Title: Evidence for a Gravitational-Wave Background

Speakers: Michael Lam

Series: Strong Gravity

Date: January 18, 2024 - 1:00 PM

URL: https://pirsa.org/24010080

Abstract: The North American Nanohertz Observatory for Gravitational Waves (NANOGrav) collaboration has recently reported evidence for the background of low-frequency gravitational waves using an array of rapidly rotating, highly stable radio pulsars distributed across the galaxy. Each pulsar emits a radio beam that passes our line of sight and is observed as regular, pulsed emission. We measure the times of arrival of pulses and compare with a model that includes: the rotational motion of the pulsar, orbital motions, and interstellar propagation delays; random timing noise from pulsars themselves and from the interstellar medium; and finally a correlated gravitational-wave signal recently reported on in a suite of papers. I will highlight our recent results, including implications for the dynamics of supermassive black hole binary at the centers of merging galaxies, searches for individual supermassive black hole binary systems, and searches of gravitational wave signals from new physics. I will end by highlighting future prospects for radio facilities that will advance our look into this newly opened window to the Universe.

Zoom link

NORTH AMERICAN NANOHERTZ OBSERVATORY
for
GRAVITATIONAL WAVES

NANOGrav
Physics Frontiers Center

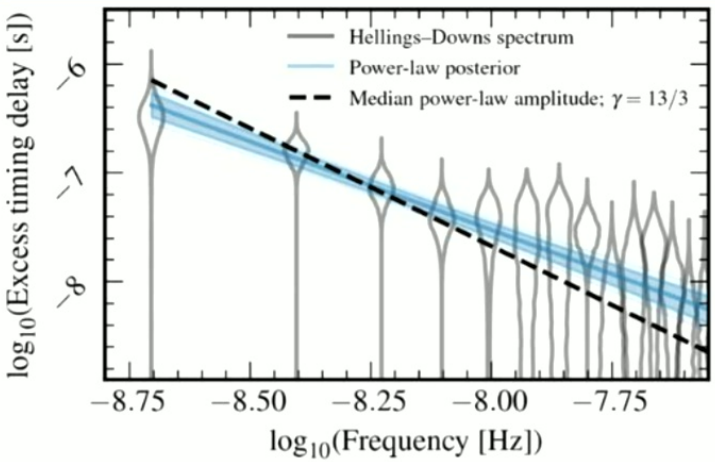
Evidence for a Gravitational-Wave Background

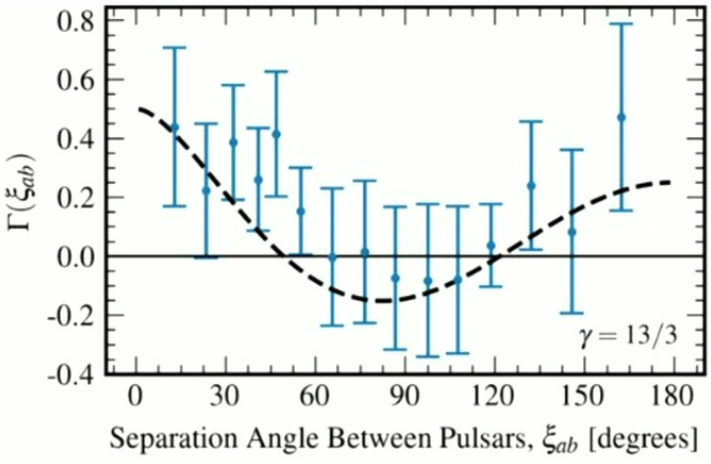
Michael T. Lam

Perimeter Institute Seminar – 18 Jan 2024

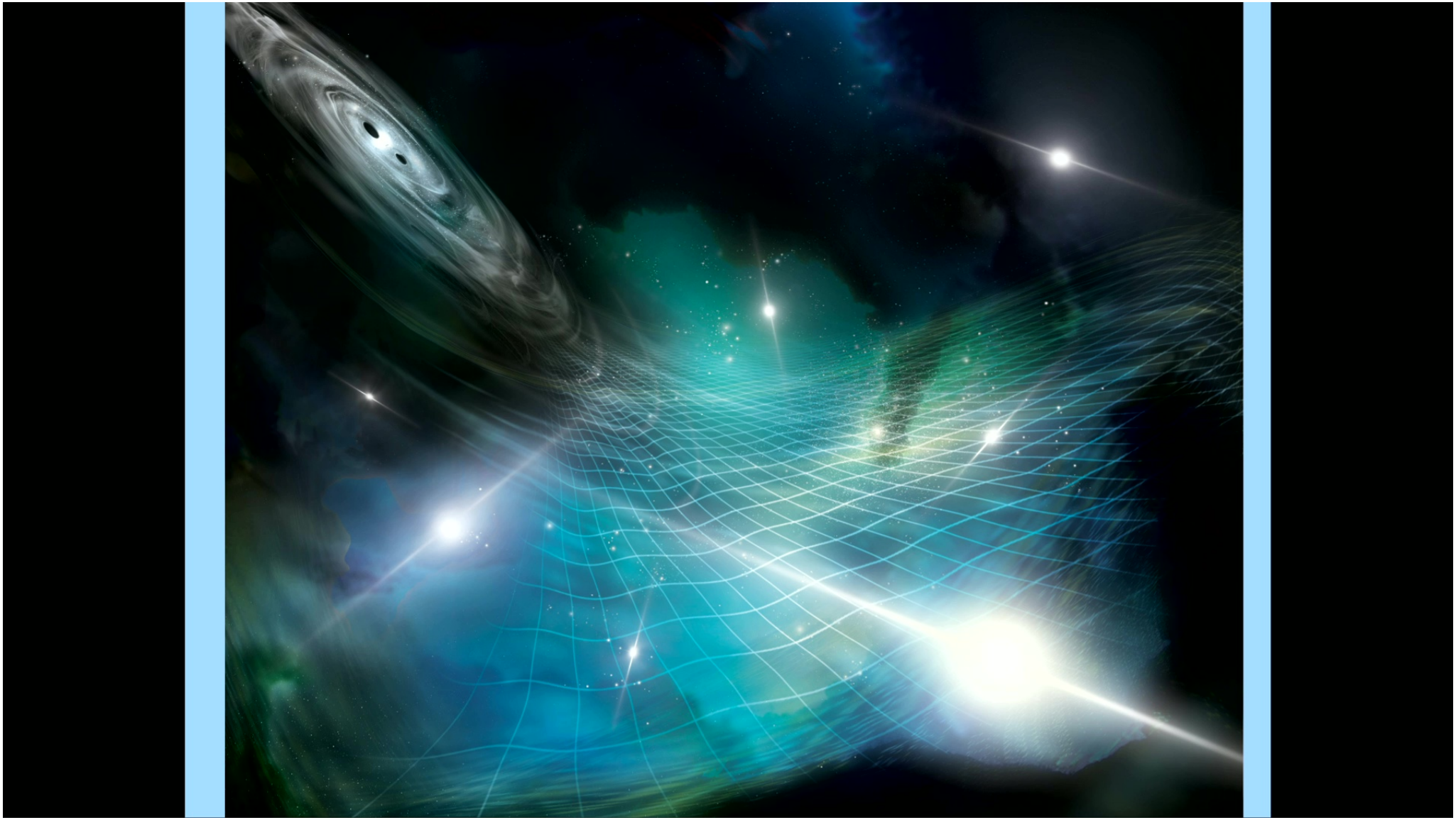
?ETI INSTITUTE
RIT College of Science Astrophysical Sciences and Technology

The Evidence





Agazie et al 2023




NANOGrav
Physics Frontiers Center
UBC
McGill
UWM
OBERLIN
PENNSTATE
LAFAYETTE COLLEGE
UNIVERSITY of VIRGINIA
L,M: NRAO/AUI, R: NAIC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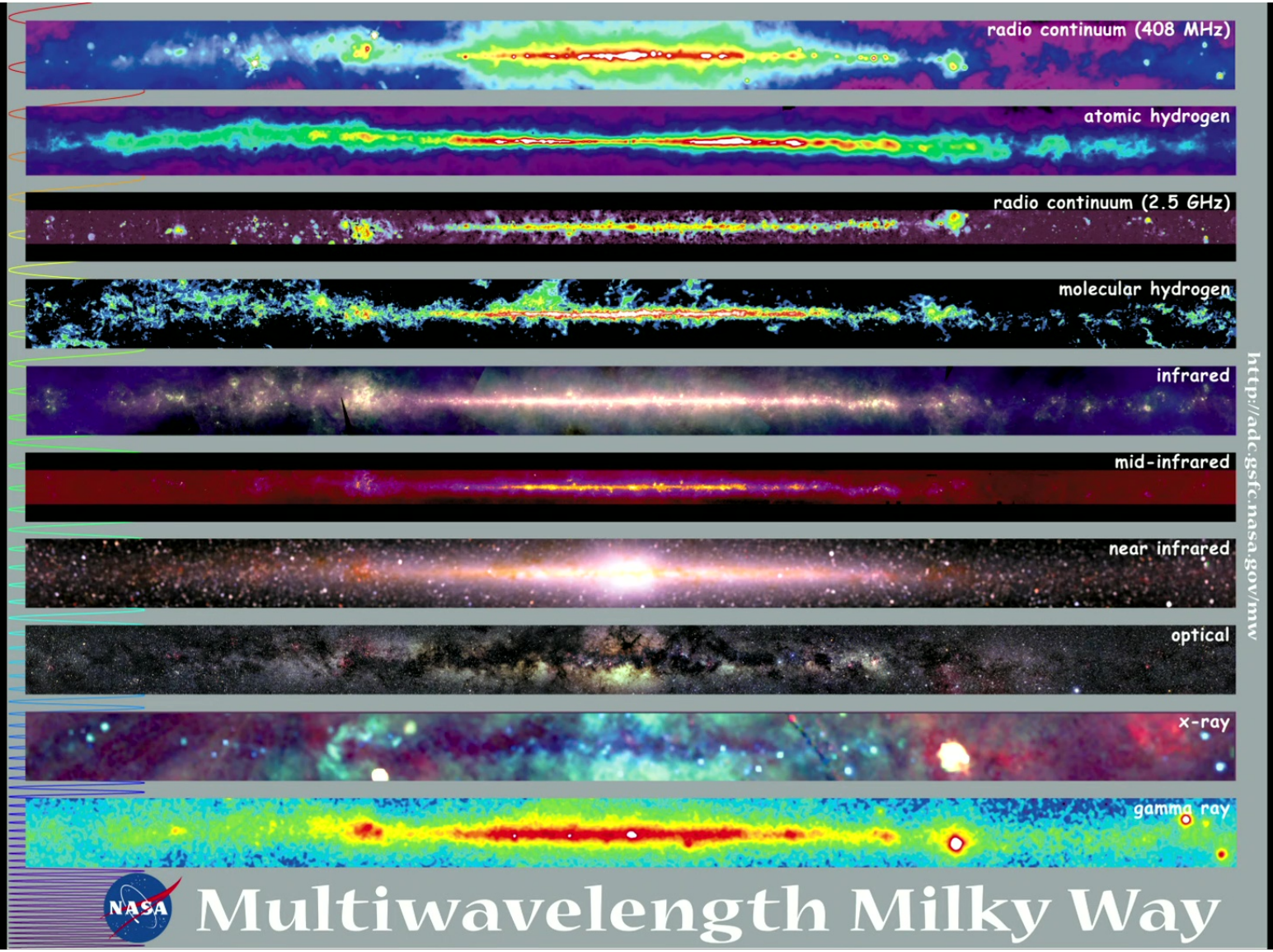
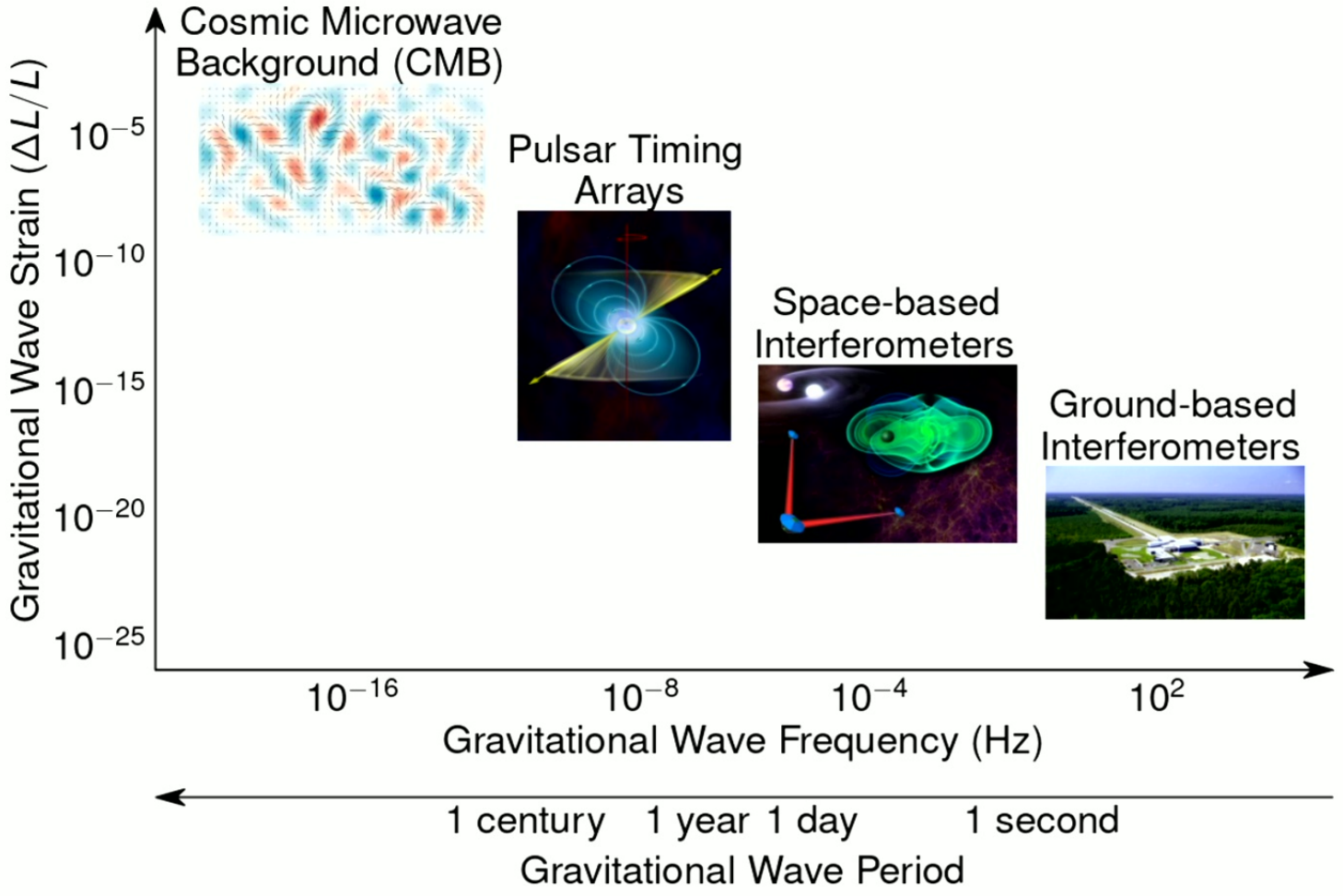
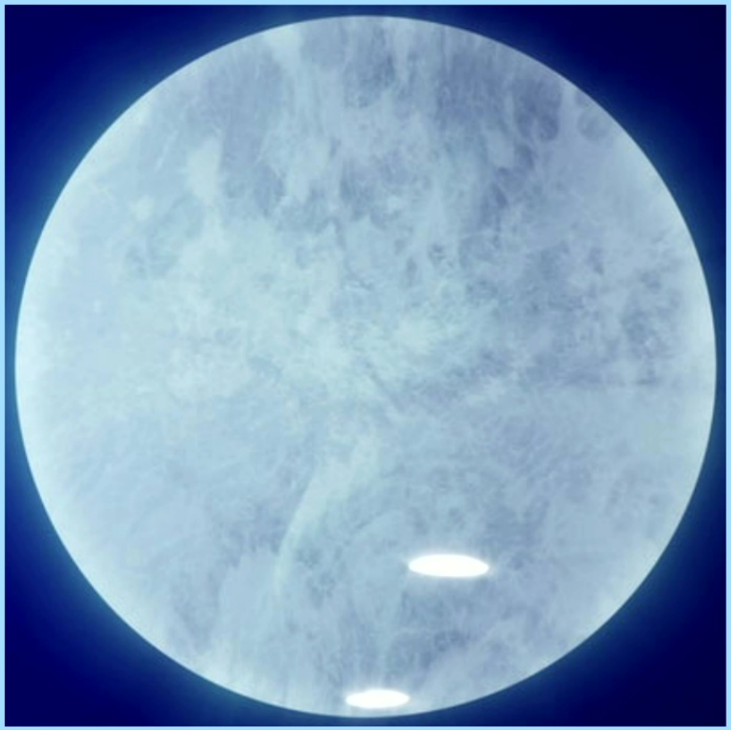

radio continuum (408 MHz)
atomic hydrogen
radio continuum (2.5 GHz)
molecular hydrogen
infrared
mid-infrared
near infrared
optical
x-ray
gamma ray
http://adc.gsfc.nasa.gov/mw
NASA
Multiwavelength Milky Way

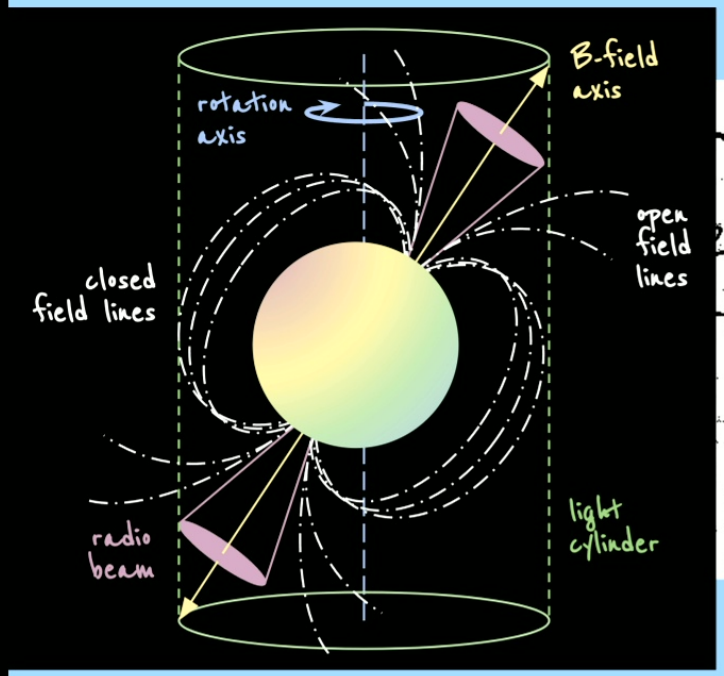

Cosmic Microwave Background (CMB)
Pulsar Timing Arrays
Space-based Interferometers
Ground-based Interferometers
Gravitational Wave Strain (ΔL/L)
10^−5
10^−10
10^−15
10^−20
10^−25
10^−16
10^−8
10^−4
10^2
Gravitational Wave Frequency (Hz)
1 century
1 year
1 day
1 second
Gravitational Wave Period

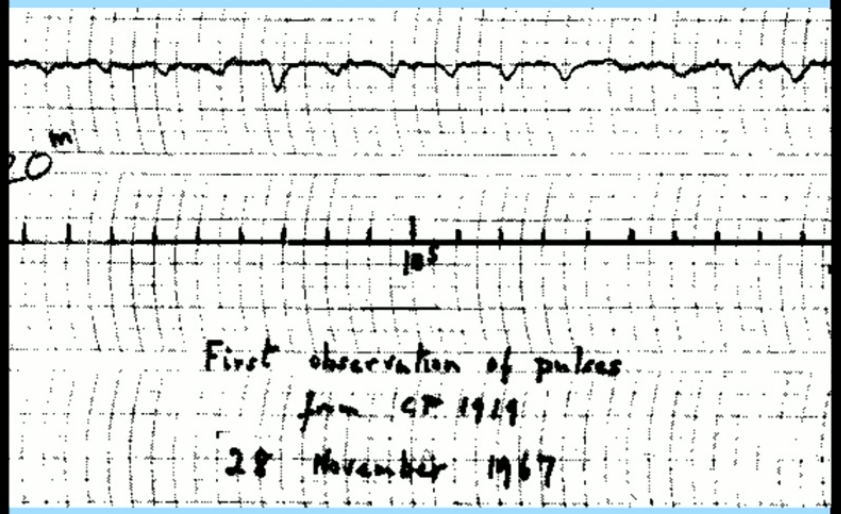
Neutron Stars

$M \sim 1\text{-}2\ M_{\odot}$, $R \sim 12$ km



NASA, NICER, GSFC

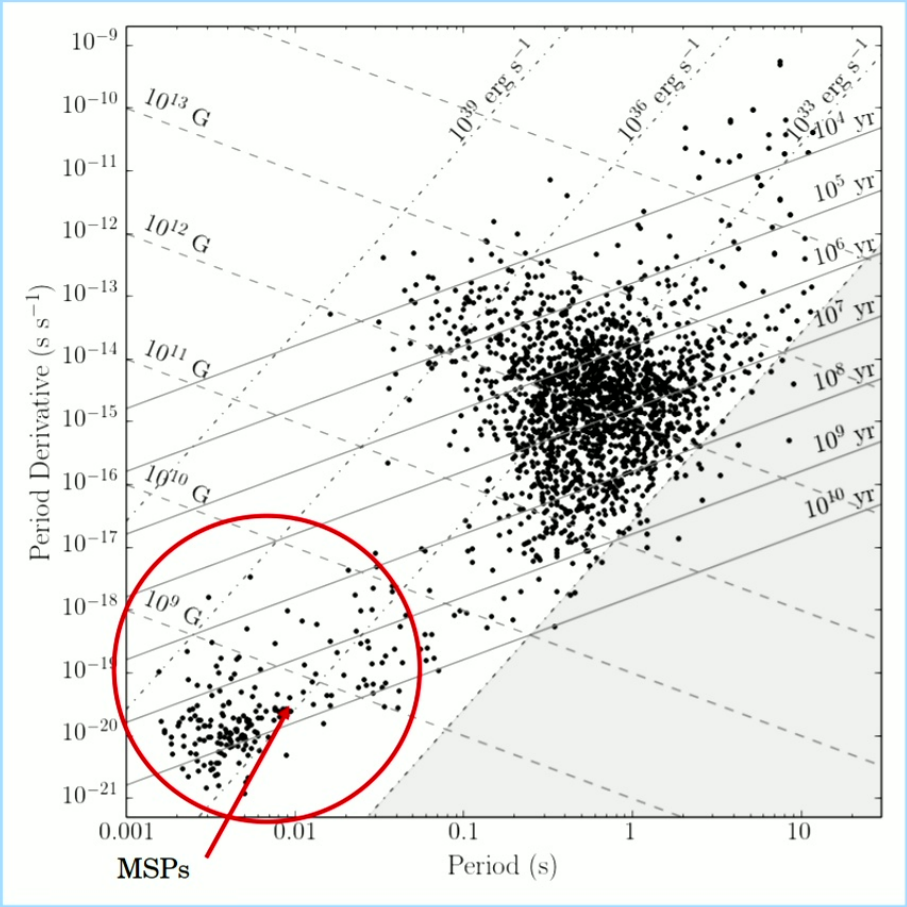




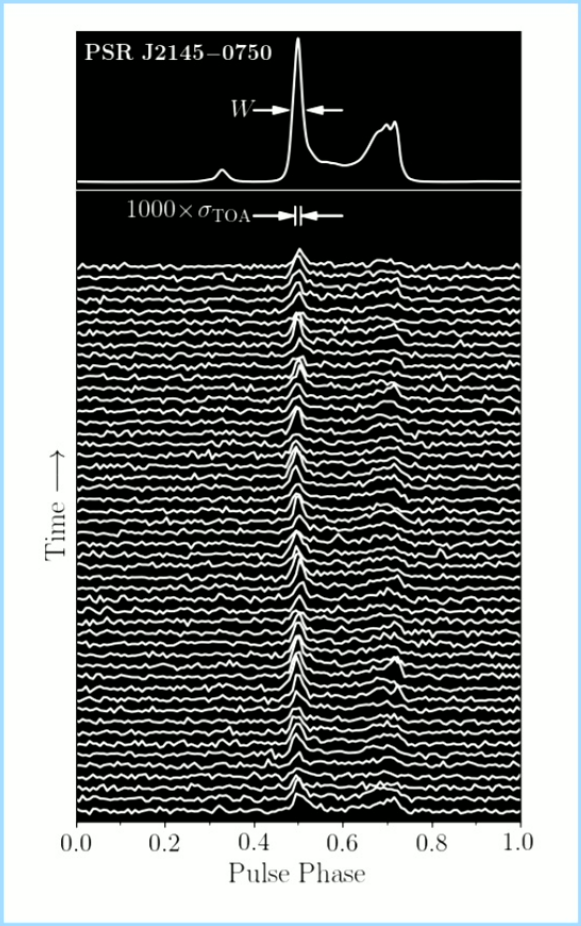
L: Thankful Cromartie

R: http://www.cv.nrao.edu/course/astr534/images/PSRs_discovery.jpg

Millisecond Pulsars



Measuring Pulses



Pulsars as Precise Clocks: J1909-3744

On July 13, 2012 at 00:00:00 UTC:

P = 2.947108025429647 ± 0.000000000000002 ms

The last digit changes by 1 every 713 seconds

This digit changes by 1 every 226 years

Between that time and the start of this seminar, Jan 18, 2024 at 18:00 UTC, the pulsar has completed just over 123,328,767,235 rotations (0.35 over!)

Data: NANOGrav

More fun with J1909-3744

It's also completed over 2743 orbits around its companion white dwarf (0.32 over!)

Smallest eccentricity of any known binary in the Universe:

$e = 0.000000109 \pm 0.000000008$

Orbit has radius=$(5.7014 \pm 0.0004) \cdot 10^8$ m (0.82 R_{sun})

But, we know the difference between the semi-major and semi-minor axis is 3.4 ± 0.5 μm!

Data: NANOGrav

The Tiny Effects of GWs

$$h \sim \frac{G}{Dc^4}\ddot{I} \sim \frac{G}{Dc^4}\frac{MR^2}{T^2} \sim \frac{G}{4\pi^2 Dc^4} MR\Omega^2 \sim \frac{(GM)^2}{4\pi^2 c^4 DR}$$
$$\approx 6 \times 10^{-16} \left(\frac{M}{10^8\, M_\odot}\right)^2 \left(\frac{\mathrm{Mpc}}{D}\right)^2 \left(\frac{\mathrm{mpc}}{R}\right)^2$$

$$f \sim \frac{1}{2\pi}\left(\frac{GM}{R^3}\right)^{1/2}$$
$$\approx 100\ \mathrm{nHz} \left(\frac{M}{10^8\, M_\odot}\right)^{1/2} \left(\frac{\mathrm{mpc}}{R}\right)^{3/2}$$

The Tiny Effects of GWs

$$h \sim \frac{(GM)^2}{4\pi^2 c^4 DR}$$

$$\approx 6$$

$$\Delta L \sim hL \sim hcT$$

$$\approx 100 \text{ m} \left(\frac{h}{10^{-15}}\right)\left(\frac{T}{10 \text{ yr}}\right)$$

$$\Delta t \sim \frac{\Delta L}{c} \sim hT$$

$$\approx 300 \text{ ns} \left(\frac{h}{10^{-15}}\right)\left(\frac{T}{10 \text{ yr}}\right)$$

$$f$$

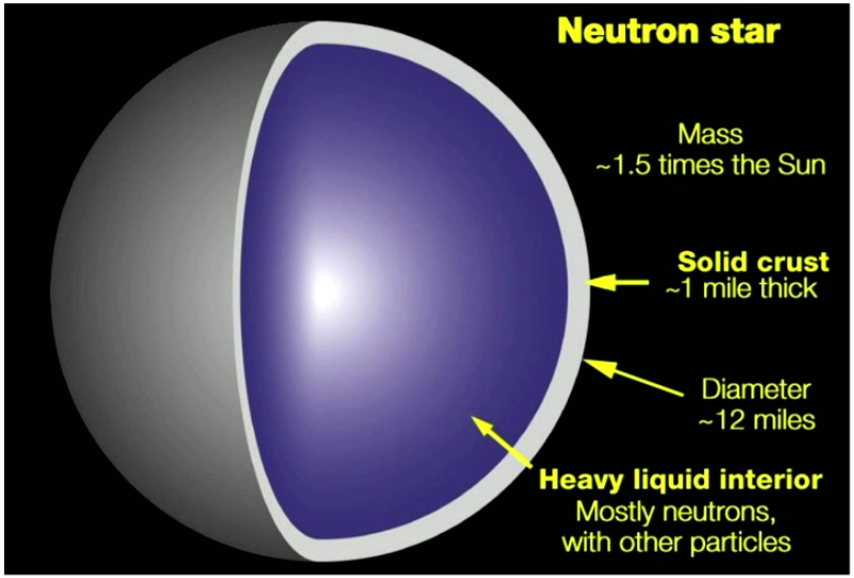
$$\approx 100 \text{ nHz} \left(\frac{M}{10^8 M_\odot}\right)$$

The Tiny Effects of GWs

$$h \sim \frac{(GM)^2}{4\pi^2 c^4 DR}$$

$$\Delta L \sim hL \sim hcT$$

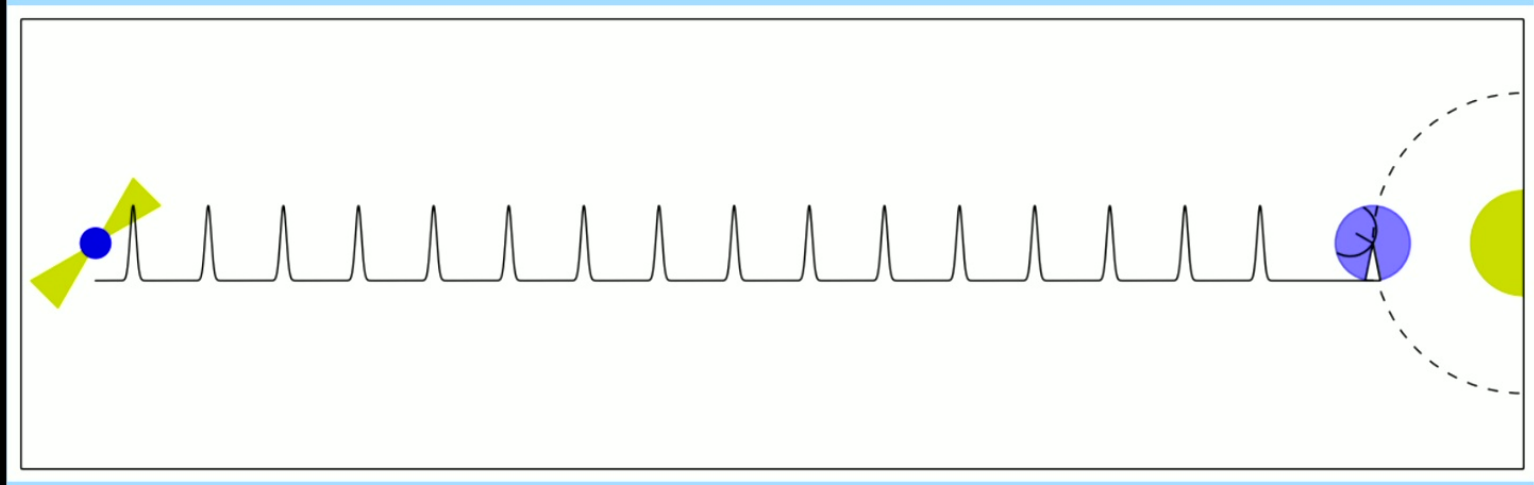
$$\approx 100 \text{ m} \left(\frac{h}{10^{-15}}\right)\left(\frac{T}{10 \text{ yr}}\right)$$



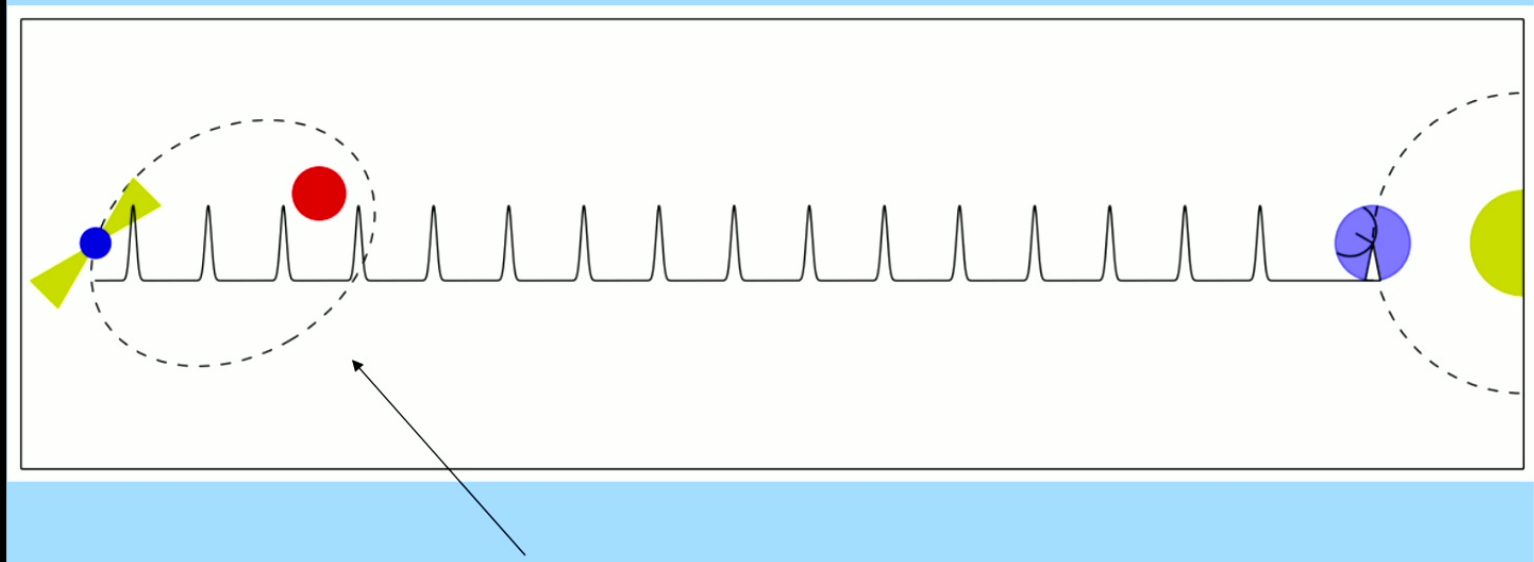
$$\approx 0.01 \, R_{NS}$$

http://astro.hopkinsschools.org/course_documents/stars/smallest/neutron_structure.jpg

Timing Model

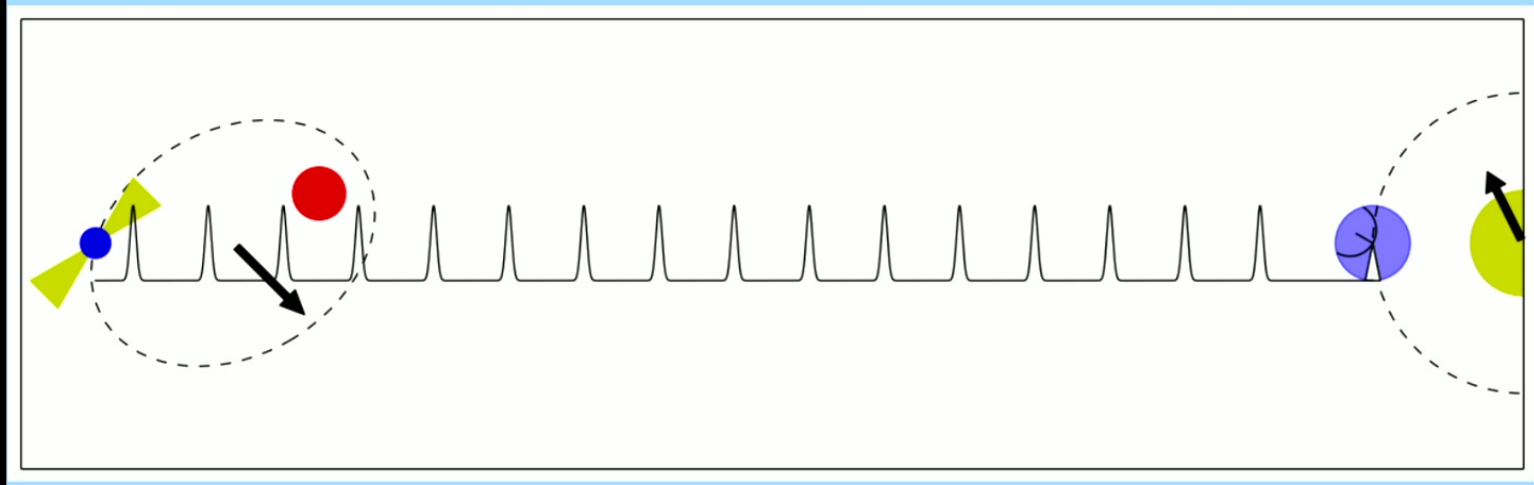


Timing Model

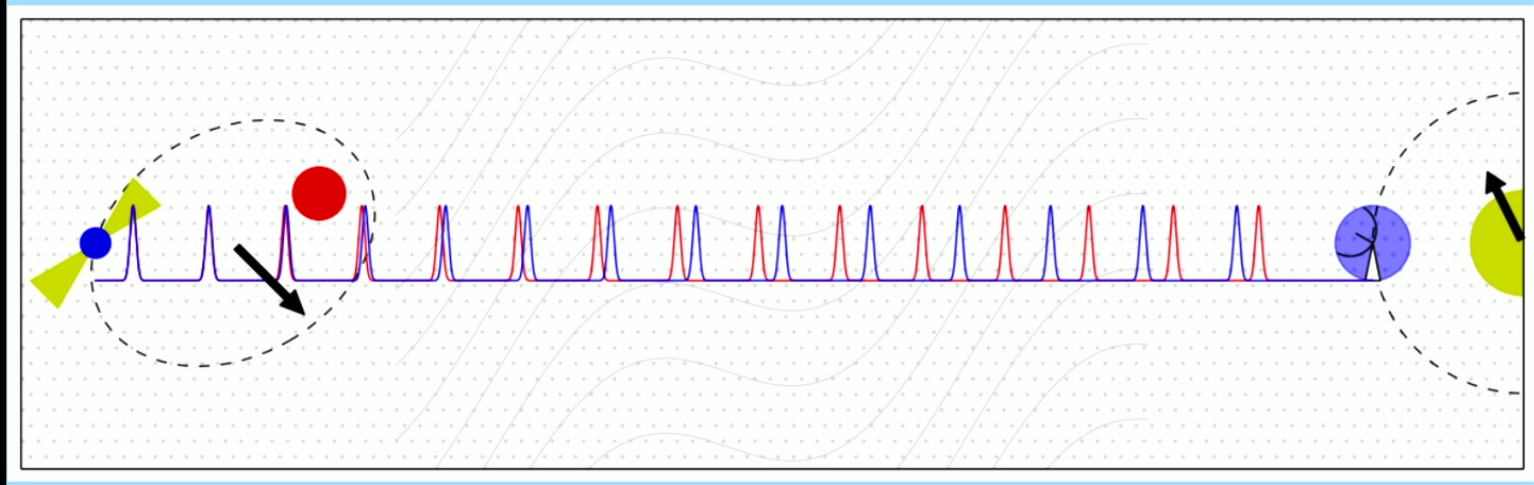


Lots of cool tests of gravity here too

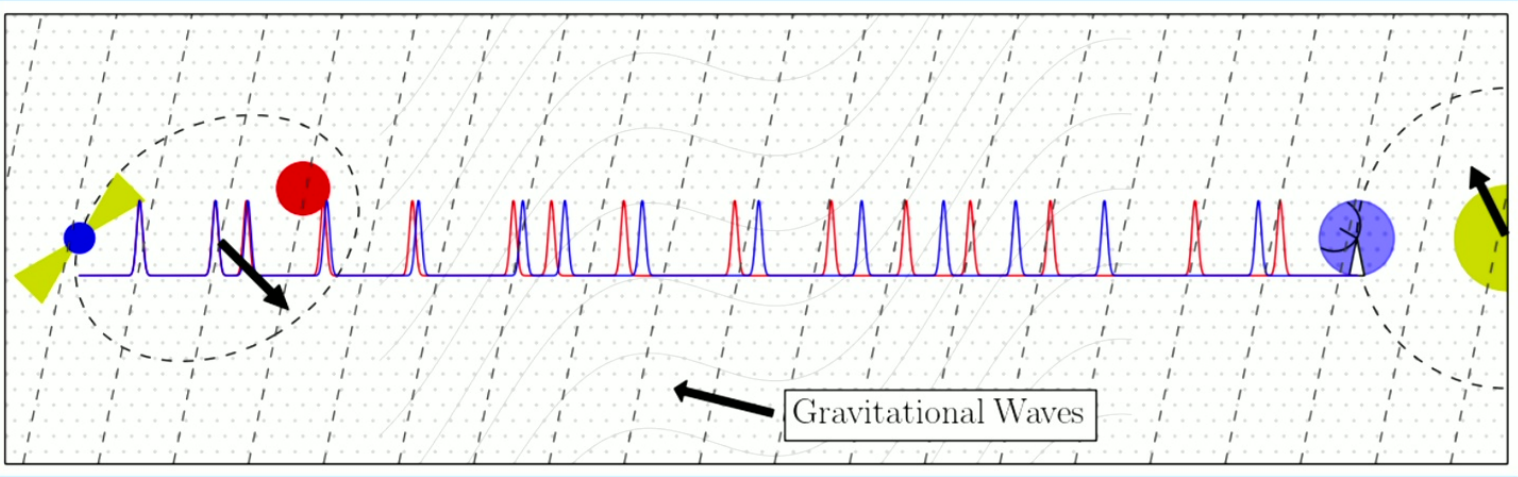
Timing Model



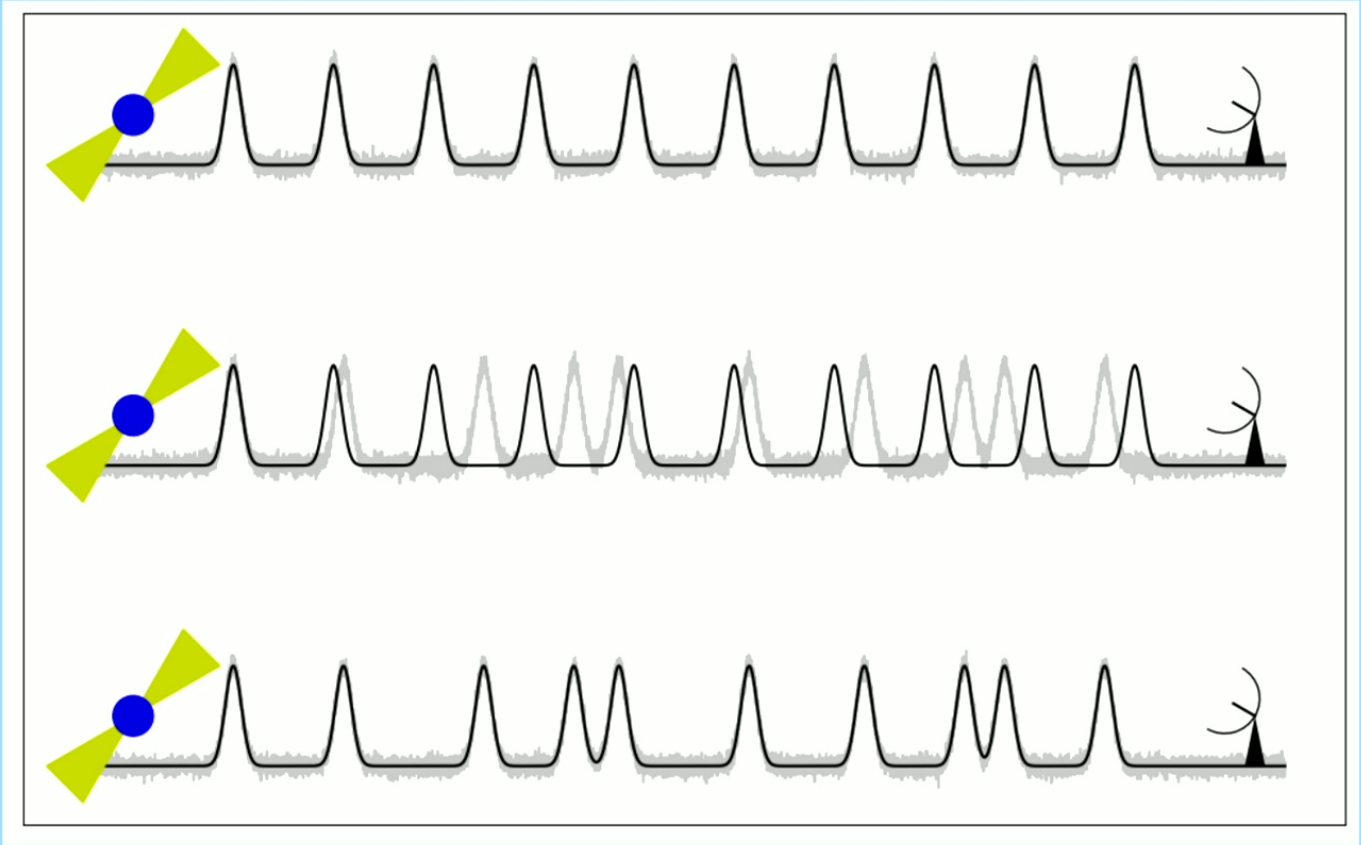
Timing Model



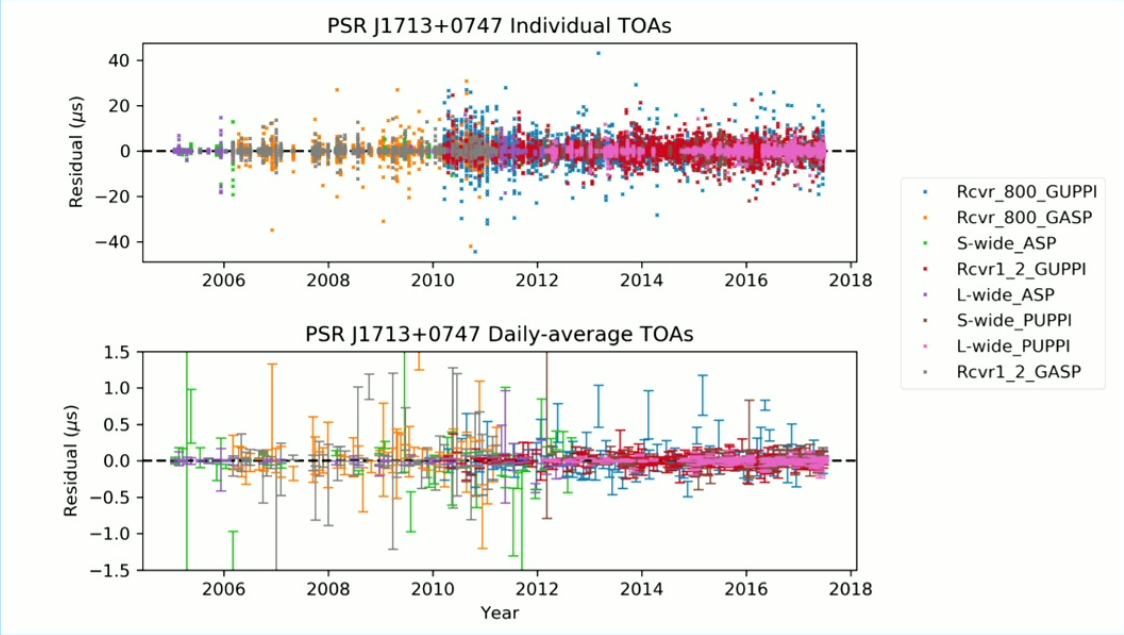
Timing Model



Pulsar Timing

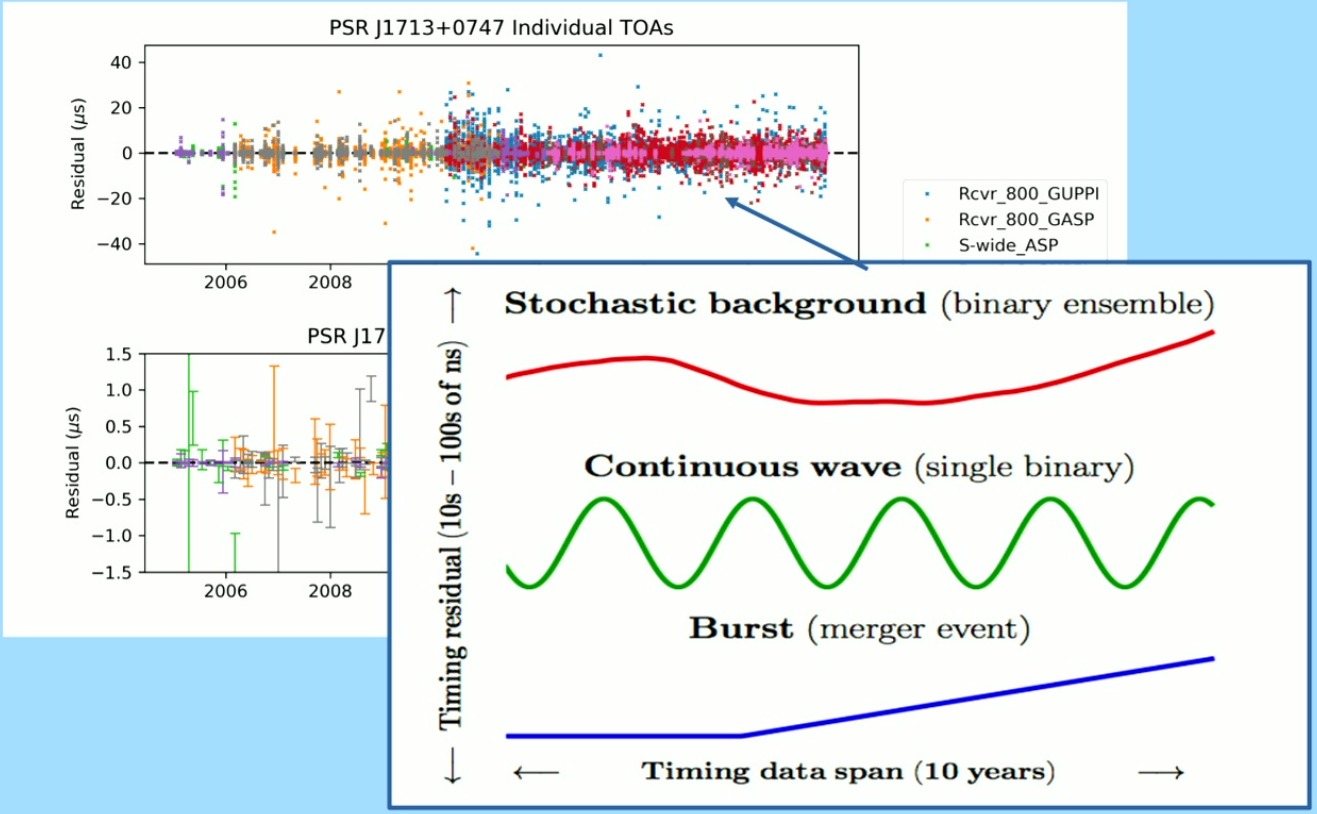


Residuals and GW Signatures



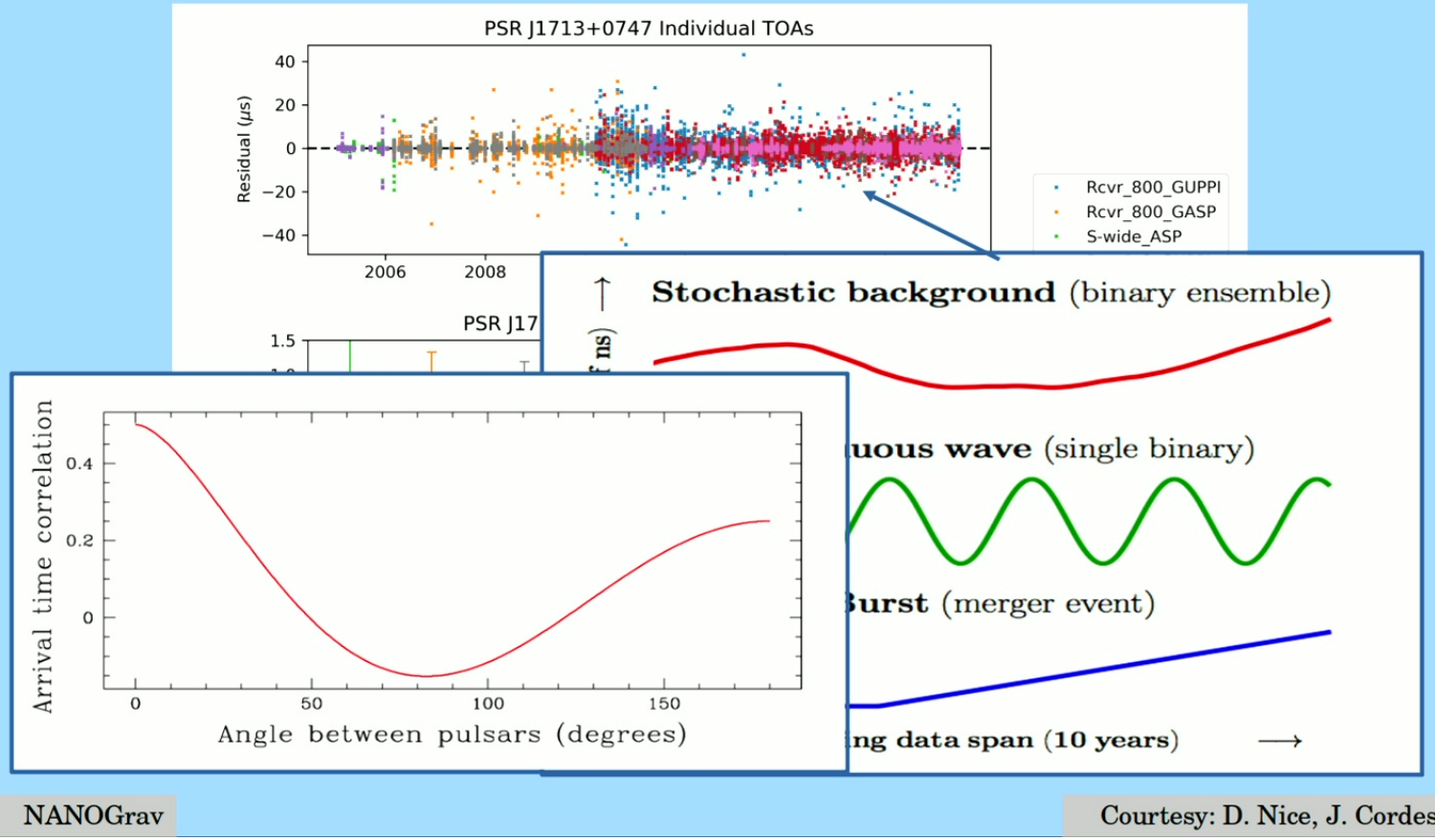
Courtesy: D. Nice

Residuals and GW Signatures



Courtesy: D. Nice, J. Cordes

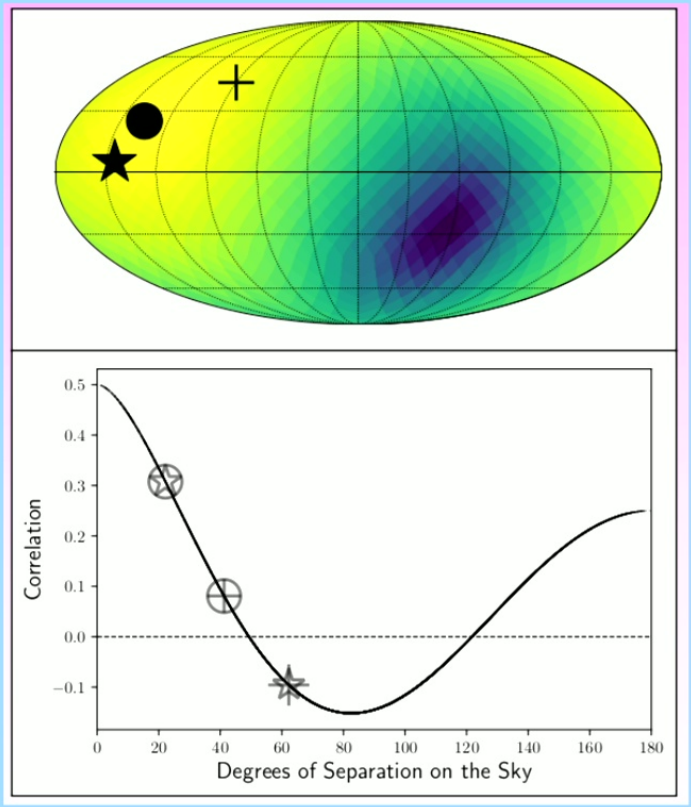
Residuals and GW Signatures



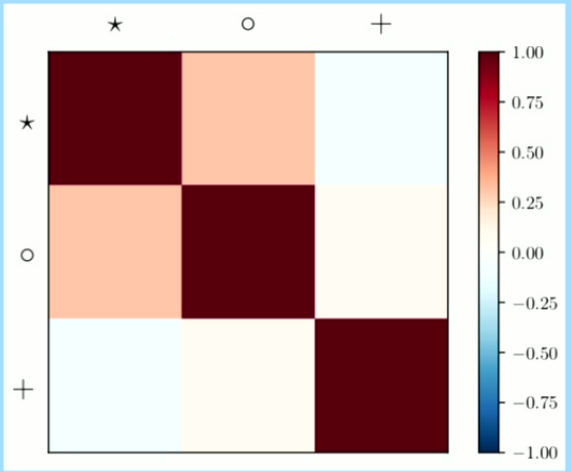
NANOGrav

Courtesy: D. Nice, J. Cordes

PTAs and Angular Correlations

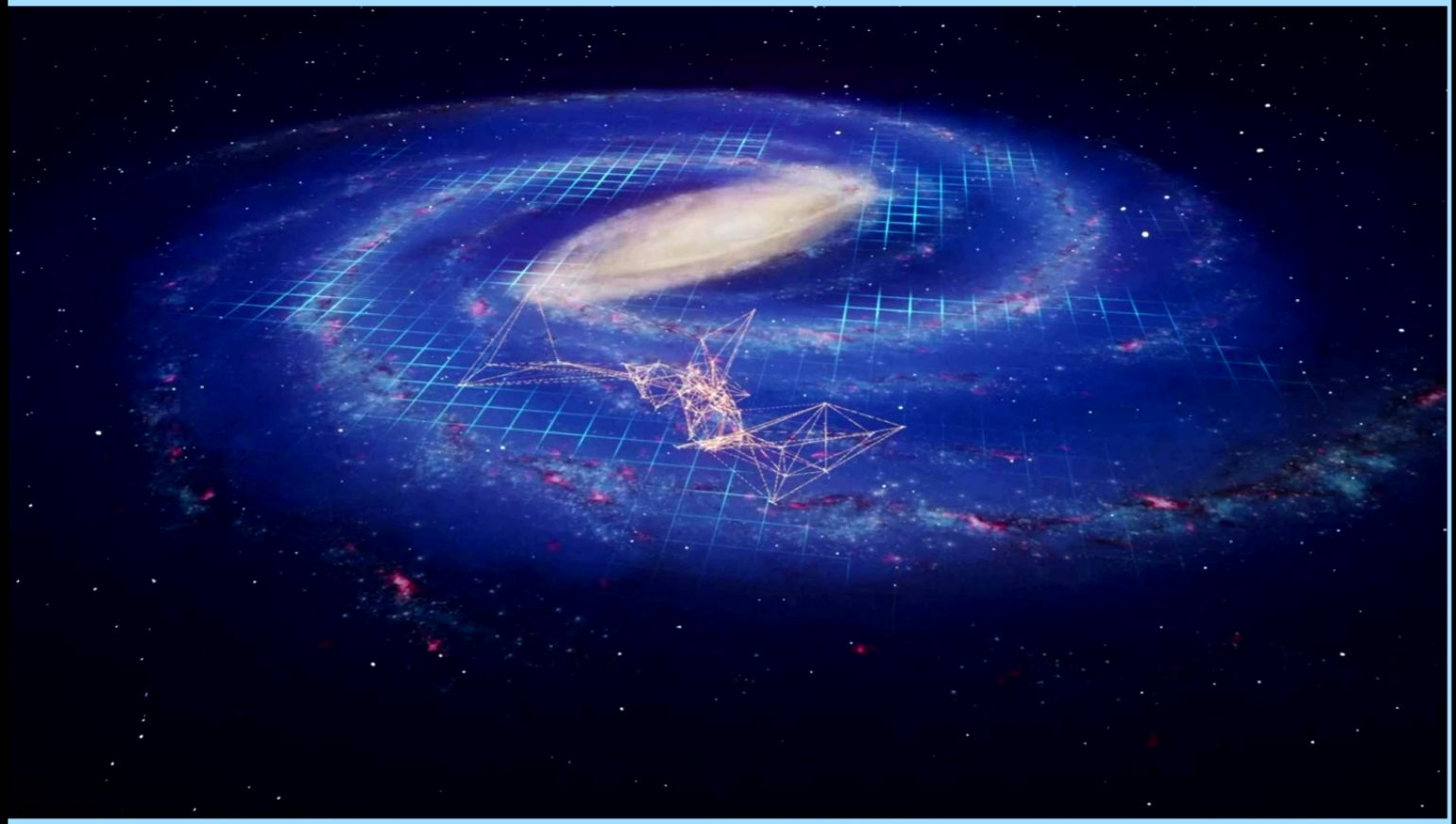


Correlation Matrix



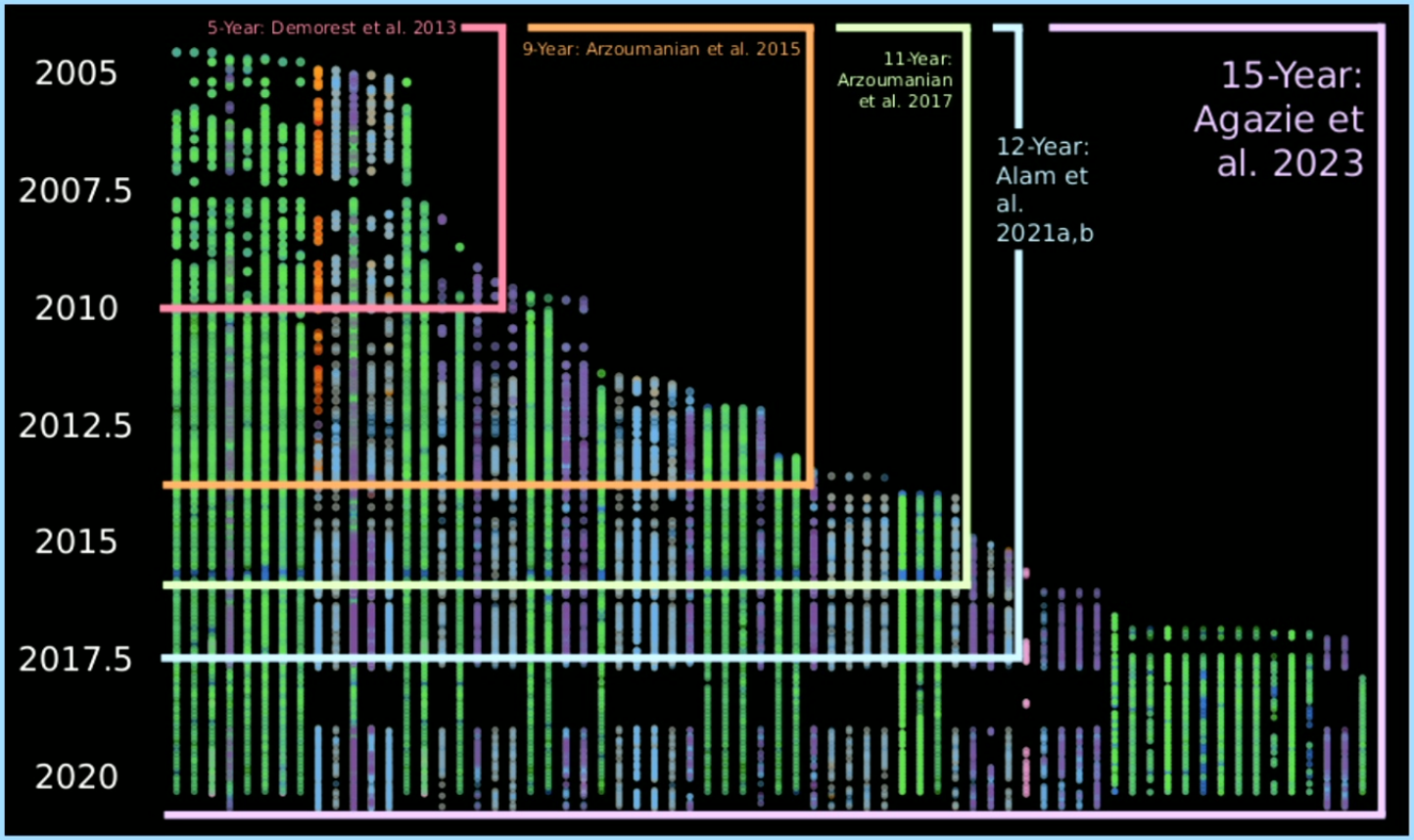
Courtesy: J. Hazboun

The Pulsar Timing Array



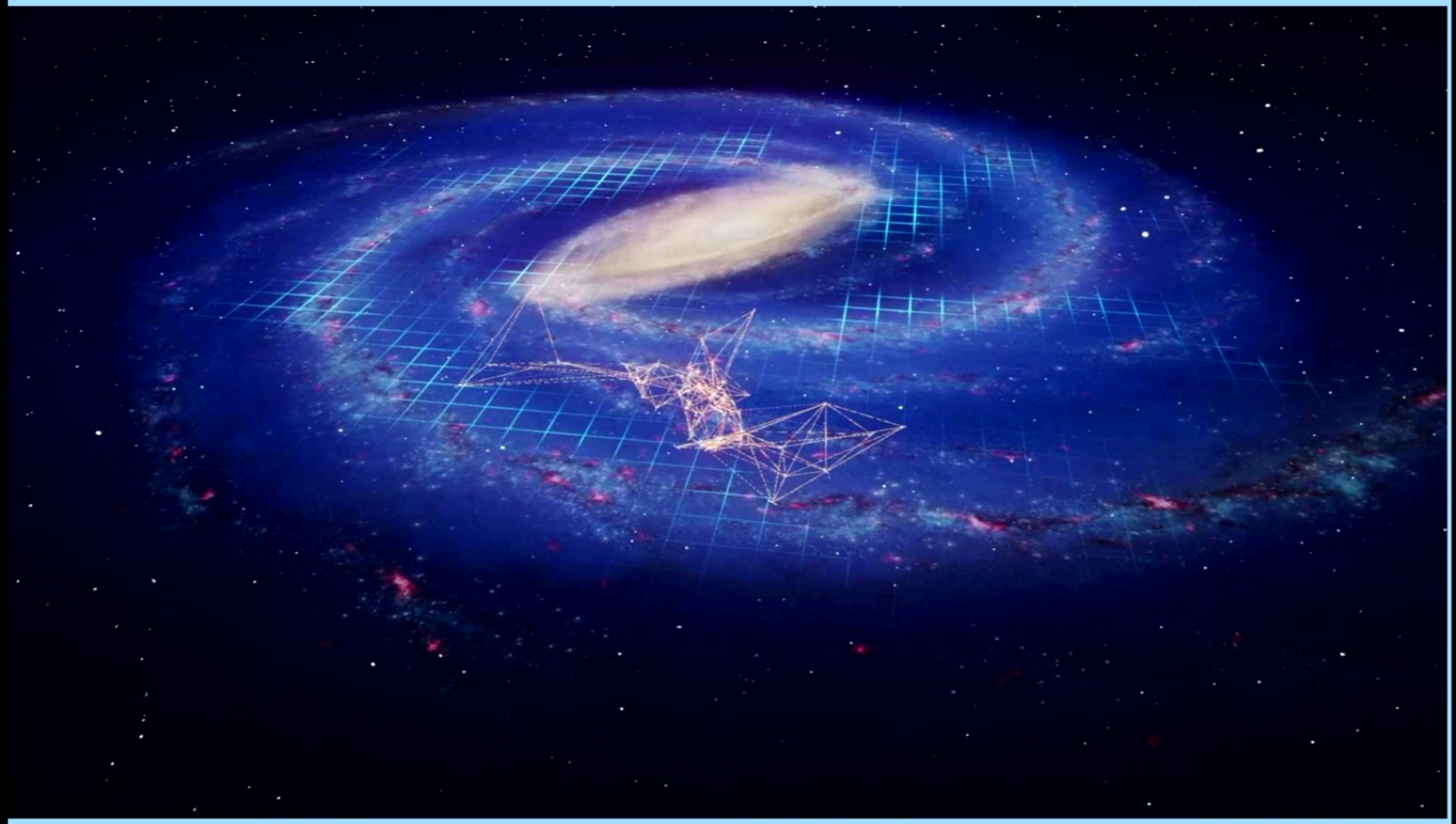
Animation by NSF/Onyx Lee

The Datasets



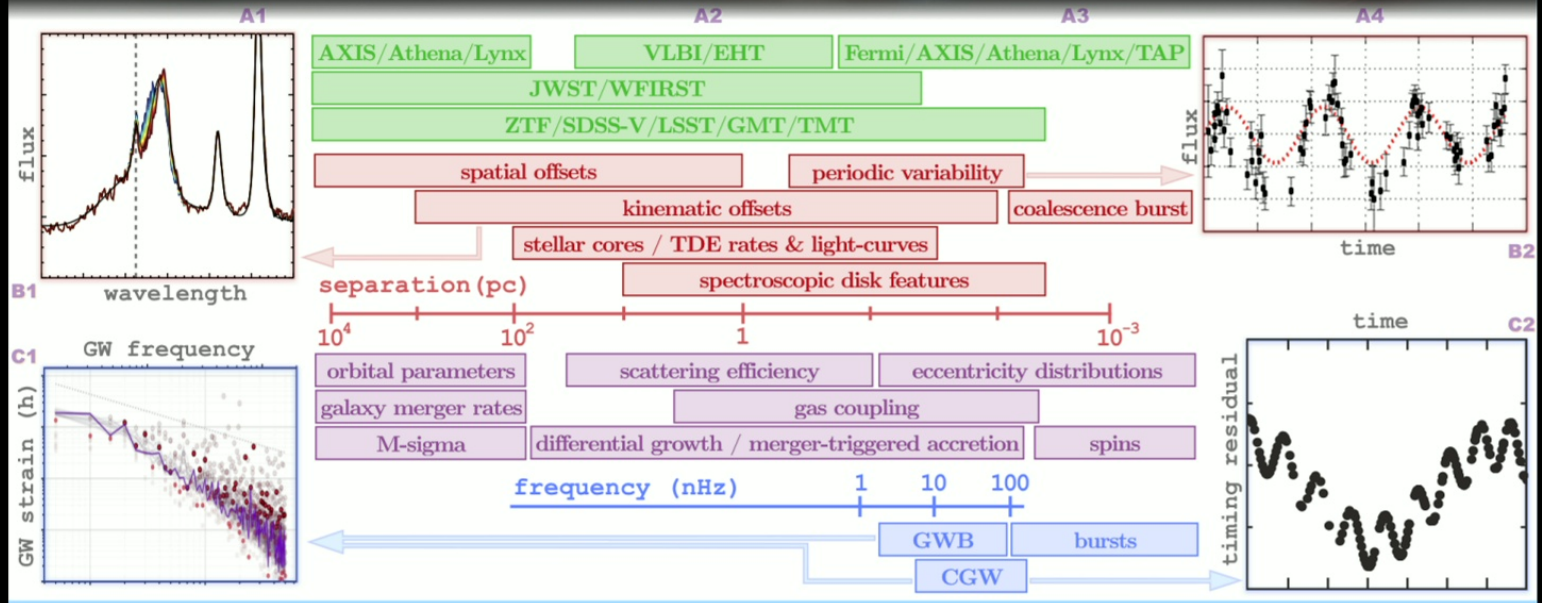
Courtesy: T. Cromartie, E .Ferrara

The Pulsar Timing Array



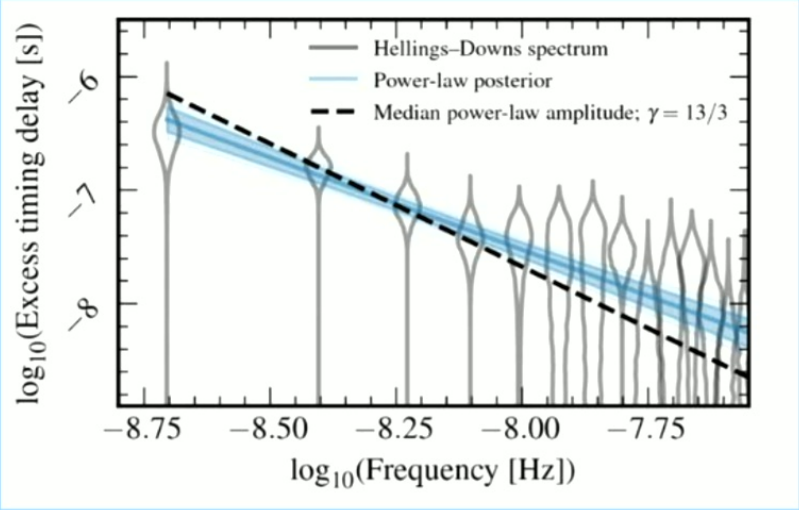
Animation by NSF/Onyx Lee

Multimessenger Science



Modified from Kelley et al. 2019

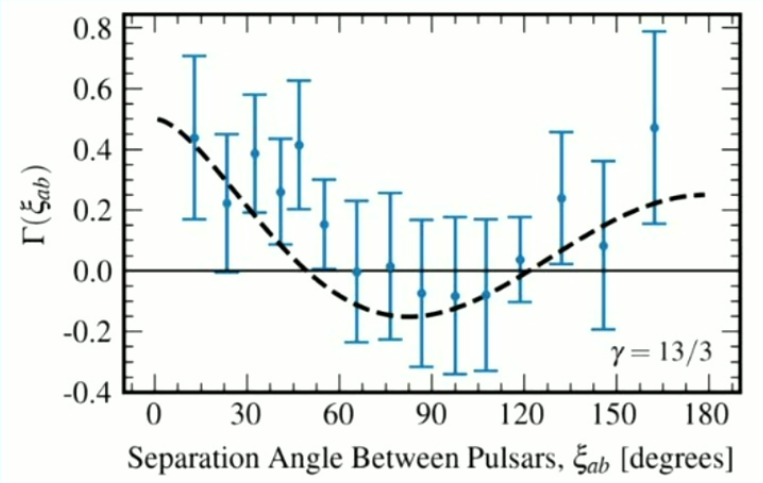
15-Year Data Set GWB Analysis



BF~10^{12} for Common Process

Agazie et al 2023

15-Year Data Set GWB Analysis



BF~10^{12} for Common Process,

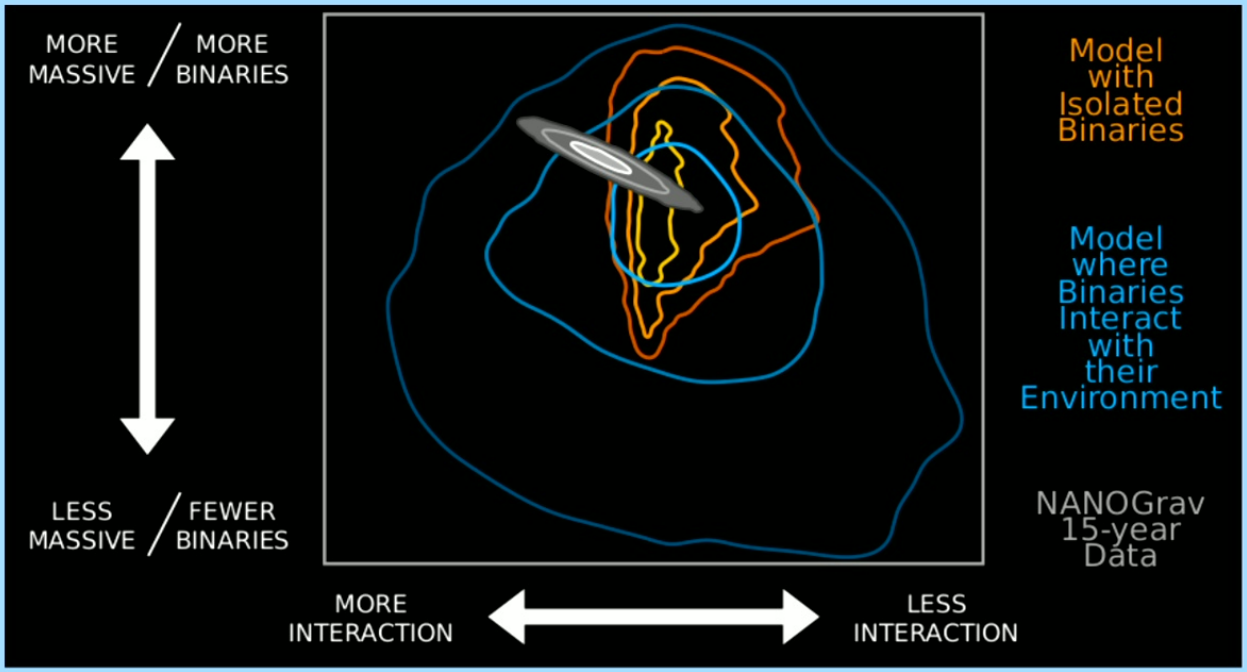
BF~200-1000 for Hellings-Downs

Null Distribution Tests

$p = 10^{-3} - 5\times10^{-5}$ (3-4σ)

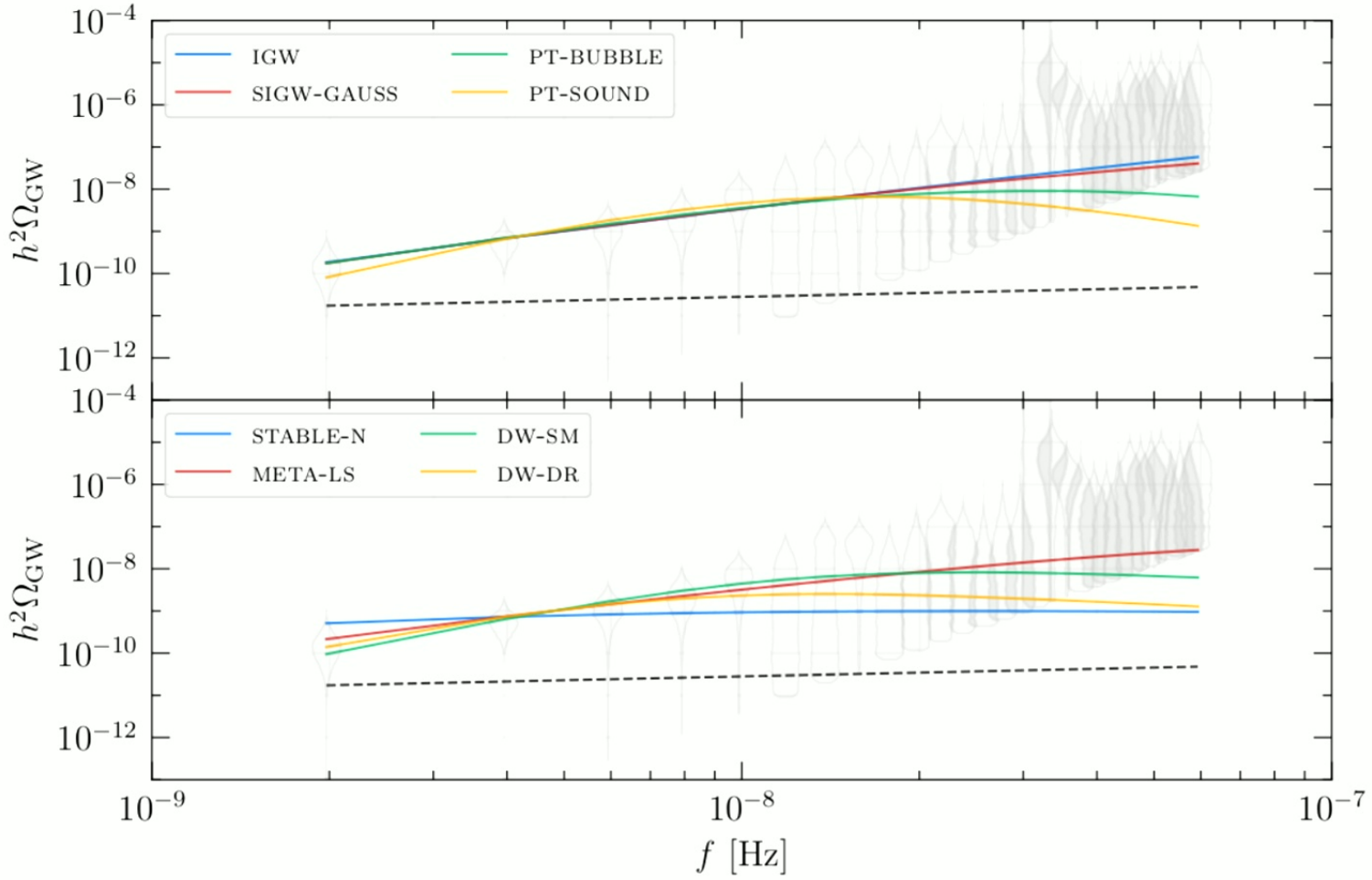
Agazie et al 2023

Astrophysics: Supermassive Black Hole Binaries



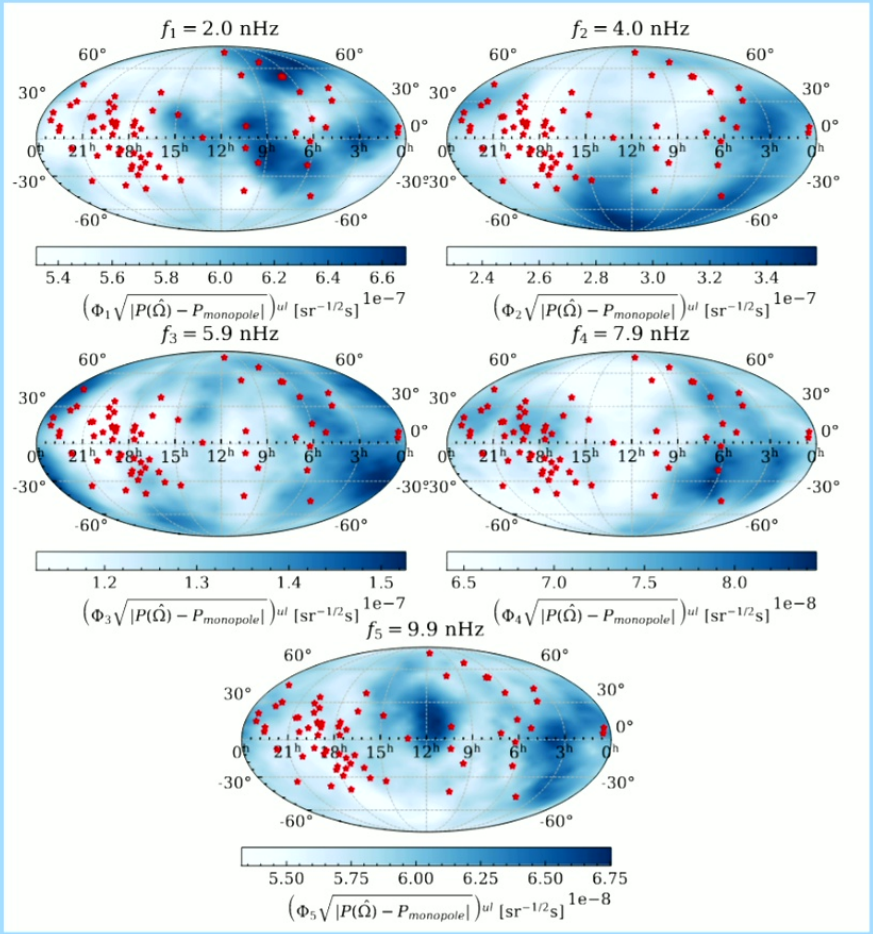
Modified from Agazie et al 2023

Astrophysics: New Physics



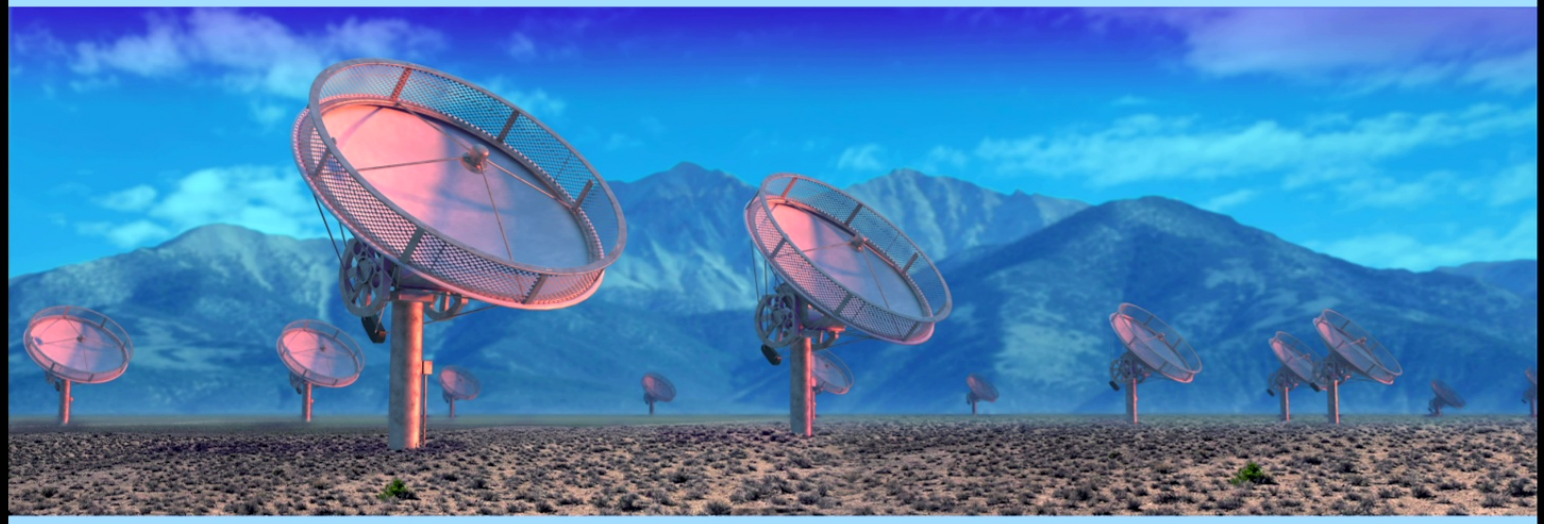
Afzal et al 2023

Mapping the Low-Frequency Gravitational Wave Universe



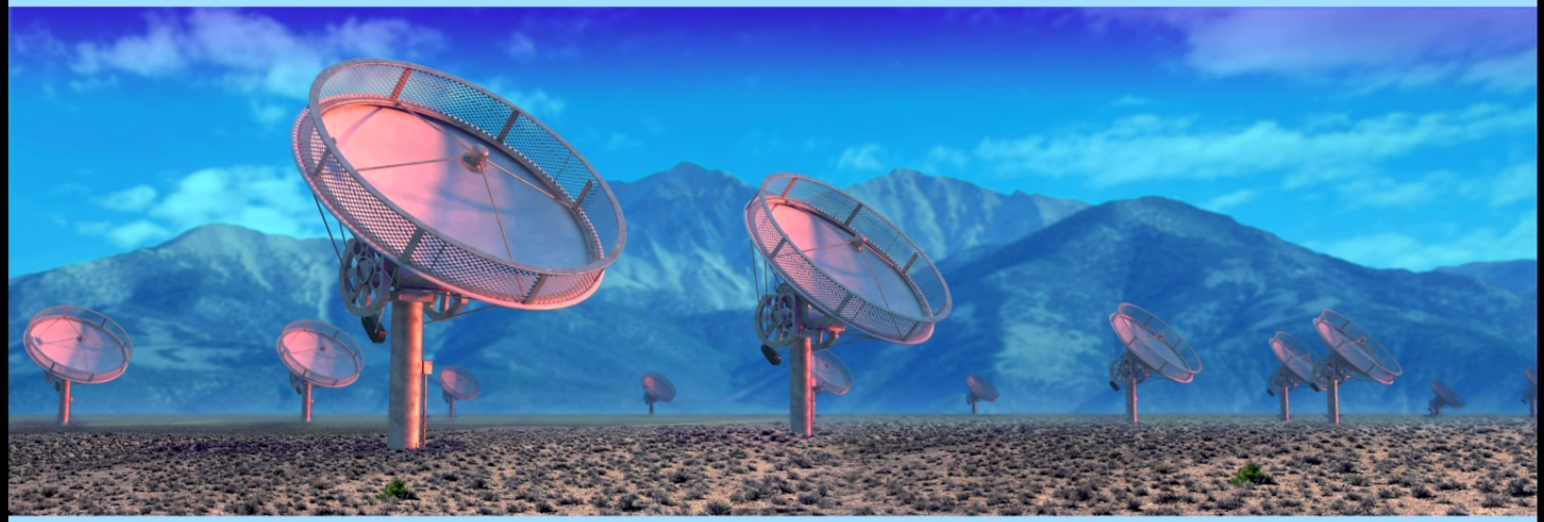
Agazie et al 2023

Future Facilities



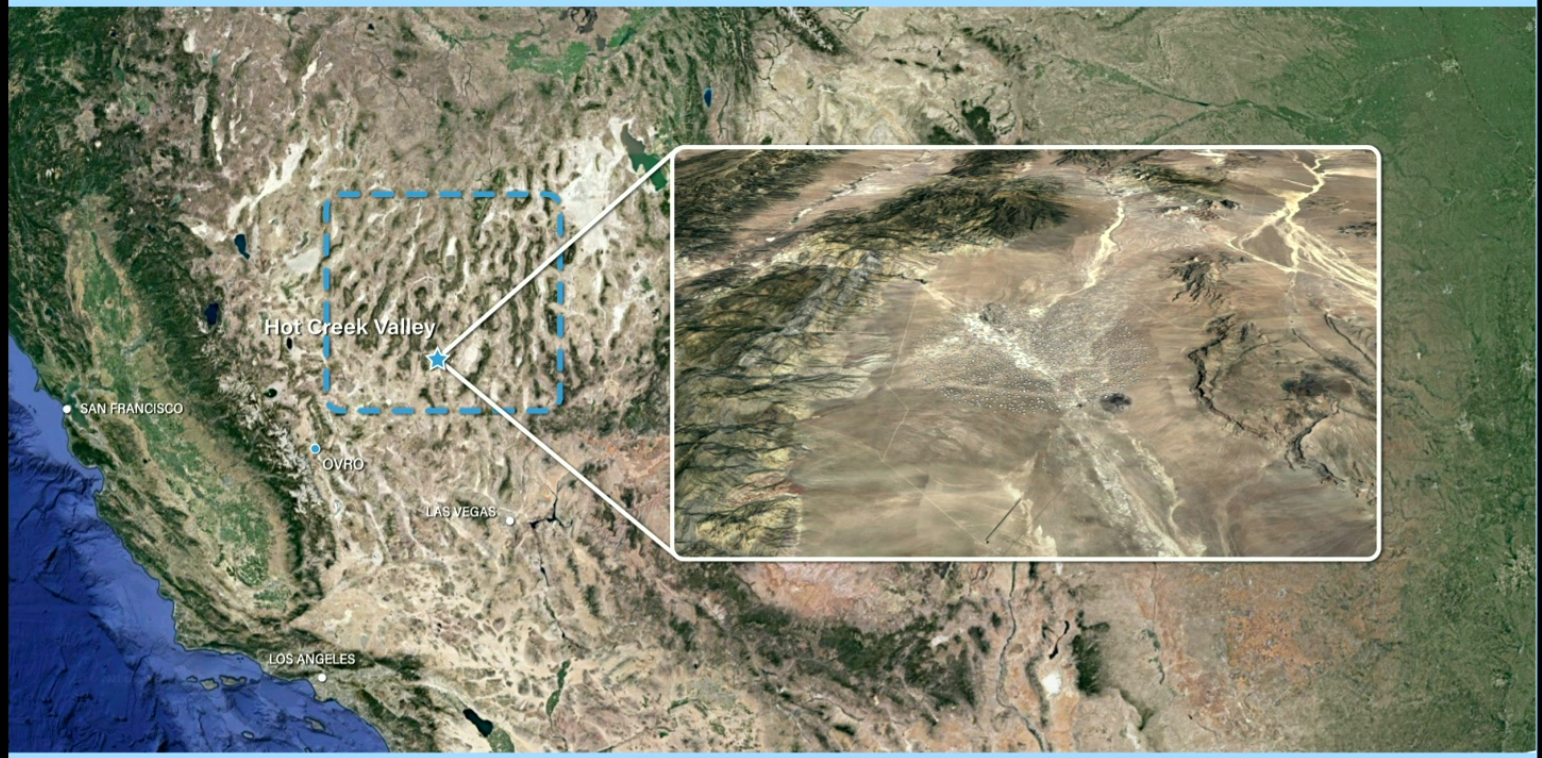
DSA-2000 / C. Carter

Future Facilities



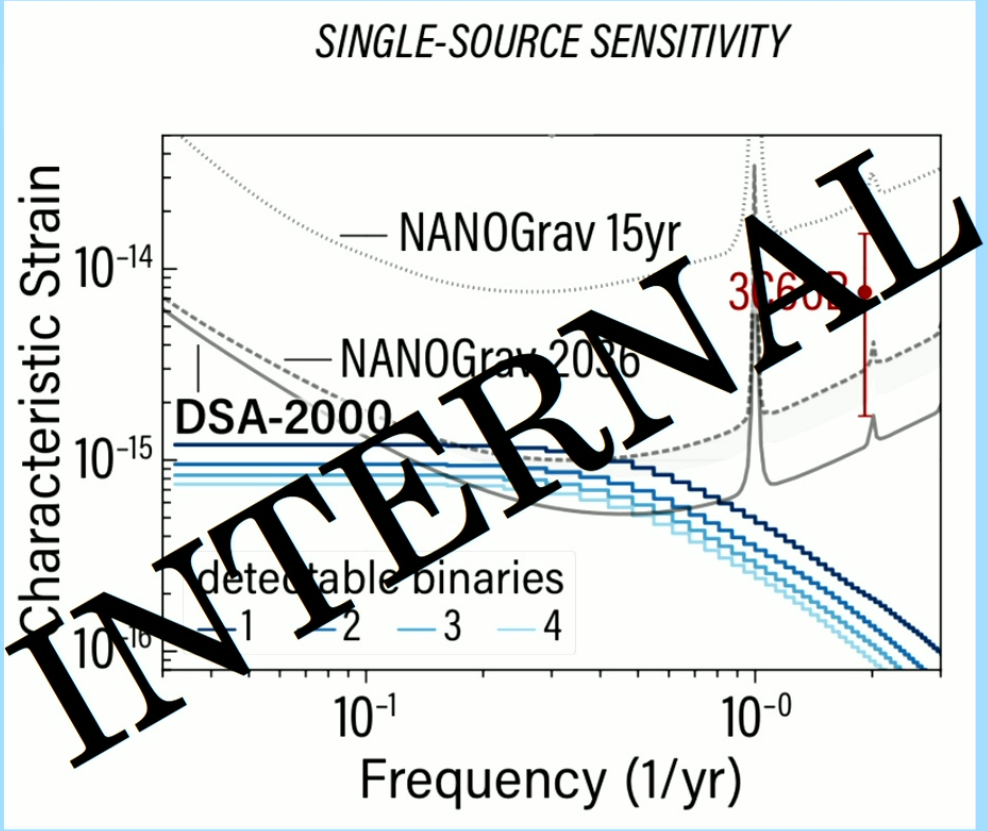
DSA-2000 / C. Carter

Future Facilities



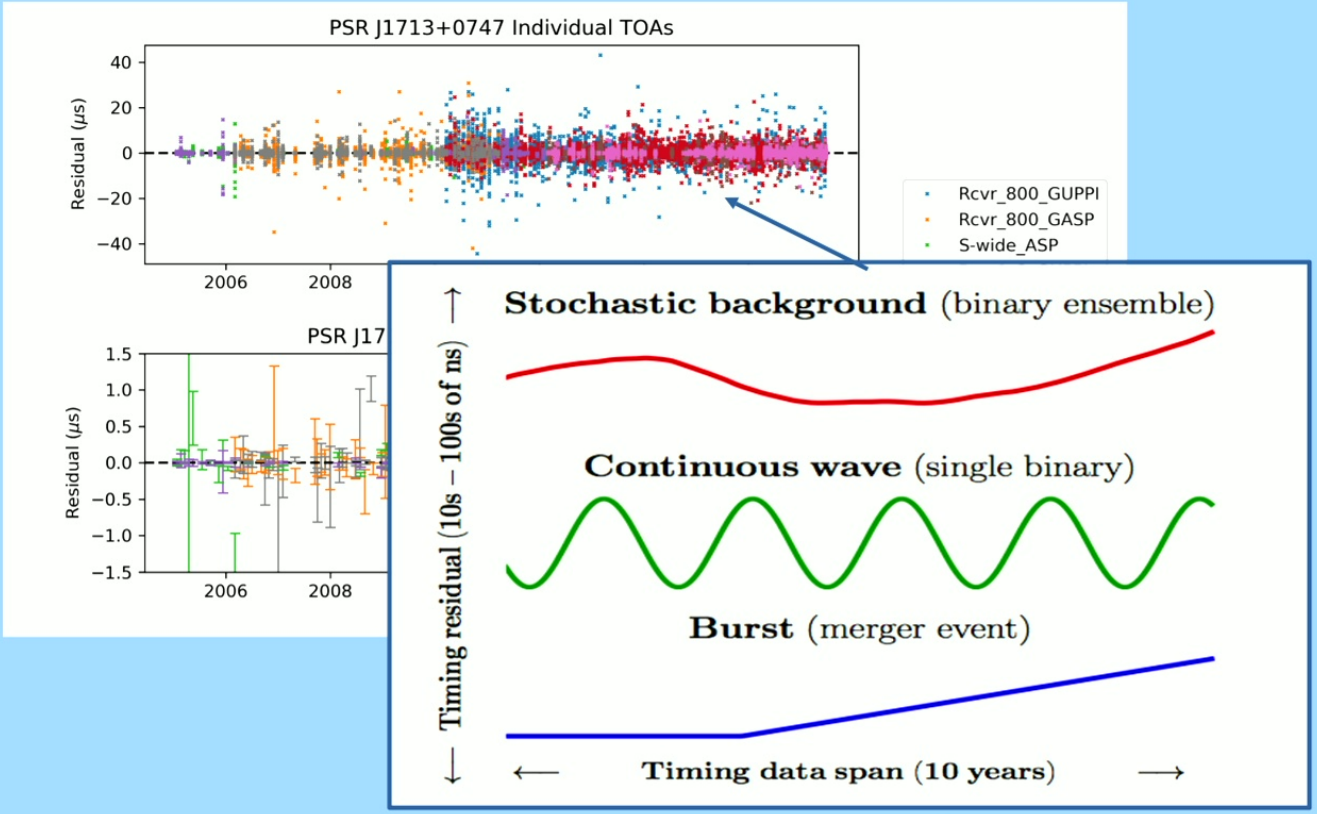
DSA-2000

Future Facilities



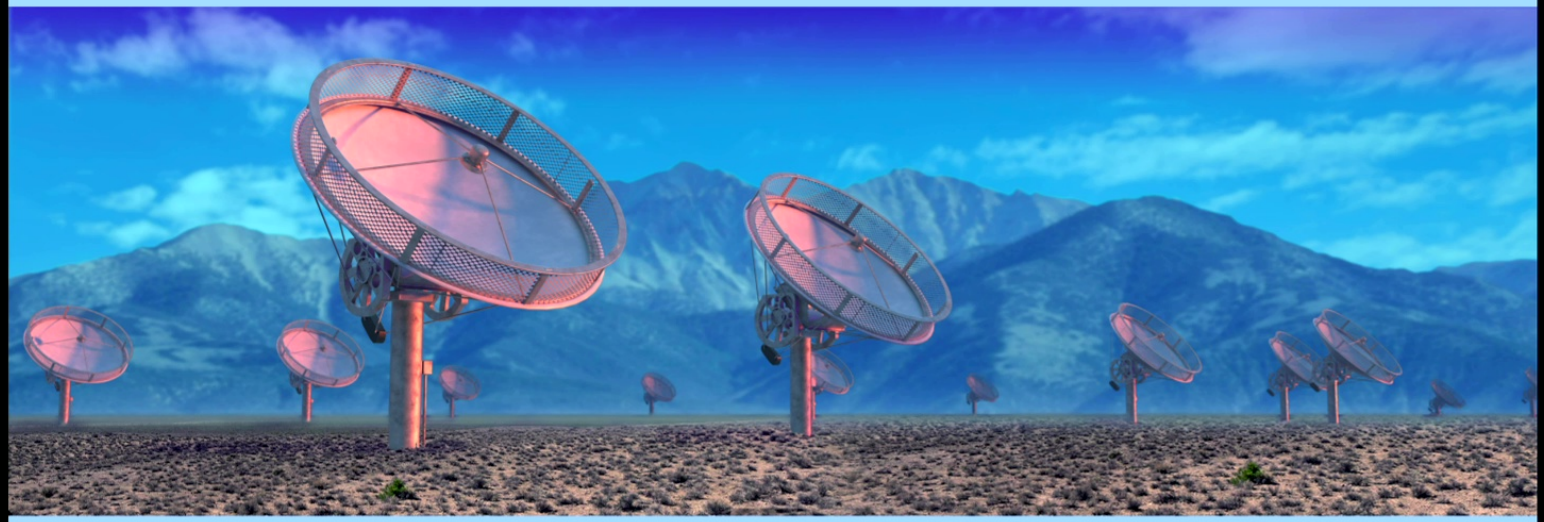
DSA-2000

Residuals and GW Signatures



Courtesy: D. Nice, J. Cordes

Future Facilities



DSA-2000 / C. Carter