Prospects for the Detection of Low Frequency Gravitational Waves

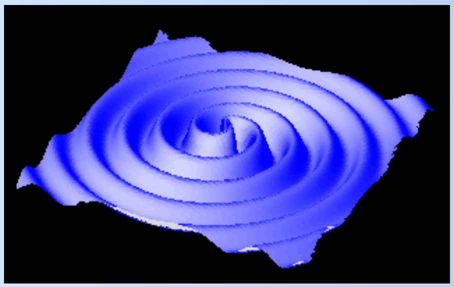
Fredrick Jenet, Andrea Lommen, Jim Cordes, Xavi Siemens, Maura McLaughlin
for the NANOGrav collaboration

Outline

- Introduction and Overview
  - Fredrick Jenet
- The Astrophysics of GWs
  - Andrea Lommen
- Astrophysics of the Timing Precision needed for GW Detection
  - Jim Cordes
- Current and Future GW Sensitivity of the NANOGrav IPTA effort
  - Xavi Siemens
- Status of Current Pulsar Surveys and Prospects for Discovering More MSPs
  - Maura McLaughlin

Gravitational Waves (GWs)

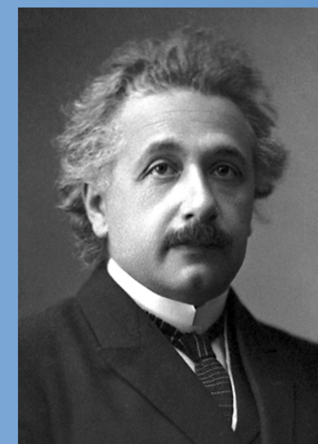
“Ripples in the fabric of space and time.”



$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

$$G_{\mu\nu}(g) = 8\pi T_{\mu\nu}$$

$$-\partial^2 h_{\mu\nu} / \partial^2 t + \nabla^2 h_{\mu\nu} = -16\pi T_{\mu\nu}$$

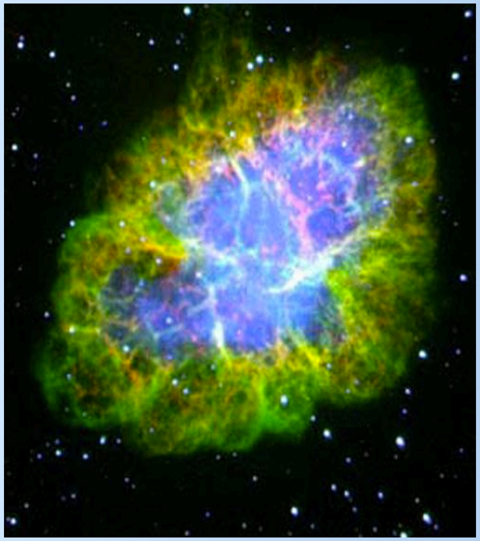


They are a key prediction of General Relativity (GR) and general metric theories, but have never been directly detected.

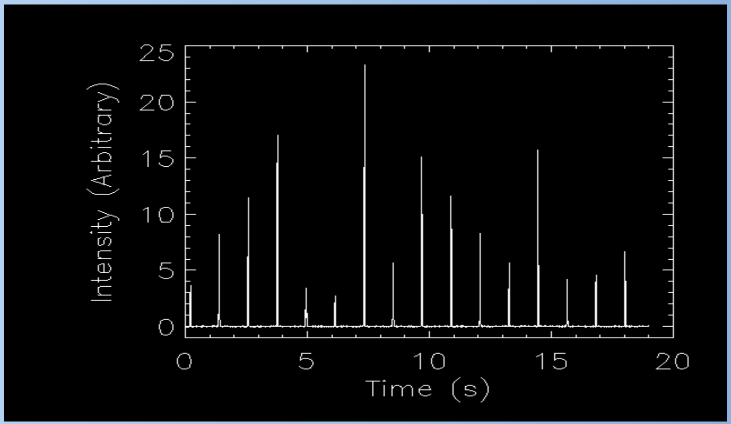
GW detection will allow us to us to test GR, detect previously invisible matter, and to probe some of the most energetic processes in the universe.

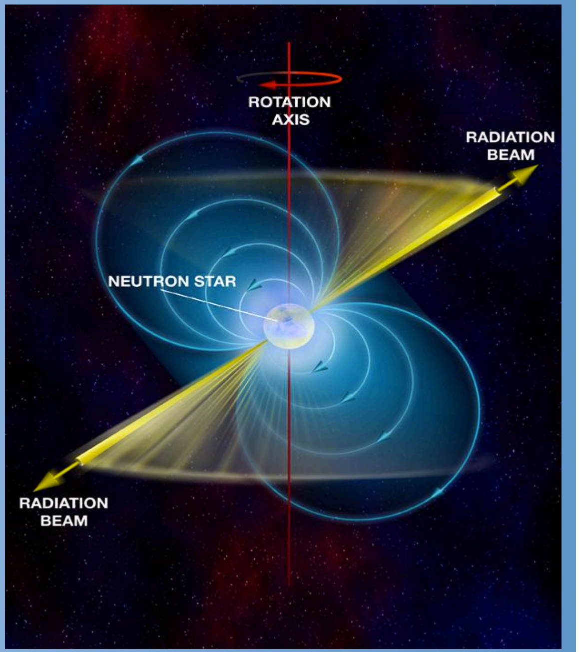
Pulsars

Pulsars are highly magnetized, rotating neutron stars born in supernova explosions. They have spin periods from 1 ms to 10 s, magnetic fields of 10^8 to 10^{14} G, and spin-down luminosities greater than Sun's total luminosity.



Millisecond pulsars (MSPs) have spin periods < 10 ms and are remarkably stable celestial clocks. Out of 2000 known pulsars, roughly 10% are MSPs.



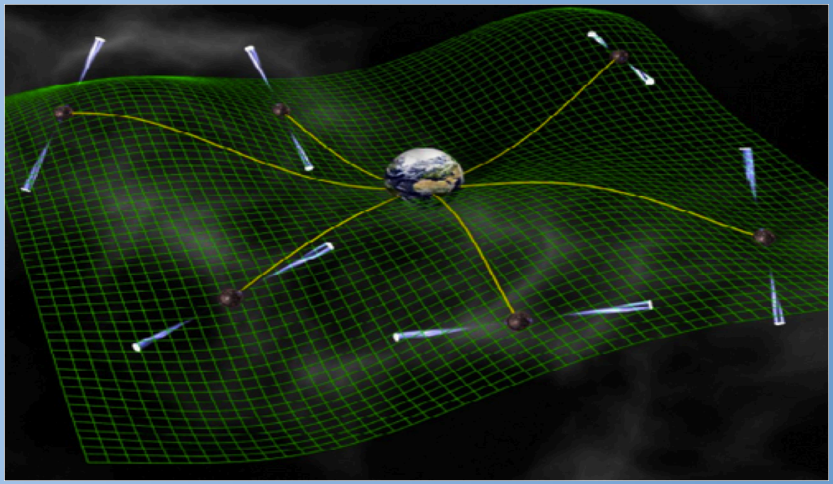


Pulsar Timing Arrays (PTAs)

A PTA is set of radio pulsars that are observed at regular intervals.

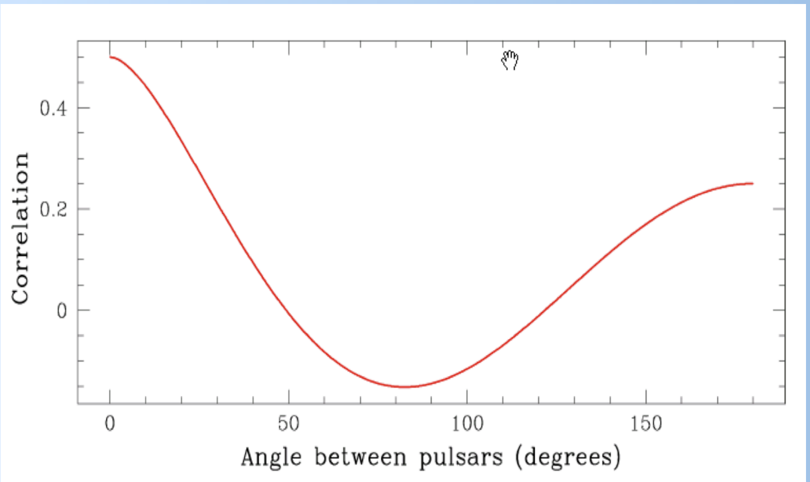
The times of arrival (TOAs) of pulses for each pulsar are measured.

We look for specific correlations in the TOAs between different pulsars.



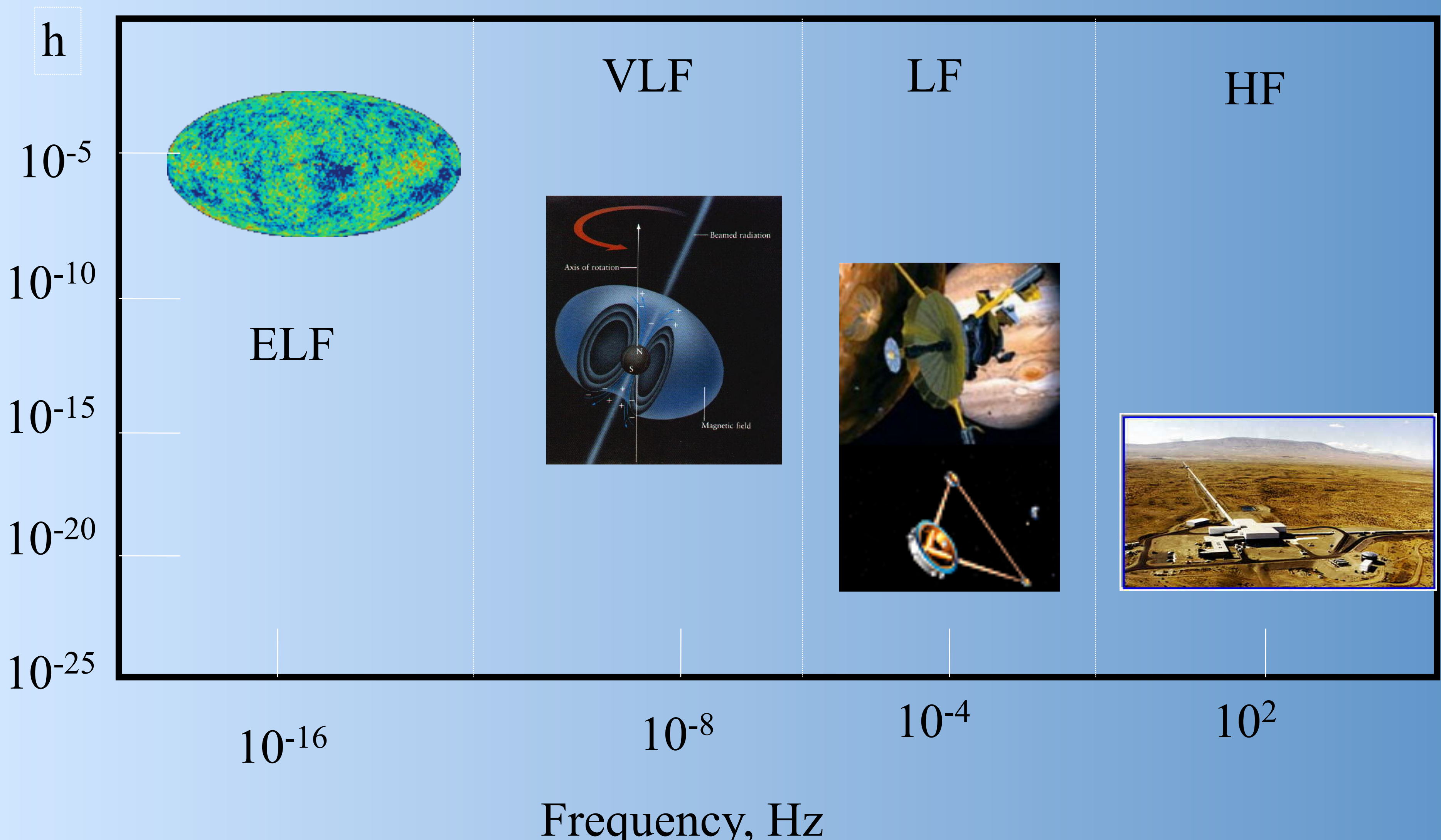
The details of the correlation depend on the type of signal:

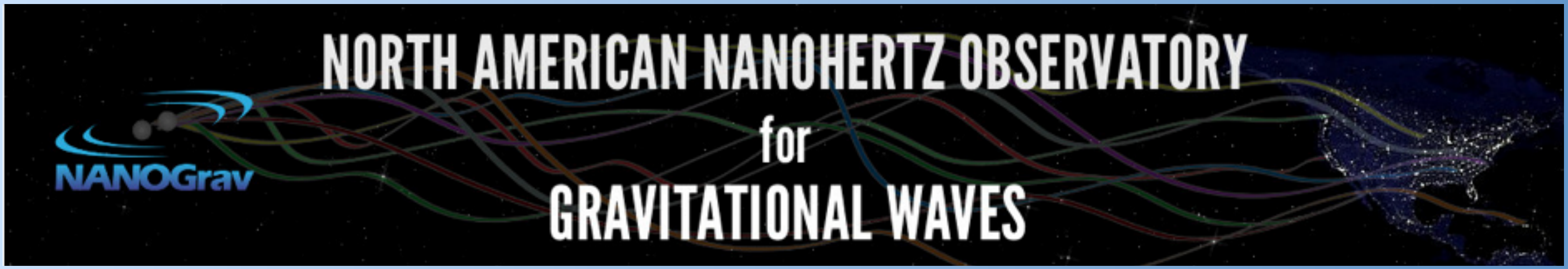
- Stochastic
- Continuous Wave
- Burst



An isotropic stochastic background of GWs induces a specific TOA correlation between observed pulsars

The Big Picture of G-wave Detection





The North American Nanohertz Observatory for Gravitational Waves is a consortium of astronomers who share a common goal of detecting GWs via observations of MSPs using the Green Bank Telescope (GBT) and Arecibo Observatory (AO). We have personnel at 14 institutions and include 20 senior personnel, 13 postdoctoral scholar, 16 graduate student, and 14 undergraduate student members.

Home PIRE Participants Governance Publications International Collaboration Outreach Meetings Links

NORTH AMERICAN NANOHERTZ OBSERVATORY for GRAVITATIONAL WAVES

Leadership | By Laws | Membership Policy | Publication Policy

NANOGrav Management Team

Chair	Fredrick Jenet	University of Texas, Brownsville
Former Chair	Maura McLaughlin	West Virginia University
Member	Zaven Arzoumanian	Universities Space Research Association & Nasa Goddard Space Flight Center
Member	Jim Cordes	Cornell University
Member	Victoria Kaspi	McGill University
Member	Andrea Lommen	Franklin & Marshall

NANOGrav Working Group Leads

Cyber-Infrastructure	Ingrid Stairs	University of British Colombia
Data Analysis	Xavier Siemens	University of Wisconsin-Milwaukee
Education and Outreach	Ryan Lynch	McGill University
Instrumentation	Scott Ransom	NRAO
International Engagement	Andrea Lommen	Franklin & Marshall College
Interstellar Medium Mitigation	Dan Stinebring	Oberlin College
Noise Budget	Jim Cordes	Cornell University
Searching	Duncan Lorimer	West Virginia University
Strategic Planning	Jim Cordes	Cornell University
Timing	David Nice	Lafayette College

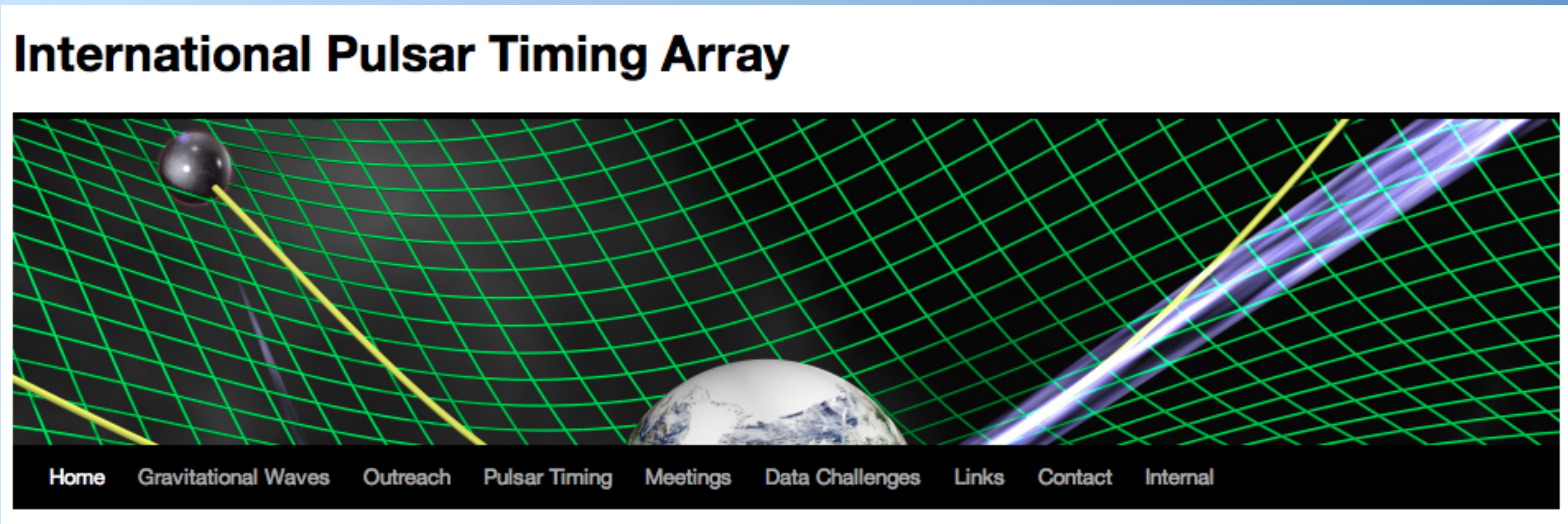
http://nanograv.org

The IPTA

The IPTA (International Pulsar Timing Array) is a consortium consisting of NANOGrav, the European Pulsar Timing Array (EPTA), and the Parkes Pulsar Timing Array (PPTA). The goal of the IPTA is to detect GWs and build a pulsar GW observatory by combining data and resources from all PTAs.

NANOGrav routinely sends students and researchers to work at international locations.

The IPTA meets yearly. The next meeting is this summer at Banff, Canada. It will be coordinated with GWIC.



http://www.ipta4gw.org/

Gravitational Waves in slightly more detail......

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

$$R_{\mu\alpha\nu\beta}$$

$$\frac{d^2x^\mu}{d\tau^2} = R^\mu{}_{\alpha\nu\beta}\frac{dx^\alpha}{d\tau}\frac{dx^\beta}{d\tau}x^\nu$$

$$\frac{\partial R_{\mu\alpha\nu\beta}}{\partial x^\delta} + \frac{\partial R_{\mu\alpha\beta\delta}}{\partial x^\nu} + \frac{\partial R_{\mu\alpha\delta\nu}}{\partial x^\beta} = 0$$

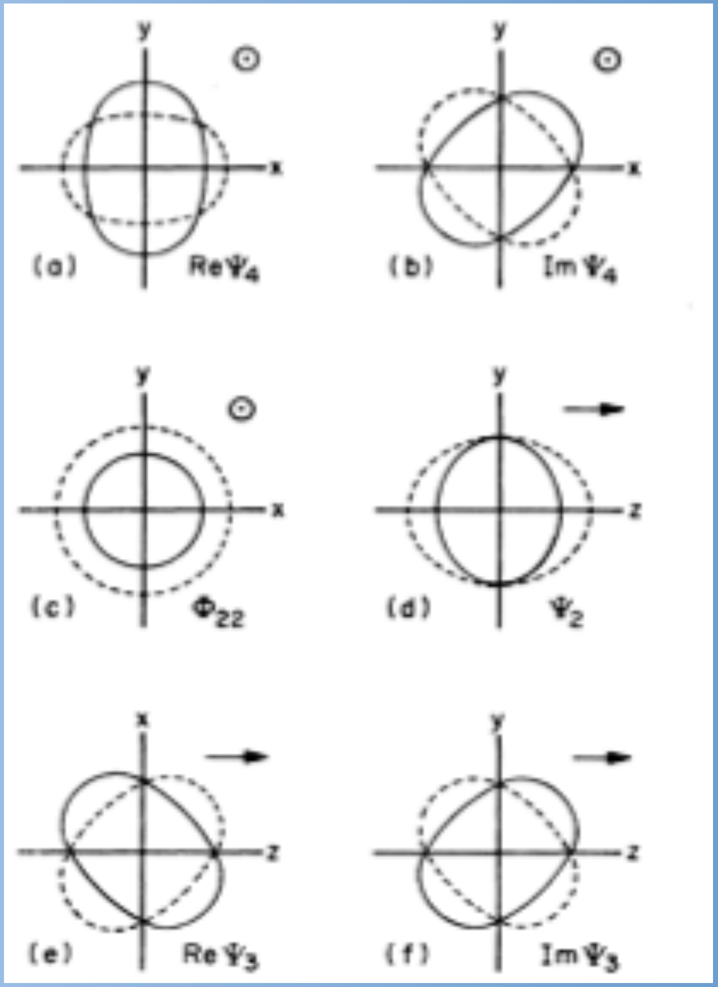
$$R^\mu_{\alpha\mu\beta} - \frac{1}{2}\eta_{\alpha\beta}R^{\mu\alpha}{}_{\mu\alpha} = 8\pi T_{\mu\nu}$$

This whole mess together says that we have 2 possible polarizations states.

If we remove the last equations, we can have up to 6 possible states.

Gravitational Waves in slightly more detail......

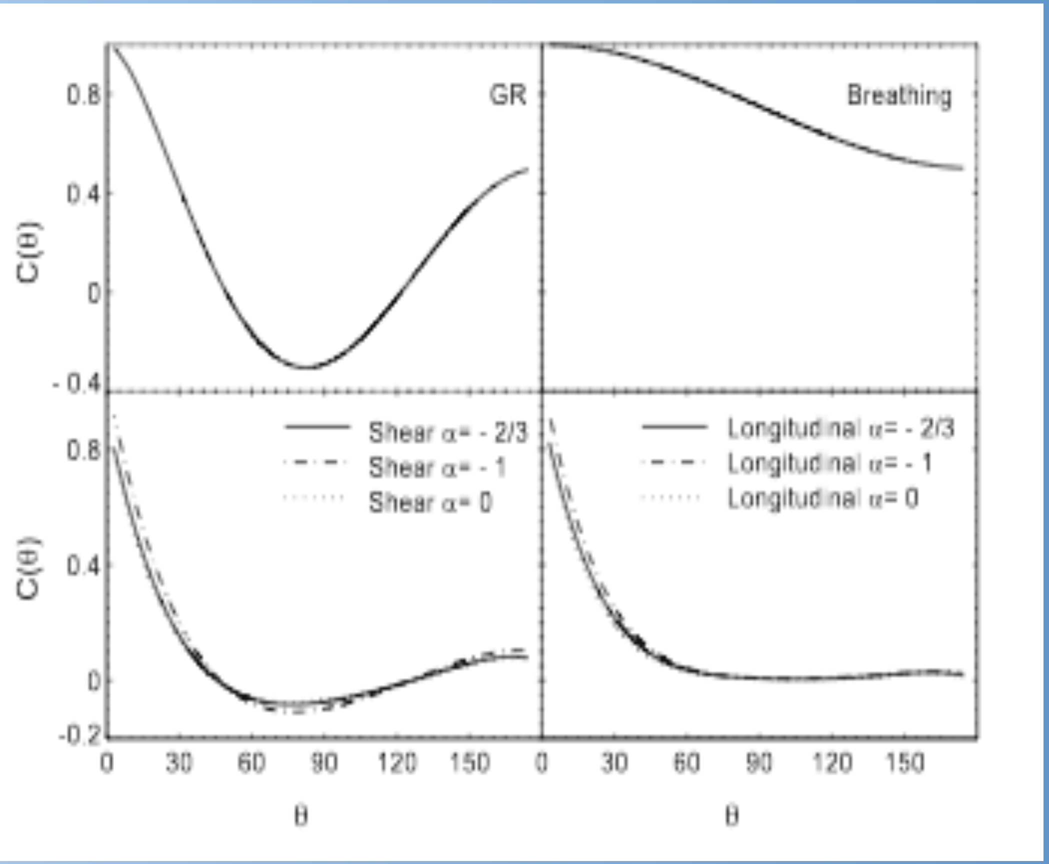
- GR predicts only two polarization modes.
- A general metric theory has 4 more.
- The observed correlation seen in pulsar pulse TOAs will depend on the polarizations present.



(Figure from: Eardly, Lee, Lightman '73)

Gravitational Waves in slightly more detail......

- Different polarization modes will have different curves.
- The actual correlation curve will be a weighted sum of these curves.



(Lee, Jenet, Price, ApJ 2008)

In order to have a hope of discriminating between different modes, one needs:

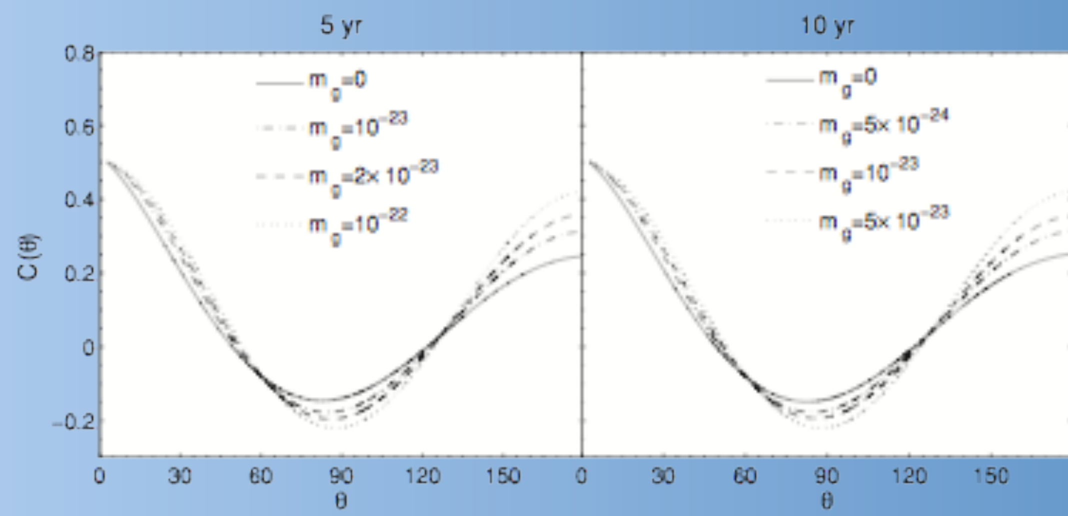
# pulsars	Mode
40	Breathing
100	Longitudinal
500	Shear

(Lee, Jenet, Price, ApJ 2008)

Massive Gravitons....

$$\mathbf{k}_g(\omega_g) = \frac{(\omega_g^2 - \omega_{\rm cut}^2)^{\frac{1}{2}}}{c}\,\hat{\mathbf{e}}_z$$

$$\omega_{\rm cut} \equiv m_g c^2/\hbar$$



(Lee, Jenet, Price, ApJ 2010)

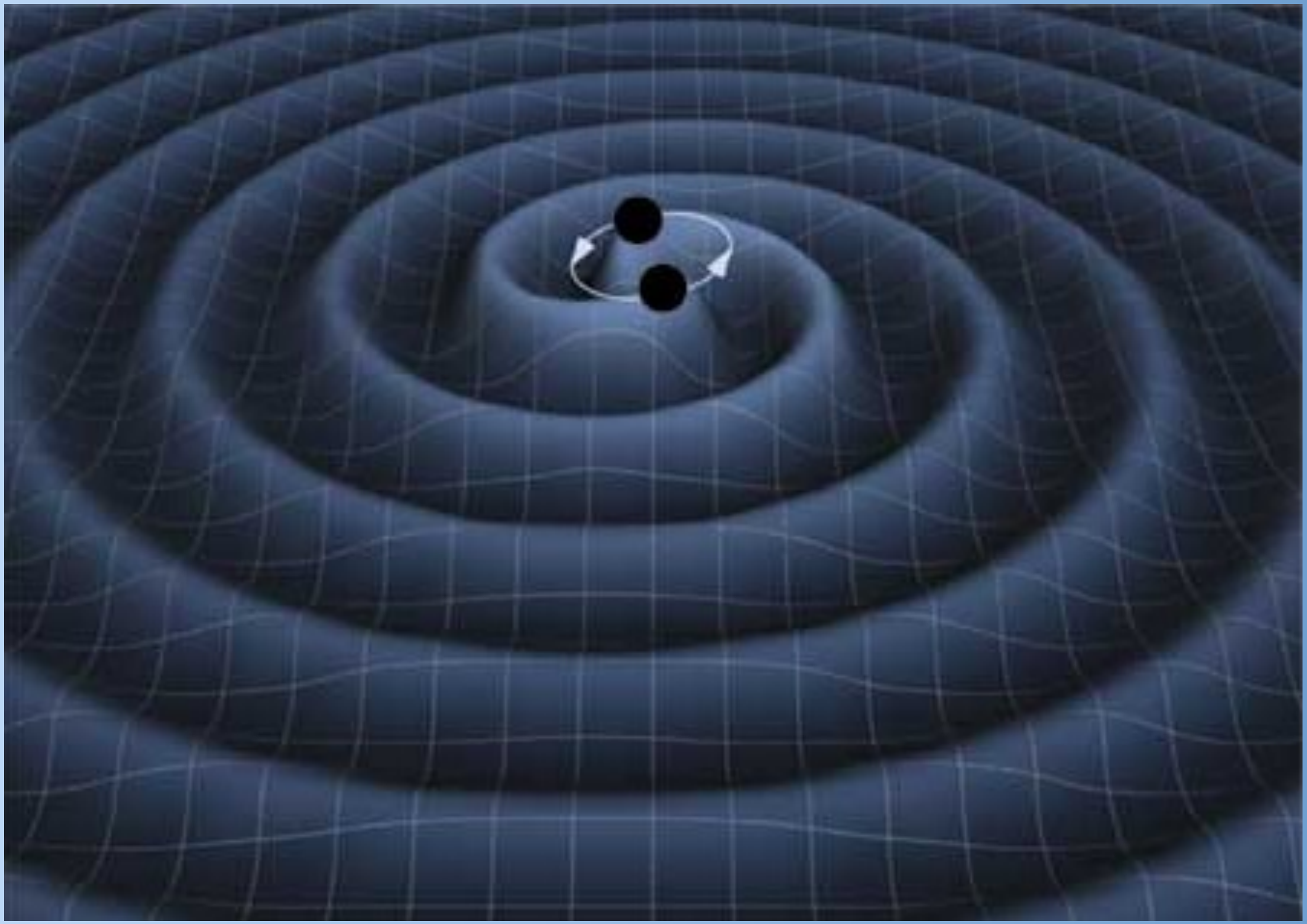
The Graviton Mass will effect the observed correlation function

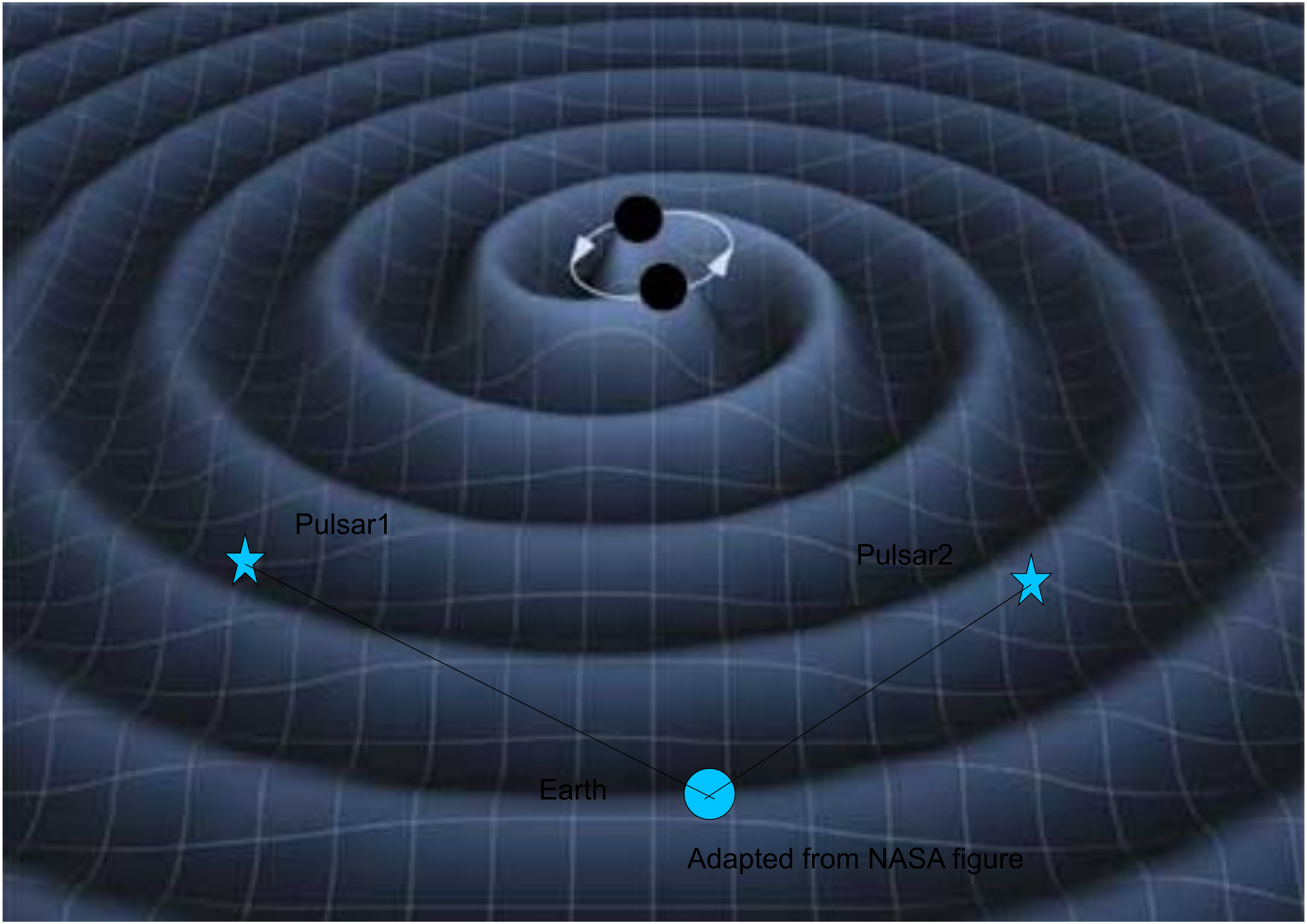
Using the shape of the correlation curves:

60 pulsars @100ns timed every two weeks for five years yields:

$$m_g \leqslant 2 \times 10^{-23}\ \mathrm{eV}$$

The Astrophysics of Gravitational Waves





Pulsar1
Pulsar2
Earth
Adapted from NASA figure

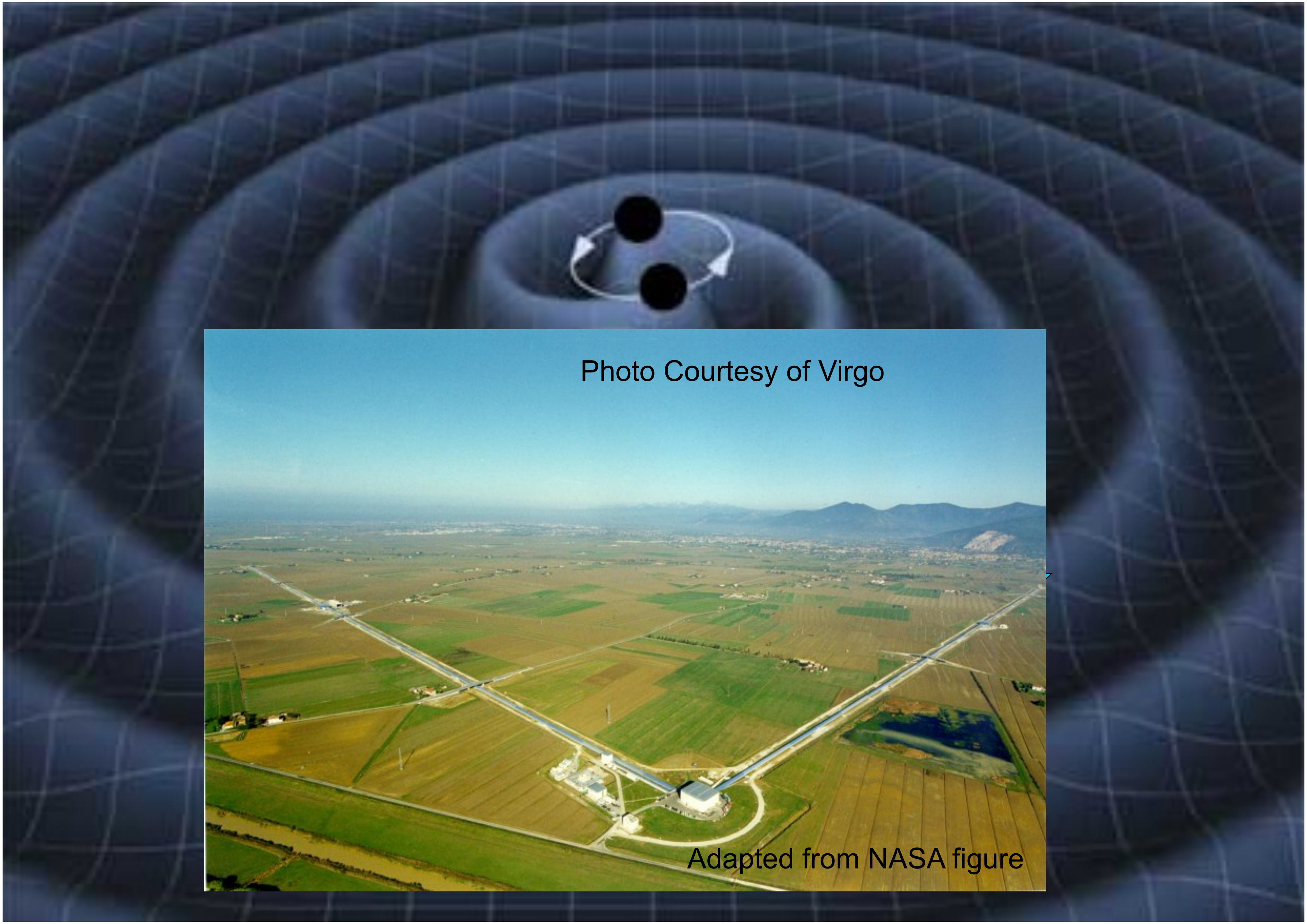


Photo Courtesy of Virgo
Adapted from NASA figure

A sense of what's detectable

$$\tau = 50ns \frac{\left(\dfrac{M}{2\times10^{9} M_{\Theta}}\right)^{5/3} \left(\dfrac{P}{1 year}\right)^{1/3}}{\left(\dfrac{d}{100 Mpc}\right)}$$

NANOGrav 5-year timing results summary

Source	Per-channel RMS, μs	χ^2	Daily RMS, μs	Hi-freq RMS, μs
J1713+0747	0.106	1.48	0.030	0.041
J1909–3744	0.181	1.95	0.038	0.047
B1855+09	0.395	2.19	0.111	0.101
J0030+0451	0.604	1.44	0.148	0.328
J1600–3053	1.293	1.45	0.163	0.141
J0613–0200	0.781	1.21	0.178	0.519
J1744–1134	0.617	3.58	0.198	0.229
J2145–0750	1.252	1.97	0.202	0.494
J1918–0642	1.271	1.21	0.203	0.211
J2317+1439	0.496	3.03	0.251	0.155
J1853+1308	1.028	1.06	0.254	0.271
J1012+5307	1.327	1.40	0.276	0.345
J1640+2224	0.562	4.36	0.409	0.601
J1910+1256	1.394	2.09	0.708	0.710
J1455–3330	4.010	1.01	0.787	1.080
B1953+29	3.981	0.98	1.437	1.879
J1643–1224	2.892	2.78	1.467	1.887

Demorest et al. 2013, ApJ, 762, 94

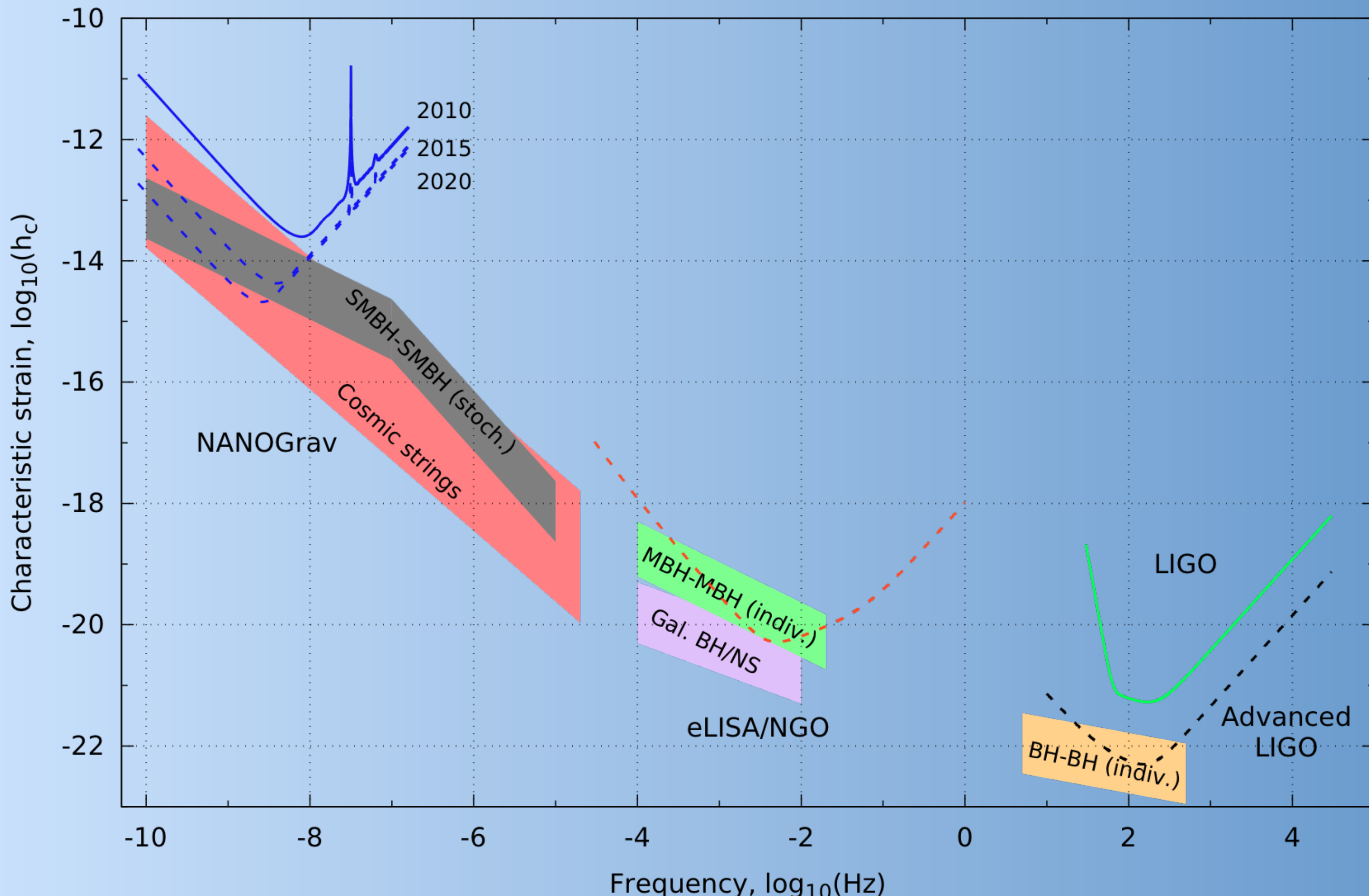
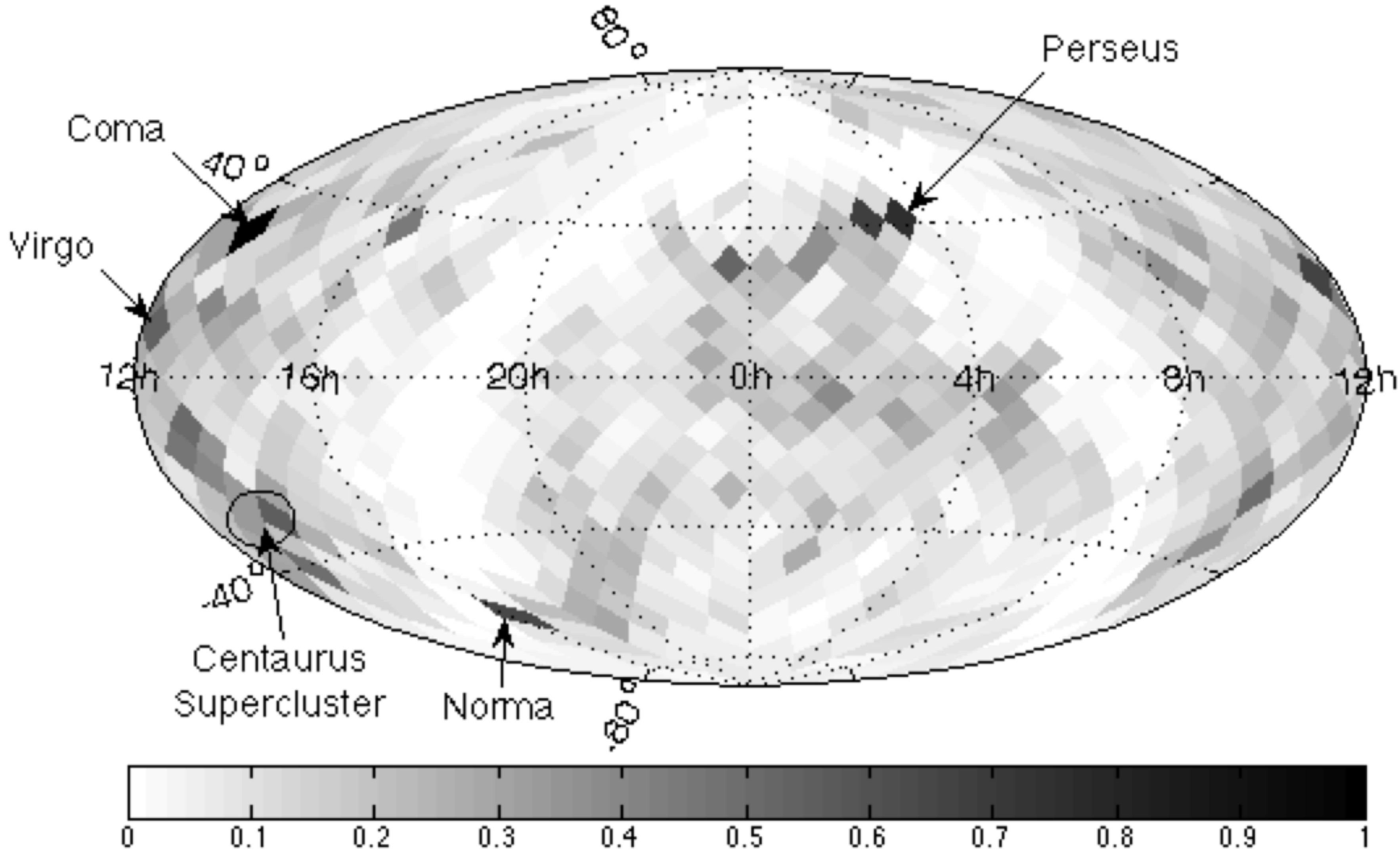
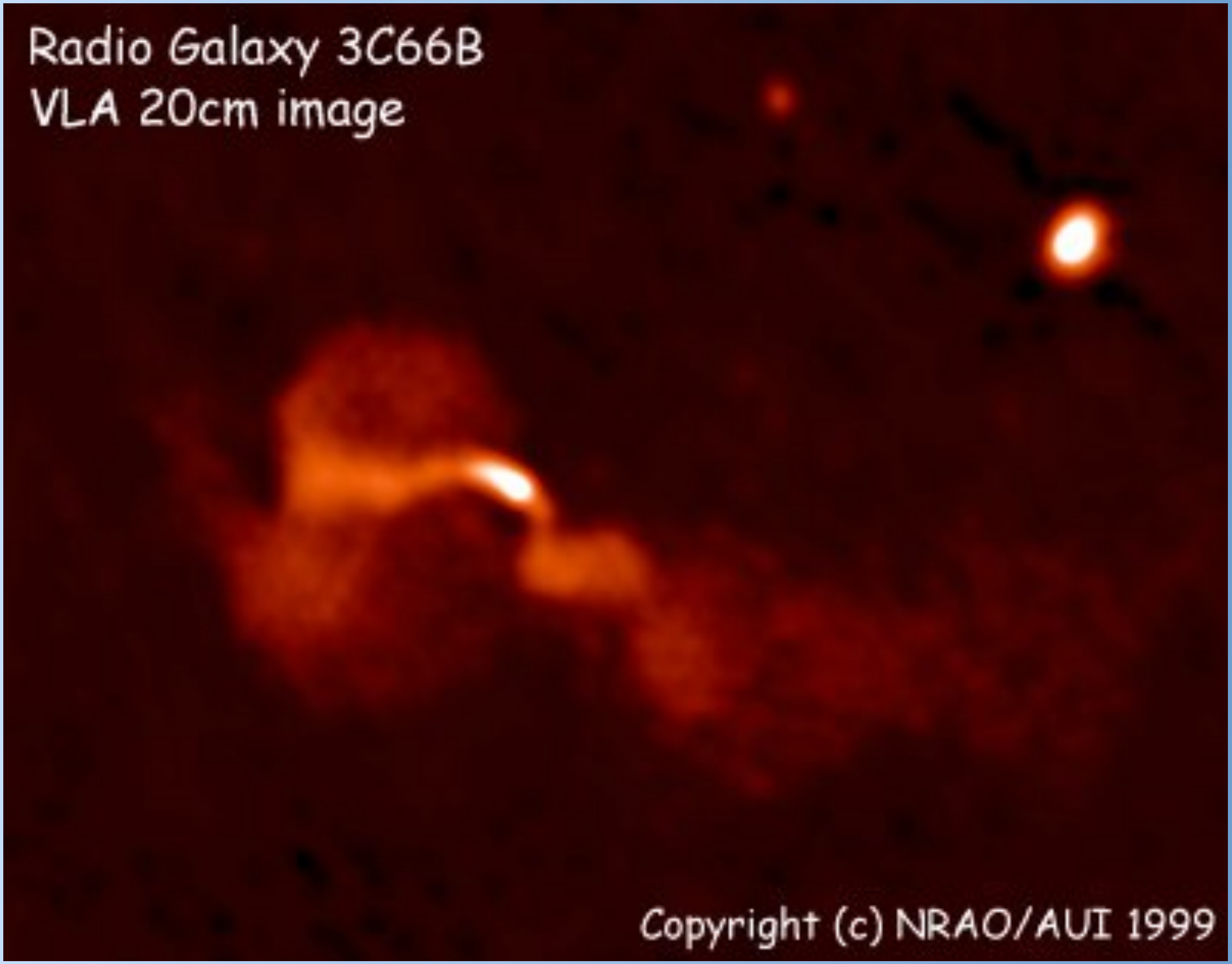


Figure by Paul Demorest (see arXiv:0902.2968)

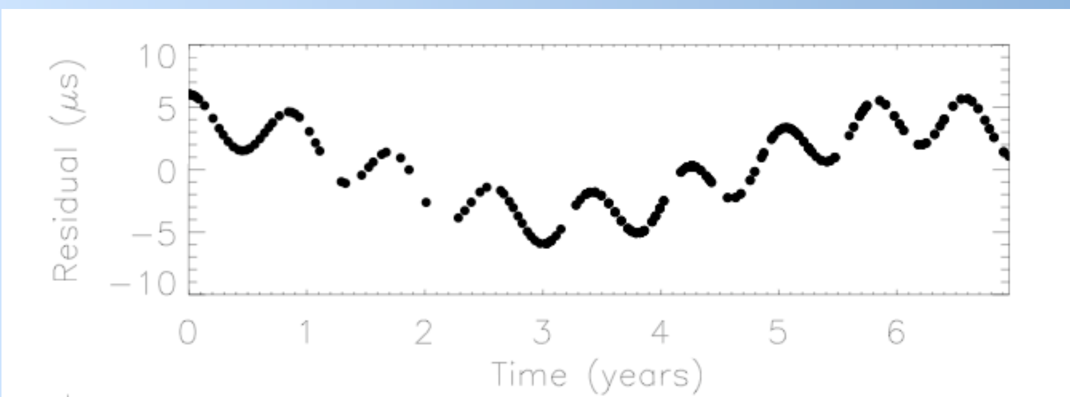


The non-isotropic nanohertz GW sky (Simon et al., ApJ, submitted)

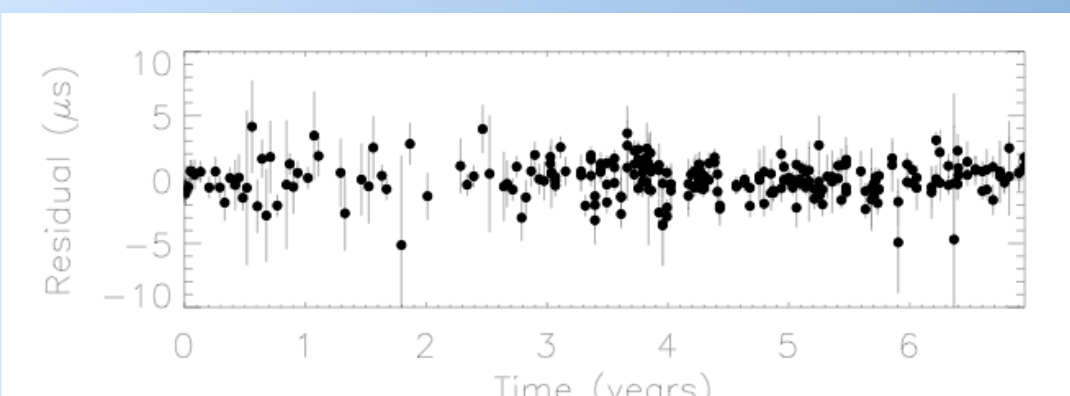

Radio Galaxy 3C66B
VLA 20cm image
Copyright (c) NRAO/AUI 1999

Orbital Motion in the Radio Galaxy 3C 66B: Evidence for a Supermassive Black Hole Binary Sudou, Iguchi, Murata, Taniguchi (2003) Science 300: 1263-1265.

Constraining the Properties of Supermassive Black Hole Systems Using Pulsar Timing: Application to 3C 66B, Jenet, Lommen, Larson and Wen (2004) ApJ 606:799-803.



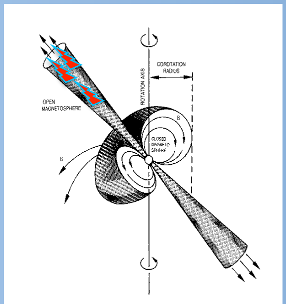
Simulated residuals due to 3C66B

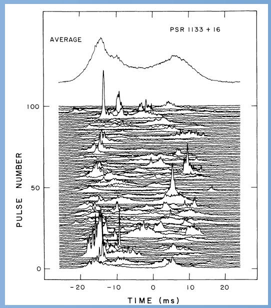


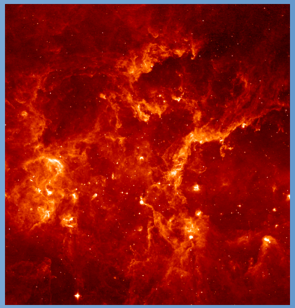
Data from Kaspi, Taylor, & Ryba (1994)

The Astrophysics of Precision Timing for Gravitational Wave Detection

- Spinning neutron stars are used as astrophysical clocks.
- Received pulses = clock ticks
- Departures from perfect timekeeping are the basis for GW detection
- Our sensitivity to GWs is affected by neutron star physics, interstellar medium effects, and instrumentation
- We can control GW sensitivity by mitigating all of these effects
  - Observing protocols
  - New algorithms
  - Additional MSPs







Challenges of GW Detection
ΔL/L~ h

Pulsar Timing Array

L ~ cT ~ 3 pc

h_{min} ~ 10^{-16} – 10^{-14}

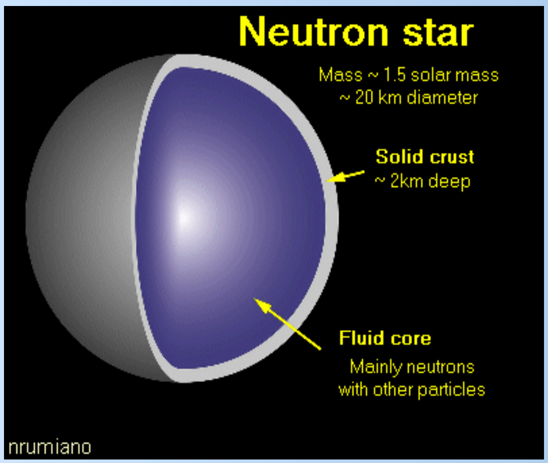
ΔL ~ 10^3 to 10^5 cm

Ground-based Interferometer

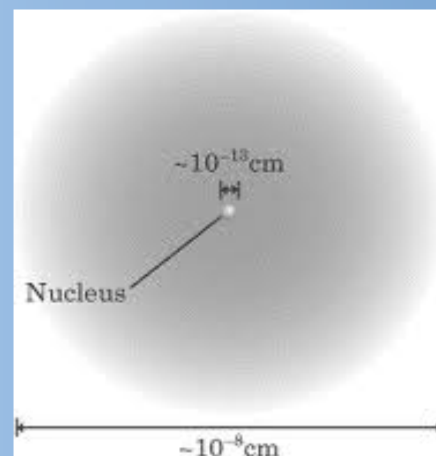
L ~ 4 km x 50 reflections

h_{min} ~ 10^{-23}

ΔL ~ 10^{-16} cm



10^{-3} R_{NS}



10^{-3} $R_{nucleus}$

GW detection using pulsars is equivalent to tracking the location of a neutron star to within a fraction of its radius over time spans of 5 to 10 years.

NANOGrav Timing with GBT and Arecibo

- GASP (2004 – 2011)
- GUPPI (2011 – present): Factor of up to 3 improvement in timing precision!

- Mark4 + ABPP (1998 –2005)
- ASP (2004 – 2012)
- WAPP (2004 – 2012)
- PUPPI (2012 – present): Similar improvements.

Timing Measurement Model

Pulse arrival times = deterministic terms

(spindown, orbits, astrometric)

+ **deterministic pulsar effec**ts

(profile evolution with frequency)

+ **stochastic terms in puls**ar

(spin, magnetosphere, mode changes, …)

+ **stochastic terms in ISM**

(dispersion, scattering, scintillation)

+ **radiometer noise and finite S/N**

(interplay with scintillation)

+ **measurement biase**s

(e.g. polarization calibration)

+ solar system ephemeris errors

+ DSP effects (bits)

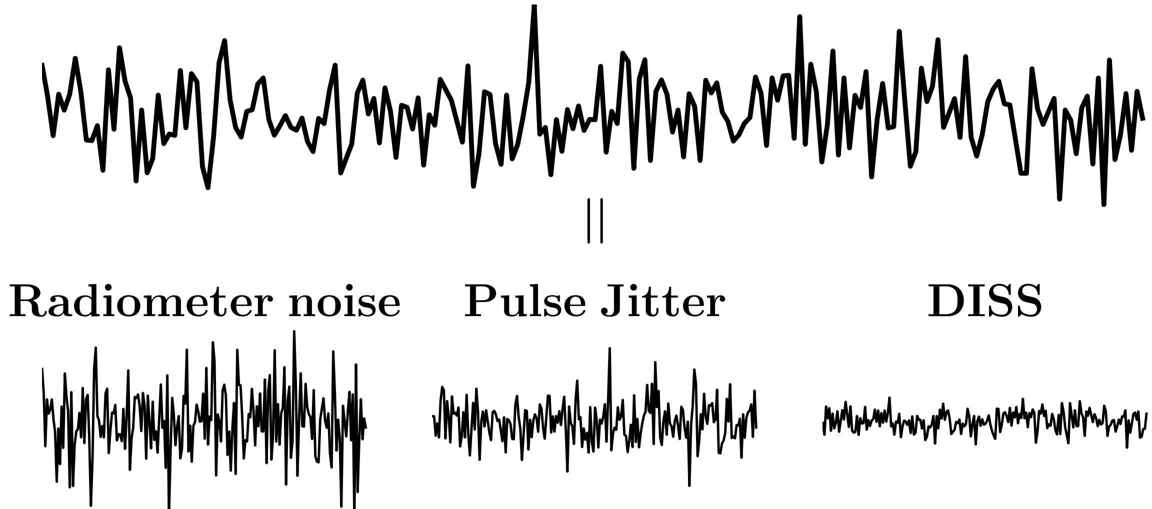
+ **unexpected terms** (no others?)

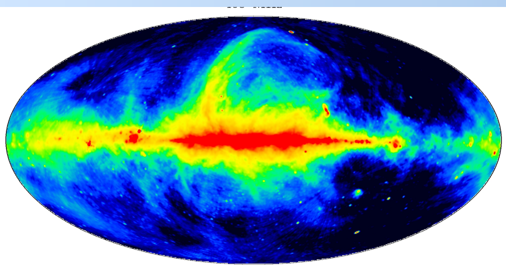
+ Gravitational waves

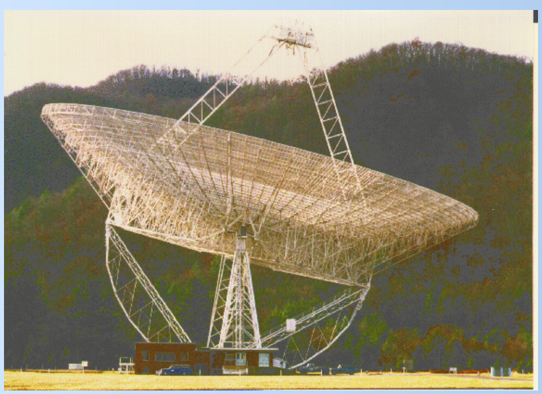
Characterization of Millisecond Pulsar Timing

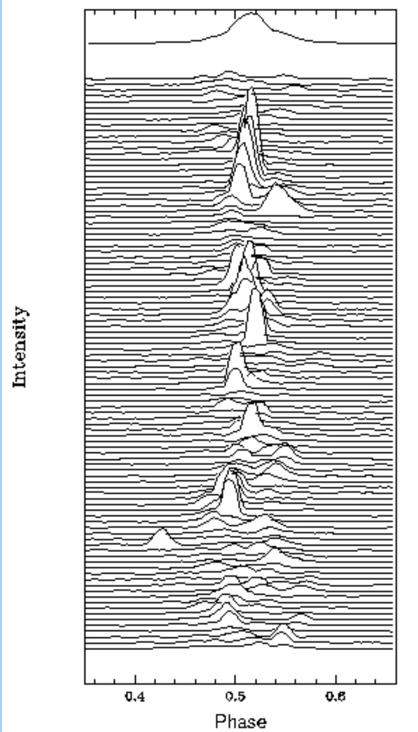
- **We understand MSP timing precision down to tens of nanoseconds**
  - **Random errors in arrival times**
    - Pulse jitter from emission region dynamics in pulsar magnetospheres
    - Additive noise from sky backgrounds and receiver noise
    - Scintillation noise (interstellar)
  - **Systematic errors in arrival times**
    - Variation of pulse profiles with frequency (pulsar magnetosphere)
    - Pulse broadening from interstellar scattering
  - **Non-gaussianity**
    - The only non-gaussianity is from a combination of scintillation intensity modulations of the signal-to-noise ratio
  - **Departures from white noise:** We see "red-noise" effects from
    - Variations in interstellar dispersion measure
    - Noise in the spin rate of MSPs due to magnetospheric torques or torques internal to the neutron star

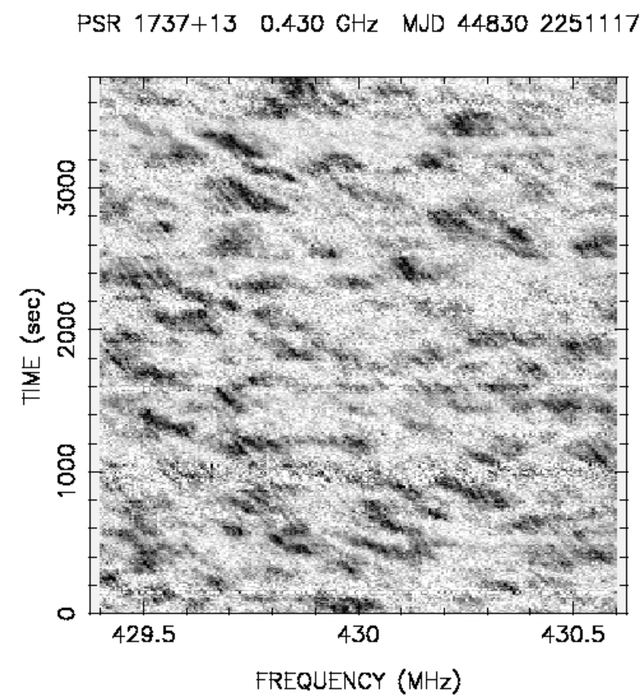
White noise residuals



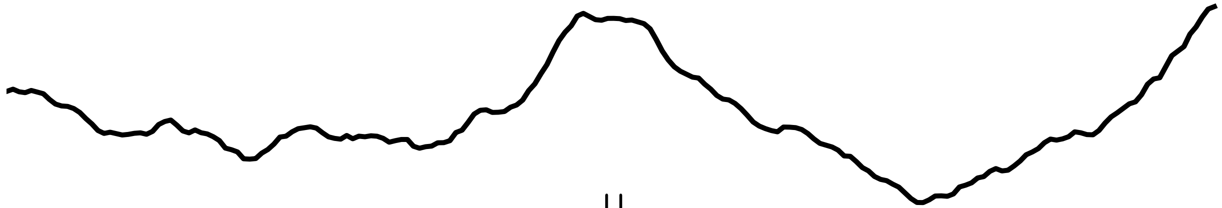








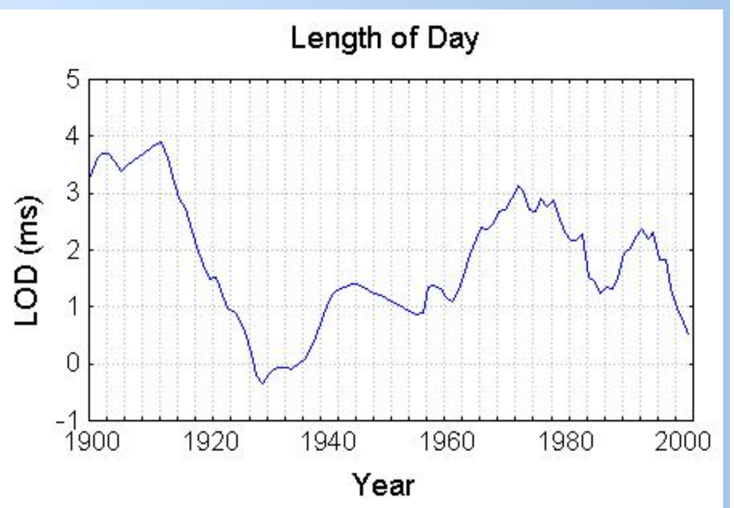
Red noise residuals

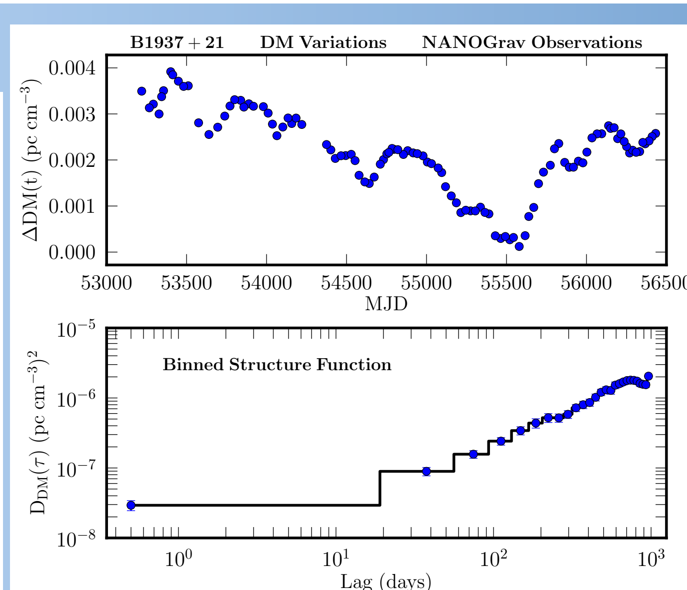


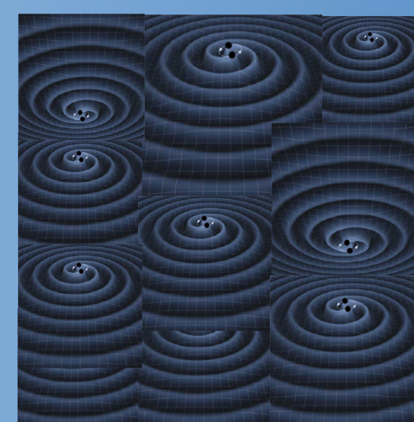
||

Spin noise + **DM variations** + **GWs (stochastic)**

f^{-5} $f^{-8/3}$ $f^{-13/3}$



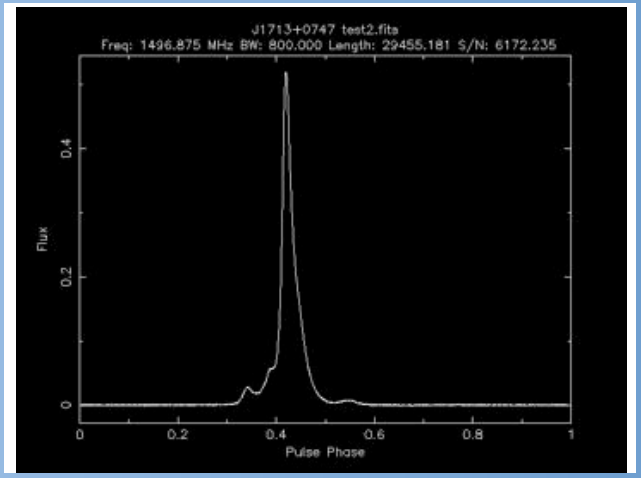




Global Campaign on J1713+0747

Concept: Study the best MSP (30 ns rms) in a global 24-hr campaign to determine the limits of timing precision.

- Emerged from the June 2012 IPTA meeting in Kiama, Australia during open discussion among the ~80 participants
- NANOGrav has led the campaign:
  - Telescope proposals
  - Organization of observing (June 2013)
  - Aggregation of data and data products
  - Planning of first publication (in prep)



→ Insights on how to mitigate ISM effects in standard-cadence observations and demonstration that longer integration times will yield smaller timing errors, as expected.

Global Campaign:
IPTA telescopes + GMRT + LOFAR


Green Bank Telescope, WV, US


Arecibo Observatory, PR, US


Nancay Radio Telescope, Nancay, France


Lovell Telescope, Cheshire, UK


Parkes Observatory, Parkes, Australia


LOFAR, Exloo, Netherlands

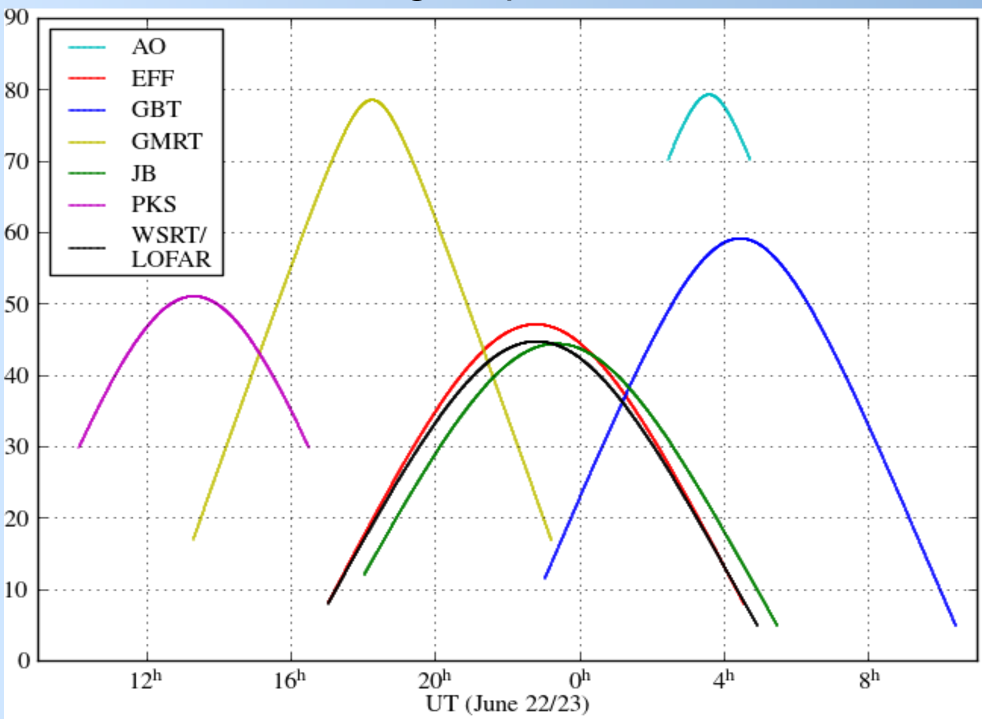

GMRT, Pune, India


WSRT, Westerbork, Netherlands

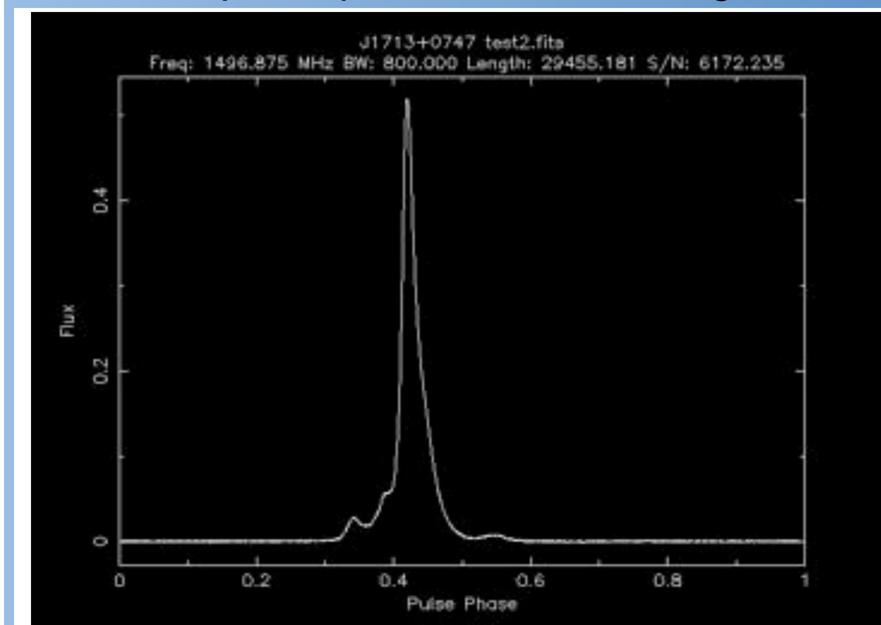

Effelsberg 100-m Radio Telescope, Effelsberg, Germany

Global Campaign on J1713+0747
218.8118439157321 Hz

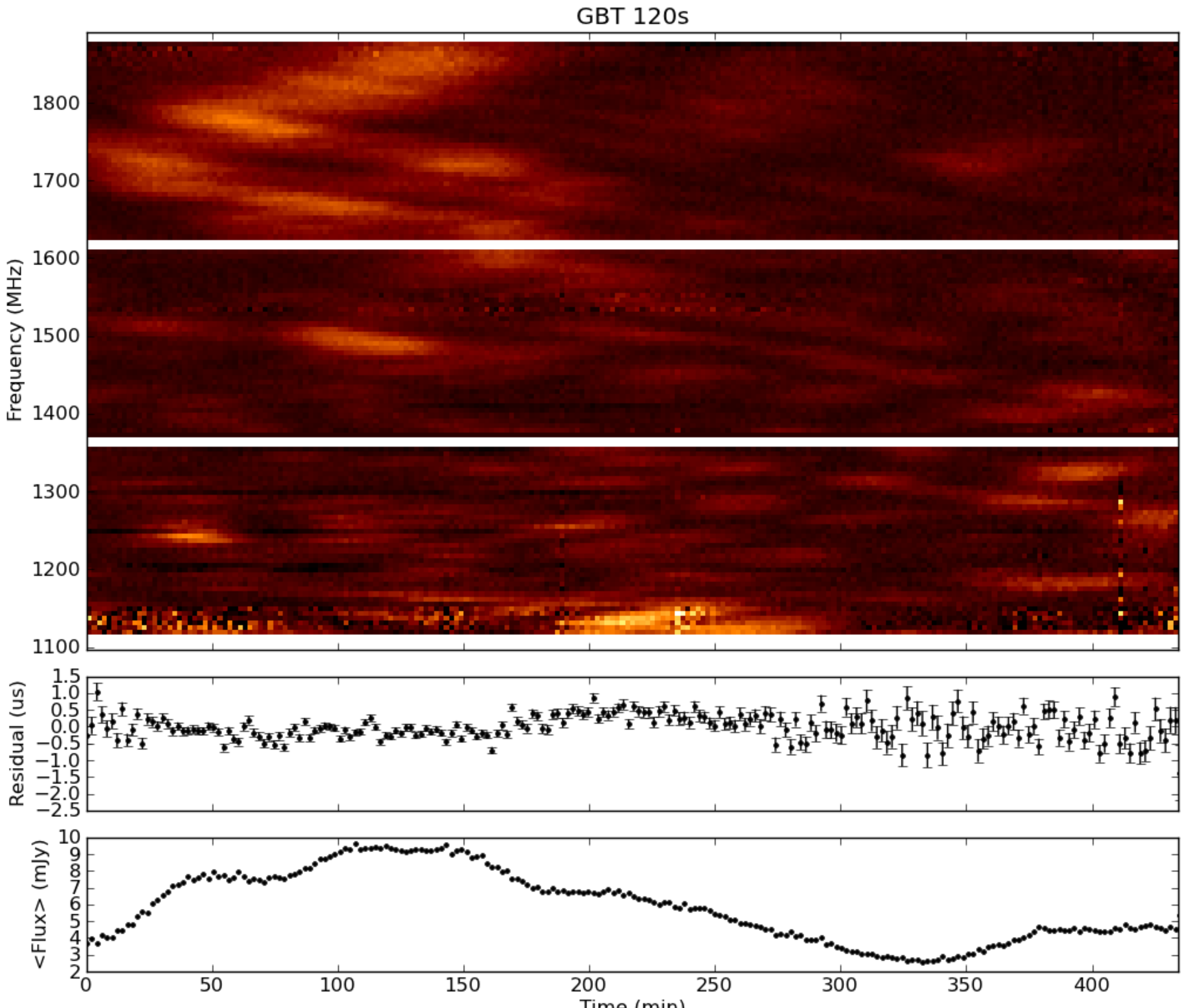
Observing sequence vs UT



GBT pulse profile – 7 hr average



GBT Dynamic Spectrum, TOAs, Flux Density



Current and Next Steps: Improving TOAs and GW Sensitivity

Characterization of existing and current data:

Measurement error budget for TOAs: pulsar, ISM, instrumentation

Mitigation of controllable effects with new algorithms:

Pulse shape changes in time and frequency

Interstellar medium pulse smearing and delays

Observing optimization:

Cadence (monthly → weekly?), integration times

Polarization calibration

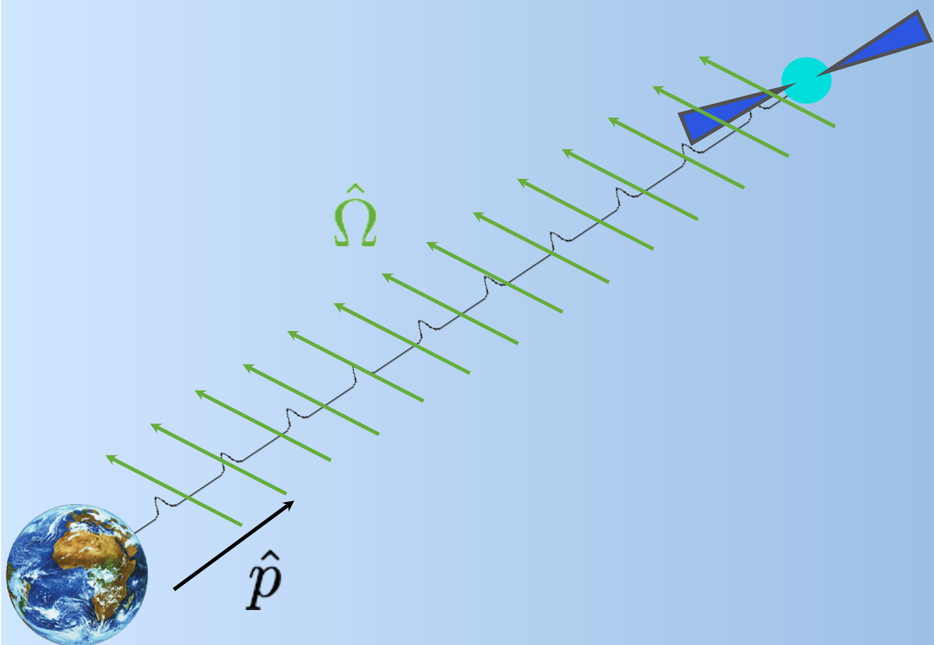
Additional high-quality millisecond pulsars:

Pulsar surveys

Vetting of new MSPs using characterization protocols

Current and future GW sensitivities of NANOGrav the and IPTA and the importance of adding pulsars to PTAs

Effect of a gravitational wave



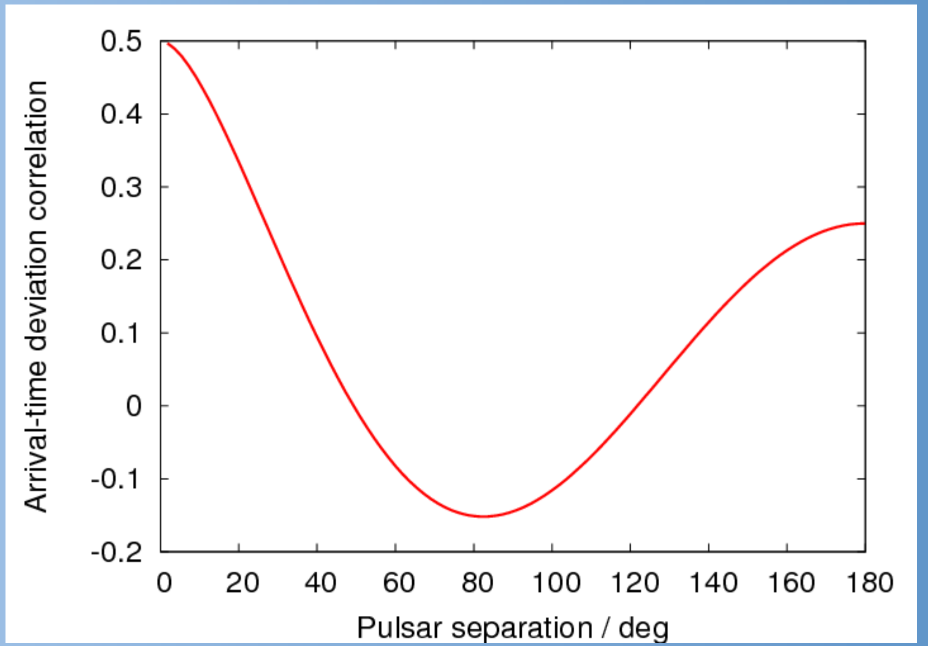
Pulses get red(blue)-shifted

$$z = \frac{1}{2}\frac{\hat{p}^i\hat{p}^j}{1+\hat{\Omega}\cdot\hat{p}}\left[h_{ij}^{\mathrm{E}} - h_{ij}^{\mathrm{P}}\right]$$

Earth Term   Pulsar term

For a stochastic background the signal is correlated: *but only half of it* (the Earth term)

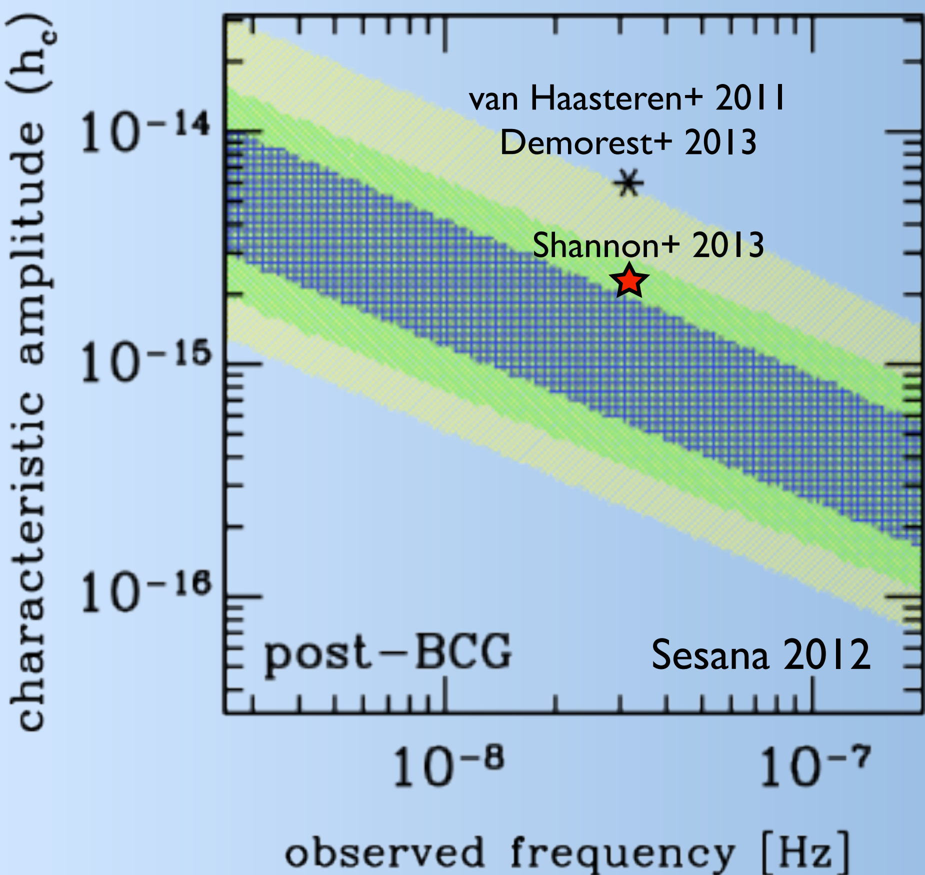
This means the GW background is a source of (red) noise



Signal Types & Sources

	Stochastic BG	Continuous	Bursts
SMBHBs	✓	✓	✓
Cosmic strings	✓	✓	✓
Inflation	✓		
Phase transitions	✓		

Amplitude of the SMBBH stochastic background



$$h_c = A\left(\frac{f}{\mathrm{yr}^{-1}}\right)^{-2/3}$$

$$5.6 \times 10^{-16} < A < 2 \times 10^{-15}$$

Varied BH host mass relationship, merger rate, ...

Realistic PTA simulations

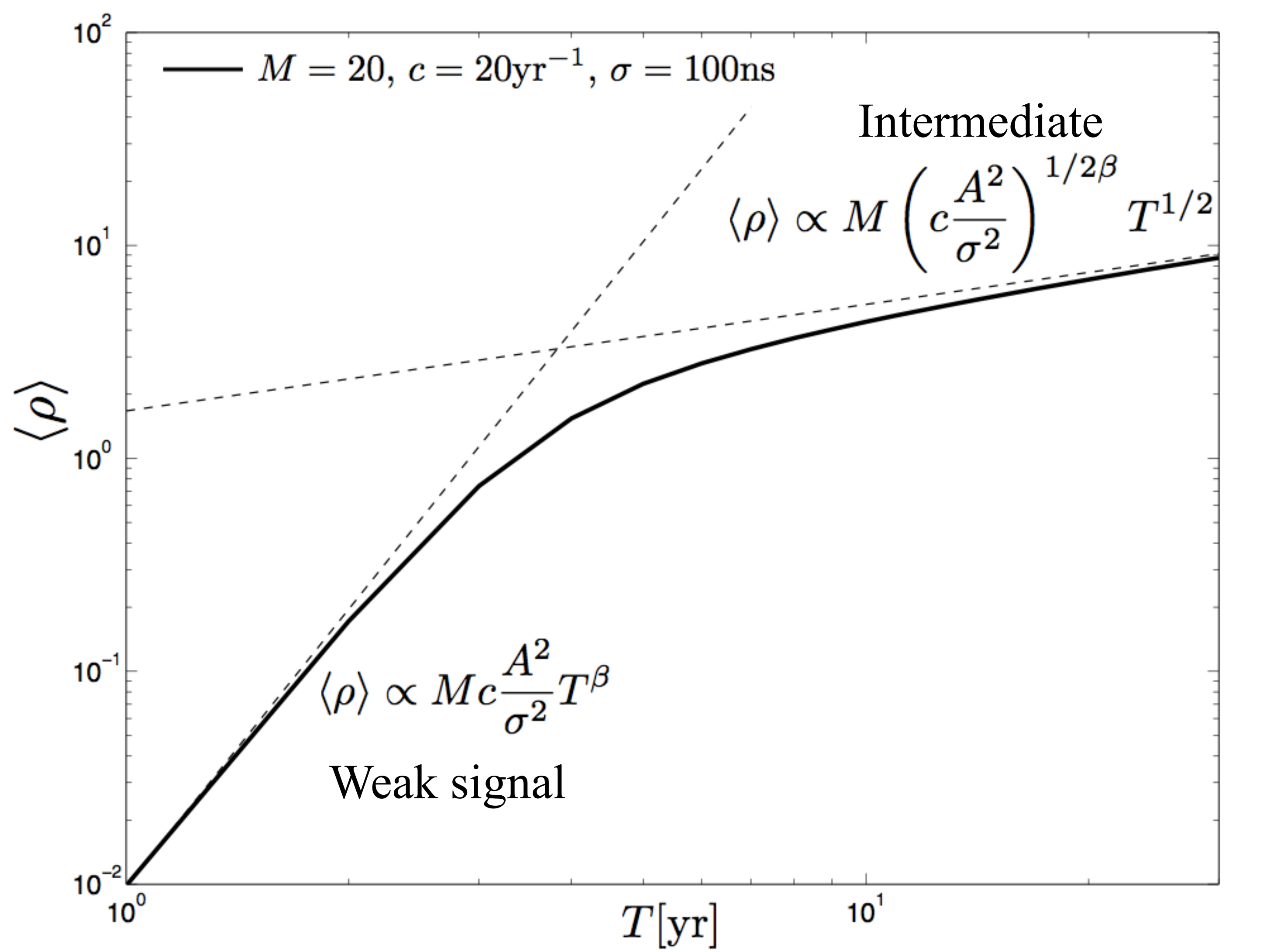
For a number of years we have been using “canonical” pulsar timing array to make predictions... 20 pulsars, 100 ns RMS, 5-10 years. Wanted to simulate a pulsar timing array with realistic properties (we have one!!).

The understanding was that the signal to noise ratio in the cross-correlation grows like some large power law of time, so all we have to do is just wait.

But we were surprised! And not in a good way.

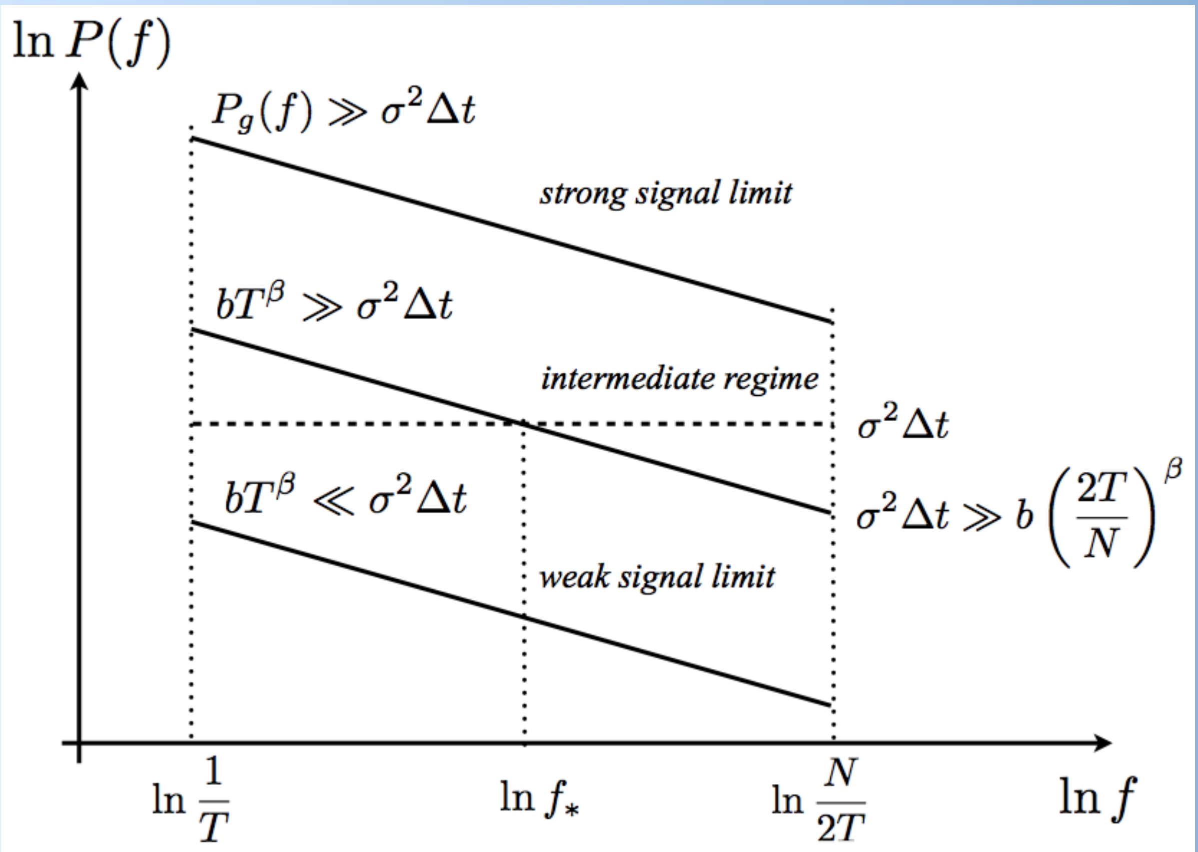
Canonical PTA

$A = 10^{-15},\ \beta = 13/3$ (SMBBH background)



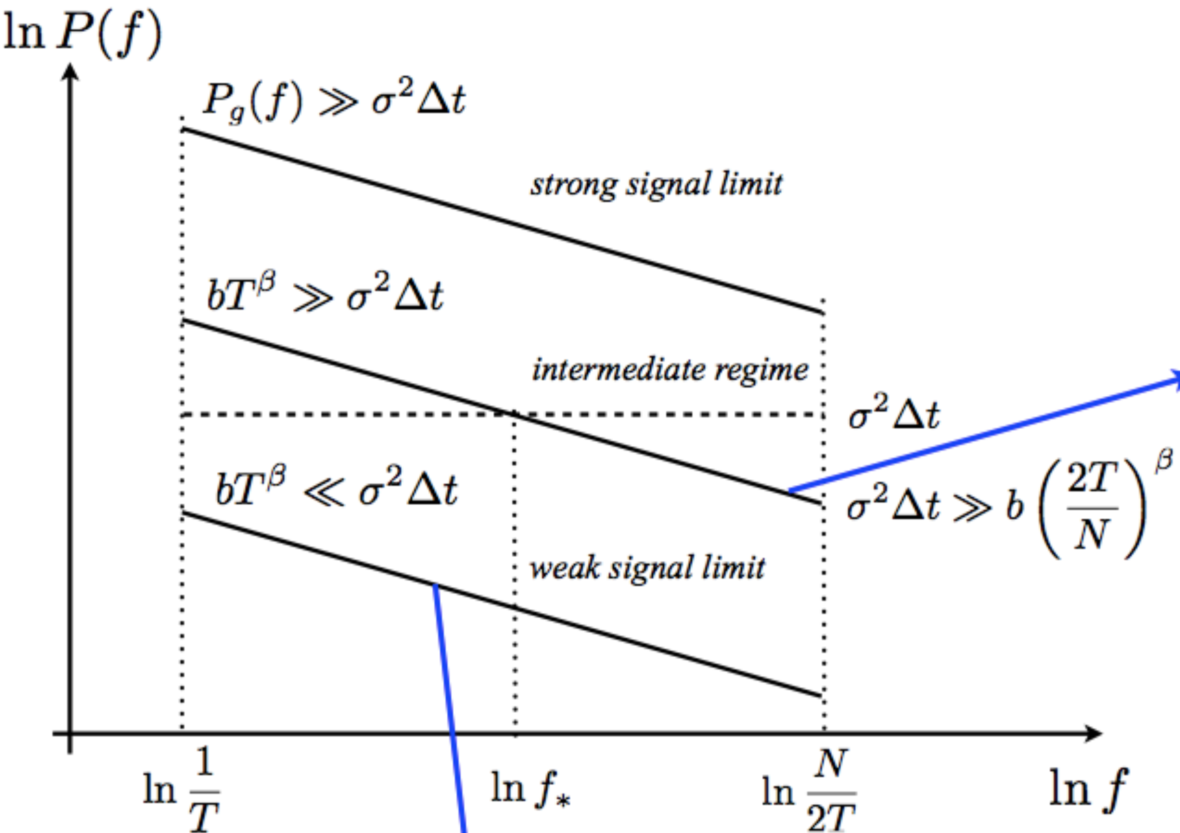
Scaling behavior depends on the timing residual power spectrum

$$P(f) = P_g(f) + \sigma^2 \Delta t \qquad P_g(f) = \frac{A^2}{24\pi^2}\left(\frac{f}{f_{\rm ref}}\right)^{2\alpha} f^{-3} = b f^{-\beta}$$



σ pulsar RMS
T total time

SNR in cross-correlation



$$\langle \rho \rangle \propto M \left(c \frac{A^2}{\sigma^2} \right)^{1/2\beta} T^{1/2}$$

$$\langle \rho \rangle \propto M c \frac{A^2}{\sigma^2} T^\beta$$

$\beta = 13/3$

M # of pulsars

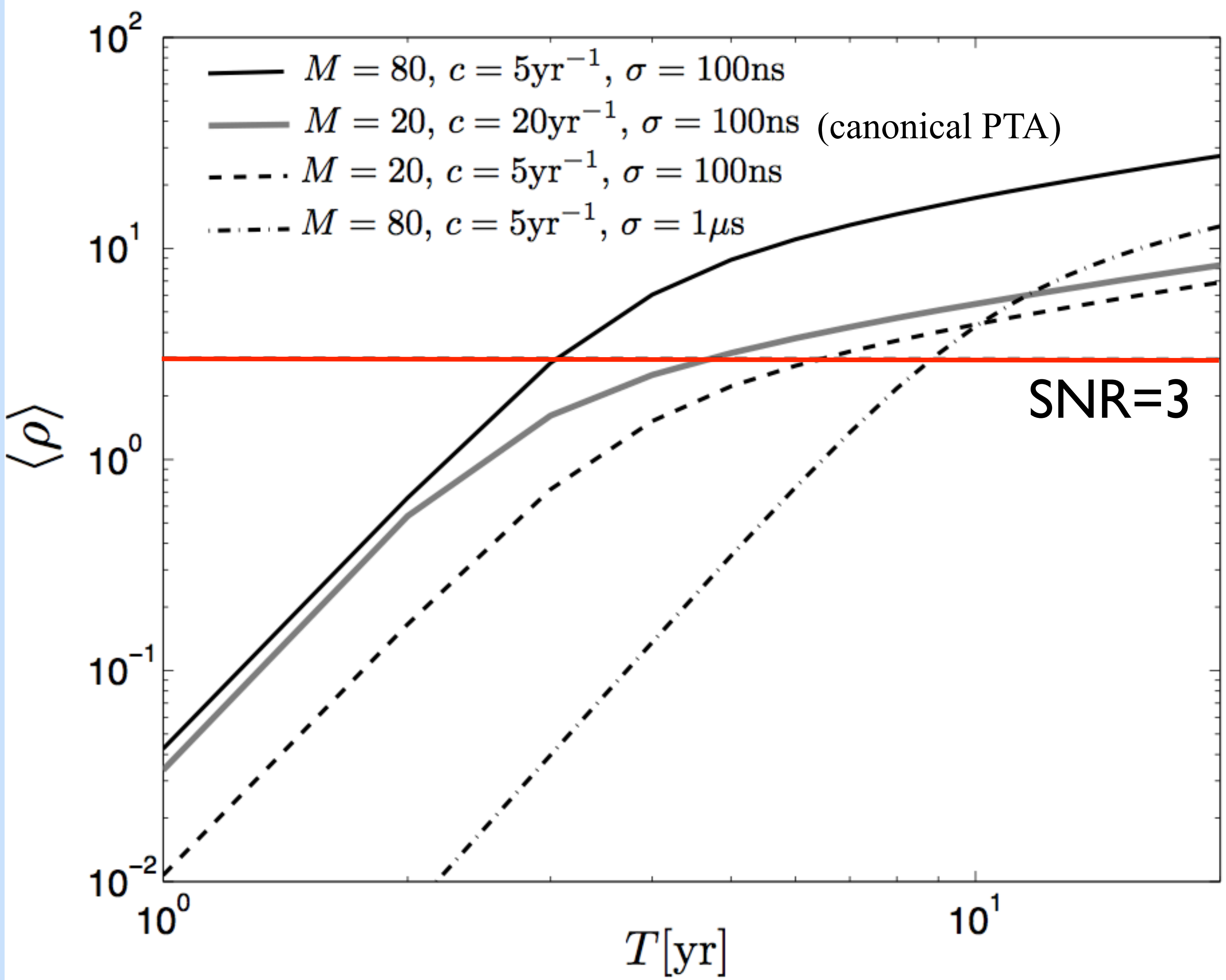
c cadence

σ pulsar RMS

T total time

Notice how the scaling with the number of pulsars M does not change: important consequences!

The consequences



Are we in that regime?

Comparing lowest frequency bin of background to white noise levels:

$$bT^{\beta} > \Delta t \sigma^2 \rightarrow \sigma < \frac{A}{\pi}\sqrt{\frac{cT^{\beta}}{24}}$$

	$T = 5 \quad \mathrm{yr}$	$T = 10 \quad \mathrm{yr}$	$T = 15 \quad \mathrm{yr}$	$T = 20 \quad \mathrm{yr}$
$A = 5.6 \times 10^{-16}$	170 ns	764 ns	$1.8\ \mu\mathrm{s}$	$3.4\ \mu\mathrm{s}$
$A = 1 \times 10^{-15}$	304 ns	$1.4\ \mu\mathrm{s}$	$3.2\ \mu\mathrm{s}$	$6.1\ \mu\mathrm{s}$
$A = 2 \times 10^{-15}$	608 ns	$2.7\ \mu\mathrm{s}$	$6.5\ \mu\mathrm{s}$	$12\ \mu\mathrm{s}$

Note that in our latest analysis 6 of the 17 pulsars had RMS residuals less than 304 ns (Demorest et al 2013)

Conclusions for stochastic backgrounds

1) Increasing the cadence and improving the white noise RMS helps greatly in the weak signal limit but their impact on the SNR in the intermediate regime is not as significant.

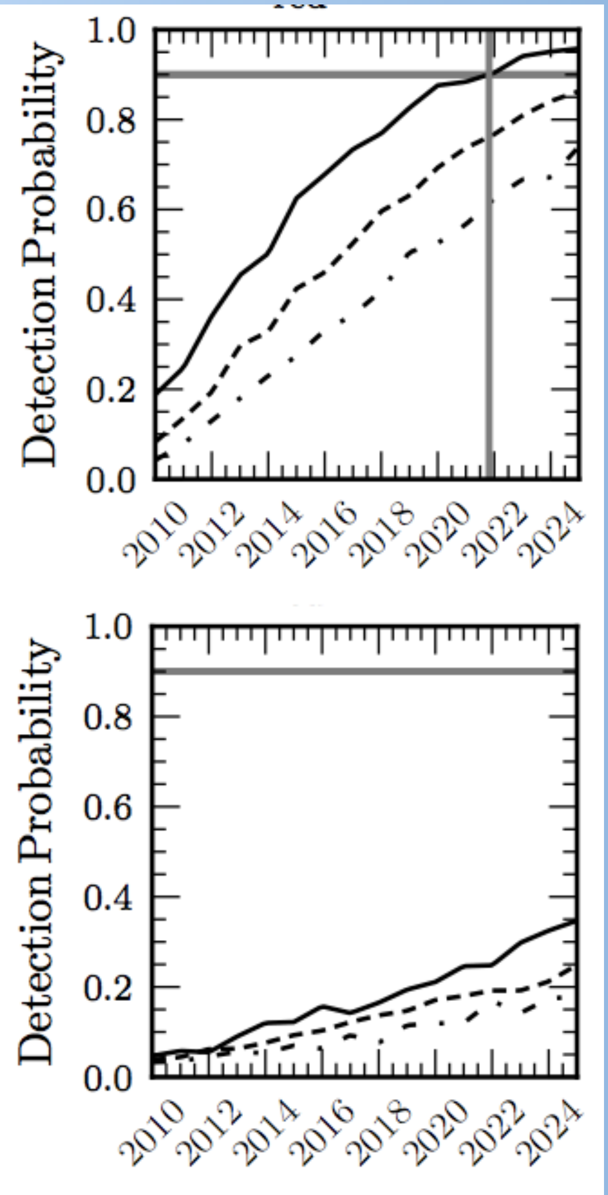
The reason for this is that the SNR is dominated by the lowest frequency bins. When these bins become gravitational-wave dominated, the dominant contribution to the noise is the uncorrelated pulsar-term GW red noise

2) The most effective way to beat down the uncorrelated part of the GW signal (the pulsar term) is to add more pulsars to the PTA.

3) This does not mean we shouldn't work hard to improve our RMSs and cadences, which are critical for individual sources (continuous waves and bursts)

E.g. for CWs $\langle \rho^2 \rangle = (h|h) \propto M \frac{cT}{\sigma^2}$

What if we didn't add more pulsars?

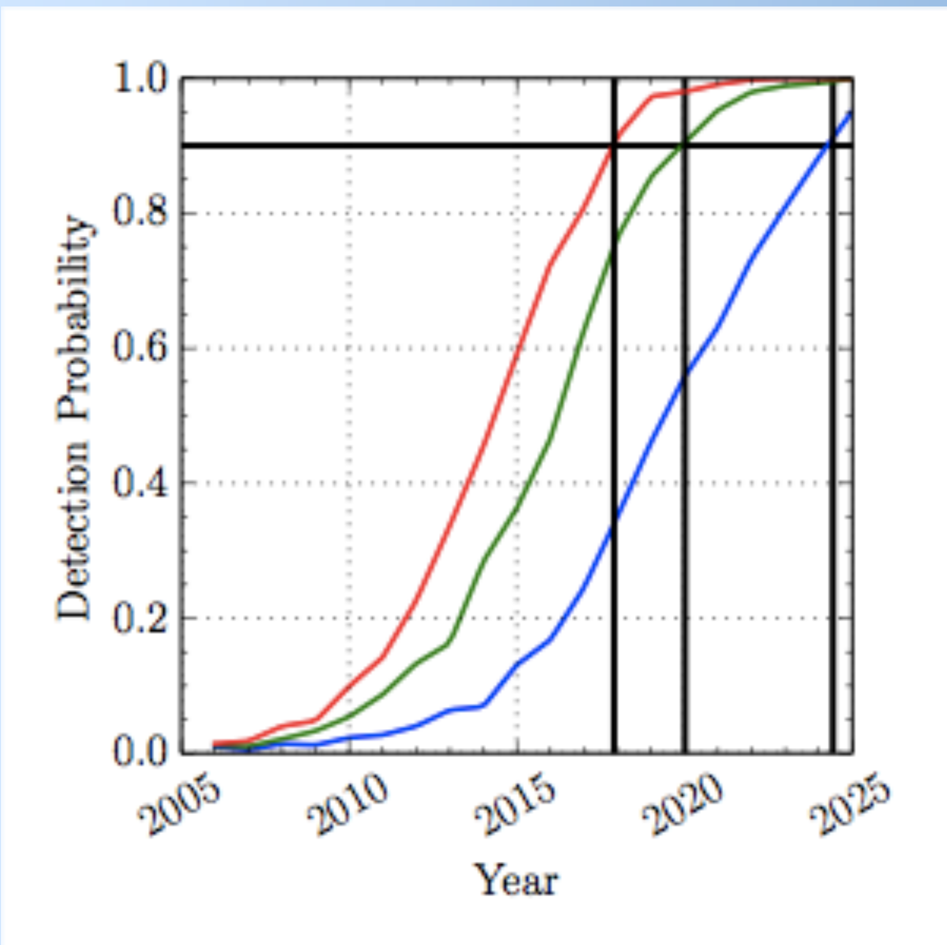


17 pulsars
(Demorest+ 2013)

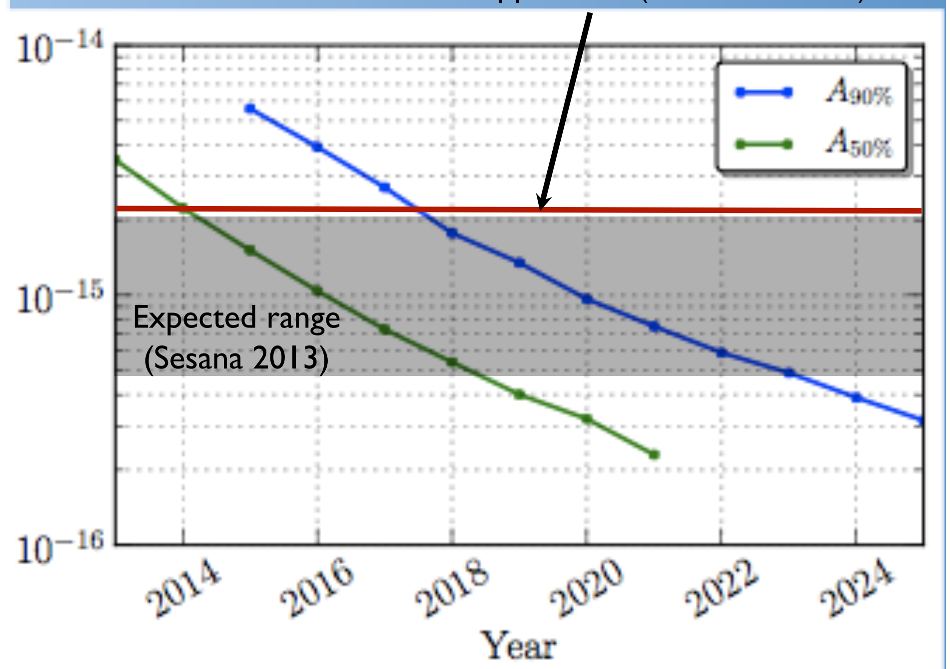
6 pulsars
(10 ns residuals)

What we're actually doing

Demorest et al 2013 had 17 pulsars. We will be timing 44 MSPs by 2014, for about 4 additions per year. The plots below assume we add 4 new pulsars per year with a precision which is the median of the 40 we currently have data for.



Most recent upper limit (Shannon+ 2013)



Adding MSPs, even "mediocre" ones, **is critical**!!

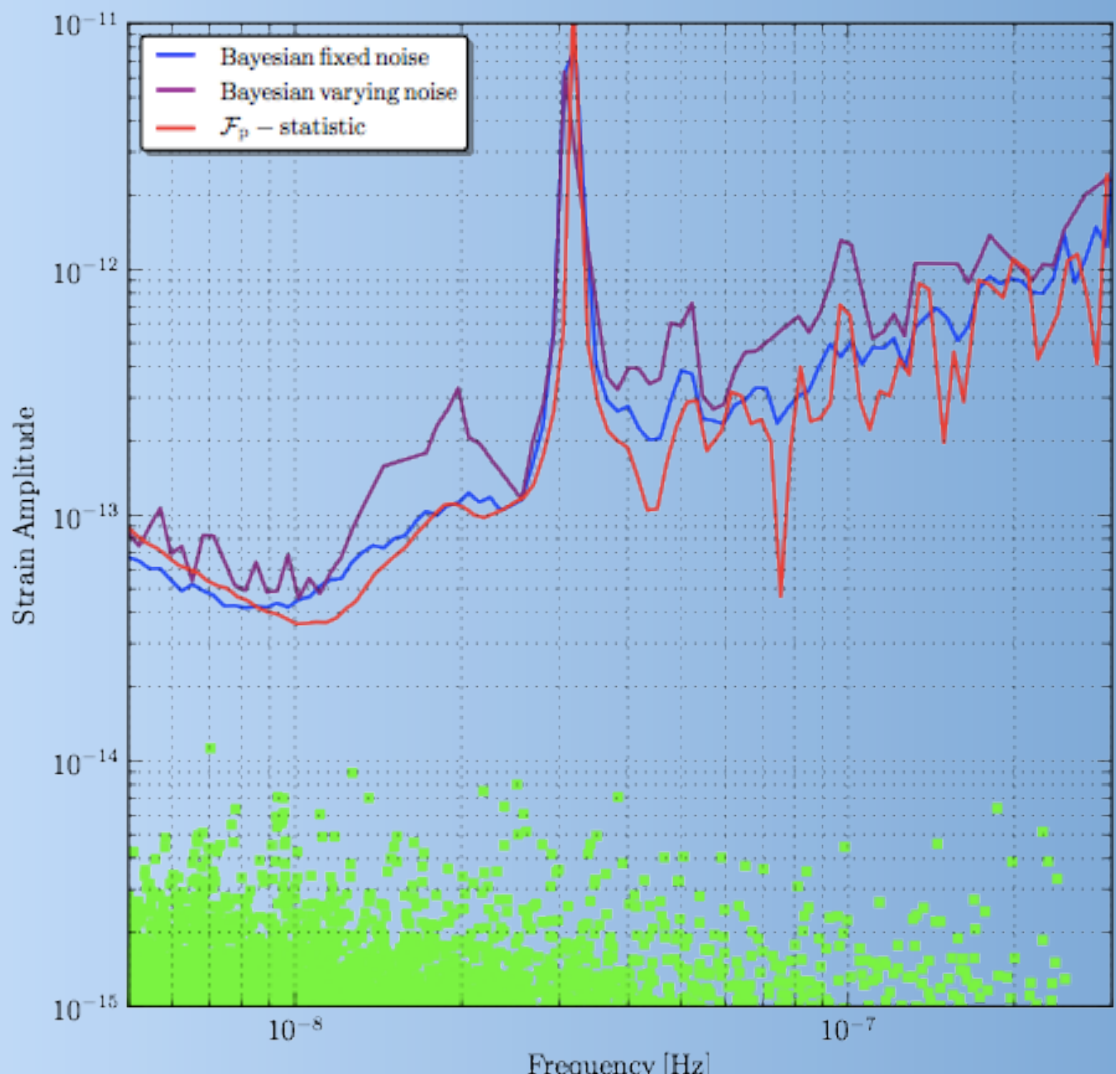
Continuous waves

CW searches are sensitivity limited.

$$\langle \rho^2 \rangle = (h|h) \propto M \frac{cT}{\sigma^2}$$

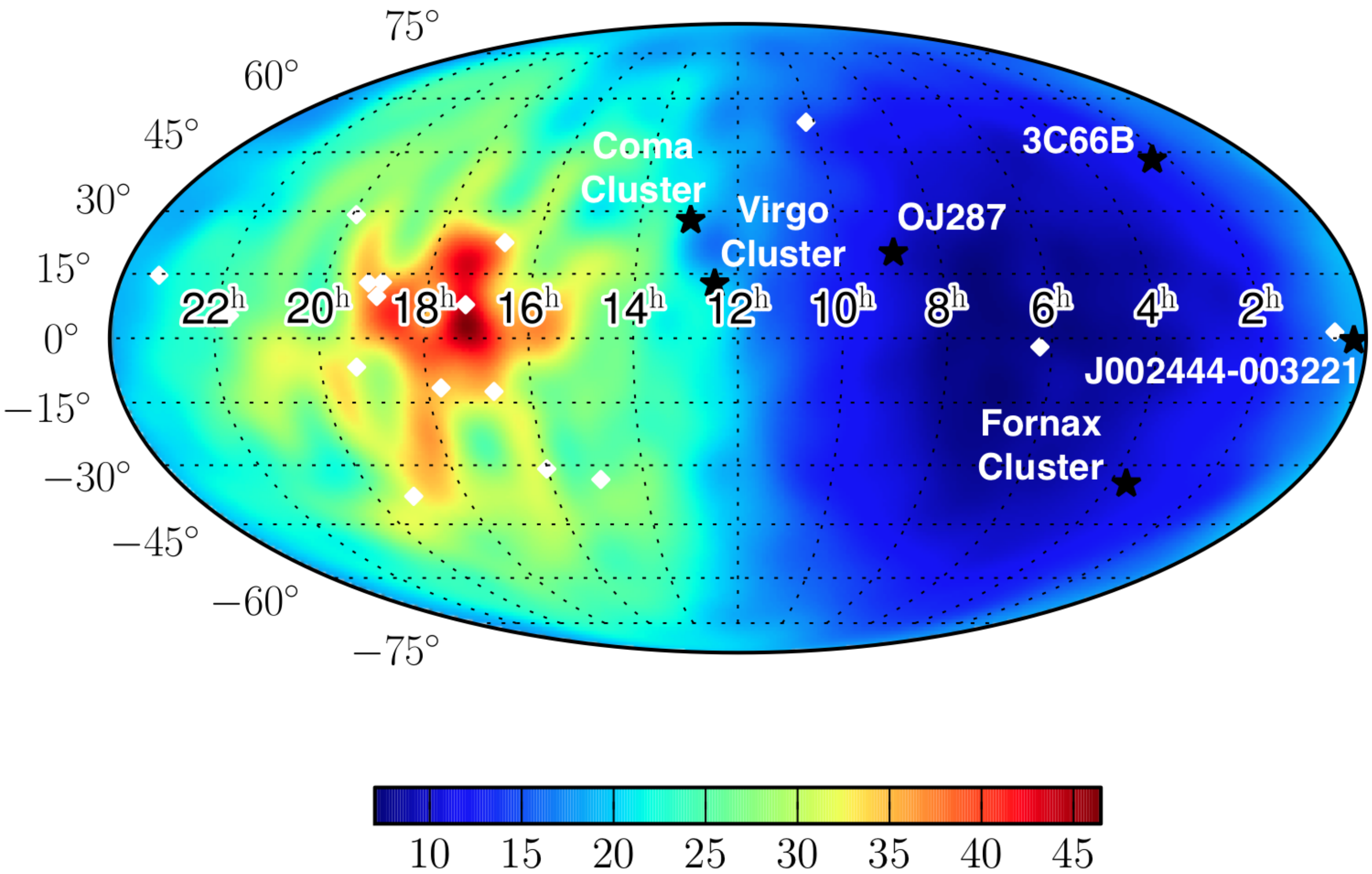
All sky limits dominated by best timed pulsars.

Continuous waves



NANOGrav (preliminary!) current upper limits, about a factor of 3 better than published upper limits from PPTA.

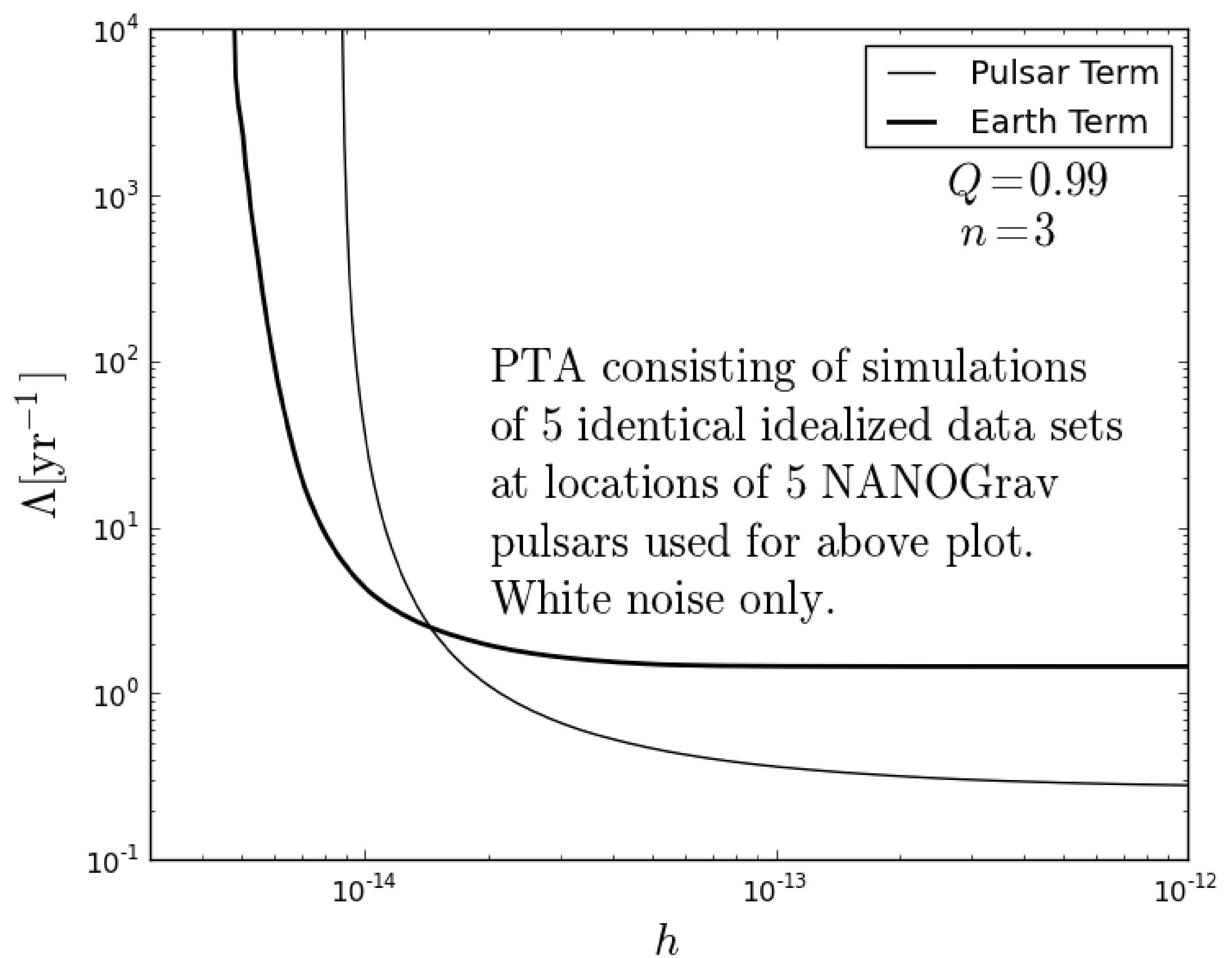
Continuous waves



$$D_{95} \times \left(\frac{\mathcal{M}}{10^9\, M_\odot}\right)^{5/3} \left(\frac{f_{\rm gw}}{10^{-8}\,{\rm Hz}}\right)^{2/3} \,[\mathrm{Mpc}]$$

Current sensitivities rule out sources 10^9 solar masses in the Virgo Cluster (upcoming NANOGrav paper).

Bursts of memory



Conclusions

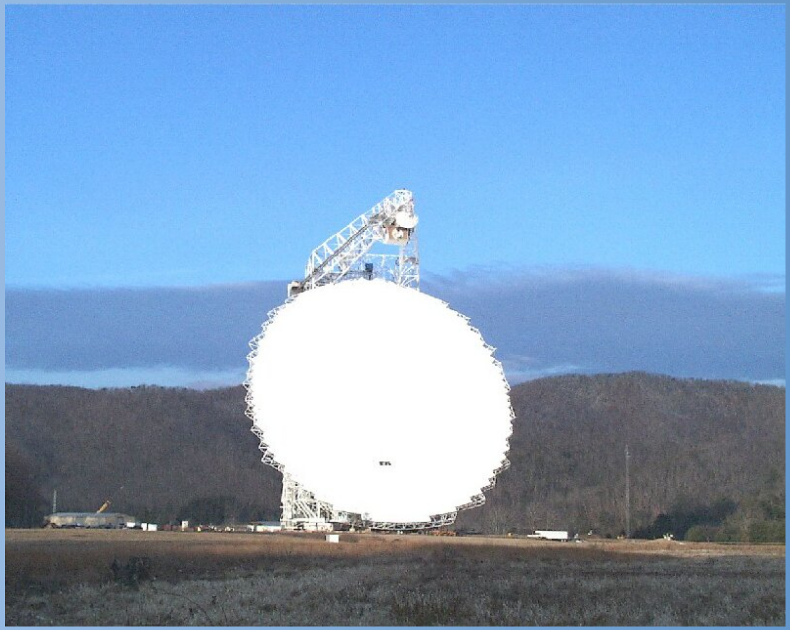
Detection of the stochastic background produced by supermassive binary black hole binaries could occur as early as 2017, and is likely by the end of the decade.

For individual sources, the best pulsars determine sensitivity.

Currently working on sensitivity estimates for bursts.

IPTA data sets (waiting on data release) need a full noise modeling assessment. Will likely help with stochastic backgrounds, less likely to help with individual sources since NANOGrav has best telescopes/sensitivity.

Pulsar Searches with the GBT and Arecibo: Producing a steady stream of MSPs and students



Do we need more pulsars?

YES!

- Detect GWs faster! (Why? To provide synergy with ground-based detectors, make use of (and save our!) our telescopes, and attract the best students/theorists/collaborators).
- Better characterize stochastic/continuous/burst GW sources in the post-detection era.
- Find the very best timers – there may be MSPs that can be timed to higher precisions than our current favorites (0437, 1713, or 1909).
- Pulsar searches are lots of fun and motivate students.
- They are important for other important and exciting science, including GW searches with LIGO, tests of GR, mass measurements, etc.

What kinds of MSPs do we want?

$$h_{c,min} \sim \sigma_{RMS} \sim \sigma_{TOA} \sim \text{Width/SNR}$$

- **Bright.**
- **Narrow profiles.**
- **No messy binaries.**

Essential

- Low red spin noise.
- Low scattering and dispersion.

Important

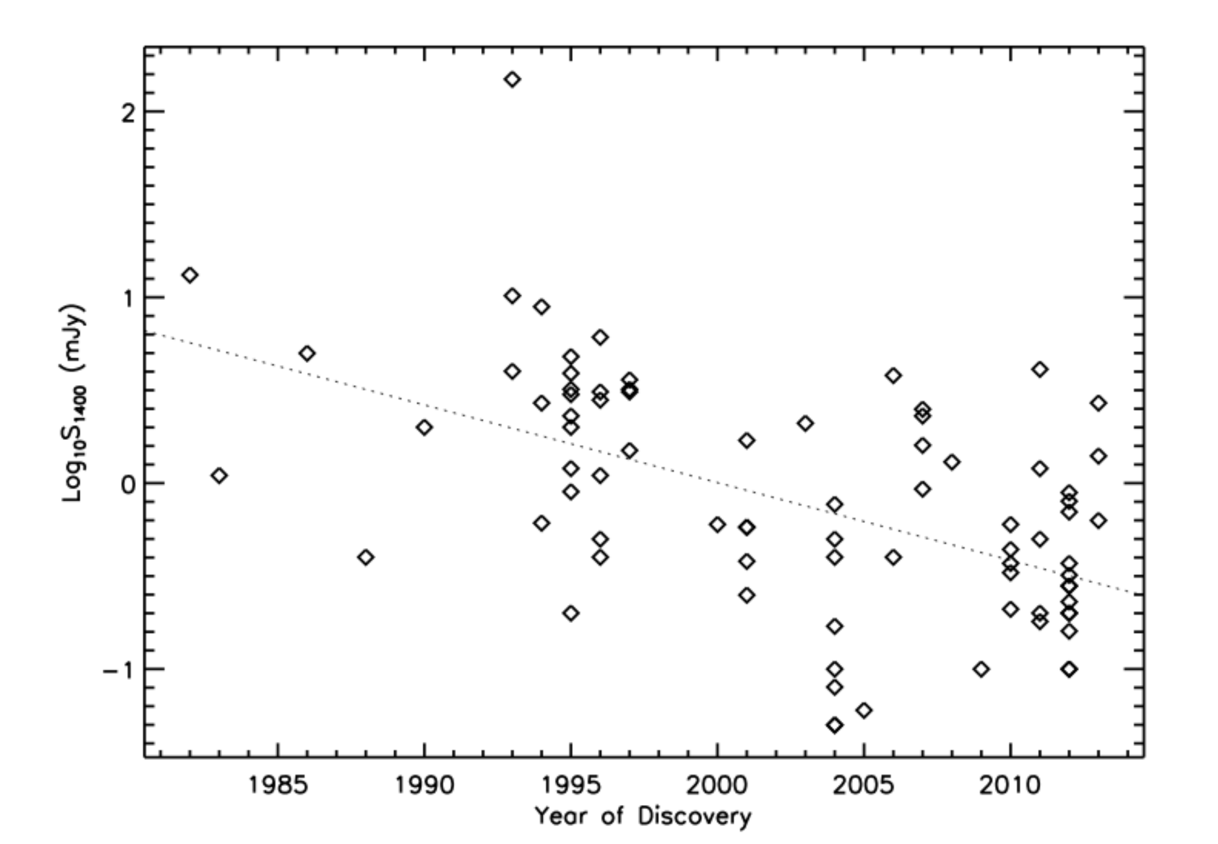
- *Nearby – with measureable distances in future.*
- *Positions that fill in gaps in our sky coverage.*

Helpful

Are there more of these MSPs to be found?

YES!

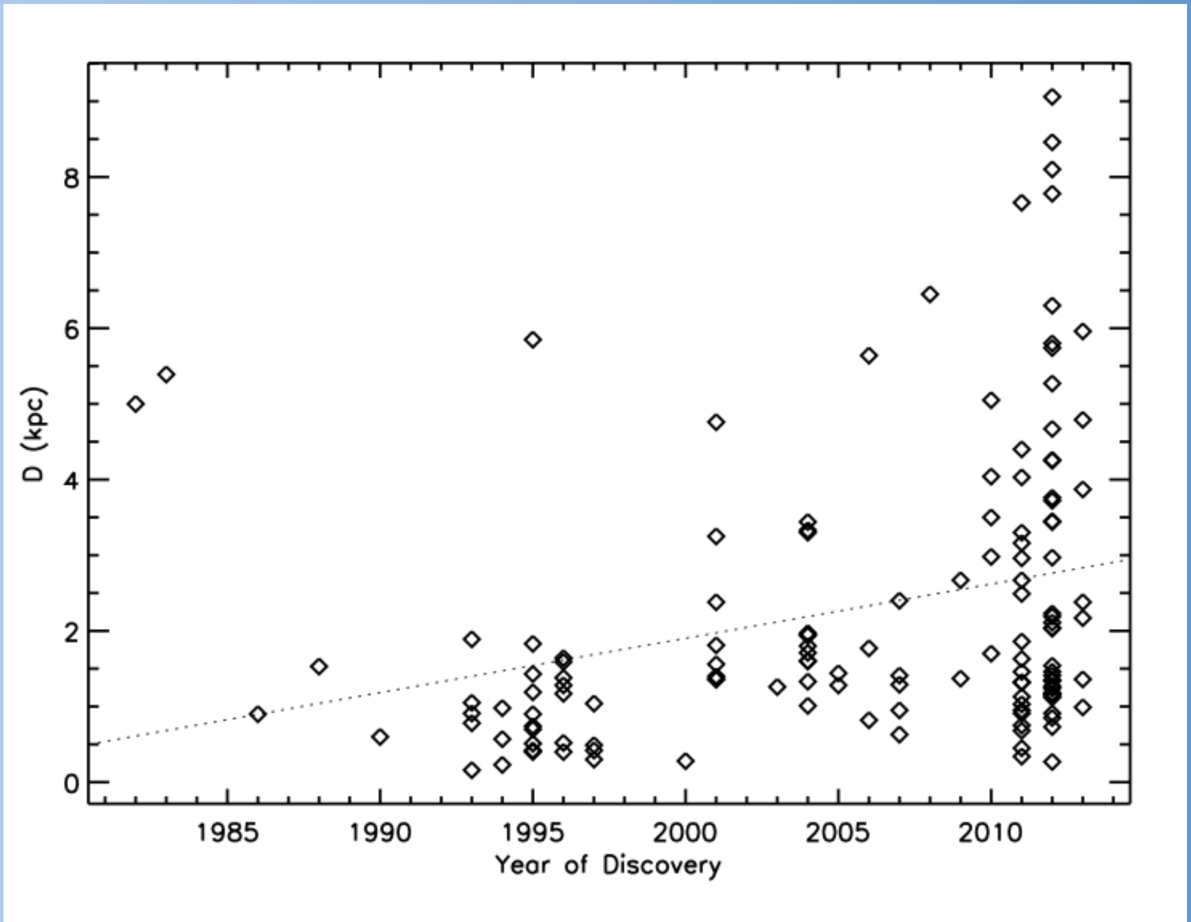
- 30,000 MSPs potentially detectable in the Galaxy.
- We are still finding bright ones.



Are there more of these MSPs to be found?

YES!

- 30,000 MSPs potentially detectable in the Galaxy.
- We are still finding bright ones.
- We are still finding nearby ones.



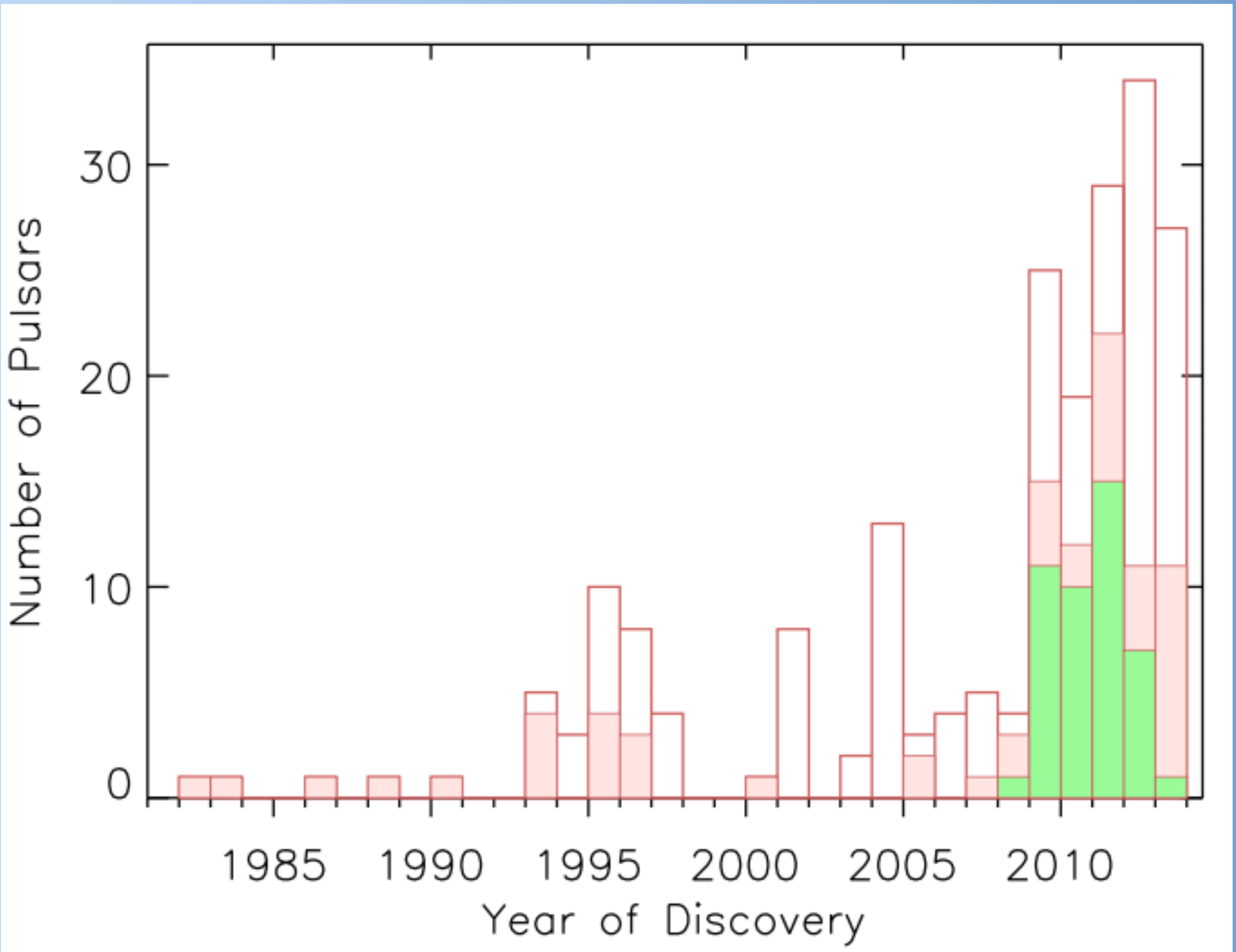
How do we find them?

- Low-frequency surveys optimal for wider FOV, higher sensitivity, and for nearby pulsars for which propagation effects are unimportant.
- Higher frequency surveys important for pulsars in the Galactic plane and for a more complete census.
- We want to cover the entire sky, particularly where there are MSP holes.
- We need acceleration searches OR short integrations to retain sensitivity to binaries.

Current Surveys for MSPs

- **Pulsar Arecibo L-band Feed Array (PALFA) survey at 1.4 GHz.**
- **Arecibo 327-MHz drift-scan survey (AODrift).**
- **Green Bank Telescope 350-MHz drift-scan survey (GBTDrift).**
- **350-MHz Green Bank Telescope Northern Celestial Cap Survey (GBNCC).**
- **Fermi surveys with several telescopes.**
- High Time Resolution Universe (HTRU) with Parkes at 1.4 GHz.
- LOFAR surveys at 140 MHz.
- Effelsberg (HTRU-N) survey at 1.4 GHz.

Current Surveys for MSPs

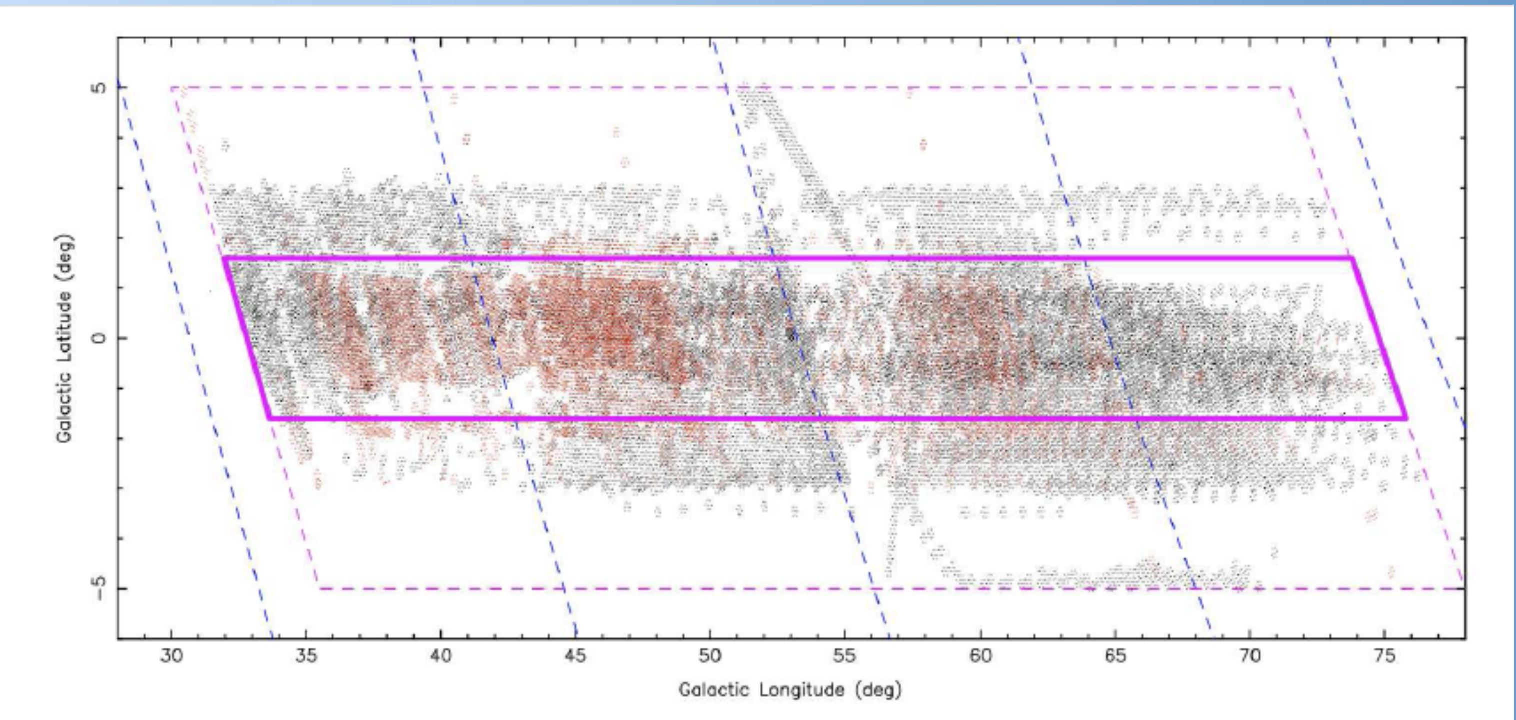


We know of 209 Galactic MSPs as of today at 7:14 am.
See http://astro.phys.wvu.edu/GalacticMSPs.

PALFA

1.4 GHz survey covering five degrees above/below Galactic plane.

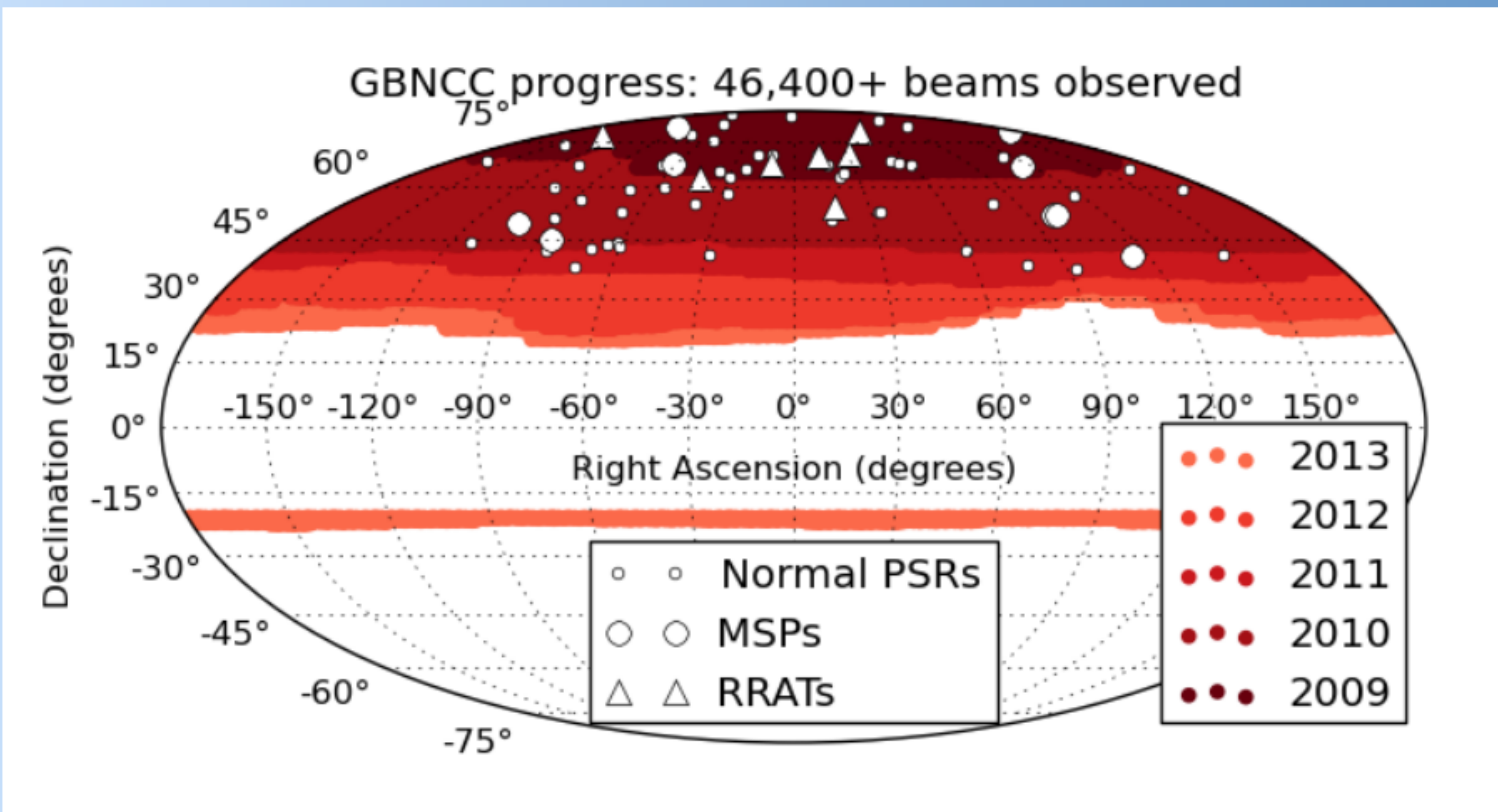
So far discovered 126 pulsars including 18 MSPs – two are being timed by NANOGrav. We expect another 60 MSPs over next 5 years.



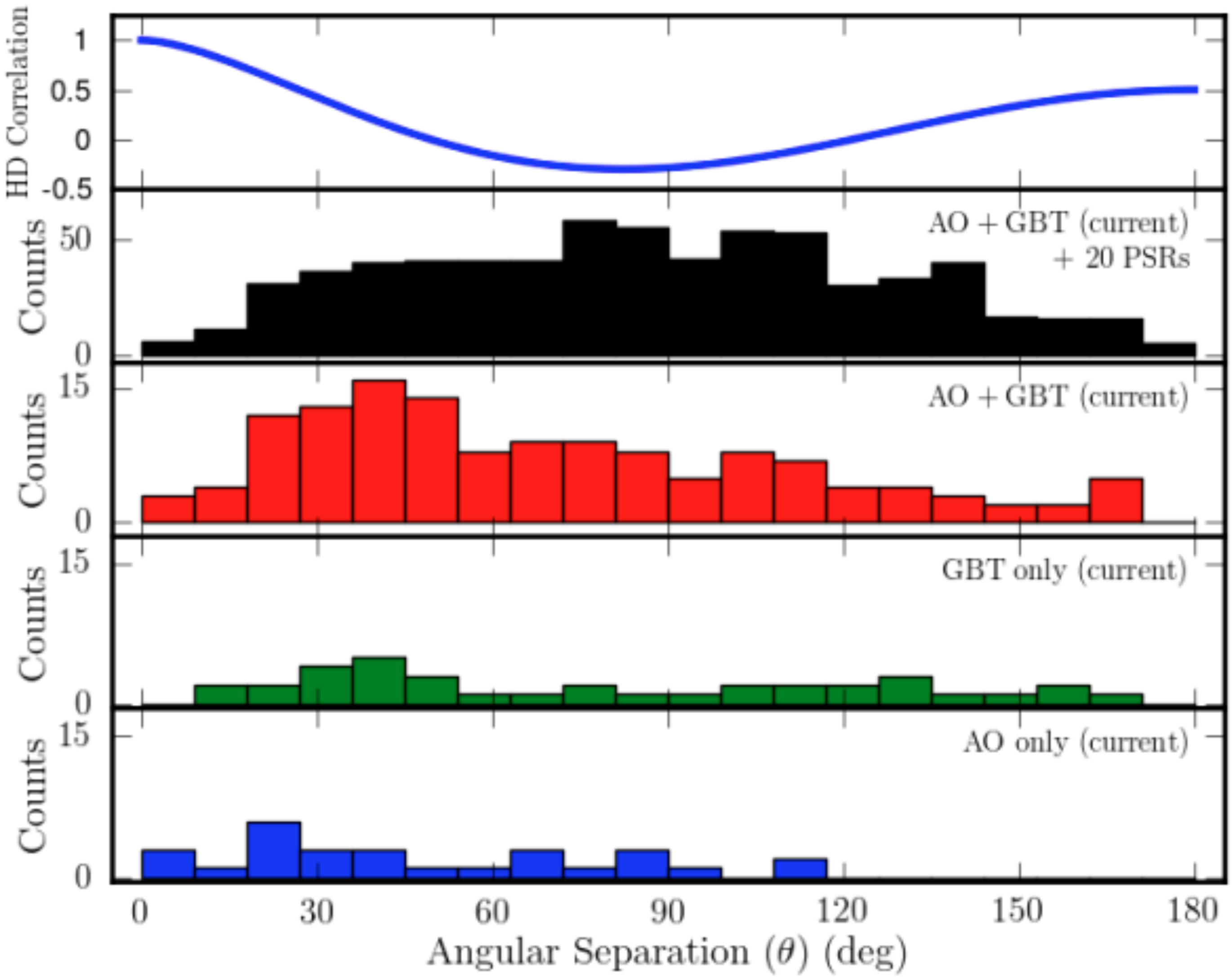
GBNCC

350 MHz survey covering North Celestial Cap and working downwards.

So far discovered 62 pulsars, including 9 MSPs. We expect 50 MSPs over the next 5 years.

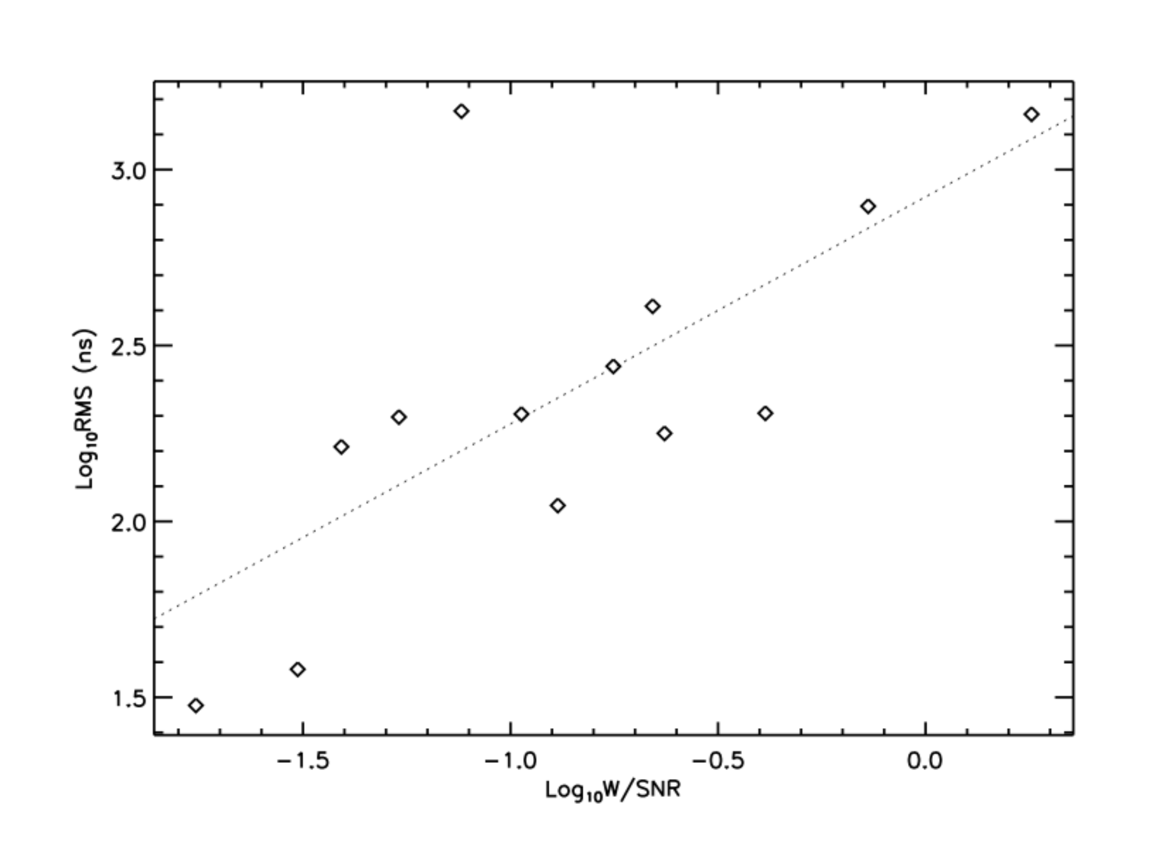


Both GBT and Arecibo are crucial



How do we decide which MSPs to time?

Many variables (RMS, TOA precision, availability of telescope time, proximity to other PTA pulsars) enter into decision, most of which are a proxy for “how will the addition of this MSP affect our sensitivity?”



Important in light of decreasing telescope availability for follow-up observations.

Search Statement of Intent

Enabled by the IPTA collaboration

Allows rapid release of ephemerides to all PTA by discoverers.

Benefits for PTAs: add new pulsars to arrays faster.

Benefits for searchers: get more TOAs to use in papers and for other experiments.

The Future I

- Many of the pulsars discovered in these surveys were found by high-school and undergraduate students. Pulsar searching is an excellent gateway activity to GW detection!

Pulsar Search Collaboratory

Arecibo Remote Command Center

- These activities provide a large (and diverse!) pool of students for the emerging area of GW astrophysics.

- We are further integrating these outreach activities into NANOGrav so that students are a real part of our collaboration.

The Future II

- Concentrate on intensive searches over next few years then intensive timing (and astrometry!) with a large sample of pulsars.
- We expect to discover *at least* roughly 20 MSPs per year over next five years, with ~20% of those added to the NANOGrav array.
- Must develop metrics for MSP “goodness” and procedures for inclusion into PTAs.
- Development of AI for candidate inspection and cross-correlation of results from different surveys crucial. Will begin to use the IPTA for pulsar searching too.
- Expect another ~100 MSPs over next several years from worldwide surveys. (Lots of amazing “secondary” science!)

Thank you!