The NANOGrav 11-Year Data Set: New Insights into Galaxy Growth and Evolution

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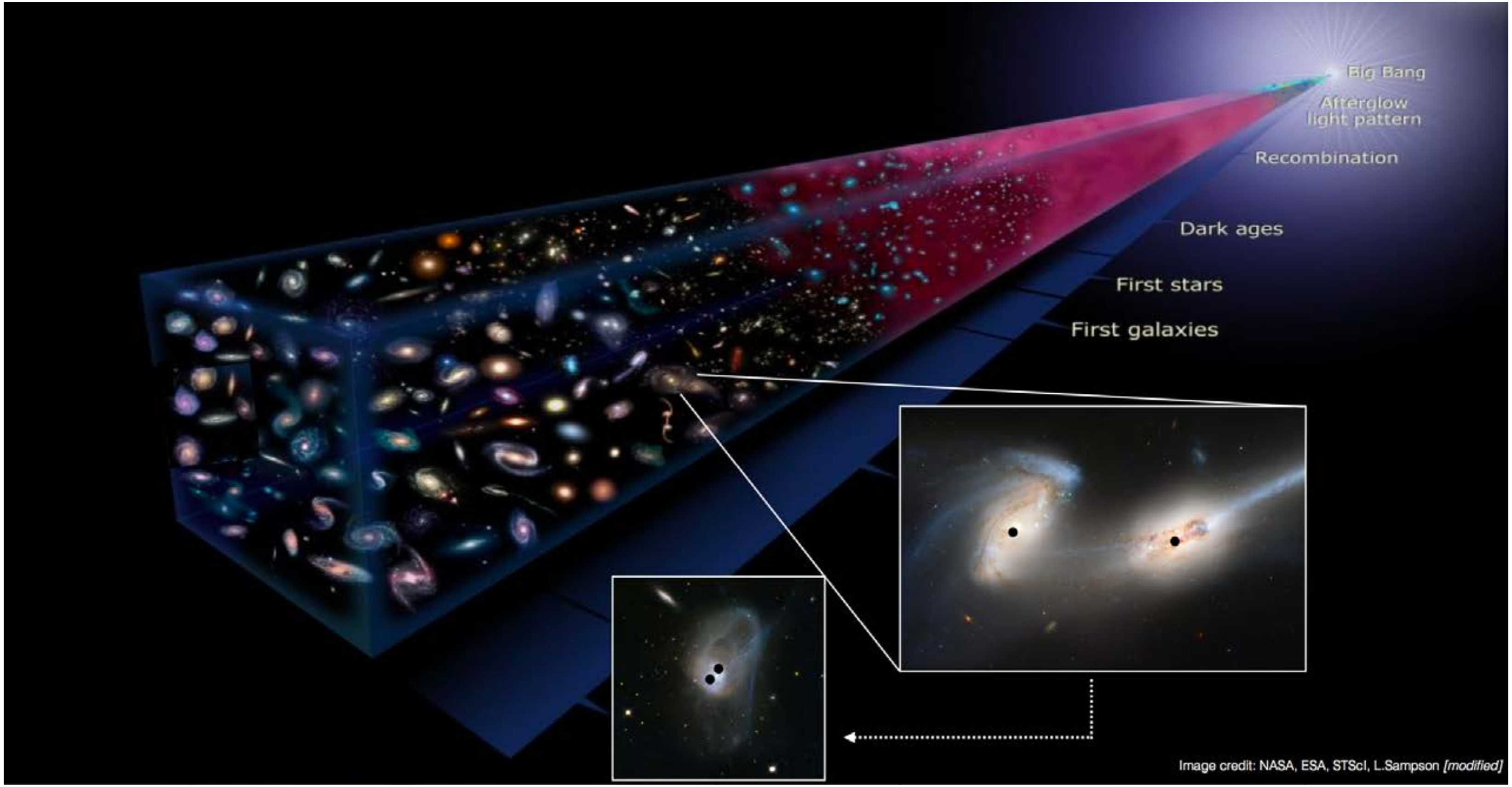
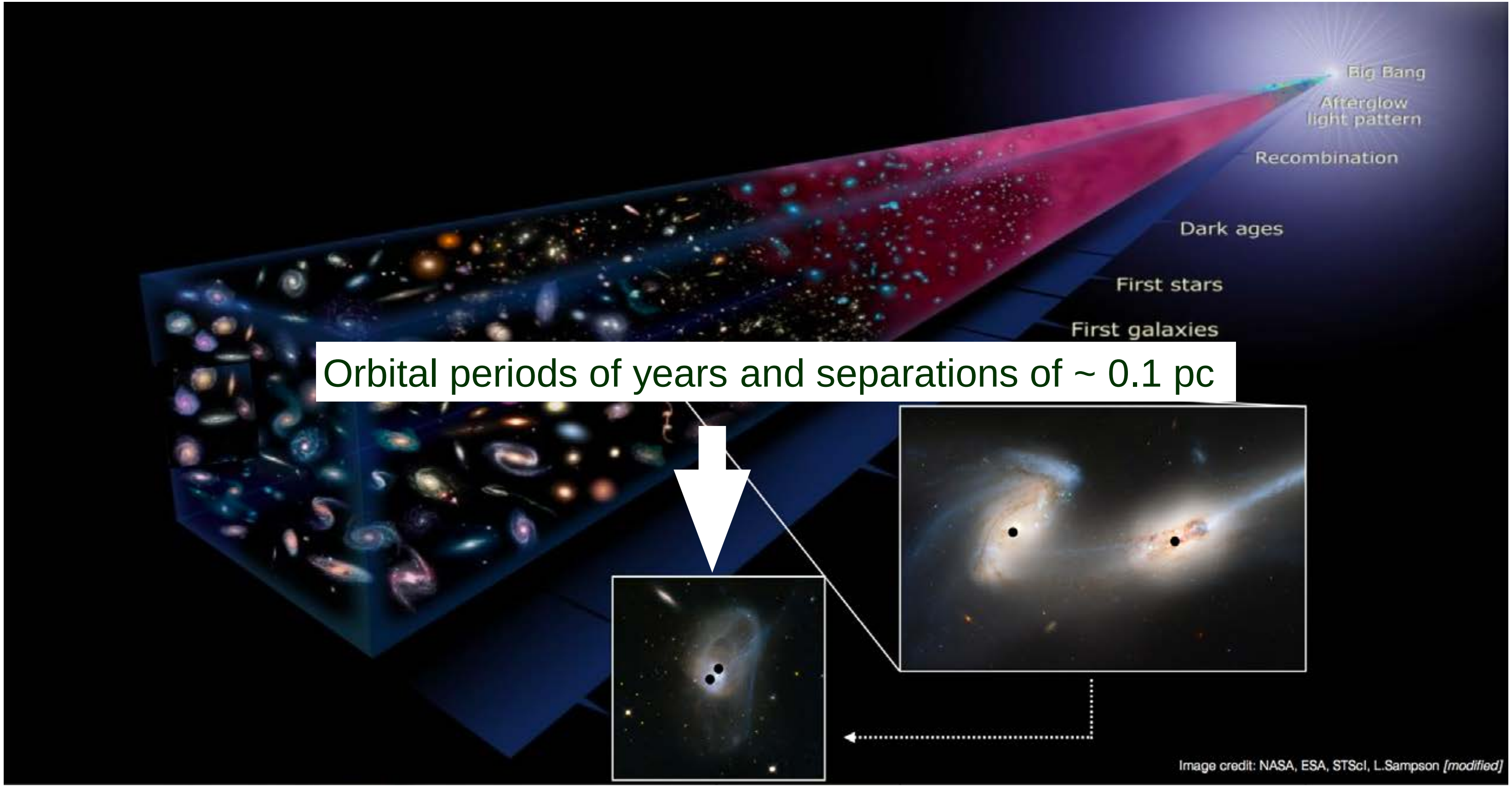
NANOGrav
Physics Frontiers Center

INTERNATIONAL PULSAR TIMING ARRAY
IPTA

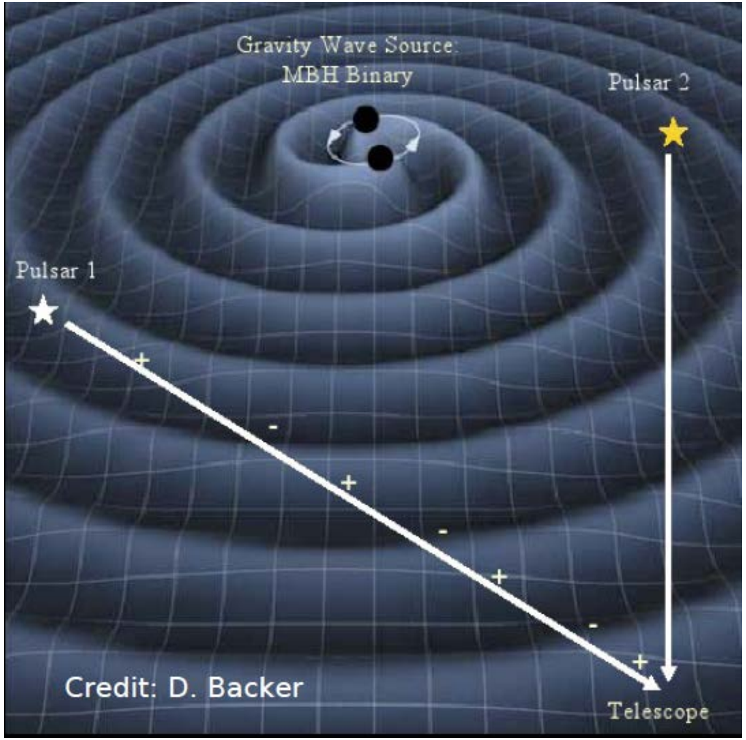
Galaxy Evolution 101

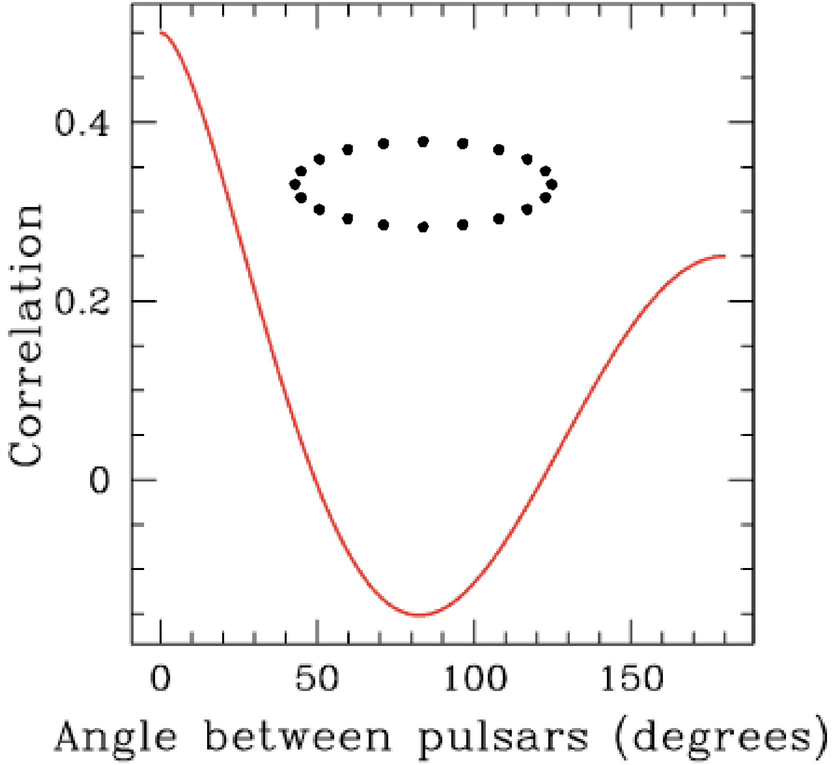


Galaxy Evolution 101



Low-Frequency GW Detection





Hellings & Downs, 1983, ApJ, 265, L39

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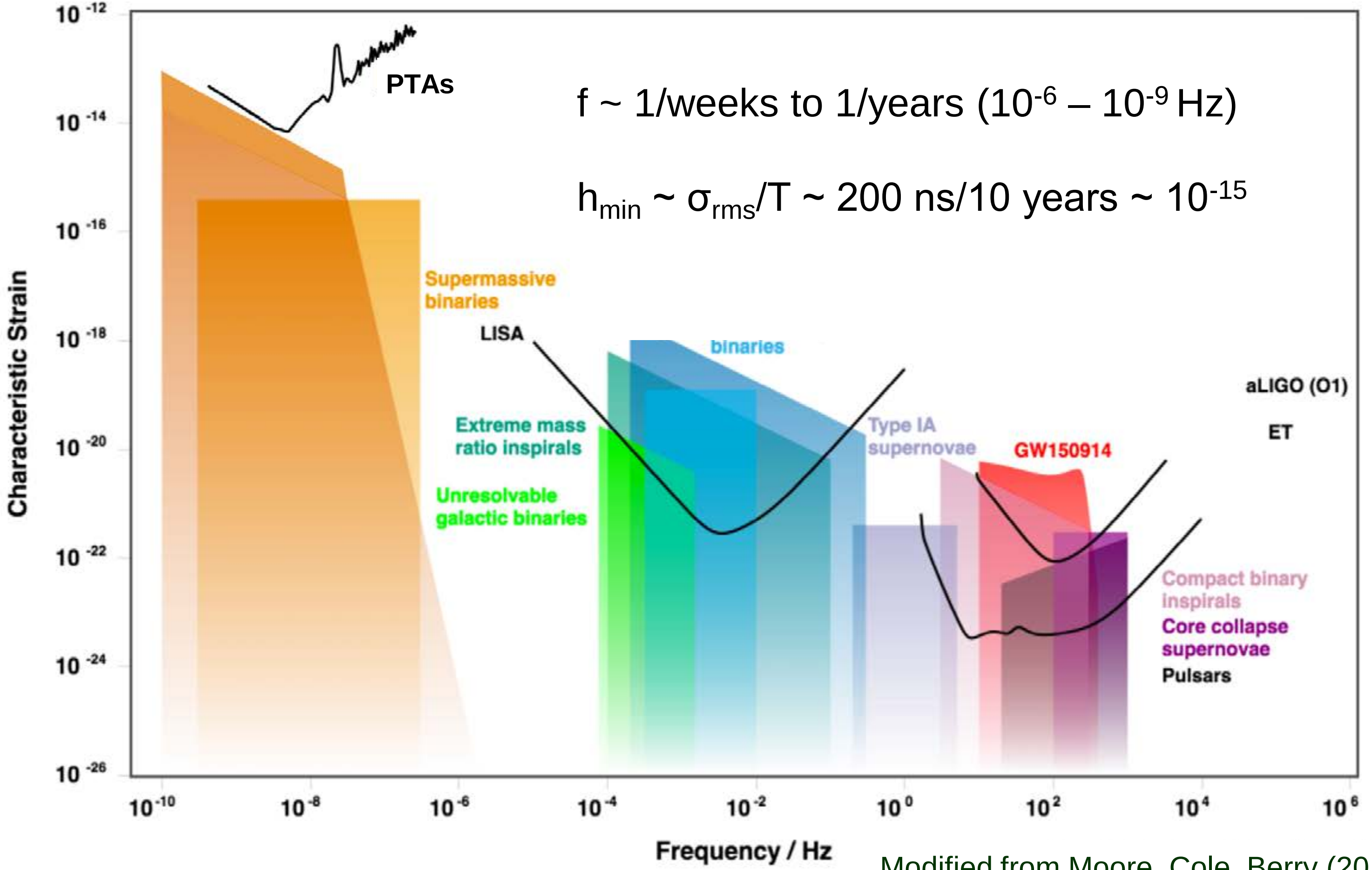
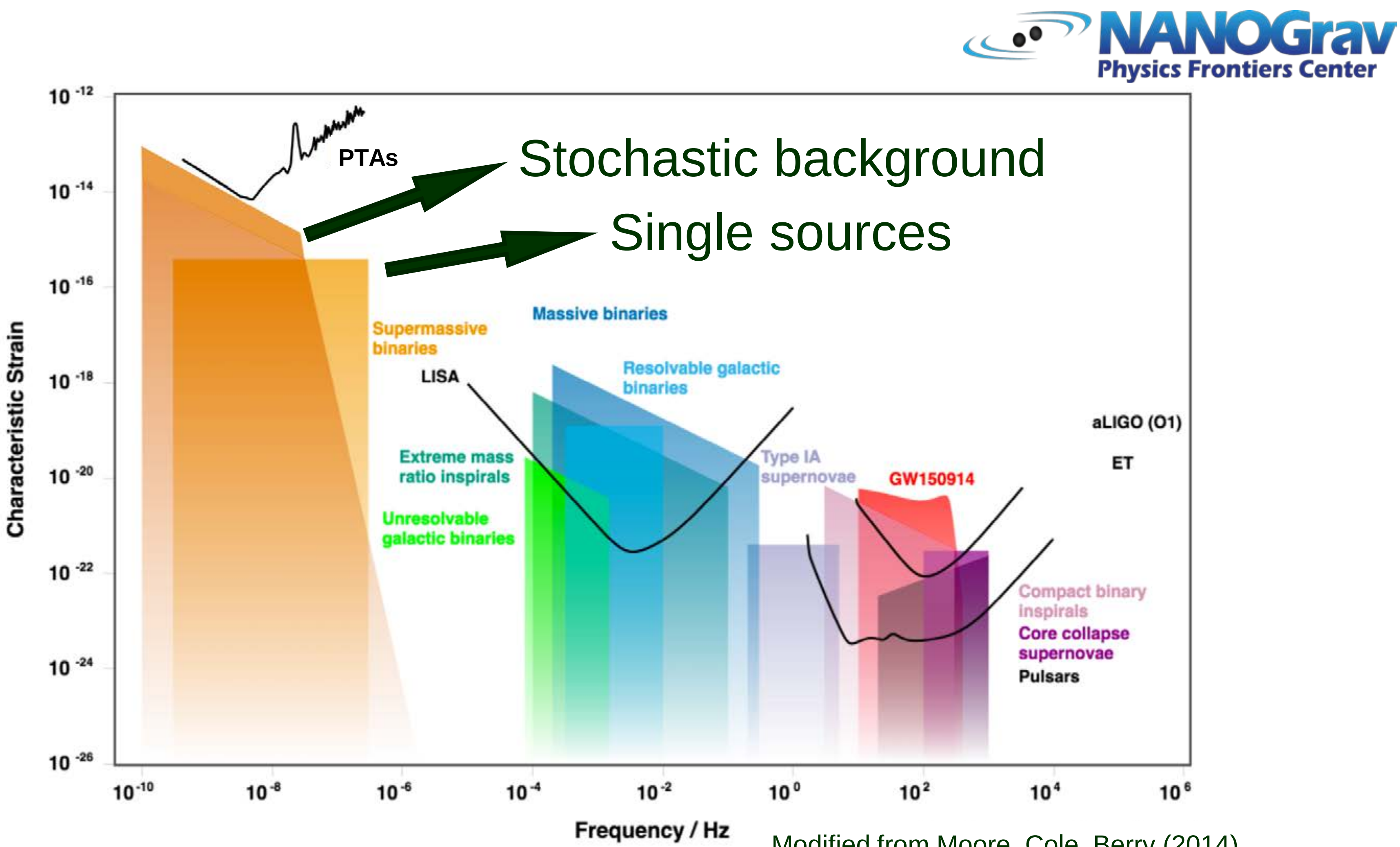


f ~ 1/weeks to 1/years (10^{-6} – 10^{-9} Hz)

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

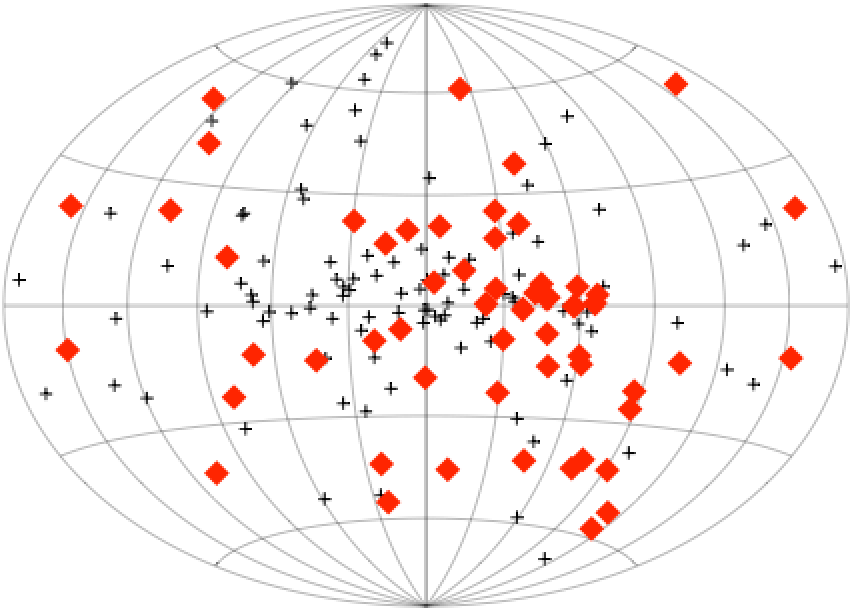
Modified from Moore, Cole, Berry (2014)

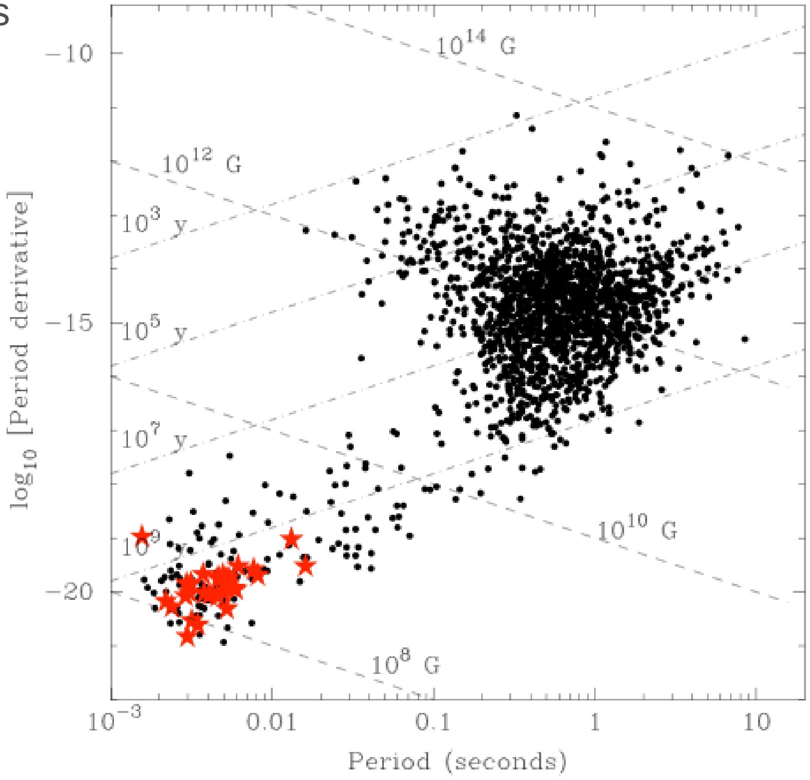


Modified from Moore, Cole, Berry (2014)

Millisecond Pulsars (MSPs)

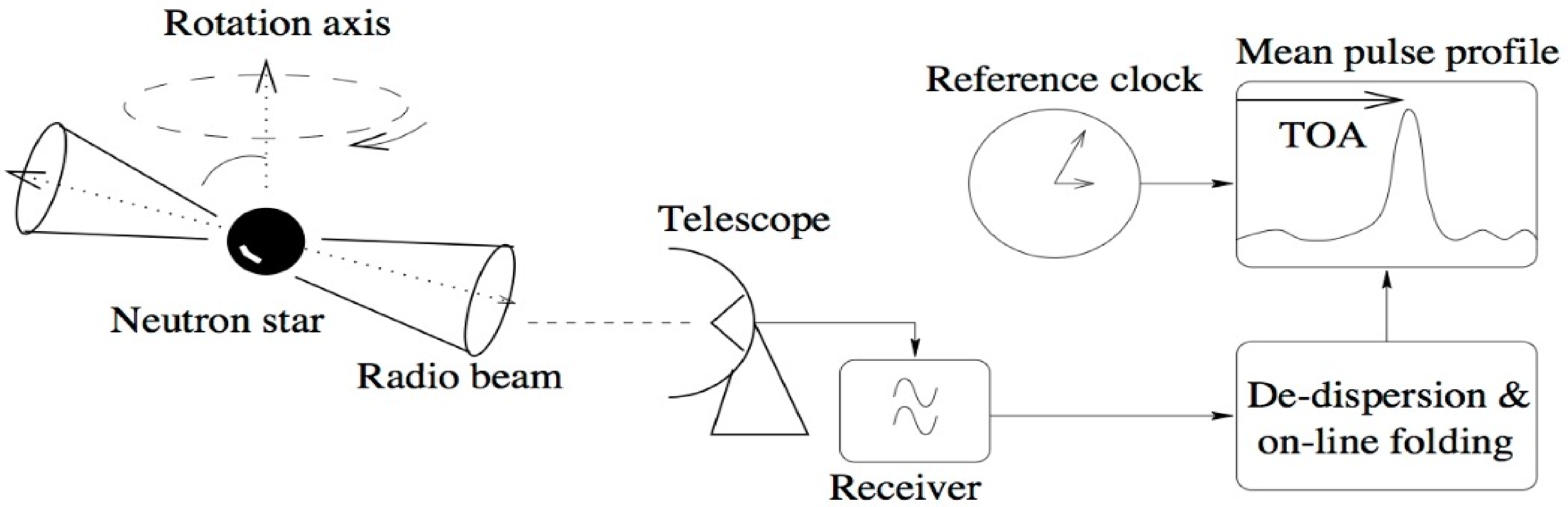
Out of over 2600 known pulsars, there are now 274 MSPs (P < 20 ms) in our Galaxy, out of roughly 30,000-80,0000 detectable. *Roughly 100 timed for PTA purposes.*





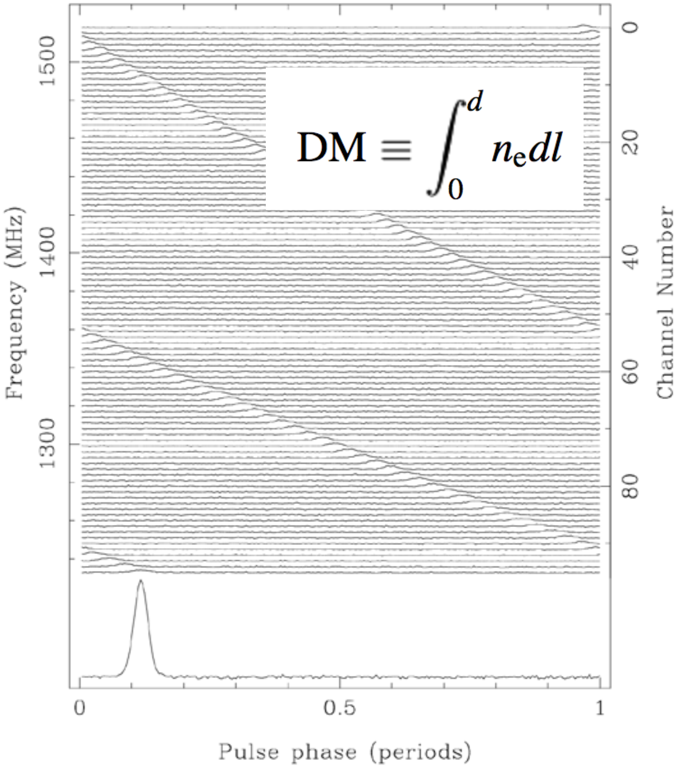
Red = part of worldwide PTA timing programs

Pulsar Timing

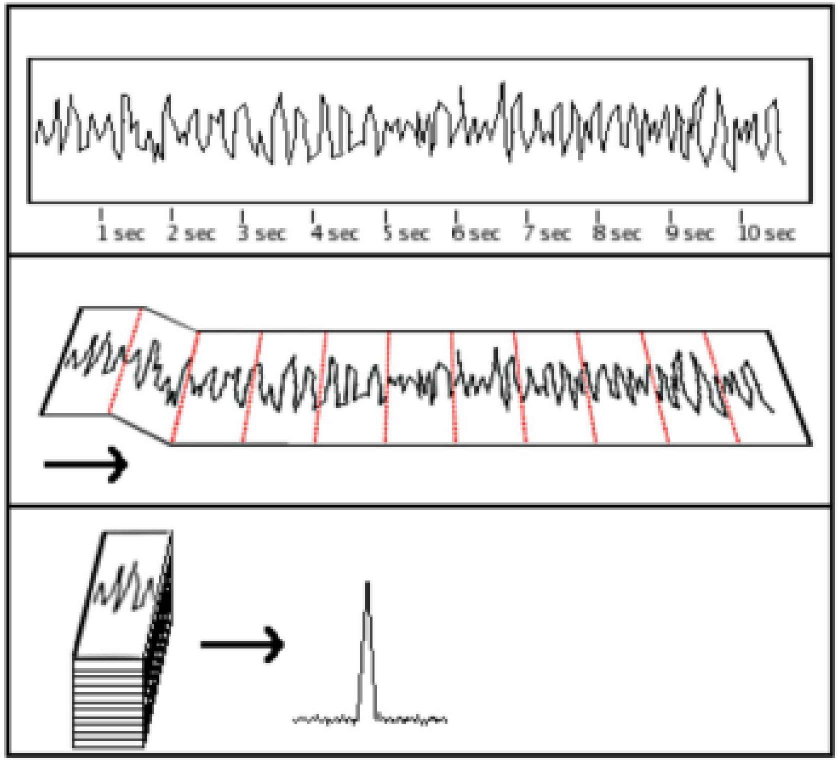


Credit: “Handbook of Pulsar Astronomy”, Lorimer & Kramer (2005)

Pulsar Timing

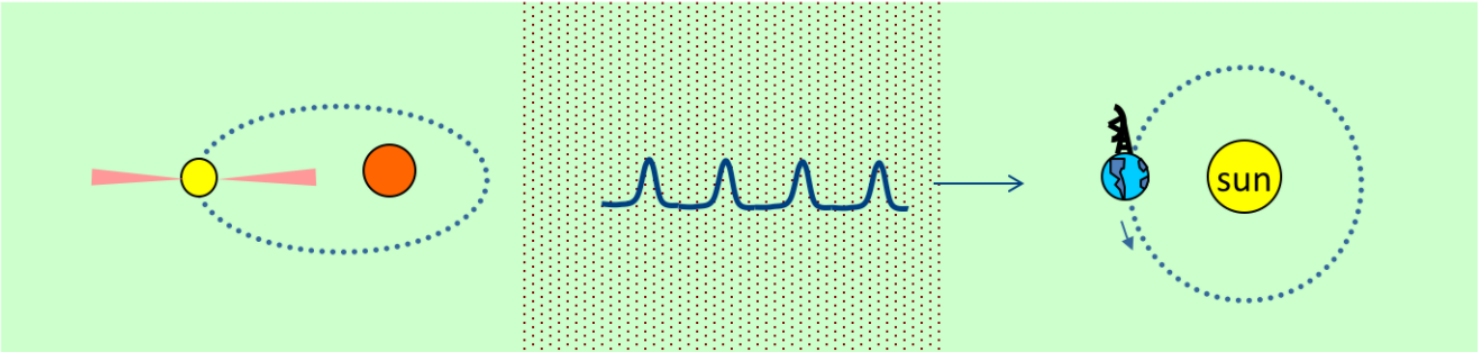


De-dispersion: corrects for *variable* frequency dependent delays



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

Many things affect arrival times

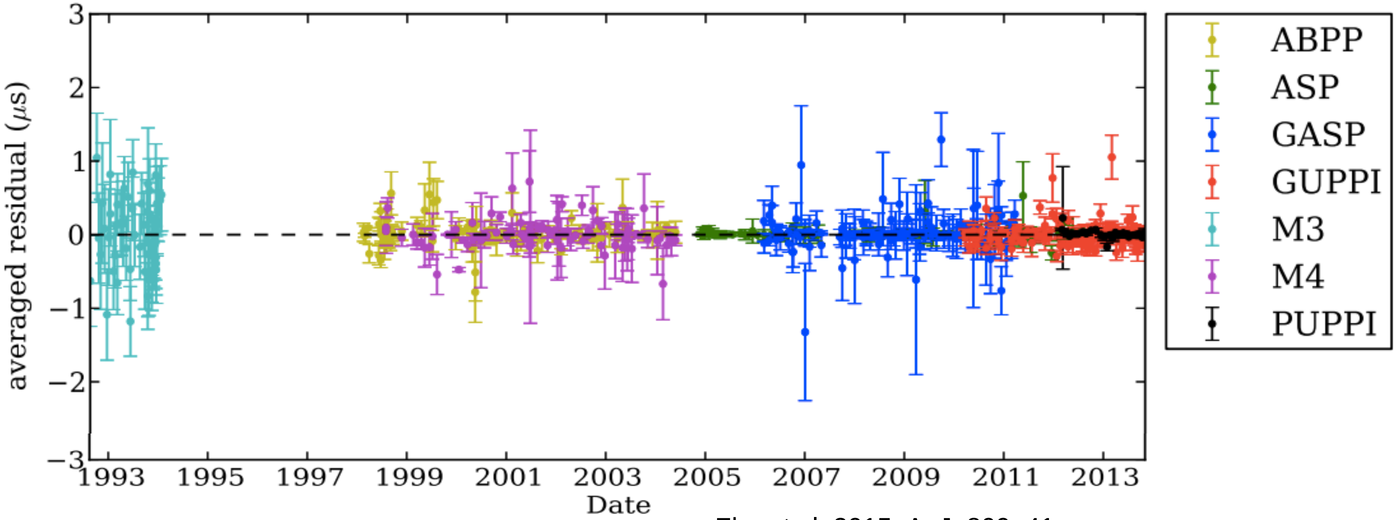


rotation period rotation period derivative timing noise Keplerian orbital elements relativistic orbital elements kinematic perturbations of orbital elements (secular and annual phenomena)	dispersion measure dispersion meas. variations	position proper motion parallax solar electron density

Credit: David Nice

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

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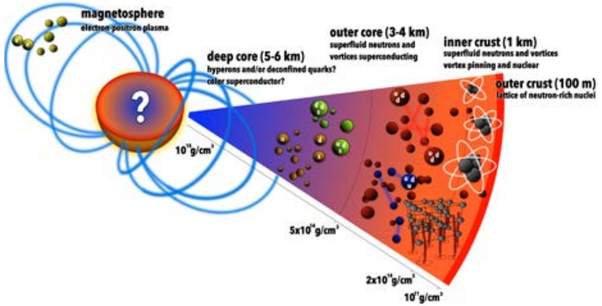
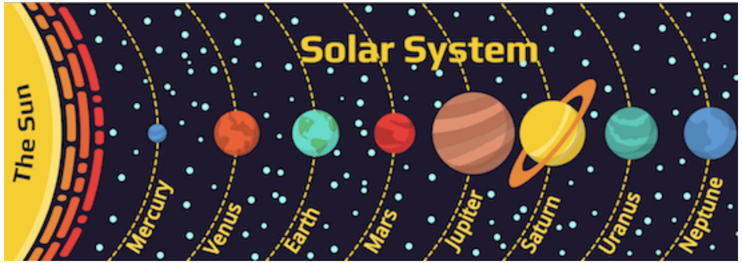
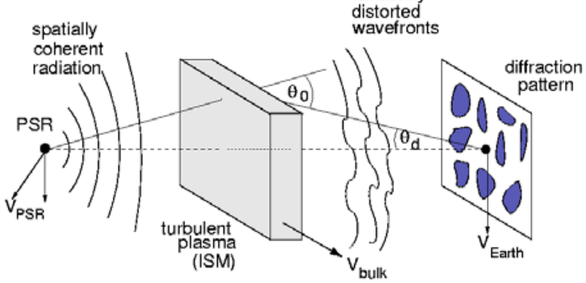
	Noise source	Achromatic?	Correlated in time?	Correlated in space?	Quadrupolar?
Intrinsic	Pulsar rotational irregularities	✓	✓	✗	✗
Intrinsic	Pulse jitter	✓	✗	✗	✗
Extrinsic	Scattering and dispersion measure variations	✗	✓	✗	✗
Extrinsic	Planetary ephemerides	✓	✓	✓	✗
Extrinsic	Clock errors/offsets	✓	✓	✗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



Watts et al. 2015, arXiv: 1501.00042



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



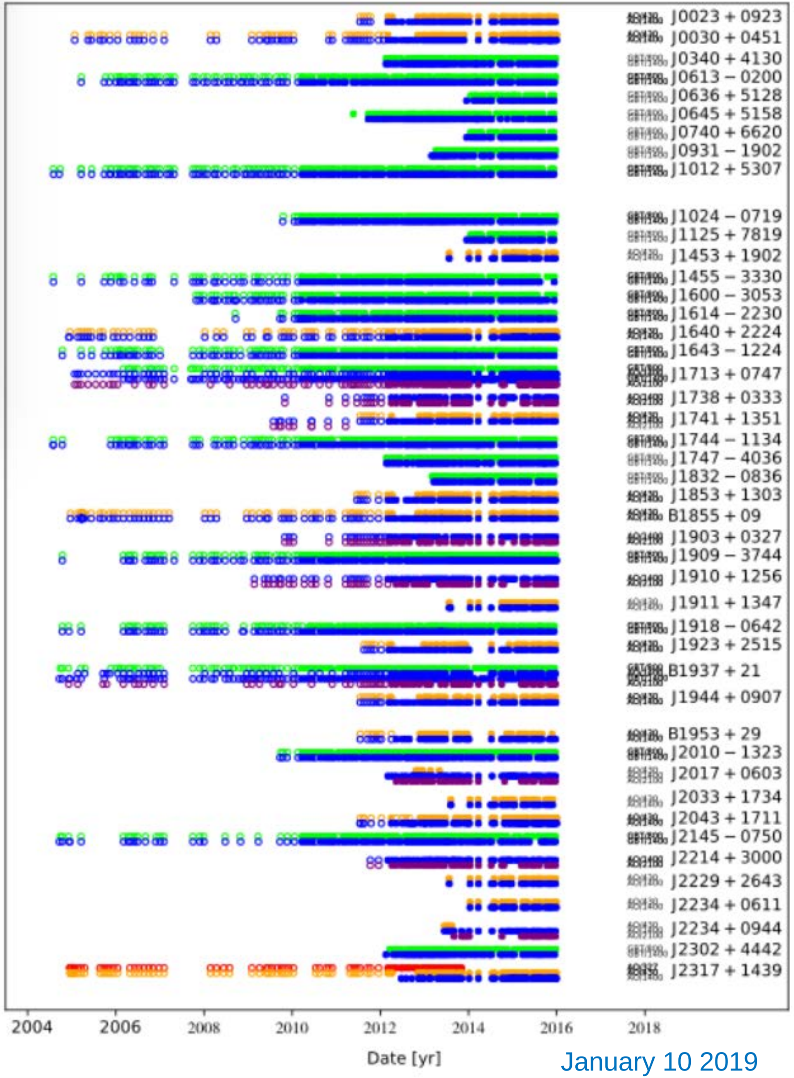
NANOGrav's Program

We observe 77 pulsars at two radio frequencies every one to four weeks for roughly 20-30 min.

Eleven-year data release includes 45 pulsars, including 31 binaries, 20 with parallax measurements, and 11 with measurable red noise.

New: better outlier analysis and procedures for mitigating solar effects

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



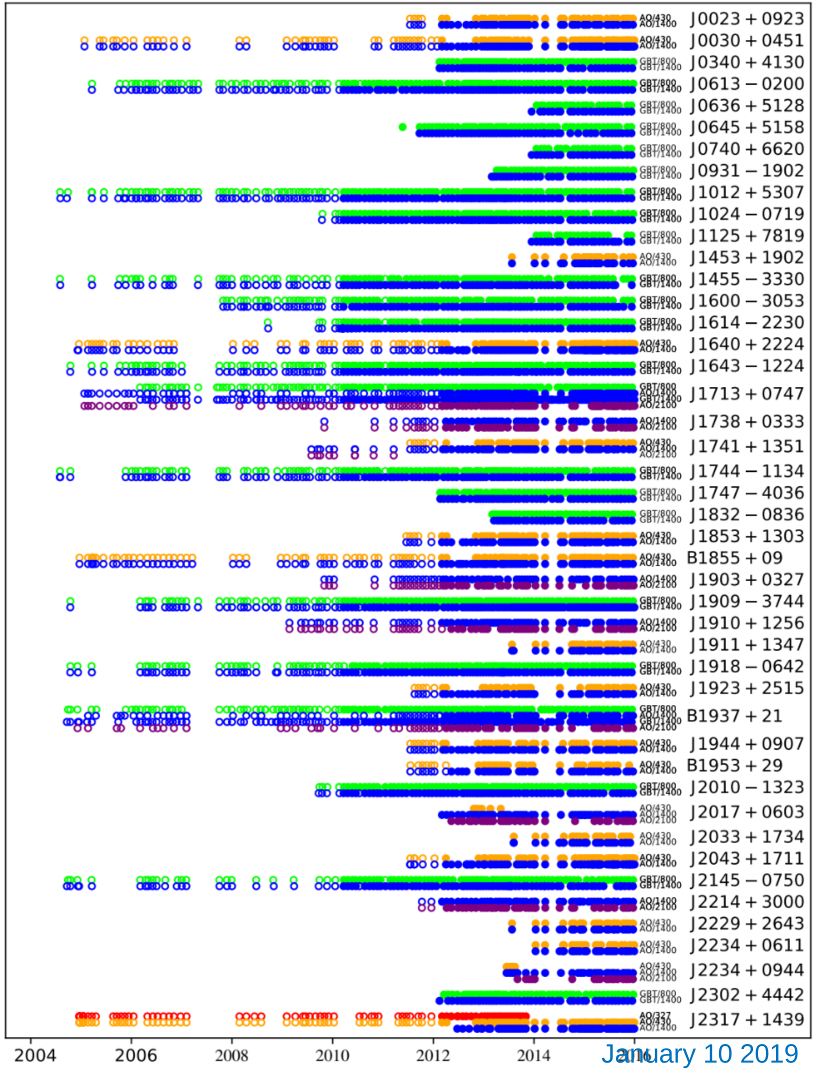
The NANOGrav Collaboration, ApJS, 235, 37

NANOGrav’s Program

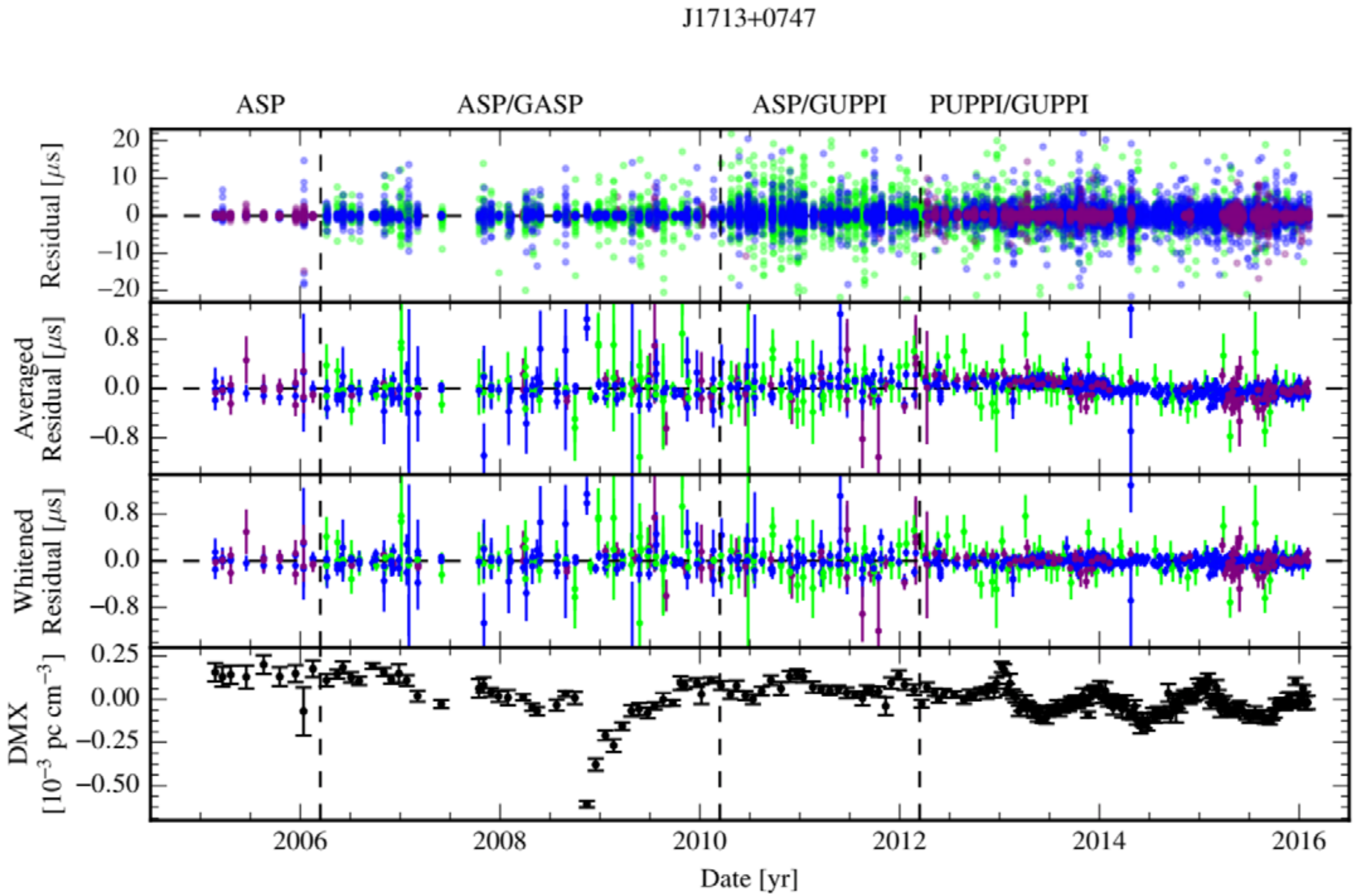
We observe 77 pulsars at two radio frequencies every one to four weeks for roughly 20-30 min.

12.5-year data release includes 48 pulsars.

New: wideband timing, new timing package (PINT)

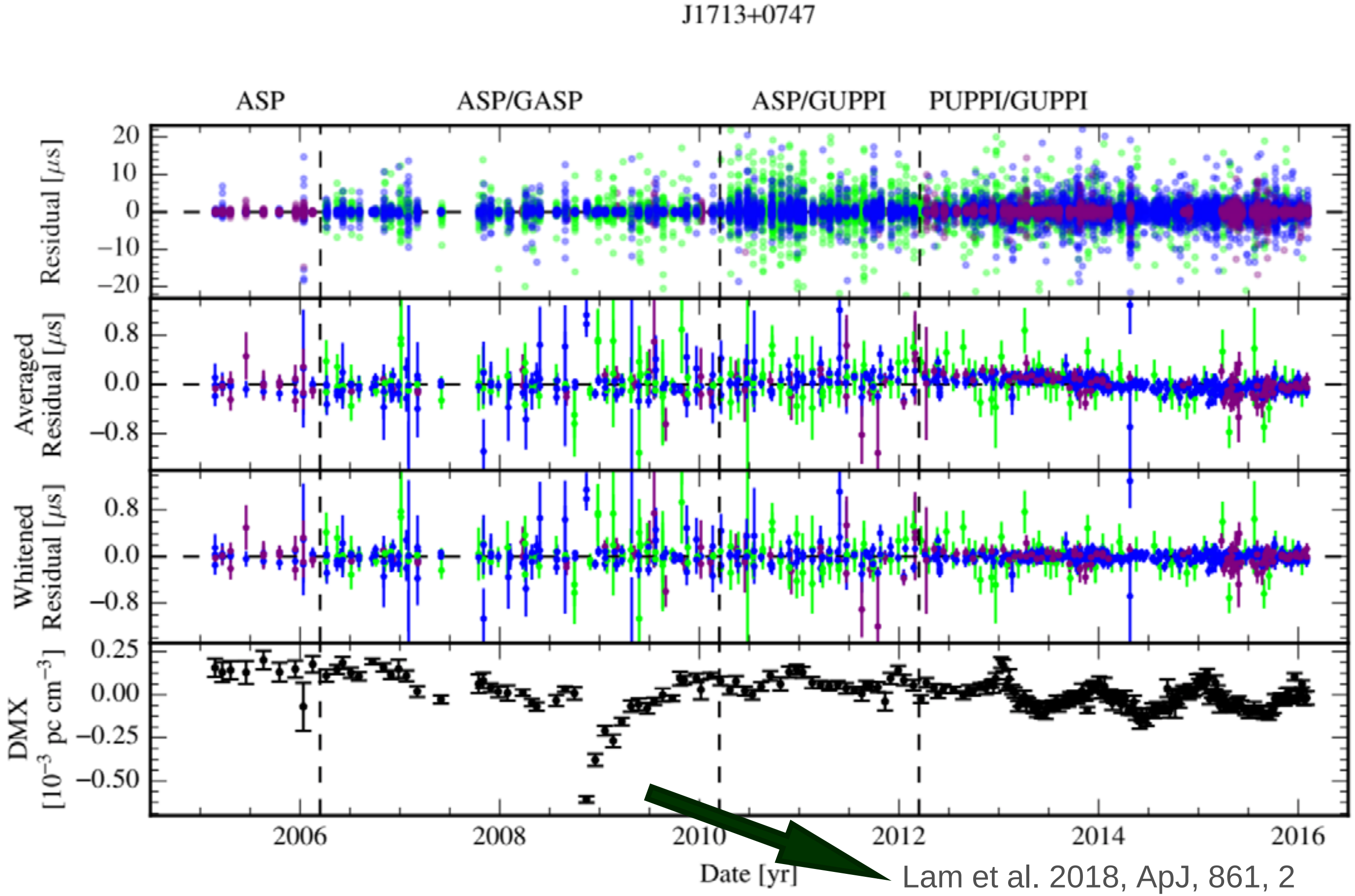


Eleven-Year Residuals



The NANOGrav Collaboration, ApJS, 235, 37

Eleven-Year Residuals



Lam et al. 2018, ApJ, 861, 2

The NANOGrav Collaboration, ApJS, 235, 37

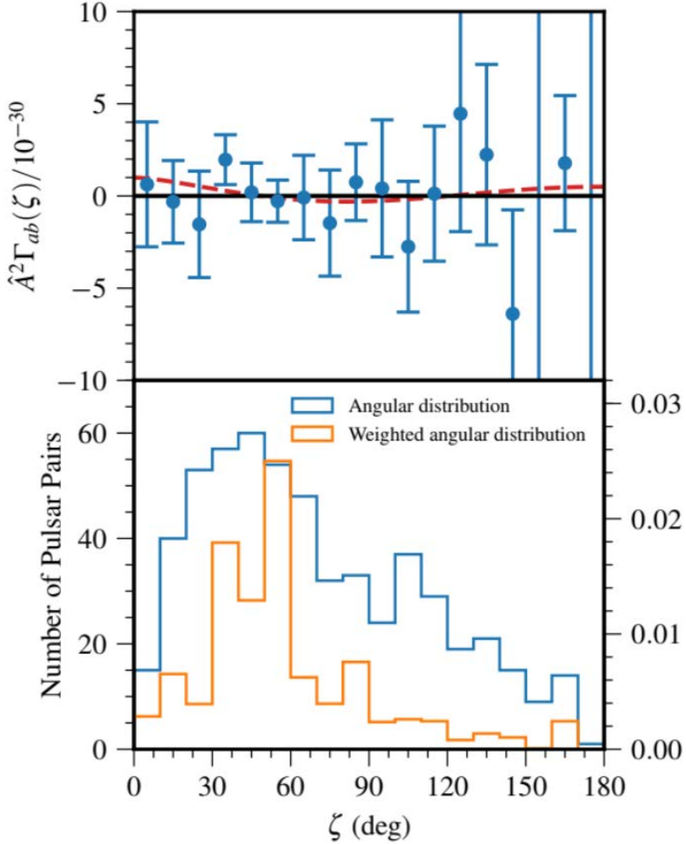
Eleven-year Stochastic Background Analysis

Used 34 pulsars with > 3 yrs of data.

Fit for three white noise and two red noise parameters.

New: modeled solar system ephemeris errors and set limits including spatial correlations.

Code is publicly available!

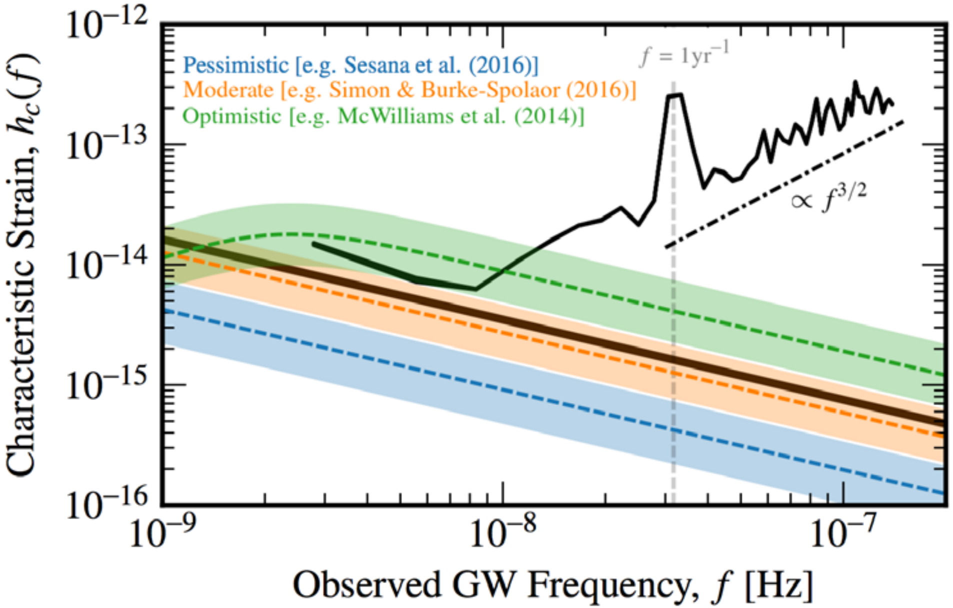


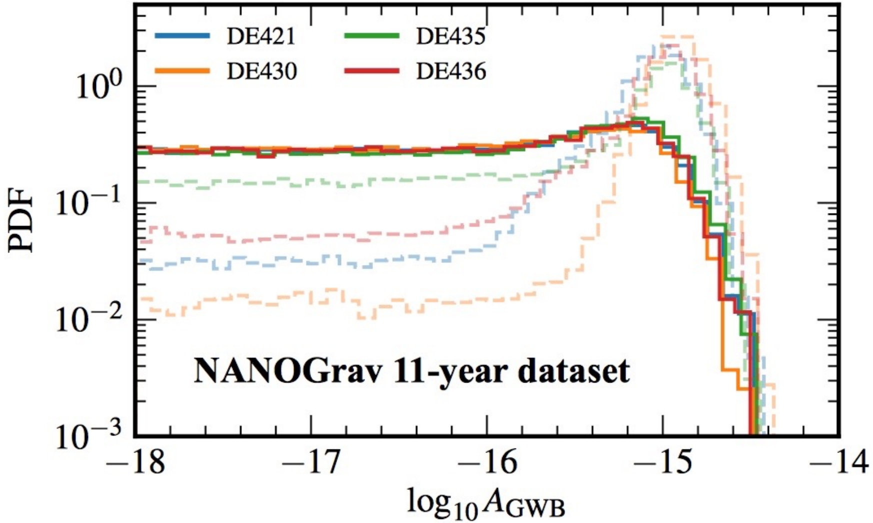
The NANOGrav Collaboration, 2018, ApJ, 859, 47

Eleven-year Stochastic Background Analysis

11-year limit is: $h_c < 1.45 \times 10^{-15}$ (f=1 yr^{-1})

9-year limit is: $h_c < 2.5 \times 10^{-15}$ (f=1 yr^{-1})

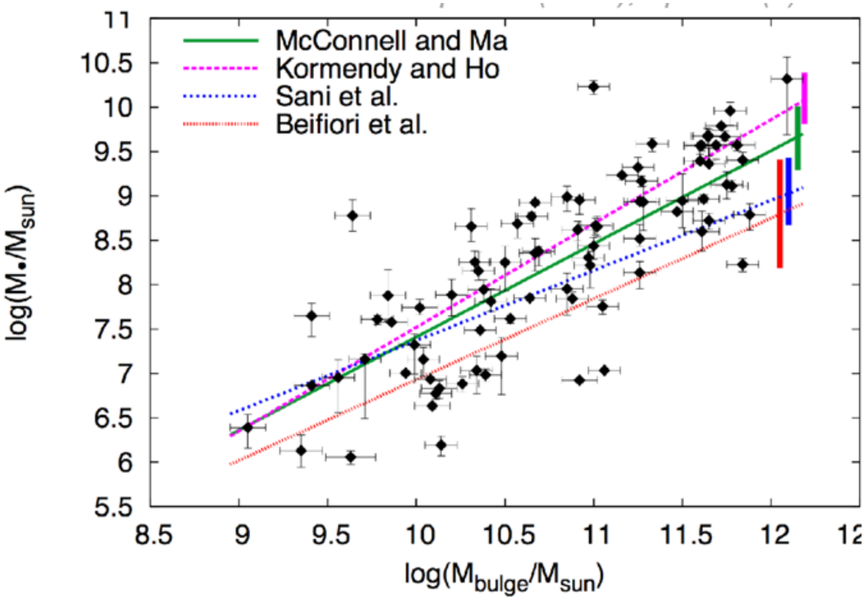




The NANOGrav Collaboration, 2018, ApJ, 859, 47

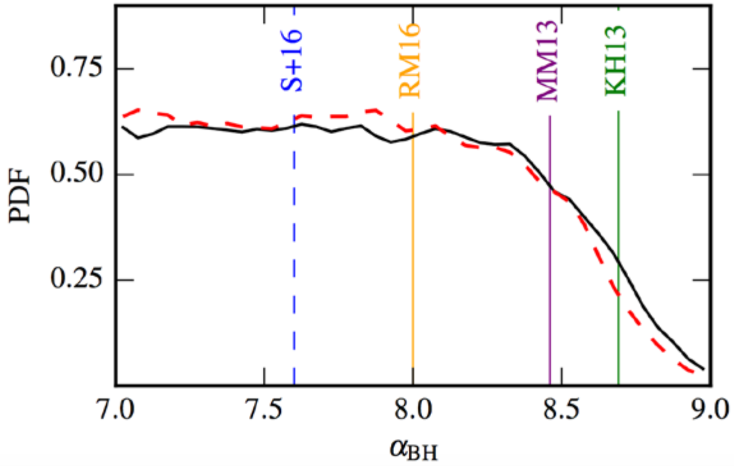
Errors dominated by Jupiter and correspond to position offsets of order ~100 km.

We can set astrophysical constraints



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

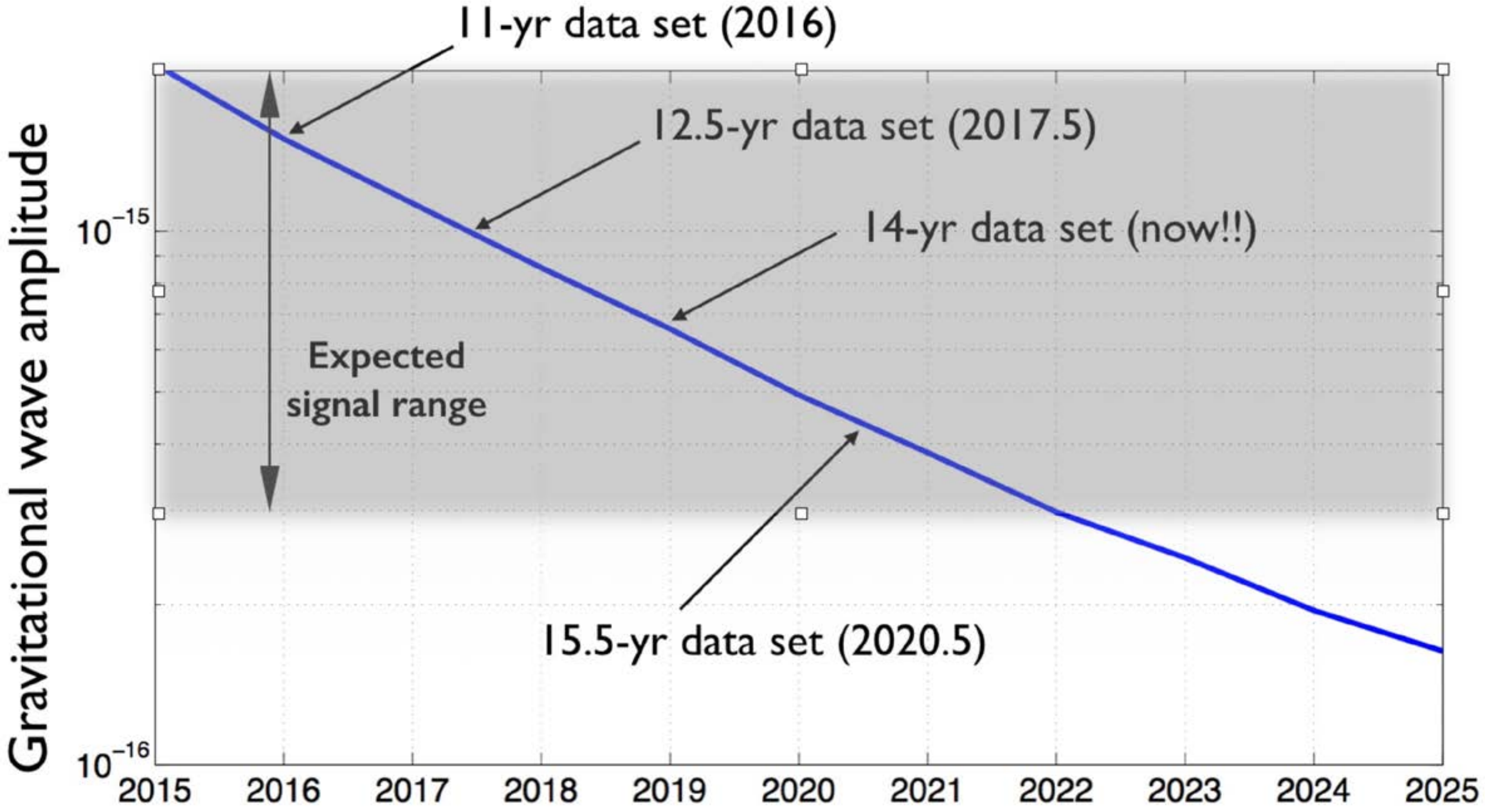
$$\log_{10} M_\bullet = \alpha + \beta \log_{10}\left(\frac{M_{\rm bulge}}{10^{11}\,\mathrm{M}_\odot}\right)$$



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.

When we will make a SB detection?



Assumes same observing program and modest sensitivity improvements from adding 4 pulsars per year.

When we will make a SB detection?

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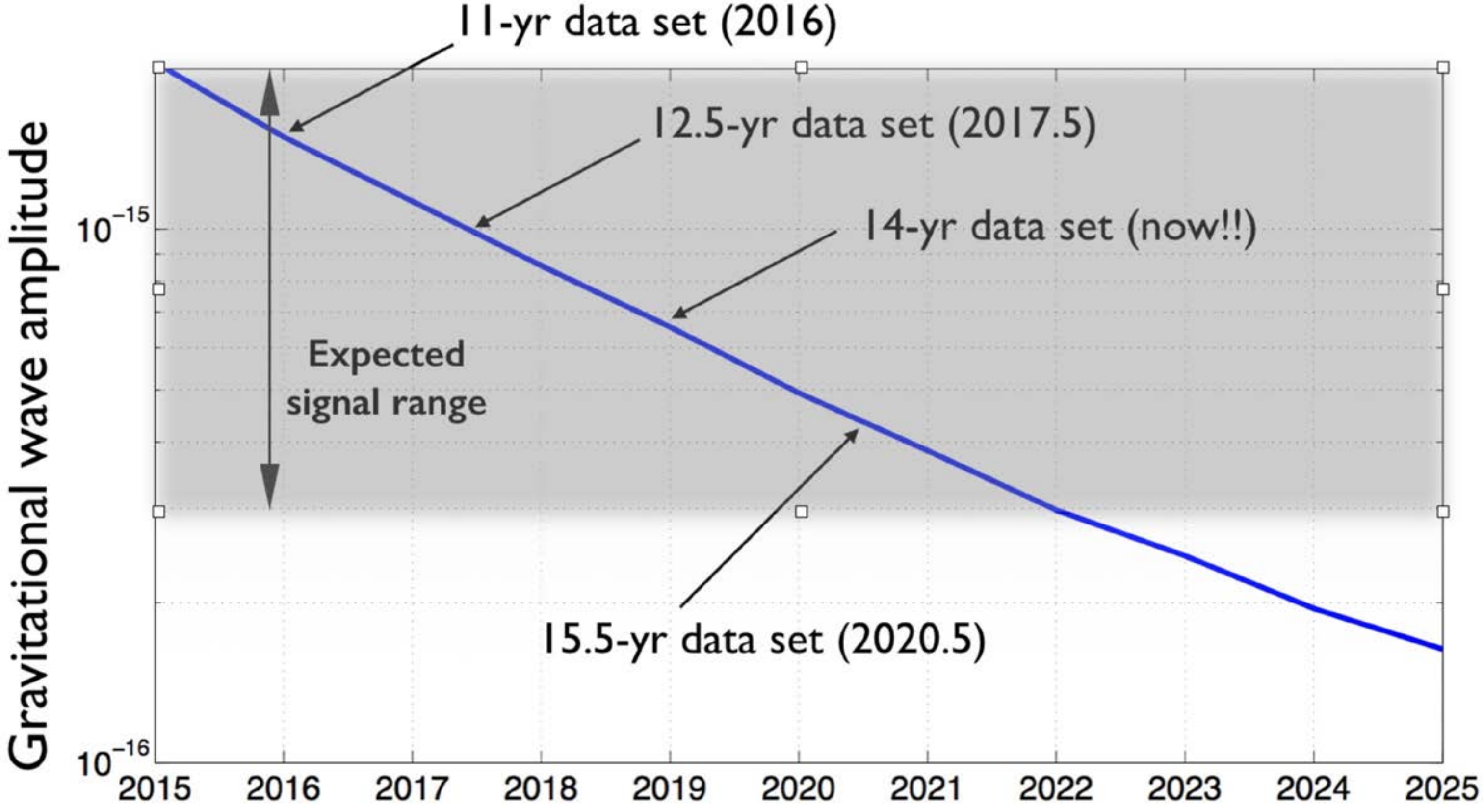
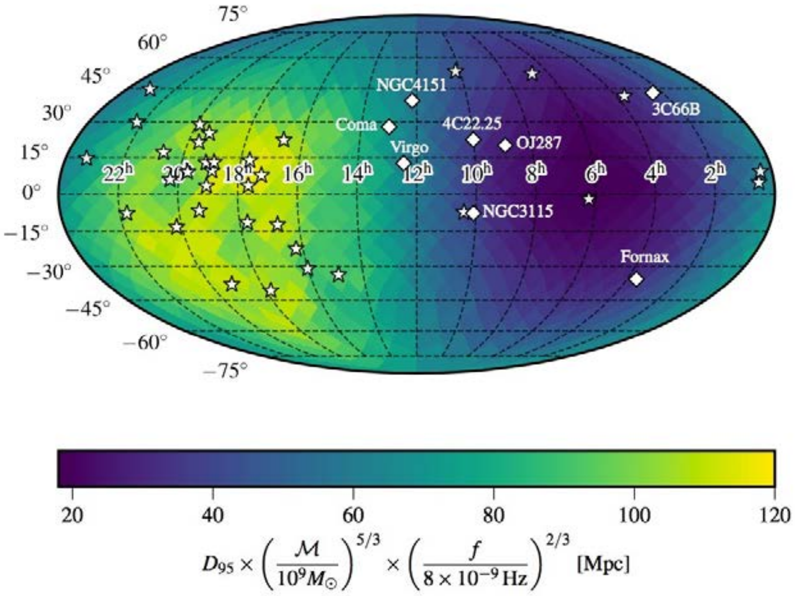


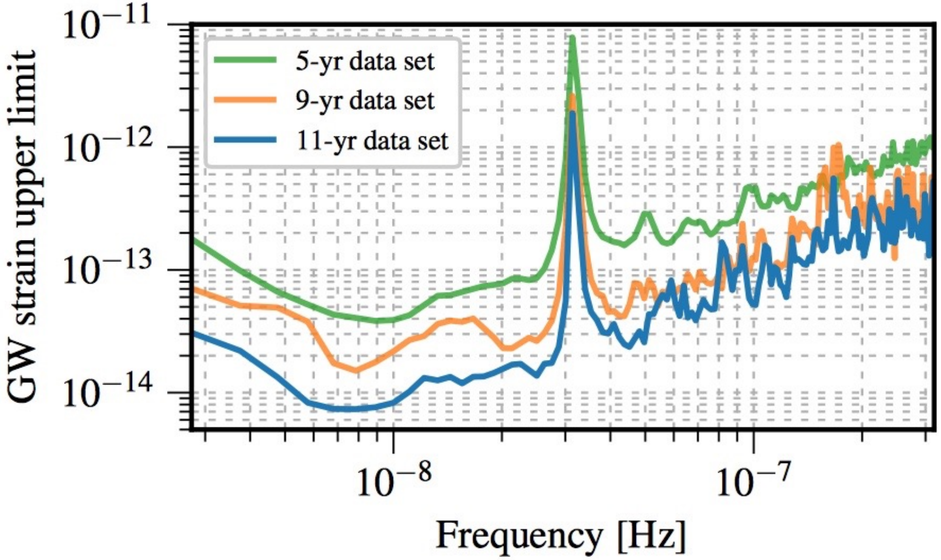
Even faster with more pulsars, more telescope time, wider bandwidth receivers, and international collaboration.

Continuous Wave Results

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

Highly direction dependent!

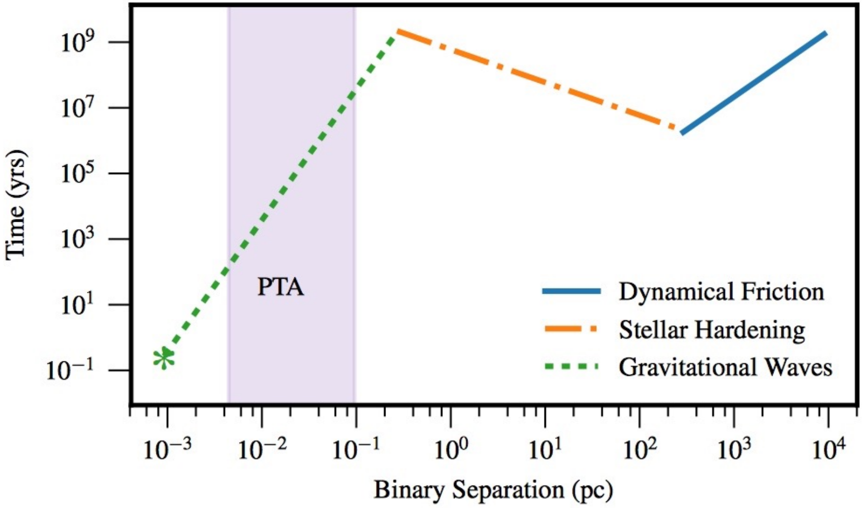




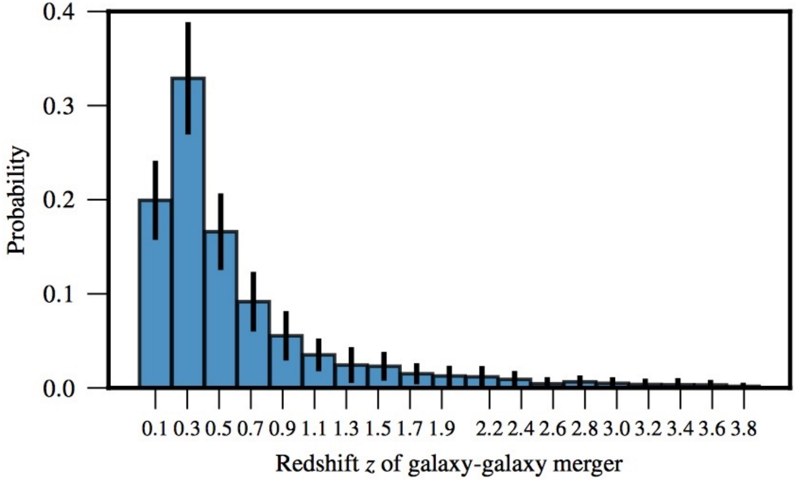
No SMBHBs with M > 1.6 x 10^9 solar masses in Virgo.

The NANOGrav Collaboration, 2018, arXiv:1812.11585

Future Prospects for MMA



Mingarelli et al. simulated the local Universe started with galaxies detected in 2MASS and taking merger rates from Illustrius.

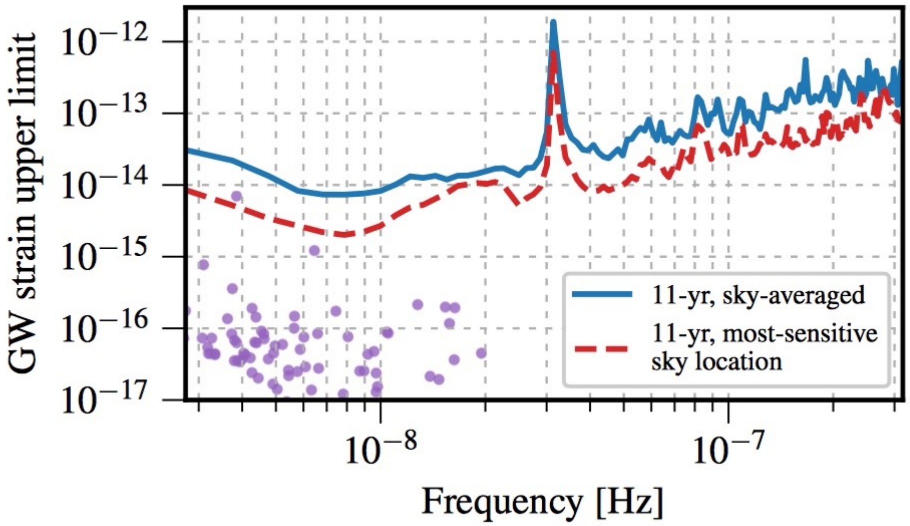


(c) Redshift of parent galaxy mergers

Roughly 10% of galaxies stall, never making it to the GW-driven merger regime.

Mingarelli, et al. 2018, Nature Astronomy, 1, 886

Future Prospects for MMA



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

The NANOGrav Collaboration, 2018, arXiv:1812.11585

We expect a detection of at least one local merger within 10 years.