

NANOGrav Long-Term High-Precision Timing of Millisecond Pulsars

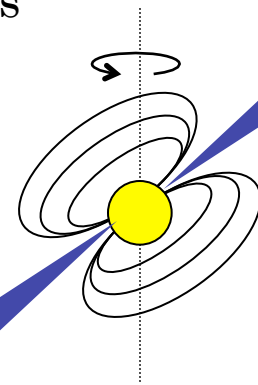
David Nice
Lafayette College

On behalf of the NANOGrav collaboration

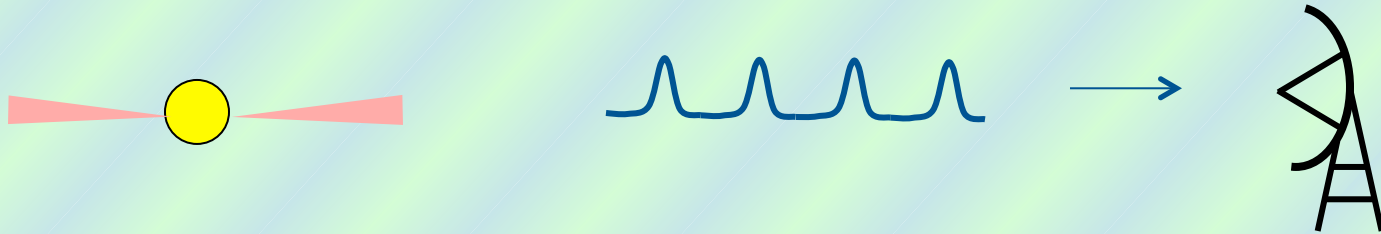
This work is supported by:

- NSF NANOGrav Physics Frontier Center
- NSF support of Arecibo and Green Bank Observatories
- Additional NSF and NSERC grants

21st International Conference on General Relativity and Gravitation
Columbia University, New York
14 July 2016

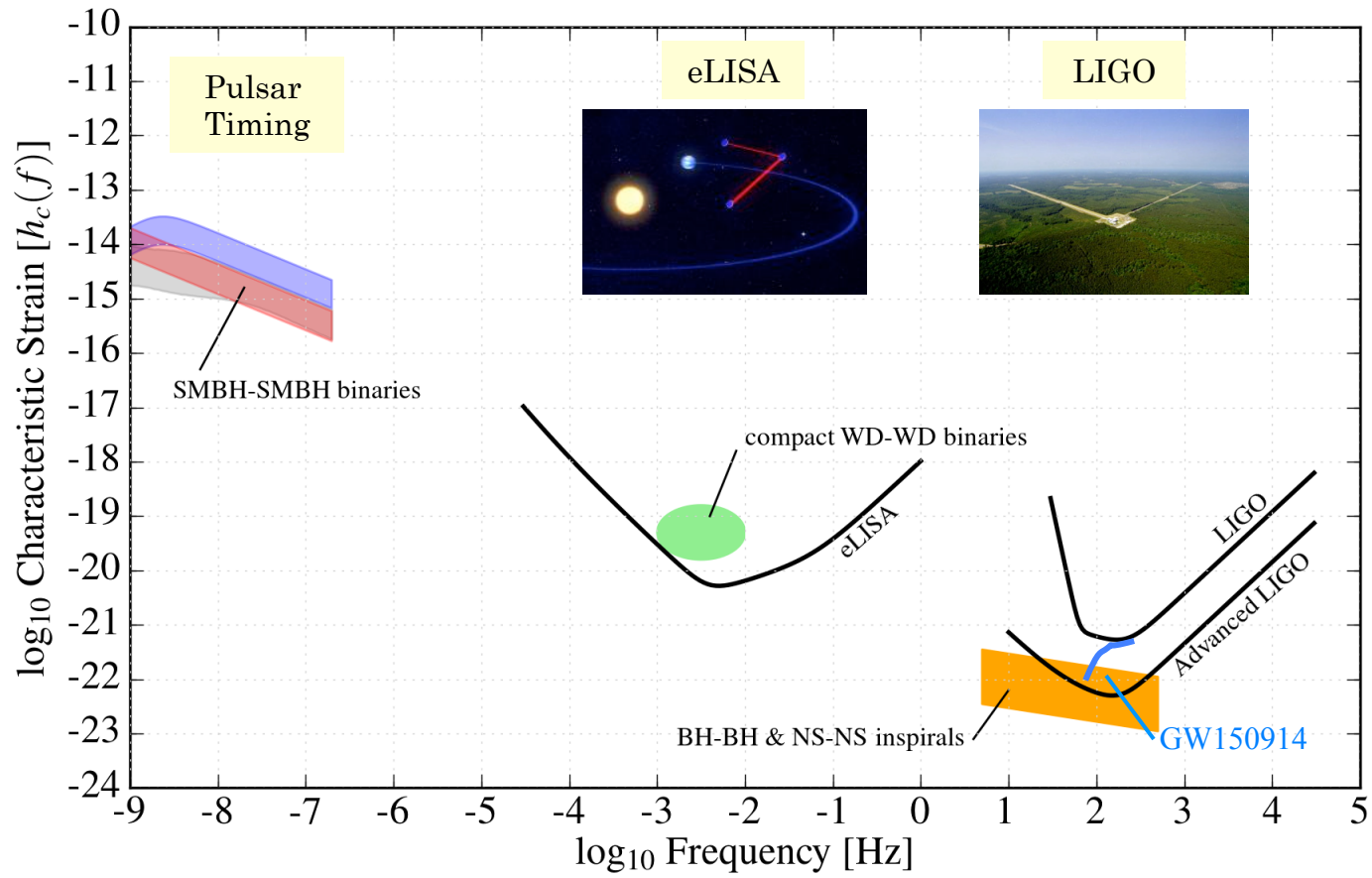


Gravitational Waves: Toward direct detection by Pulsar Timing



1. A pulsar emits pulses. These pulses travel to our telescope, where we measure their times of arrival (TOAs).
2. The passage of a gravitational wave perturbs the TOAs. We will measure these perturbations and thereby detect gravitational waves.
3. We are sensitive to gravitational waves with periods comparable to our observing time spans – months to decades. This corresponds to frequencies of 3×10^{-7} to 3×10^{-9} Hz.

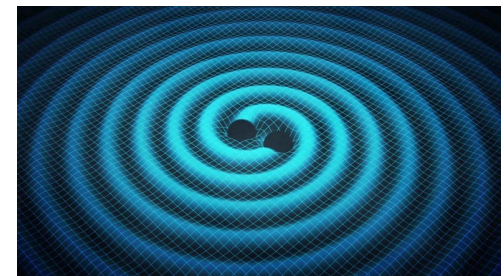
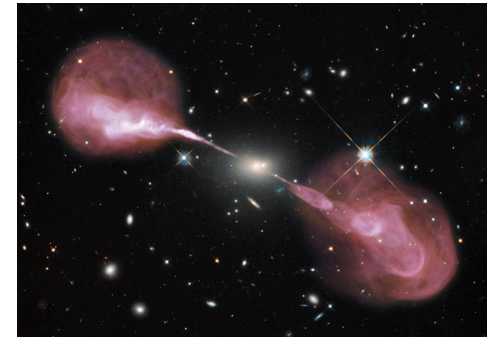
Gravitational Wave Spectrum



Gravitational Waves:

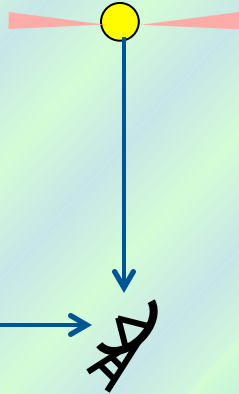
Toward direct detection by Pulsar Timing

1. Some galaxies harbor supermassive, $\sim 10^9 M_{\odot}$, black holes.
2. Galaxies Merge.
3. Black holes from merged galaxies fall toward each other and form tight binaries, emitting gravitational waves.
4. The combination of all supermassive black hole binaries in the universe forms a gravitational wave background. We will detect perturbations in pulsar timing from this gravitational wave background.
5. Or maybe we will be really lucky and a strong binary source will be sufficiently close for us to detect it as an individual source.

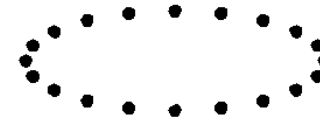
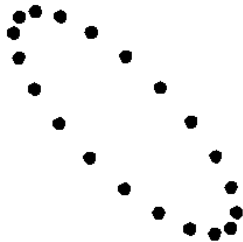
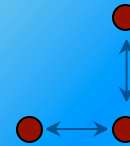


Gravitational Wave Polarization

Pulsar Timing



Interferometer (LIGO, eLISA, etc.)



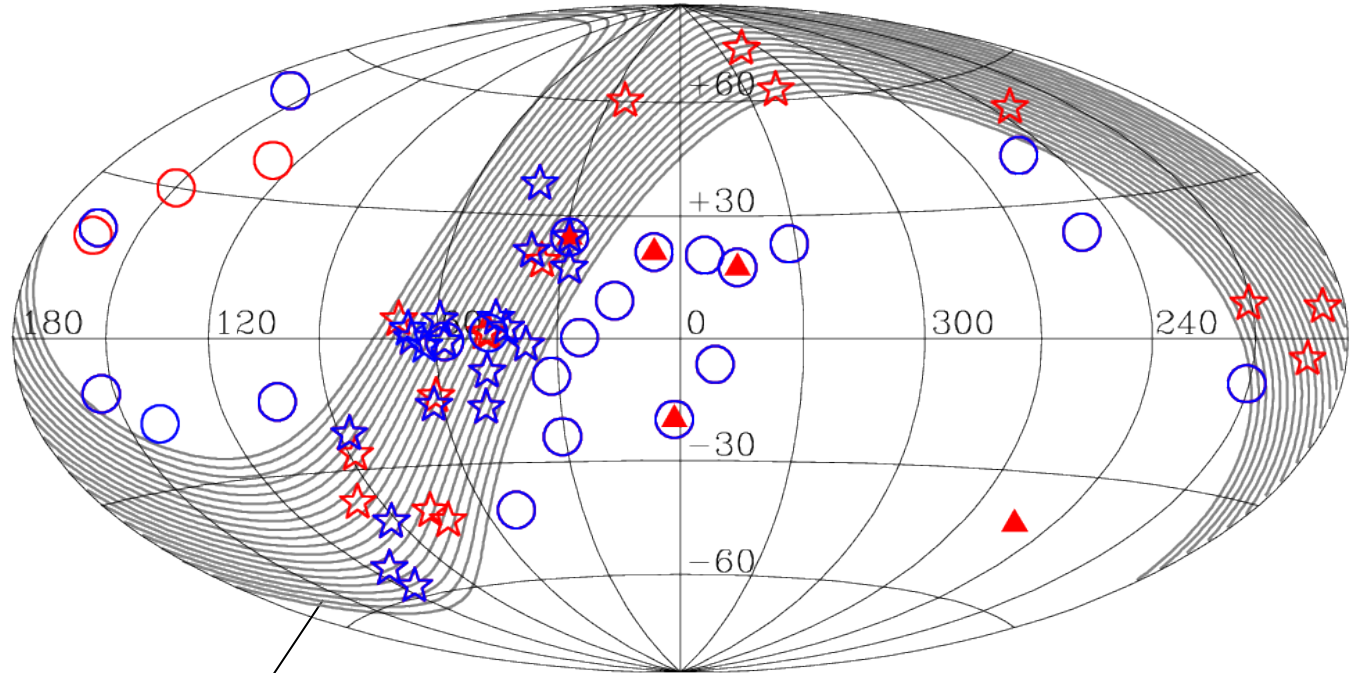
NANOGrav pulsar timing array

Galactic coordinates

Arecibo Observatory



Green Bank Telescope



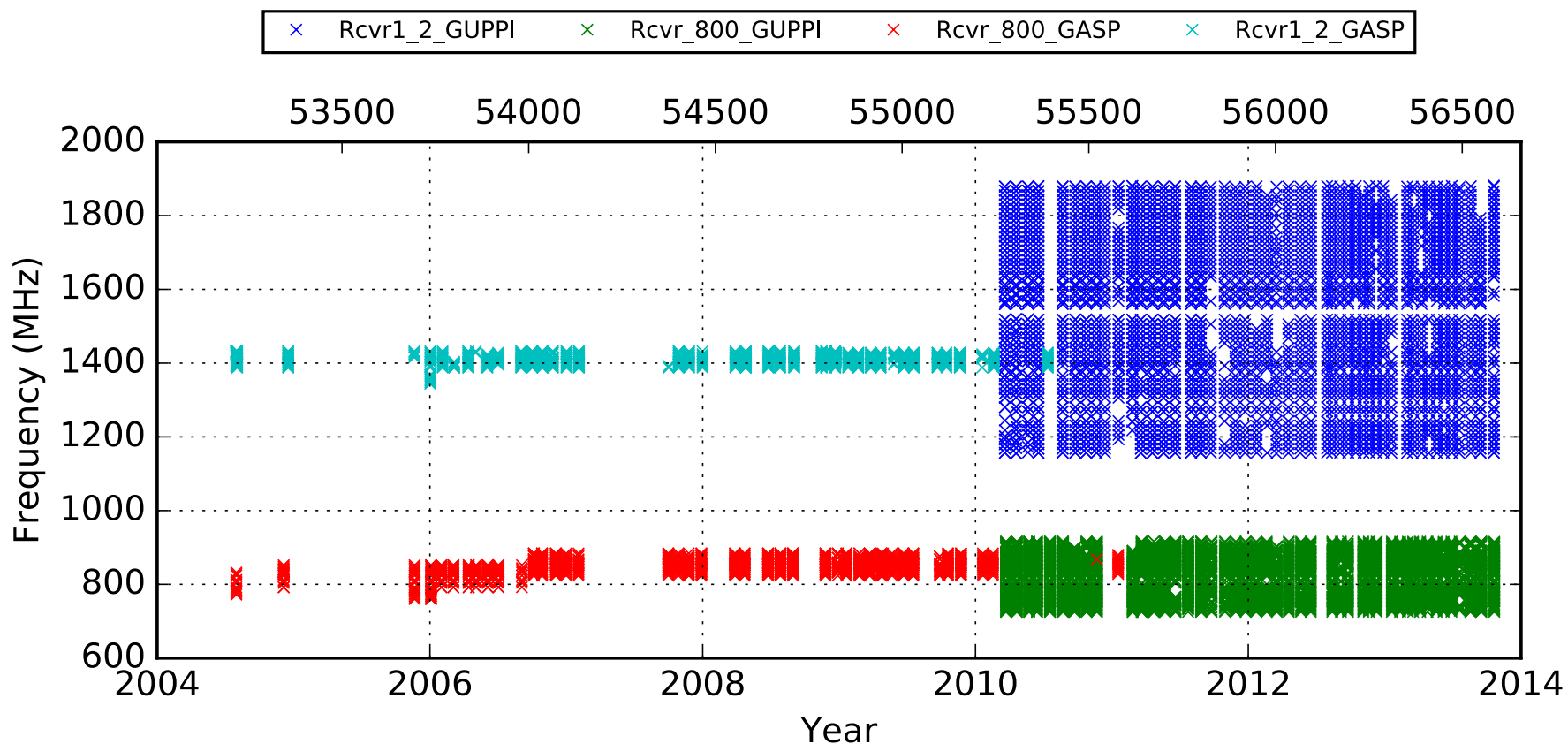
Sky visible from Arecibo

Nine Year Data Set (2005-2013)	★ Arecibo	19
	○ Green Bank	20
More Recent Additions	★ Arecibo	33
	○ Green Bank	23
	▲ VLA	5

NANOGrav Nine-Year Data Set

Typical frequency coverage

J1744-1134



NANOGrav Nine-Year Data Set

39 pulsars, cadence 3-4 weeks

4,138 unique observations*

169,453 TOAs

Many TOAs per observation

Smooth variation of TOA w/frequency (FD)

DM measured over short intervals (DMX)

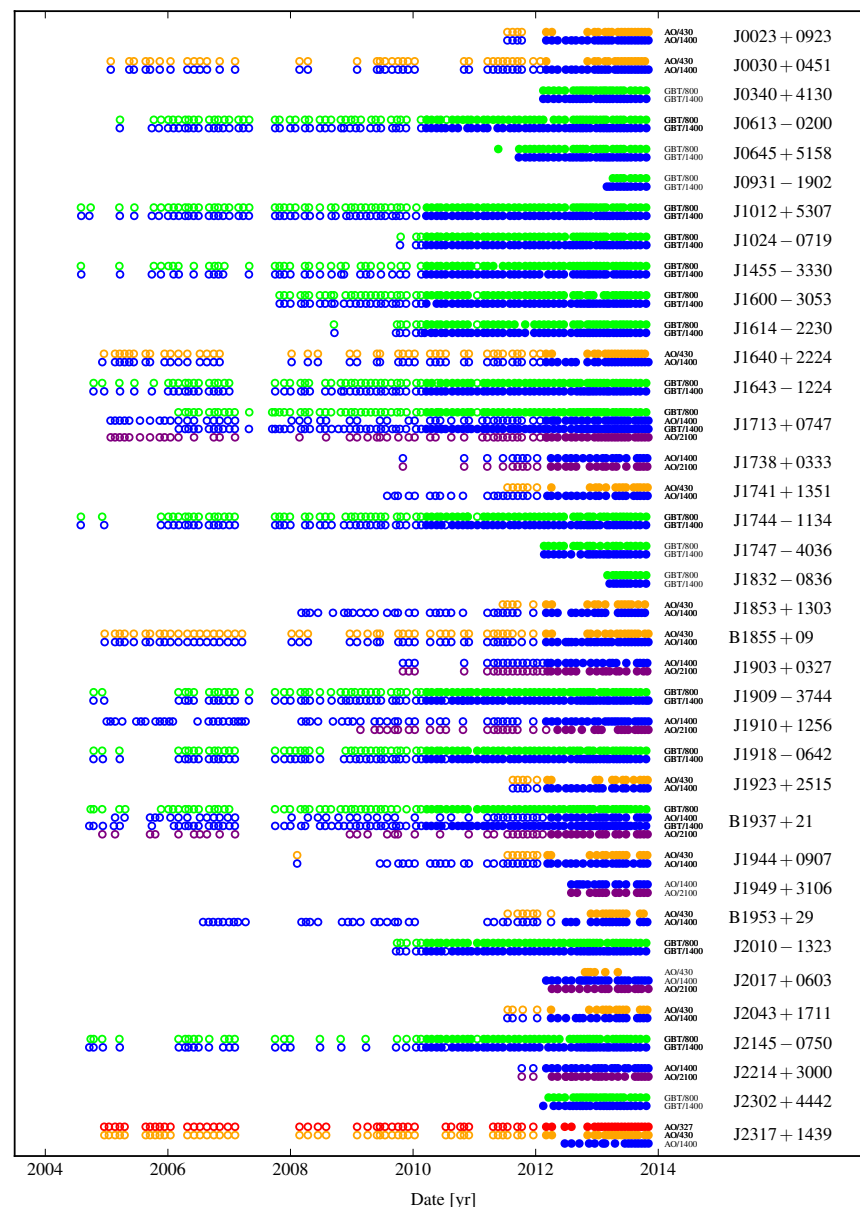
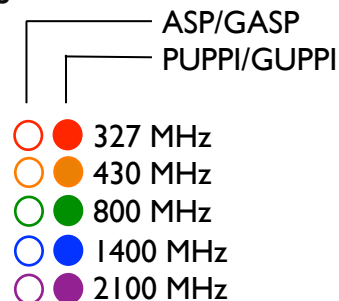
Use systematic rules, e.g.:

- F-test for parameter inclusion
- SNR < 8 TOAs rejected
- IPTA format TOAs

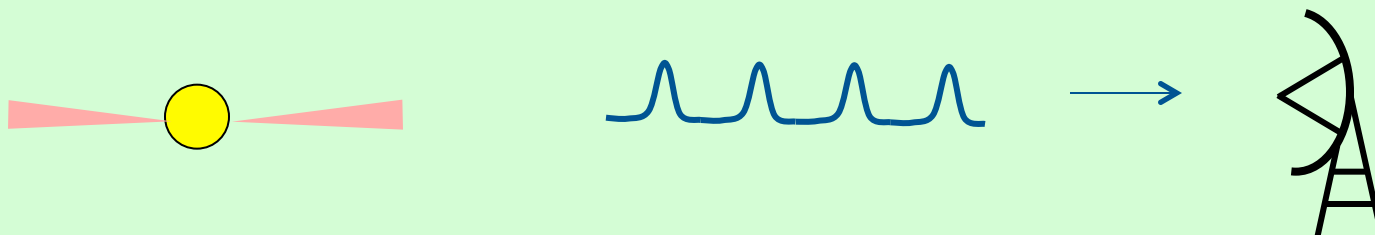
Introduce noise model:

- Red noise
- Correlations in simultaneous TOAs
- Scaling and Quadrature terms

**Observation* is defined as a unique combination of pulsar and receiver observed within a single day



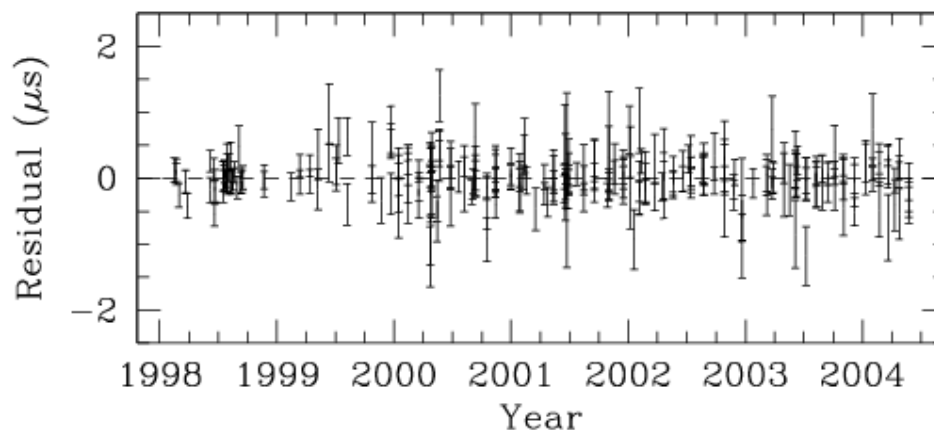
Observing The Pulsar Signal



“Residuals” are differences between measured pulses times of arrival and expected times of arrival:

$$\text{residual} = \text{observed TOA} - \text{computed TOA}$$

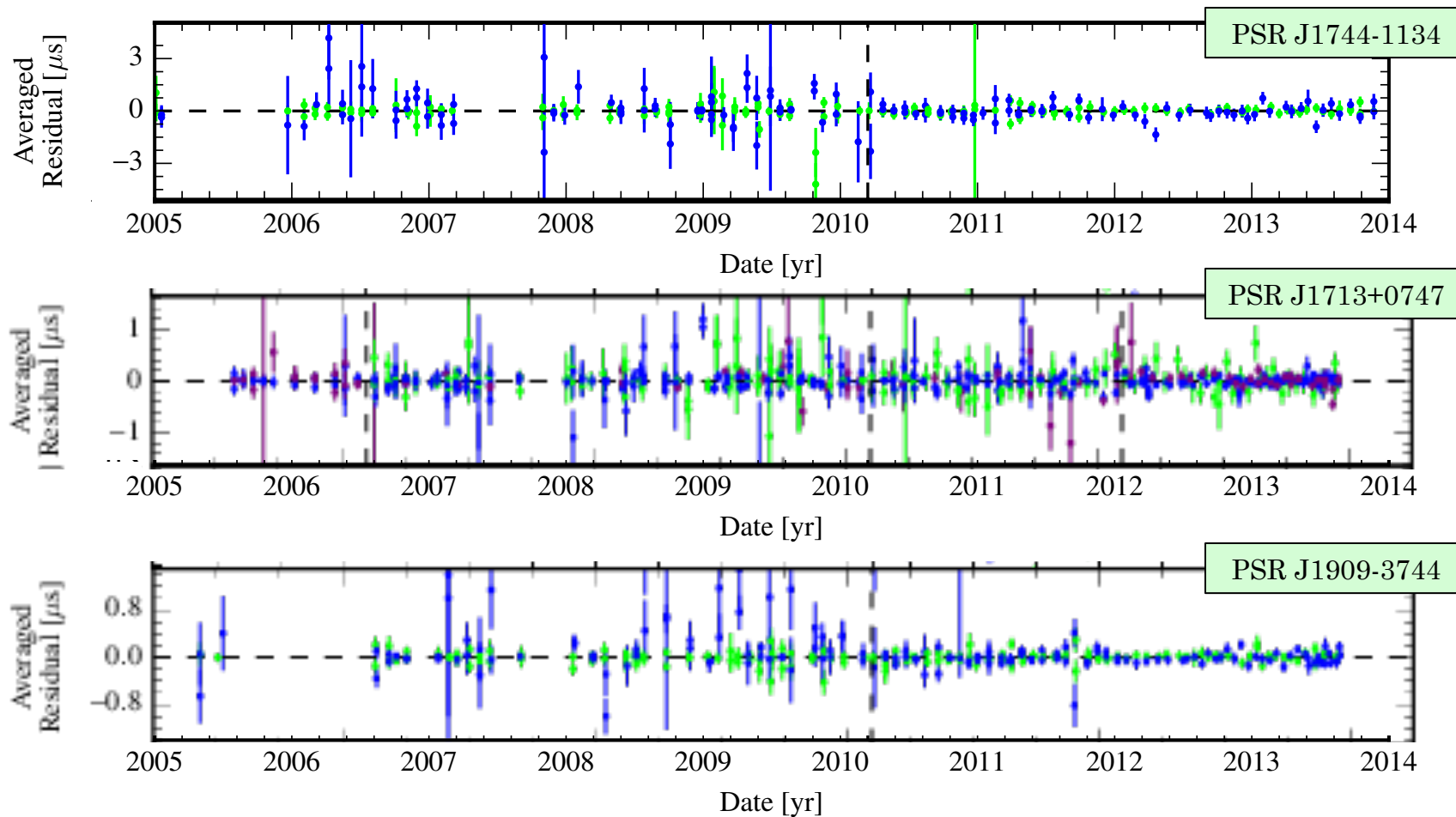
We hope to detect gravitational wave signals as perturbations of these residuals.



PSR J1713+0747
Splaver et al. 2005
ApJ 620: 405
astro-ph/0410488

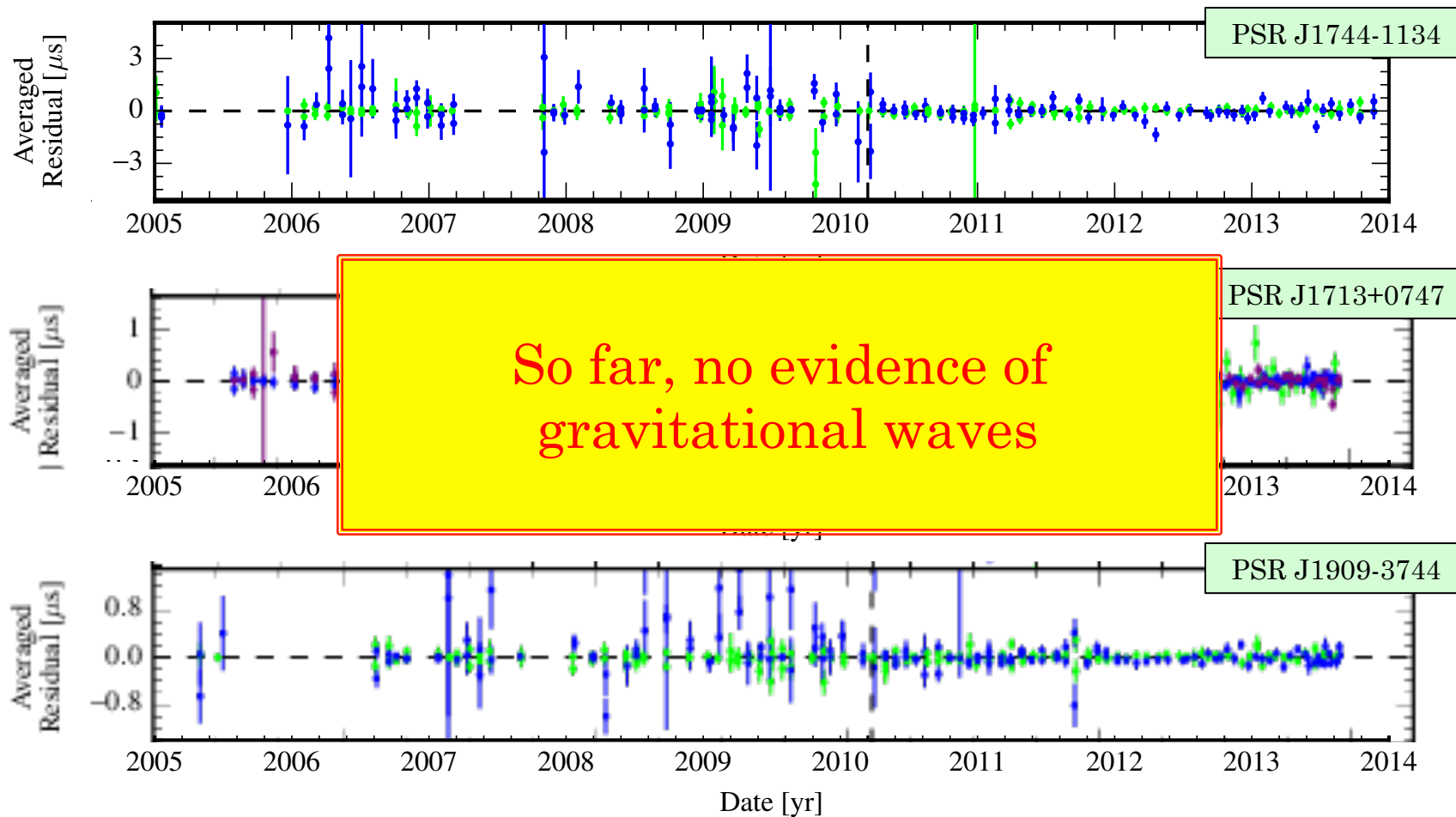
Show Me The Residuals

NANOGrav Nine-year data set

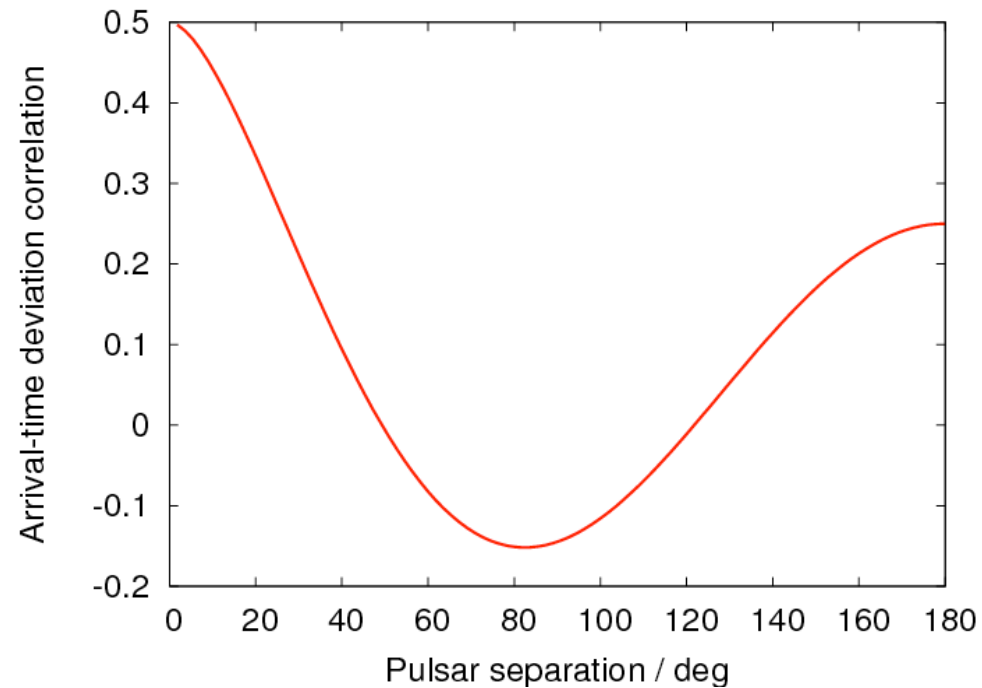
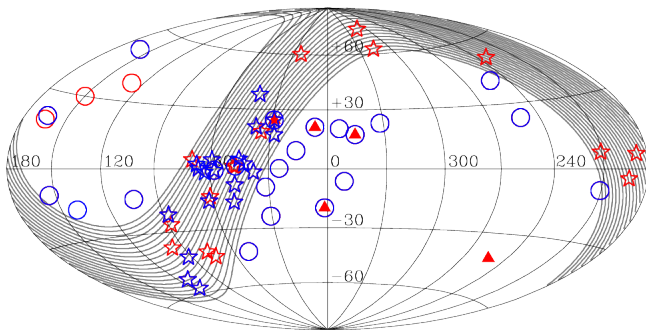
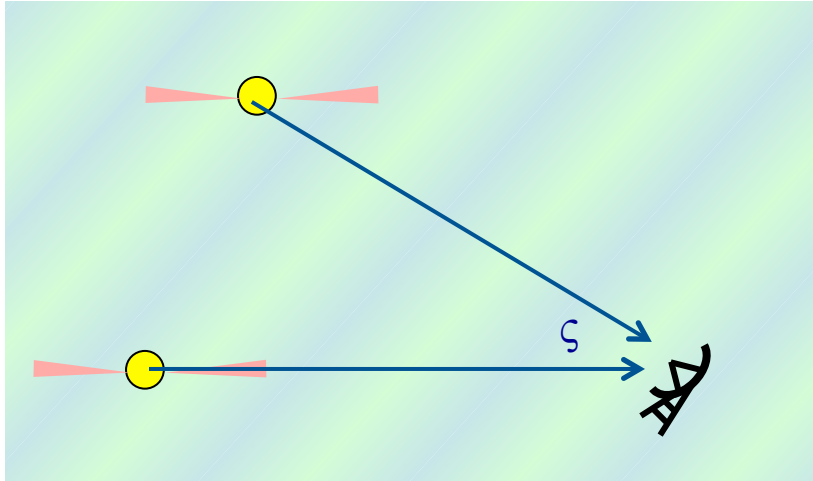


Show Me The Residuals

NANOGrav Nine-year data set

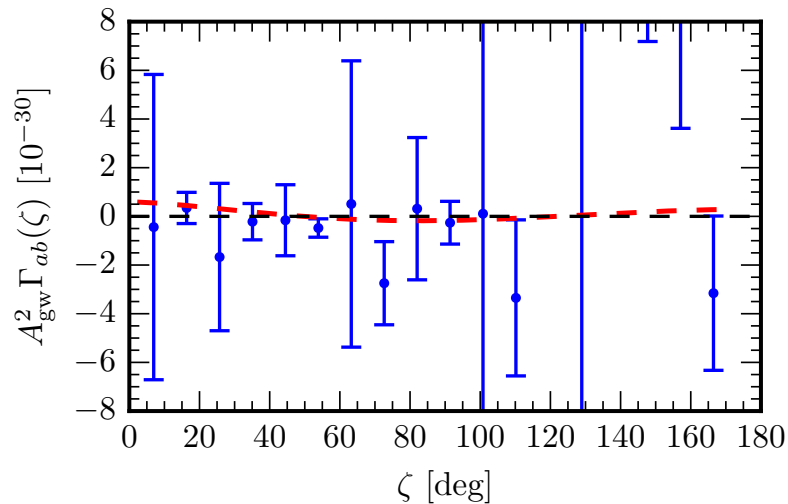


Predicted correlation by angular separation on the sky (Hellings-Downs curve)



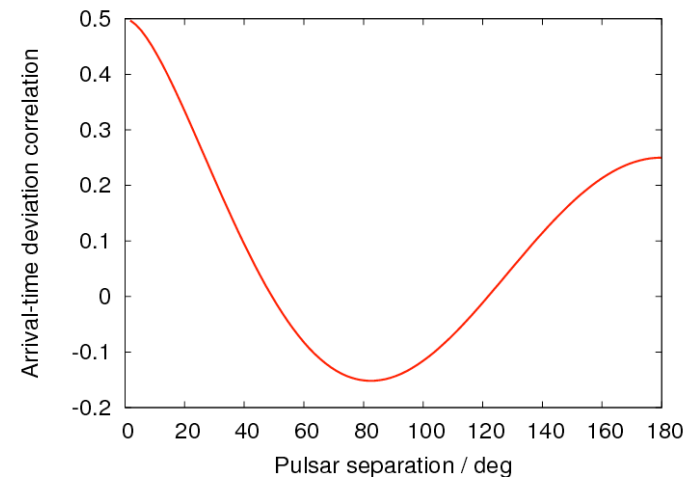
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NANOGrav 9-year data set
Measured angular correlation



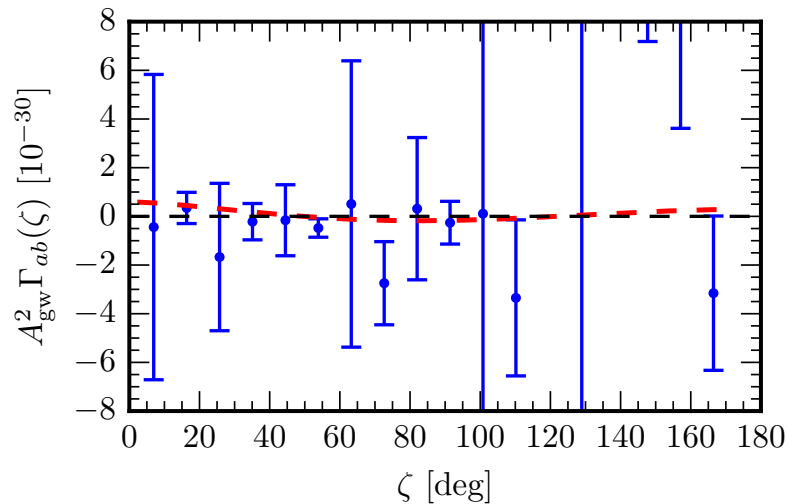
VS

Theoretical correlation for
Isotropic background signal



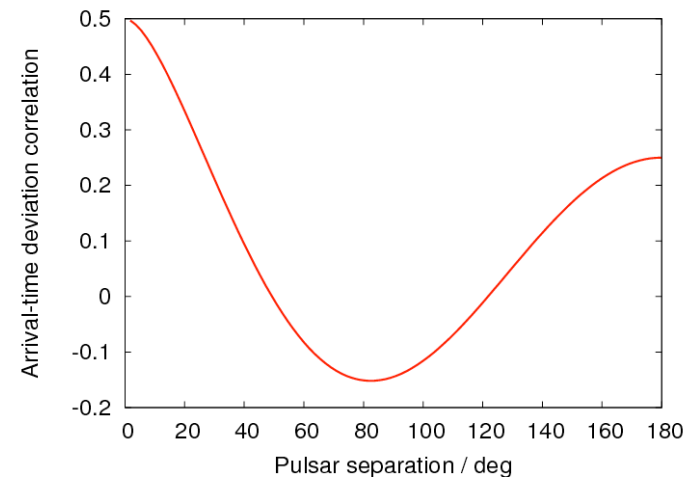
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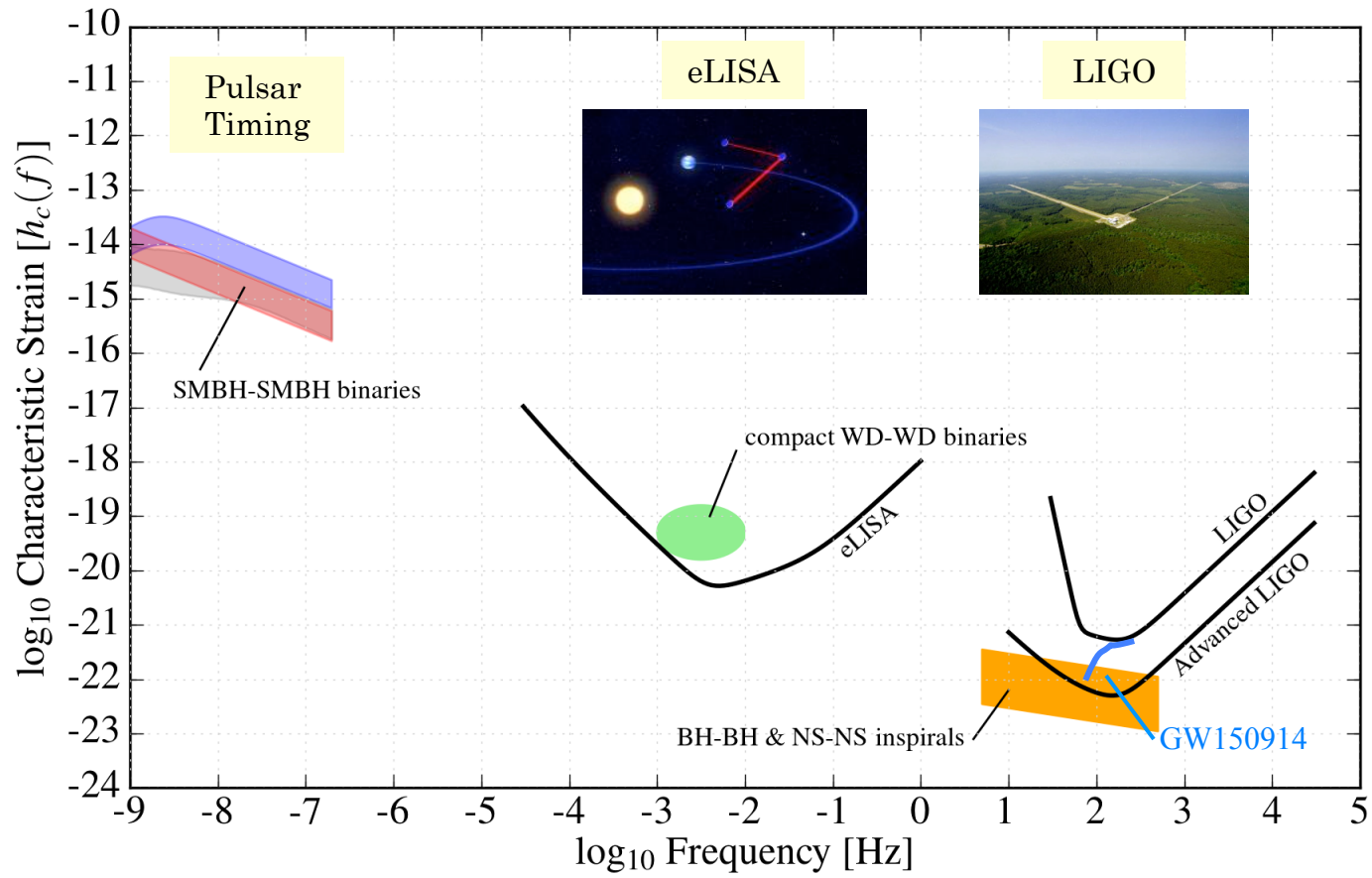
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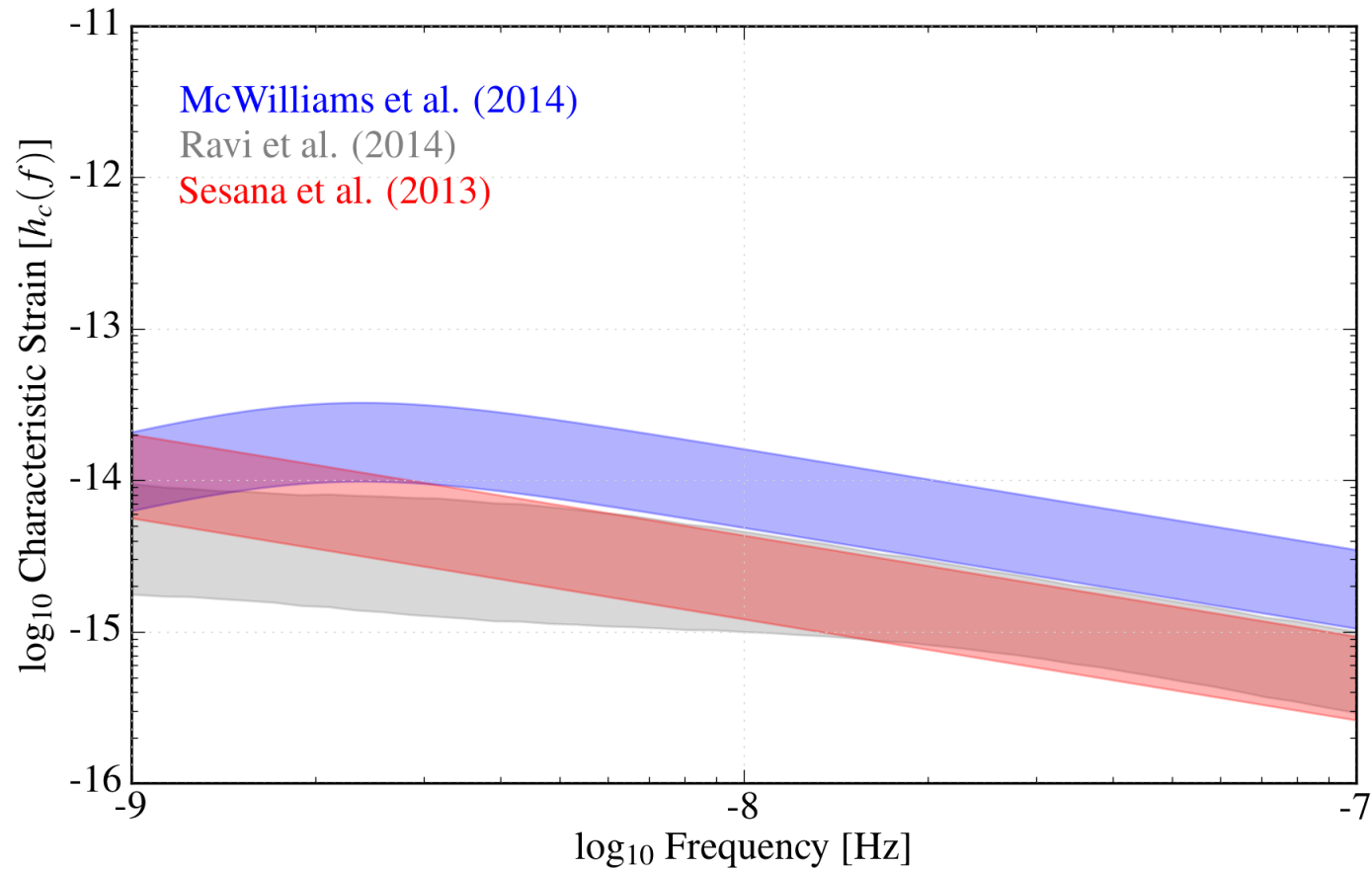


➔ No detection of gravitational waves (yet)

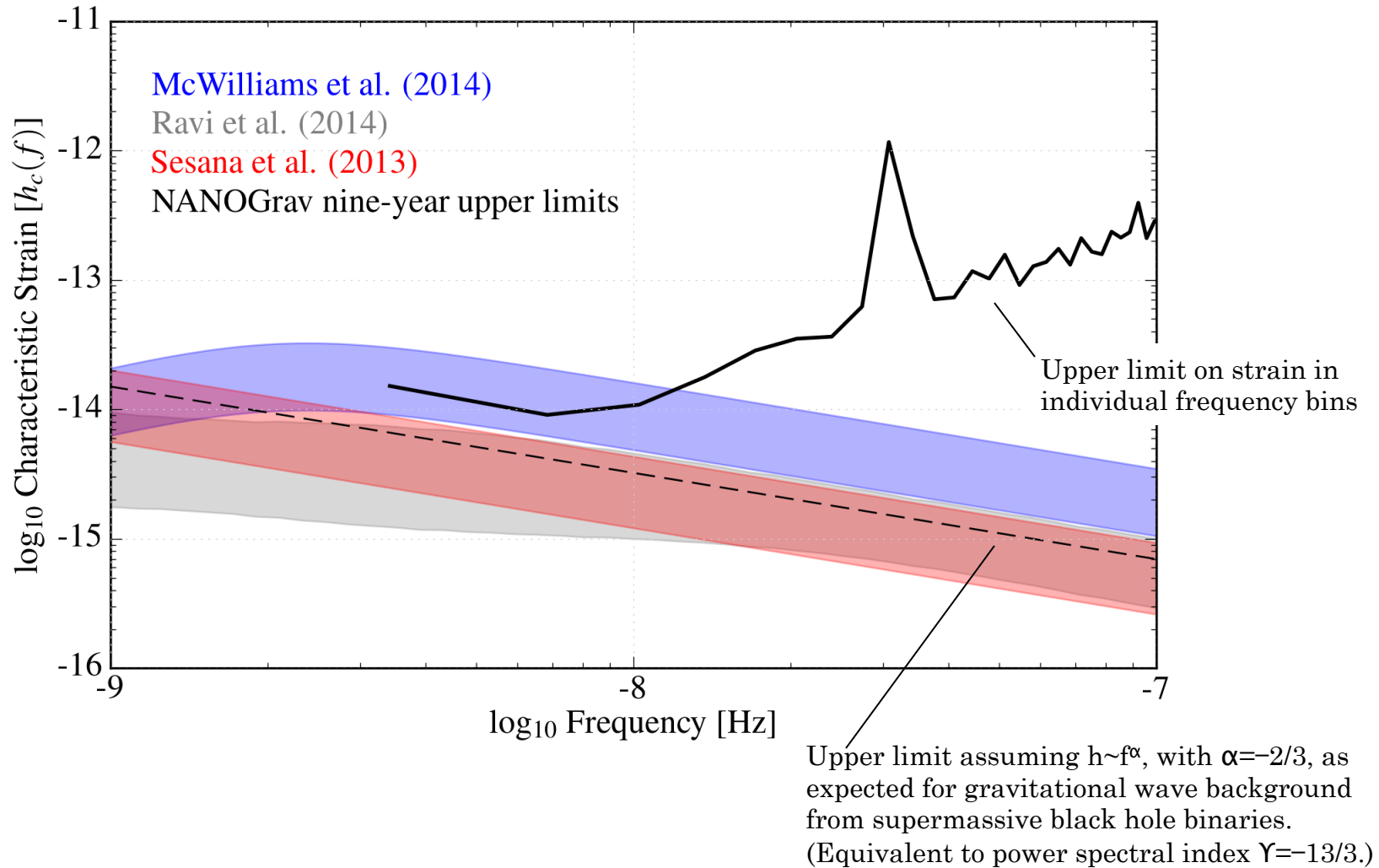
Gravitational Wave Spectrum



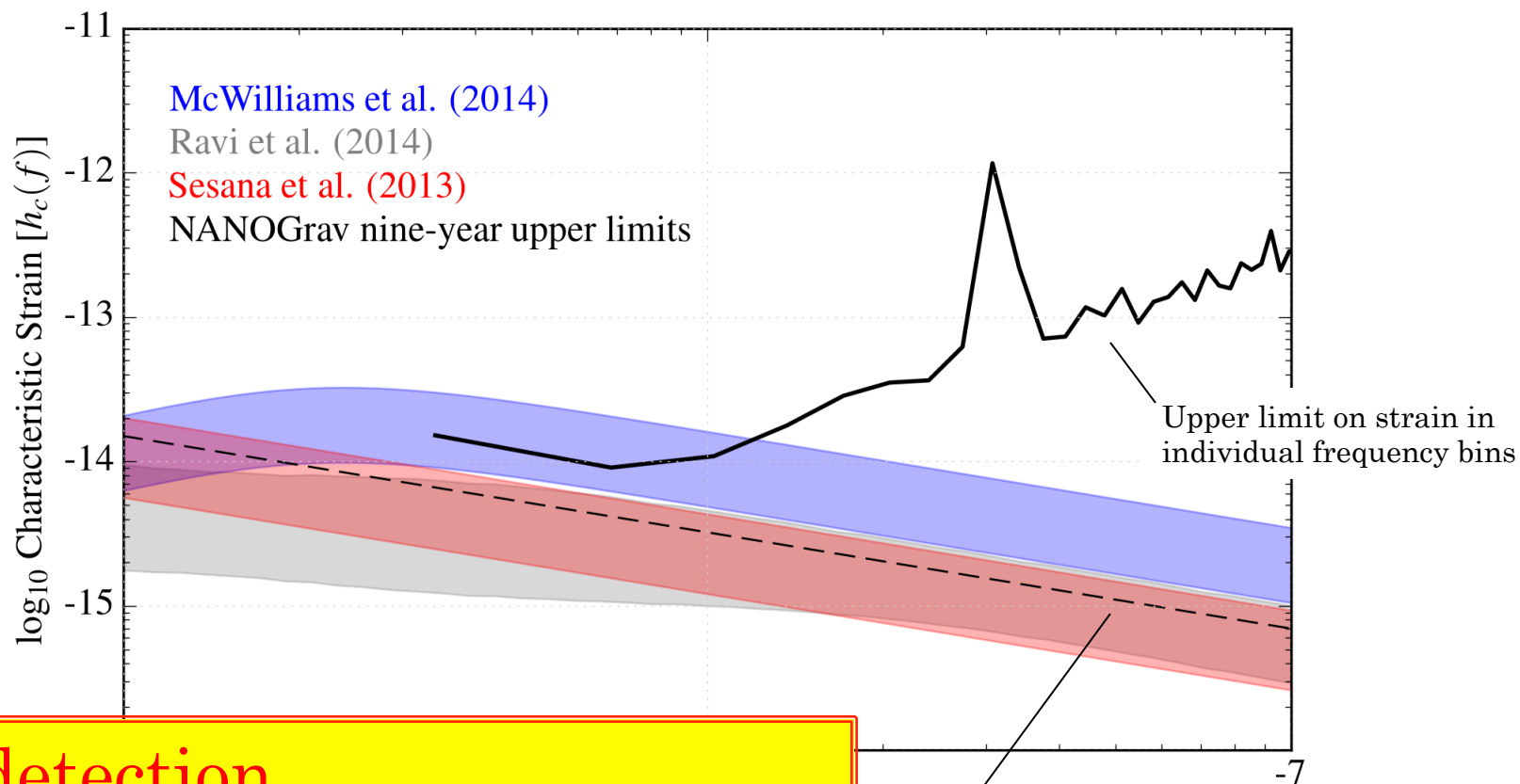
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Gravitational Wave Spectrum



Gravitational Wave Spectrum

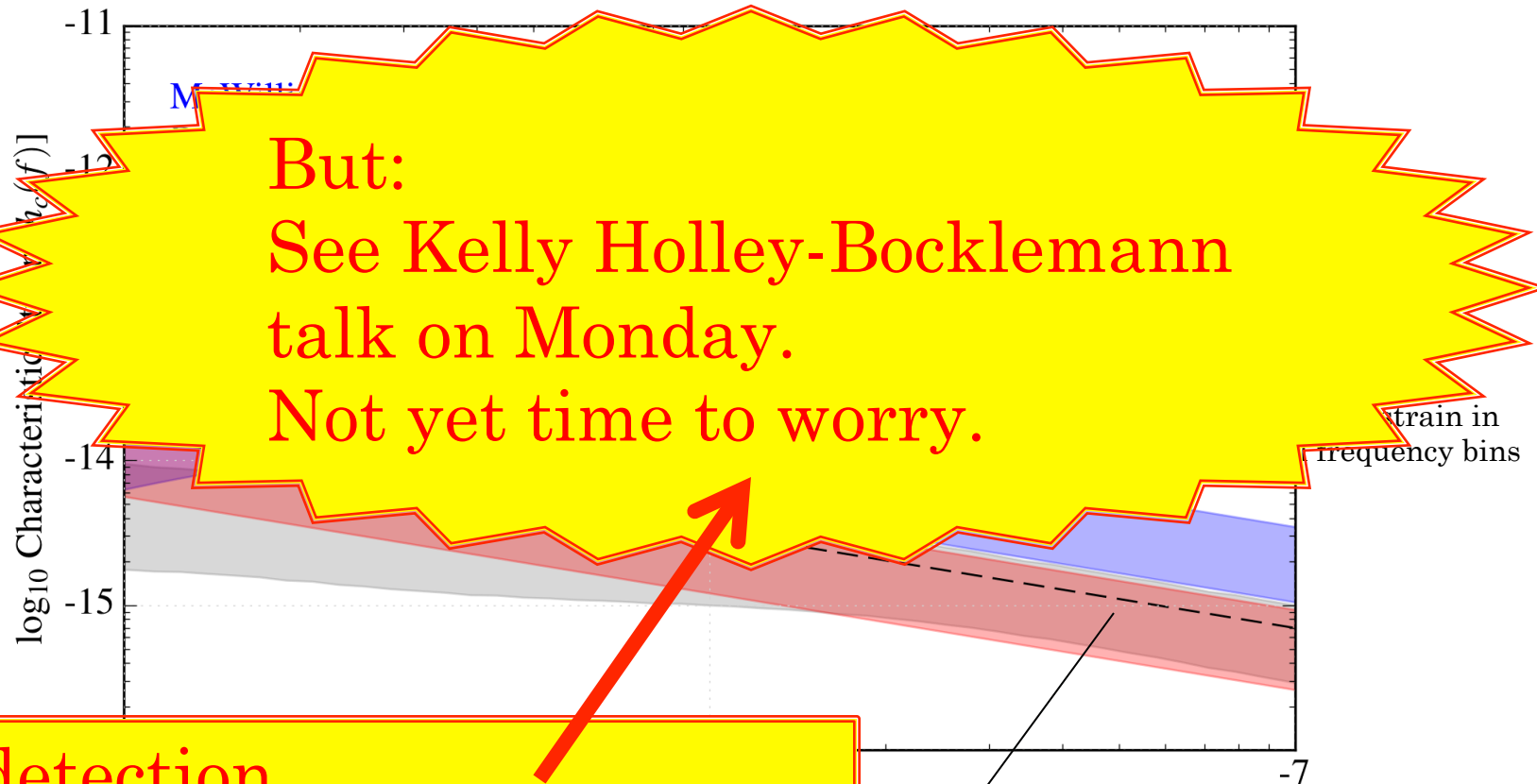


Non-detection

→ Tension with theoretical predictions

Upper limit assuming $h \sim f^\alpha$, with $\alpha = -2/3$, as expected for gravitational wave background from supermassive black hole binaries. (Equivalent to power spectral index $\gamma = -13/3$.)

Gravitational Wave Spectrum



Non-detection

→ Tension with theoretical predictions

Context for Nanohertz Gravitational Waves

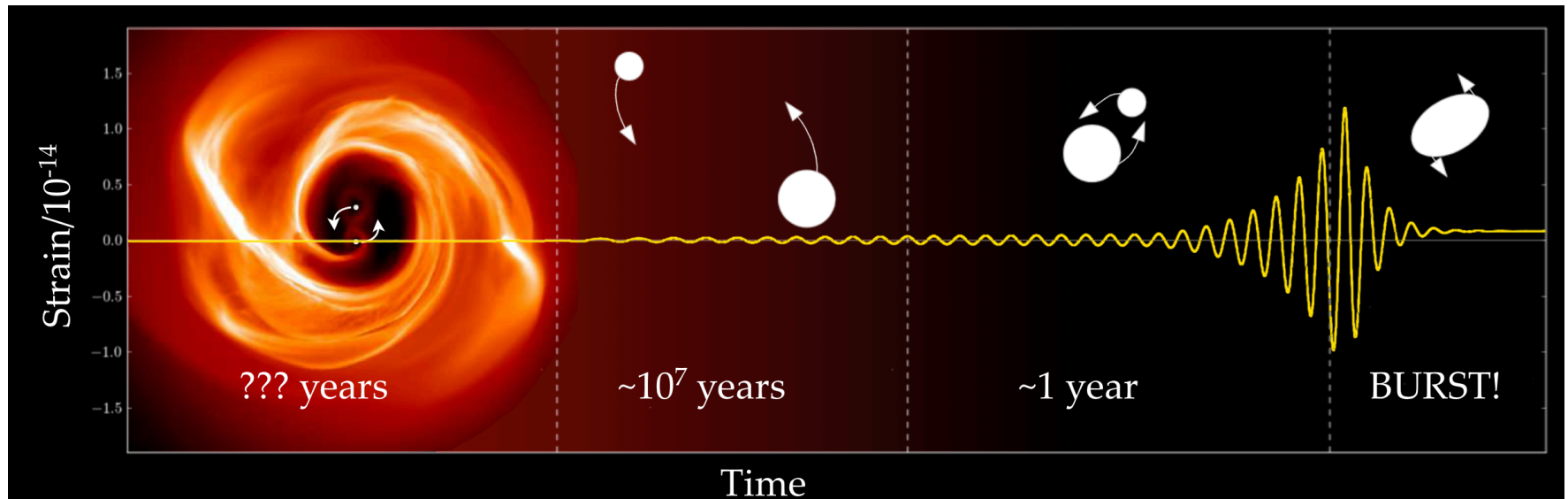
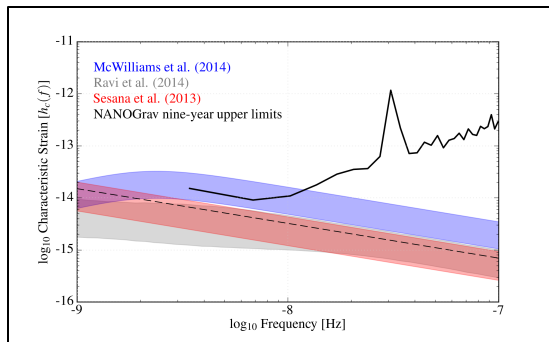


Figure: Sarah Burke-Spolaor

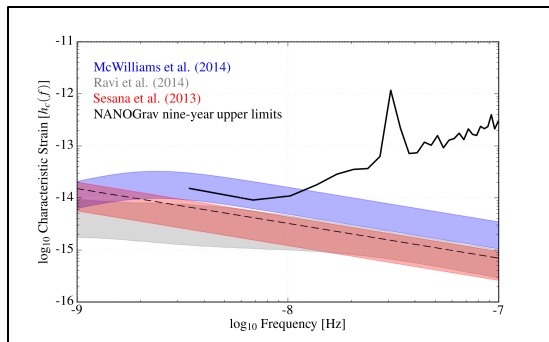


Tension between theory and observation: Possible explanations

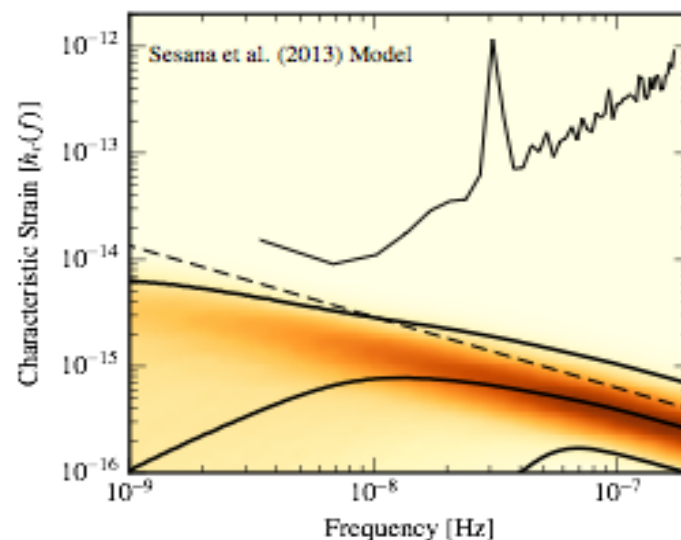
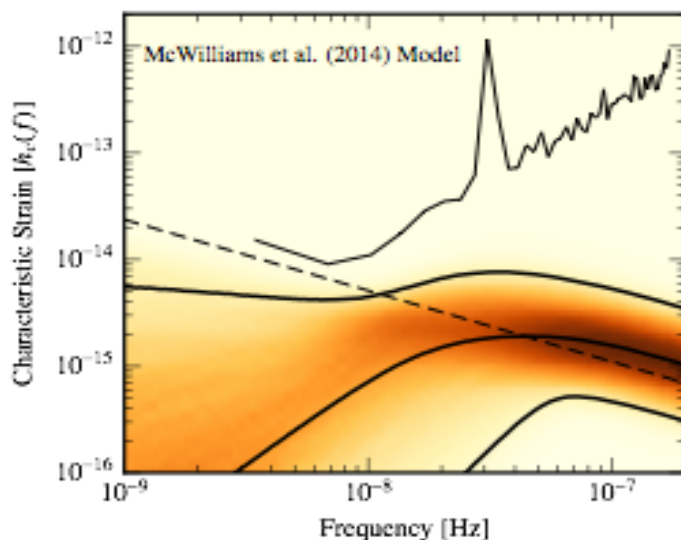
- *Power is lower than expected at all observed frequencies.*

Possible causes:

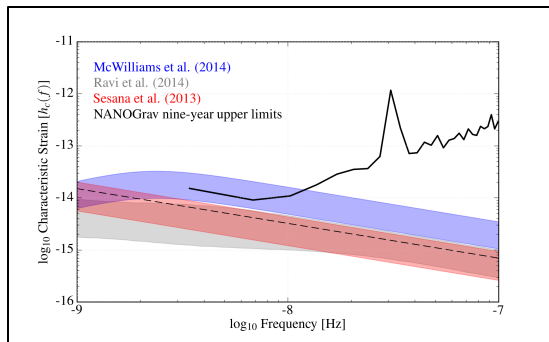
- Overestimated supermassive black hole population (Sesana et al 2016)
- Supermassive black hole binary systems “stall” at long periods; most do not reach the short orbital periods necessary for us to see them. (“last parsec problem.”)
- Supermassive black hole binary systems have significant eccentricity, emit more gravitational radiation than circular systems, and therefore evolve more quickly (so fewer of them are around at any point in time).



Tension between theory and observation: Possible explanations



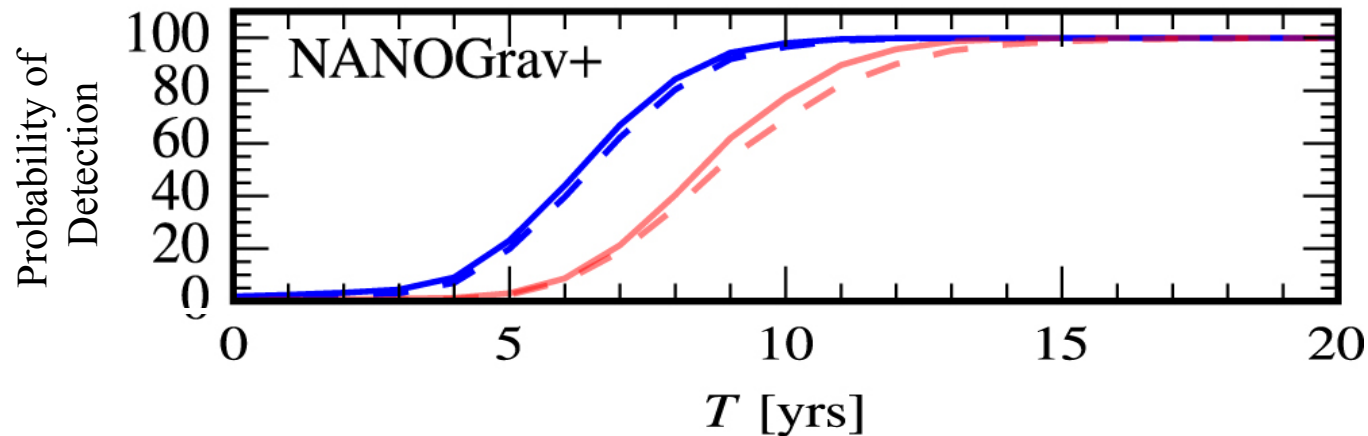
- *Broken power spectrum.* Observed gravitational wave power is low at the lowest observed frequencies, but matches expectations at high frequencies. Possible cause:
 - Supermassive black hole binaries with periods of a few years (i.e., our lowest observed frequencies) evolve more quickly than expected due to interactions with stars and gas.



Tension between theory and observation:
The key point.

Although we have not yet detected gravitational waves, our observations are challenging some theoretical models and are allowing us to make astrophysical inferences from the data: constraints on population and evolution of supermassive black hole binaries.

Time to Detection



Probability of detection as a function of time beyond the nine-year data set

- “Detection” means detection of gravitational wave background with 0.13% false-alarm probability.
- Assumes a gravitational wave background signal based on prior from Sesana et al (2013) combined with all existing pulsar timing array upper limits.
- Assumes existing NANOGrav array and noise properties plus modest growth.

- Pure power law, no stalling
- - Broken power law, knee at $1/(11 \text{ yr})$, no stalling
- Pure power law, 90% stalling
- - Broken power law, knee at $1/(11 \text{ yr})$, 90% stalling

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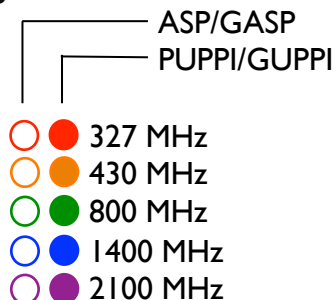
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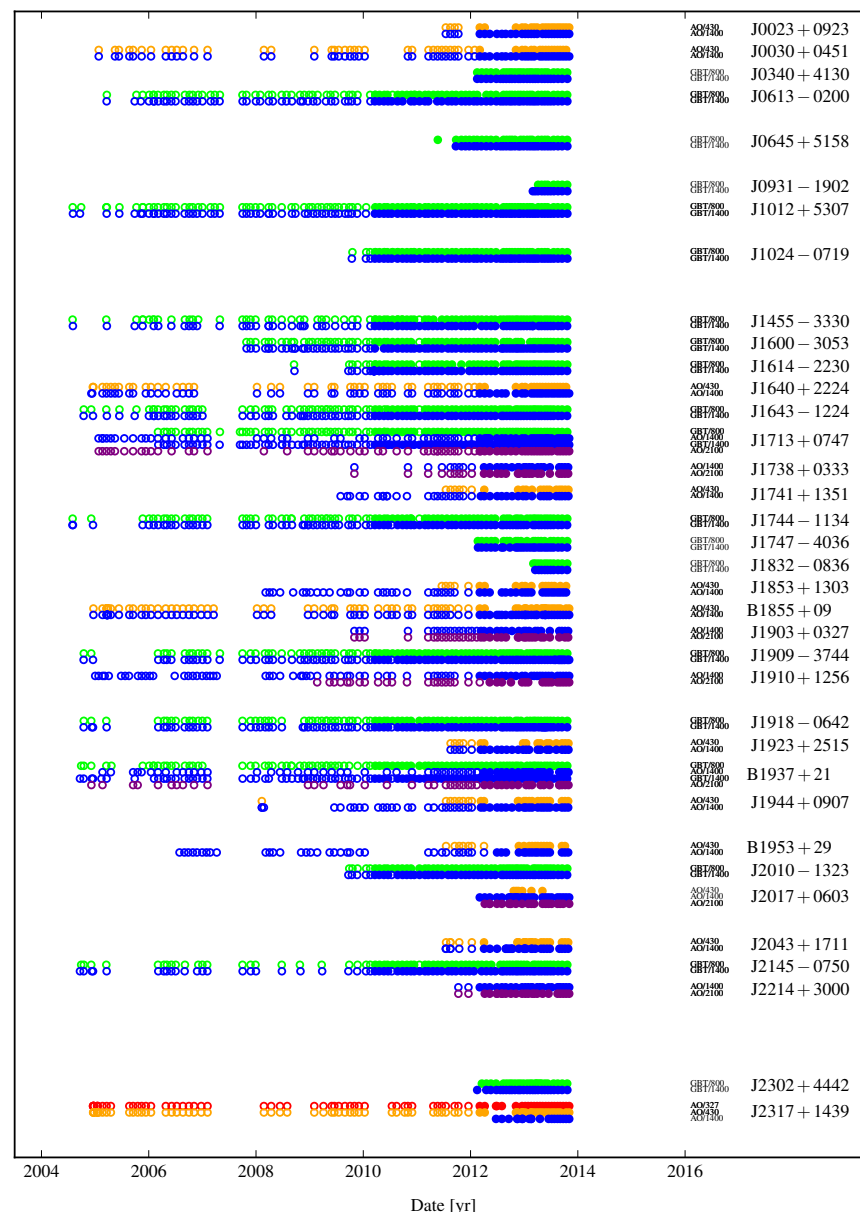
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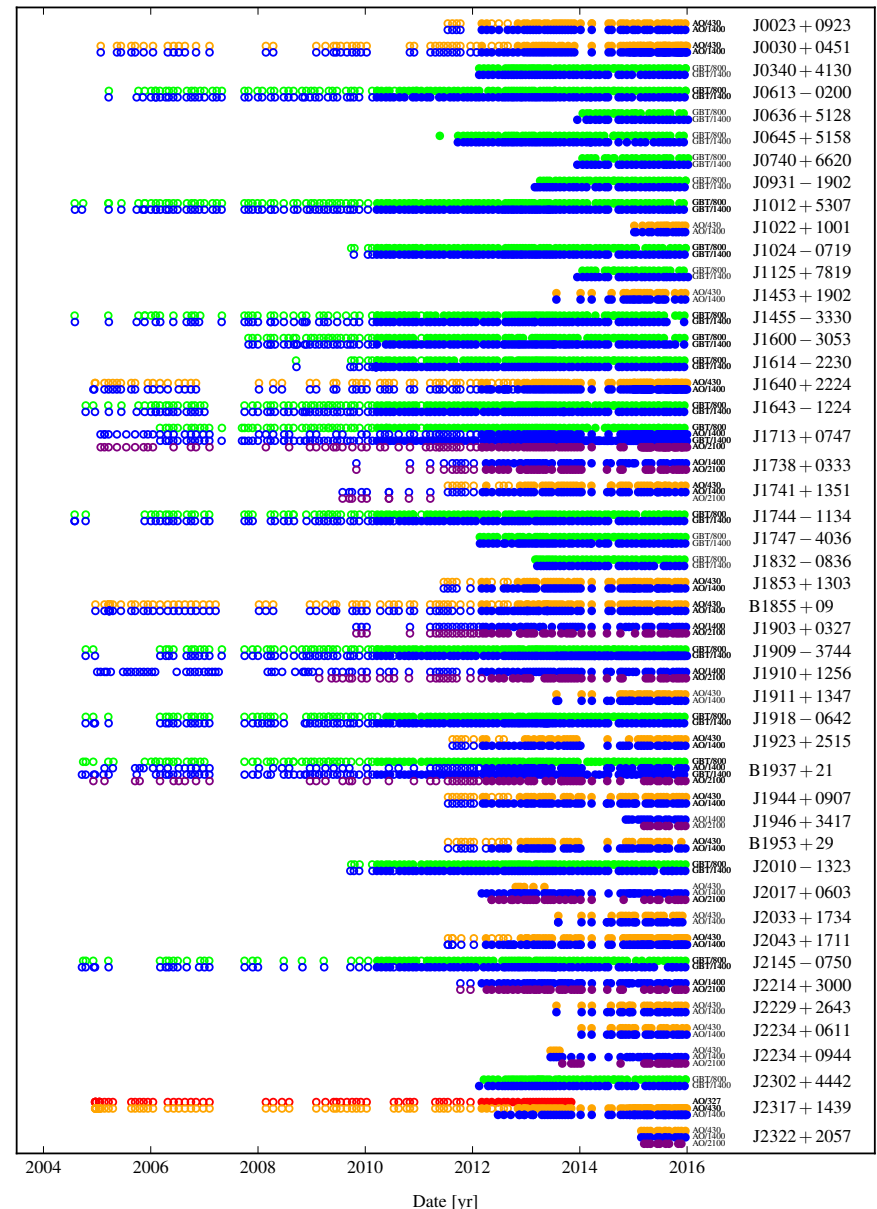
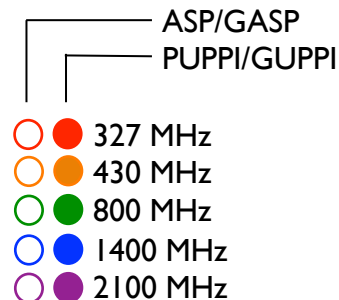
NANOGrav Eleven-Year Data Set

48 pulsars; 3-4 weeks; except 7 weekly
6,951 unique observations*
314,971 TOAs

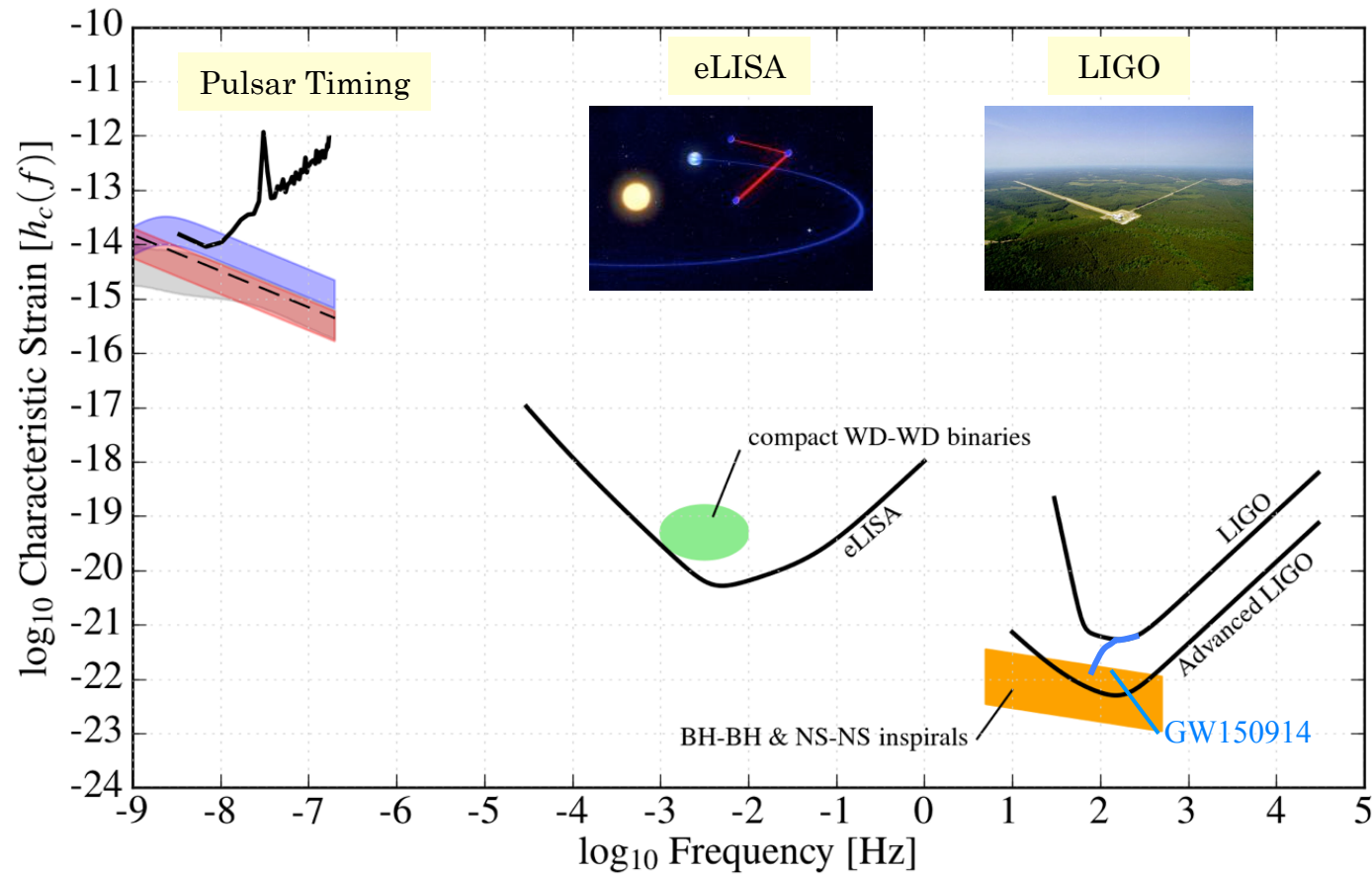
Re-use the structure and pipeline of the
Eleven-Year Data Set as much as possible.



**Observation* is defined as a
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Summary



Data are available → data.nanograv.org