The NANOGrav 12.5-Year Data Set: Are we nearly there?

Maura McLaughlin
West Virginia University

NANOGrav Physics Frontiers Center

INTERNATIONAL PULSAR TIMING ARRAY

IPTA

NSF

North American Nanohertz Observatory for GWs

NANOGrav Physics Frontiers Center

Over 100 students and scientists working to characterize the GW universe at low frequencies using pulsar timing. An NSF Physics Frontiers Center since March 2015. We welcome new members and participants at meetings! http://nanograv.org

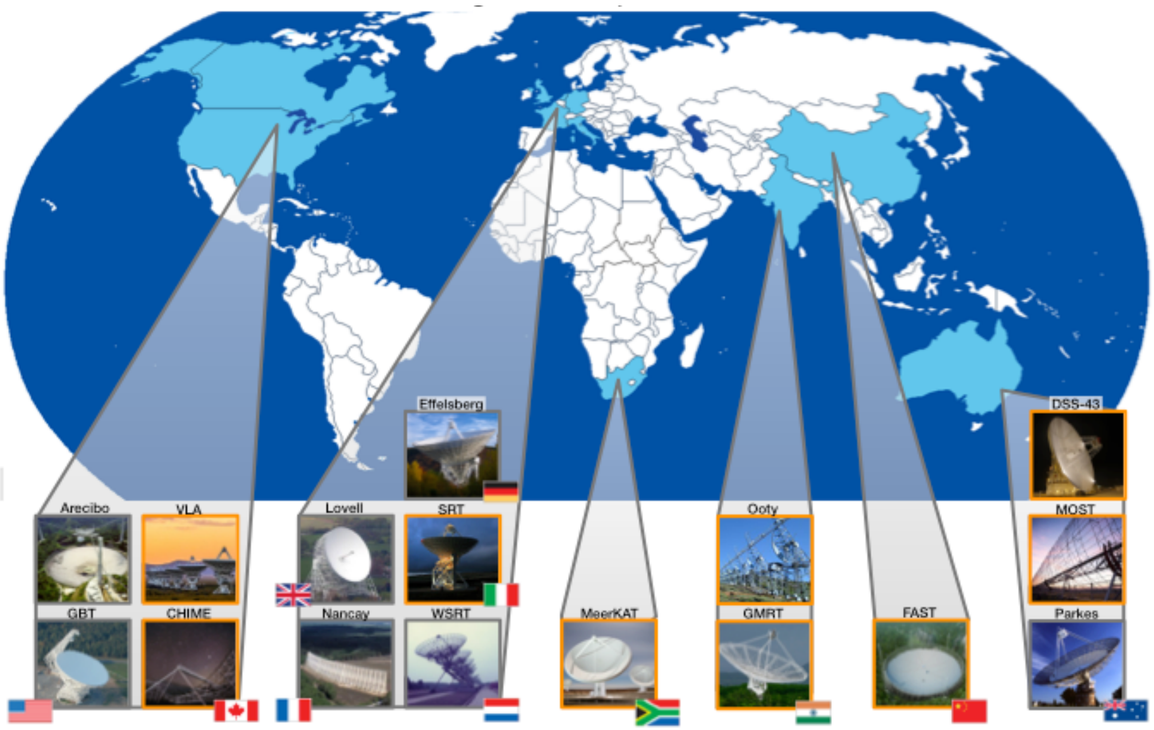
The International Pulsar Timing Array

NANOGrav Physics Frontiers Center

European Pulsar Timing Array

North American Nanohertz Observatory for Gravitational Waves

Parkes Pulsar Timing Array

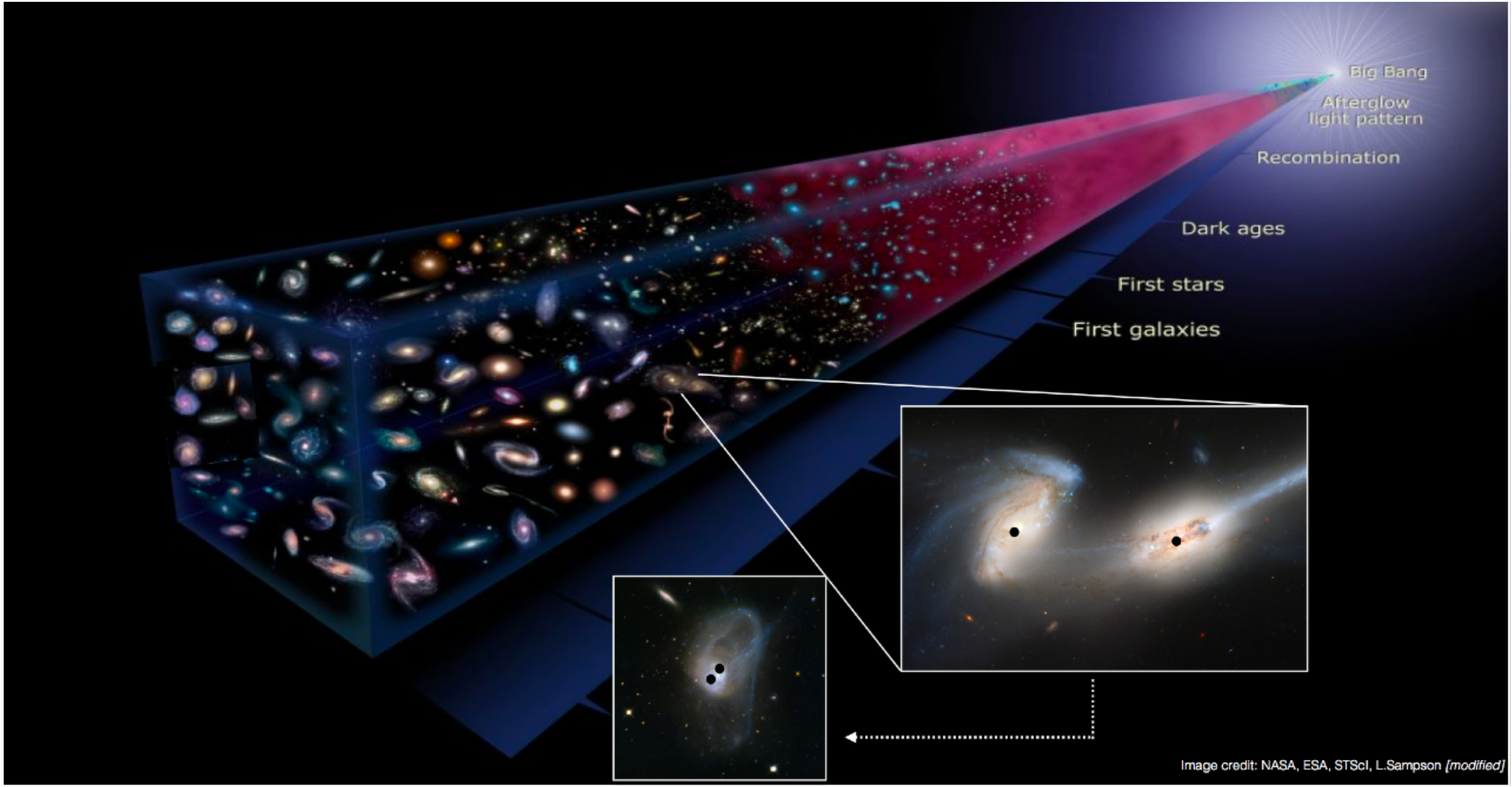


Credit: Shami Chatterjee

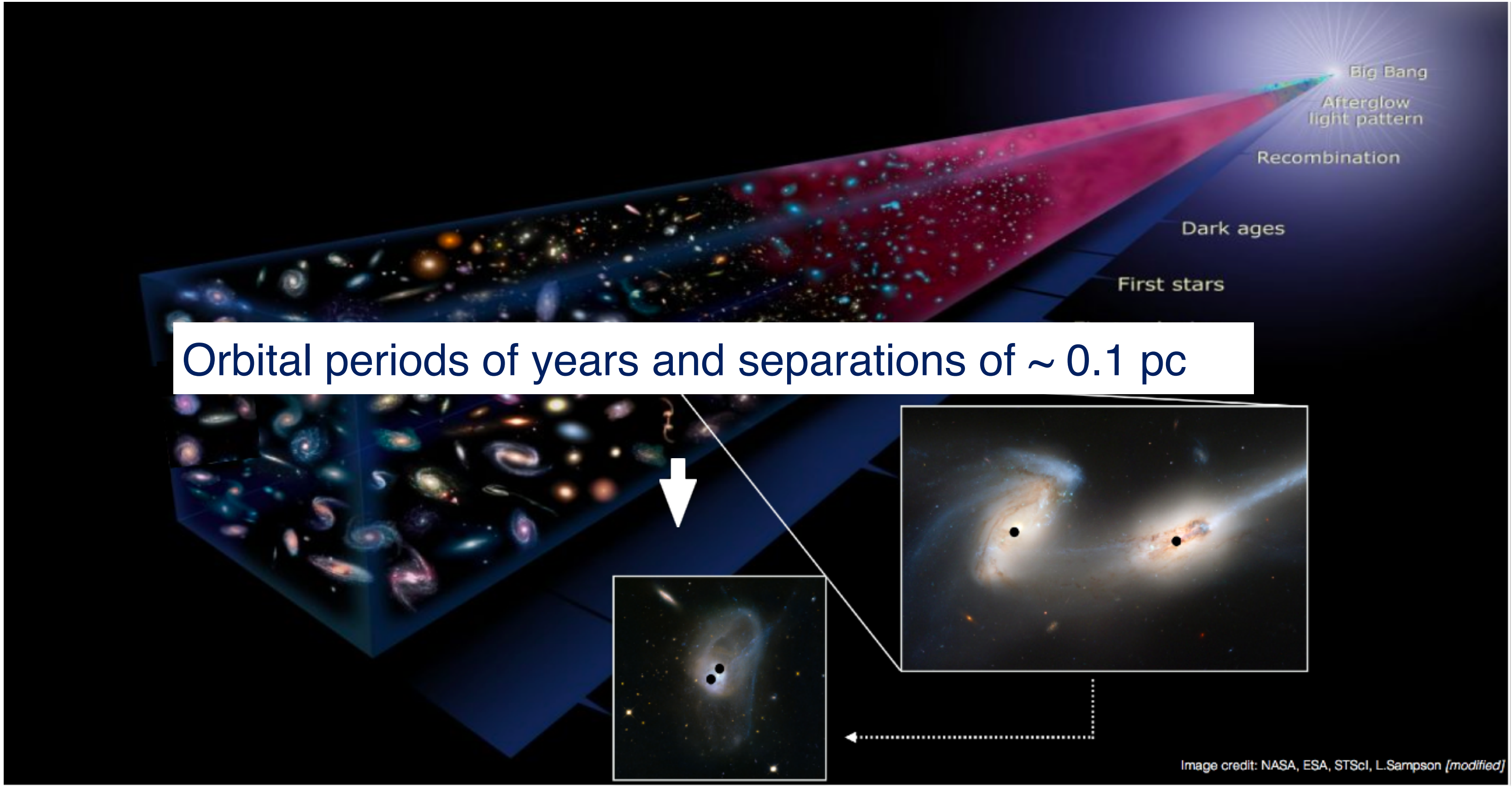
http://ipta4gw.org

Expanding to include data from 16 telescopes in 11 countries!

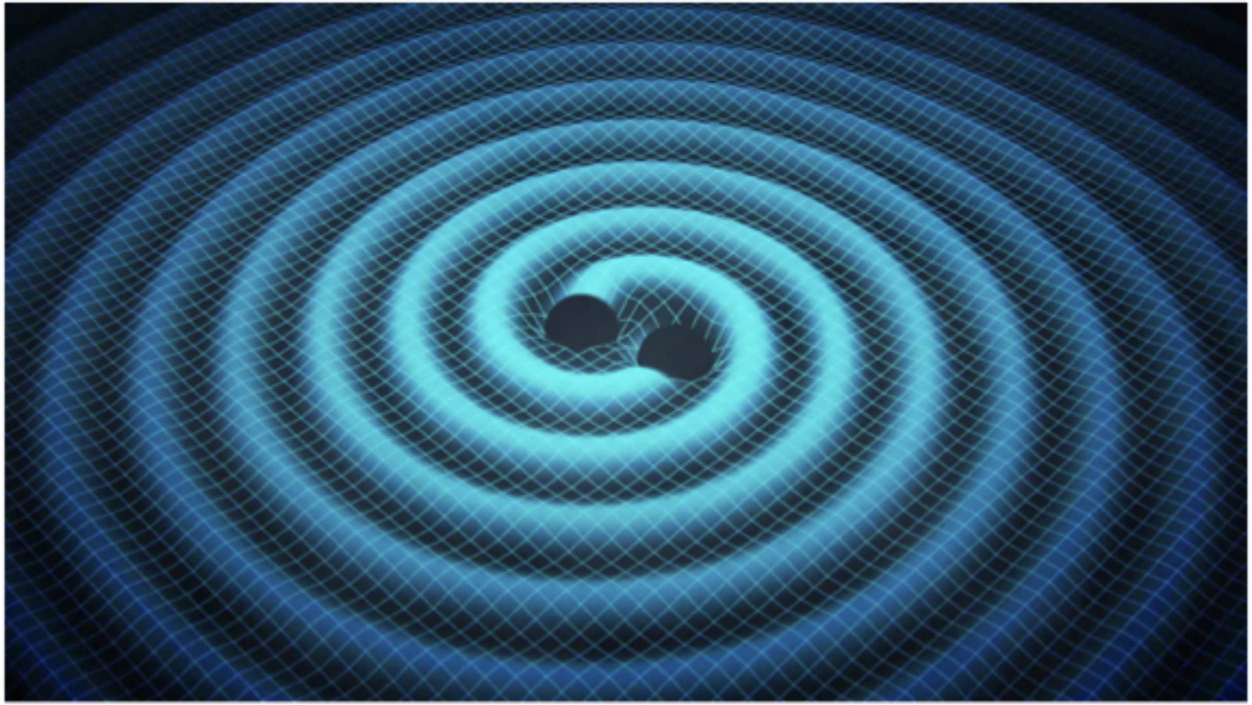
Galaxy Evolution 101



Galaxy Evolution 101



Gravitational Waves

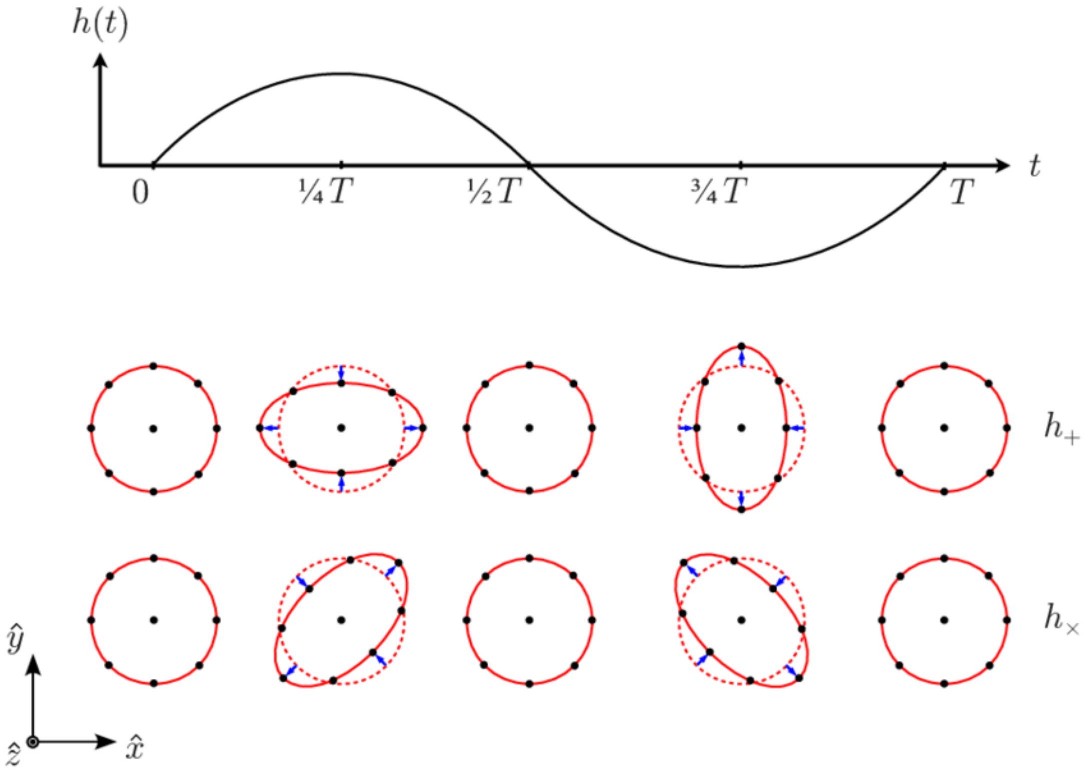


Gravitational waves (GW) are ripples in spacetime predicted by General Relativity.

They are produced by massive, accelerating objects.

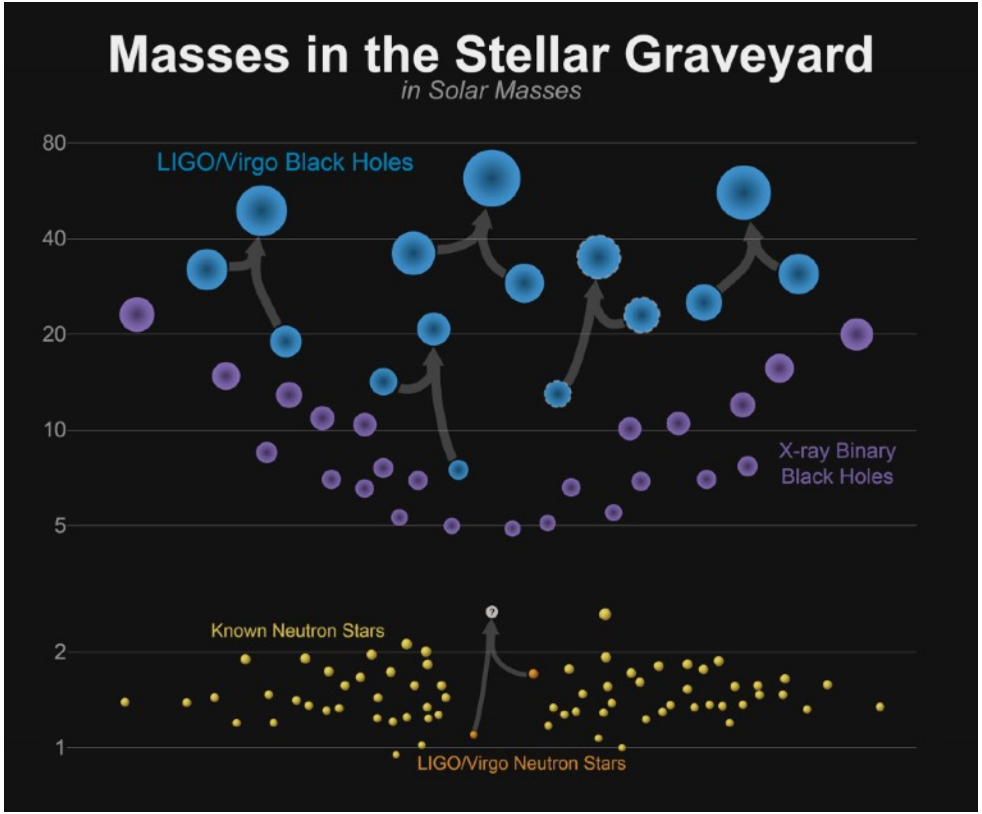
They travel at the speed of light and are not dispersed by matter.

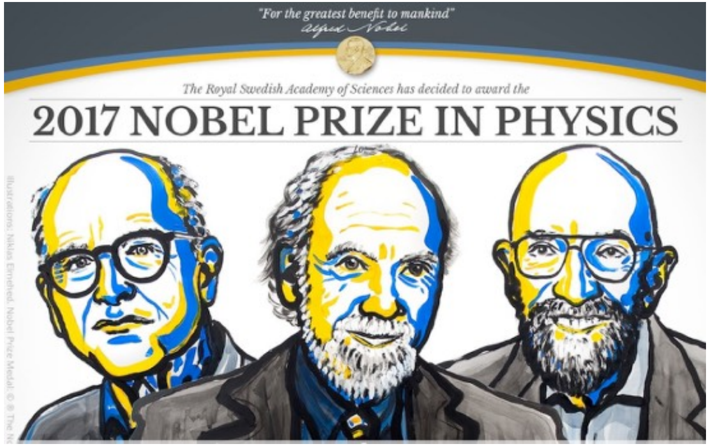
Gravitational Wave Detection



Gravitational waves change the (proper) distance between objects.

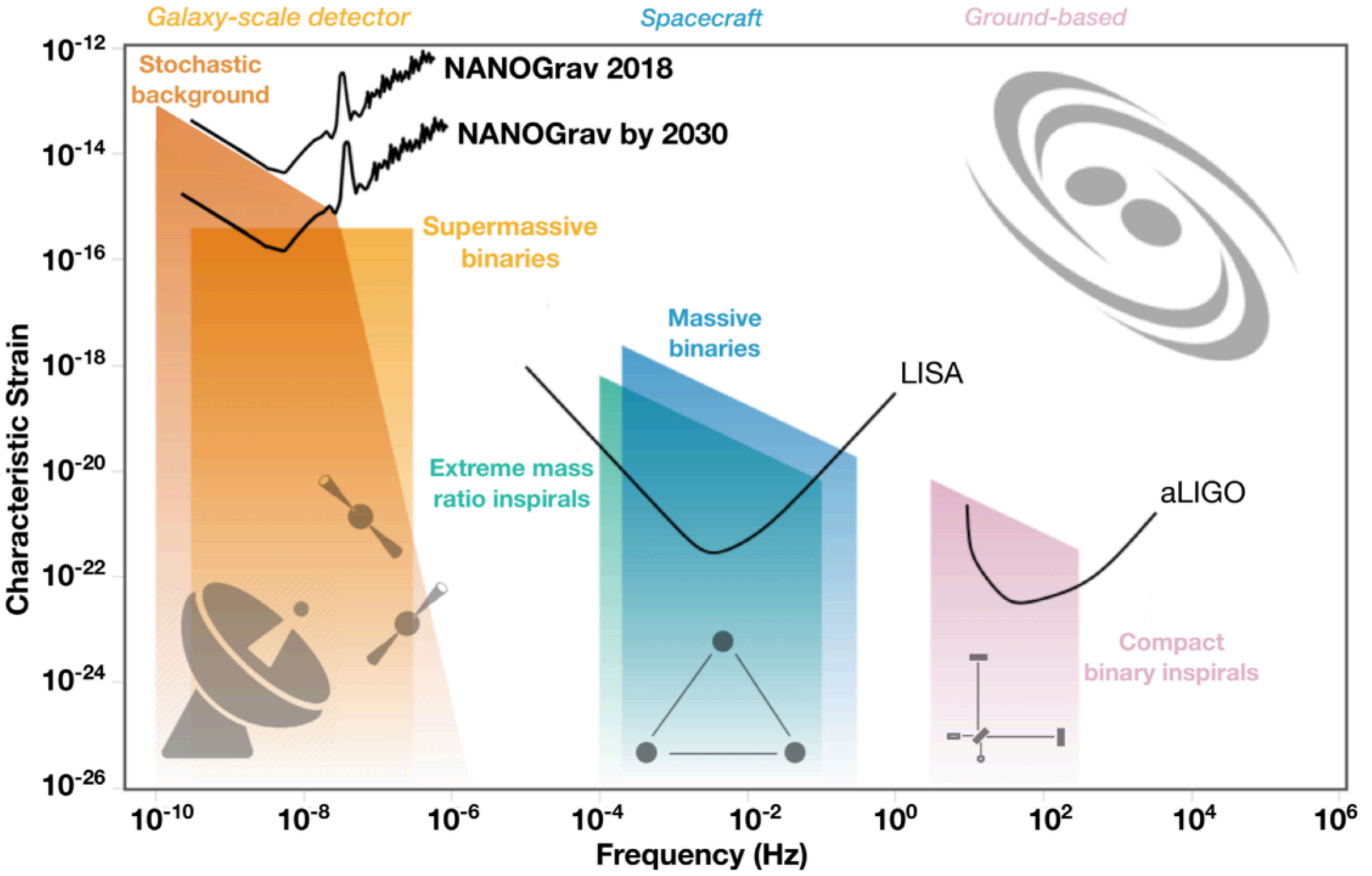
LIGO Detection in September 2015





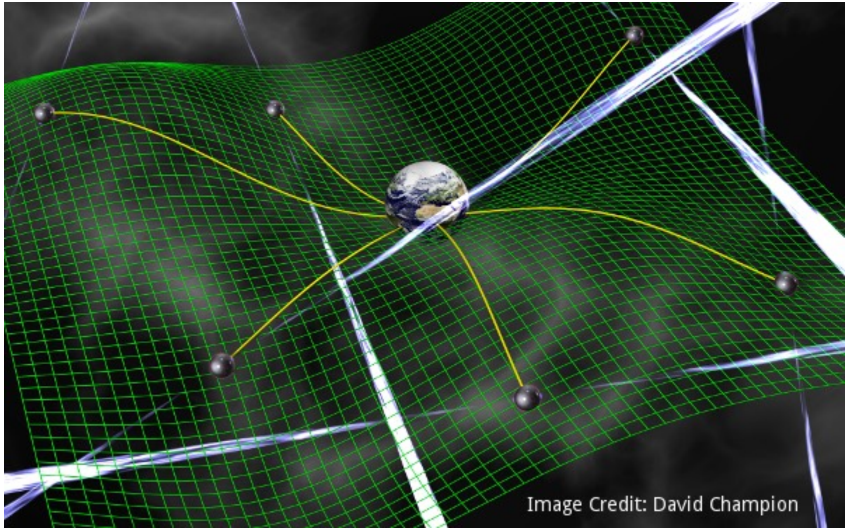
The Gravitational Wave Spectrum

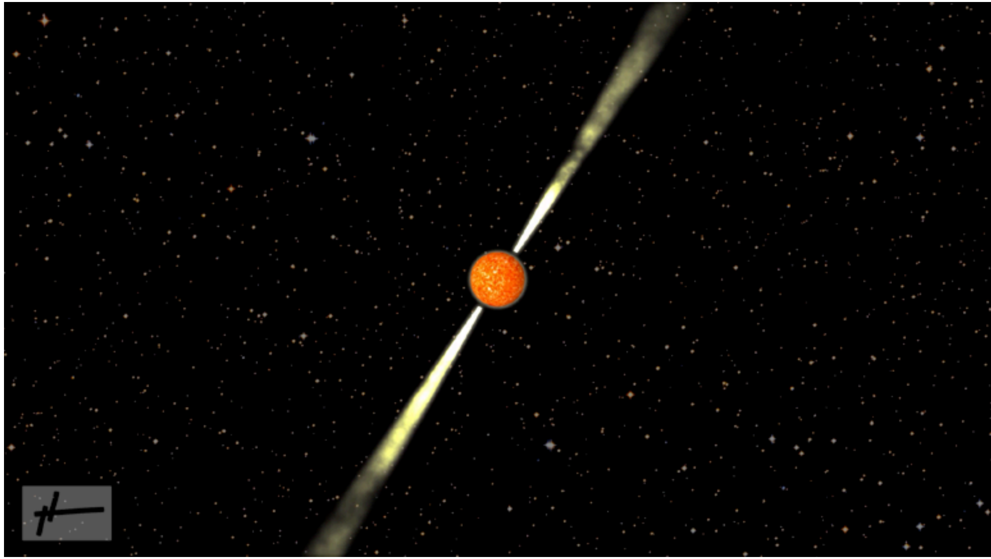
NANOGrav Physics Frontiers Center



Ransom et al., 2019, NANOGrav Decadal Whitepaper, arXiv: 1908.05356

Pulsar Timing Arrays (PTAs)





Pulsars are neutron stars born in supernova explosions.

PTA: 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.

Millisecond Pulsars (MSPs)

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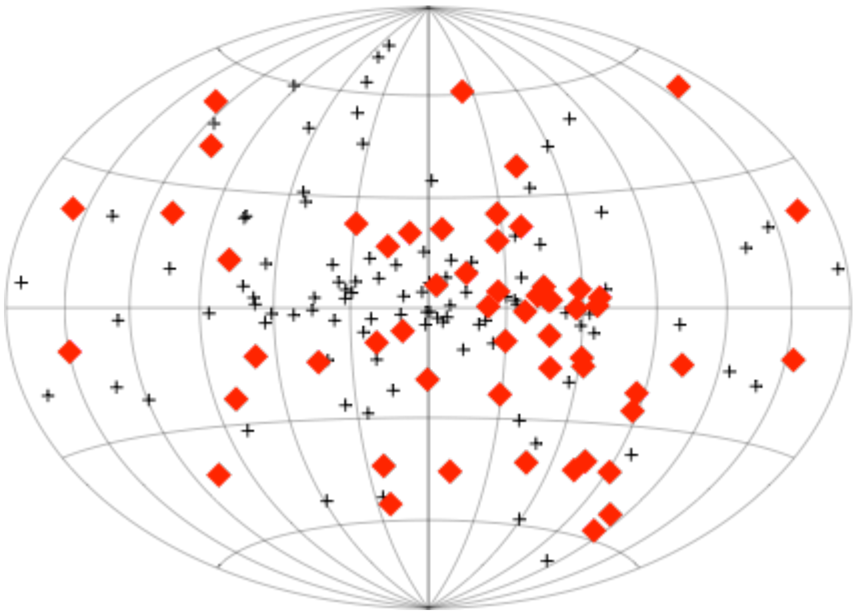
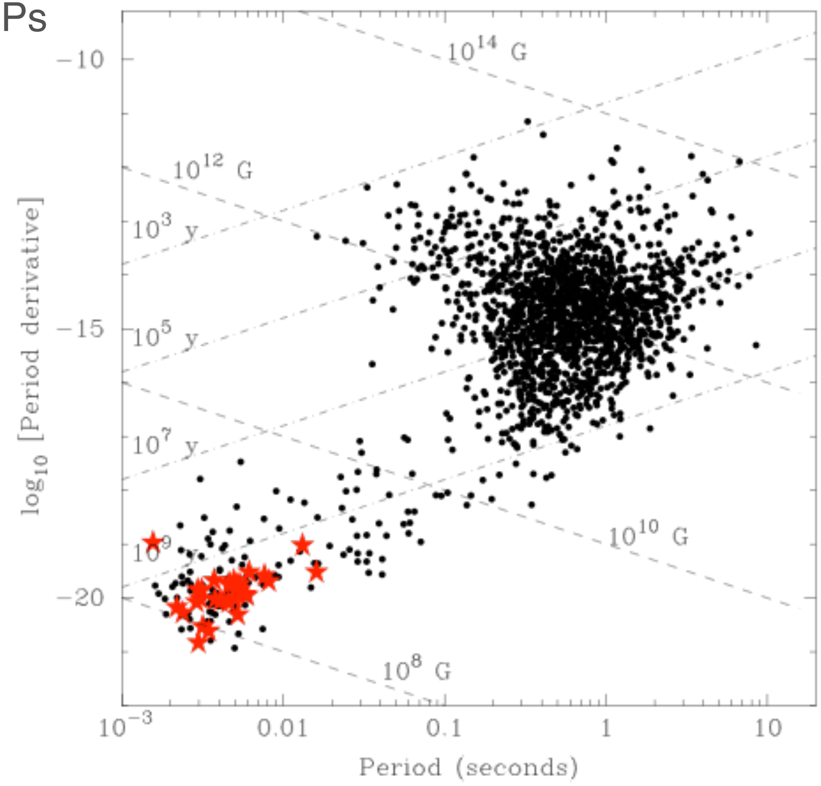
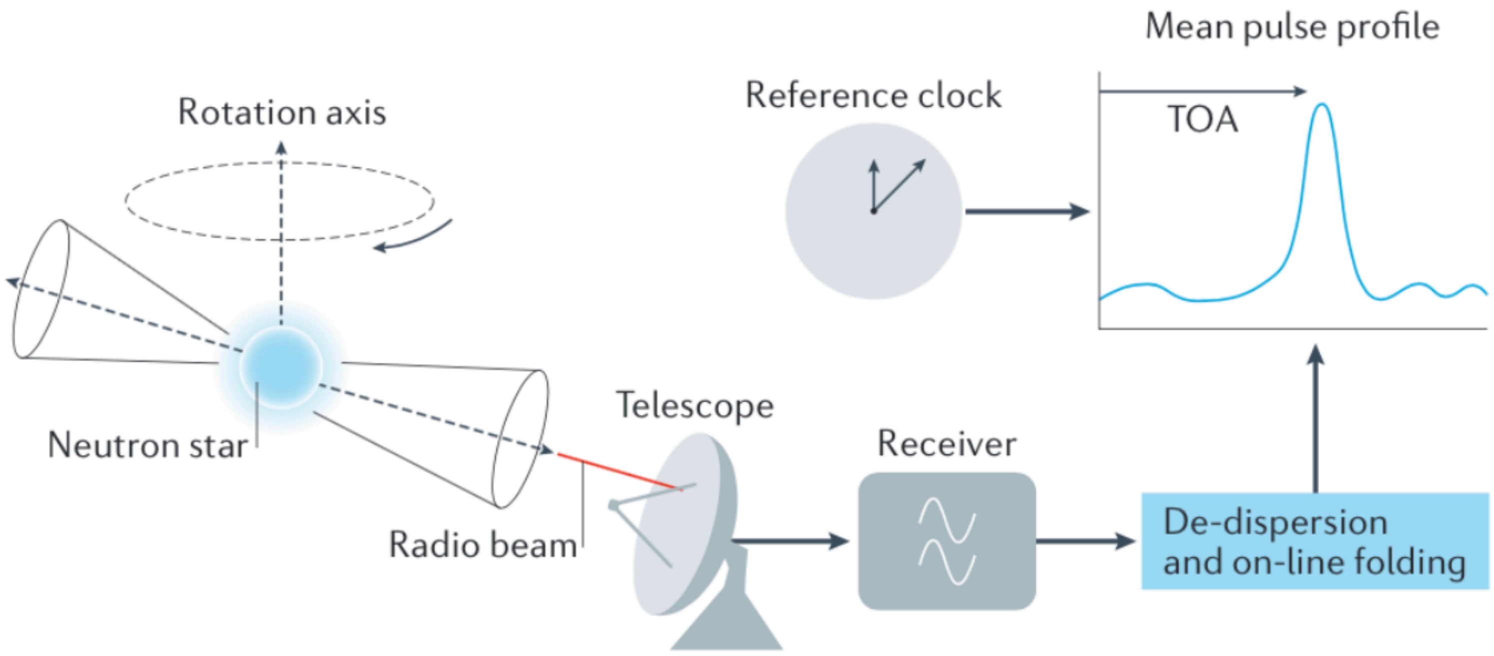
Out of over 2600 known pulsars, there are about 300 MSPs ($P < 30$ ms) in our Galaxy, out of roughly 30,000-80,0000 detectable. *Roughly 100 timed for PTA purposes.*





Red = part of worldwide PTA timing programs

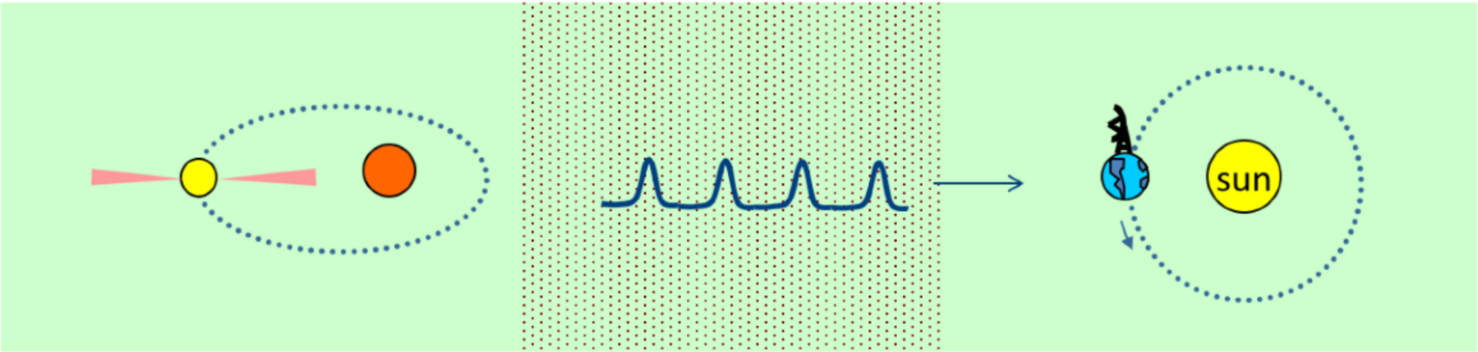
Pulsar Timing



Credit: “Handbook of Pulsar Astronomy”, Lorimer & Kramer (2005)

Many things affect arrival times

NANOGrav Physics Frontiers Center



rotation period rotation period derivative timing noise Keplerian orbital elements relativistic orbital elements kinematic perturbations of orbital elements (secular and annual phenomena)	dispersion measure dispersion meas. variations	position proper motion parallax solar electron density

Credit: David Nice

Pulsar Timing Model

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Measured Parameters	
R.A., α (J2000)	17:13:49.5320251(5)
decl., δ (J2000)	7:47:37.506131(12)
Spin frequecy ν (s^{-1})	218.81184385472585(6)
Spin down rate $\dot{\nu}$ (s^{-2})	$-4.083889(4) \times 10^{-16}$
Proper motion in α, $\mu_\alpha = \dot{\alpha}\cos\delta$ (mas yr^{-1})	4.9177(11)
Proper motion in δ, $\mu_\delta = \dot{\delta}$ (mas yr^{-1})	−3.917(2)
Parallax, ϖ (mas)	0.858(15)
Dispersion measure[b] (pc cm^{-3})	15.9700
Orbital period, P_b (day)	67.82513682426(16)
Change rate of P_b, $\dot{P}_b$ (10^{-12} s s^{-1})	0.23(12)
Eccentricity, e	0.0000749394(3)
Time of periastron passage, T_0 (MJD)	53761.03227(11)
Angle of periastron[c], ω (deg)	176.1941(6)
Projected semimajor axis, x (lt-s)	32.34242243(5)
sin i, where i is the orbital inclination angle	0.9672(11)
Companion mass, M_c ($M_\odot$)	0.233(4)
Apparent change rate of x, $\dot{x}$ (lt-s s^{-1})	0.00637(7)
Profile frequency dependency parameter, FD1	−0.00016317(19)
Profile frequency dependency parameter, FD2	0.0001357(3)
Profile frequency dependency parameter, FD3	−0.0000664(6)
Profile frequency dependency parameter, FD4	0.0000147(4)
Fixed Parameters	
Solar system ephemeris	DE421
Reference epoch for α, δ, and ν (MJD)	53729
Solar wind electron density n_0 (cm^{-3})	0
Rate of periastron advance, $\dot{\omega}$ (deg yr^{-1})[d]	0.00020
Position angle of ascending node, Ω (deg)[e]	88.43
Red noise amplitude (μs $year^{1/2}$)	...
Red noise spectral index, γ_{red}	...
Derived Parameters	
Intrinsic period derivative, $\dot{P}_{Int}$(s s^{-1})[g]	$8.966(12) \times 10^{-21}$
Dipole magnetic field, B (G)[g]	$2.0485(14) \times 10^{8}$
Characteristic age, τ_c (year)[g]	$8.076(11) \times 10^{9}$
Pulsar mass, M_{PSR} ($M_\odot$)	0.97(3)

Spin and spin-down

Astrometric

Interstellar medium

Binary

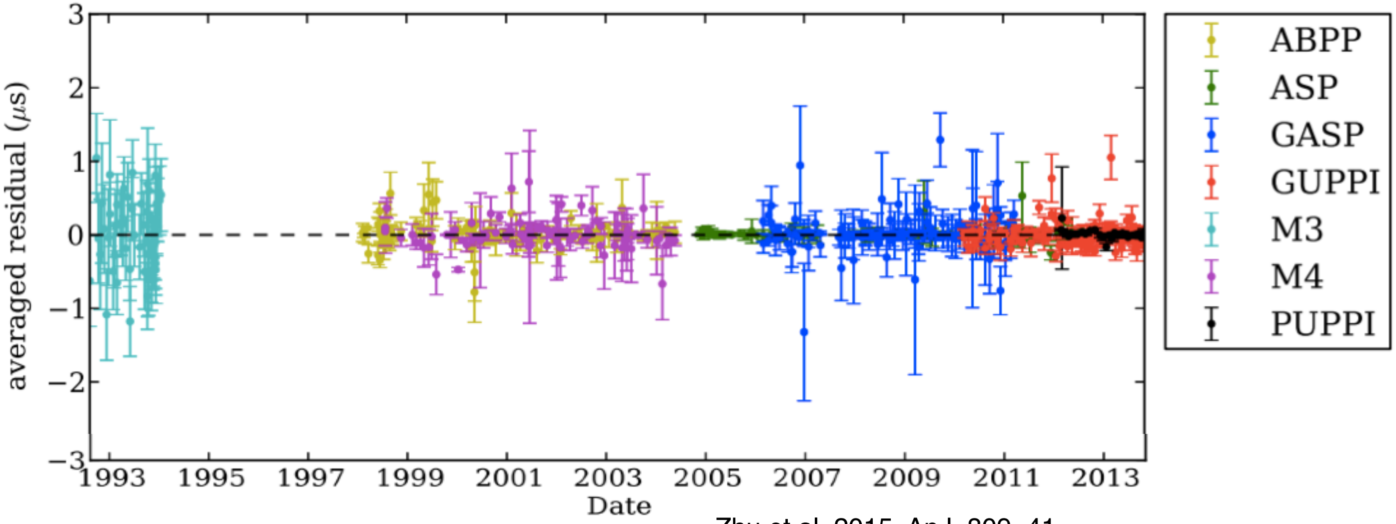
Pulsar profile evolution

Red and white noise

Zhu et al. 2015, ApJ, 809, 41

Timing Residuals

Model – Measured
Barycentric TOAs



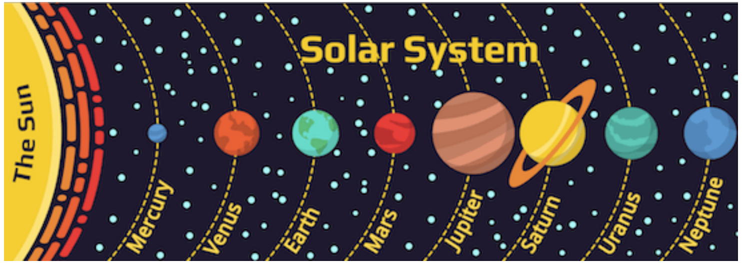
Zhu et al. 2015, ApJ, 809, 41

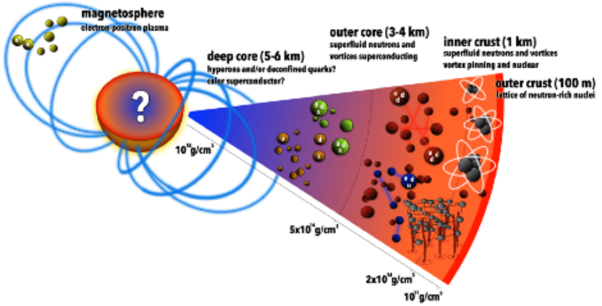
PSR J1713+0747 (P=4.57 ms).

TOAs measured to tens of ns - RMS ~ 70 ns over *decades* timescales.

Sources of Noise in PTA Data

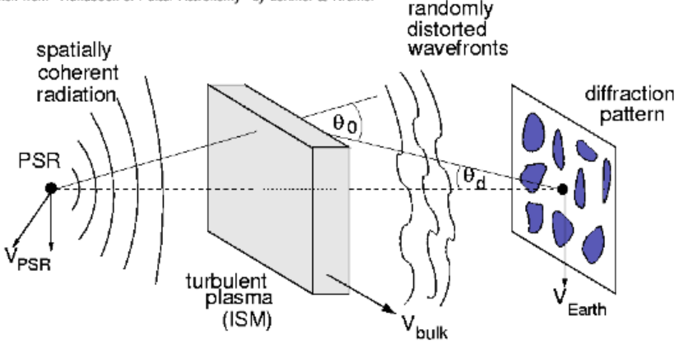
	Noise source	Achromatic?	Correlated in time?	Correlated in space?
Intrinsic	Pulsar rotational irregularities	✓	✓	✗
Intrinsic	Pulse jitter	✓	✗	✗
Extrinsic	Scattering and dispersion measure variations	✗	✓	✗
Extrinsic	Planetary ephemerides	✓	✓	✓
Extrinsic	Clock errors/offsets	✓	✓	✗



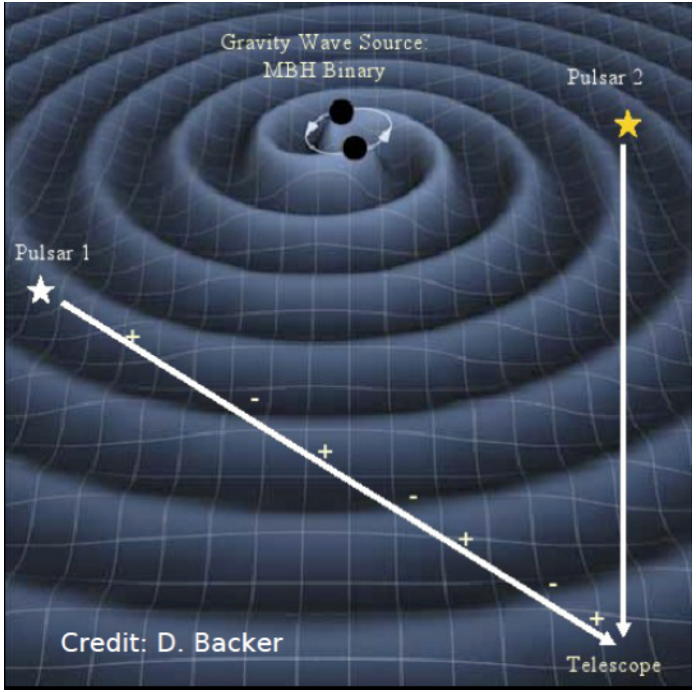


Watts et al. 2015, arXiv: 1501.00042

Taken from "Handbook of Pulsar Astronomy" by Lorimer & Kramer



Detection Big Picture

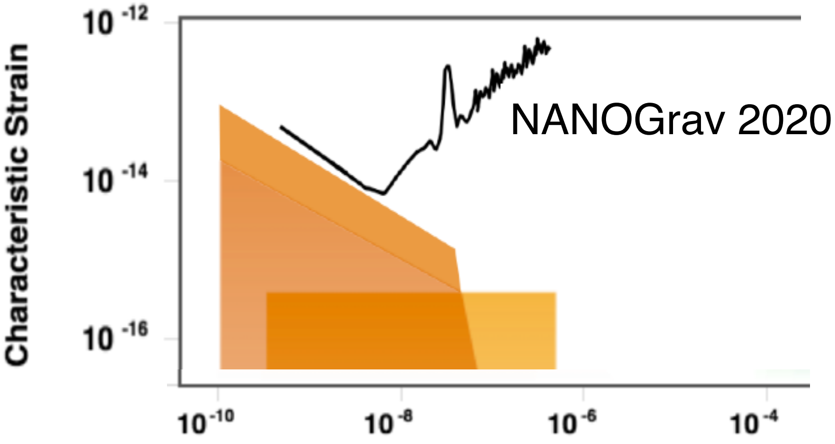


f ~ 1/weeks to 1/years (10^{-6} – 10^{-9} Hz)

The induced residual Δt ~ h/f and will have pulsar and Earth terms.

$h_{min} \sim \sigma_{rms}/T \sim 200$ ns/10 years ~ 10^{-15}

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



PTA Sources

For a binary system,

$$h \simeq 10^{-17} M_8^{5/3} f_{\mathrm{yr}^{-1}}^{2/3} D_{\mathrm{Gly}}^{-1} \frac{q}{(1+q)^2}$$

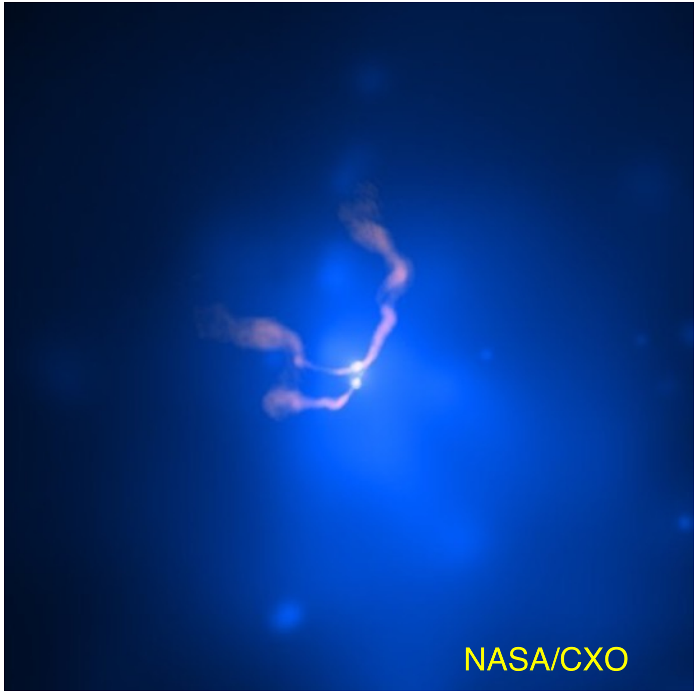
$$\tau = 10^6 M_8^{-5/3} f_{\mathrm{yr}^{-1}}^{-8/3} \frac{(1+q)^2}{q} \mathrm{yr}$$

For a stochastic background,

$$h_c(f) = A_{\mathrm{GWB}} \left(\frac{f}{\mathrm{yr}^{-1}} \right)^{\alpha}$$

$$\alpha = -2/3$$

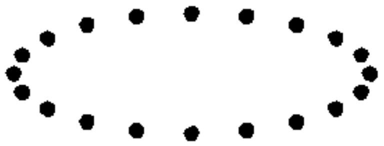
(under the simplest assumptions)



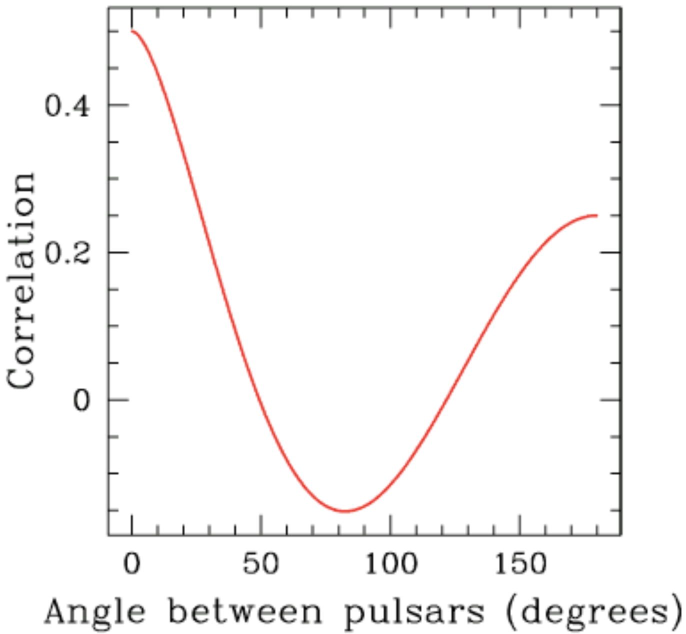
Will look like correlated RED noise in our data.

The Expected Correlation

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



Clock errors monopole.
Ephemeris errors dipole.
GWs quadrupole.



Hellings & Downs, 1983, ApJ, 265, L39

Can we distinguish GWs from noise?

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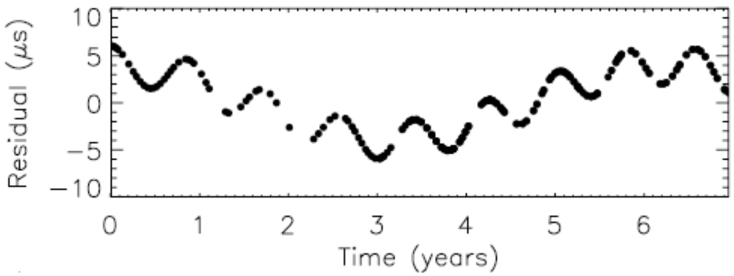
	Noise source	Achromatic?	Correlated in time?	Correlated in space?	Quadrupolar?
Intrinsic	Pulsar rotational irregularities	✓	✓	✗	✗
Intrinsic	Pulse jitter	✓	✗	✗	✗
Extrinsic	Scattering and dispersion measure variations	✗	✓	✗	✗
Extrinsic	Planetary ephemerides	✓	✓	✓	✗
Extrinsic	Clock errors/offsets	✓	✓	✗	✗
	GW background	✓	✓	✓	✓

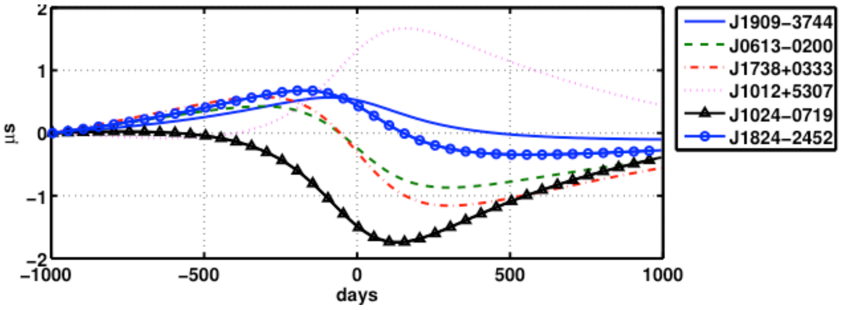
Yes!

And detect single sources through continuous wave and burst searches



Jenet et al. 2004, ApJ, 606, 799

50 billion solar mass binary with period of one year at 100 Mpc (3C66B).

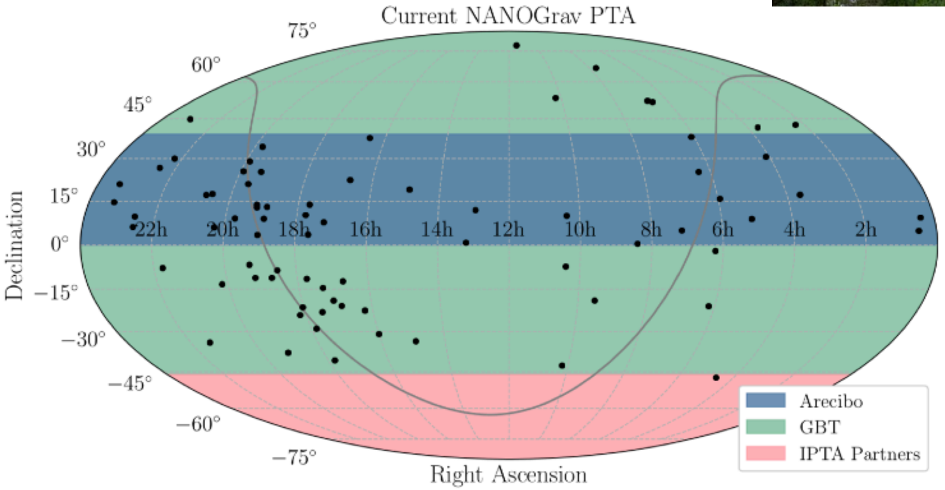


Finn & Lommen, ApJ, 2000, 718 1400

Parabolic encounter of two billion solar mass black holes at 20 Mpc.

NANOGrav’s Observing Program

We have been observing 79 MSPs at two frequencies (from 800 MHz to 3 GHz) every one to four weeks for roughly 20-30 min using Arecibo (41 MSPs, 5 weekly), the GBT (39 MSPs, 2 weekly), and the VLA (7 MSPs).



The NANOGrav Collaboration, 2018, ApJS, 235, 37

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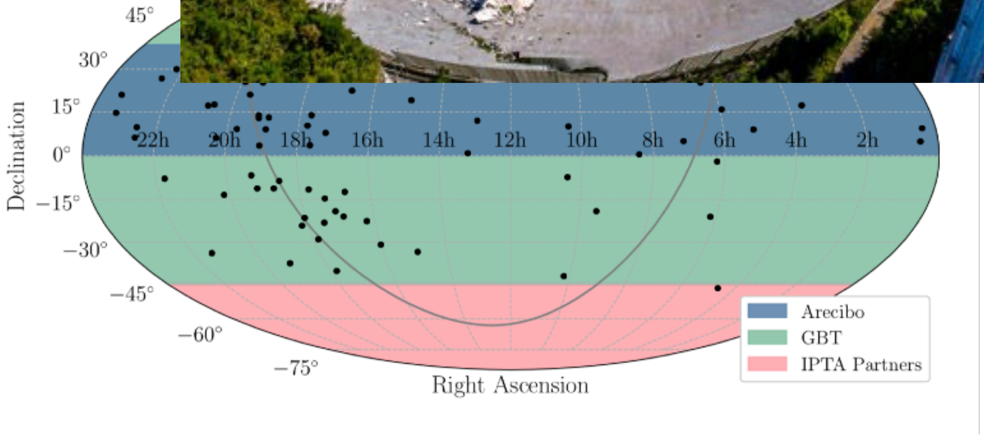


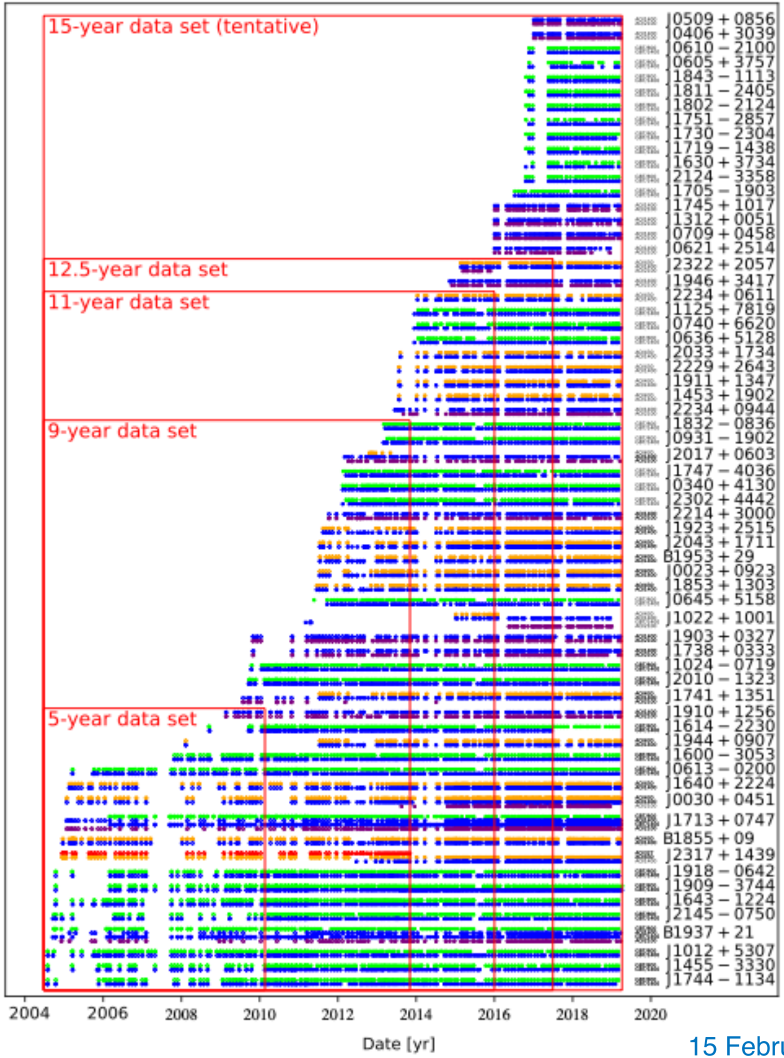
The NANOGrav Collaboration, 2018, ApJS, 235, 37

NANOGrav’s Data Releases

We release data and carry out new gravitational wave searches every ~two years.

Publicly available at http://data.nanograv.org

The NANOGrav Collaboration, 2018, ApJS, 235, 37
The NANOGrav Collaboration, 2021, APSS, 252, 48
The NANOGrav Collaboration, 2021, APSS, 252, 53



NANOGrav's Data Releases

The NANOGrav Collaboration, ApJS, 235, 37

```
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guppi_57378_J0613-0200_0006.11y.x.ff 872.343018 57378.246733896636763 1.697 gbt -fe Rcvr_800 -be GUPPI
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```
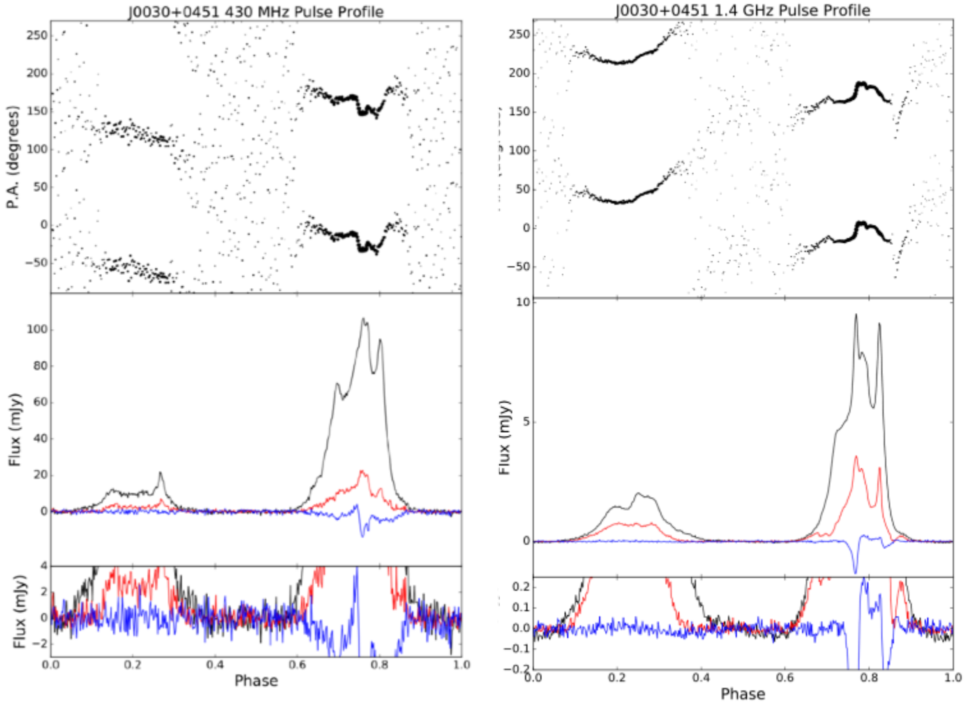

Contain full Stokes profiles, per frequency times of arrival, and timing parameter files



Gentile et al., 2018, ApJ, 862, 47

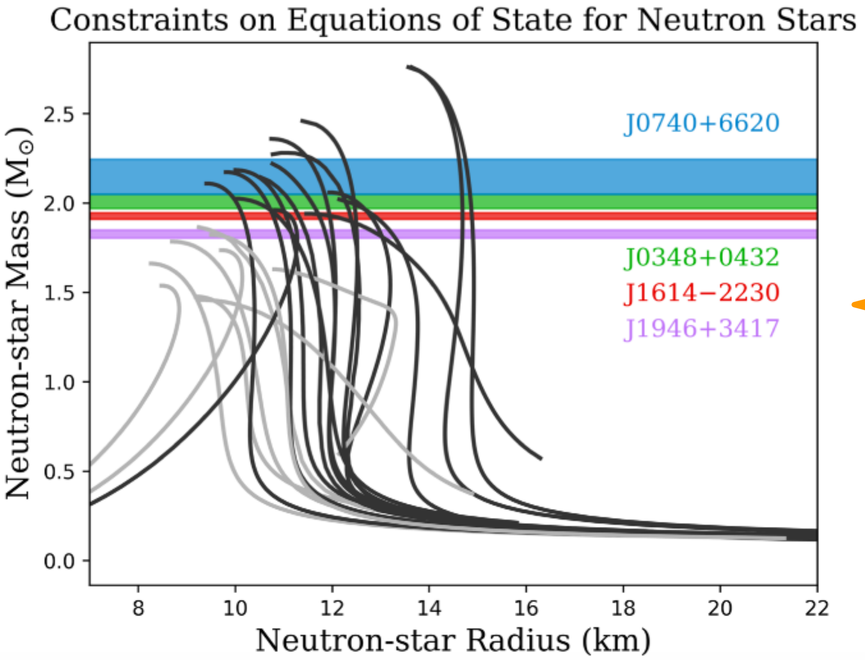
Table 1: PSR J0740+6620 Best-Fit Parameters

Pulsar name	J0740+6620
Dates of Observations (MJD)	56640 – 58462
Number of TOAs	7419
Measured Quantities	
Ecliptic longitude, λ (degrees)	103.75913607(1)
Ecliptic latitude, β (degrees)	44.10248468(2)
Epoch of position & period (MJD)	57551.0
Proper motion in ecliptic longitude (mas yr^{-1})	$-2.75(3)$
Proper motion in ecliptic latitude (mas yr^{-1})	$-32.43(4)$
Parallax (mas)	0.5(3)
Spin frequency, ν (Hz)	346.5319964932129(6)
Spin frequency derivative, $\dot{\nu}$ (s^{-2})	$-1.46389(2)\times10^{-15}$
Dispersion measure, DM (pc cm^{-3})*	14.961787
Profile frequency dependency parameter, FD1	$-1.17(4)\times10^{-5}$
Binary model	ELL1
Projected semi-major axis of orbit, x (lt-s)	3.9775561(2)
Binary orbital period, P_b (days)	4.7669446191(1)
Epoch of ascending node, TASC (MJD)	57552.08324415(2)
EPS1 (first Laplace-Lagrange parameter), $e \sin\omega$	$-5.70(4)\times10^{-6}$
EPS2 (second Laplace-Lagrange parameter), $e \cos\omega$	$-1.89(3)\times10^{-6}$
Sine of inclination angle i	0.9990(2)
Companion mass, m_c ($M_\odot$)	0.258(8)

Cromartie et al., 2019, Nature Astronomy, 439

Lots of other cool science!

Our timing data can be used for neutron star mass measurements, tests of general relativity, studies of the interstellar medium and the solar wind, and Galactic astrometry.



Fonseca et al., 2019, arXiv:1903.0819

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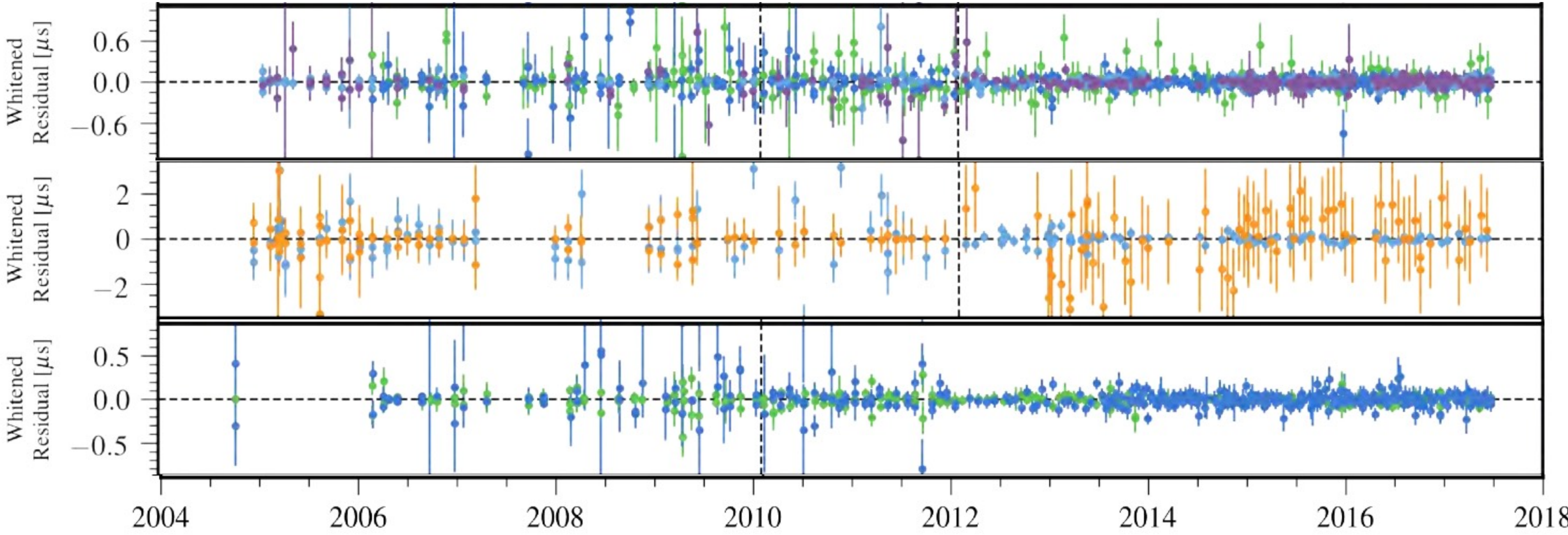
Cromartie et al., 2019, Nature Astronomy, 439

NANOGrav Analysis

Residuals = model - measured times of arrival (TOAs)

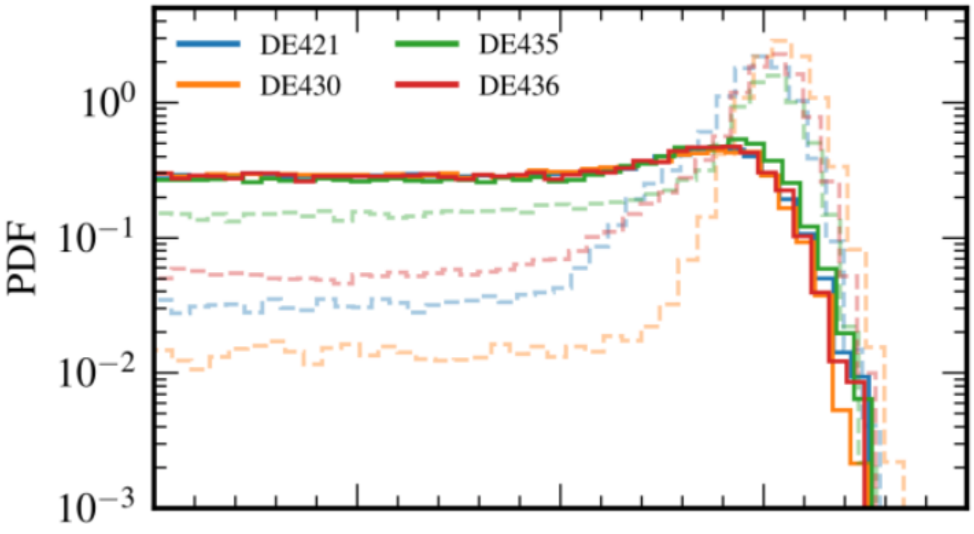


The NANOGrav Collaboration, 2021, APSS, 252, 48

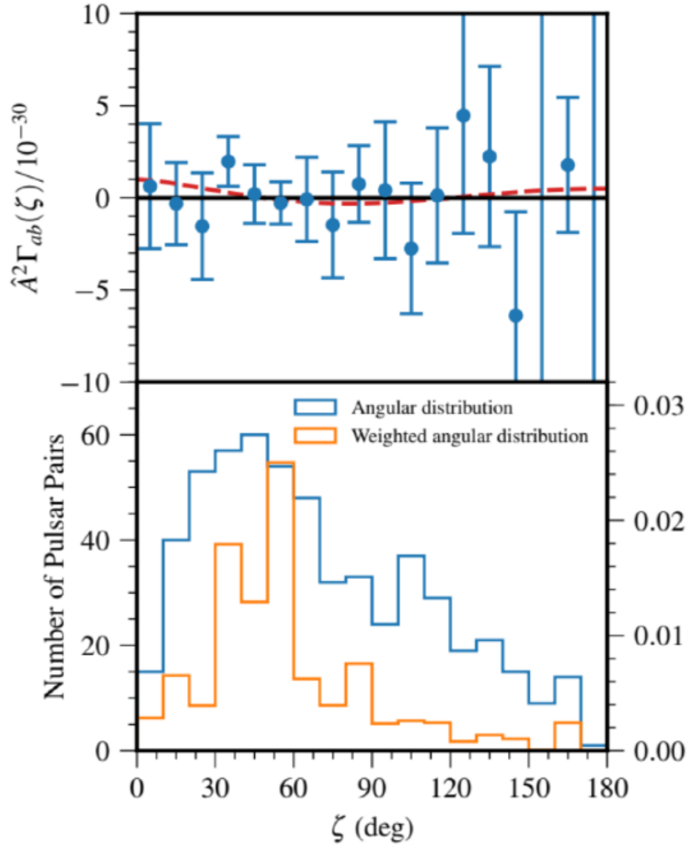
We search residuals for red noise (stochastic background), sine waves (single sources), or step functions (bursts with memory) that are correlated among pulsars.

Eleven-year Stochastic Background Analysis

No detection yet!



Developed new Bayesian methods to model Solar System ephemeris uncertainties

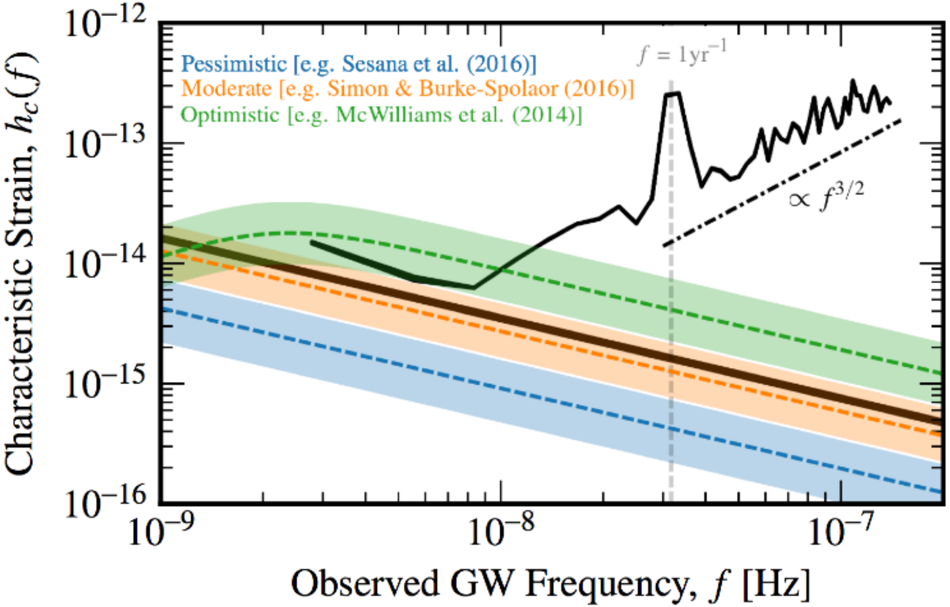


The NANOGrav Collaboration, 2018, ApJ, 859, 47

Our limit can rule out SMBBH formation and evolution models

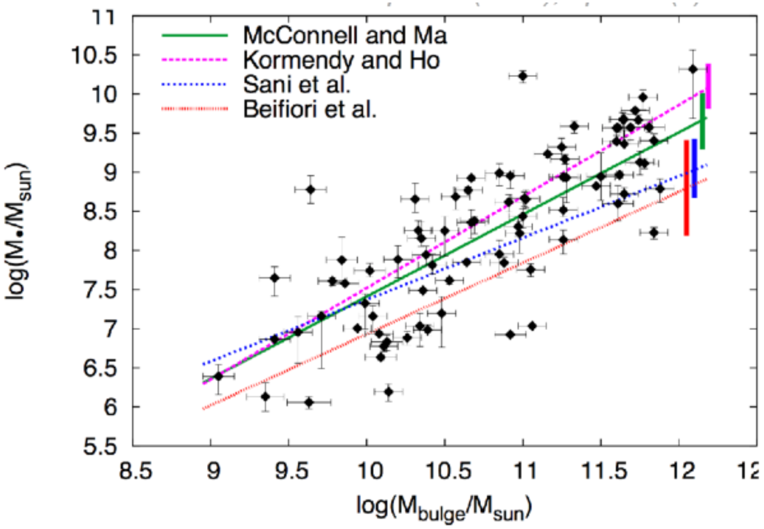
Can constrain astrophysical effects:

- stellar hardening
- circumbinary disk interaction
- binary eccentricity



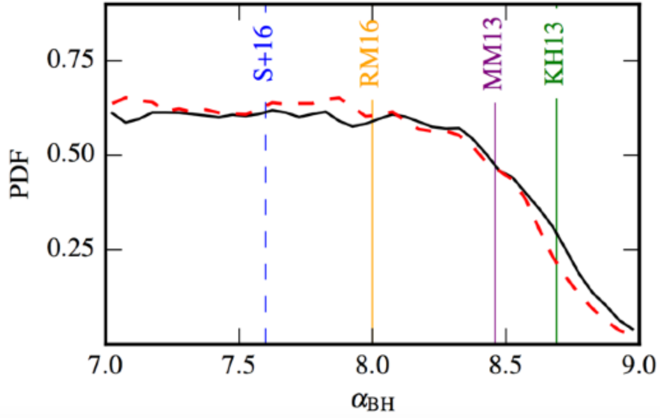
The NANOGrav Collaboration, 2018, ApJ, 859, 47

And make robust astrophysical constraints



Simon & Burke-Spolaor, 2016, ApJ, 826, 1

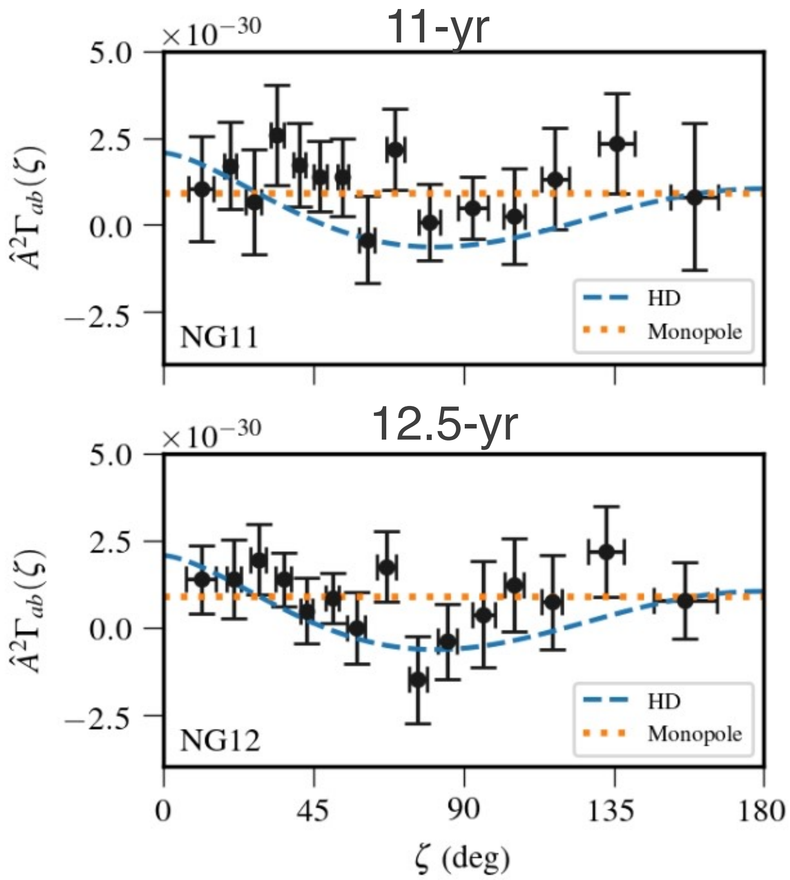
$$\log_{10} M_\bullet = \alpha + \beta \log_{10}\left(\frac{M_{\text{bulge}}}{10^{11}\,\mathrm{M}_\odot}\right)$$

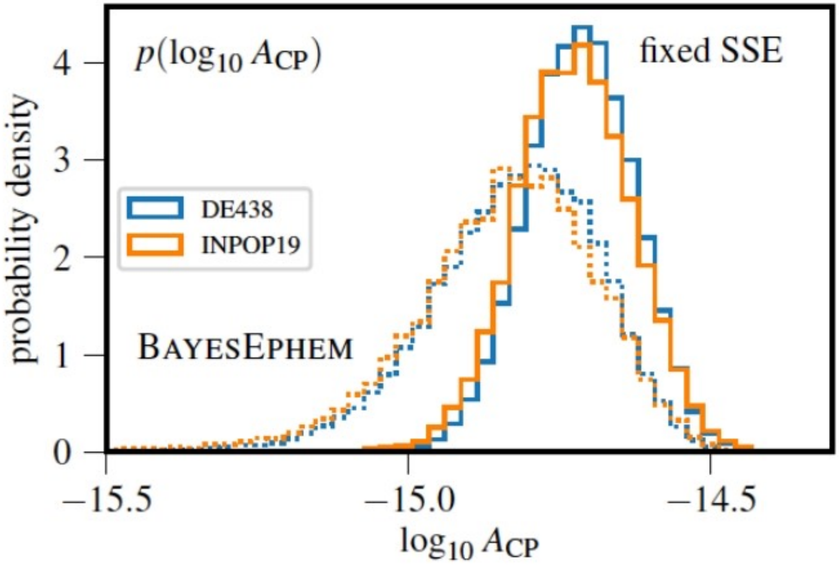


The NANOGrav Collaboration, 2018, ApJ, 859, 47

Can rule out astrophysical parameter space and place constraints on eccentricity, galaxy-bulge mass relationship, and galactic core mass density.

12.5-Yr Results

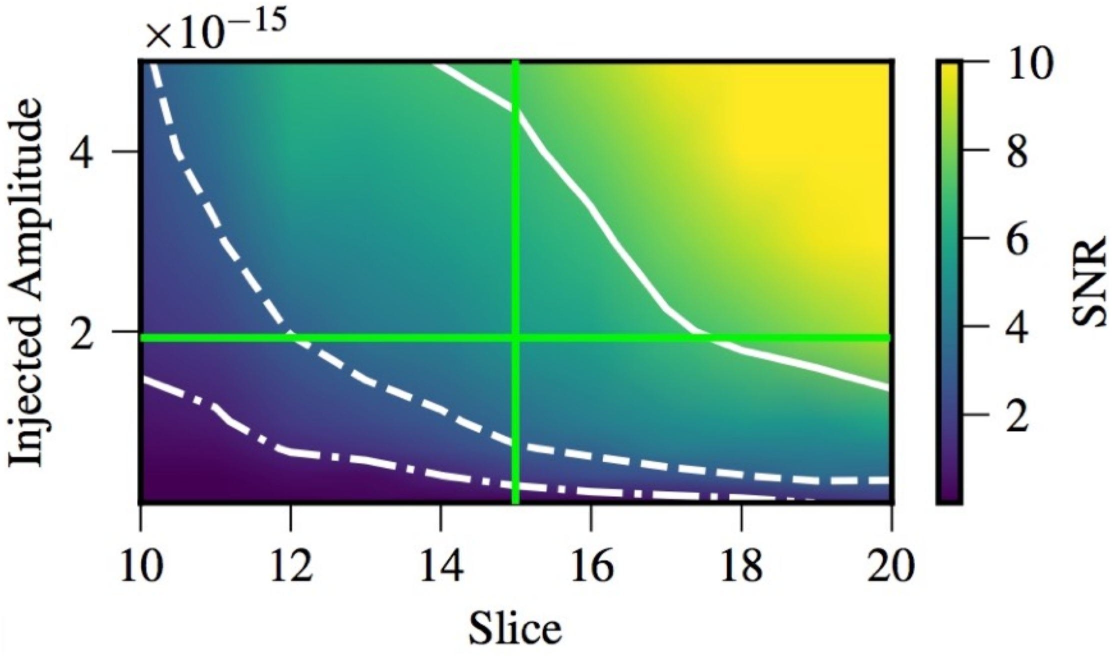




Strong common red noise process among all pulsars. But cannot yet distinguish quadrupolar signature.

The NANOGrav Collaboration, 2020, ApJ, 905, 34

When will we get there?



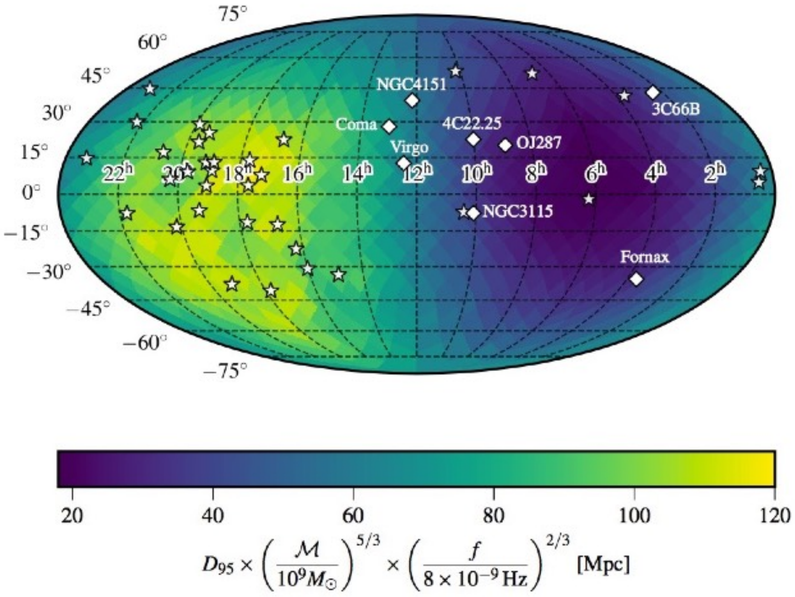
We expect evidence at a SNR of 4-7 in our upcoming 15-yr data set.

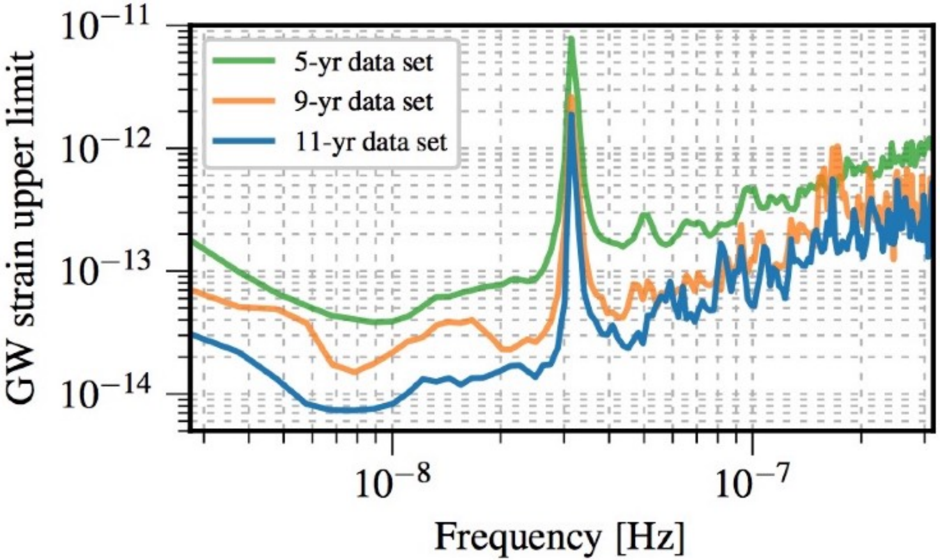
Measurement of amplitude and spectrum will allow unique constraints on galaxy formation and evolution.

Eleven-year Continuous Wave Results

Sky-averaged limit of 7 x 10^{-15} (f=8 nHz)

Highly direction dependent!





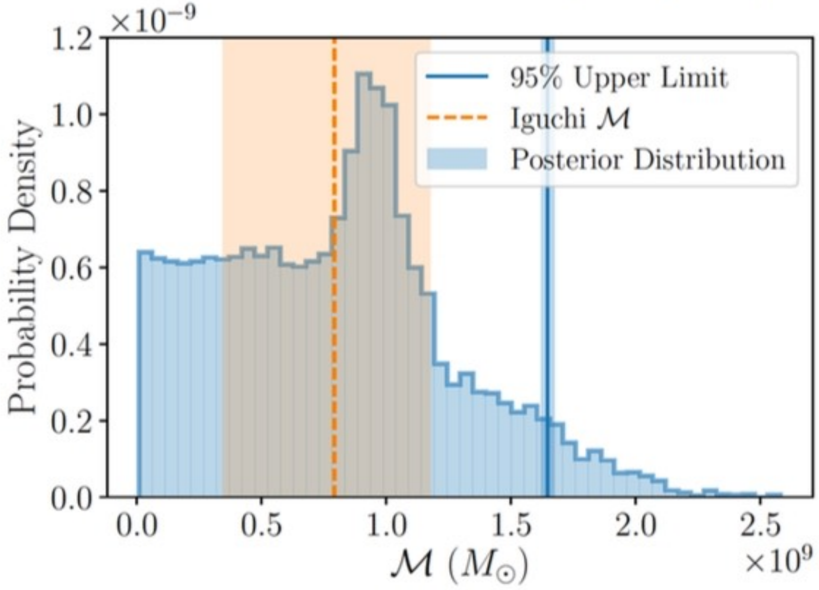
No Virgo SMBHBs with
M > 1.6 x 10^9 solar masses.

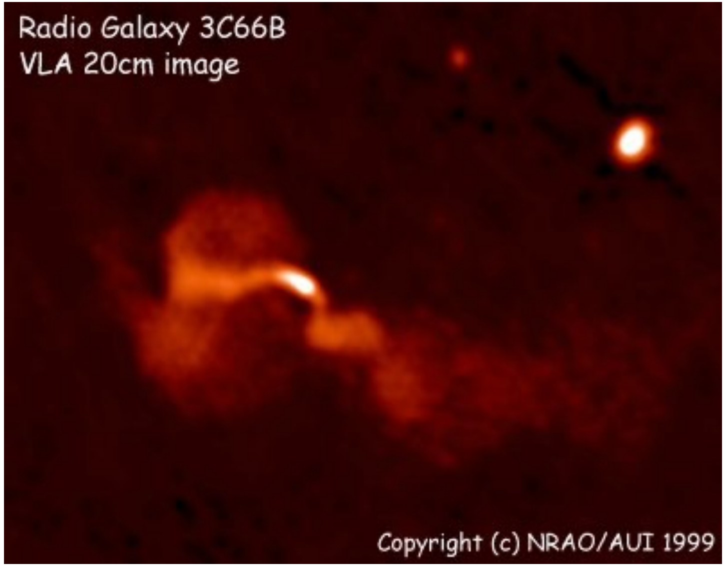
The NANOGrav Collaboration, 2019, ApJ, 880, 116

Targeted GW Searches

Nearby (85 Mpc) galaxy which shows evidence for binary black hole at core.

First mass estimates revised due to previous GW non-detections (Jenet et al. 2004).



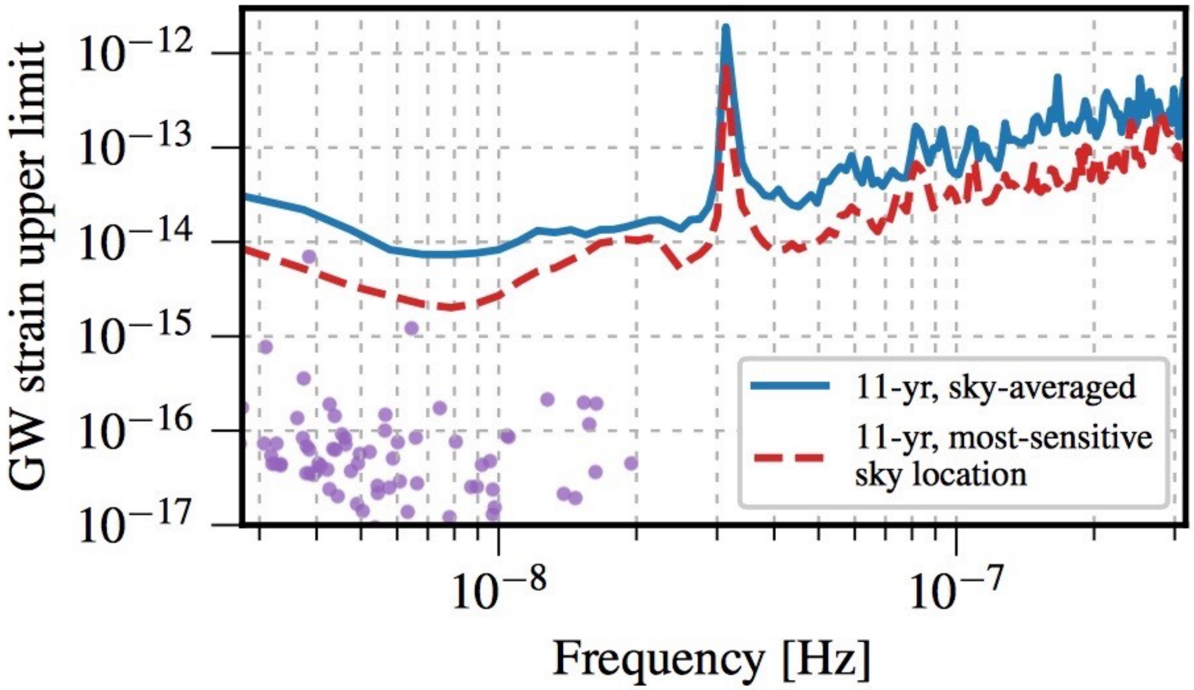


Our current limit is getting very close to the published mass estimate.

The NANOGrav Collaboration, 2020, ApJ, 900, 2

Continuous Wave Detection

NANOGrav Physics Frontiers Center



A simulated realization of the local universe based on galaxies detected by 2MASS. In 34 out of 75,000 simulations single sources are detectable.

We expect a detection within next 10 years.

The NANOGrav Collaboration, 2019, ApJ, 880 116 and Mingarelli et al. 2018, Nature Astronomy, 1, 886

Want to get there faster?

$$SNR \propto N_{\mathrm{MSP}}\, T^{1/2} \left(\frac{c}{\sigma^2_{\mathrm{RMS}}} \right)^{3/26}$$

Siemens et al. 2013

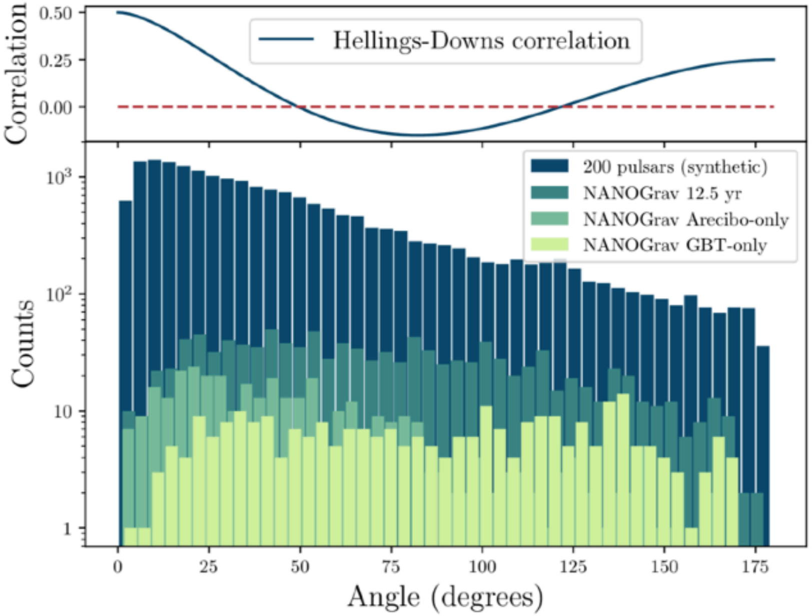
We need ***more pulsars (in the right places)***, higher cadences, better timing precisions (bigger telescopes and bandwidths).

For single sources, cadence and precision are more important.

(+ better ISM mitigation, noise characterization, ephemerides, etc.)

Going Forward

Increase to 200 MSPs by 2030.

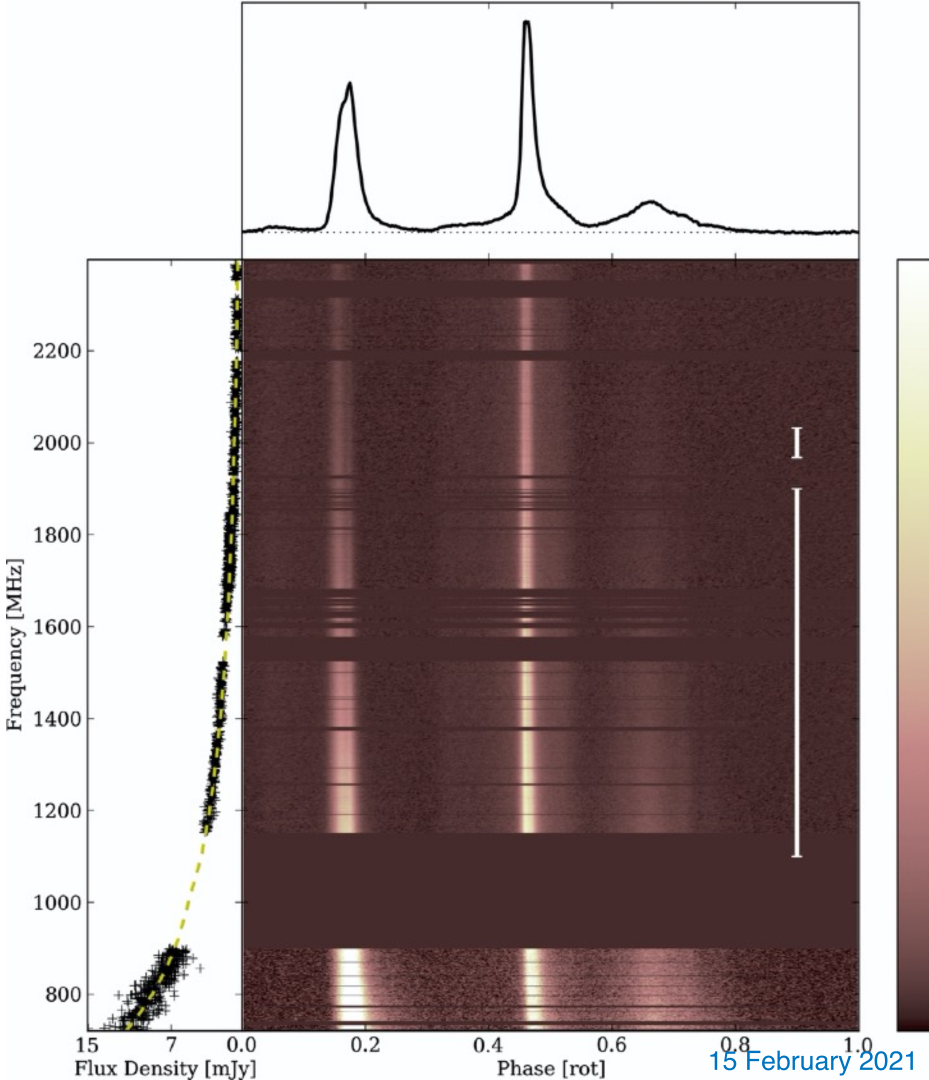


Ransom et al., 2019, NANOGrav
Decadal Whitepaper, arXiv: 1908.05356

Going Forward

Increase to 200 MSPs by 2030.

Develop a wideband receivers for the GBT.



Pennucci et al. 2014, ApJ, 790, 93

Going Forward

Increase to 200 MSPs by 2030.

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Incorporate CHIME data.

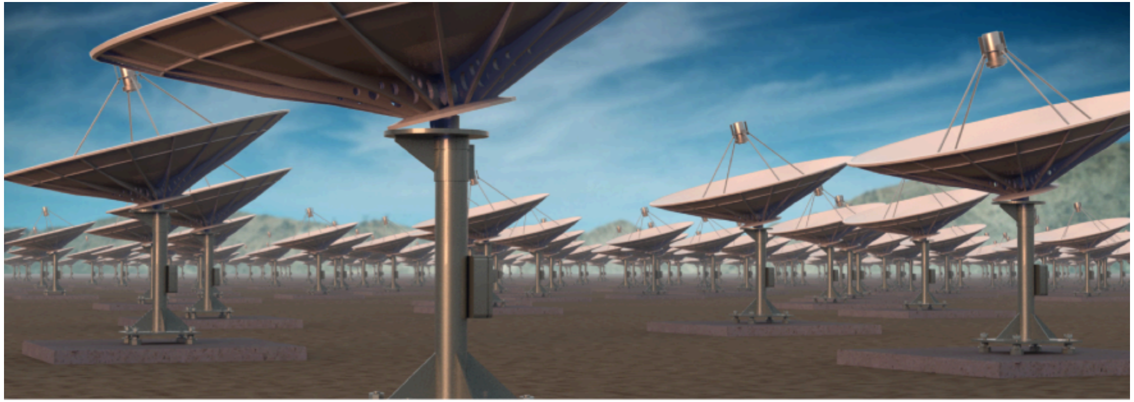
Going Forward

Increase to 200 MSPs by 2030.

Develop a wideband receivers for the GBT.

Incorporate CHIME data.

Contribute to the development of next generation radio arrays.

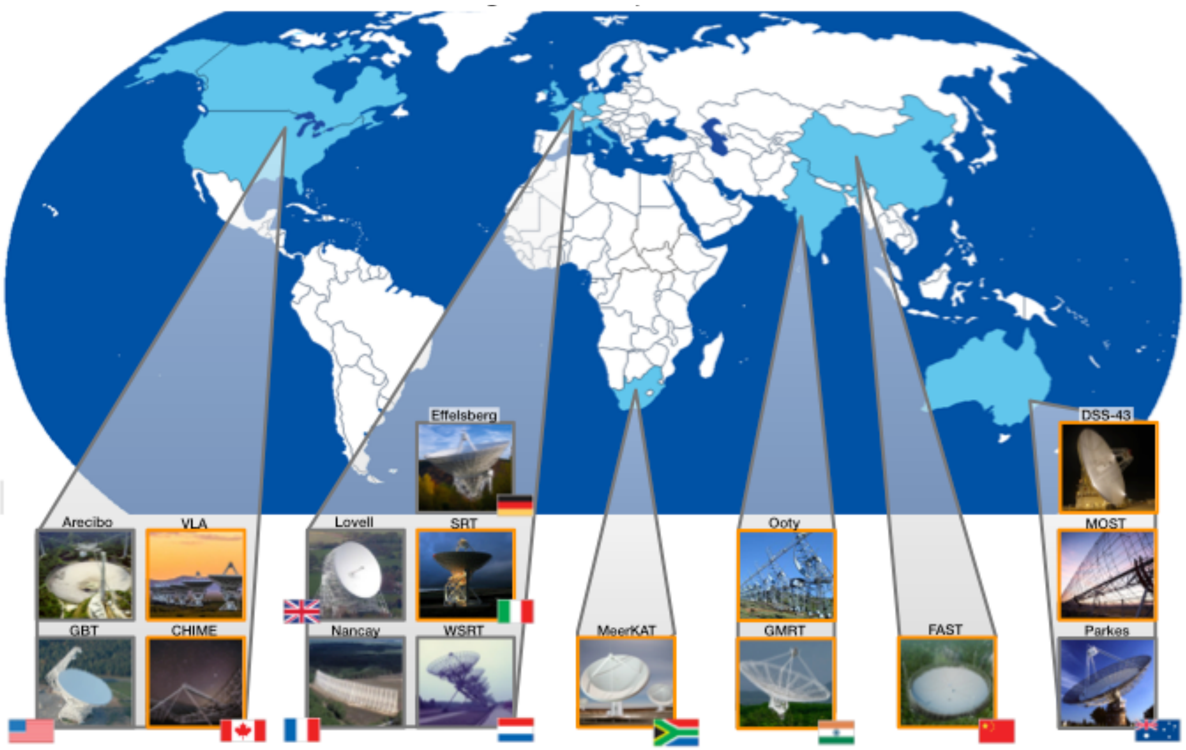


Hallinan, Ravi, et al., 2019, DSA-2000 Decadal Whitepaper, arXiv:1907.07648

The Expanded IPTA

Will soon be using 16 telescopes in 11 countries, bringing China, India, and South Africa into the collaboration.

This will be the most sensitive dataset in the world for low-frequency GW detection.



Credit: Shami Chatterjee

Summary

- We are currently timing 40 MSPs with Green Bank and the VLA and hope to increase our GBT observation to compensate for loss of Arecibo.
- Our 12.5-yr dataset shows strong evidence for a common noise process consistent with gravitational waves. Spatial correlations should be detectable in our 15-yr dataset.
- Measurement of the amplitude and spectrum will provide unique insights into galaxy formation and evolution.
- Sensitivity has increased dramatically due to additional pulsars and improved instrumentation. Will continue to increase with even more pulsars, wider bandwidths, and **continued telescope access.**
- Looking to the future, new telescopes – most likely a large N, small D array – will be needed to characterize the low-frequency GW universe.