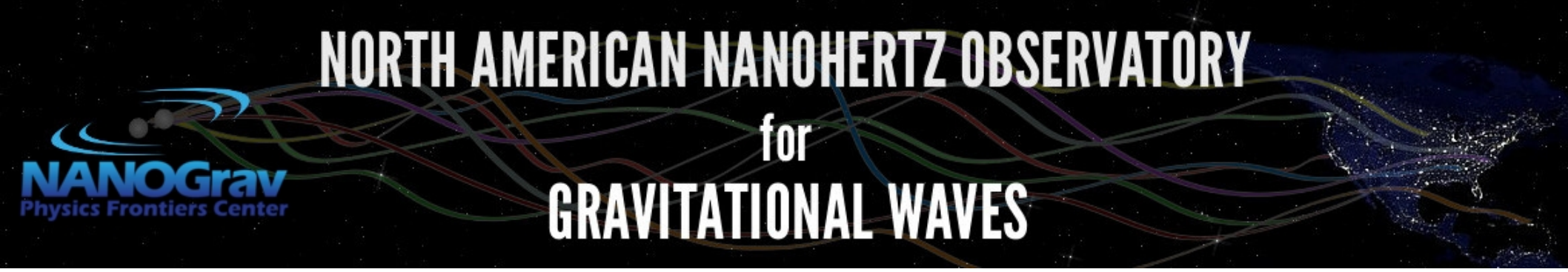


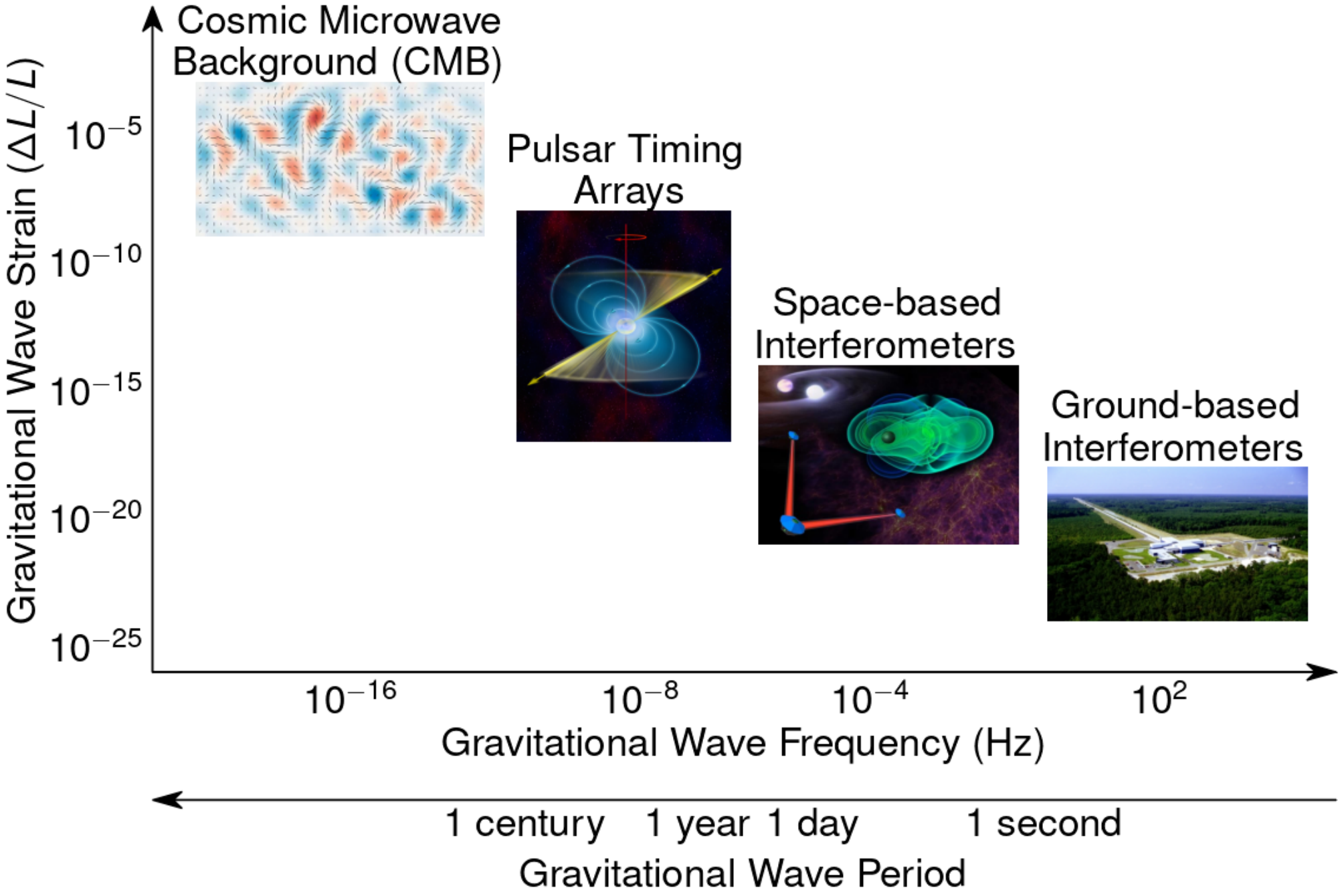
Pulsar Timing Arrays and the Low-Frequency Gravitational Wave Sky

Michael T. Lam

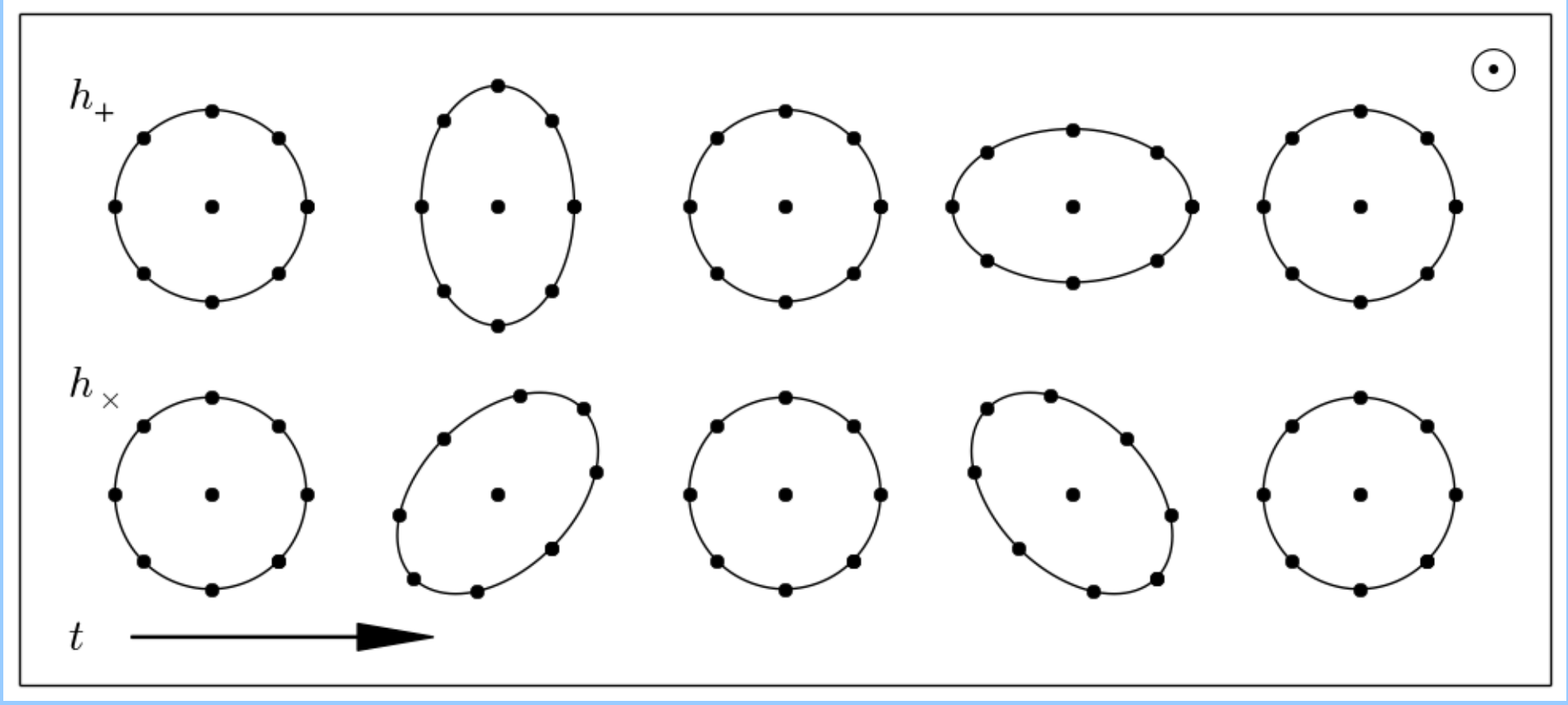
NRAO Synthesis Imaging Workshop – 21 May 2024

SETI INSTITUTE
RIT College of Science Astrophysical Sciences and Technology

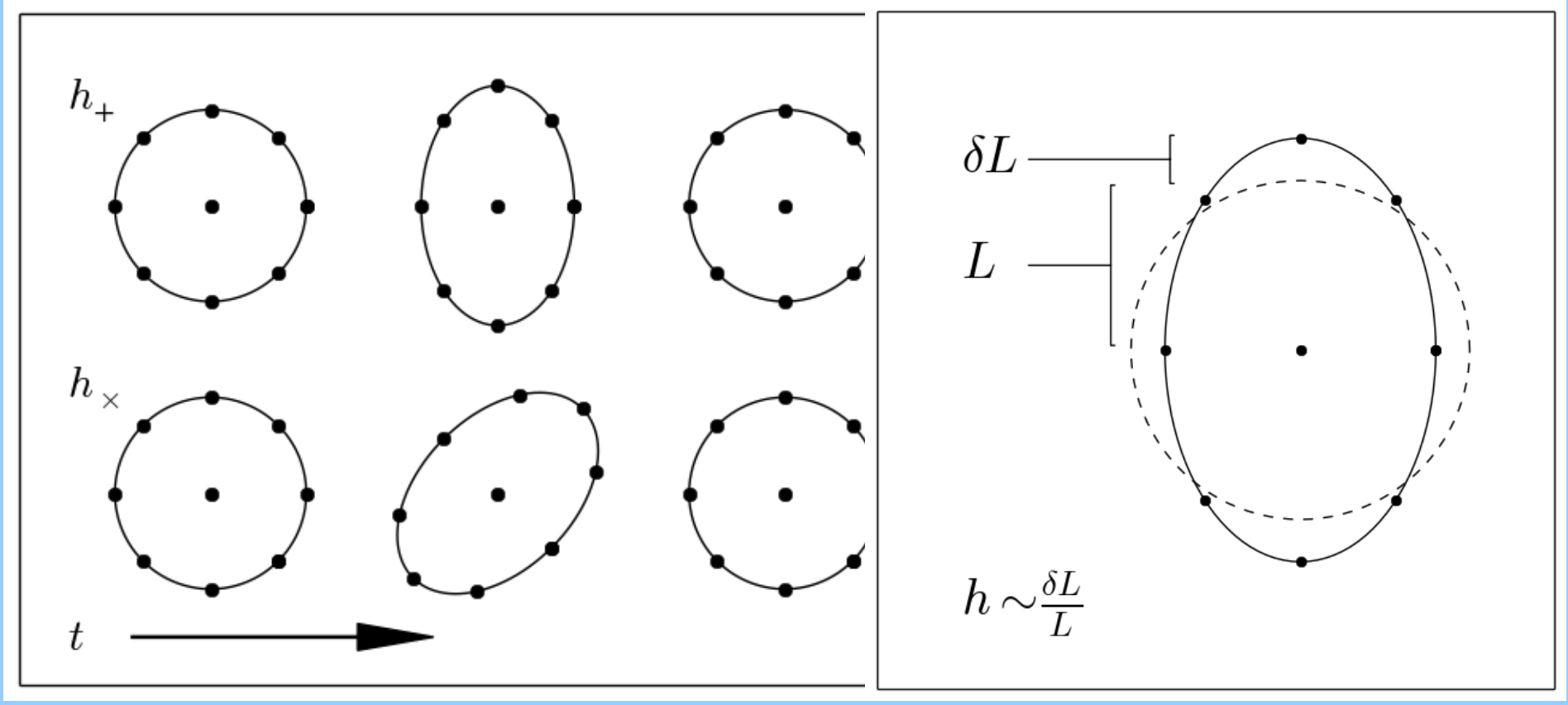
L,M: NRAO/AUI, R: NAIC


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
10²
Gravitational Wave Frequency (Hz)
1 century
1 year
1 day
1 second
Gravitational Wave Period

Effects of Gravitational Waves

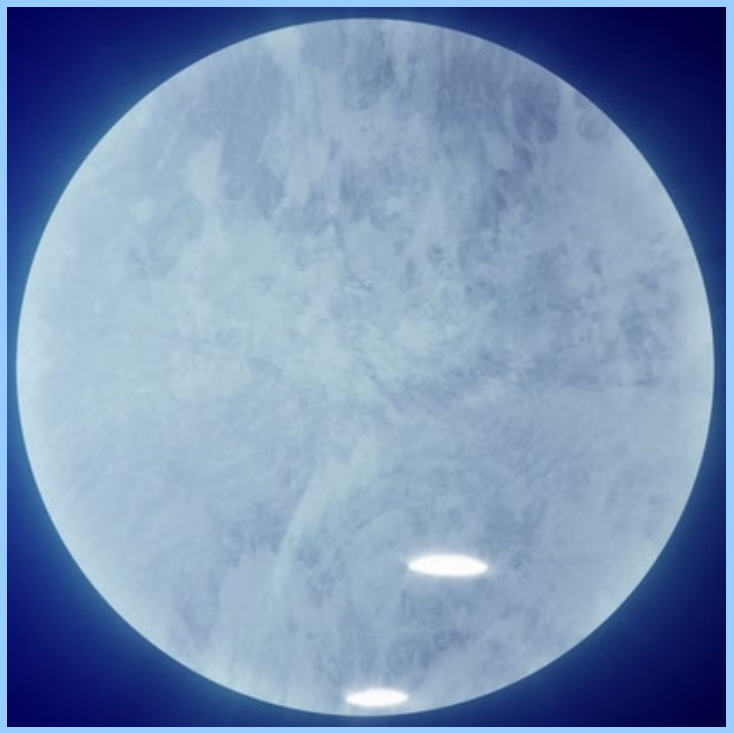


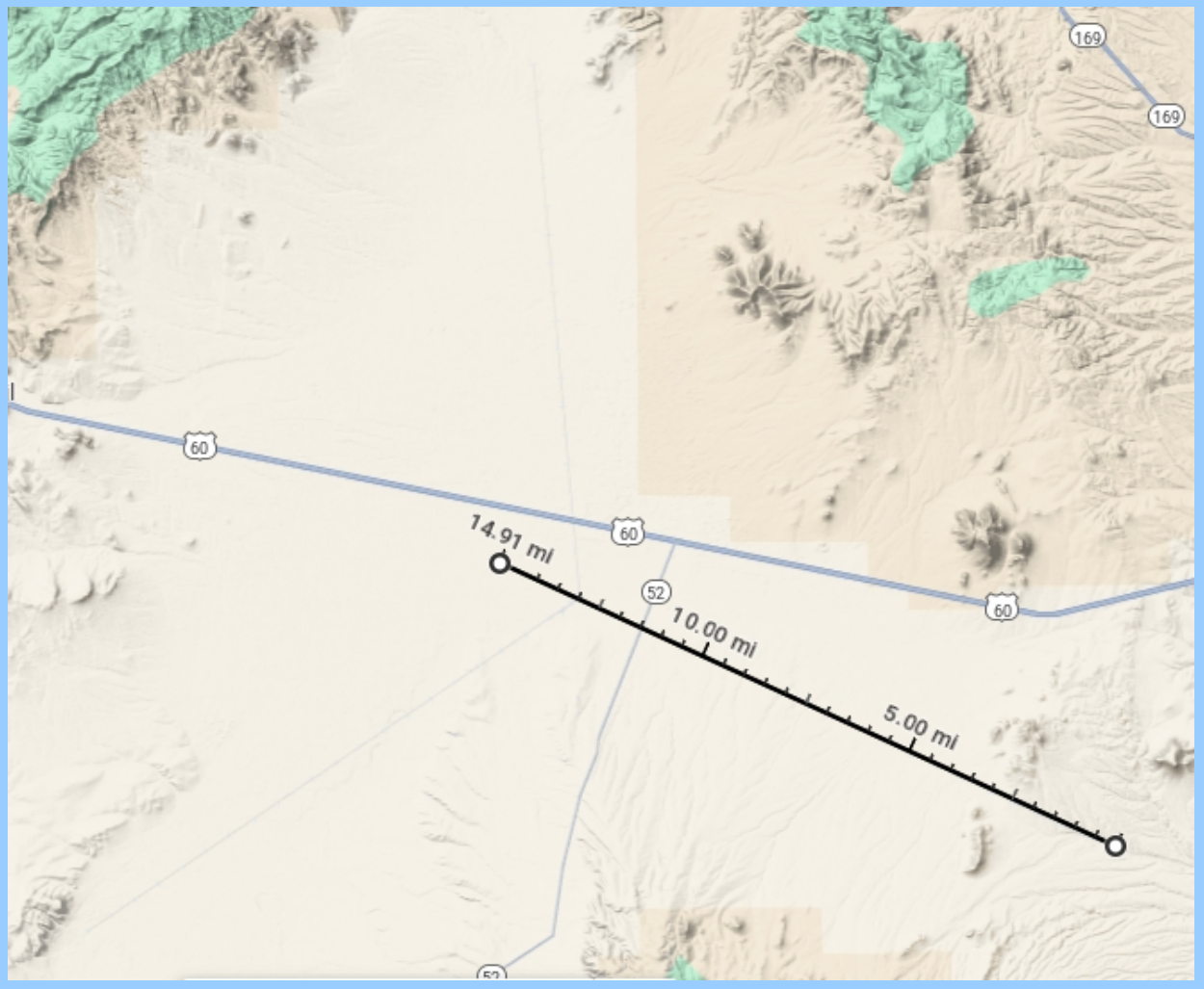
Effects of Gravitational Waves



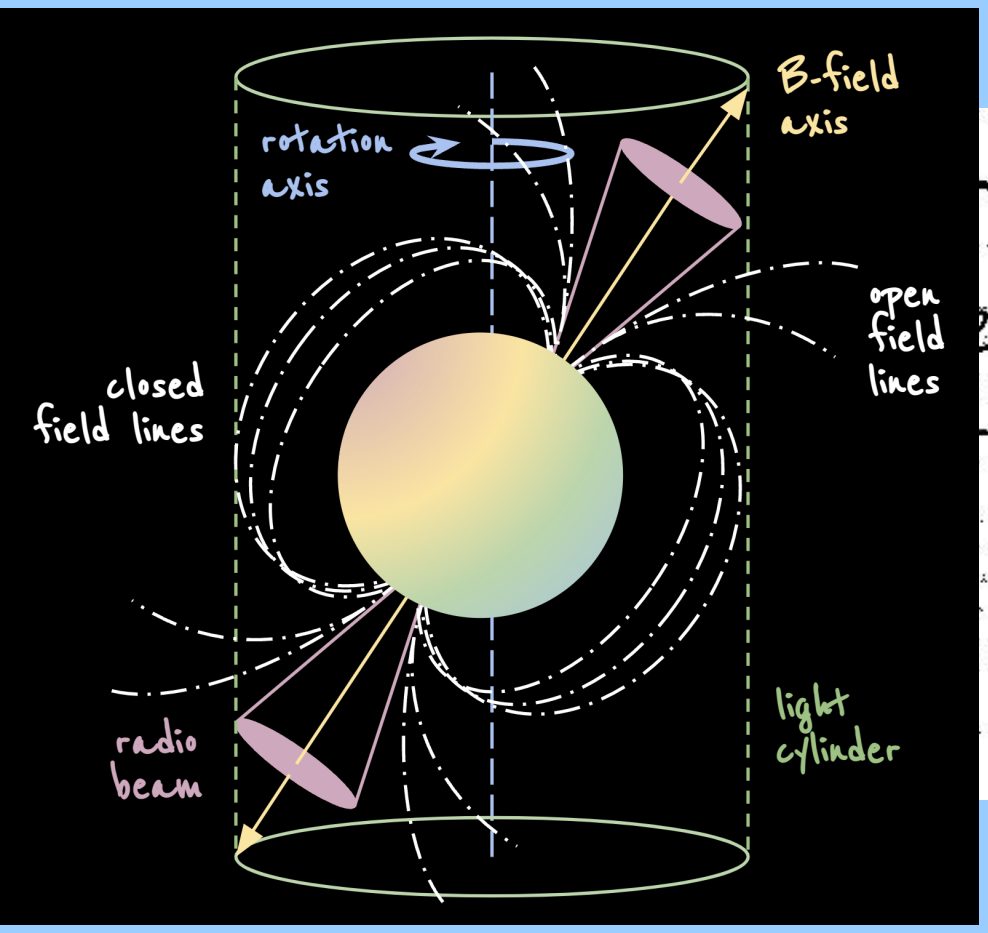
Neutron Stars

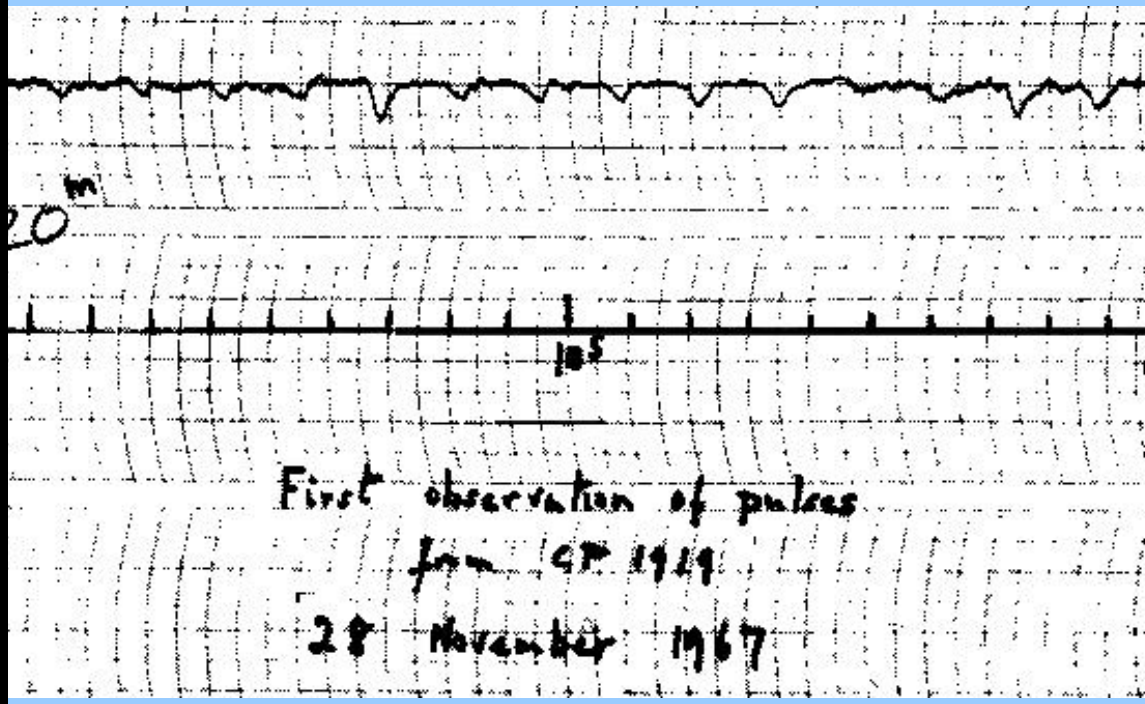
$M \sim 1\text{-}2\ M_{\odot}$, $R \sim 12$ km





NASA, NICER, GSFC

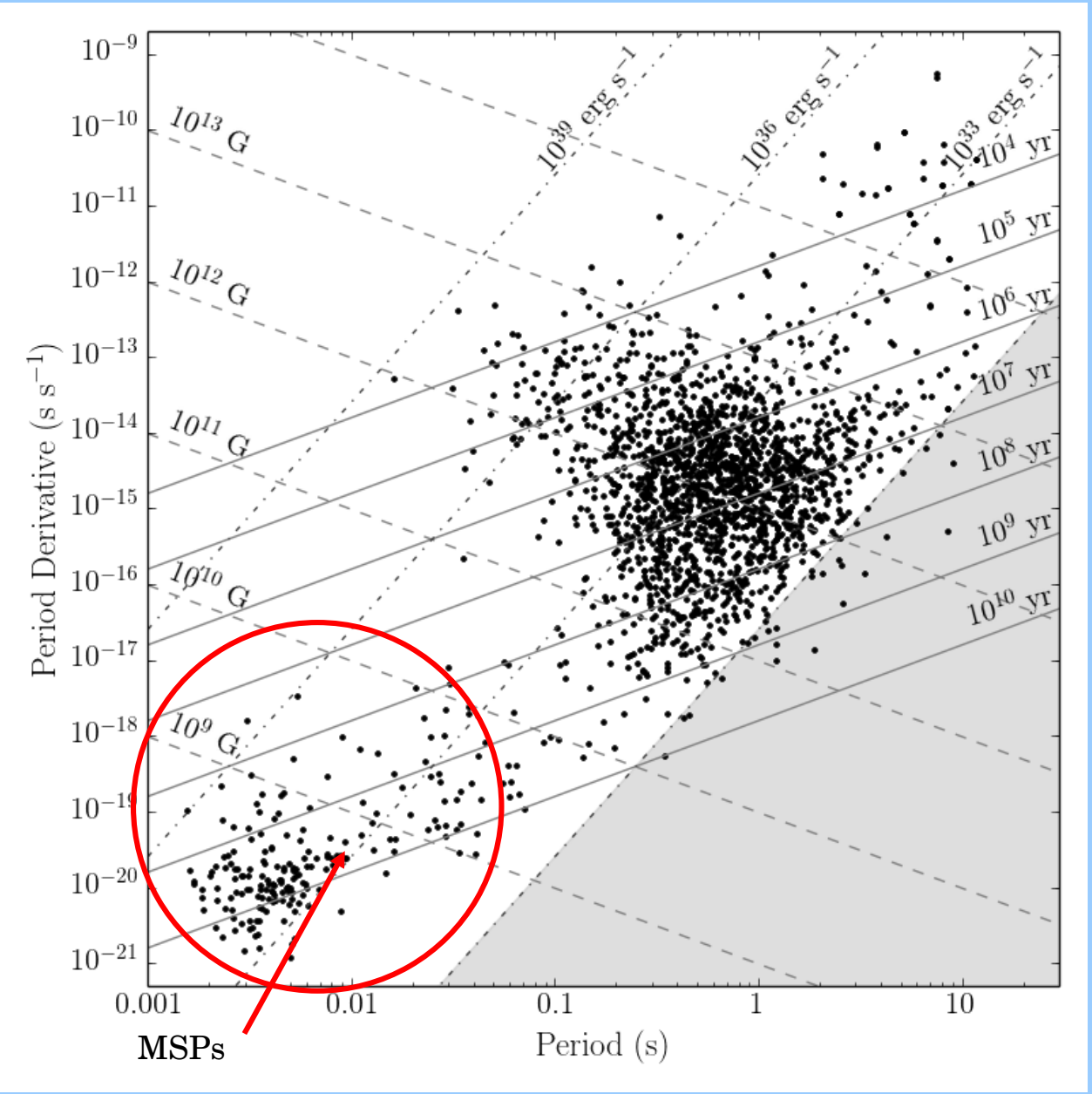




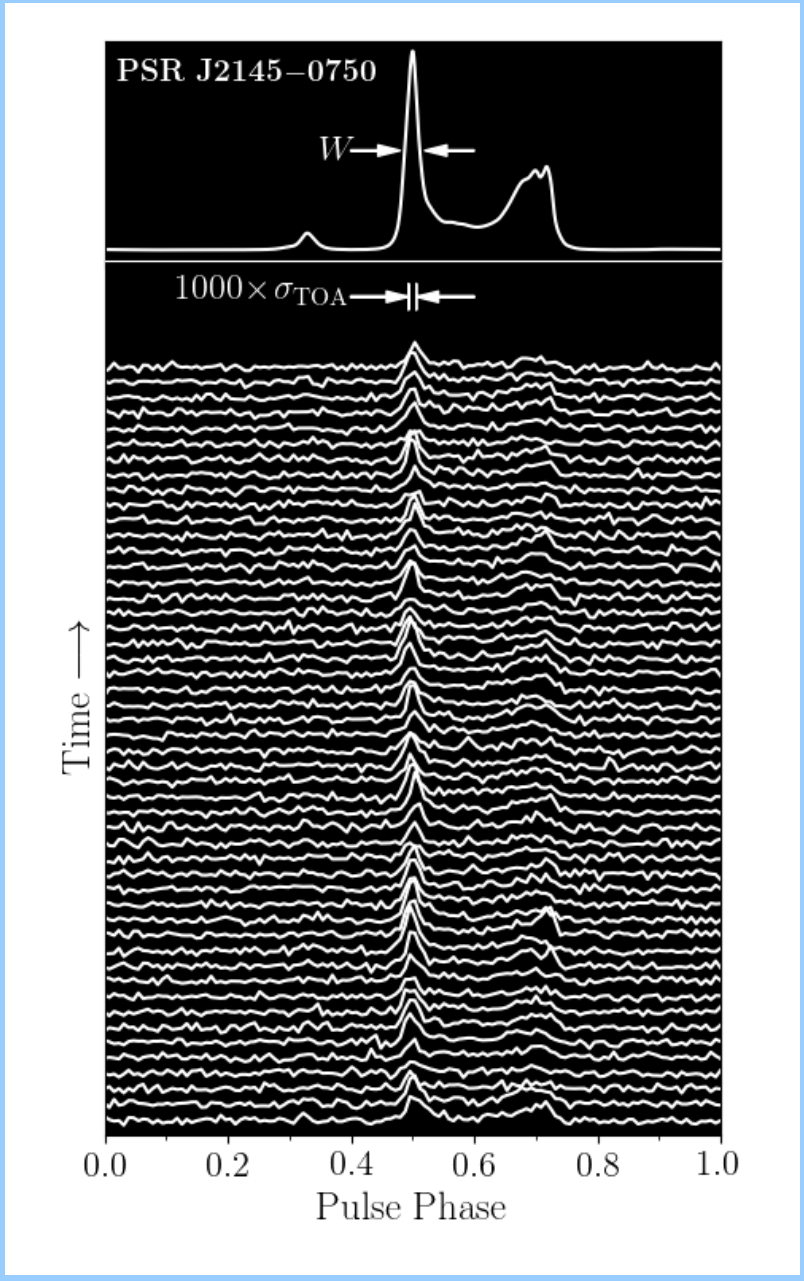
L: Thankful Cromartie

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:

$P = 2.947108025429647 \pm 0.000000000000002$ ms

Data: NANOGrav

Pulsars as Precise Clocks: J1909-3744

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

$P = 2.947108025429647 \pm 0.000000000000002$ ms

The last digit changes by 1 every 713 seconds

Data: NANOGrav

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

Data: NANOGrav

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 talk, May 21, 2024 at 15:00 UTC, the pulsar has completed nearly 126,960,395,221 rotations (0.22 shy!)

Data: NANOGrav

More fun with J1909-3744

It's also completed over 2824 orbits around its companion white dwarf (0.11 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

$$h \sim \frac{G}{c^4}\frac{2\times\frac{1}{2}I\omega^2}{D} \sim \frac{GMa^2\omega^2}{c^4 D} \sim \frac{GMa^2}{c^4 D}\left(\frac{G(2M)}{a^3}\right) \sim \frac{2G^2M^2}{c^4 Da}$$

$$\approx 4.5\times10^{-15}\left(\frac{M}{10^8\,M_\odot}\right)^2\left(\frac{D}{10\text{ Mpc}}\right)^{-1}\left(\frac{a}{\text{mpc}}\right)^{-1}$$

$$f \sim \frac{1}{2\pi}\left(\frac{G(2M)}{a^3}\right)^{1/2}$$

$$\approx 150\text{ nHz}\left(\frac{M}{10^8\,M_\odot}\right)^{1/2}\left(\frac{a}{\text{mpc}}\right)^{-3/2}$$

The Tiny Effects of GWs

$$h \sim \frac{G}{c^4}\frac{2}{} \approx 4.5$$

$$\sim \frac{2G^2M^2}{c^4Da}$$

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

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

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

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

$$f \approx 150 \text{ nHz} \left(\frac{M}{10^8\, M_\odot}\right) \left(\frac{a}{\text{mpc}}\right)^{-3/2}$$

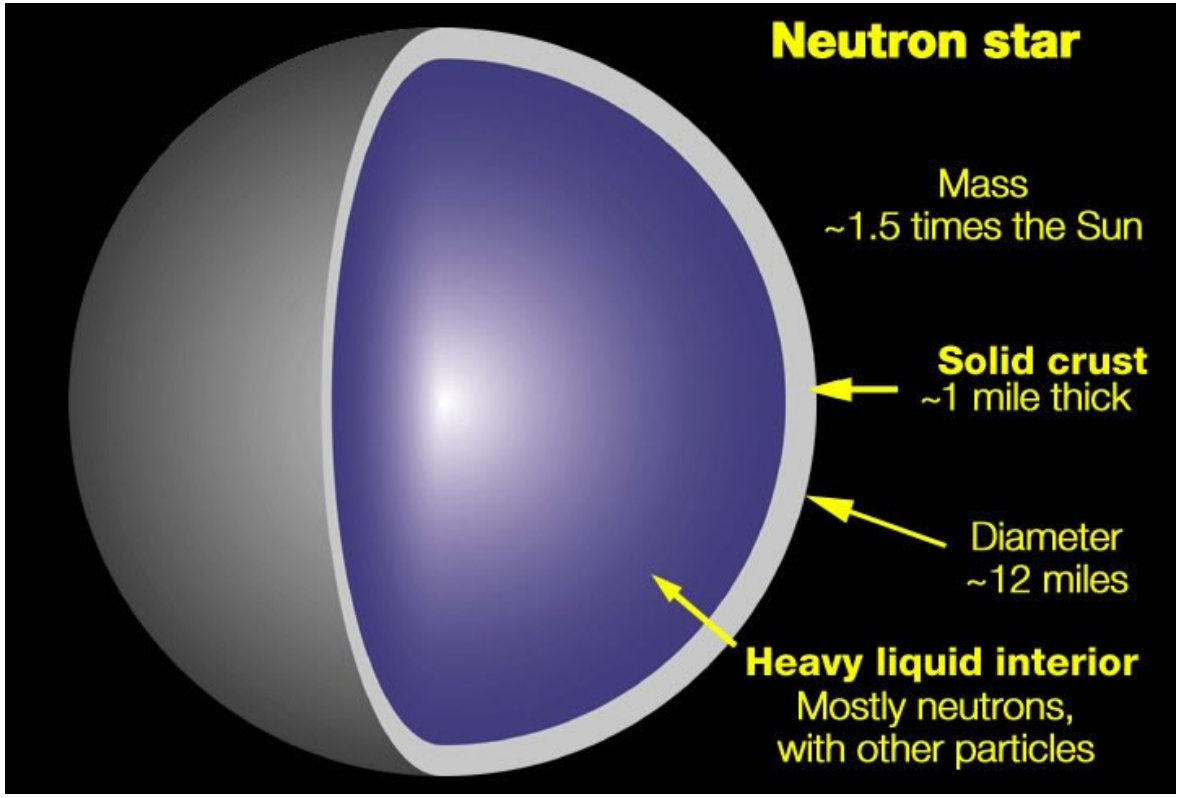
$$^{-1}$$

The Tiny Effects of GWs

$$h \sim \frac{G}{c^4}\frac{2}{-} \qquad \Delta L \sim hL \sim hcT$$

$$\approx 100\ \mathrm{m} \left(\frac{h}{10^{-15}}\right)\left(\frac{T}{10\ \mathrm{yr}}\right) \qquad \sim \frac{2G^2M^2}{c^4 Da}$$

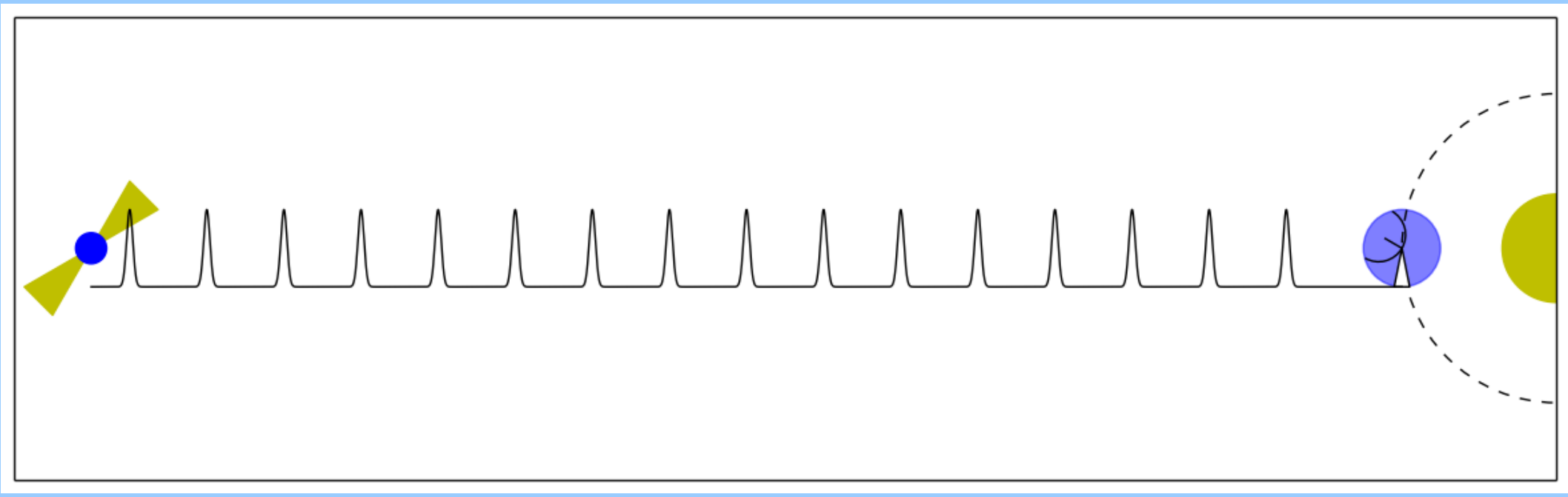
$$\approx \qquad -1$$



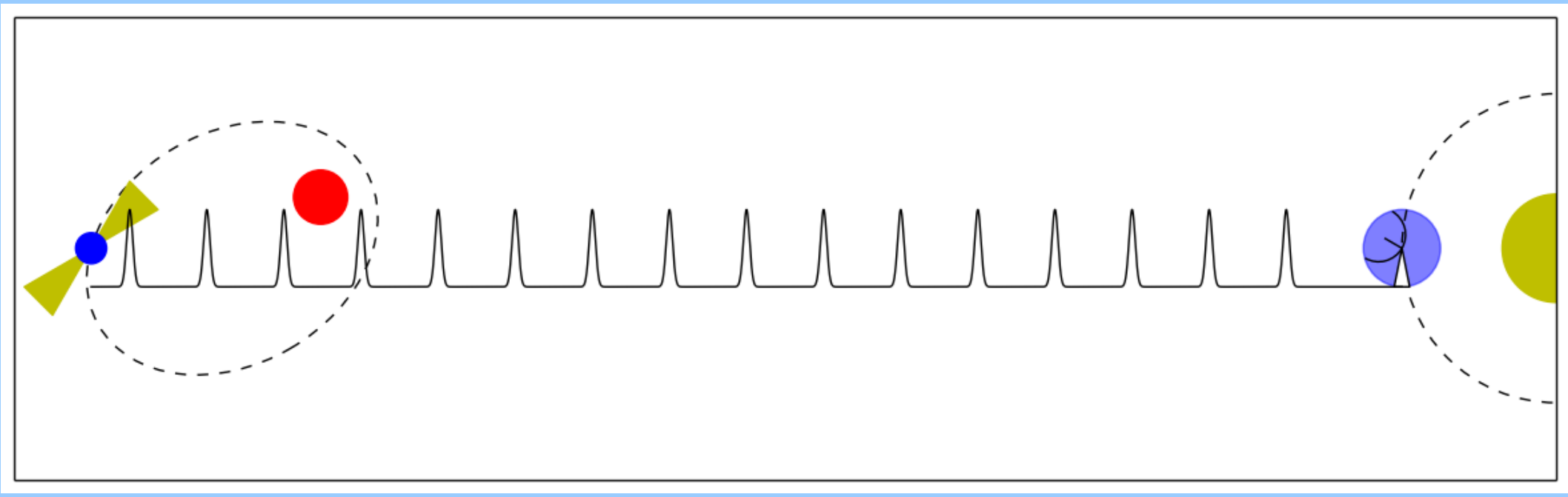
$\approx 0.01\ R_{NS}$

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

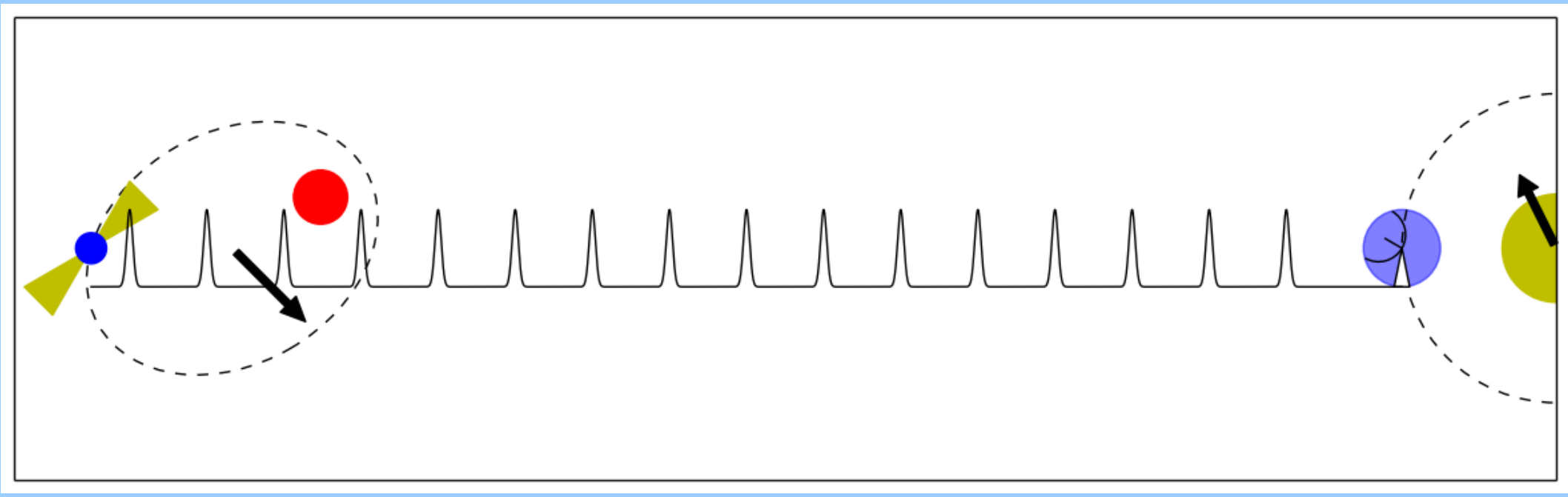
Timing Model



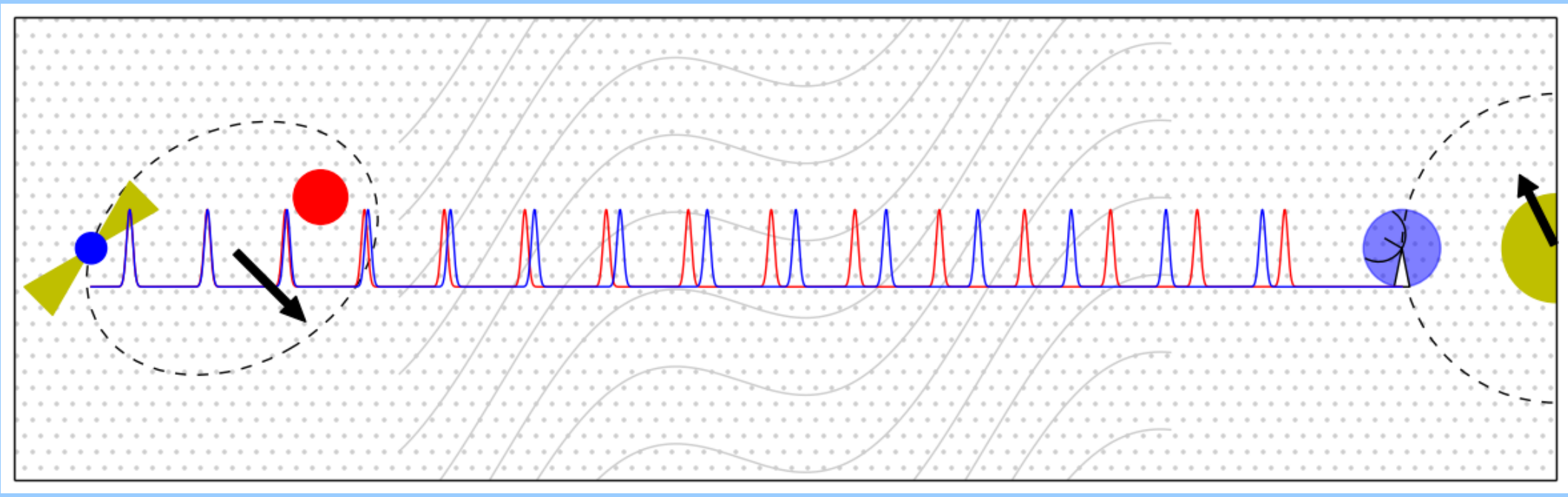
Timing Model



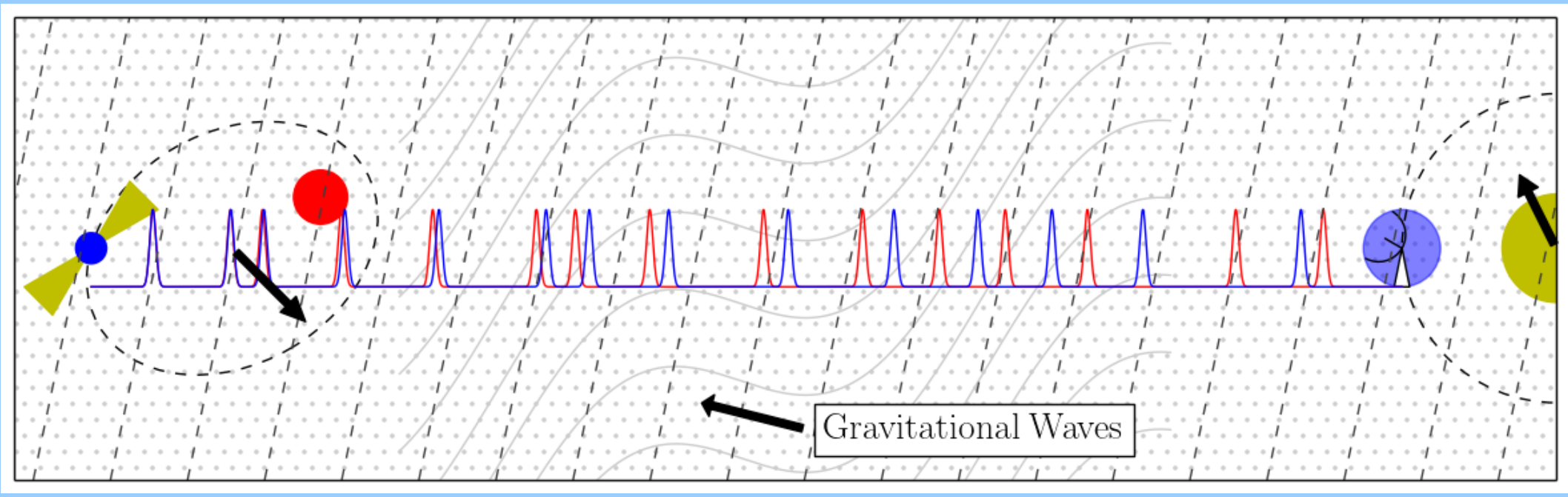
Timing Model



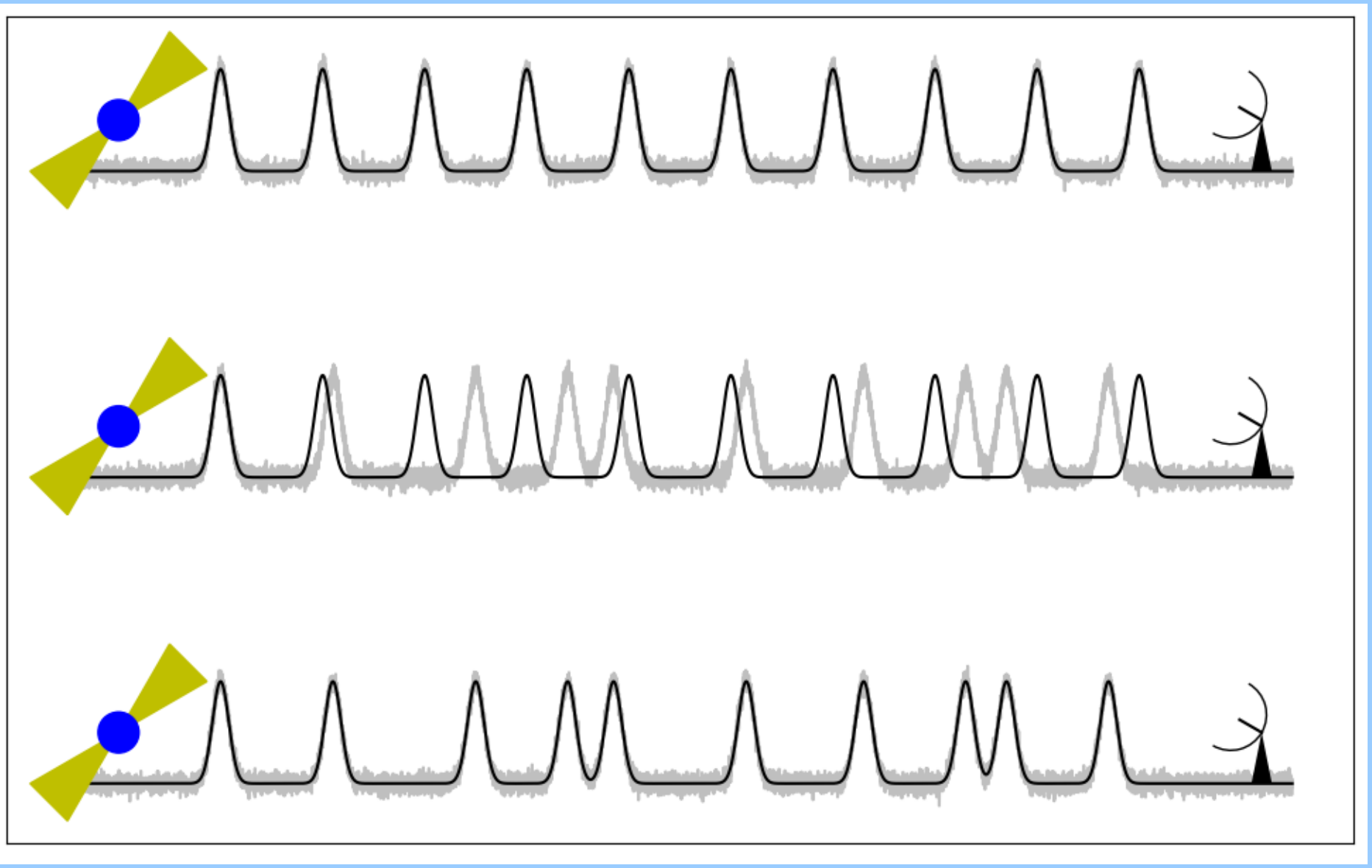
Timing Model



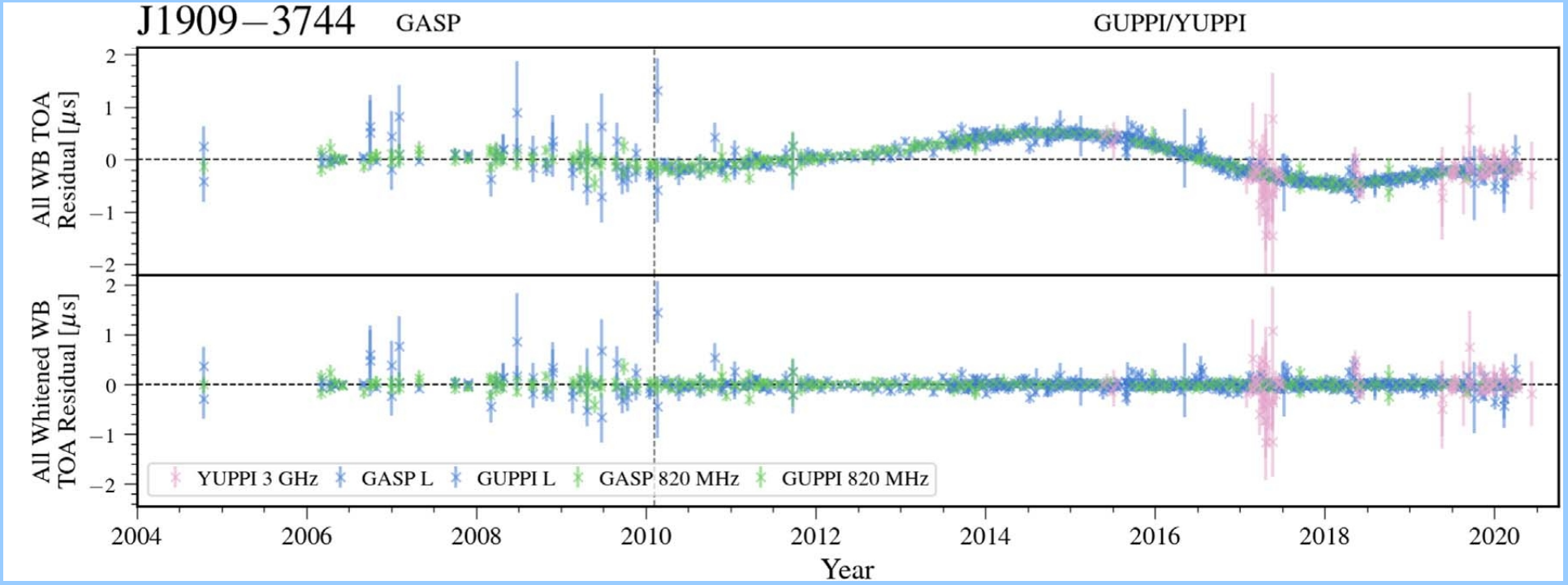
Timing Model



Pulsar Timing

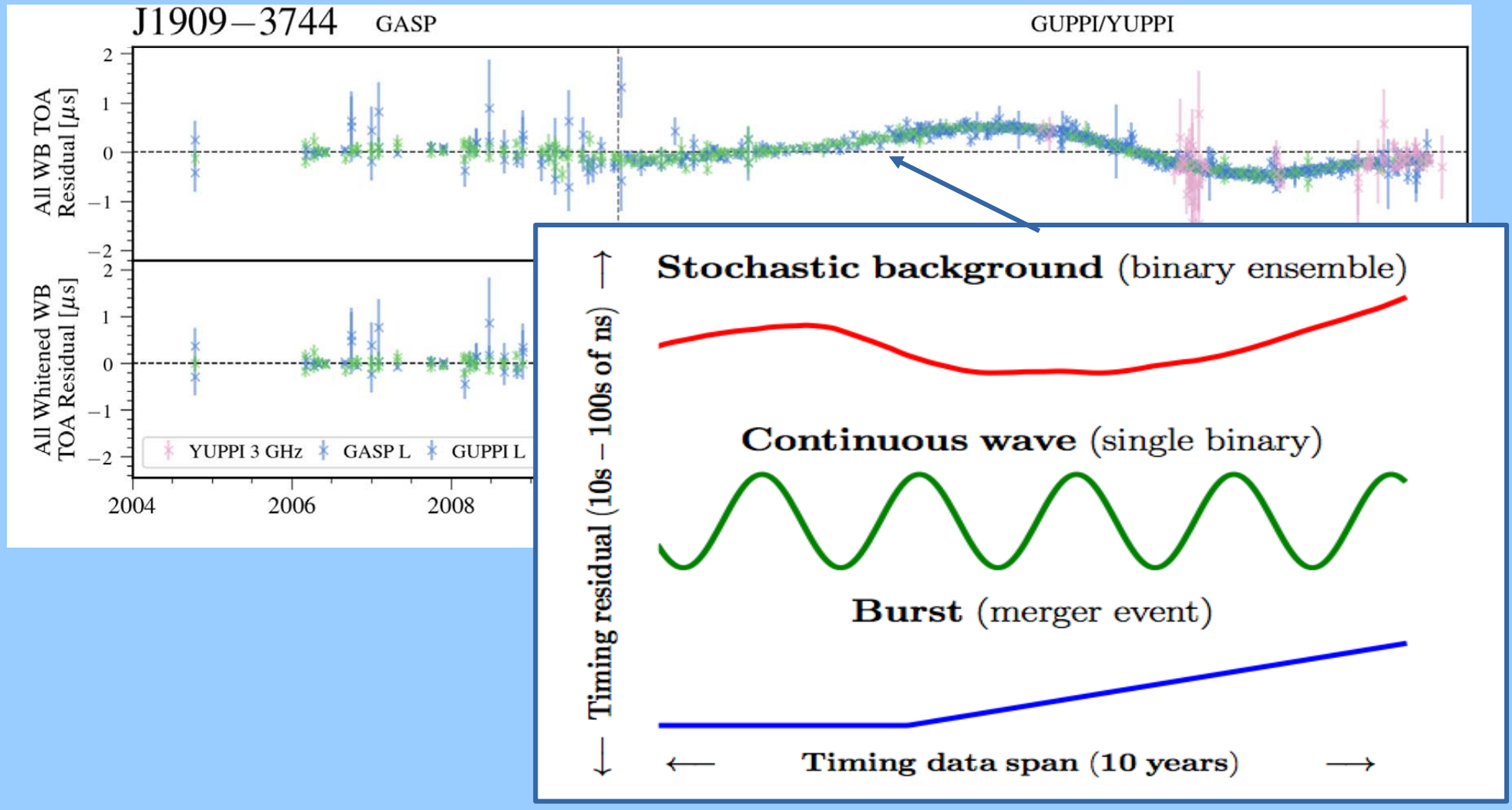


Residuals and GW Signatures



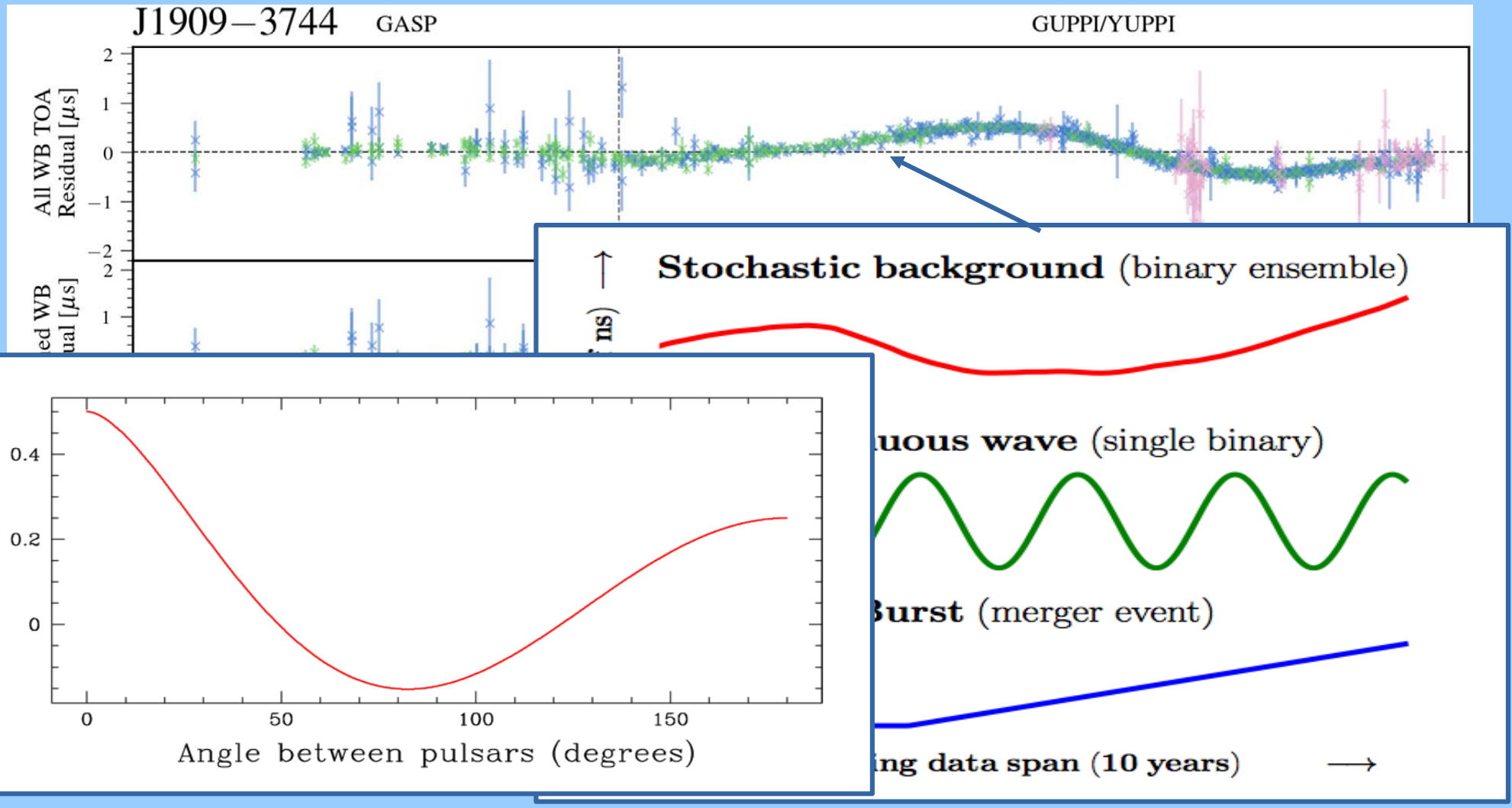
Agazie et al. 2023

Residuals and GW Signatures



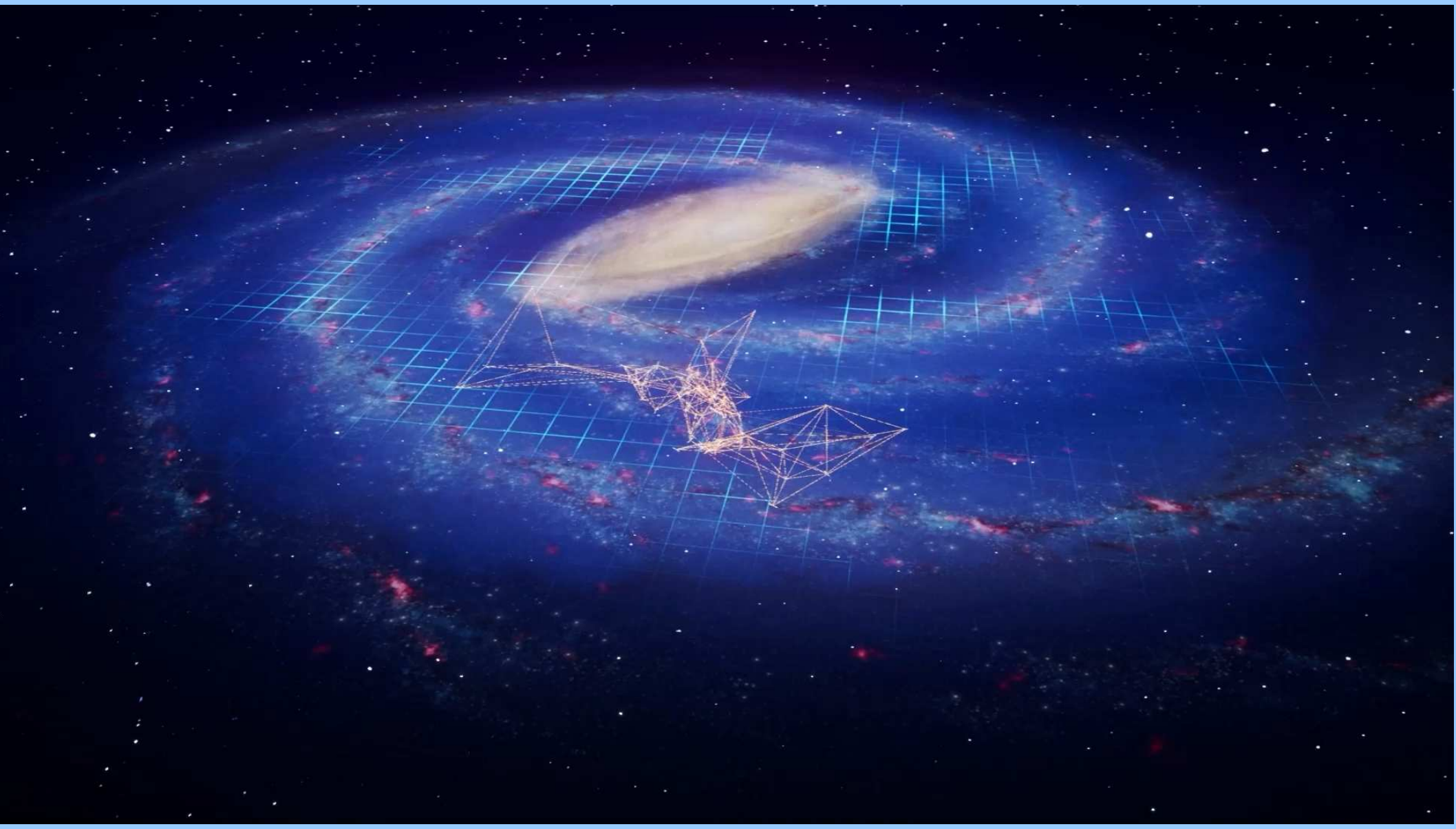
Courtesy: J. Cordes

Residuals and GW Signatures



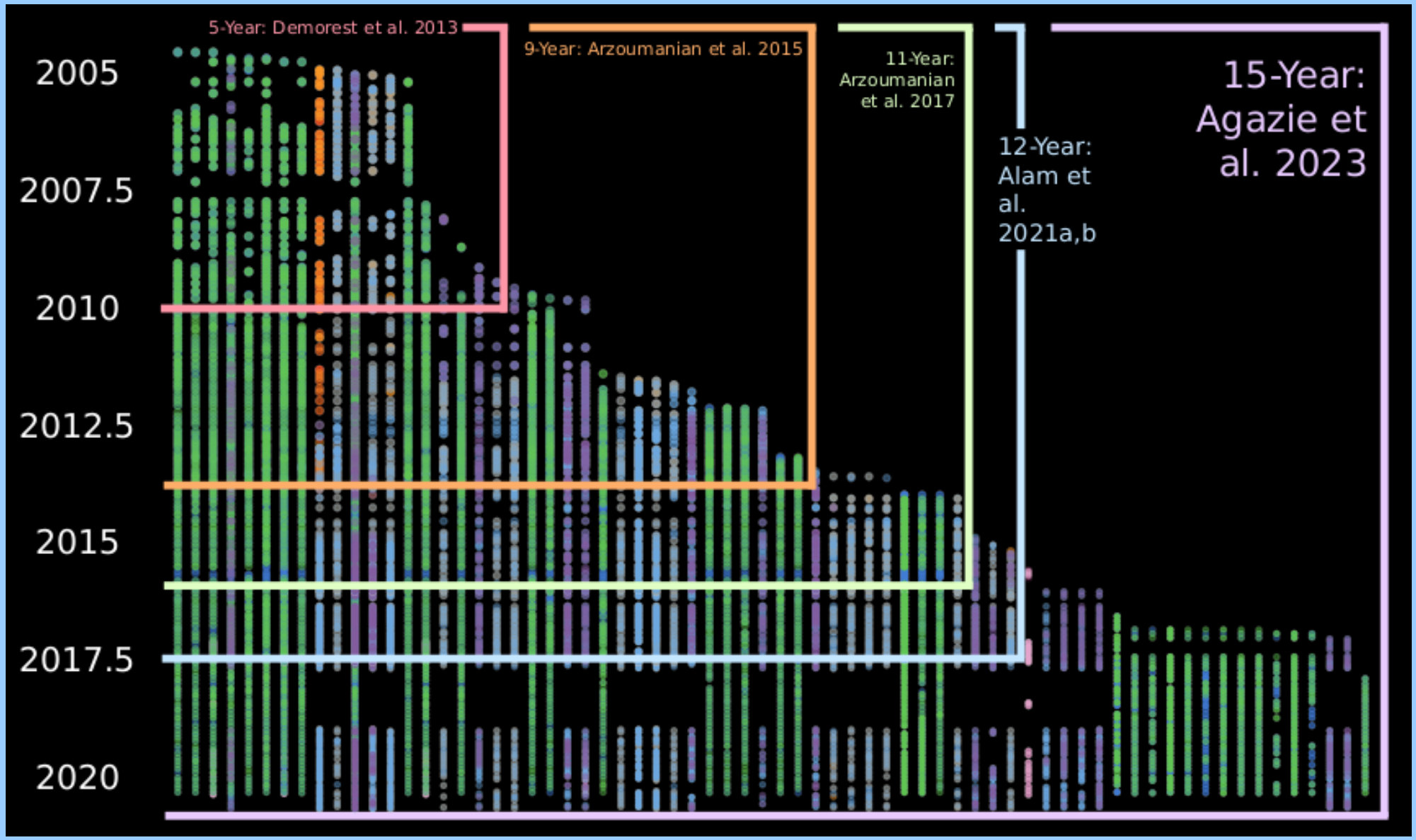
Courtesy: J. Cordes

The Pulsar Timing Array



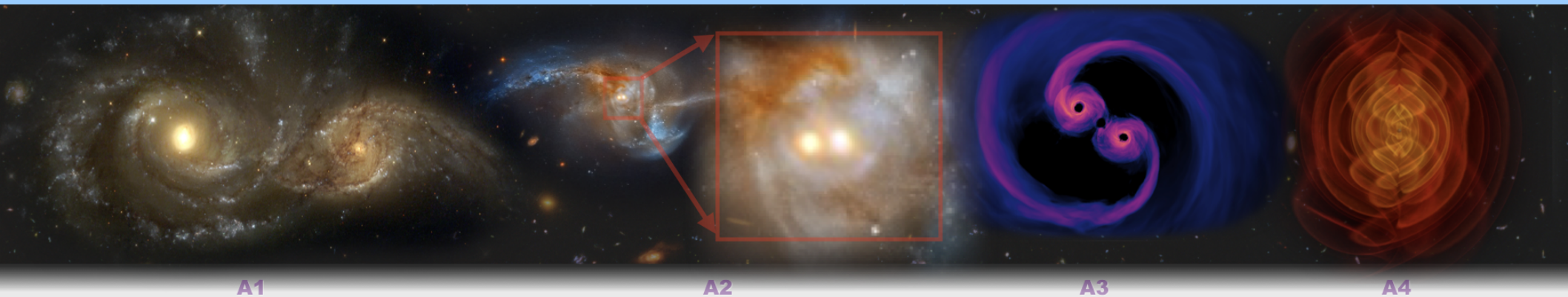
Animation by NSF/Onyx Lee

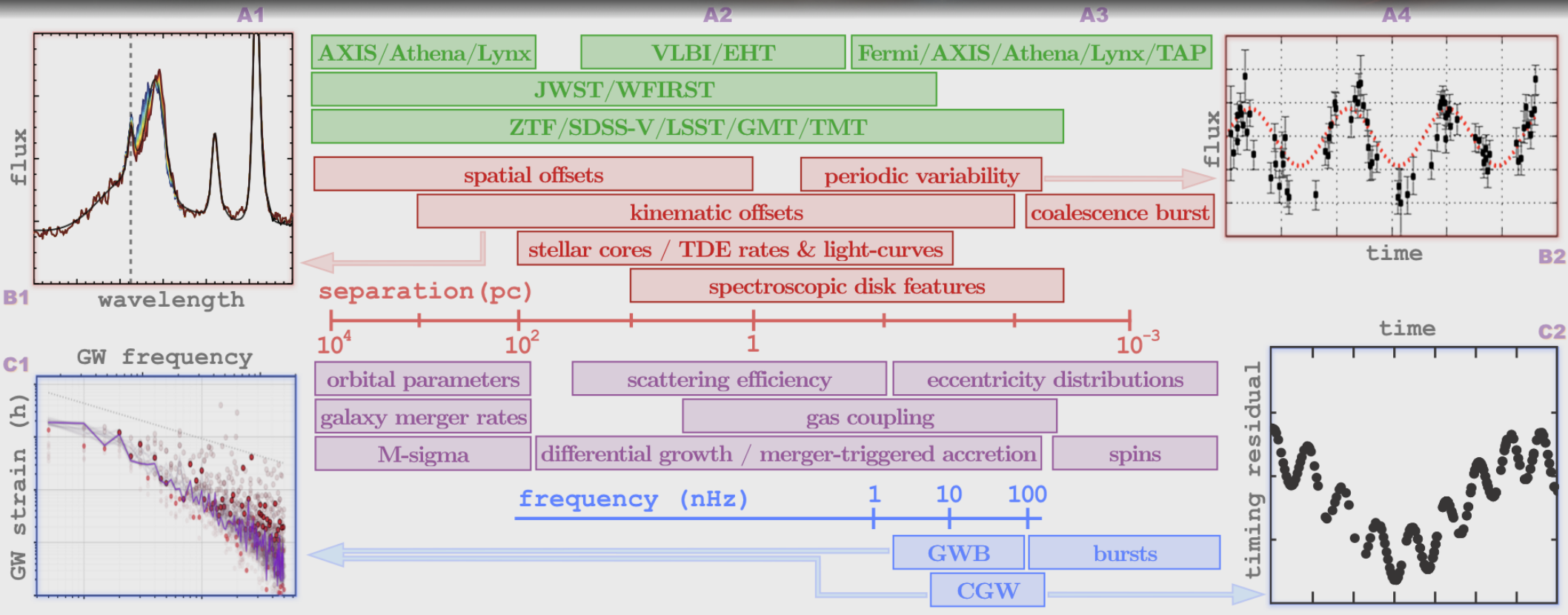
The Datasets



Courtesy: T. Cromartie, E .Ferrara

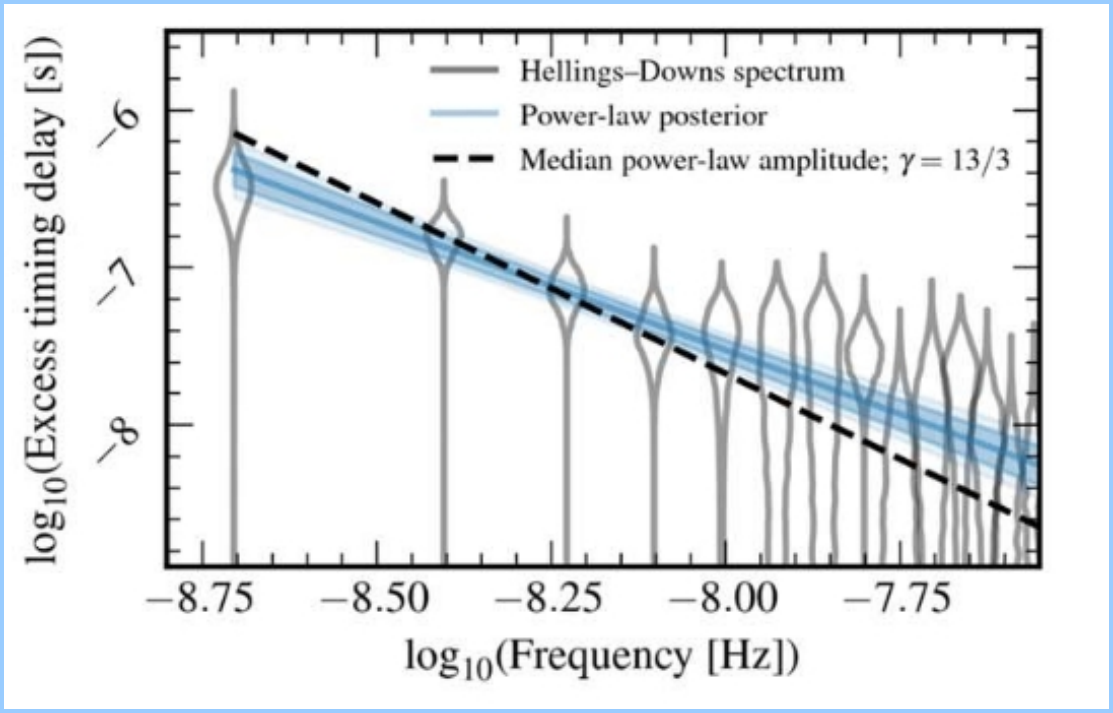
Multimessenger Science





Modified from Kelley et al. 2019

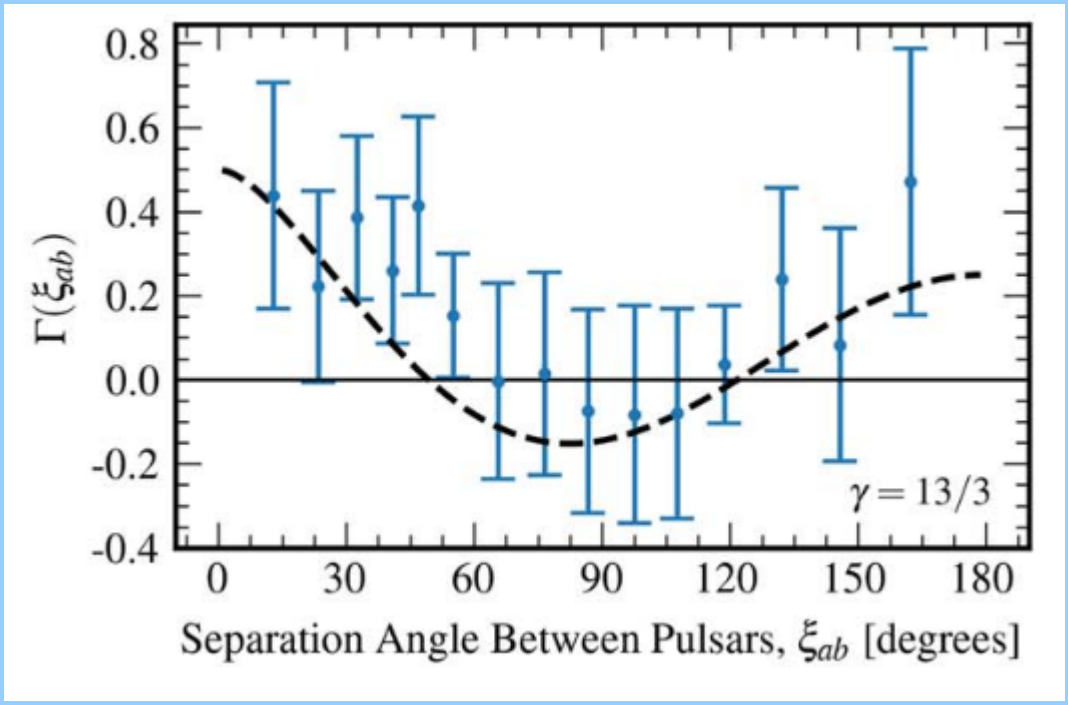
15-Year Data Set GWB Analysis



BF~10^{12} for Common Process

Agazie et al 2023

15-Year Data Set GWB Analysis



BF~10^{12} for Common Process,

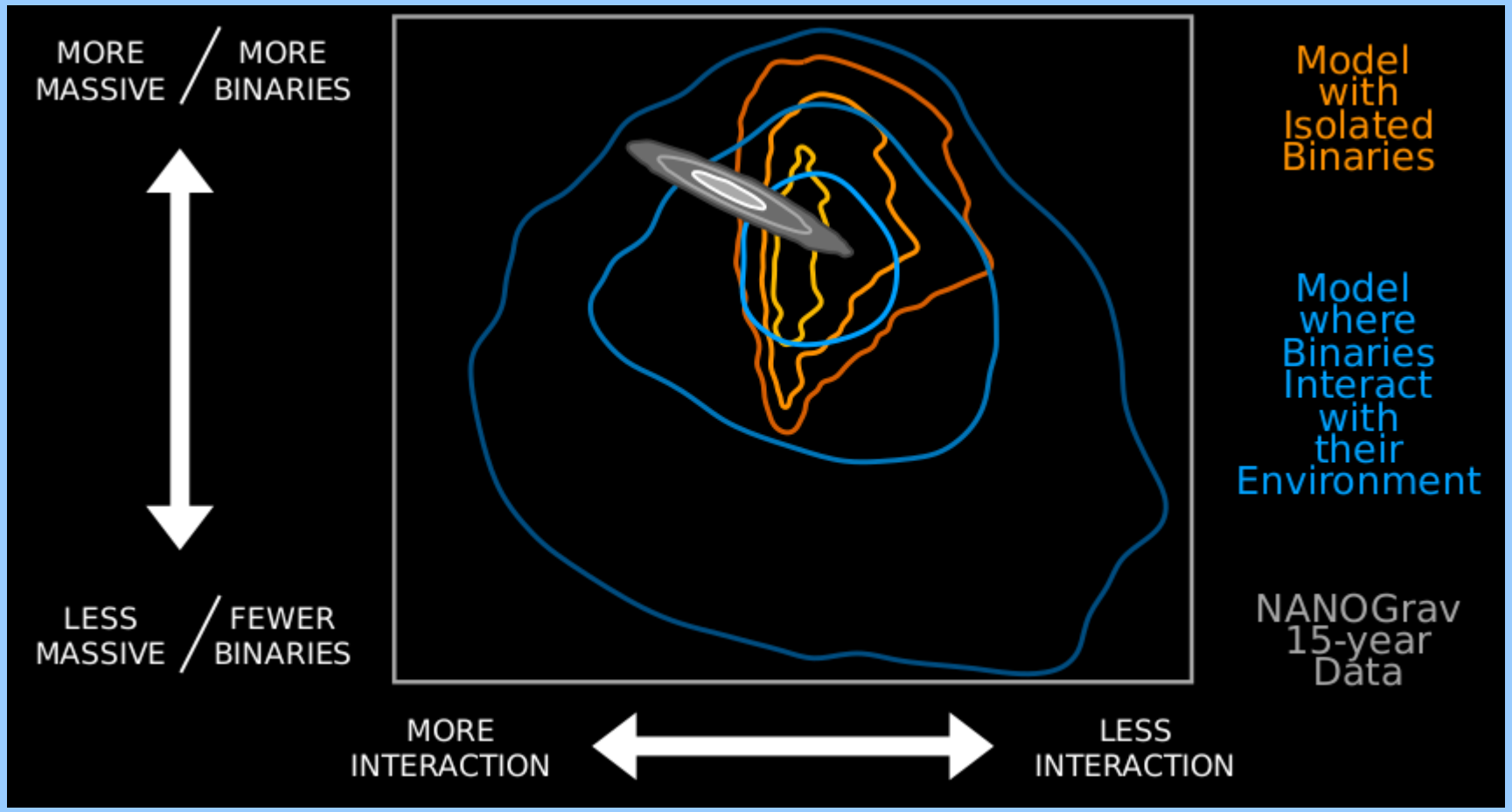
BF~200-1000 for Hellings-Downs

Null Distribution Tests

$p = 10^{-3} - 5\times10^{-5}$ (3-4σ)

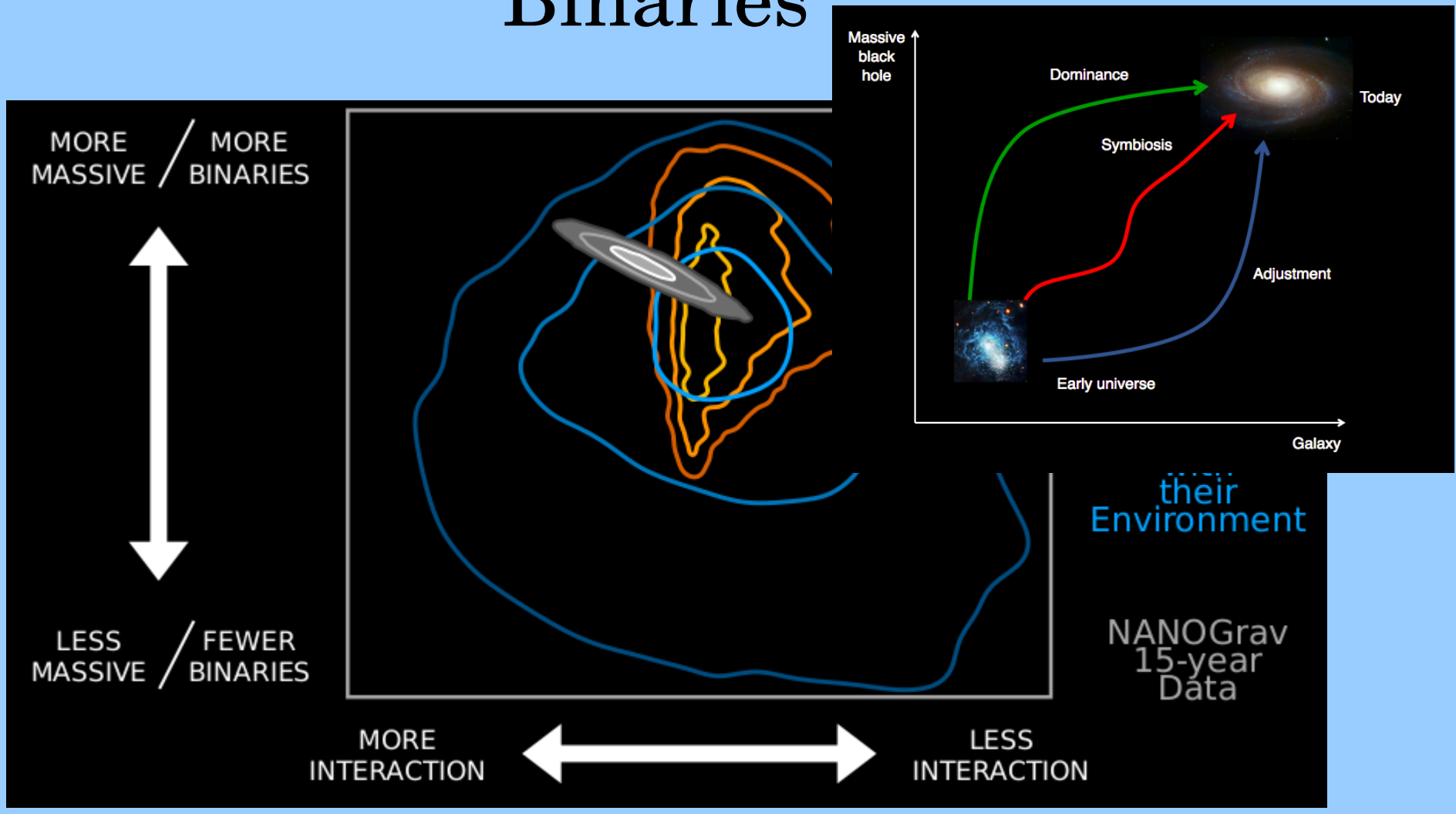
Agazie et al 2023

Astrophysics: Supermassive Black Hole Binaries



Modified from Agazie et al 2023

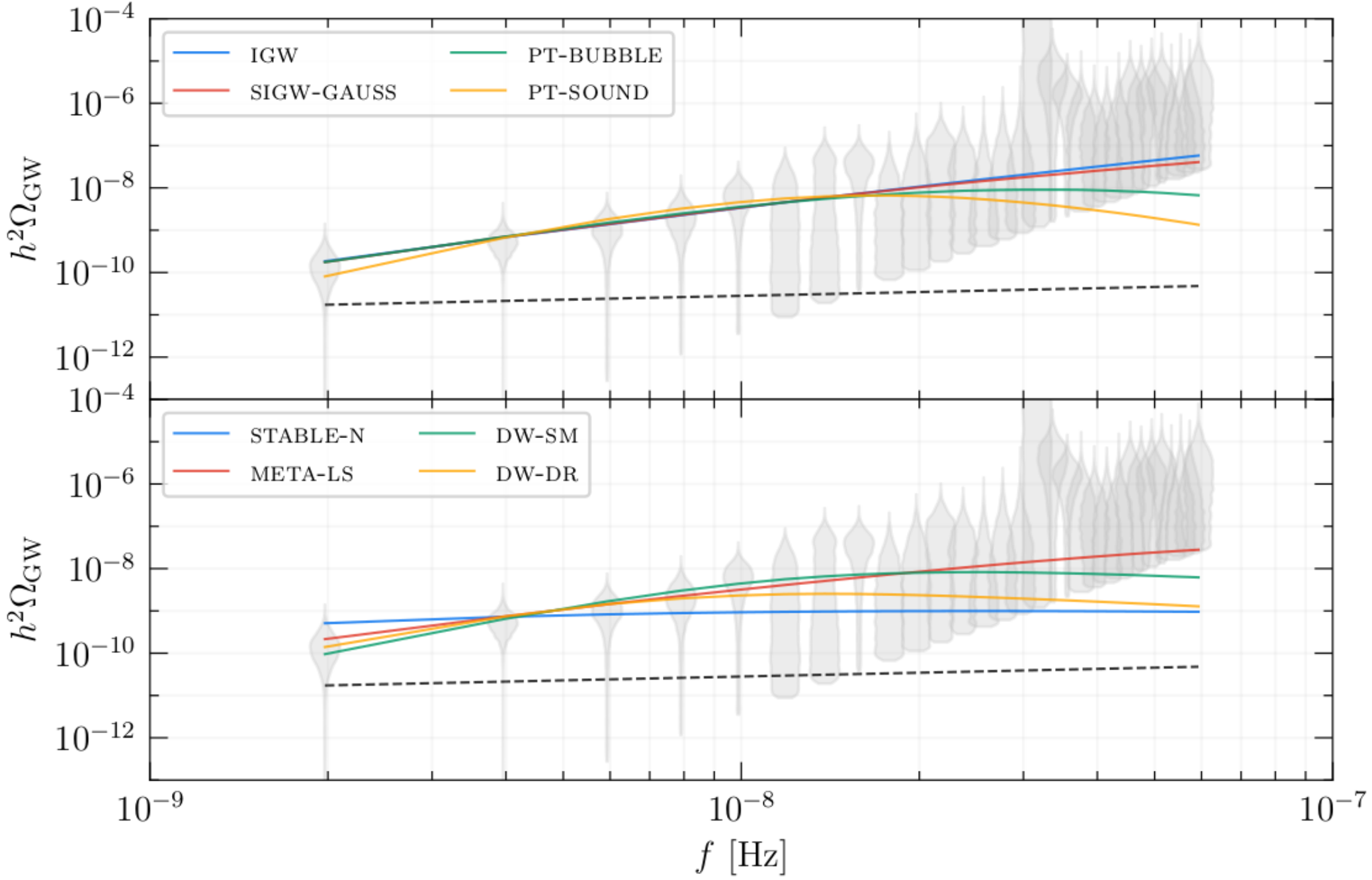
Astrophysics: Supermassive Black Hole Binaries



Courtesy: M. Volonteri

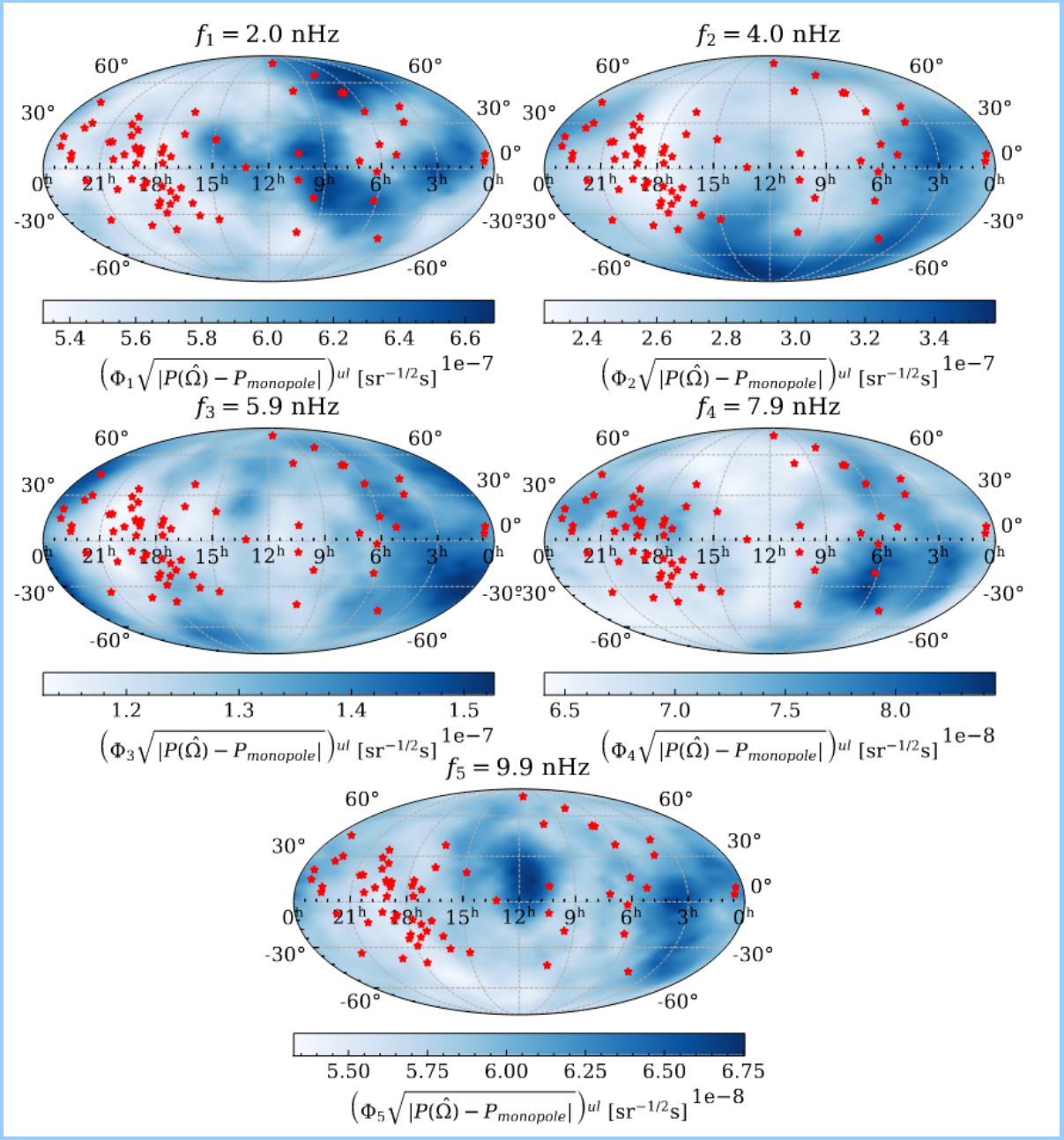
Modified from Agazie et al 2023

Astrophysics: New Physics



Afzal et al 2023

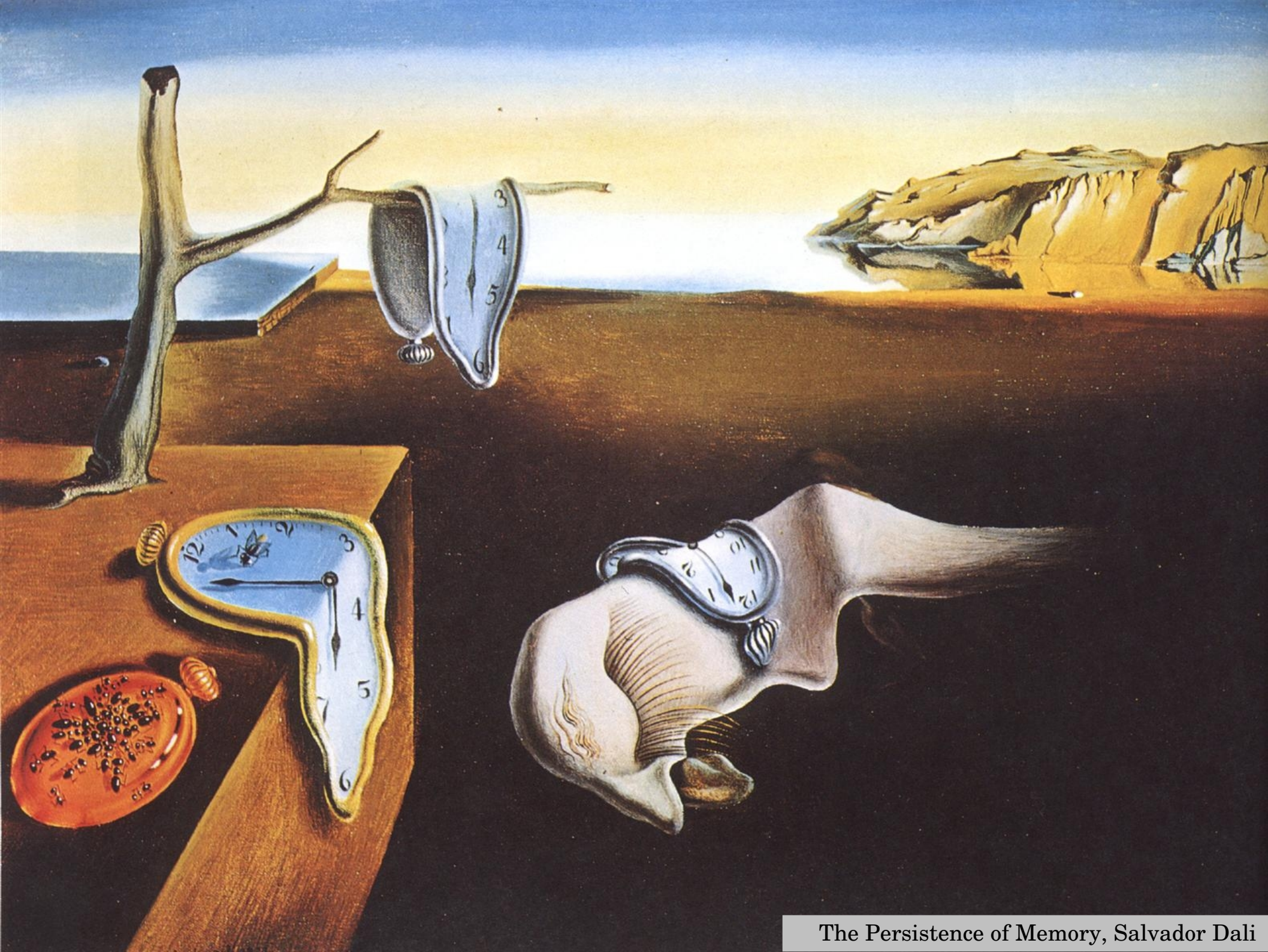
Mapping the Low-Frequency Gravitational Wave Universe



Agazie et al 2023

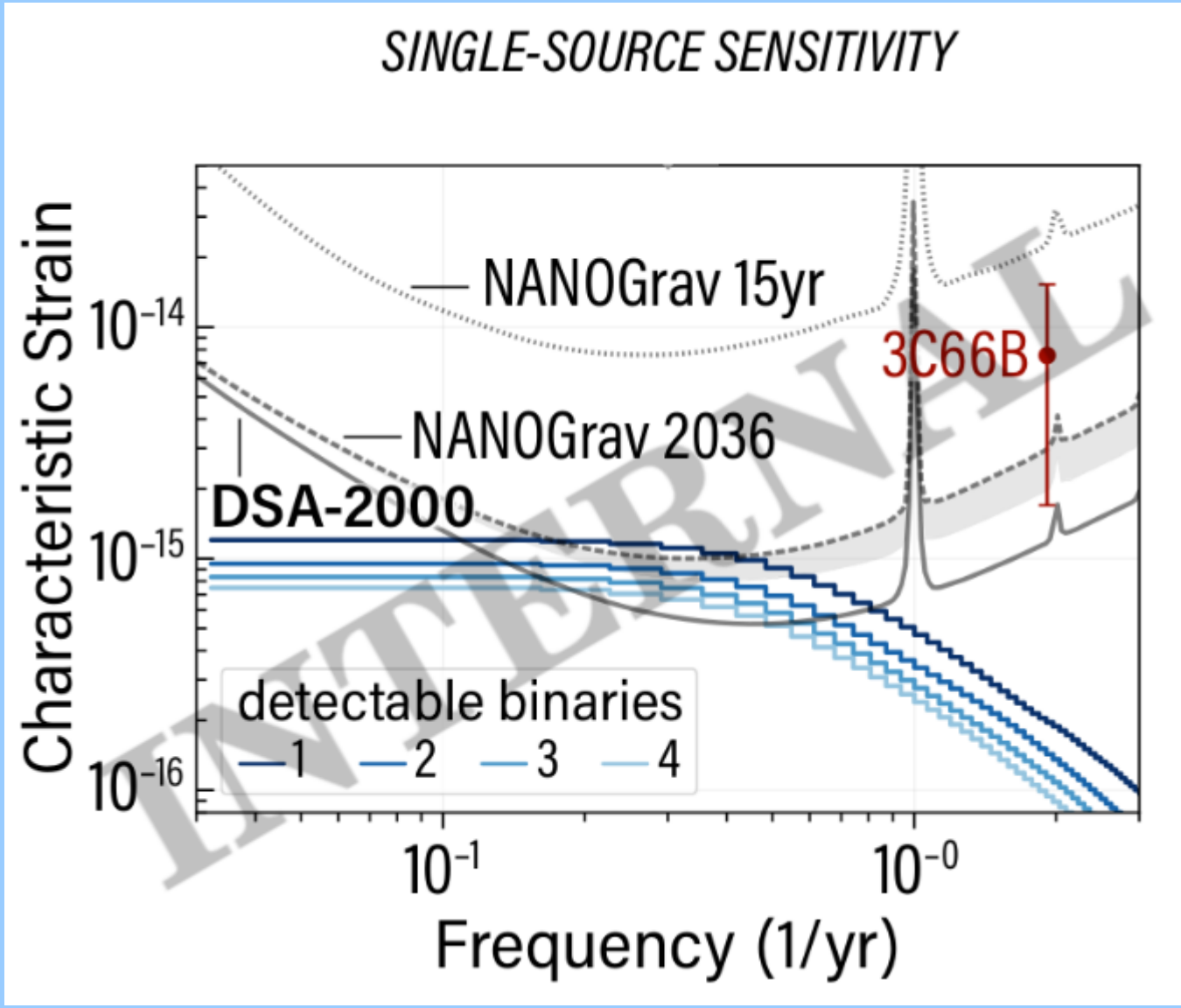
Future Facilities

Top: NSF/AUI/NRAO, Bottom: DSA-2000 / C. Carter

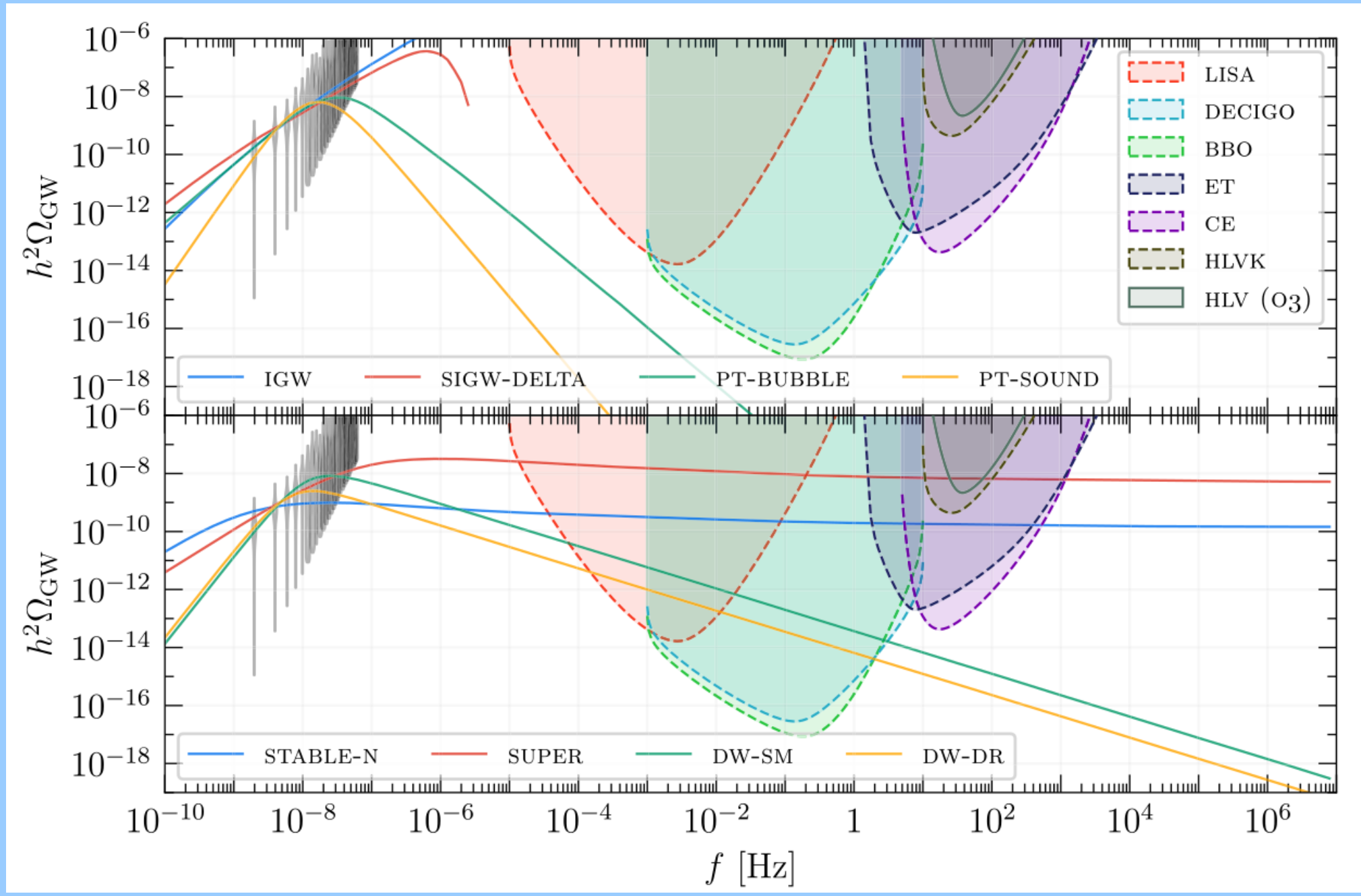


The Persistence of Memory, Salvador Dali

Future Facilities



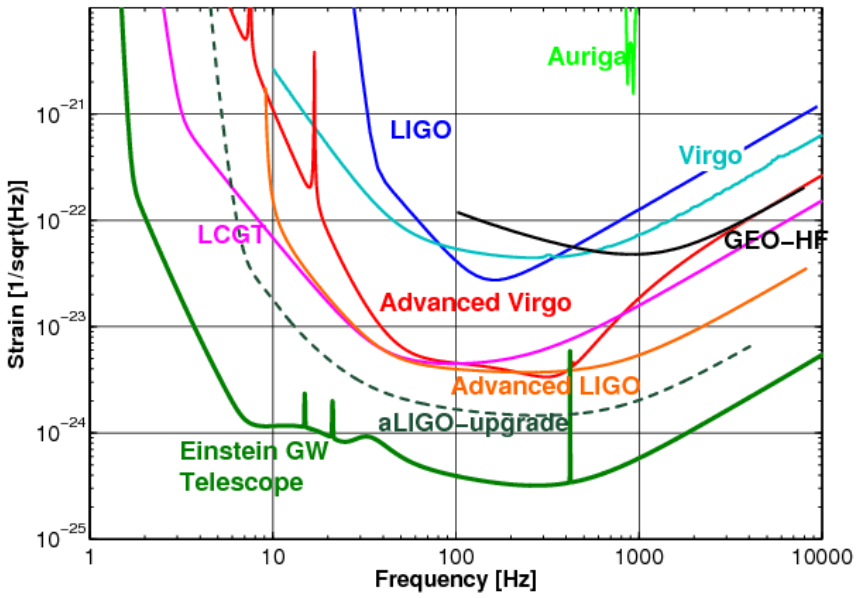
Astrophysics: New Physics

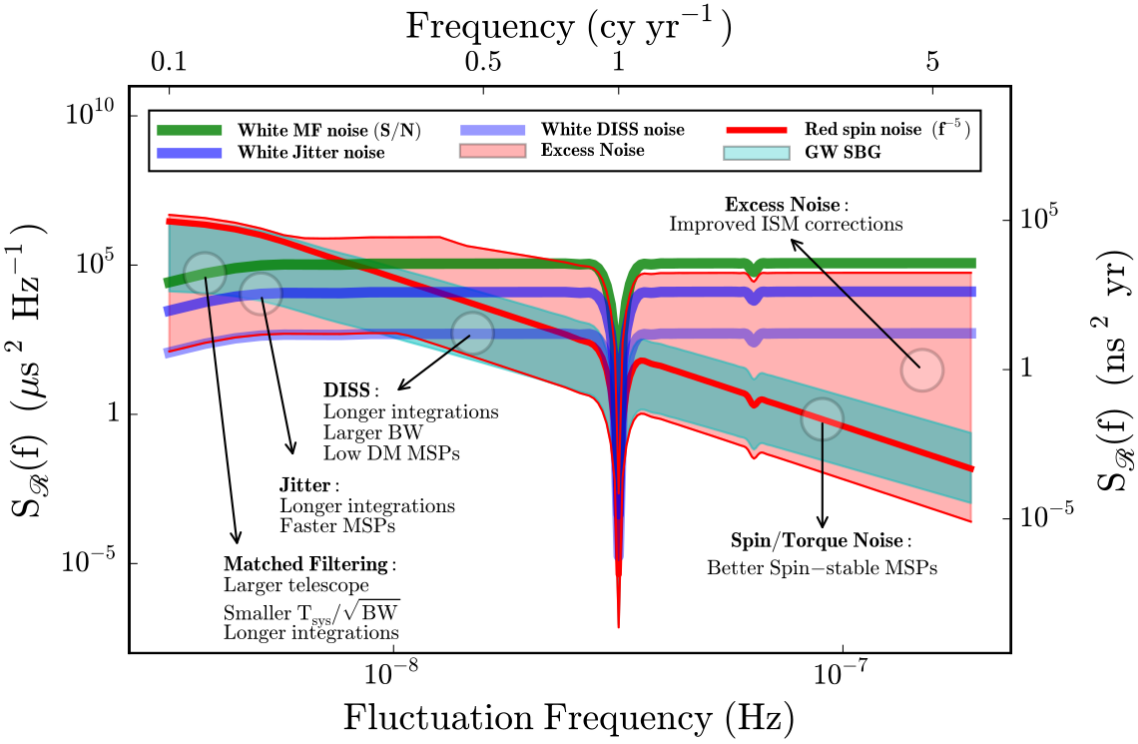


Afzal et al 2023

The Next Generation

LIGO → aLIGO NANOGrav → "aNANOGrav"





L: Hild et al 2012

R: Courtesy J. Cordes