Announcements

Welcome to Gravitational Waves Msc course at Nikhef!

Instructor: Dr. Sarah Caudill (physarah@gmail.com)
Teaching Assistants: Ka Wa Tsang & Pawan Gupta

Course Website: https://www.nikhef.nl/~caudills/teaching.html

Please pick up a Homework assignment and a Syllabus.

Please fill out your name and preferred email address.

Summary of the field

Lecture 1: Gravitational Waves MSc Course

- What are gravitational waves?
    - Detectors
    - Sources
- A brief history of the field
- Some terminology
- Current state of the field
    - Detections
    - Science results
- Next steps
    - Detectors
- Homework

What are gravitational waves?

Einstein field equations:

$$G_{\mu\nu} = 8\pi \frac{G}{c^4} T_{\mu\nu}$$

description of geometry of spacetime

description of how matter/energy is distributed

Spacetime tells matter how to move; matter tells spacetime how to curve. - John Wheeler

What are gravitational waves?

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$$G_{\mu\nu} = 8\pi \frac{G}{c^4} T_{\mu\nu} = 0 \, (\text{in vacuum})$$

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What are gravitational waves?

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Far from the source: metric is flat with small perturbation

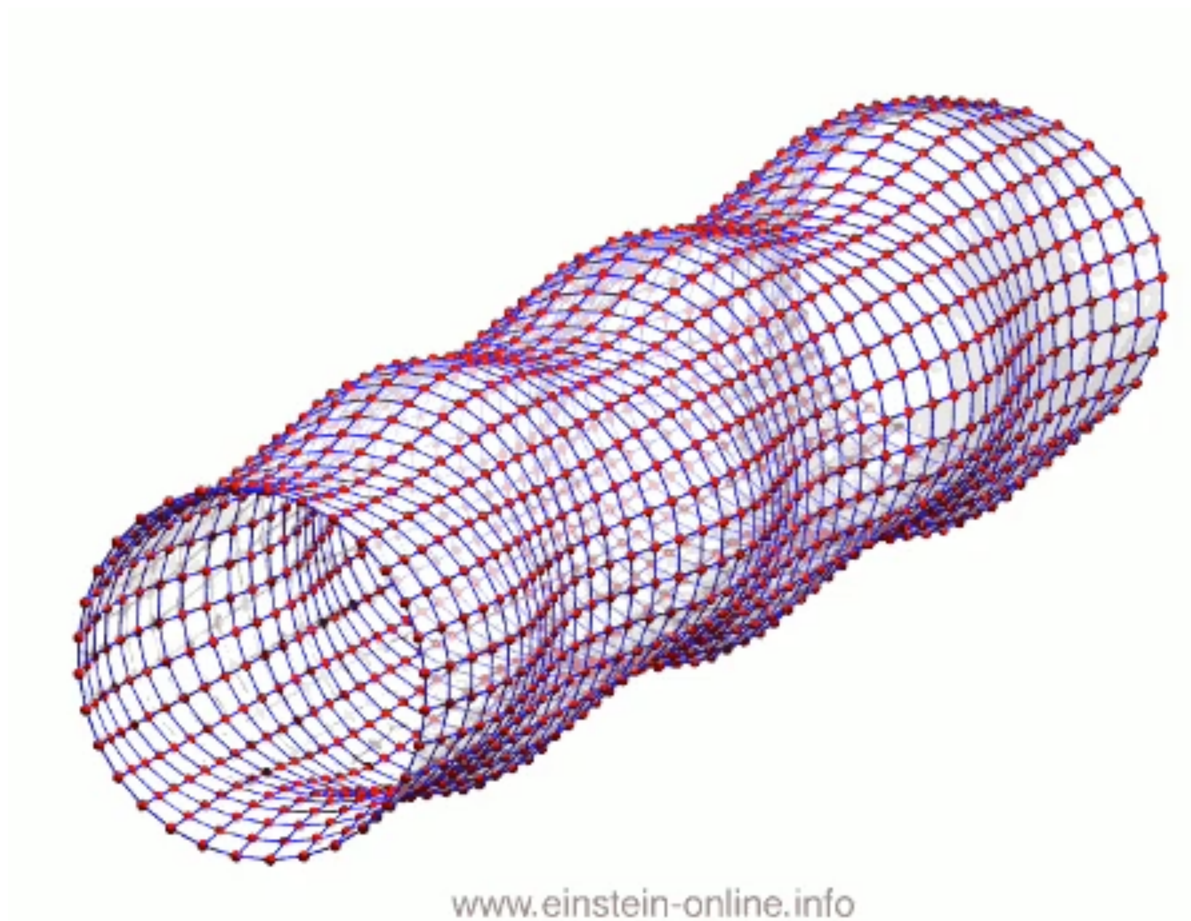
$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

Far from the source: Einstein equations reduce to wave equation for the perturbation

$$\left(-\frac{\partial^2}{c^2 \partial t^2} + \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}\right) h_{\mu\nu}^{\mathrm{TT}} = 0$$

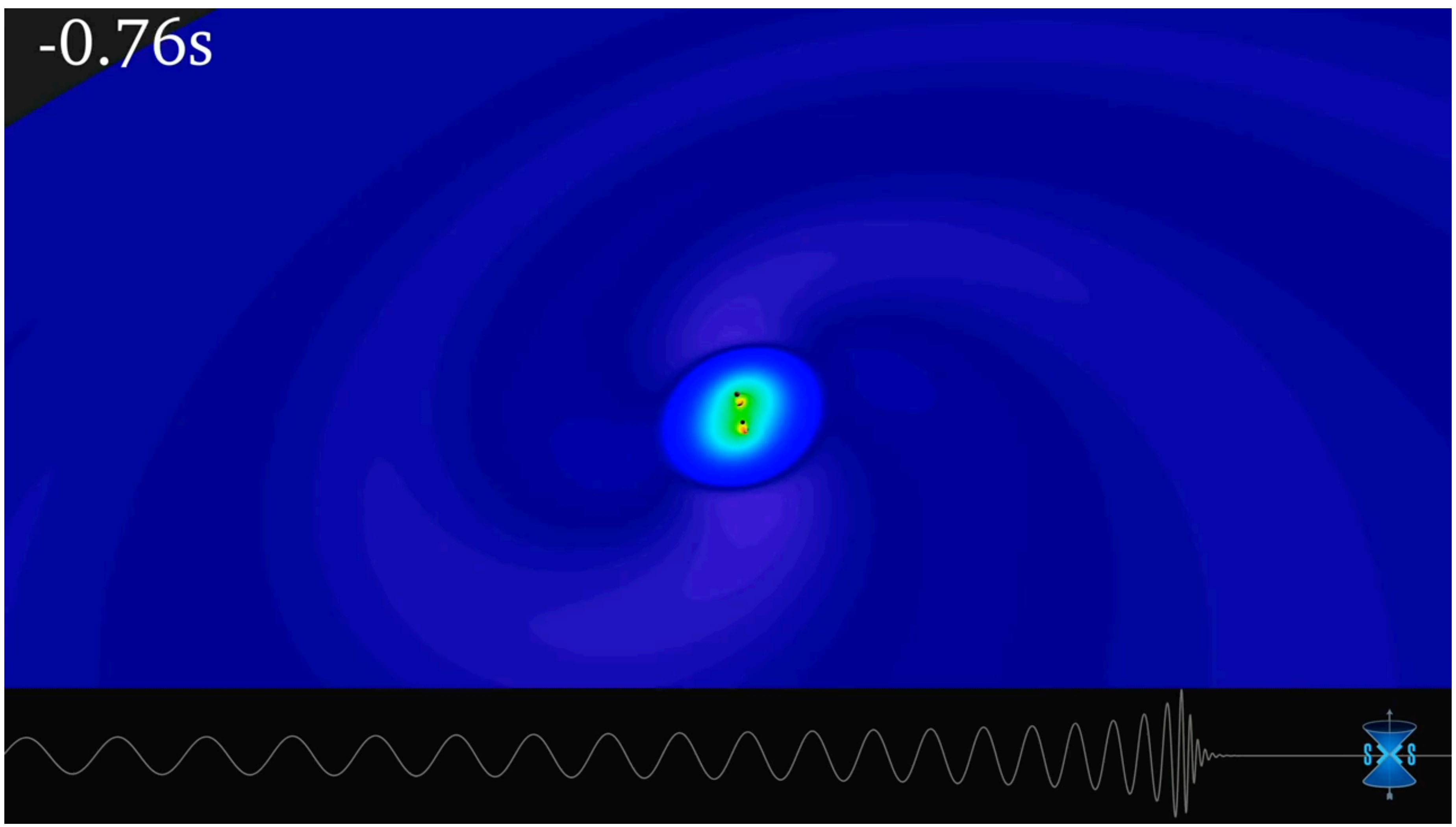
What are the properties of these waves?

Propagation: light speed, have effect of traveling tidal waves



What are the properties of these waves?

Generation: Accelerating masses (changing quadrupole and higher multipole moments)



$$h_{\mu\nu} \sim \frac{1}{R}\frac{d^2 Q_{\mu\nu}}{dt^2}$$

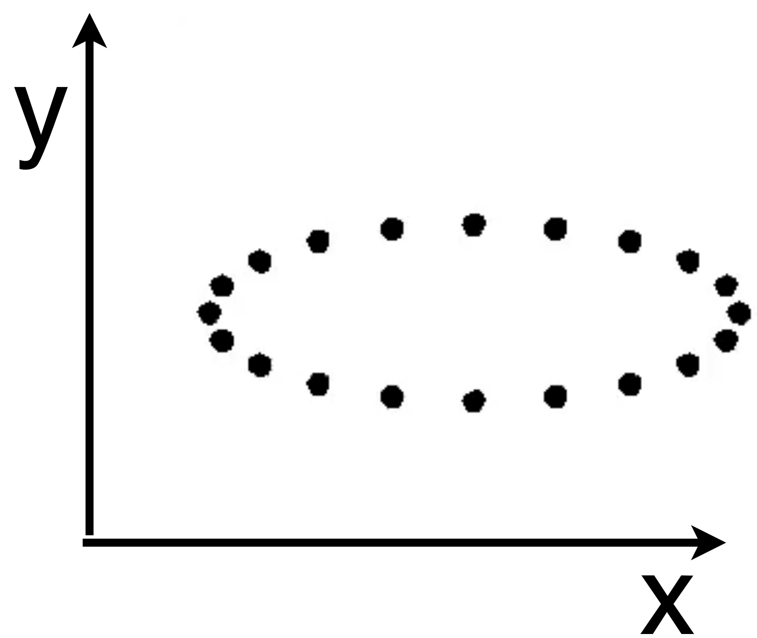
$$\sim \frac{G}{c^4}\frac{\mathrm{T}}{R}$$

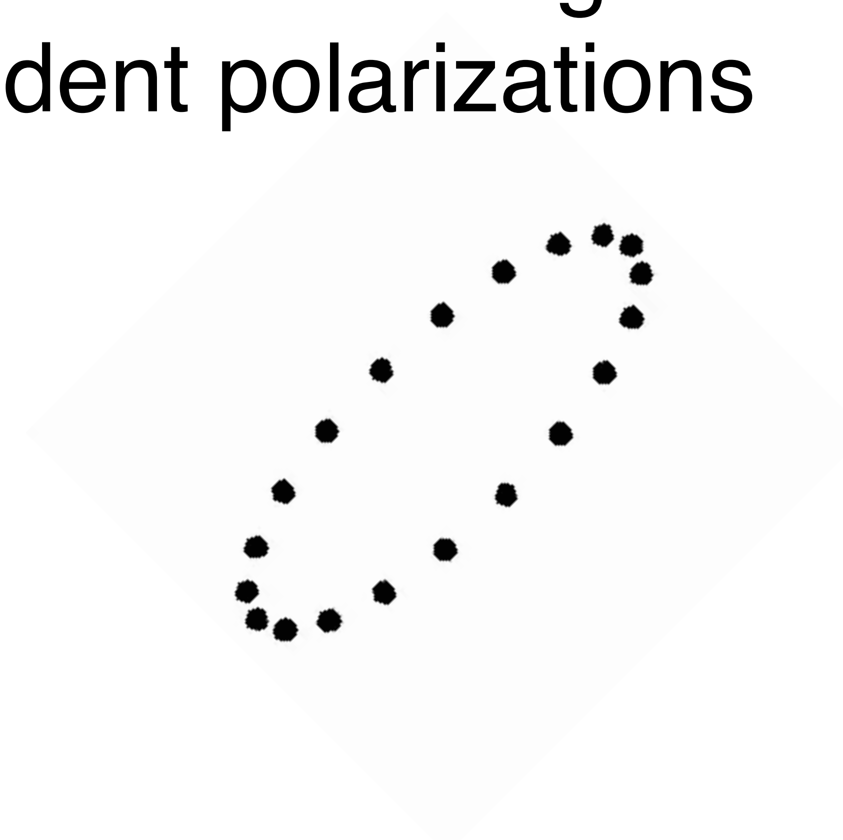
$$\sim 10^{-22}$$

T = Kinetic Energy

What are the properties of these waves?

Measurability: Induce a strain on a ring of test masses; two independent polarizations

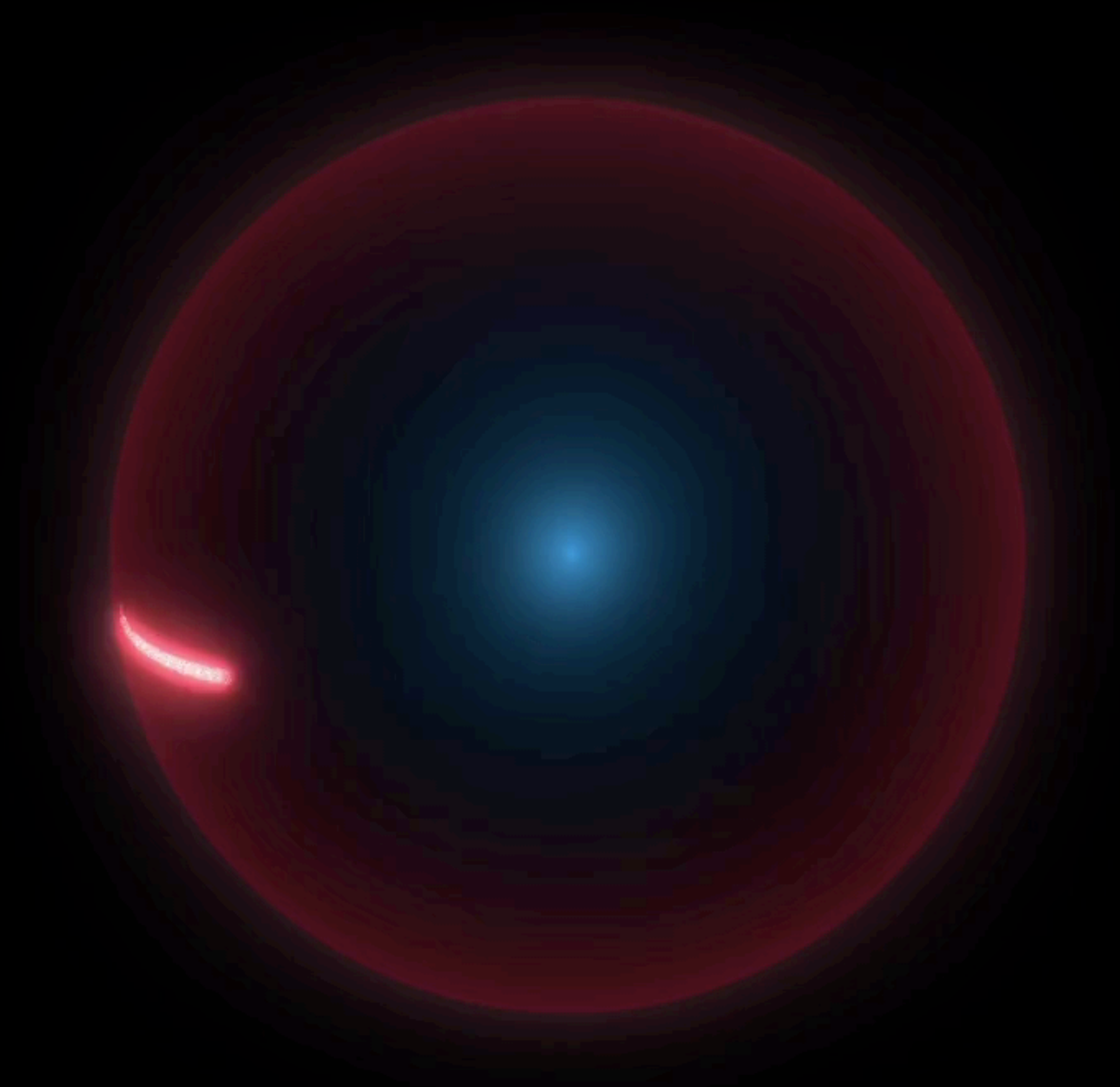




$$h = \frac{\delta L}{L}$$

$$\Delta L = L_x - L_y = hL$$

Example: Binary star system in Virgo cluster (16.5 Mpc away) would produce $h \sim 10^{-21}$. Over a distance of $L = 1$ AU, ΔL would be ~ 1 atomic diameter.



Credit: LIGO

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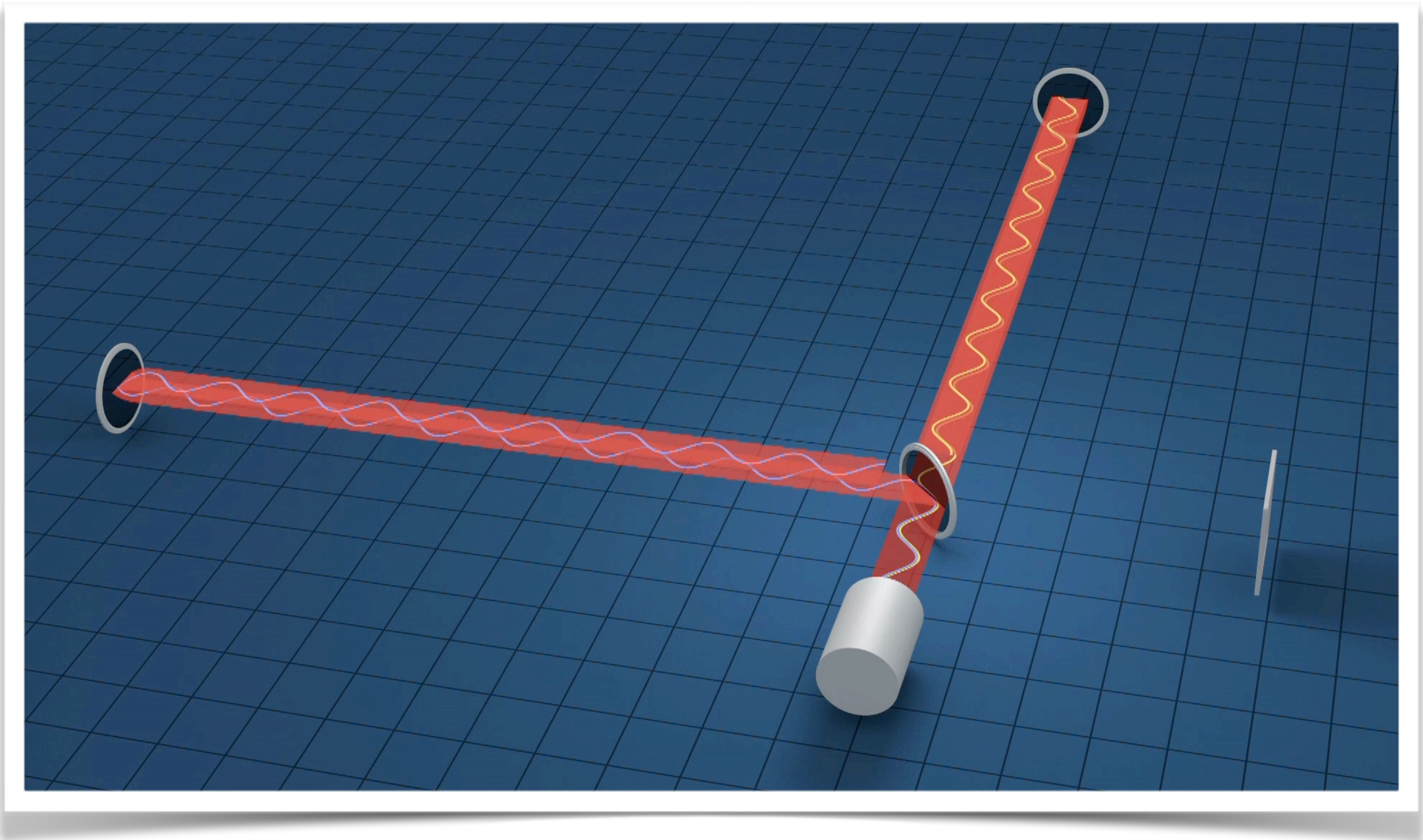
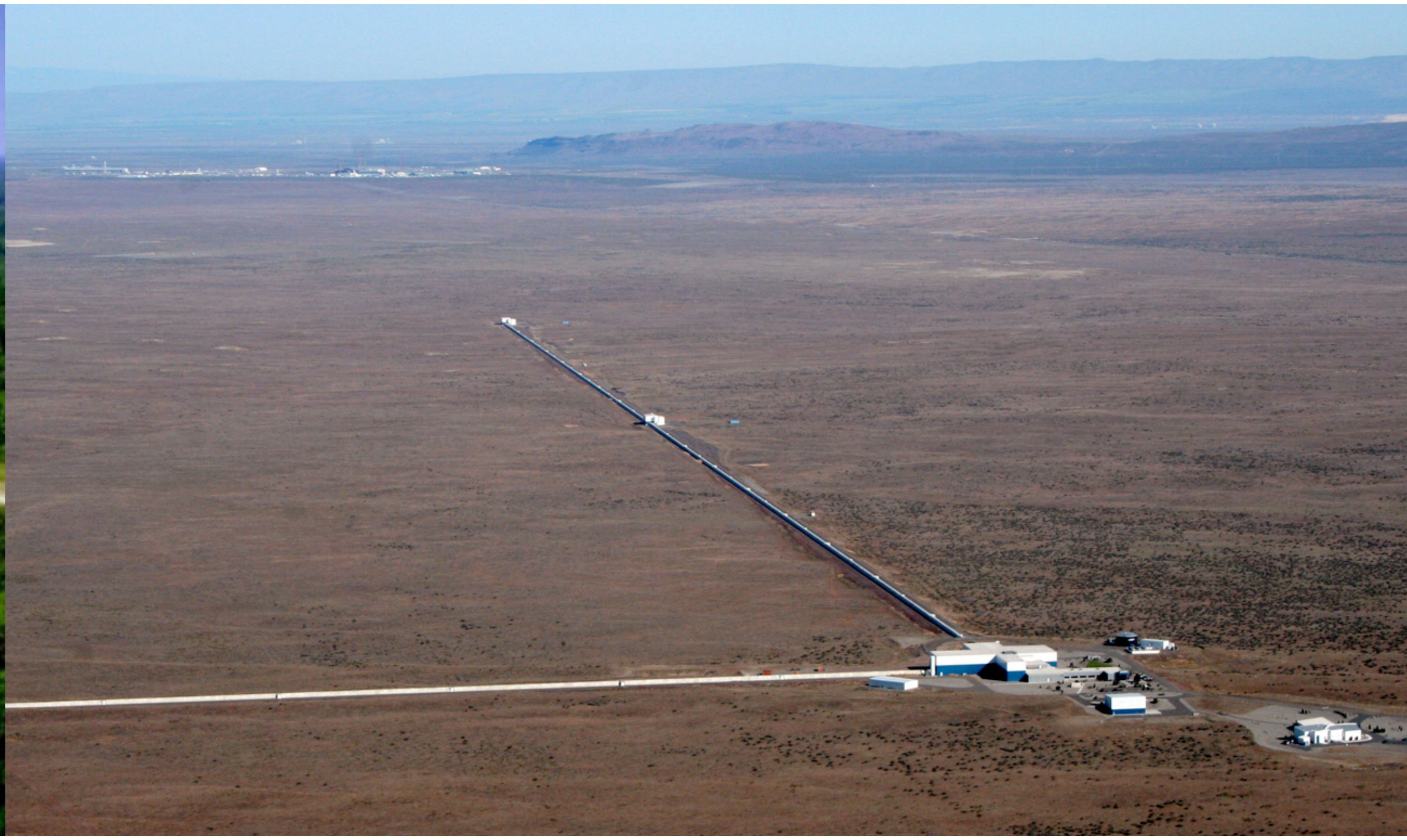
Ground-based Detector Network

$$h = \frac{\delta L}{L}$$



Credit: LIGO

The Advanced LIGO Detectors

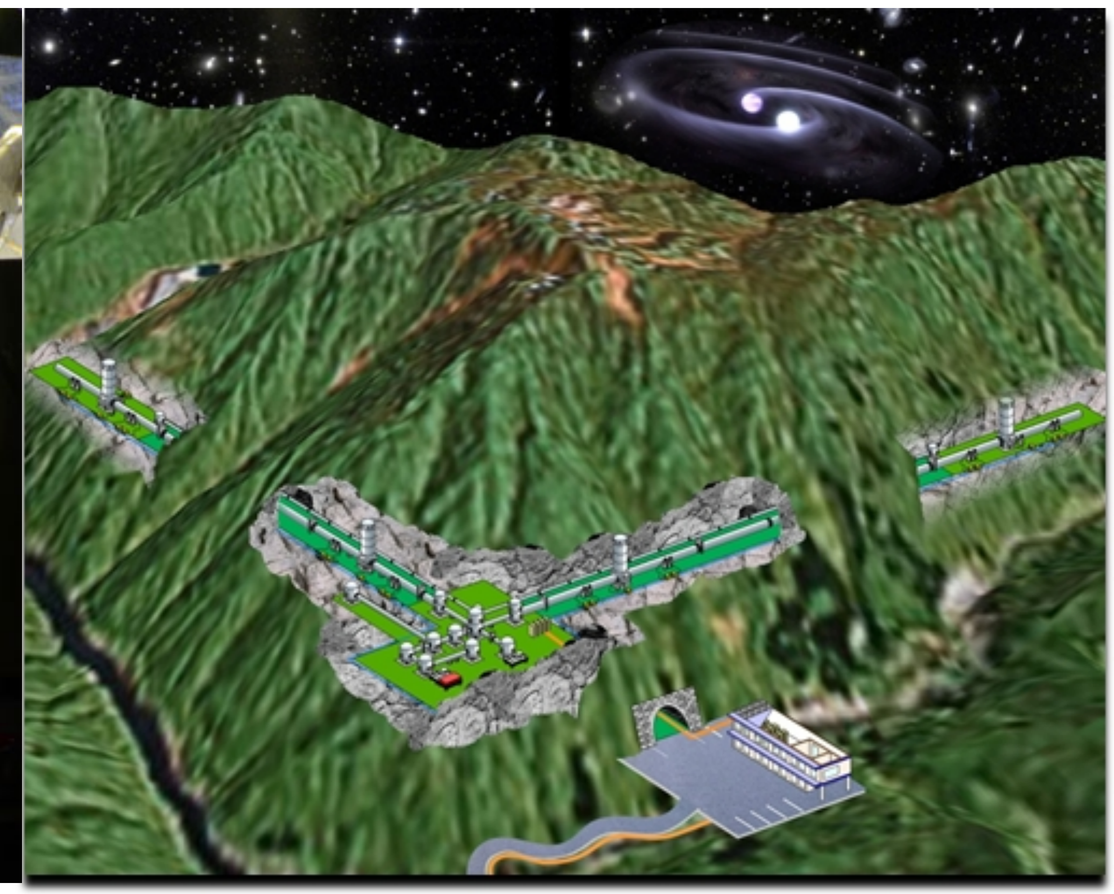



- LIGO - Laser Interferometer Gravitational-wave Observatory
- Operated in Hanford, WA and Livingston, LA USA
- 4 km-long arms

Advanced Virgo

- Operated in Cascina, Italy
- 3 km-long arms
- France, Italy, Netherlands, Poland, Hungary

Kamioka Gravitational-wave Detector (KAGRA)



- Operated in Kamioka Observatory, Japan
- 3-km arms
- First major underground GW observatory
- Will use cryogenic mirrors

GEO

- GEO600, test-bed for new technologies: laser stabilization, absorption-free optics, control engineering, vibration damping, etc.
- “Squeezed light” technology - mitigating shot-noise

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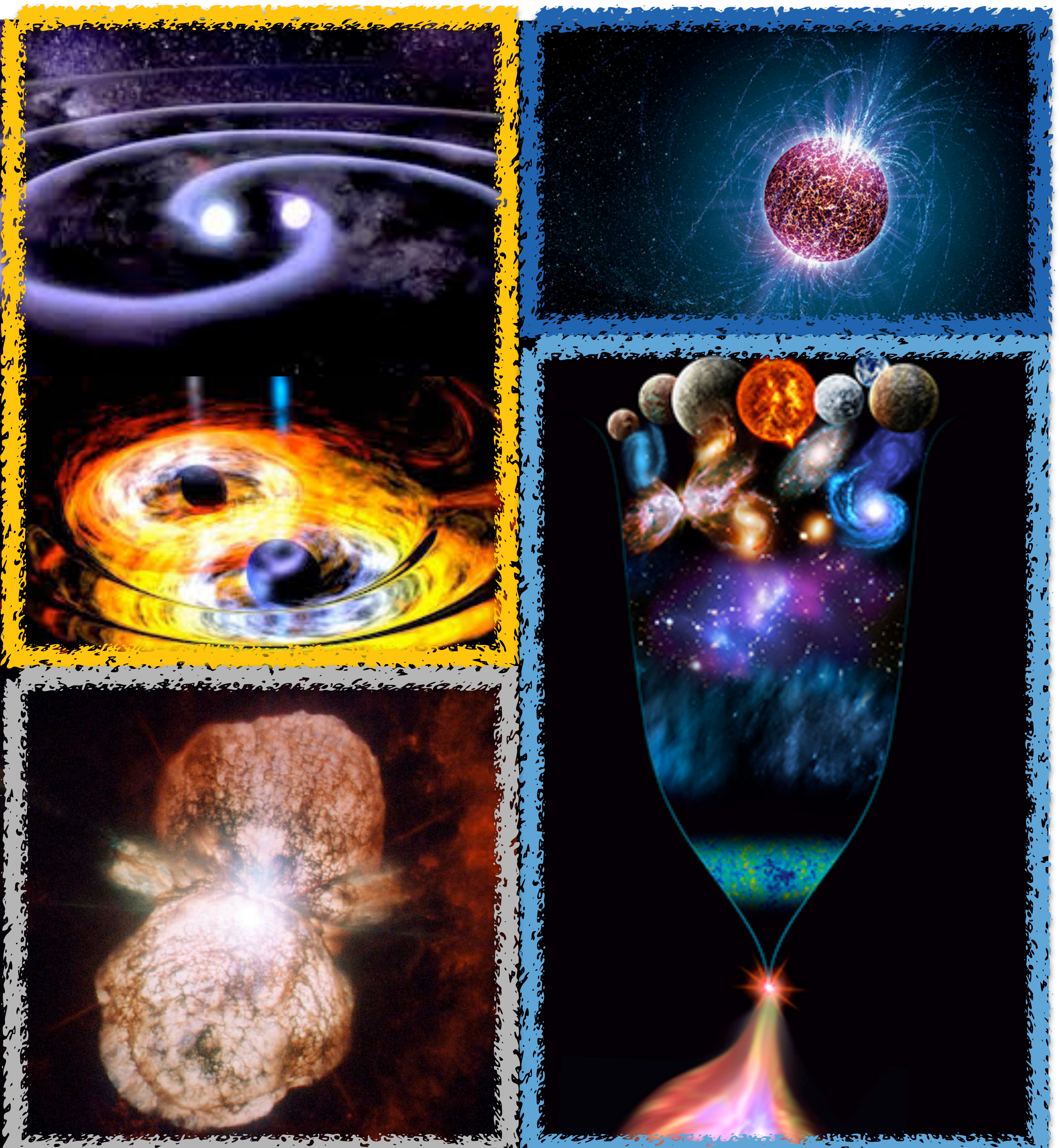
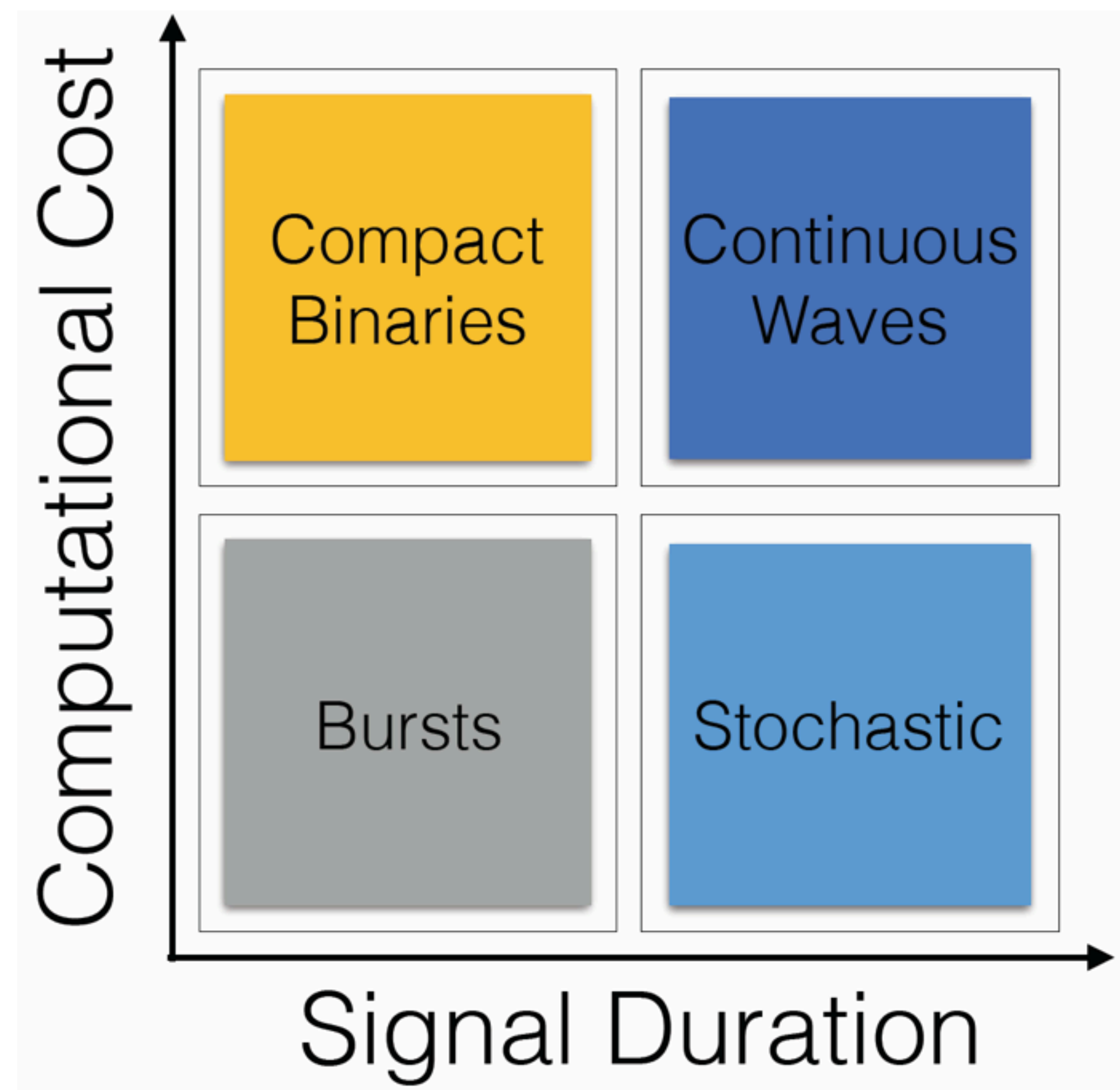
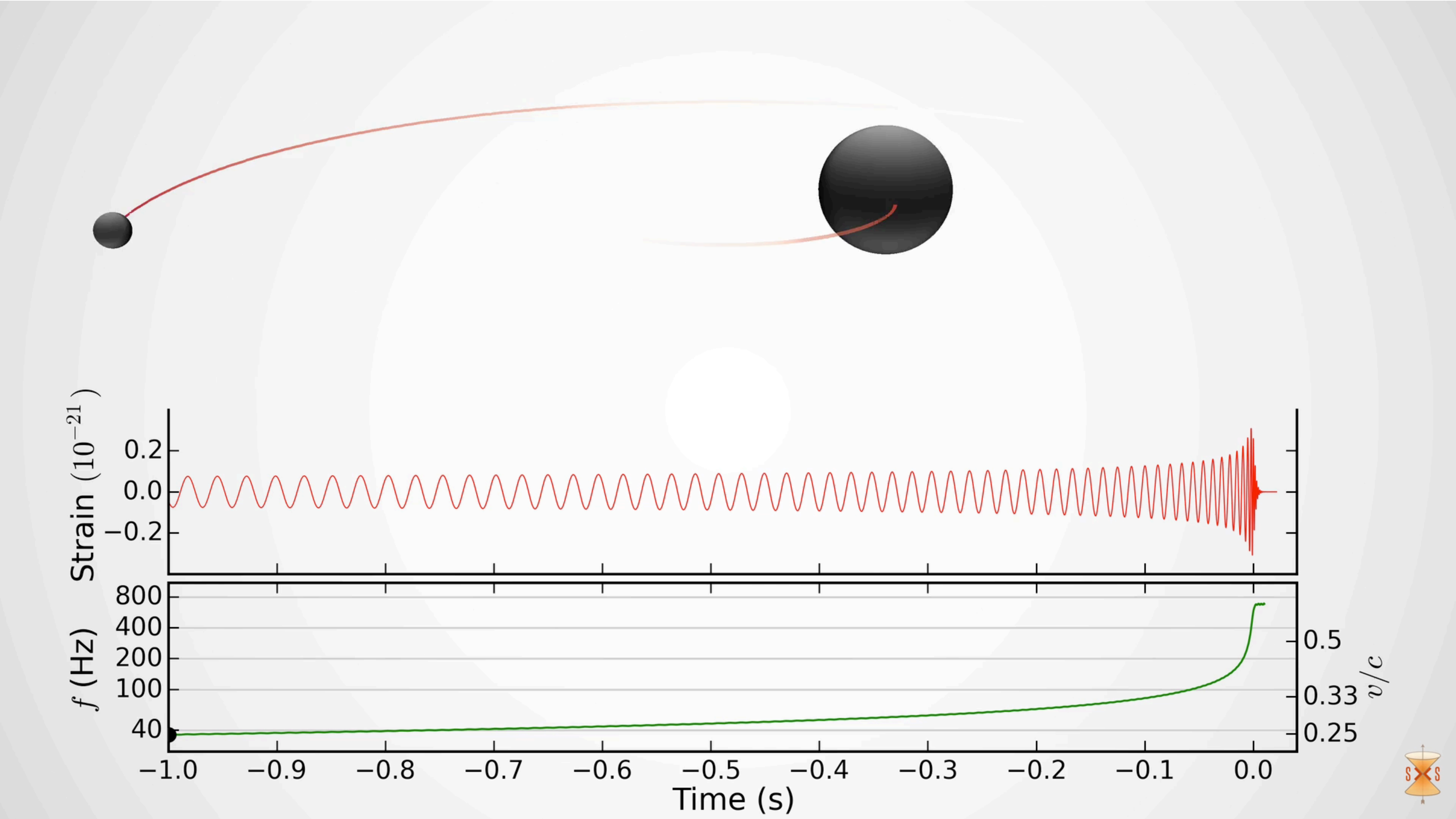
Gravitational-wave Sources for Ground-based Detectors





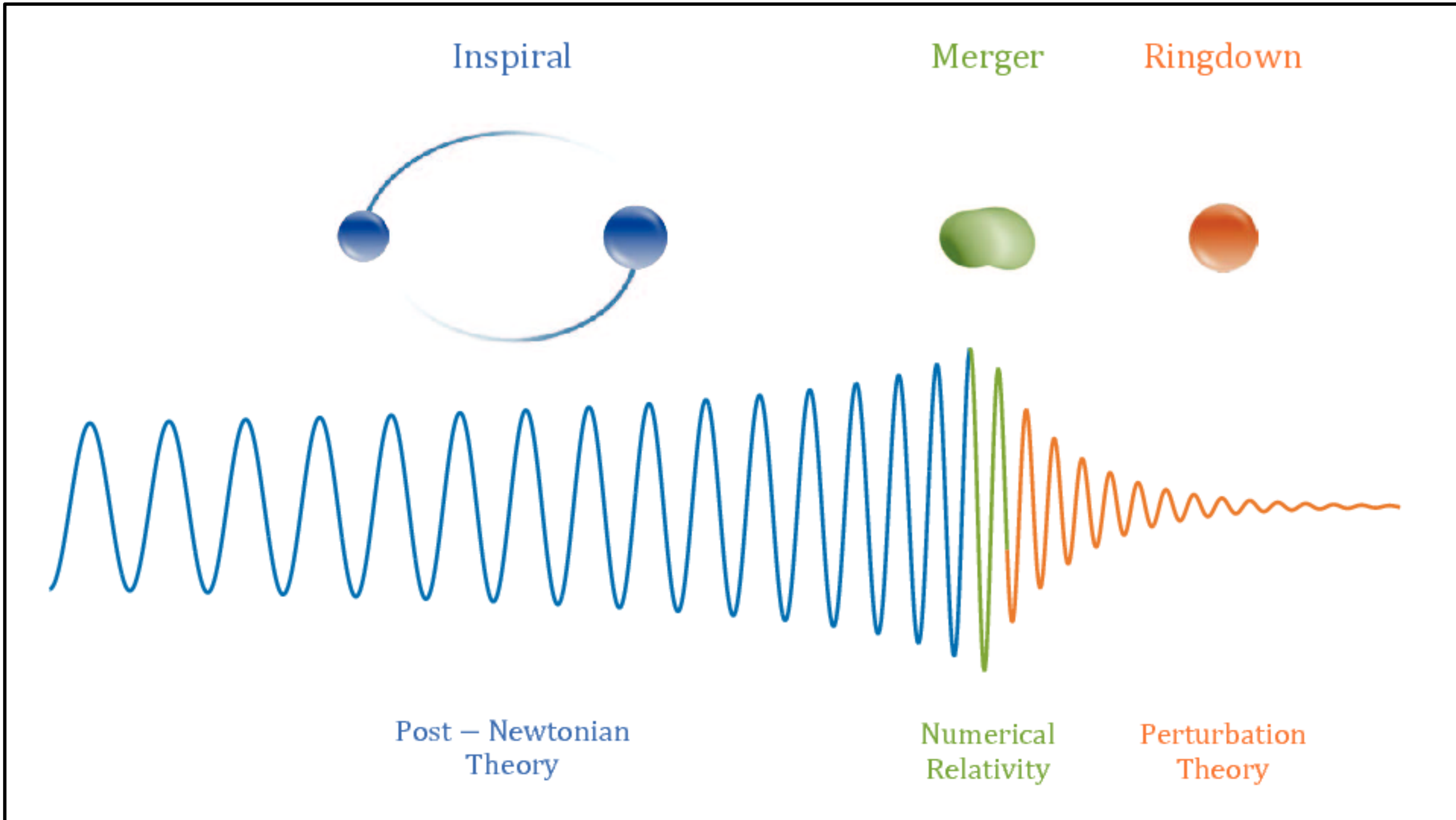
Compact Binary Coalescence Sources



Binaries in the last few seconds before merger:

- neutron stars
- stellar mass black holes
- intermediate mass black holes

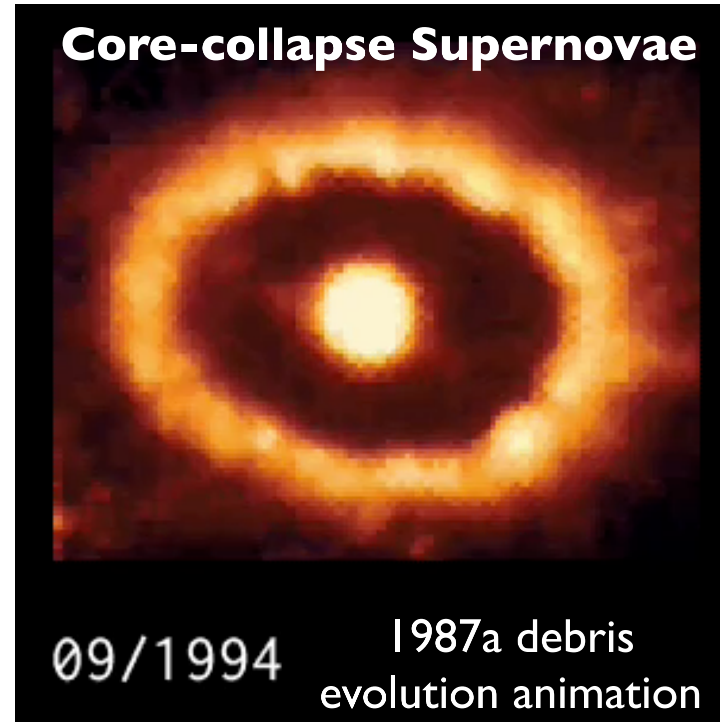
Compact Binary Coalescence Waveforms

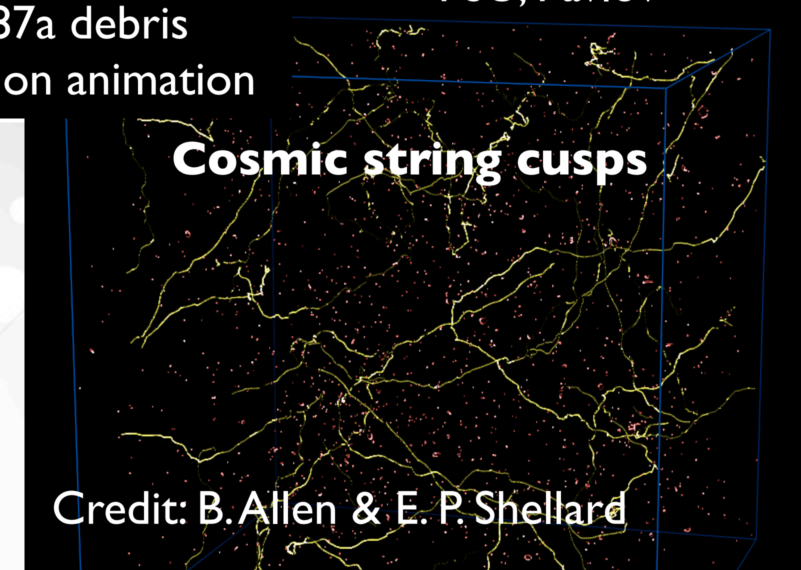


Burst Sources of Gravitational Waves

Transient GW astronomy using minimal assumptions. Sources could include:

- core collapse SN
- merger phase of heavy binary compact objects
- NS instabilities
- accretion disk instabilities
- fall back accretion, cosmic string cusps/kinks
- unexpected...

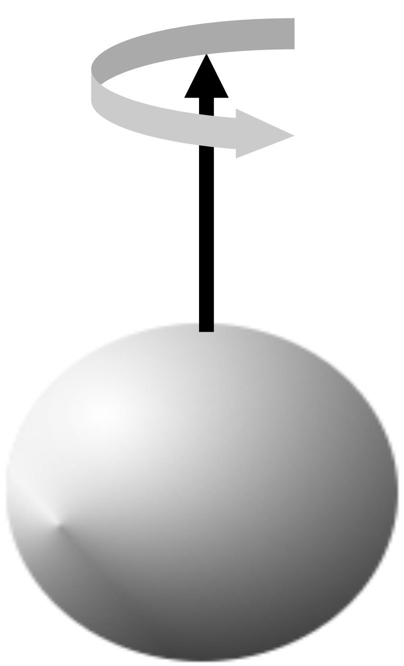


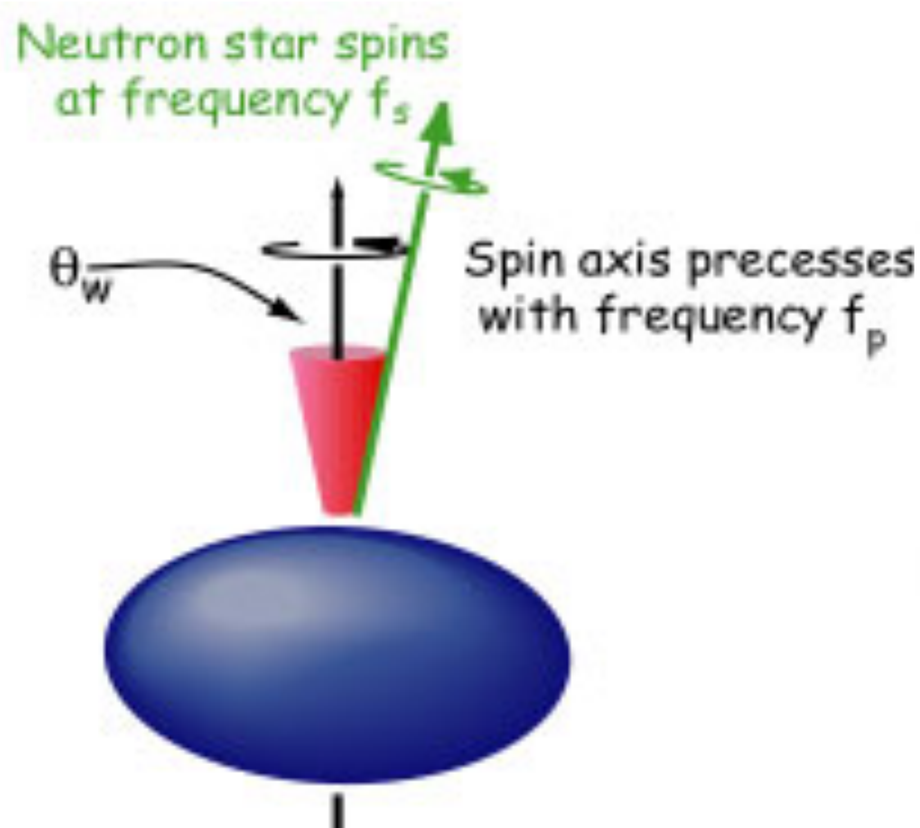


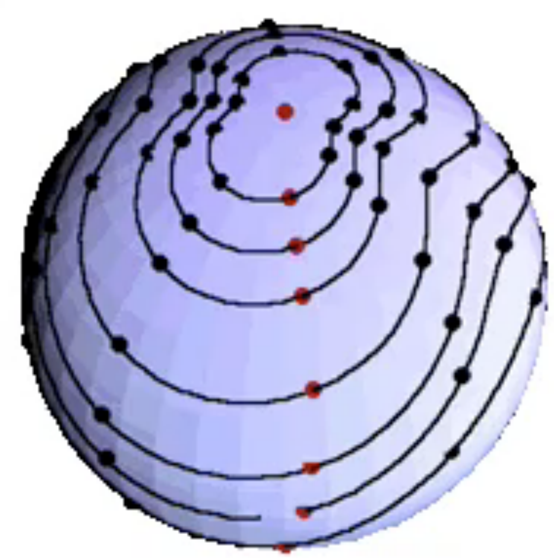
Continuous Gravitational Wave Sources

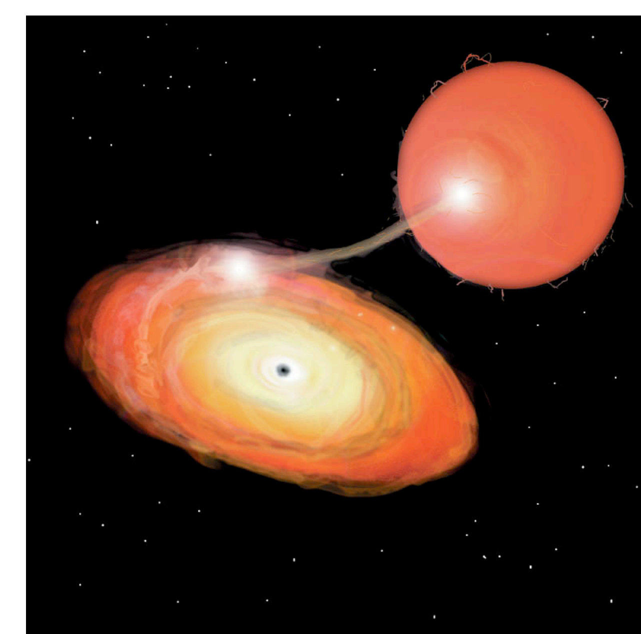
Non-axisymmetric rotating neutron stars; asymmetry could arise from:

- equatorial ellipticity (mm-high mountain) $f_{\rm GW} = 2 f_{\rm rot}$
- free precession around rotation axis $f_{\rm GW} \sim f_{\rm rot} + f_{\rm prec}$
- excitation of long-lasting oscillations $f_{\rm GW} \sim 4/3 f_{\rm rot}$
- deformation due to matter accretion $f_{\rm GW} = 2 f_{\rm rot}$

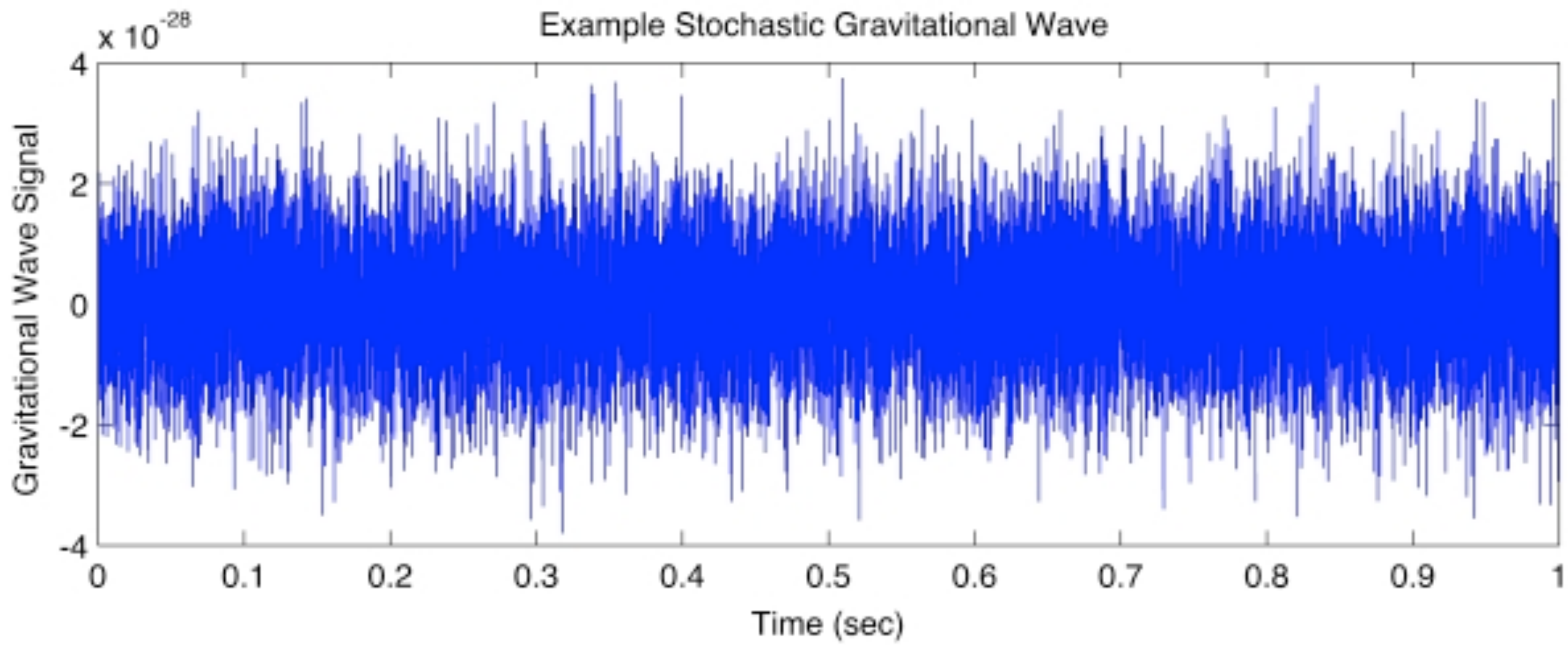




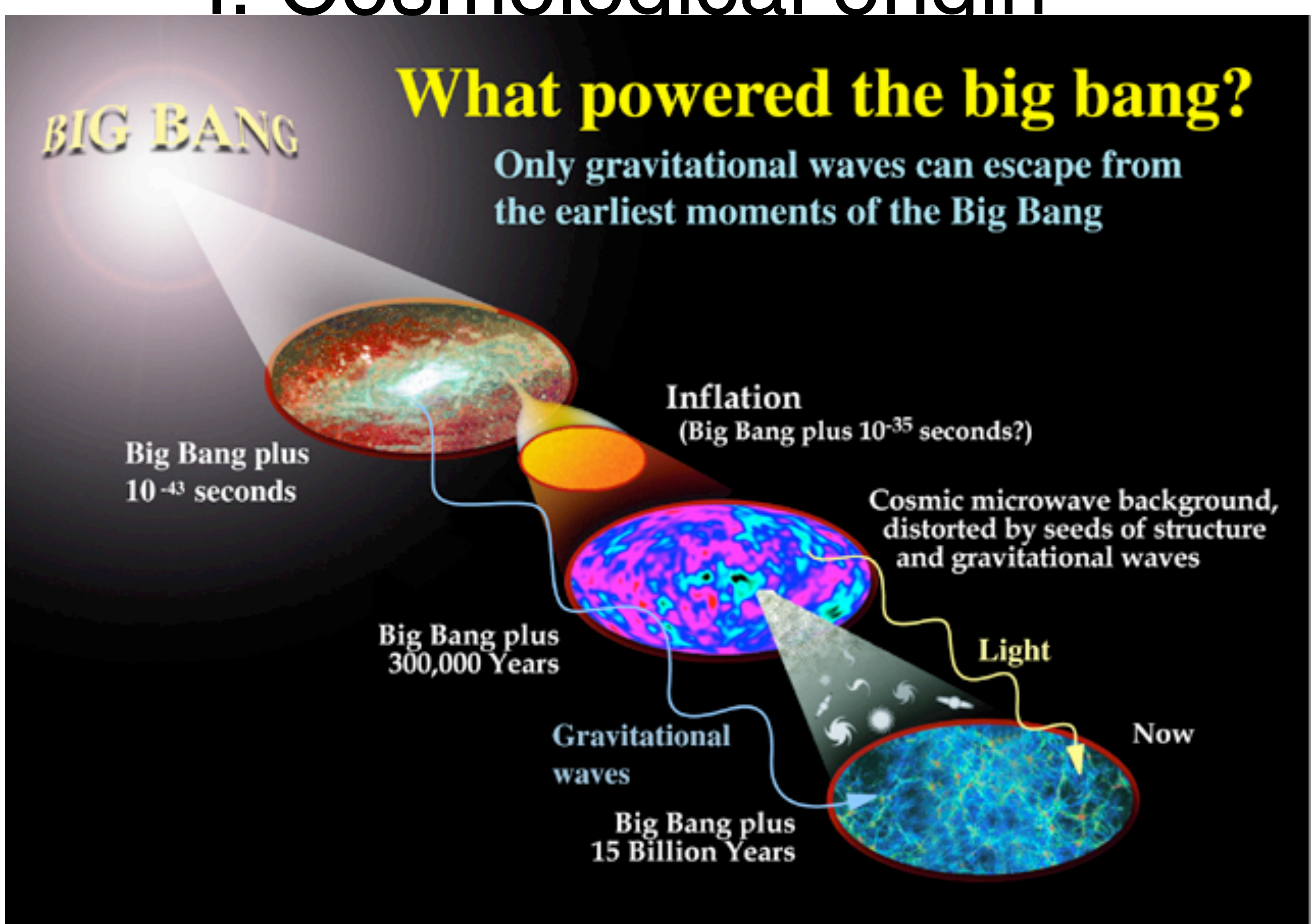




Stochastic Gravitational Waves



I. Cosmological origin



II. Astrophysical origin

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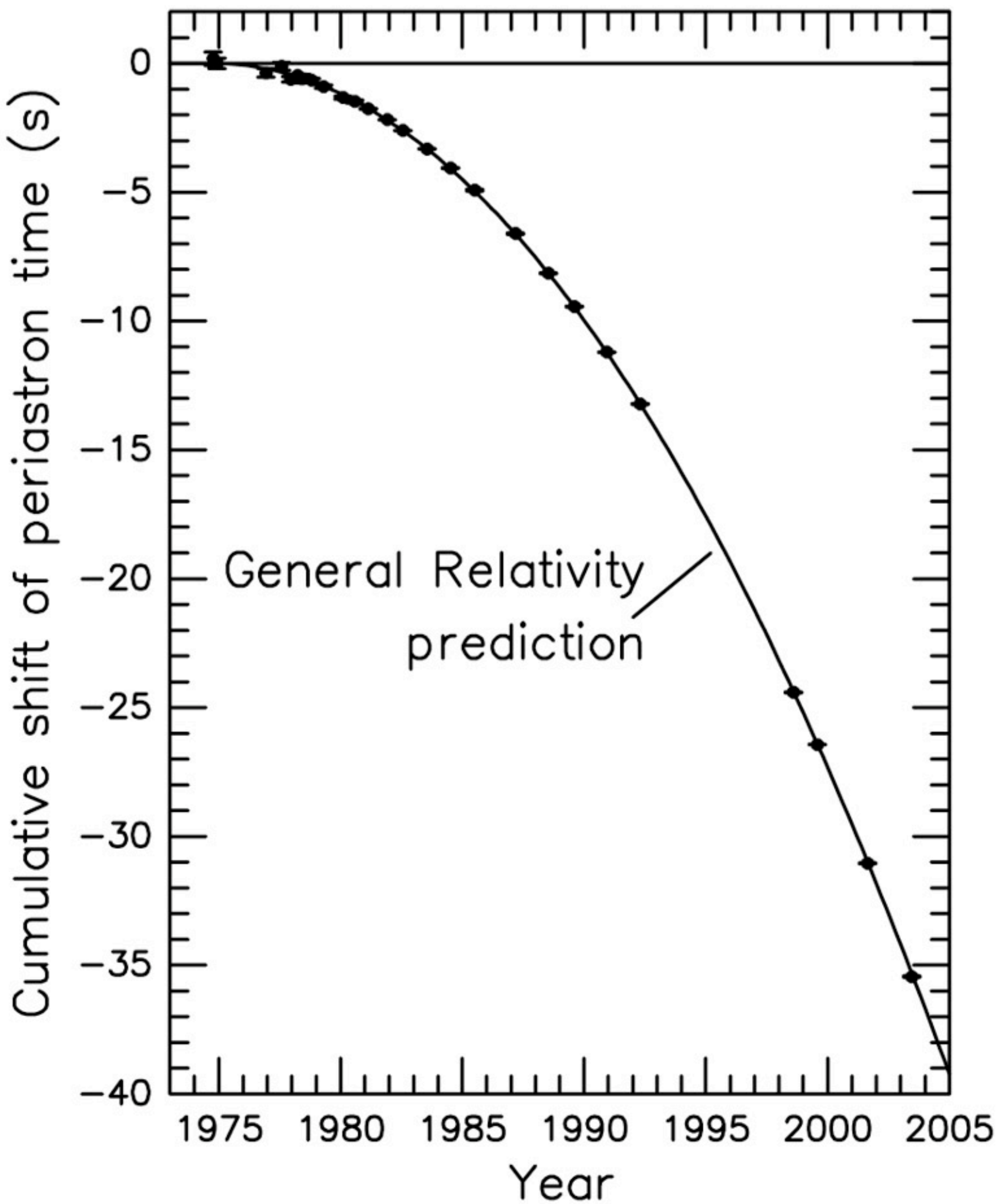
First Observational Evidence

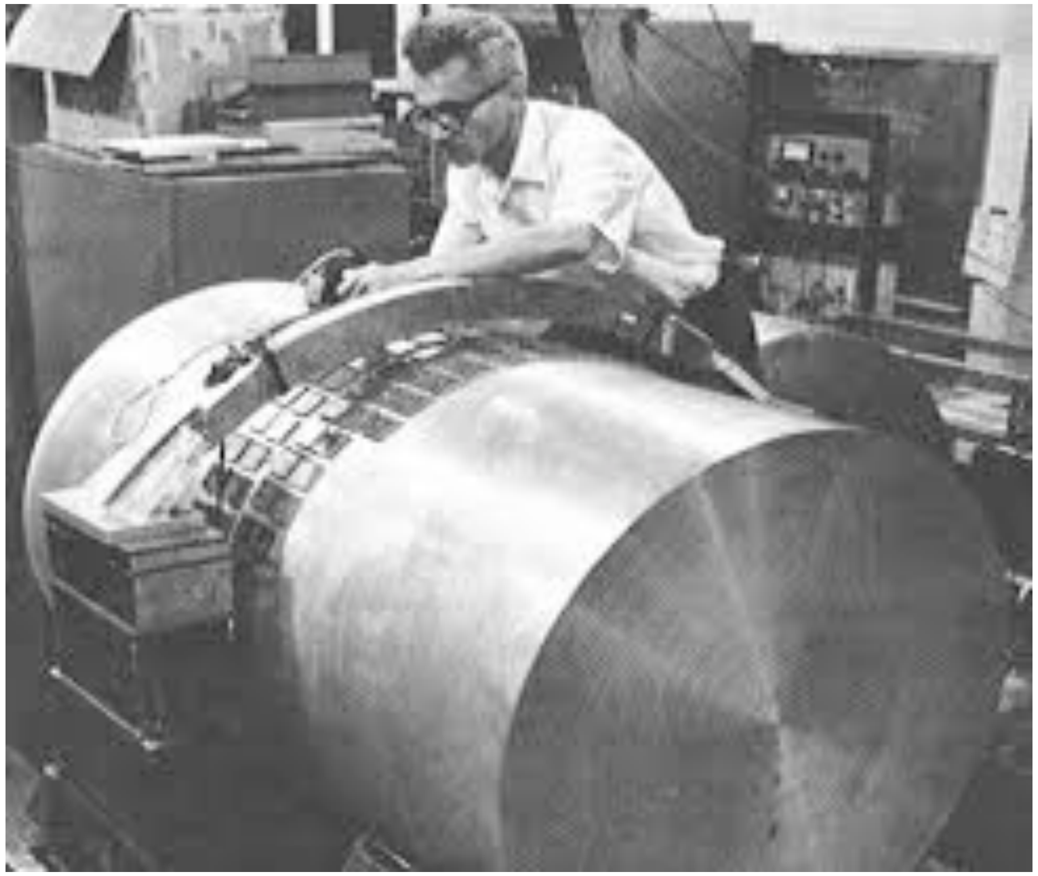
Hulse-Taylor Binary Pulsar



Pulsar-Neutron Star System

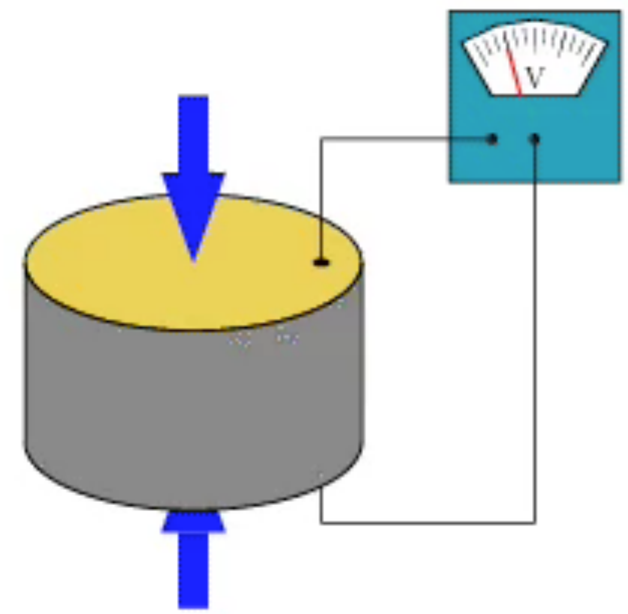
- Period: 7.75 hours
- Discovered by R. Hulse and J. Taylor
- Awarded 1993 Nobel prize

Bar Detectors



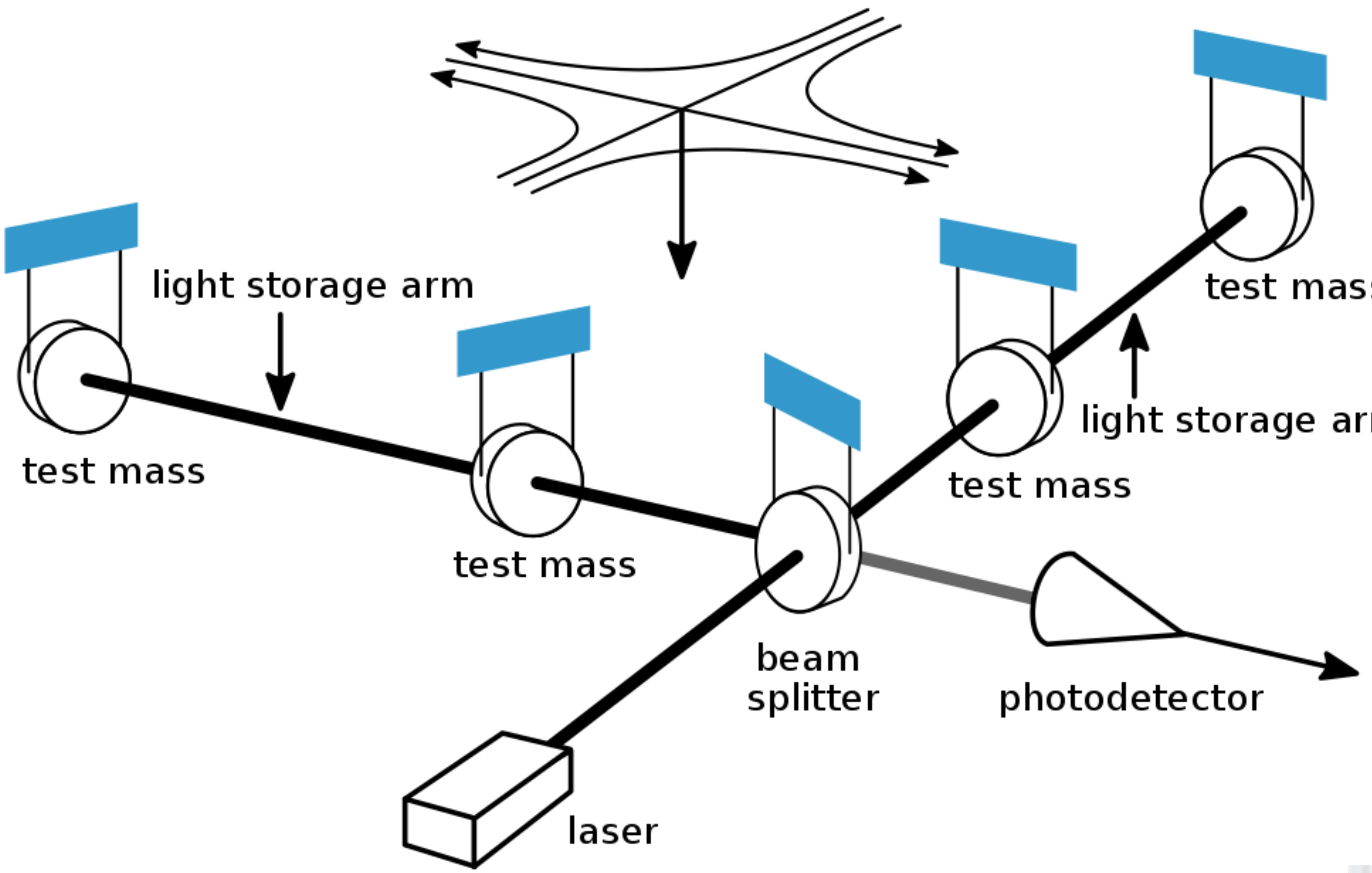
Joseph Webber -
University of Maryland
1961: proposed to use resonant bar detectors to detect GWs

Piezoelectric sensors

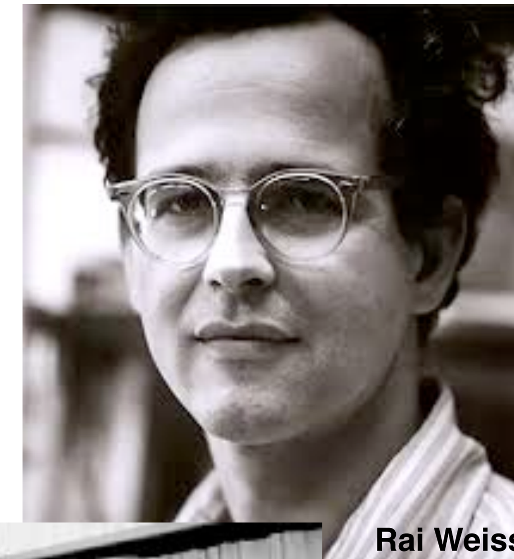


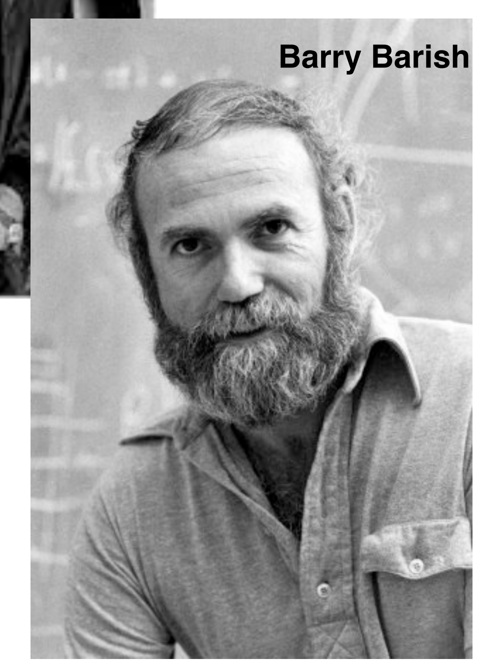
Only sensitive over very narrow range of frequencies

Interferometric Detectors



- 1970s: Development of precision measurement laser technology
- Early 1980s: Prototypes built in Glasgow, Garching, MIT
- 1994: LIGO construction begins...
- 1996: Virgo construction begins





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Power Spectral Density

$$s(t) = n(t) + h(t)$$

$$\tilde{x}(f) = \mathcal{F}\left\{x(t)\right\}(f) = \int_{-\infty}^{\infty} \mathrm{d}t\, x(t) \exp(-2\pi \mathrm{i} f t)$$

Energy in time series is $E = \int_{\infty}^{\infty} |n(t)|^2 \, dt = \int_{\infty}^{\infty} |\tilde{n}(f)|^2 \, df$

Parseval's theorem

f - frequency in Hz, i.e. cycles per second

$|\tilde{n}(f)|^2$ - density function describing energy per unit frequency in time series at frequency f

Energy spectral density of signal is defined as $S(f) = |\tilde{n}(f)|^2$

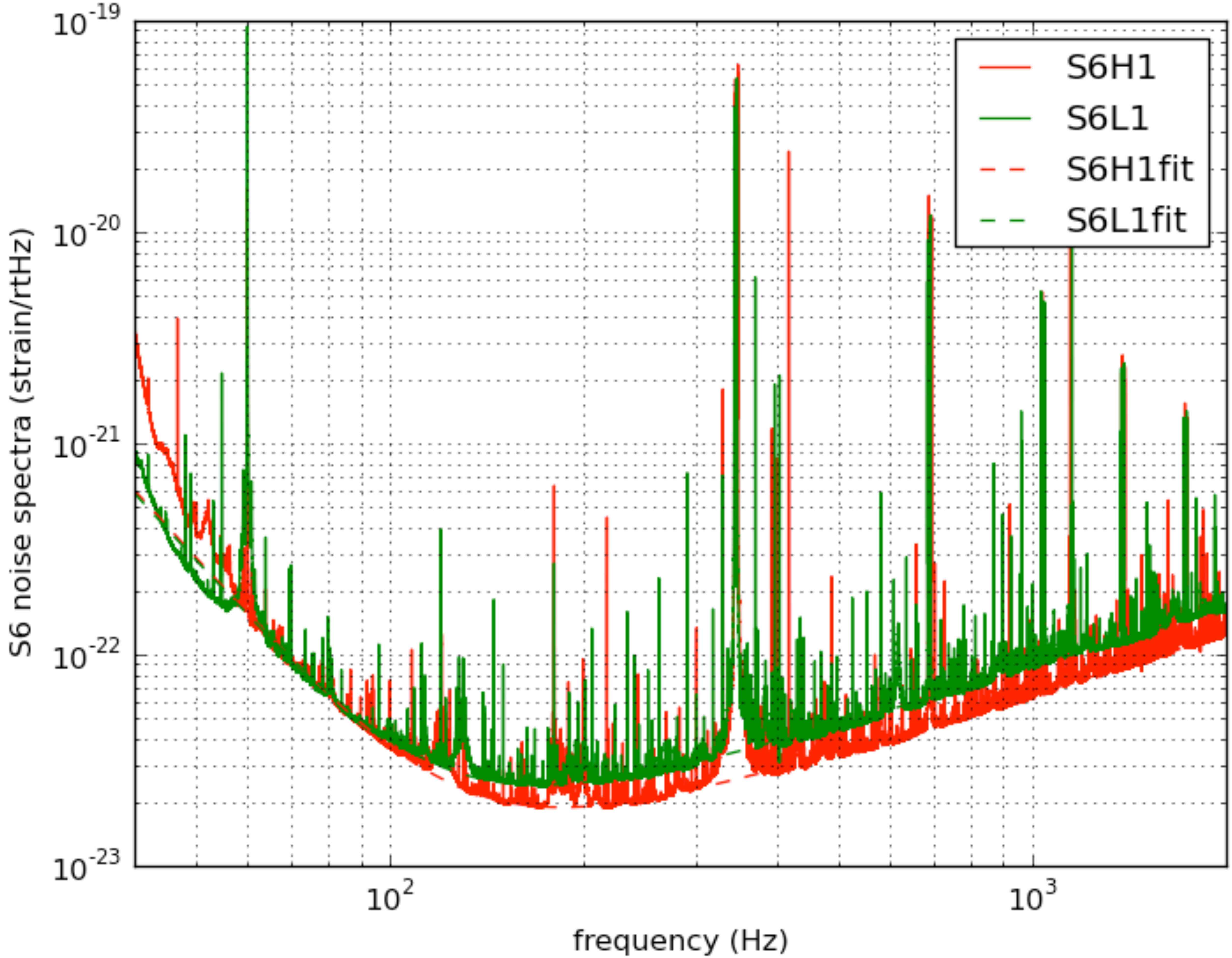
Power Spectral Density

If the energy is spread over long-ish time interval, we instead define the power spectral density (PSD):

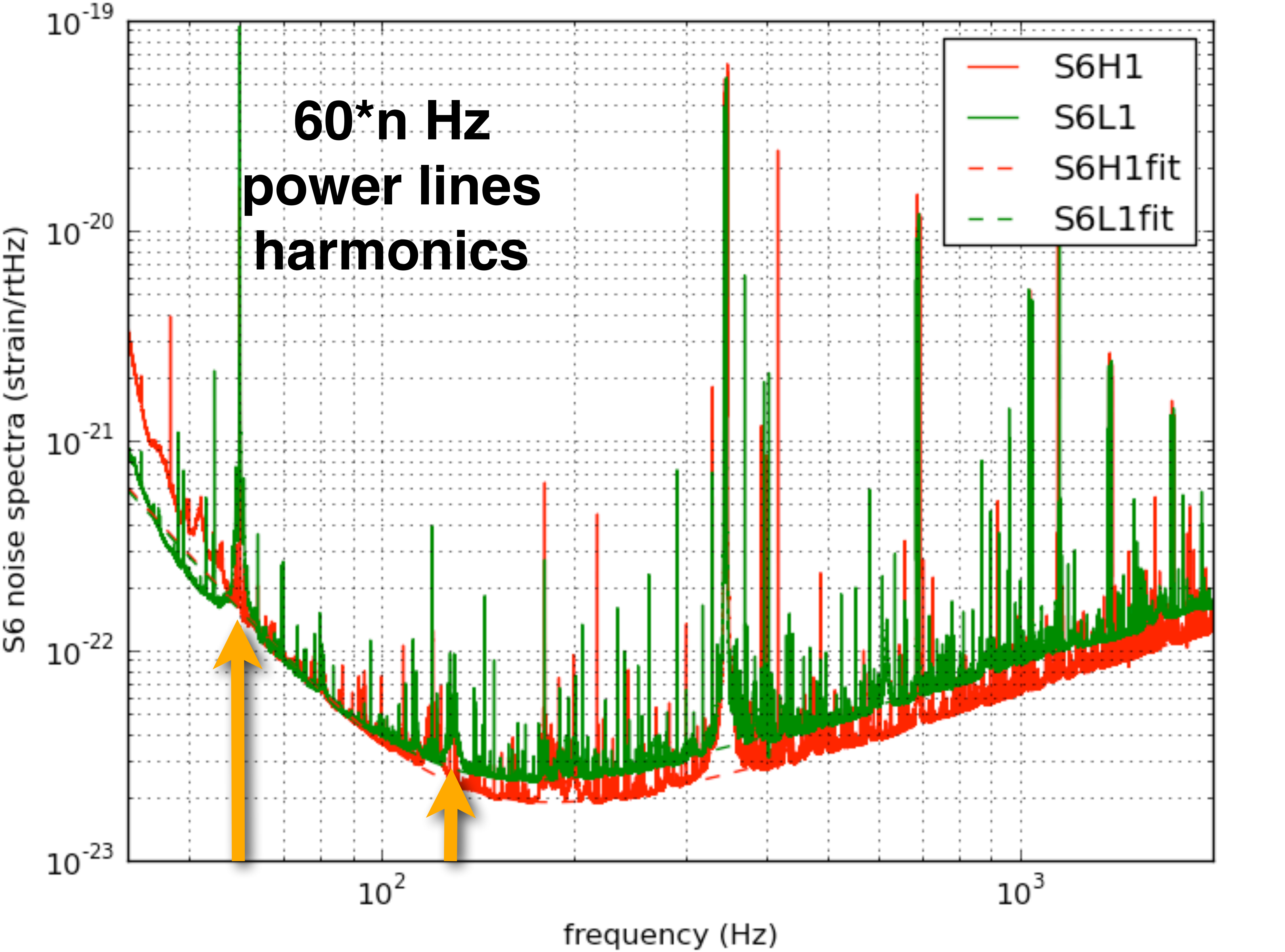
$$S(f) = \lim_{T\to\infty} \mathbb{E}\left[|\tilde{n}(f)|^2\right]$$

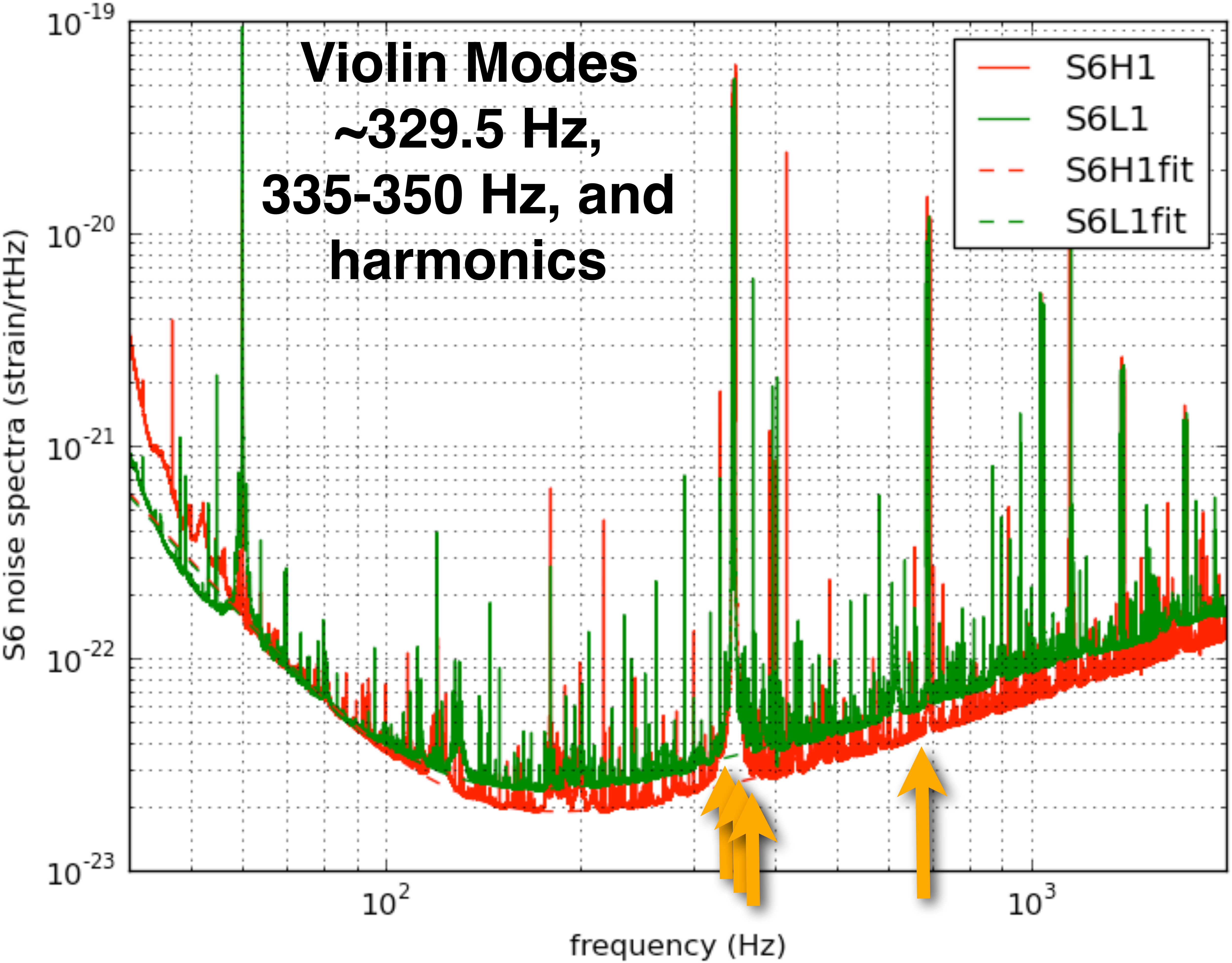
Power spectral density (PSD): $S(f) \sim \frac{\mathrm{strain}^2}{\mathrm{Hz}}$

Amplitude spectral density (ASD): $\sqrt{S(f)} \sim \frac{\mathrm{strain}}{\sqrt{\mathrm{Hz}}}$

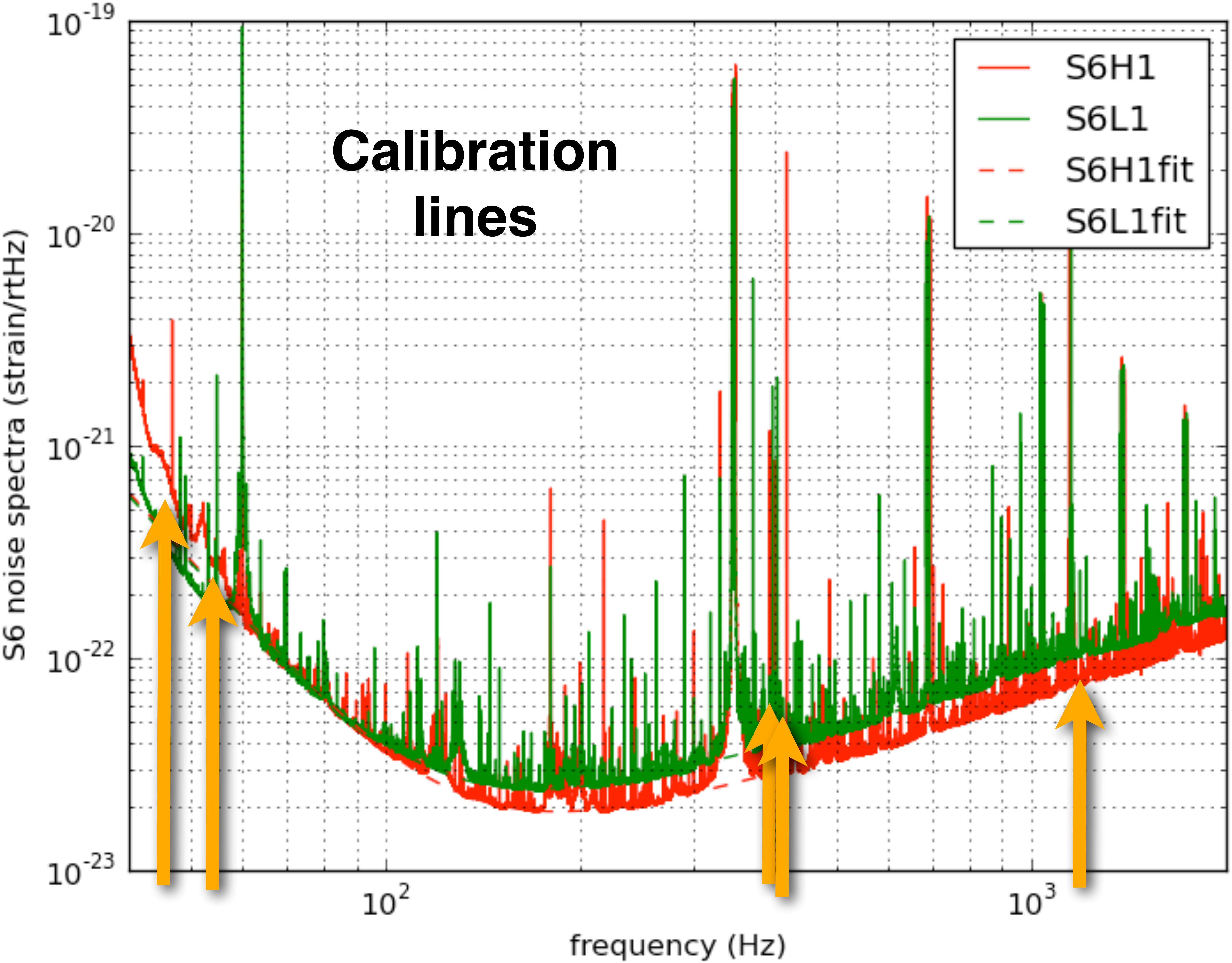


S6H1
S6L1
S6H1fit
S6L1fit
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-23}
S6 noise spectra (strain/rtHz)
10^{2}
10^{3}
frequency (Hz)

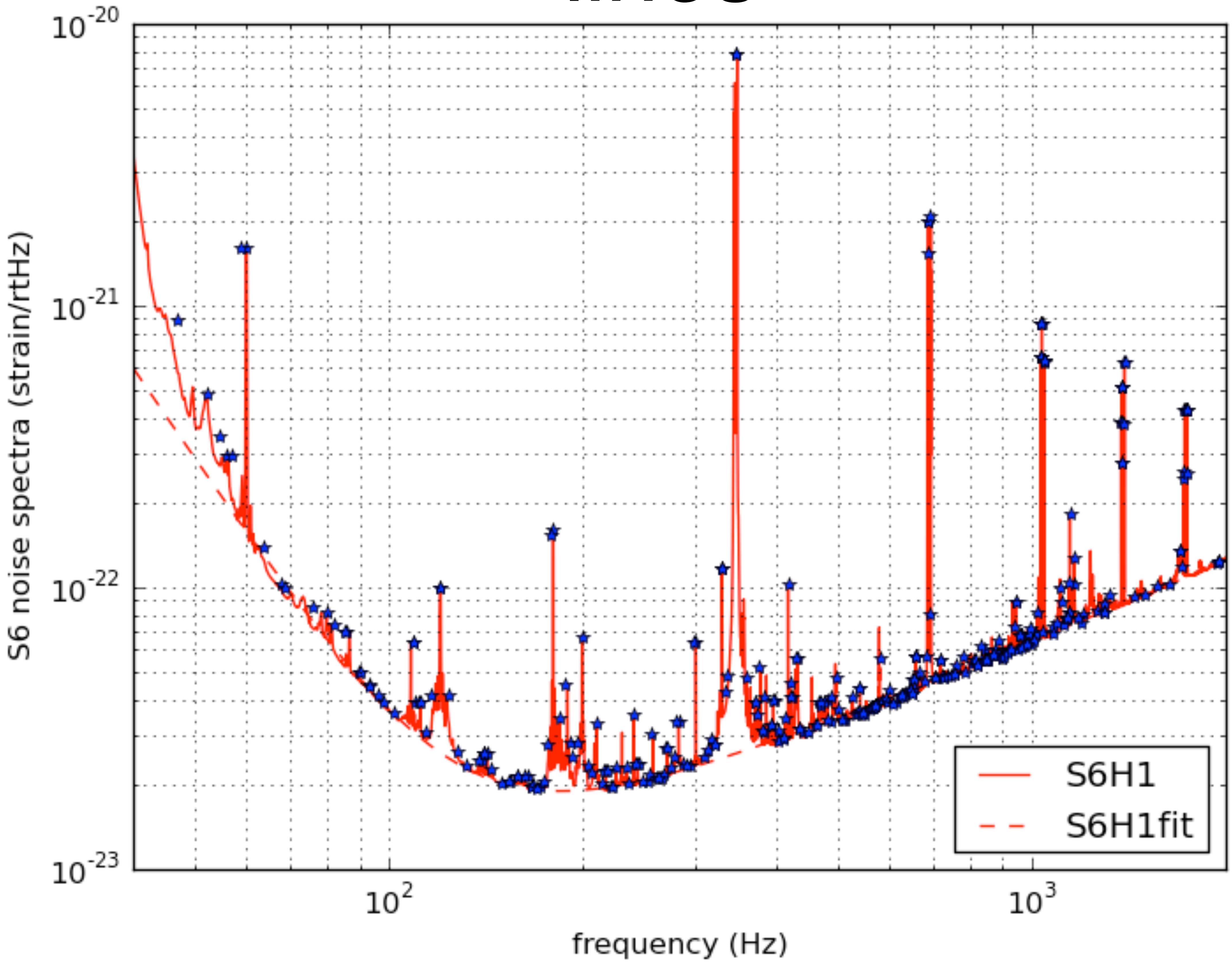

60*n Hz
power lines
harmonics
S6H1
S6L1
S6H1fit
S6L1fit
S6 noise spectra (strain/rtHz)
frequency (Hz)
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{2}
10^{3}



Violin Modes
~329.5 Hz,
335-350 Hz, and
harmonics
S6H1
S6L1
S6H1fit
S6L1fit
S6 noise spectra (strain/rtHz)
frequency (Hz)
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{2}
10^{3}


Calibration lines
S6H1
S6L1
S6H1fit
S6L1fit
S6 noise spectra (strain/rtHz)
frequency (Hz)
10^-19
10^-20
10^-21
10^-22
10^-23
10^2
10^3

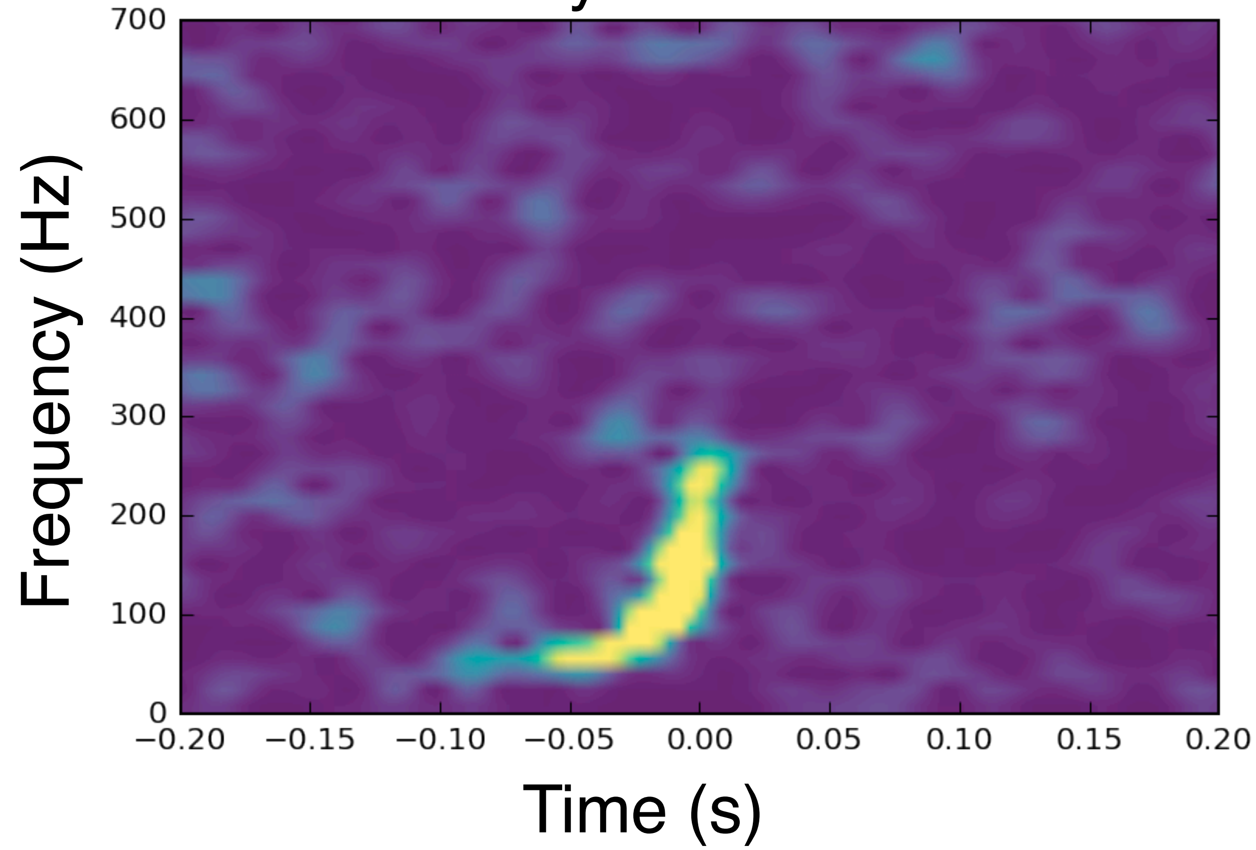
An example of identified spectral lines



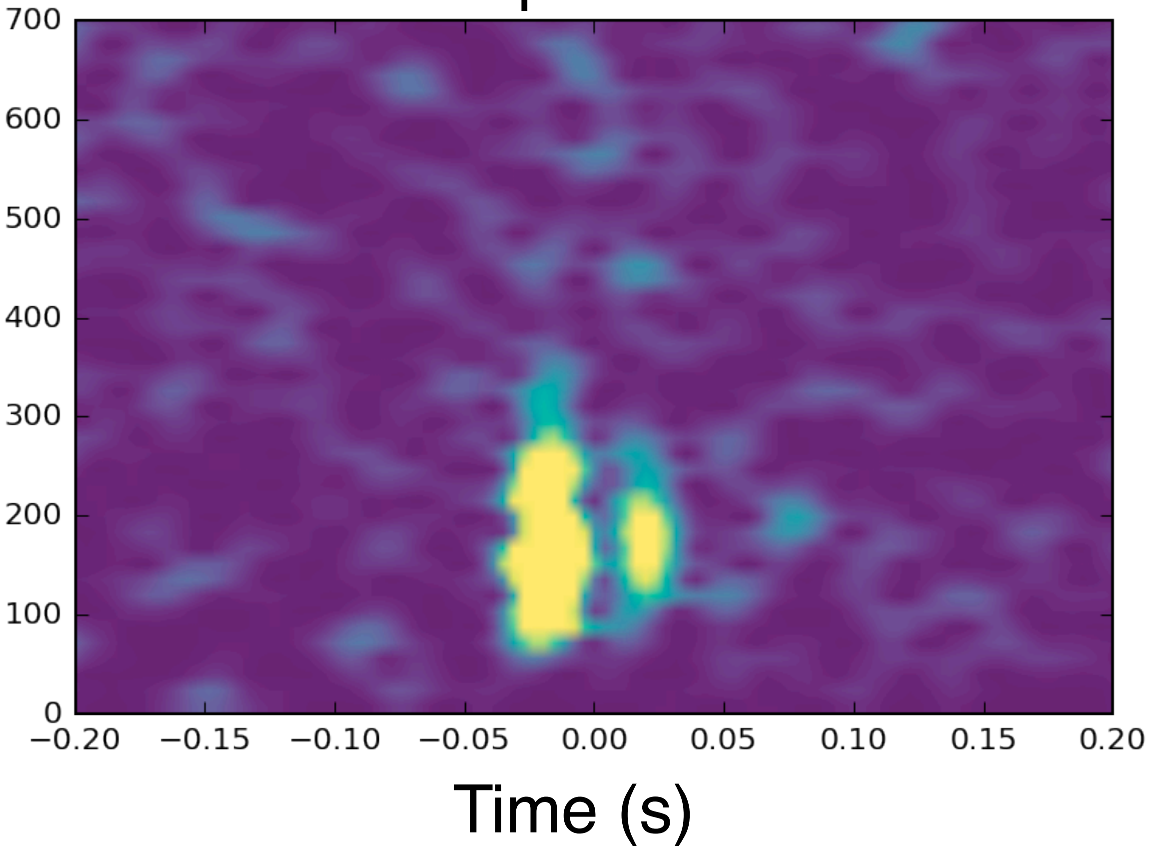
Spectrogram

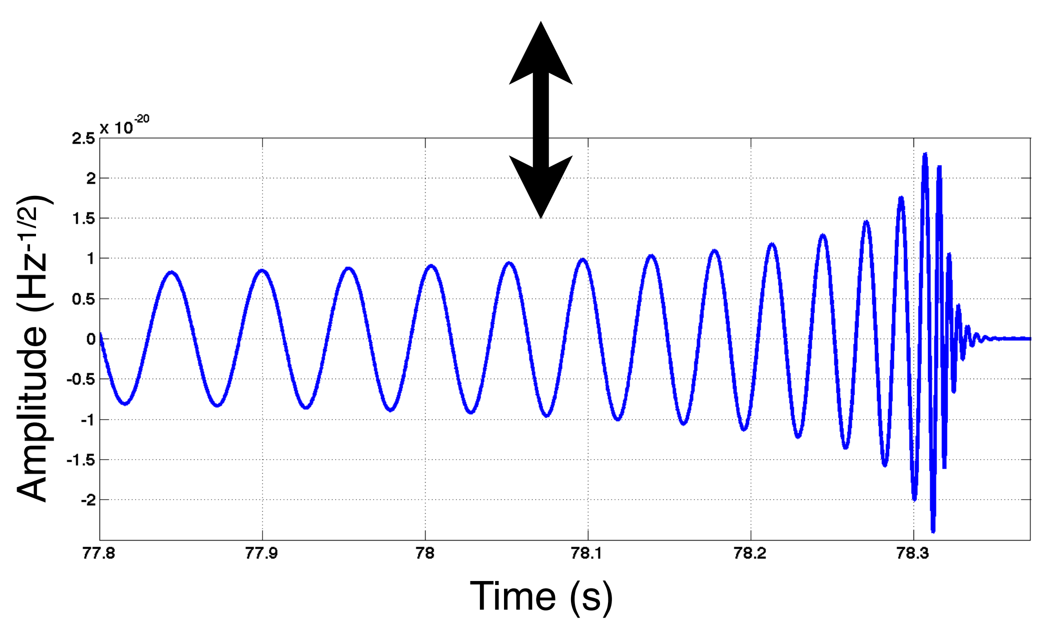
Visual representation of power at certain frequencies as a function of time.

I. Binary black hole



II. Supernova





Also known as a "chirp" signal.

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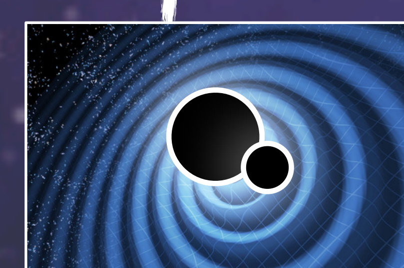
Sept 12, 2015

Advanced LIGO's First Observing Run (O1)

Sep 2015	Oct 2015	Nov 2015	Dec 2015	Jan 2016

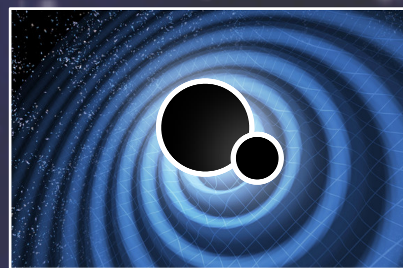
GW150914
Sept 14, 2015

LVT151012
Oct 12, 2015

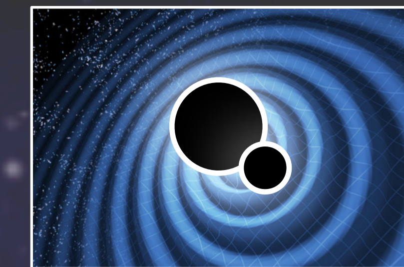


GW151226
Dec 26, 2015

GW170104
Jan 4, 2017



GW170814
Aug 14, 2017

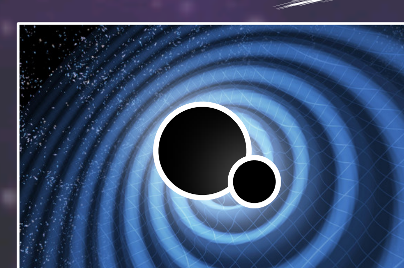


Advanced LIGO's Second Observing Run (O2)

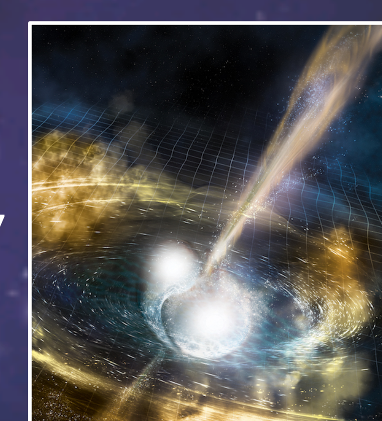
Virgo turns on

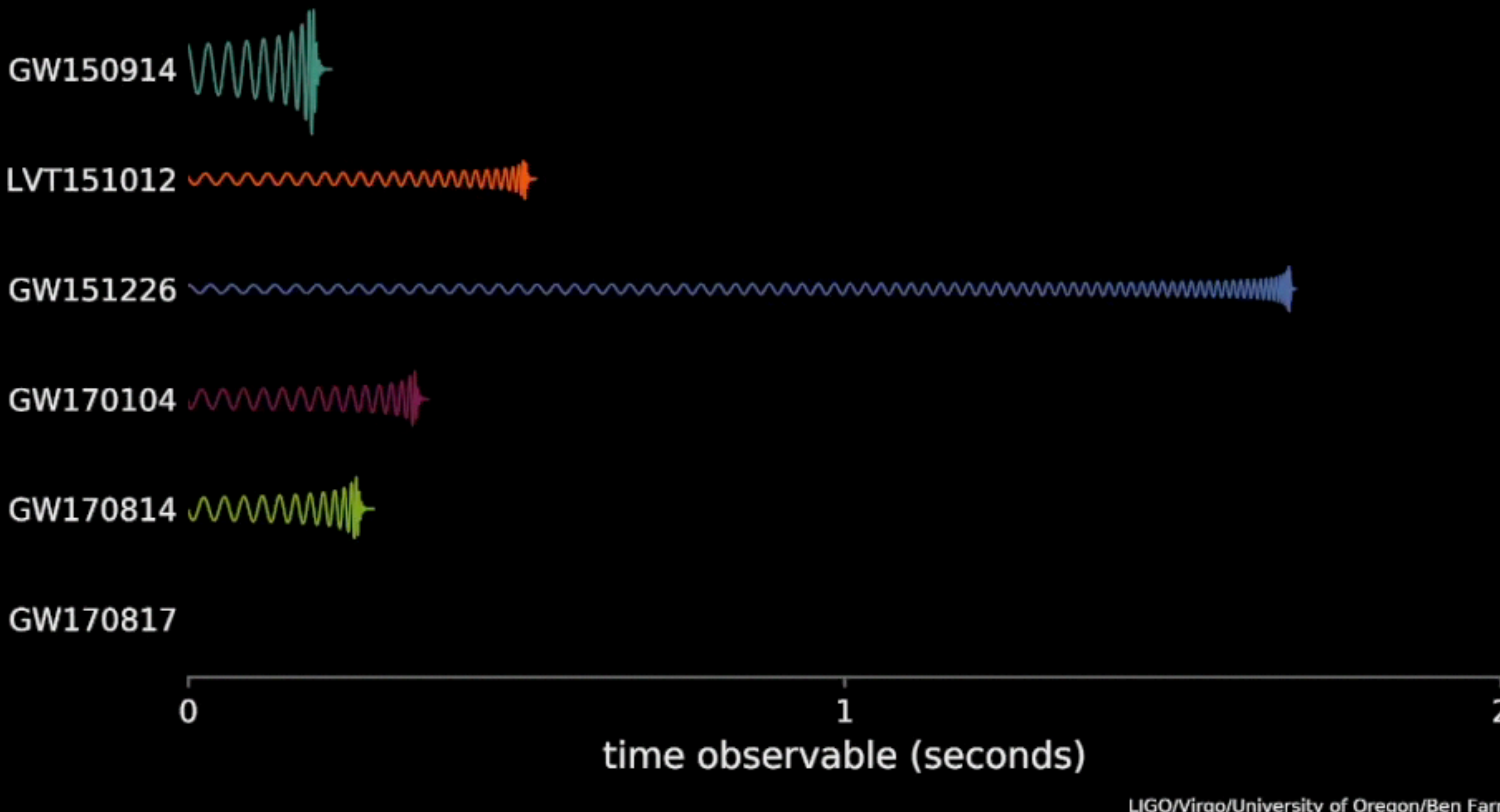
Nov 2016	Dec 2016	Jan 2017	Feb 2017	Mar 2017	Apr 2017	May 2017	Jun 2017	Jul 2017	Aug 2017

GW170608
Jun 6, 2017



GW170817
Aug 17, 2017




GW150914
LVT151012
GW151226
GW170104
GW170814
GW170817
0
1
2
time observable (seconds)
LIGO/Virgo/University of Oregon/Ben Farr

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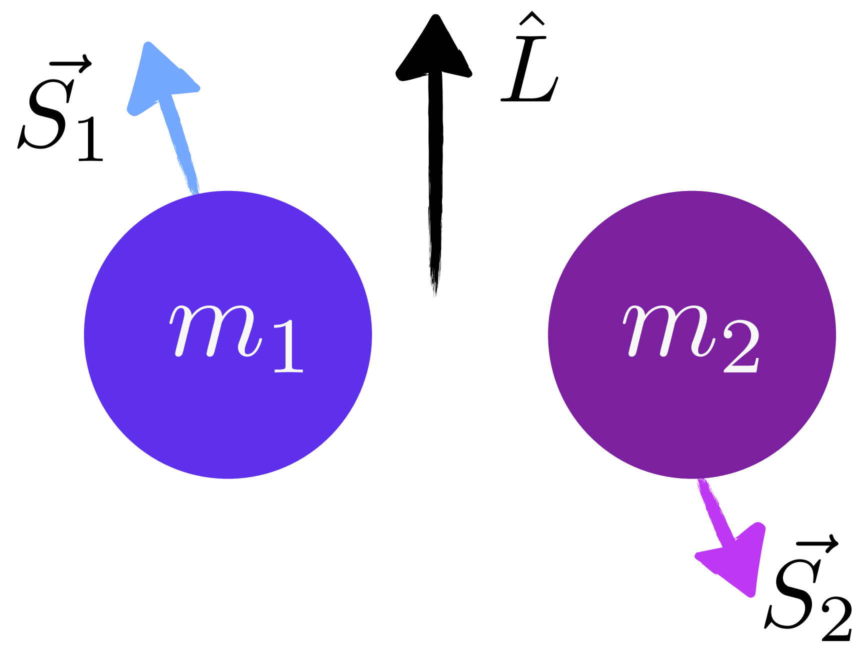
Matched Filtering

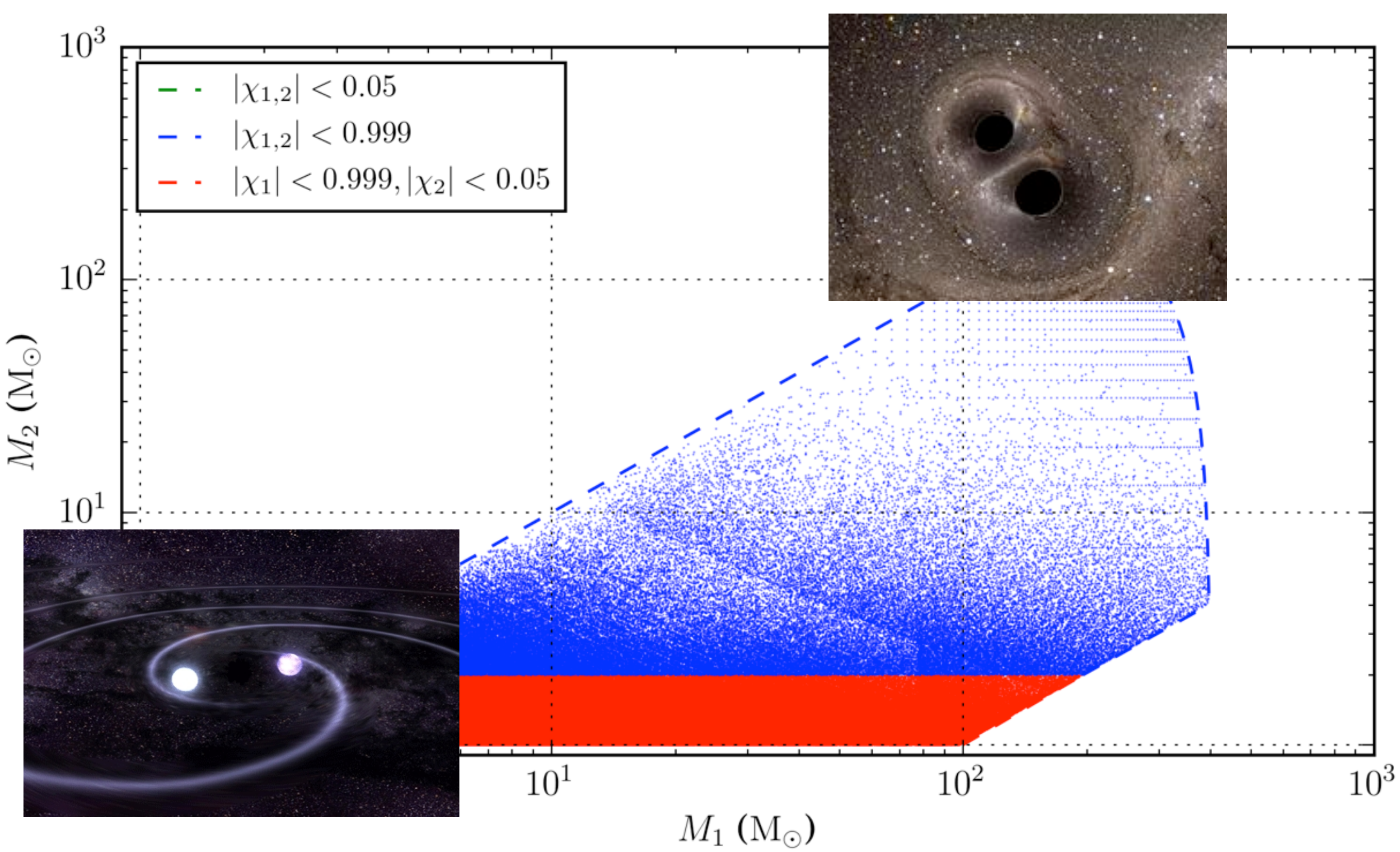
gstreamer

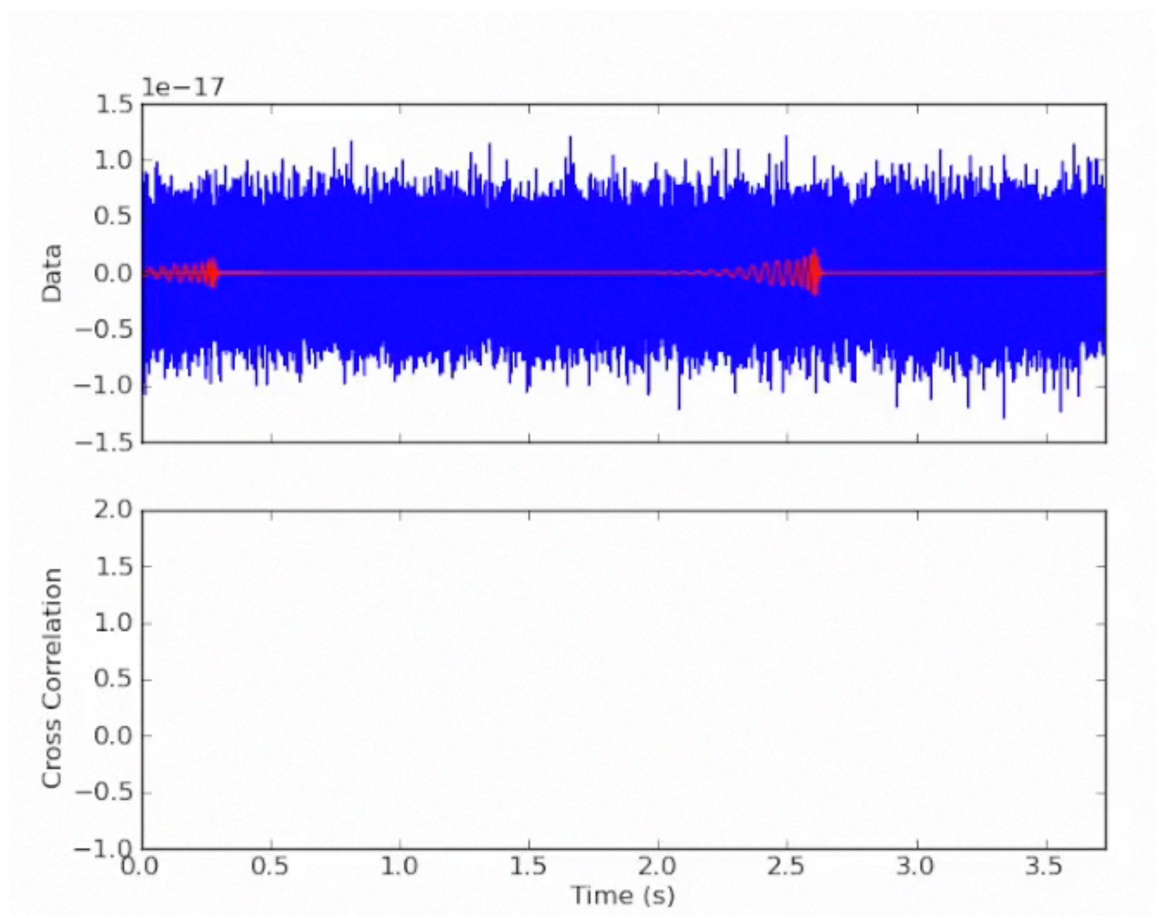
LALSuite

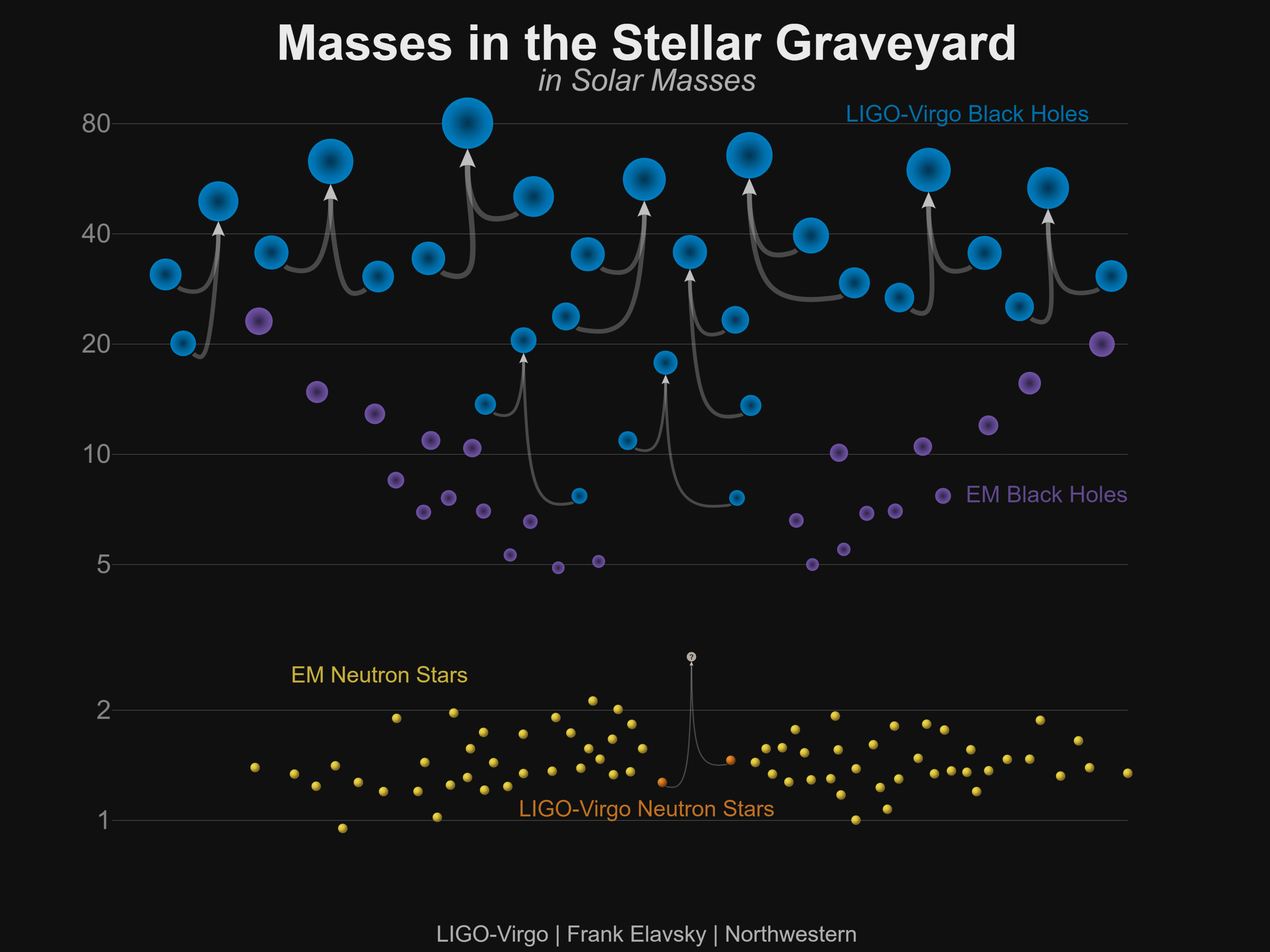
gstLAL

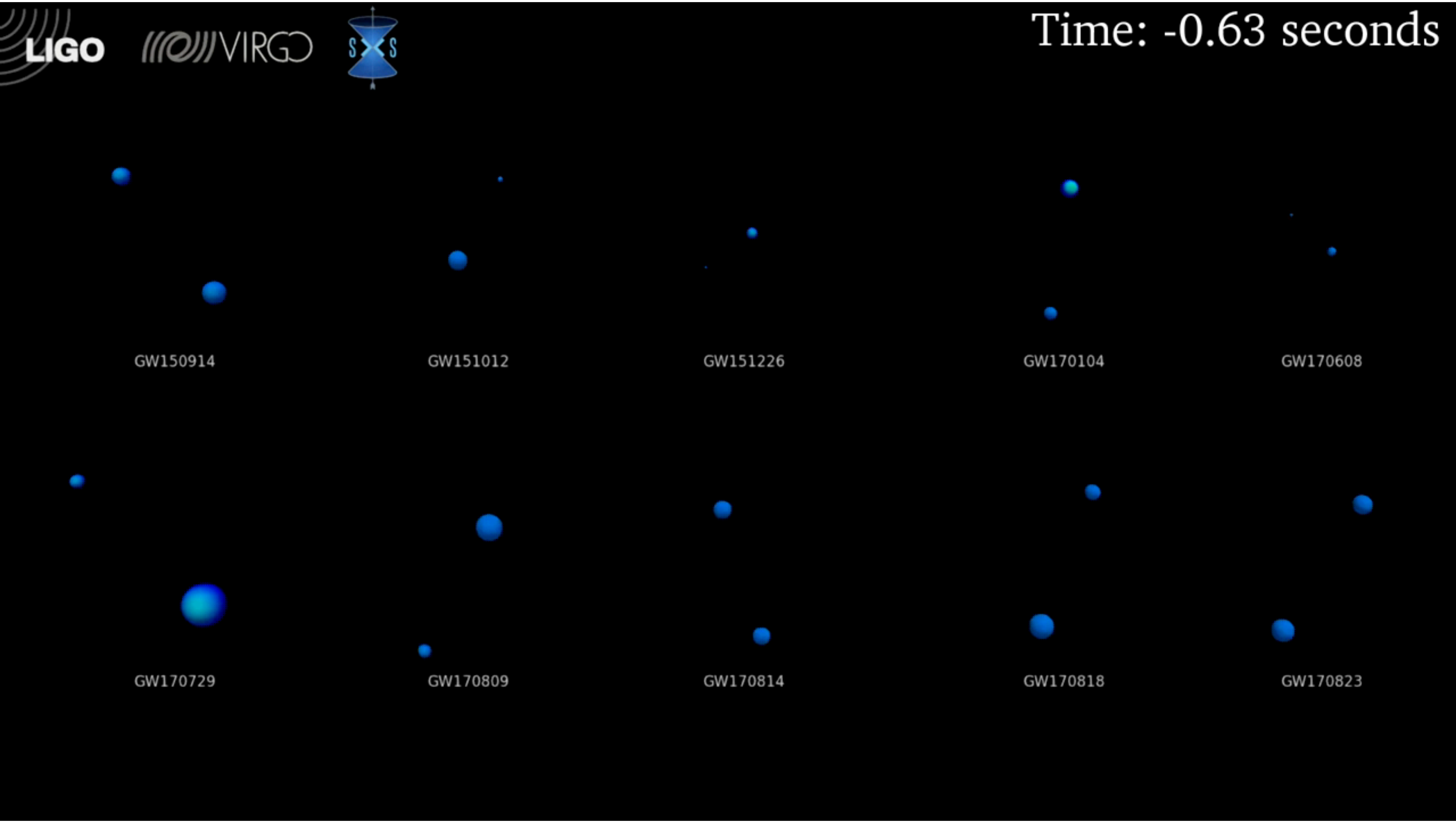


$$\chi_{1,2} \propto \vec{S_{1,2}} \cdot \hat{L}$$

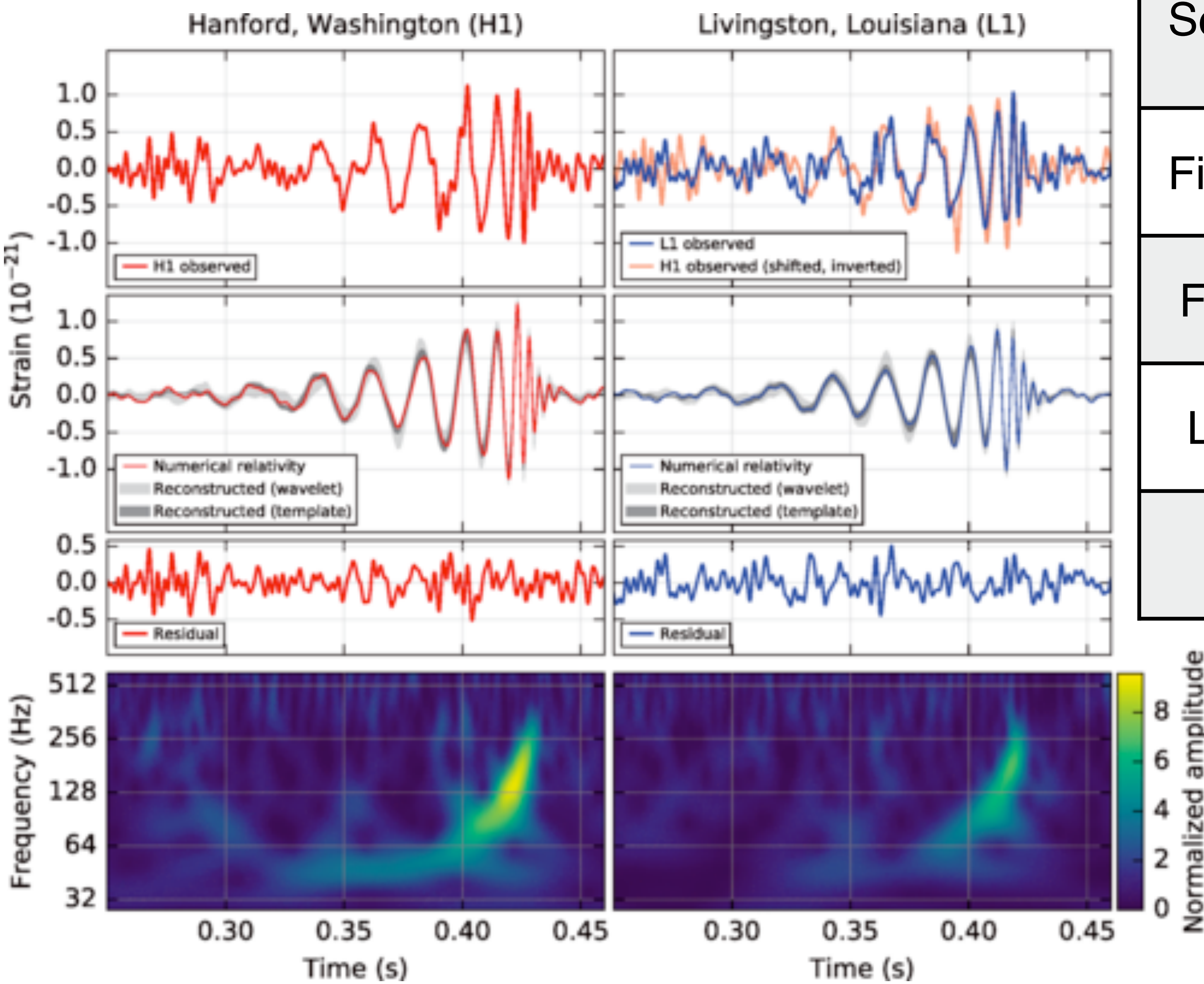





Masses in the Stellar Graveyard
in Solar Masses
80
40
20
10
5
2
1
LIGO-Virgo Black Holes
EM Black Holes
EM Neutron Stars
LIGO-Virgo Neutron Stars
?
LIGO-Virgo | Frank Elavsky | Northwestern

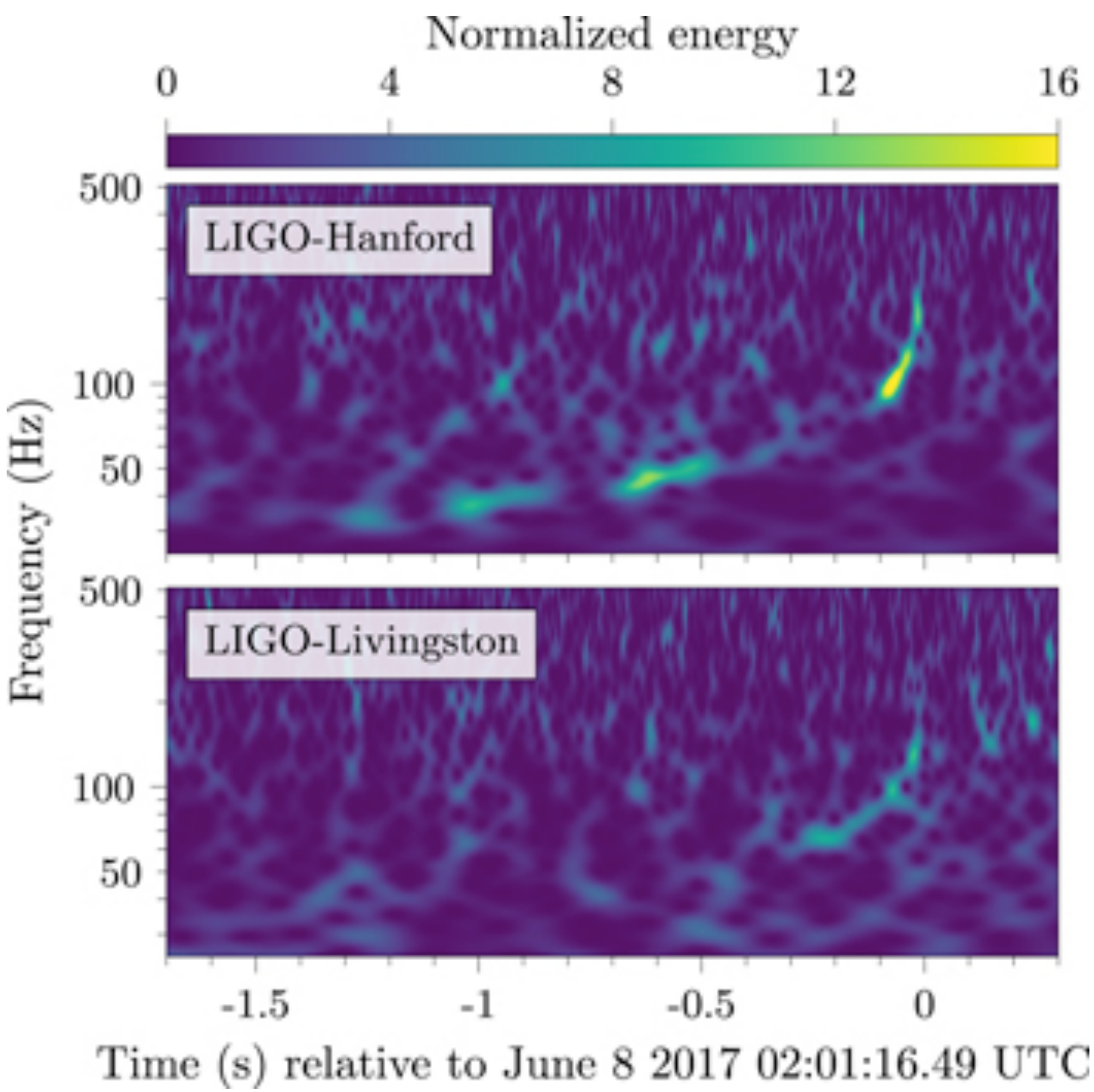

LIGO
VIRGO
Time: -0.63 seconds
GW150914
GW151012
GW151226
GW170104
GW170608
GW170729
GW170809
GW170814
GW170818
GW170823

GW150914: The First Direct Detection of Gravitational Waves



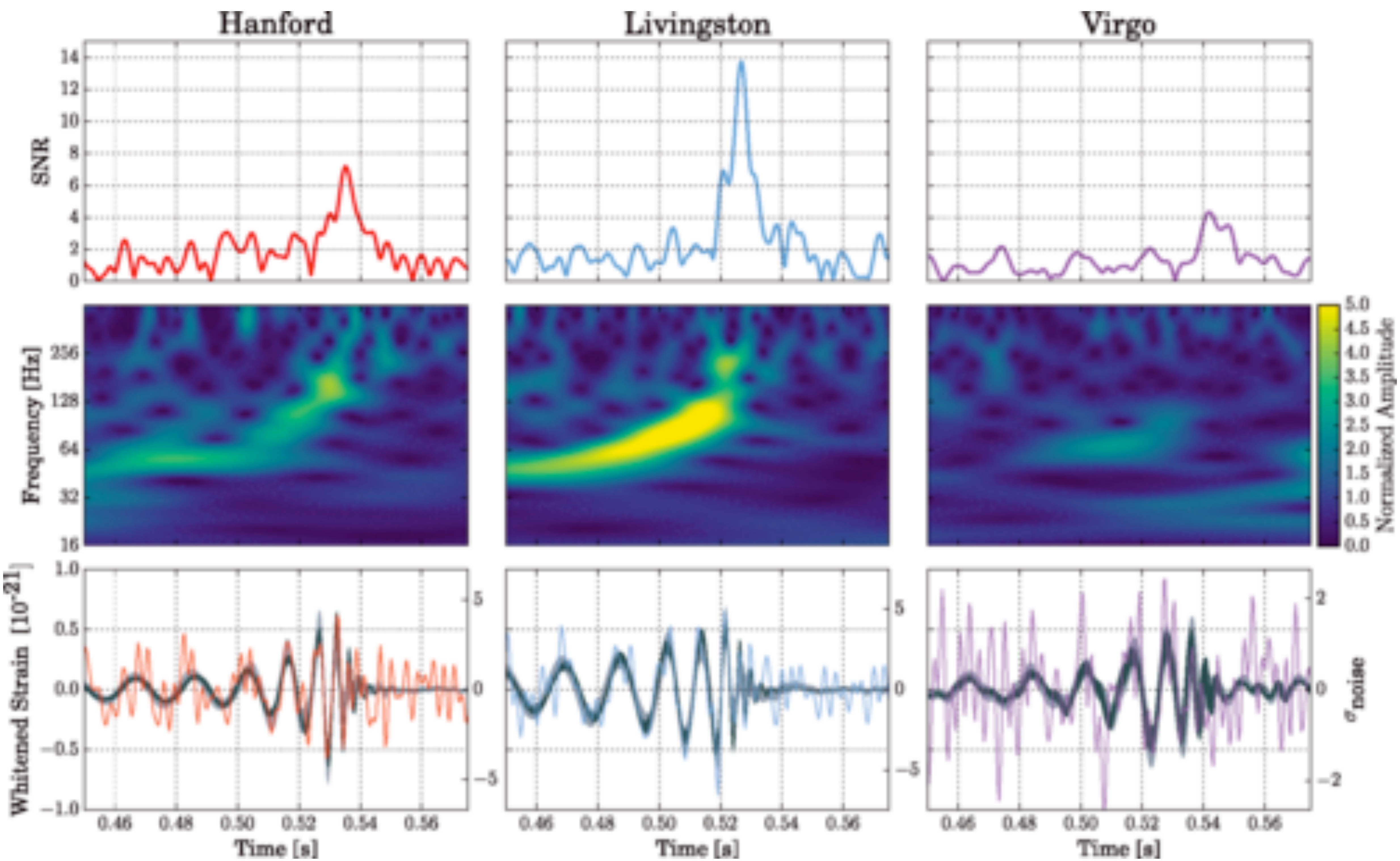
Primary black hole mass	$36^{+5}_{-4} M_\odot$
Secondary black hole mass	$29^{+4}_{-4} M_\odot$
Final black hole mass	$62^{+4}_{-4} M_\odot$
Final black hole spin	$0.67^{+0.05}_{-0.07}$
Luminosity distance	$410^{+160}_{-180}\mathrm{Mpc}$
Source redshift z	$0.09^{+0.03}_{-0.04}$

GW170608: Least Massive Binary Black Hole Observed So Far



Primary black hole mass	$12^{+7}_{-2} M_\odot$
Secondary black hole mass	$7^{+2}_{-2} M_\odot$
Final black hole mass	$18.0^{+4.8}_{-0.9} M_\odot$
Final black hole spin	$0.69^{+0.04}_{-0.05}$
Luminosity distance	$340^{+140}_{-140}\mathrm{Mpc}$
Source redshift z	$0.07^{+0.03}_{-0.03}$

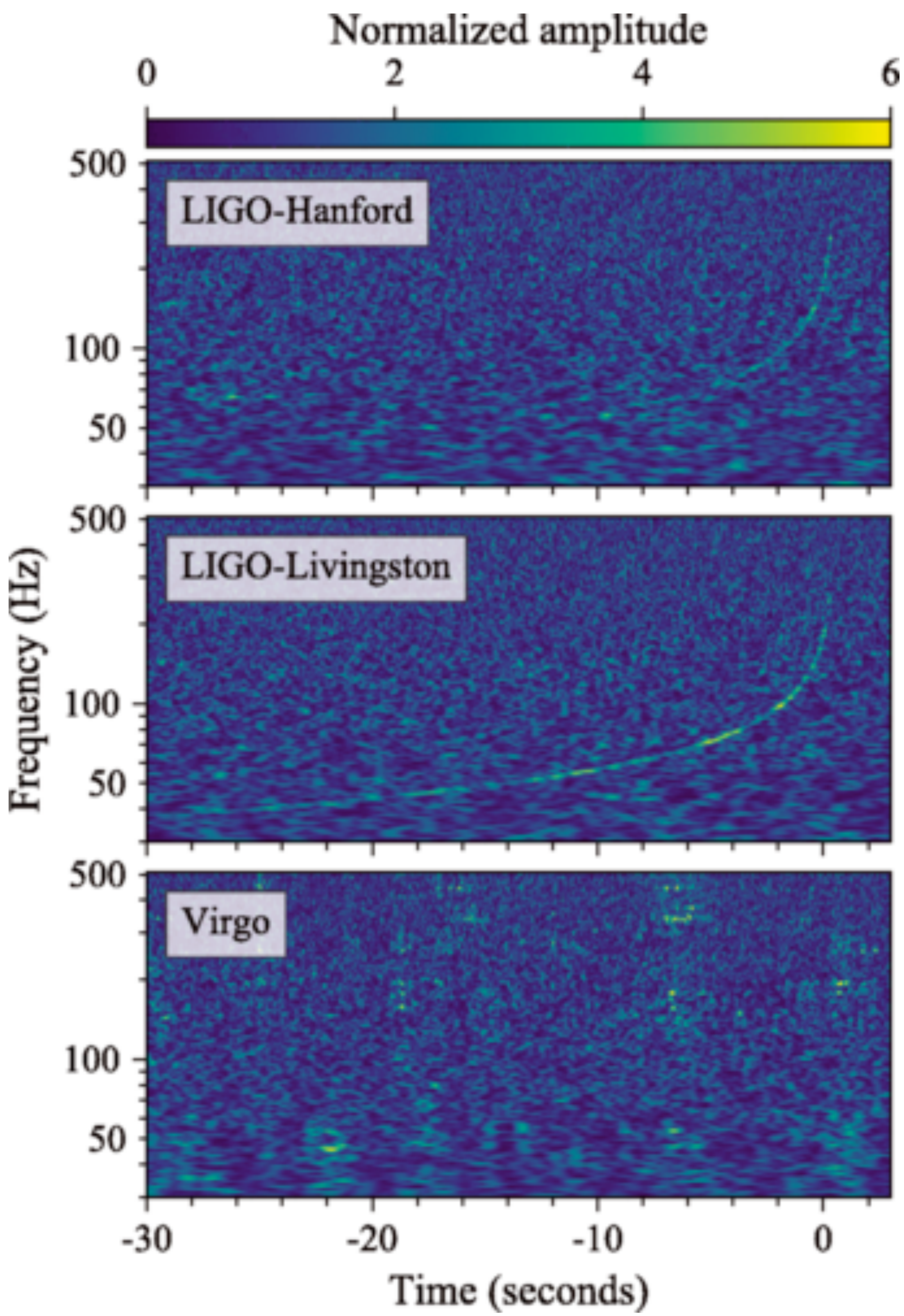
GW170814: First Event Seen By LIGO and Virgo Detectors



GW170814: First Event Seen By LIGO and Virgo Detectors

Primary black hole mass	$30.5^{+5.7}_{-3.0} M_{\odot}$
Secondary black hole mass	$25.3^{+2.8}_{-4.2} M_{\odot}$
Final black hole mass	$53.2^{+3.2}_{-2.5} M_{\odot}$
Final black hole spin	$0.07^{+0.07}_{-0.05}$
Luminosity distance	$540^{+130}_{-210} \mathrm{Mpc}$
Source redshift z	$0.11^{+0.03}_{-0.04}$

GW170817: The First Detection of Gravitational Waves from a Binary Neutron Star Coalescence



	Assuming low spin	Allowing for high spin
Primary mass	$1.36 - 1.60 M_\odot$	$1.36 - 2.26 M_\odot$
Secondary mass	$1.17 - 1.36 M_\odot$	$0.86 - 1.36 M_\odot$
Luminosity distance	$40^{+8}_{-14}\,\mathrm{Mpc}$	

And the closest GW signal so far.

Least massive binary black hole detected so far

Only signal with significant aligned spin

Event	$m_1/\mathrm{M}_\odot$	$m_2/\mathrm{M}_\odot$	$\mathcal{M}/\mathrm{M}_\odot$	χ_{eff}	$M_{\mathrm{f}}/\mathrm{M}_\odot$	a_{f}	$E_{\mathrm{rad}}/(\mathrm{M}_\odot c^2)$	$\ell_{\mathrm{peak}}/(\mathrm{erg\,s}^{-1})$	d_L/Mpc	z	$\Delta\Omega/\mathrm{deg}^2$
GW150914	$35.6^{+4.8}_{-3.0}$	$30.6^{+3.0}_{-4.4}$	$28.6^{+1.6}_{-1.5}$	$-0.01^{+0.12}_{-0.13}$	$63.1^{+3.3}_{-3.0}$	$0.69^{+0.05}_{-0.04}$	$3.1^{+0.4}_{-0.4}$	$3.6^{+0.4}_{-0.4} \times 10^{56}$	430^{+150}_{-170}	$0.09^{+0.03}_{-0.03}$	180
GW151012	$23.3^{+14.0}_{-5.5}$	$13.6^{+4.1}_{-4.8}$	$15.2^{+2.0}_{-1.1}$	$0.04^{+0.28}_{-0.19}$	$35.7^{+9.9}_{-3.8}$	$0.67^{+0.13}_{-0.11}$	$1.5^{+0.5}_{-0.5}$	$3.2^{+0.8}_{-1.7} \times 10^{56}$	1060^{+540}_{-480}	$0.21^{+0.09}_{-0.09}$	1555
GW151226	$13.7^{+8.8}_{-3.2}$	$7.7^{+2.2}_{-2.6}$	$8.9^{+0.3}_{-0.3}$	$0.18^{+0.20}_{-0.12}$	$20.5^{+6.4}_{-1.5}$	$0.74^{+0.07}_{-0.05}$	$1.0^{+0.1}_{-0.2}$	$3.4^{+0.7}_{-1.7} \times 10^{56}$	440^{+180}_{-190}	$0.09^{+0.04}_{-0.04}$	1033
GW170104	$31.0^{+7.2}_{-5.6}$	$20.1^{+4.9}_{-4.5}$	$21.5^{+2.1}_{-1.7}$	$-0.04^{+0.17}_{-0.20}$	$49.1^{+5.2}_{-3.9}$	$0.66^{+0.08}_{-0.10}$	$2.2^{+0.5}_{-0.5}$	$3.3^{+0.6}_{-0.9} \times 10^{56}$	960^{+430}_{-410}	$0.19^{+0.07}_{-0.08}$	924
GW170608	$10.9^{+5.3}_{-1.7}$	$7.6^{+1.3}_{-2.1}$	$7.9^{+0.2}_{-0.2}$	$0.03^{+0.19}_{-0.07}$	$17.8^{+3.2}_{-0.7}$	$0.69^{+0.04}_{-0.04}$	$0.9^{+0.05}_{-0.1}$	$3.5^{+0.4}_{-1.3} \times 10^{56}$	320^{+120}_{-110}	$0.07^{+0.02}_{-0.02}$	396
GW170729	$50.6^{+16.6}_{-10.2}$	$34.3^{+9.1}_{-10.1}$	$35.7^{+6.5}_{-4.7}$	$0.36^{+0.21}_{-0.25}$	$80.3^{+14.6}_{-10.2}$	$0.81^{+0.07}_{-0.13}$	$4.8^{+1.7}_{-1.7}$	$4.2^{+0.9}_{-1.5} \times 10^{56}$	2750^{+1350}_{-1320}	$0.48^{+0.19}_{-0.20}$	1033
GW170809	$35.2^{+8.3}_{-6.0}$	$23.8^{+5.2}_{-5.1}$	$25.0^{+2.1}_{-1.6}$	$0.07^{+0.16}_{-0.16}$	$56.4^{+5.2}_{-3.7}$	$0.70^{+0.08}_{-0.09}$	$2.7^{+0.6}_{-0.6}$	$3.5^{+0.6}_{-0.9} \times 10^{56}$	990^{+320}_{-380}	$0.20^{+0.05}_{-0.07}$	340
GW170814	$30.7^{+5.7}_{-3.0}$	$25.3^{+2.9}_{-4.1}$	$24.2^{+1.4}_{-1.1}$	$0.07^{+0.12}_{-0.11}$	$53.4^{+3.2}_{-2.4}$	$0.72^{+0.07}_{-0.05}$	$2.7^{+0.4}_{-0.3}$	$3.7^{+0.4}_{-0.5} \times 10^{56}$	580^{+160}_{-210}	$0.12^{+0.03}_{-0.04}$	87
GW170817	$1.46^{+0.12}_{-0.10}$	$1.27^{+0.09}_{-0.09}$	$1.186^{+0.001}_{-0.001}$	$0.00^{+0.02}_{-0.01}$	≤ 2.8	≤ 0.89	≥ 0.04	$\geq 0.1 \times 10^{56}$	40^{+10}_{-10}	$0.01^{+0.00}_{-0.00}$	16
GW170818	$35.5^{+7.5}_{-4.7}$	$26.8^{+4.3}_{-5.2}$	$26.7^{+2.1}_{-1.7}$	$-0.09^{+0.18}_{-0.21}$	$59.8^{+4.8}_{-3.8}$	$0.67^{+0.07}_{-0.08}$	$2.7^{+0.5}_{-0.5}$	$3.4^{+0.5}_{-0.7} \times 10^{56}$	1020^{+430}_{-360}	$0.20^{+0.07}_{-0.07}$	39
GW170823	$39.6^{+10.0}_{-6.6}$	$29.4^{+6.3}_{-7.1}$	$29.3^{+4.2}_{-3.2}$	$0.08^{+0.20}_{-0.22}$	$65.6^{+9.4}_{-6.6}$	$0.71^{+0.08}_{-0.10}$	$3.3^{+0.9}_{-0.8}$	$3.6^{+0.6}_{-0.9} \times 10^{56}$	1850^{+840}_{-840}	$0.34^{+0.13}_{-0.14}$	1651

Most massive signal detected so far.

Only binary neutron star detected so far.

Furthest signal detected so far.

Best localised signal

Best localised binary black hole

- What are gravitational waves?
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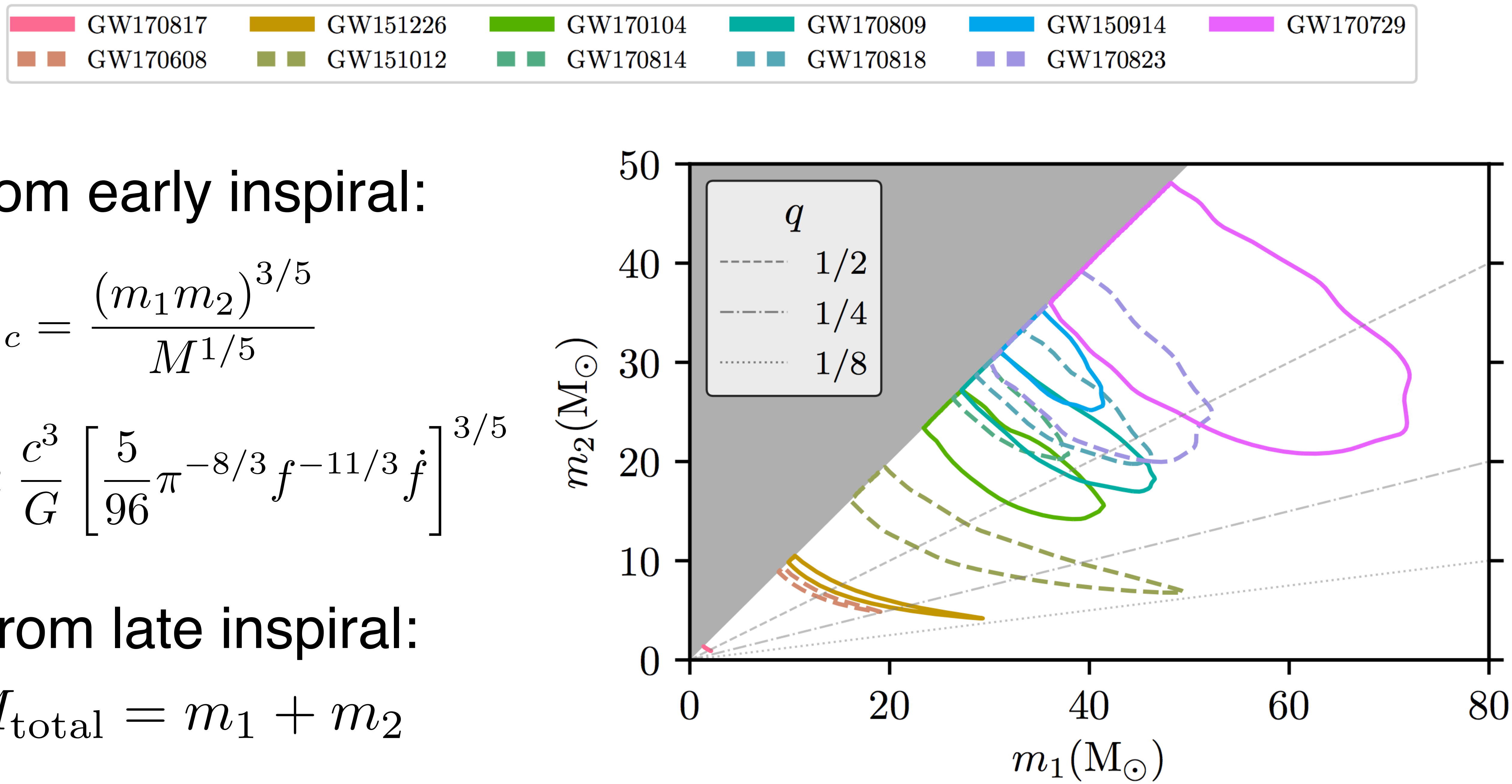
BBH Science: Measuring a Mass Distribution



From early inspiral:

$$\mathcal{M}_c = \frac{(m_1 m_2)^{3/5}}{M^{1/5}}$$

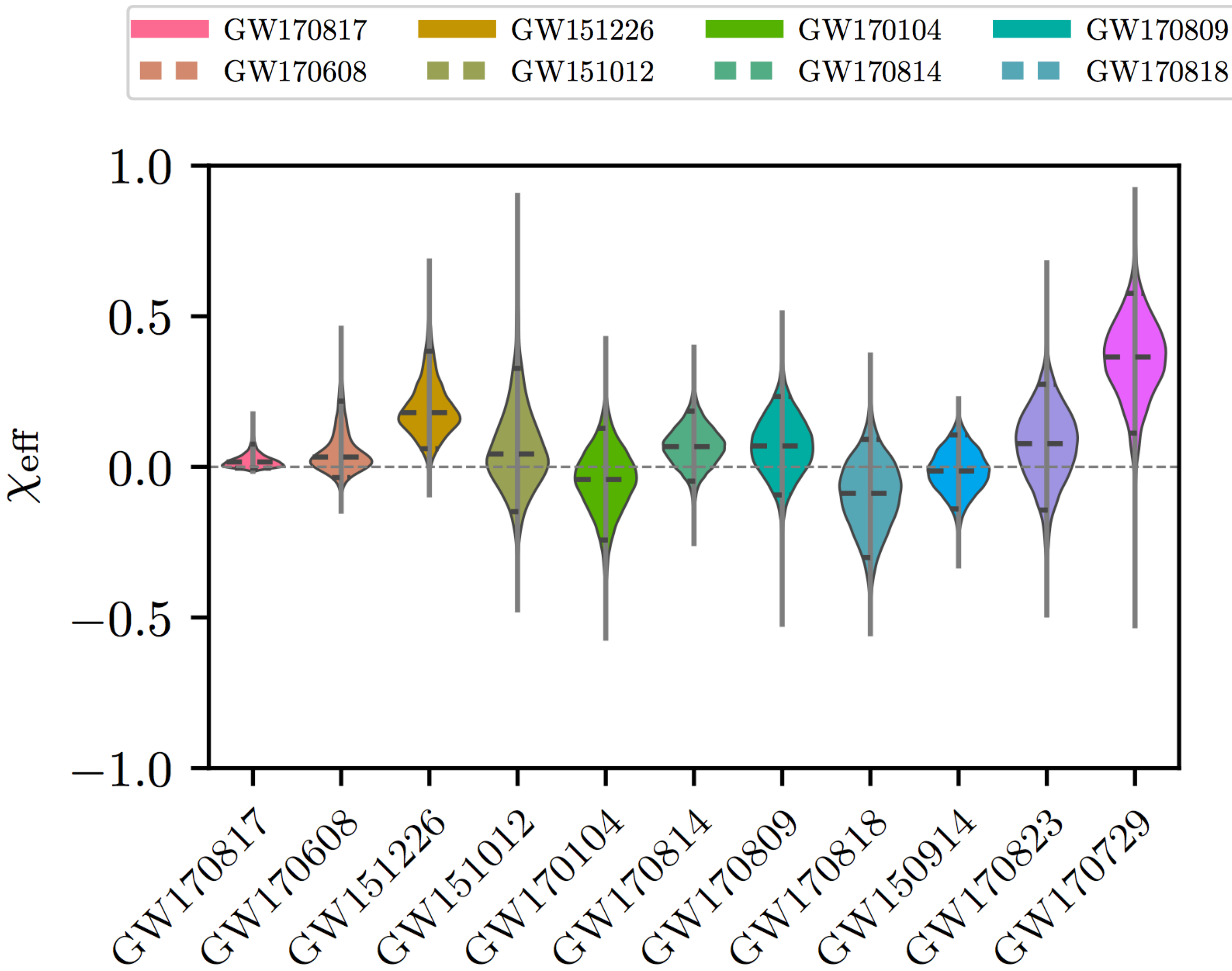
$$\simeq \frac{c^3}{G}\left[\frac{5}{96}\pi^{-8/3} f^{-11/3} \dot{f}\right]^{3/5}$$

From late inspiral:

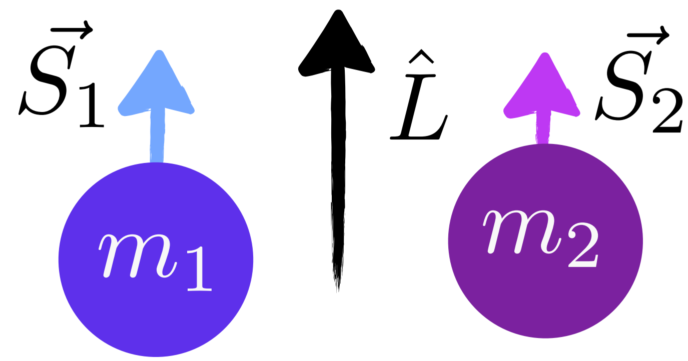
$$M_{\mathrm{total}} = m_1 + m_2$$

Revealing a new population of heavy stellar-mass black holes.

BBH Science: Measuring Effective Spins

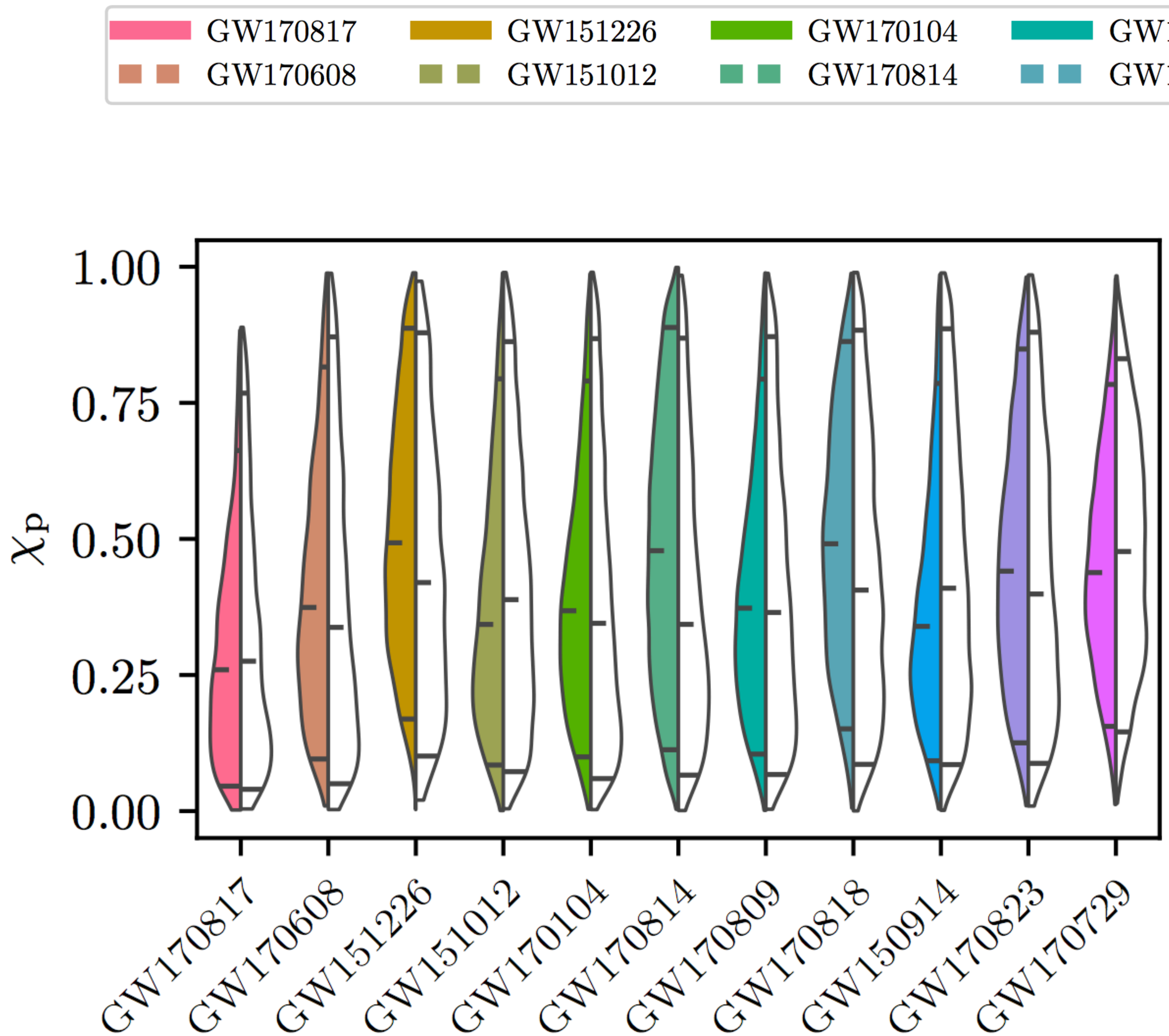


$$\chi_{\rm eff} = \frac{c}{GM}\left(\frac{\vec{S}_1}{m_1} + \frac{\vec{S}_2}{m_2}\right)$$

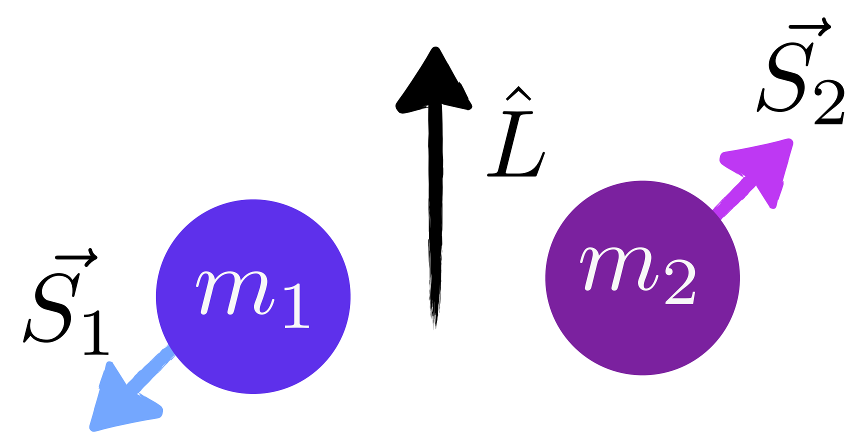


Helping to distinguish between binary formation channels.

BBH Science: Measuring Precessing Spins



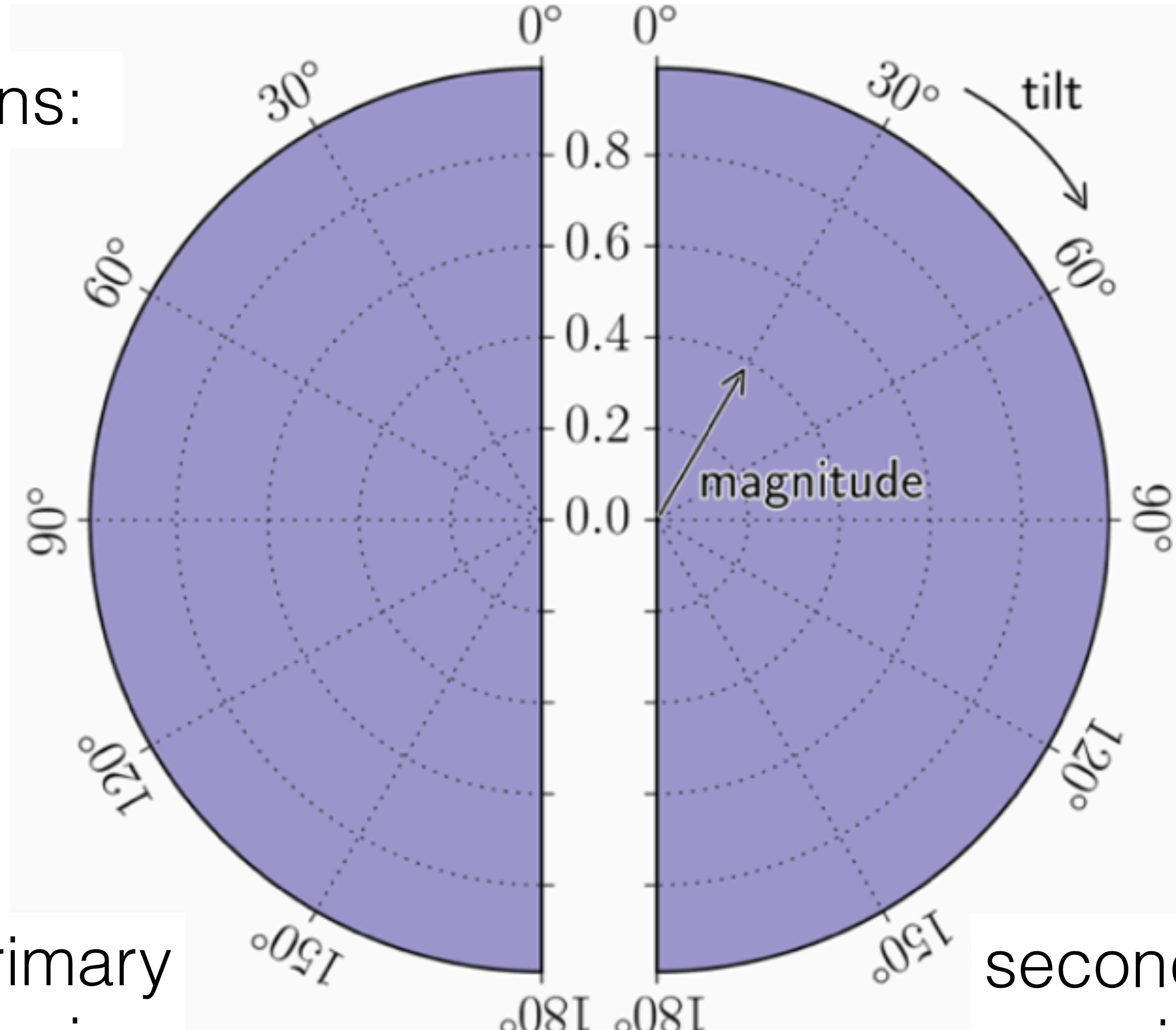
χ_p - amount of in-plane spin



Helping to distinguish between binary formation channels.

BBH Science: Measured Component Spins

Prior on spins:

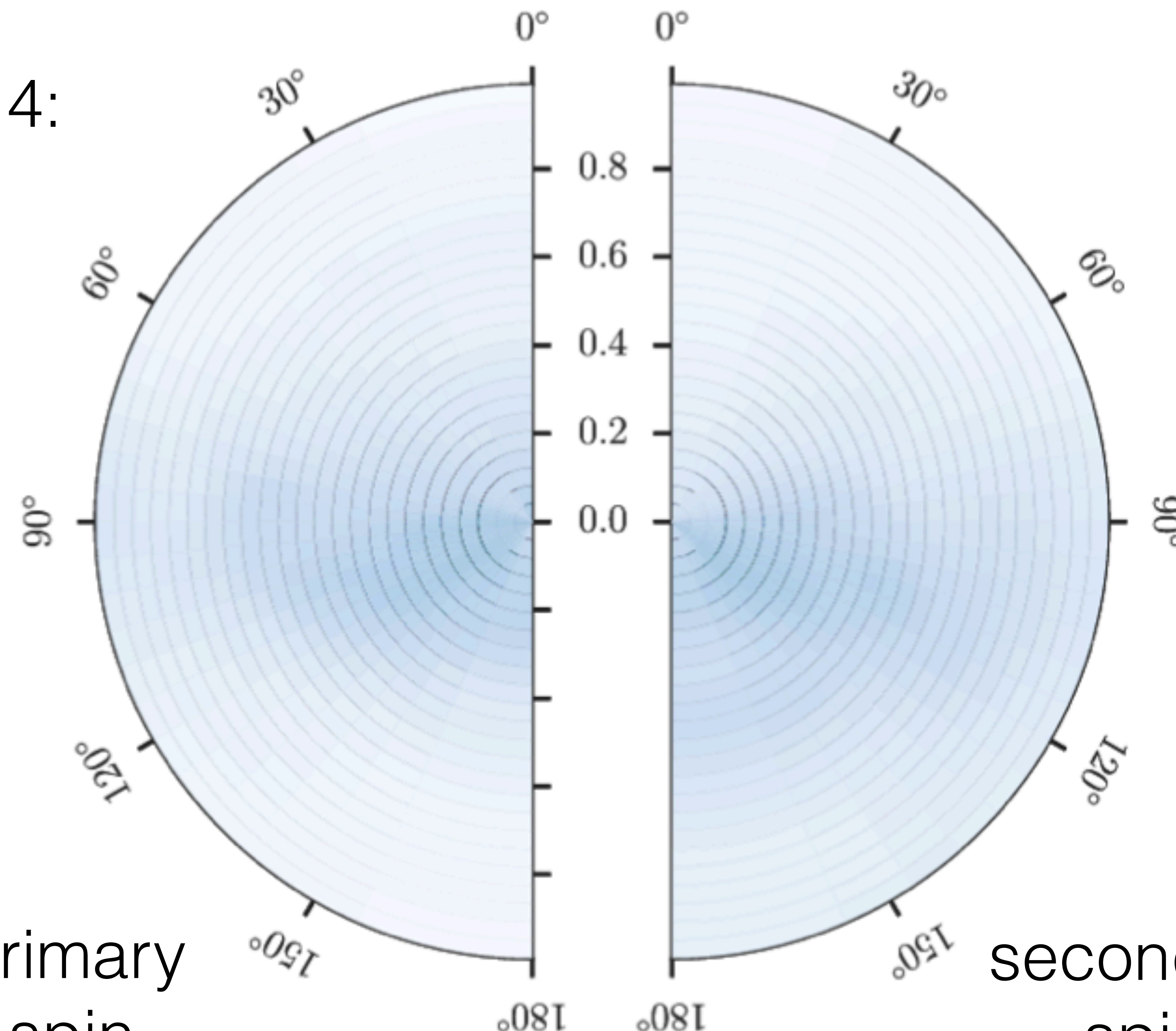


primary spin

secondary spin

BBH Science: Measured Component Spins

GW150914:



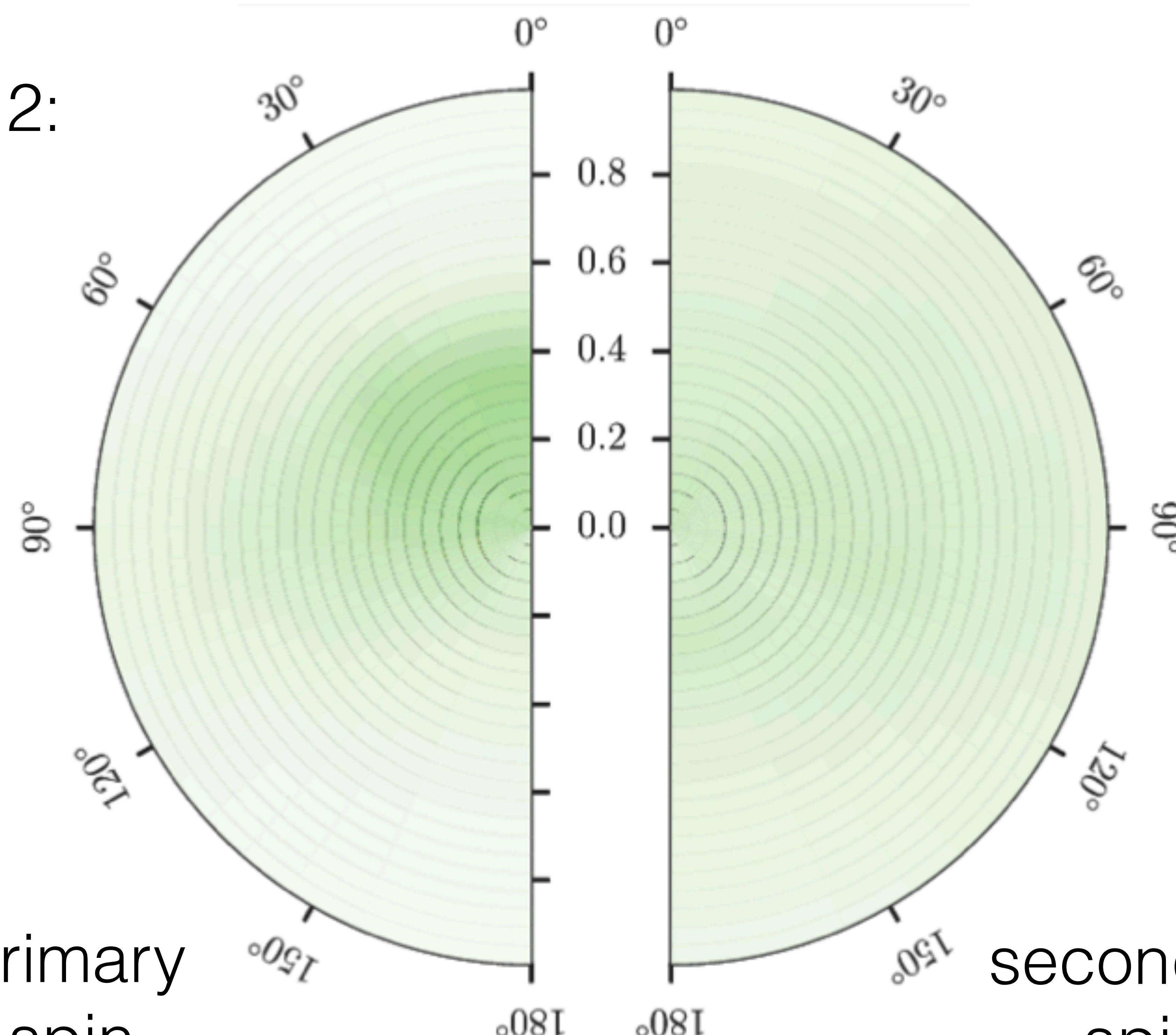
primary spin

secondary spin

LVC, PRX 6, 041015 (2016)

BBH Science: Measured Component Spins

LVT151012:



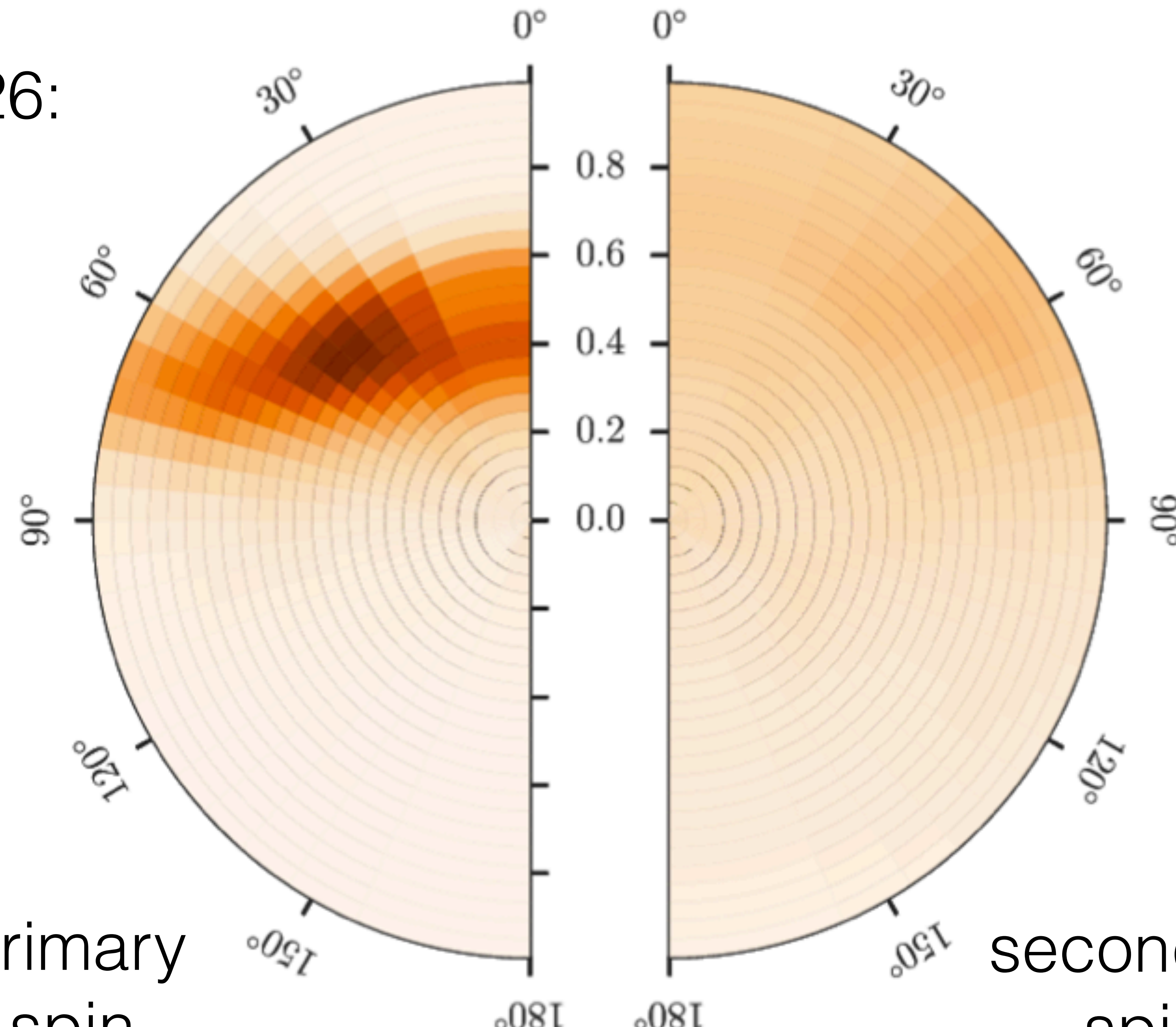
primary spin

secondary spin

LVC, PRX 6, 041015 (2016)

BBH Science: Measured Component Spins

GW151226:



primary spin

secondary spin

LVC, PRX 6, 041015 (2016)

BBH Science: Do the signals agree with General Relativity?

These systems give us empirical access to genuinely strong-field dynamics of spacetime.

	Solar system	Binary pulsars	Compact binary
$\frac{GM}{c^2R}$	$\sim 10^{-8}$	$\sim 10^{-6}$	~ 0.2
$\frac{v}{c}$	$\sim 10^{-5}$	$\sim 10^{-3}$	~ 0.4

BBH Science: Parameterized Tests of General Relativity?

Allow for fractional changes with respect to the General Relativity value.

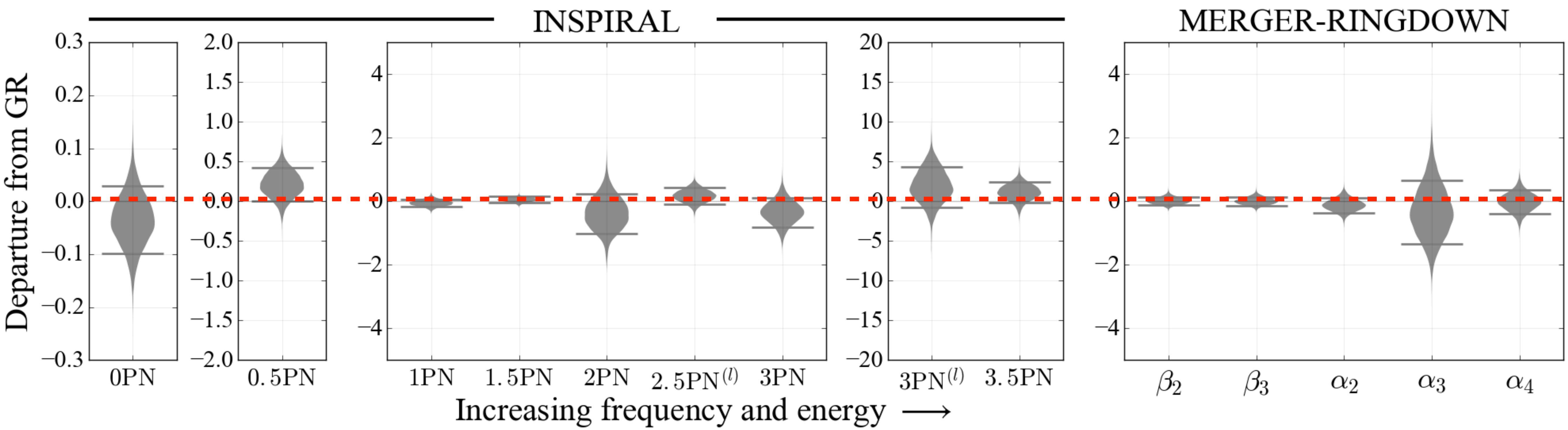
For example, the inspiral phase can be expressed in terms of characteristic speed $v(t)$

$$\Phi\left(v(t)\right) = \left(\frac{v}{c}\right)^{-5} \sum_{n=0}^{7} \left[\phi_n + \phi_n^{(l)} \ln\left(\frac{v}{c}\right)\right] \left(\frac{v}{c}\right)^{n}$$

Fractional changes of the form: $p_i \rightarrow (1 + \delta\hat{p}_i)\, p_i$

Inspiral $\left\{\delta\hat{\phi}_i\right\}$ Intermediate $\left\{\delta\hat{\beta}_i\right\}$ Merger-Ringdown $\{\delta\hat{\alpha}_i\}$

BBH Science: Parameterized Tests of General Relativity?



No evidence for disagreement with the predictions of General Relativity.

BBH Science: Testing for Lorentz Invariance

Graviton energy:

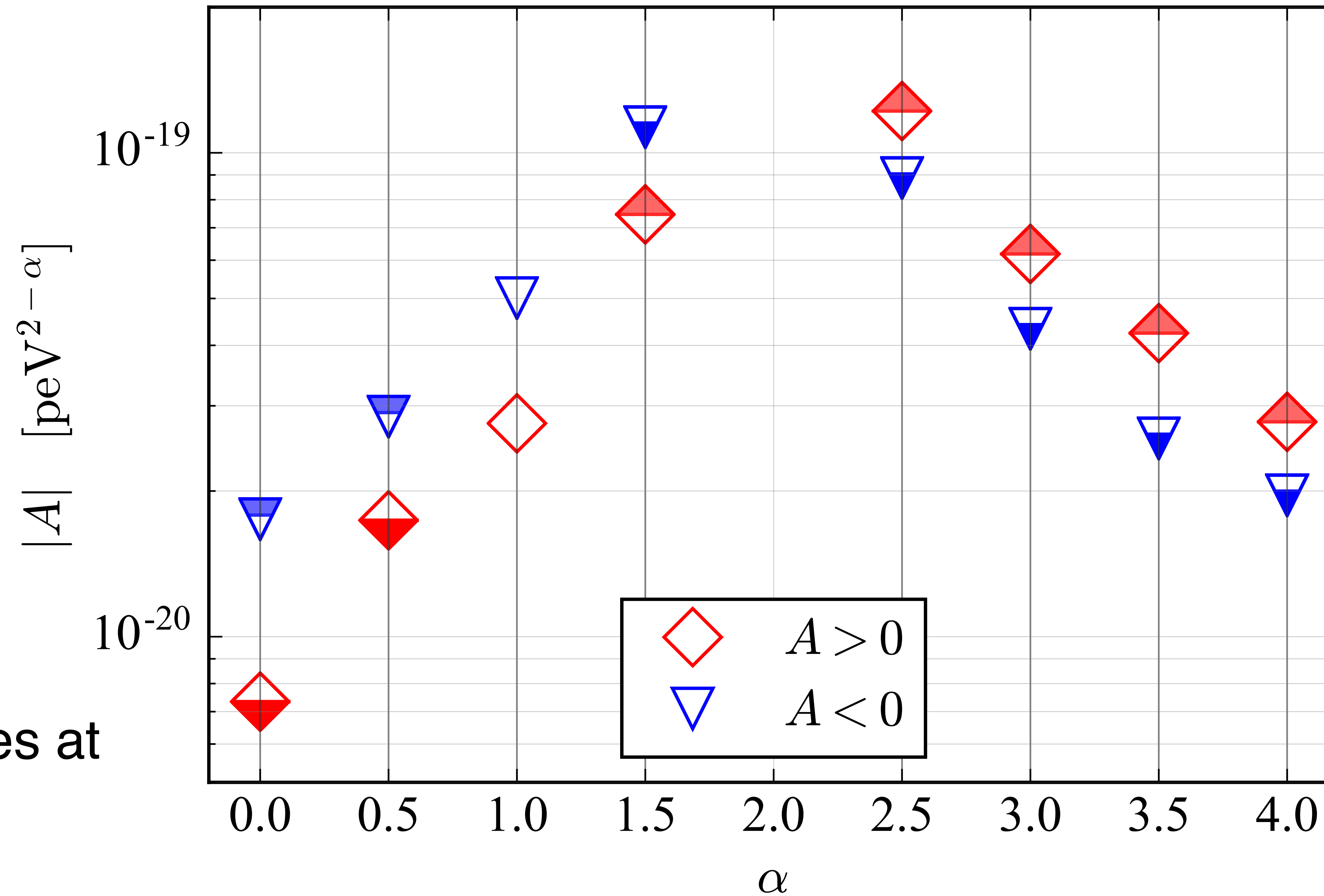
$$E^2 = p^2c^2 + m_g^2c^4 + Ap^\alpha c^\alpha$$

Graviton's Compton wavelength:

$$\lambda_g = \frac{h}{m_g c}$$

Massive graviton propagates at energy (or frequency) dependent speed:

$$\frac{v_g^2}{c^2} \equiv \frac{c^2p^2}{E^2} \simeq 1 - \frac{h^2c^2}{\lambda_g^2E^2}$$

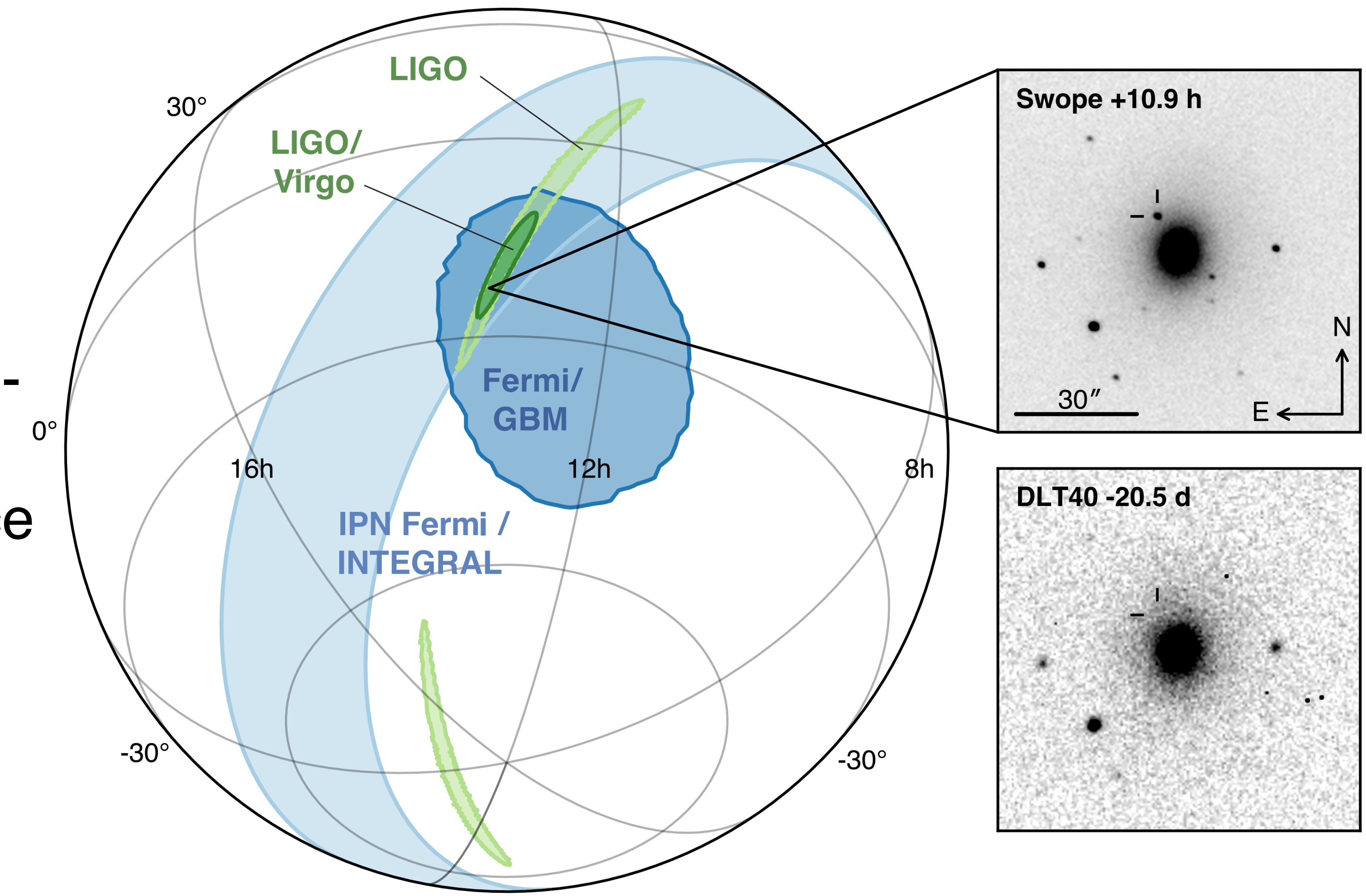


$$m_g \leq 7.7 \times 10^{-23}\mathrm{ev}/c^2$$

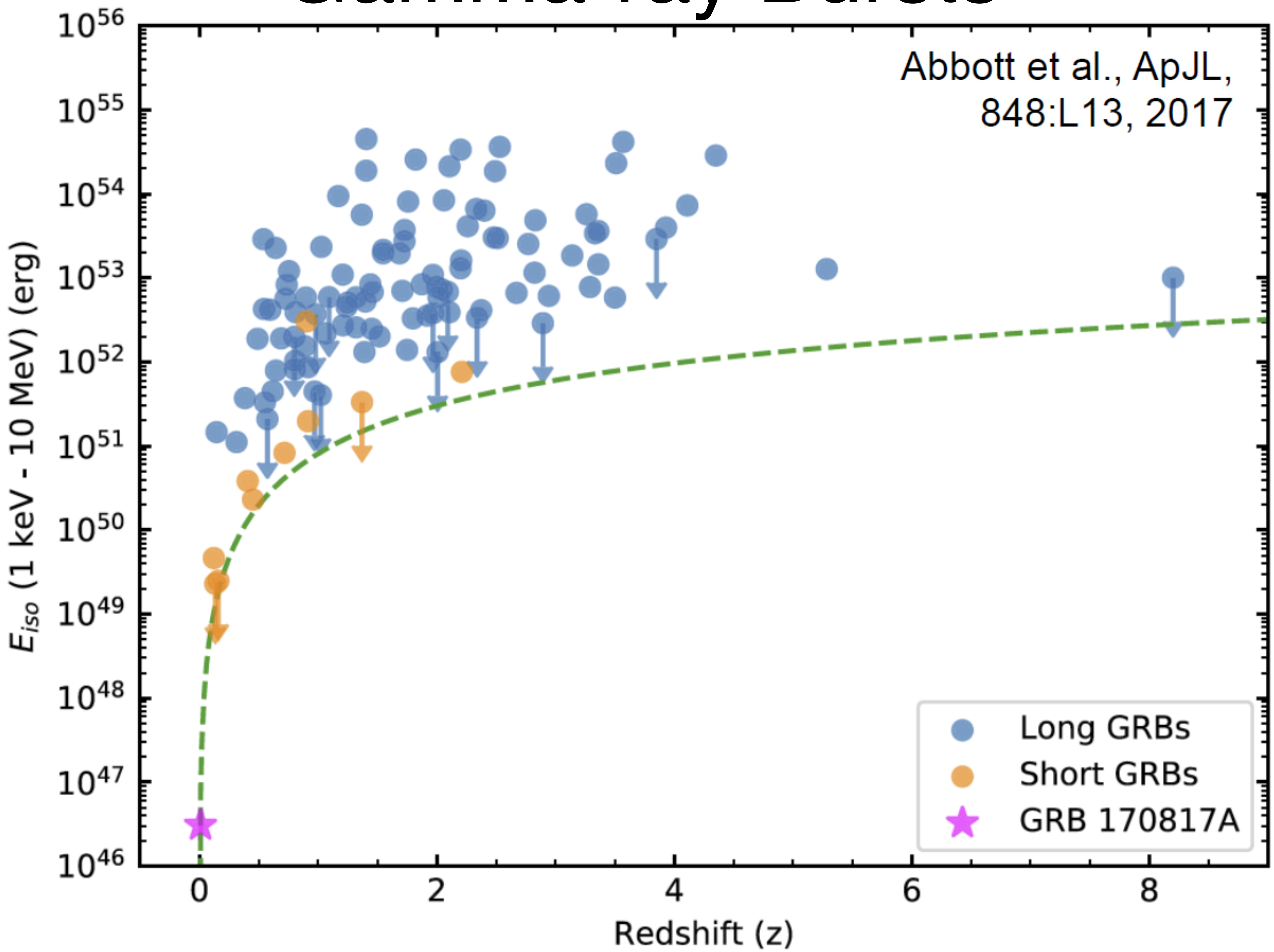
$$\lambda_g > 10^{13}\mathrm{km}$$

BNS Science: Start of Multi-messenger Astronomy with Gravitational Waves

Around 70 observatories world-wide observed the event by using space and ground-based telescopes.

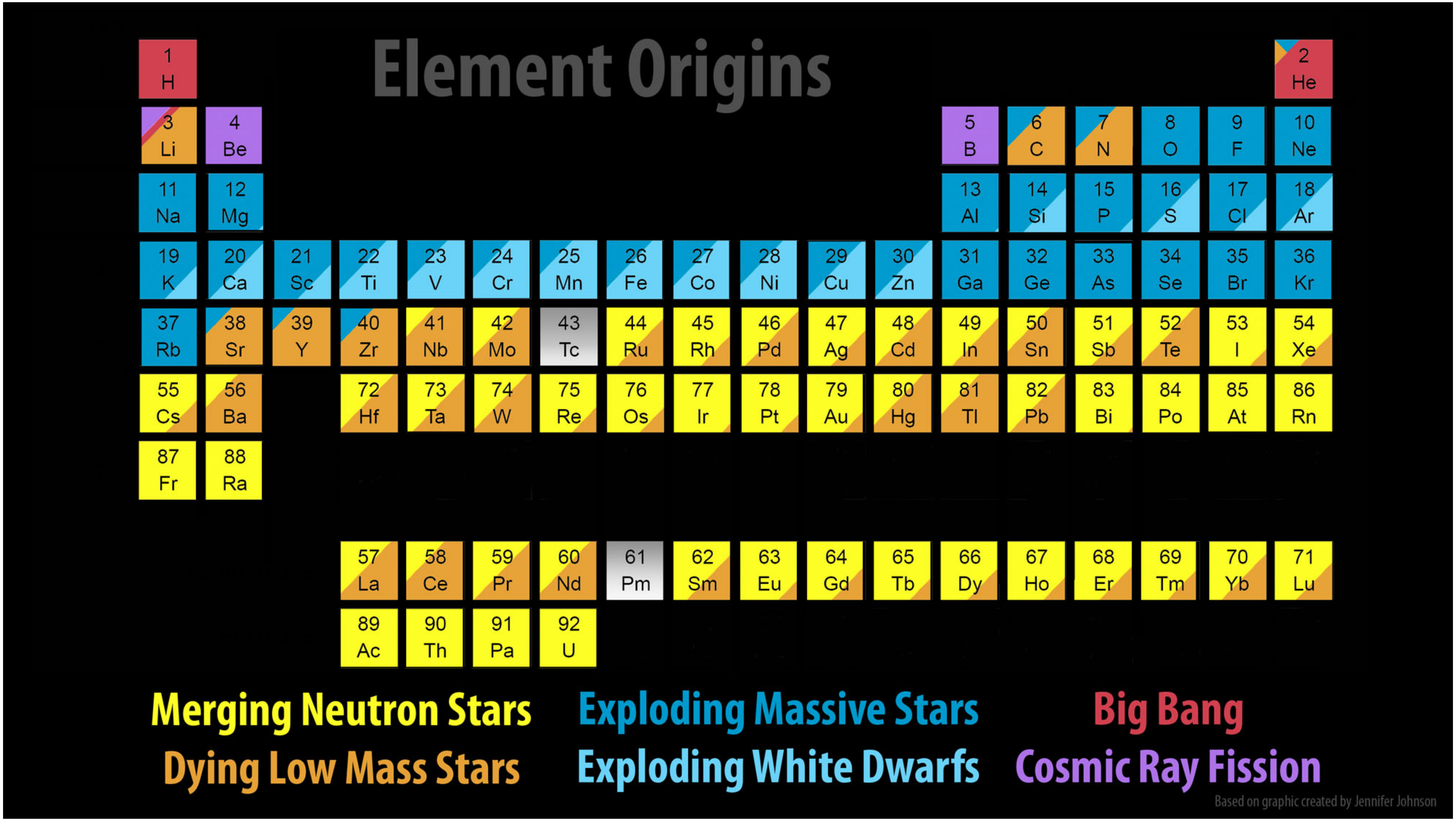


BNS Science: Association with Short Gamma-ray Bursts



GWs identified the progenitor of the short gamma-ray burst. This was found to be the closest by and weakest short gamma-ray burst with redshift measured.

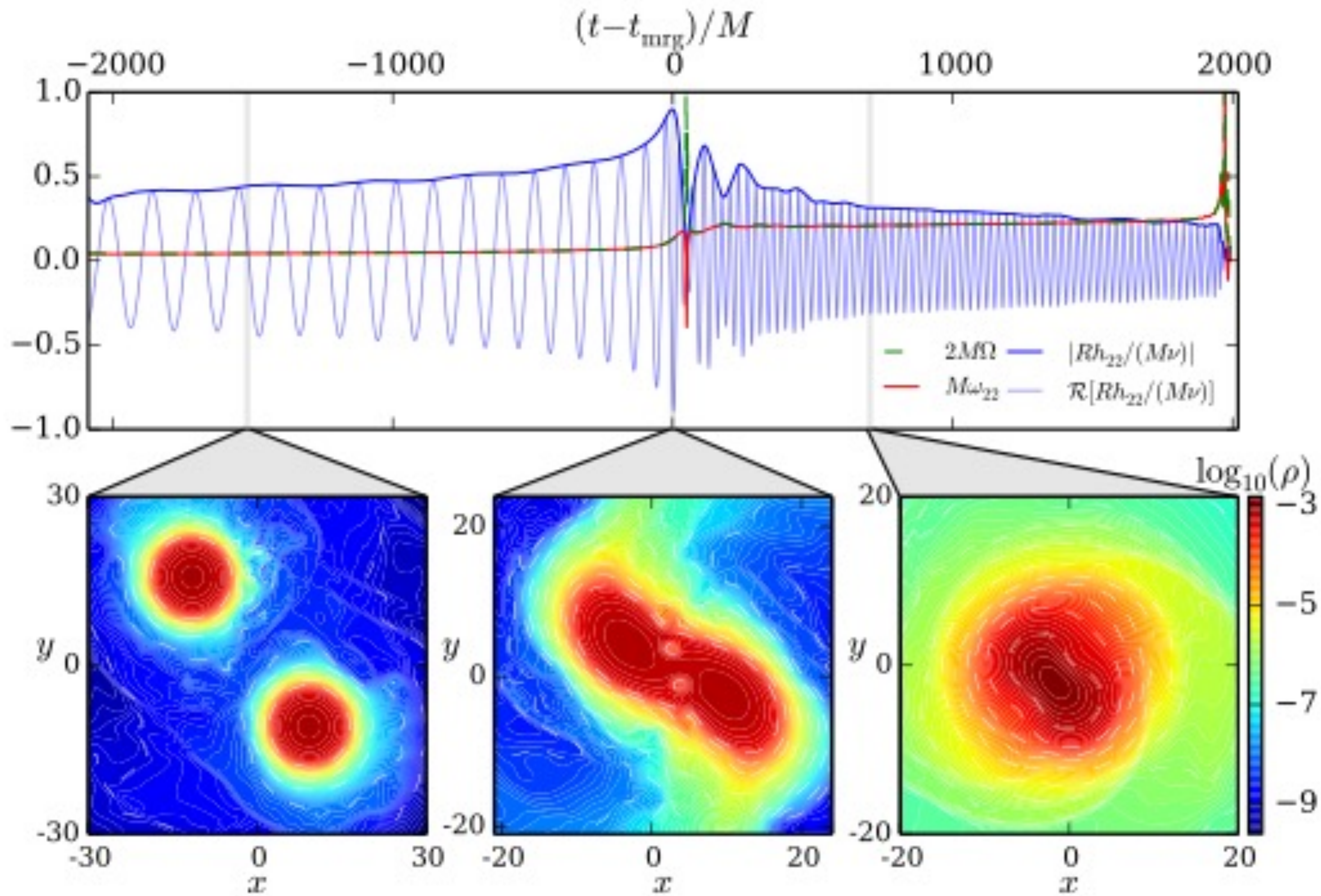
BNS Science: In-depth Study of Kilonova



Astronomers performed in-depth study of a kilonova and witnessed the creation of heavy elements.

BNS Science: Neutron Star Equation of State (EOS)

Neutron stars are similar density to atomic nuclei.



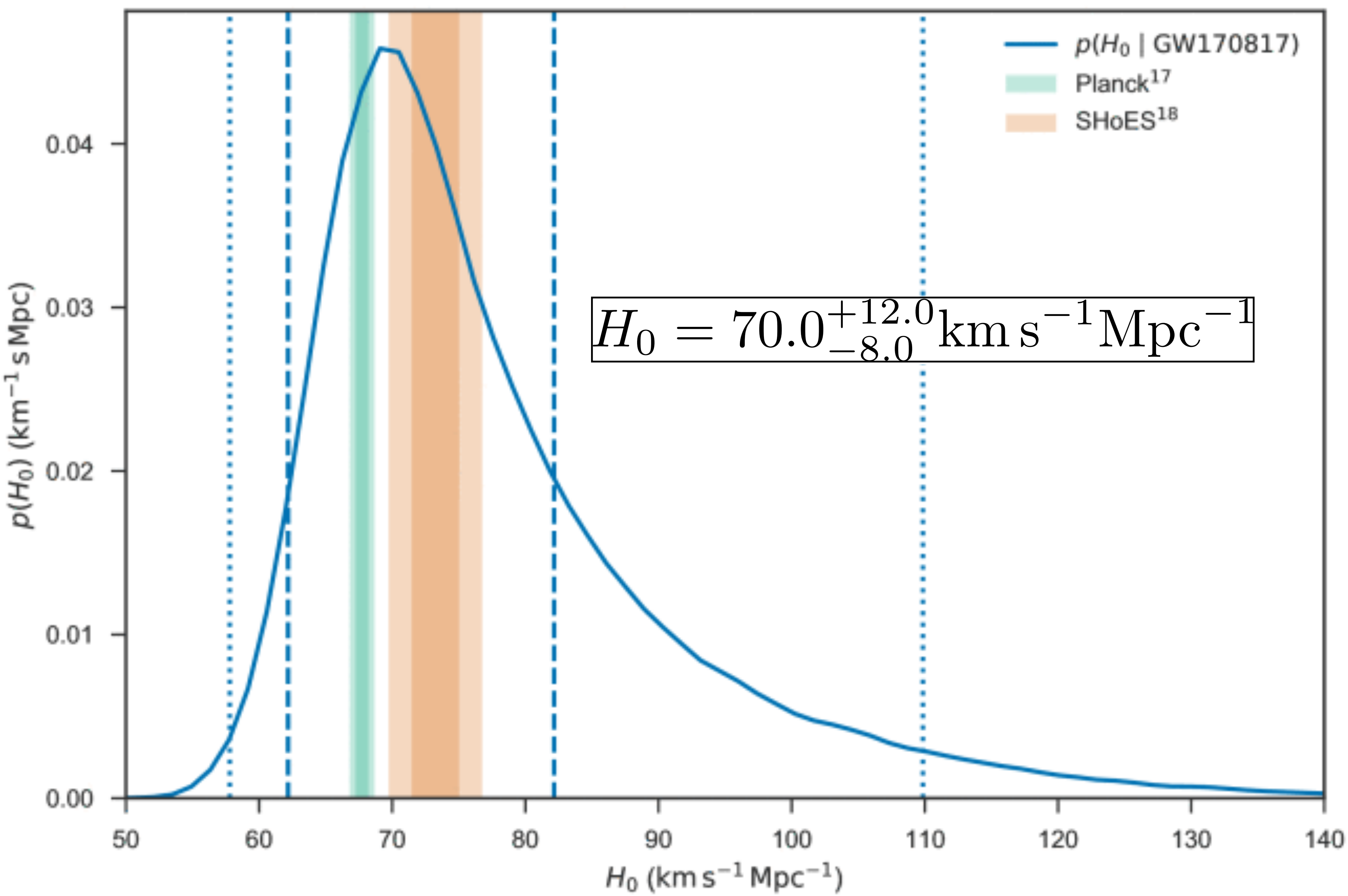
Tidal effects leave their imprint on GW signal from binary neutron stars.

BNS Science: Measuring the Hubble Constant

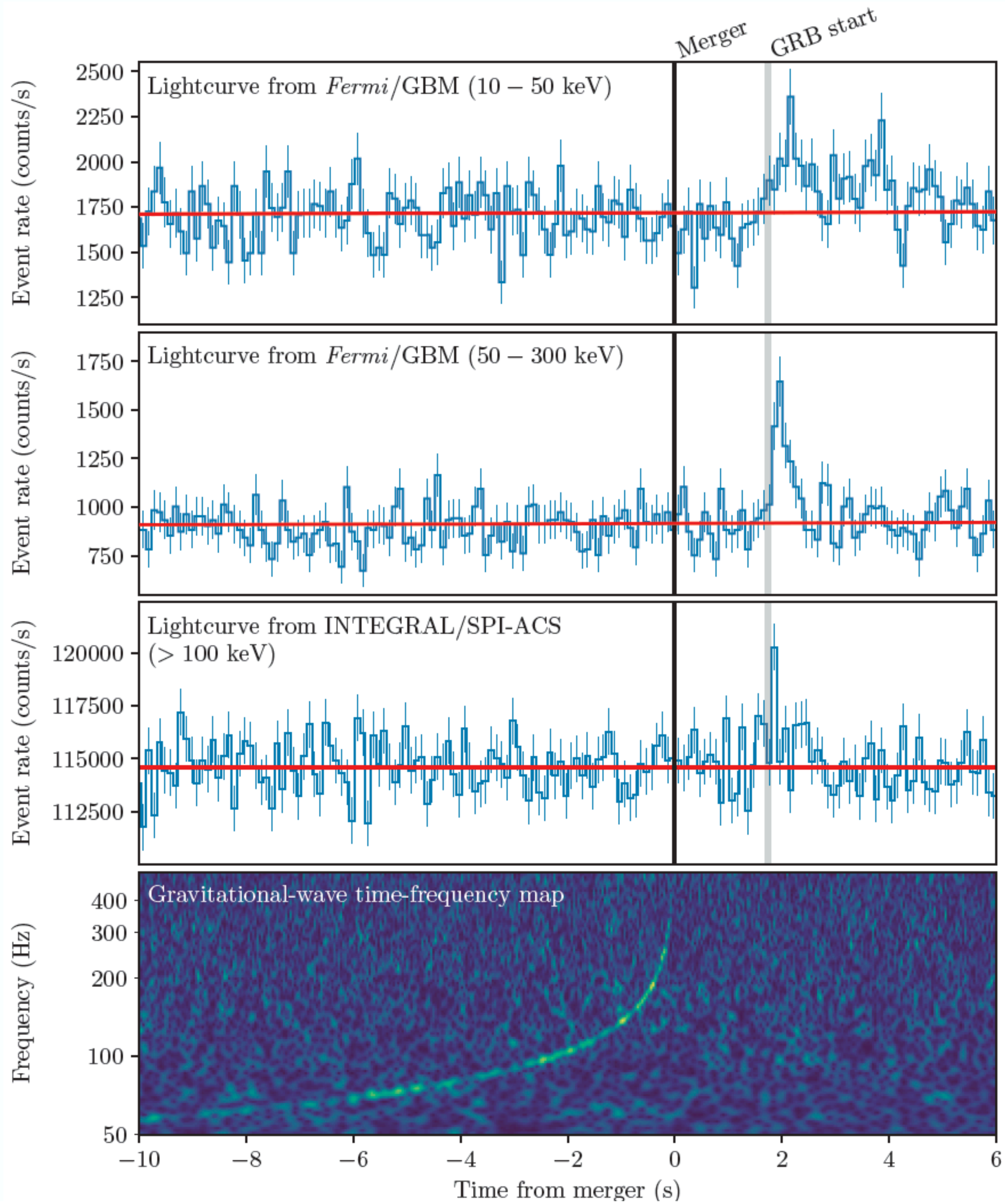
$$v_H = H_0 d$$

Distance from GW signal: $d = 44\,\mathrm{Mpc}$

Recessional velocity from galaxy: $v_H = 3000\,\mathrm{km/s}$



BNS Science: Measuring the speed of gravity



Gamma-rays reached Earth 1.7s after GW event. Nearly identical speeds of GWs and light propagation.

$$c_{\mathrm{gw}} = c_{\mathrm{light}} \pm \frac{(\sim 2\,\text{light seconds})}{(\sim 100\,000\,000\,\text{years})}$$

$$= 299\,792\,458.000\,000\,0^{+0.000\,000\,2}_{-0.000\,000\,9}\,\mathrm{ms}^{-1}$$

- What are gravitational waves?
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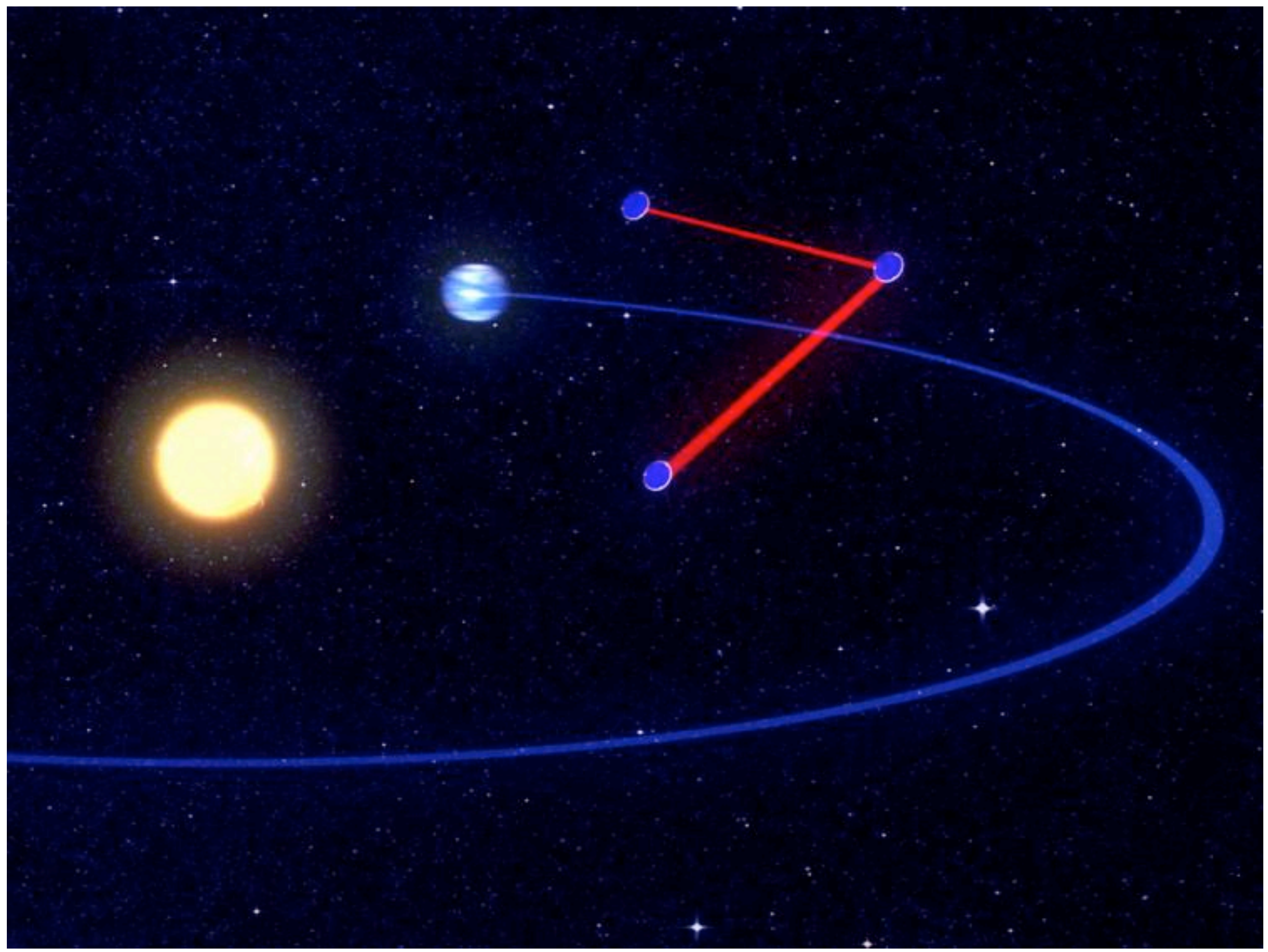
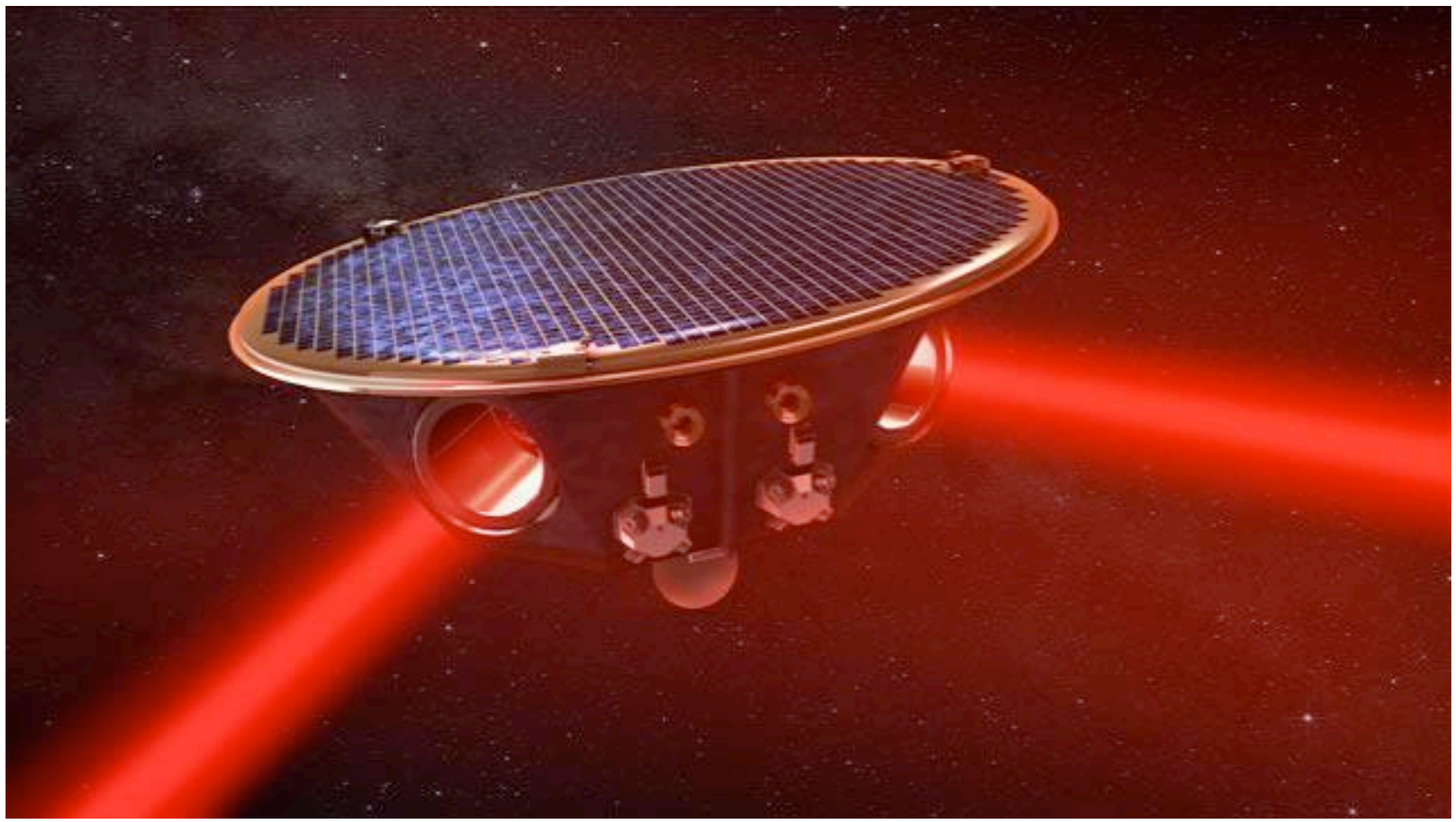
Space-based Detectors: eLISA



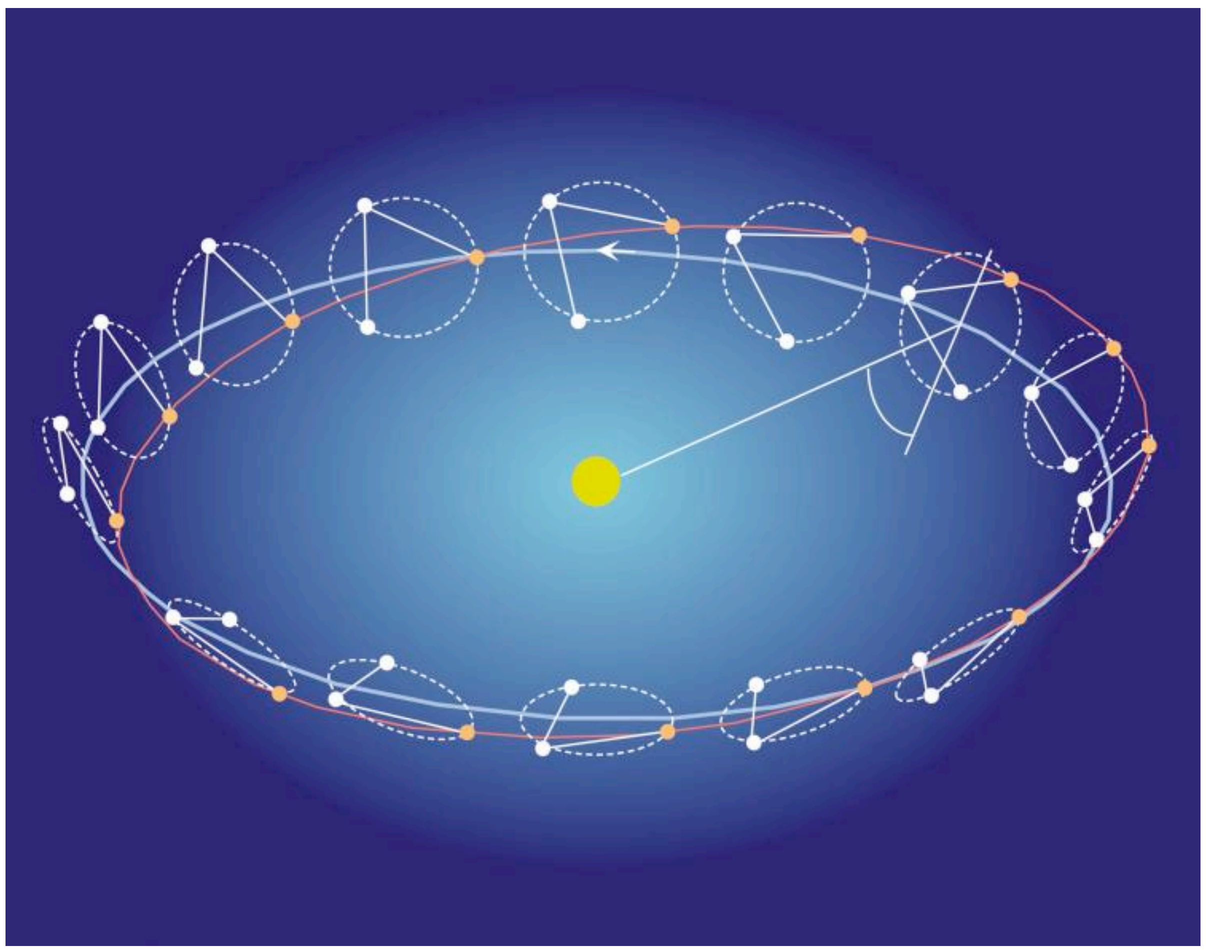
Three spacecraft in Earth-like orbits around Sun.
Arm length of 1 million km, equilateral triangle formation.

Space-based Detectors: eLISA



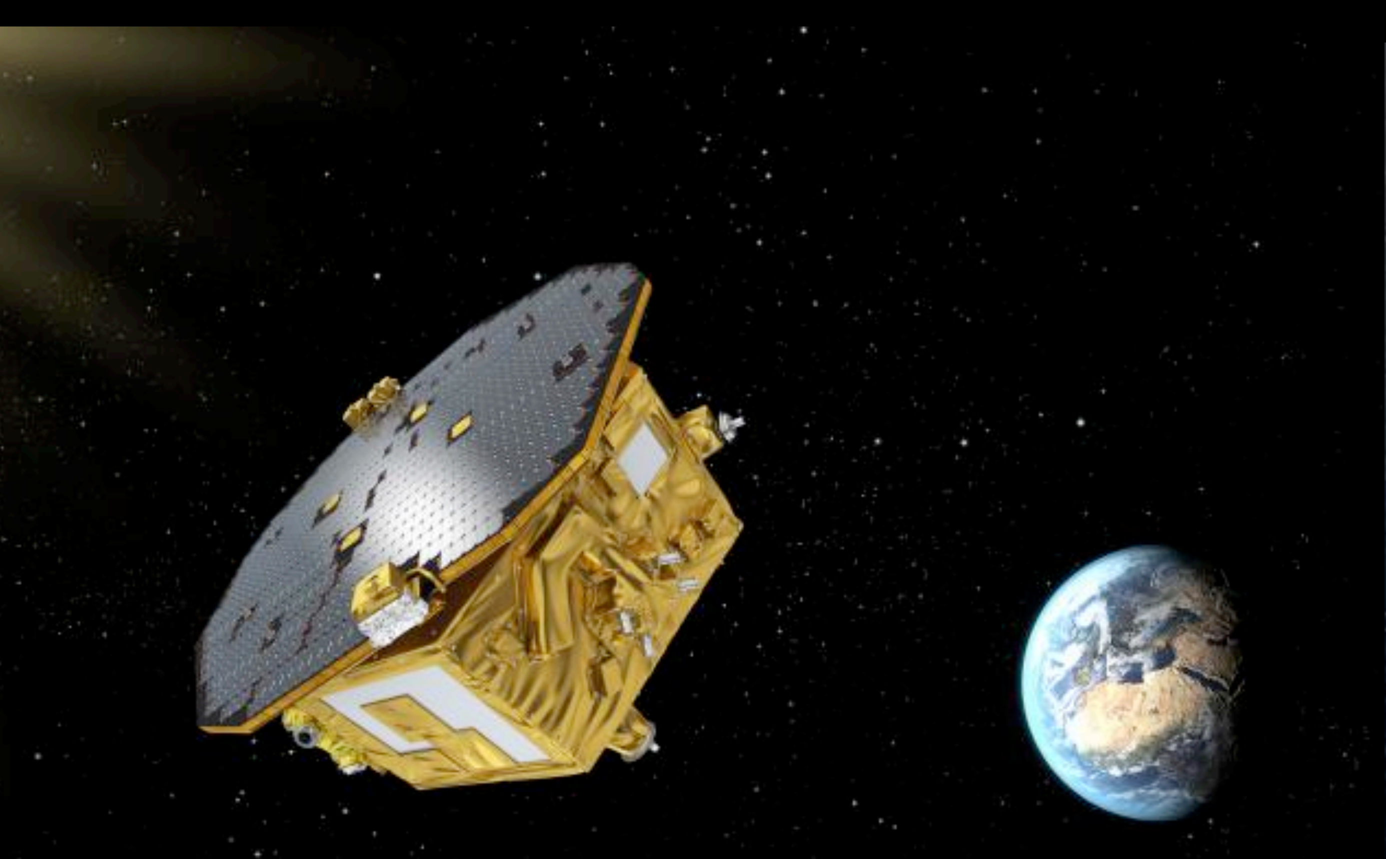
Each spacecraft carries lasers. They’re too far apart for the laser light to reflect back and forth. Instead, when light from one arrives at the other, the onboard laser of receiving craft amplifies and returns it (like reflection): active mirrors.

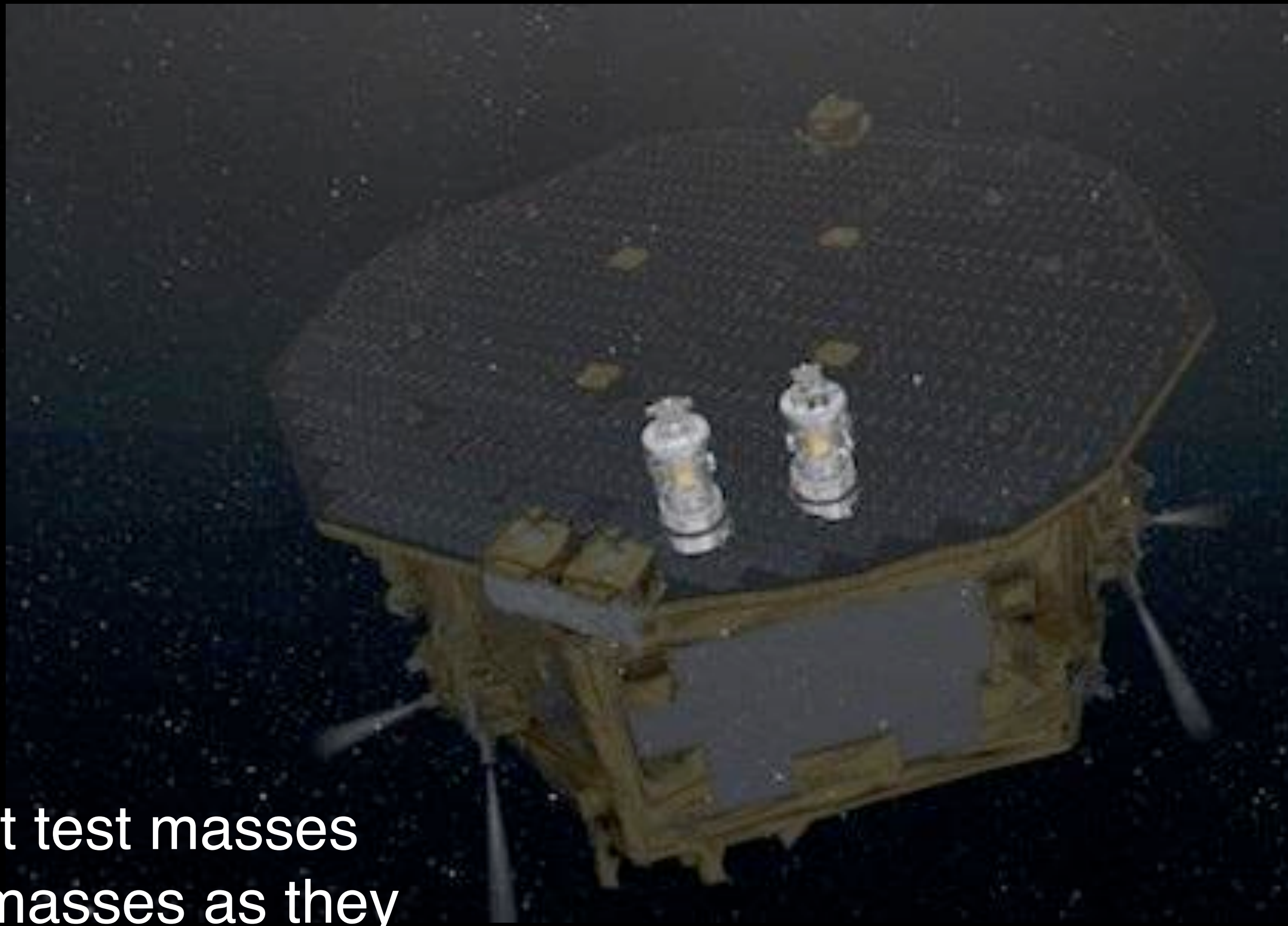
Space-based Detectors: eLISA



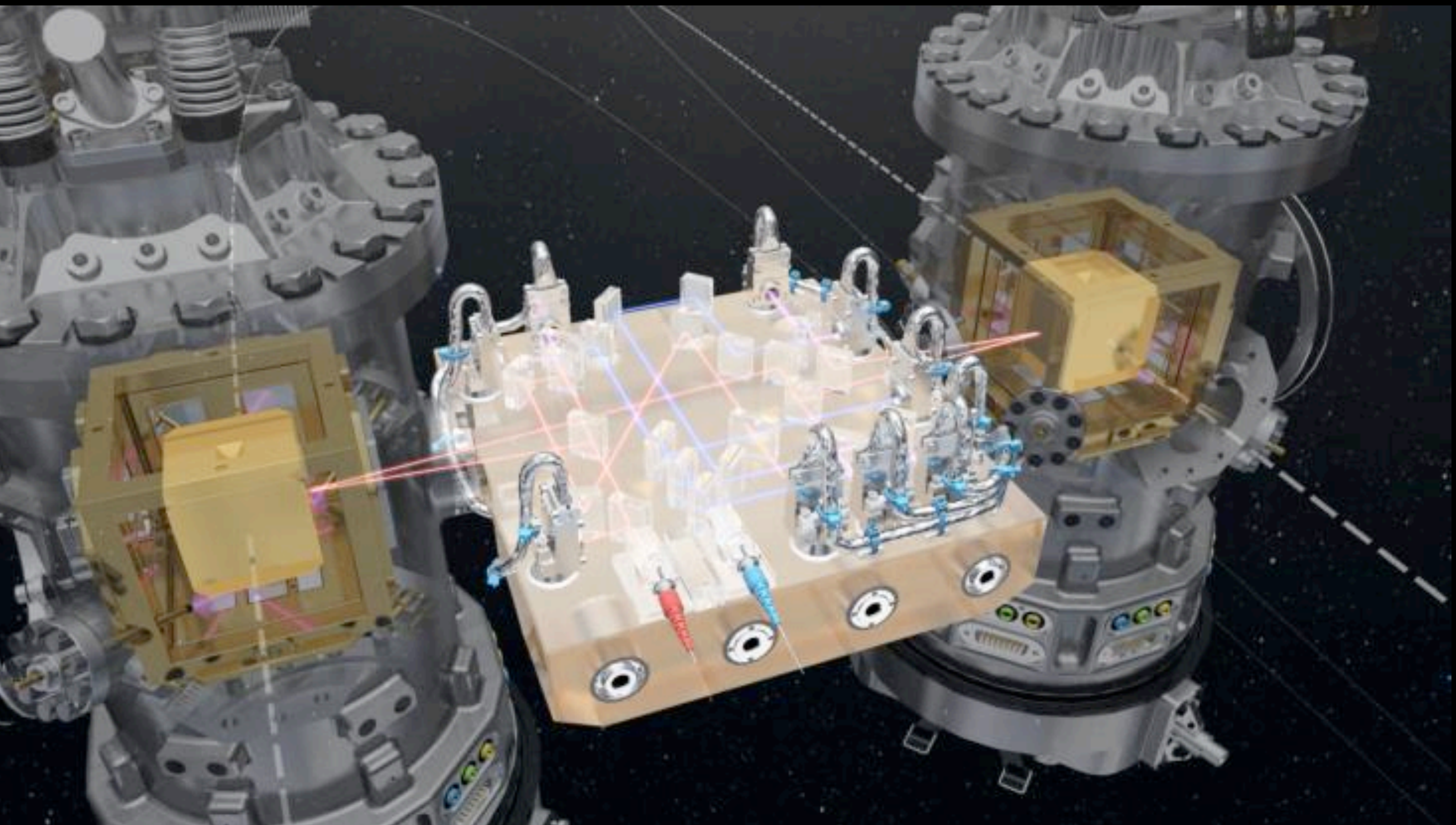
Changing orientation of triangle through one orbit will allow observers to determine direction of sources.

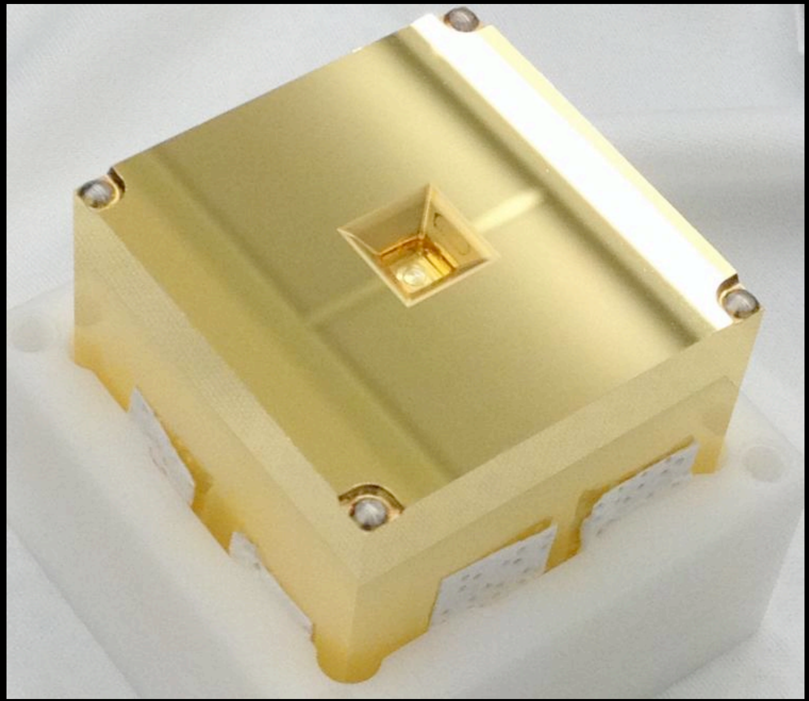
LISA pathfinder operates 1.5 mill km from Earth toward the Sun, orbiting the Sun-Earth langrangian point L1.





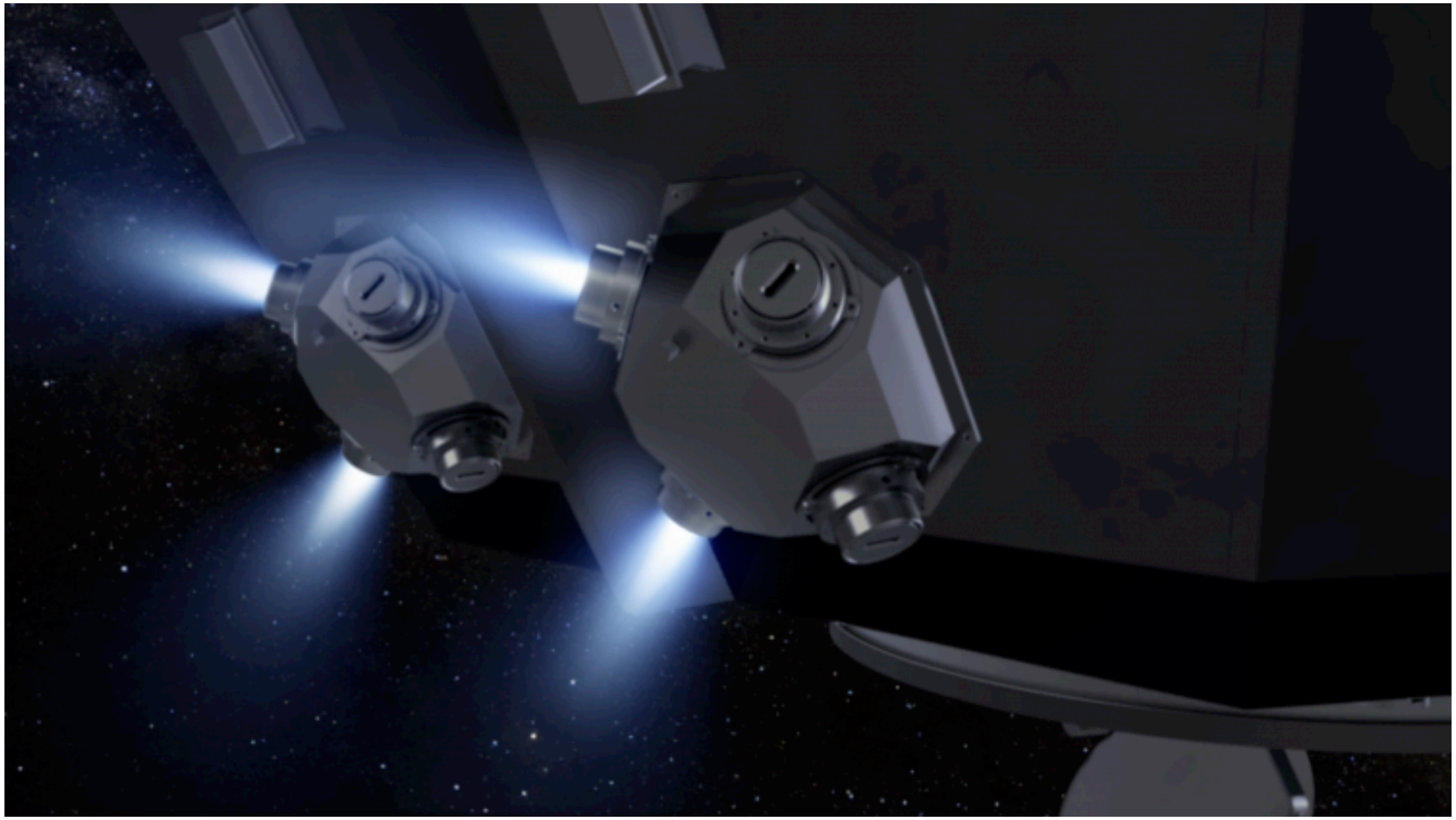
Two inertial sensors surrounding independent test masses and an optical bench in-between monitor test masses as they free-fall through space





One of LISA Pathfinder's two test masses, cube of solid gold-platinum alloy, 1.96kg.

Space-based Detectors: eLISA

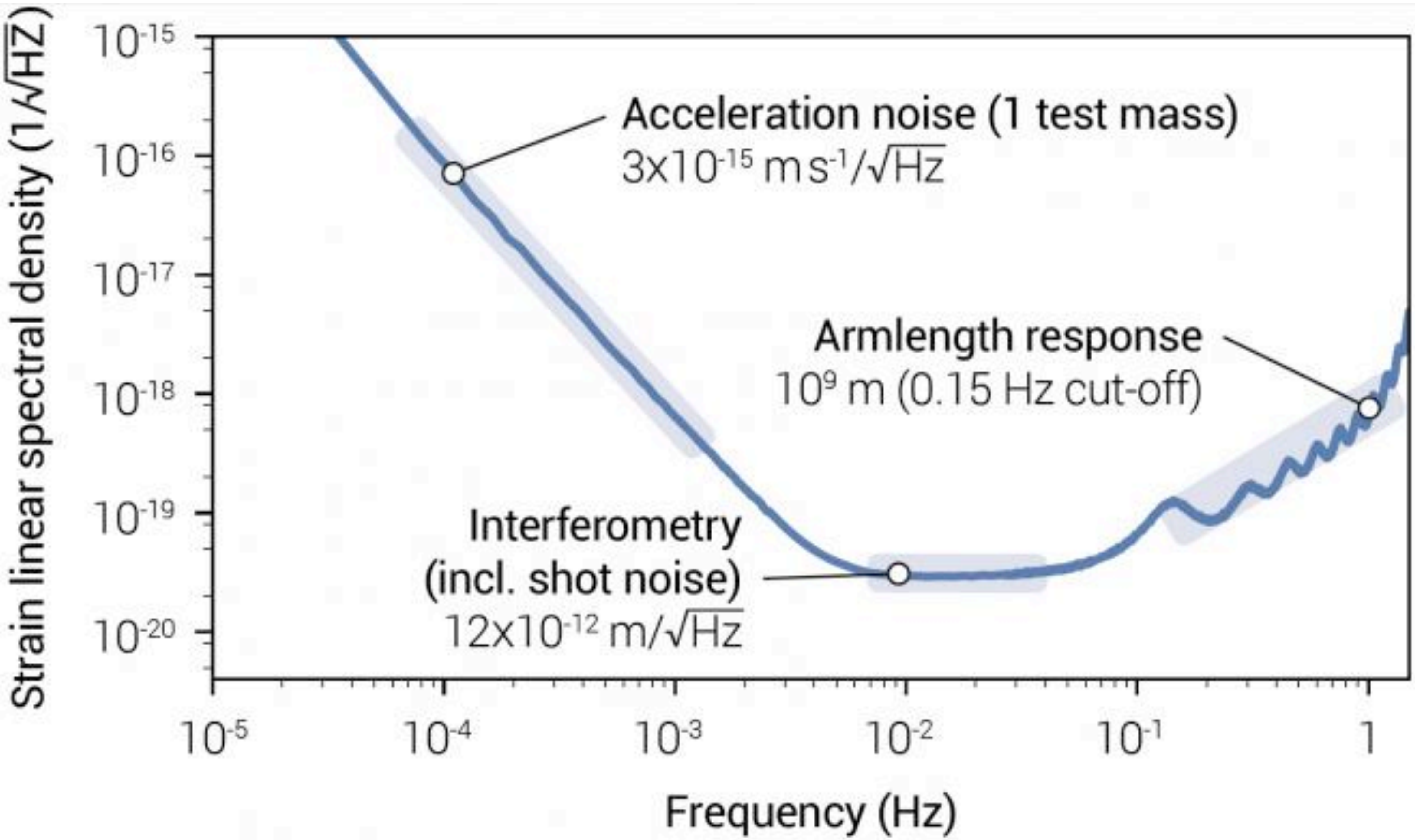


Microthrusters will make minuscule shifts in order to keep the spacecraft centered on one of the masses.

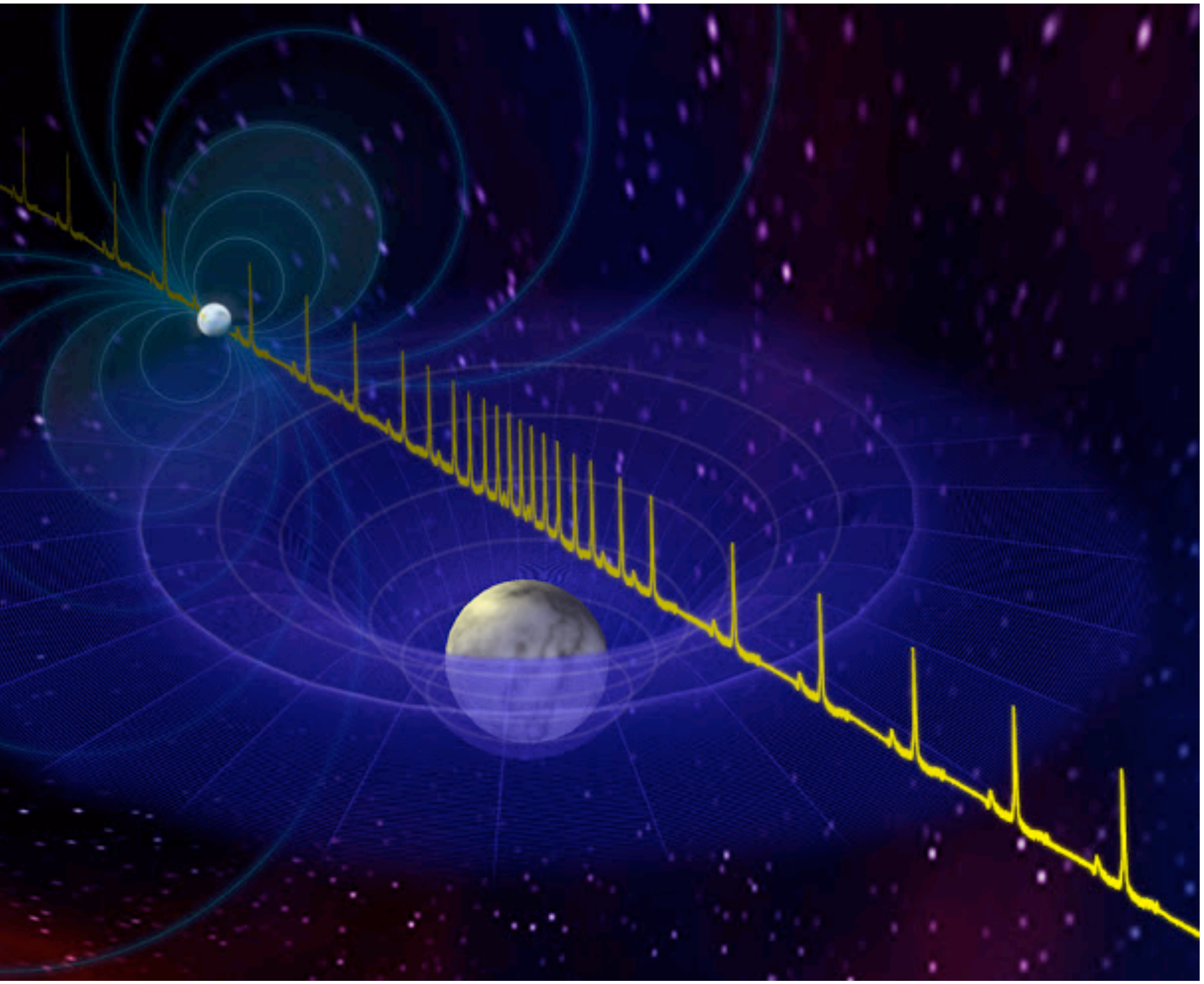
This will isolate the two cubes from all external and internal forces except gravity, placing them in the most precise freefall ever obtained.

esa

LISA Sensitivity



Pulsar Timing Arrays



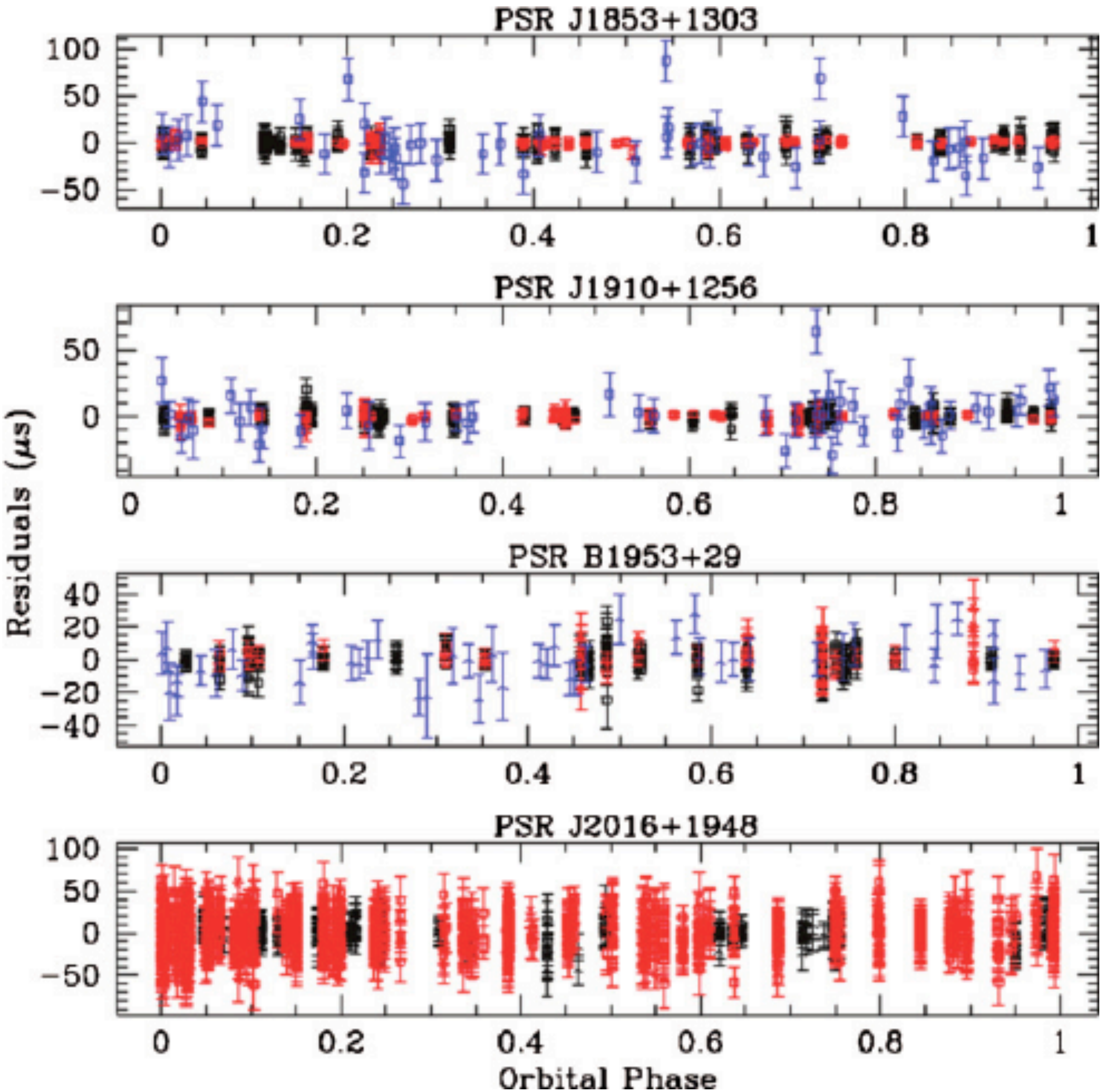
Millisecond pulsars - rotate with incredible stability, can be used as precise clocks.

The time of arrival (TOA) of pulse can be usually measured to:

$$\frac{\delta}{\mathrm{SNR}}$$

δ - pulse width; few hundred microseconds

Pulsar Timing Arrays



Gonzalez, et al., ApJ 2011

Difference between predicted and measured TOAs can have RMS scatter as little as 100 nanoseconds over timescales of many years.

Pulsar Timing Arrays

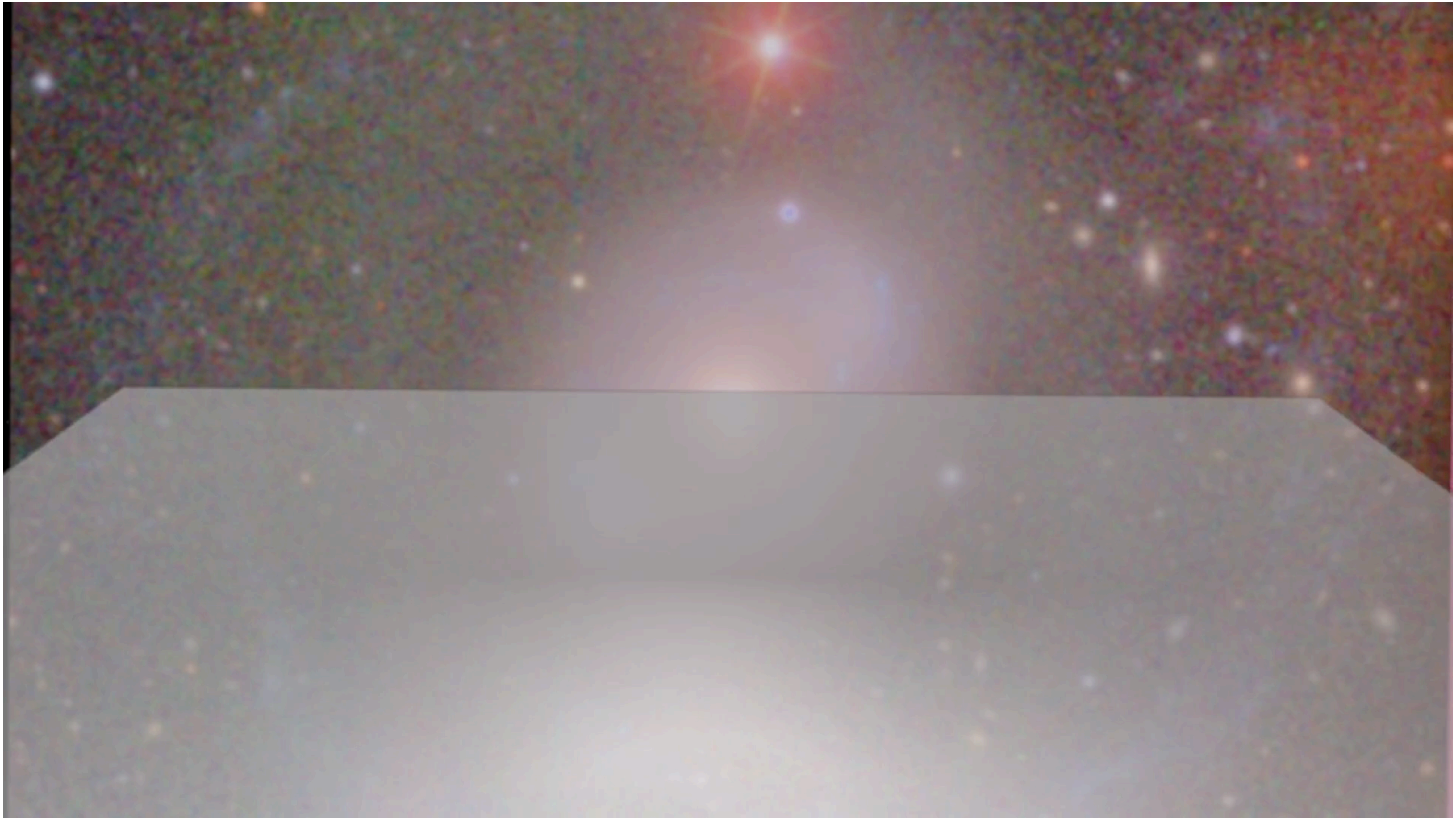
Germany
UK
France
Italy
Netherlands
US
Puerto Rico
Australia

Pulsar Timing Arrays

Pulsar timing brings together astronomers who use the world's most sensitive radio telescopes to observe and discover millisecond pulsars.

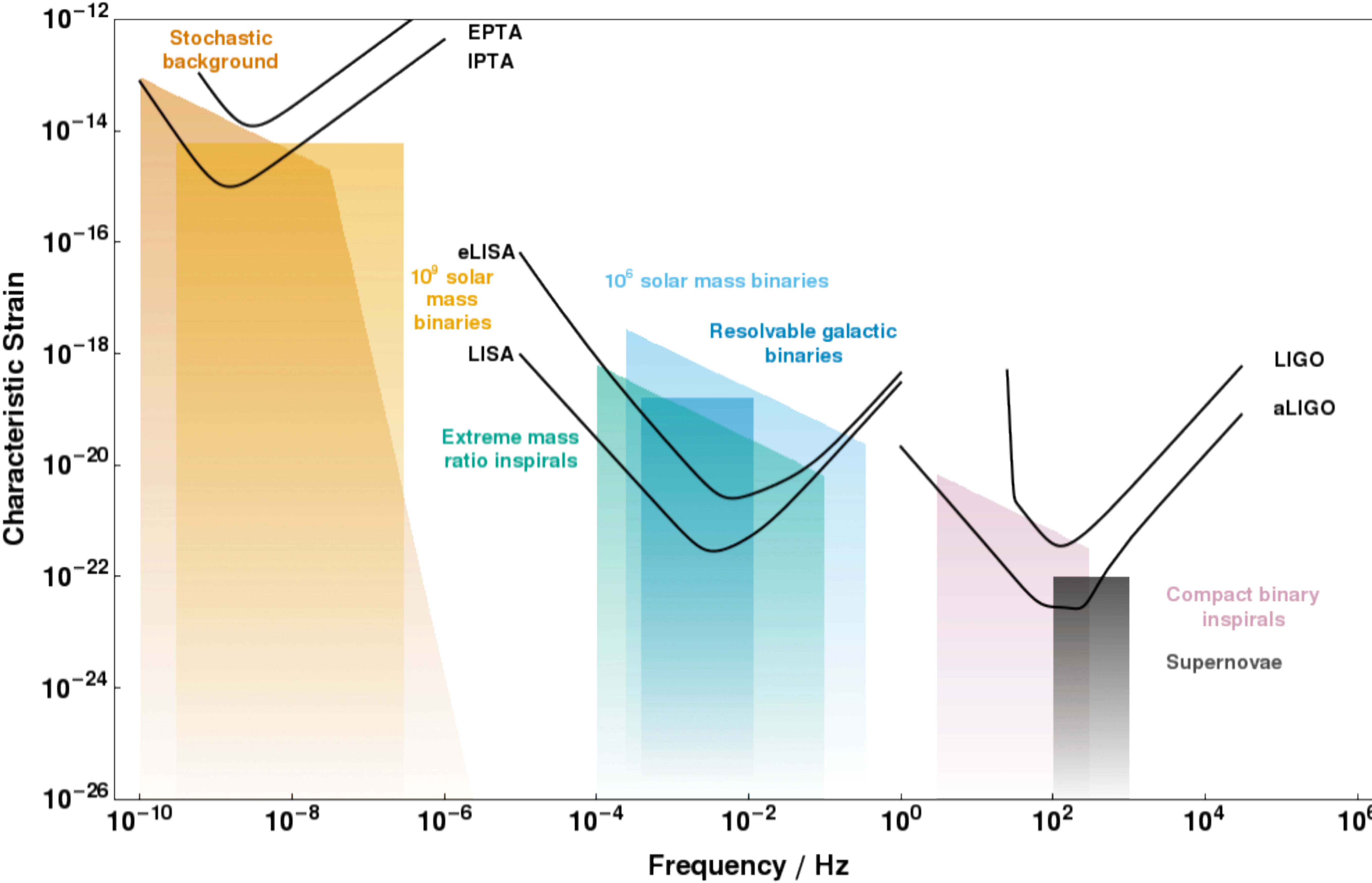
They look for the influence of GWs on timing residuals from ultra-precise millisecond pulsars, in particular for correlations in timing residuals between pairs of pulsars

Pulsar Timing Arrays



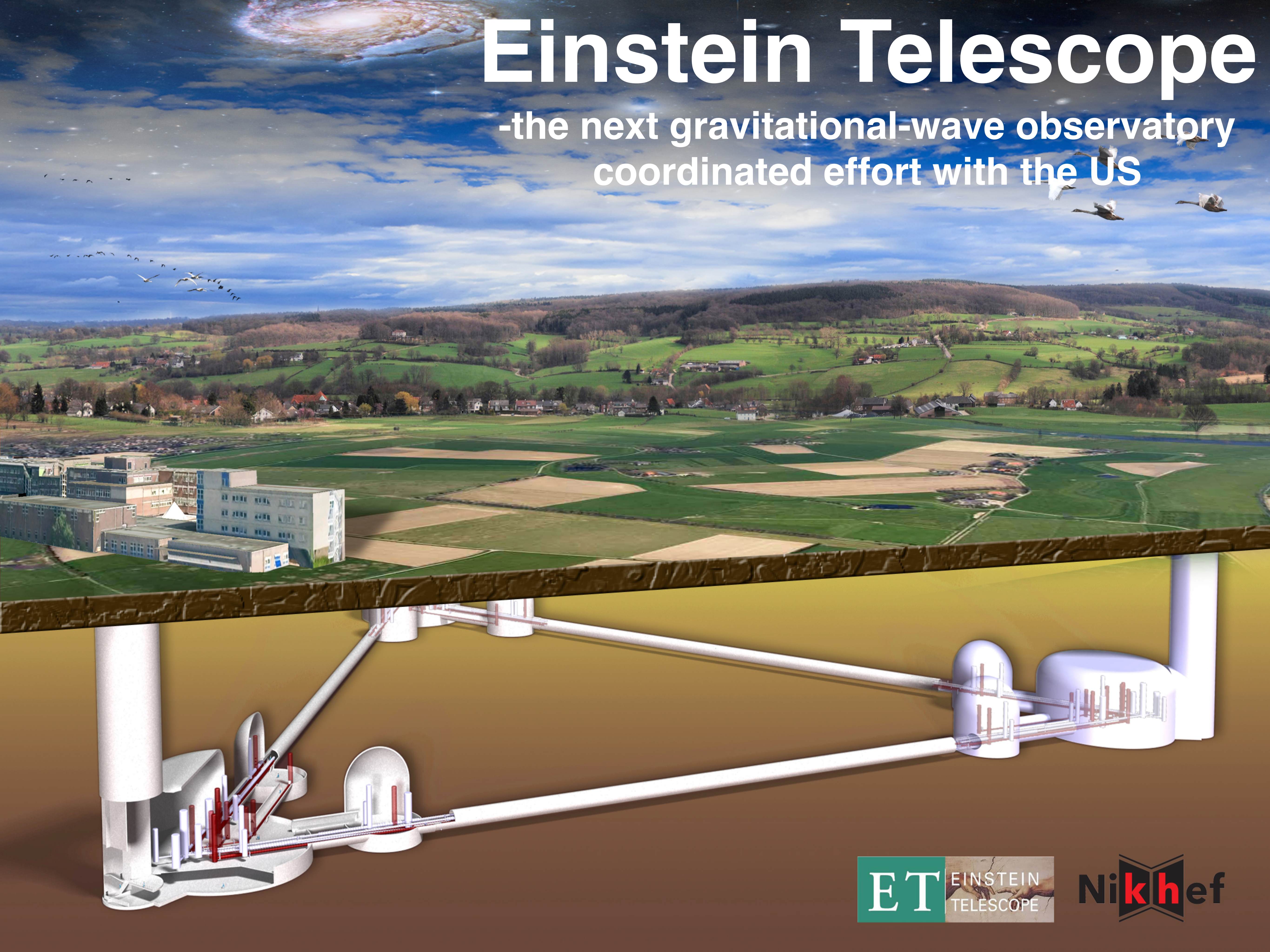
Sensitive to GWs with periods between the cadence of pulsar timing observations (weeks) and the span of the dataset (years), ie nanohertz frequencies.

Gravitational-wave Spectrum

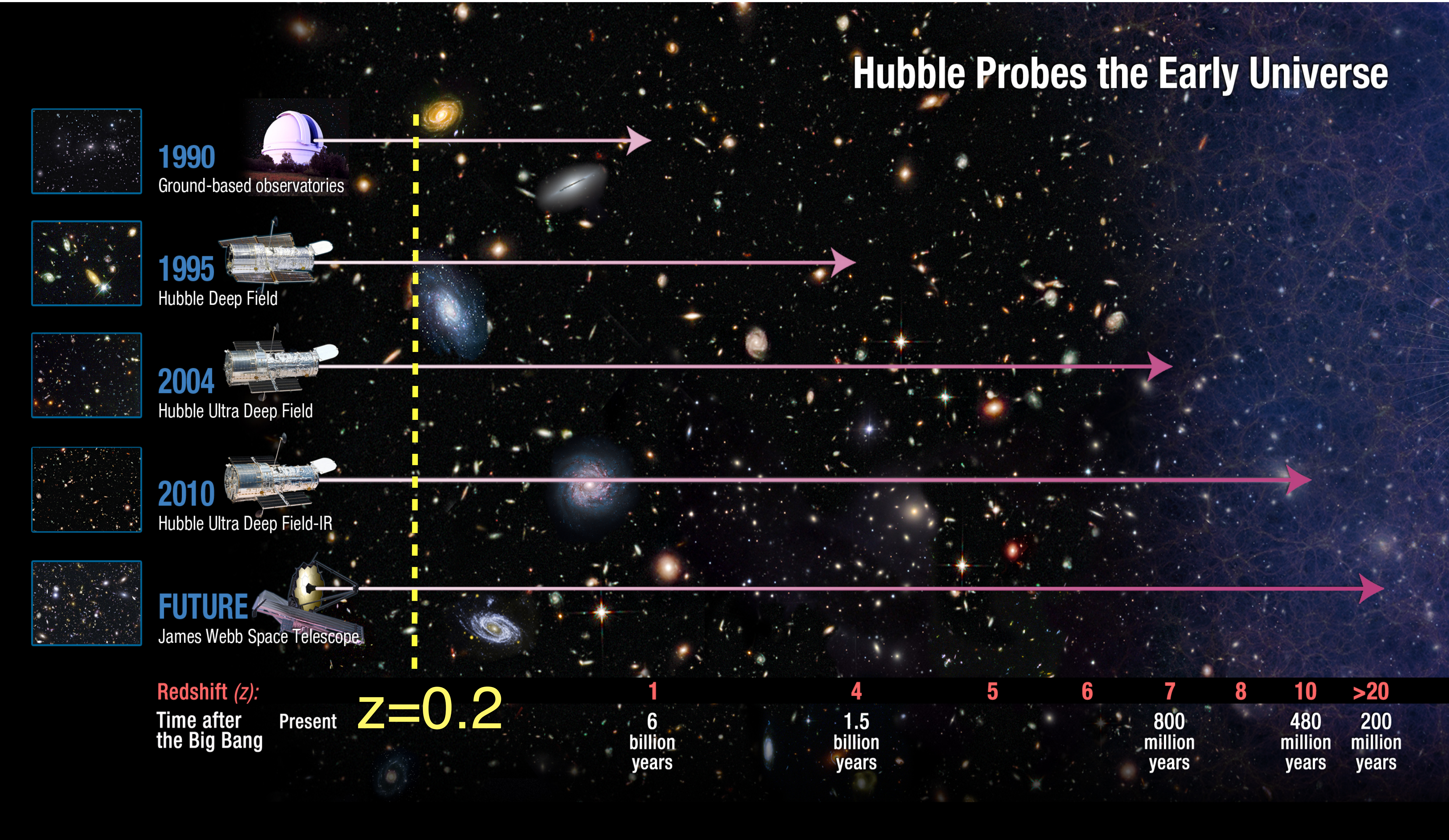


Einstein Telescope

-the next gravitational-wave observatory
coordinated effort with the US



Einstein Telescope: observing all BBH mergers in the Universe



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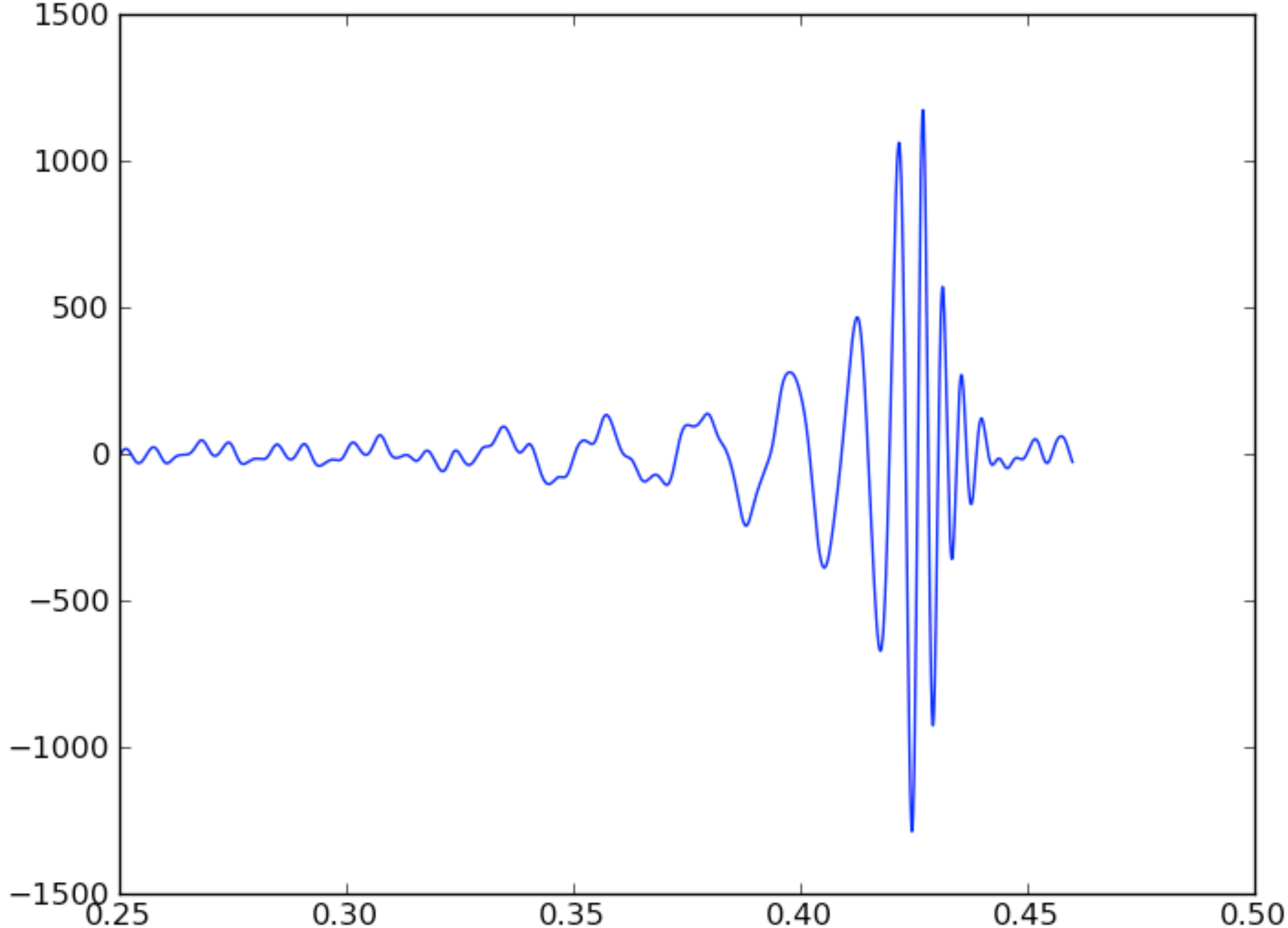
Python Tutorials:

- https://wiki.python.org/moin/BeginnersGuide/Programmers
- Also check out Coursera

Homework is based on paper here about the basic physics of binary black hole merger GW150914:

- https://arxiv.org/abs/1608.01940

Problem 2: Waveform should look like:



Problem 2: Determine zero crossings: