

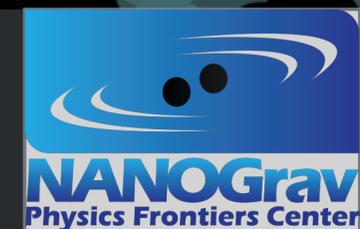
# Gravitational Wave Detection with Pulsar Timing Arrays

Sarah Vigeland

University of Wisconsin-Milwaukee



Aspects of Gravity Workshop  
October 7, 2020



# Gravitational Wave Spectrum

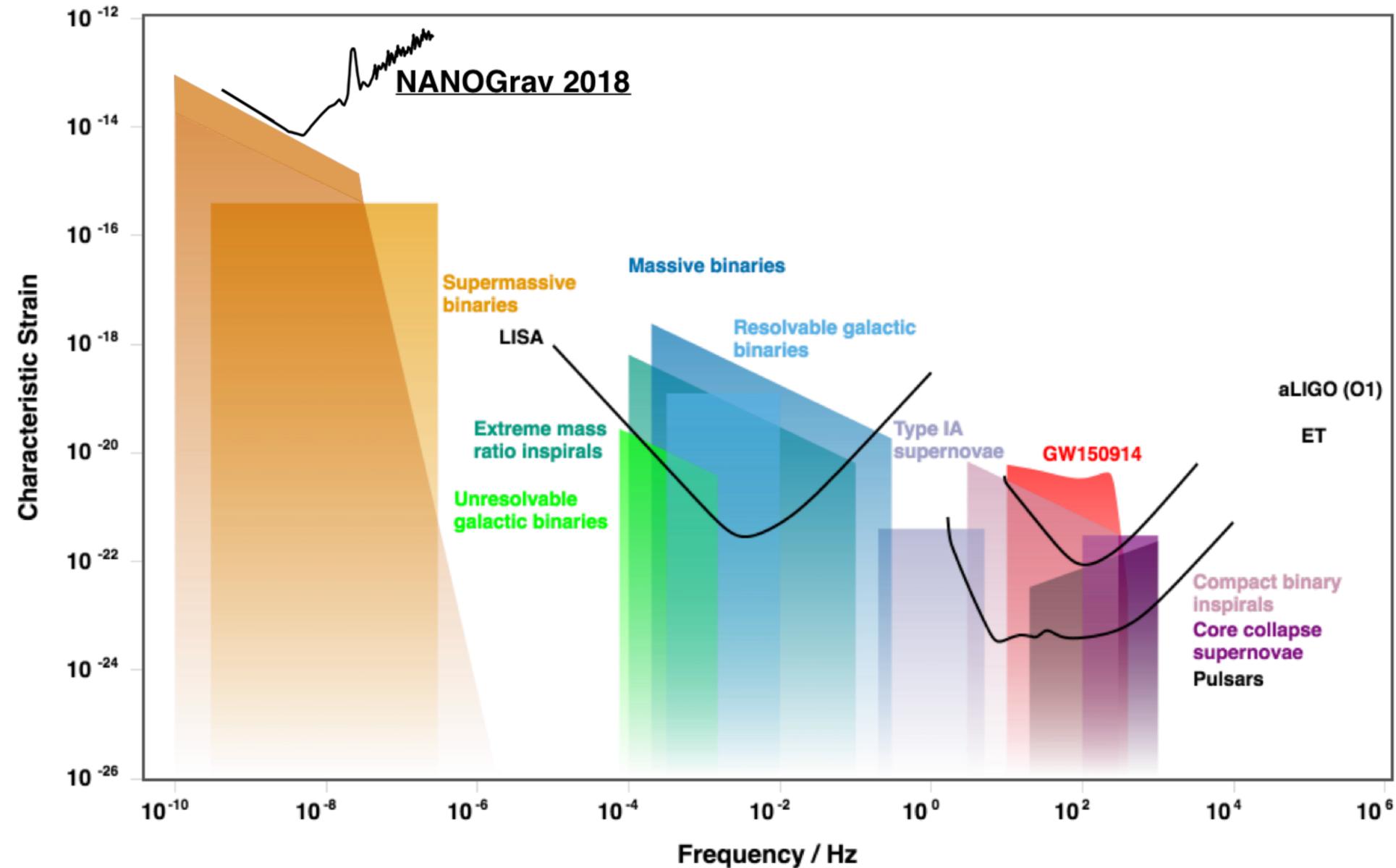
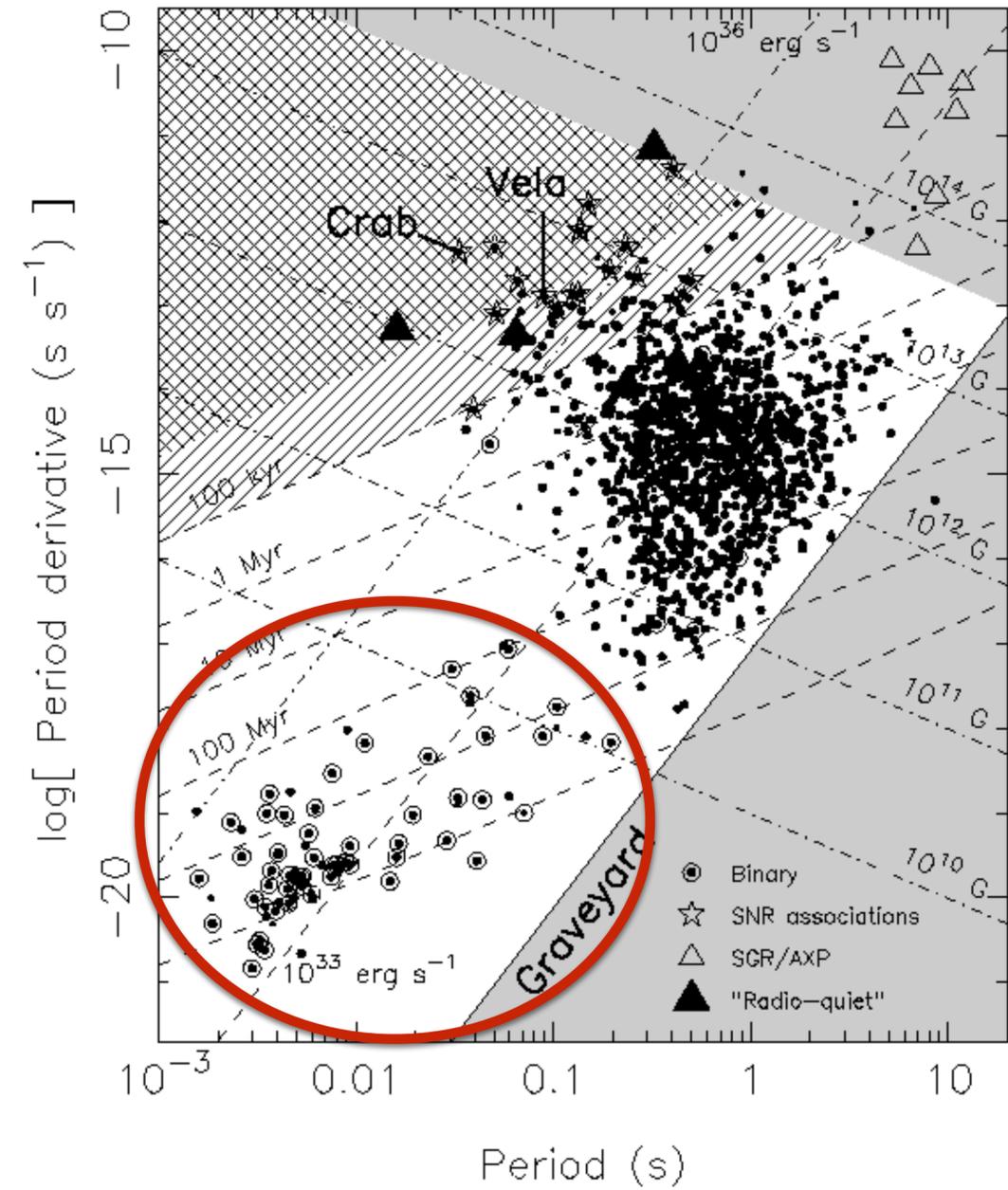
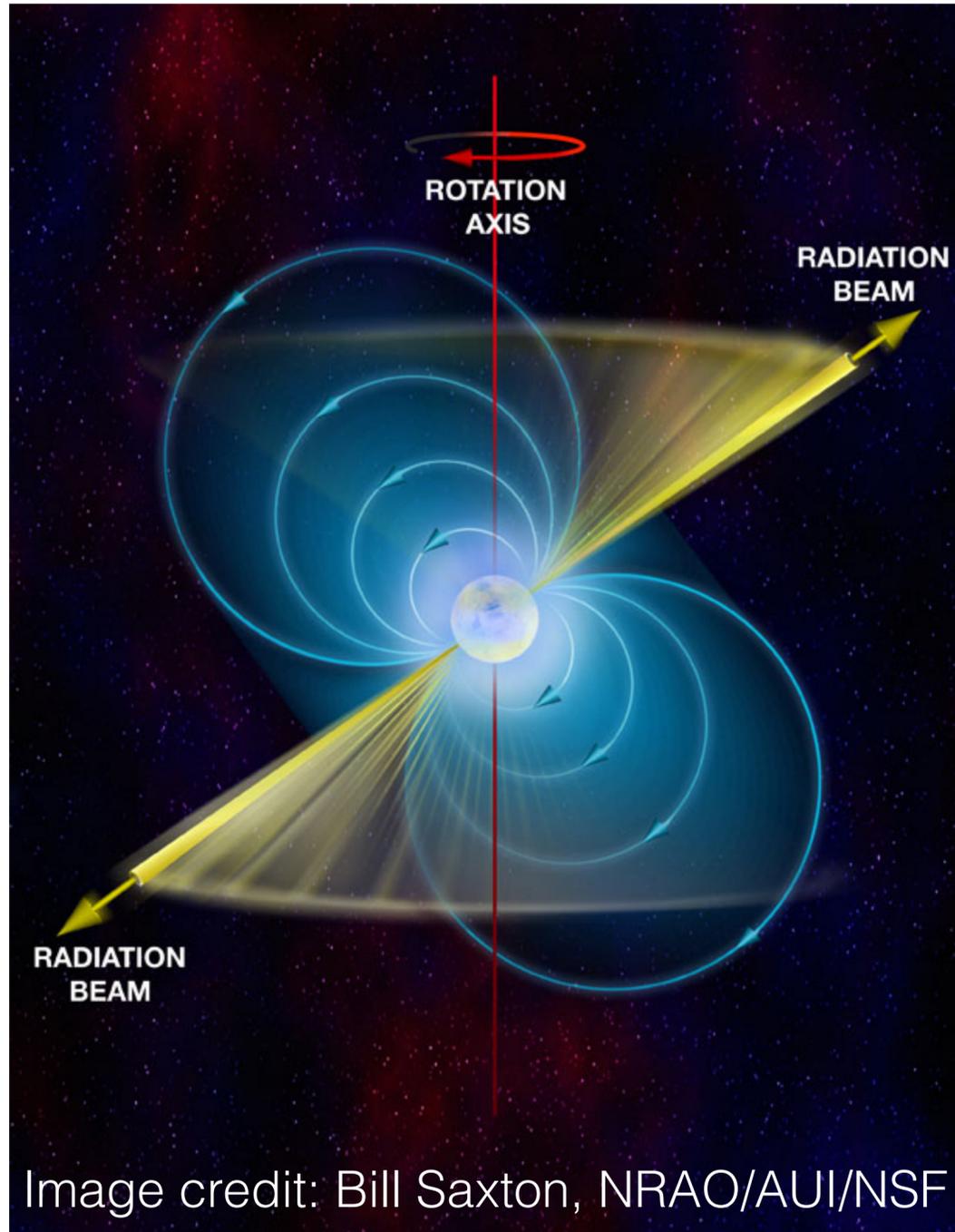


Figure credit: Moore, Cole, Berry (2014); modified by S.R. Taylor

# Pulsars



From the *Handbook of Pulsar Astronomy*  
by Lorimer and Kramer

# Pulsar Timing

Observed times of arrival are fit to a **timing model** to produce residuals.

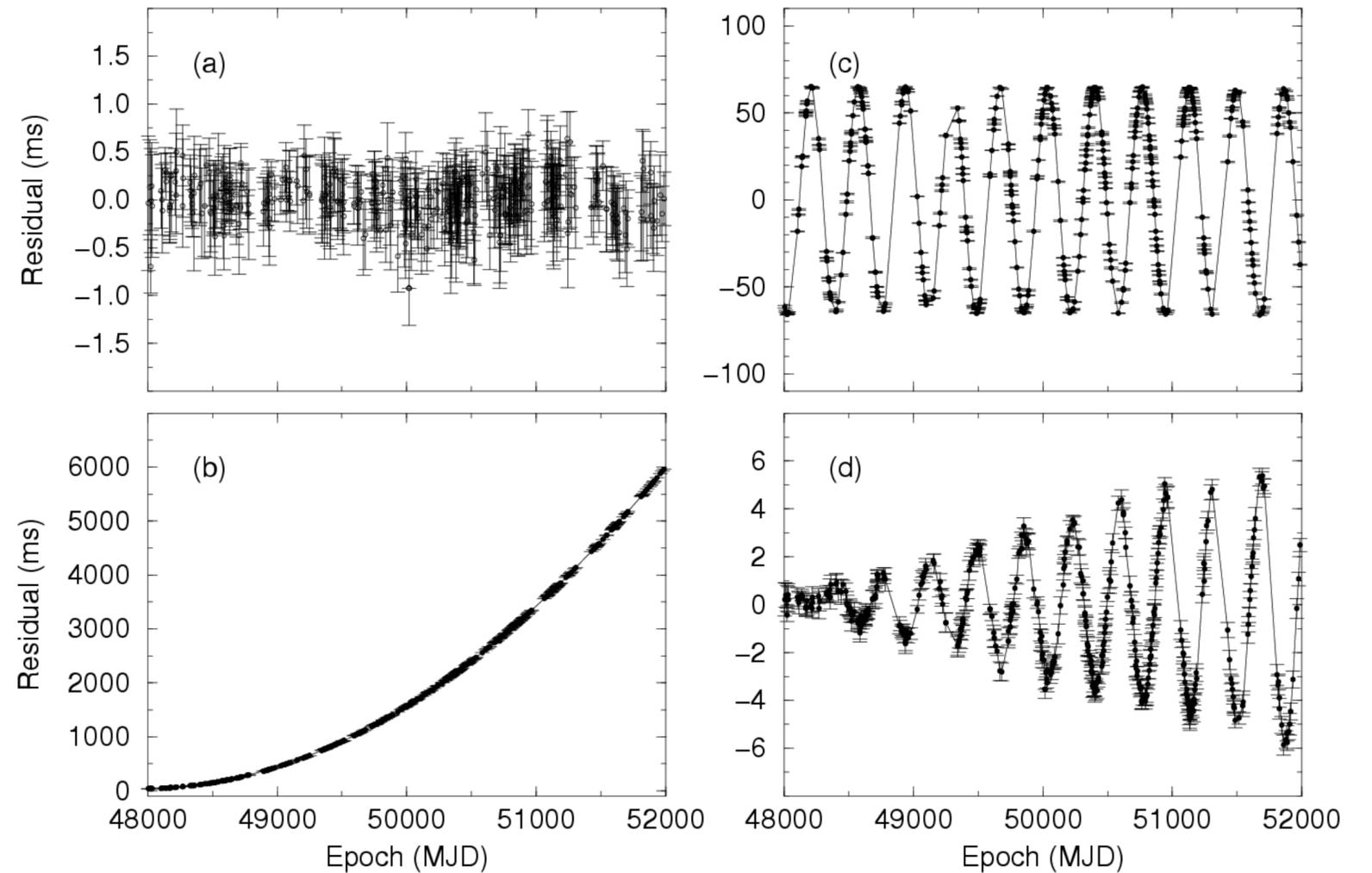


Image credit: Lorimer and Kramer,  
*The Handbook of Pulsar Astronomy*

# Pulsar Timing Arrays

Gravitational waves induce correlated changes in the pulse times of arrival.

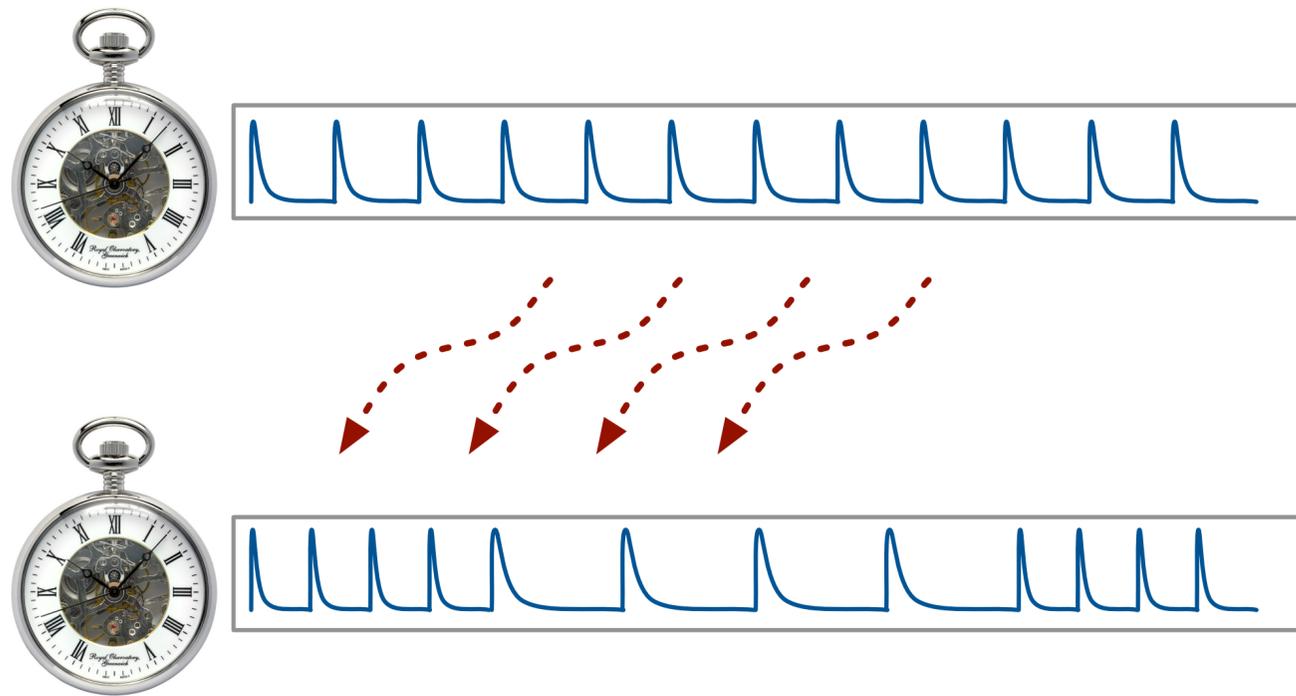


Image credit: S. Chatterjee

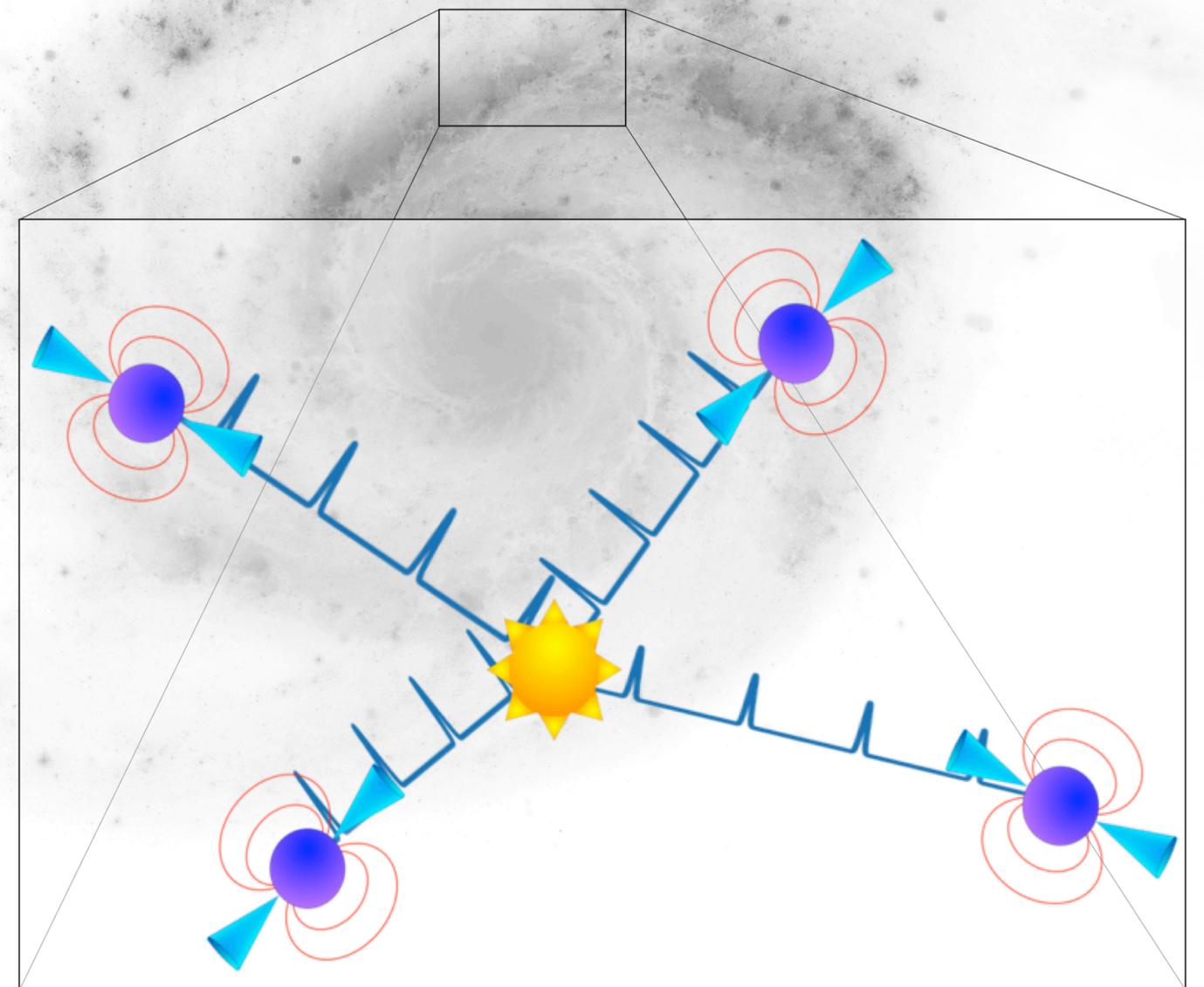


Image credit: J. Hazboun; NASA

# Signal Model

Pulsar 1



+

Pulsar 2



+

Pulsar 3



+



+



# The Solar System Ephemeris

The **Roemer delay** is the time it takes the pulses to travel across the Earth's orbit. The different ephemerides give difference values for the Roemer delay.

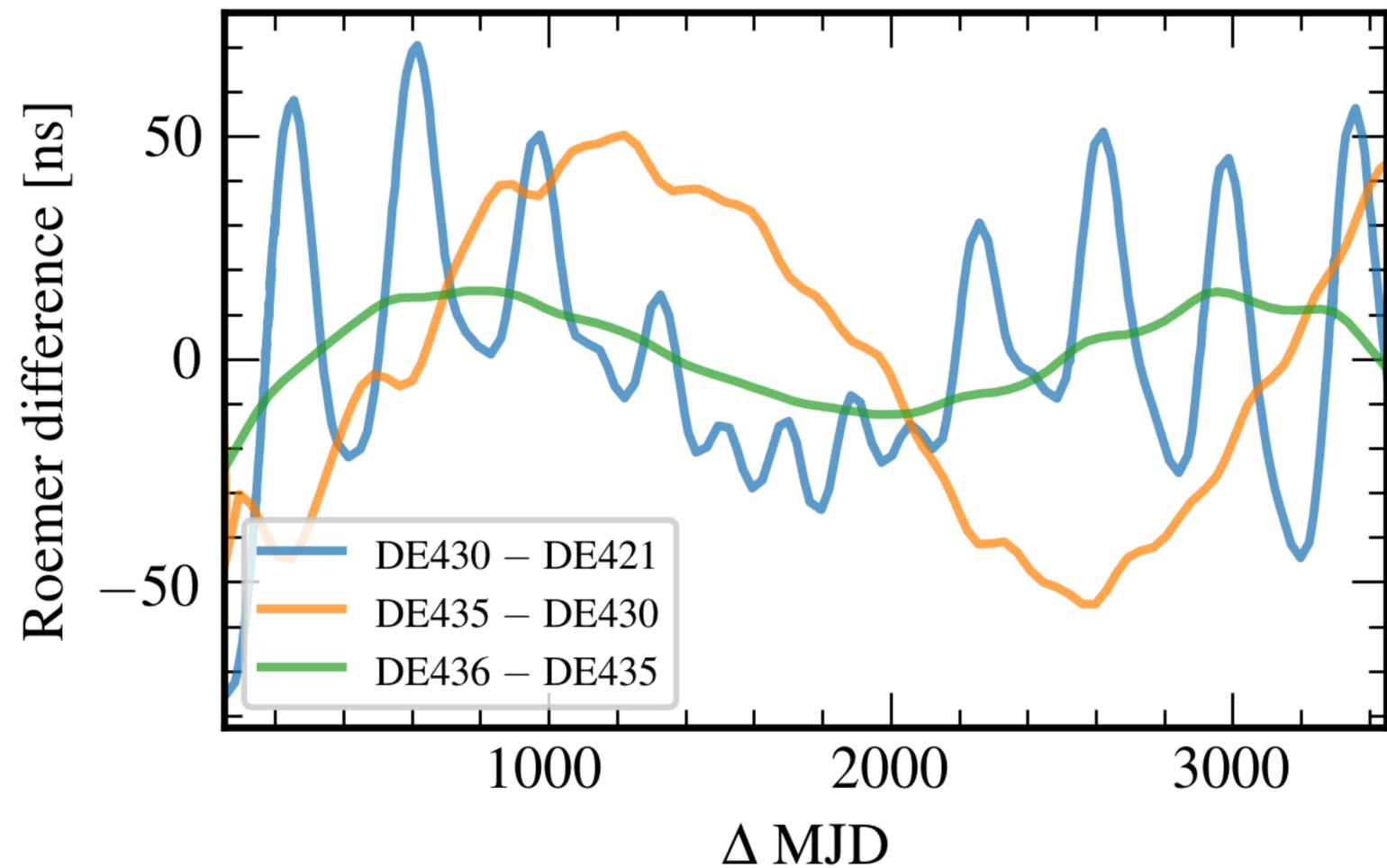
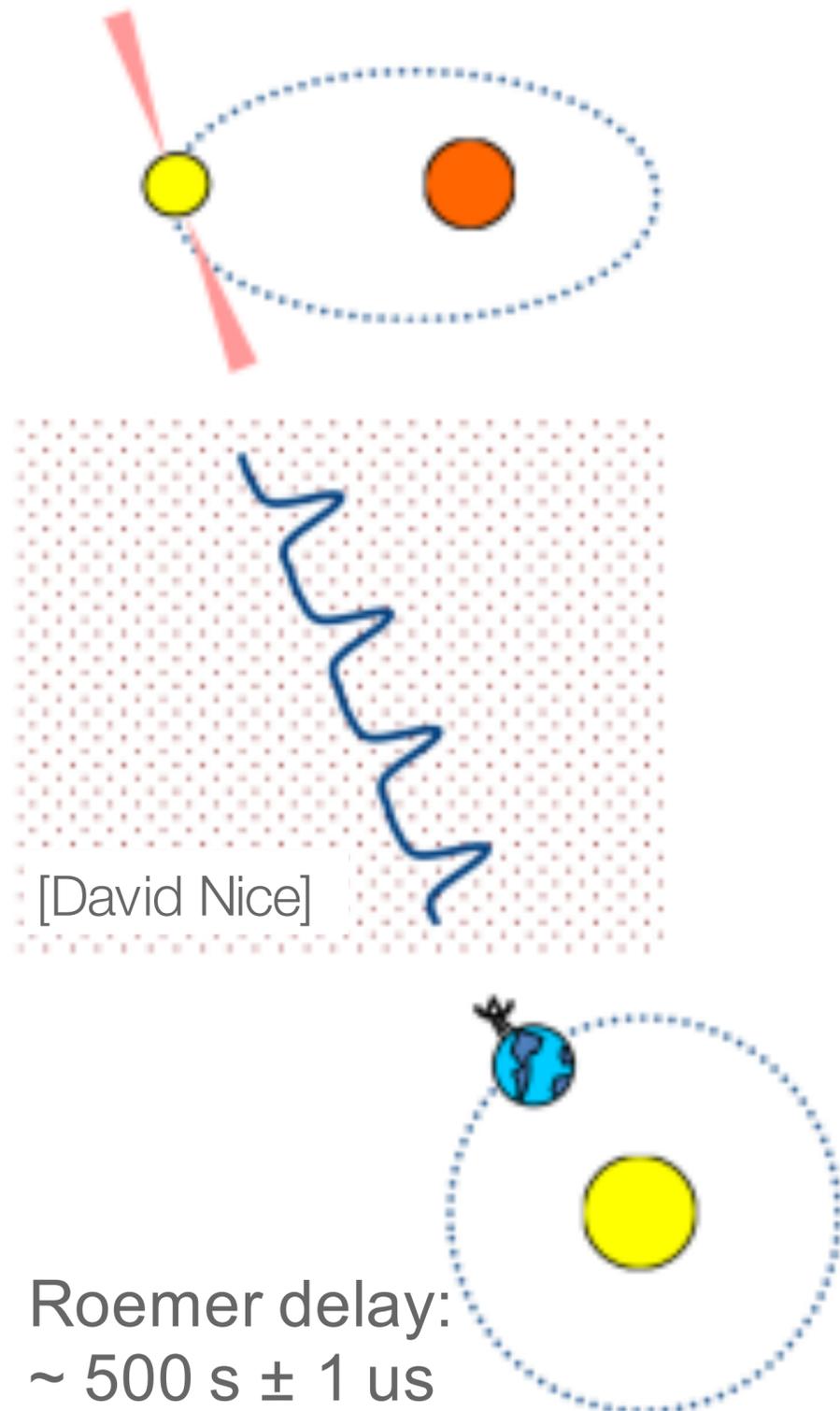


Figure from Michele Vallisneri

# Supermassive Black Hole Binaries

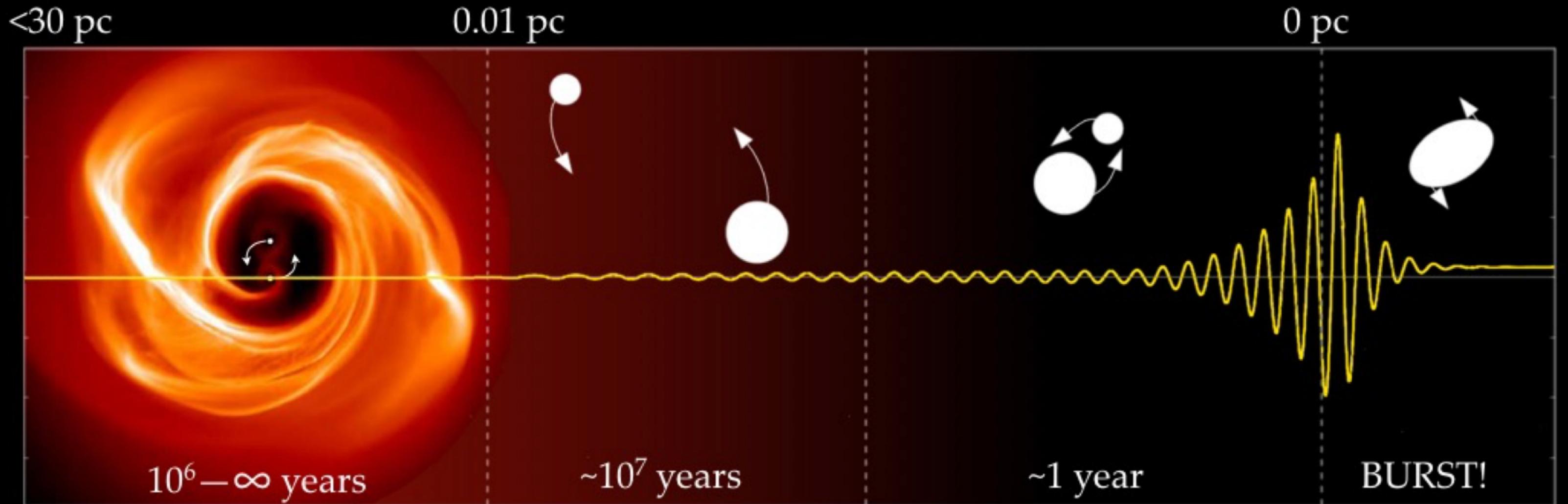
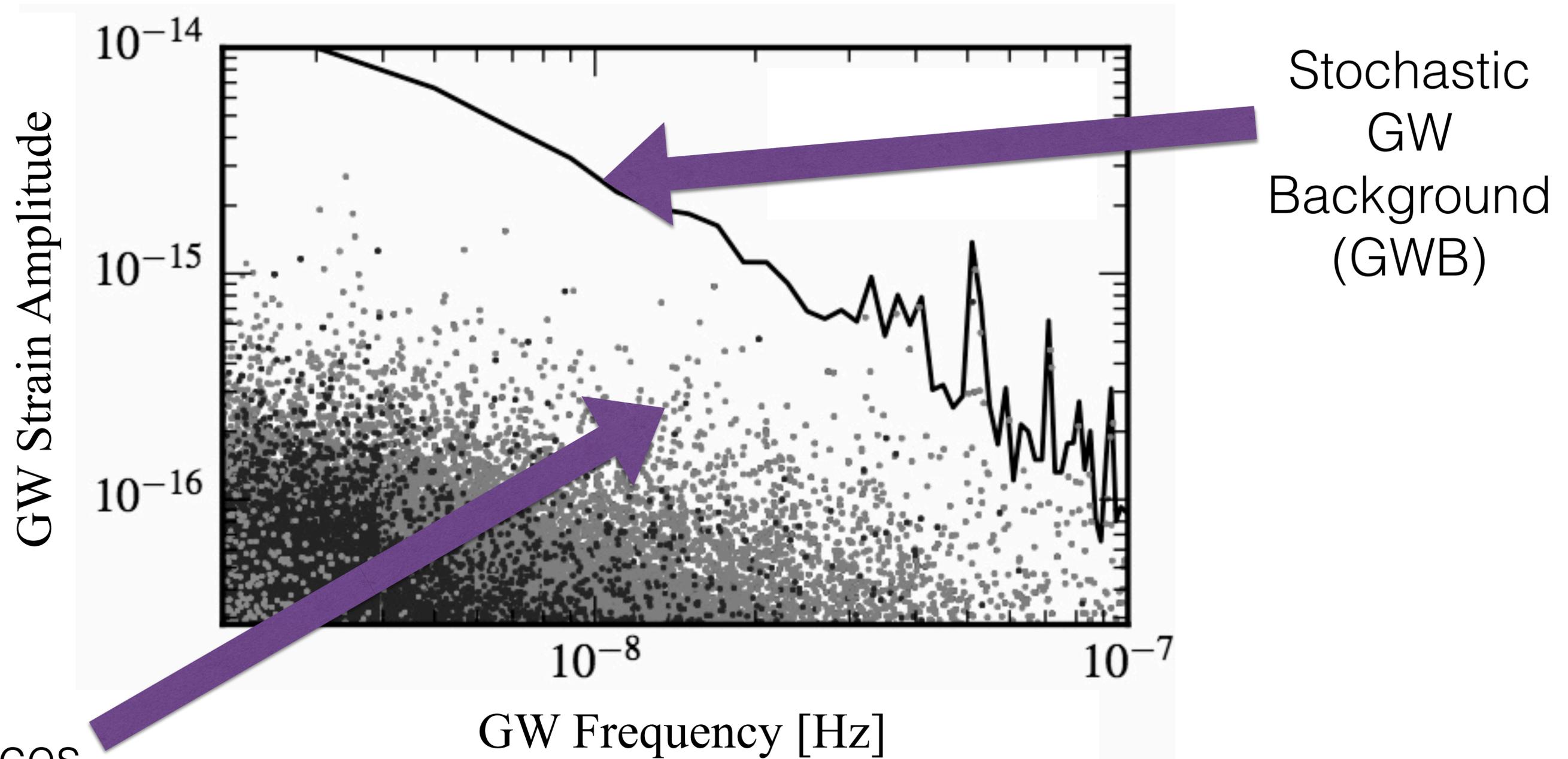
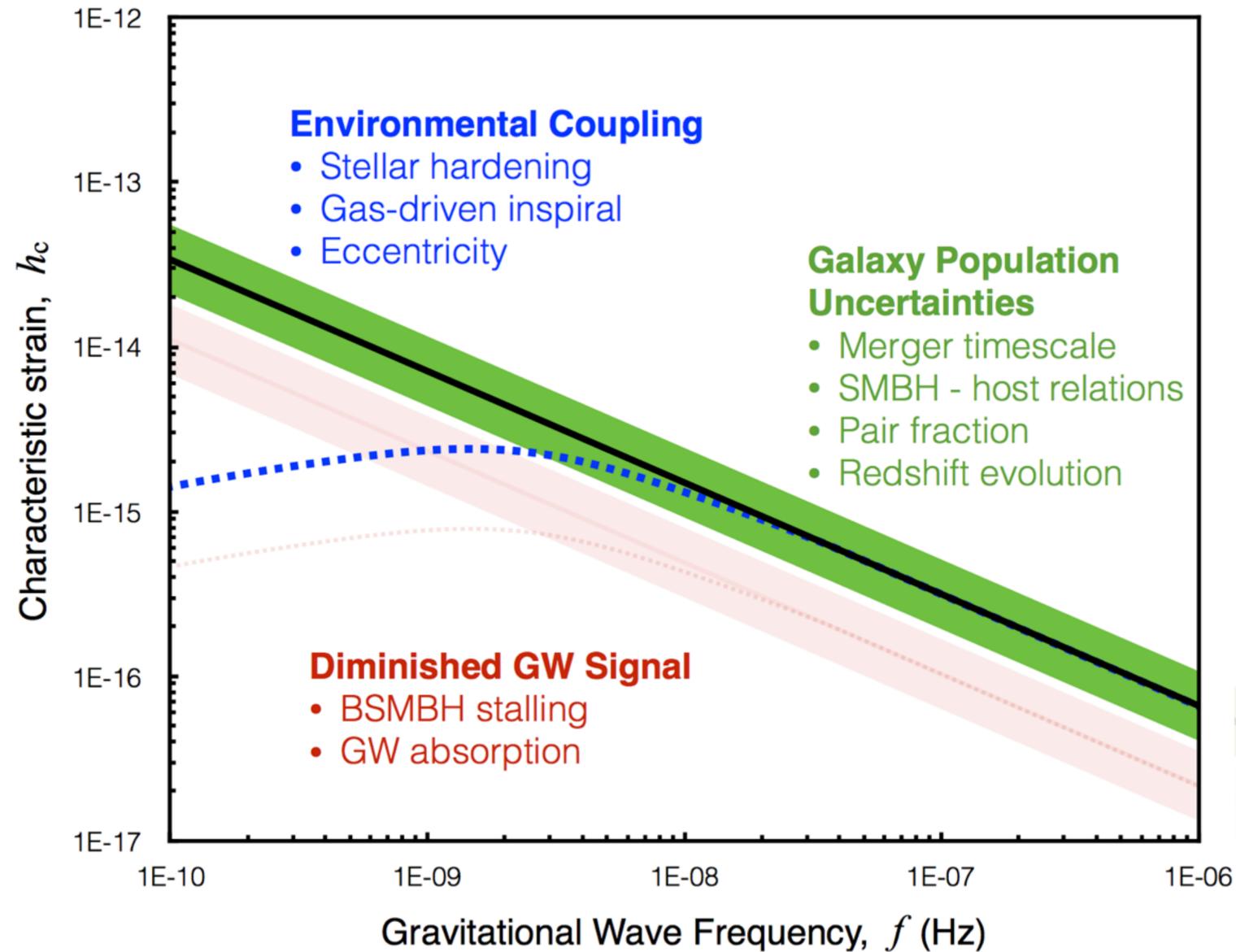


Image credits: J. Cuadra, D. Madison, S. Burke-Spolaor

# Supermassive Black Hole Binaries



# Stochastic GW Background



The GWB produces correlations in the residuals of different pulsars (Hellings & Downs 1983).

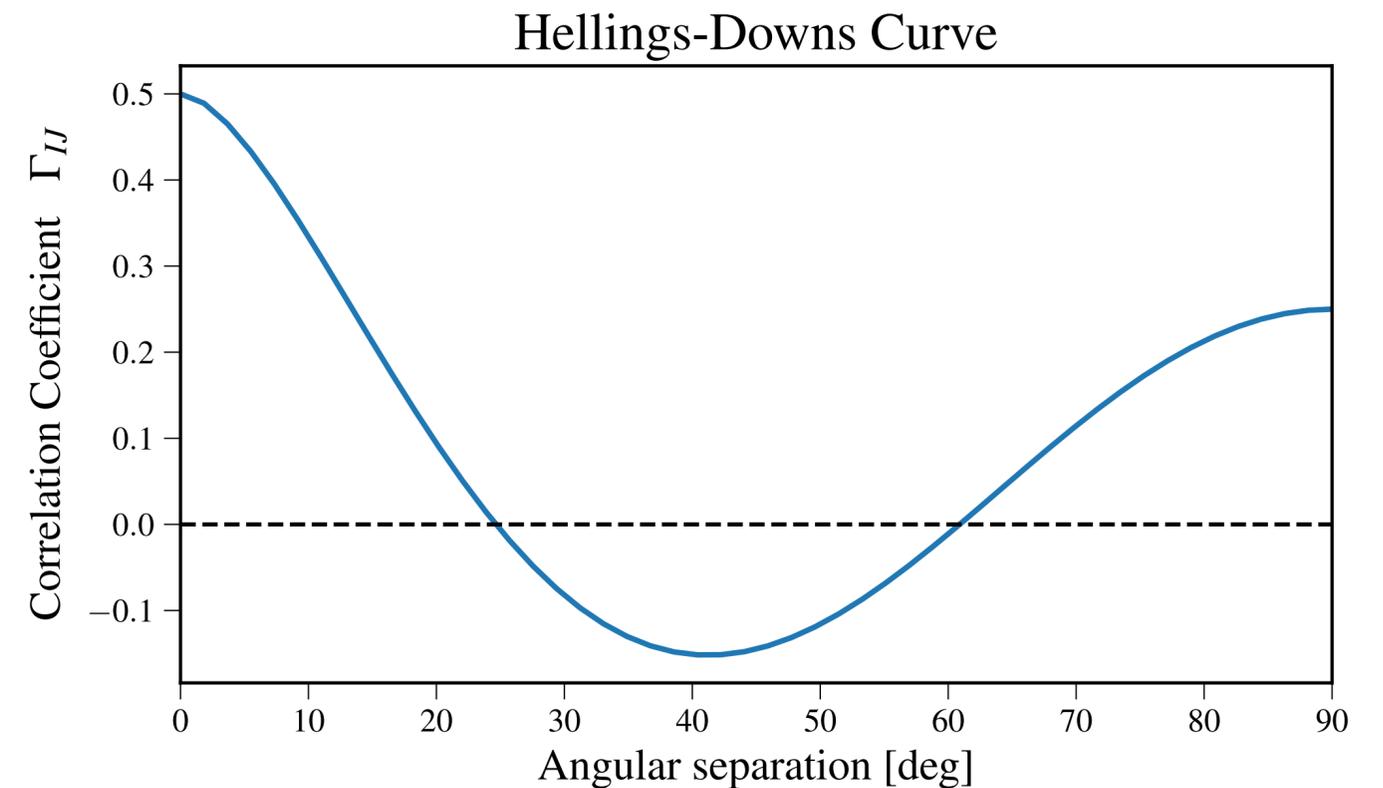


Image credit: S. Burke Spolaor 2015

# North American Nanohertz Observatory for Gravitational Waves



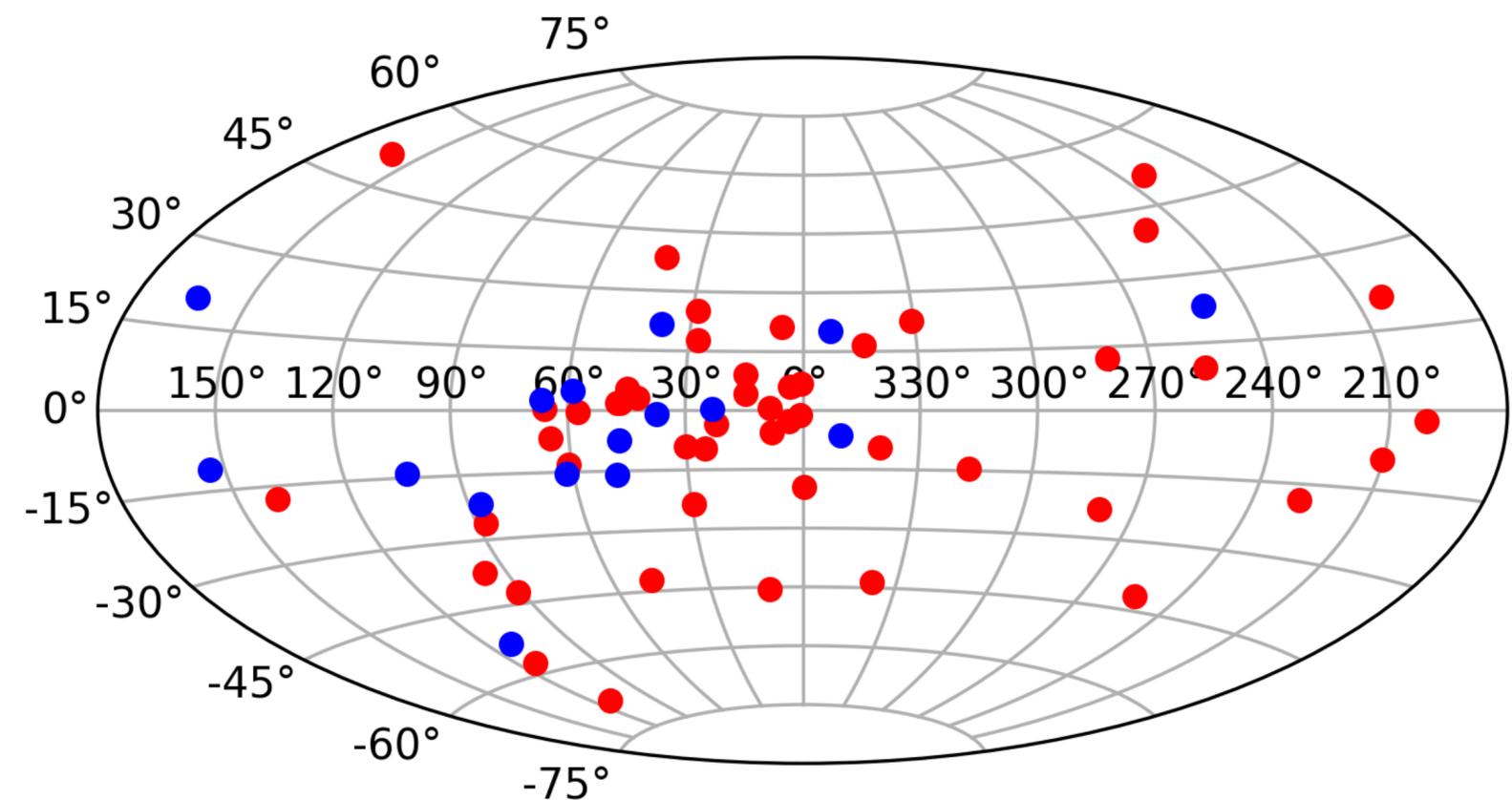
Image credits: NRAO/AUI, NAIC,  
CHIME Collaboration



# The International Pulsar Timing Array

The IPTA has released two data sets that combine observations made by the EPTA, PPTA, and NANOGrav:

- DR1: 49 millisecond pulsars, observed for up to 27 years (J. Verbiest et al. 2016)
- DR2: 65 millisecond pulsars, observed for up to 29.4 years (B. Perera et al. 2019)



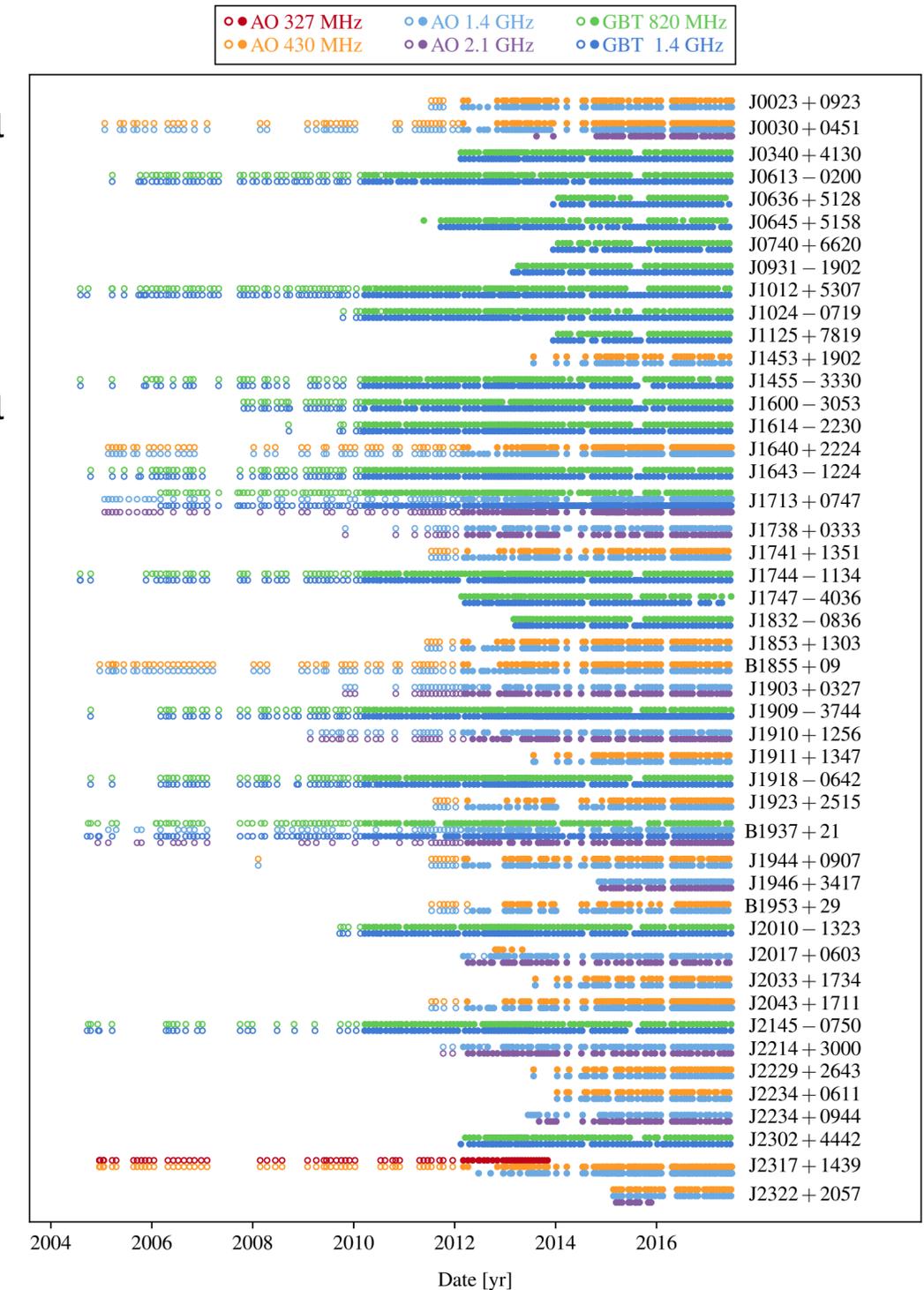
# NANOGrav 12.5-yr Data Set

M. Alam et al. (NANOGrav collaboration), “The NANOGrav 12.5-year Data Set: High-Precision Timing of 47 Millisecond Pulsars, submitted to *ApJS*.  
Lead author: M. DeCesar

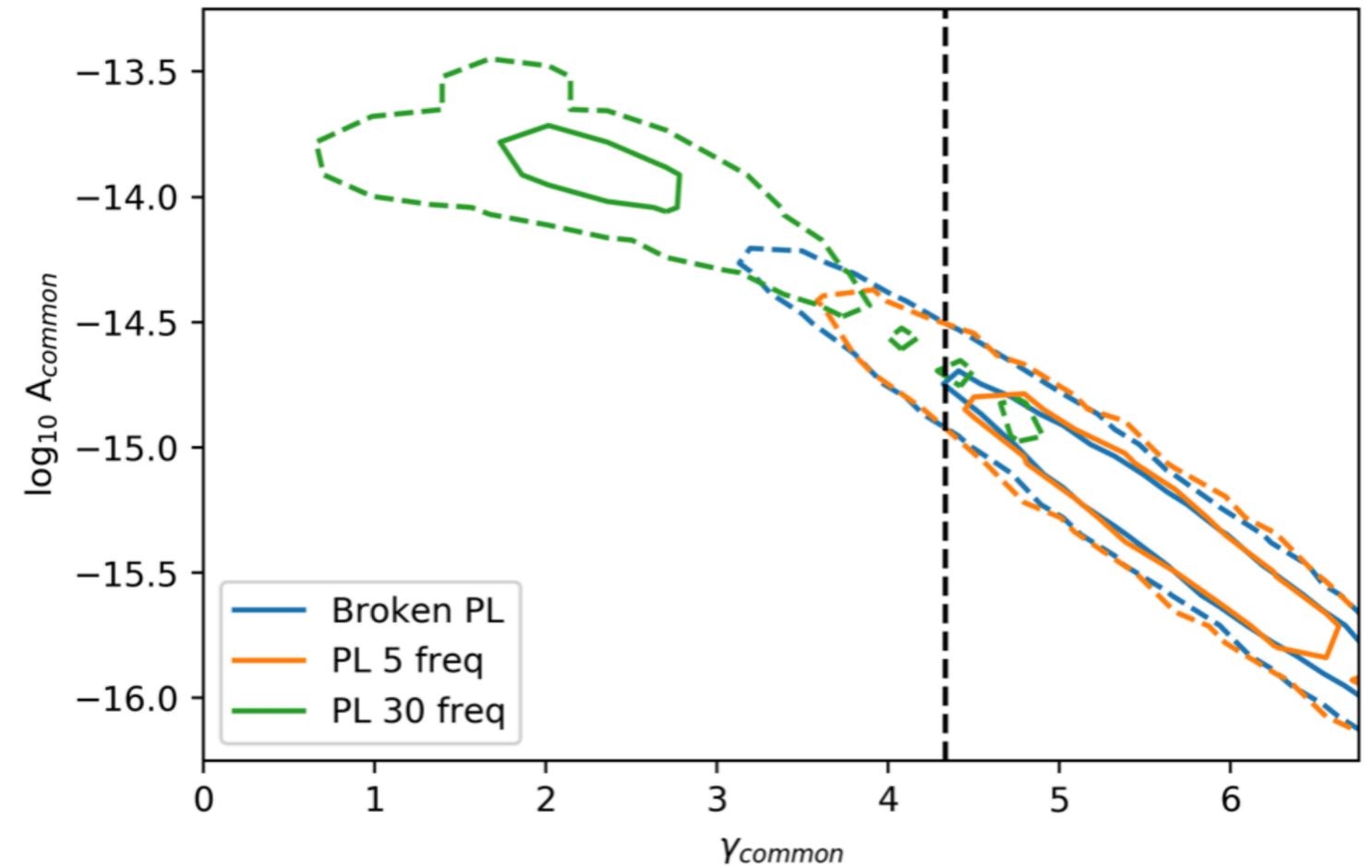
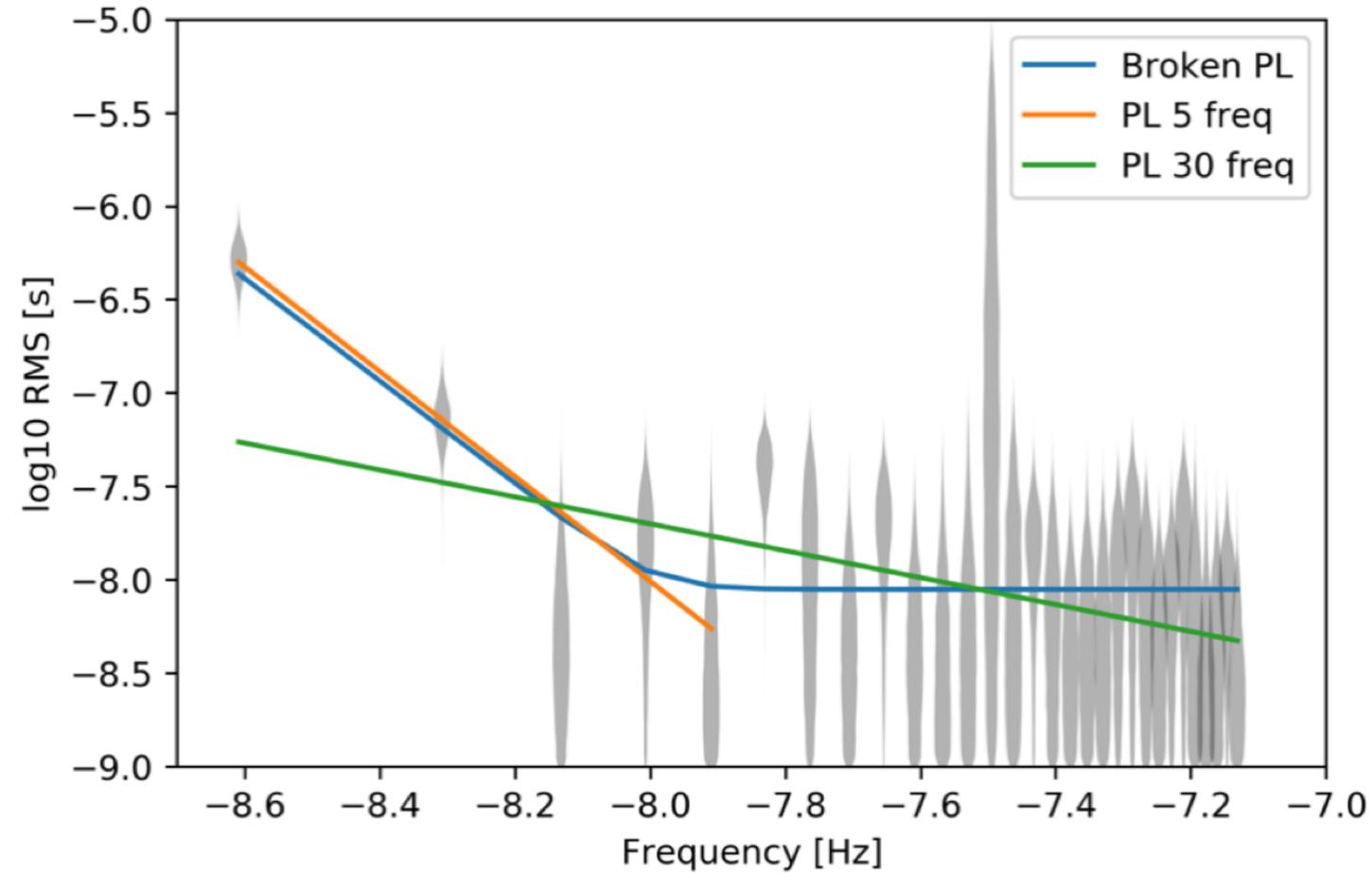
M. Alam et al. (NANOGrav collaboration), “The NANOGrav 12.5-year Data Set: Wideband Timing of 47 Millisecond Pulsars, submitted to *ApJS*.  
Lead author: T. Pennucci

Latest data set contains 47 pulsars observed for up to 12.9 years

Two data sets produced: one using conventional narrowband timing, the other using new wideband timing

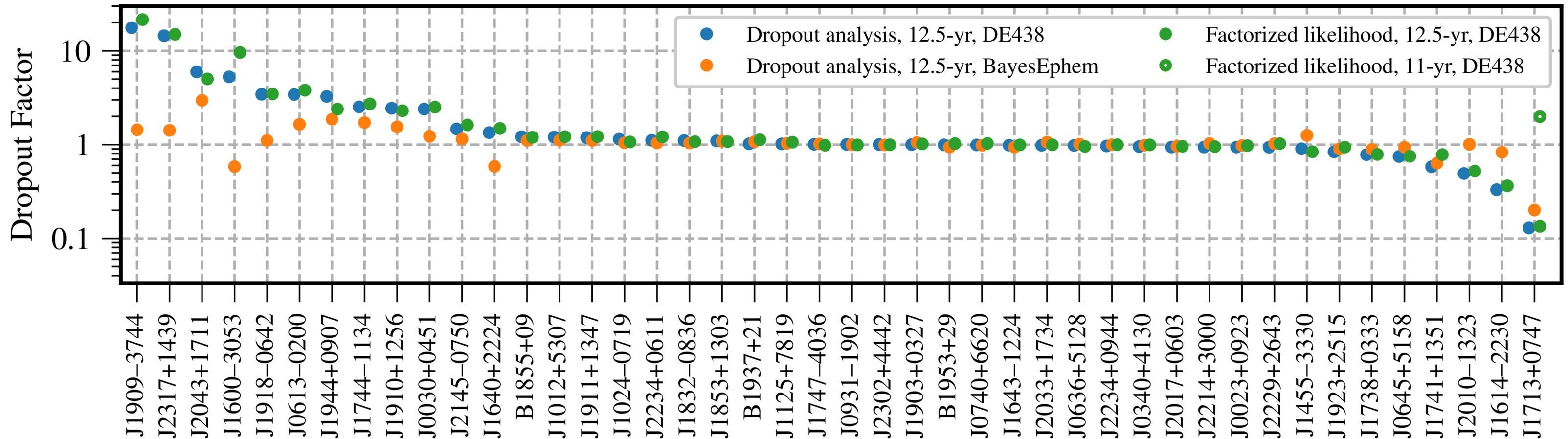


# NANOGrav 12.5-yr GWB Search



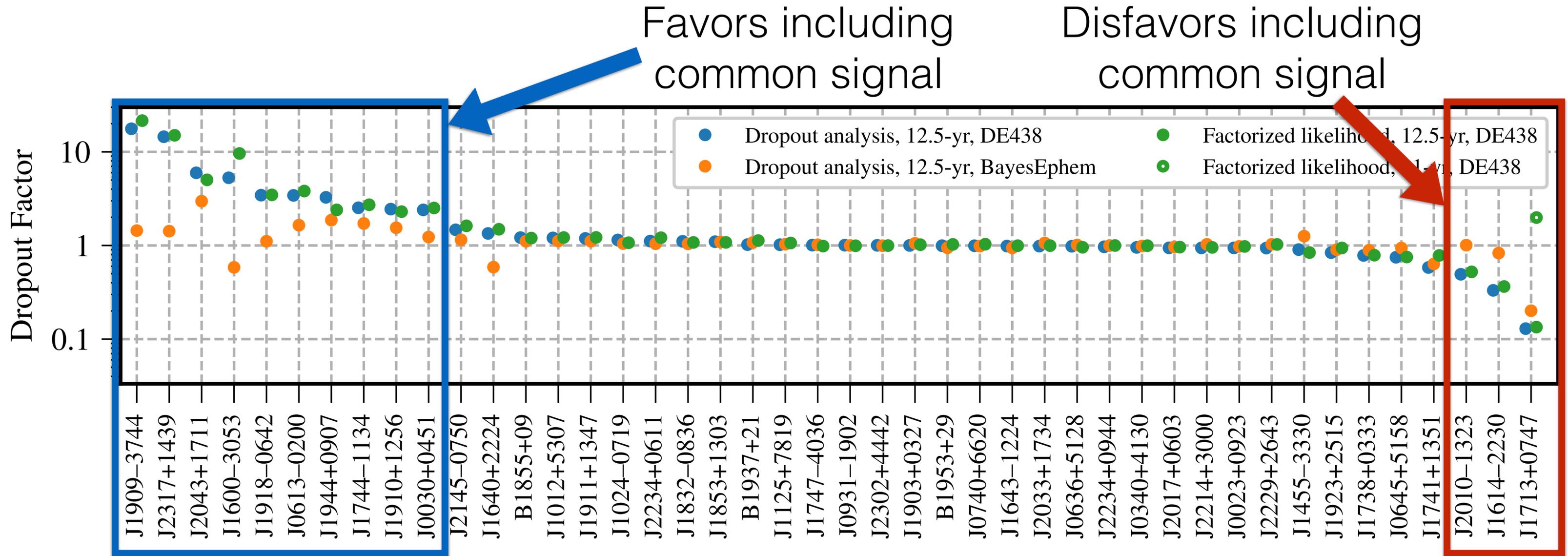
Z. Arzoumanian et al. (NANOGrav collaboration), submitted to *ApJL*.  
Lead author: J. Simon

# NANOGrav 12.5-yr GWB Search



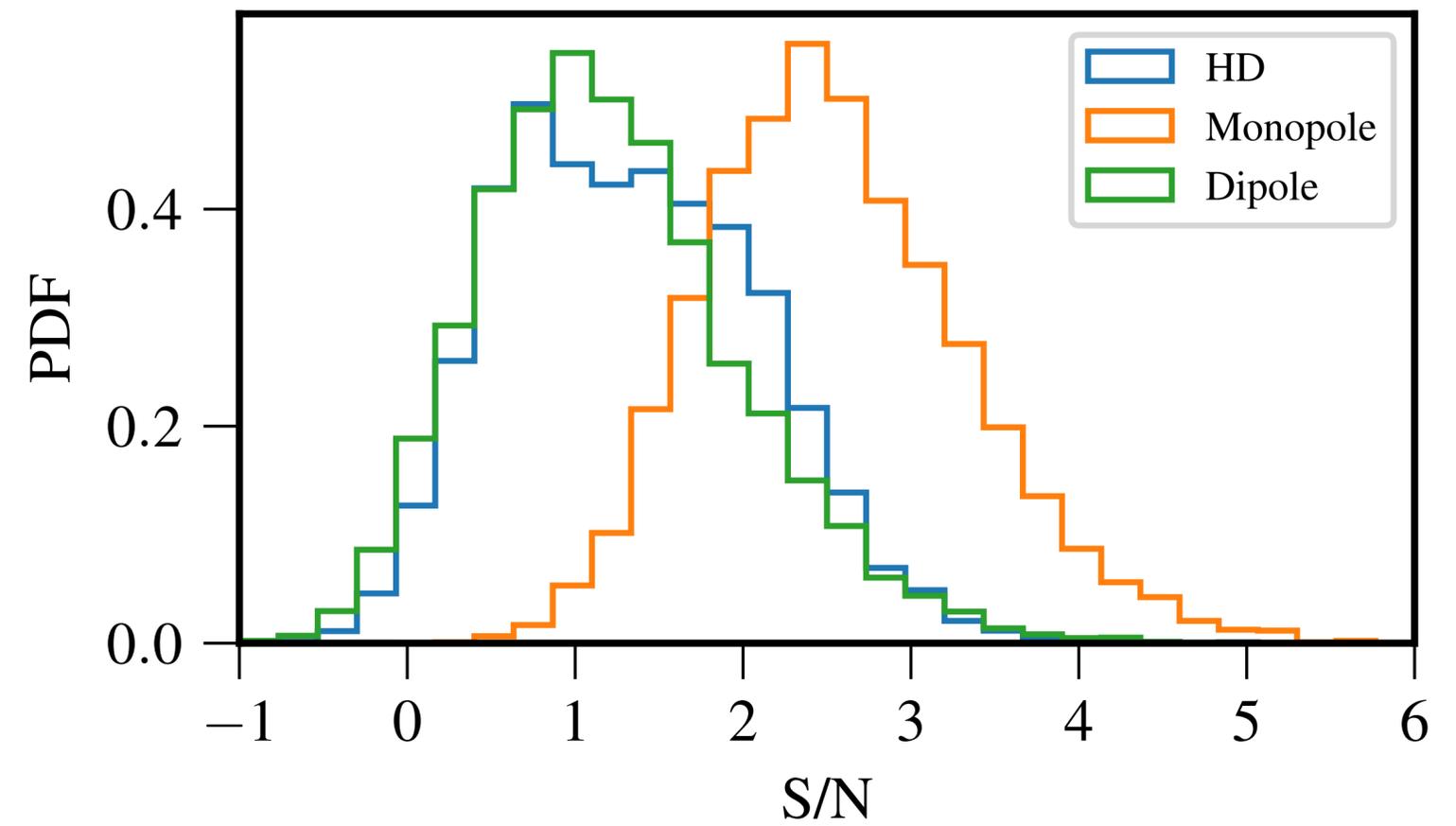
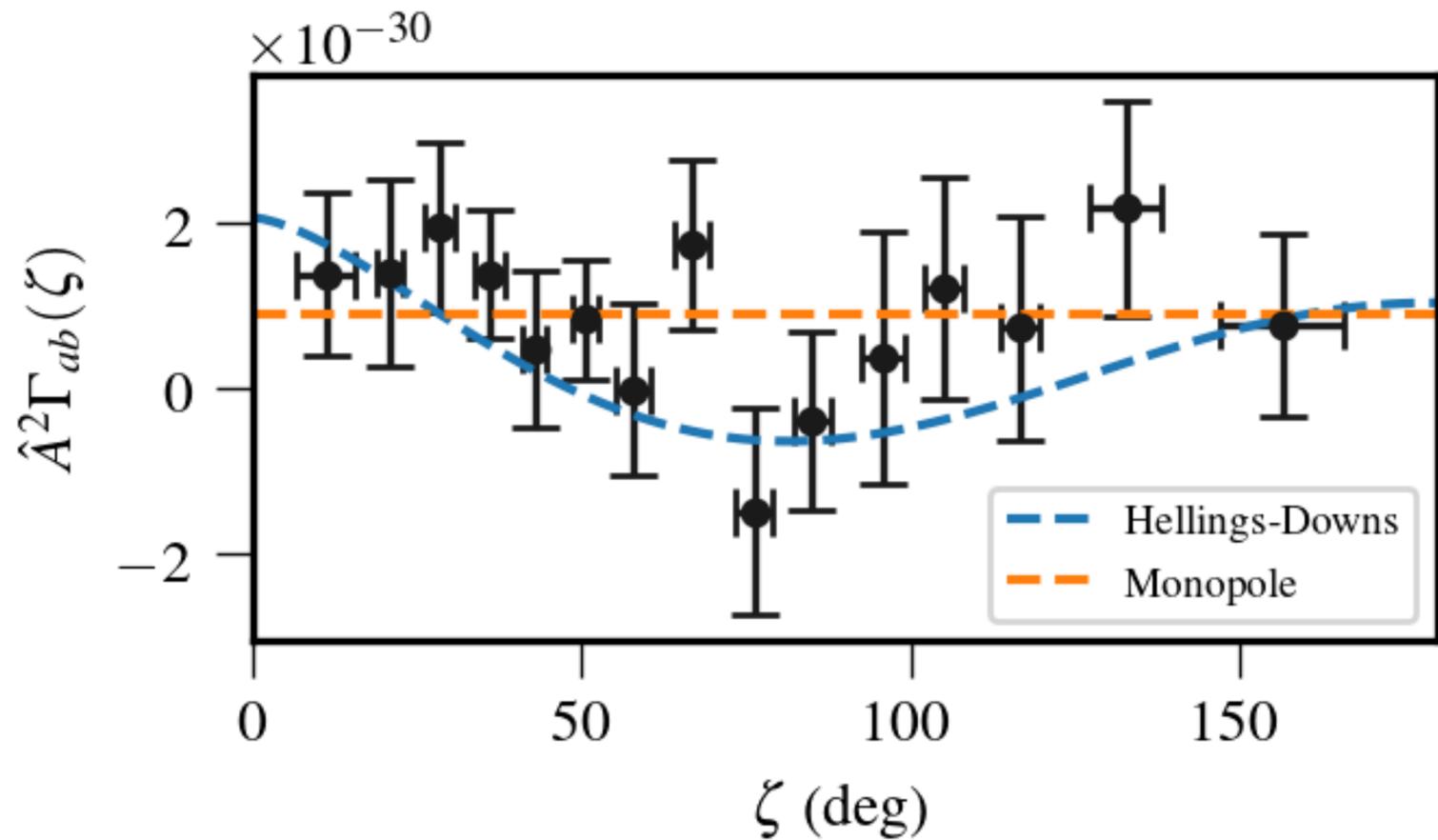
Z. Arzoumanian et al. (NANOGrav collaboration), submitted to *ApJL*.  
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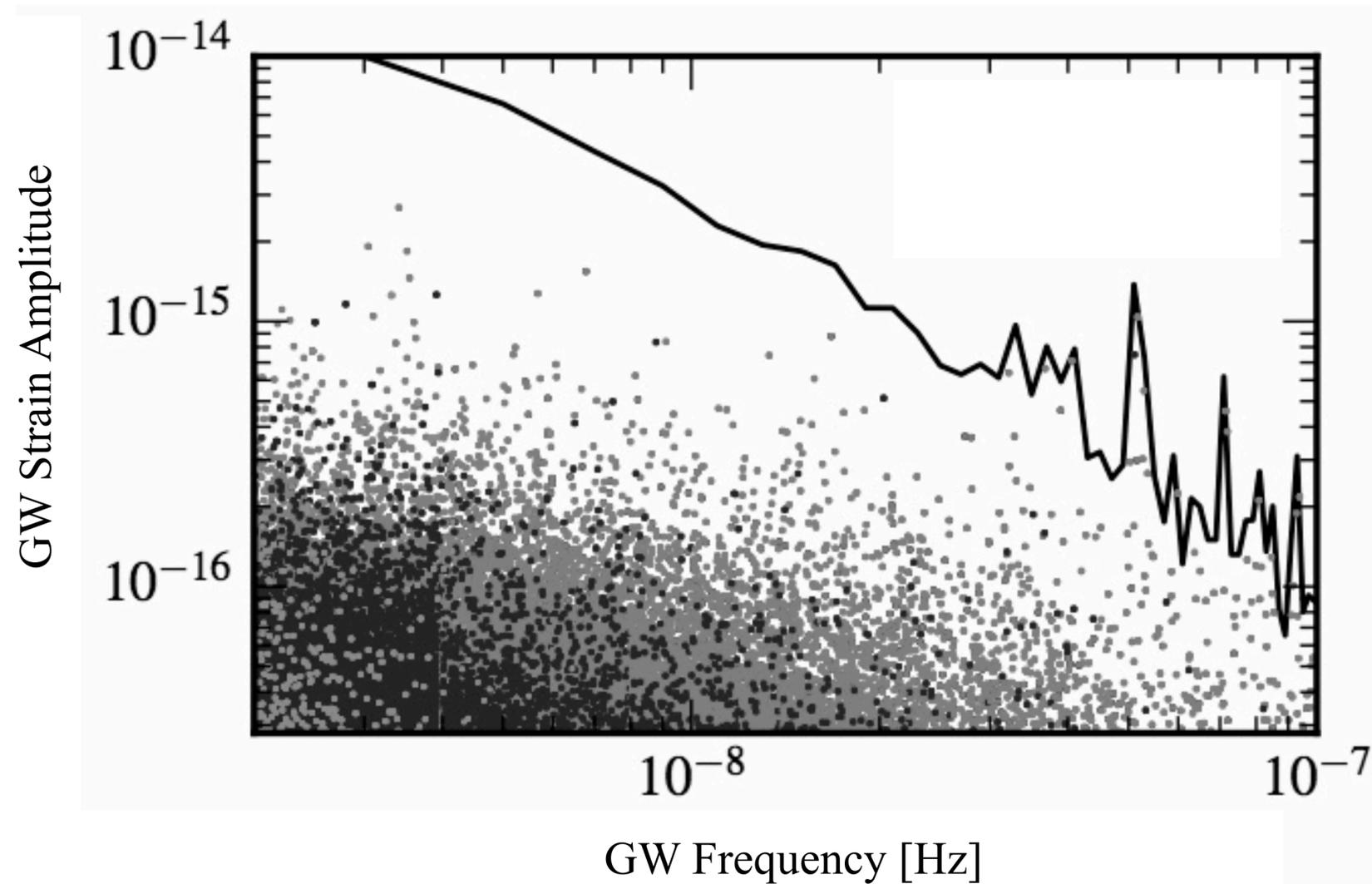
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# NANOGrav 12.5-yr GWB Search

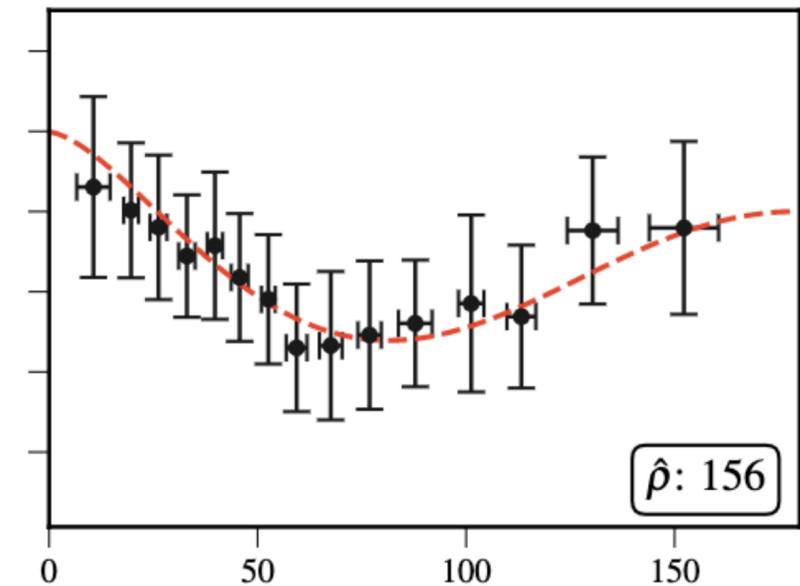
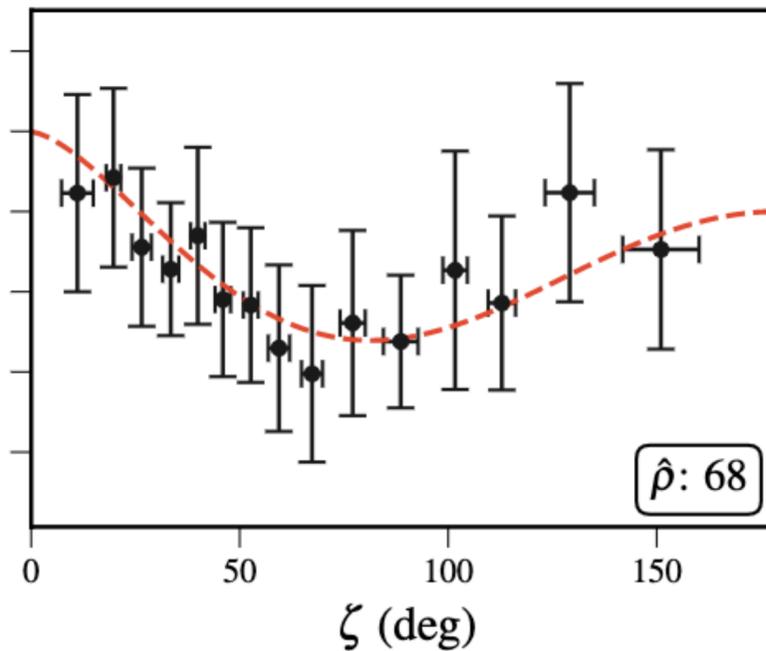
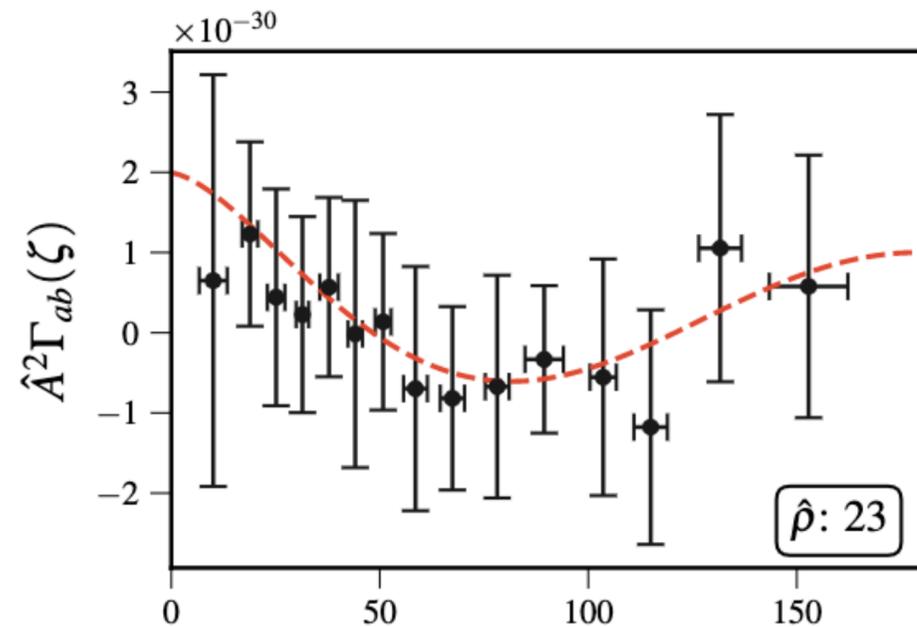
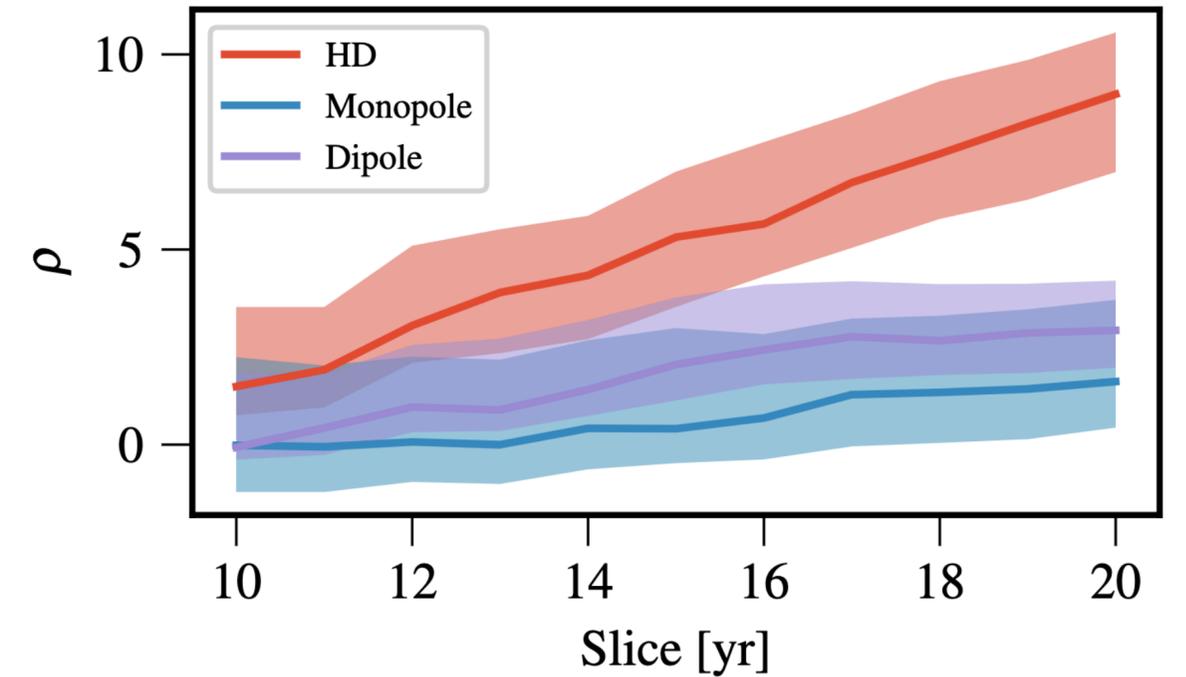


The stochastic GWB:

- ✓ Appears in many pulsars
- ? Quadrupole cross-correlations between different pulsars (Hellings-Downs curve)
- ? Strain spectrum is power-law with spectral index  $-2/3$  (if produced by SMBHBs)

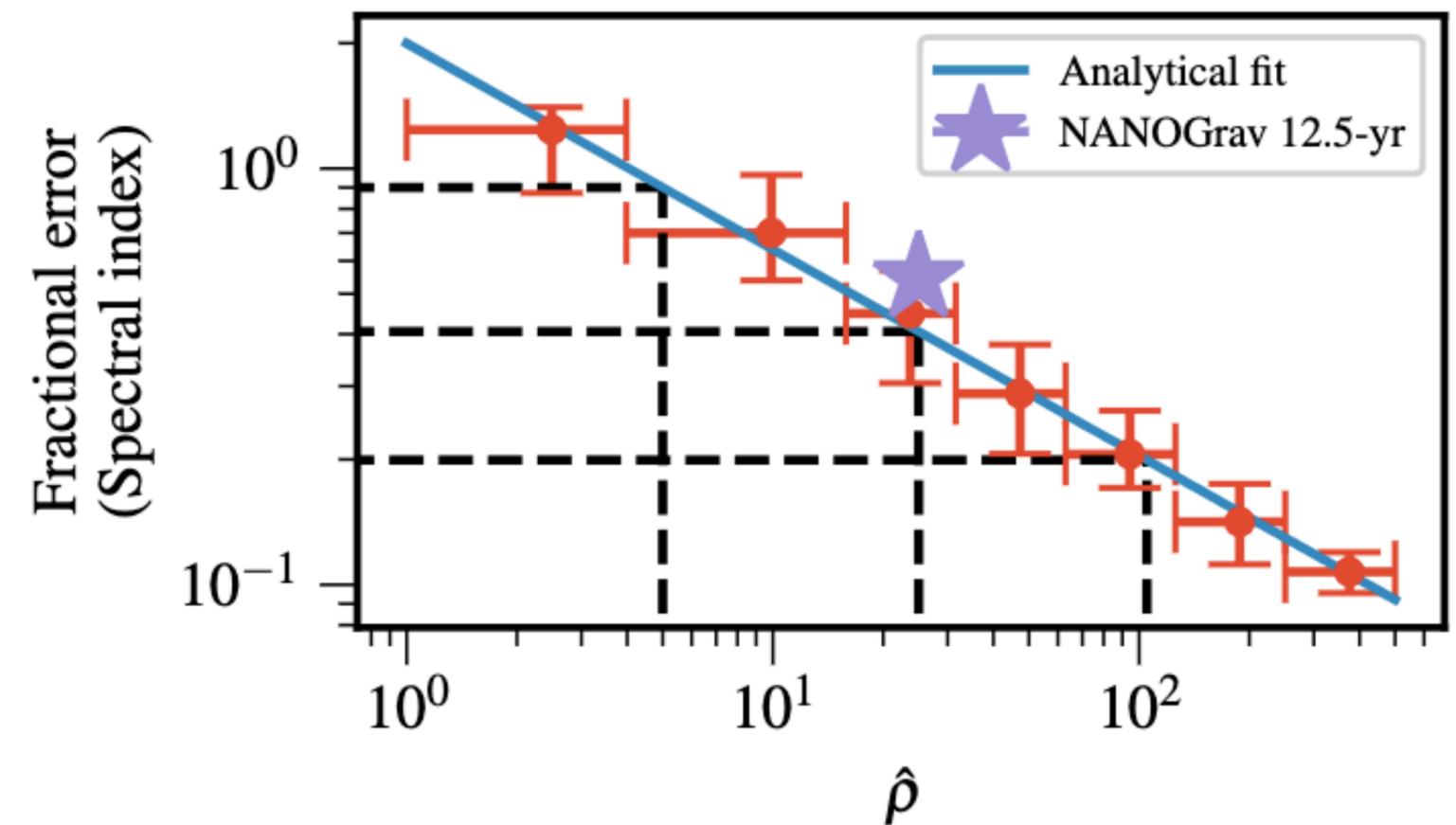
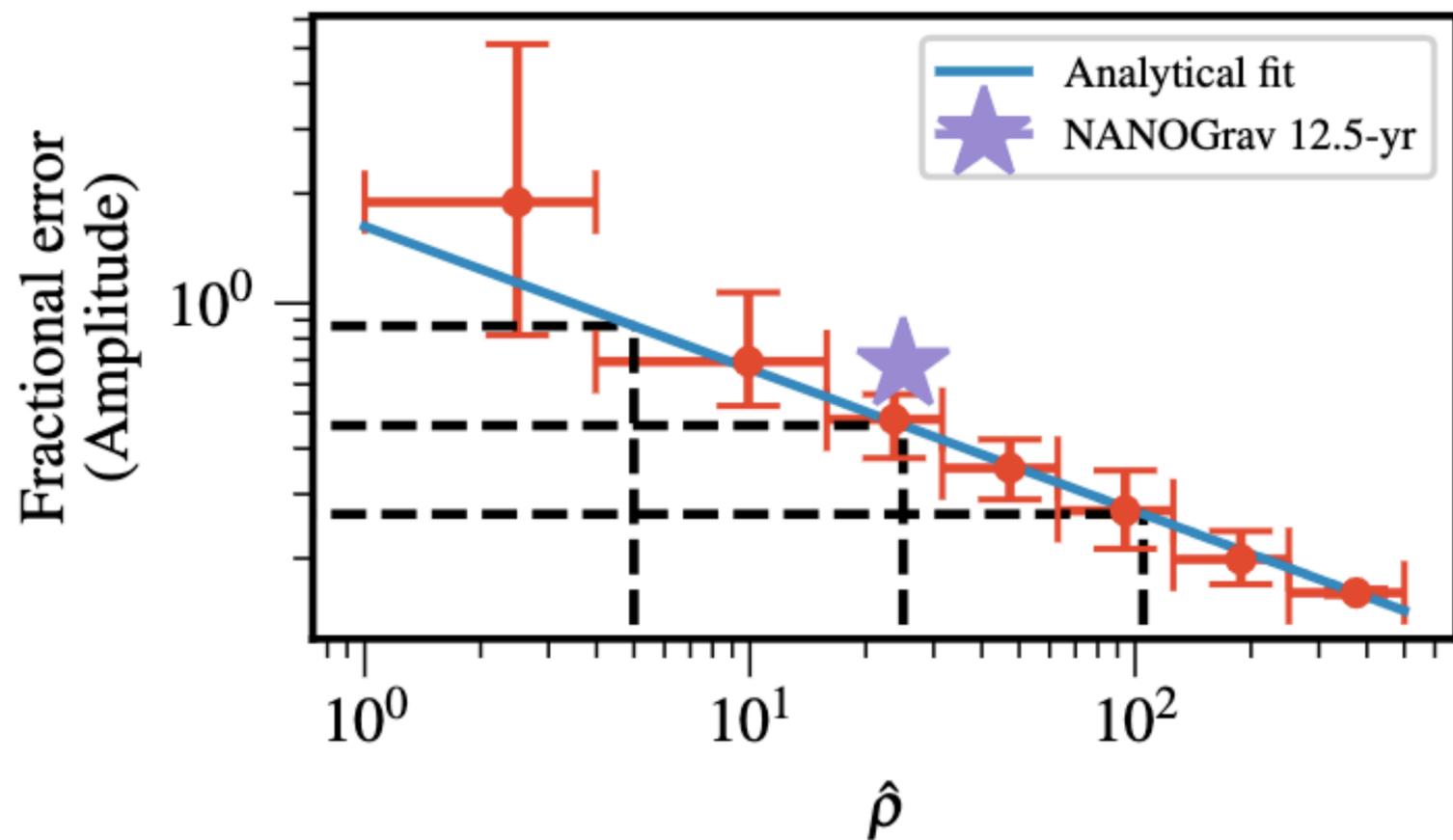
# What to Expect When You're Expecting a GWB

If what we are seeing is the GWB, we expect the significance of the spatial correlations to increase over the next several years.

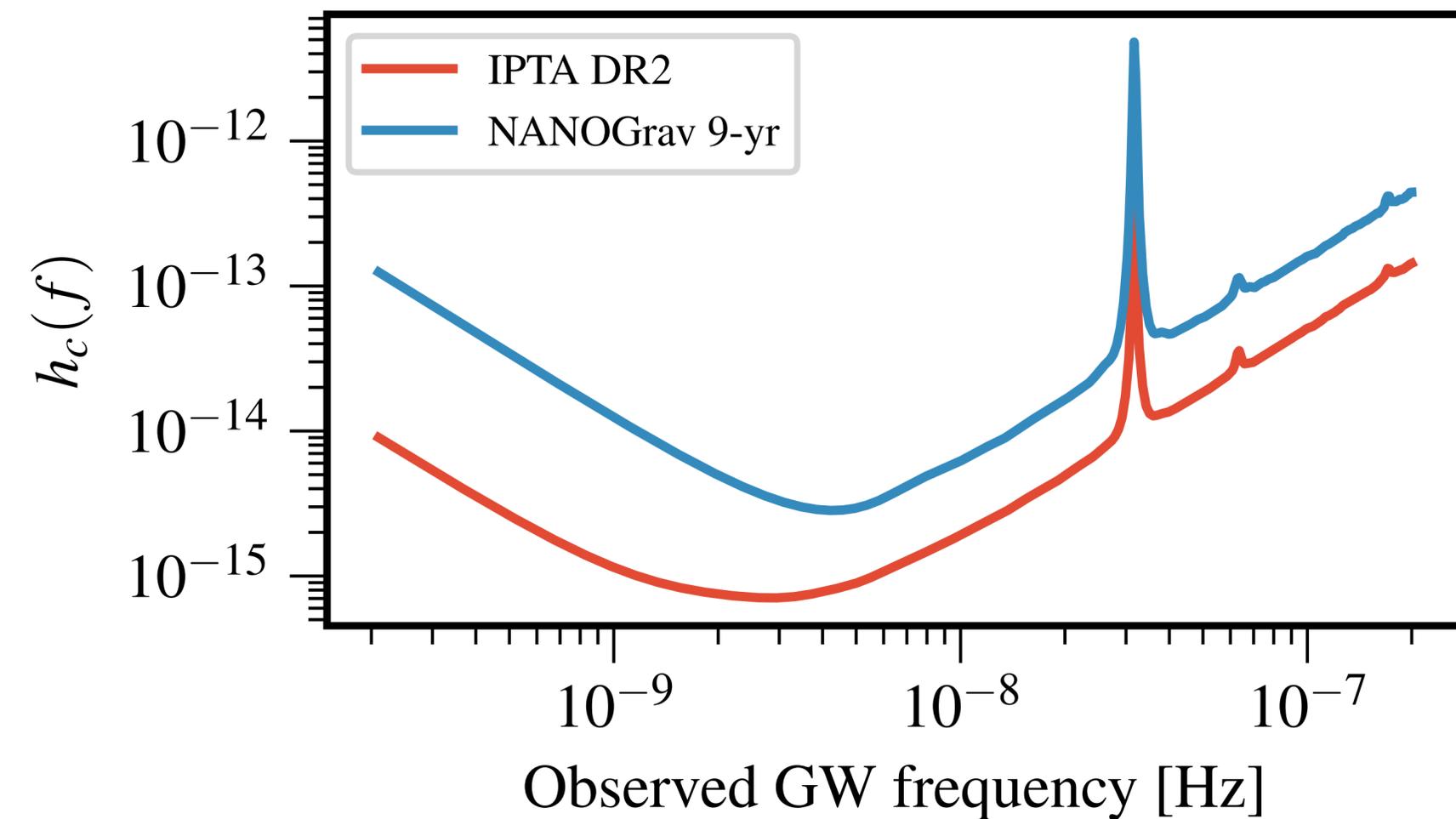


# What to Expect When You're Expecting a GWB

If what we are seeing is the GWB, measurement of the amplitude and spectral index of the GWB will improve as the SNR increases.



# What to Expect When You're Expecting a GWB



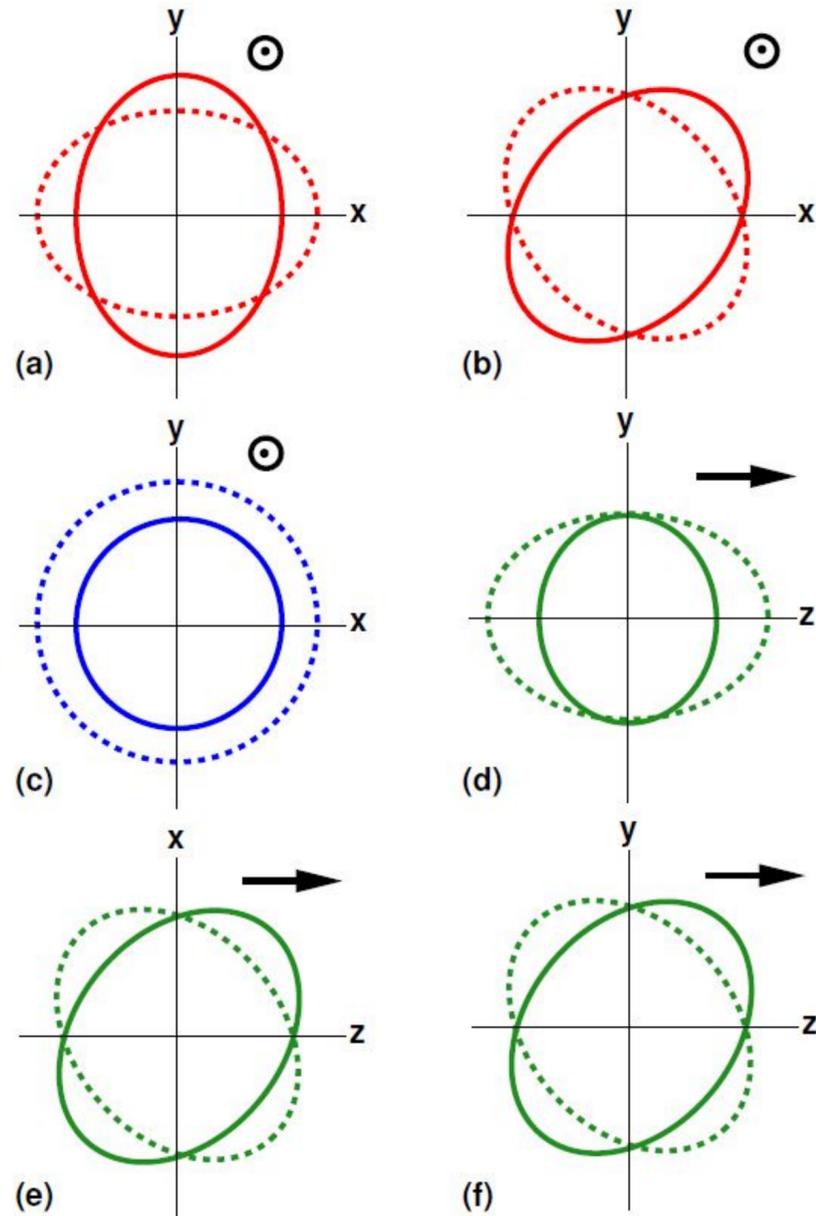
More pulsars and longer observing baselines increase the sensitivity to the GWB (Hazboun et al. 2019)

Combined IPTA data sets are more sensitive than individual PTA data sets

N. S. Pol et al., in prep.

# Alternate Polarizations

## Gravitational-Wave Polarization



In GR, there are only two GW polarizations. Alternate theories of gravity may allow other polarizations to exist.

PTAs can put constraints on the power in alternate polarizations (Chamberlin & Siemens 2012; Cornish, O’Beirne, Taylor, and Yunes 2018)

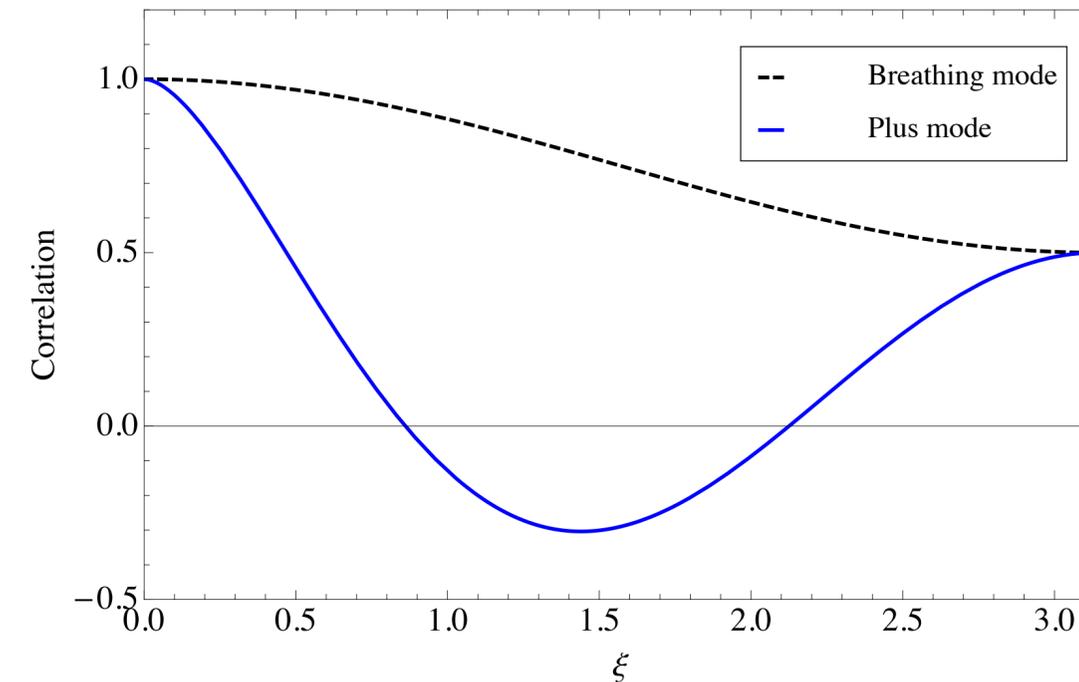
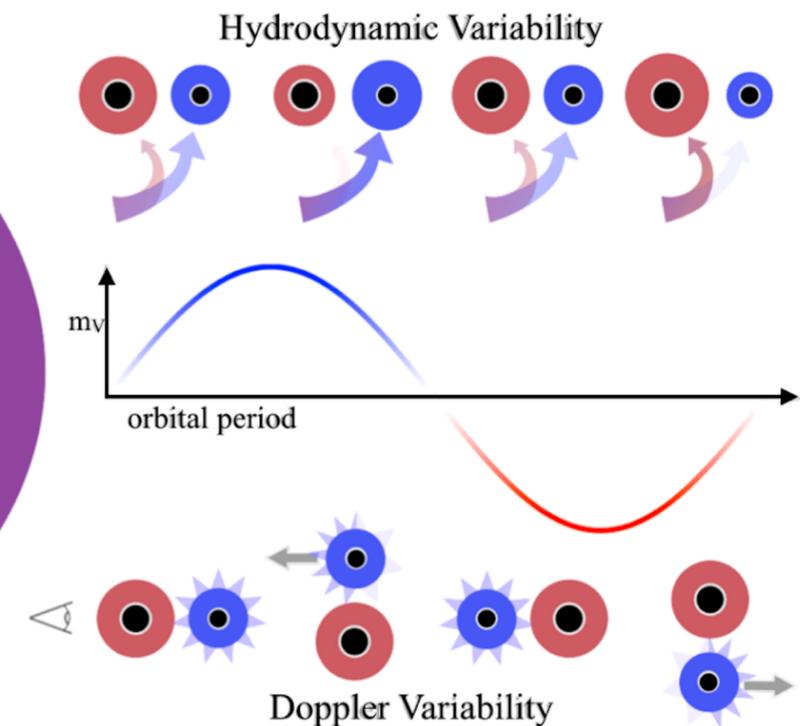
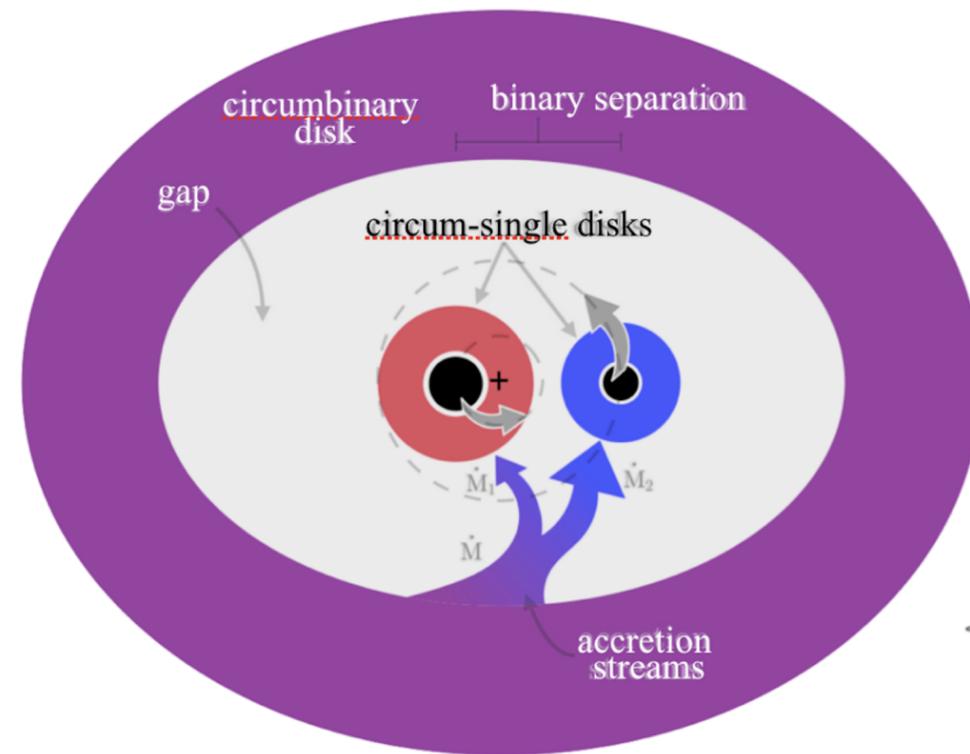
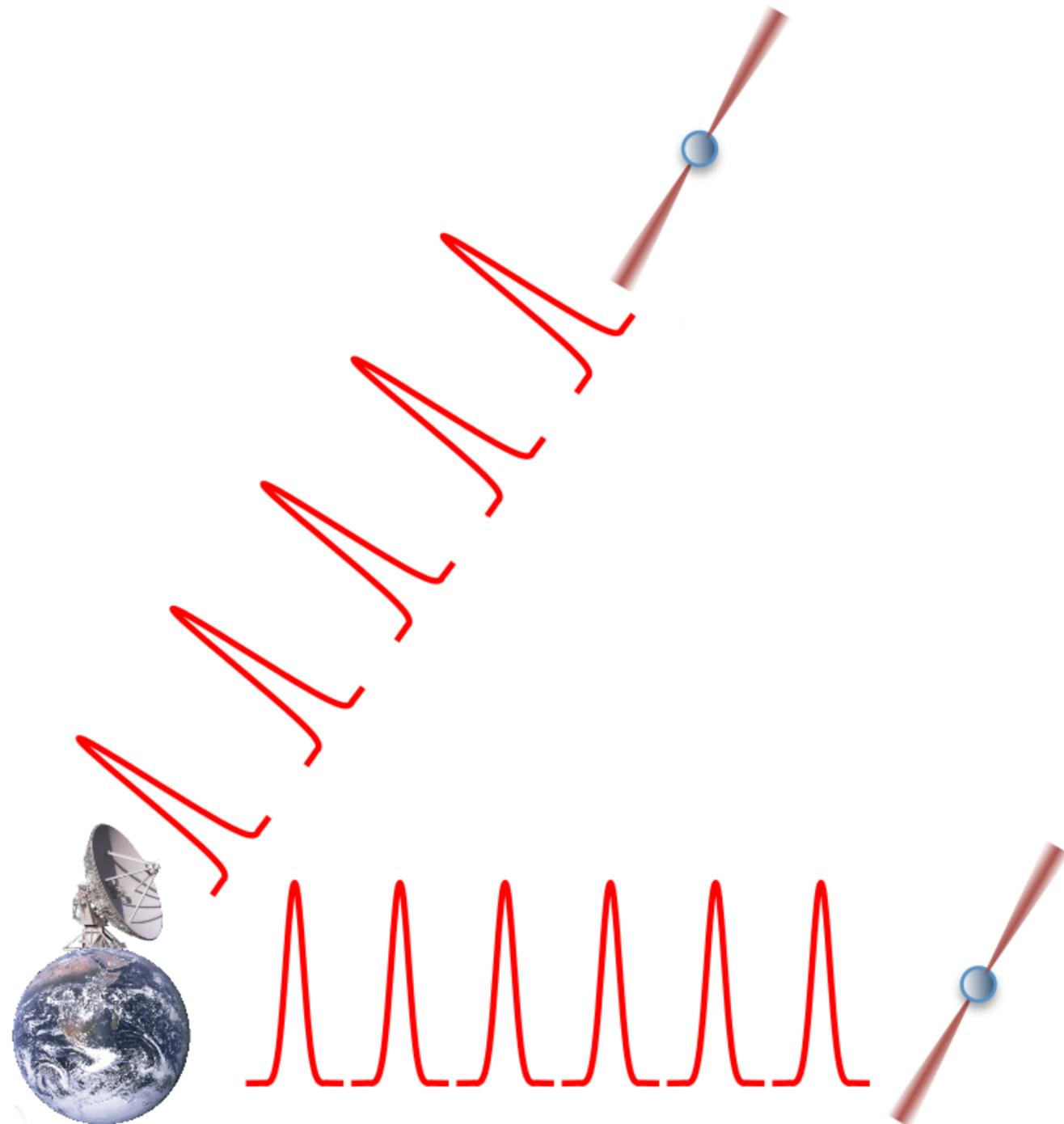


Figure credit: C. Will (2014)

# Individual SMBHBs

Binary candidates can be identified by looking for light curve periodicities



Kelley et al. (2018), arXiv:1809.02138

Figure credit: NANOGrav (modified)

# Limits on Individual SMBHBs

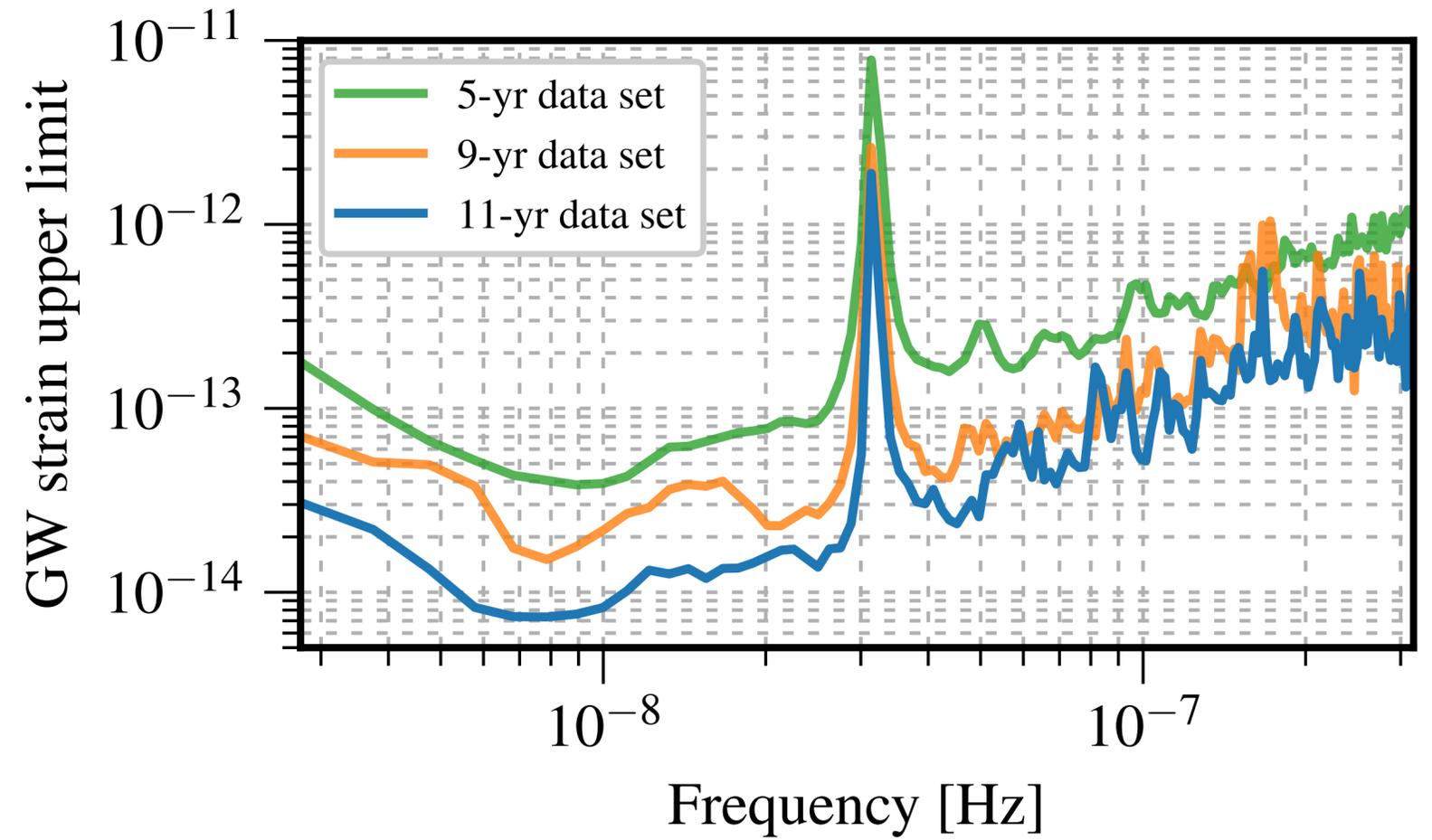
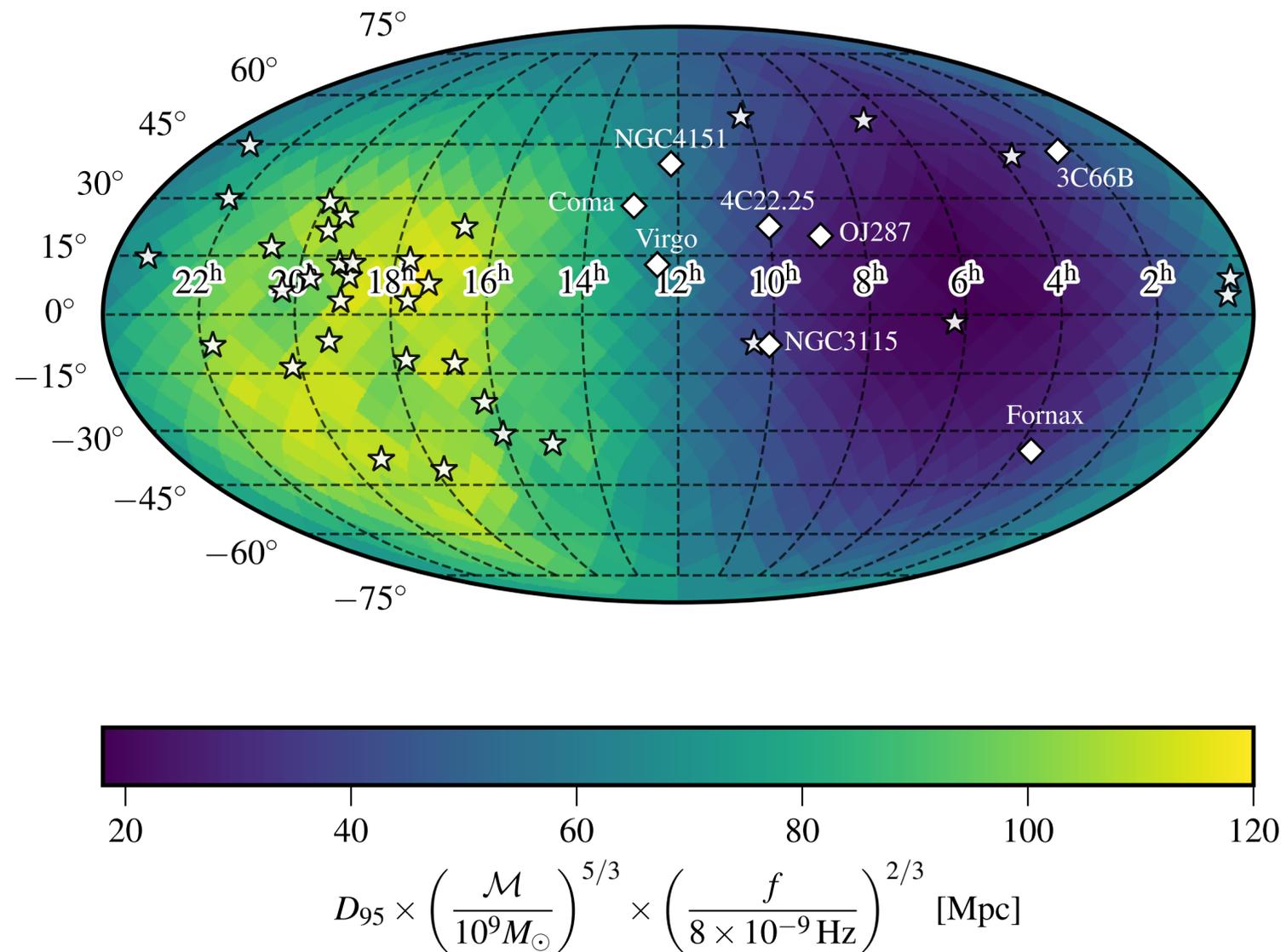
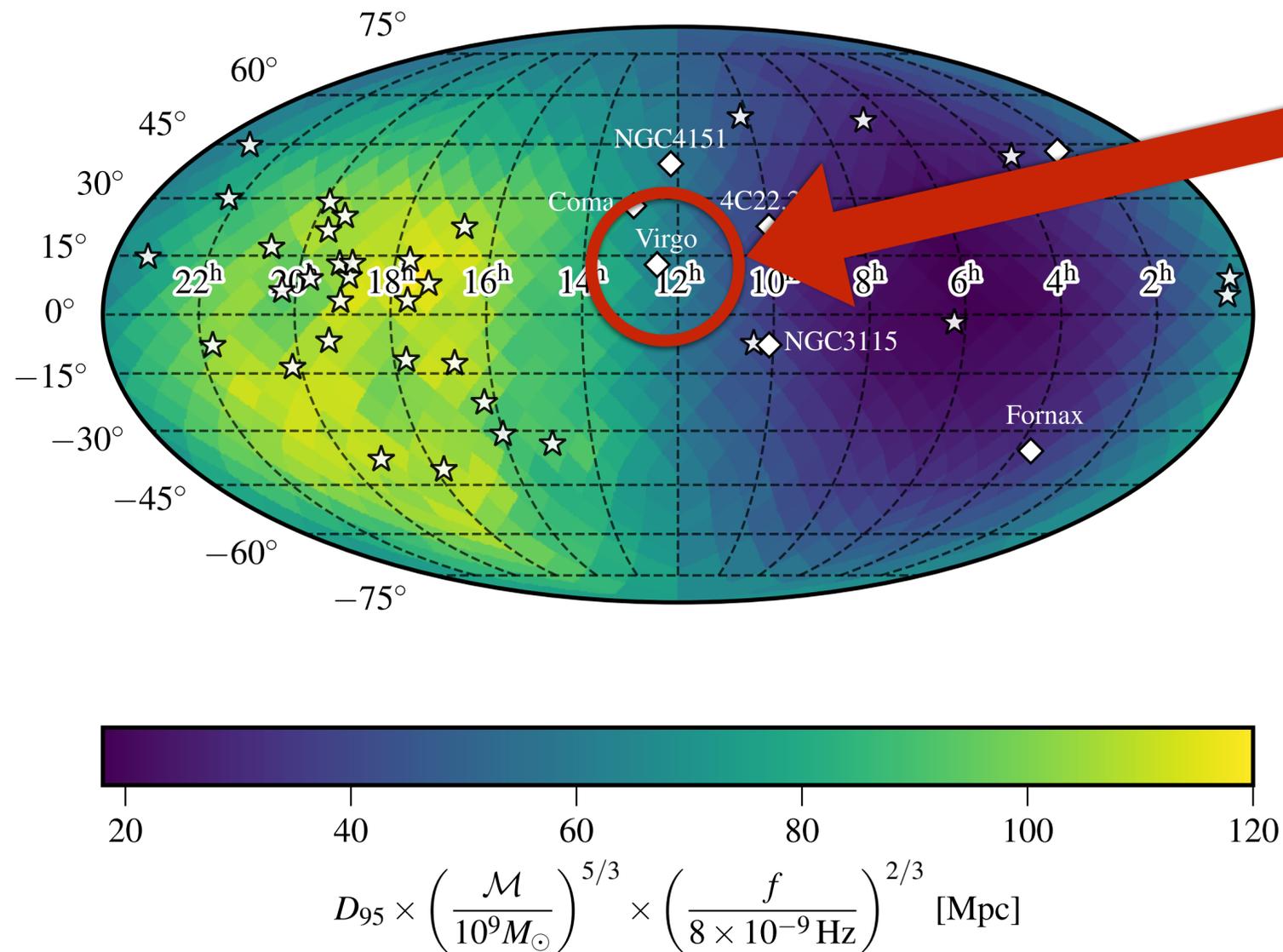


Figure credit: K. Aggarwal et al. (2019)  
Lead author S. J. Vigeland

# Limits on Individual SMBHBs



There are no SMBHBs in the Virgo Cluster with  $\mathcal{M} > 1.6 \times 10^9 M_{\odot}$ .

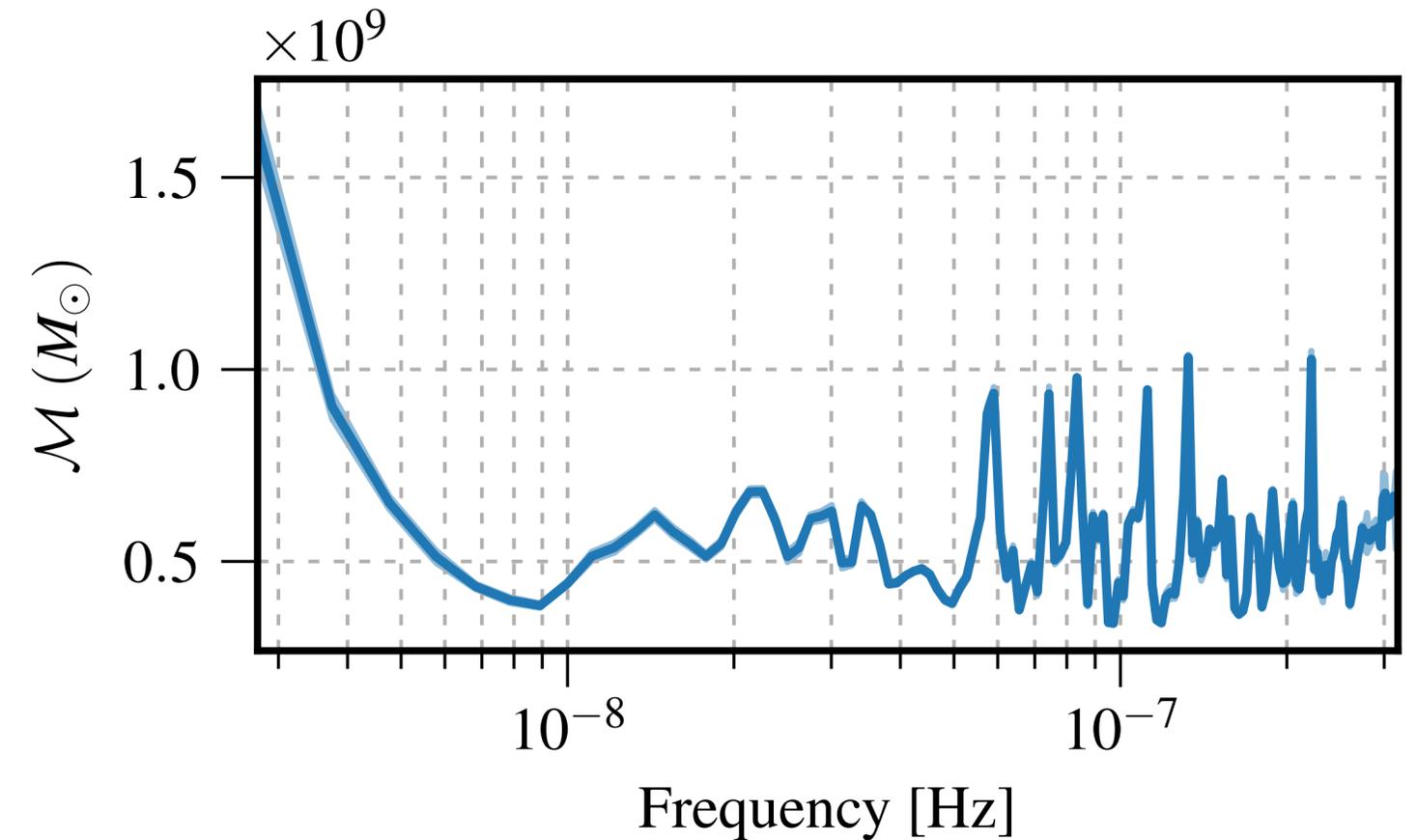
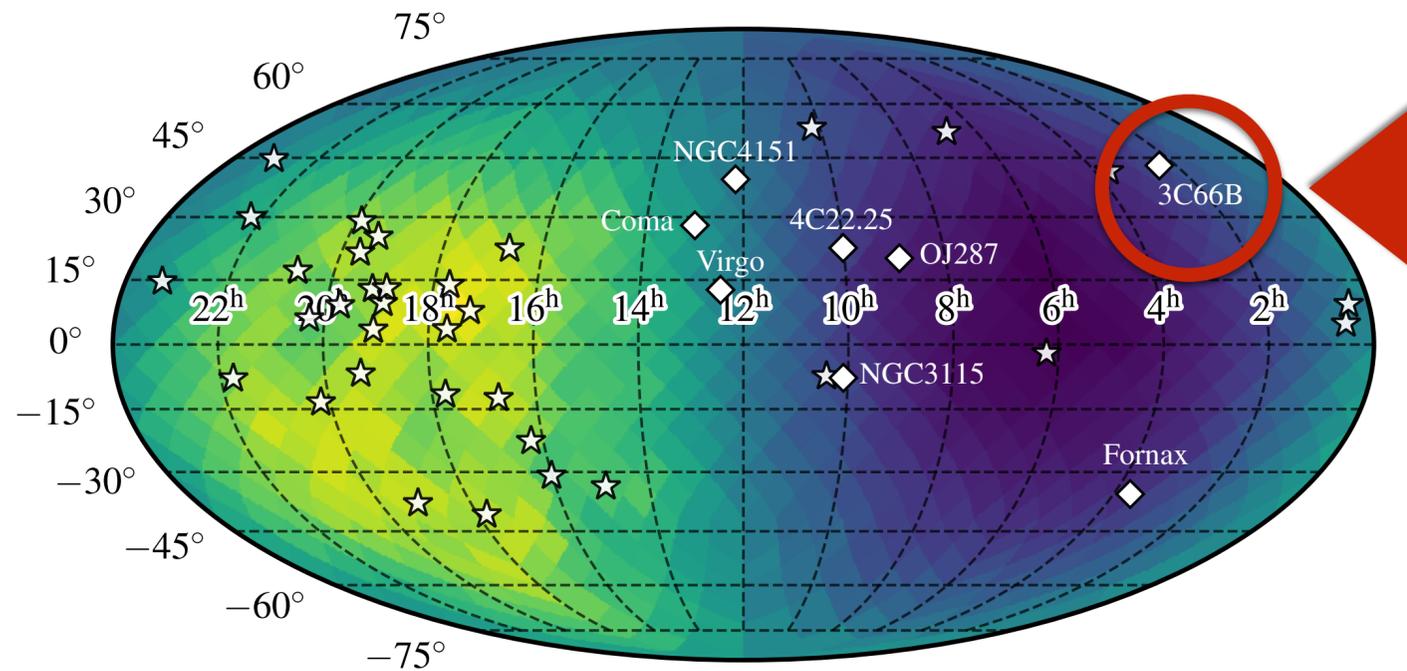
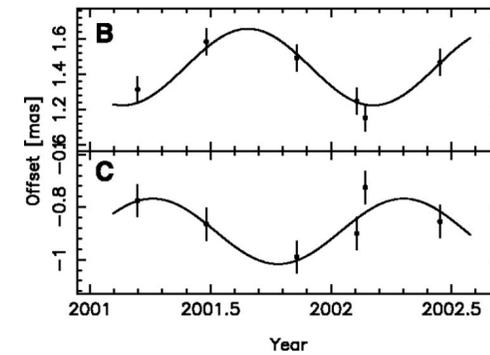
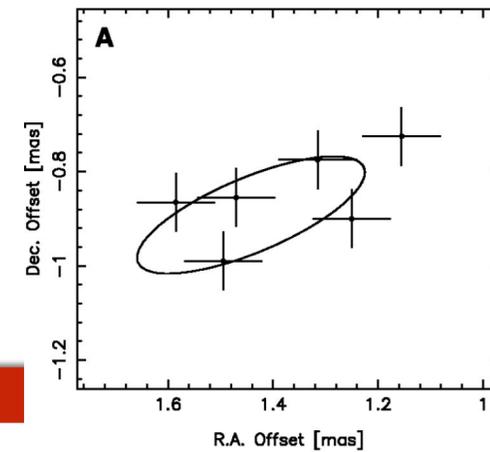


Figure credit: K. Aggarwal et al. (2019)

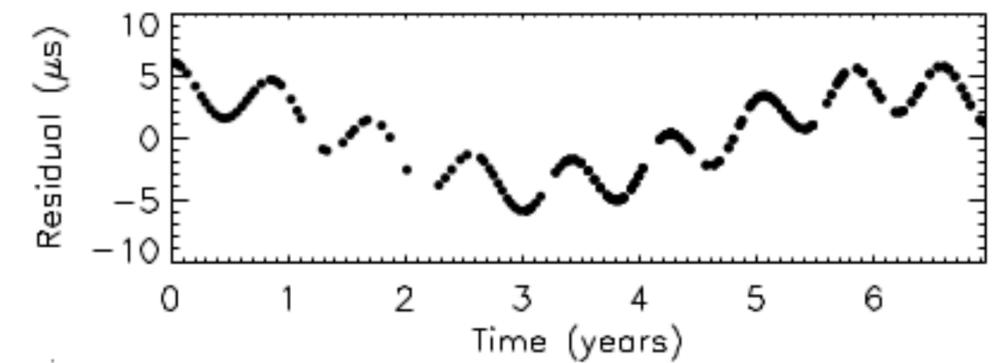
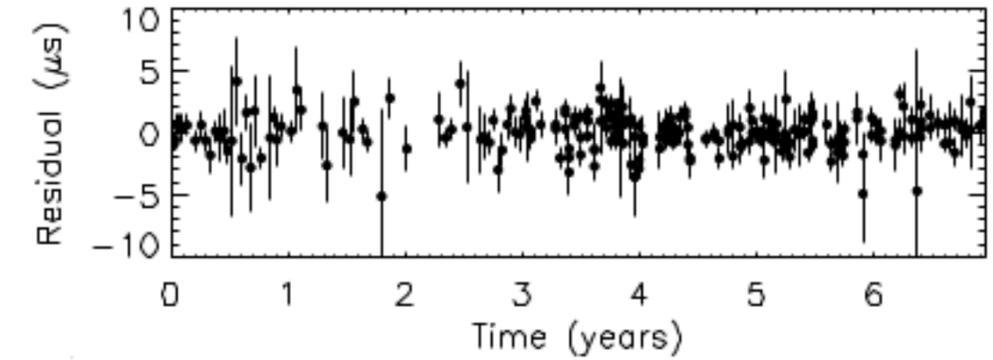
# Limits on Individual SMBHBs



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



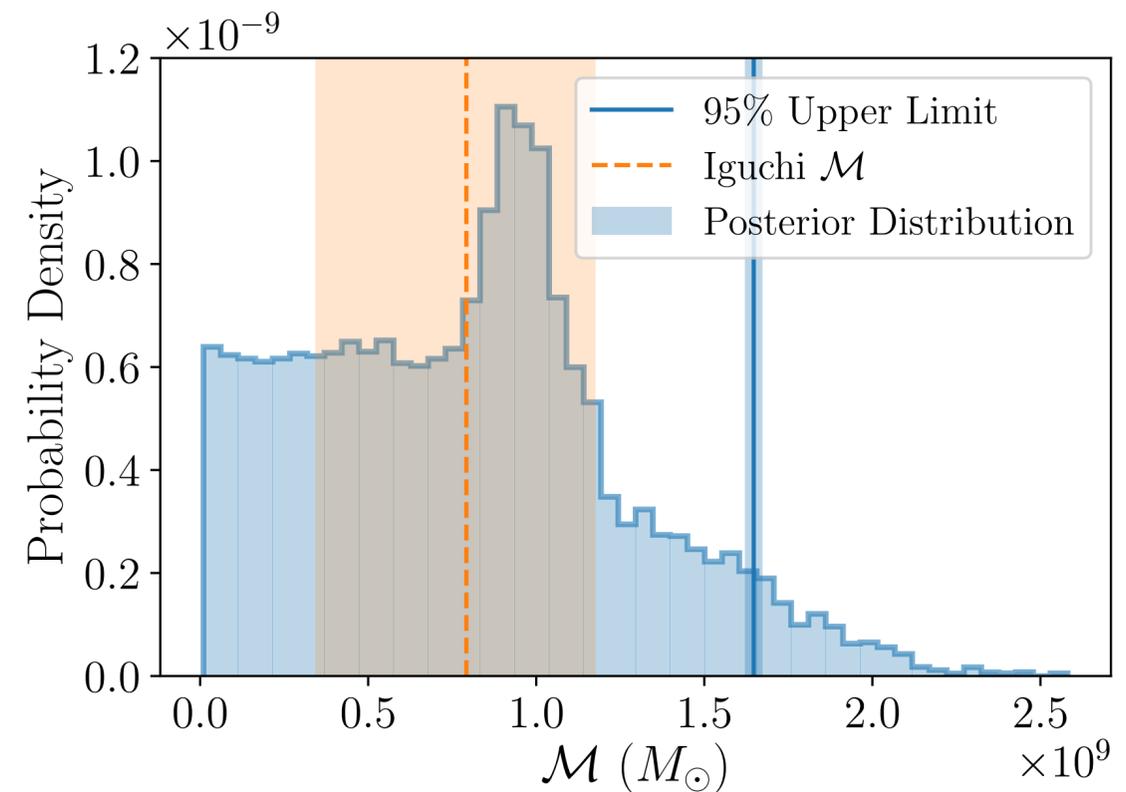
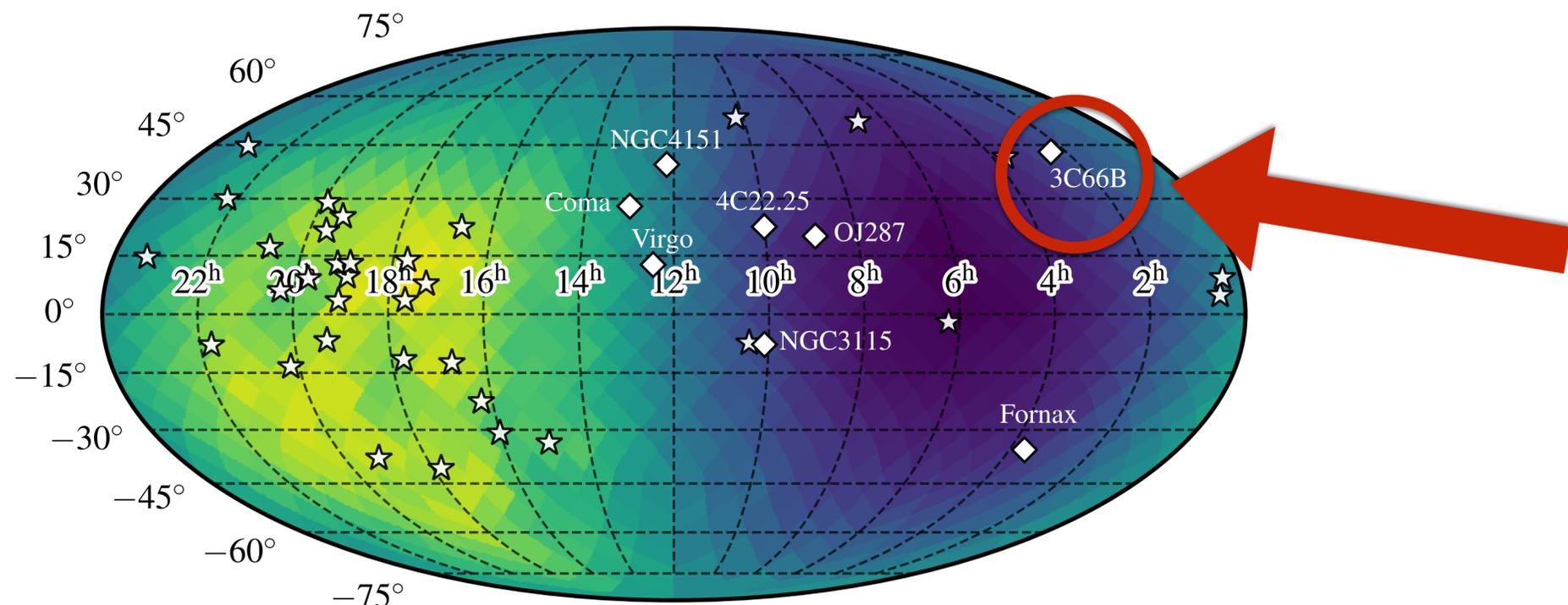
Sodou et al. (2003)



Jenet et al. (2004)

Figure credit: K. Aggarwal et al. (2019)

# Limits on Individual SMBHBs



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

Figure credit: K. Aggarwal et al. (2019)

New constraints on the chirp mass using the NANOGrav 11-year data set (Z. Arzoumanian et al. 2020, lead author C. Witt)

# Constraints on Galaxy Mergers

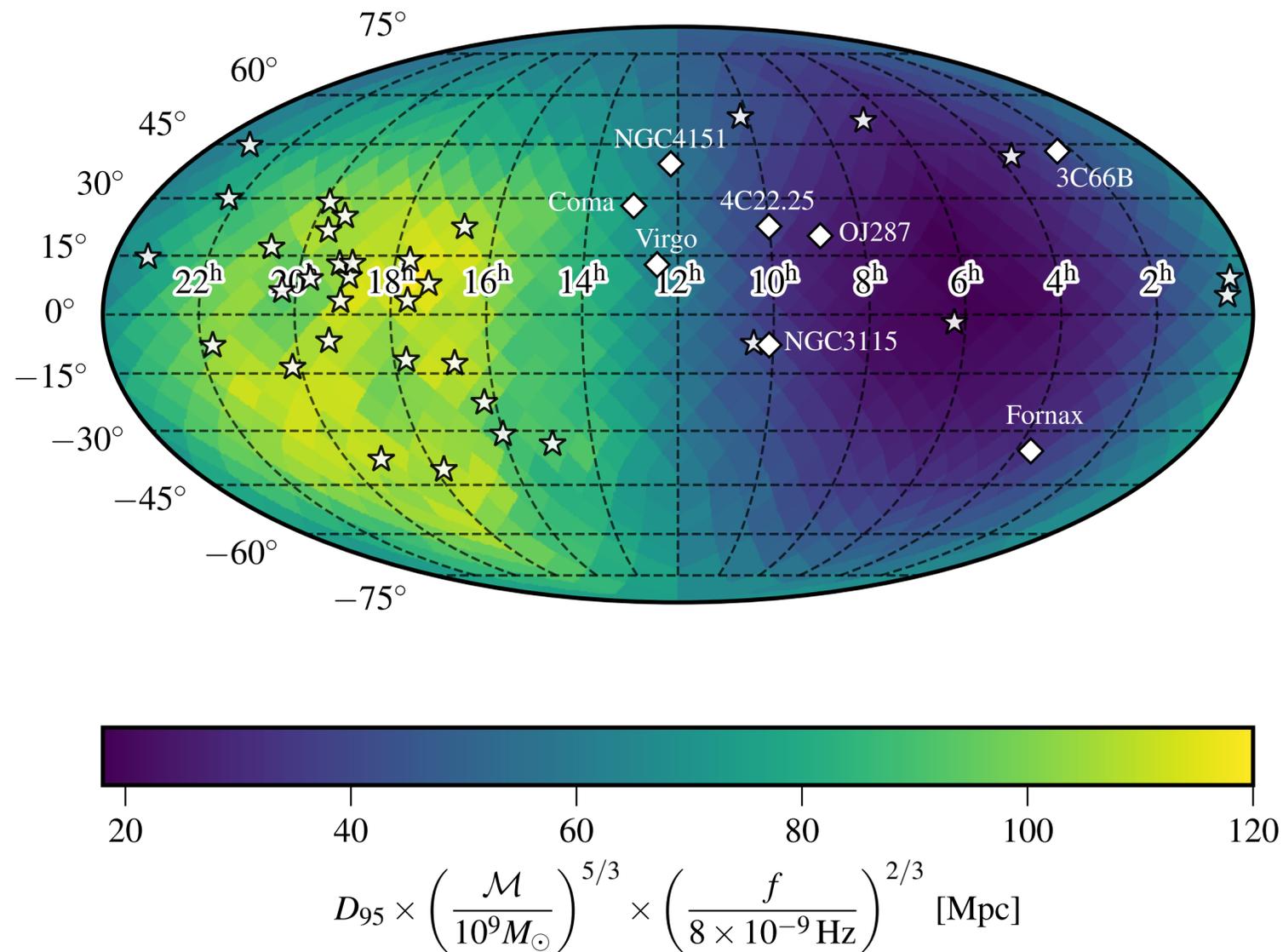


Figure credit: K. Aggarwal et al. (2019)

Major mergers involve two galaxies of similar masses. The resulting SMBBH will have a large mass ratio ( $q > 0.25$ ).

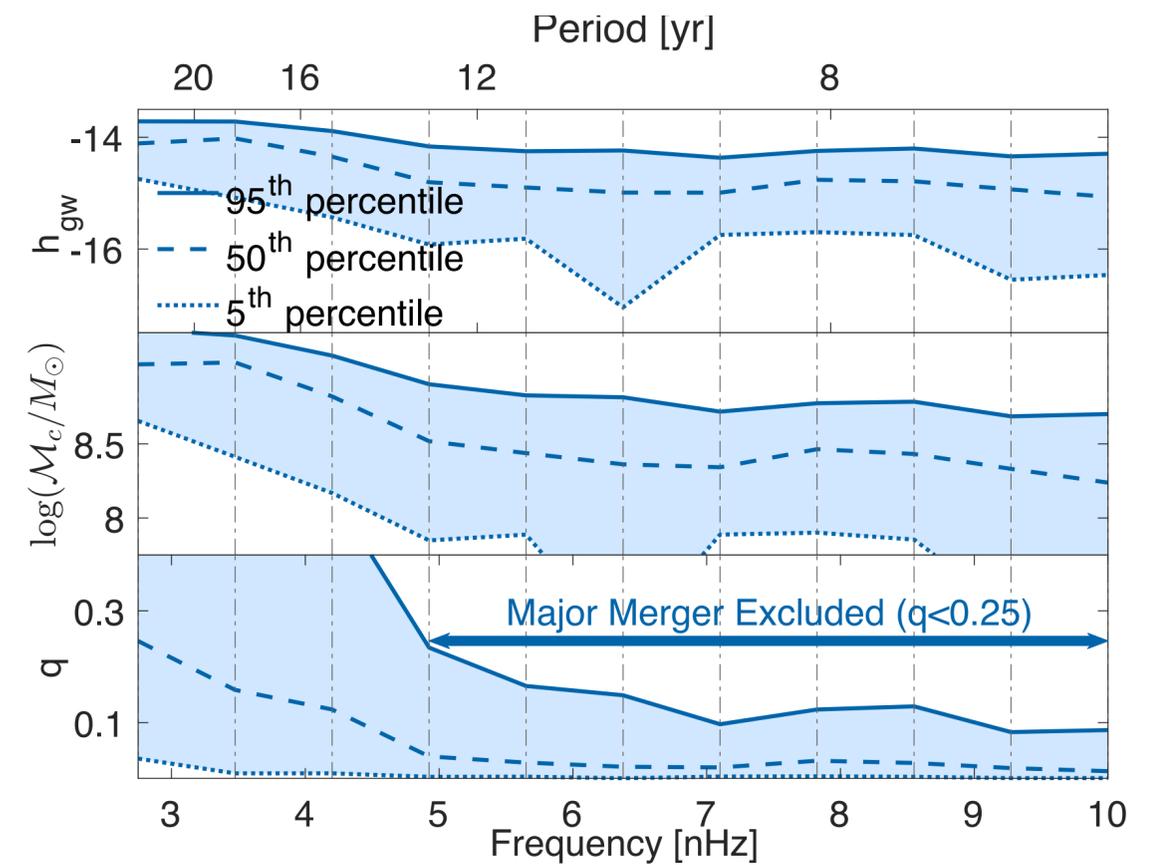


Figure credit: Z. Arzoumanian et al., in prep.  
Lead author Maria Charisi

# Conclusions

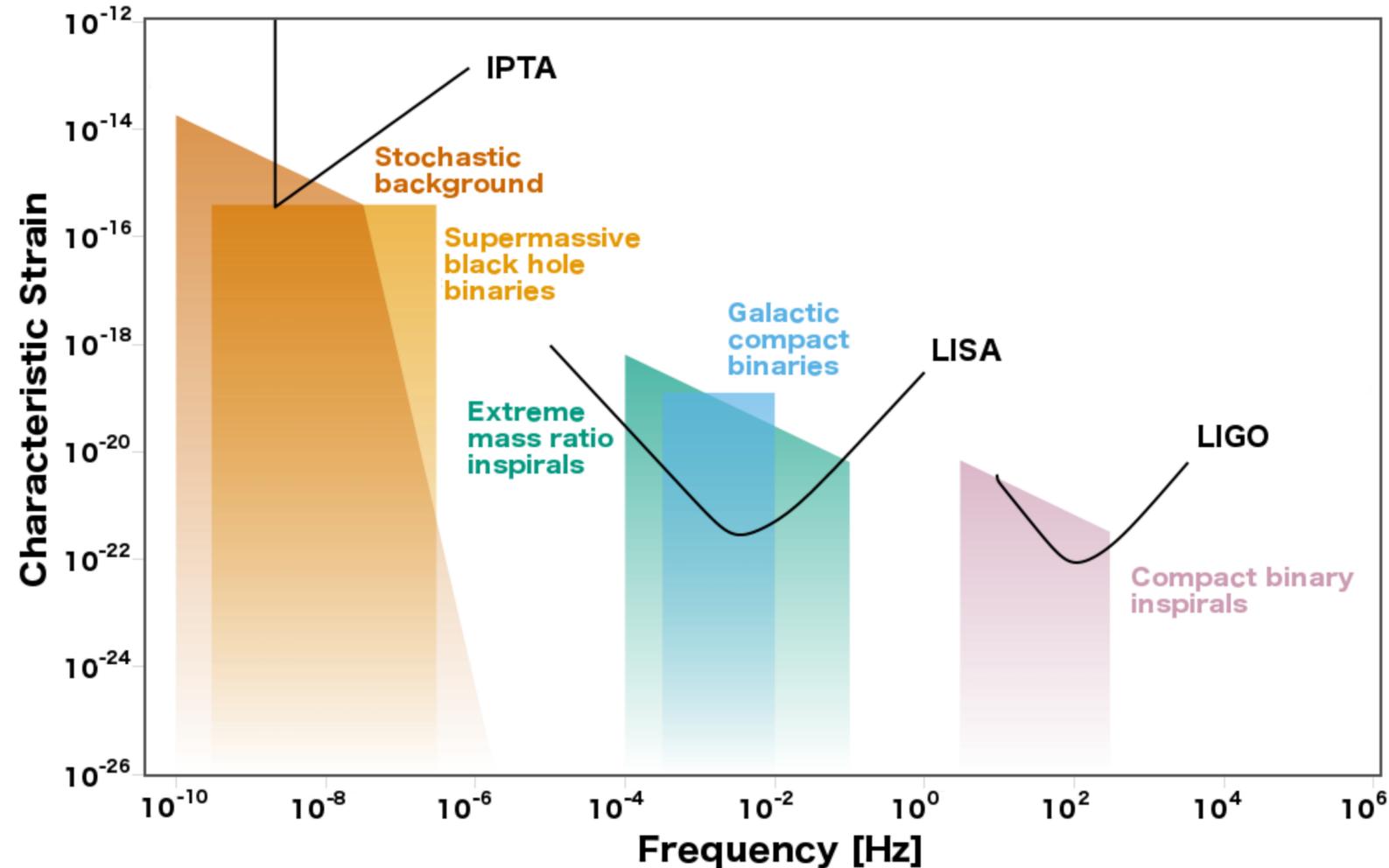


Figure credit: Moore, Cole, Berry 2014.

- PTAs are sensitive to nanohertz GWs inaccessible to ground-based or space-based interferometers.
- PTAs are already putting constraints on the astrophysical properties of nearby SMBBHs.
- The NANOGrav 12.5-year data set shows evidence for a stochastic signal; however, there is not yet evidence for the spatial correlations characteristic of the GWB.