Pulsar Timing Arrays: Current Status and Future Prospects

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NANOGrav
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International Pulsar Timing Array
IPTA

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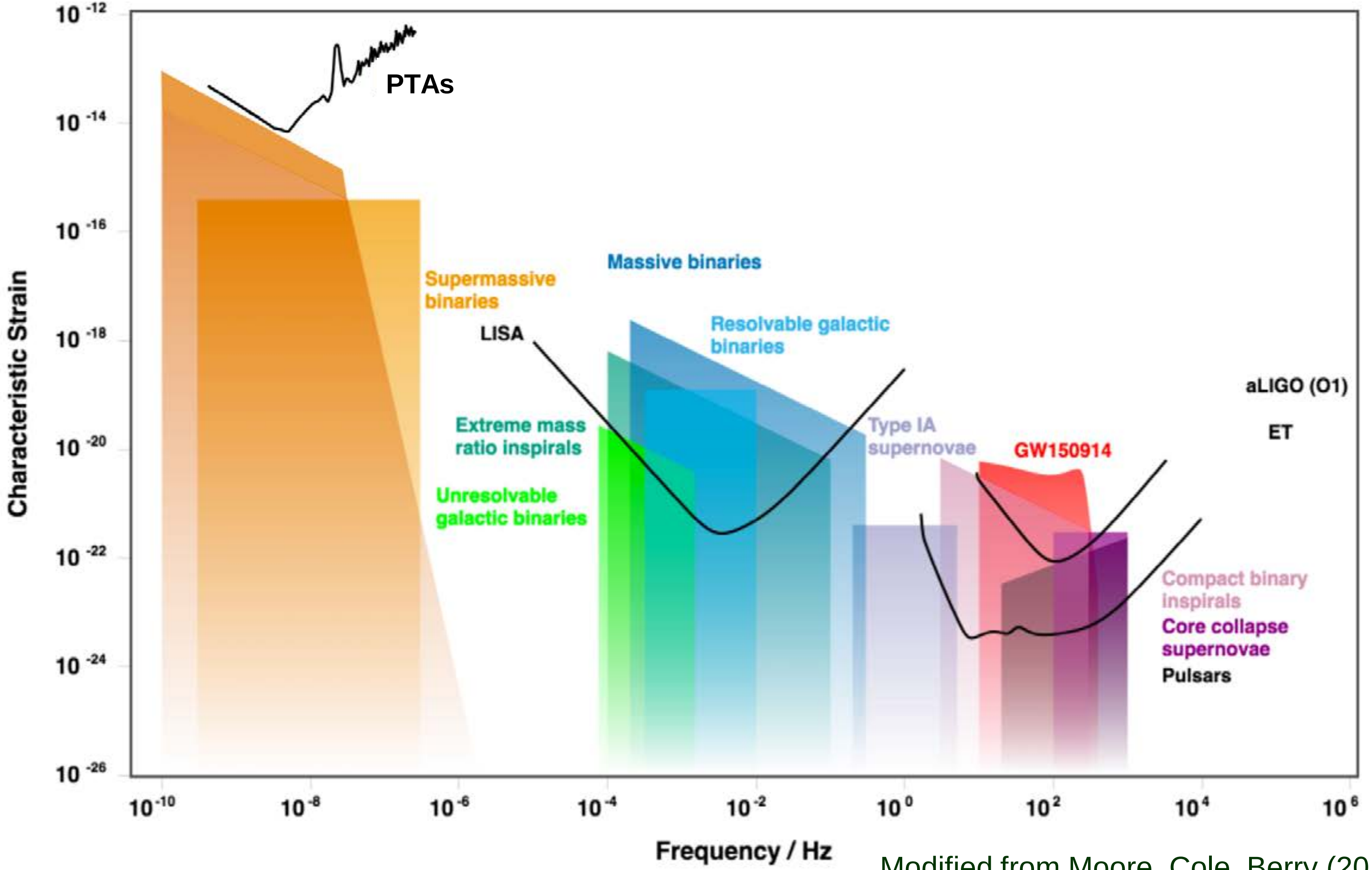
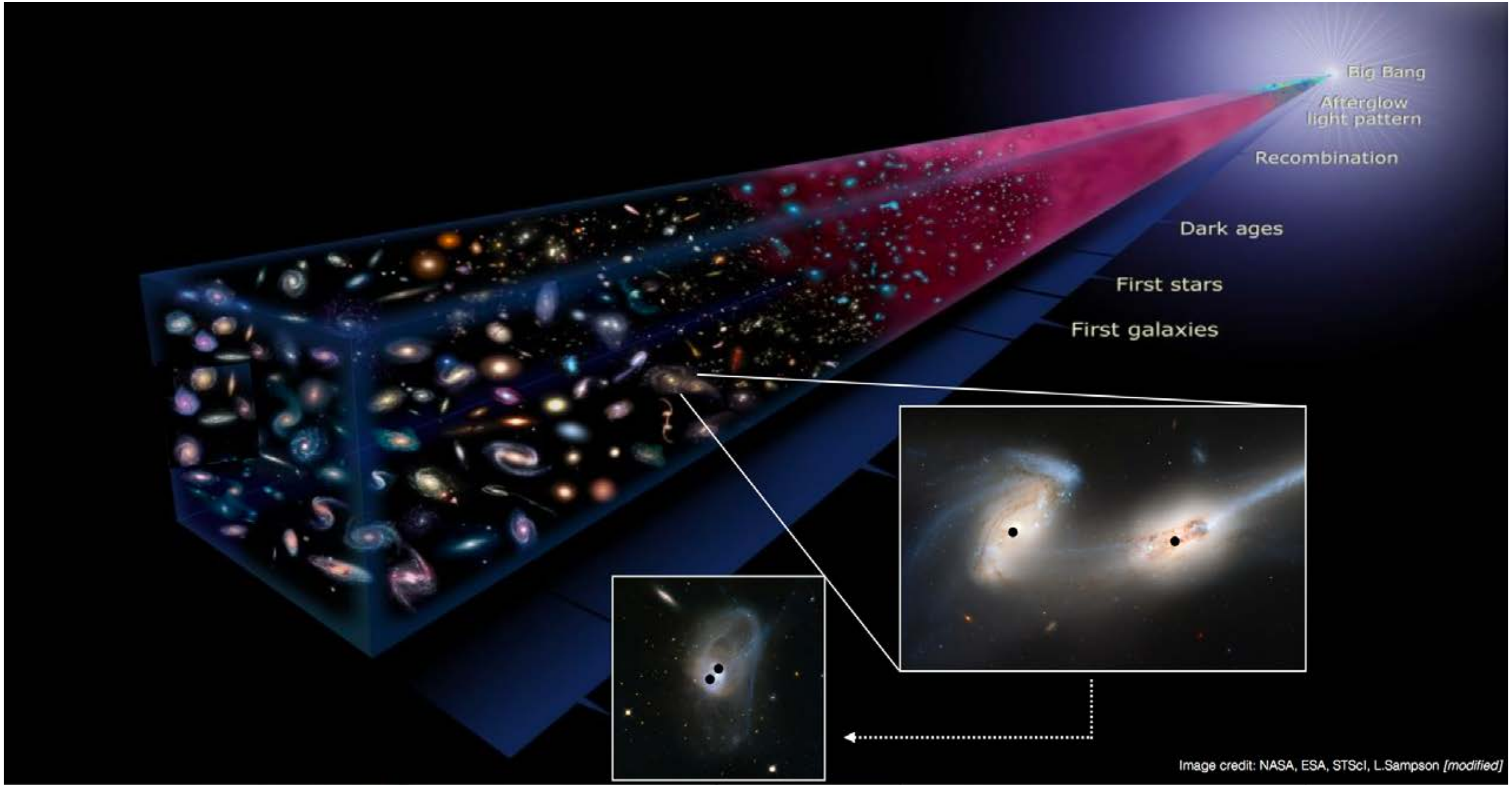


Modified from Moore, Cole, Berry (2014)

Galaxy Evolution 101



Pulsar Timing Arrays (PTAs)

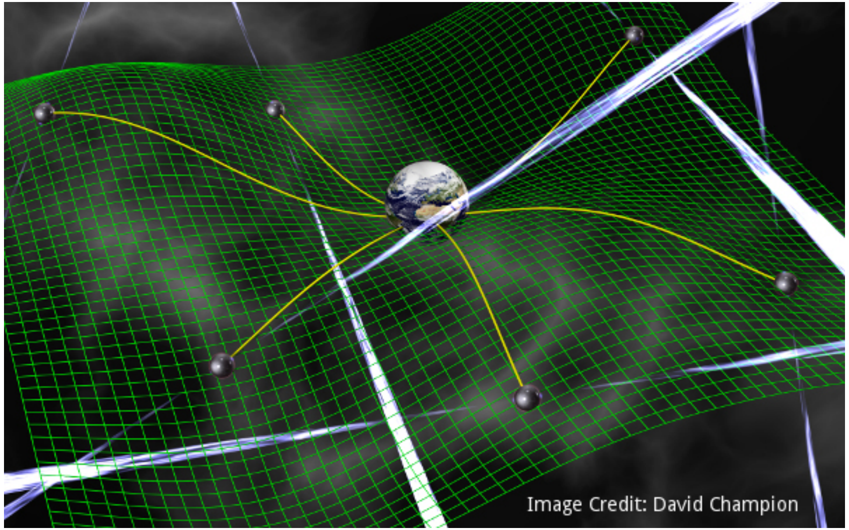
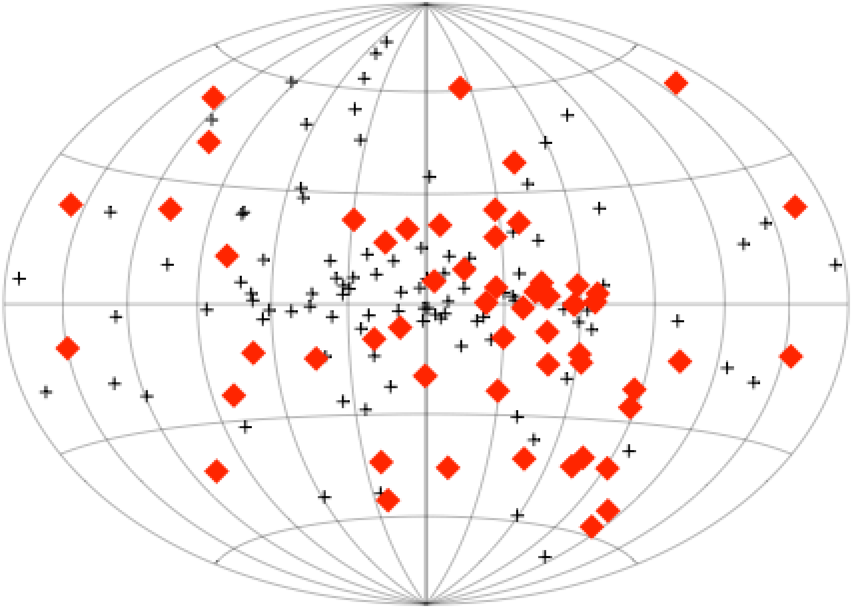


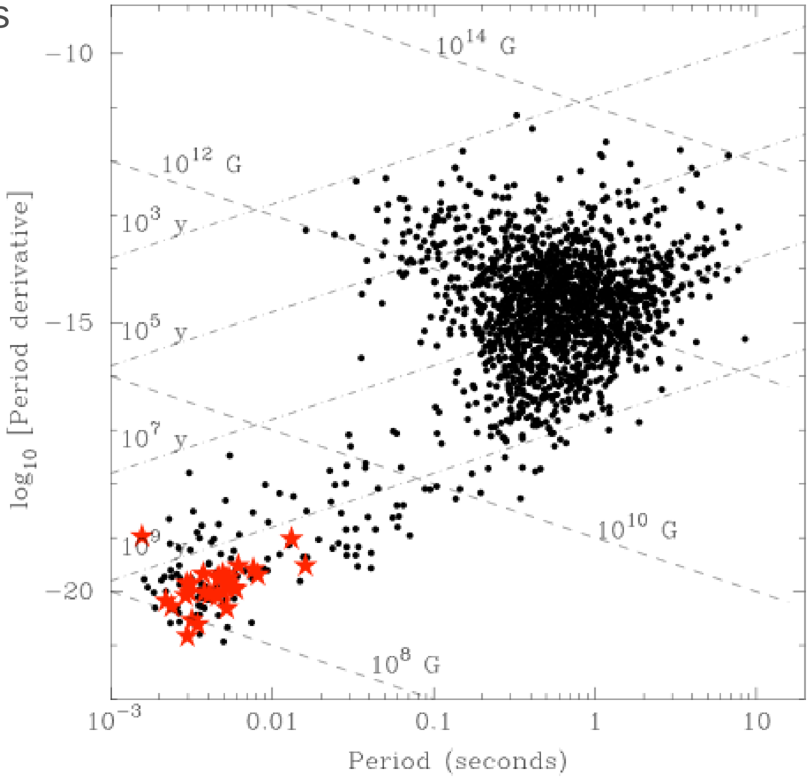
Image Credit: David Champion

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)

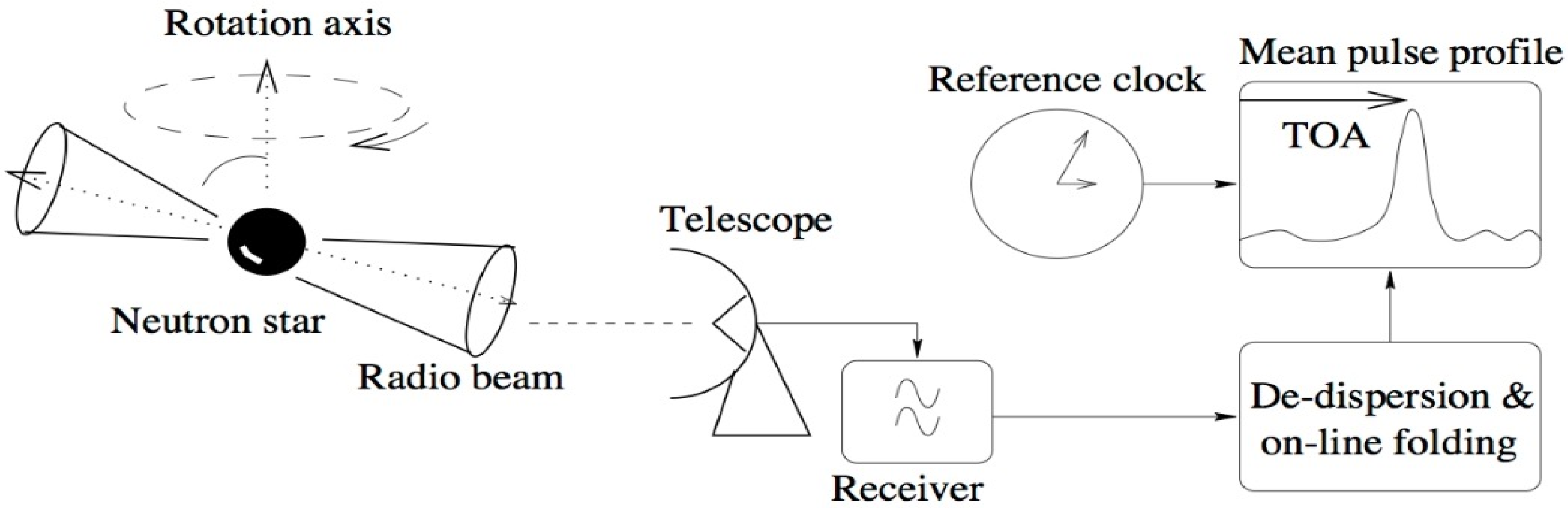
Out of over 2600 known pulsars, there are now 272 MSPs (P < 20 ms) in our Galaxy, out of roughly 30,000-80,0000 detectable. *Roughly 100 timed for PTA purposes.*





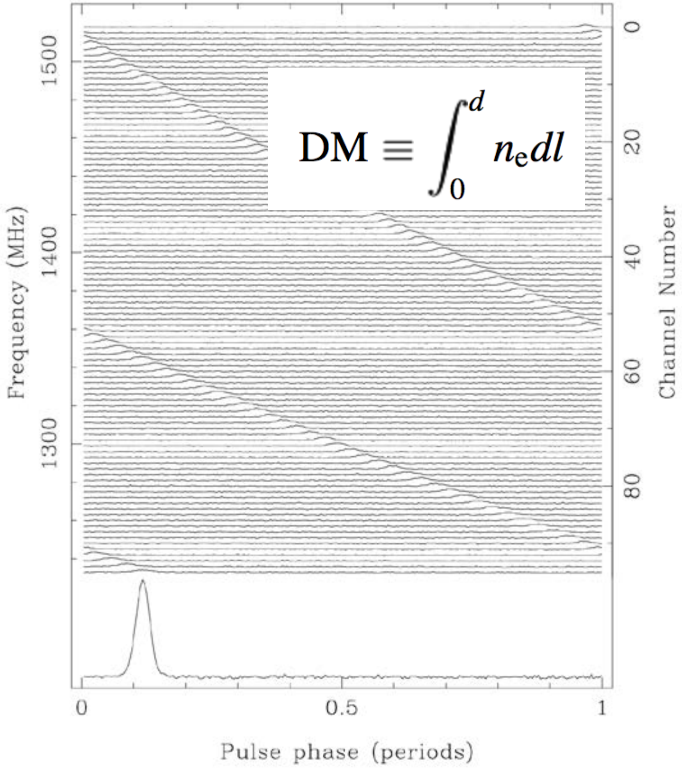
Red = part of worldwide PTA timing programs

Pulsar Timing



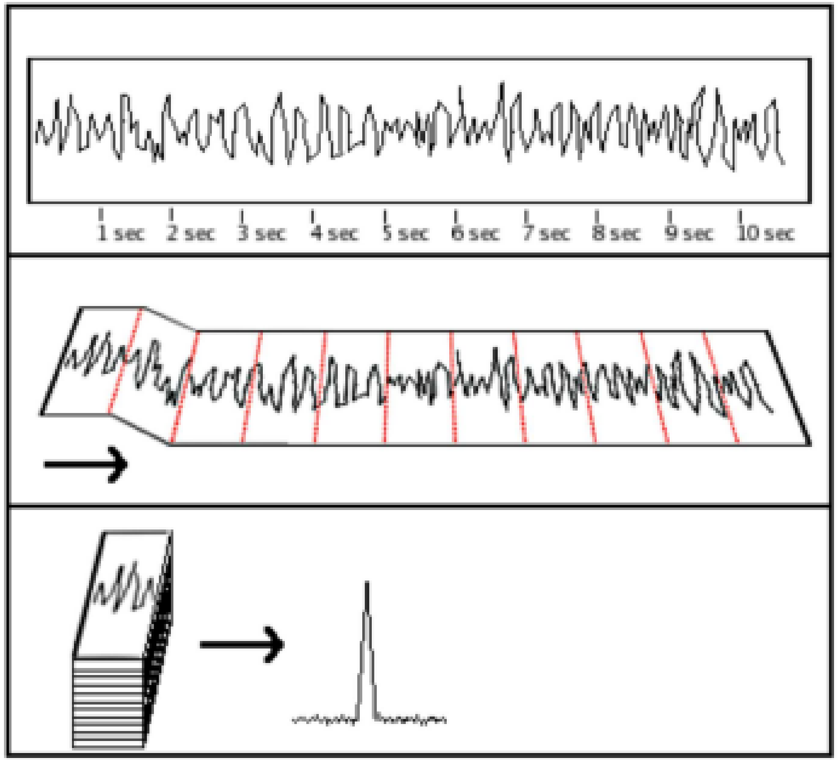
Credit: “Handbook of Pulsar Astronomy”, Lorimer & Kramer (2005)

Pulsar Timing



$$\mathrm{DM} \equiv \int_0^d n_e \, dl$$

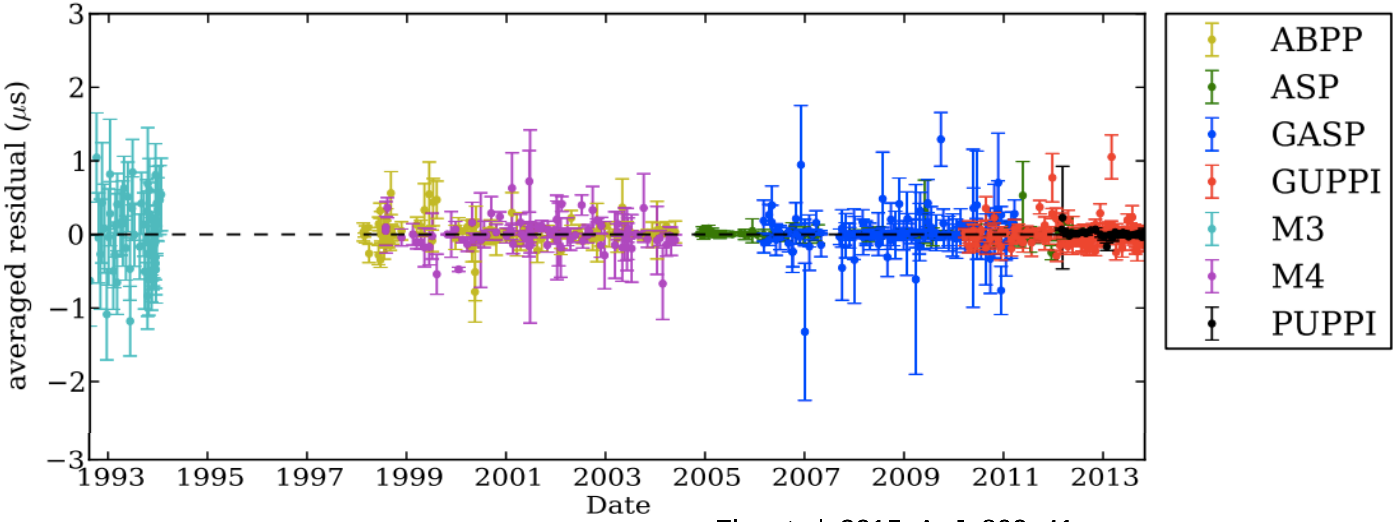
De-dispersion: corrects for *variable* frequency dependent delays



Folding: Roughly a million *variable* pulses added per TOA

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.

Timing Model

Timing Model Parameters[a] from *TEMPO*

Parameter	EFAC and EQUAD	With Jitter Model	Jitter and Red Noise Model
Measured Parameters			
R.A., α (J2000)	17:13:49.5320251(5)	17:13:49.5320248(7)	17:13:49.5320252(8)
decl., δ (J2000)	7:47:37.506131(12)	7:47:37.506155(19)	7:47:37.50614(2)
Spin frequecy ν (s^{-1})	218.81184385472585(6)	218.81184385472594(10)	218.8118438547251(9)
Spin down rate $\dot{\nu}$ (s^{-2})	$-4.083889(4) \times 10^{-16}$	$-4.083894(7) \times 10^{-16}$	$-4.08382(5) \times 10^{-16}$
Proper motion in α, $\mu_\alpha = \dot{\alpha} \cos \delta$ (mas yr^{-1})	4.9177(11)	4.9179(18)	4.917(2)
Proper motion in δ, $\mu_\delta = \dot{\delta}$ (mas yr^{-1})	−3.917(2)	−3.915(3)	−3.913(4)
Parallax, ϖ (mas)	0.858(15)	0.84(3)	0.85(3)
Dispersion measure[b] (pc cm^{-3})	15.9700	15.9700	15.9700
Orbital period, P_b (day)	67.82513682426(16)	67.82513826935(19)	67.82513826930(19)
Change rate of P_b, $\dot{P}_b$ (10^{-12} s s^{-1})	0.23(12)	0.41(16)	0.44(17)
Eccentricity, e	0.0000749394(3)	0.0000749399(6)	0.0000749402(6)
Time of periastron passage, T_0 (MJD)	53761.03227(11)	53761.0328(3)	53761.0327(3)
Angle of periastron[c], ω (deg)	176.1941(6)	176.1967(15)	176.1963(16)
Projected semimajor axis, x (lt-s)	32.34242243(5)	32.34242188(14)	32.34242188(14)
sin i, where i is the orbital inclination angle	0.9672(11)	0.951(4)	0.951(4)
Companion mass, M_c ($M_\odot$)	0.233(4)	0.287(13)	0.286(13)
Apparent change rate of x, $\dot{x}$ (lt-s s^{-1})	0.00637(7)	0.00640(10)	0.00645(11)
Profile frequency dependency parameter, FD1	−0.00016317(19)	−0.0001623(2)	−0.00016(3)
Profile frequency dependency parameter, FD2	0.0001357(3)	0.0001350(3)	0.00014(3)
Profile frequency dependency parameter, FD3	−0.0000664(6)	−0.0000668(6)	−0.000067(17)
Profile frequency dependency parameter, FD4	0.0000147(4)	0.0000153(4)	0.000015(5)
Fixed Parameters			
Solar system ephemeris	DE421	DE421	DE421
Reference epoch for α, δ, and ν (MJD)	53729	53729	53729
Solar wind electron density n_0 (cm^{-3})	0	0	0
Rate of periastron advance, $\dot{\omega}$ (deg yr^{-1})[d]	0.00020	0.00024	0.00024
Position angle of ascending node, Ω (deg)[e]	88.43	88.43	88.43
Red noise amplitude (μs $year^{1/2}$)	...	...	0.025[f]
Red noise spectral index, γ_{red}	...	...	−2.92
Derived Parameters			
Intrinsic period derivative, $\dot{P}_{Int}$(s s^{-1})[g]	$8.966(12) \times 10^{-21}$	$8.98(2) \times 10^{-21}$	$8.97(2) \times 10^{-21}$
Dipole magnetic field, B (G)[g]	$2.0485(14) \times 10^{8}$	$2.050(3) \times 10^{8}$	$2.049(3) \times 10^{8}$
Characteristic age, τ_c (year)[g]	$8.076(11) \times 10^{9}$	$8.07(2) \times 10^{9}$	$8.07(2) \times 10^{9}$
Pulsar mass, M_{PSR} ($M_\odot$)	0.97(3)	1.32(11)	1.31(11)

Spin and spin-down

Astrometric

Interstellar medium

Binary

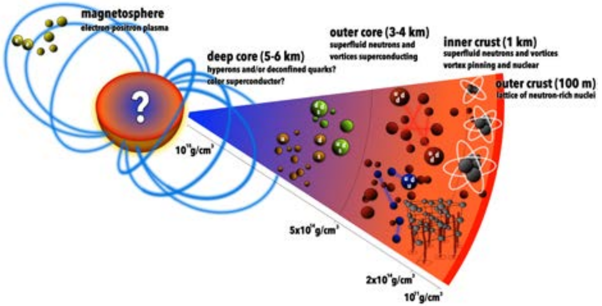
Pulsar profile evolution

Red and white noise

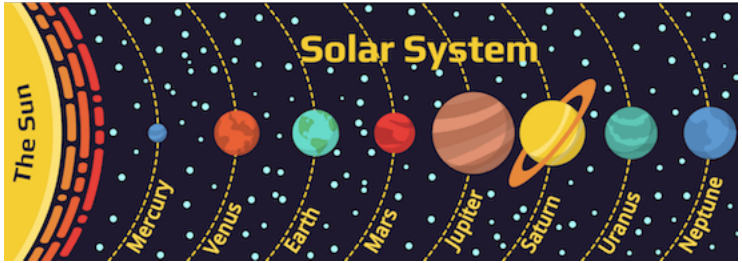
Zhu et al. 2015, ApJ, 809, 41

Sources of Noise in PTA Data

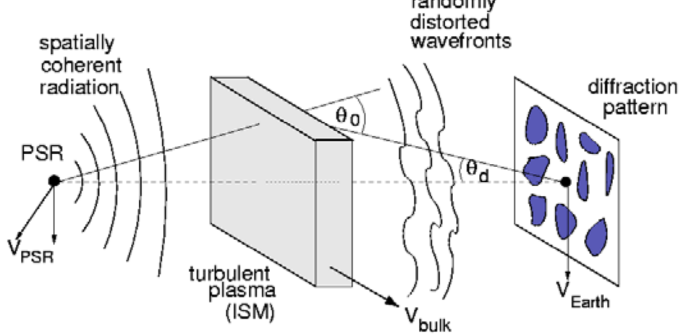
	Noise source	Achromatic?	Correlated in time?	Correlated in space?
Intrinsic	Pulsar rotational irregularities	✓	✓	✗
Intrinsic	Pulse jitter	✓	✗	✗
Extrinsic	Scattering and dispersion measure variations	✗	✓	✗
Extrinsic	Planetary ephemerides	✓	✓	✓
Extrinsic	Clock errors/offsets	✓	✓	✗



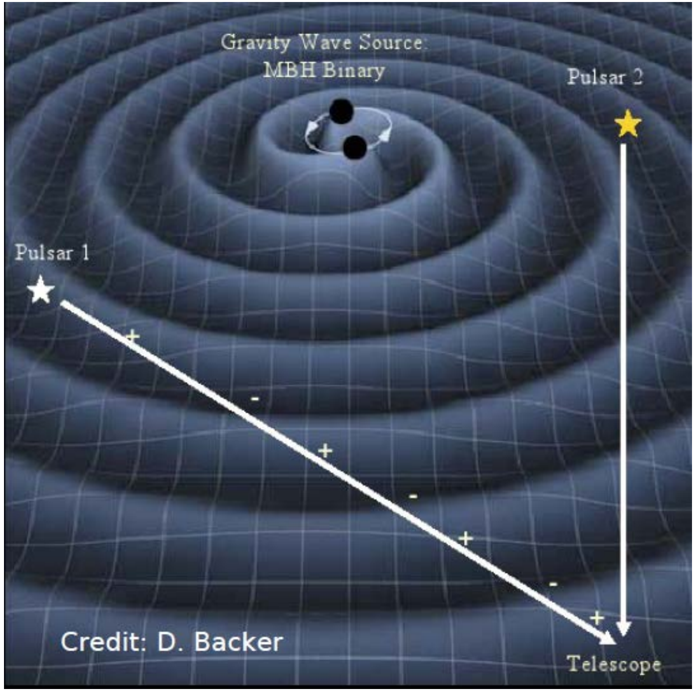
Watts et al. 2015, arXiv: 1501.00042



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



Detection Big Picture

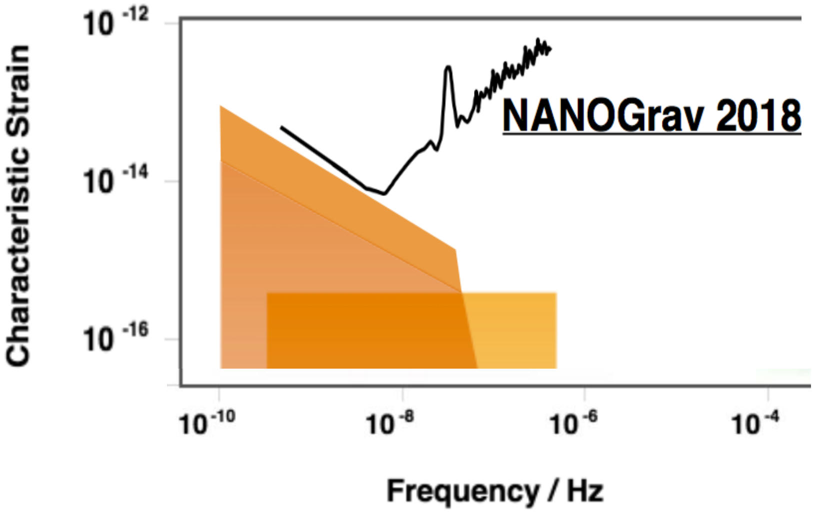


f ~ 1/weeks to 1/years (10^{-6} – 10^{-9} Hz)

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

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

λ_{gw} ~ 1-10 lyr; D_{psr} ~ 1000 lyr



PTA Sources

For a binary system,

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

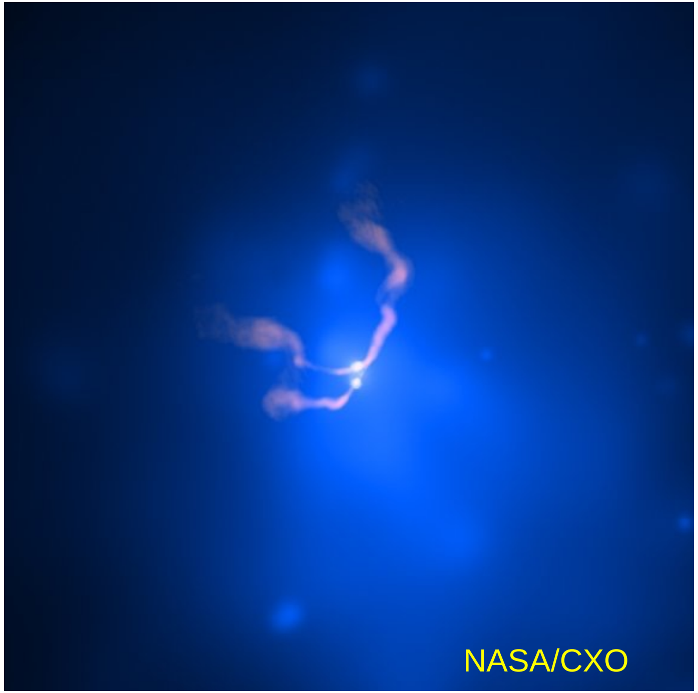
$$\tau = 10^6 M_8^{-5/3} f_{\mathrm{yr}^{-1}}^{-8/3} \frac{(1+q)^2}{q} \mathrm{yr}$$

For a stochastic background,

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

$$\alpha = -2/3$$

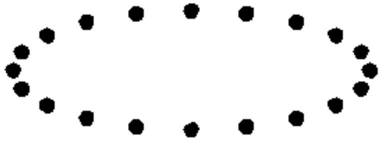
(under the simplest assumptions)

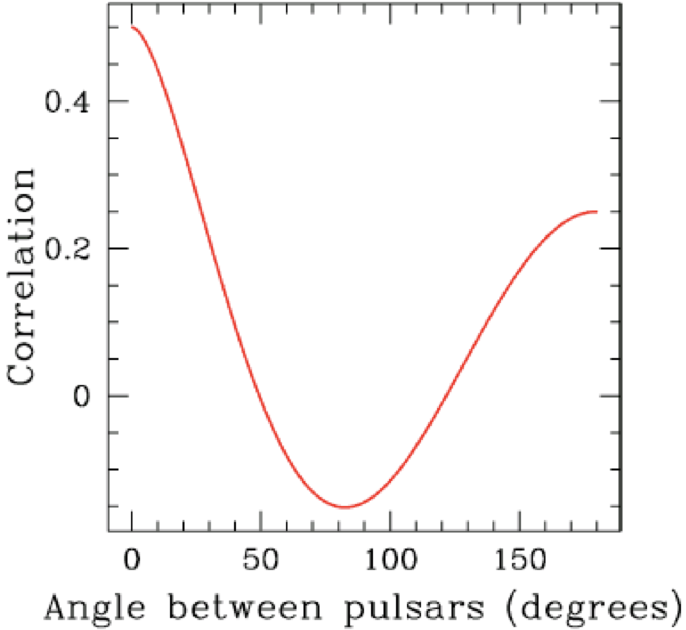


Will look like correlated RED noise in our data.

Hellings-Downs Curve

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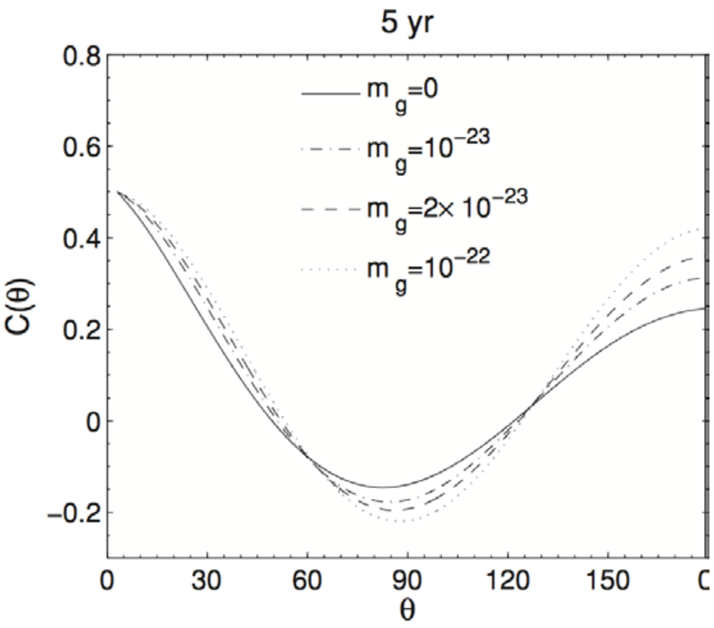
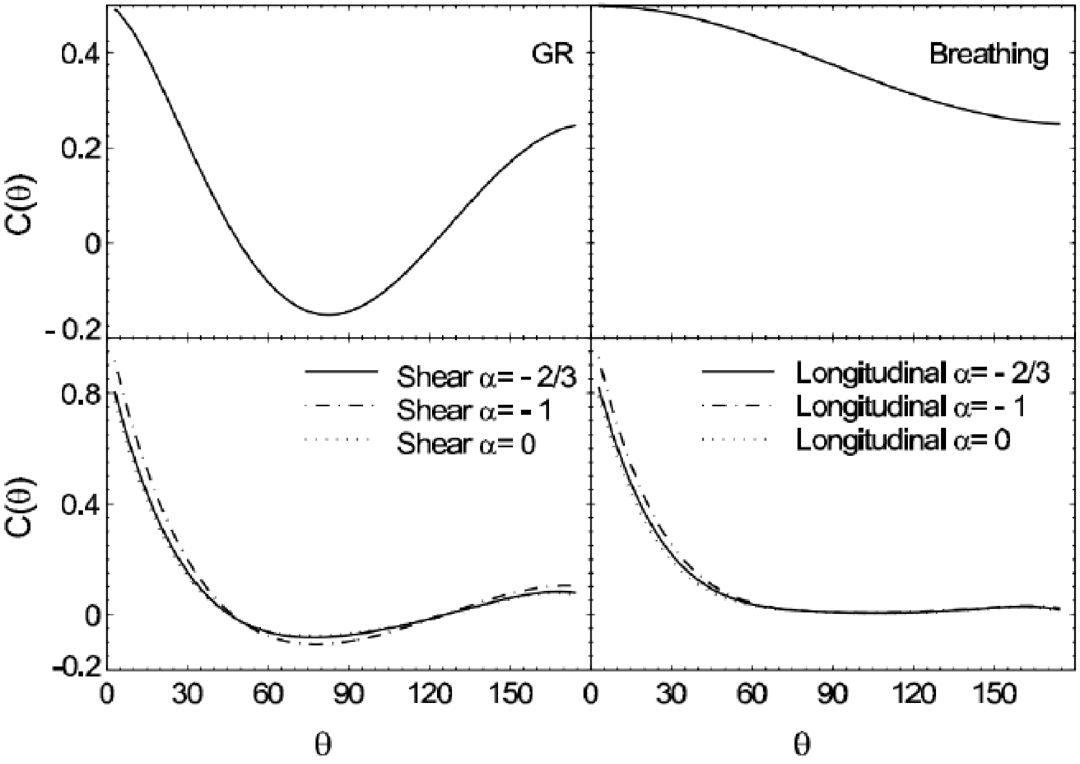
	Noise source	Achromatic?	Correlated in time?	Correlated in space?	Quadrupolar?
Intrinsic	Pulsar rotational irregularities	✓	✓	✗	✗
Intrinsic	Pulse jitter	✓	✗	✗	✗
Extrinsic	Scattering and dispersion measure variations	✗	✓	✗	✗
Extrinsic	Planetary ephemerides	✓	✓	✓	✗
Extrinsic	Clock errors/offsets	✓	✓	✗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

Yes!

We can also test GR

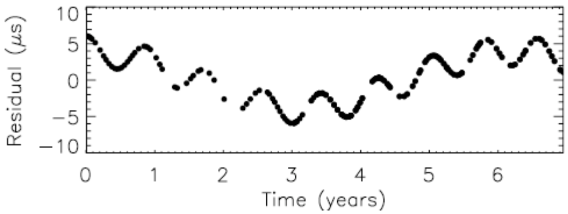


Lee et al. 2010, ApJ, 722, 1589



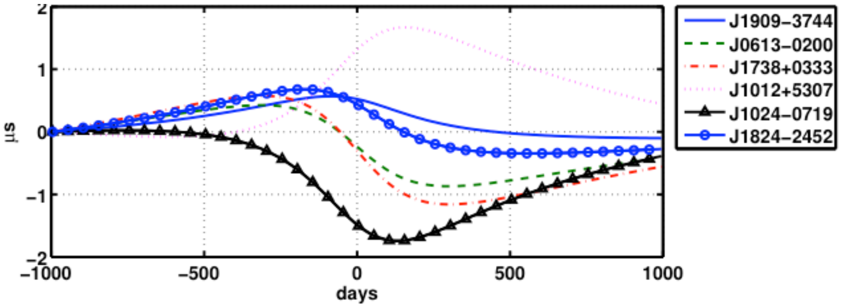
Lee et al. 2008, ApJ, 685, 1304

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.

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

NANOGrav's Program

100-m Green Bank Telescope in Green Bank, WV

We use roughly 15% of the time on each telescope to observe over 70 pulsars at two radio frequencies every one to four weeks for roughly 20-30 minutes.

(Lots more time for pulsar searches!)

300-m Arecibo Observatory in Arecibo, PR

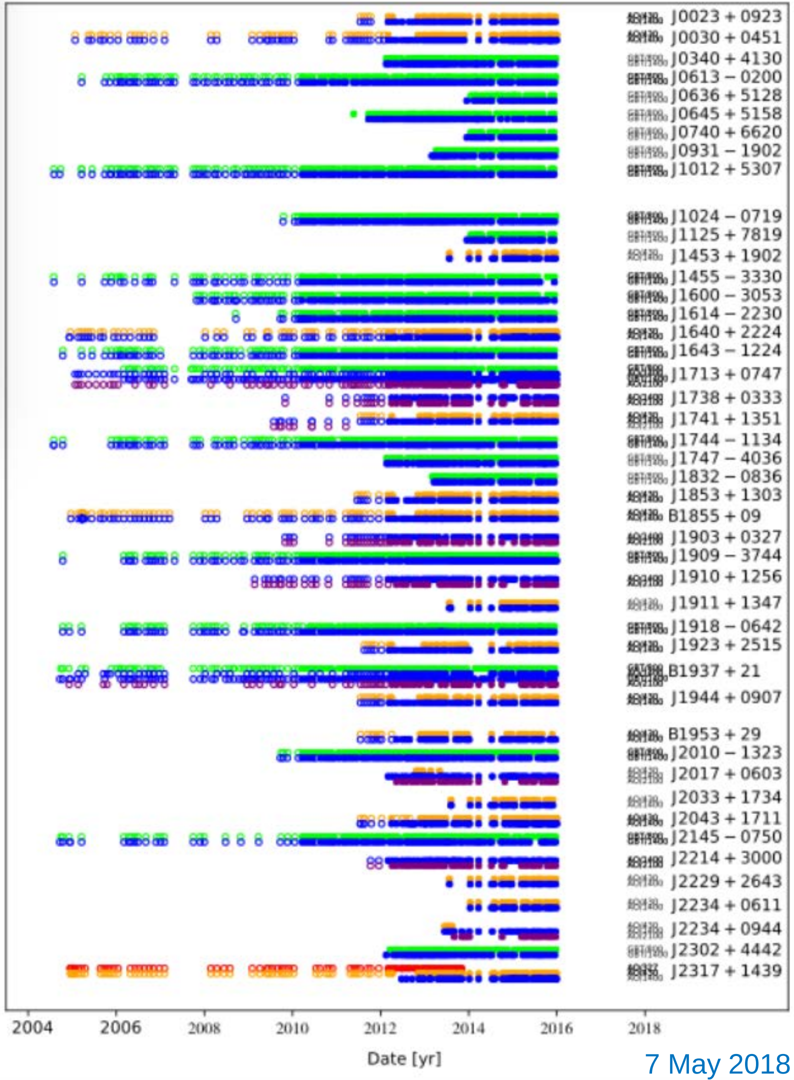
NANOGrav Eleven-Year Data Release

Includes 45 pulsars

Data are public at http://data.nanograv.org

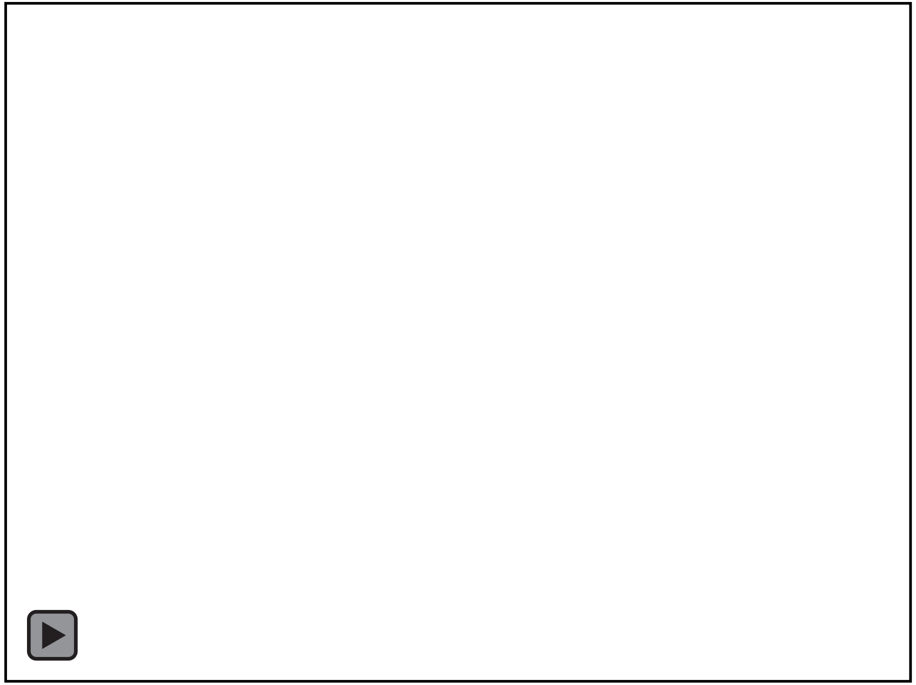
arXiv:1801.01837

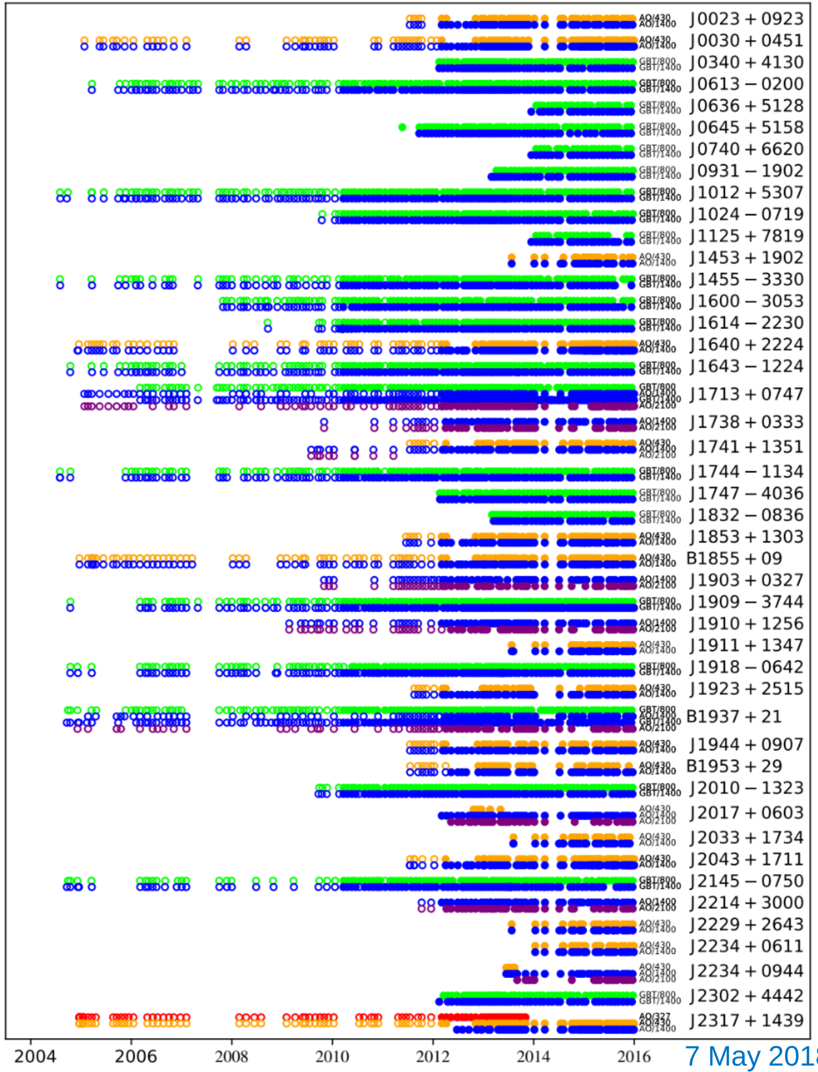
The NANOGrav Collaboration, ApJS, 235, 37



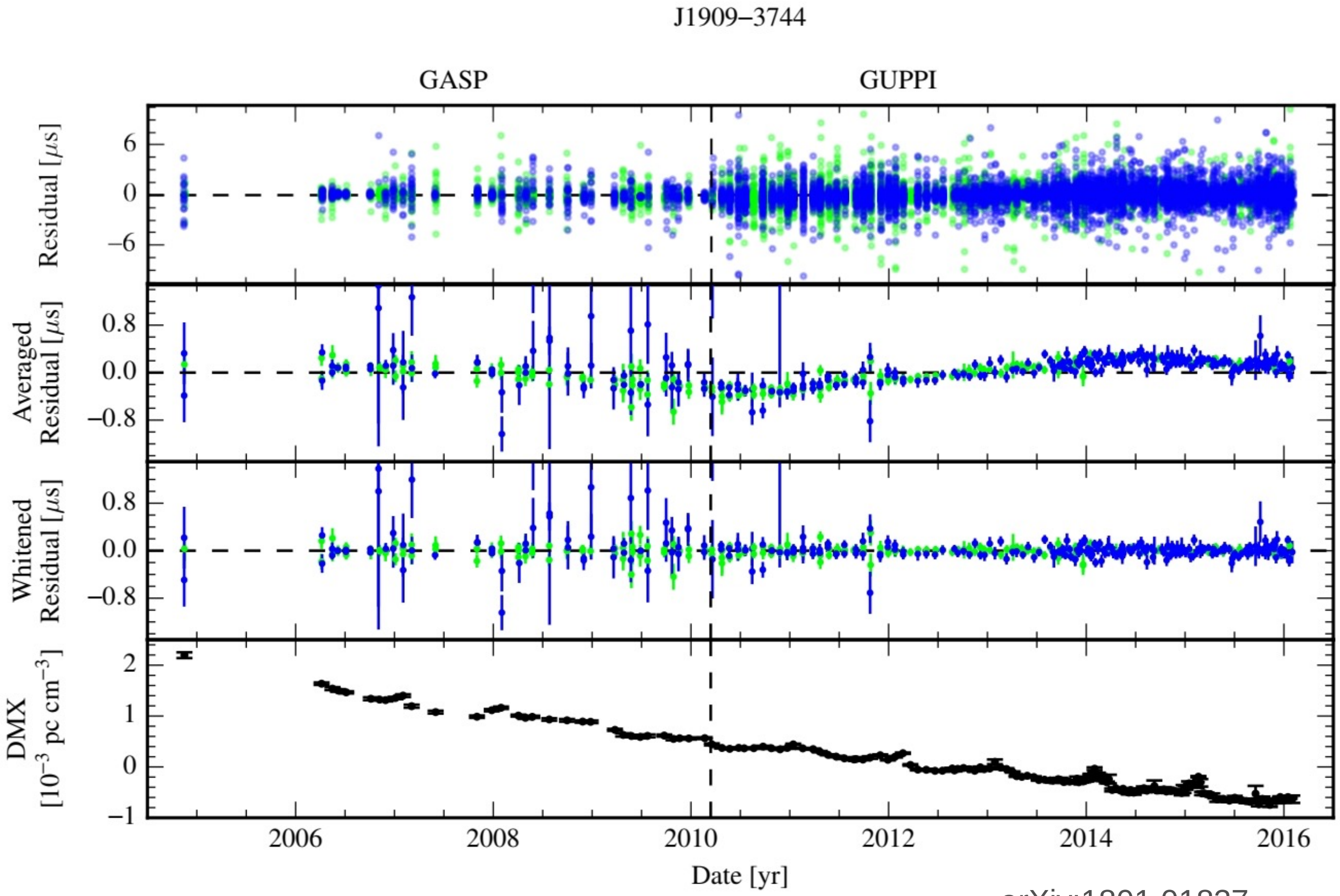
NANOGrav Twelve-Year Data Release

Will include 47 pulsars.
We are currently timing 71!



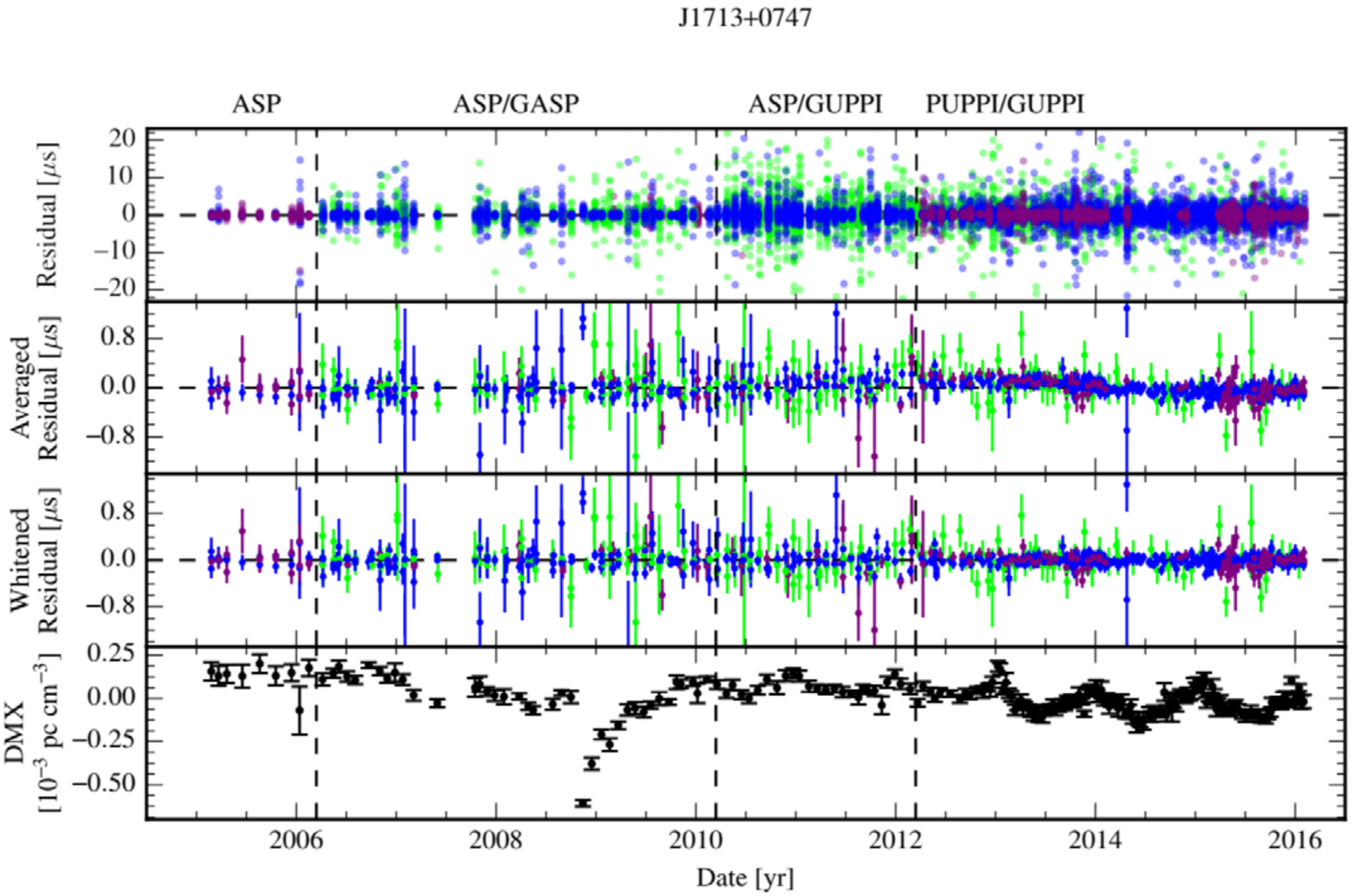


Some Eleven-Year Residuals



arXiv:1801.01837

More Eleven-Year Residuals



arXiv:1801.01837

Sensitivity Improvements

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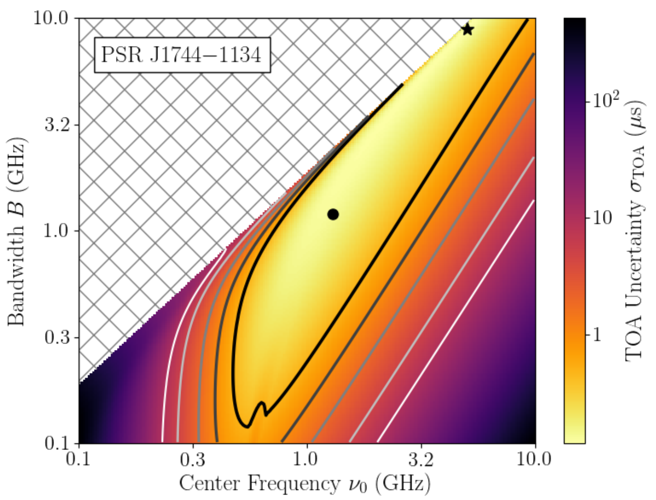
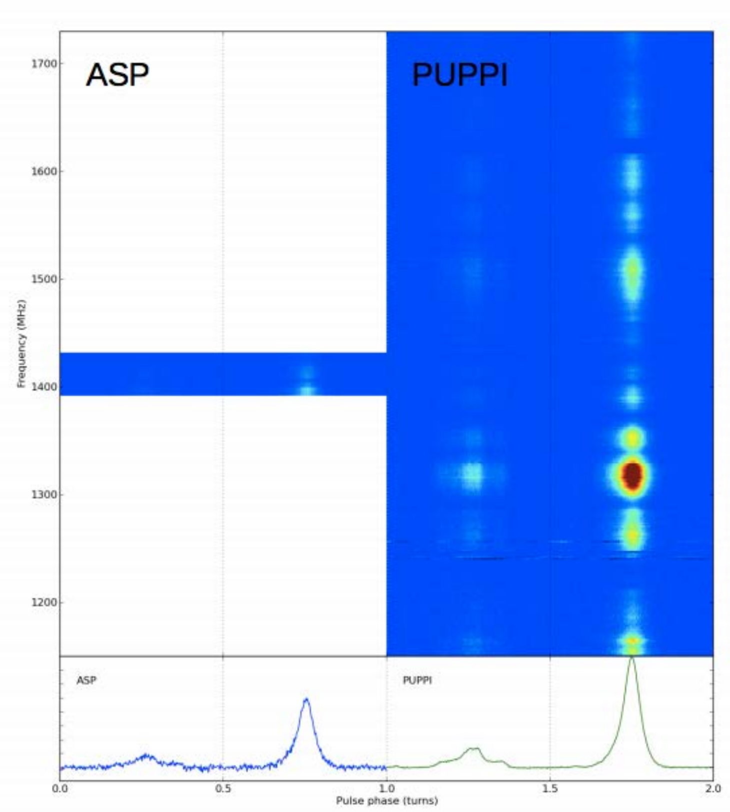
Huge increase in timing precision since our five-year data release due to new backends!

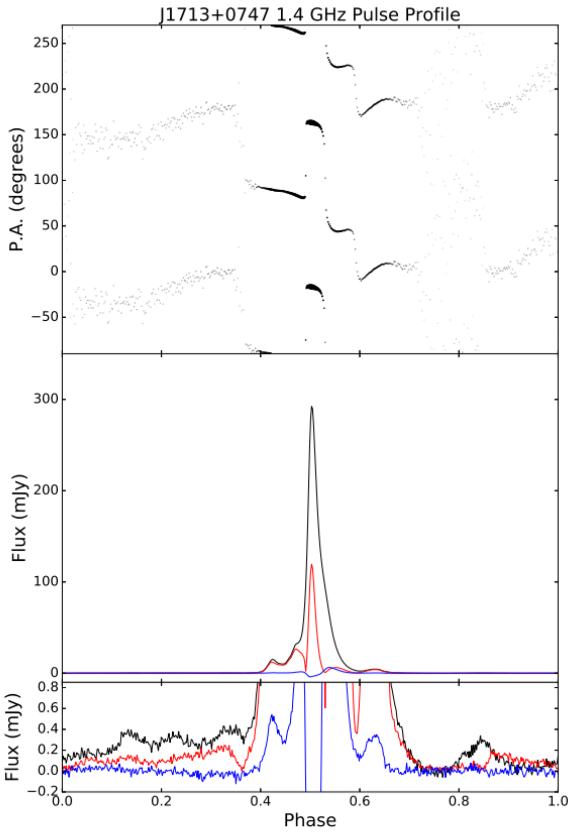


Optimal frequencies analysis (Lam et al. submitted) shows we can do even better with wider bandwidths at higher frequencies.

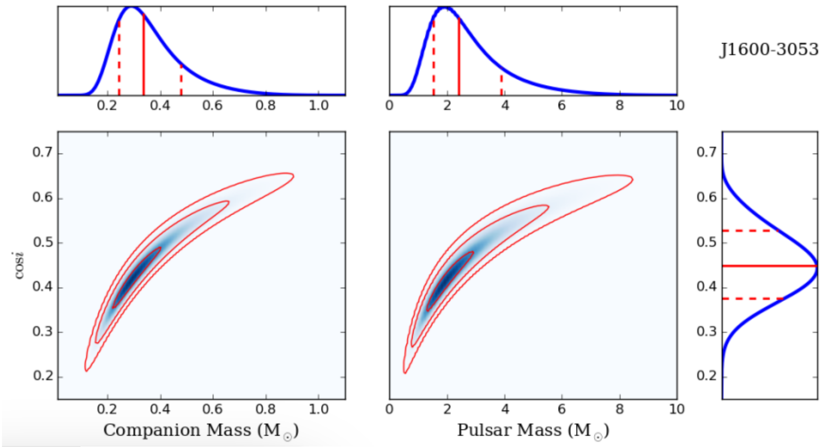


Credit: Paul Demorest

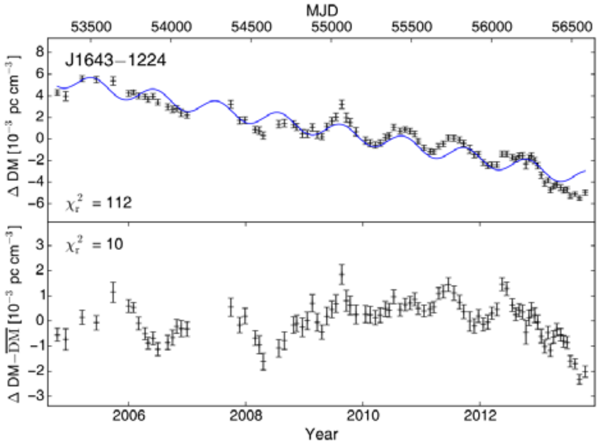
(Lots of Non-Gravitational Wave Science)



Gentile et al., submitted



Fonseca et al., ApJ, 2016, 832, 167



Jones et al., ApJ, 2017, 841, 2

Eleven-year Stochastic Background Analysis

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Accepted by ApJ
arXiv:1801.02617

https://nanograv.github.io/11yr_stochastic_analysis/

Full Bayesian analysis.

Accounts for correlated and uncorrelated noise, including ephemeris errors.

For the first time, can set limits with likelihoods including spatial correlations.

Table 2
Prior distributions used in all analyses performed in this paper.

parameter	description	prior	comments
		White Noise	
E_k	EFAC per backend/receiver system	Uniform $[0, 10]$	single-pulsar analysis only
Q_k [s]	EQUAD per backend/receiver system	log-Uniform $[-8.5, -5]$	single-pulsar analysis only
J_k [s]	ECORR per backend/receiver system	log-Uniform $[-8.5, -5]$	single-pulsar analysis only
		Red Noise	
$A_{\rm red}$	red-noise power-law amplitude	Uniform $[10^{-20}, 10^{-11}]$ (upper limits)	
		log-Uniform $[-20, -11]$ (model comparison)	one parameter per pulsar
$\gamma_{\rm red}$	red-noise power-law spectral index	Uniform $[0, 7]$	one parameter per pulsar
		BayesEphem	
$z_{\rm drift}$ [rad/yr]	drift-rate of Earth's orbit about ecliptic z-axis	Uniform $[-10^{-9}, 10^{-9}]$	one parameter for PTA
$\Delta M_{\rm jupiter}$ $[M_\odot]$	perturbation to Jupiter's mass	$\mathcal{N}(0, 1.55 \times 10^{-11})$	one parameter for PTA
$\Delta M_{\rm saturn}$ $[M_\odot]$	perturbation to Saturn's mass	$\mathcal{N}(0, 8.17 \times 10^{-12})$	one parameter for PTA
$\Delta M_{\rm uranus}$ $[M_\odot]$	perturbation to Uranus' mass	$\mathcal{N}(0, 5.72 \times 10^{-11})$	one parameter for PTA
$\Delta M_{\rm neptune}$ $[M_\odot]$	perturbation to Neptune's mass	$\mathcal{N}(0, 7.96 \times 10^{-11})$	one parameter for PTA
PCA_i	ith PCA component of Jupiter's orbit	Uniform $[-0.05, 0.05]$	six parameters for PTA
		Monopole-correlated clock-error signal, power-law spectrum	
$A_{\rm mono}$	Equivalent strain amplitude	Uniform $[10^{-18}, 10^{-11}]$ (upper limits)	
		log-Uniform $[-18, -14]$ (model comp., $\gamma = 13/3$)	one parameter for PTA
		log-Uniform $[-18, -11]$ (model comp., γ varied)	one parameter for PTA
$\gamma_{\rm mono}$	GWB power-law spectral index	delta function	fixed, depends on analysis
		Dipole-correlated SSE-error signal, power-law spectrum	
$A_{\rm dip}$	Equivalent strain amplitude	Uniform $[10^{-18}, 10^{-11}]$ (upper limits)	
		log-Uniform $[-18, -14]$ (model comp., $\gamma = 13/3$)	one parameter for PTA
		log-Uniform $[-18, -11]$ (model comp., γ varied)	one parameter for PTA
$\gamma_{\rm dip}$	GWB power-law spectral index	delta function	fixed, depends on analysis
		GWB, power-law spectrum	
$A_{\rm GWB}$	GWB strain amplitude	Uniform $[10^{-18}, 10^{-11}]$ (upper limits)	
		log-Uniform $[-18, -14]$ (model comp., $\gamma_{\rm GWB} = 13/3$)	one parameter for PTA
		log-Uniform $[-18, -11]$ (model comp., $\gamma_{\rm GWB}$ varied)	one parameter for PTA
$\gamma_{\rm GWB}$	GWB power-law spectral index	delta function	fixed, depends on analysis
		GWB, free spectrum	
ρ_i $[\text{s}^2]$	GWB power-spectrum coefficients at $f = i/T$	uniform in $\rho_i^{1/2}$ $[10^{-18}, 10^{-8}]$[a]	one parameter per frequency
		GWB, broken–power-law spectrum	
$A_{\rm GWB}$	GWB broken power-law amplitude	log-Normal	one parameter for PTA
		$\mathcal{N}(-14.4, 0.26)$	MOP14
		$\mathcal{N}(-15, 0.22)$	S13
		$\mathcal{N}(-14.95, 0.12)$	Simon & Burke-Spolaor (2016)[b]
		$\mathcal{N}(-14.82, 0.08)$	Simon & Burke-Spolaor (2016)[c]
$\gamma_{\rm GWB}$	GWB power-law spectral index	delta function	fixed to 13/3
κ	GWB broken power-law low-freq. spectral index	Uniform $[0,7]$	one parameter for PTA
$f_{\rm bend}$ [Hz]	GWB broken power-law bend frequency	log-Uniform $[-9,-7]$	one parameter for PTA
		GWB, Gaussian-process–interpolated spectrum	
ρ_i $[\text{s}^2]$	GWB power-spectrum coefficients at $f = i/T$	$\mathcal{N}(0, V(\alpha_{\rm BH}, \rho_{\rm stars}, e_0))$	one parameter per frequency
$\alpha_{\rm BH}$	y-intercept of $M_{\rm BH} - M_{\rm bulge}$ relation	Uniform $[7, 9]$	one parameter for PTA
$\rho_{\rm stars}$ $[M_\odot \text{pc}^{-3}]$	mass density of galactic-core stars	log-Uniform $[1, 4]$	one parameter for PTA
e_0	binary eccentricity at formation	Uniform $[0, 0.95]$	one parameter for PTA

Eleven-year Stochastic Background Analysis

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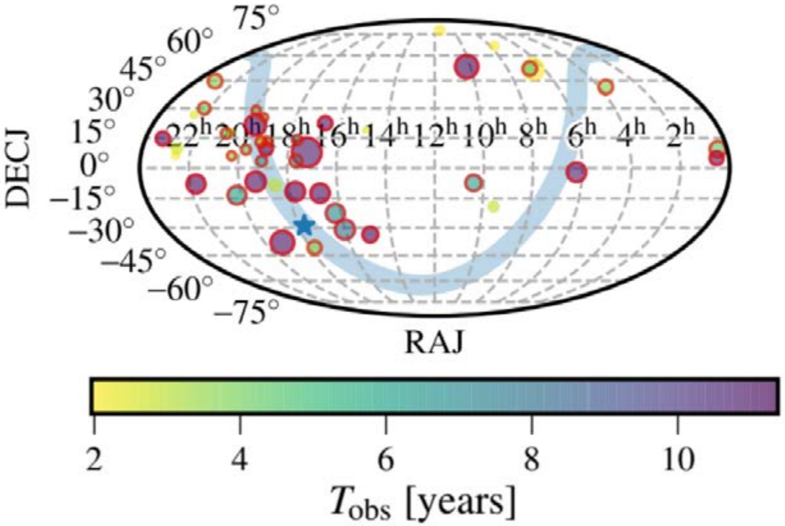
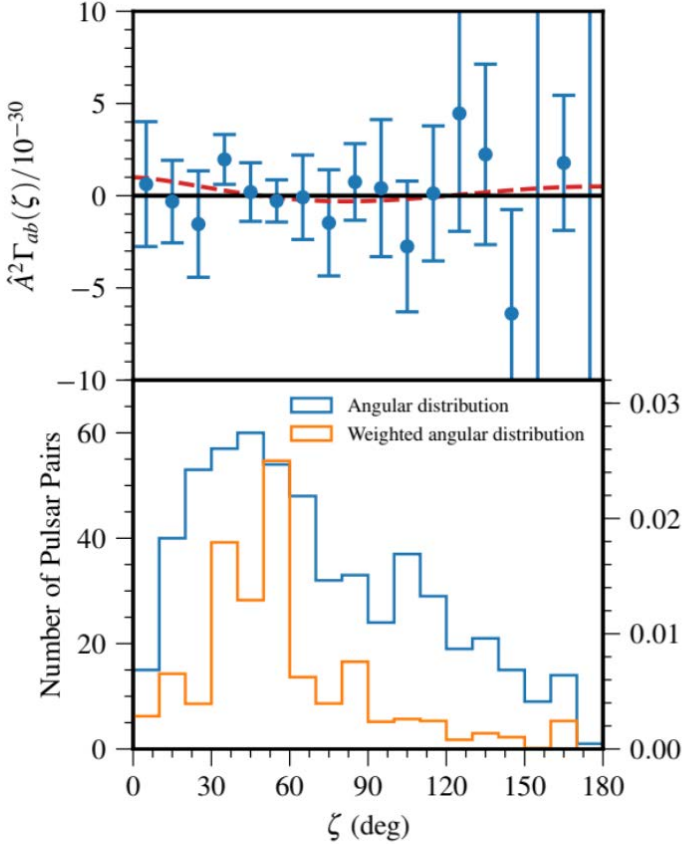
No detection yet!





arXiv: 1801.02617

But, A Puzzle

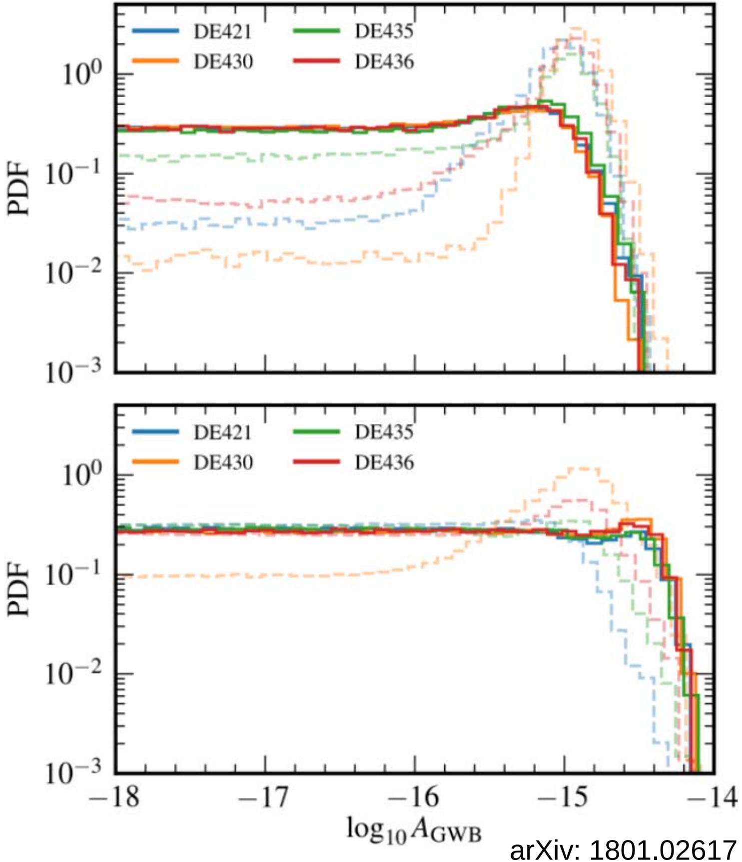
Originally, our limit did not improve over our 9-year limit!

For both,

$h_c < 1.5 \times 10^{-15}$ $(f=1\ yr^{-1})$

??????

Five year limit was 7×10^{-15} $(f=1\ yr^{-1})$



11-yr

9-yr

arXiv: 1801.02617

Ephemerides Matter

Ephemerides are not accurate enough!

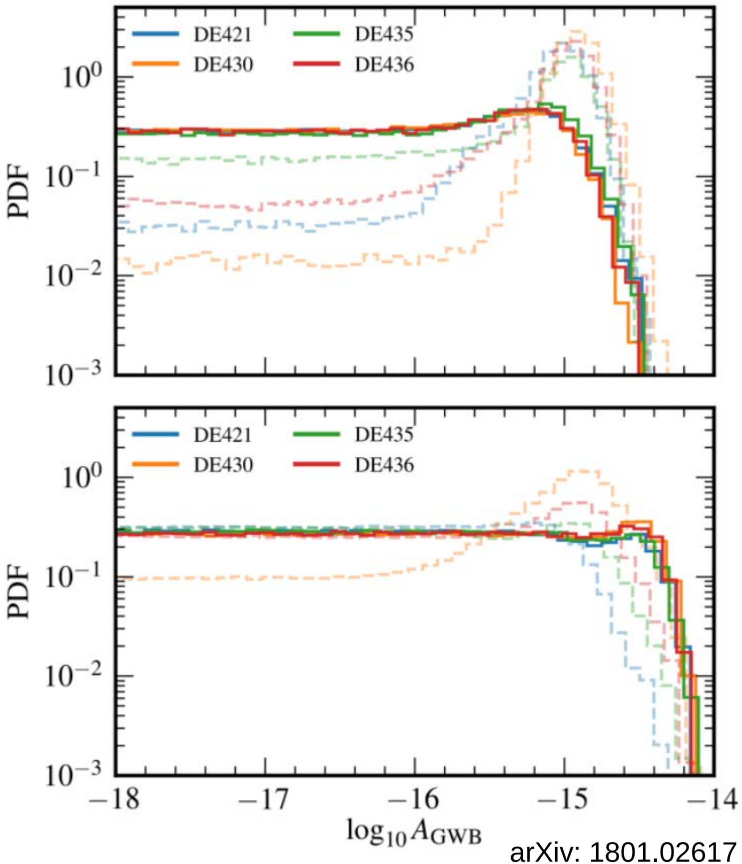
When accounting for this, 11-year limit is:

$h_c <$ 1.45 x 10^{-15} (f=1 yr^{-1})

9-year limit is:

$h_c <$ 2.5 x 10^{-15} (f=1 yr^{-1})

Whew!



11-yr

9-yr

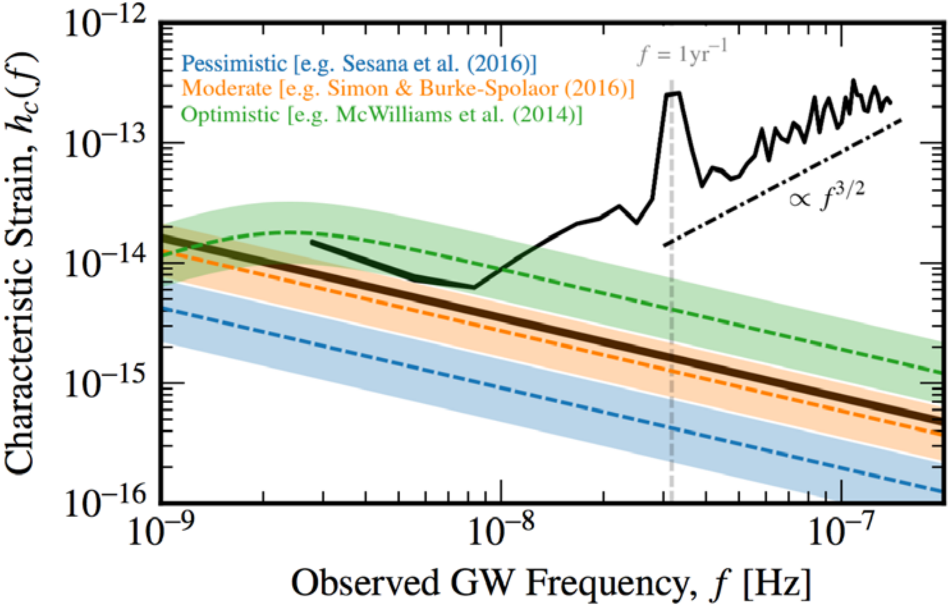
arXiv: 1801.02617

Most recent SB limits are beginning to rule out SMBH formation and evolution models

NANOGrav Physics Frontiers Center

Can constrain astrophysical effects:

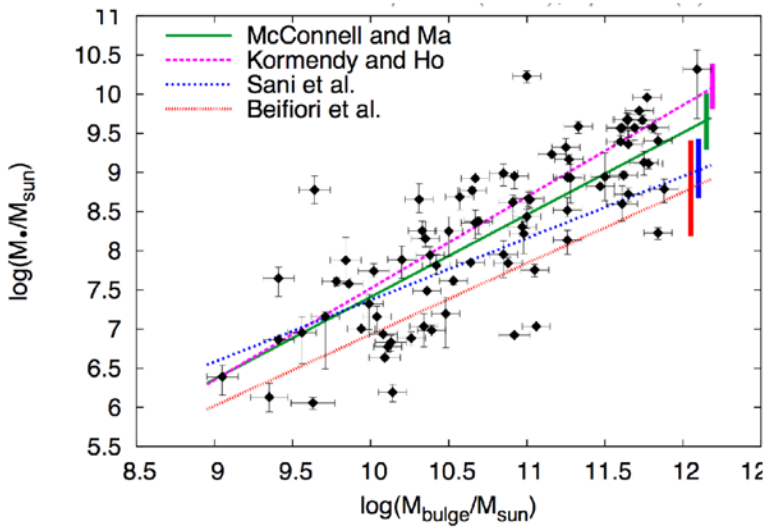
- stellar hardening
- circumbinary disk interaction
- binary eccentricity



arXiv: 1801.02617

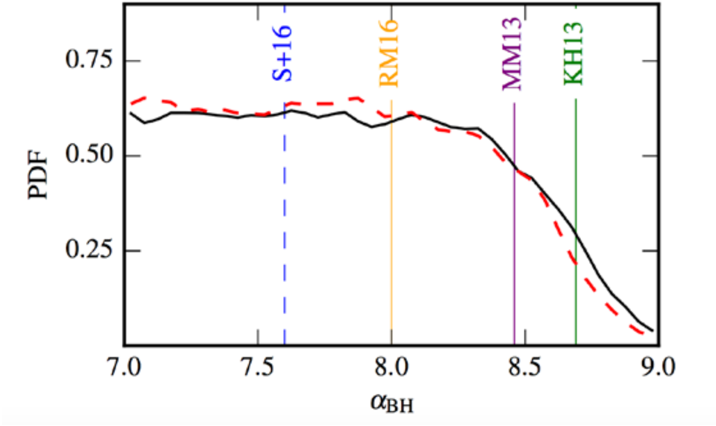
We can set astrophysical constraints

Astrophysical interpretation by “emulated” spectra trained by simulations.



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

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

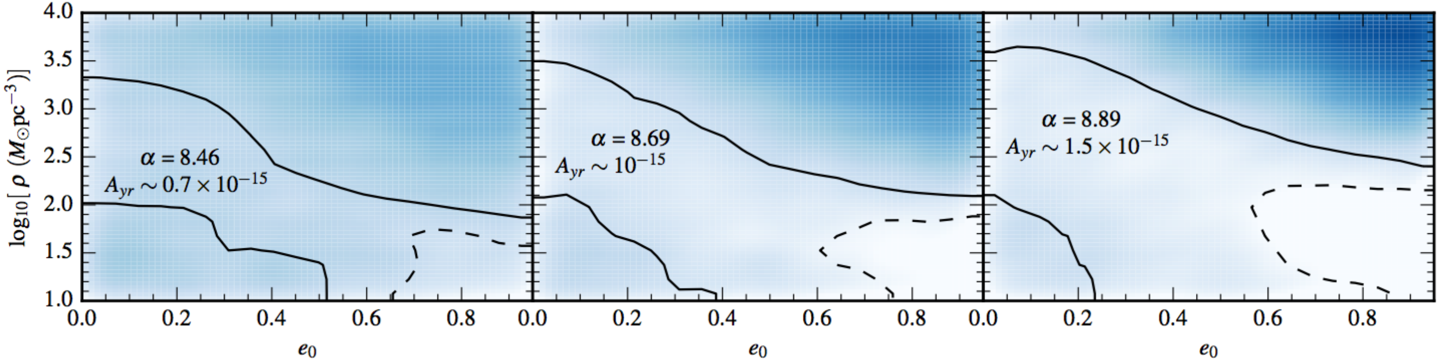


arXiv: 1801.02617

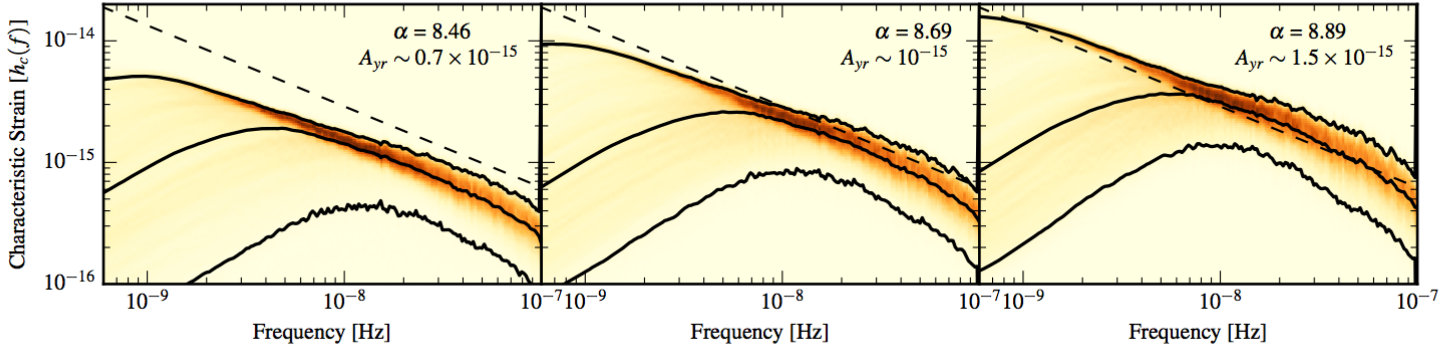
Can rule out astrophysical parameter space and place constraints on eccentricity, galaxy-bulge mass relationship, and galactic core mass density.

More astrophysical constraints

NANOGrav Physics Frontiers Center



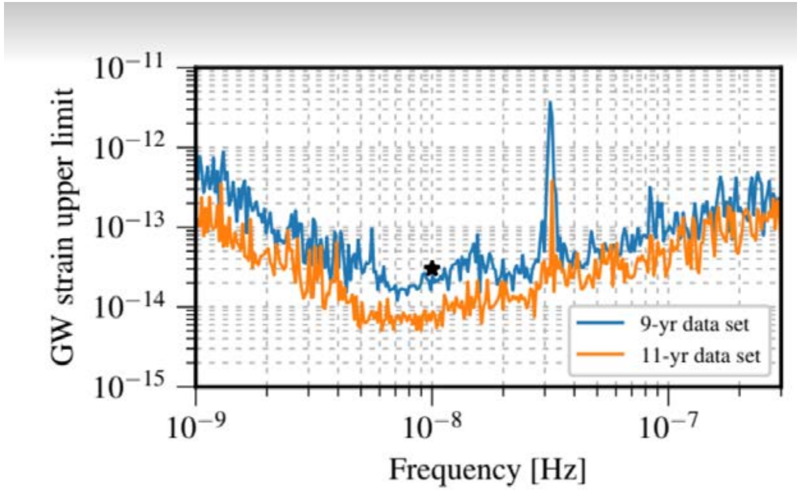
(a) 2D posterior for $\rho_{\rm stars}$ and e_0 for fixed $\alpha_{\rm BH}$

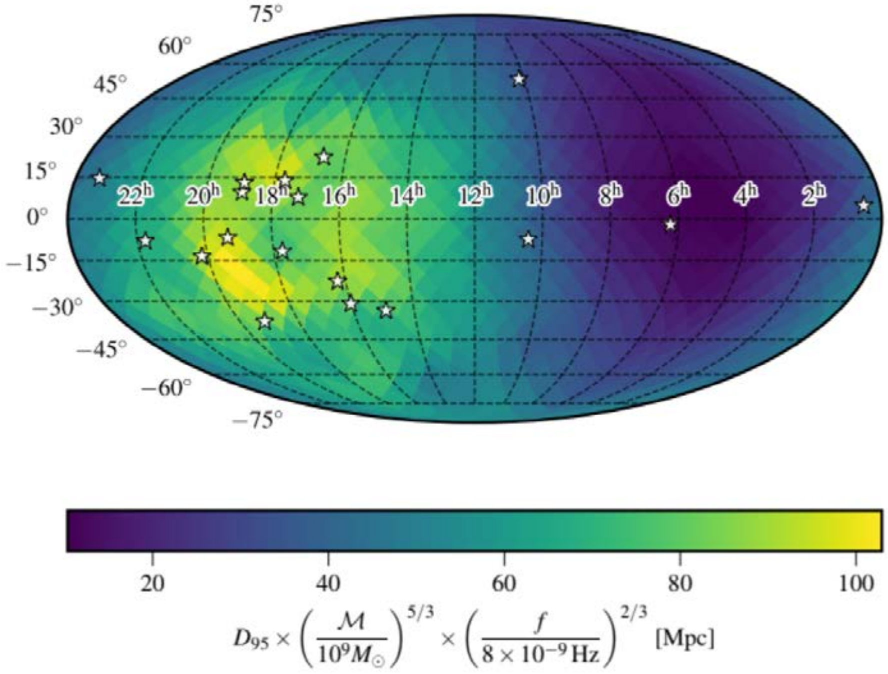


(b) Marginalized spectral shape of GWB

arXiv: 1801.02617

Continuous Wave Limits

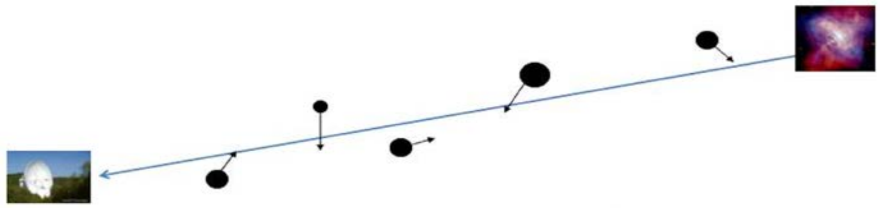




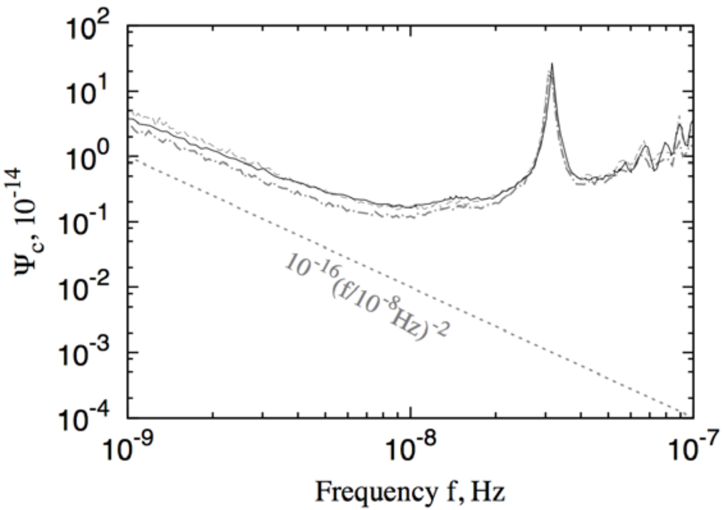
The NANOGrav Collaboration, in preparation

We an also search for more exotic stuff…

Dark matter substructure would cause Shapiro delays and Doppler effects (Baghram et al. 2011)



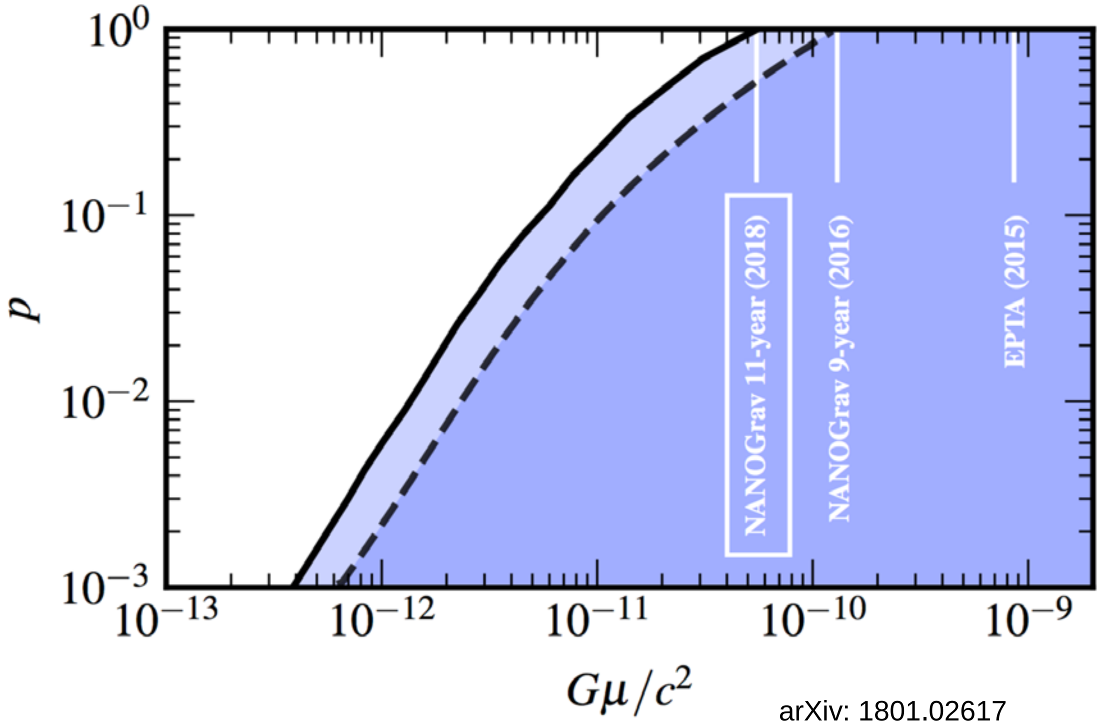
Hertzberg, Siegel, Fry 2007



Porayko & Postnov 2014

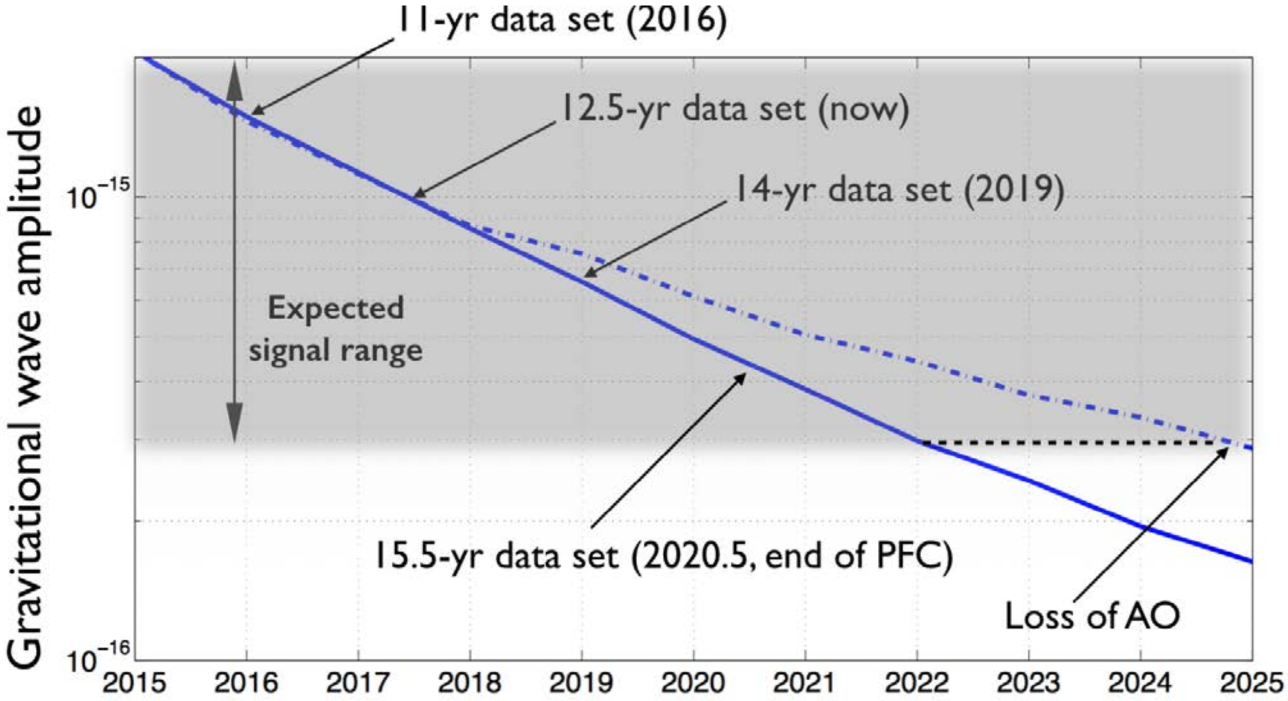
Warm dark matter could be an ultralight scalar field, creating a time-dependent galactic gravitational potential (Khmelnitsky & Robakov 2014, Porayko & Postnov 2014)

We can also set the best limits on cosmic strings



arXiv: 1801.02617

When we will make a SB detection?



We need to hold onto our telescopes (roughly $10M/year each).

Want to get there faster?

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

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.

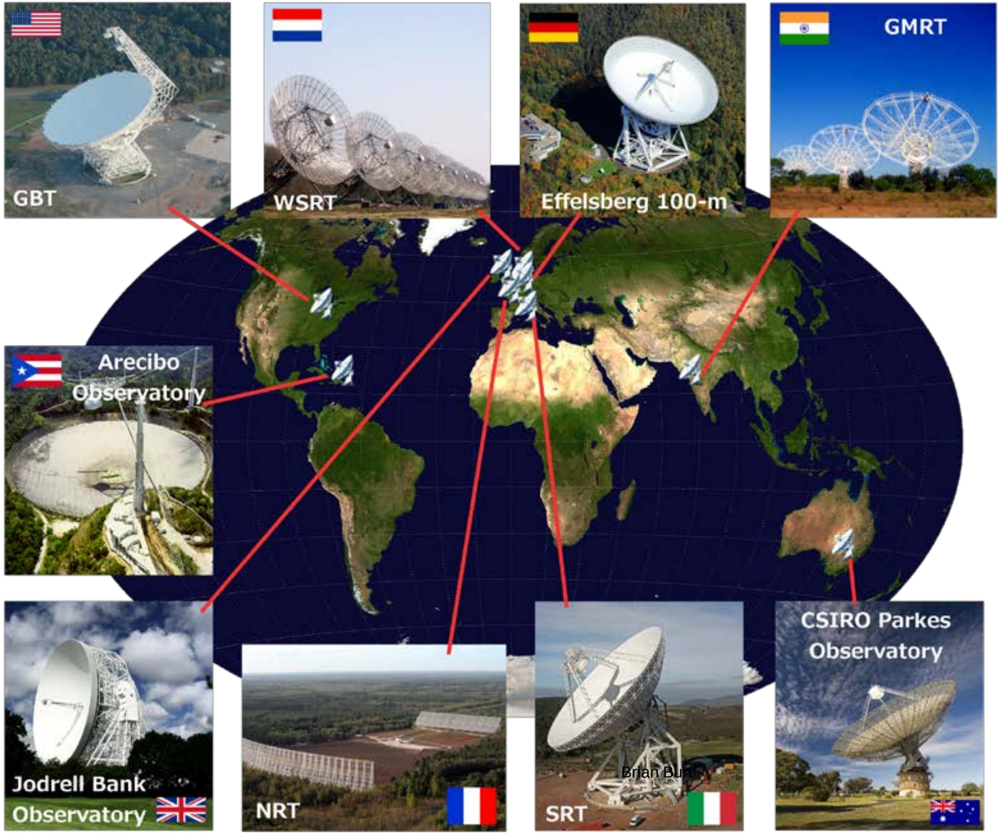
(+ better ISM mitigation, noise characterization, ephemerides, etc.)

The International Pulsar Timing Array

European Pulsar Timing Array

North American Nanohertz Observatory for Gravitational Waves

Parkes Pulsar Timing Array

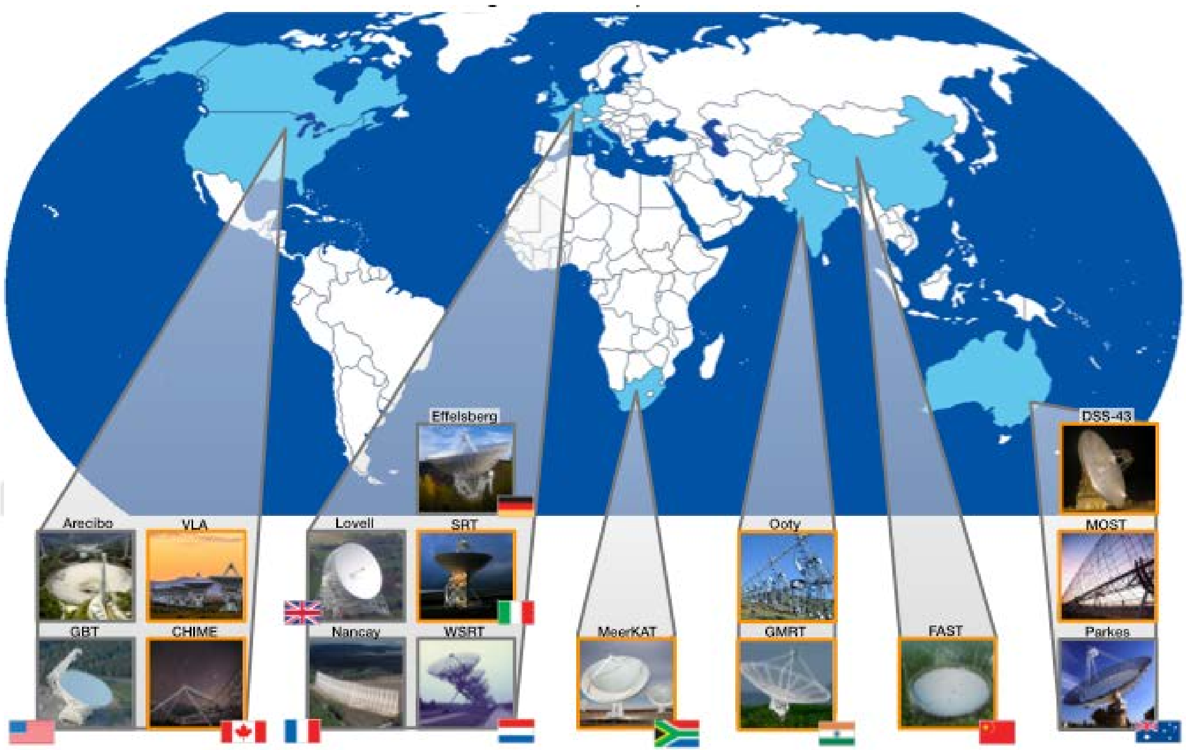


http://ipta4gw.org

The Expanded IPTA

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

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



Credit: Shami Chatterjee

Summary and the Future

- The detection and subsequent study of the universe through pulsar timing will allow insights into galaxy evolution and cosmology not possible through other means, complimenting LIGO at the low-frequency end of the GW spectrum.

- NANOGrav's 11-year data set is the most sensitive in the world for low-frequency gravitational wave detection. You can grab it at http://data.nanograv.org.

- For the first time, we are able to constrain models for galaxy mergers.

- Our sensitivity has increased dramatically over the past few years, due to additional pulsars and improved instrumentation. It will continue to increase over the next several years with even more pulsars, wider bandwidth receivers, and ***continued access to our telescopes***.

- Our 12.5 year data release will be published within the next year. 71 MSPs are currently being timed!

- Please come to the IPTA meeting and student workshop in New Mexico from June 11-22! http://ipta.phys.wvu.edu