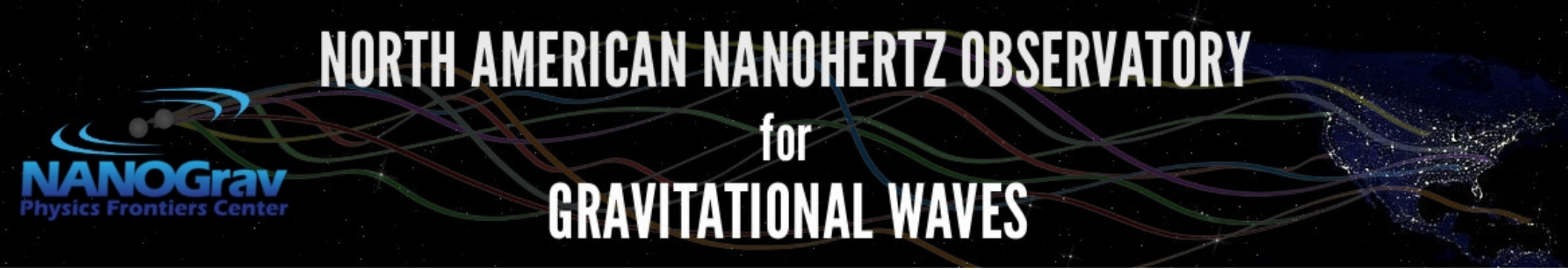


Celestial Clocks and Ripples in Spacetime

Dr. Michael T. Lam

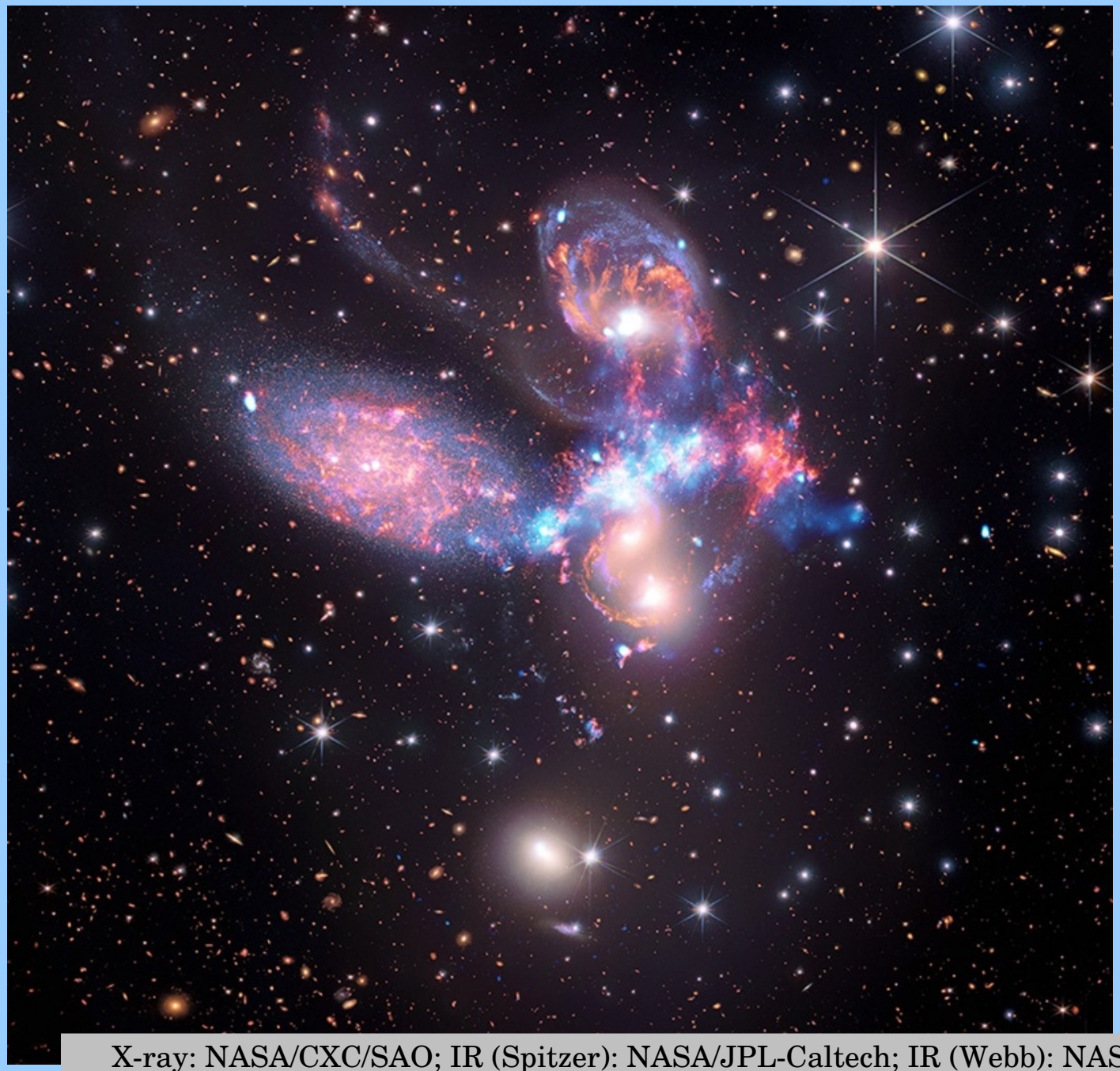
Ruckman Public Lecture – 21 Oct 2022

RIT | College of Science
Astrophysical Sciences and Technology

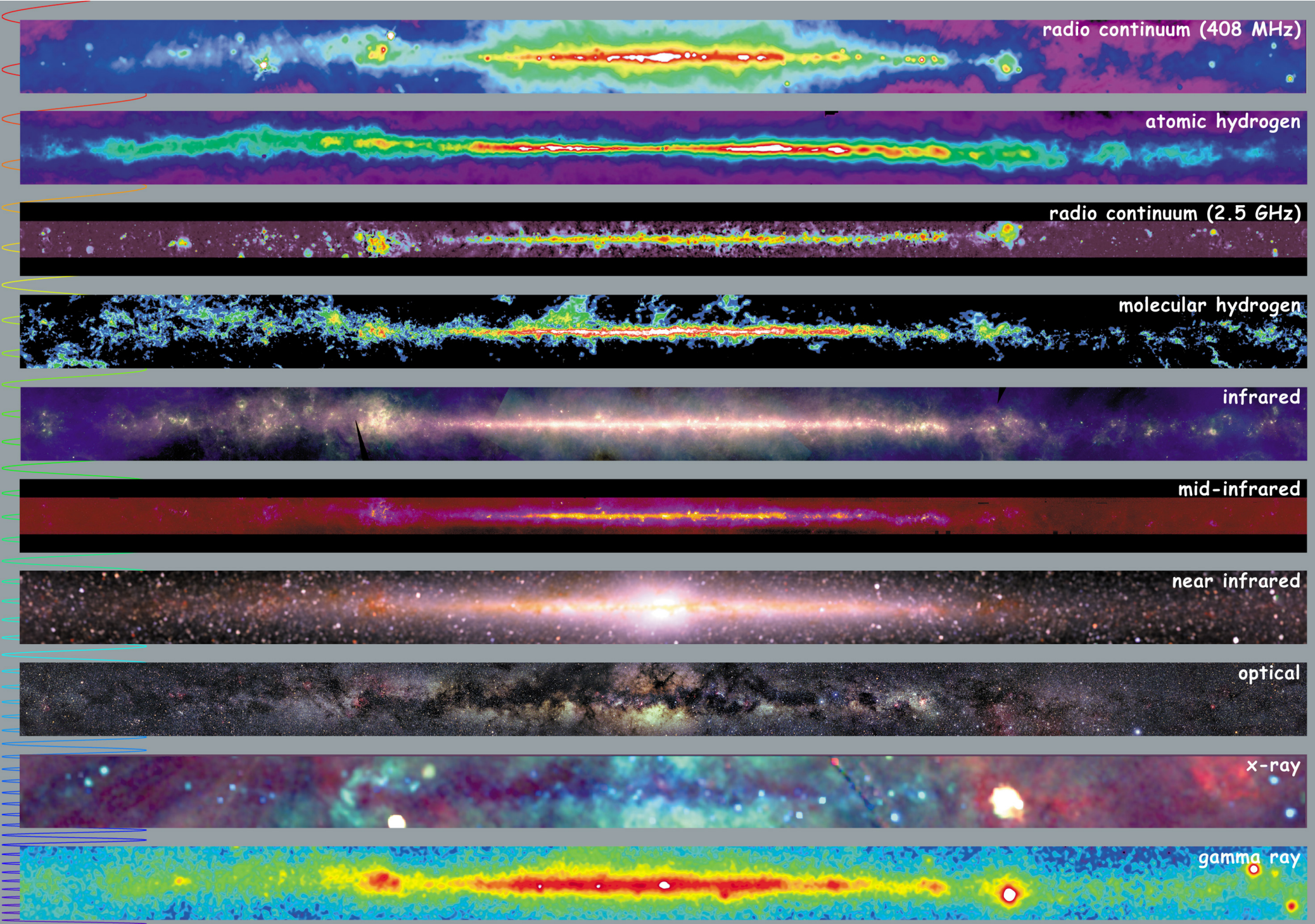
©Babak Tafreshi-TWAN

NRAO/AUI

Multiwavelength Combination



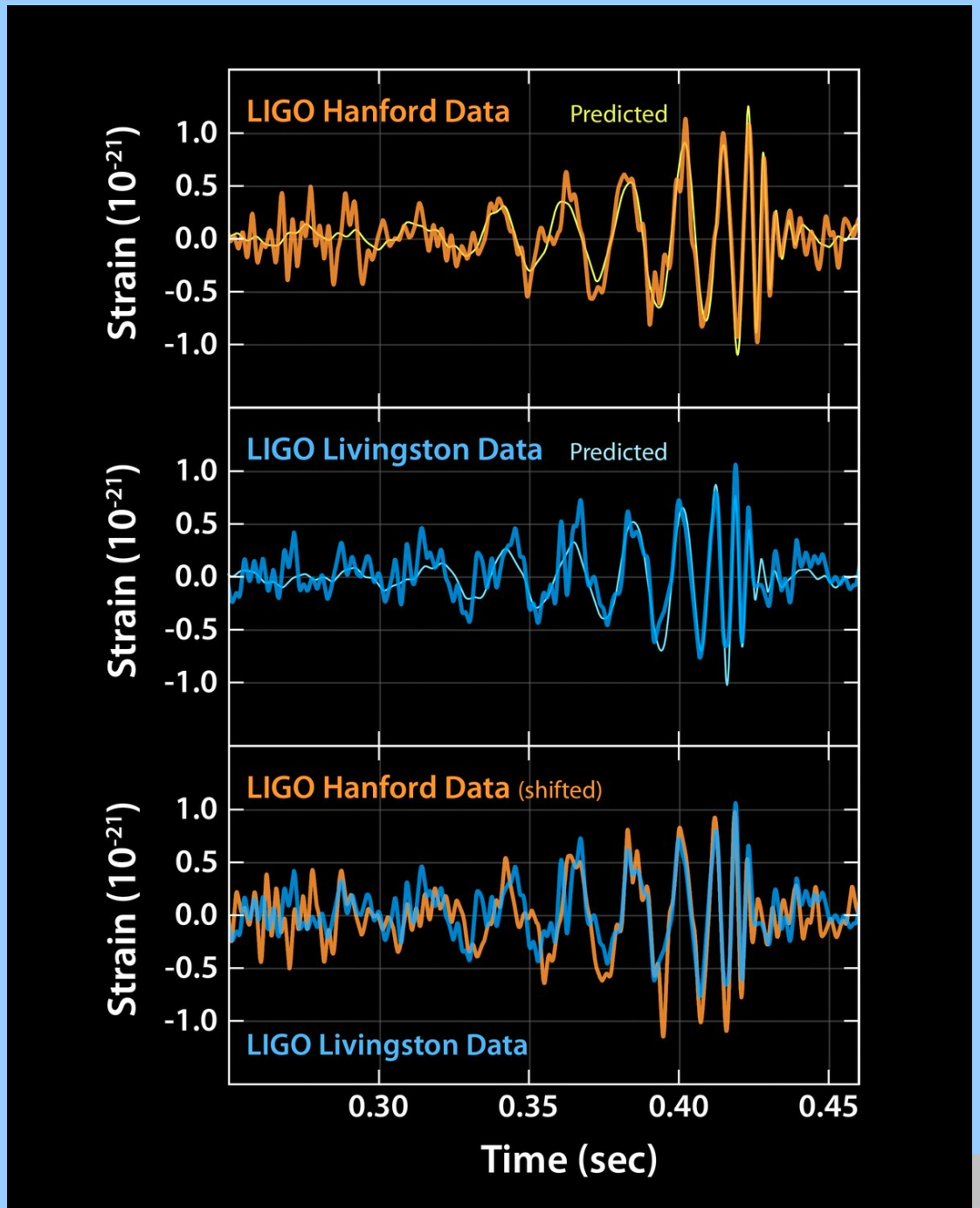
X-ray: NASA/CXC/SAO; IR (Spitzer): NASA/JPL-Caltech; IR (Webb): NASA/ESA/CSA/STScI



Multiwavelength Milky Way

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

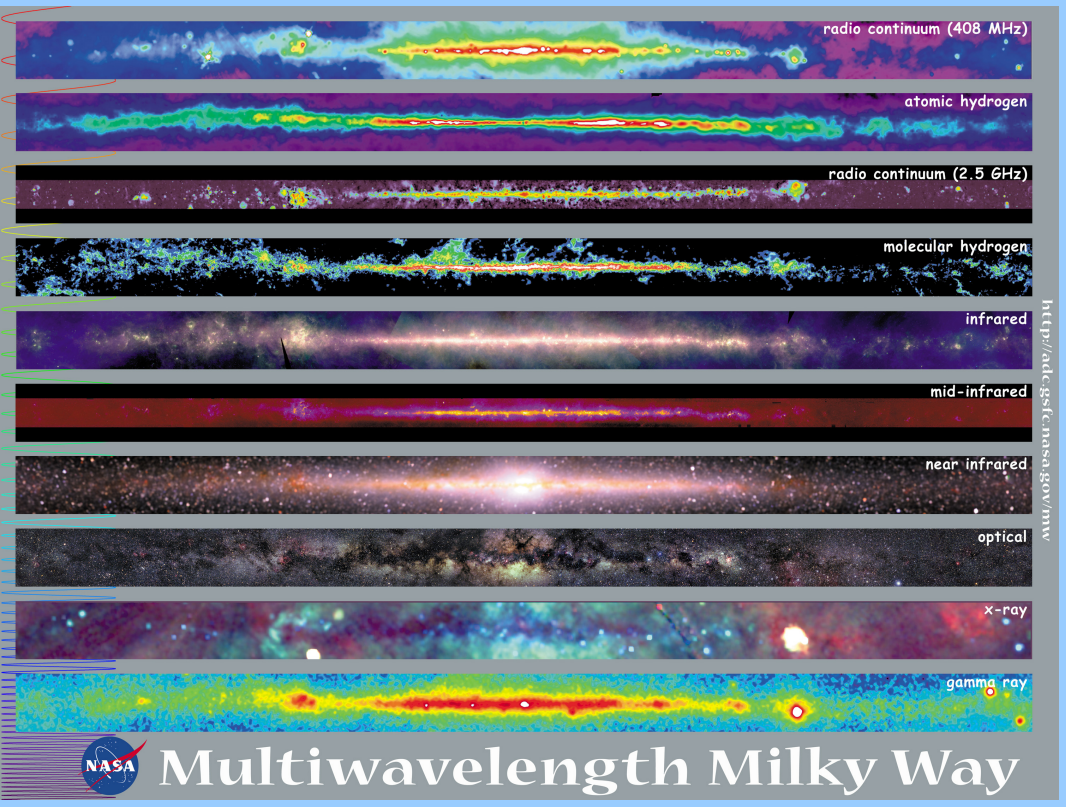
A New Window to the Universe



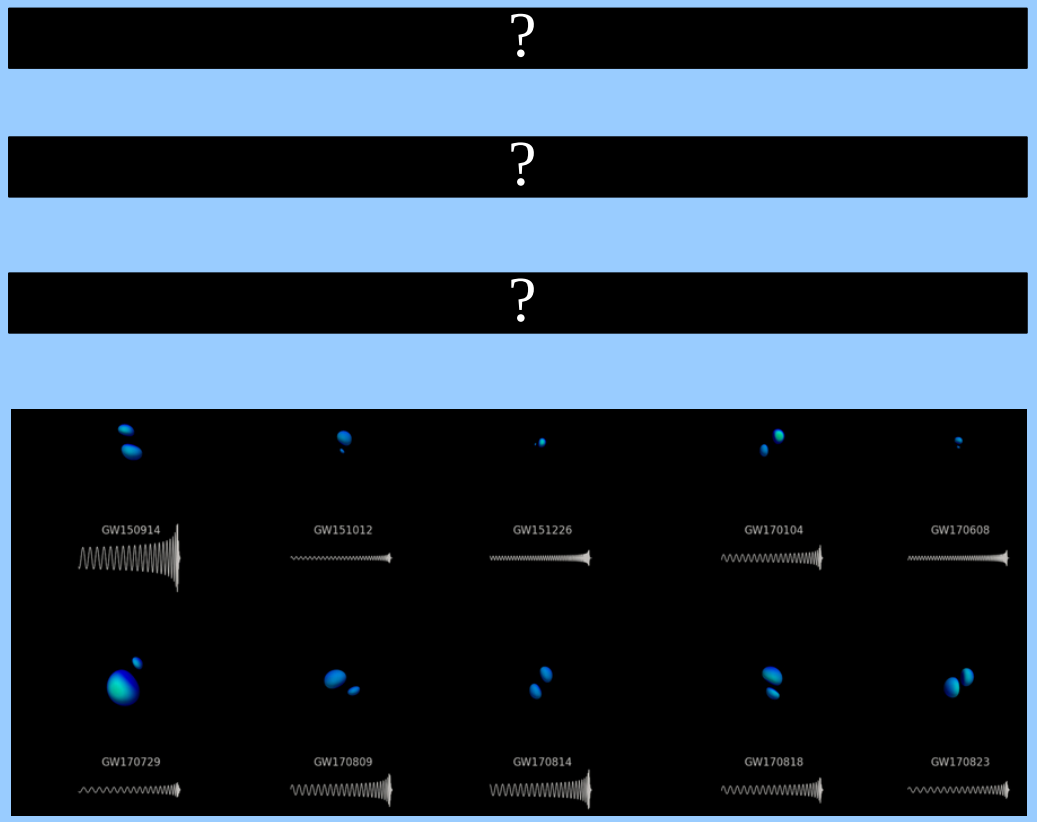
Caltech/MIT/LIGO Lab

Multimessenger Combination

Electromagnetic

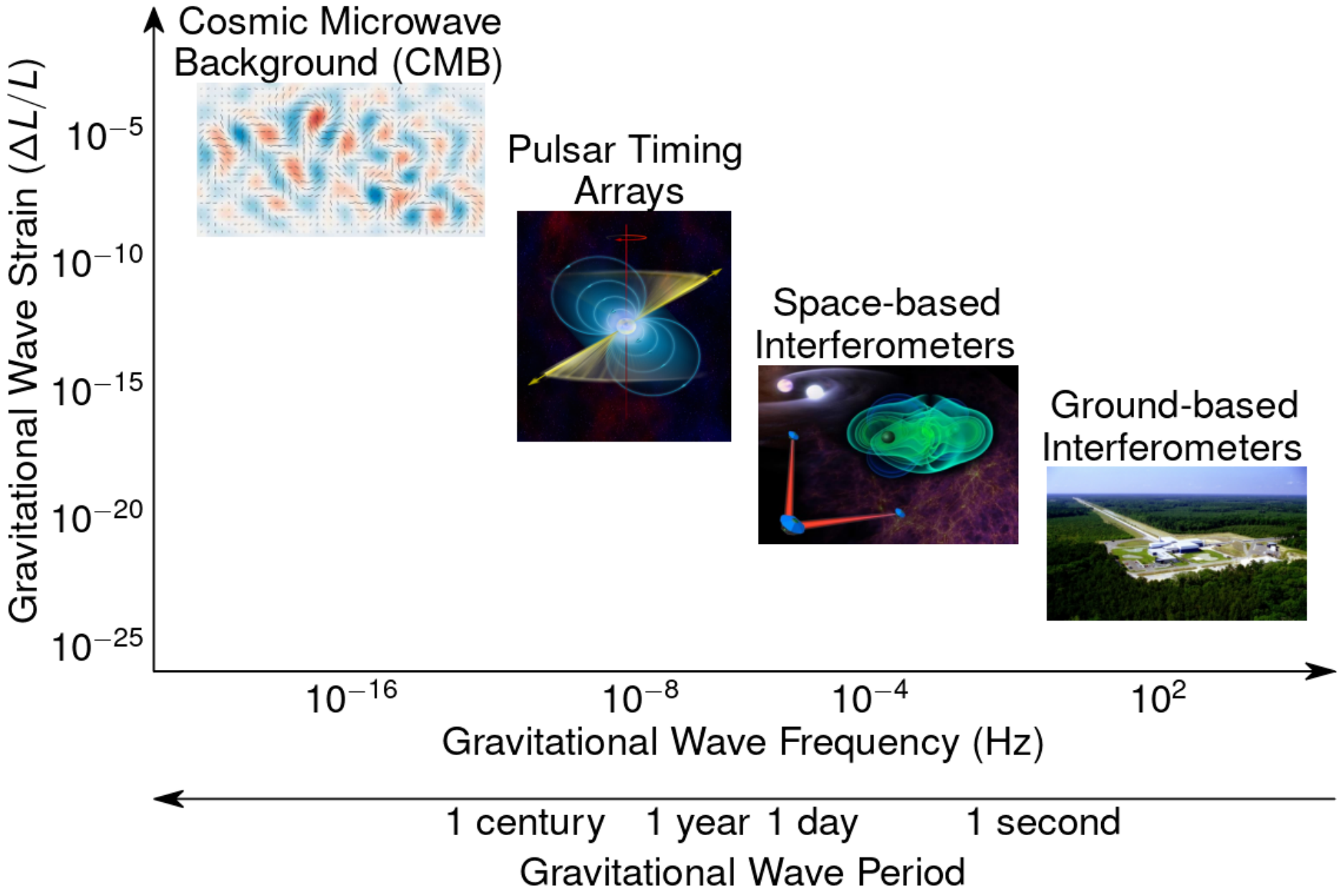


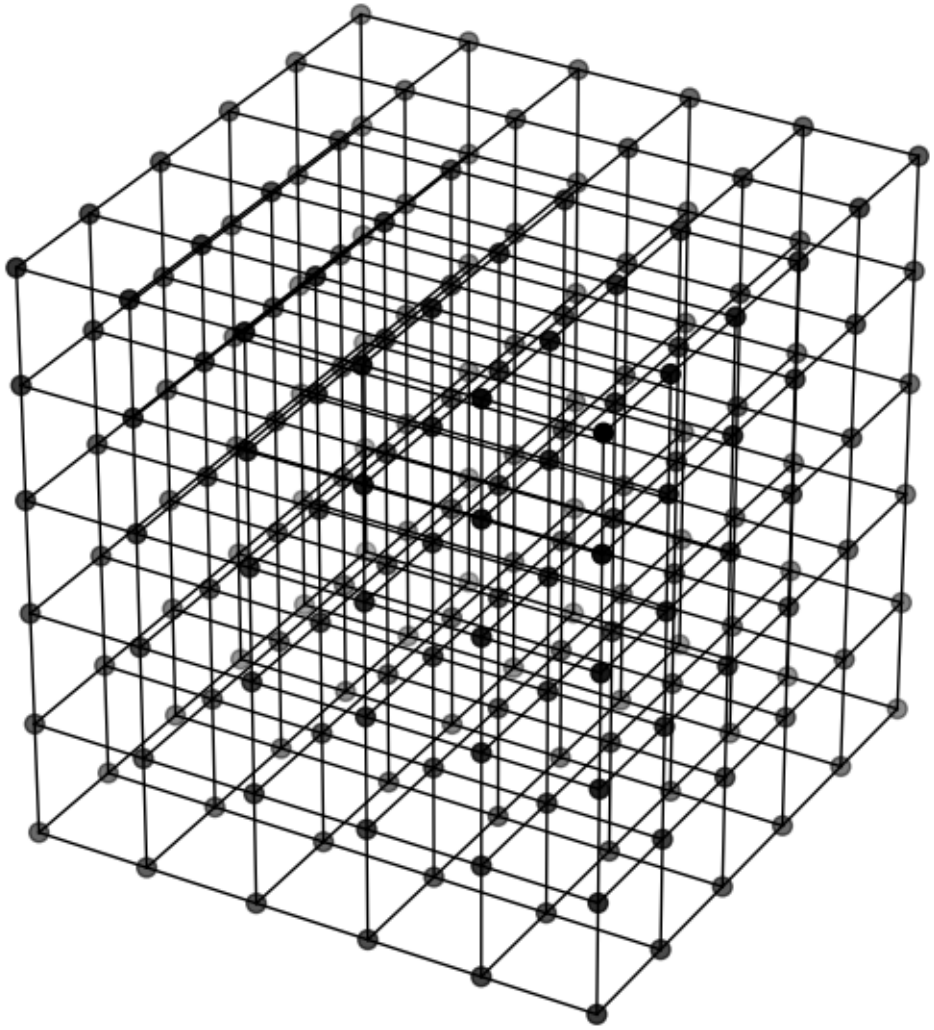
Gravitational

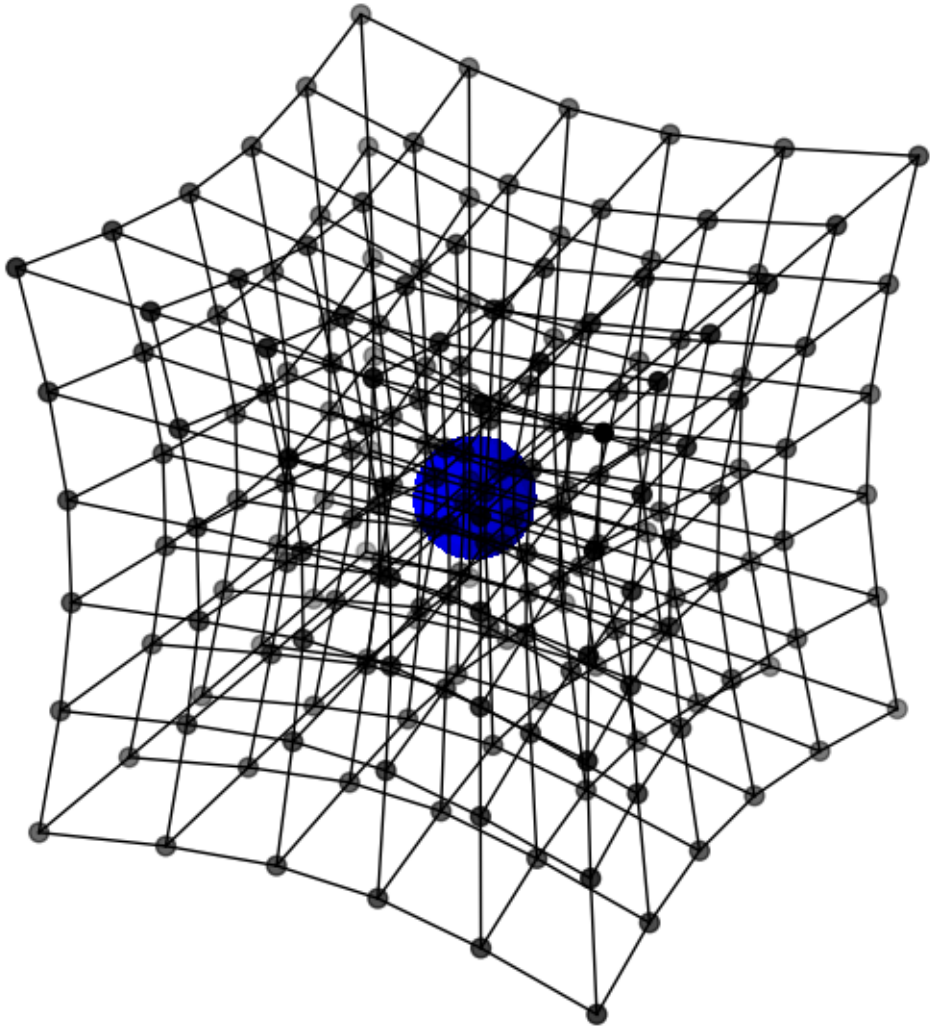


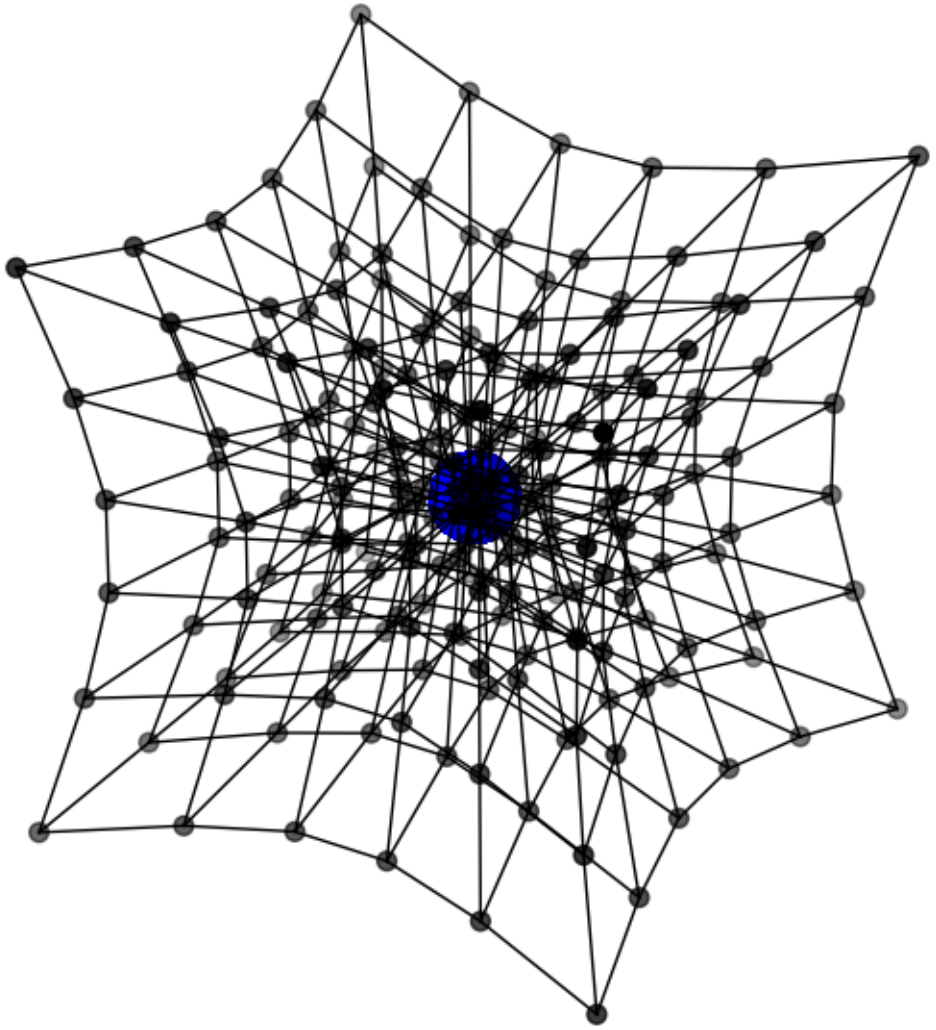
LIGO/Virgo Orrery, Teresita Ramirez/Geoffrey Lovelace/SXS Collaboration/LIGO-Virgo Collaboration

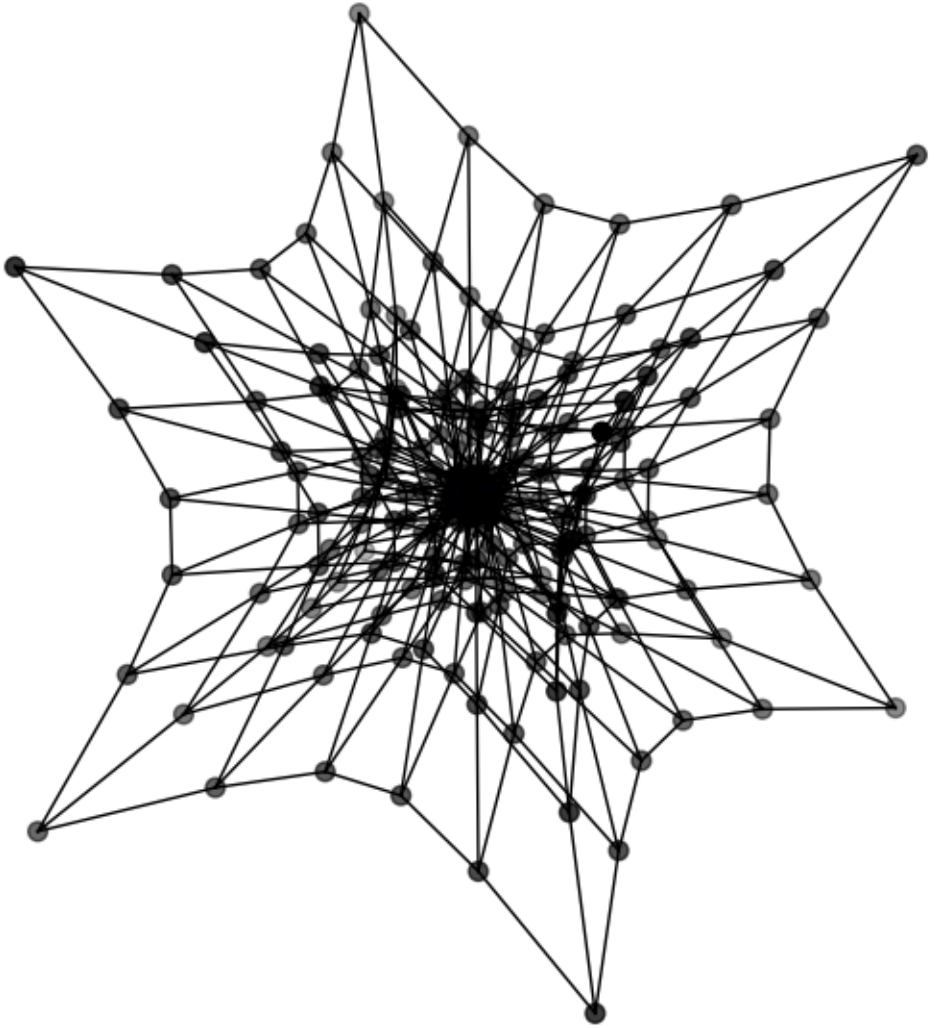
Gravitational Wave Spectrum

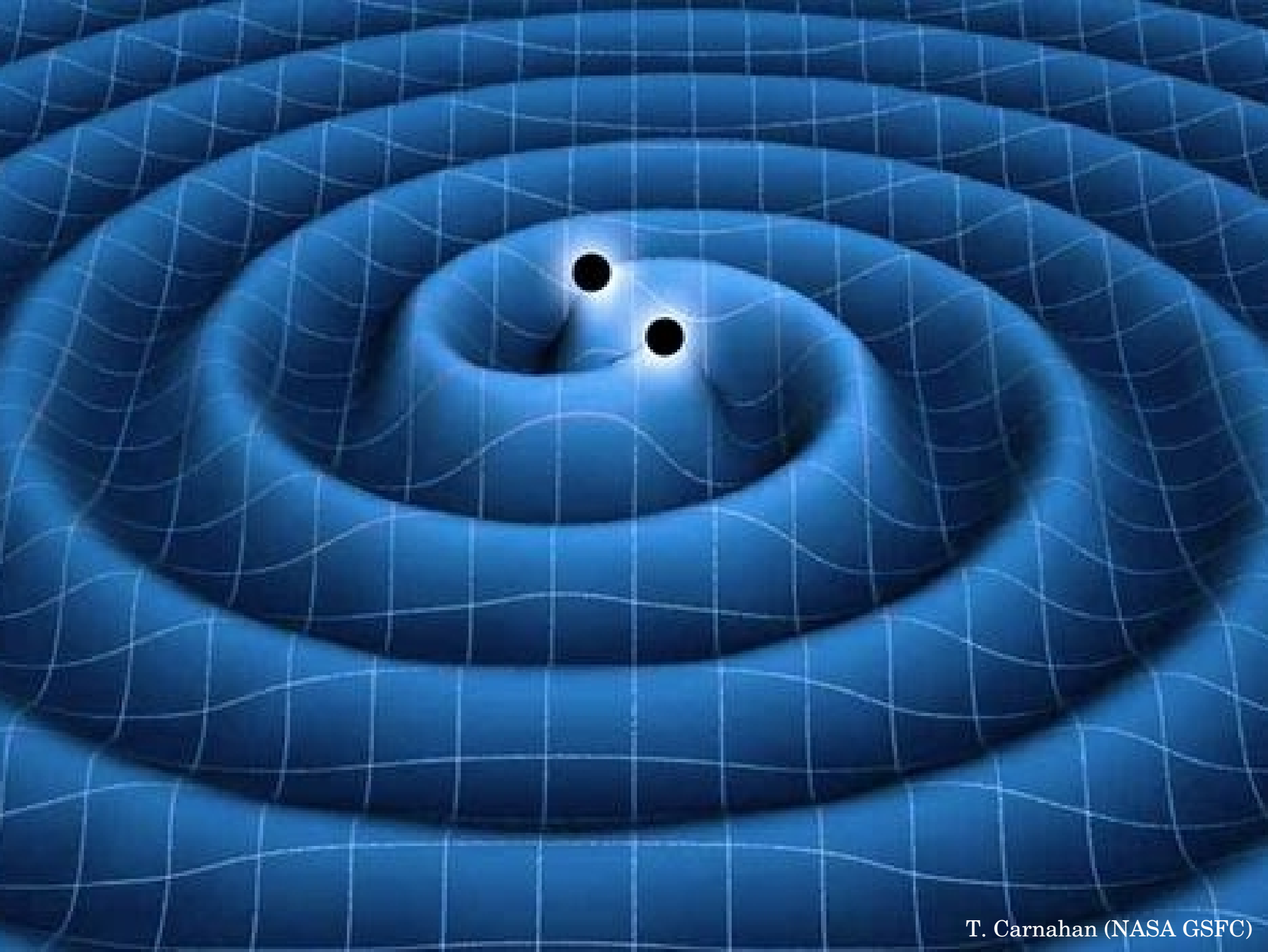




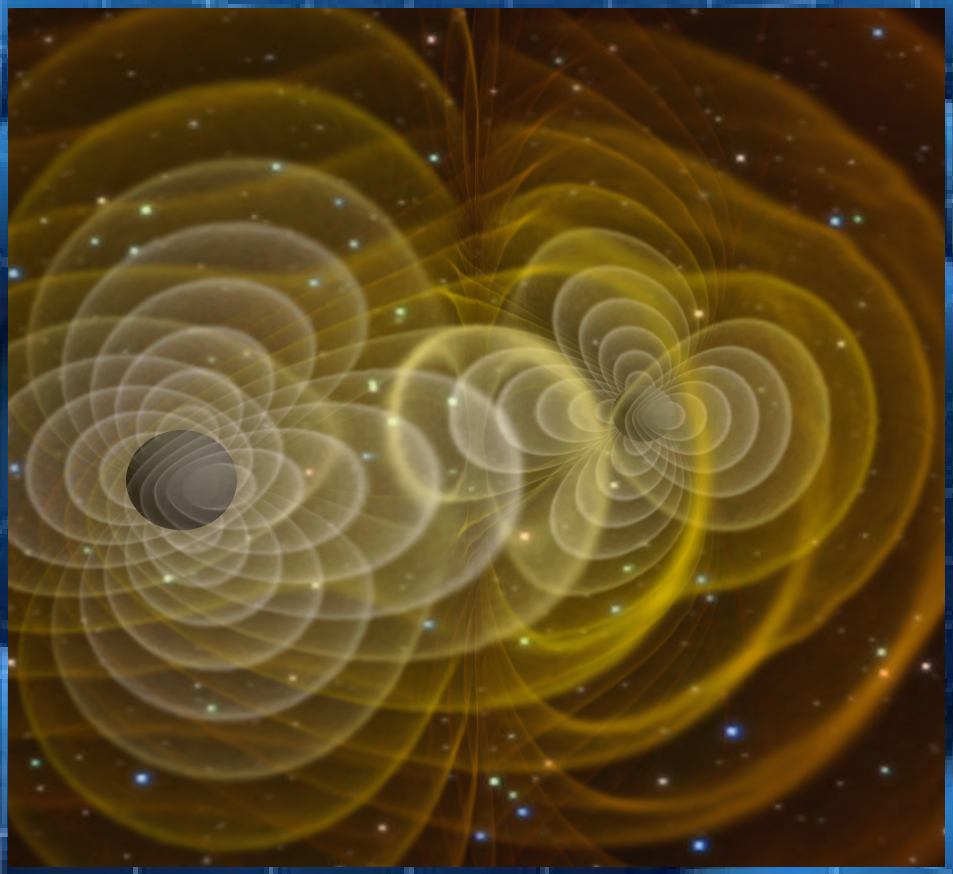






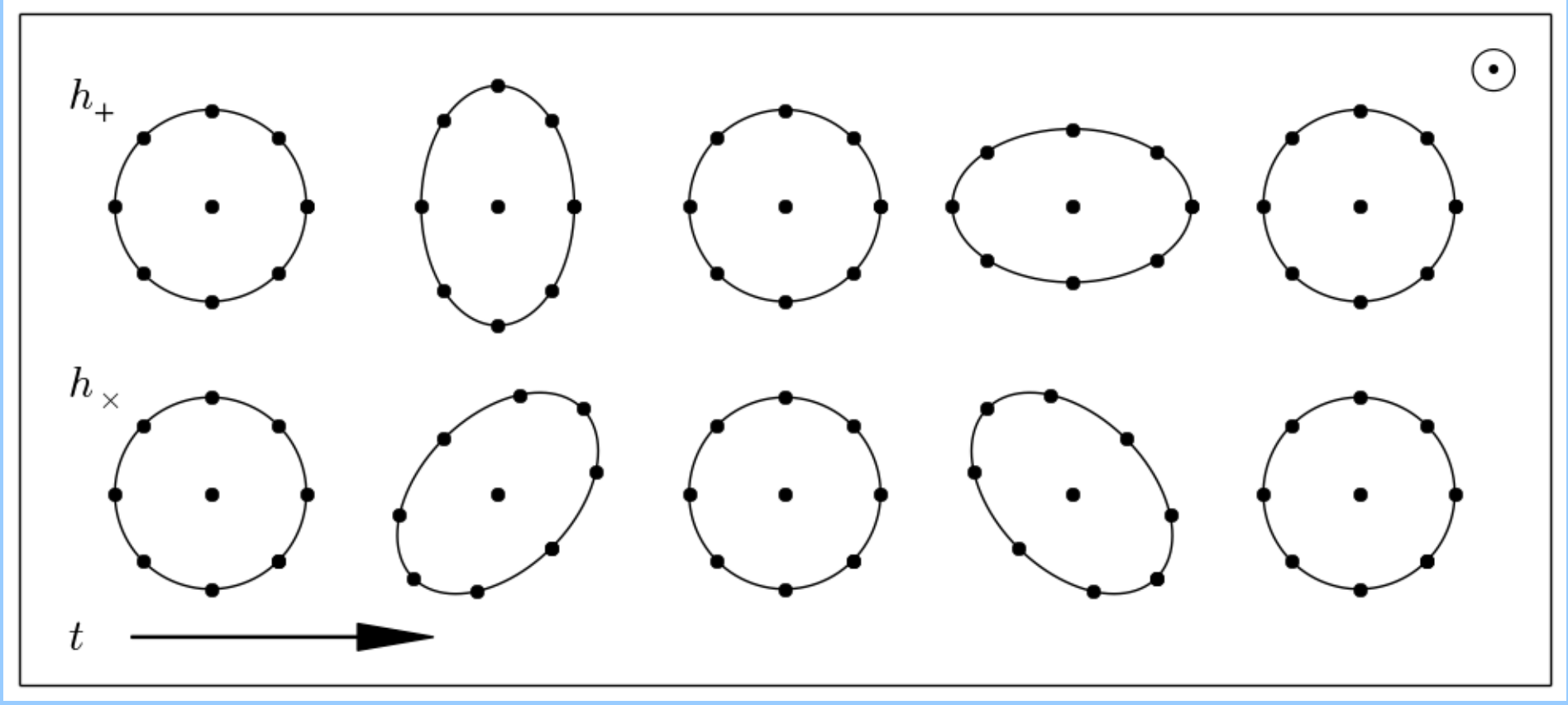


T. Carnahan (NASA GSFC)

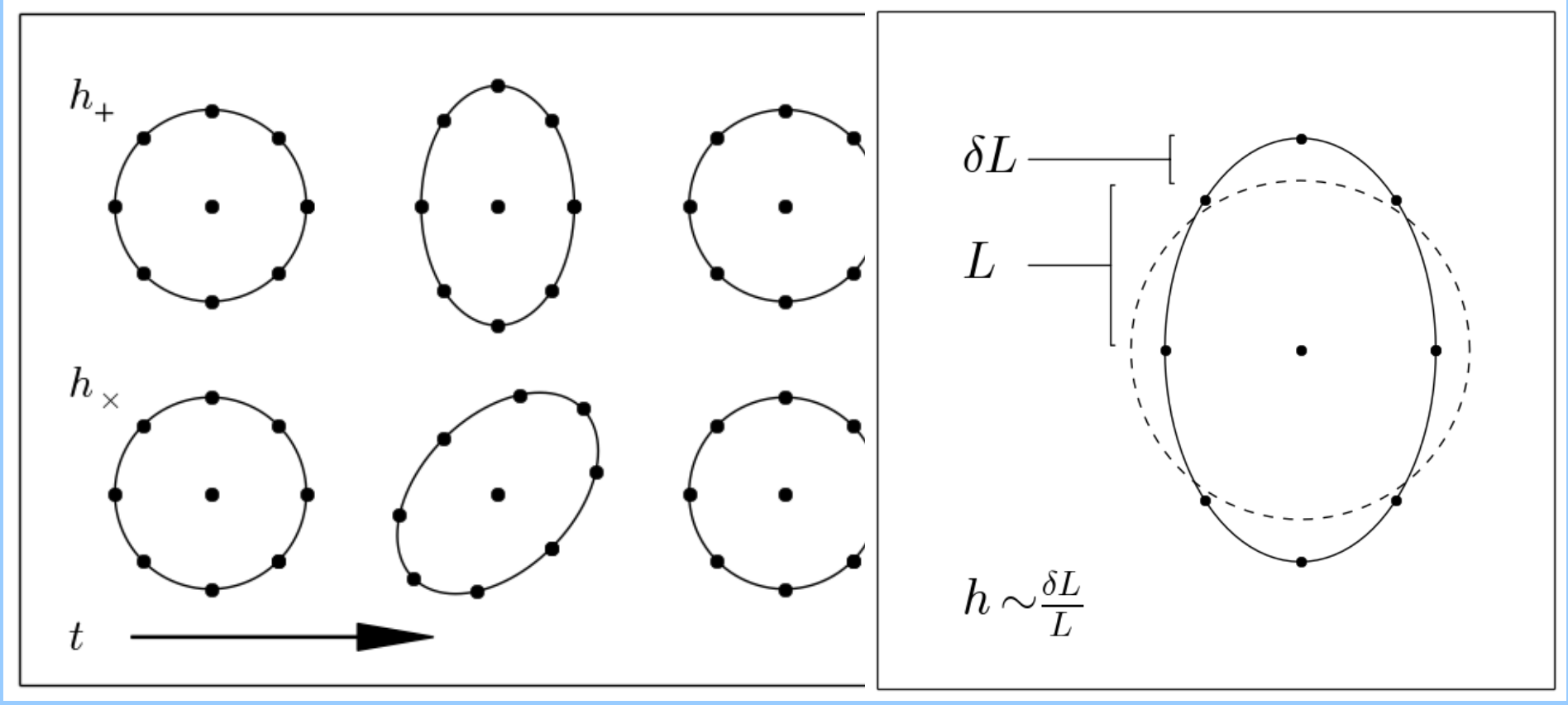


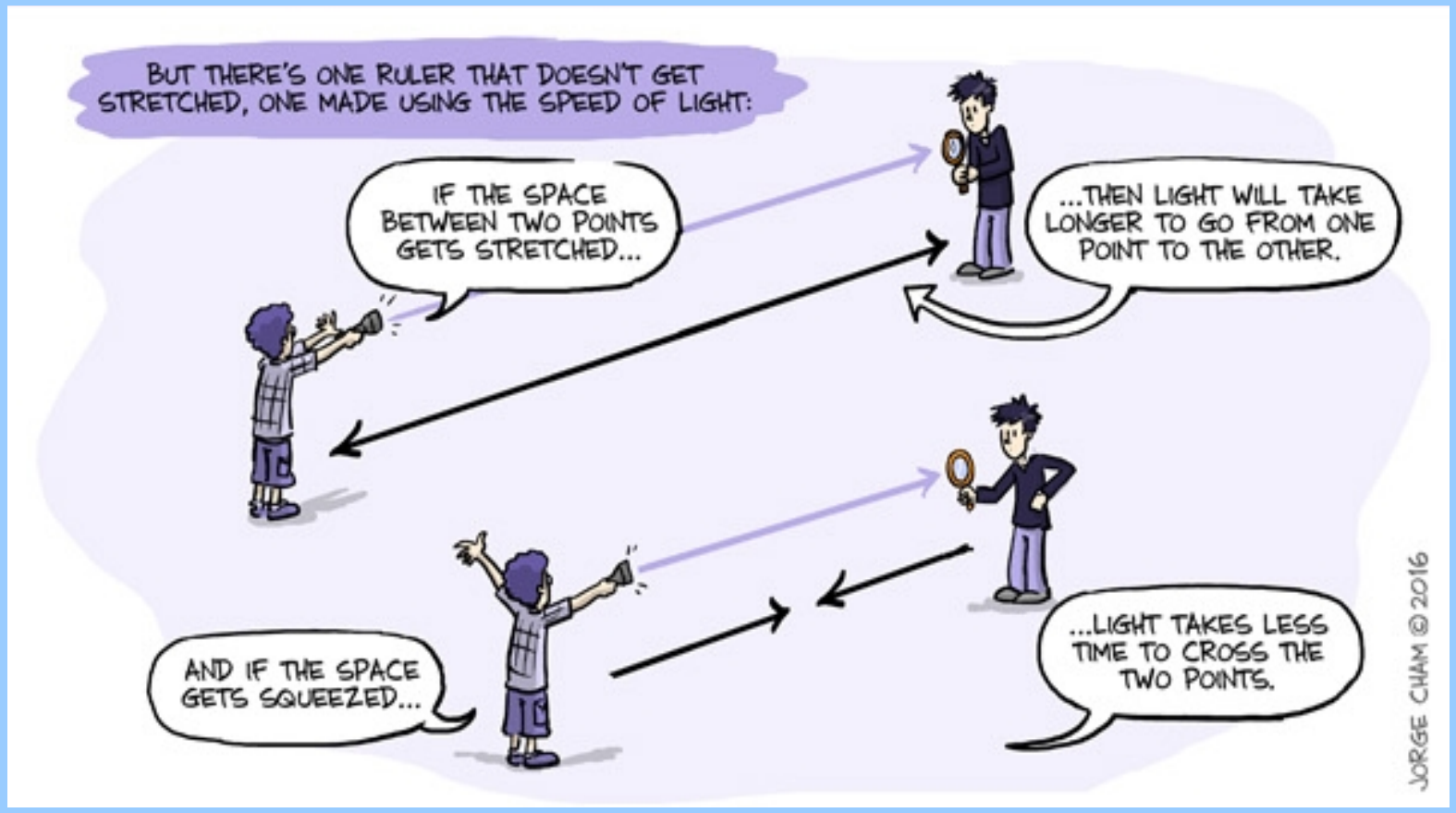
NASA, ESA, and the Hubble Heritage Team (STScI/AURA)-ESA/Hubble Collaboration
T. Carnahan (NASA GSFC)

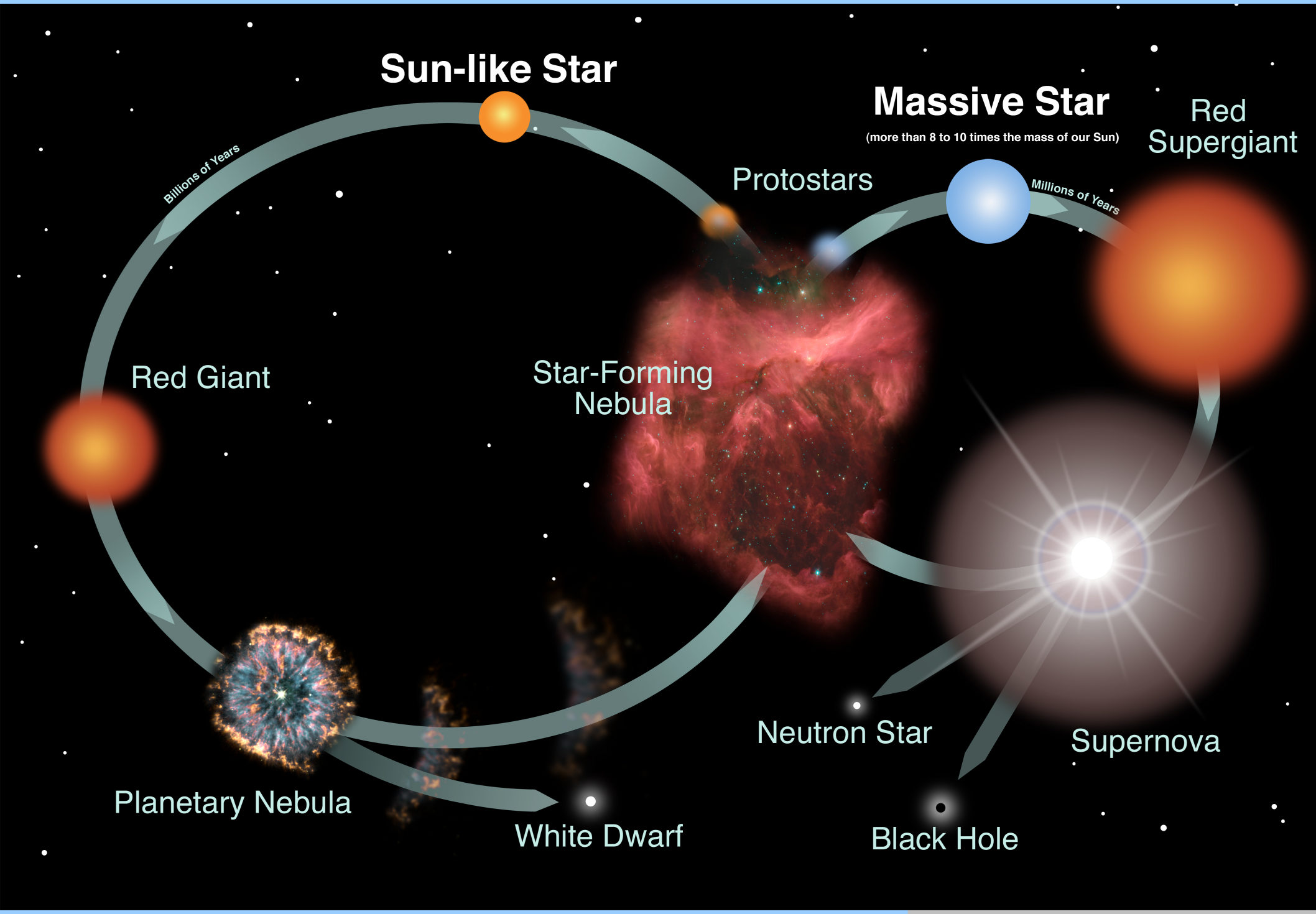
Effects of Gravitational Waves



Effects of Gravitational Waves

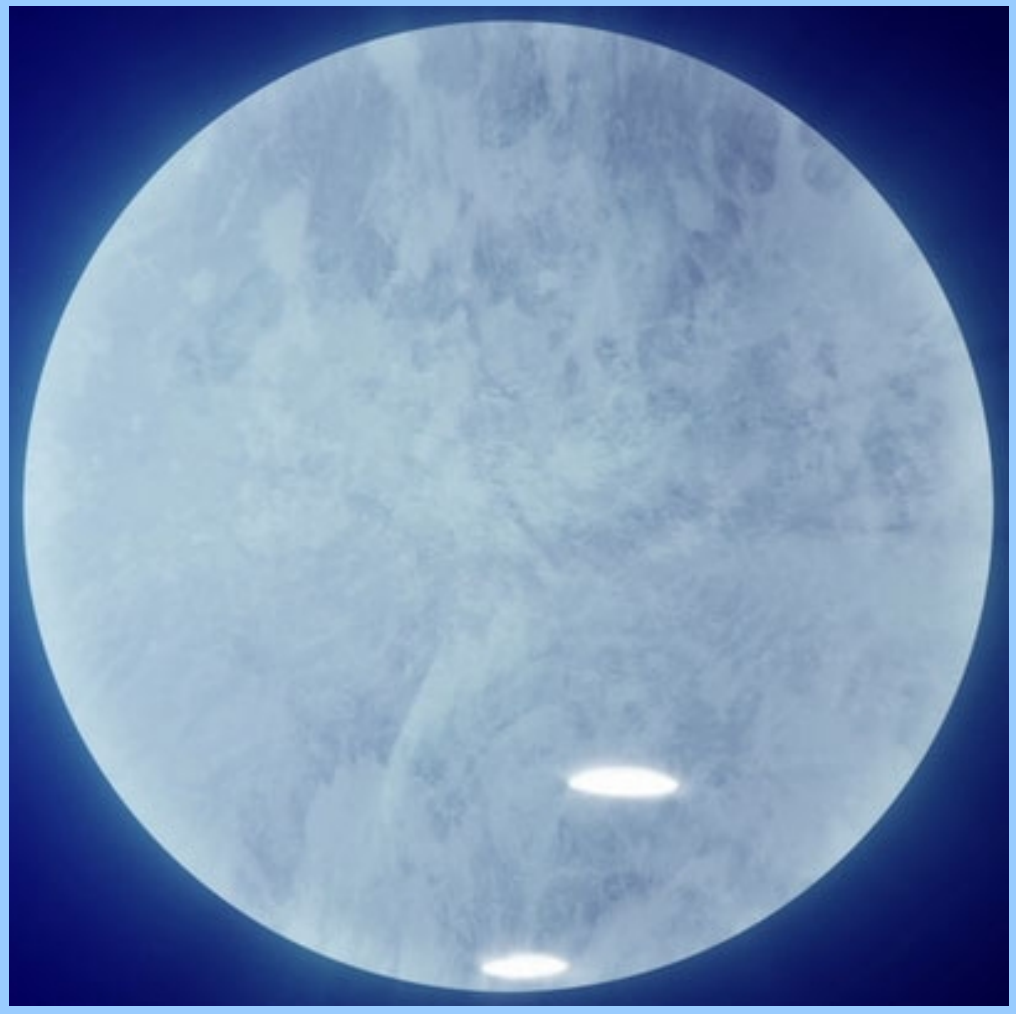


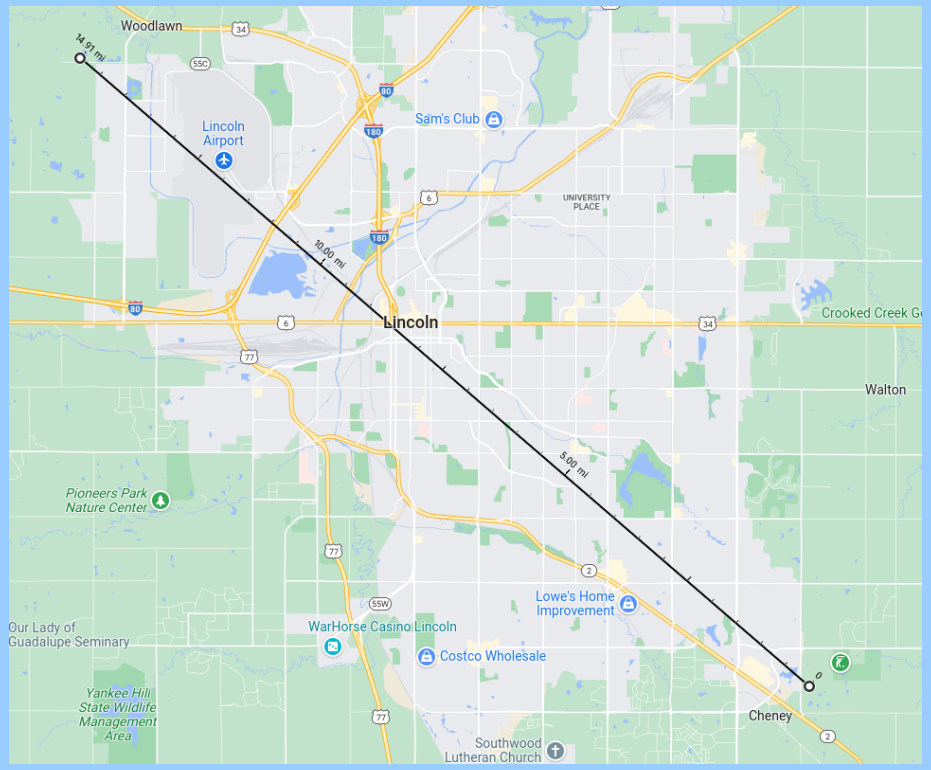

BUT THERE'S ONE RULER THAT DOESN'T GET STRETCHED, ONE MADE USING THE SPEED OF LIGHT:
IF THE SPACE BETWEEN TWO POINTS GETS STRETCHED...
...THEN LIGHT WILL TAKE LONGER TO GO FROM ONE POINT TO THE OTHER.
AND IF THE SPACE GETS SQUEEZED...
...LIGHT TAKES LESS TIME TO CROSS THE TWO POINTS.
JORGE CHAM © 2016


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

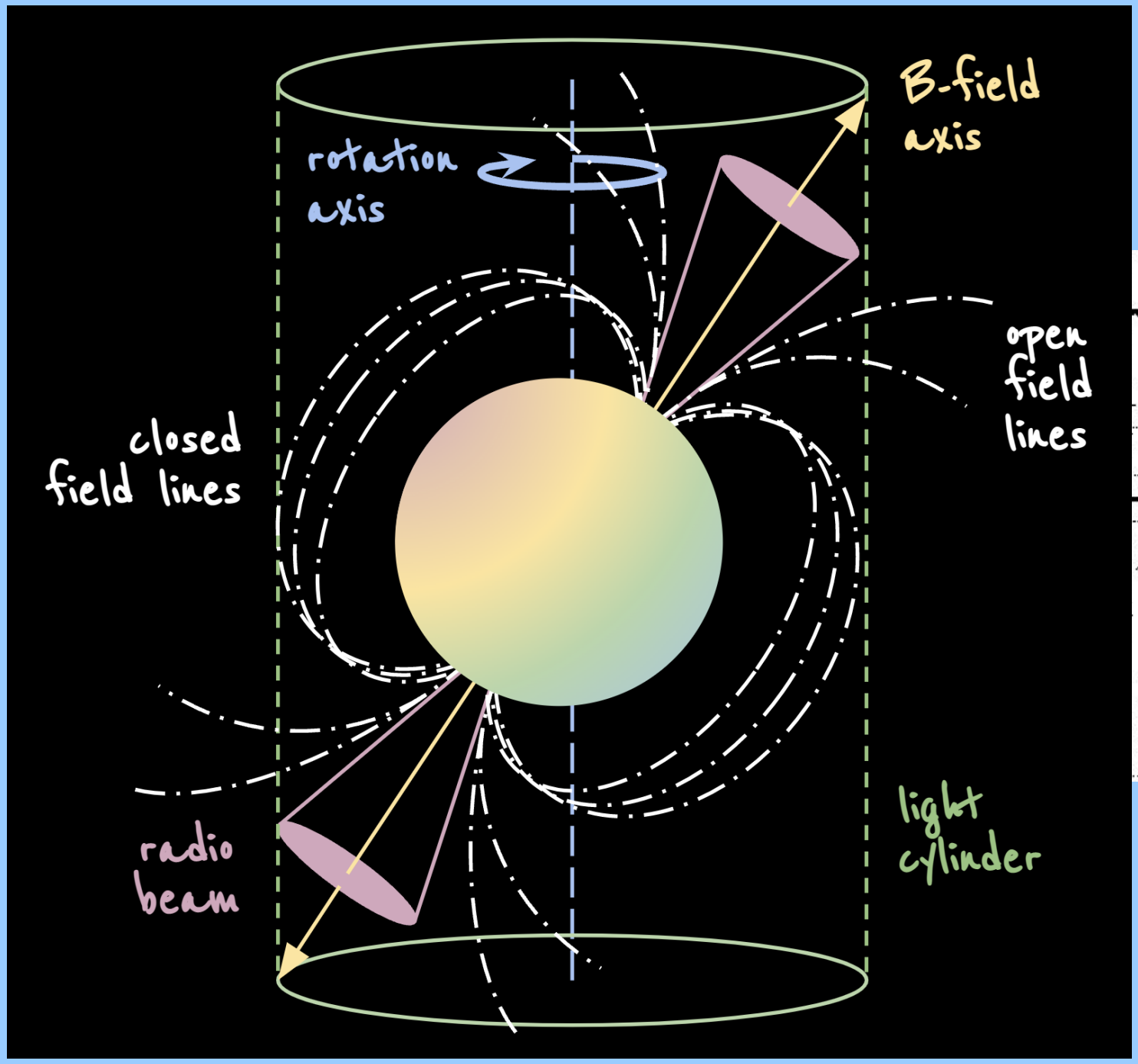
Neutron Stars

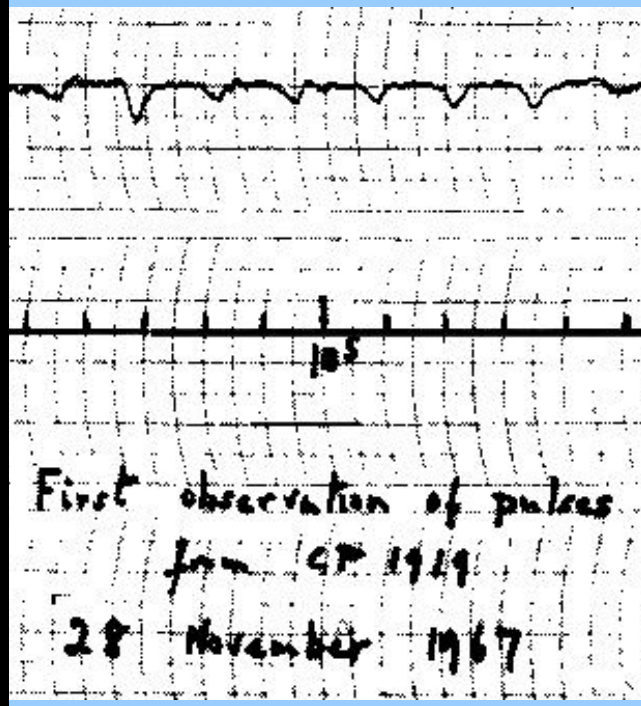
$M \sim 1\text{-}2\ M_{\odot}$, $R \sim 12$ km





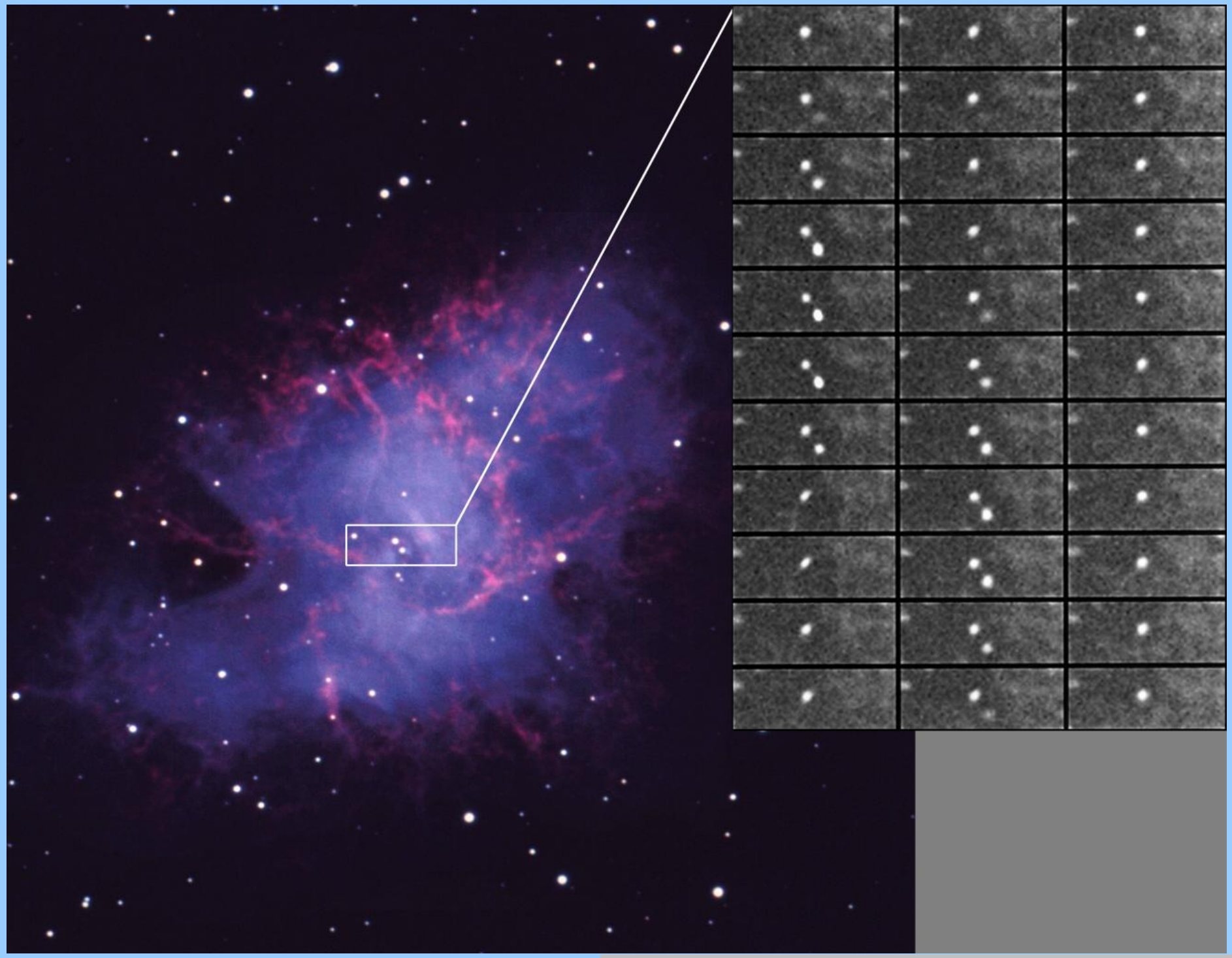
NASA, NICER, GSFC



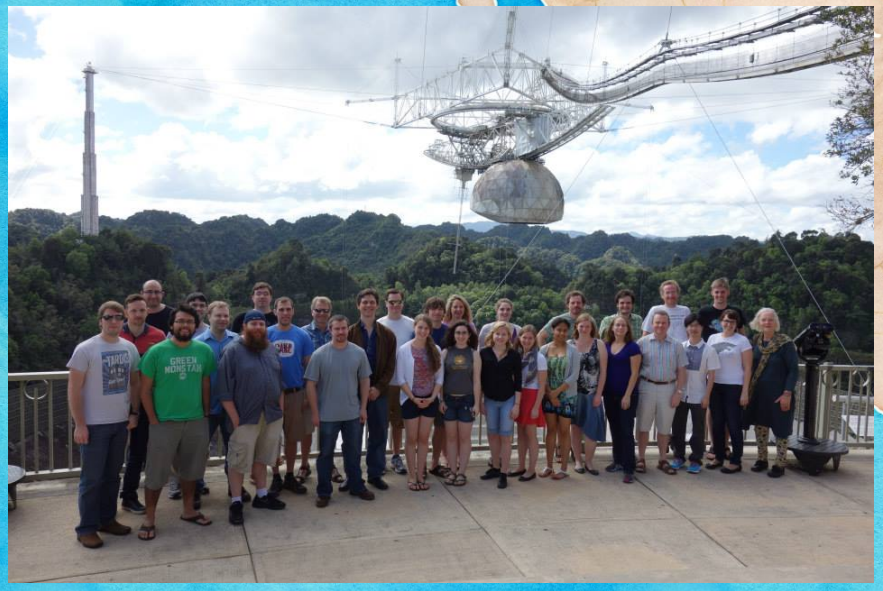


L: Thankful Cromartie

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

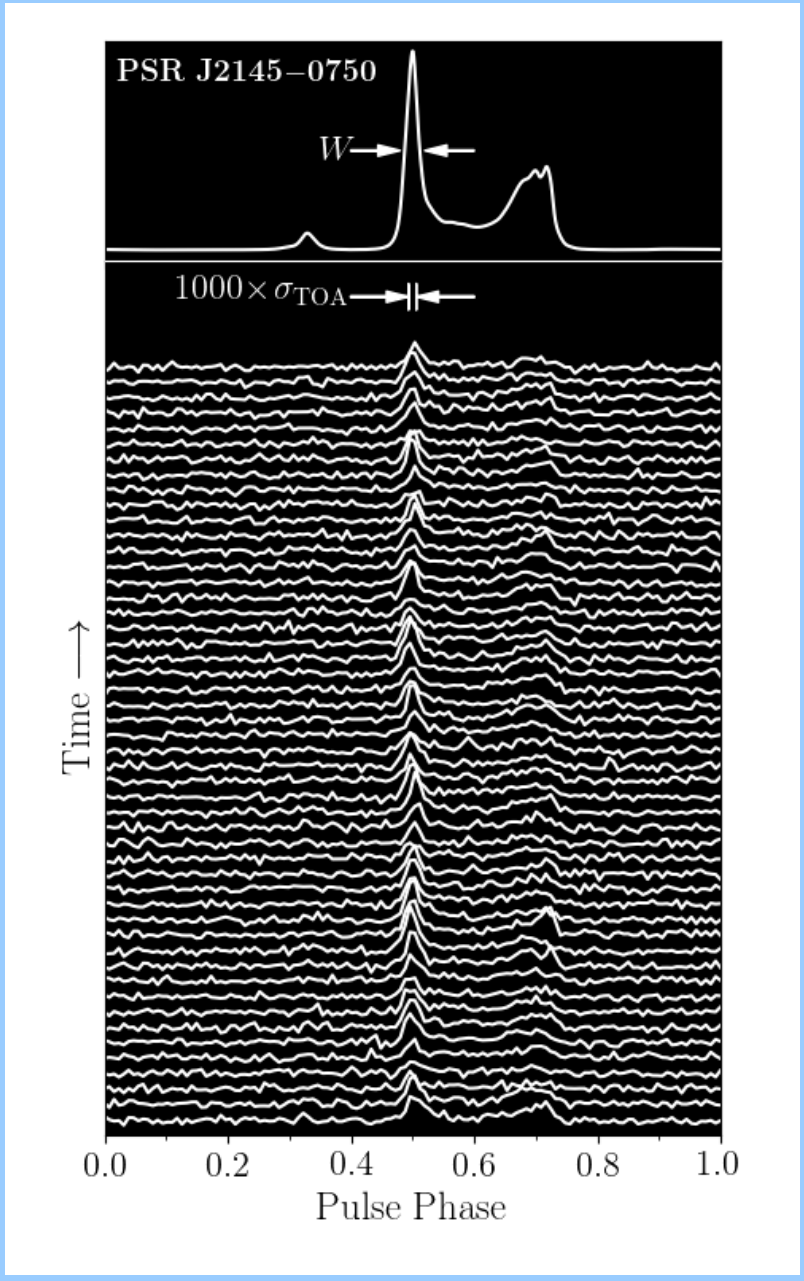


https://www.noao.edu/image_gallery/images/d5/03036y.jpg



L,M: NRAO/AUI, R: NAIC

Measuring Pulses



Pulsars as Precise Clocks: J1909-3744

On February 18, 2011 at 00:00:00 UTC:

$P = 2.947108024810317 \pm 0.000000000000009$ ms

Data: NANOGrav

Pulsars as Precise Clocks: J1909-3744

On February 18, 2011 at 00:00:00 UTC:

P = 2.947108024810317 ± 0.000000000000009 ms

The last digit changes by 1 every 71 seconds

Data: NANOGrav

Pulsars as Precise Clocks: J1909-3744

On February 18, 2011 at 00:00:00 UTC:

P = 2.947108024810317 ± 0.000000000000009 ms

The last digit changes by 1 every 71 seconds

This digit changes by 1 every 226 years

Data: NANOGrav

Pulsars as Precise Clocks: J1909-3744

On February 18, 2011 at 00:00:00 UTC:

P = 2.947108024810317 ± 0.000000000000009 ms

The last digit changes by 1 every 71 seconds

This digit changes by 1 every 226 years

From February 18, 2011 at 00:00:00 UTC to the start of this talk (October 22, 2022 at 00:30:00 UTC), the pulsar has completed just over 125,007,769,167 rotations (and a half!)

Data: NANOGrav

More fun with J1909-3744

Smallest eccentricity of any known binary in the Universe:

$e = 0.000000110 \pm 0.000000009$

The orbit has a radius=$(5.7018 \pm 0.0004) \cdot 10^8$ m (0.82 R_{Sun})

But, we know the difference between the semi-major and semi-minor axis is 3.5 ± 0.5 μm!

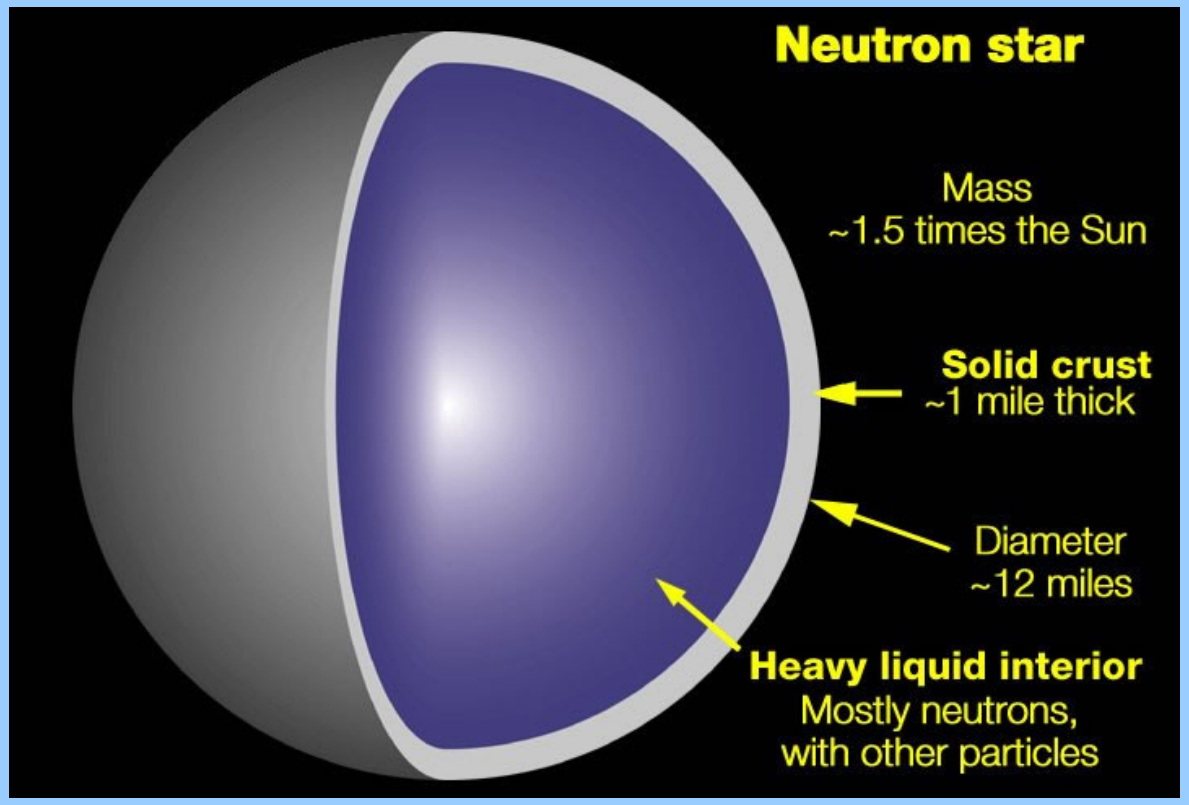
Data: NANOGrav

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)

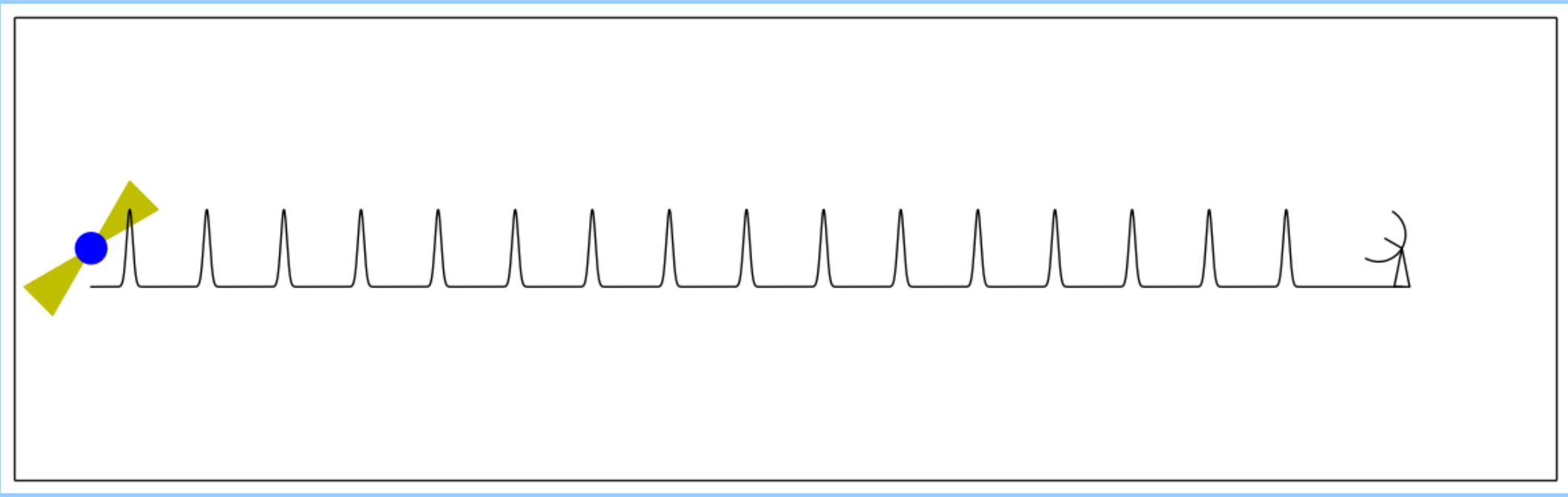
$\Delta L \sim hL \sim 10\text{-}1000$ m $\rightarrow \Delta t = \Delta L/c \sim hT \sim 30\text{-}3000$ ns



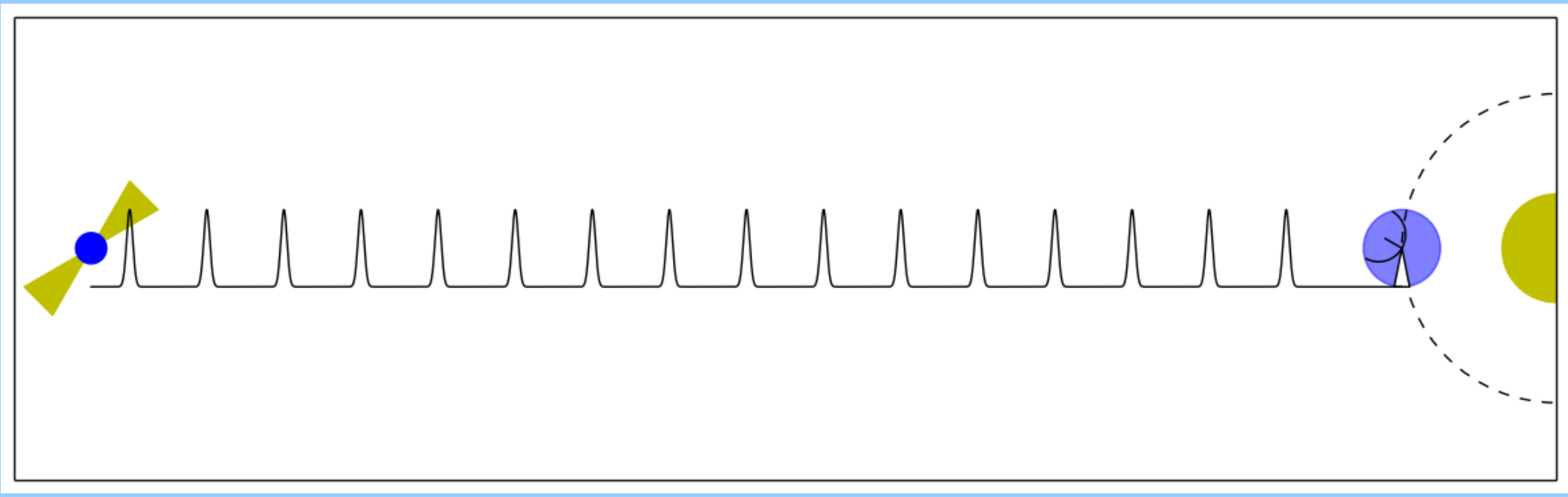
$0.001 - 0.1\ R_{NS}$

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

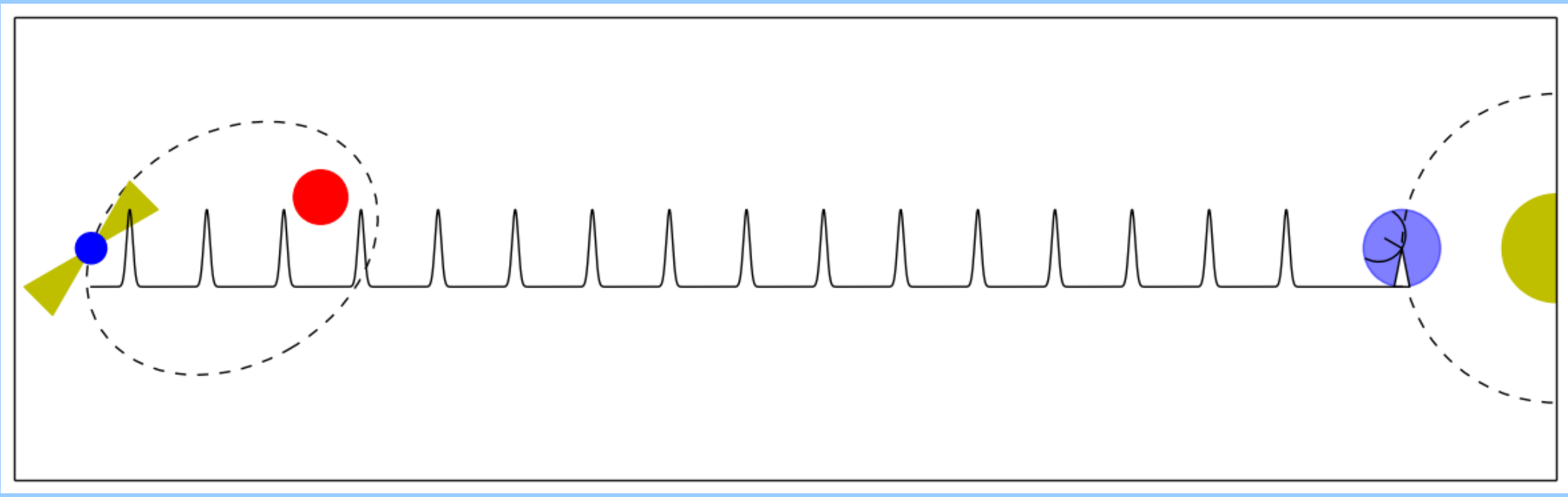
Timing Model



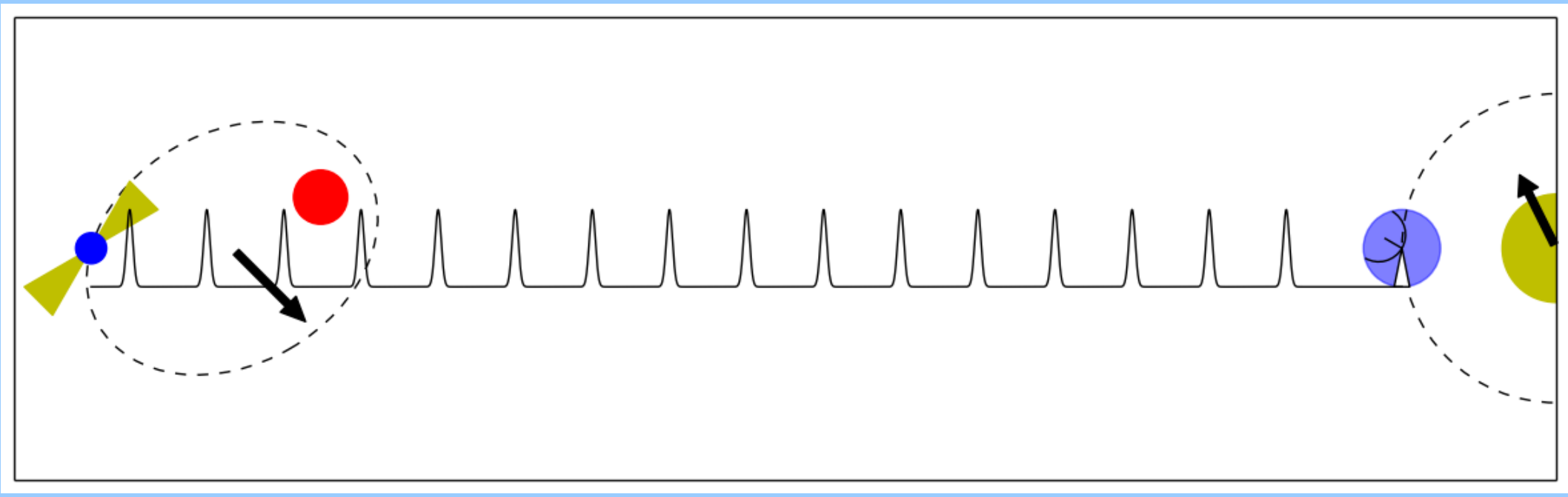
Timing Model



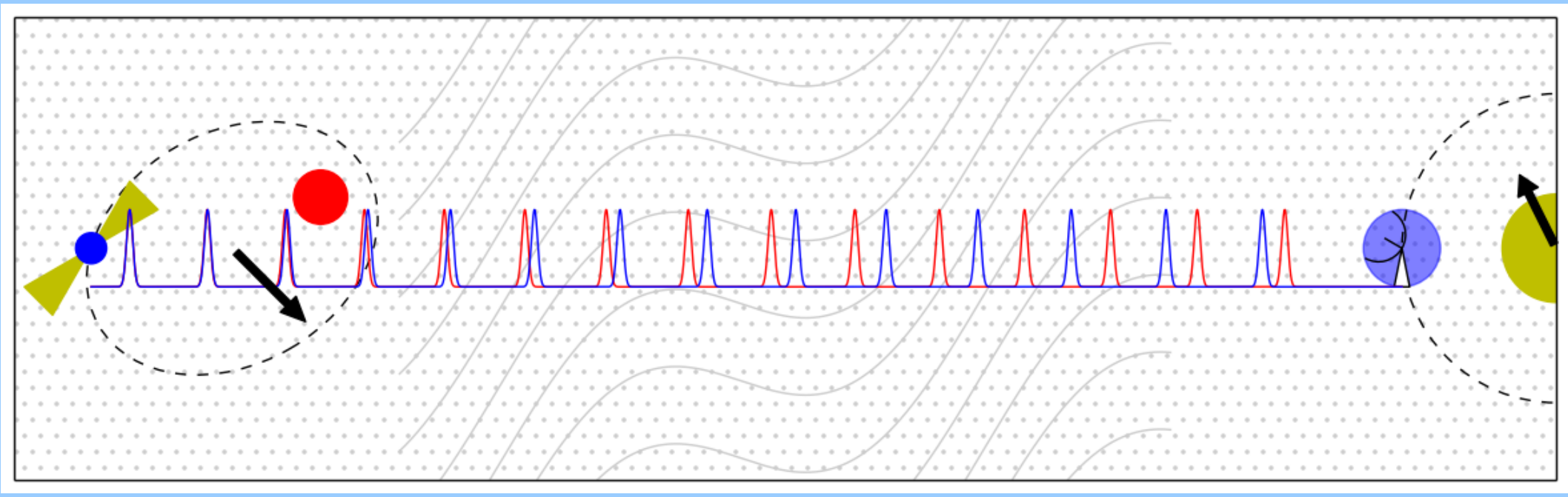
Timing Model



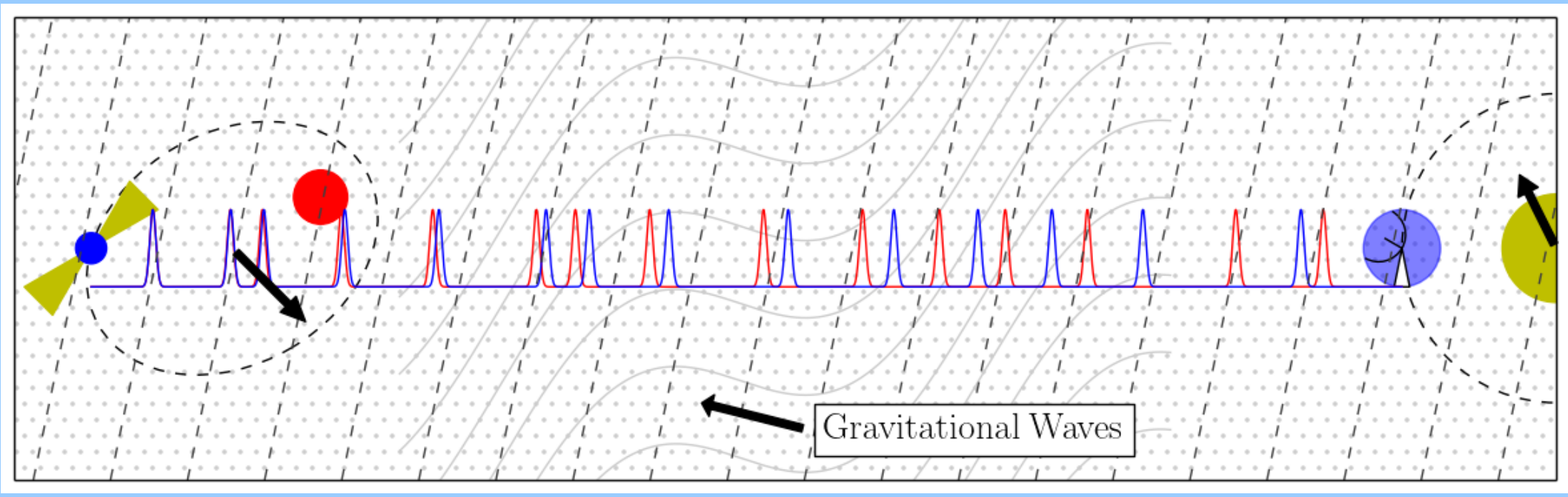
Timing Model



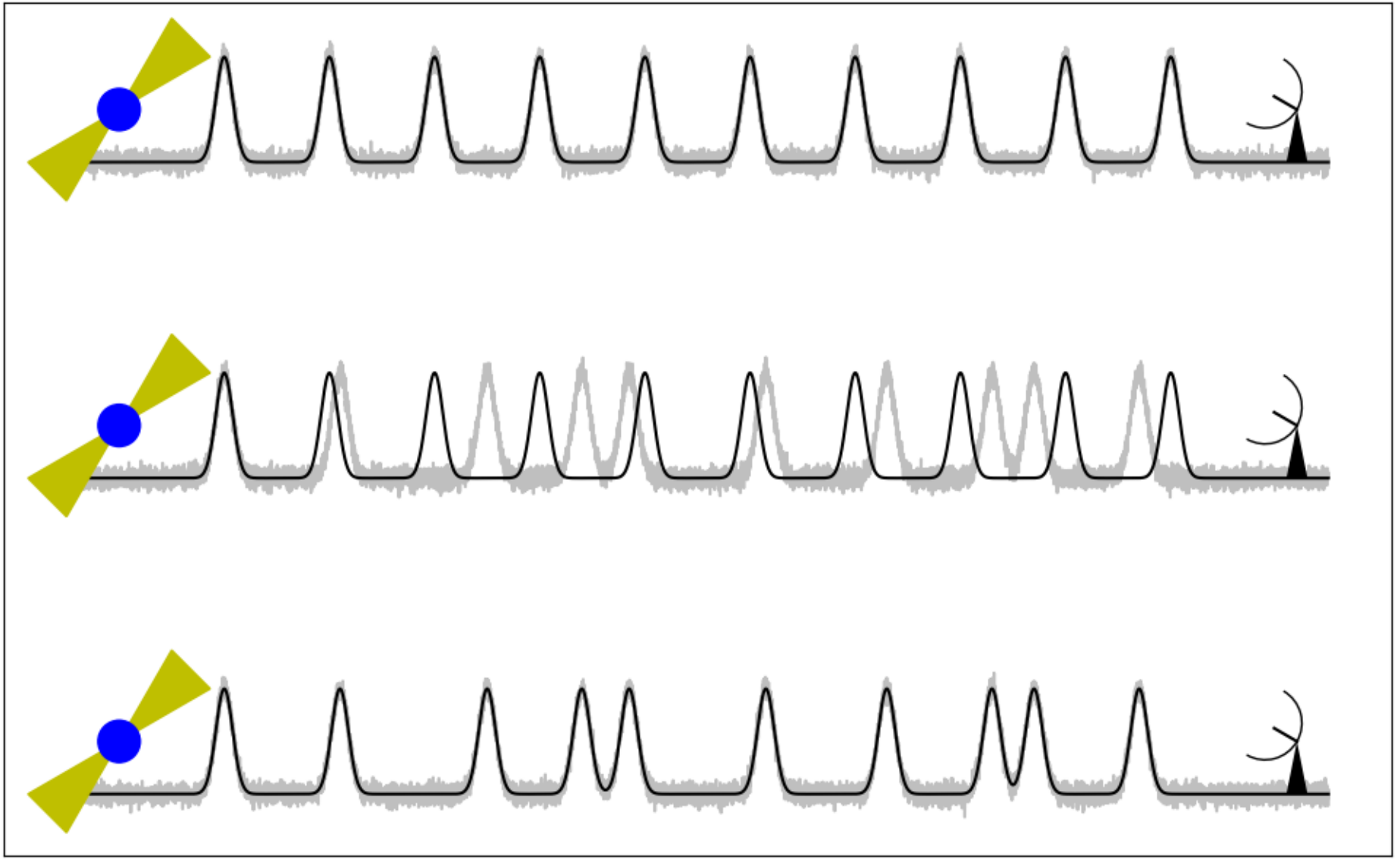
Timing Model



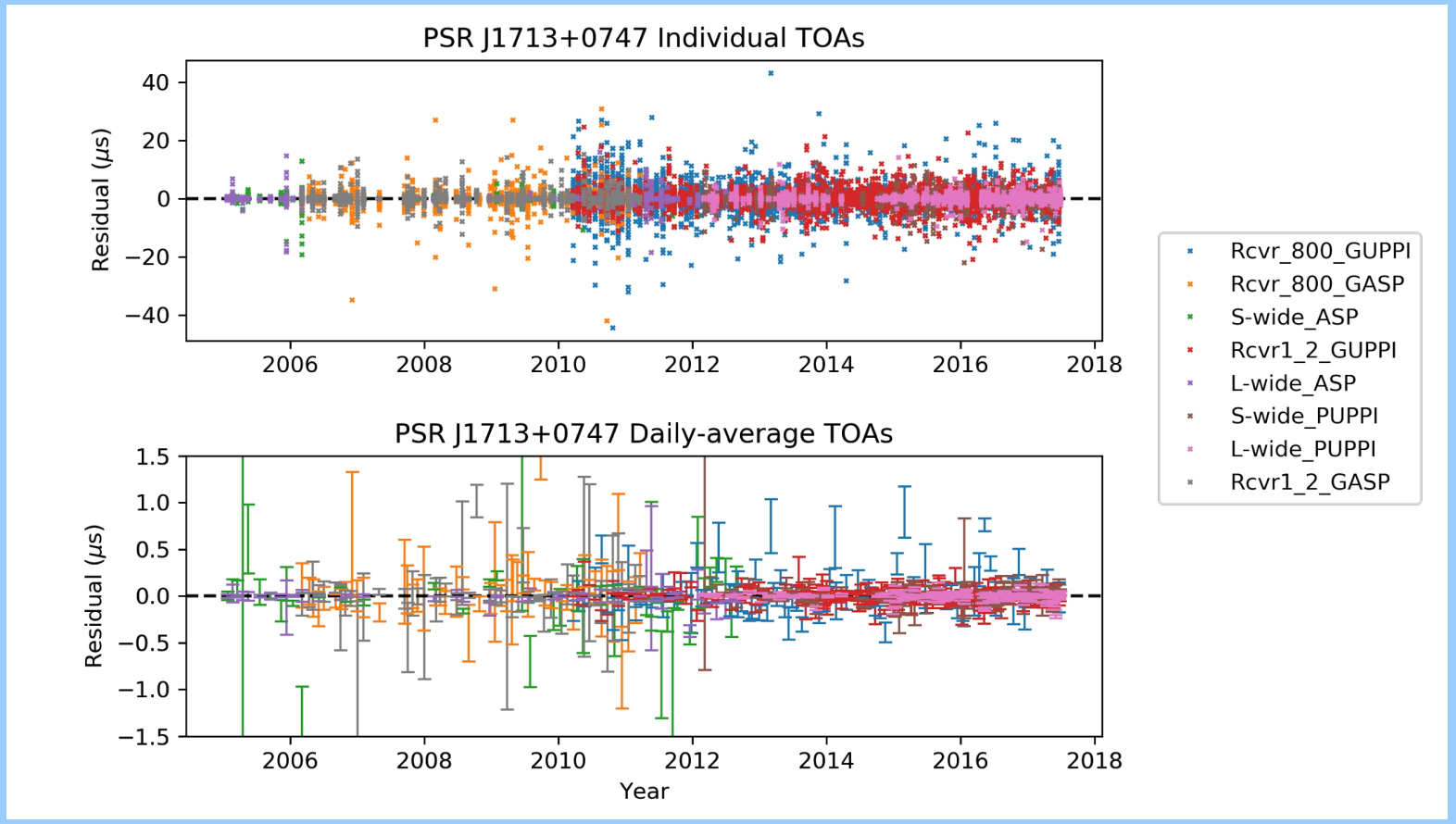
Timing Model



Pulsar Timing

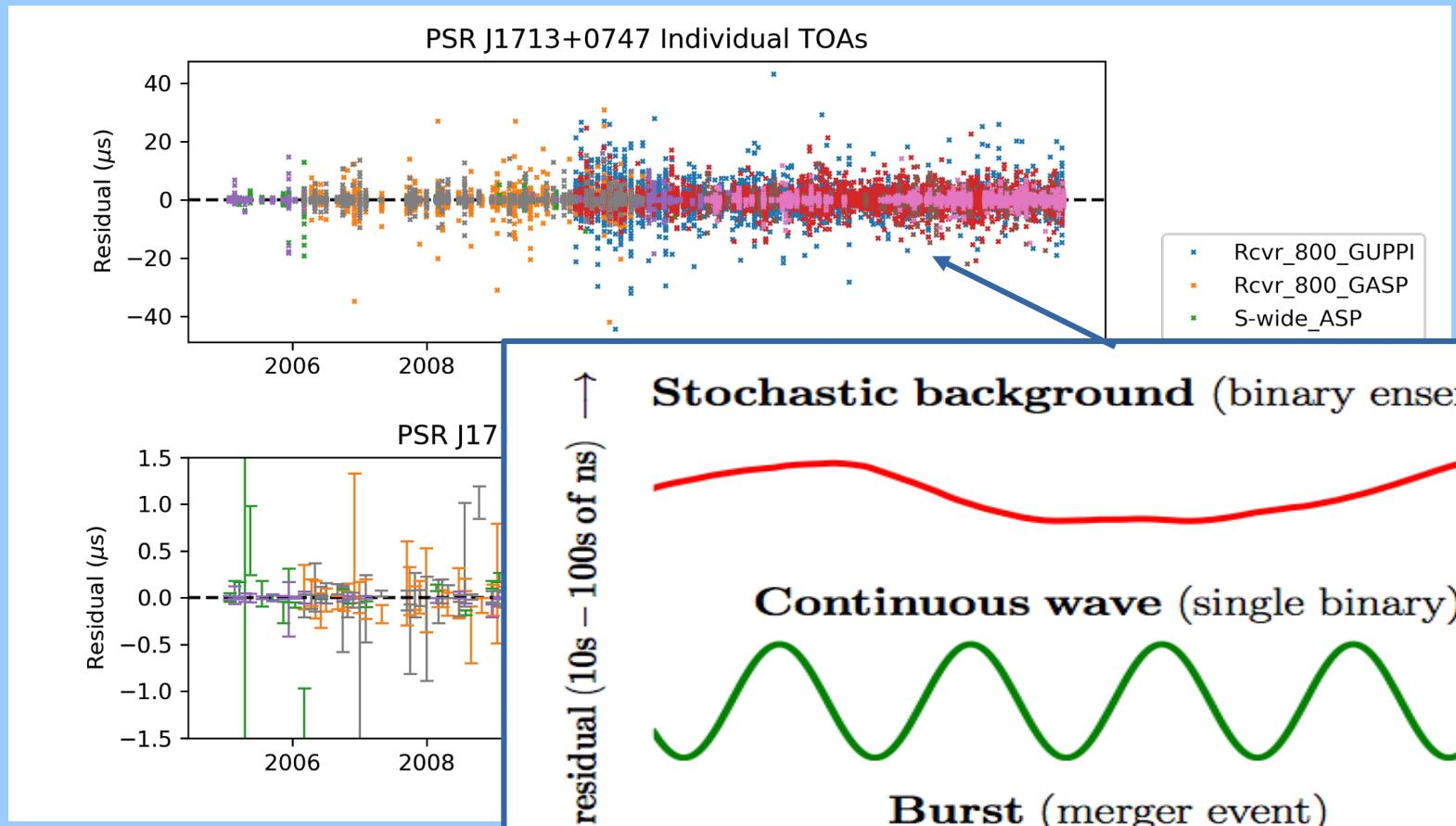


Residuals and GW Signatures



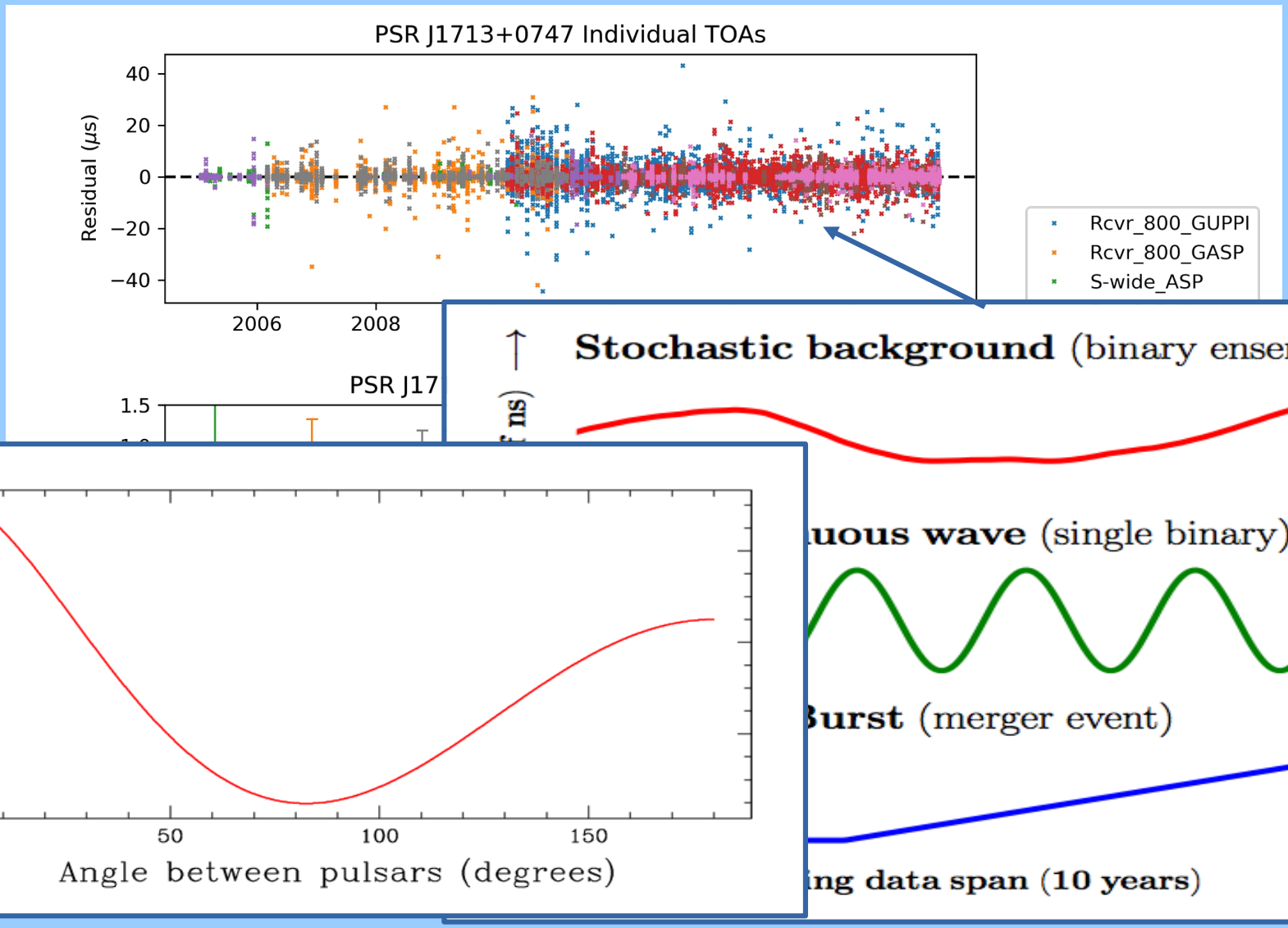
Courtesy: D. Nice

Residuals and GW Signatures



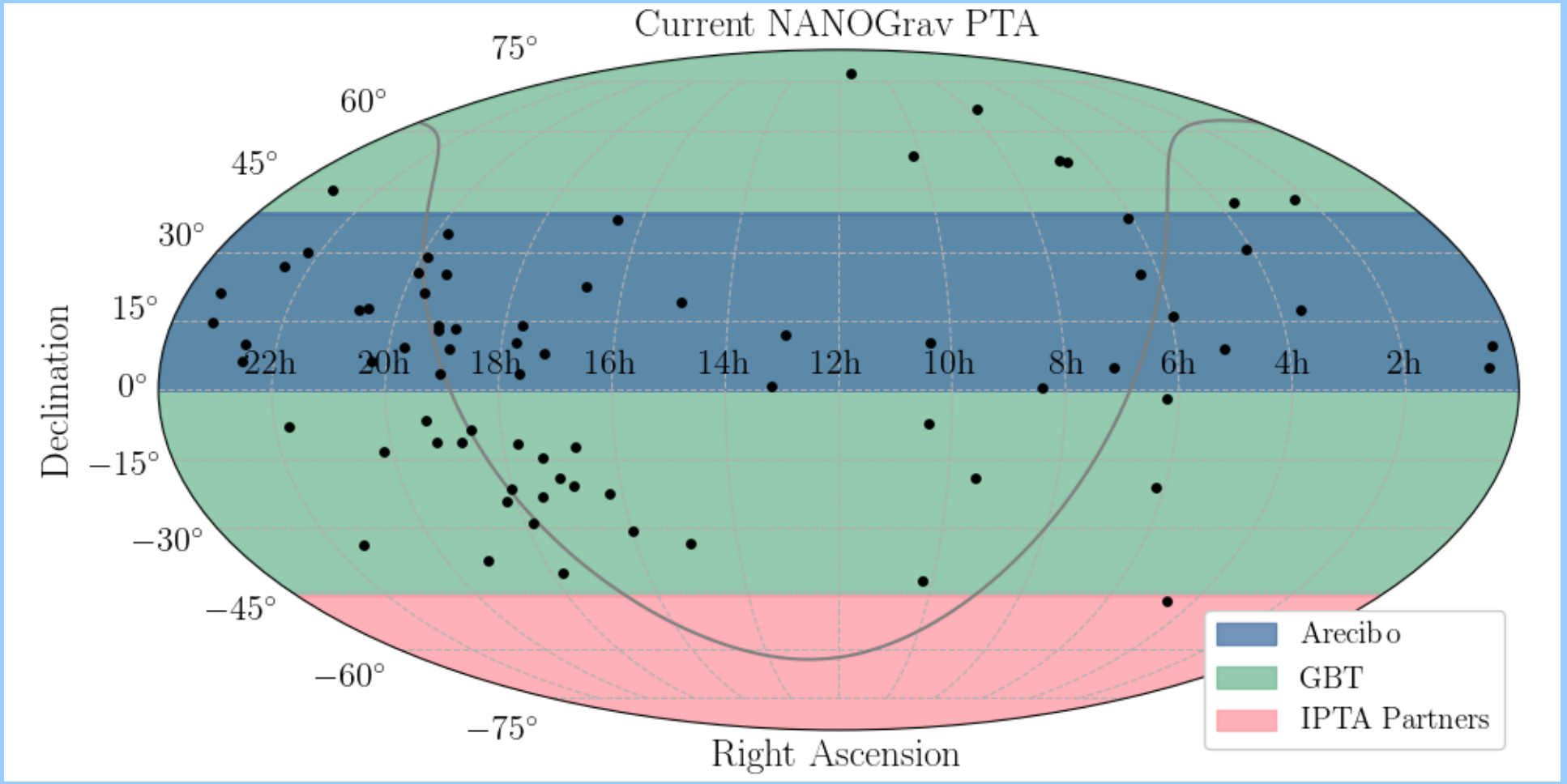
Courtesy: D. Nice, J. Cordes

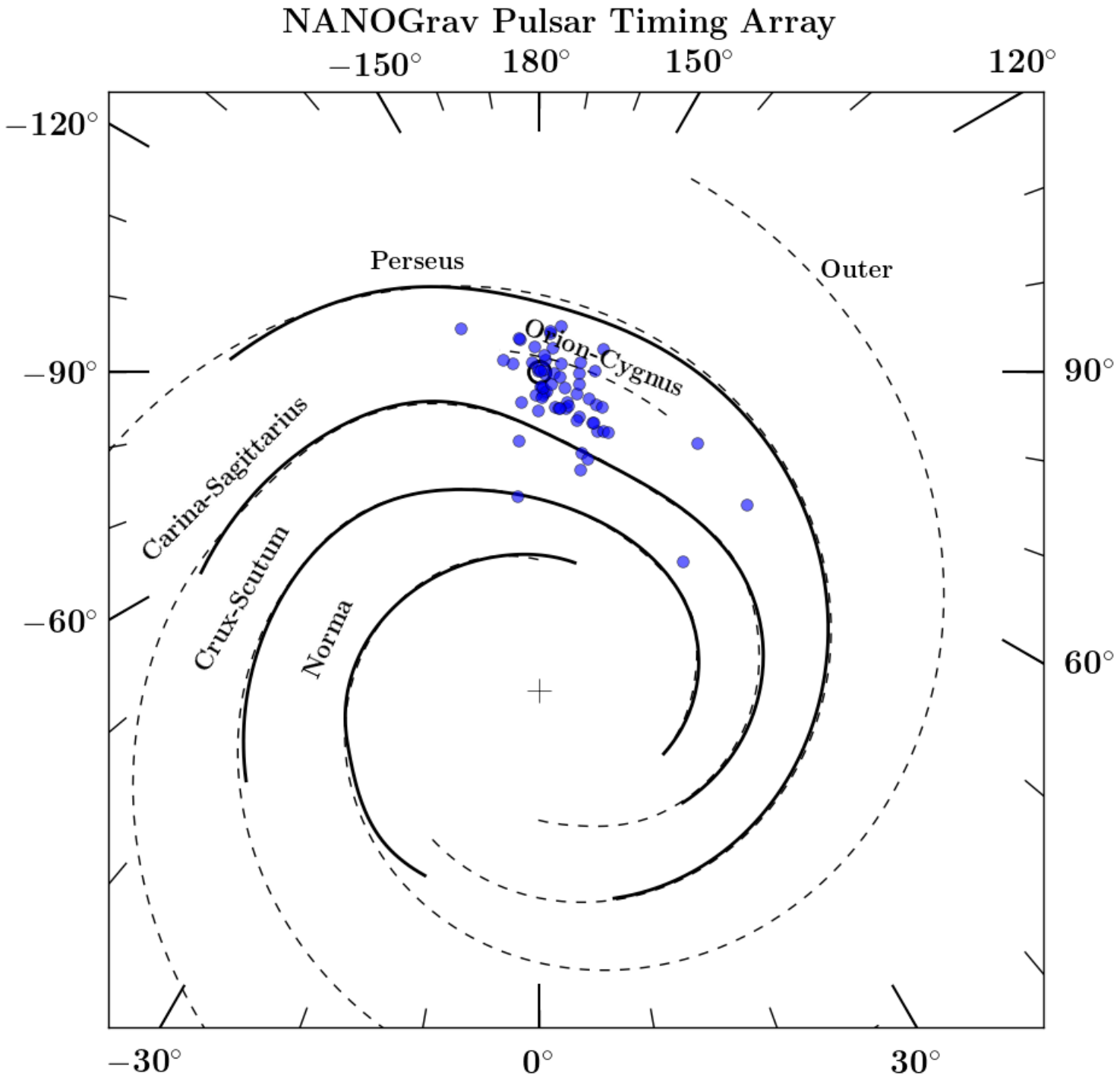
Residuals and GW Signatures



Courtesy: D. Nice, J. Cordes

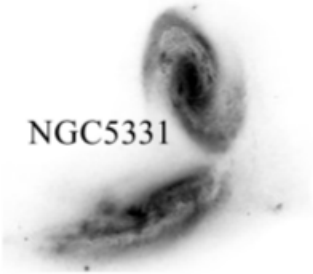
The Pulsar Timing Array




NANOGrav Pulsar Timing Array
−150°
180°
150°
120°
−120°
−90°
−60°
90°
60°
−30°
0°
30°
Perseus
Outer
Orion-Cygnus
Carina-Sagittarius
Crux-Scutum
Norma

Gravitational Wave Sources

Galaxy Merger

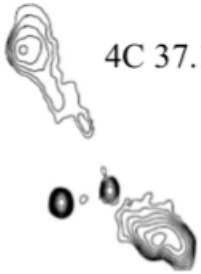


Dynamical friction drives massive objects to central positions

Stellar Core Merger

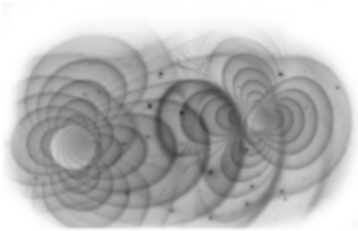
Dynamical friction less efficient as SMBHs form a binary.

Binary Formation



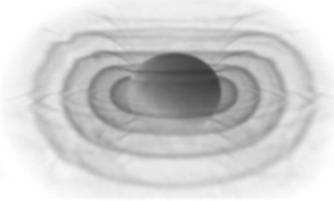
Stellar and gas interactions may dominate binary inspiral?

Continuous GWs



Gravitational radiation provides efficient inspiral. Circumbinary disk may track shrinking orbit.

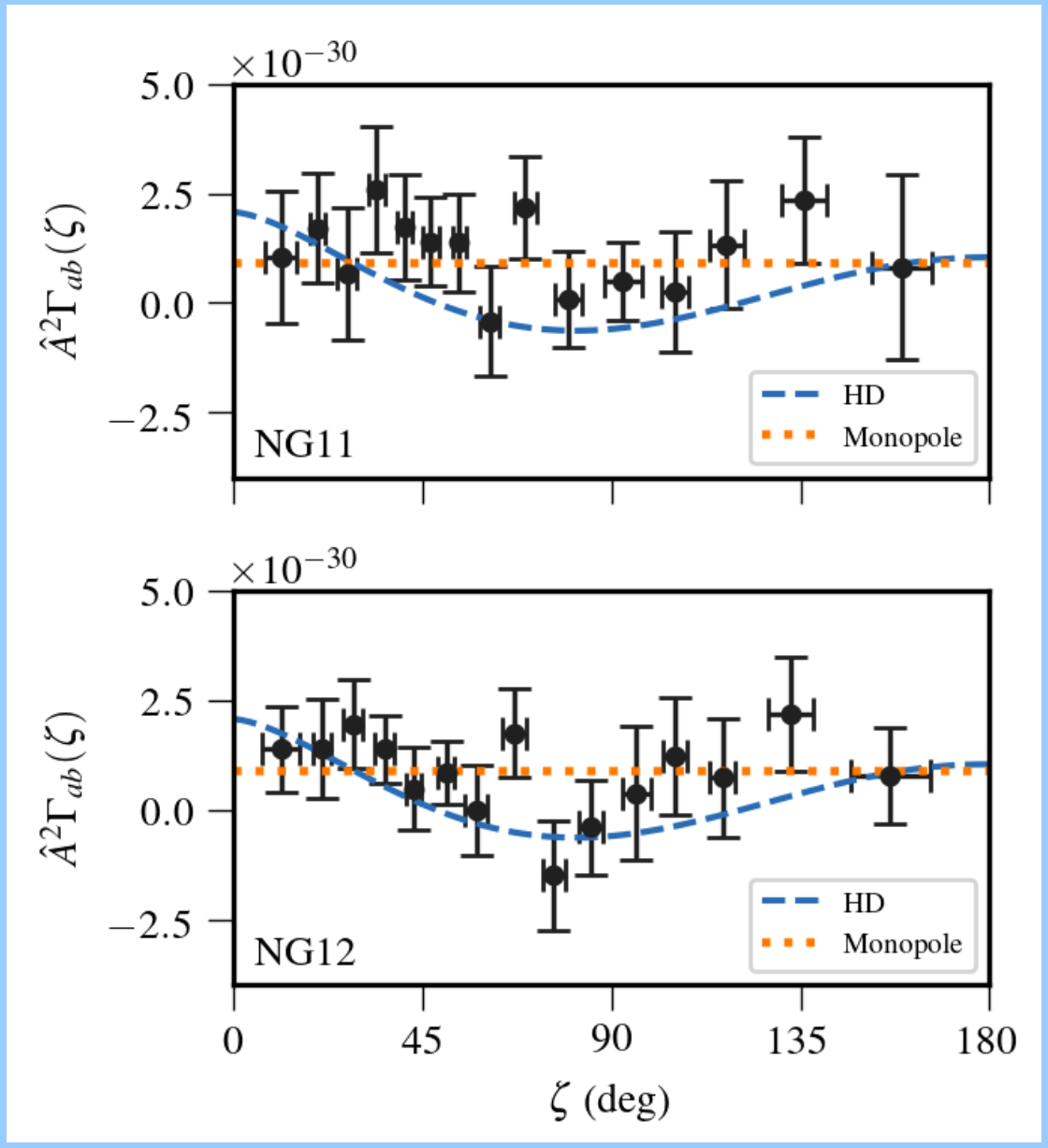
Coalescence, Memory & Recoil



Post-coalescence system may experience gravitational recoil.

Modified from Burke-Spolaor et al. 2019

Analyzing the Dataset

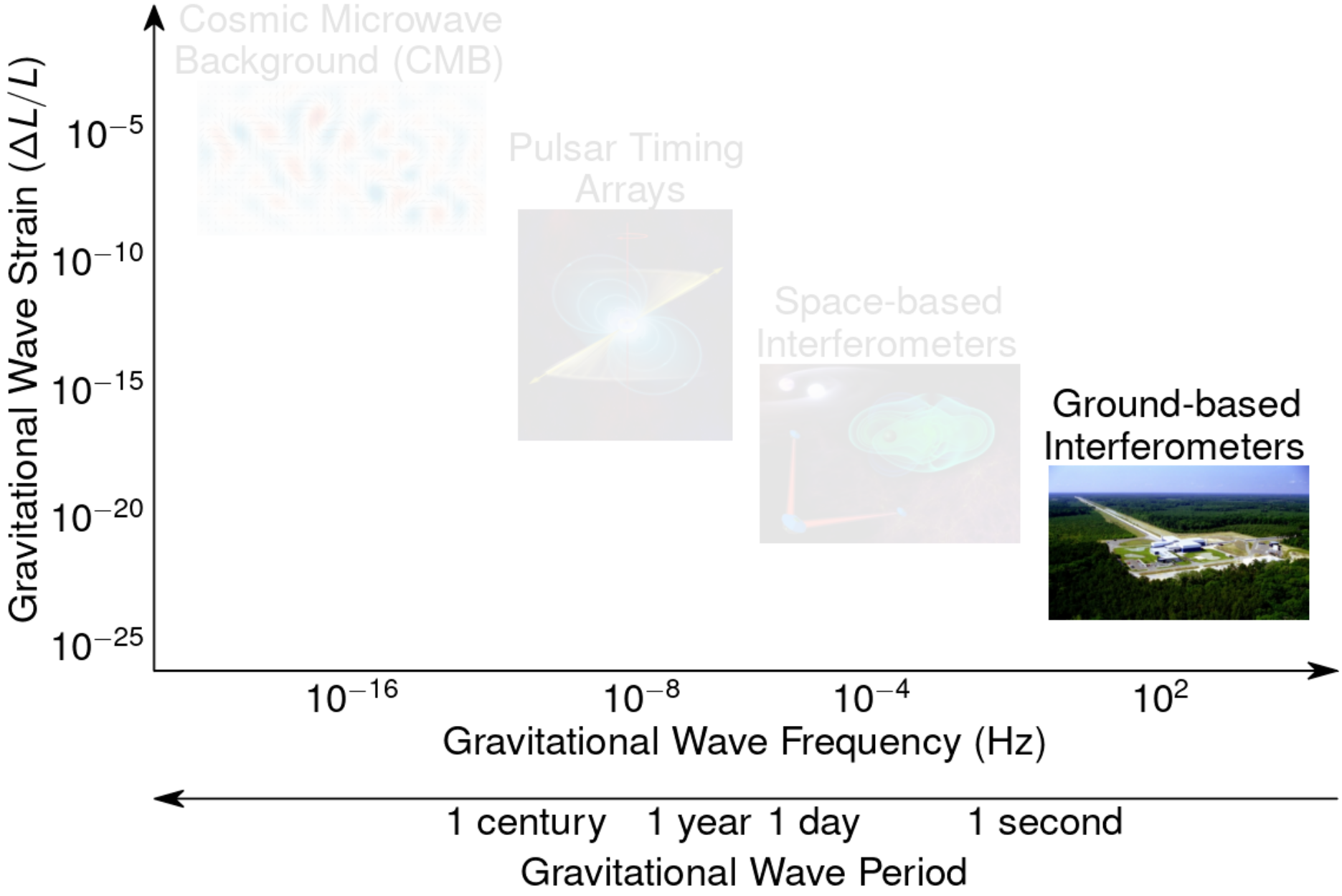


BF~10000 for Common Process,

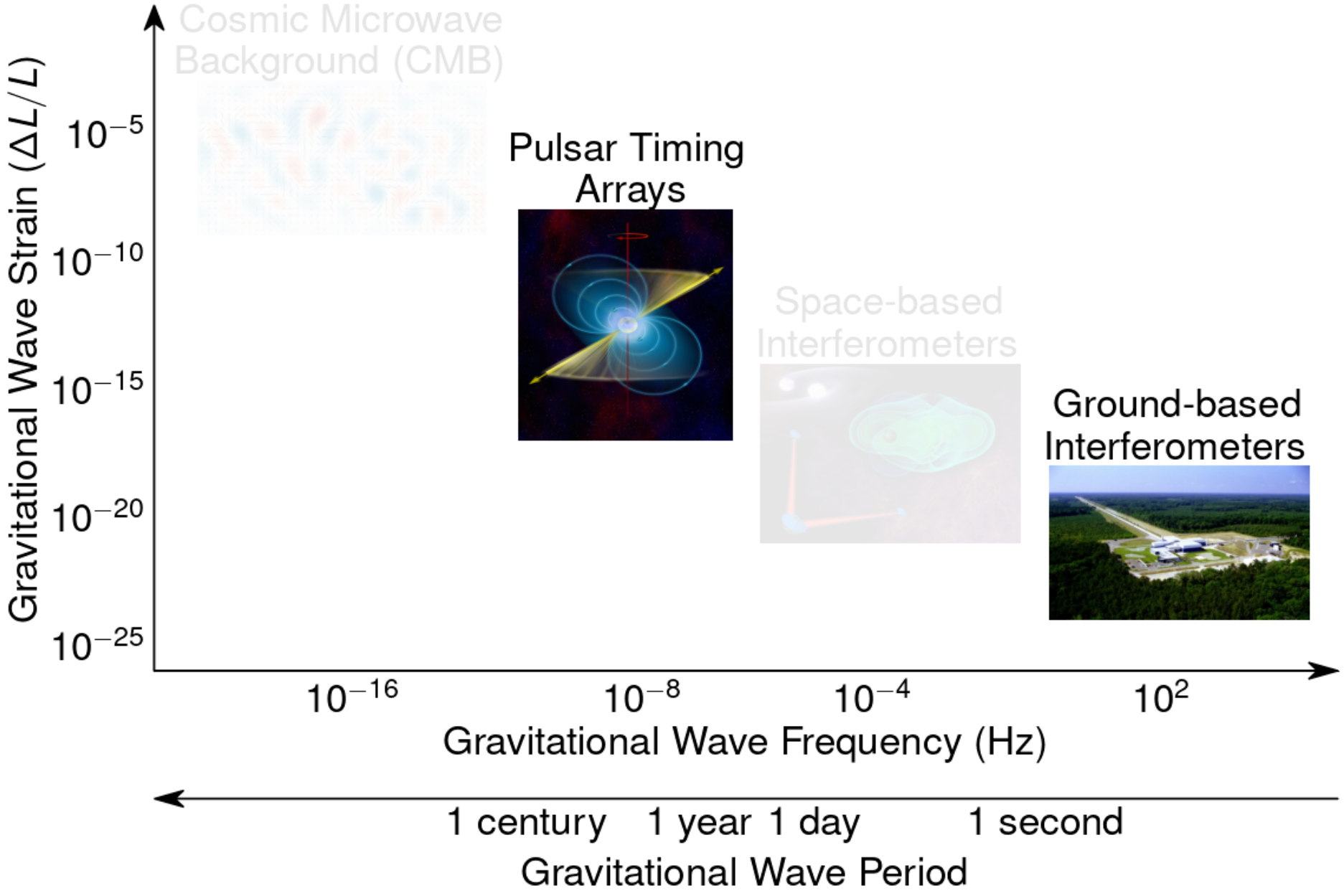
BF~2 for Hellings-Downs

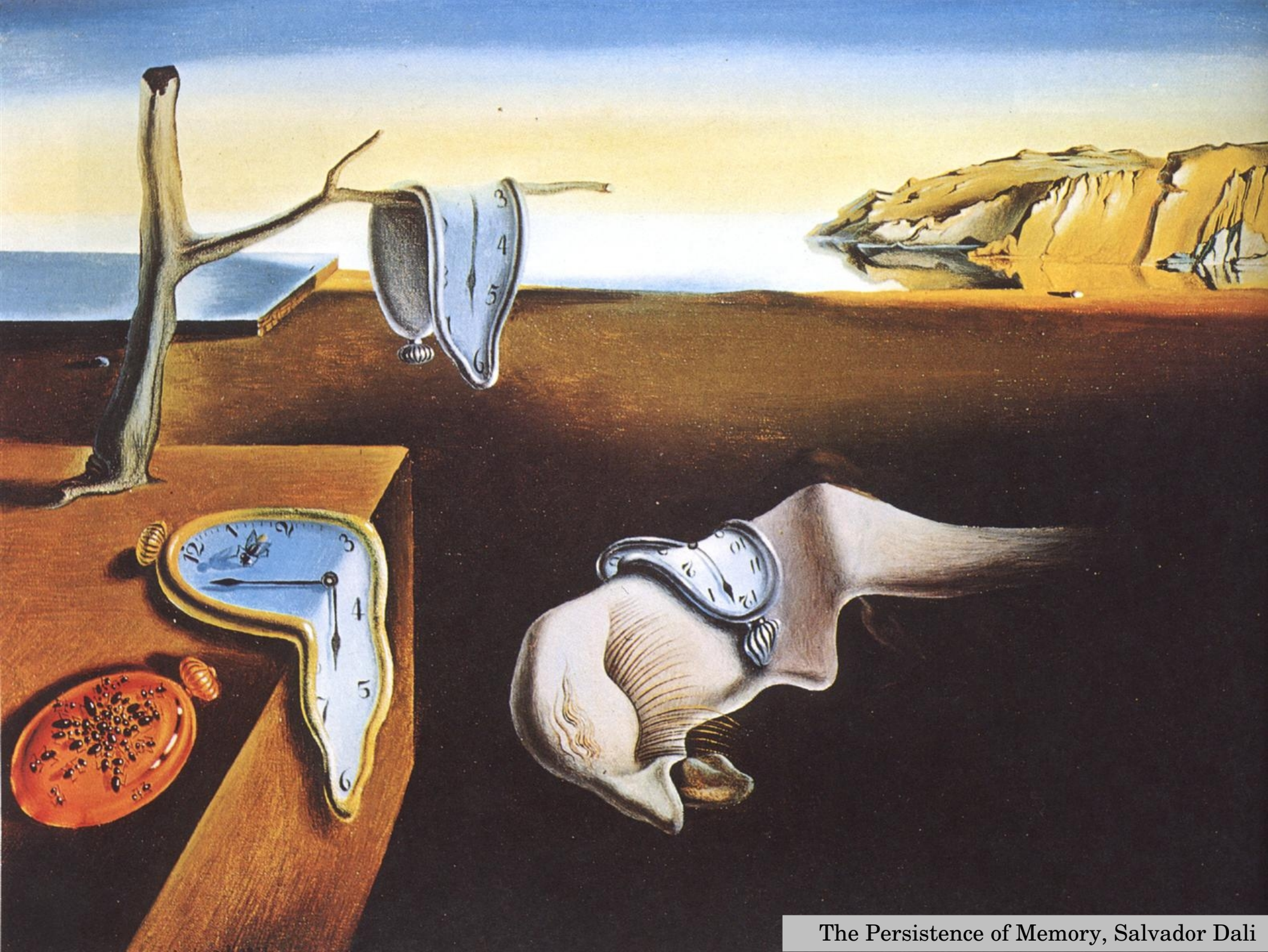
Arzoumanian et al 2020

Gravitational Wave Spectrum



Gravitational Wave Spectrum





The Persistence of Memory, Salvador Dali