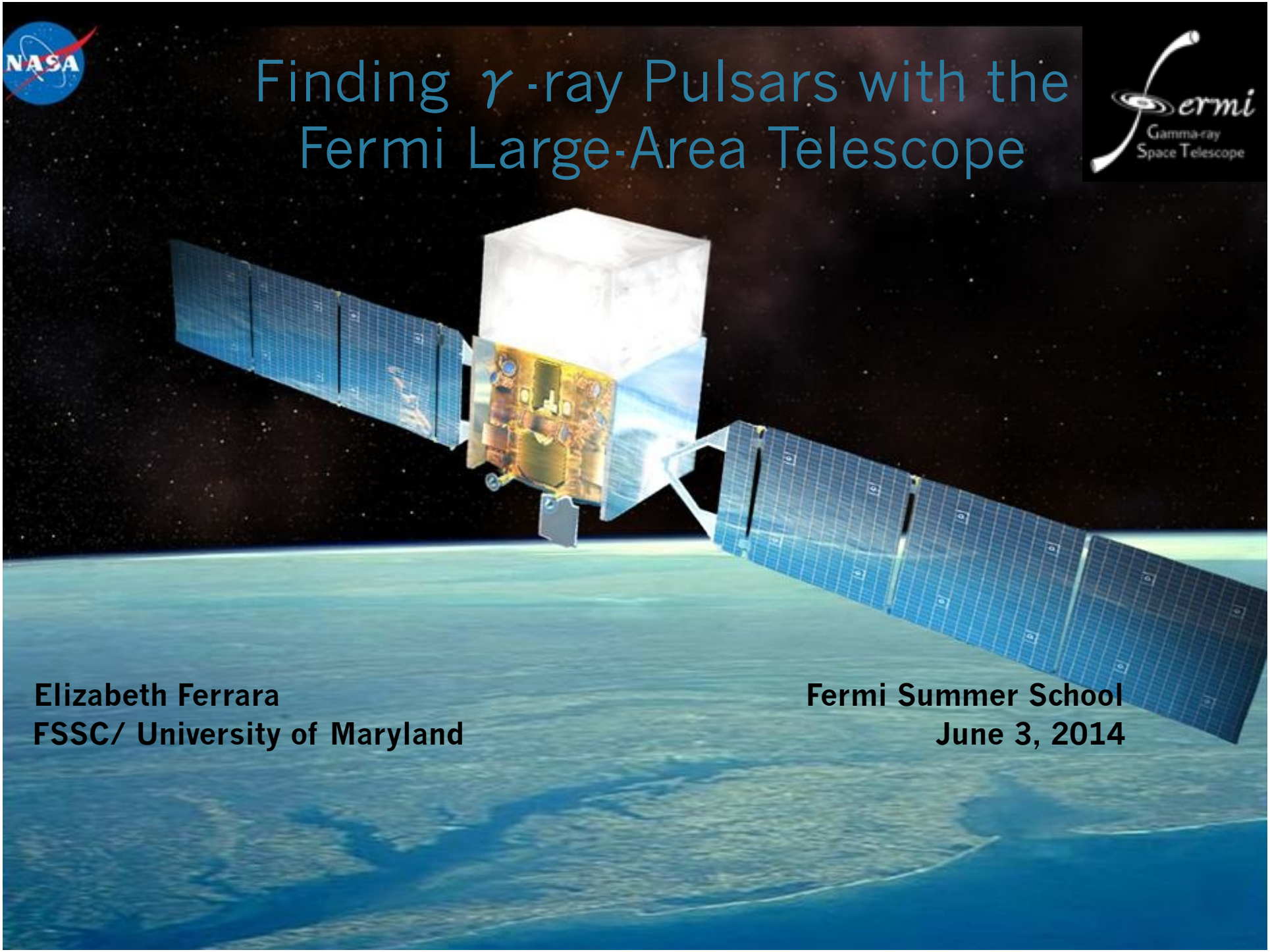
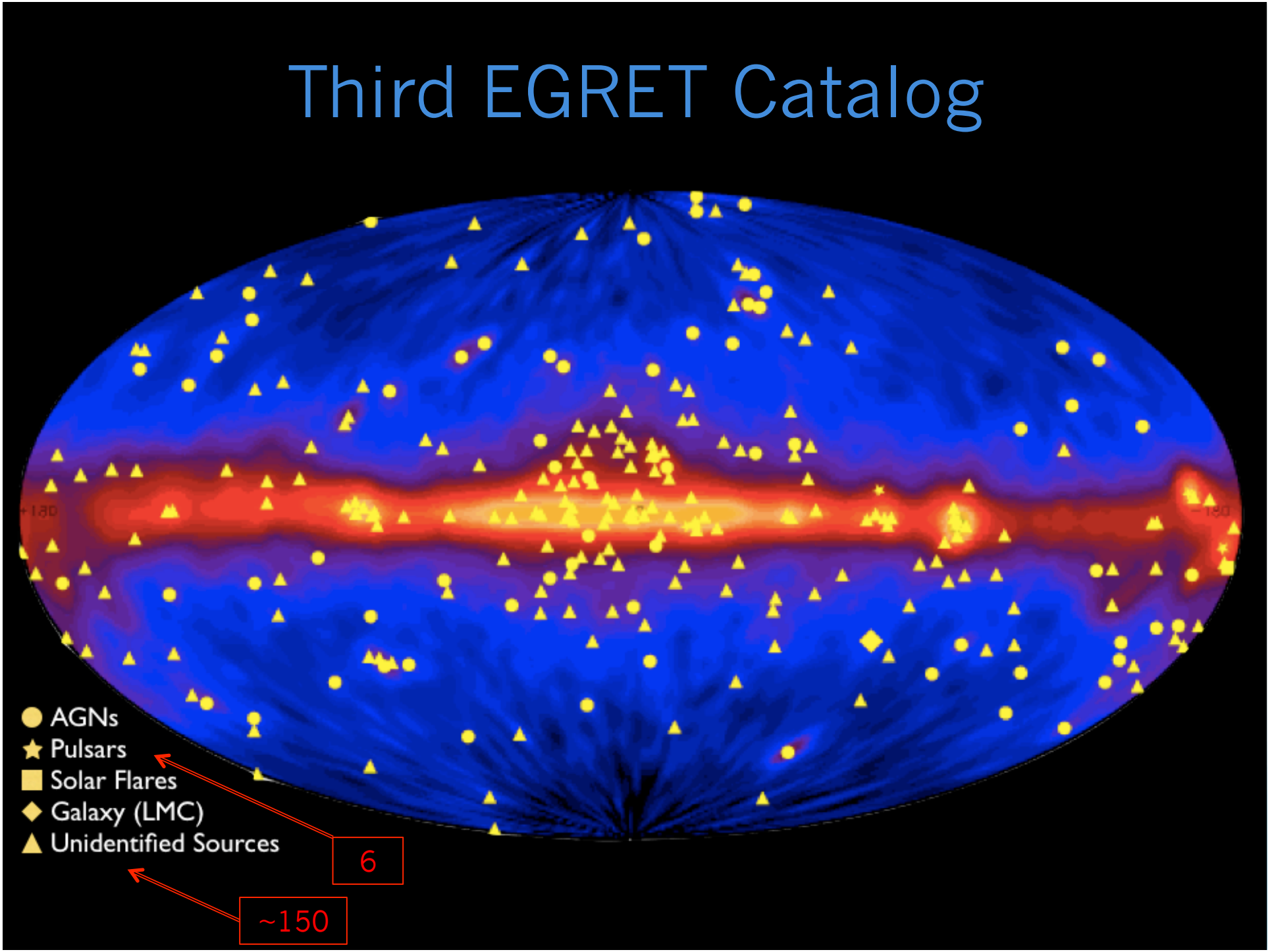
Finding γ-ray Pulsars with the Fermi Large-Area Telescope



Elizabeth Ferrara
FSSC/ University of Maryland

Fermi Summer School
June 3, 2014

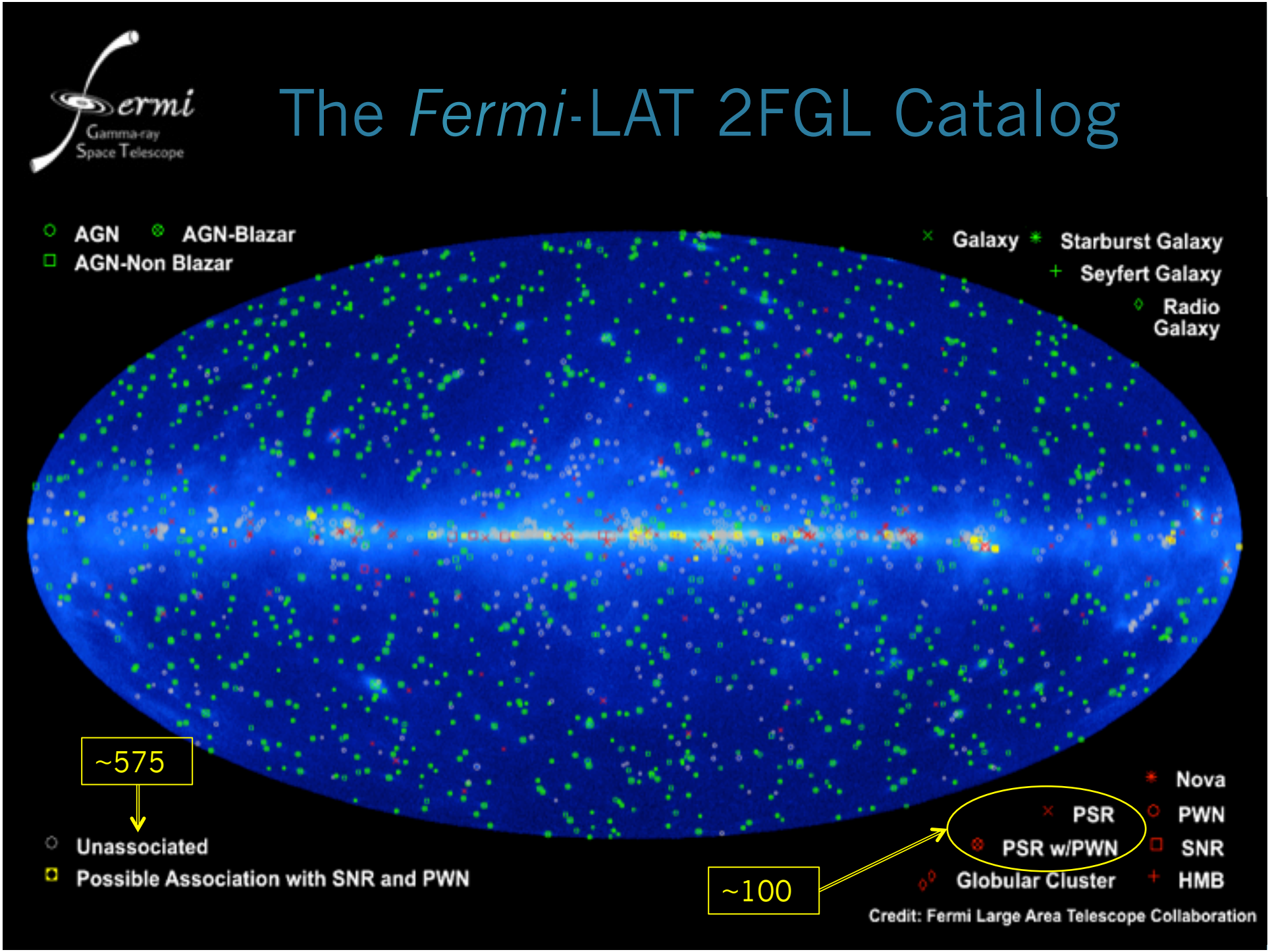
Third EGRET Catalog



Fermi Launched 2008

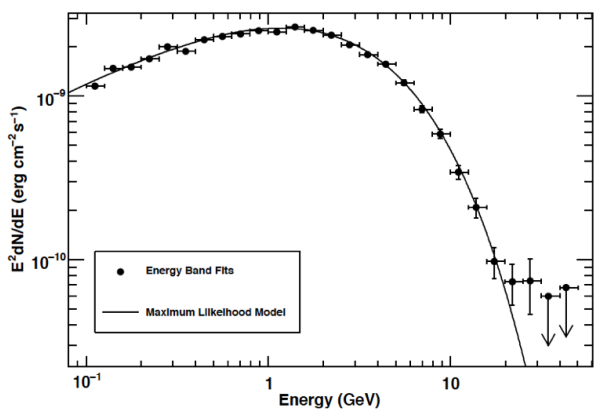
- Launch from Cape Canaveral Air Station on 11 June 2008 at 12:05PM EDT
- Circular orbit, 565km altitude (96 min period), 25.6° inclination.
- Precession period is ~54 days, ground track repeats every ~30 orbits

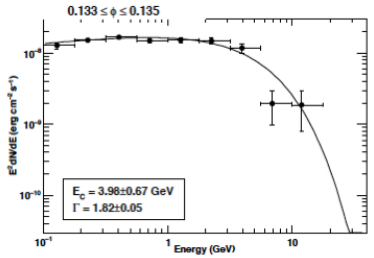
The *Fermi*-LAT 2FGL Catalog

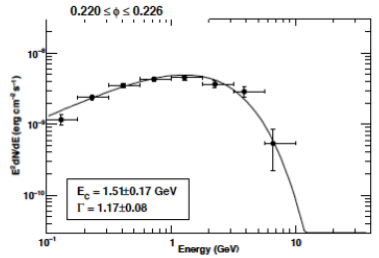


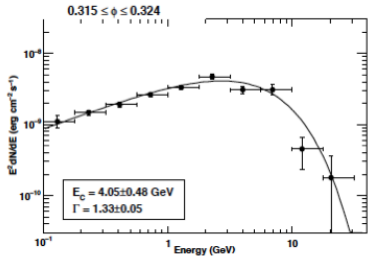
Young Pulsars

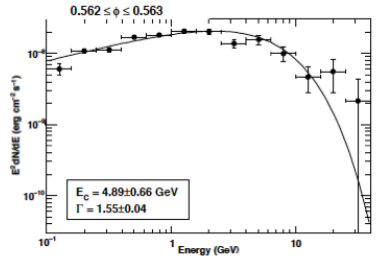
- Highly energetic pulsars have long been known to be gamma-ray emitters
  - Often detected by applying known radio ephemerides to the gamma rays
  - Can also be discovered directly in the gamma-ray data
  - Mostly non-varying, with highly curved spectra

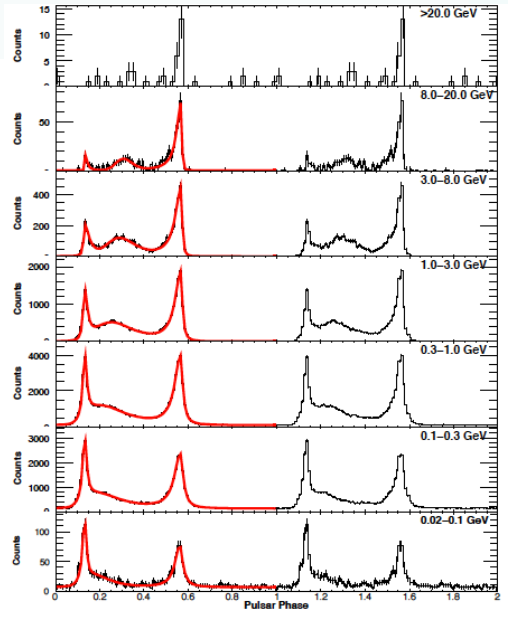


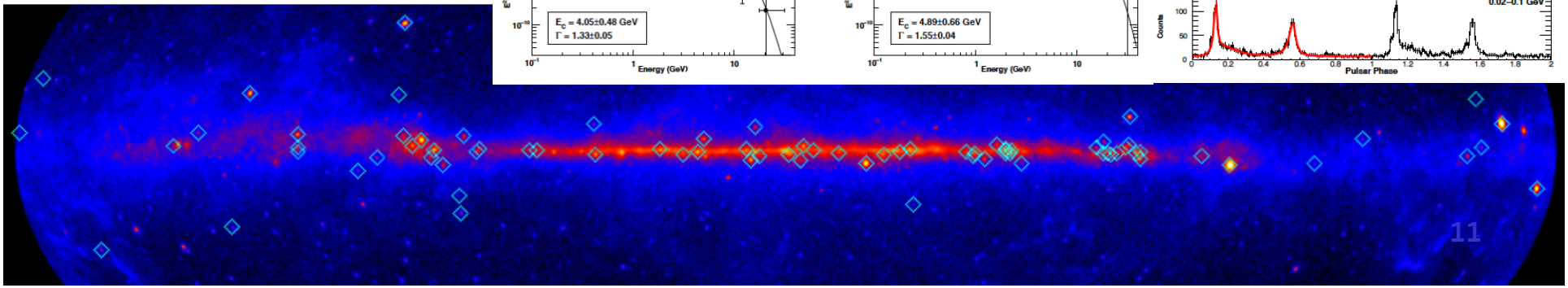








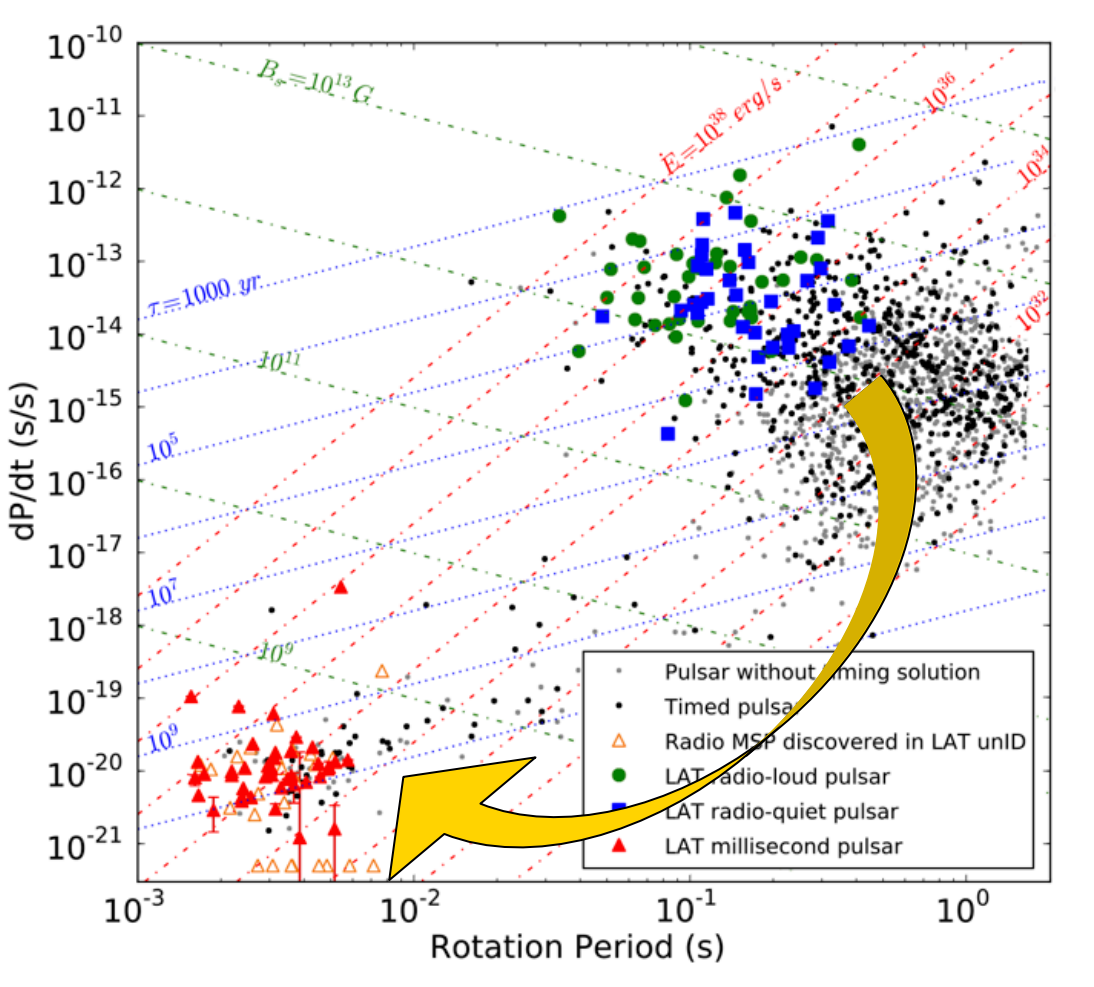




Recycled Pulsars

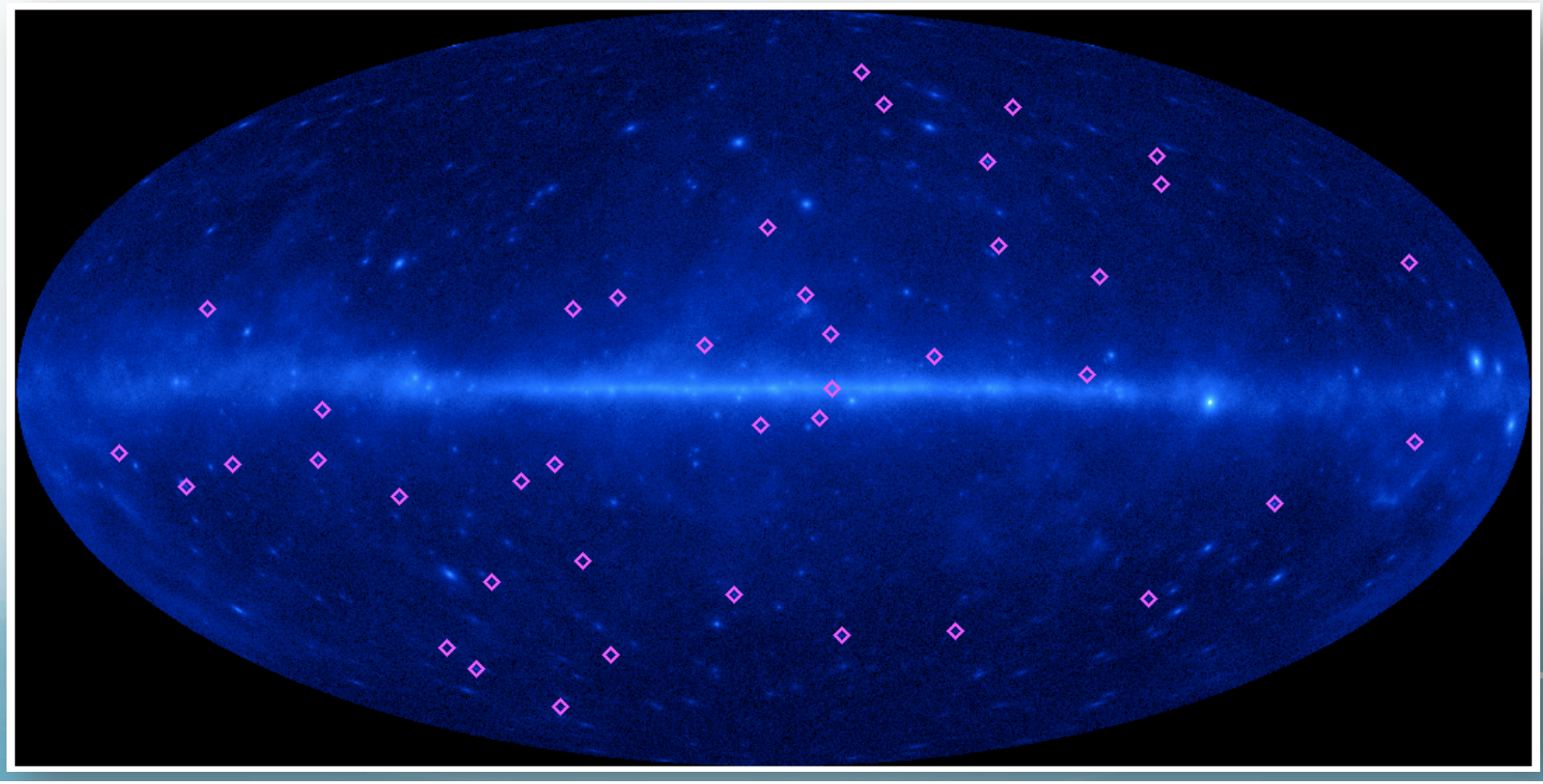
- Over time young energetic pulsars slow down
  - Power for pulsations comes from rotation
  - Once energetics are no longer favorable, pulsations cease
- Pulsars in binaries can get a second life through mass transfer
  - Increase in angular momentum produces millisecond periods, high energetics

    → gamma rays



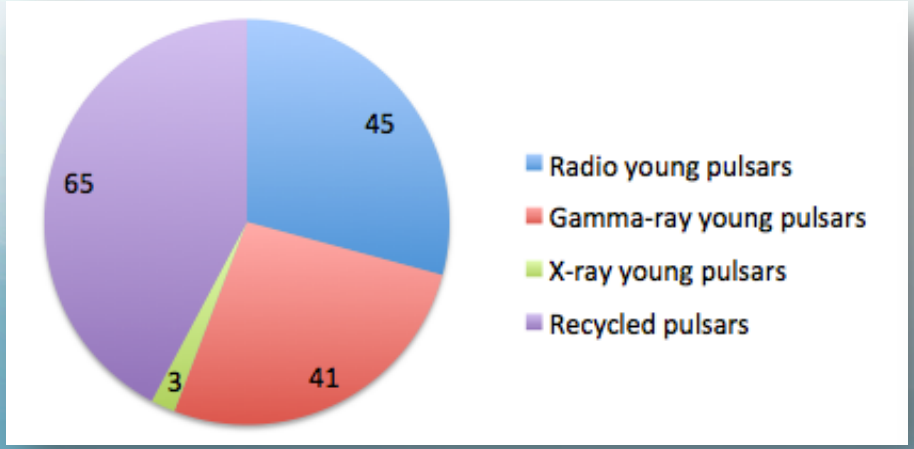
Millisecond Pulsars

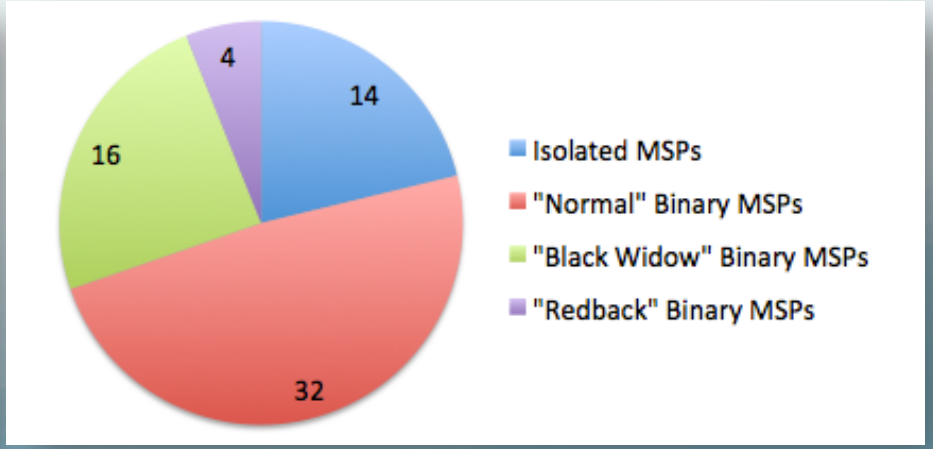
- Found in Galactic plane (~200) and in Globular clusters (many more)
- Fermi currently sees 65 of these (63 and 2)
- Distributed isotropically ⟹ very nearby



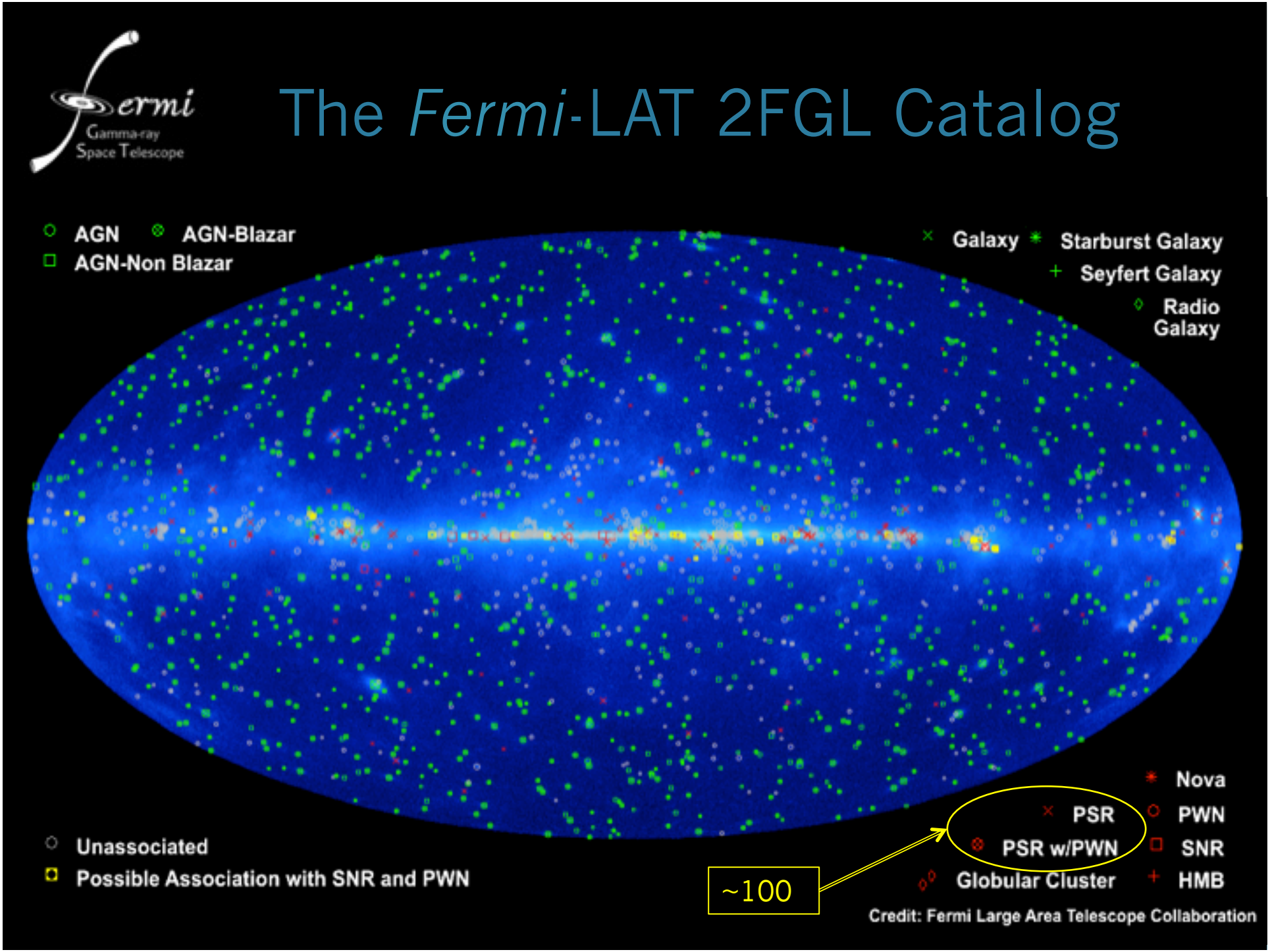
Pulsar Populations

- The young γ–ray detected pulsars are typically referred to by their discovery method
  - Radio-selected used known radio ephemerides to find the LAT pulsations
  - Gamma-selected were discovered by folding the γ–ray data (blind searches), and are usually radio-quiet (or very radio-faint)
- Most γ–ray MSPs were found using radio ephemerides
  - One MSP has been discovered using blind search techniques



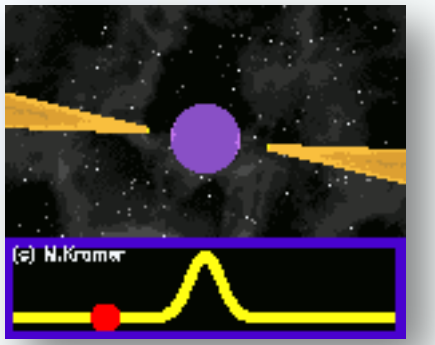


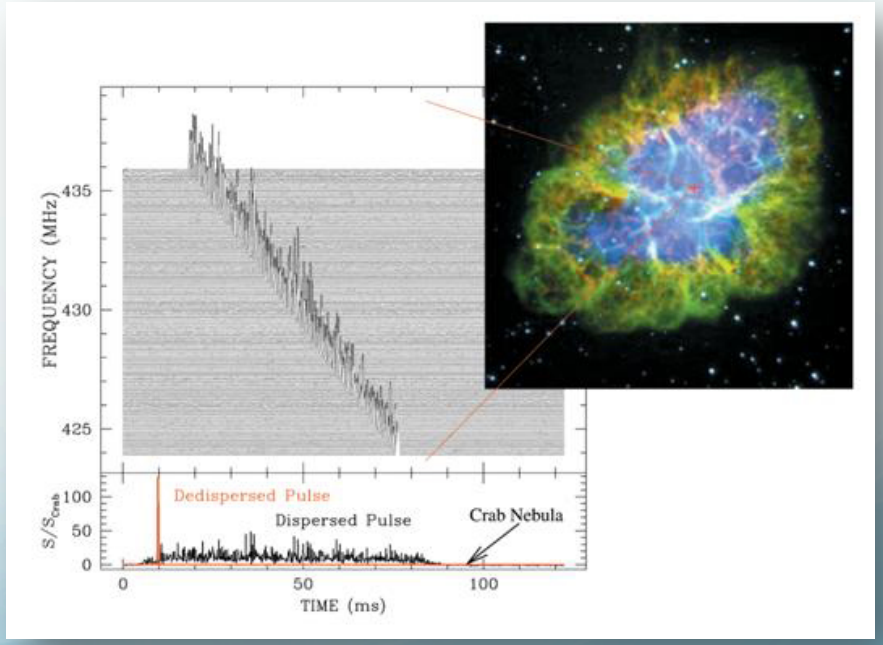
The *Fermi*-LAT 2FGL Catalog



Discovering Radio Pulsars - 1

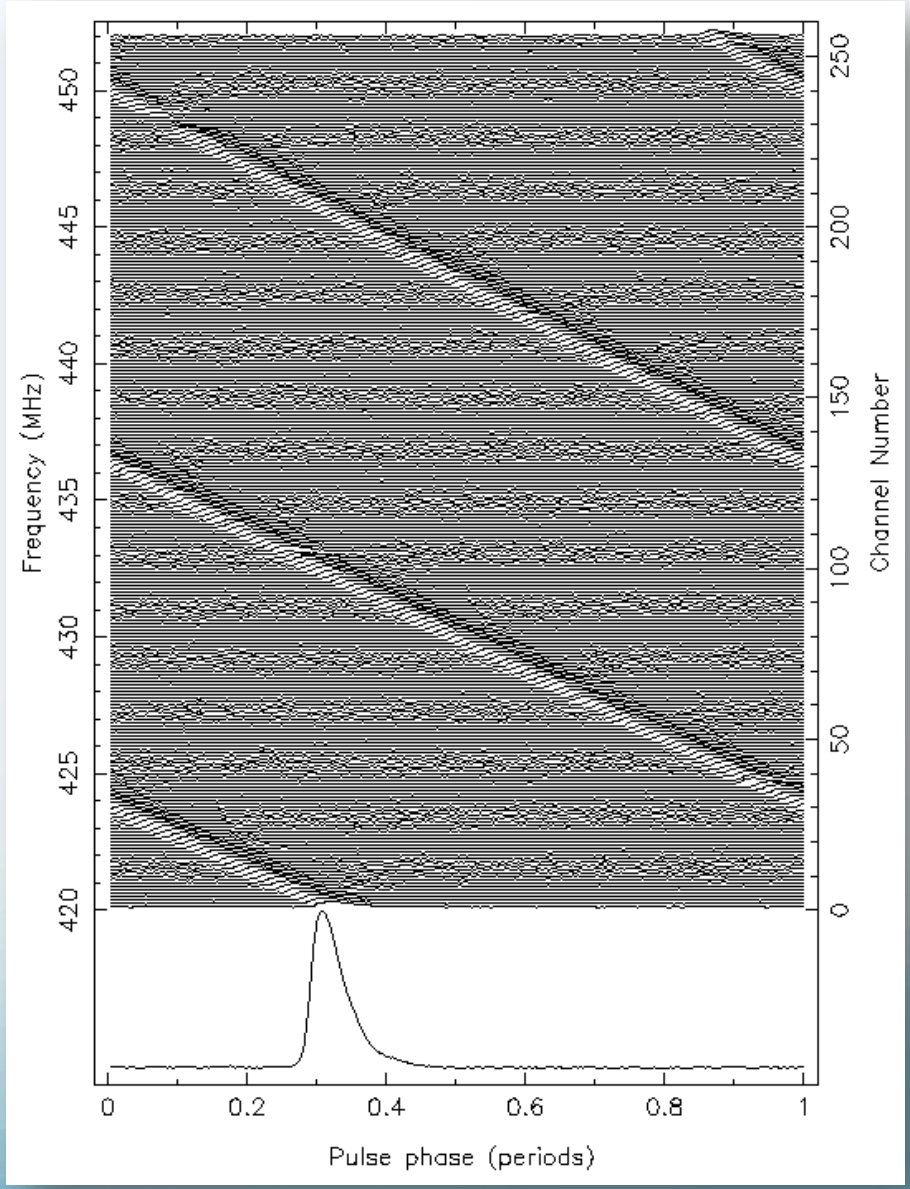
- Usually happens in the radio during large-scale surveys
- Pulsar search data consist of very high time-resolution spectra (typically 60 to 80 μ s)
- Pulse spectra get smeared out due to energy dispersion in the ISM... multiple overlapping pulses
- Longer travel time = more dispersion ⟶ Dispersion Measure





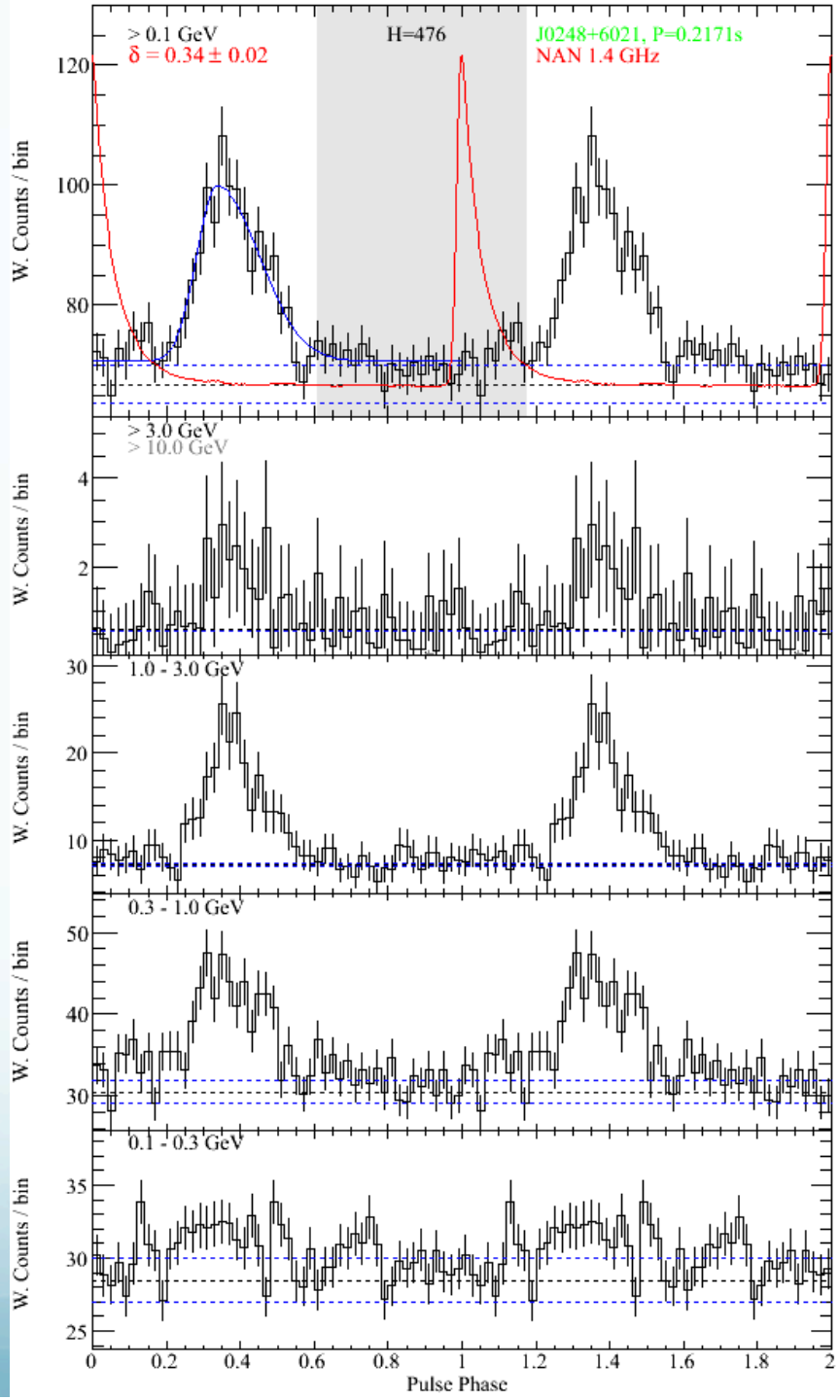
Discovering Radio Pulsars - 2

- Pulsar search code tests a grid of DMs
  - Optimized based on the hardware integration time and band pass for the receiver
- Period search is performed in the Fourier domain
  - Easier to test power in each putative signal
- Strongest signals are reviewed to look for radio frequency interference (RFI)



Radio/ γ -ray Pulsar Timing

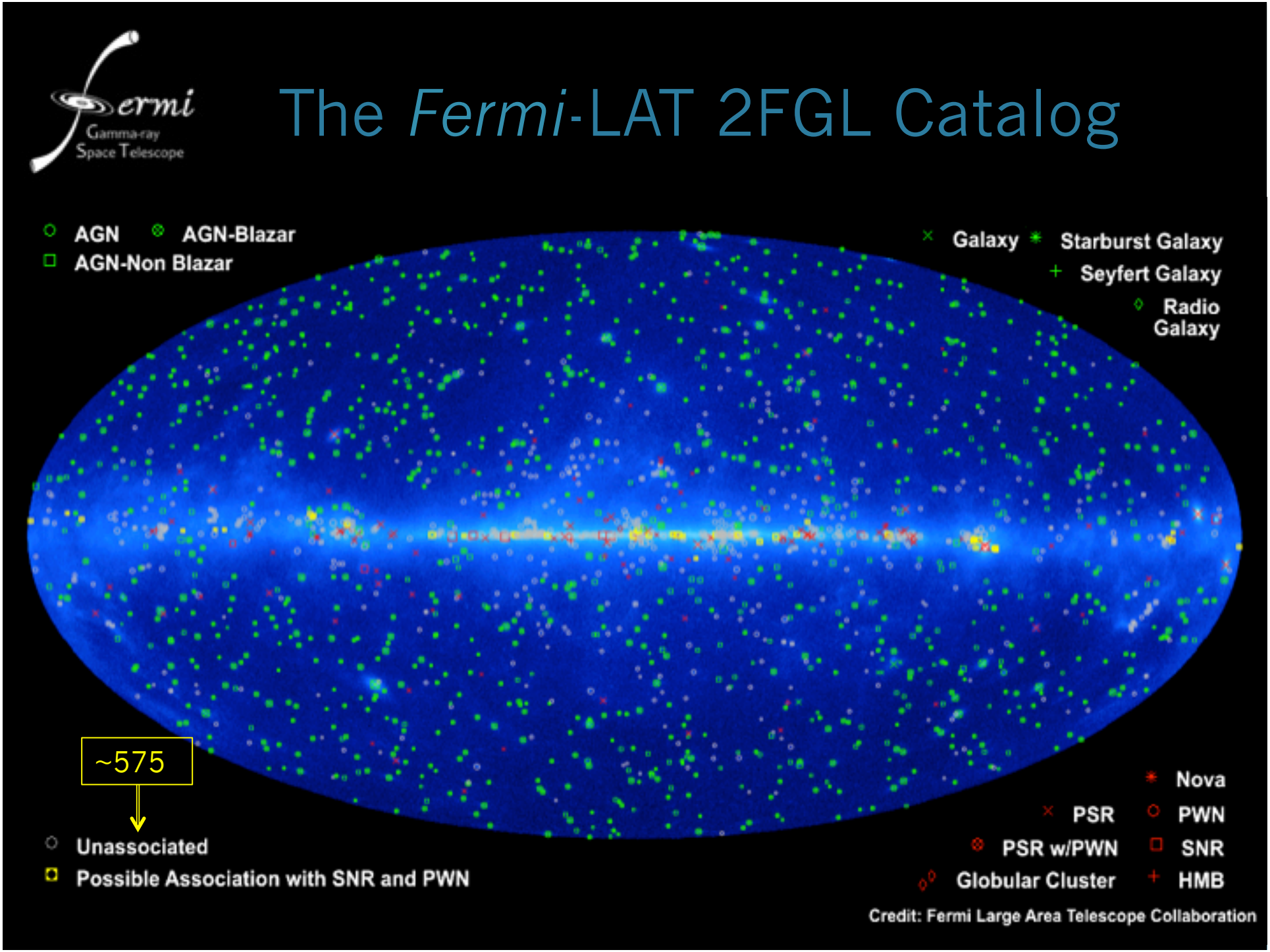
1. Regularly observe a known radio pulsar to produce very precise information about pulsar position, period, and spin-down rate
2. Gamma-ray photons are found that are consistent with pulsar position (often not in 2FGL!)
3. Apply timing model from #1 to gamma-ray photons from #2
4. Look for significant pulsations (H-test > 25)
5. Repeat with more pulsars



Pulsar Timing Consortium

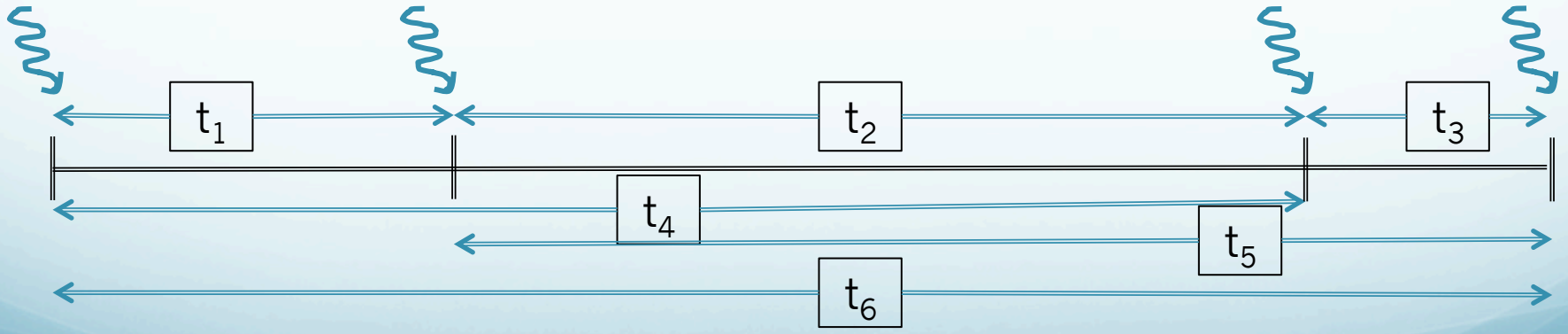
- Large campaign to provide radio/X-ray timing models for all pulsars (~200) with $E_{dot} > 10^{34}$ erg/s
  - Smith et al. 2008 A&A, 492, 923
  - Has since been extended down to $E_{dot} > 10^{33}$ erg/s
  - In total, team has searched LAT data for pulsations from 762 radio pulsars
  - GBT, Arecibo, Nançay, Parkes, Jodrell Bank, Westerbork
- Monitored pulsars are searched about every 6 months for gamma-ray pulsations
- 107 new gamma-ray pulsars found!
- Timing models have been released publicly by LAT PTC collaborators via the FSSC

The *Fermi*-LAT 2FGL Catalog



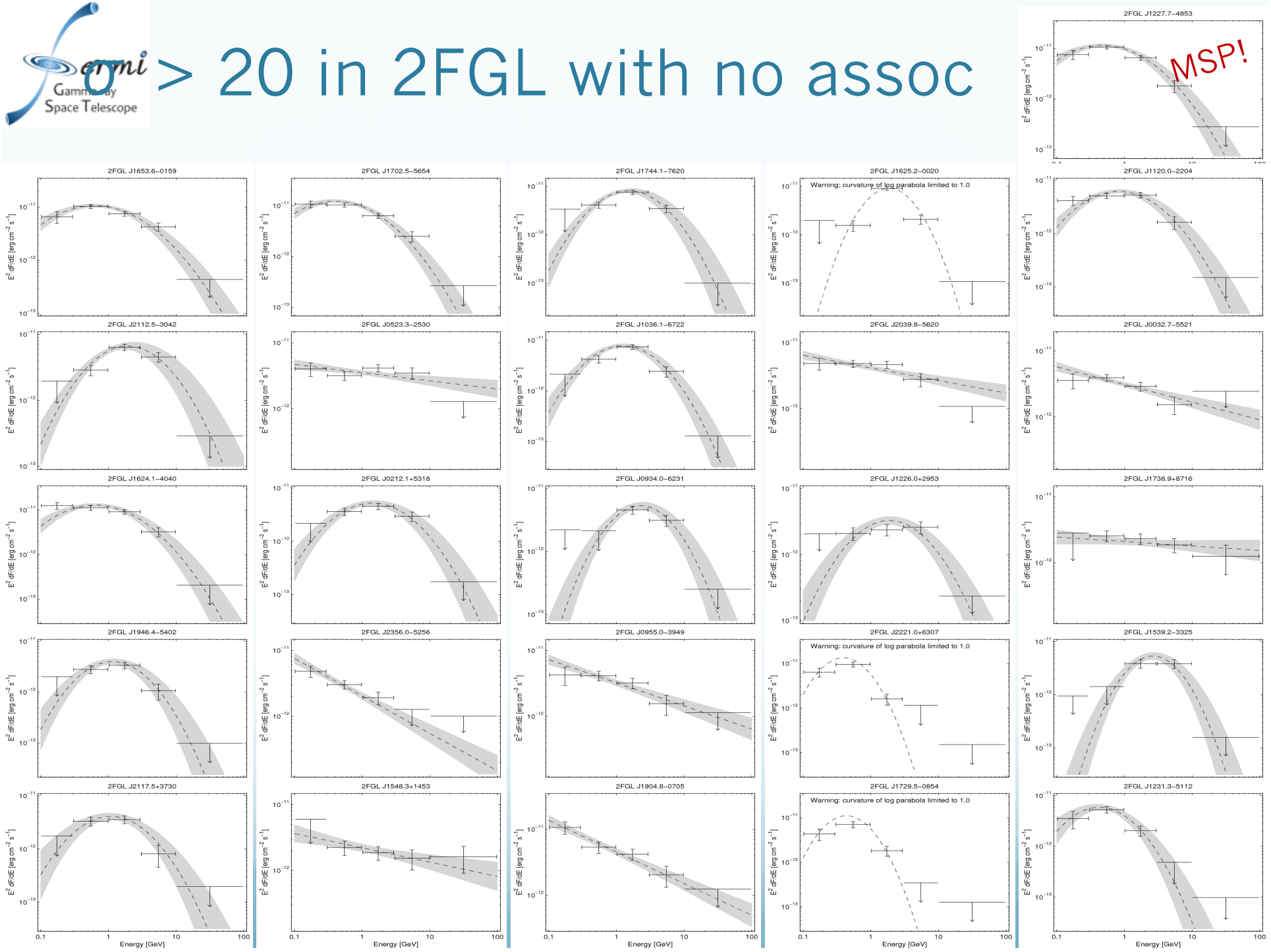
γ-ray Blind Searches

- Look for pulses from bright sources with clearly pulsar-like spectral shapes
- Pro – No dispersion!
- Con – Not enough statistics!
  - Only one photon every 2.6 minutes from Vela
- New technique: time differencing
  - First applied to EGRET data



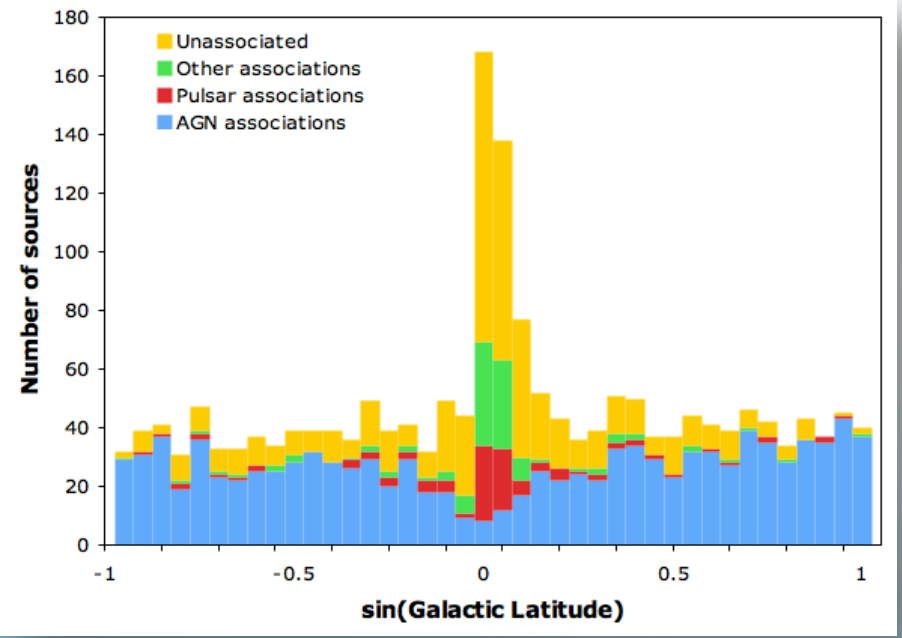
- Discovered 41 of the 42 gamma-selected pulsars

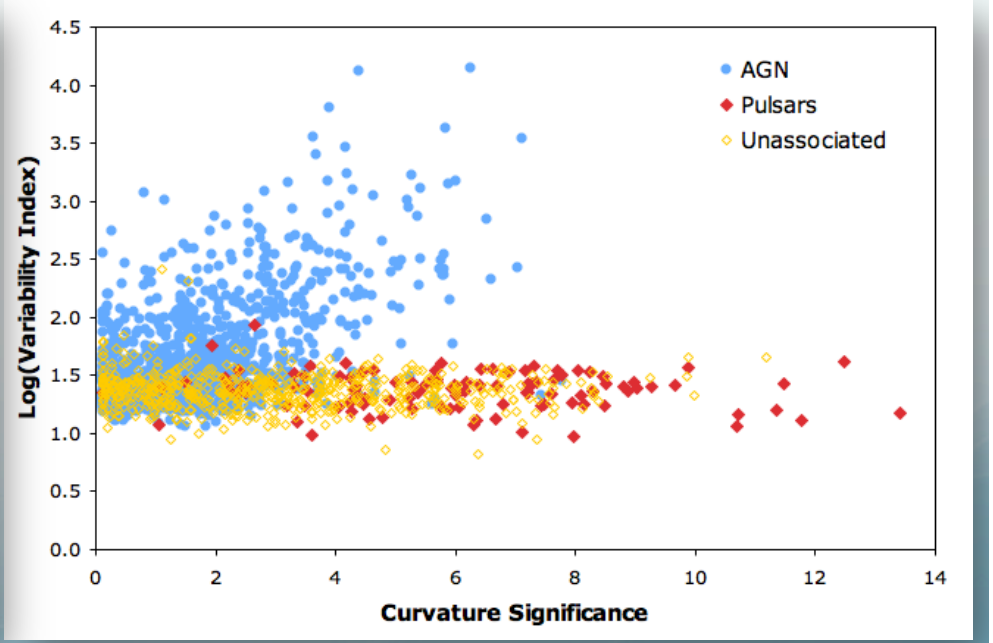
> 20 in 2FGL with no assoc



500+ Unassociated *Fermi* Sources

- What are they?
  - Mixture of known source classes
    - Sub-luminous AGN, pulsars, SNRs, etc.
  - Some fraction of false positives
  - Previously unknown classes of γ–ray emitters?

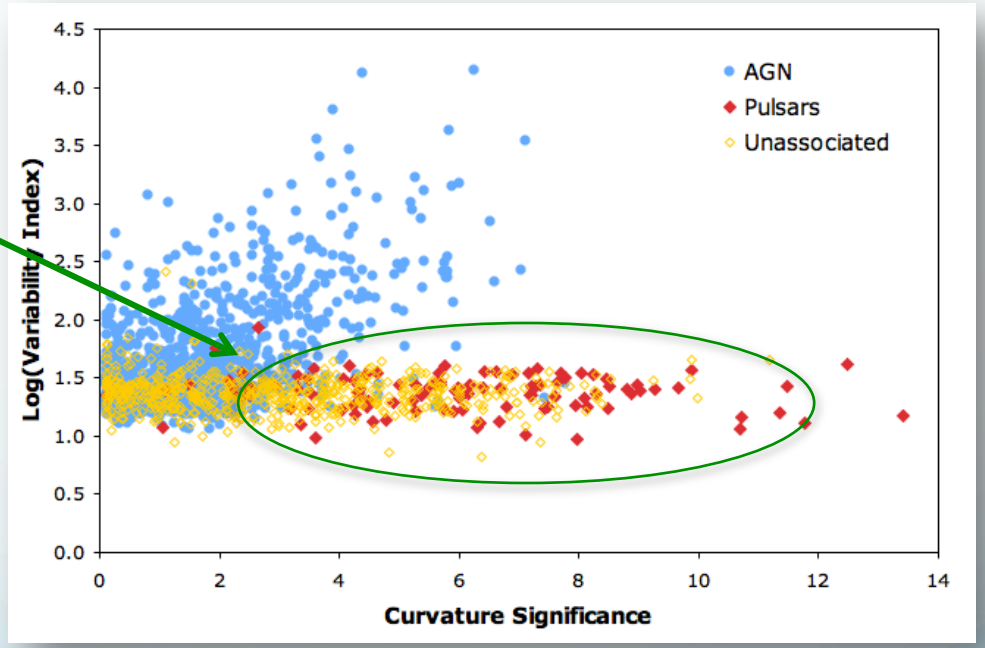




Use γ–ray info to select targets

Here is a simple recipe for finding new γ–ray pulsars:

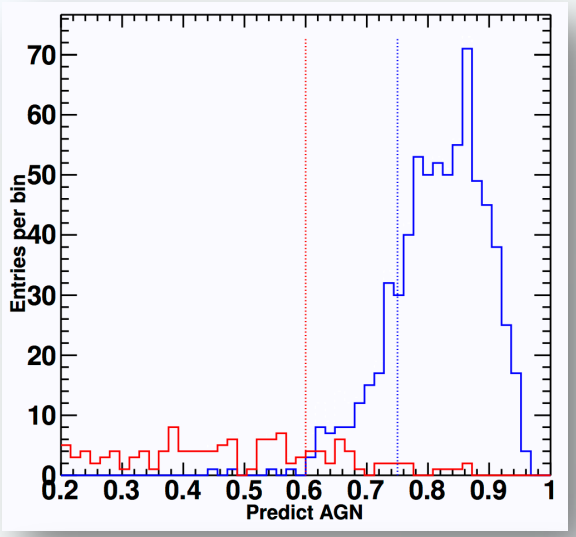
1. Select non-varying γ–ray sources with curved spectra
2. Observe at radio frequencies to search for pulsed signal
3. Find pulsars
4. Wait a year for good timing data
5. Test for γ–ray pulsations
6. Celebrate! (usually)

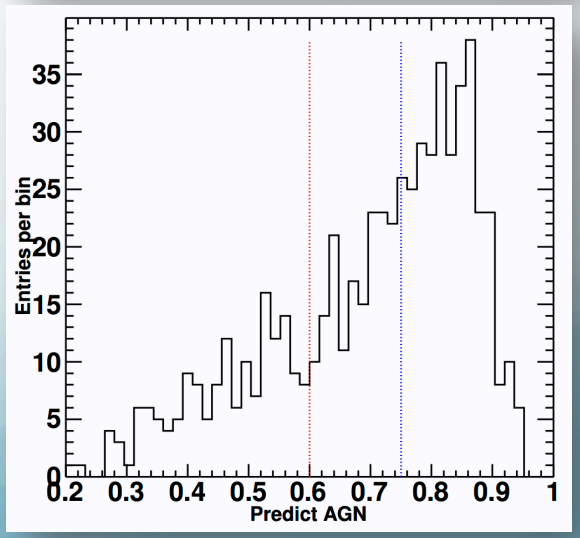


Okay, not quite that simple....

Target Selection

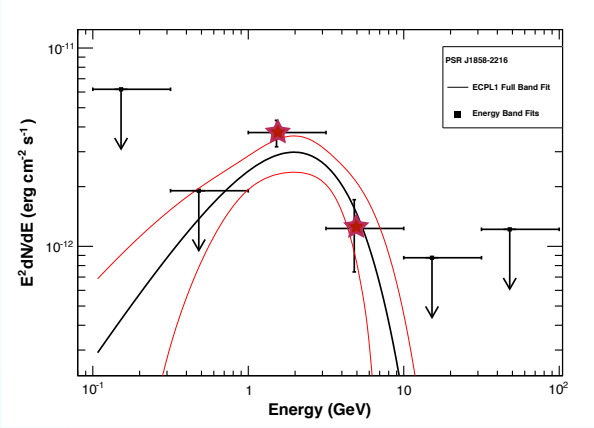
- Numerous methods of machine learning tried:
  - Classification trees
  - Logistic regression
  - Artificial Neural Networks
  - Random Forests
  - Support Vector Machines
- Train parameters with partial list of associated sources
- Test on independent set to determine efficacy
- Problem is source flux! Not enough information in the faint unassociated source population.

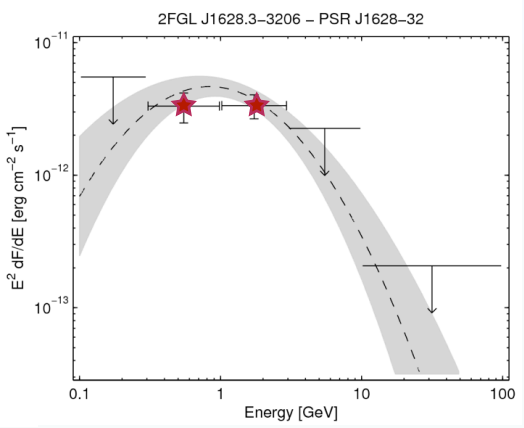


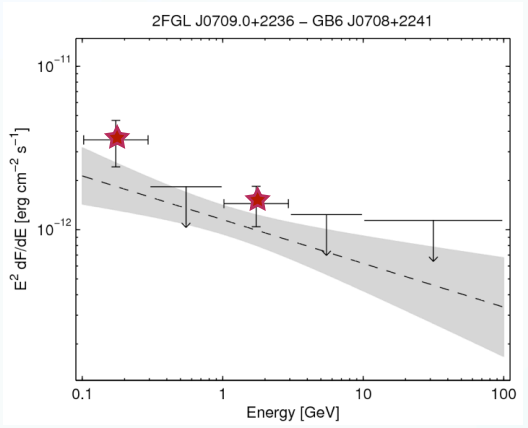


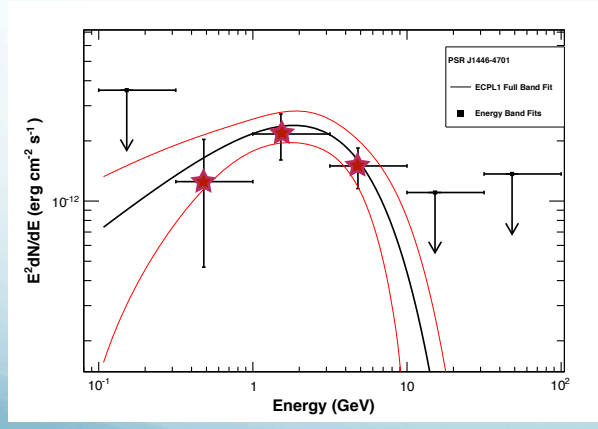
Increase source selection

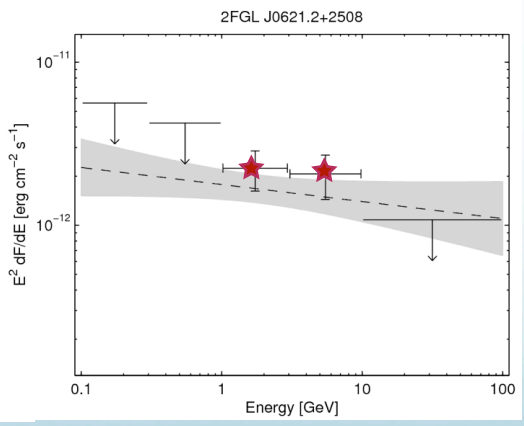
- Most Fermi unassociated sources are faint in the gamma-rays
- Few non-variable, significantly curved sources left to search

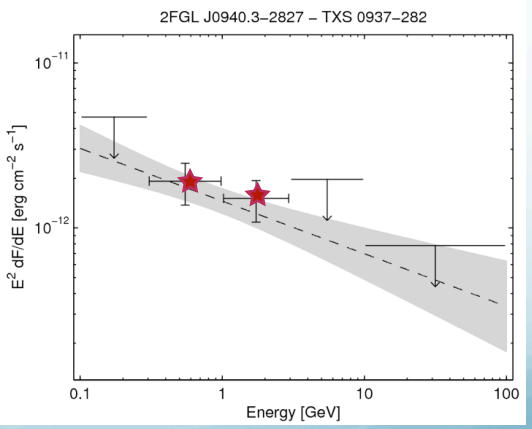












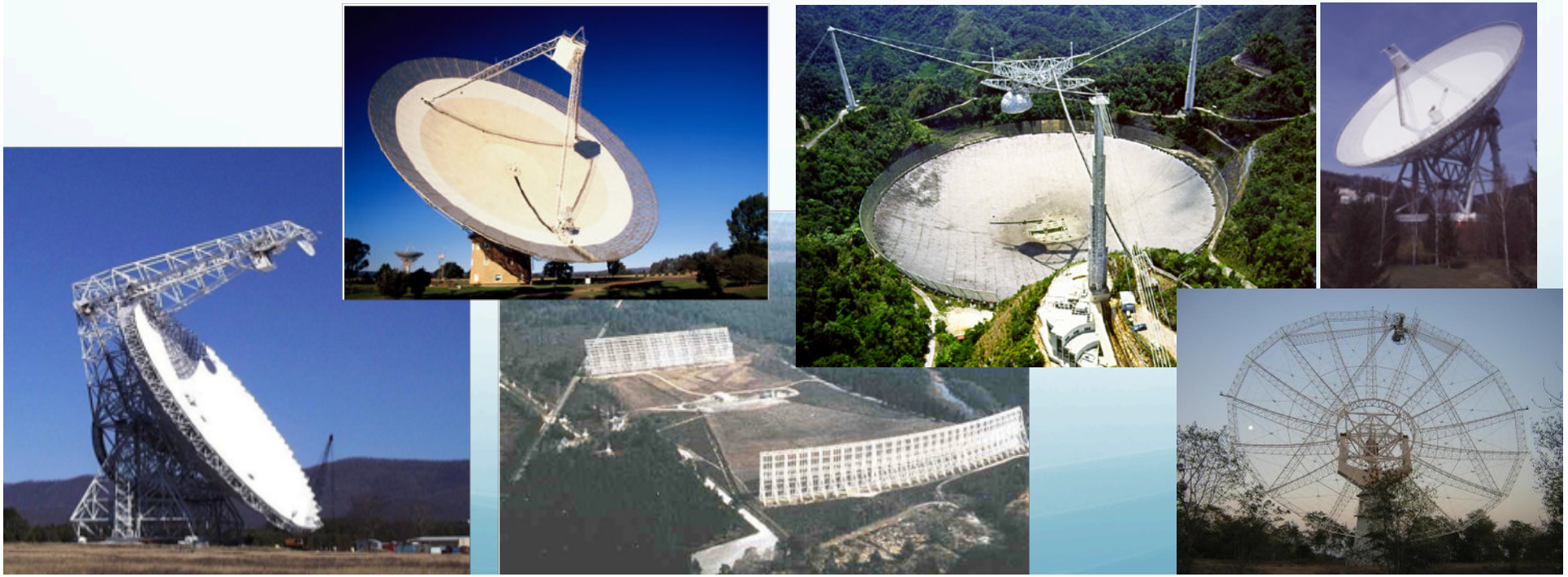
LAT-detected MSPs (from recent 2PC)

Radio MSPs found in LAT 2FGL positions

AGN of "uncertain type" (from 2FGL)

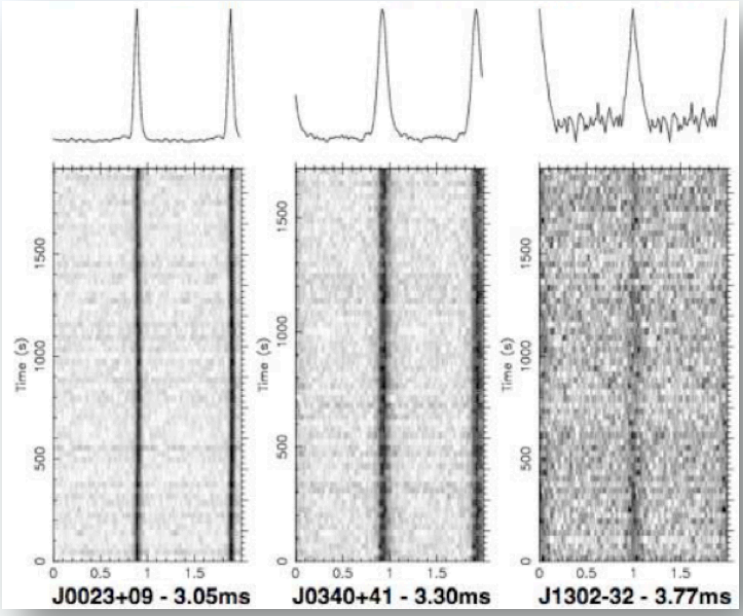
Pulsar Search Consortium

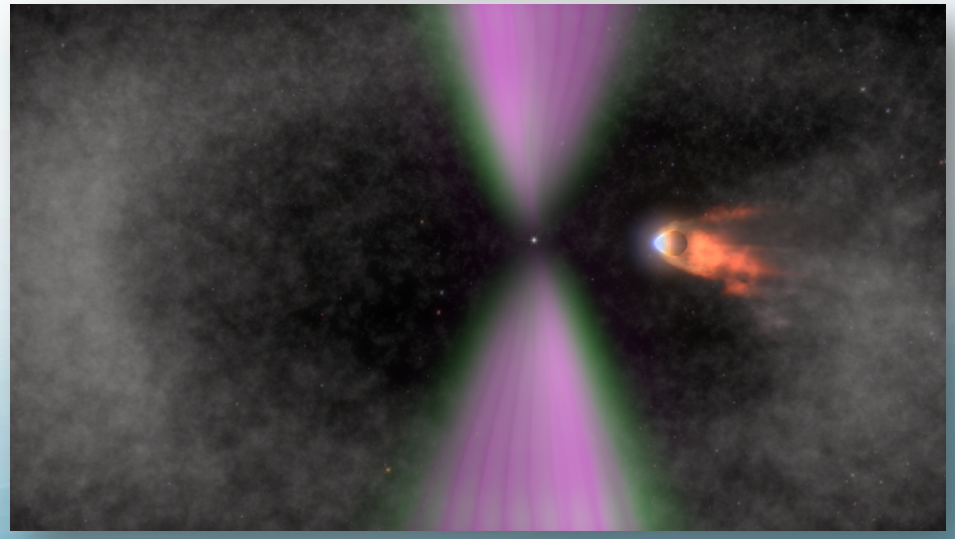
- Loose collaboration of many of the world's largest single-beam radio telescopes
  - GBT, Arecibo, Nançay, Parkes, Effelsberg, GMRT
- ~30 radio and γ–ray researchers working together
- Goal is to find new radio pulsars in *Fermi*-LAT sources
  - Mostly searching off the plane ⟶ MSPs



Not a simple task

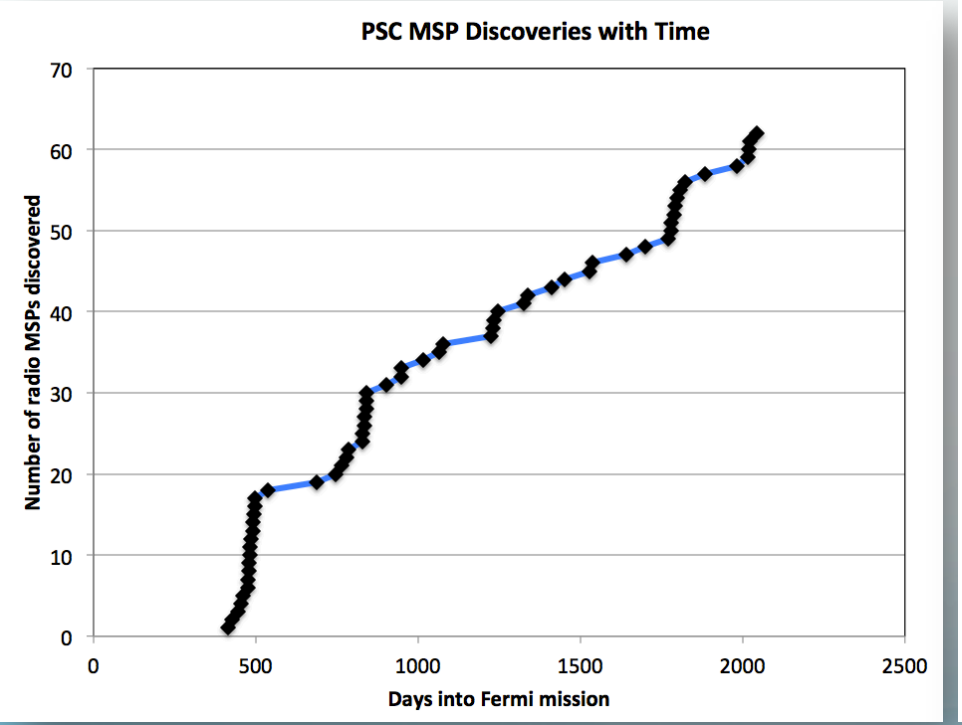
- Non-trivial time requirements
  - Data collection, analysis, follow-up of candidates
- ISM can cause scintillation of the pulsed signal
  - Fluxes can vary by a factor of 50 or more
- ~25% of γ–ray MSPs are in tight binaries
  - Pulsar emission is eating away at companion star
  - Material in system can obscure pulsation
- Some sources are detected in fewer than half of the observations!

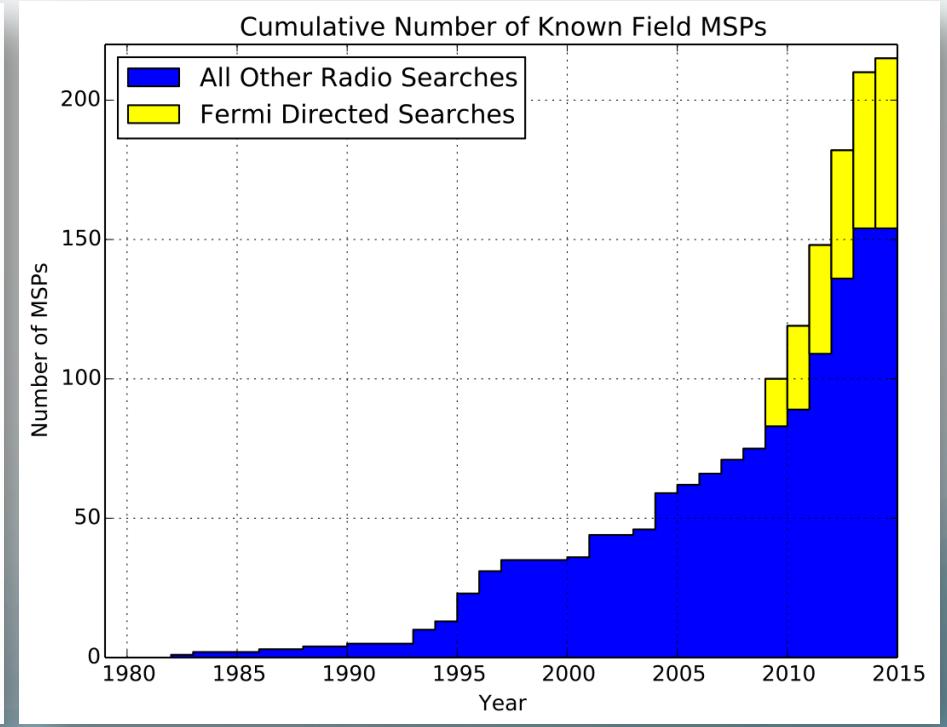




Very successful!

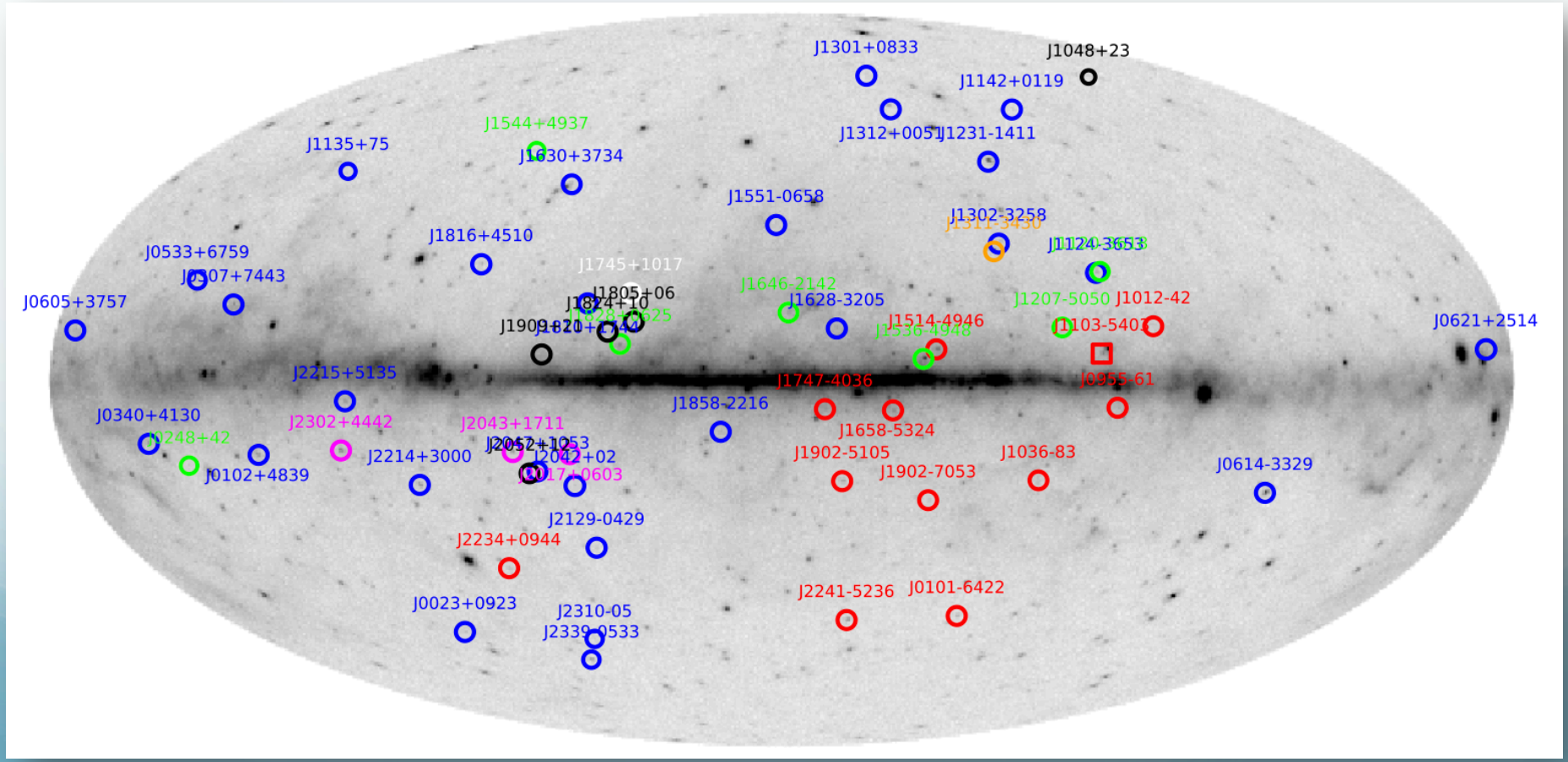
- ~60 previously unknown MSPs have been found by the Pulsar Search Consortium
  - Significant increase in Galactic MSPs since launch of *Fermi*
  - PSC-discovered MSPs are ~1/3 the total known in Galactic plane





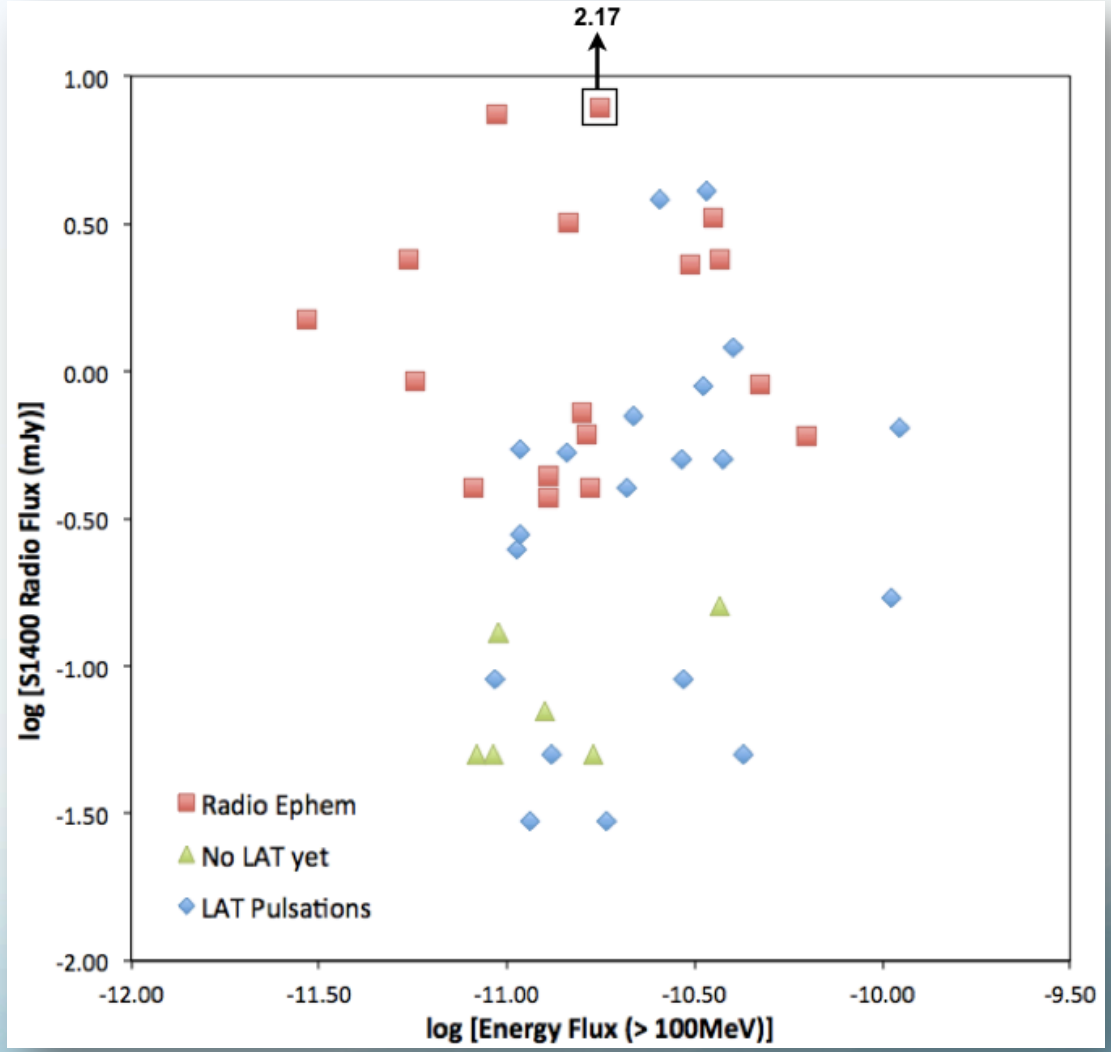
PSC discoveries

- New pulsars have been discovered by all participating observatories
  - Of 66 discoveries, four are chance coincidences

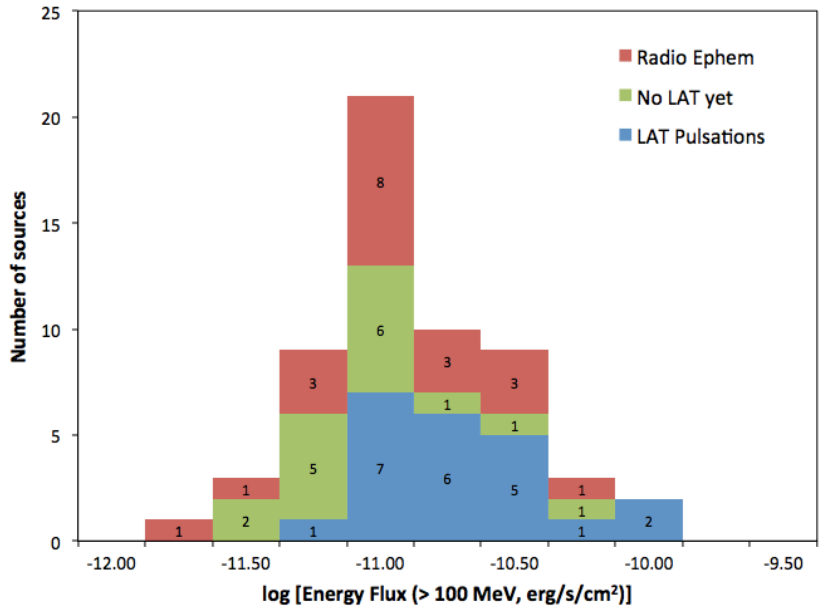


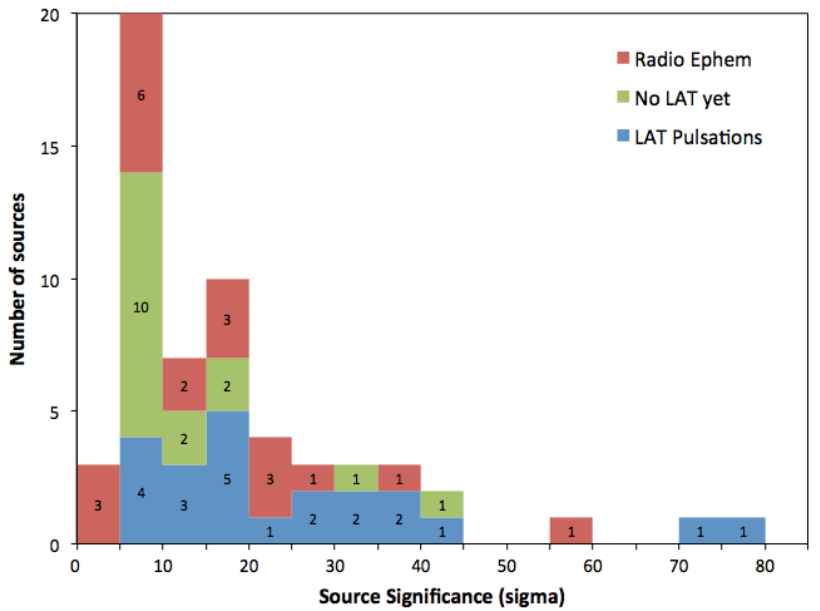
γ-ray flux not an indicator

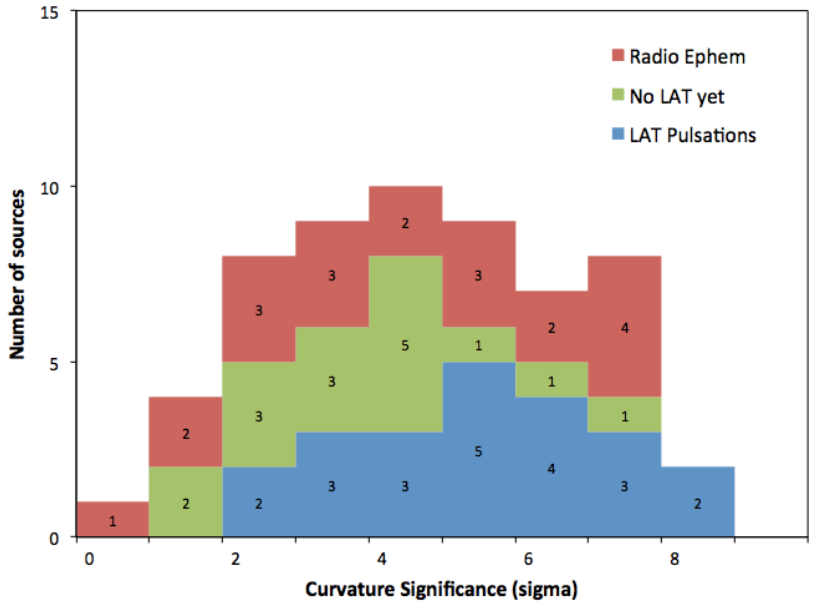
- Second pulsar catalog (2PC) showed clearly that radio flux does not correlate with γ–ray flux for LAT pulsars
- Large number of faint *Fermi* sources remain unsearched
- Also false positives expected from AGN association process

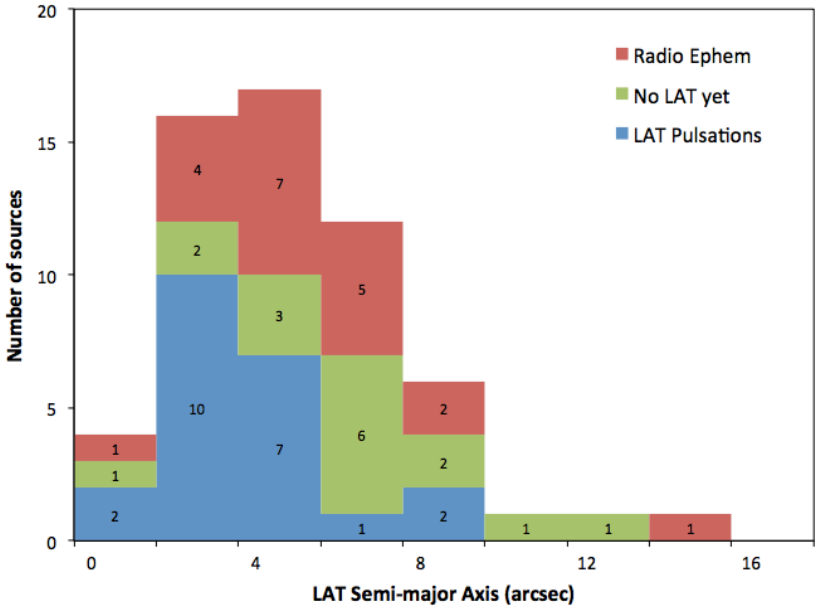


Other Pulsar Characteristics



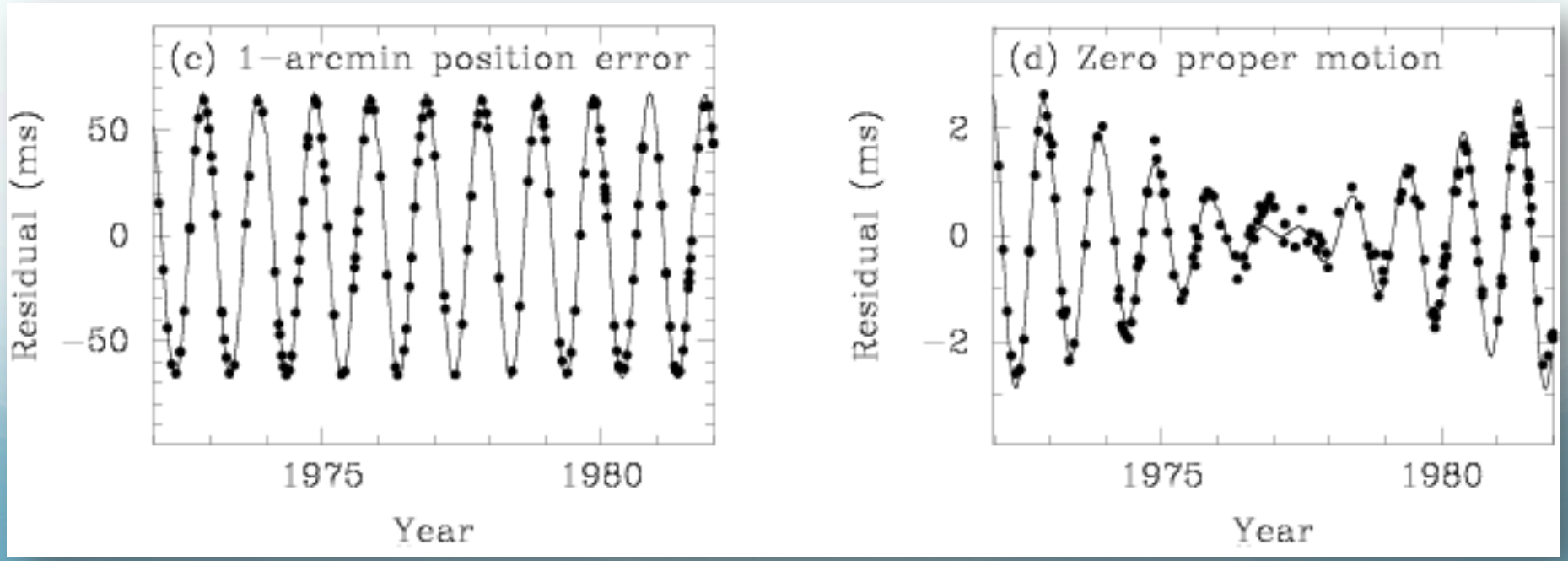




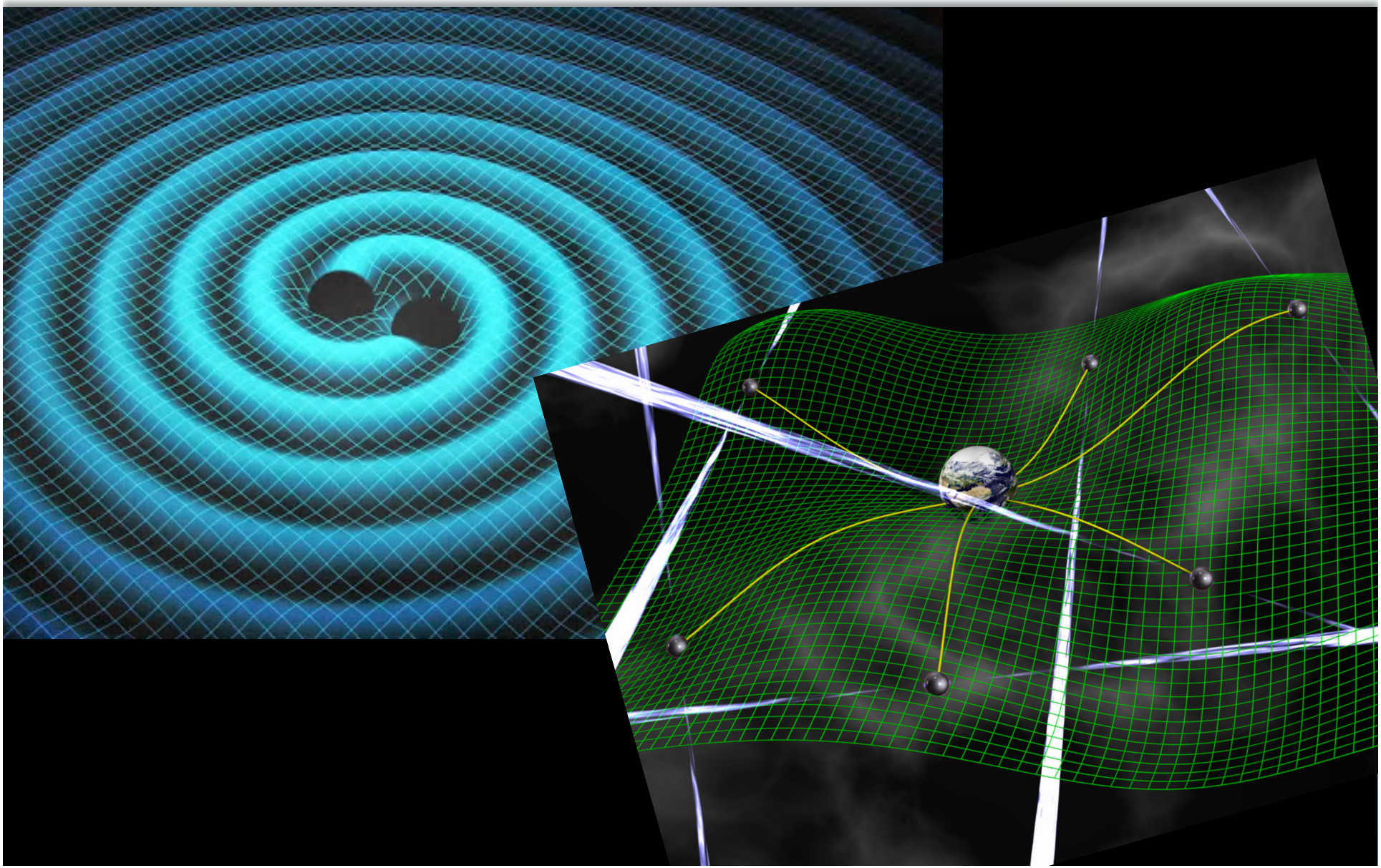


Why more MSPs?

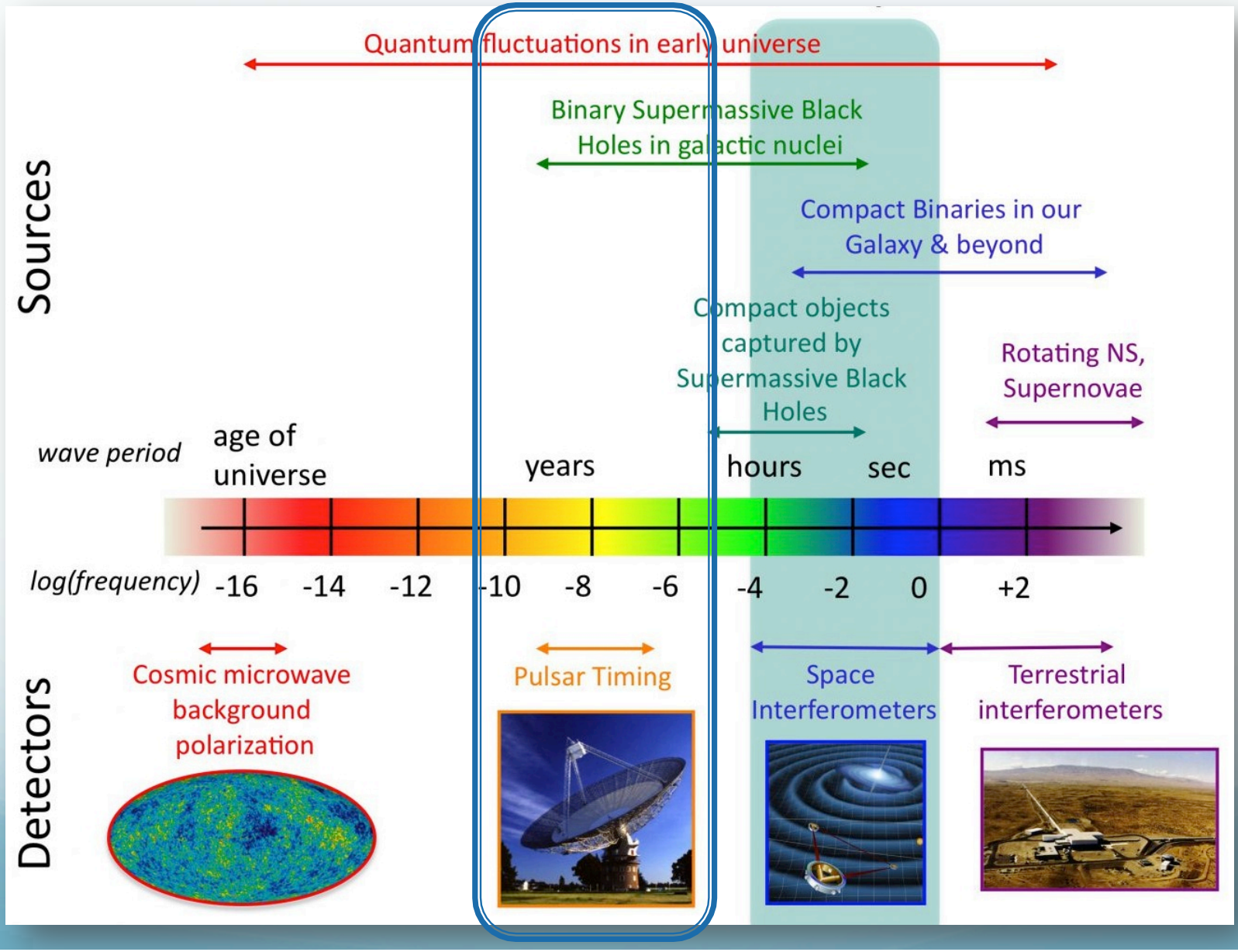
- Millisecond pulsars are extremely stable clocks
  - Change in period typically ~10^{-19} s/s
  - Can be cleanly modeled with very small residuals
  - Perturbations provide information about the system
  - Use residual signal to improve model…iterate



From Pulsars to Black Holes



Gravitational Wave Spectrum



Pulsar Timing Arrays

- Several PTAs globally
  - NANOgrav (North America), EPTA (Europe), and PPTA (Parkes)
- Large collaborations of pulsar astronomers + AGN astronomers
  - Reduce MSP timing residuals
  - Select good candidate sources
- Above 3 have combined into the IPTA
  - Need global coverage
  - Recently completed 6-telescope, 24-hour observation of PSR J1713+0737

Why more pulsars? Better GW signal!

- SMBH GW detectability requires:
  - More narrow peaked MSPs (improves timing)
  - Wide distribution of MSPs in position (RA, Dec)
- New MSPs continue to be found by *Fermi*-LAT
  - Orbital solutions take ~1 year
  - Beat down timing residuals to level needed for PTAs
  - So far, 11 Fermi MSPs added to various PTAs, all from just the first 1.5 years of *Fermi* discovery
- PTAs are the start of a new kind of instrument, tuned to observe a particular region of the gravitational wave spectrum

Looking Forward

- GW astronomy is opening a new window on the universe
  - Complementary science to E-M astronomy
- PTAs will provide a "natural" instrument for GW observations
  - Only require frequent and regular radio observations
  - No expensive space hardware to construct
  - Once characterized, an MSPs will not "wear out"
- *Fermi* will continue to deliver new MSPs
  - Even after mission ends (hopefully not soon)
  - Now > 1000 sources to search!

Single-dish radio telescopes are key for finding Fermi MSPs and future PTA detection of gravitational waves