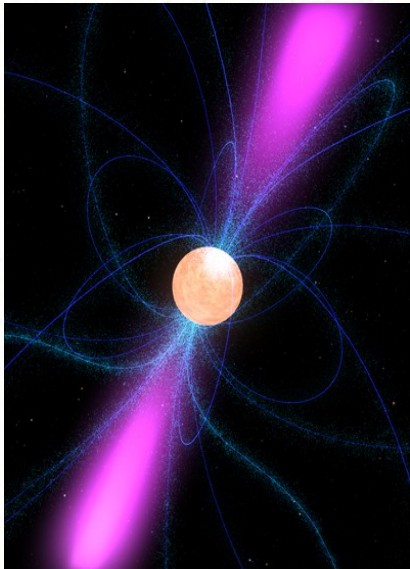


Green Bank Telescope (GBT) Radio Millisecond Pulsars Searches in *Fermi* Unassociated LAT Sources



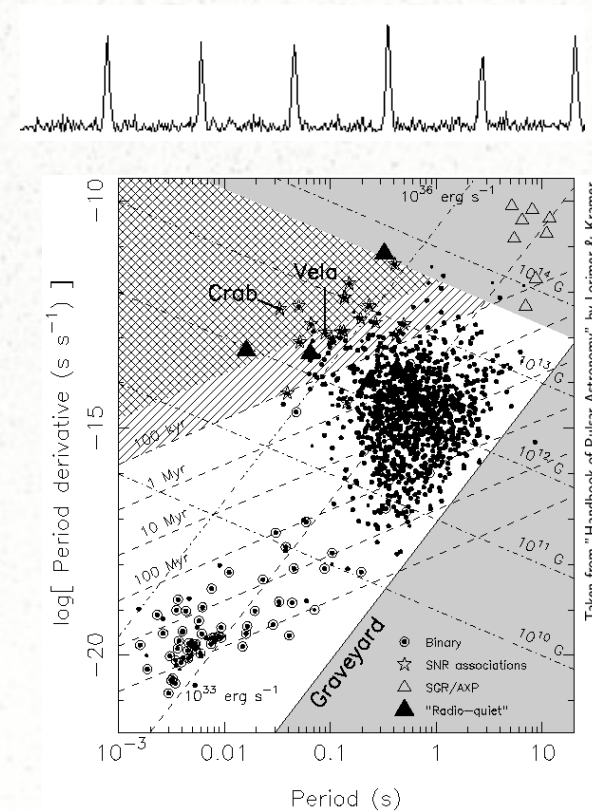
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Fermi Summer School 2014, June 2
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Outline

- What is pulsar? Duh!
- Do we need more pulsars? YES!
- Why *Fermi*? It's awesome
- Why GBT? It's awesome too
- **How to search for a new pulsar (especially MSP)?** Such a pain...

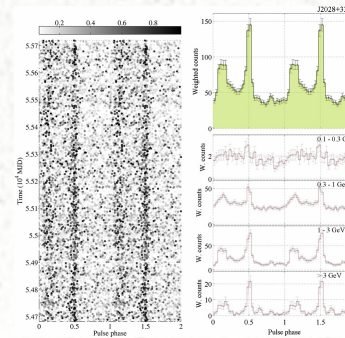
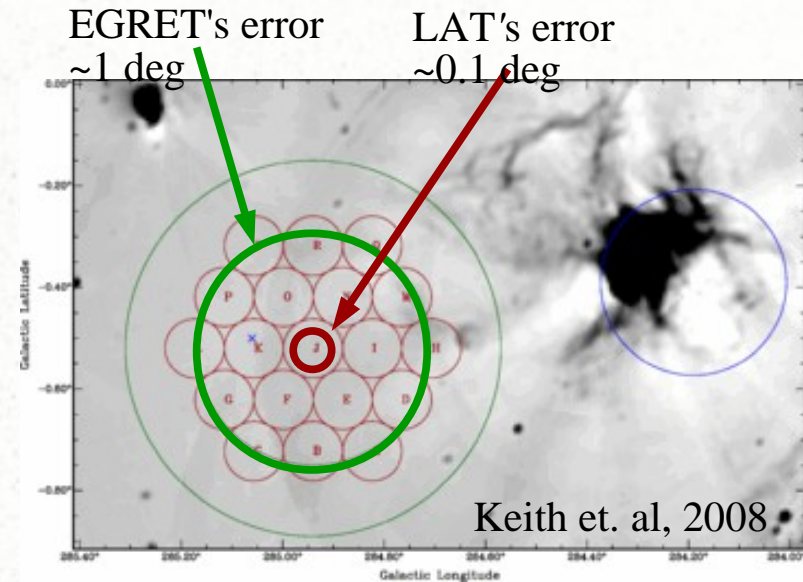
Pulsars

- Highly magnetized rotating neutron stars (spinning dead stars).
- Extreme objects: super-nuclear dense neutron star core (unknown equation of state), extreme gravity in binaries (tests of GR) and extreme magnetism ($B \sim 10^{14}$ G in Magnetars).
- Clock of the universe: normal pulsars and millisecond pulsars



Pulsars with *Fermi* LAT

- *Fermi* LAT has better sensitivity and spatial resolution, and wider energy range: **more sources and smaller positional error.**
- **148** *Fermi* pulsars were discovered so far: **41** pulsars from blind search in gamma-ray data, **59 (and counting) Galactic MSPs** from radio follow-up observations by *Fermi* Pulsar Search Consortium led by Paul Ray.
- Out of 59 MSPs, **29 MSPs were found with the GBT!** The 100-meter dish can see 85% of the sky (fully steerable) and covers 95% LAT error region with a single pointing at 820 MHz or 350 MHz beam.

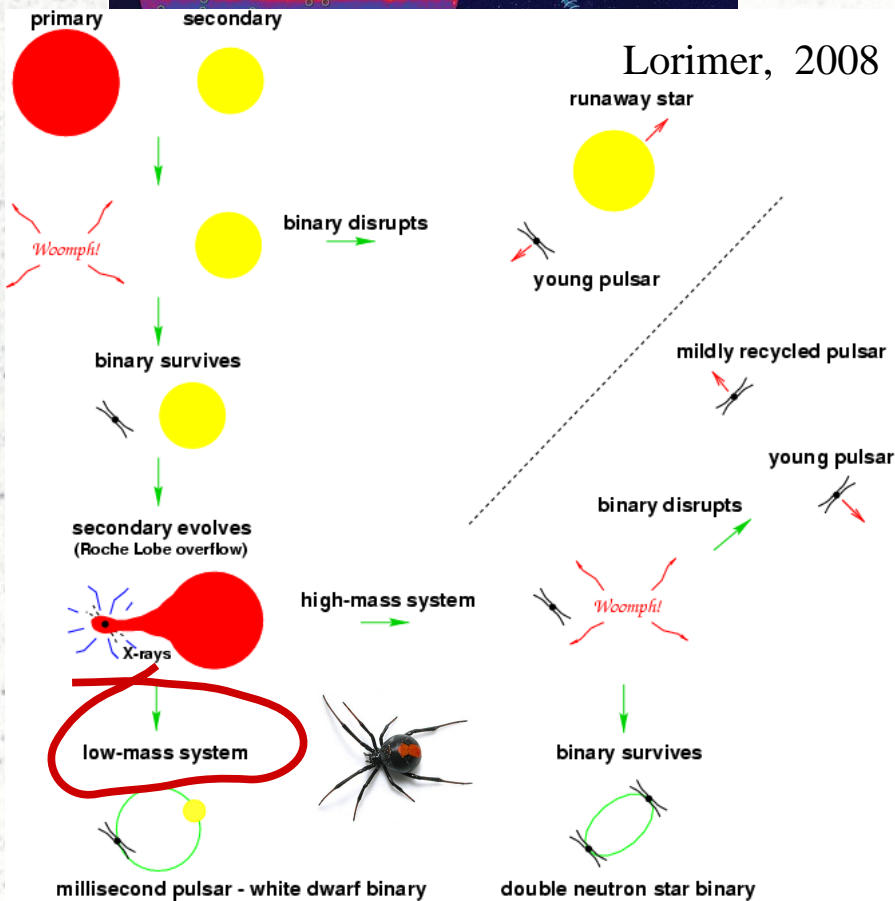
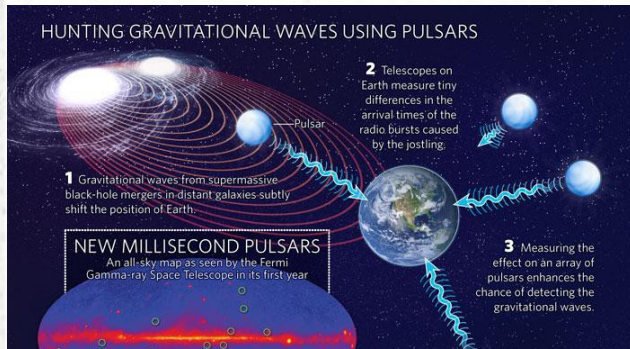


Pletsch. et.
al, 2012



Radio Quite Zone!

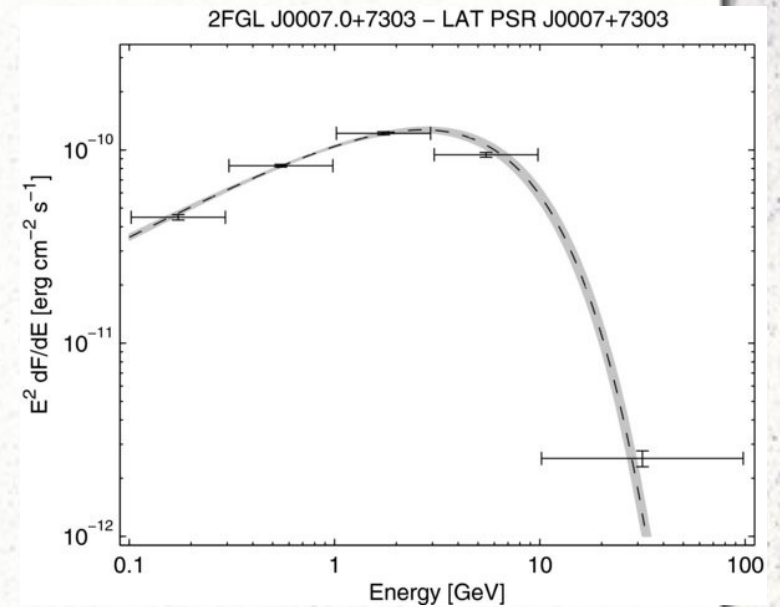
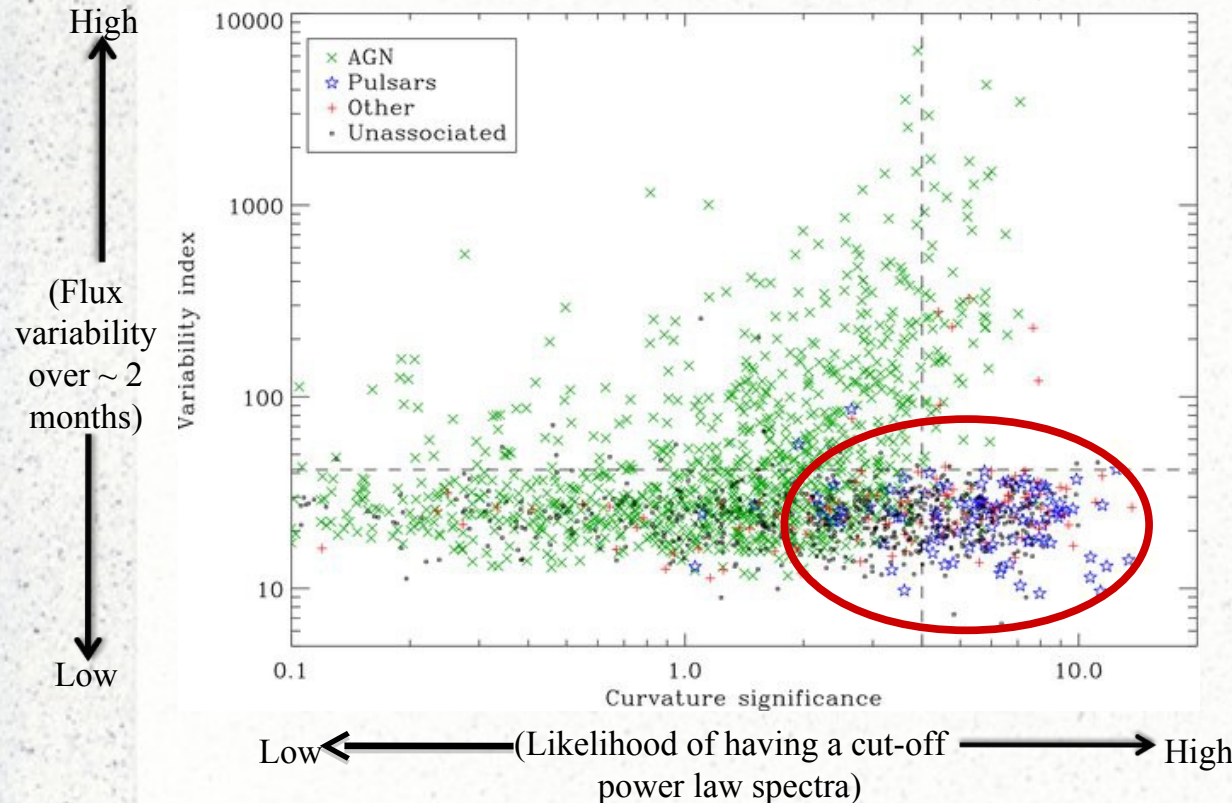
Pulsars with *Fermi* LAT



- Given that **It took nearly 25 years to find 75 Galactic MSPs prior to Fermi LAT**, the discovery of 59 MSPs in four and a half year is phenomenal.
- LAT targeted energetic pulsars, especially MSPs in binaries which are the best laboratories for the test of GR, compact object and giving the most precise timing (direct detection of gravitational waves!).
- Rare type of MSPs in binaries: Redbacks (with a main sequence companion) and Black Widows ($M_c \sim 0.01 M_{\text{sun}}$).
- Only 3 “spiders” were known at the time of the Fermi launched... We have found at least new 19 spiders and **17 of them are *Fermi* MSPs.** (Mallory, 2012)

Sources Selection

Nolan et. al, 2012

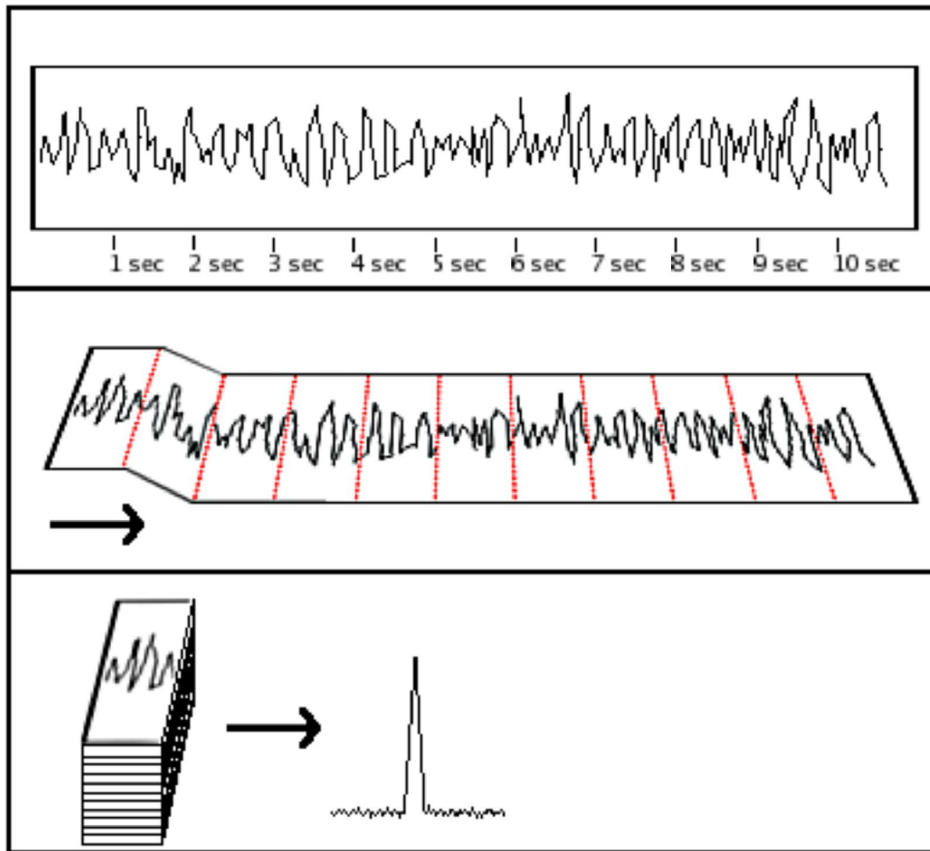


Exponentially cutoff spectrum

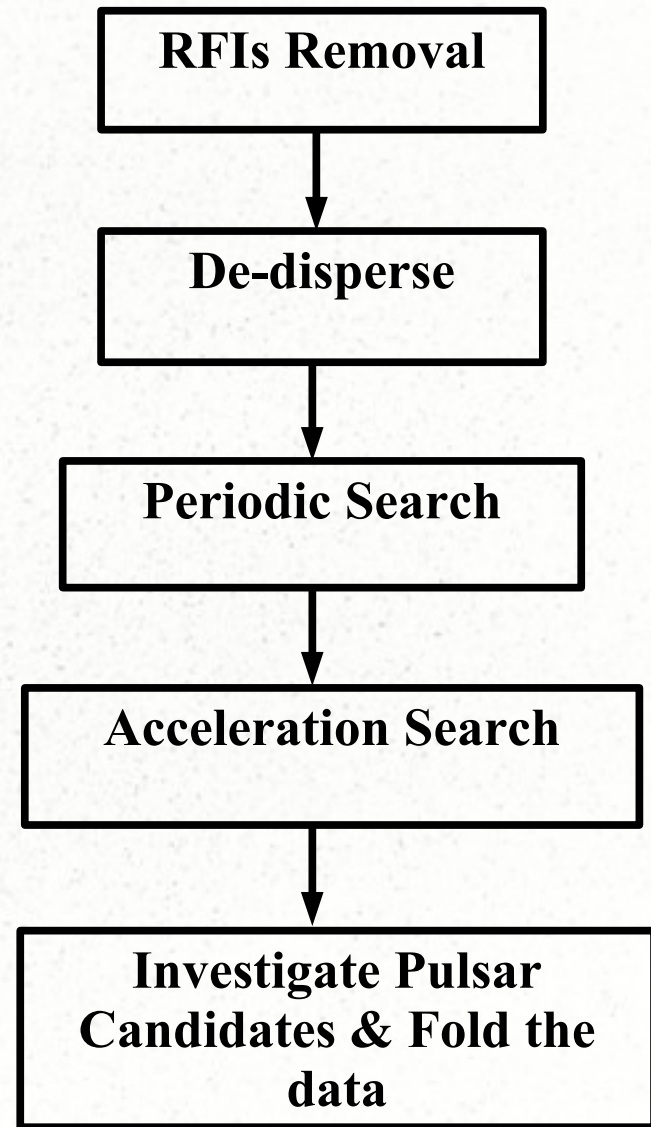
- Elizabeth Ferrara selected “pulsar-like” sources and made a source list which matched the GBT's beam (350 MHz, 820 MHz or 2 GHz)

Searching for New Pulsar

Fold the Data



- Since pulsar has a periodic signal, dividing data into small pieces at its spin period and adding them together should increase the signal of pulsar.
- It's not that simple...



PRESTO pulsar package (Ransom, 2001)

Searching for New Pulsar

RFIs Removal

De-disperse

Periodic Search

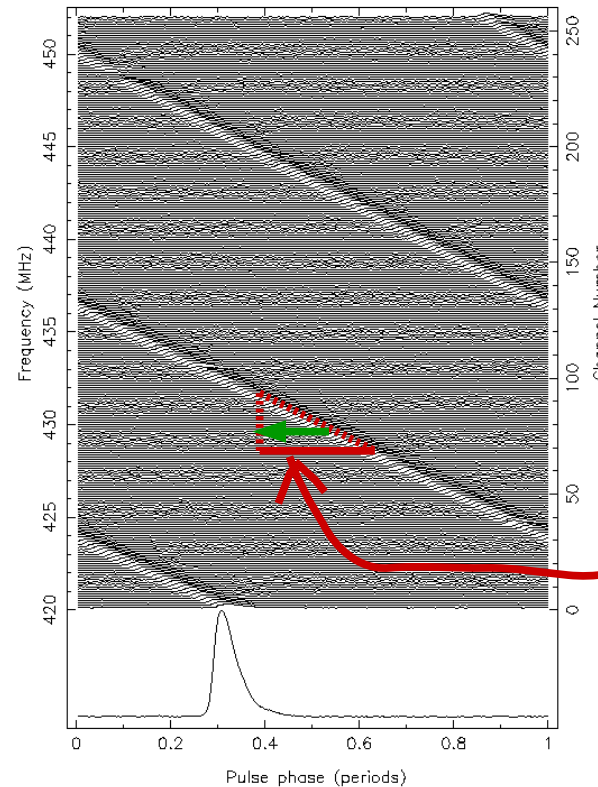
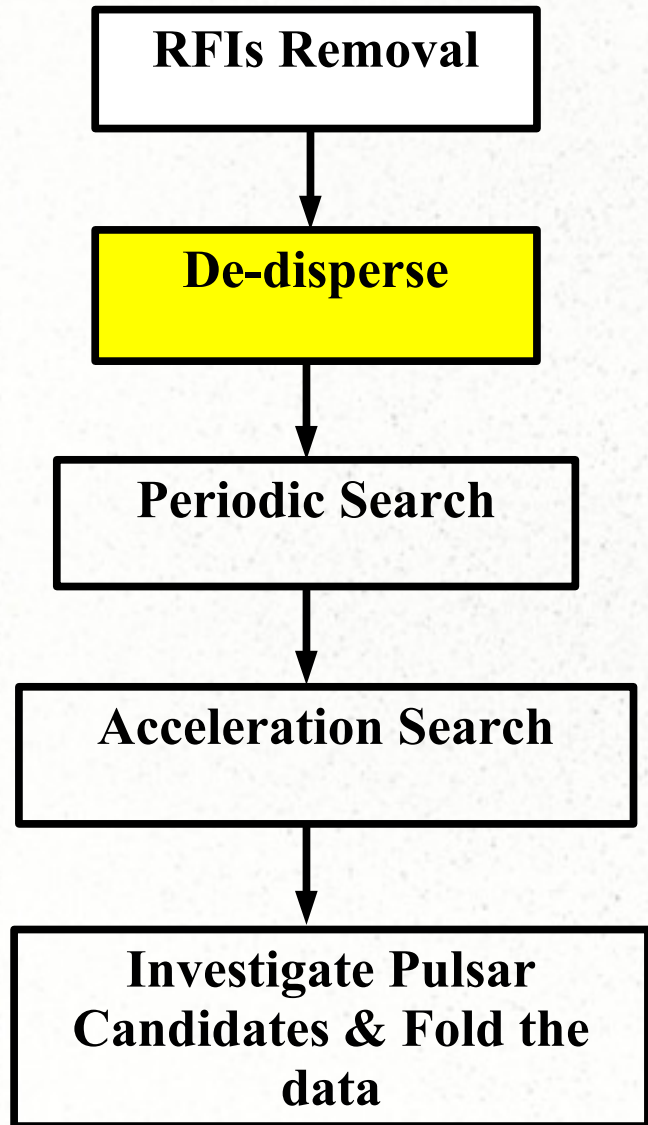
Acceleration Search

**Investigate Pulsar
Candidates & Fold the
data**



- RFI = Radio Frequency Interference
- Strong burst and low-level continuous signals
- PRESTO: rfind

Searching for New Pulsar

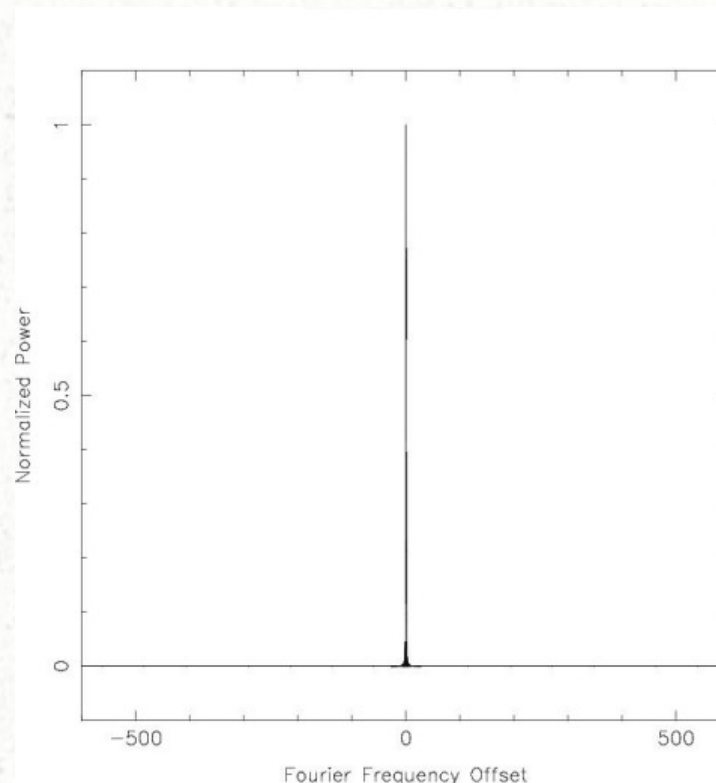
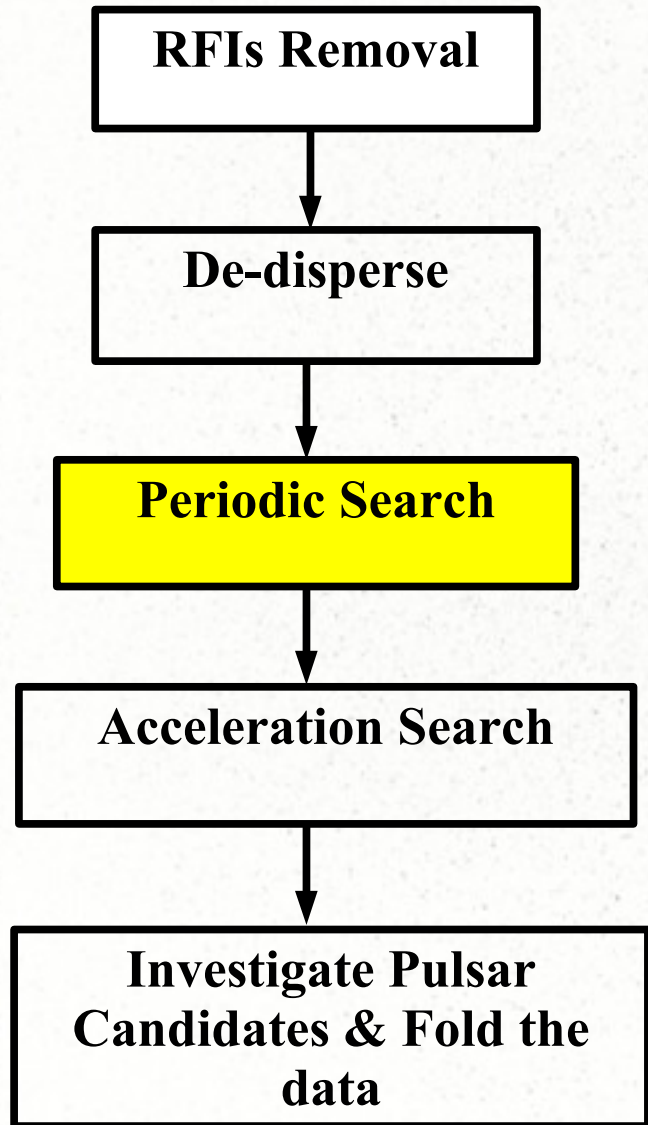


$$DM = \int n_e dl$$

$$\Delta t_{\text{delayed}} \propto \frac{DM}{f^{-2}}$$

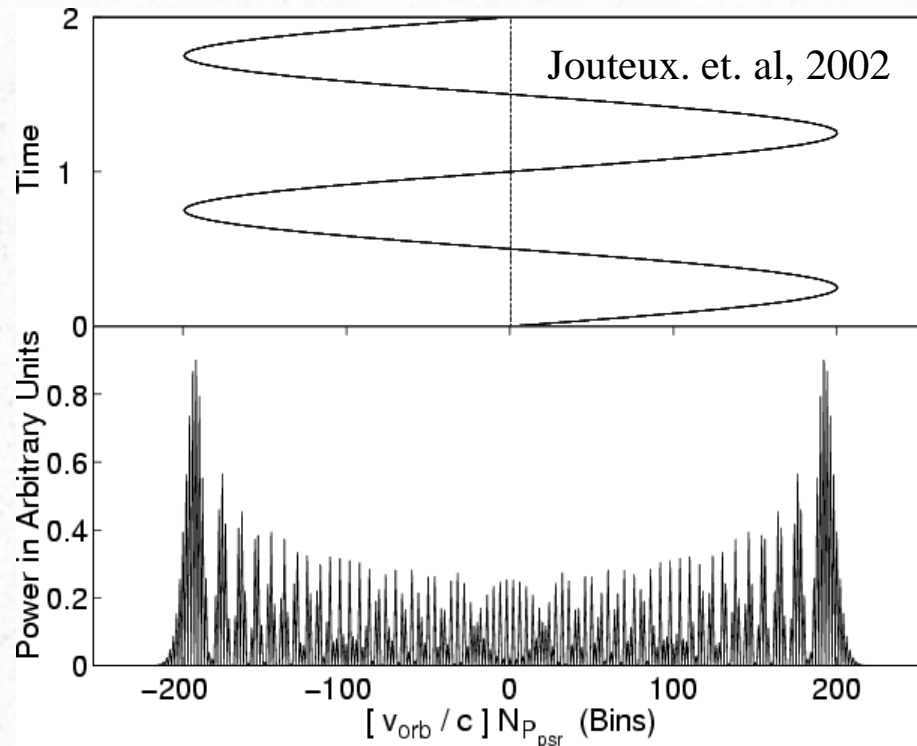
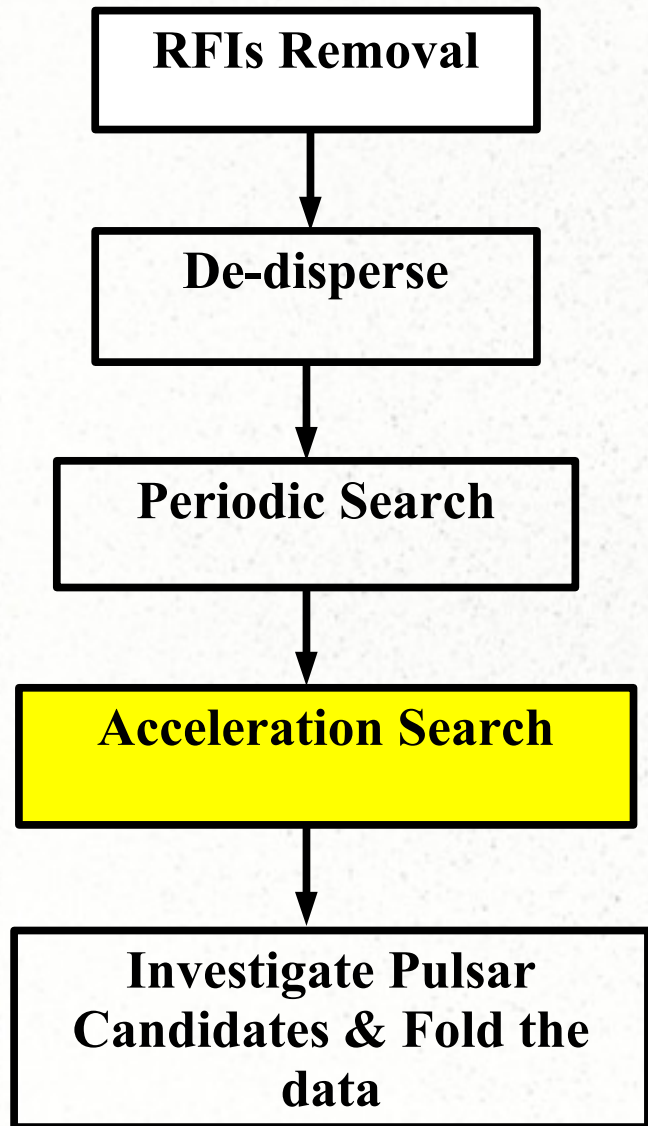
- Free electrons along the line of sight cause the “dispersion effect”. The arrival time of radio pulse was delayed: high frequency pulse arrives first.
- De-disperse data. PRESTO: prepdata, prepsubband

Searching for New Pulsar



- Perform Fast Fourier Transform (FFT) and sum harmonics to increase S/N

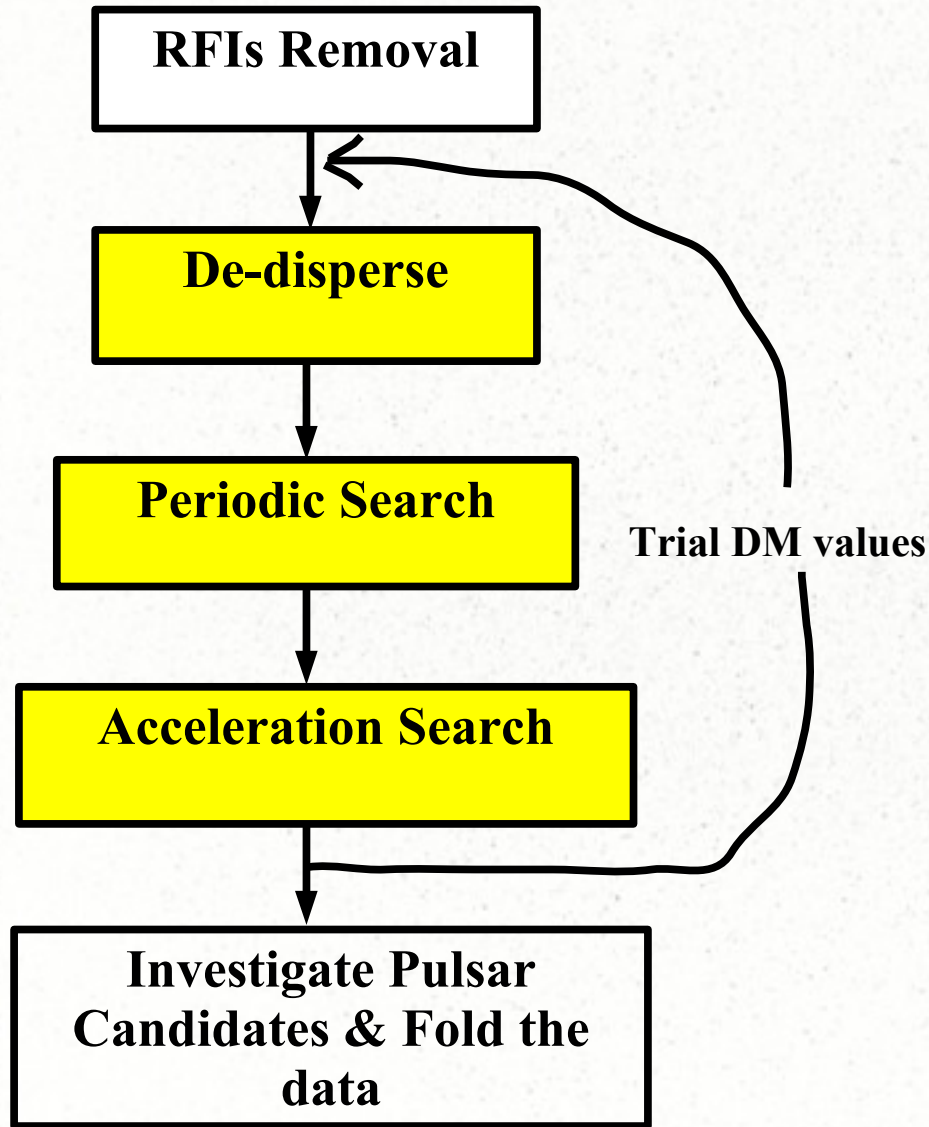
Searching for New Pulsar



$$a = \frac{zcP}{t^2}$$

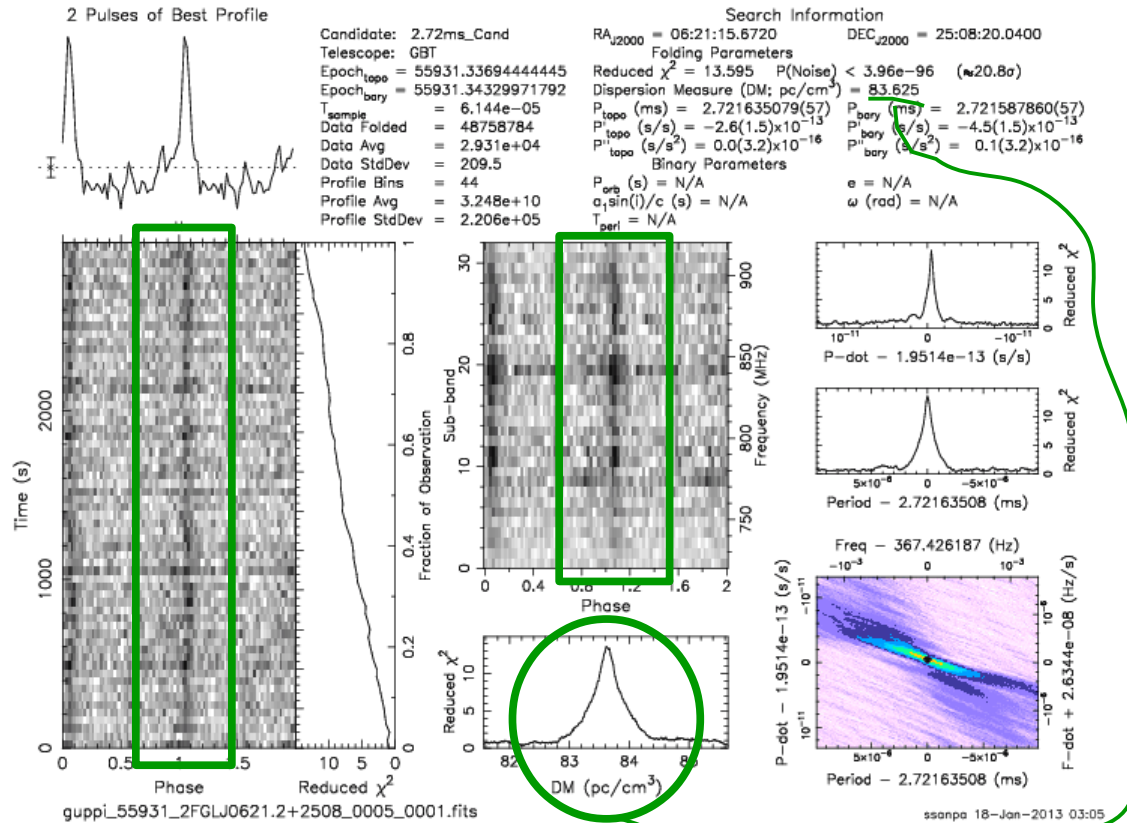
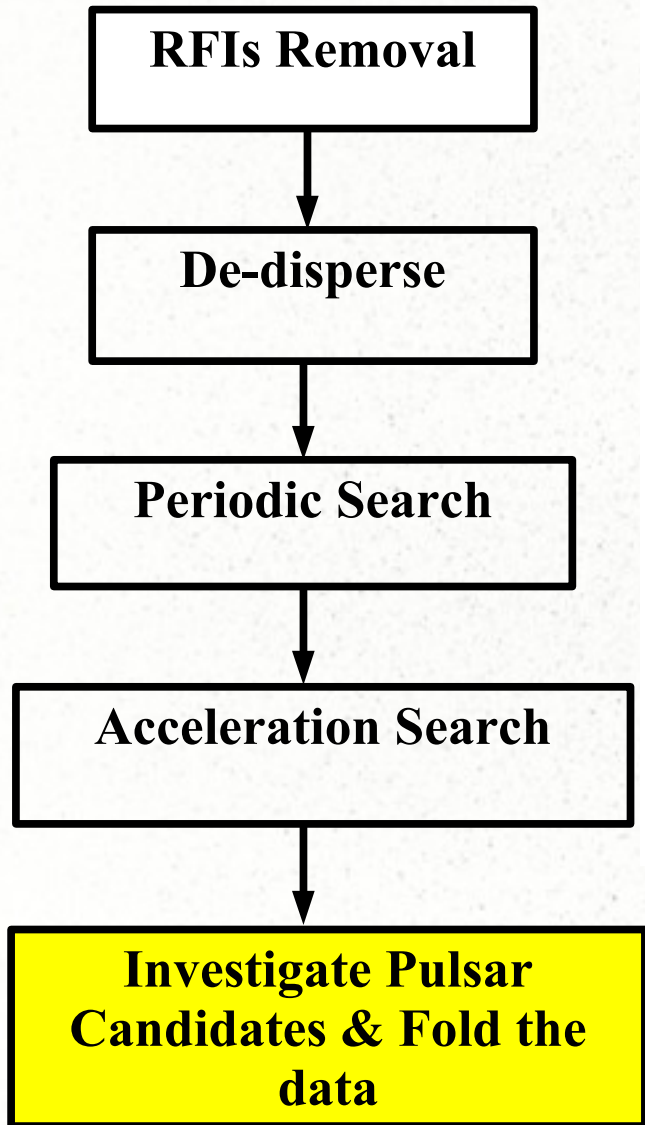
- The effect of binary motion (Doppler effect) causes a change in the apparent spin period.
- The pulsar power “spread out” over Fourier bins.
- PRESTO: accelsearch

Searching for New Pulsar



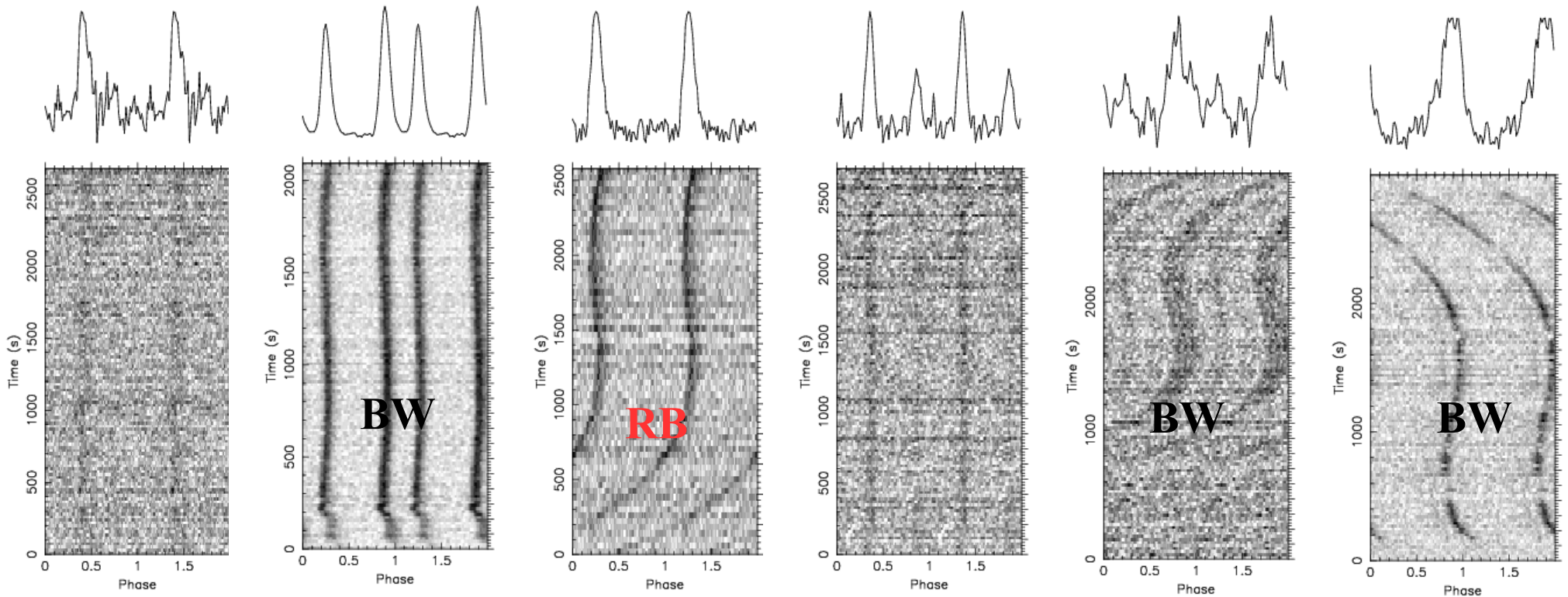
- Searching over multiple DM trials with optimized DM step size.
- “Nimrod”, a 20-node computer cluster at NRAO

Searching for New Pulsar



- Pulsar: signal presents during all observing time and observing frequency band, nice DM peak.
- PRESTO: prepfold

Sneak Peek!



- *59 Fermi* MSPs => **65 Fermi** MSPs! => **35** found by the GBT
- 17 Galactic spiders => **21 Galactic** spiders!
- **...AND COUNTING!**

Summary

- *Fermi* provides a great “treasure map” to search for MSPs. Period.
- “Pulsars are cool. Seriously” (Ransom, 2012)