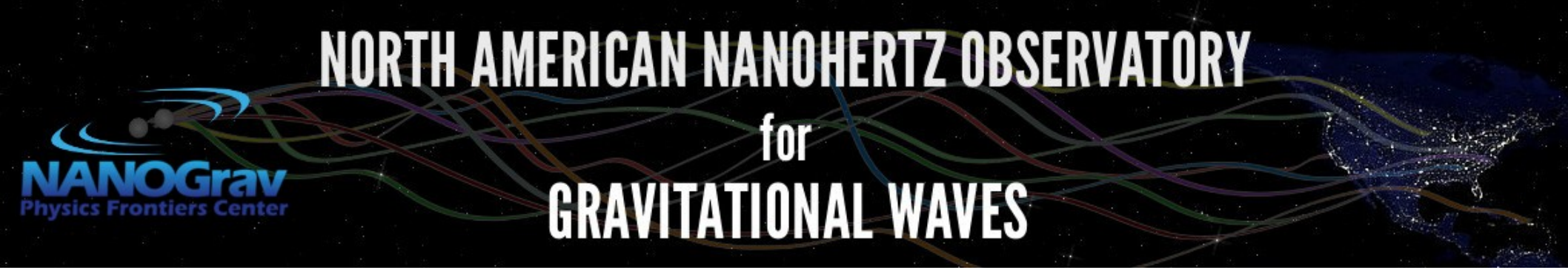


Celestial Lighthouses in a Sea of Gravitational Waves

Michael T. Lam

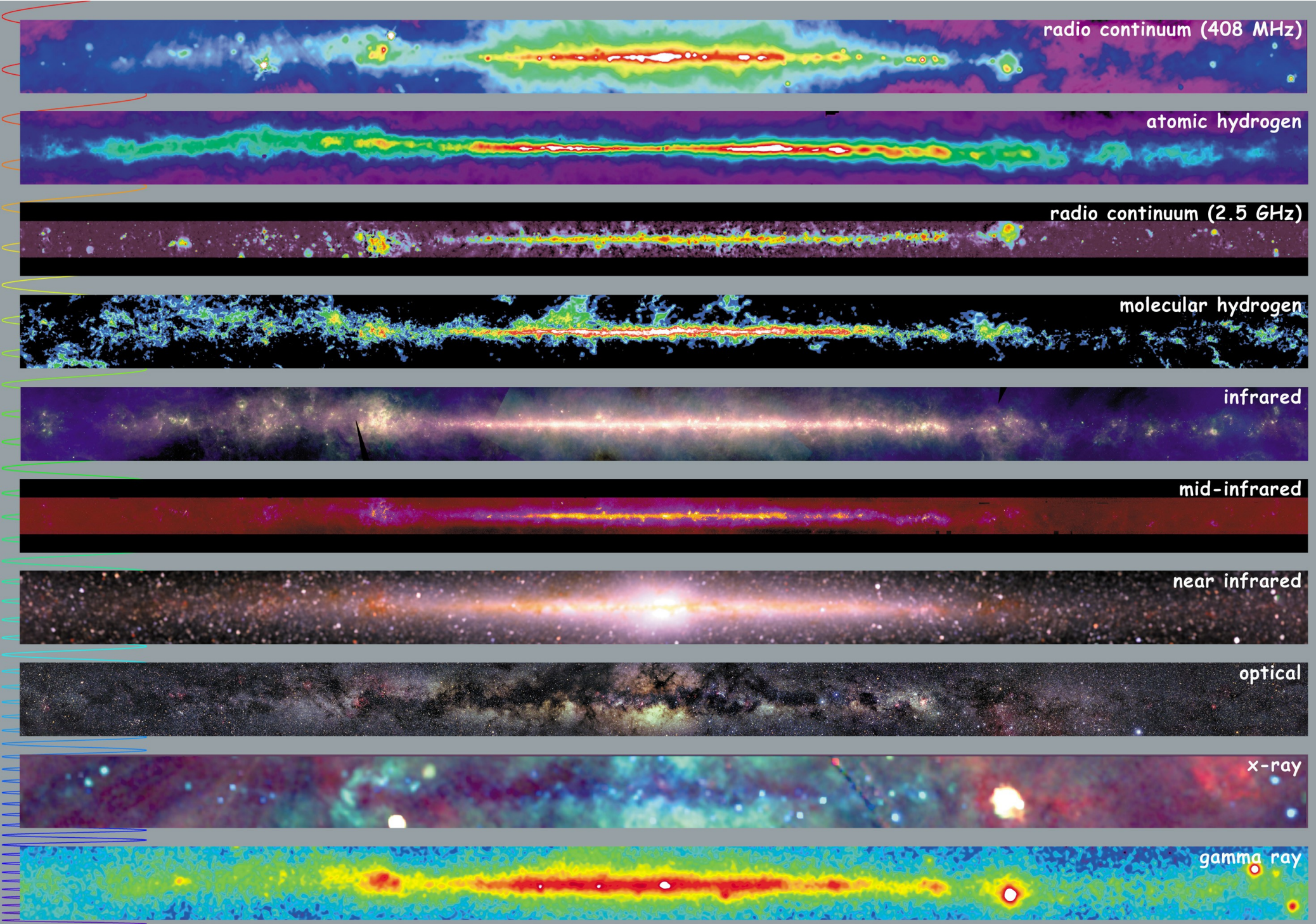
Mohawk Valley Astronomical Society Talk –
11 Sep 2024

COLGATE UNIVERSITY

SETI INSTITUTE
RIT College of Science Astrophysical Sciences and Technology

©Babak Tafreshi-TWAN

NRAO/AUI



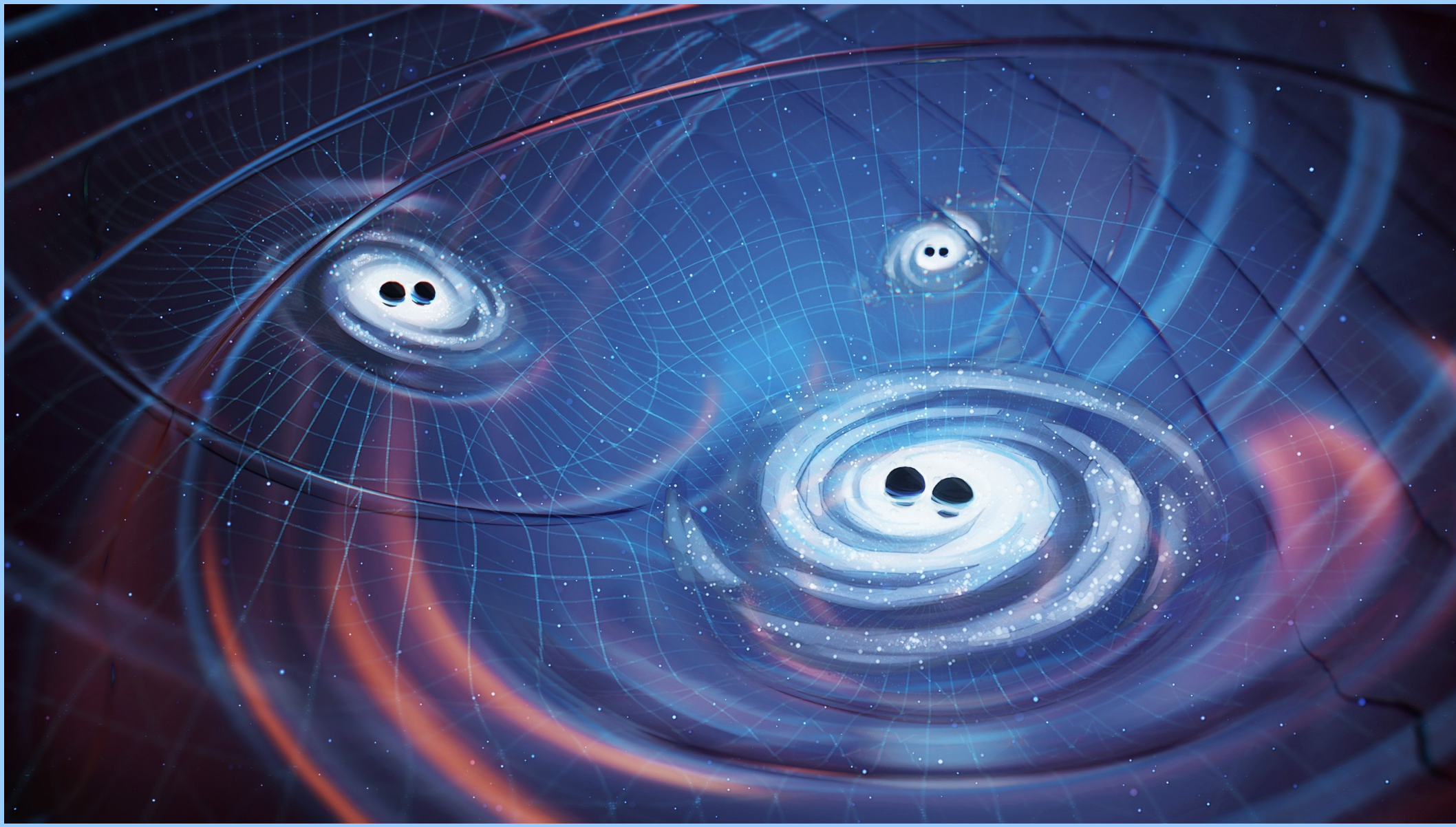
Multiwavelength Milky Way

http://adc.gsfc.nasa.gov/mw

Image Modified: BSO, Suntory Hall

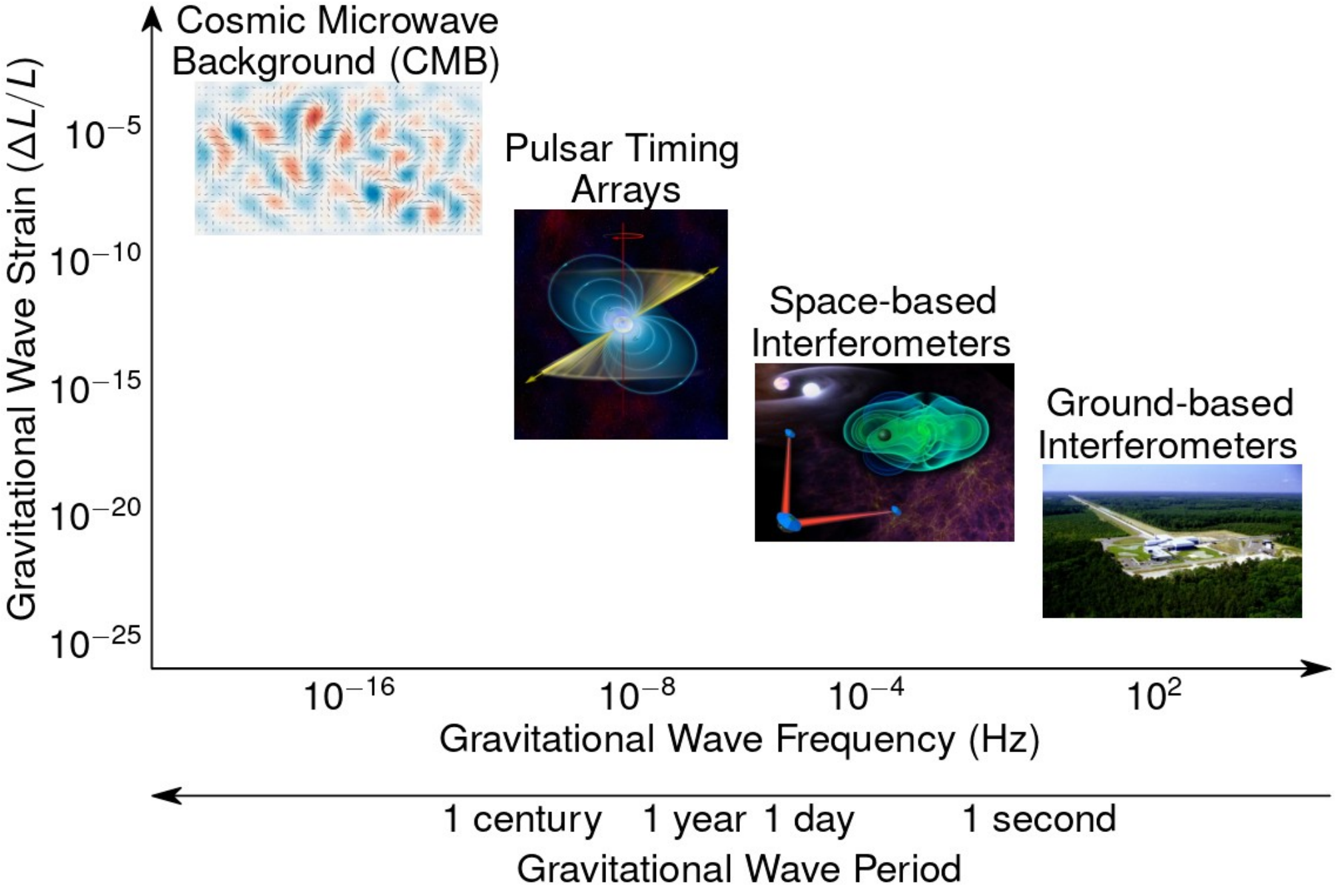
Image Modified: BSO, Suntory Hall

Image Modified: BSO, Suntory Hall

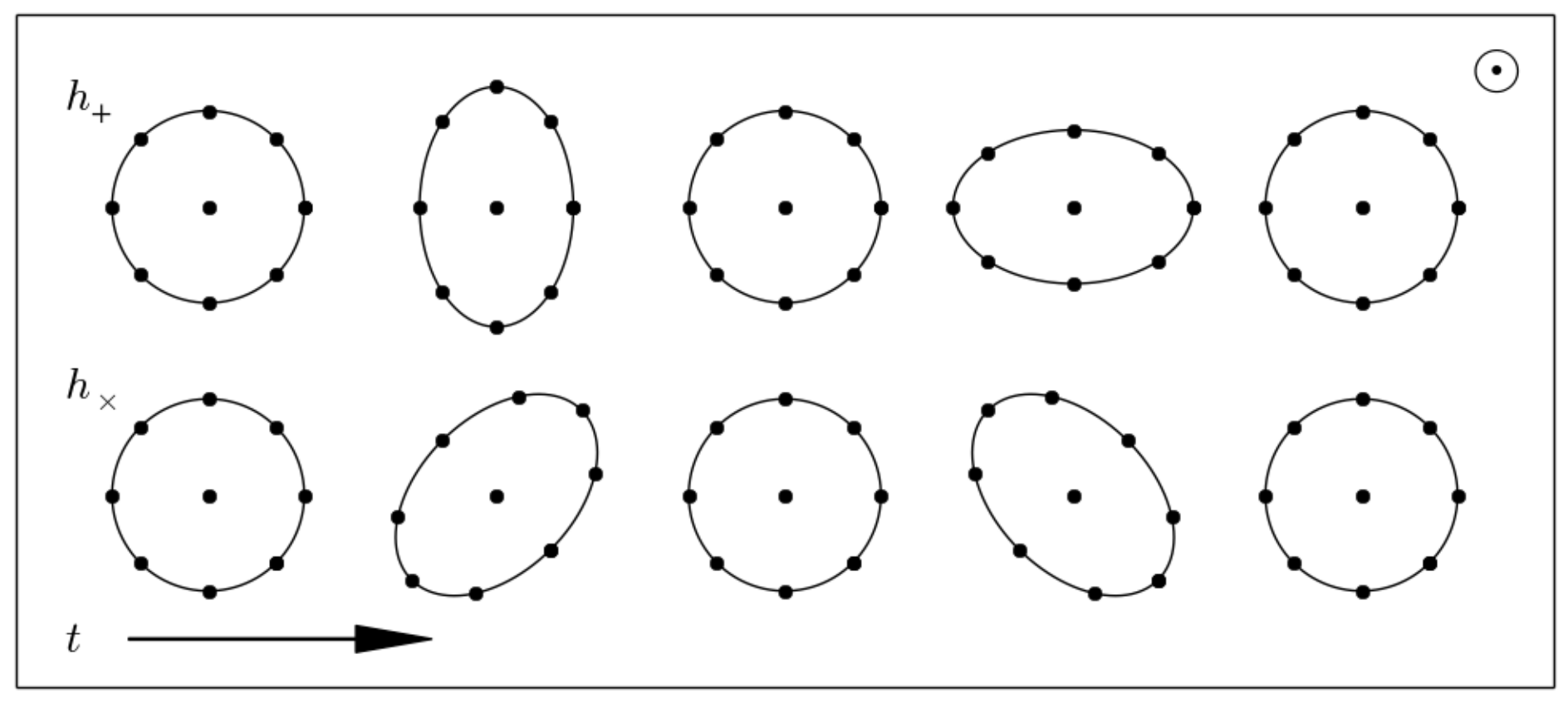


Olena Shmahalo for NANOGrav

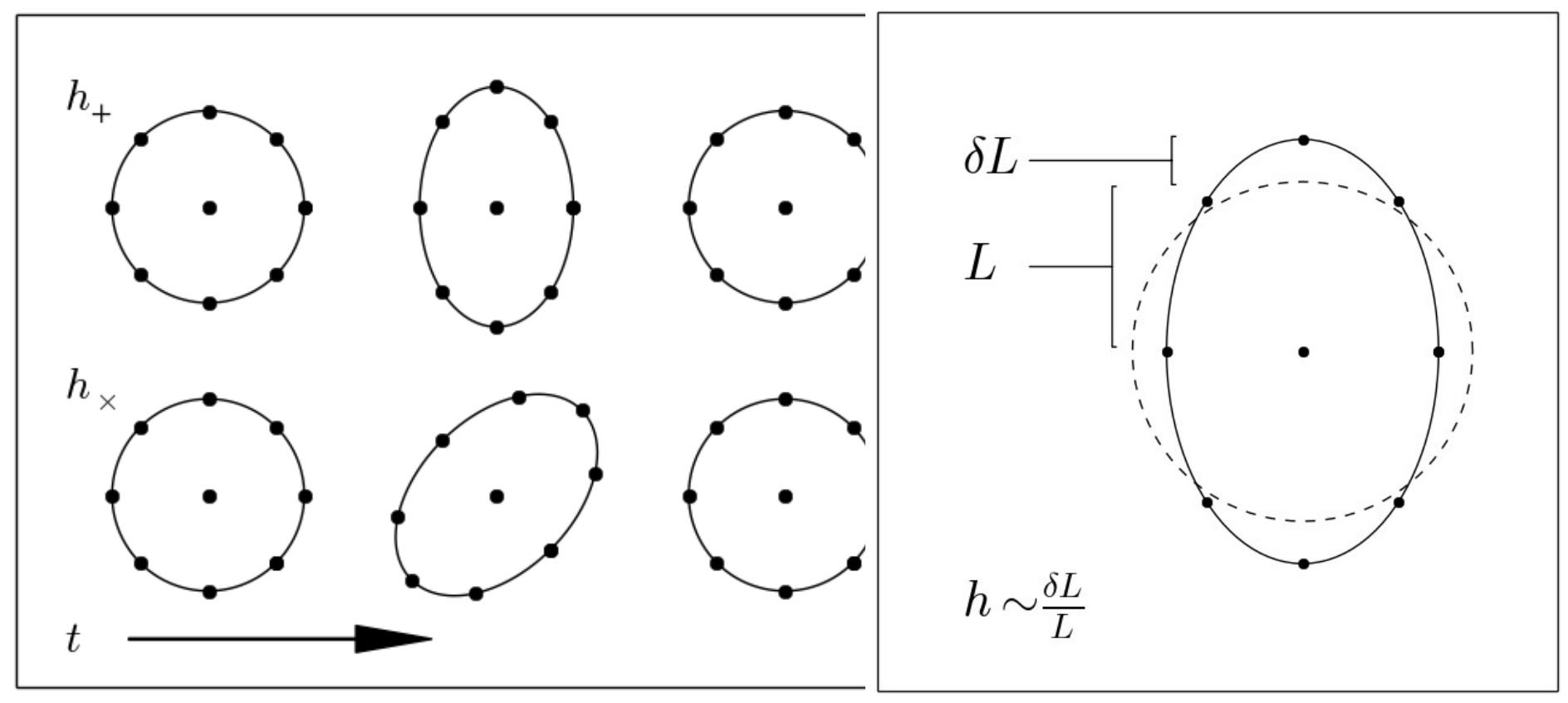
L,M: NRAO/AUI, R: NAIC

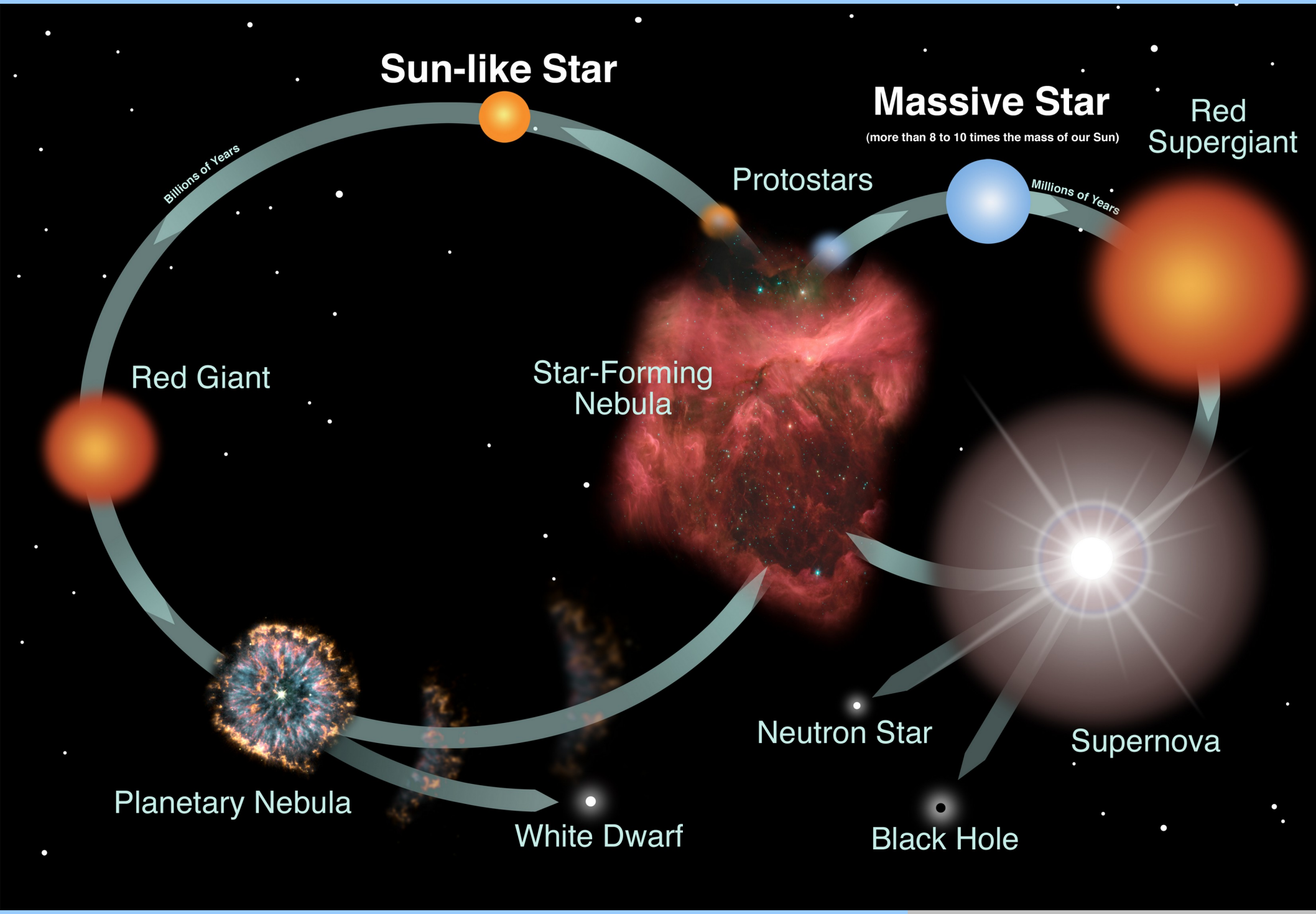

Cosmic Microwave Background (CMB)
Pulsar Timing Arrays
Space-based Interferometers
Ground-based Interferometers
Gravitational Wave Strain (ΔL/L)
10−5
10−10
10−15
10−20
10−25
10−16
10−8
10−4
10²
Gravitational Wave Frequency (Hz)
1 century
1 year
1 day
1 second
Gravitational Wave Period

Effects of Gravitational Waves



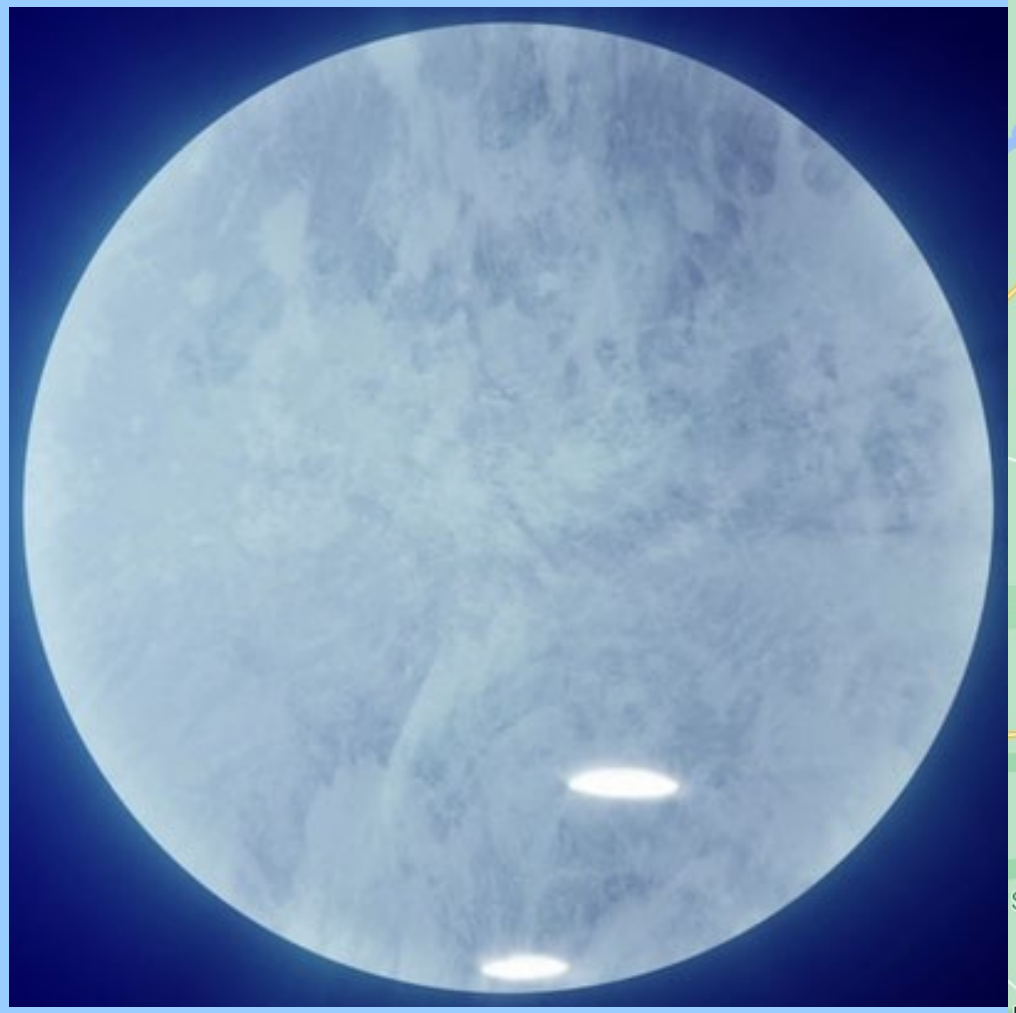
Effects of Gravitational Waves

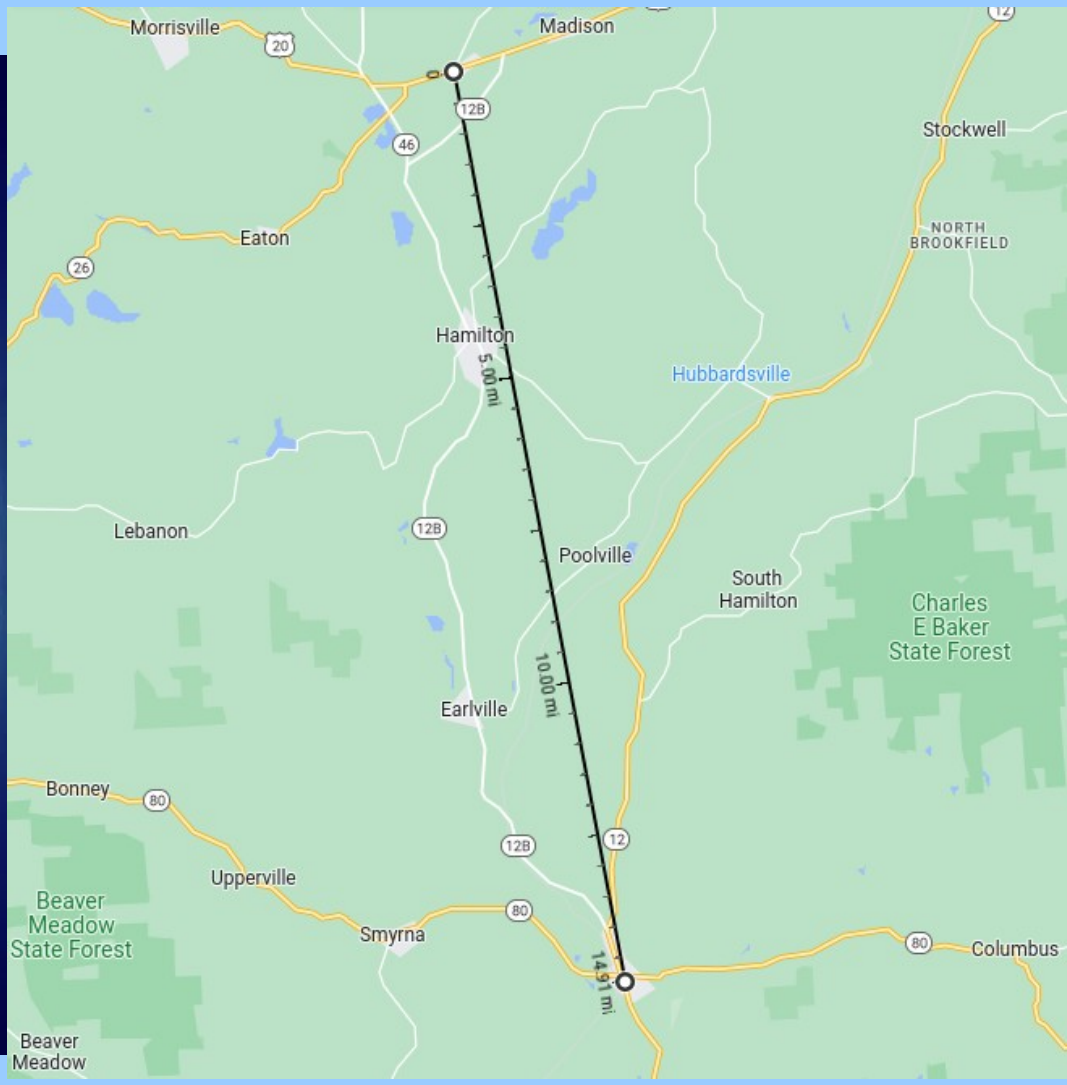



Sun-like Star
Massive Star
(more than 8 to 10 times the mass of our Sun)
Red Supergiant
Protostars
Billions of Years
Millions of Years
Red Giant
Star-Forming Nebula
Neutron Star
Supernova
Planetary Nebula
White Dwarf
Black Hole

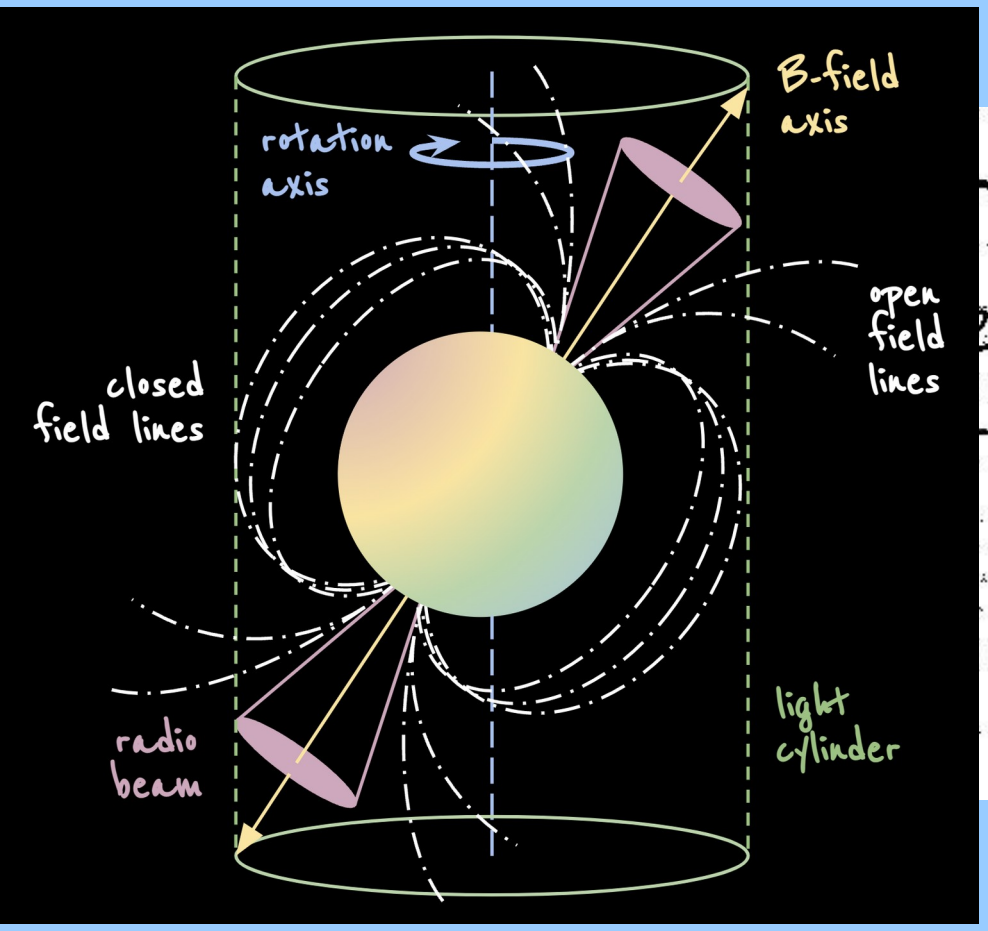
Neutron Stars

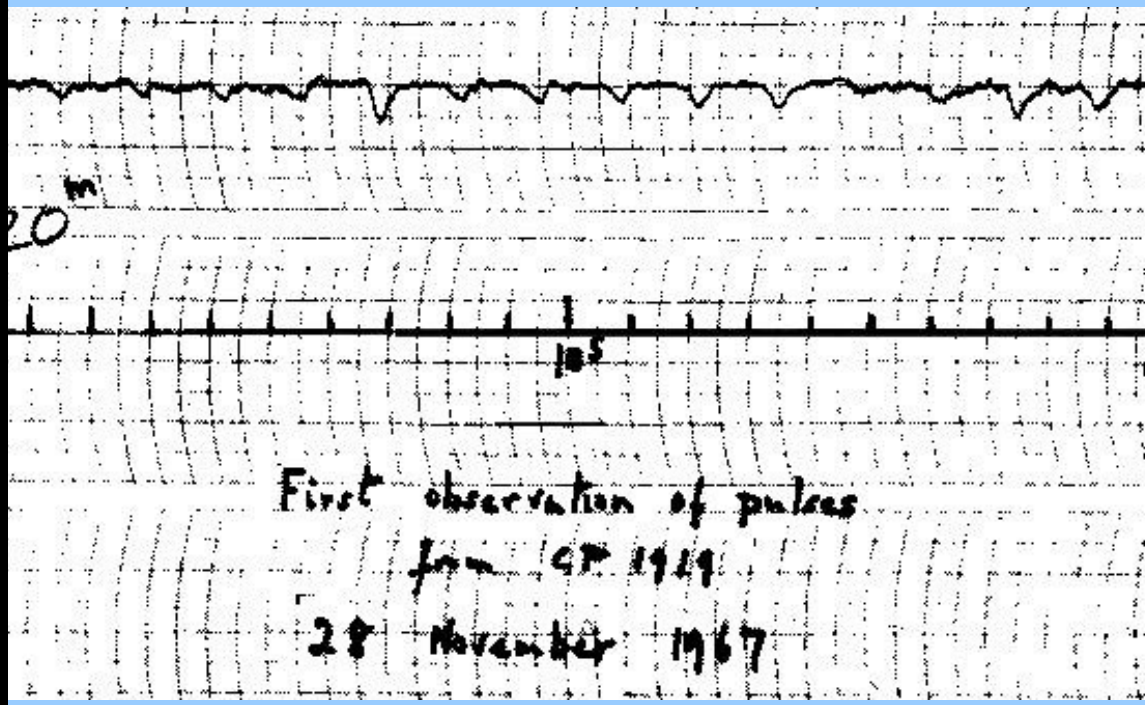
$M \sim 1\text{-}2\ M_{\odot}$, $R \sim 12$ km





NASA, NICER, GSFC





L: Thankful Cromartie

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

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 ± 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

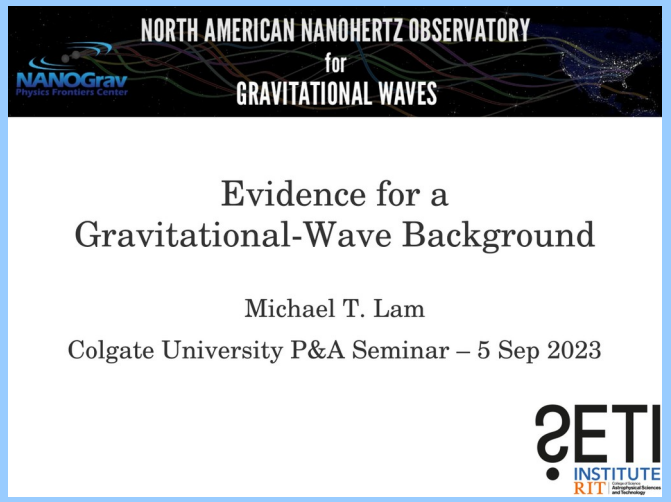
The last digit changes by 1 every 713 seconds

This digit changes by 1 every 226 years

Data: NANOGrav

Pulsars as Precise Clocks: J1909-3744

Last year I gave a seminar
at Colgate starting on
Sep 5, 2023 at 15:30:00 UTC.



Between that time and the start of this seminar,
Sep 11, 2024 at 23:30 UTC, the pulsar has completed over 10,915650,076 rotations (0.65 over!)

It's also completed almost 243 orbits around its companion white dwarf (0.19 to go!)

Data: NANOGrav

More fun with J1909-3744

Smallest eccentricity of any known binary in the Universe:

$e = 0.000000109 \pm 0.000000008$

(in 2016 it was measured to be smaller formally, $e = 0.000000092 +/- 0.000000013$)

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!

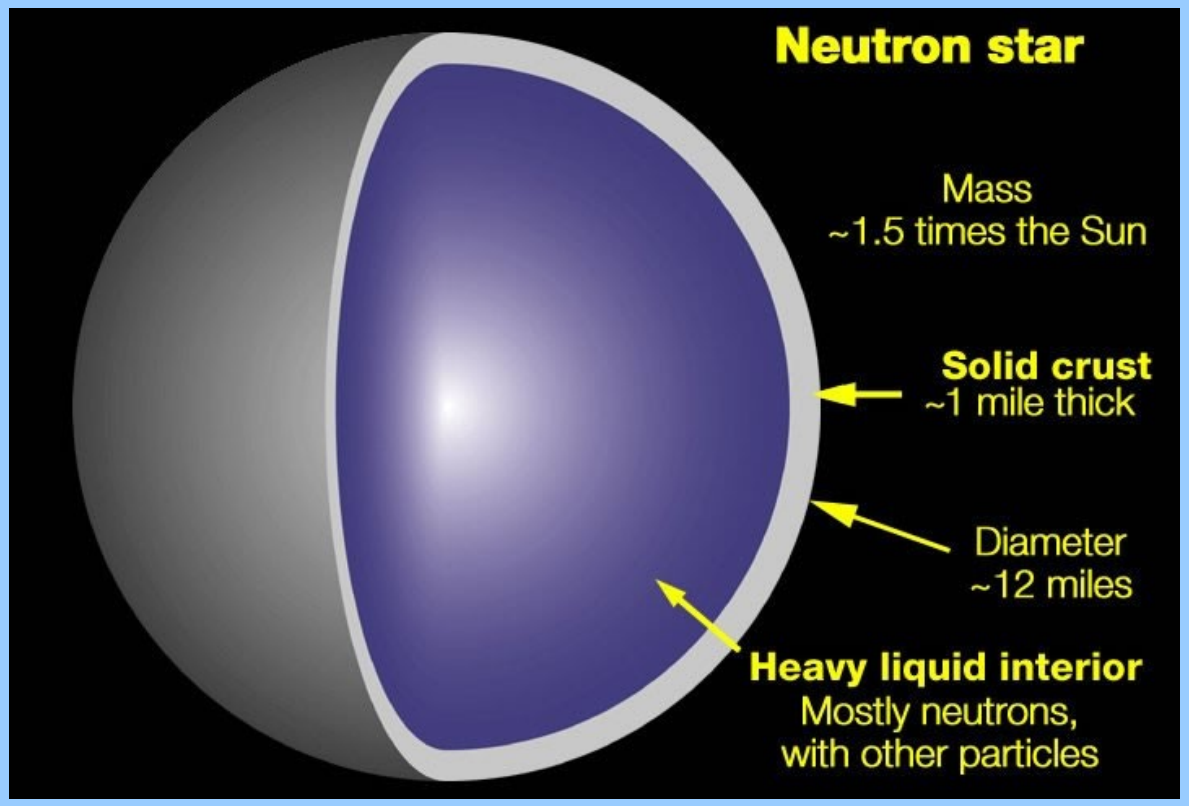
Data: NANOGrav

The Tiny Effects of GWs

$L \sim cT \sim 10$ lightyears ($= 3$ pc $= 10^{17}$ m)

$h \sim 10^{-16} - 10^{-14}$ (for our sources)

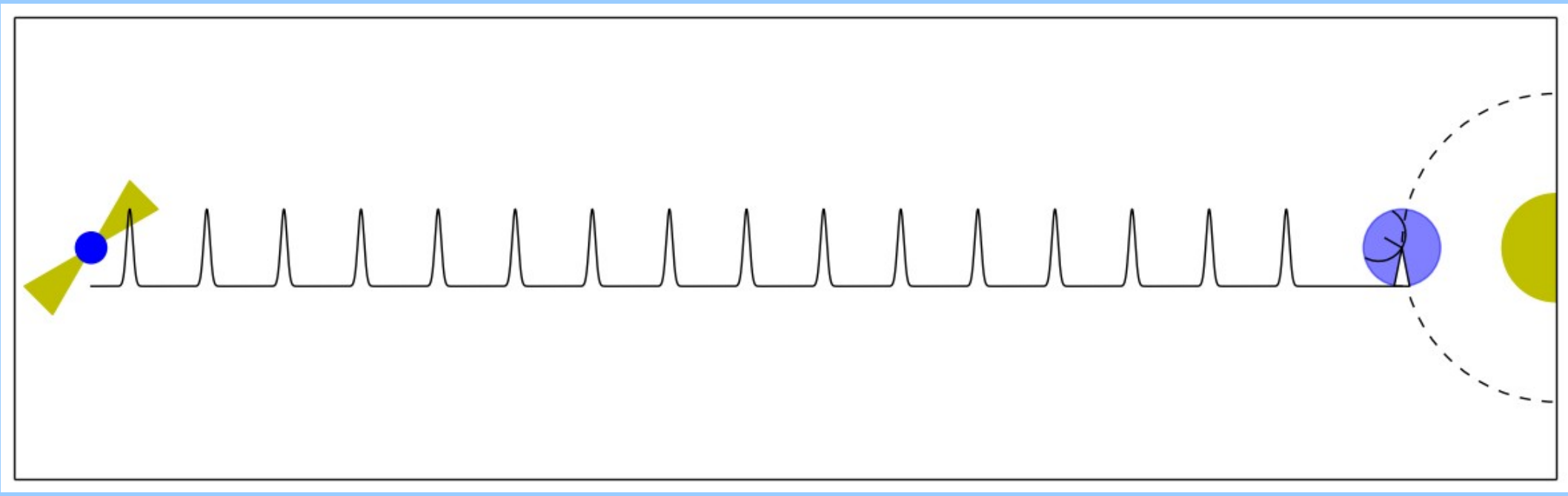
$\Delta L \sim hL \sim 10\text{-}1000$ m $\rightarrow \Delta t = \Delta L/c \sim hT \sim 30\text{-}3000$ ns



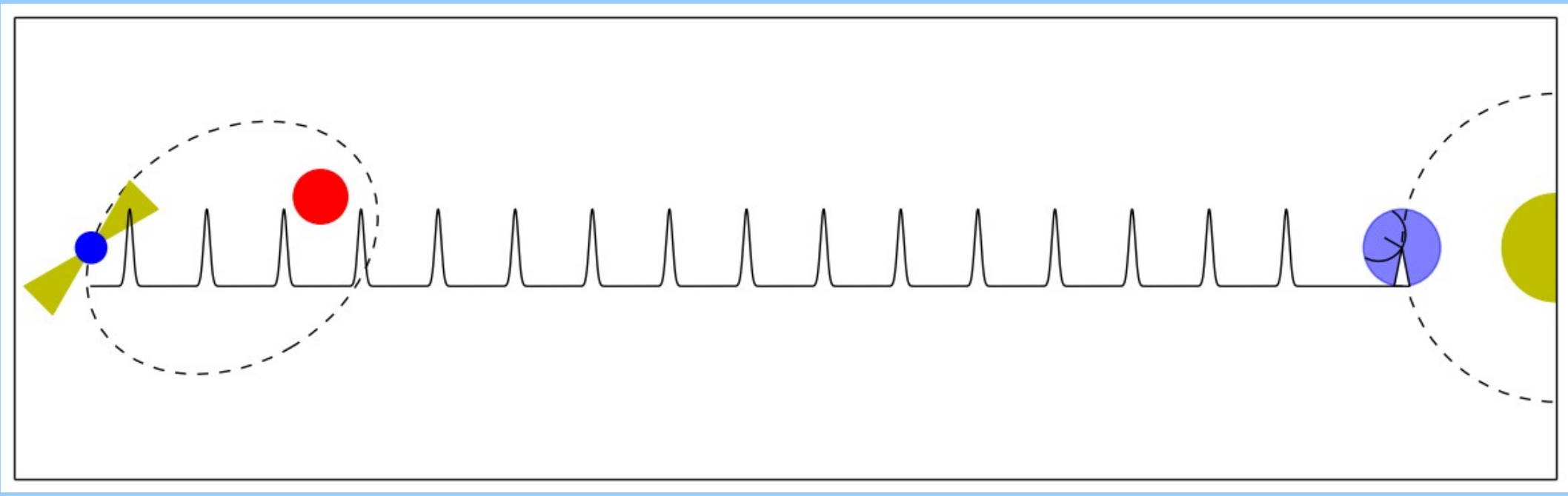
$0.001 - 0.1\ R_{NS}$

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

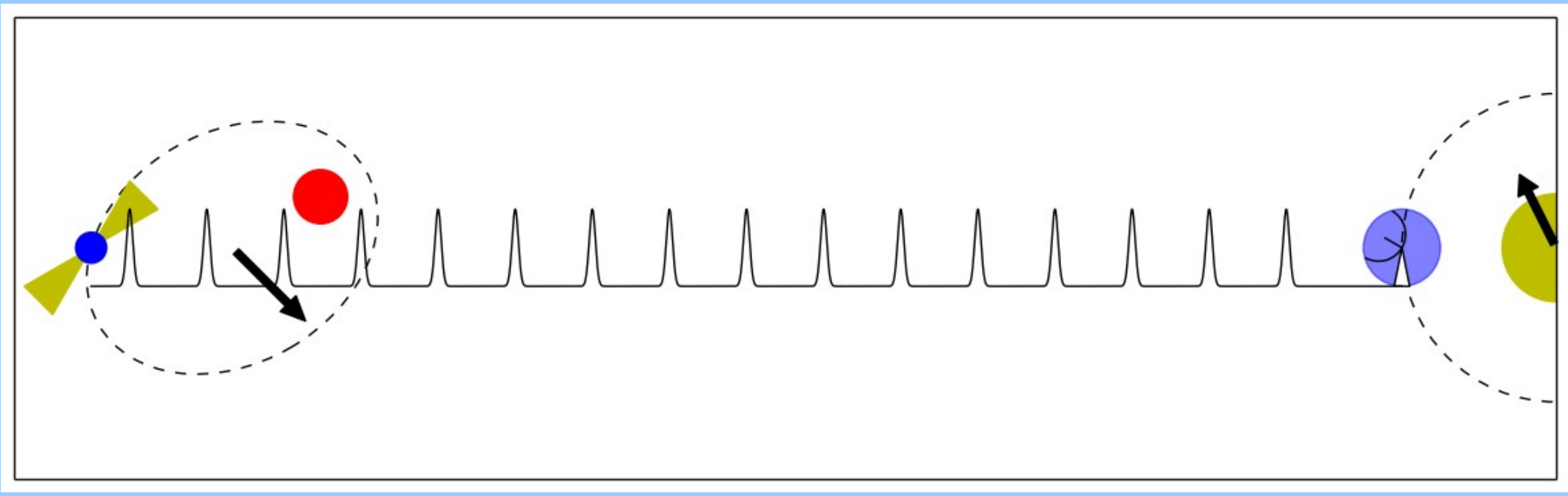
Timing Model



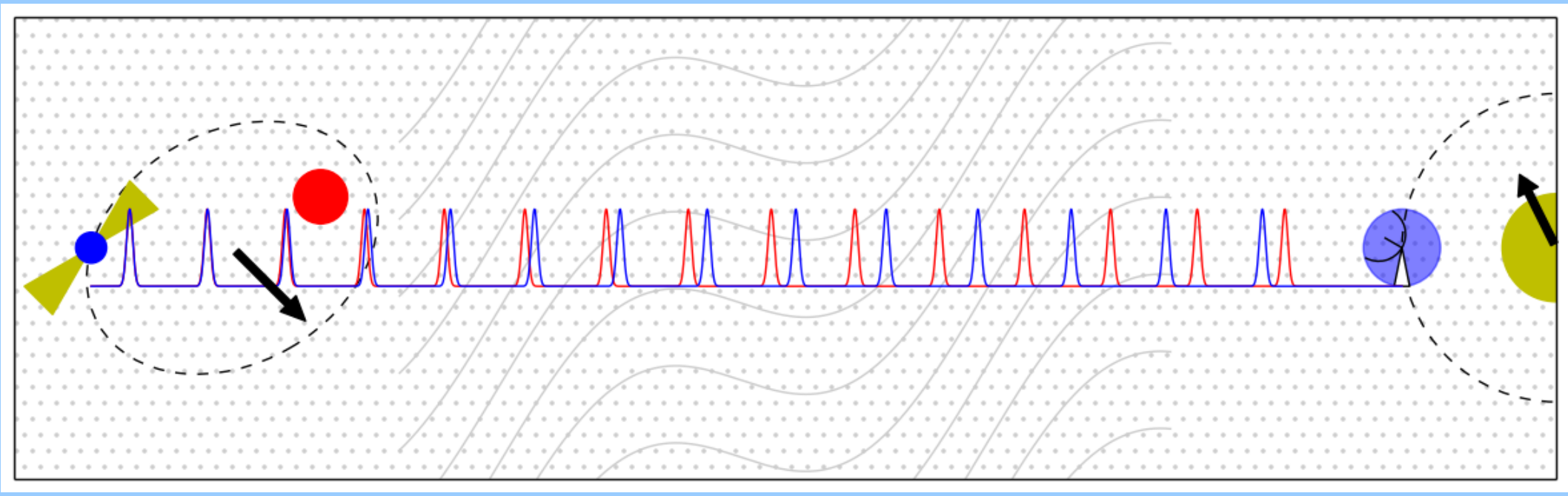
Timing Model



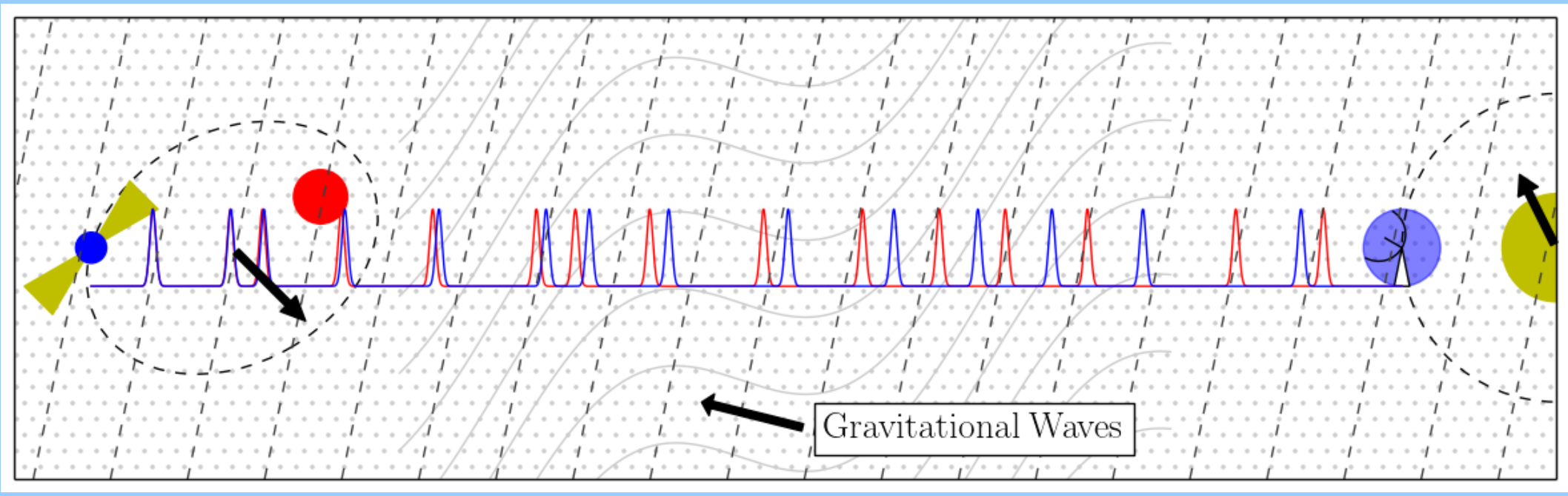
Timing Model



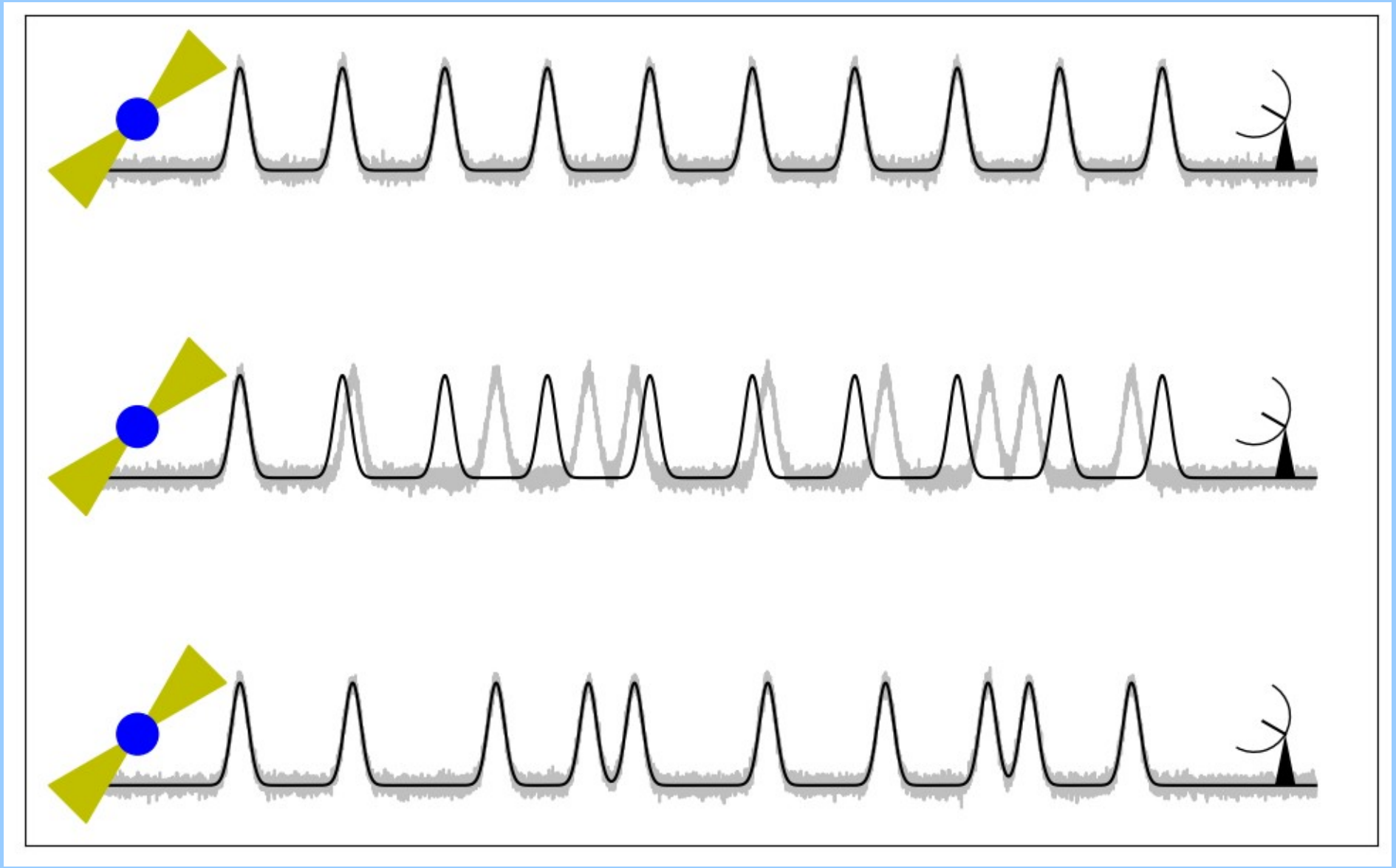
Timing Model



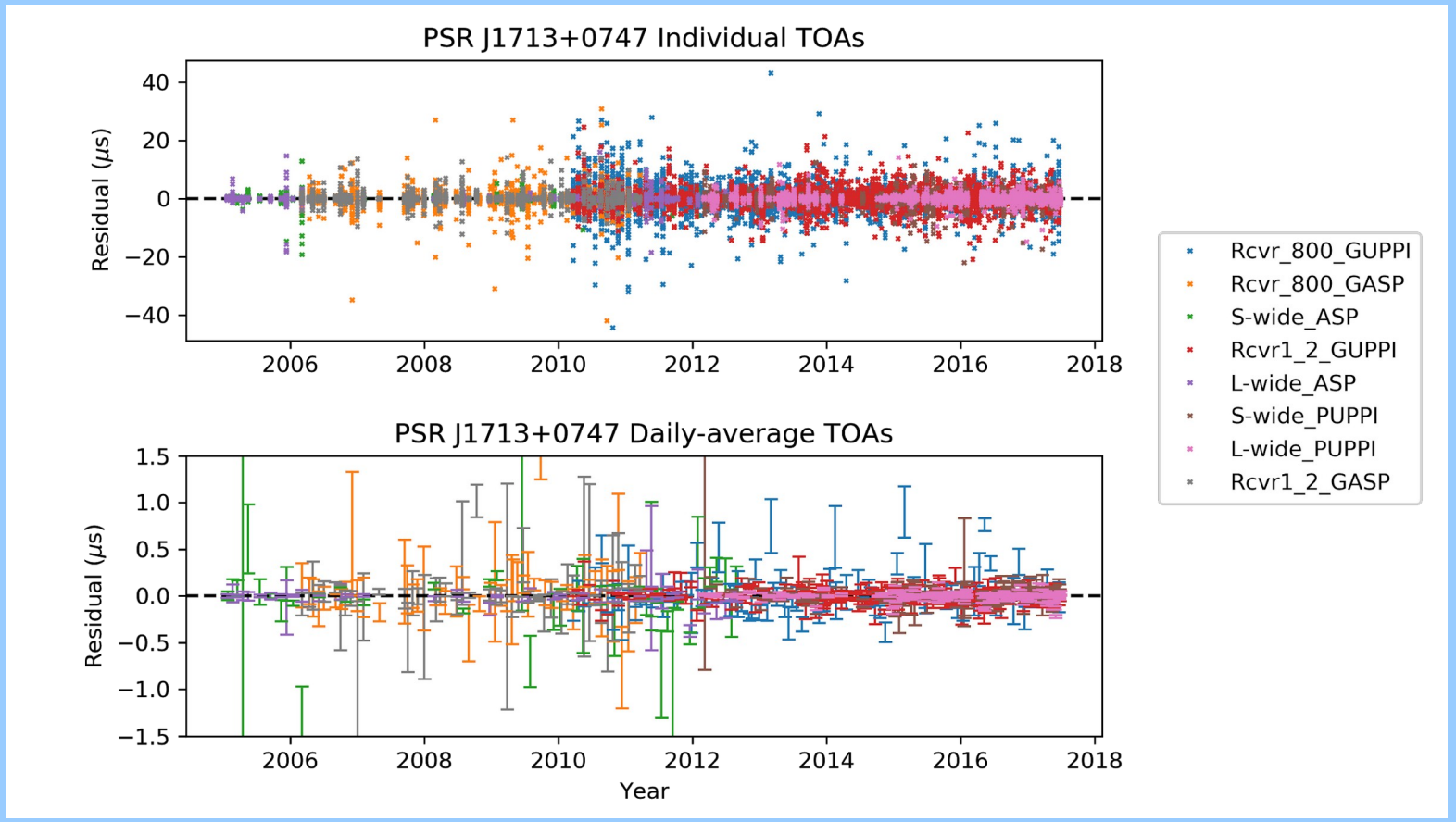
Timing Model



Pulsar Timing

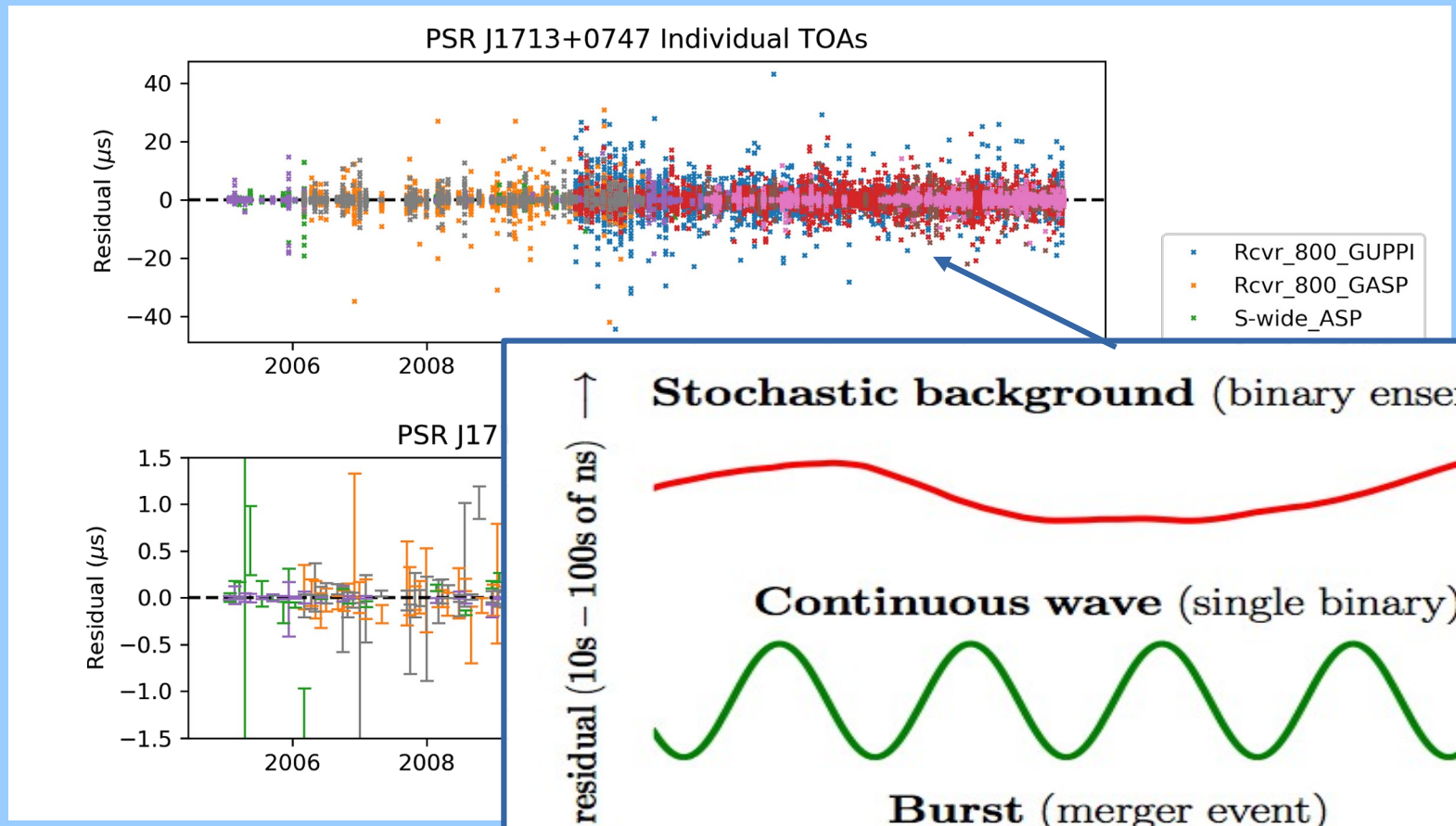


Residuals and GW Signatures



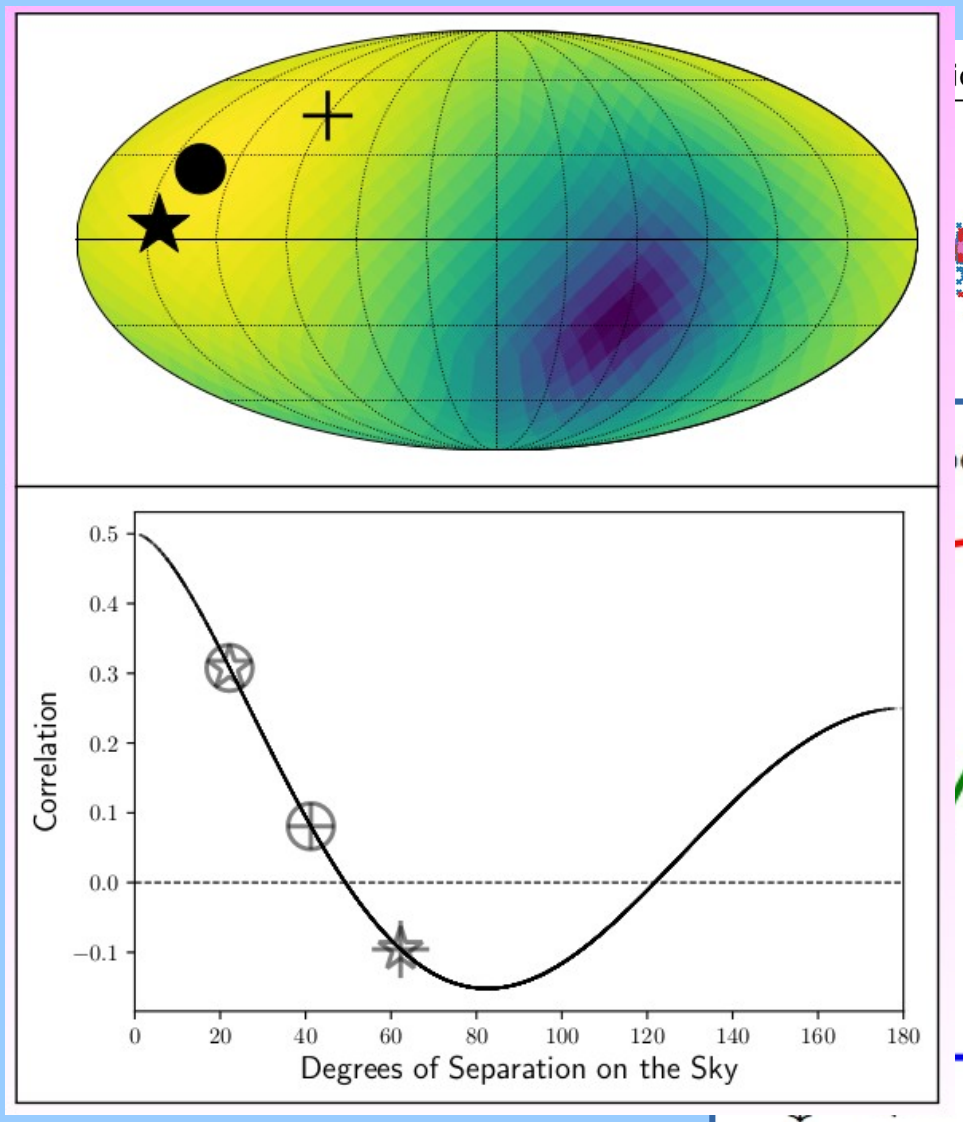
Courtesy: D. Nice

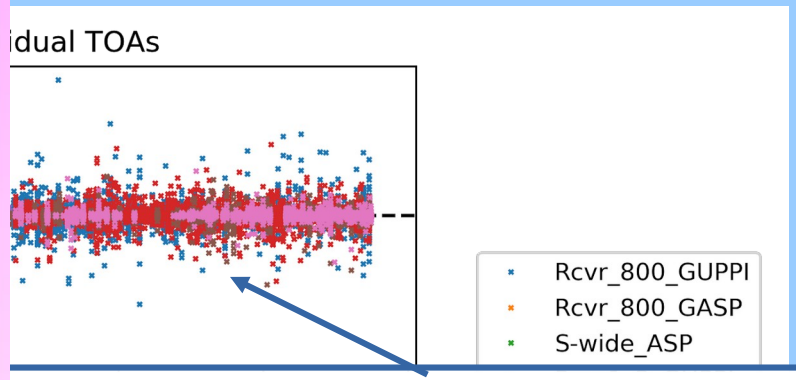
Residuals and GW Signatures

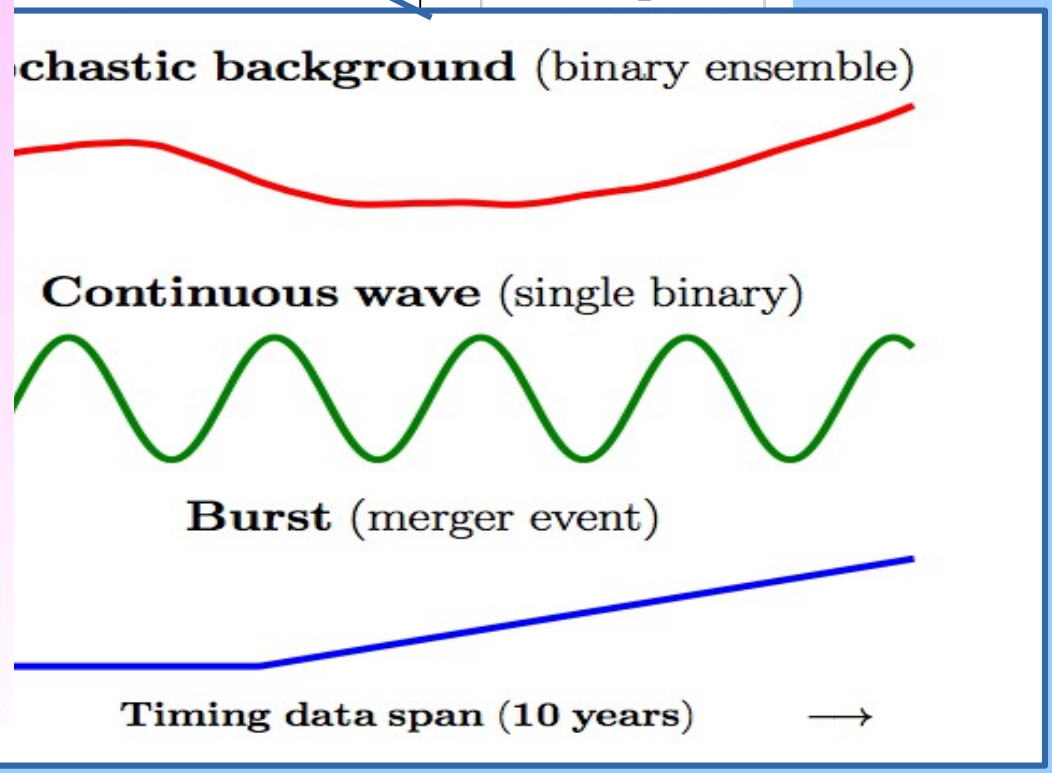


Courtesy: D. Nice, J. Cordes

Residuals and GW Signatures

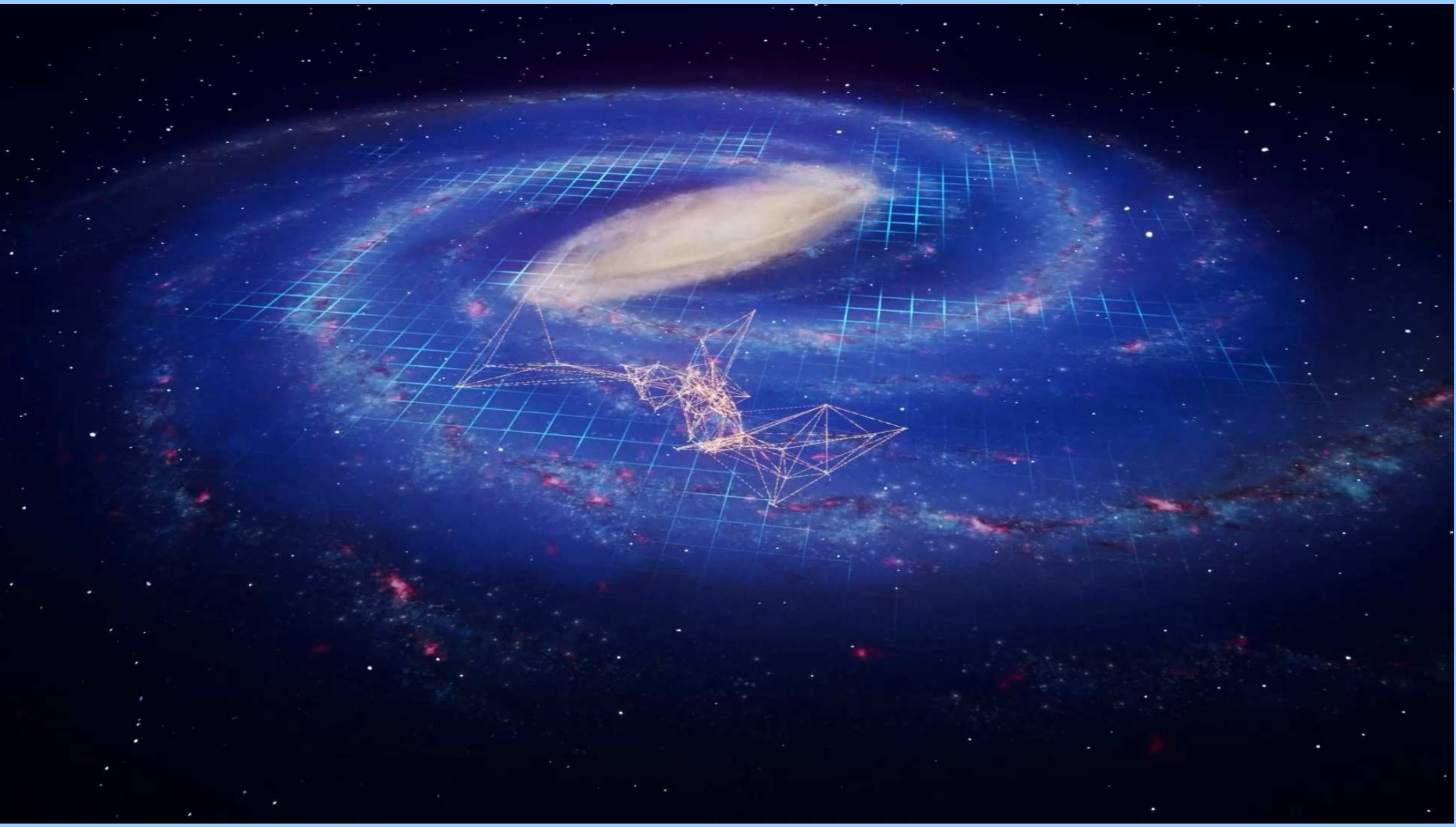






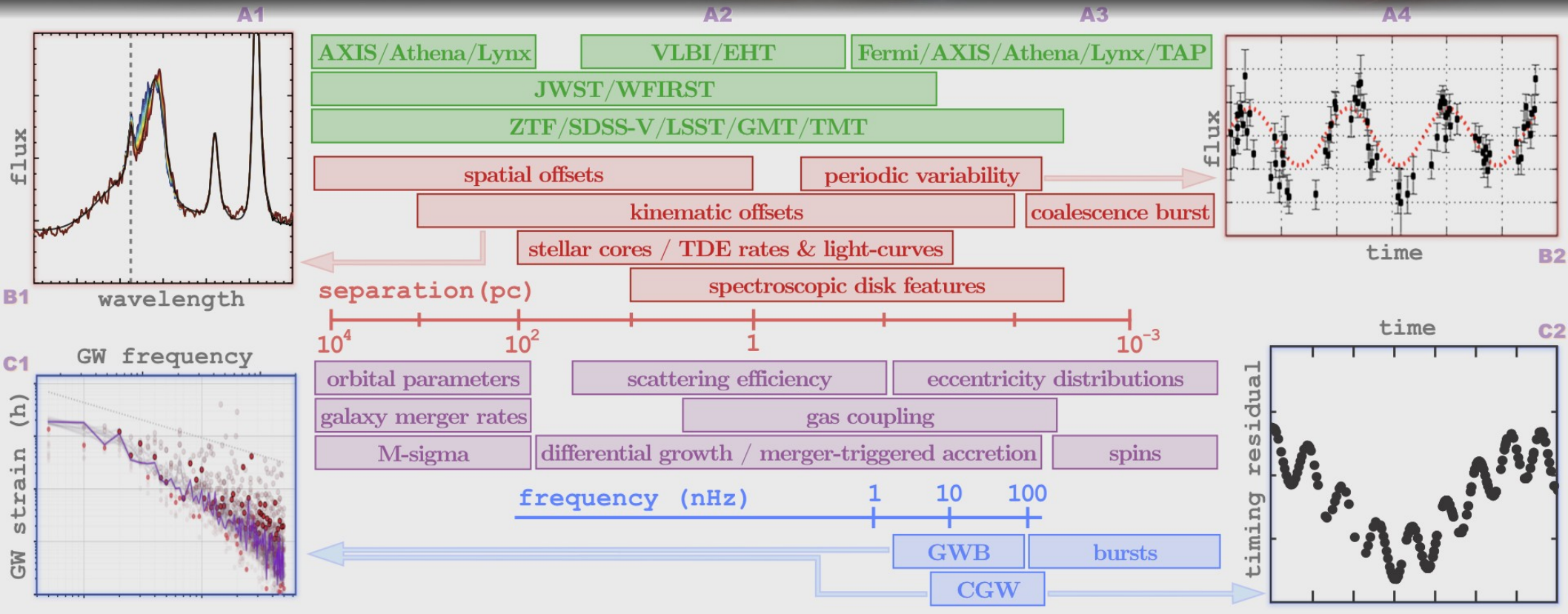
Courtesy: D. Nice, J. Cordes, J. Hazboun

The Pulsar Timing Array



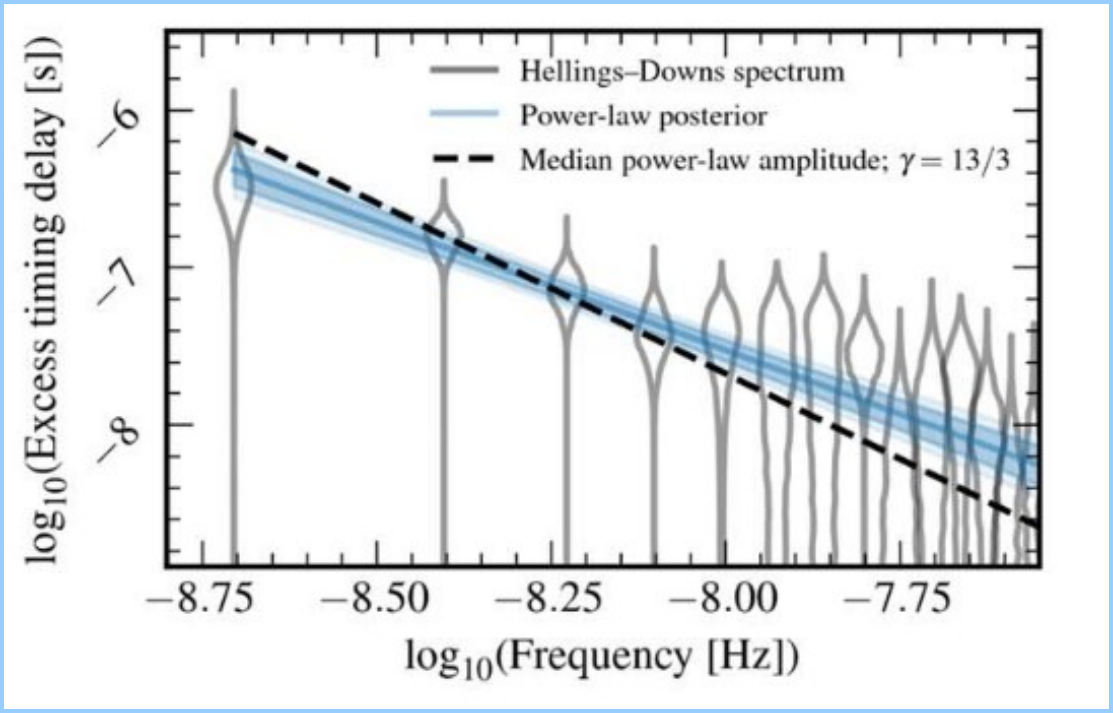
Animation by NSF/Onyx Lee

Multimessenger Science



Modified from Kelley et al. 2019

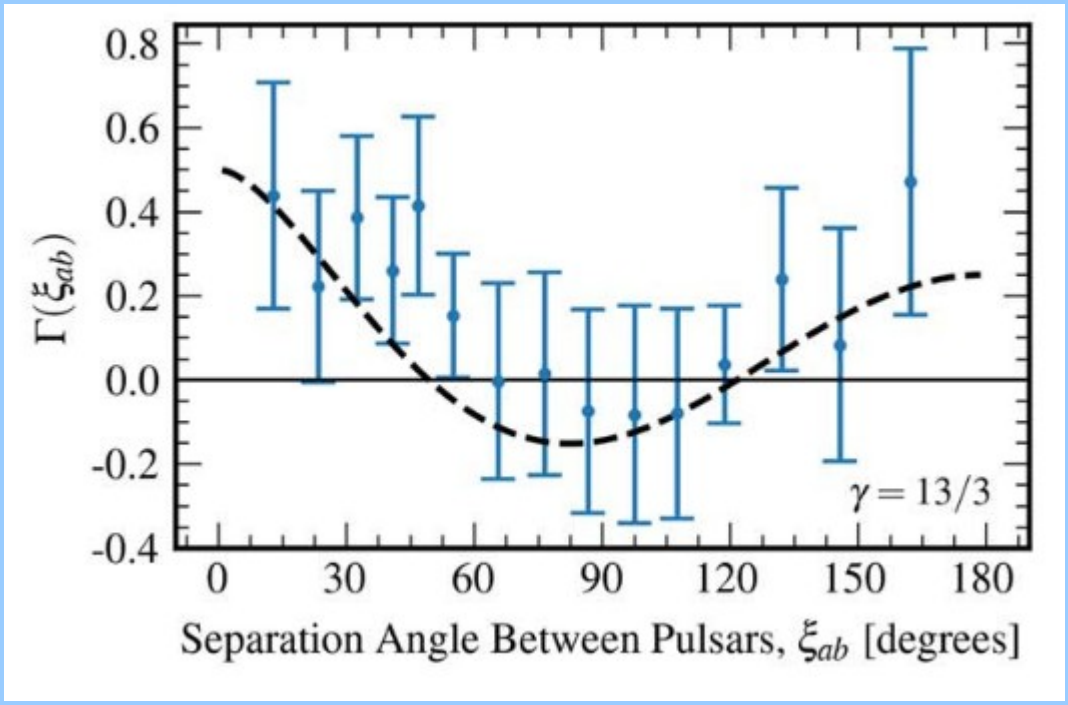
15-Year Data Set GWB Analysis



BF~10^{12} for Common Process

Agazie et al 2023

15-Year Data Set GWB Analysis



BF~10^{12} for Common Process,

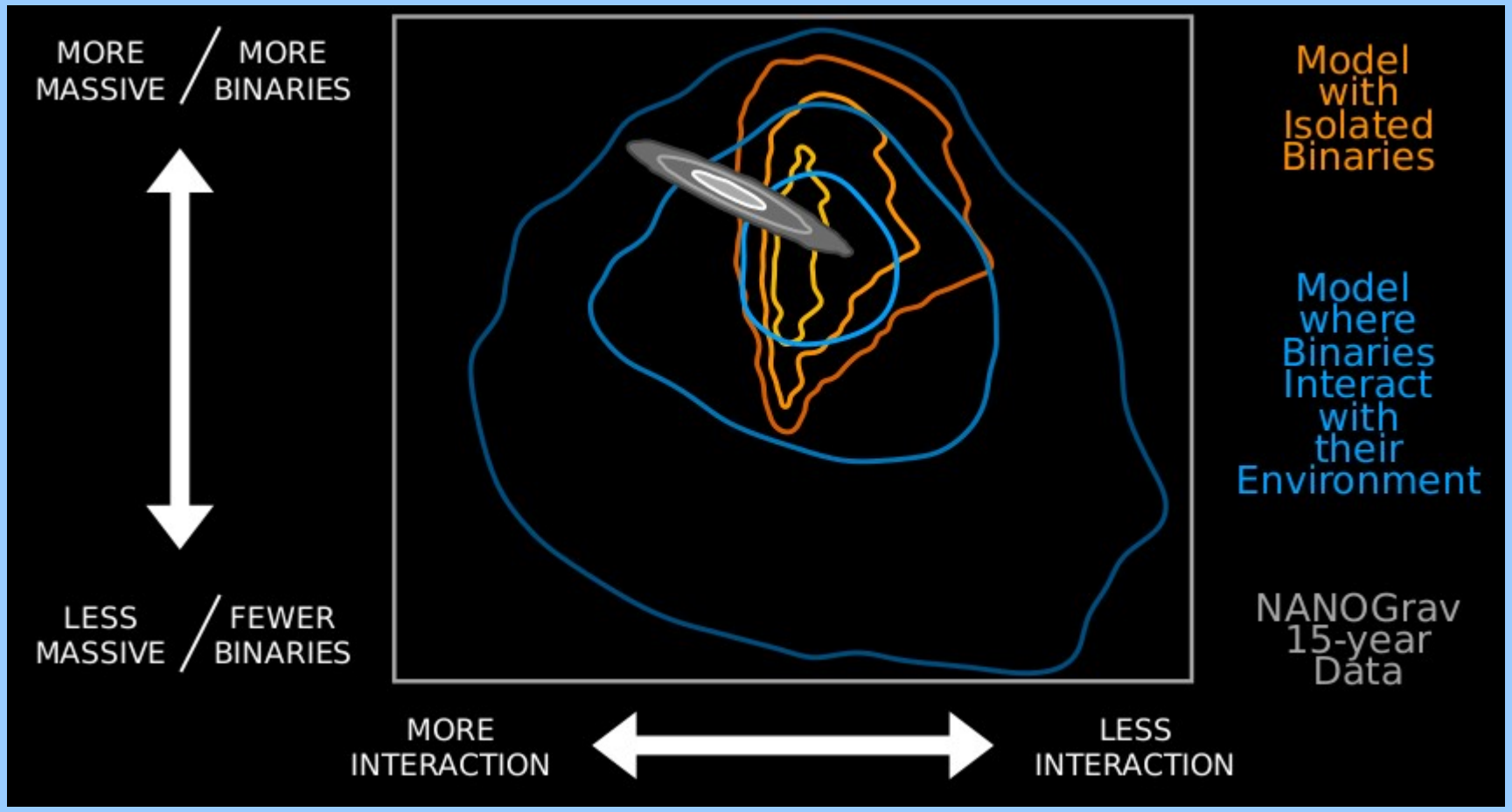
BF~200-1000 for Hellings-Downs

Null Distribution Tests

$p = 10^{-3} - 5\times10^{-5}$ (3-4σ)

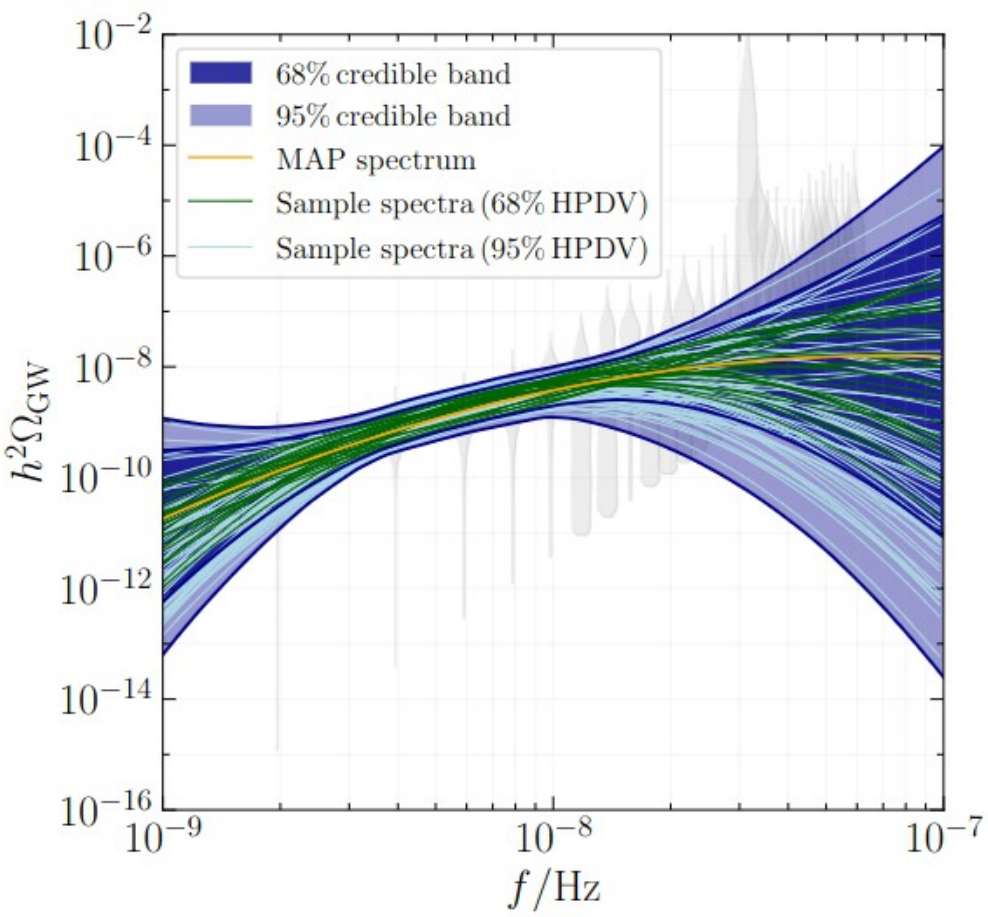
Agazie et al 2023

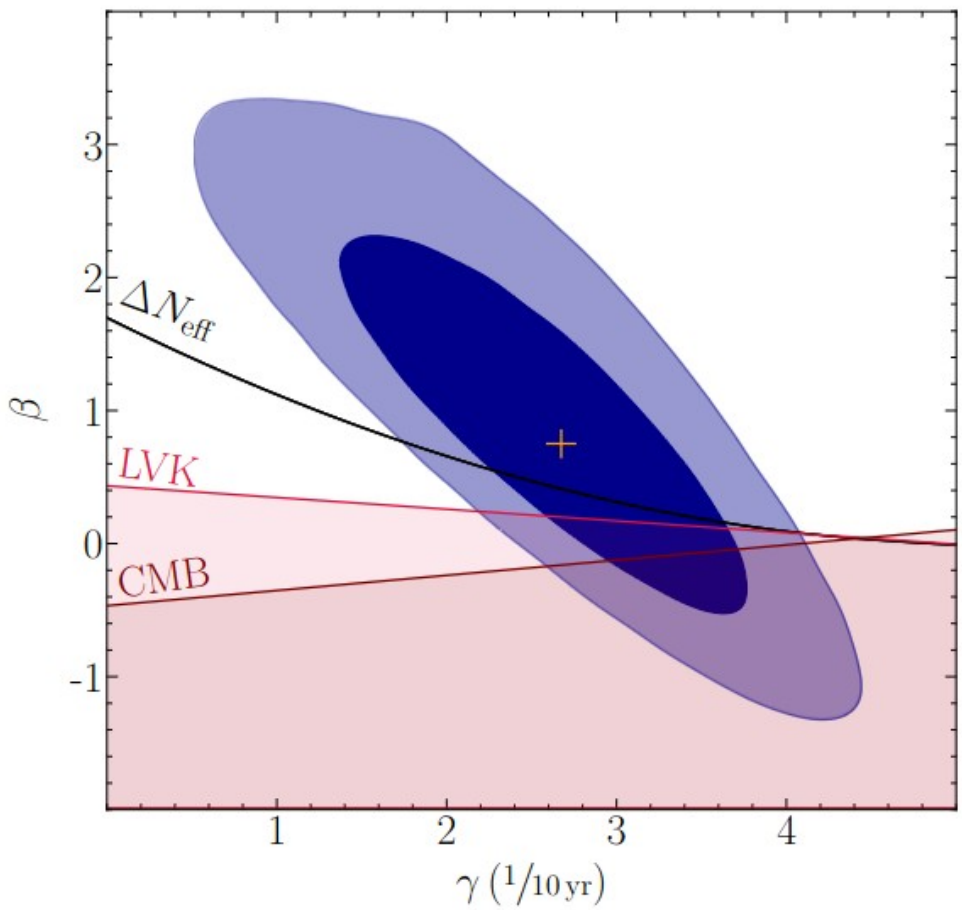
Astrophysics: Supermassive Black Hole Binaries



Modified from Agazie et al 2023

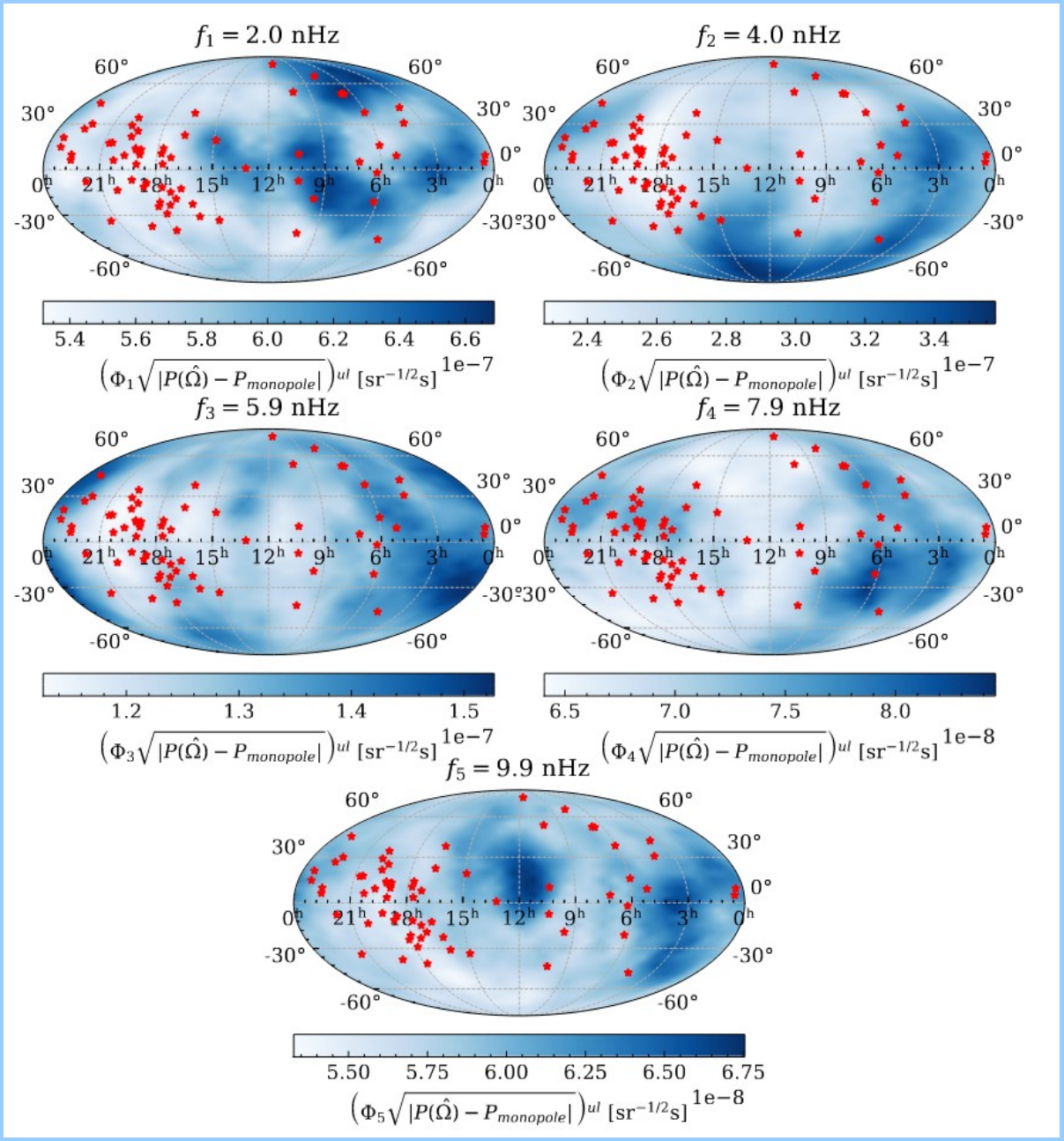
New Physics: Running of the Spectral Index





Agazie et al. submitted

Mapping the Low-Frequency Gravitational Wave Universe

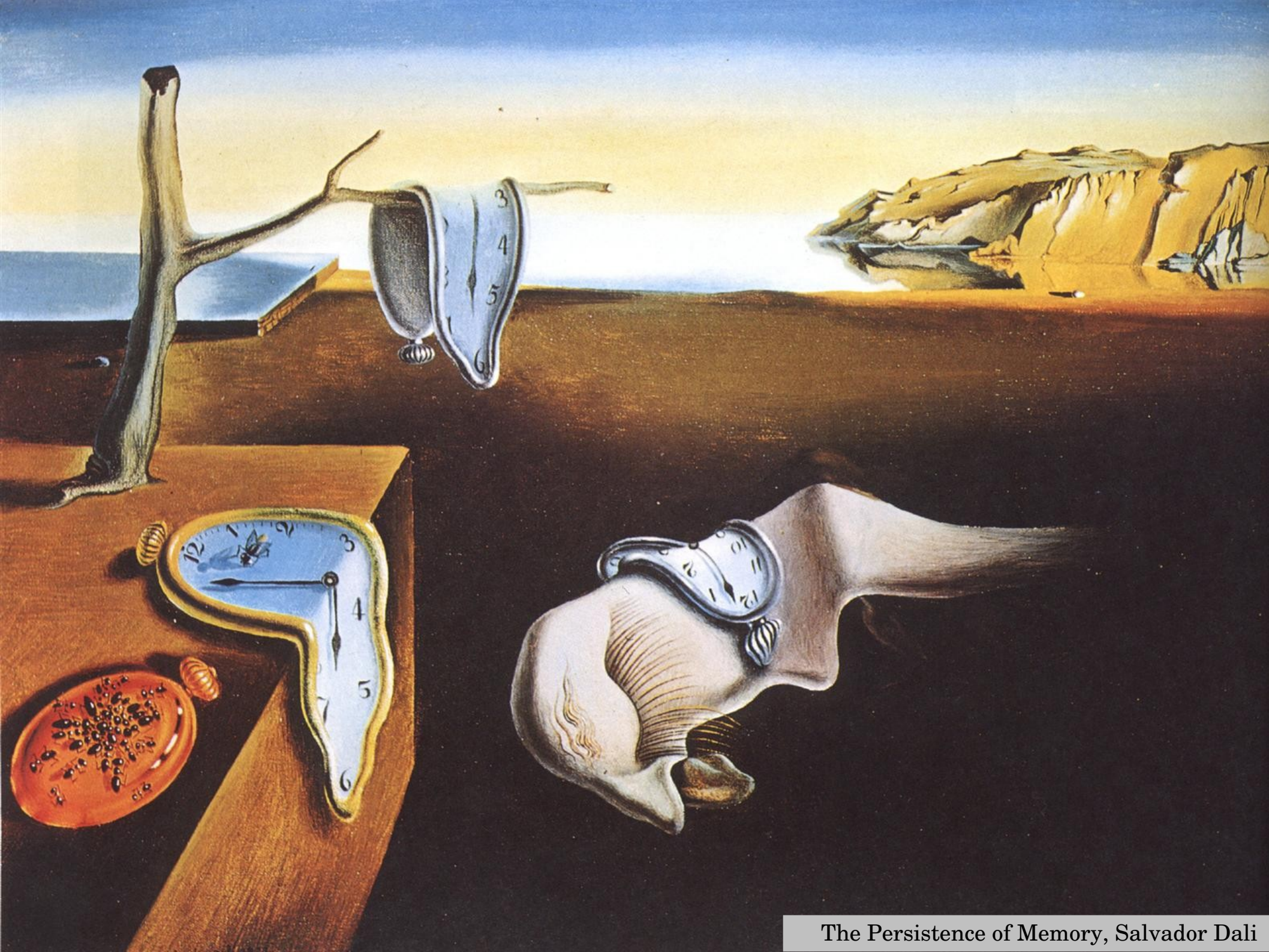


Agazie et al 2023

Future Facilities

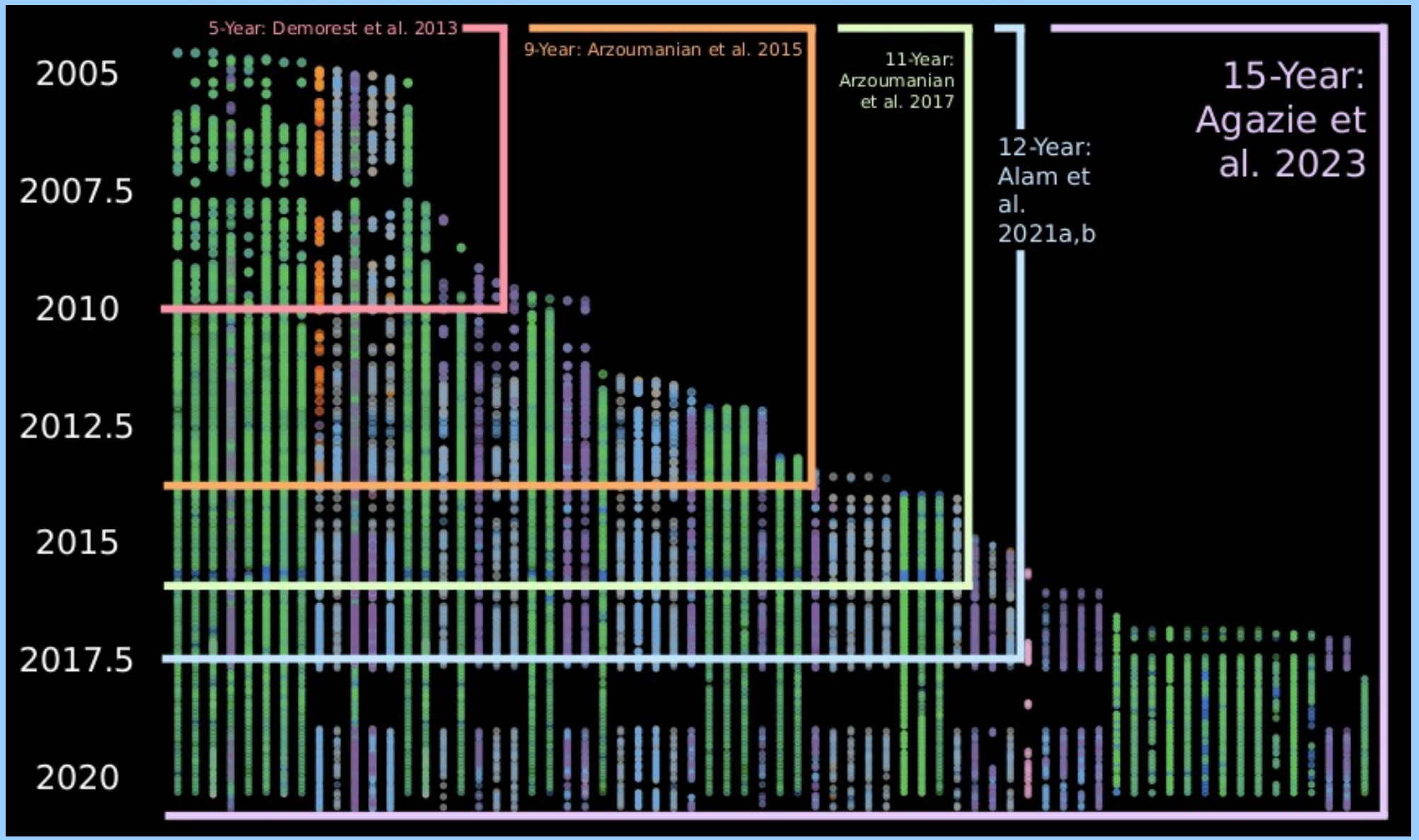
Top: NSF/AUI/NRAO, Bottom: DSA-2000 / C. Carter

Aurore Simonnet / NANOGrav



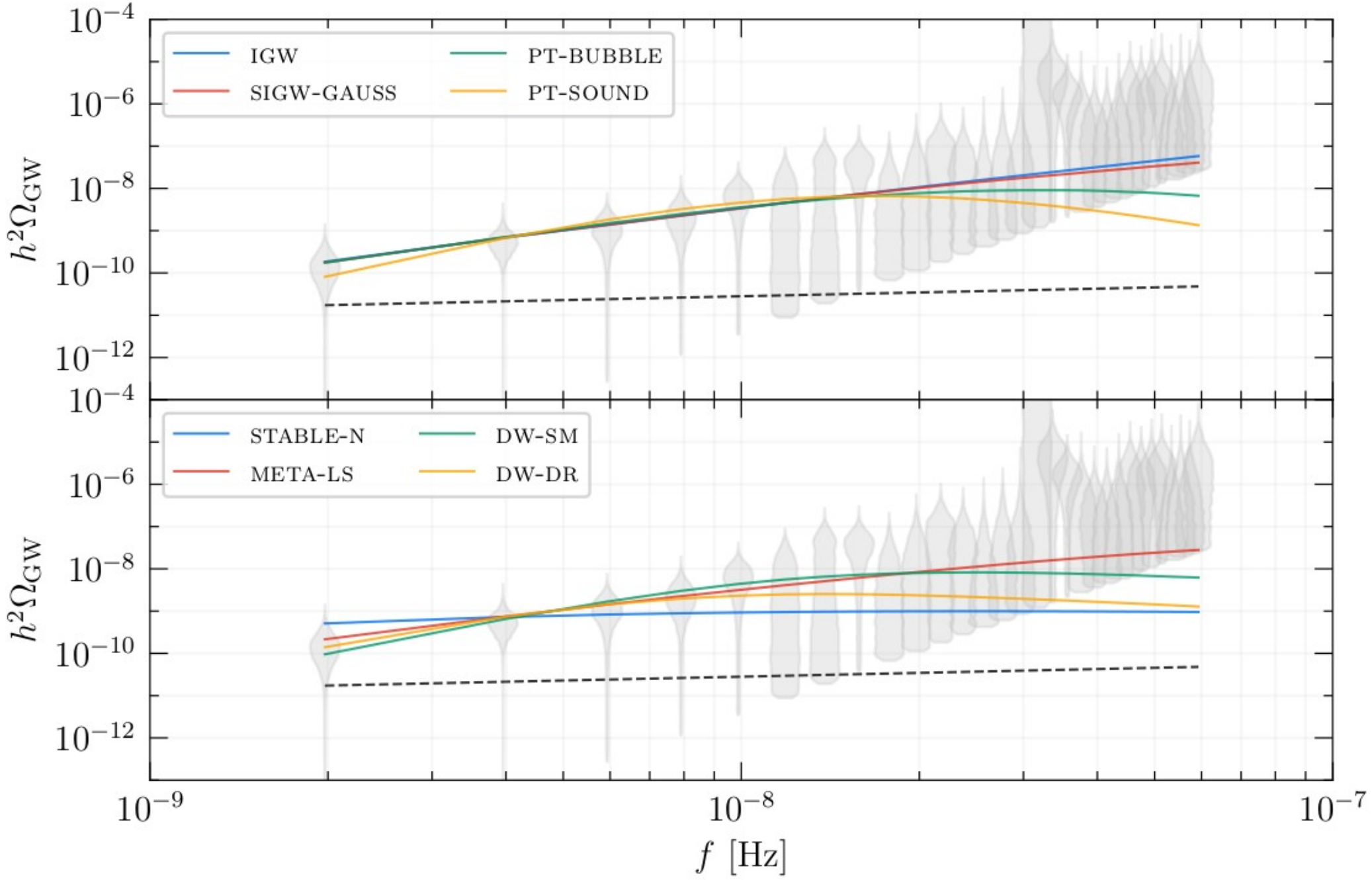
The Persistence of Memory, Salvador Dali

The Datasets



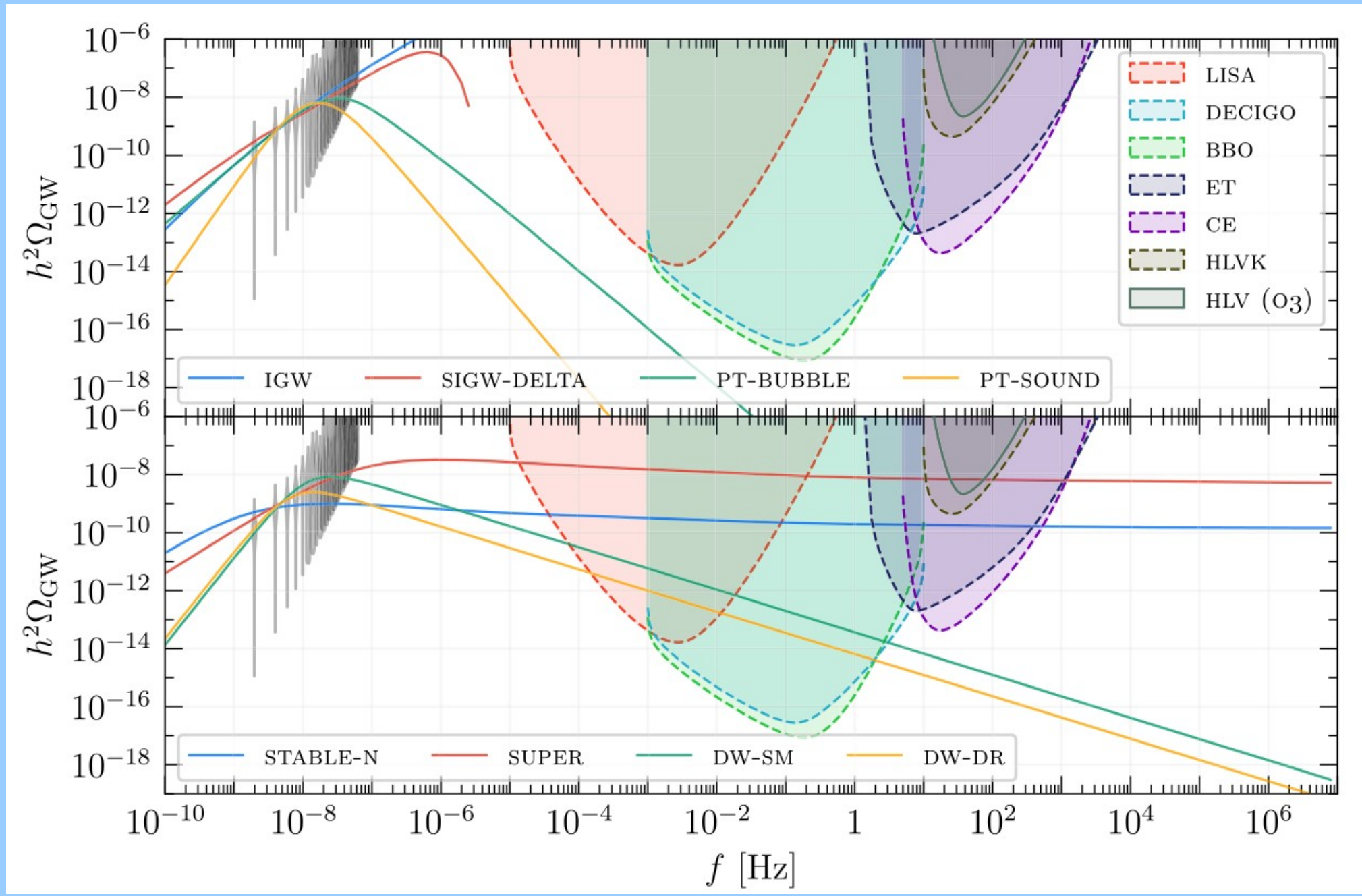
Courtesy: T. Cromartie, E .Ferrara

Astrophysics: New Physics



Afzal et al 2023

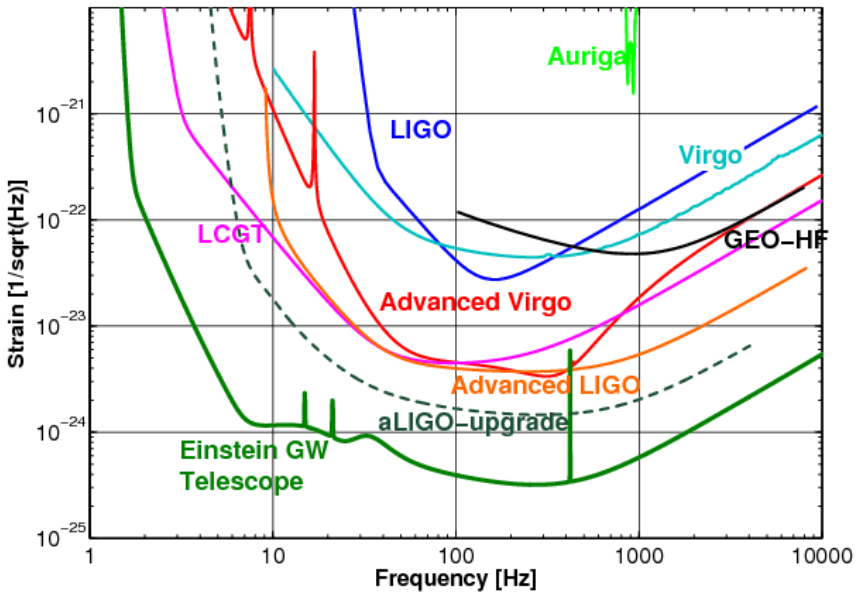
Astrophysics: New Physics



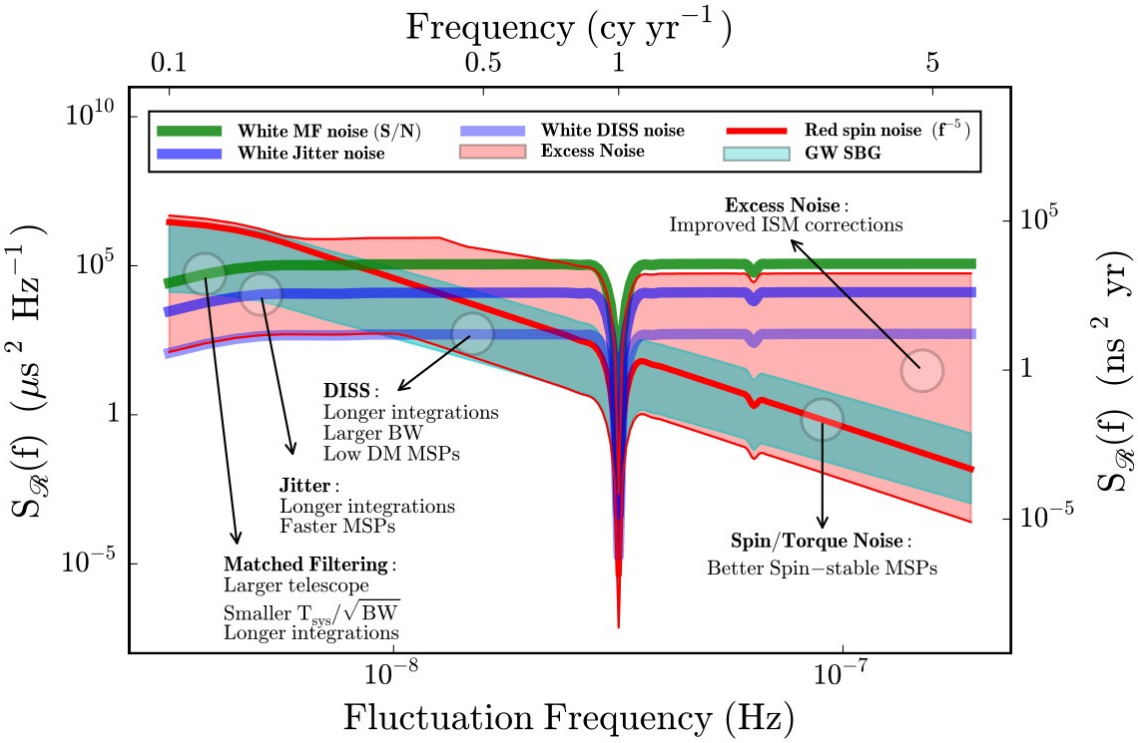
Afzal et al 2023

The Next Generation

LIGO → aLIGO



NANOGrav → "aNANOGrav"



L: Hild et al 2012

R: Courtesy J. Cordes