# Building a Galactic Scale Gravitational Wave Observatory: Increasing the Sensitivity of the NANOGrav PTA

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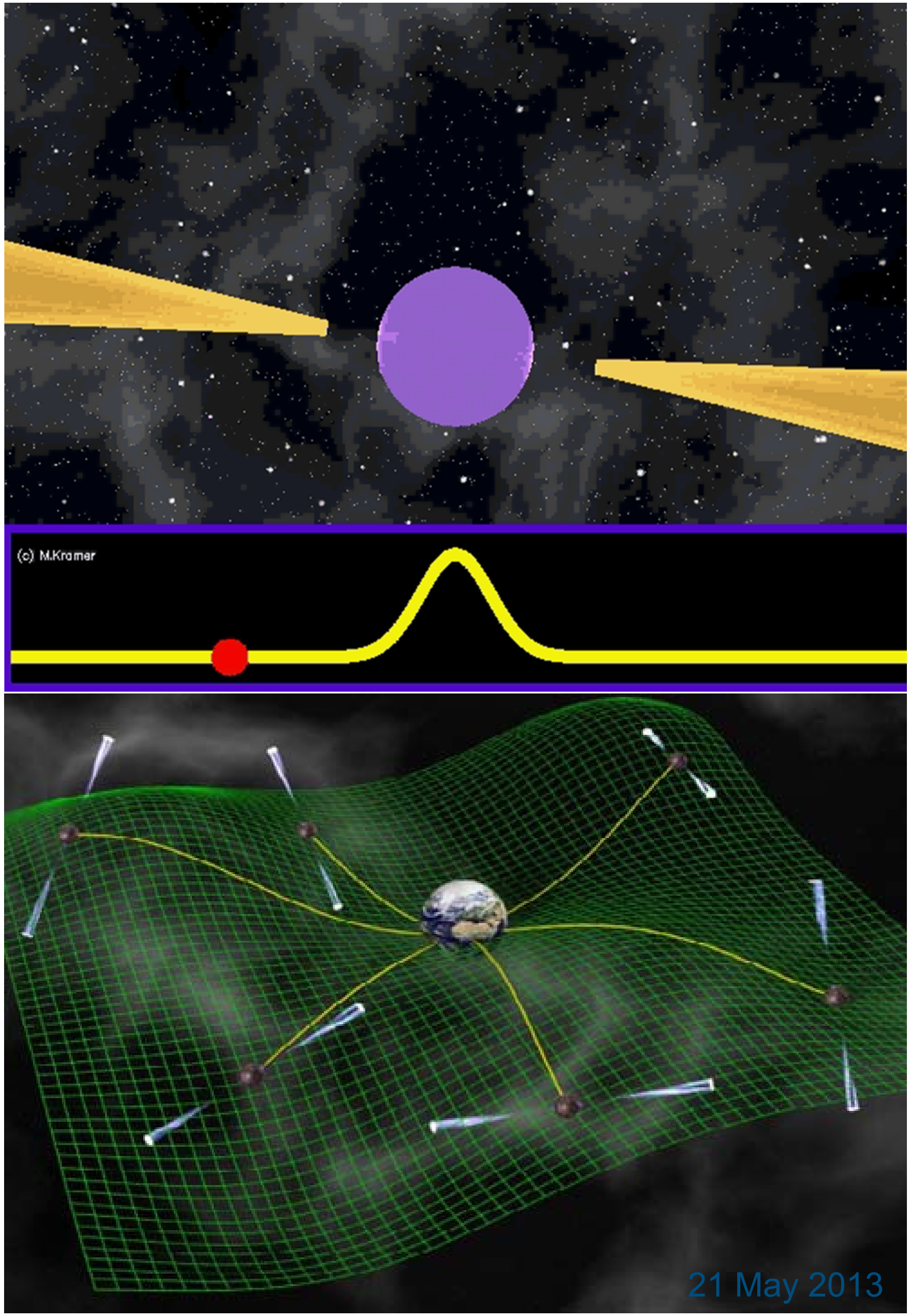
West Virginia University




GWADW2013

21 May 2013

# Outline

- Introduction
  - millisecond pulsar properties
  - millisecond pulsar timing

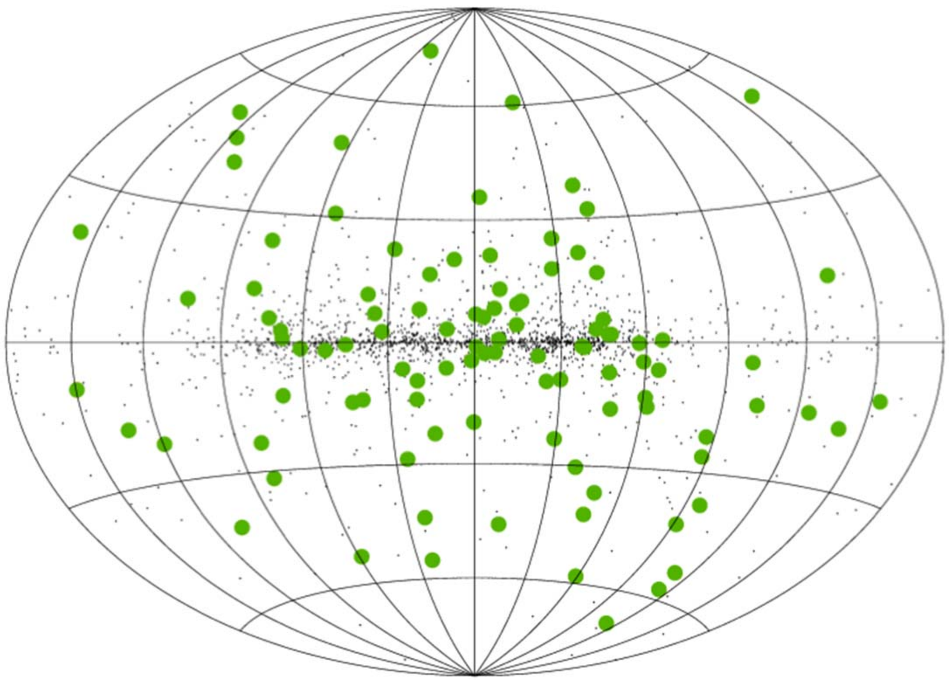
- Gravitational Wave Detection with Pulsars
  - pulsar timing arrays
  - analysis techniques
  - current stochastic background limit

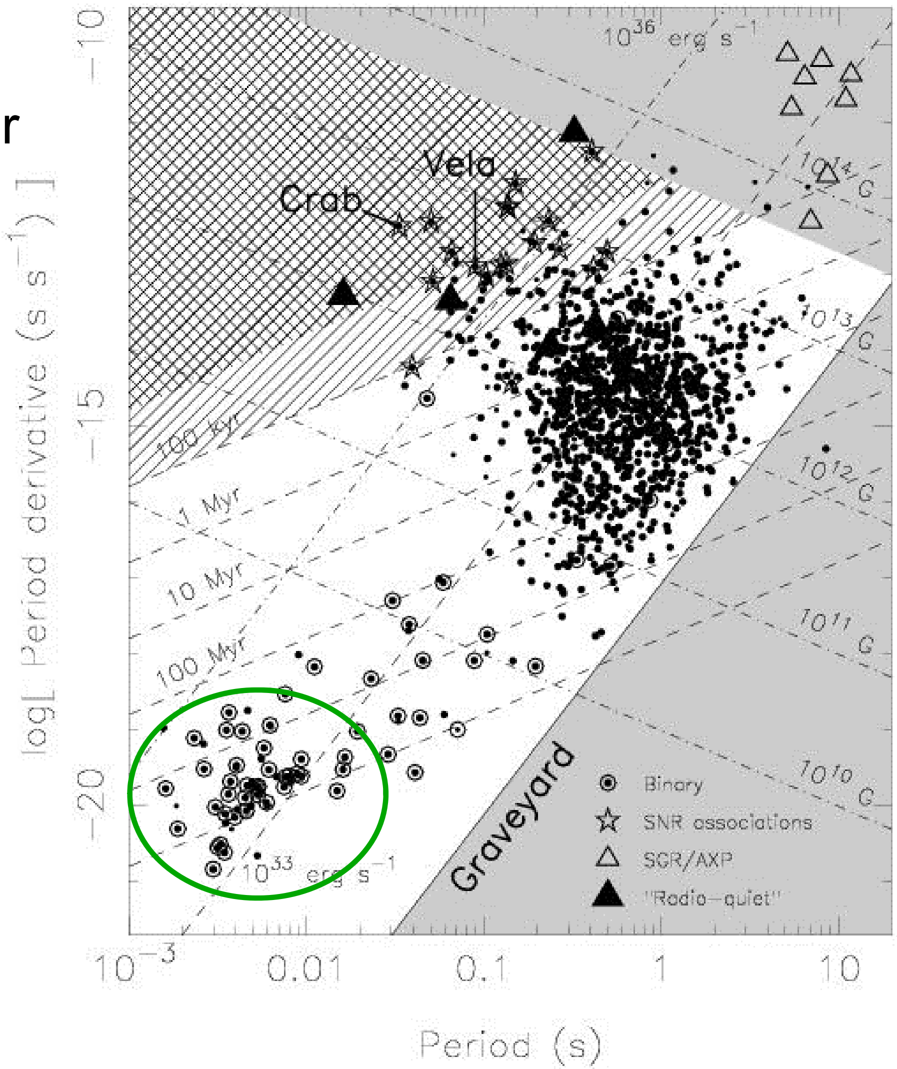
- Improving Our Detector
  - new instrumentation
  - new algorithms
  - more pulsars

- Summary
  - dramatic increases in PTA sensitivity expected over next several years

# Millisecond Pulsars

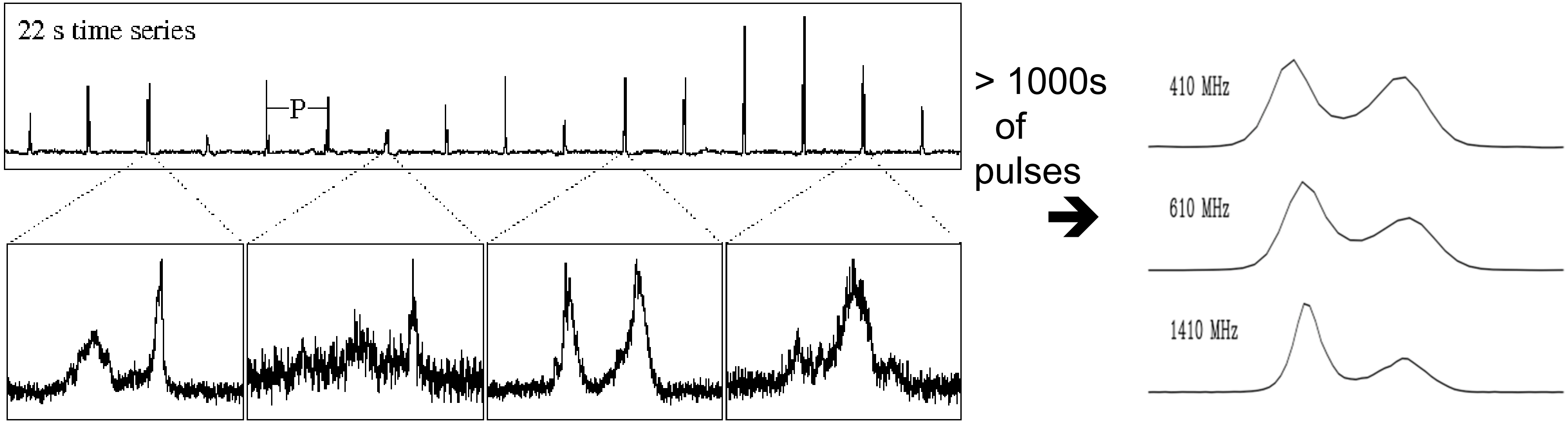
Nearly 200 known MSPs (P < 20 ms) in our Galaxy, out of roughly 30,000 detectable. Galactic MSPs are local (d ~ kly) and roughly isotropically distributed.



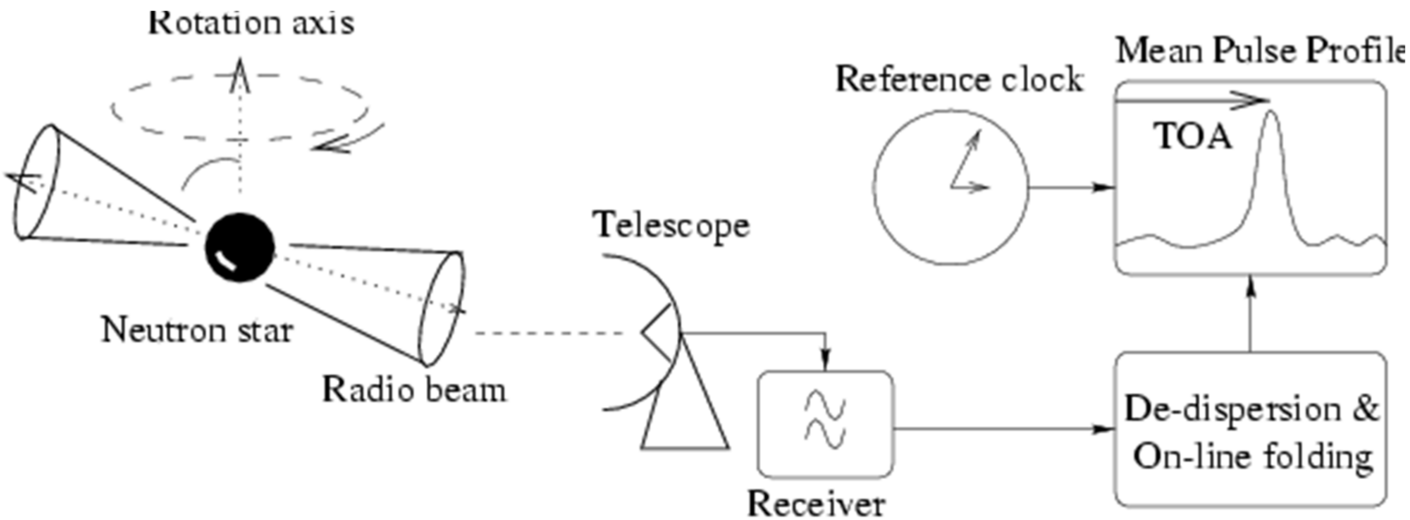



They are incredibly stable rotators, making them excellent fundamental physics laboratories.

# Measuring a pulse time-of-arrival (TOA)



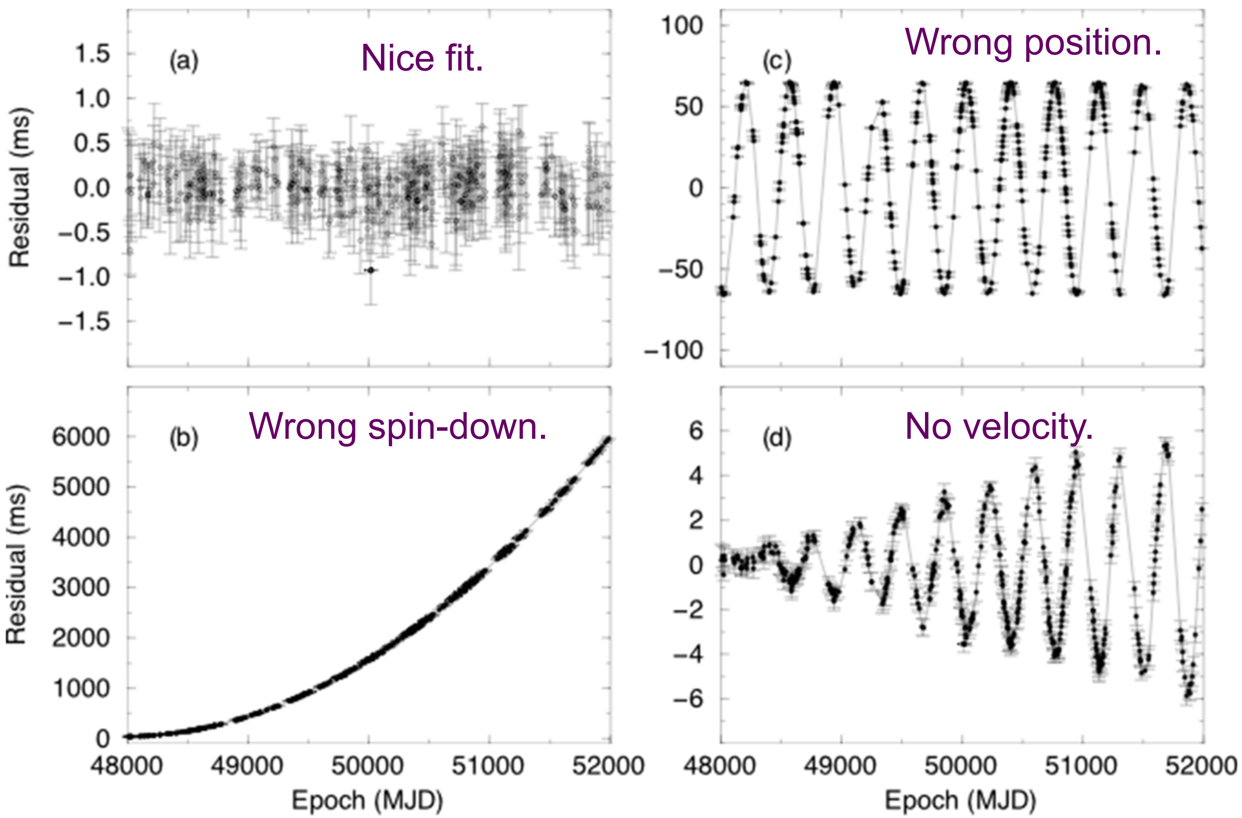

> 1000s of pulses ➔




Lorimer & Kramer, 2005, “Handbook of Pulsar Astronomy”

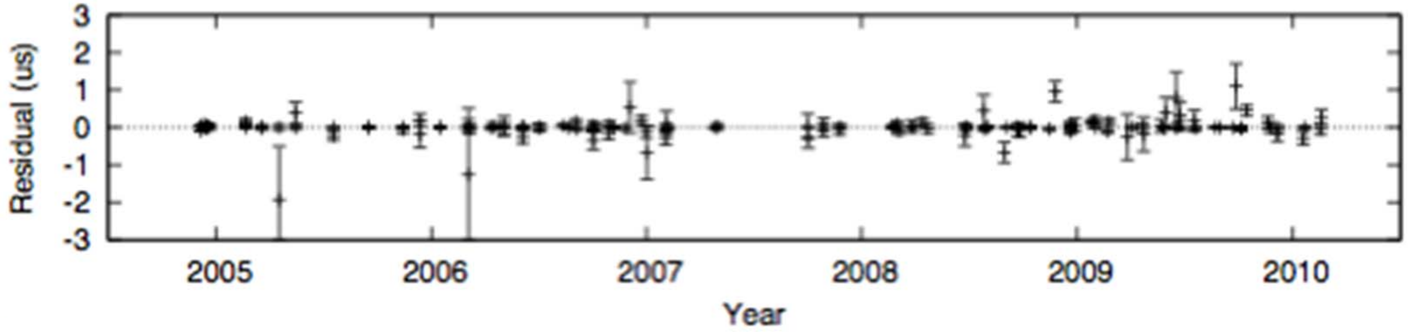
# Obtaining a Timing Model and Residuals

Timing Residuals = Model – Measured TOAs



# Typical Residuals for a Millisecond Pulsar

J1713+0747 P = 4.57 ms




Demorest et al. 2013, ApJ, 762, 94

$\sigma_{RMS}$ = root-mean-square residual = 30 ns (6 x $10^{-6}$ P)

after fitting for spin, astrometric, Keplerian, and post-Keplerian parameters and time-variable dispersion measure changes.

Today at 4:40 pm, the spin period of this pulsar is
4.57013631538007(4) milliseconds.

# Pulsars as GW Detectors

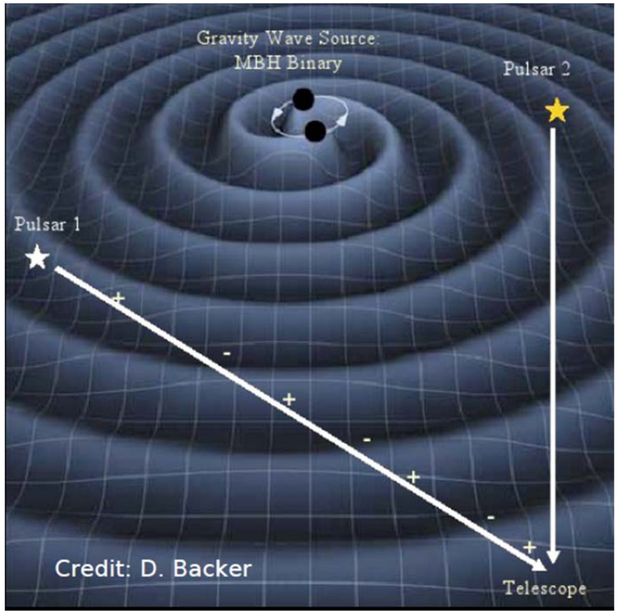
f ~ 1/weeks to 1/years ($10^{-6} - 10^{-9}$ Hz)

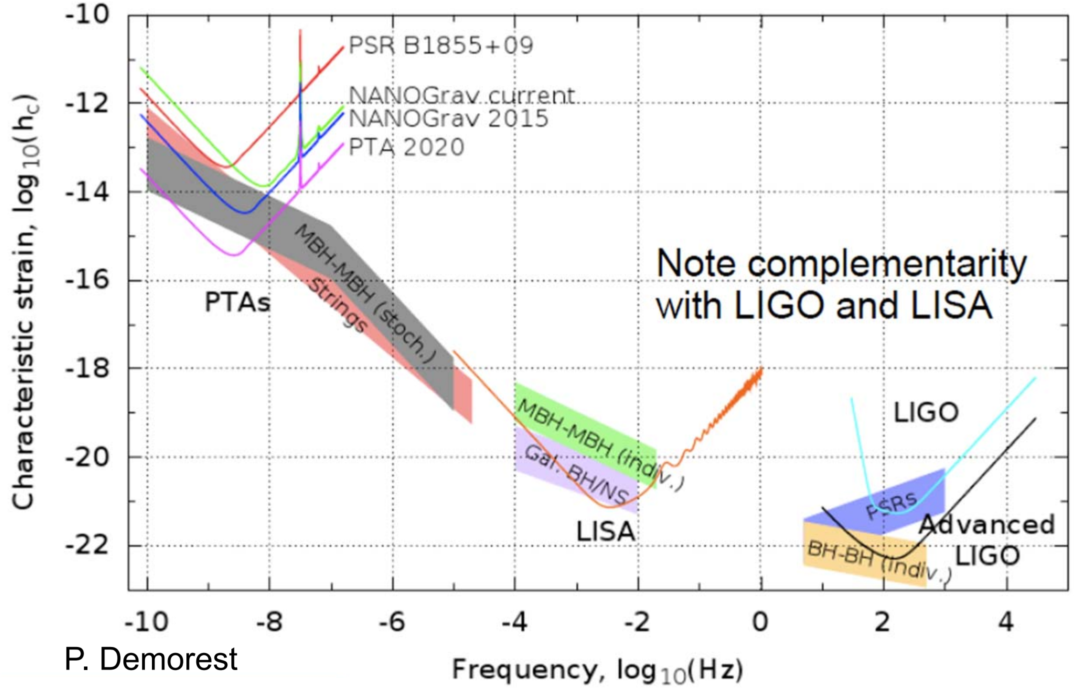
$$\Delta t \propto n_i n_j \int_0^d h_{ij}(x,t)dr$$

$\Delta t$ ~ h/f and will have pulsar and Earth terms

h ~ $\sigma_{rms}$/T ~ 100 ns/5 years ~ $10^{-15}$

$\lambda_{gw}$ ~ 1-10 lyr; $D_{psr}$ ~ 1000 lyr



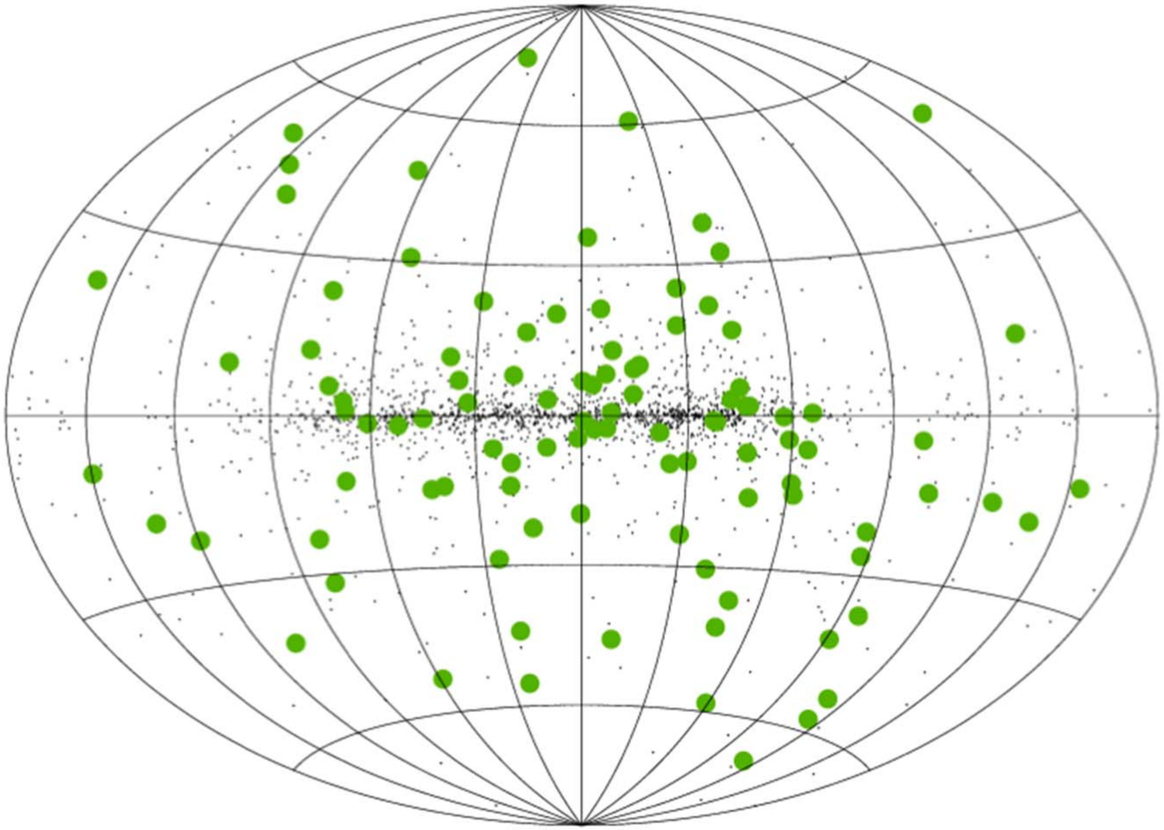




P. Demorest

First discussed by Detweiler (1979, ApJ, 234,1100) and Sazhin (1978,SA,22,36).

# Pulsar Timing Array

A network of pulsars that can be used to measure various effects that produce correlations in the arrival times of pulses from the members of the array.



First proposed by Foster and Backer (1990).

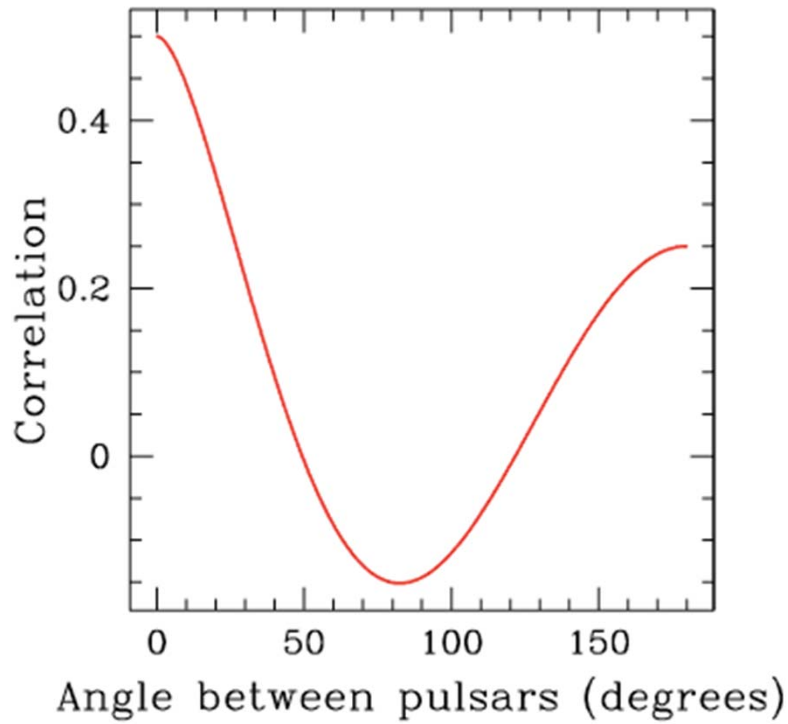
# Stochastic Background Limits from a PTA

Expected correlation of residuals for pairs of pulsars versus angular separation on sky. “Pulsar” terms uncorrelated. “Earth” terms correlated.

$$C_{y,ij}^{(ab)} = E\left\{y_a(t_i)y_b(t_j)\right\}$$

$$= C_y(t_i - t_j)\zeta(\theta_{ab})$$

Clock errors monopole.
Ephemeris errors dipole.
GWs quadrupole.



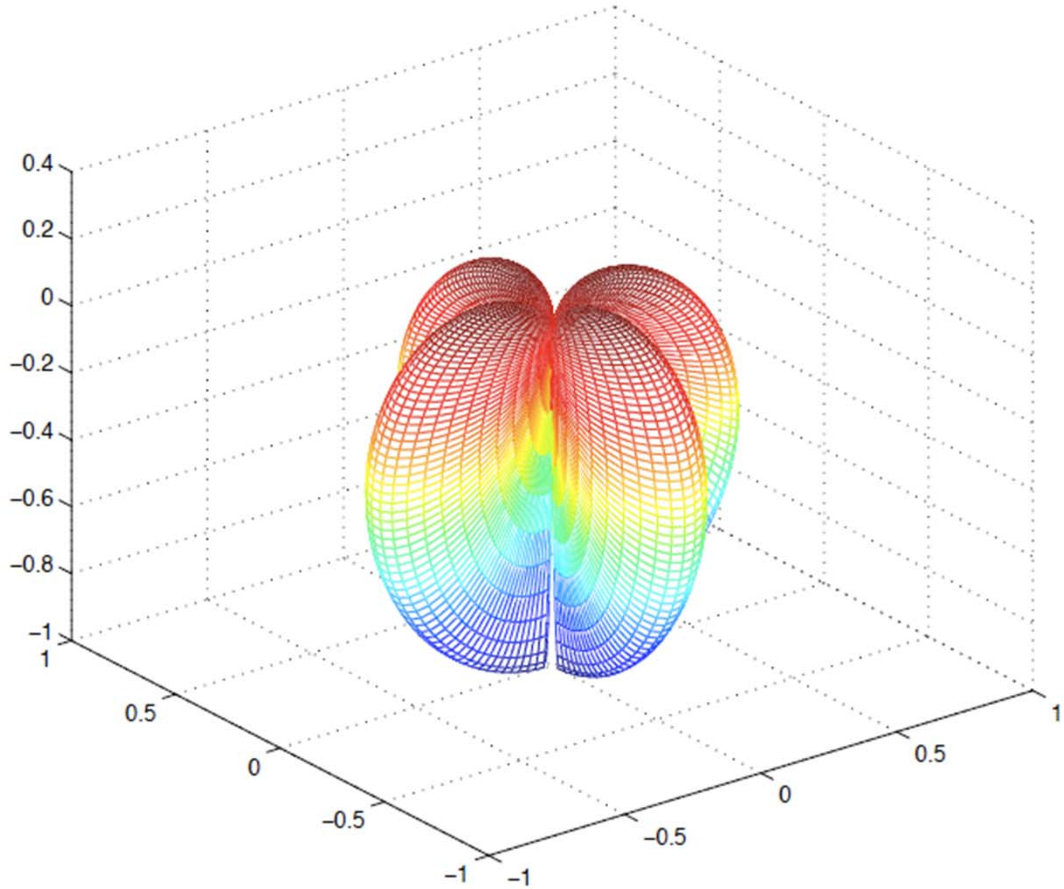

Hellings & Downs, 1983, ApJ, 265, L39

# Can use a PTA for single sources too

We can of course search for single sources too!

$$z(t,\hat{z}) \equiv \frac{\nu_0 - \nu(t)}{\nu_0}$$
$$= \frac{\alpha^2 - \beta^2}{2(1+\gamma)}(h_+^{\mathrm{p}} - h_+^{\mathrm{e}})$$
$$+ \frac{\alpha\beta}{1+\gamma}(h_\times^{\mathrm{p}} - h_\times^{\mathrm{e}})$$

Anholm et al. 2009, PhRvD, 79, 8




Antenna response for the pulsar-Earth system.

# North American Nanohertz Observatory for GWs

11 U.S. and 2 Canadian Institutions

nanograv.org

# Current Status

37 MSPs being timed with Arecibo and the GBT.
2-3 frequencies at each telescope.
Roughly bi-monthly observations.
First all-NANOGrav paper on 17 pulsars published.

OVERVIEW AND RESULTS FROM TIMING MODEL FITS.

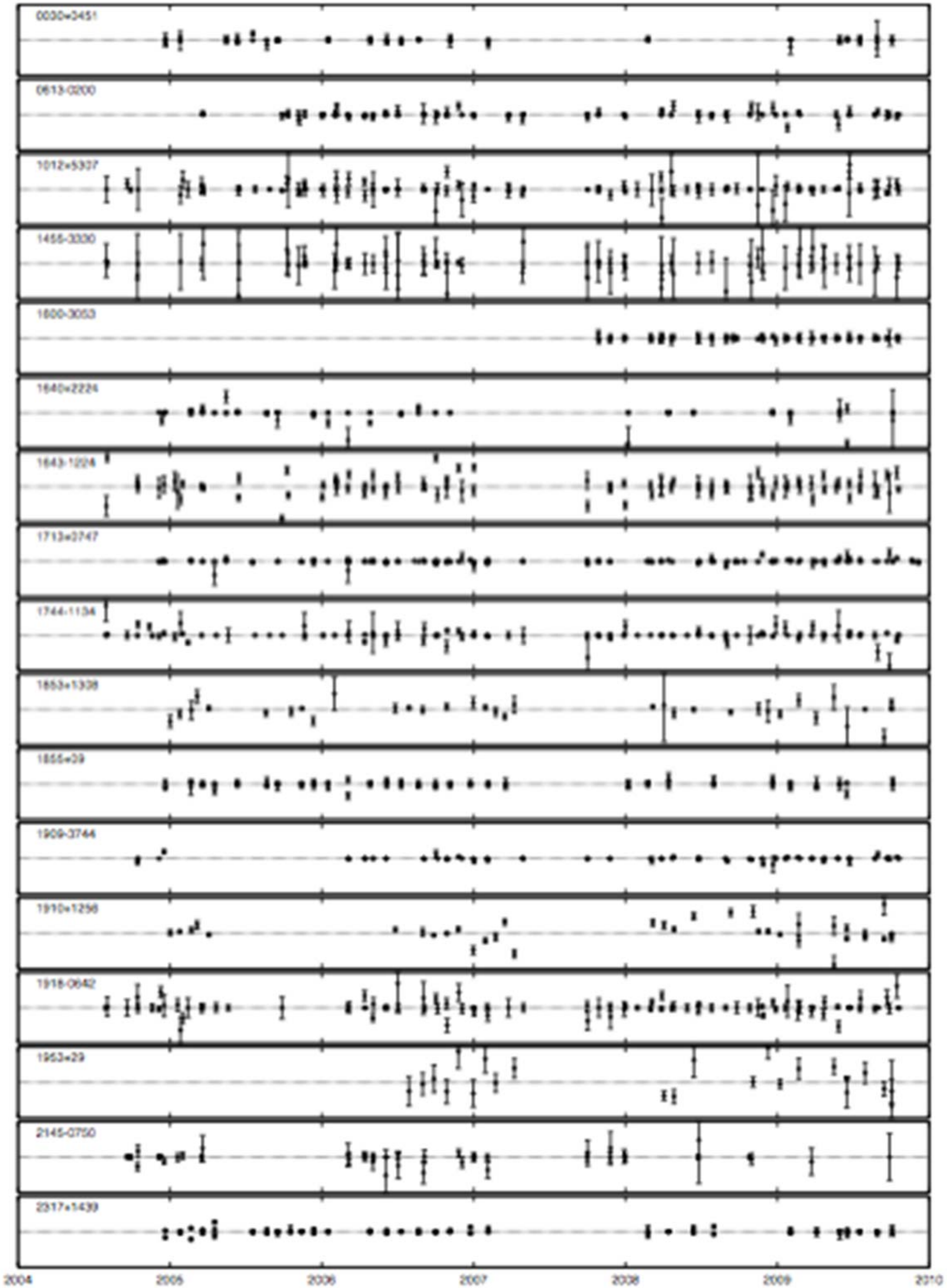
| Source | # of TOAs[a] | # of parameters DM | Profile | Other[b] | RMS ($\mu$s) | Fit $\chi^2$ | Epoch-averaged RMS ($\mu$s)[c] Low-band[d] | High-band | Combined |
|---|---|---|---|---|---|---|---|---|---|
| J0030+0451 | 545 | 20 | 26 | 7 | 0.604 | 1.44 | 0.019 | 0.328 | 0.148 |
| J0613–0200 | 1113 | 34 | 45 | 12 | 0.781 | 1.21 | 0.021 | 0.519 | 0.178 |
| J1012+5307 | 1678 | 52 | 53 | 14 | 1.327 | 1.40 | 0.192 | 0.345 | 0.276 |
| J1455–3330 | 1100 | 37 | 53 | 12 | 4.010 | 1.01 | 0.363 | 1.080 | 0.787 |
| J1600–3053 | 625 | 21 | 31 | 14 | 1.293 | 1.45 | 0.233 | 0.141 | 0.163 |
| J1640+2224 | 631 | 23 | 26 | 12 | 0.562 | 4.36 | 0.057 | 0.601 | 0.409 |
| J1643–1224 | 1266 | 40 | 48 | 13 | 2.892 | 2.78 | 0.589 | 1.880 | 1.467 |
| J1713+0747 | 2368 | 50 | 111 | 15 | 0.106 | 1.48 | 0.092 | 0.025 | 0.030 |
| J1744–1134 | 1617 | 54 | 49 | 7 | 0.617 | 3.58 | 0.139 | 0.229 | 0.198 |
| J1853+1308 | 497 | 0 | 34 | 12 | 1.028 | 1.16 | 0.271 | 0.096 | 0.255 |
| B1855+09 | 702 | 29 | 21 | 14 | 0.395 | 2.19 | 0.277 | 0.101 | 0.111 |
| J1909–3744 | 1001 | 31 | 37 | 14 | 0.181 | 1.95 | 0.011 | 0.047 | 0.038 |
| J1910+1256 | 525 | 0 | 34 | 14 | 1.394 | 2.09 | 0.712 | 0.684 | 0.708 |
| J1918–0642 | 1306 | 49 | 37 | 12 | 1.271 | 1.21 | 0.129 | 0.211 | 0.203 |
| B1953+29 | 208 | 0 | 27 | 12 | 3.981 | 0.98 | 1.879 | 0.543 | 1.437 |
| J2145–0750 | 675 | 20 | 37 | 12 | 1.252 | 1.97 | 0.068 | 0.494 | 0.202 |
| J2317+1439 | 458 | 30 | 12 | 15 | 0.496 | 3.03 | 0.373 | 0.150 | 0.251 |

Demorest et al. 2013, ApJ, 762, 94

# Residuals

RMS residuals for 17 NANOGrav pulsars range from 30 ns to 1.5 microseconds over timespans of ~ 5 years. Most of these residuals are consistent with white noise, but two have significant red noise components.

We must (most likely) reduce RMS residuals to ~ 100 ns for all of these (and more!) MSPs for gravitational wave detection within the next ~10 years.

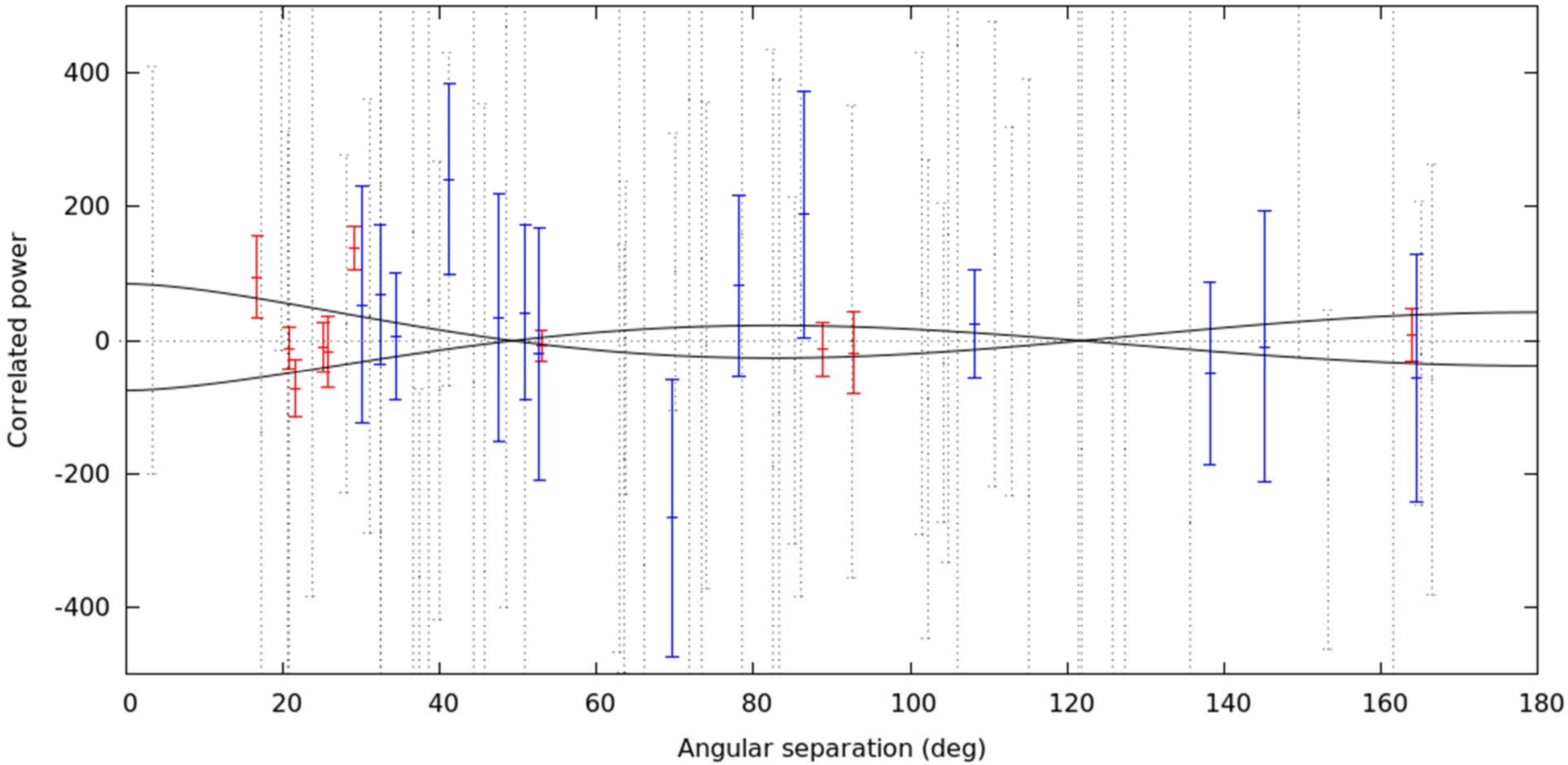


# Limit from Correlation Analysis

$h_c < 7 \times 10^{-15}$ ($f = 1\ \mathrm{yr}^{-1}$)

NANOGrav

$$\rho_{ab} = \frac{\sum_{ijkl} r_i^{(a)} \left(C^{tot(a)}\right)^{-1}_{ij} C^{GW(a,b)}_{jk} \left(C^{tot(b)}\right)^{-1}_{kl} r_l^{(b)}}{\sum_{ijkl} \left(C^{tot(a)}\right)^{-1}_{ij} C^{GW(a,b)}_{jk} \left(C^{tot(b)}\right)^{-1}_{kl} C^{GW(a,b)}_{il}}$$



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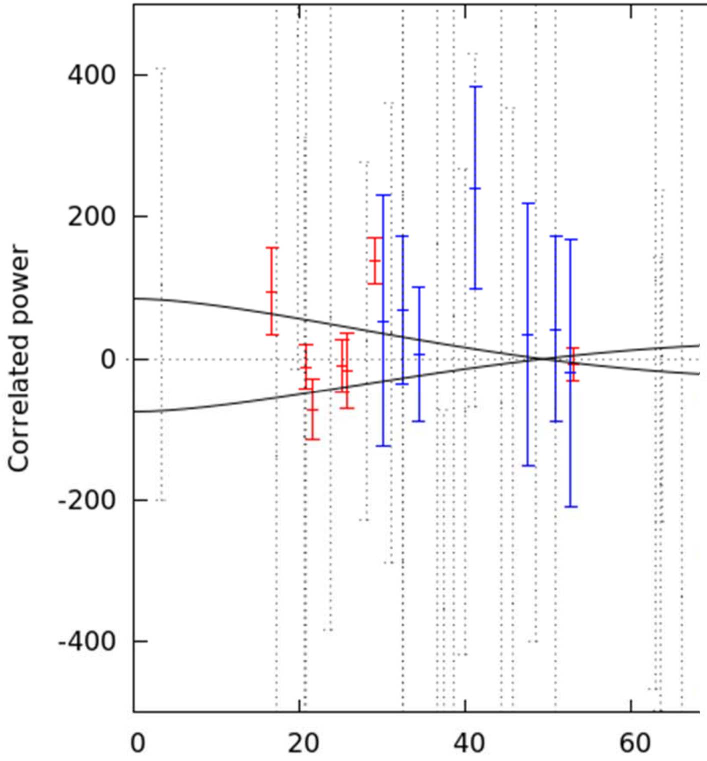
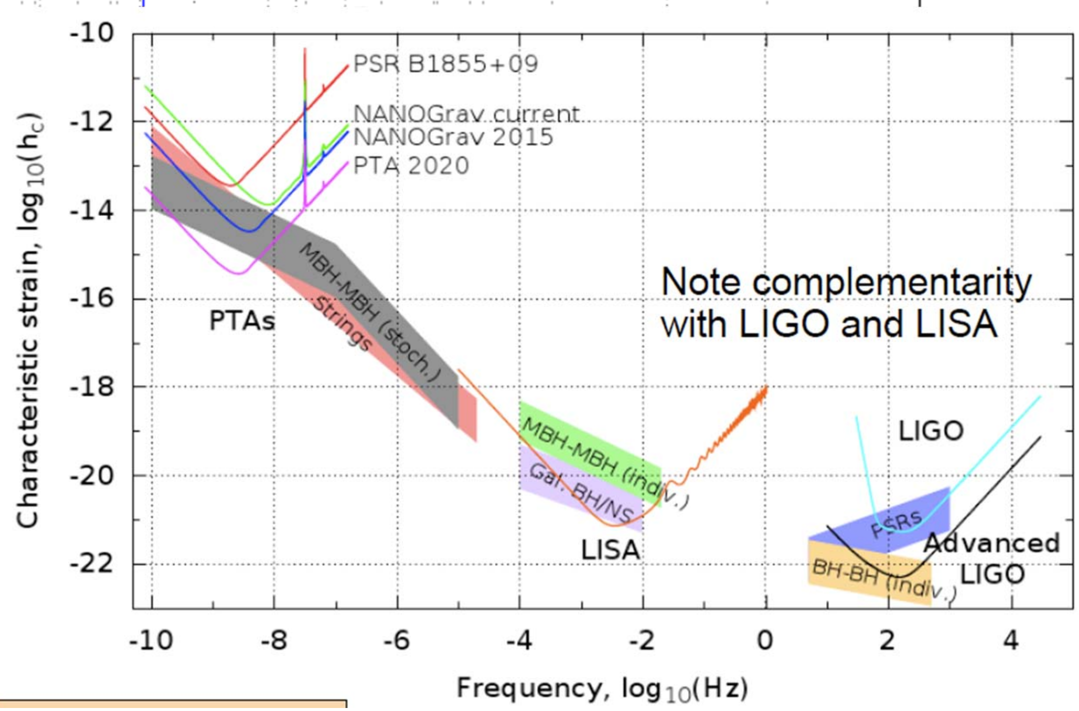
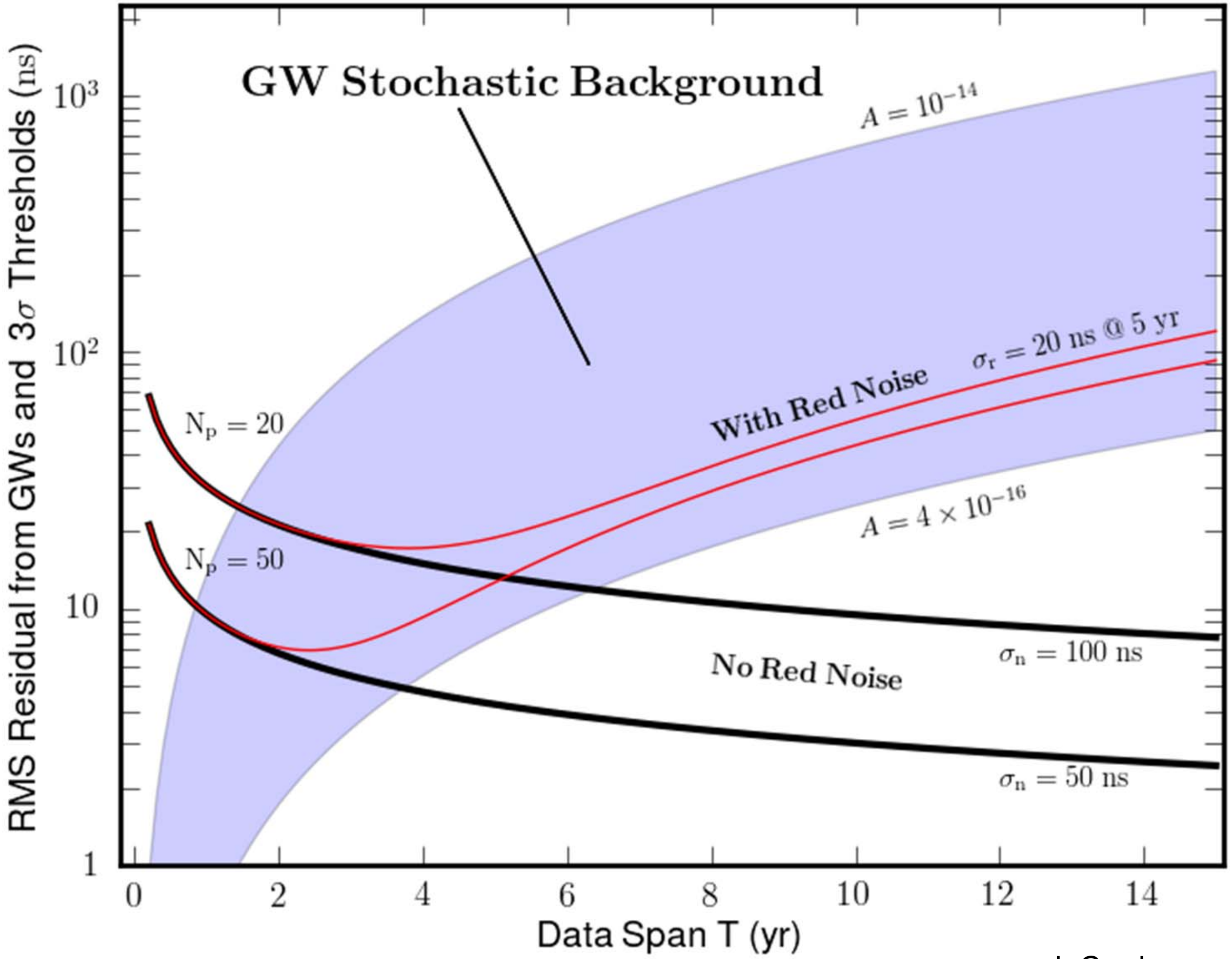


## How do we improve the sensitivity of our detector?

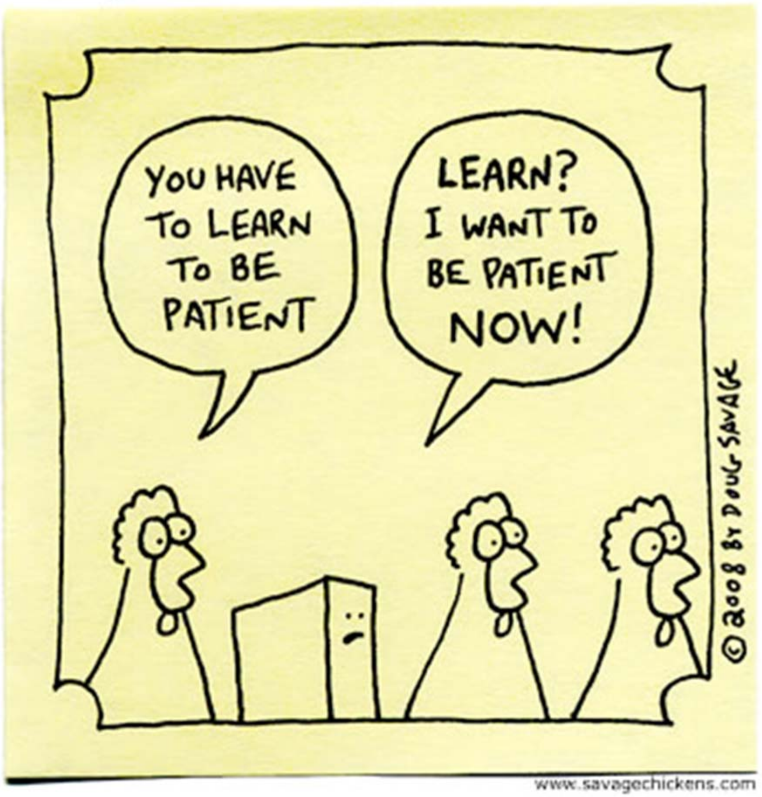
# Projected Sensitivity



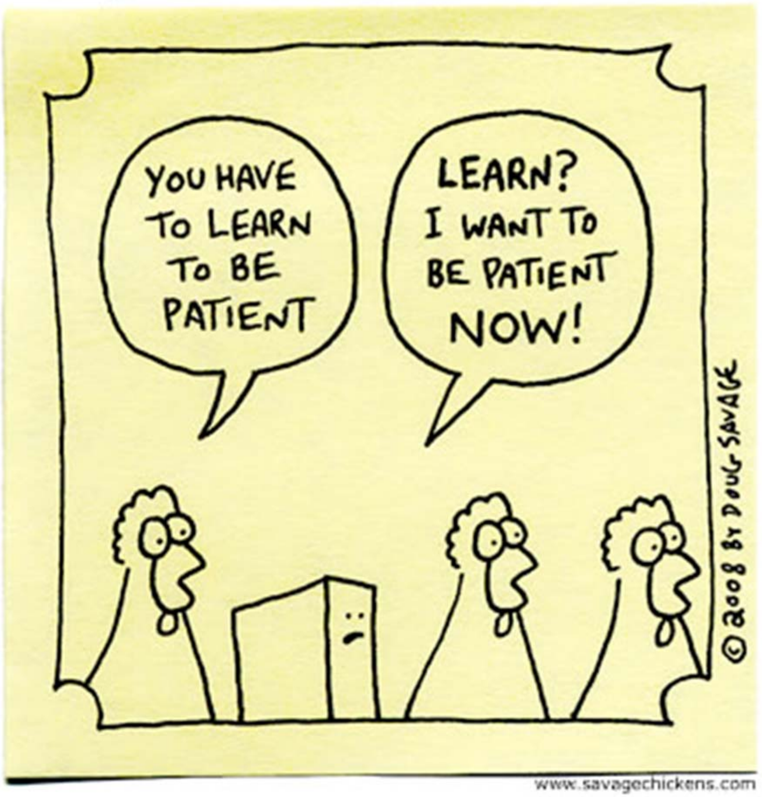

J. Cordes

In the strong source regime, sensitivity scales as $T^{1/2}$, $N_p^{1/2}$, and $N_{TOA}^{1/2}$. GWs grow as $T^{5/3}$. Assumes similar spectrum for GWs ($f^{-13/3}$) and red noise ($f^{-5}$).

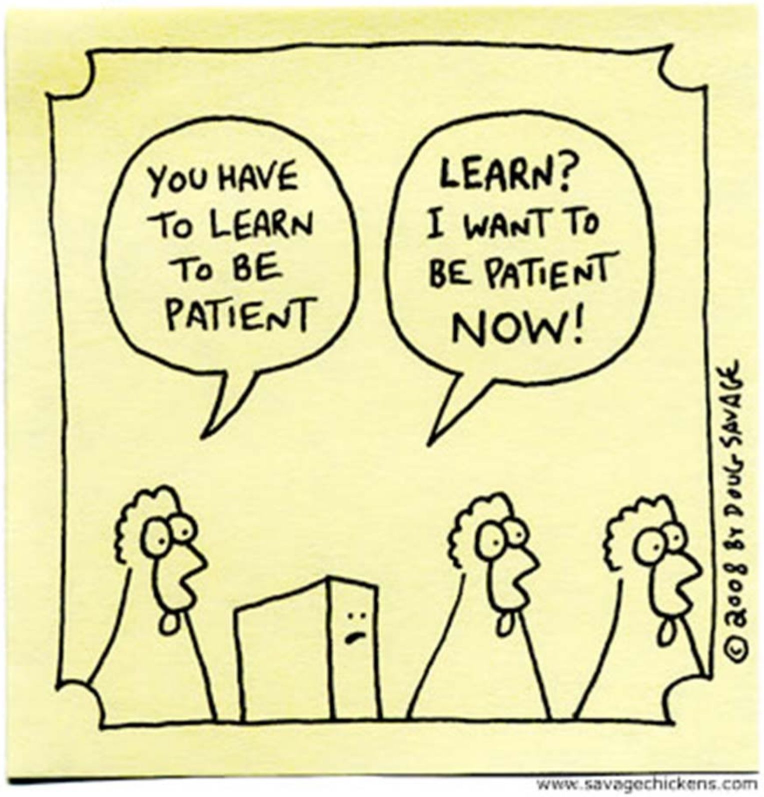
# If we are white noise dominated, we could just wait



If we are white noise dominated, we could just wait ..but we will get there faster with more precise TOA measurements and better algorithms.



# If we are red noise dominated (or if red noise is ubiquitous), we may *need* to add pulsars to the array.




Based on studies of slow pulsars, it is likely that red noise due to rotational instabilities exists at some level for all MSPs.

How do we improve the sensitivity of our detector?

1) More precise TOA measurements
2) Better algorithms for timing and detection
3) More pulsars in the array

# 1) More precise TOA measurements

Minimum detectable strain proportional to average RMS residual ($h \sim \sigma_{RMS}/T$ in simple model).

$$\sigma_{\mathrm{RMS}} \sim \quad \sigma_{\mathrm{TOA}} \sim \frac{w}{SNR} \propto \frac{w}{S_{\mathrm{PSR}}} \frac{T_{sys}}{A} \frac{1}{\sqrt{BT}}$$

Therefore, we want *bright pulsars* with *narrow pulses* observed with *sensitive receivers* with *large telescopes* over *large bandwidths* and with *long integration times*.

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Therefore, we want *bright pulsars* with *narrow pulses* observed with ***sensitive receivers*** with ***large telescopes*** over *large bandwidths* and with ***long integration times***.

105 m
Green Bank Telescope

We are steadily increasing our amount of observing time on the two largest telescopes in the world, equipped with sensitive receivers.

305 m
Arecibo Telescope

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105 m
Green Bank Telescope

New instrumentation on both telescopes is dramatically increasing our available bandwidth. But we must preserve narrow pulsar shapes over those bandwidths!

305 m
Arecibo Telescope

# 1) More precise TOA measurements

Frequency-dependent refractive index leads to frequency-dependent time delay

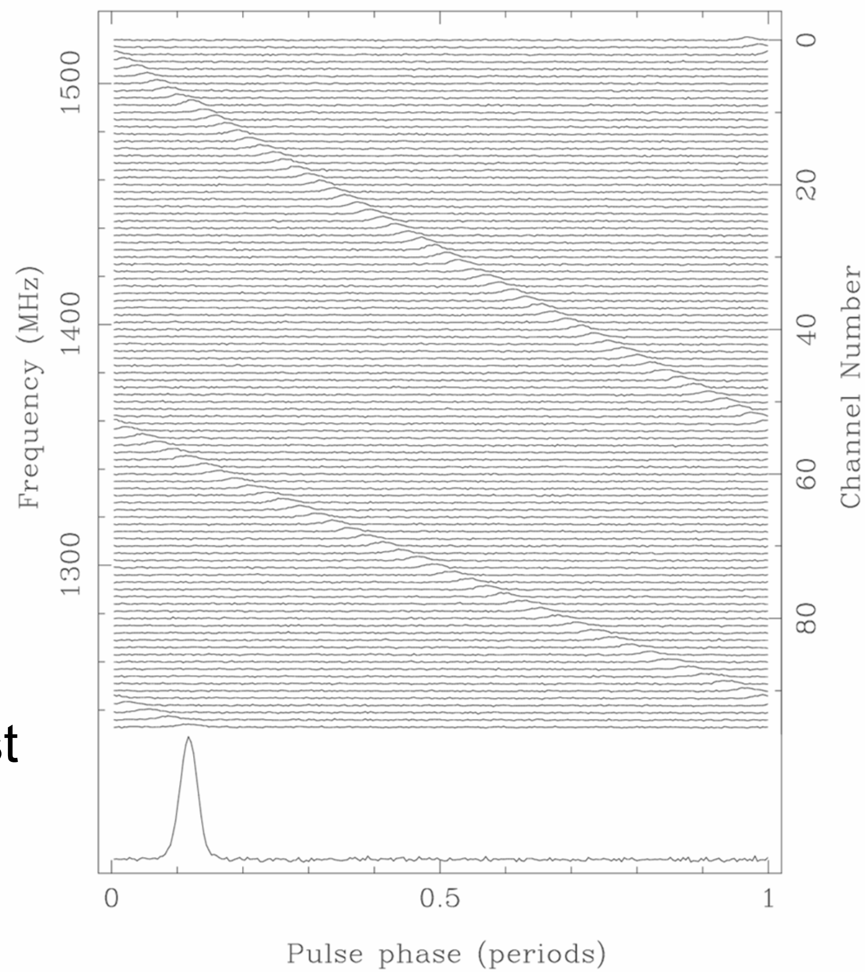
$$\Delta t \simeq 4.15 \times 10^6 \text{ ms } \times (f_1^{-2} - f_2^{-2}) \times \text{DM}$$

where $$\text{DM} = \int_0^d n_\text{e}\,\text{d}l$$

DMs range from roughly 3 to 100 pc cm$^{-3}$ for delays of 1 to 30 ms over a 100 MHz bandwidth at 1.4 GHz.

To preserve narrow pulse shapes, we must *coherently dedisperse*, or convolve raw signal voltages with inverse of interstellar medium transfer function.

Computationally expensive!!



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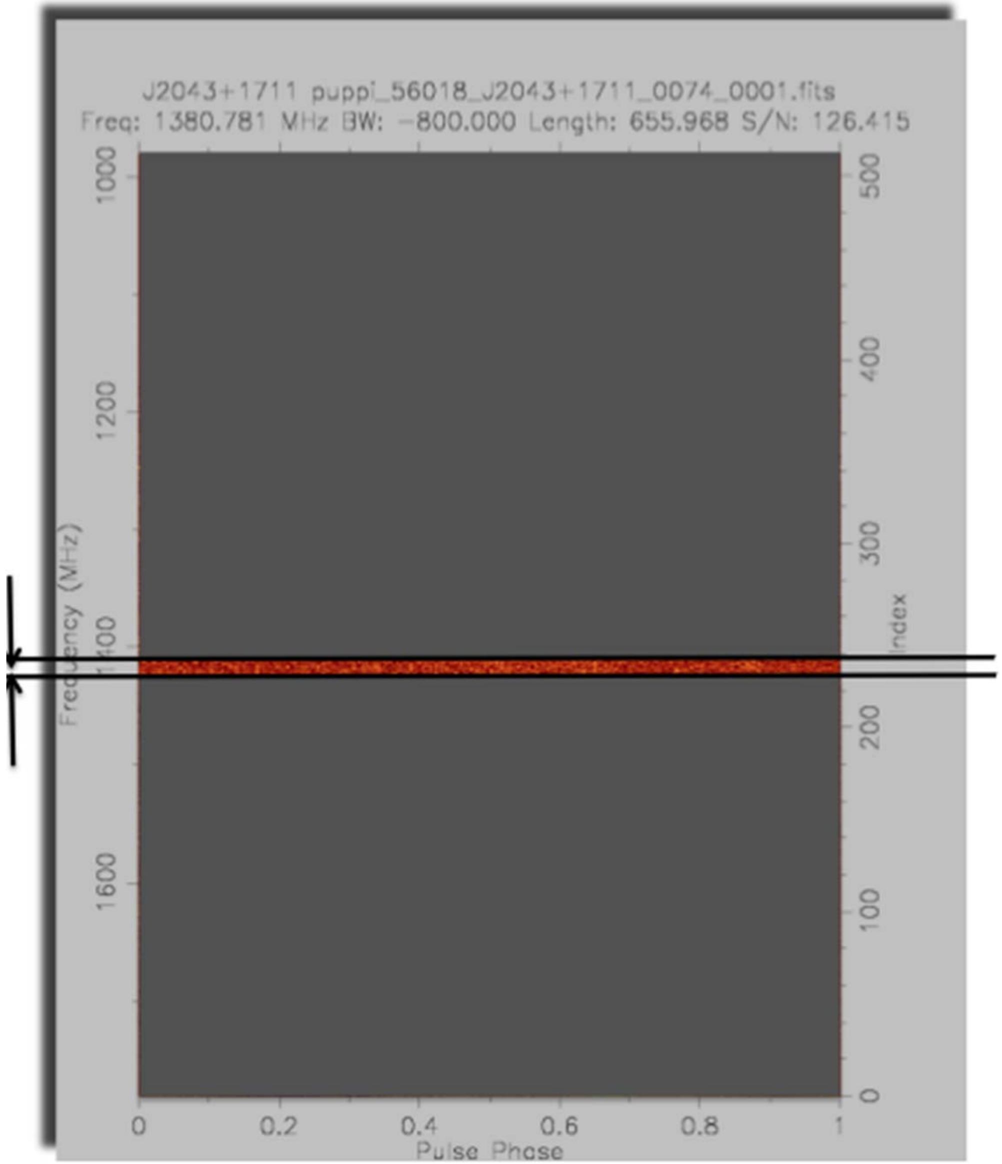
$$\sigma_{\mathrm{TOA}} \sim \frac{w}{SNR} \propto \frac{w}{S_{\mathrm{PSR}}} \frac{T_{sys}}{A} \frac{1}{\sqrt{BT}}$$

Arecibo 1998-2006:
10 MHz bandwidth



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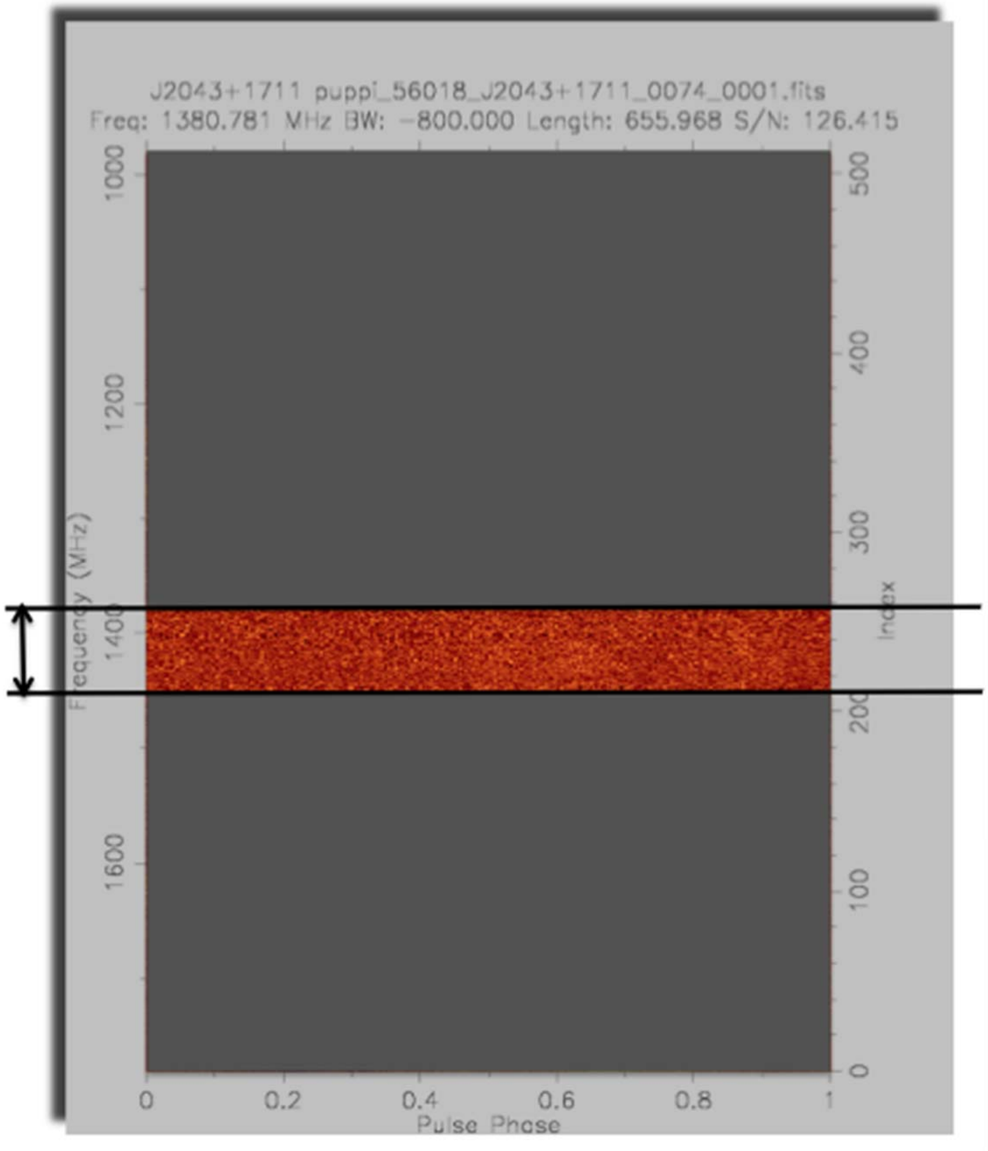
$$\sigma_{\mathrm{TOA}} \sim \frac{w}{SNR} \propto \frac{w}{S_{\mathrm{PSR}}} \frac{T_{sys}}{A} \frac{1}{\sqrt{BT}}$$

Arecibo 2005-2012: 64 MHz bandwidth available with ASP backend.

Used for recent upper limit paper.



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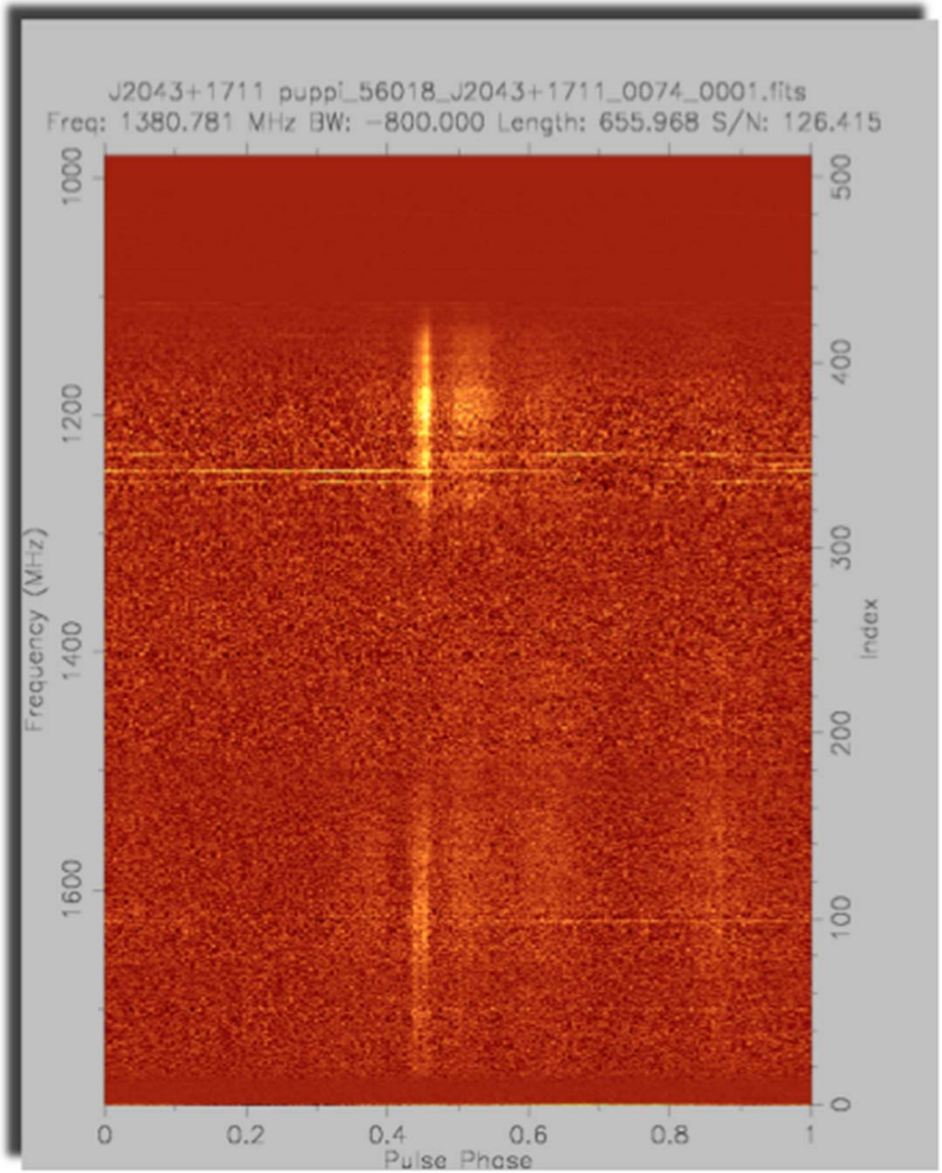
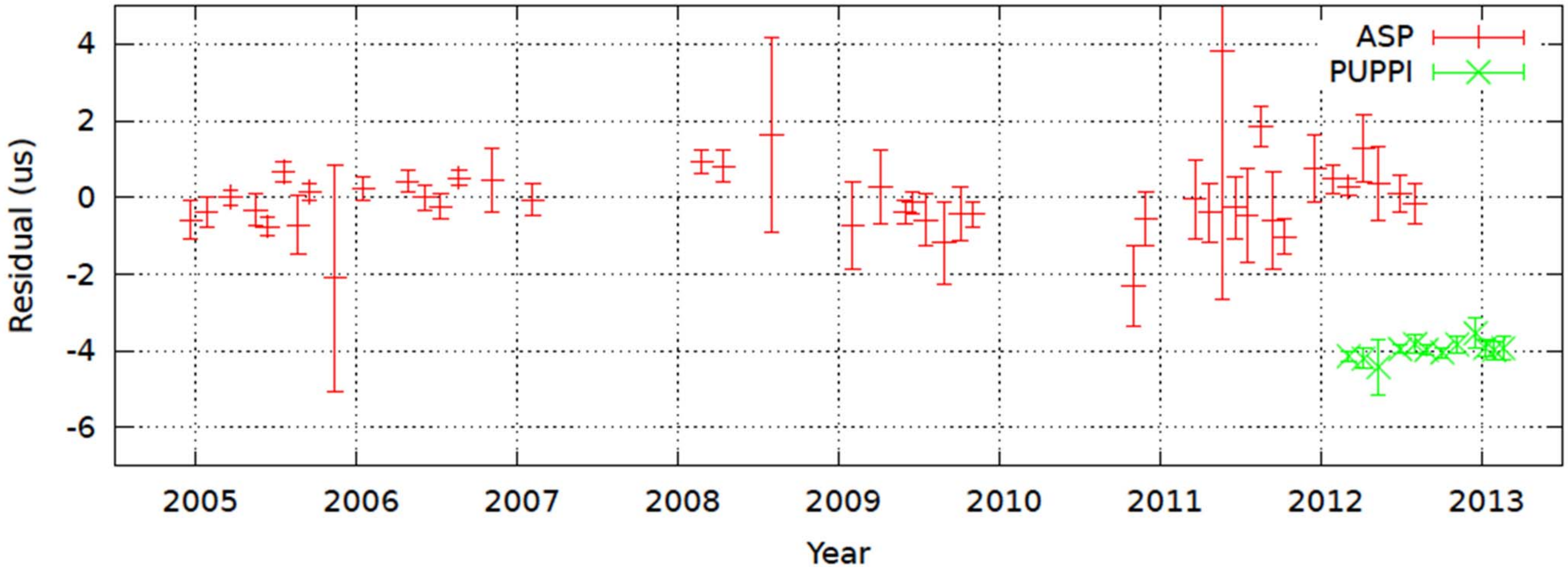


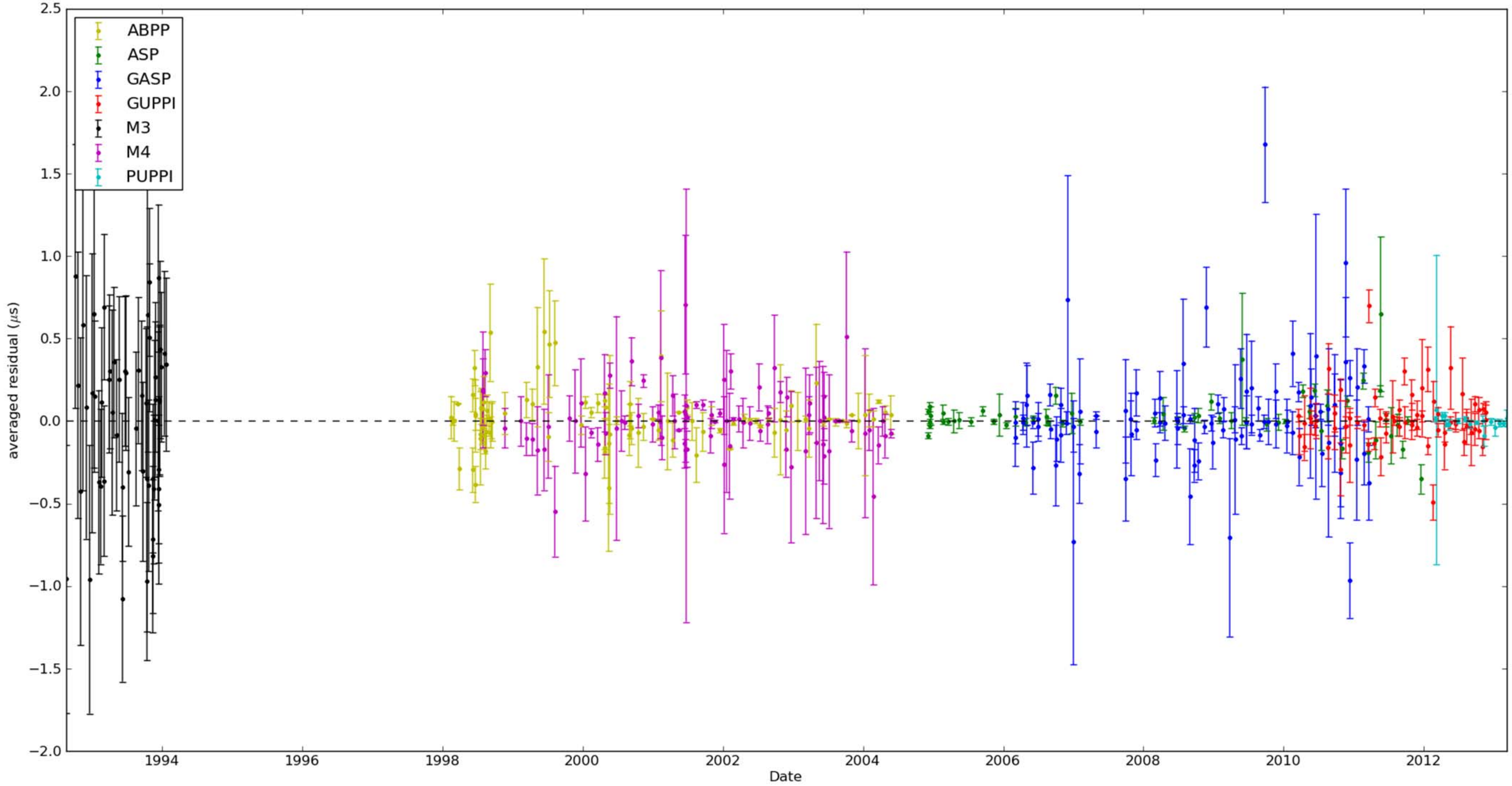

Arecibo 2012-present: 800 MHz bandwidth available with new PUPPI backend. Made possible with cheap FPGA hardware.

# 1) More precise TOA measurements




Additional bandwidth has resulted in RMS residuals a factor of three smaller, as expected.

# 1) More precise TOA measurements




Zhu et al. in preparation

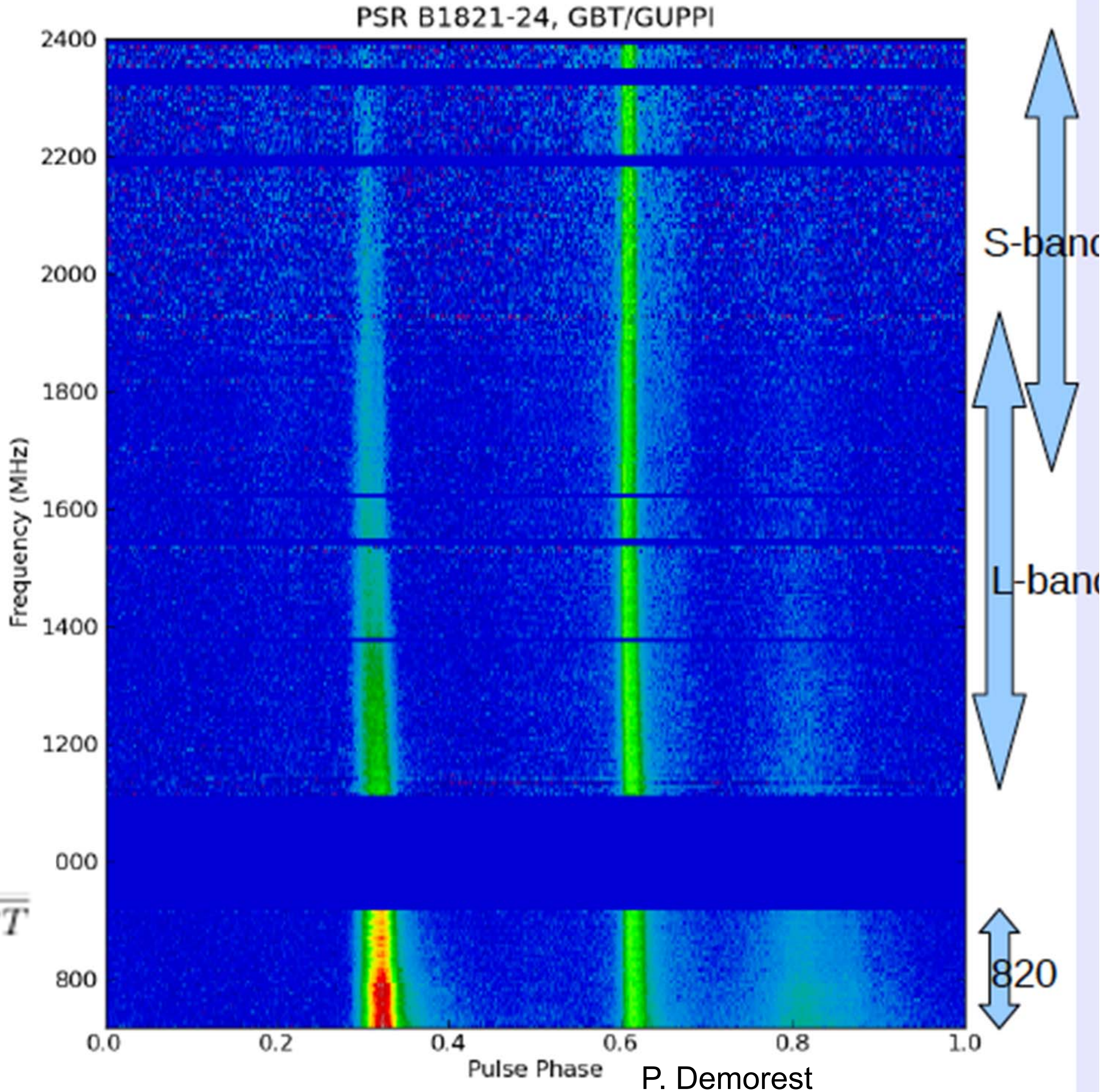
Additional bandwidth has resulted in RMS residuals a factor of three smaller, as expected (for the most part!)

# 1) More precise TOA measurements

Super-wideband receiver in development for both AO and GBT, covering 700 MHz – 3 GHz.

Challenge is getting low system temperature.

$$\sigma_{\mathrm{TOA}} \sim \frac{w}{SNR} \propto \frac{w}{S_{\mathrm{PSR}}} \frac{T_{sys}}{A} \frac{1}{\sqrt{BT}}$$




P. Demorest

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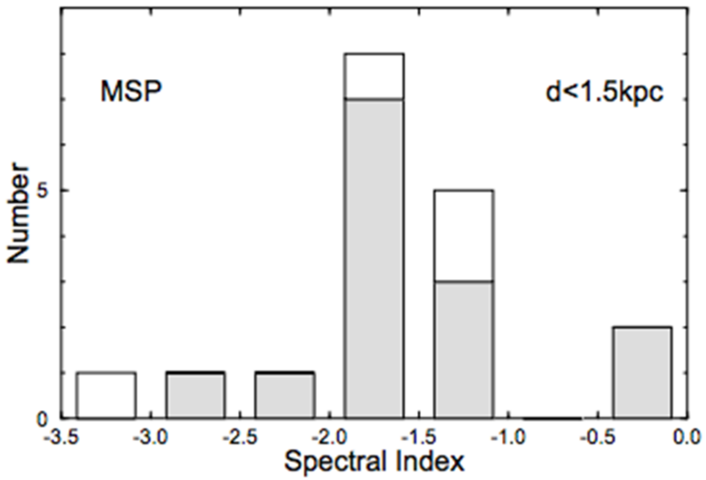
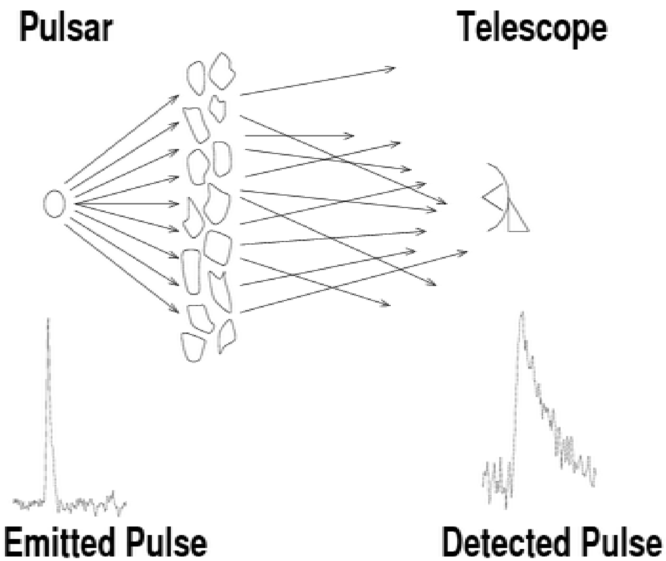



Kramer et al. 1998, ApJ, 501, 270,

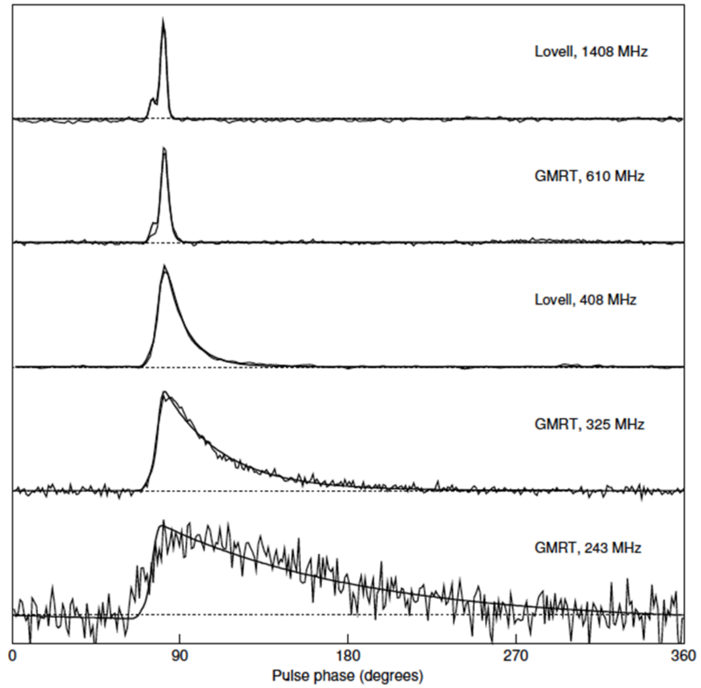
We want to observe at low frequencies where pulsars are brightest.

$S \propto freq^{-1.6}$

# 1) More precise TOA measurements




Lorimer, Living Reviews in Relativity



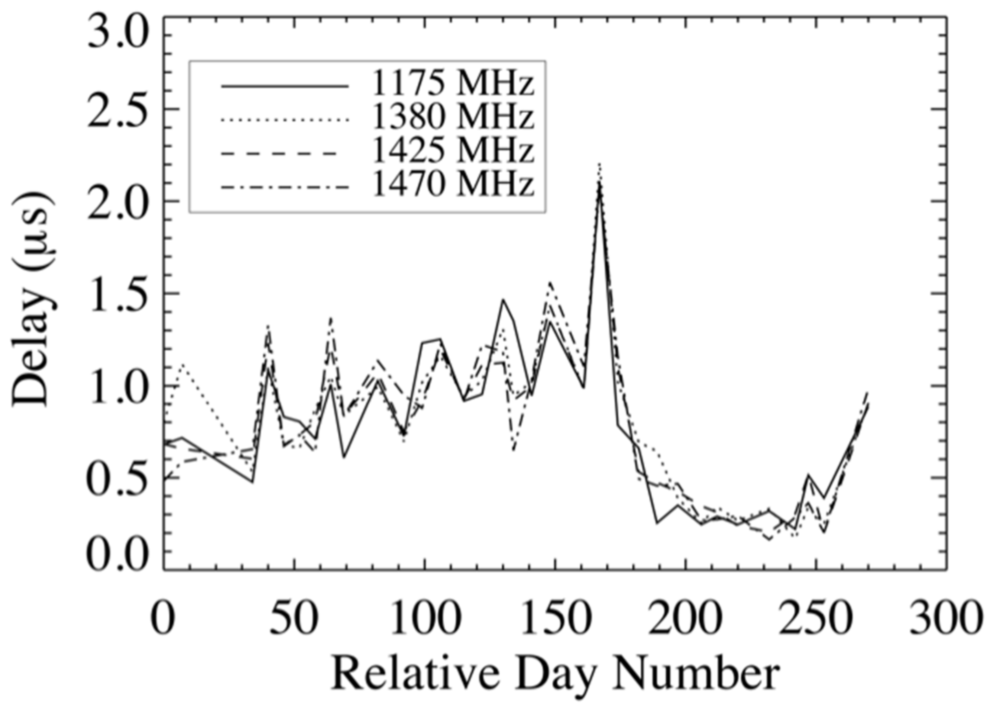

From Lorimer & Kramer, 2005, “Handbook of Pulsar Astronomy”

Pulsar signals are scattered by the interstellar medium with $\tau_s \propto freq^{-4}$, requiring either accepting fainter pulsars at high frequencies or the development of correction algorithms for scattering at low frequencies.

# 2) Better algorithms for timing and detection

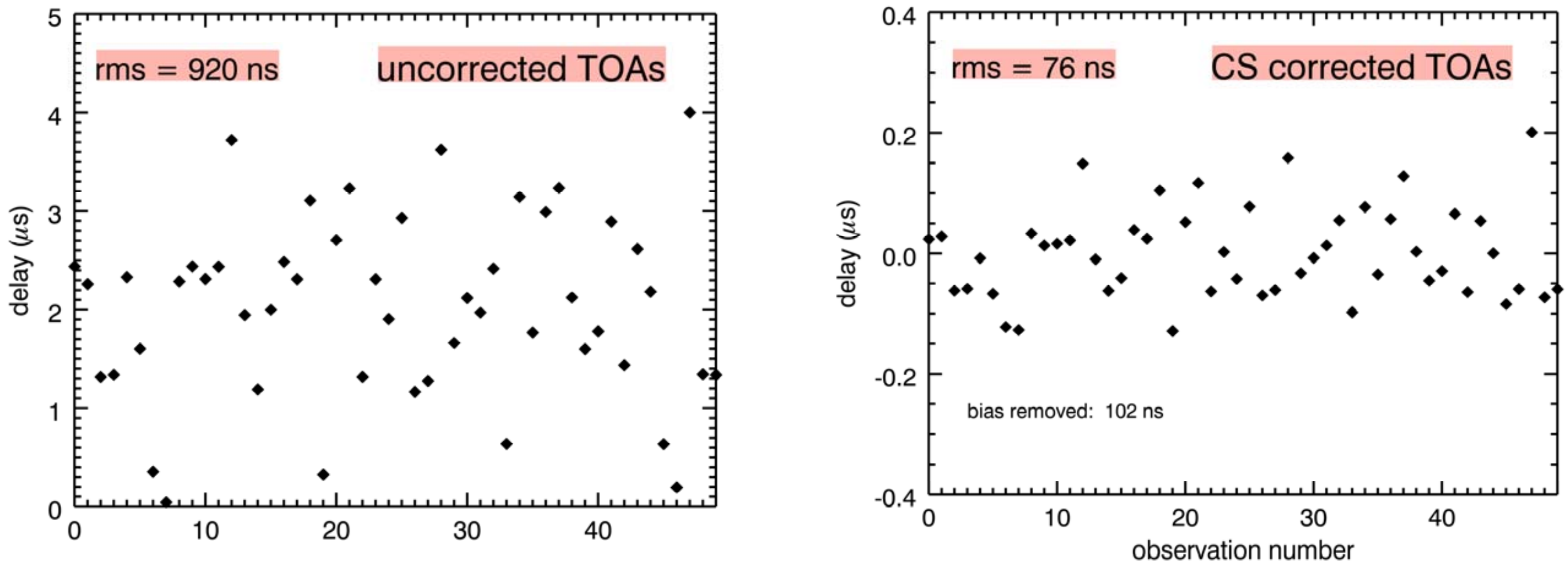
Pulsar signals are also delayed by amounts greater than or comparable to GW perturbations.

We are experimenting with correction techniques that preserve the phase information of the pulsar signal to recover the delay. This scheme requires baseband data and so we are working on GPU-based implementations (Jones et al. in preparation).




Hemberger & Stinebring, 2008, ApJ, 674, L37

# 2) Better algorithms for timing and detection




Palliyaguru et al. in preparation

Only works for a pulsed signals.

1) Take baseband data.

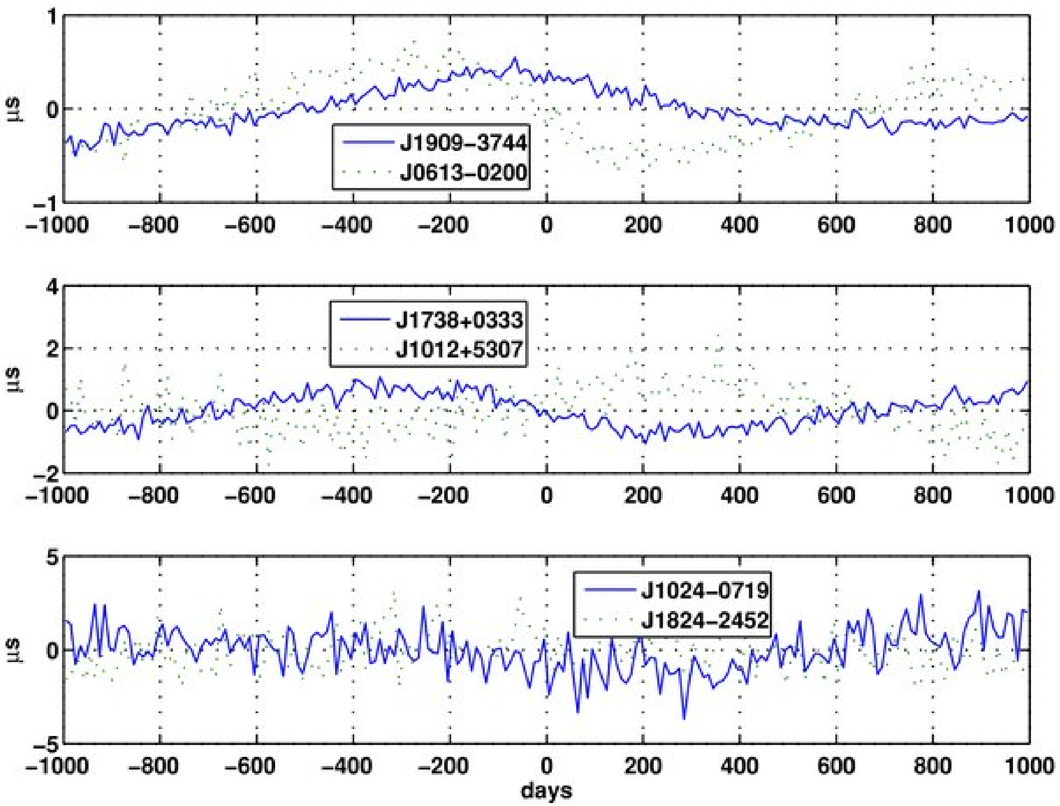
2) FT to frequency domain.

3) Shift FT and FT* in opposite directions.

4) Multiply and accumulate.

# 2) Better algorithms for timing and detection

Optimal algorithms for stochastic, continuous, and burst source detection continually under development.

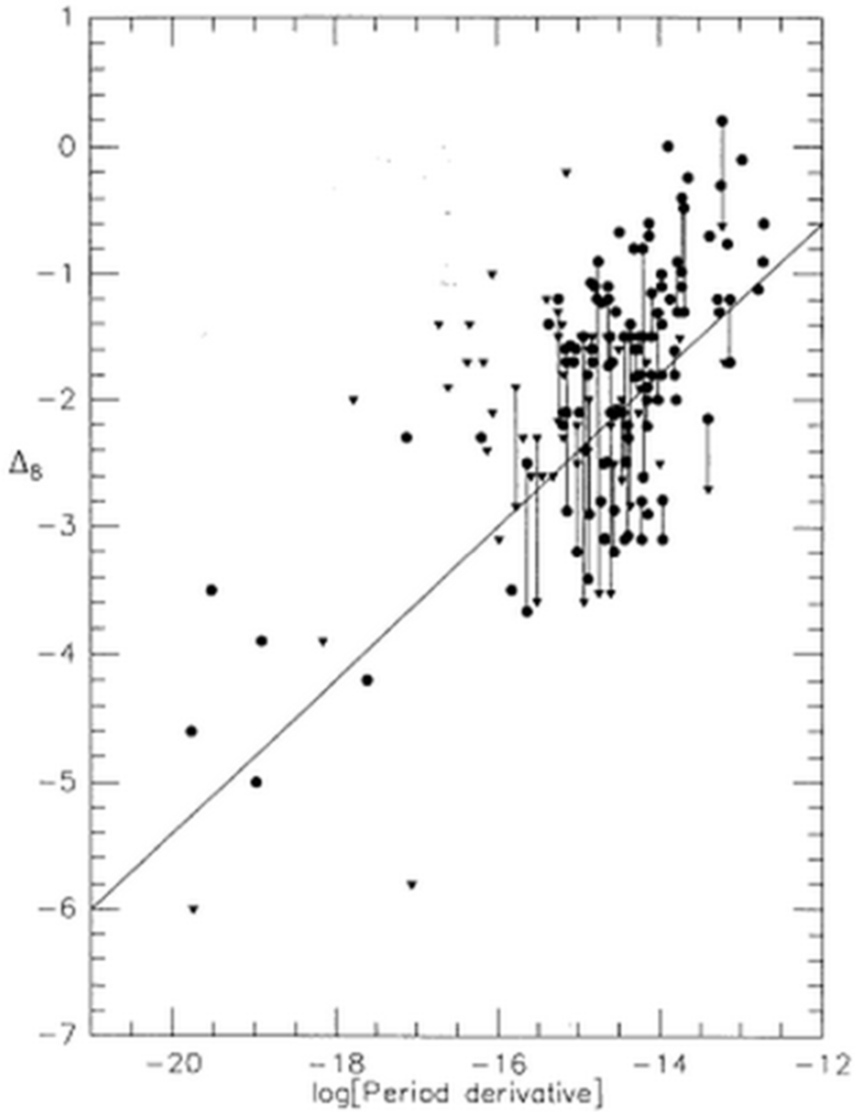



Finn & Lommen, ApJ, 718, 1400

# 3) New Pulsars!

Timing noise is correlated with period derivative (or spin-down energy loss rate) but there is not a clear prediction for a specific pulsar.

Therefore, we must carry out searches and time pulsars for ~year(s) to determine whether they are suitable for inclusion in the PTA.




Arzoumanian et al. 1994, ApJ, 422, 671

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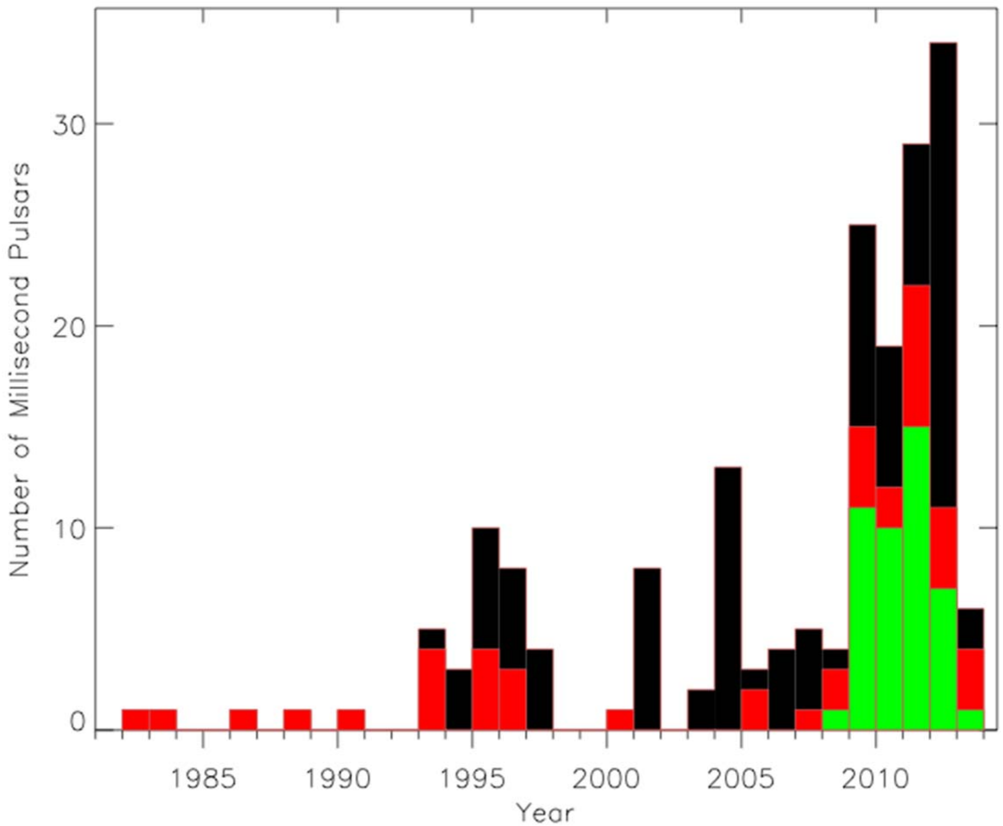
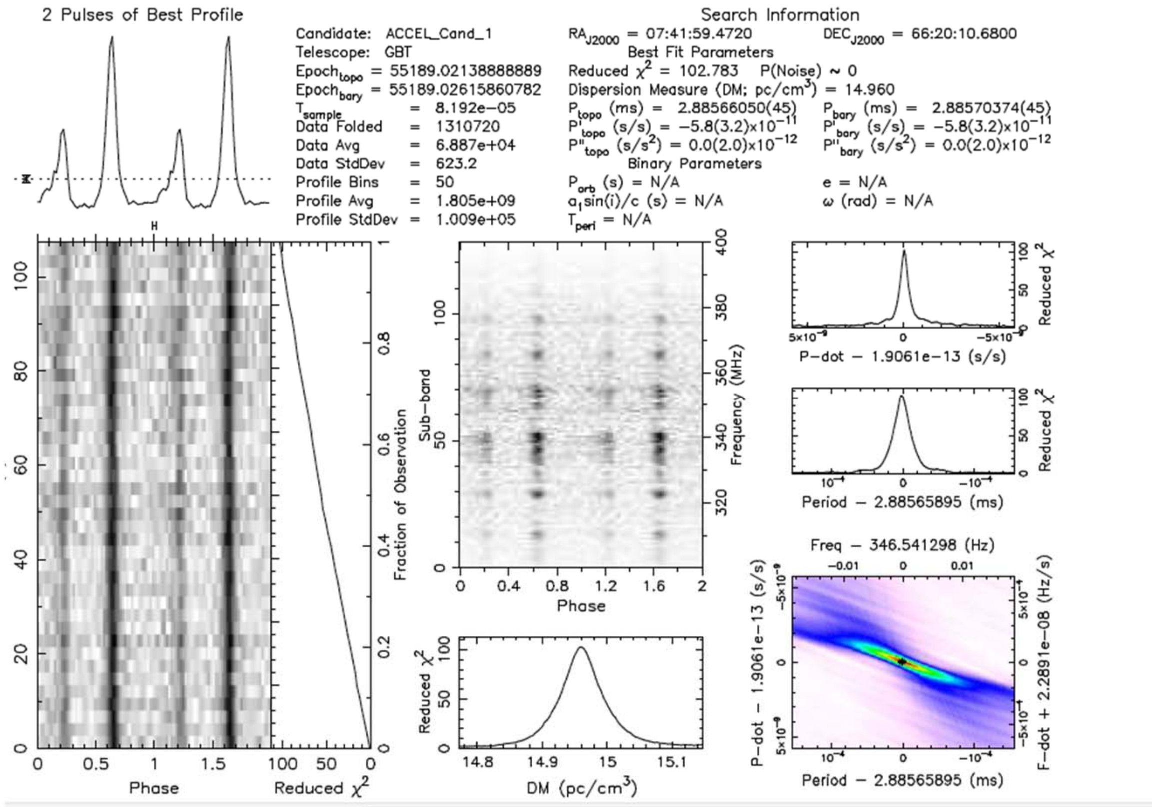



Searches underway with Arecibo and the GBT have revealed nearly 100 new MSPs over the past several years.

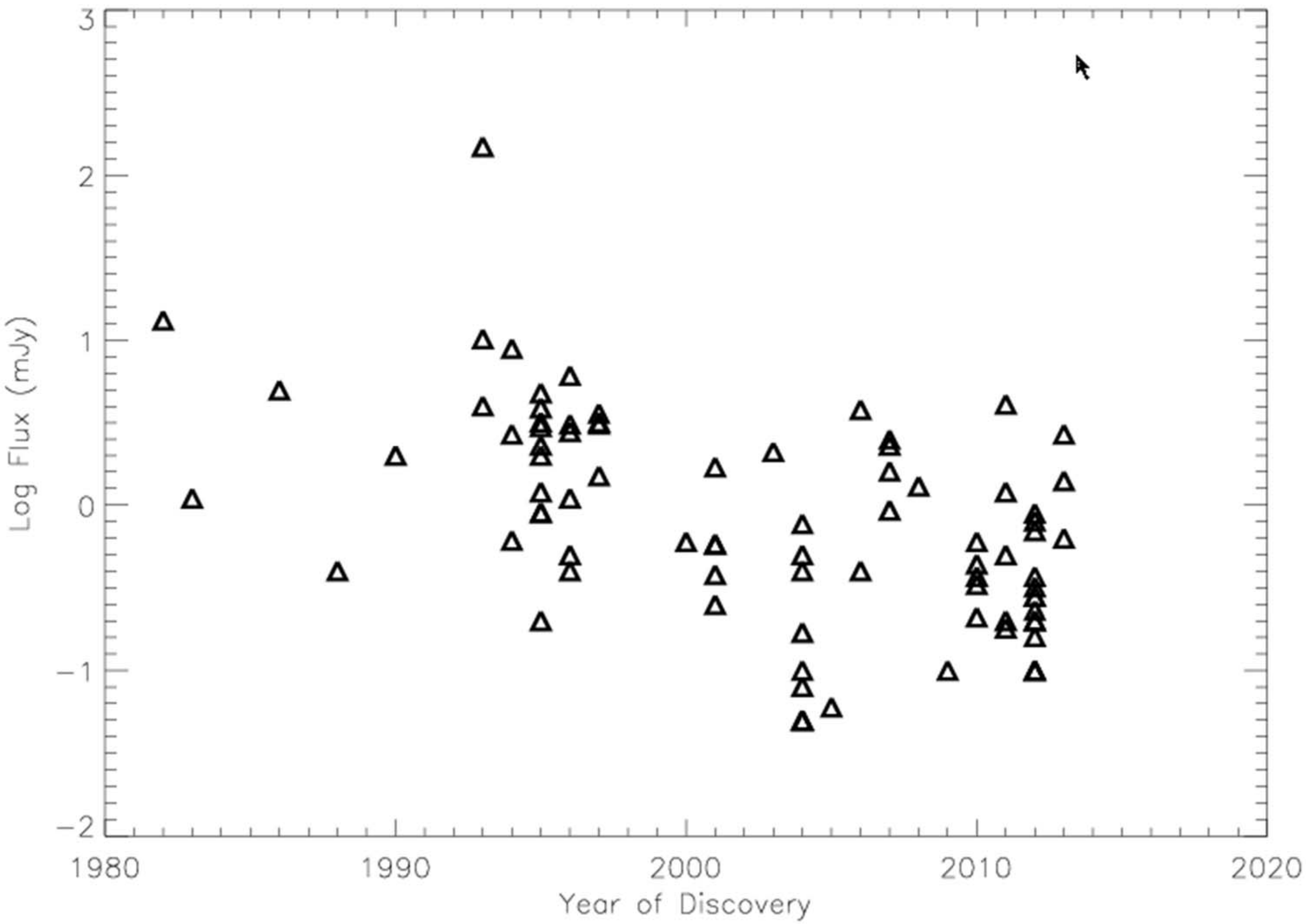
# 3) New Pulsars!

Many of these have the narrow, bright profiles required for PTAs.



# 3) New Pulsars!

Many bright MSPs remain to be found!



# Summary

- NANOGrav is timing nearly 40 pulsars with precisions of 30 ns – 1.5 μs. This number has increased from 18 only 3 years ago.

- Limits are entering ranges that are constraining for SMBH and cosmic string models.

- Most of the pulsars are white noise dominated but red noise may become dominant in time.

- New instrumentation, more sophisticated scattering removal techniques, and adding new pulsars to the array are crucial for increasing our sensitivity.

- Arecibo and the GBT are essential for continuation of our program.

- Current searches are expected to discover ~100 MSPs over the next ~3 years.

- Ample additional science is enabled through these observations!