
- Transitioning pulsars (J1023+0038 and J1227-4853)
- Much larger fraction than in other surveys... why?

Black Widows Revealed with LAT

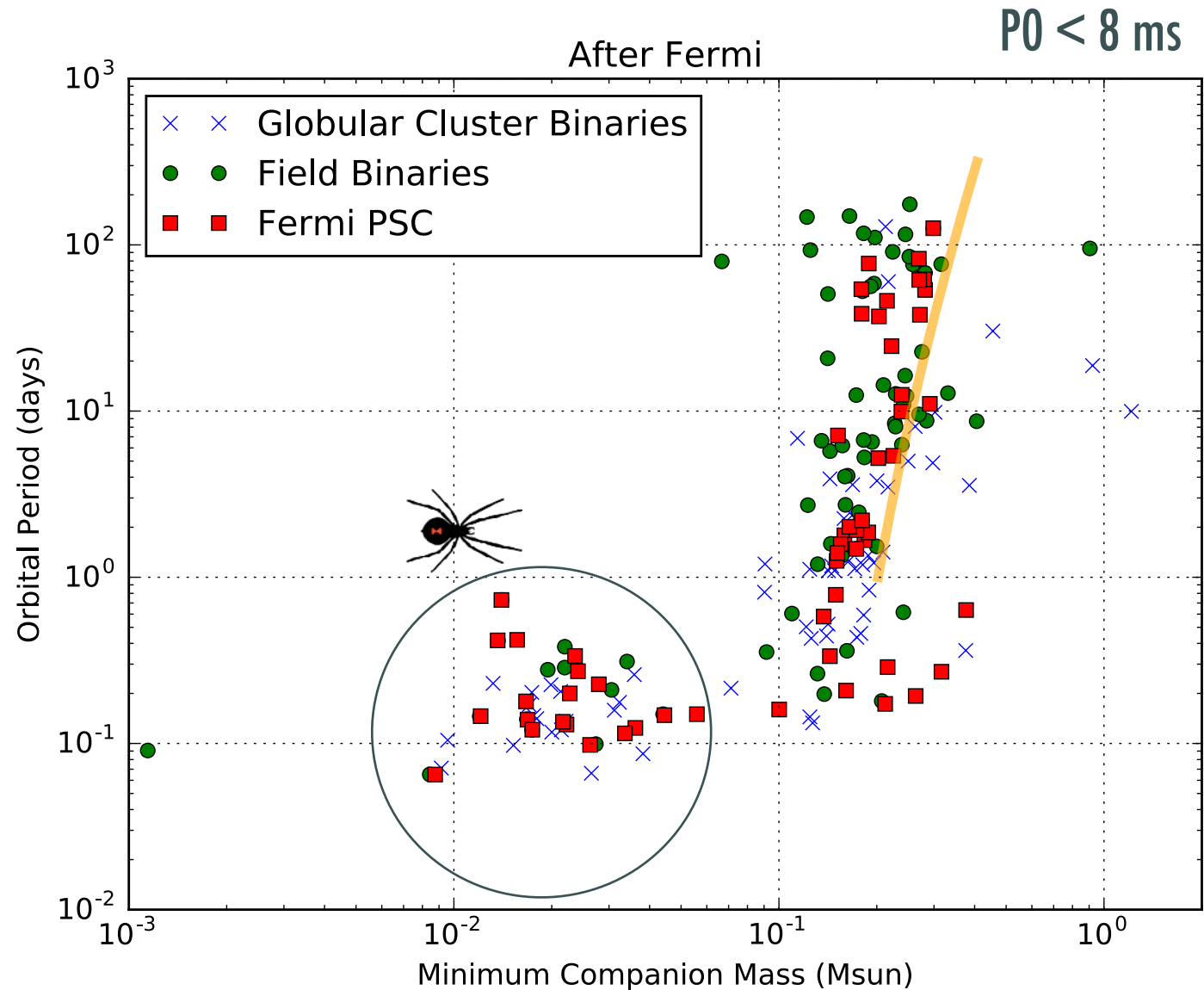
Many found in clusters
3 in figure are in the Galactic disk



Black Widows Revealed with LAT

Many found in clusters

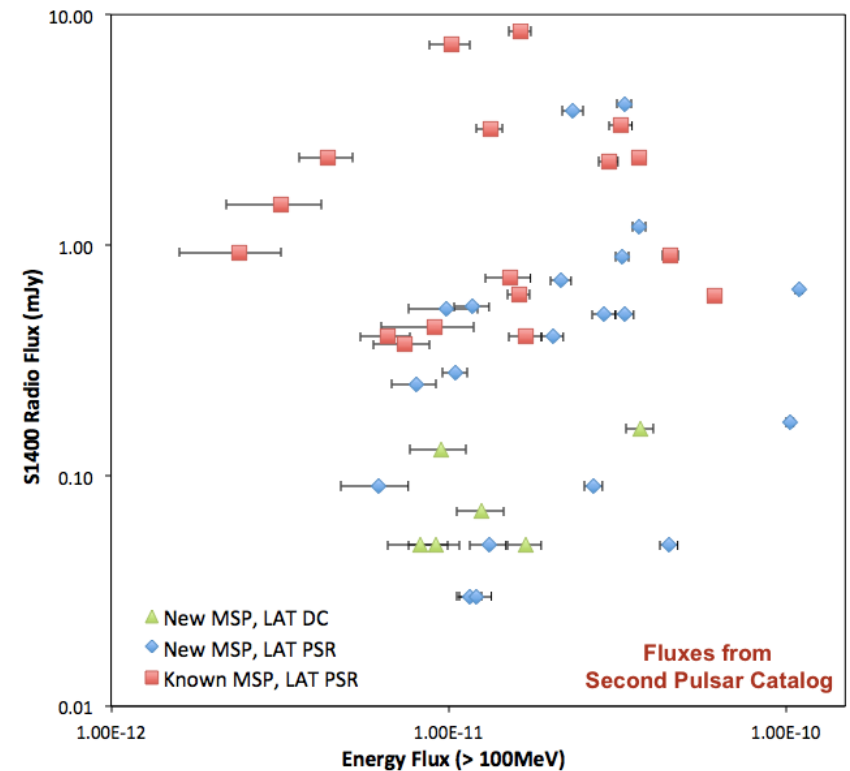
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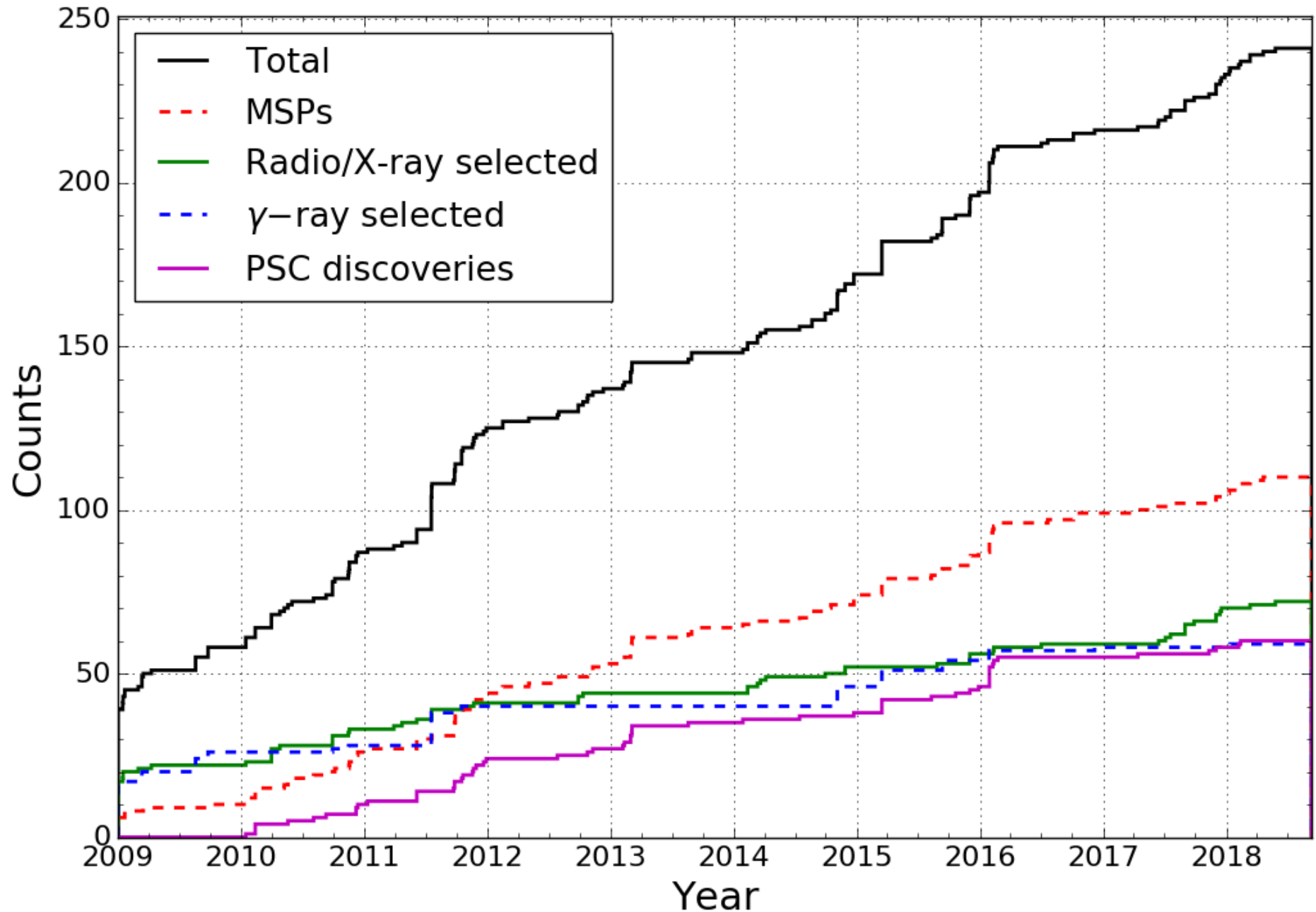
A Few Statistics

- PSC has made 1981 pointings in total, of 924 unique sources
 - (at least, sometimes I don't get complete observing log reports)
- Discoveries:
 - 90 MSPs
 - 62 with LAT pulsations so far
 - Thanks to lots of radio timing follow up, and to Lars and Colin for LAT pulsation searches
 - 14 added to Pulsar Timing Arrays so far, a couple more in evaluation
 - 22 Black Widows
 - 9 Redbacks
 - 2 Tidarren
 - 6 slow pulsars
 - 1 LAT pulsar
 - 2 nulling pulsars

- Fermi has been amazingly powerful at revealing millisecond pulsars
 - Different view of the galactic MSP population than radio surveys:
 - Faster, more energetic, many more interacting binaries
- Searches of LAT unidentified sources ongoing
 - 4FGL (based on Pass 8) preliminary source list being used now
 - Radio flux not correlated with gamma-ray so plenty more to find
 - Re-observations are important due to eclipses, scintillation, unknown pulsar spectra, RFI, etc...
 - Quite a bit of unanalyzed search data from GBT and Parkes



LAT Pulsar Discoveries vs Time

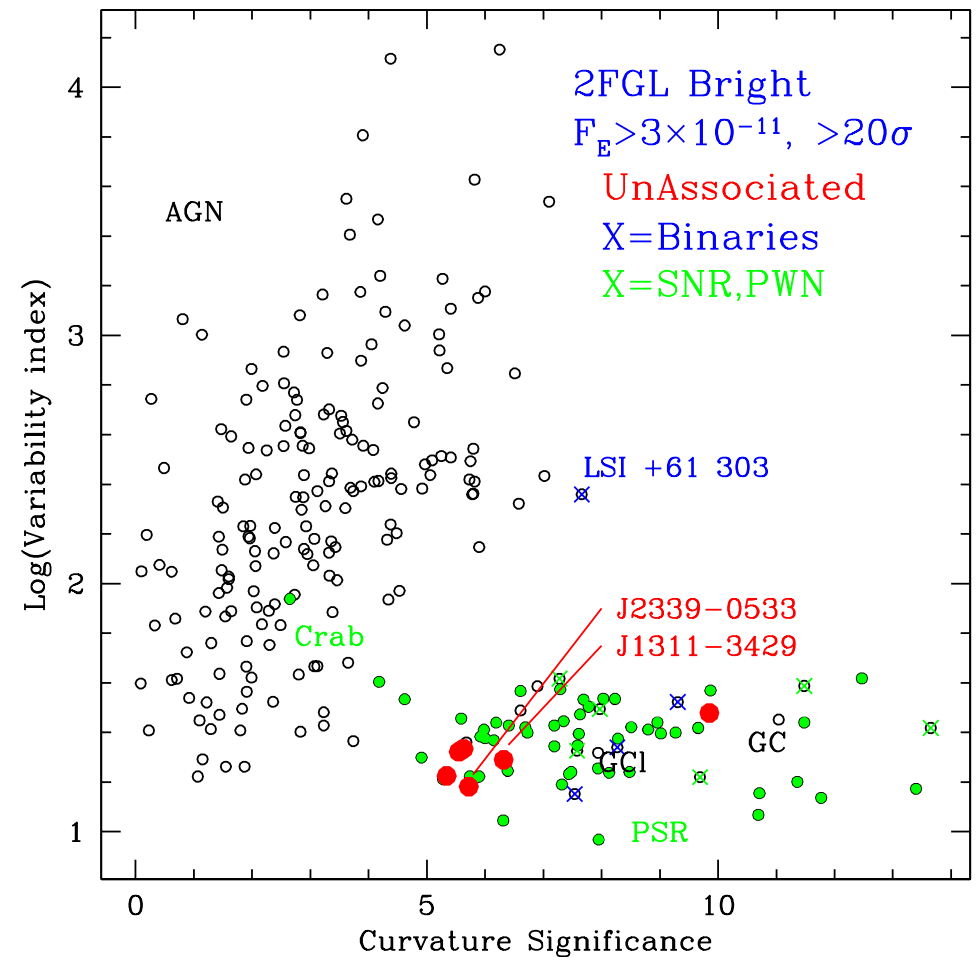


BACKUP

Explaining the UNIDs

At time of 2FGL, 6 remaining UNIDs out of 250 bright sources, all pulsar-like

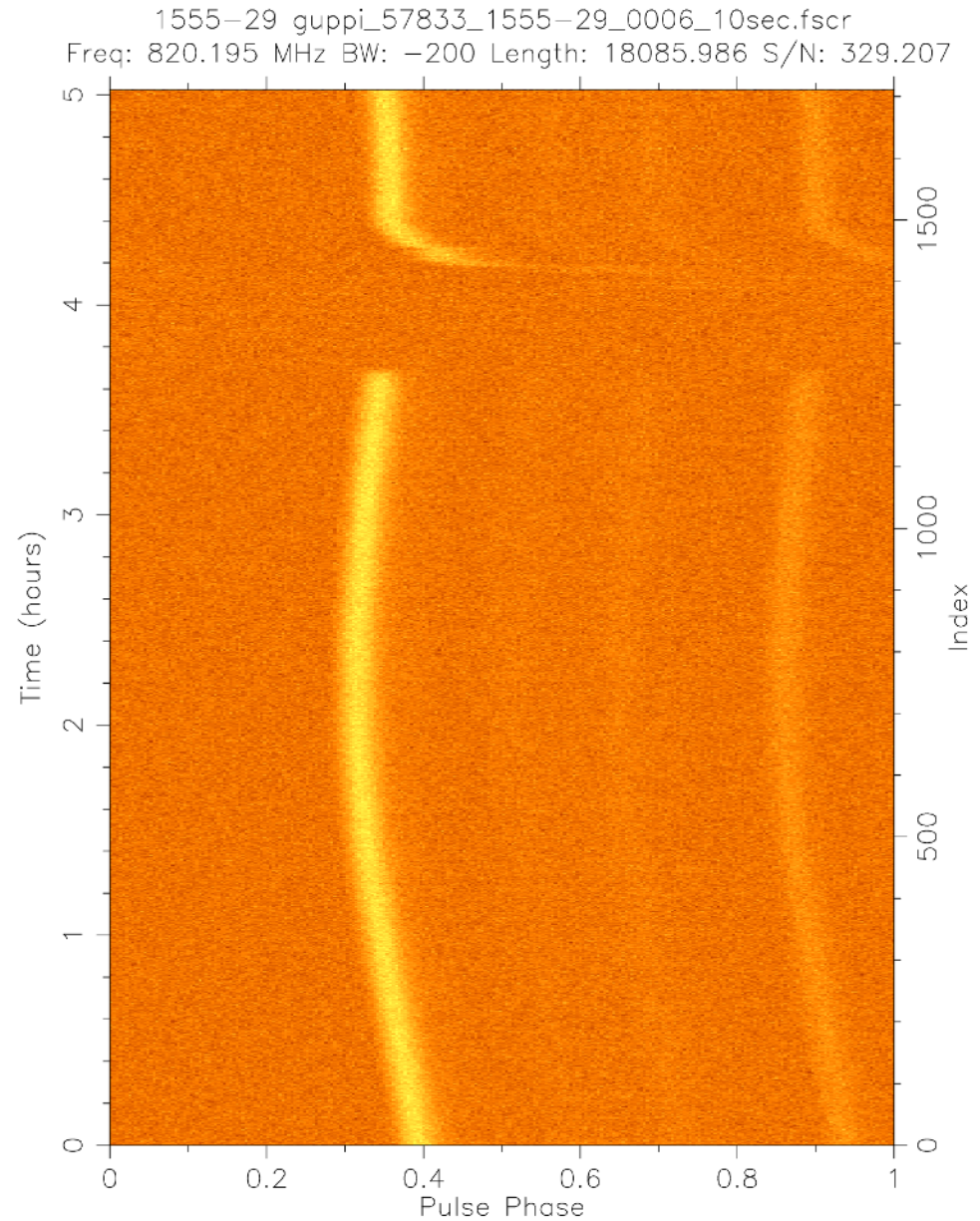
- Bright unassociated sources subjected to deep X-ray, optical and radio imaging observations to look for likely counterparts
- Could any be radio-quiet MSPs?
- 5/6 now identified
 - J2339-0533, optical, radio MSP
 - J1311-3430 optical, blind search, radio MSP
 - J1227-4853 transitional MSP
 - J1653.6-0158 optical orbit MSP
 - J1906.5+0720 blind search PSR
 - J1702.5-5654 still UNID



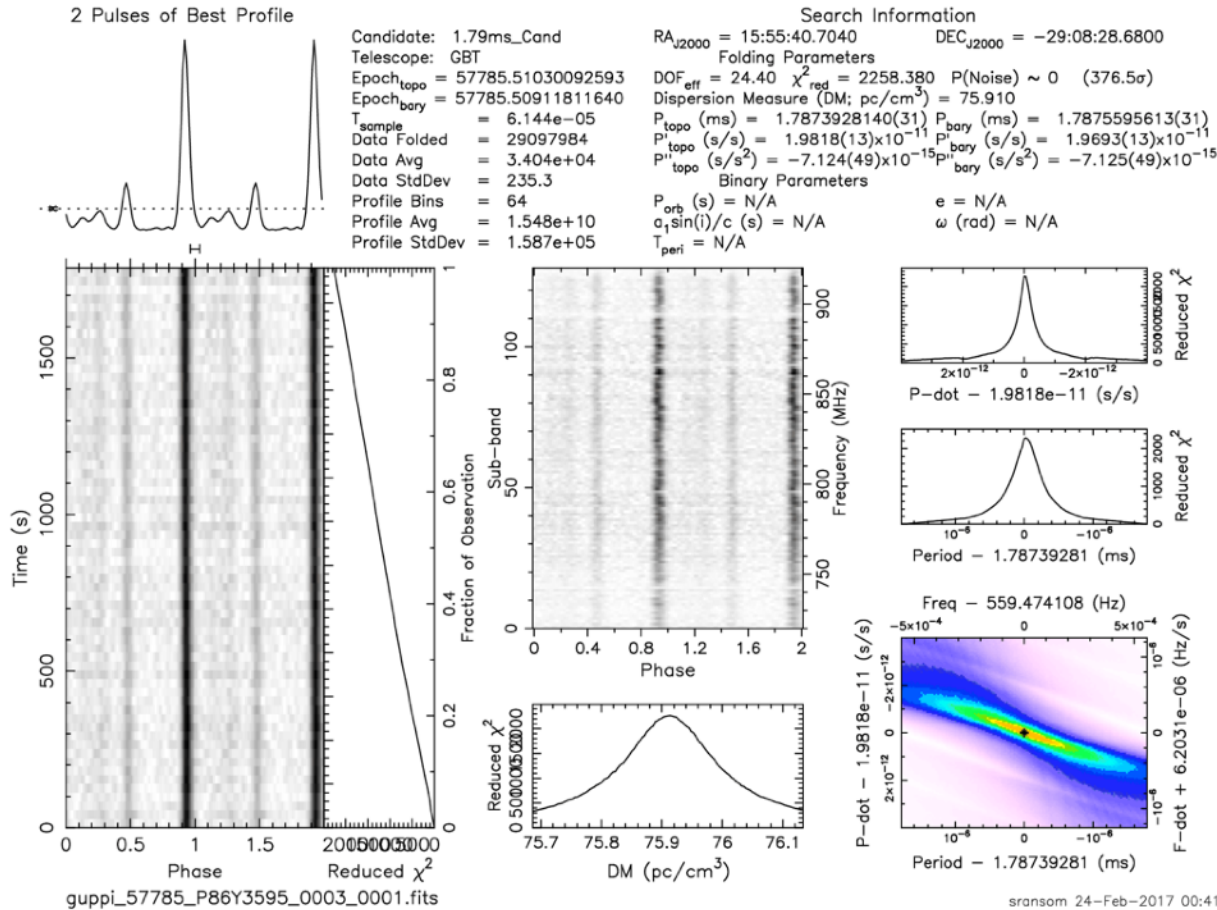
(from Romani 2012)

5 hour GBT observation showing spectacular eclipse!

Optical studies in progress



PSR J1555-2908



1.78 ms
5.5 hour orbit

Found by my 11-year old son, Nick

Optical/X-ray Identified Candidates

Optical/X-ray studies have been productive, revealing positions, orbital periods, companion types, and energetics for many likely MSP-powered counterparts to LAT sources

Name	Class	Discoverer	PB (d)	Radio	LAT PSR?	Notes
2FGL J1653.6-0159	BW/RB?	Romani	0.05			75 min orbit! H poor
PSR J1311-3430	BW/Tidarren	Romani	0.07	Y	Y	extremely H poor
PSR J2339-0533	RB	Romani/Kong	0.19	Y	Y	
PSR J1023+0038	tMSP	Archibald	0.20	Y/N	Y?	pre-Fermi, transitioned 2013
3FGL J2039.6-5618	RB?	Romani	0.22			Orb variability at X-ray and optical
3FGL J1544.6-1125	tMSP	Bogdanov	0.22?			Binary period not certain, no transition yet
PSR J1227-4853	RB/tMSP	de Martino/Hill/ Bassa	0.29	Y/N	Y	transitioned 2012
1FGL J0523.5-2529	RB?	Strader	0.69			$M_c > 0.8$, $e=0.04?$
PSR J1417-4402	RB/Huntsman	Strader	5.38	Y		Giant/subgiant companion?

Back to Low Latitudes

- Improved diffuse models, longer data spans and improved event classification and catalog processing provided useful source lists in the plane
- J. Deneva searched several sources at $|b| < 5\text{deg}$ and found one new MSP (J1845+02)
- Searches require multiple pointings at L-band to mitigate the effects of dispersion and scattering in the plane