Image credit: LIGO/T. Pyle

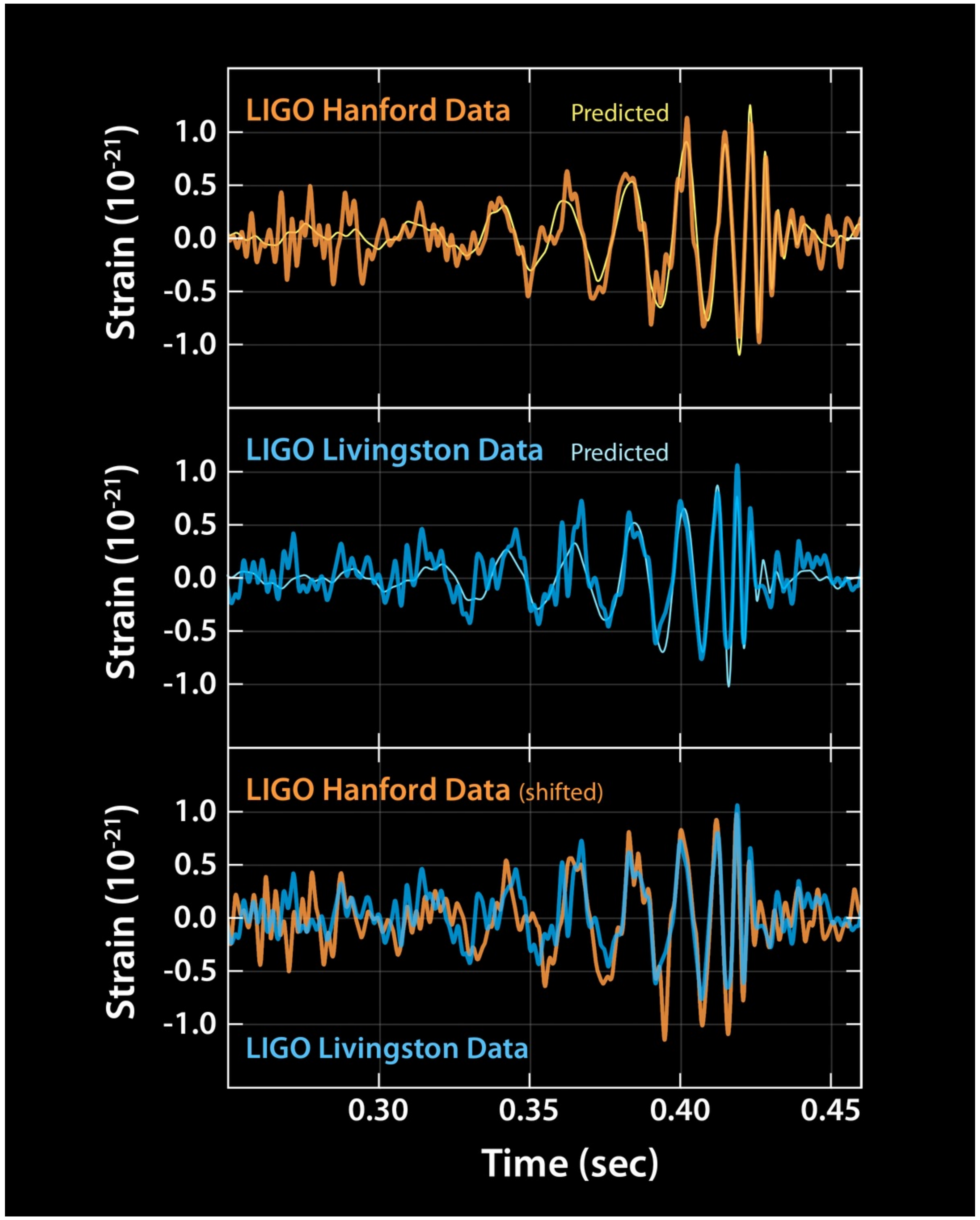
Gravitational Wave Astrophysics

Pablo Marchant

Part 1: Overview of GW astrophysics

A new messenger in astrophysics

Credit: Caltech/MIT/LIGO Lab



Physical Review Letters 116, 061102 (2016)

- GW150914: first detection of two merging binary black holes through gravitational wave radiation.

- A new messenger to compliment electromagnetic and astroparticle observations.

- Rapidly growing from a field with a handful of detections to large samples.

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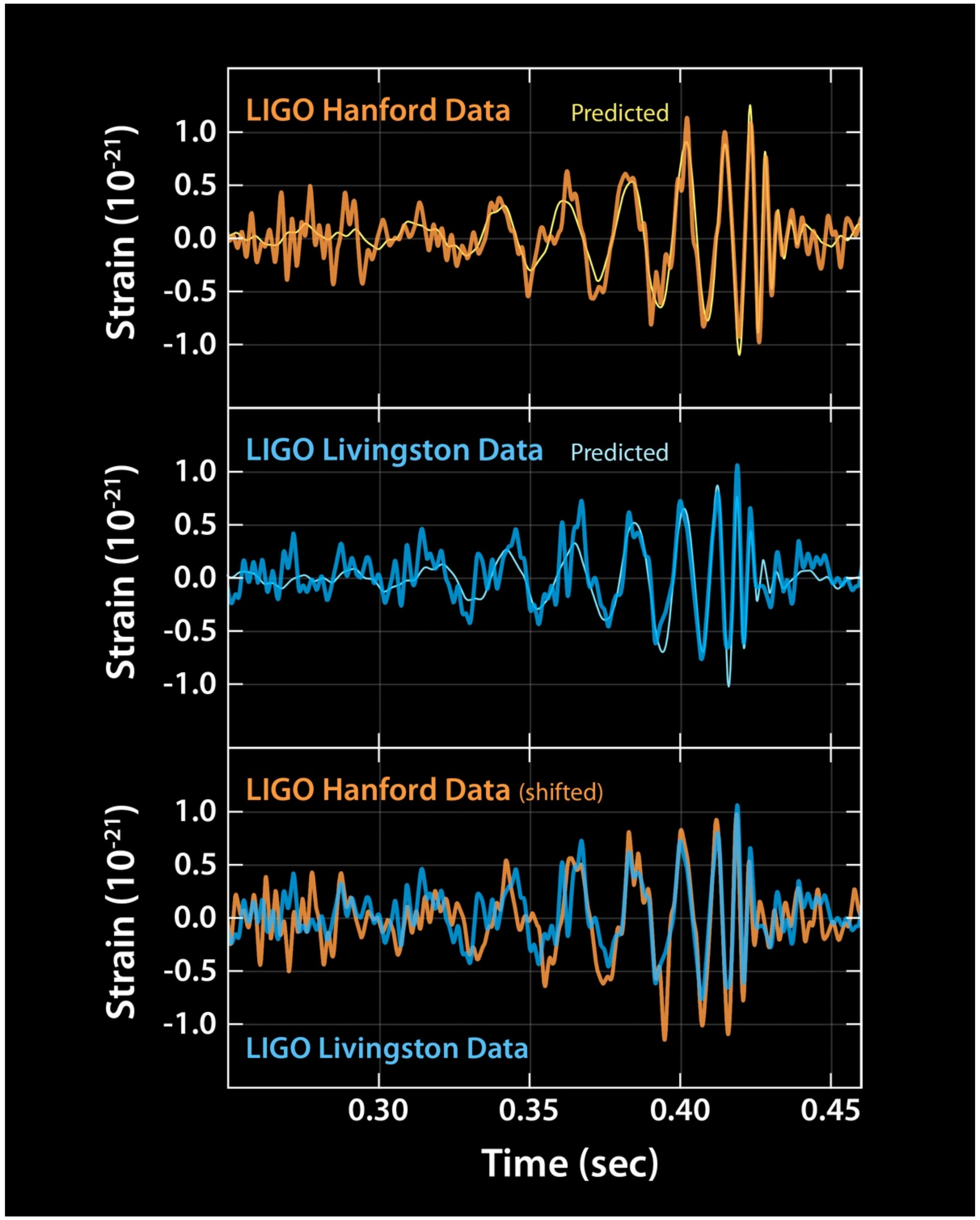

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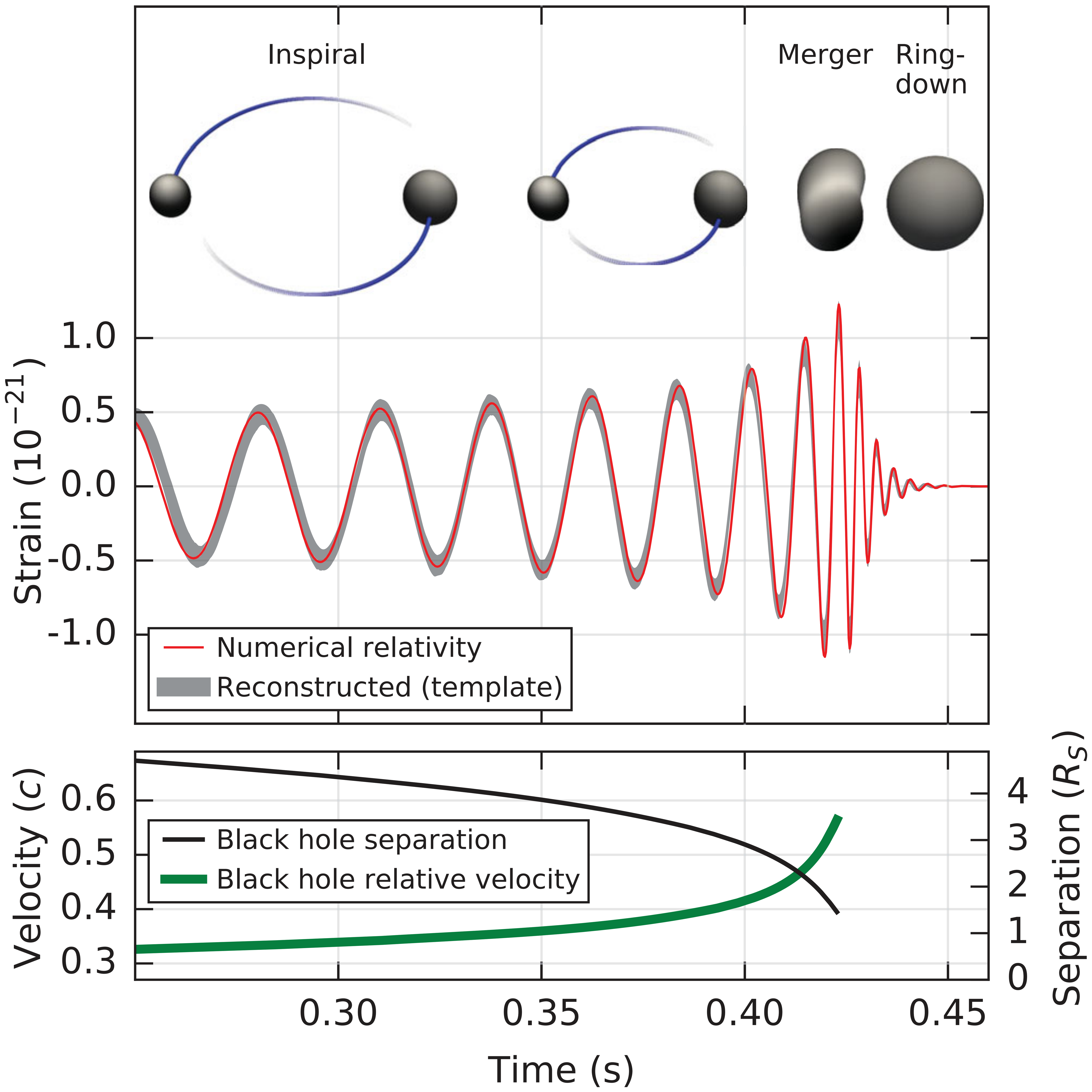
$$\text{strain } h = \frac{\Delta L}{L}$$

A new messenger in astrophysics

What makes GW150914 a high energy event?

$$\sim 36 M_\odot + 29 M_\odot \rightarrow 62 M_\odot$$



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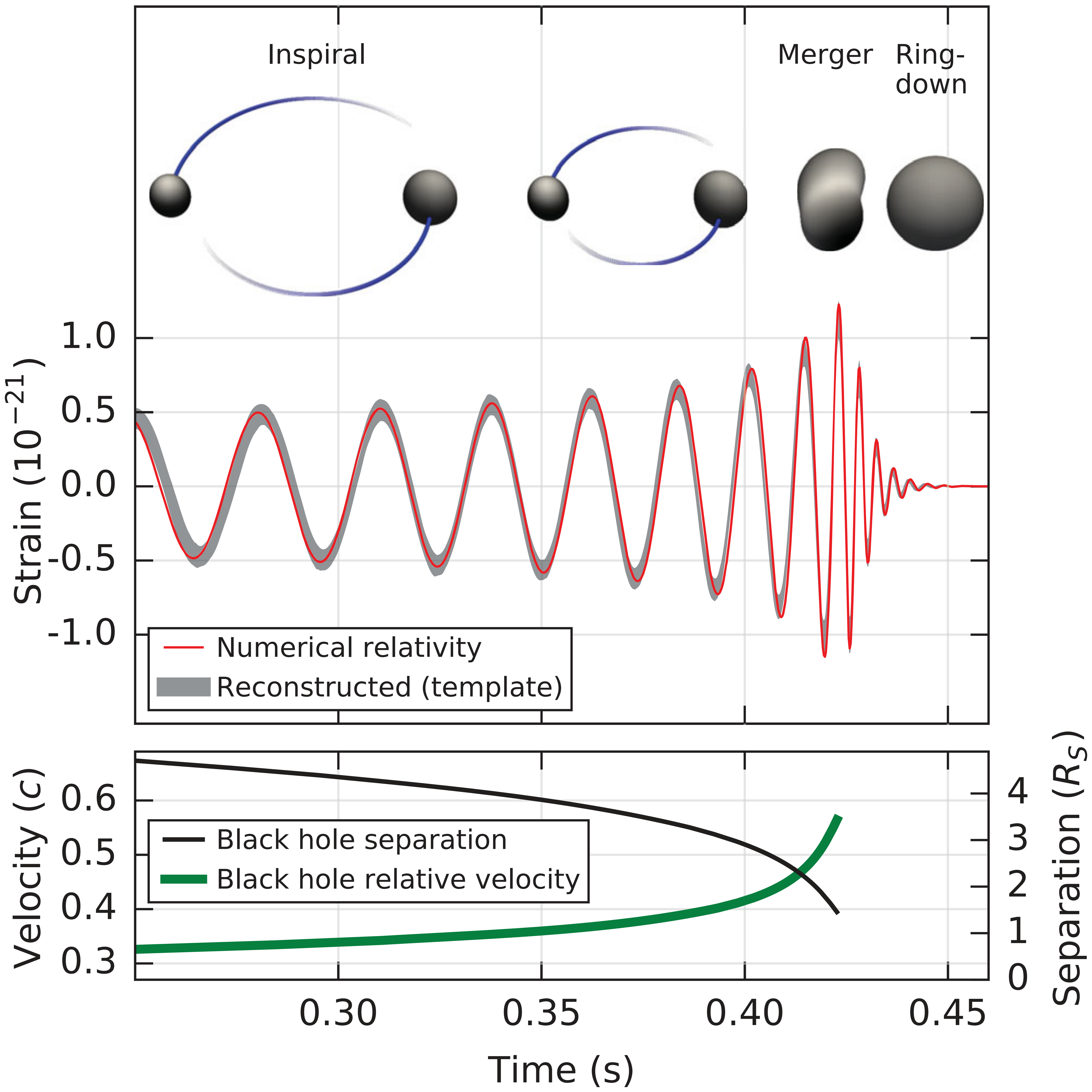

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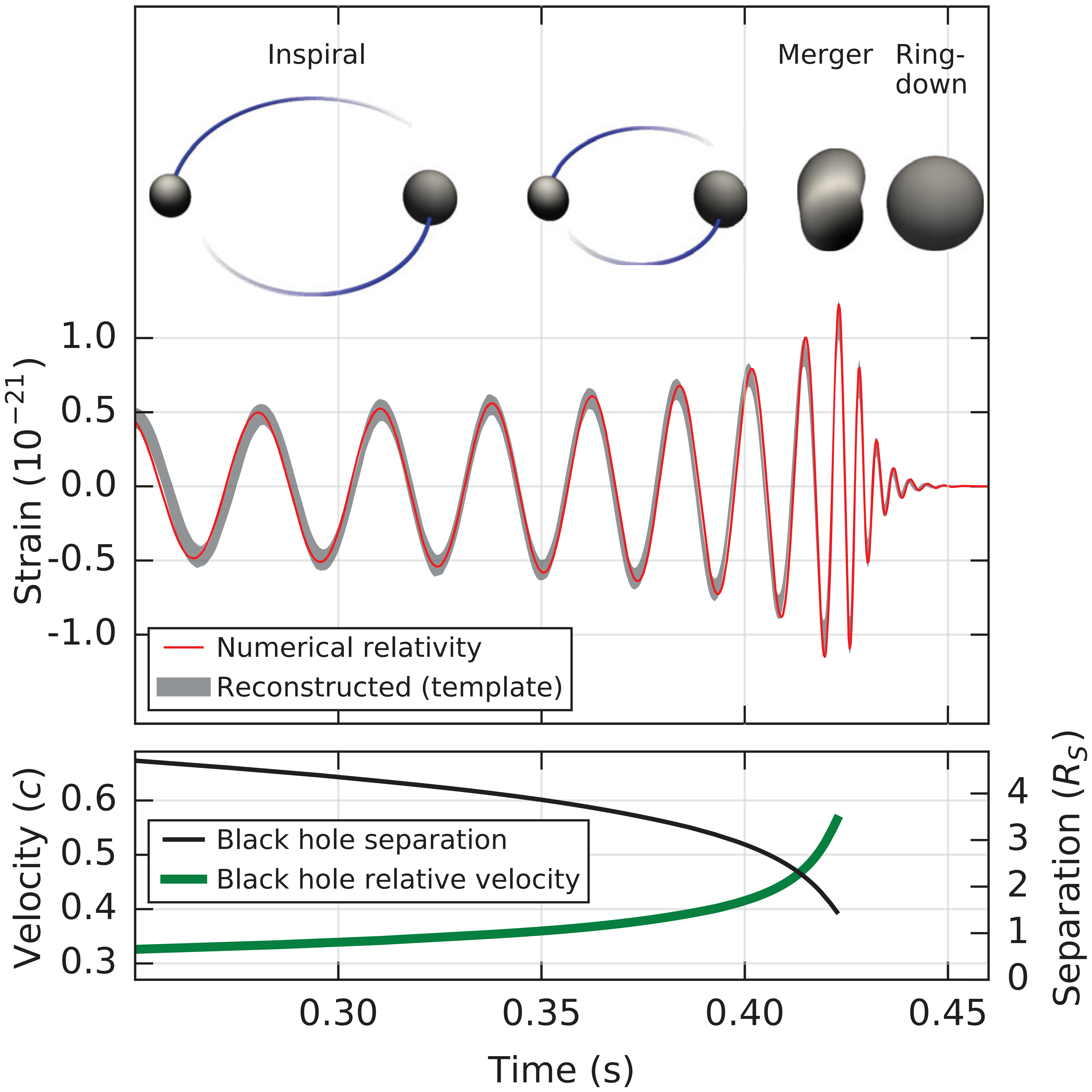
peak luminosity of $\sim 10^{23} L_\odot$



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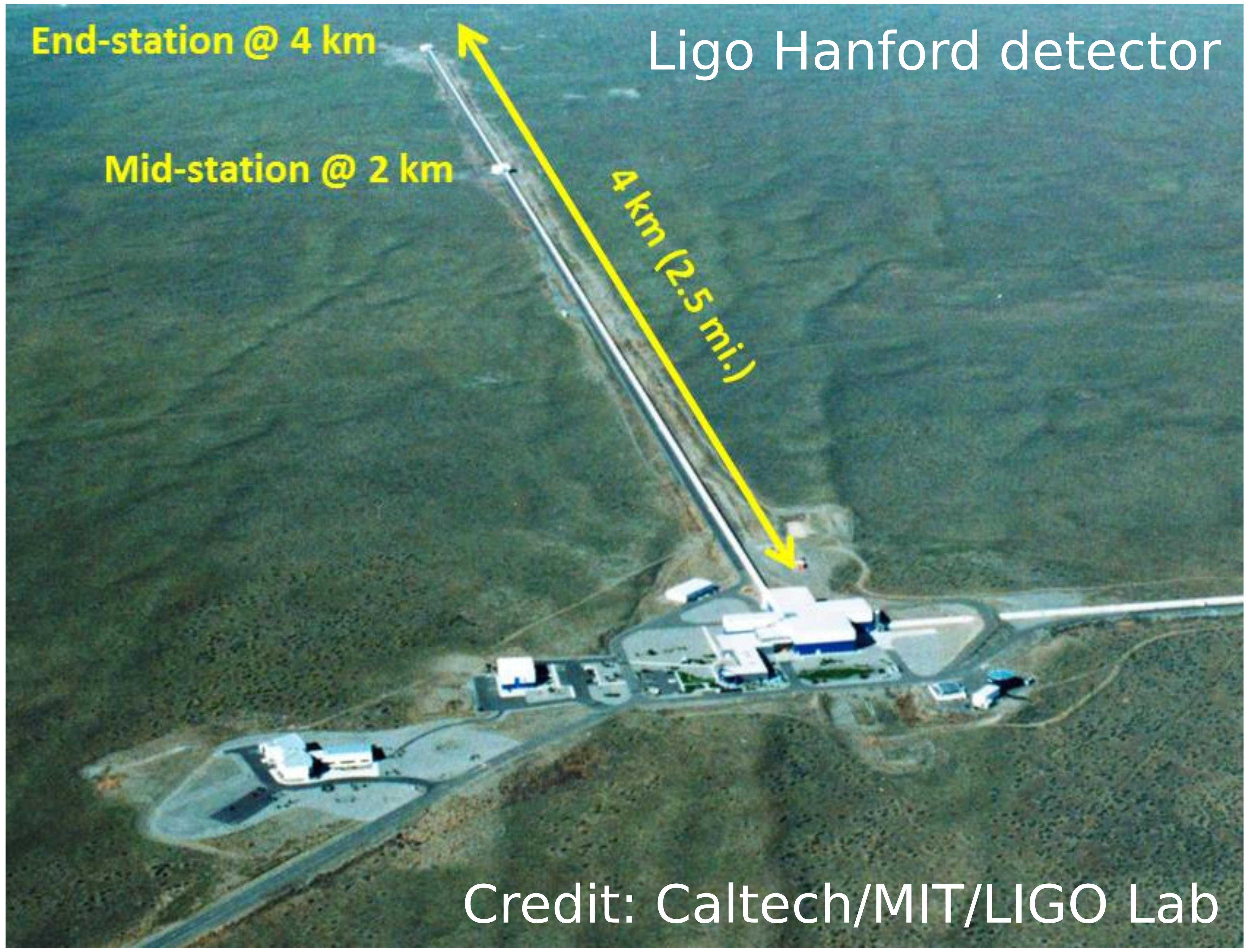

$$\Delta L = 4 \times 10^{-17} \ [\mathrm{m}]$$

A new messenger in astrophysics

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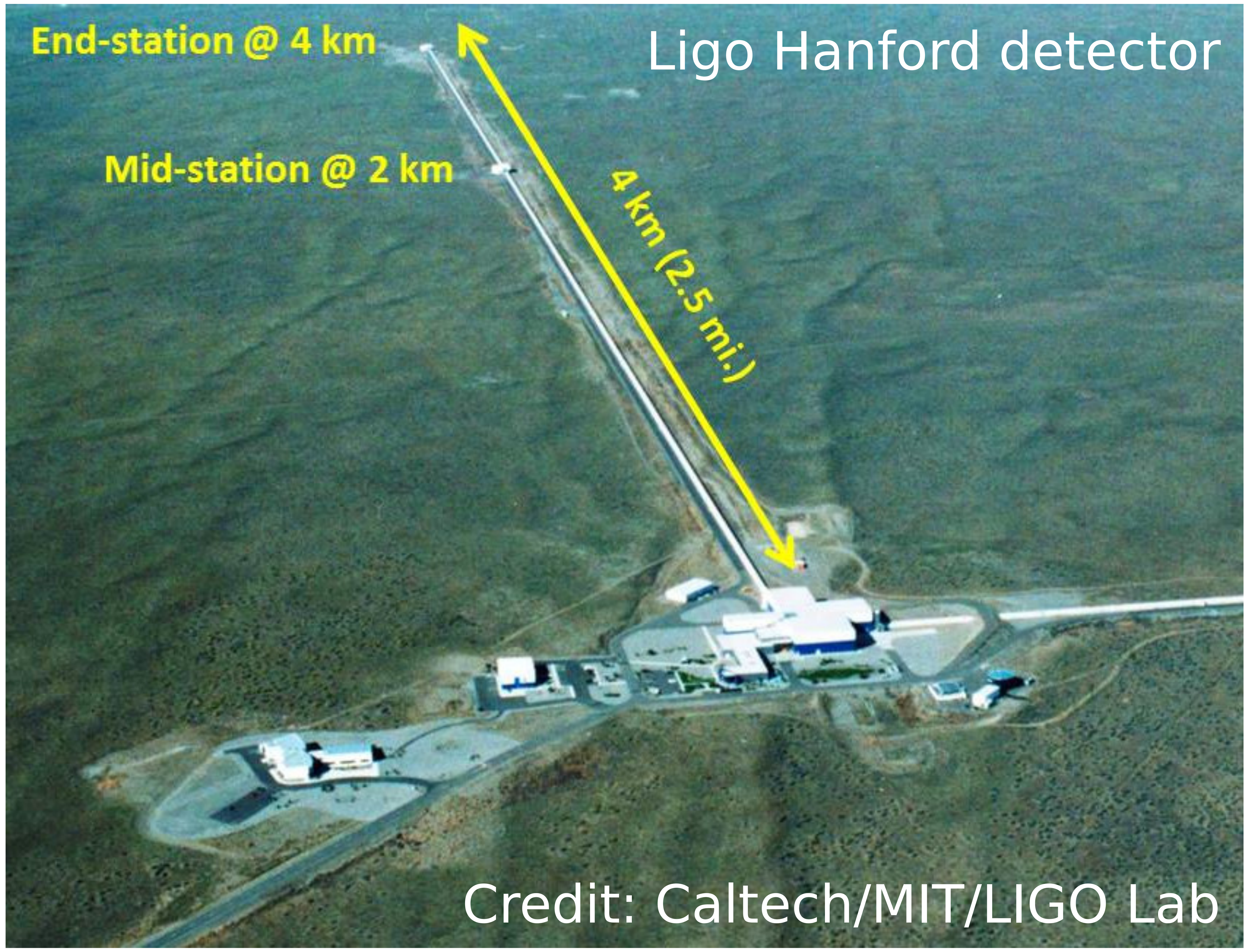


$$\Delta L = 4 \times 10^{-17} \text{ [m]}$$

Human hair: $\sim 10^{-4}$ [m]

Visible light: $\sim 5 \times 10^{-7}$ [m]

Bohr radius: $\sim 5 \times 10^{-11}$ [m]

Proton radius: $\sim 10^{-15}$ [m]

A new messenger in astrophysics

Image credit: myself

Vending machine at the LIGO Livingston detector

Outline

Outline

Today 12/5 19/5

Outline

Today

- History of the field
- Types of detectors
- Types of sources
- Current state of the field
- Future advancements

12/5

- Ground based interferometers
- Production of GWs from compact object binaries

19/5

- Parameter estimation from observed compact object coalescences
- Astrophysics of observed GW sources

Useful resources

https://astro-gr.org/online-course-gravitational-waves/

Astro-GR

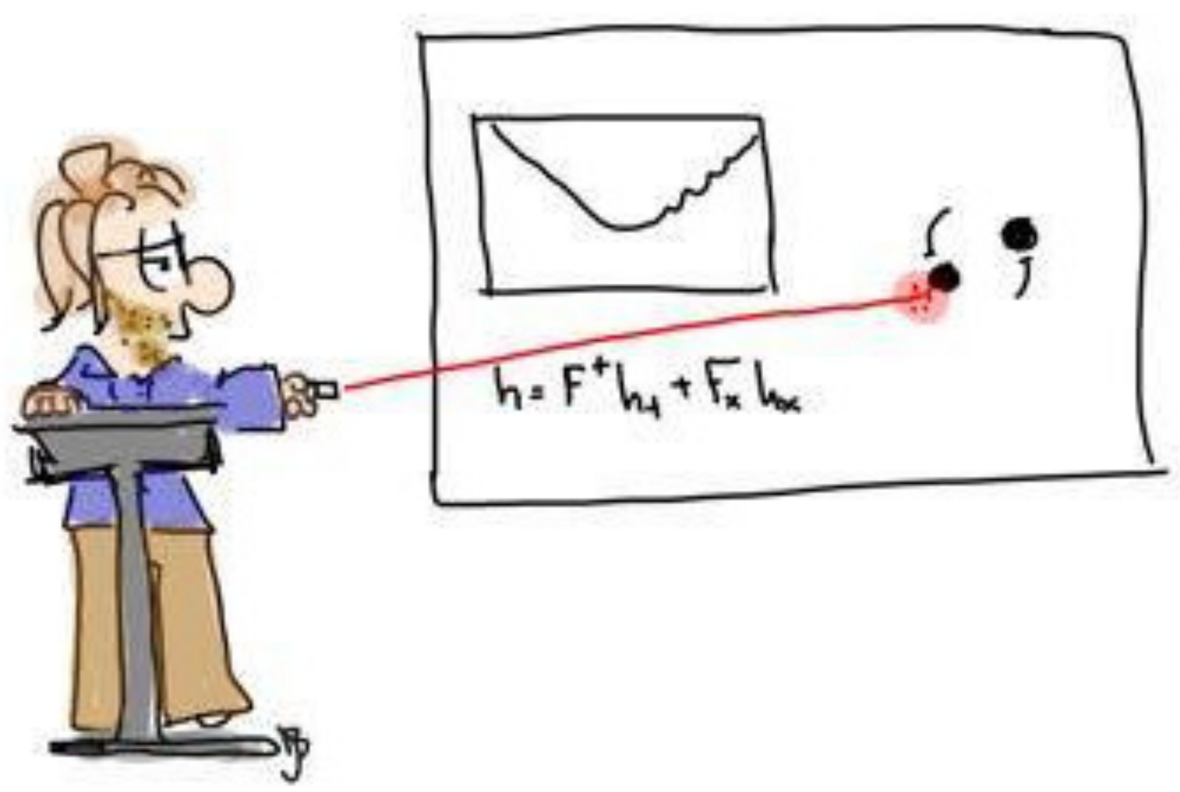
Home Me Contact Focus About Team Grav. Wave Course GW Notes Stellar Collisions Workshops

Papers Codes Pygmalion OpenBSD WP Life Comments et al

An Online Course On Gravitational Waves

An Online Course On Gravitational Waves Organised and designed by Kip S Thorne, Mihai Bondarescu and Yabei Chen

COURSE DESCRIPTION



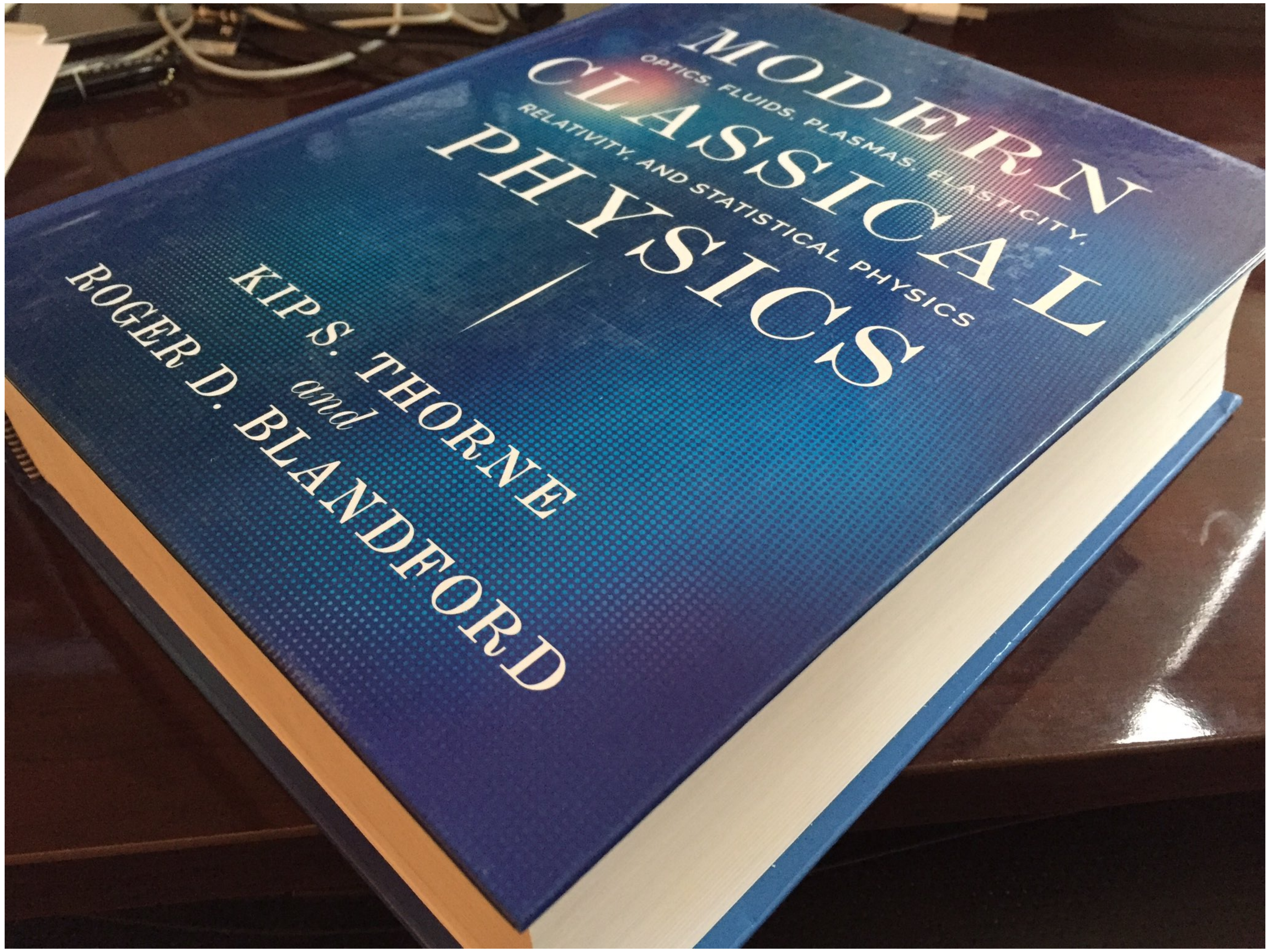
This course is an introduction to all major aspects of gravitational waves, as imparted in Caltech Gravitational Waves course ph237 (see this URL and this URL):

1. Their physical and mathematical descriptions;
2. Their generation, propagation and interaction withdetectors;
3. Their astrophysical sources (the big bang, early-universe phenomena, binary stars, black holes, supernovae, neutron stars, ...); and
4. Gravitational wave detectors (their design, underlying physics, noise and noise control, and data analysis) with emphasis on earth-based interferometers (LIGO, VIRGO, GEO600, TAMA) and space-based interferometers (LISA), but also including resonant-mass detectors, doppler tracking of spacecraft, pulsar timing, and polarization of the cosmic microwave background.

The course is divided in

A. Gravitational-wave theory and sources
B. Gravitational-wave detectors

Useful resources

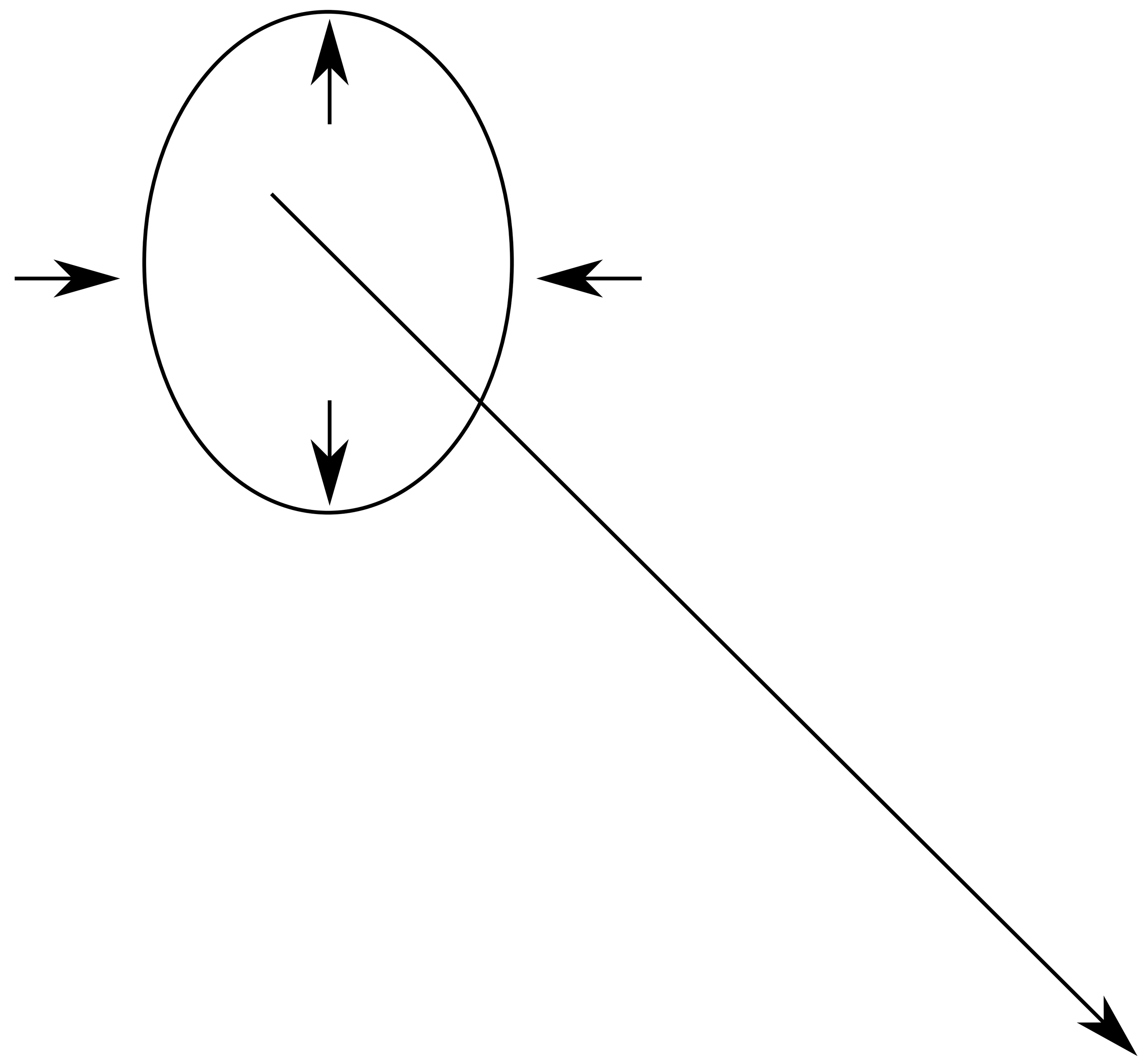


Extremely comprehensive 1500 page monster, you don't need to read the whole thing to get to the parts on gravitational waves

Based on a course given at Caltech, free pdf notes available at:
http://www.cns.gatech.edu/PHYS-4421/caltech136/index.html

Basic properties of GWs

- Gravitational waves produce perturbations **transverse** to their propagation direction and travel at the **speed of light**.



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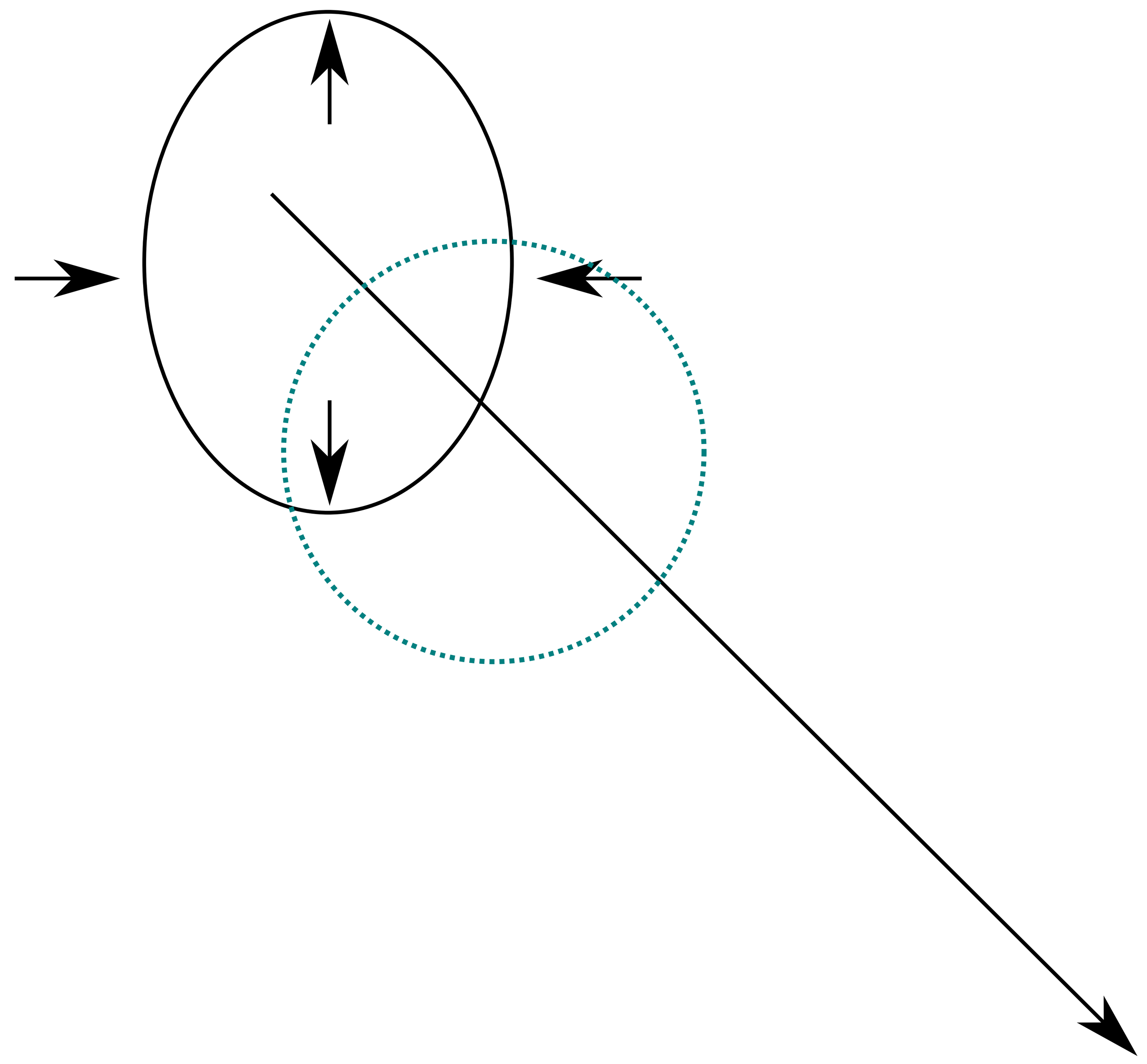

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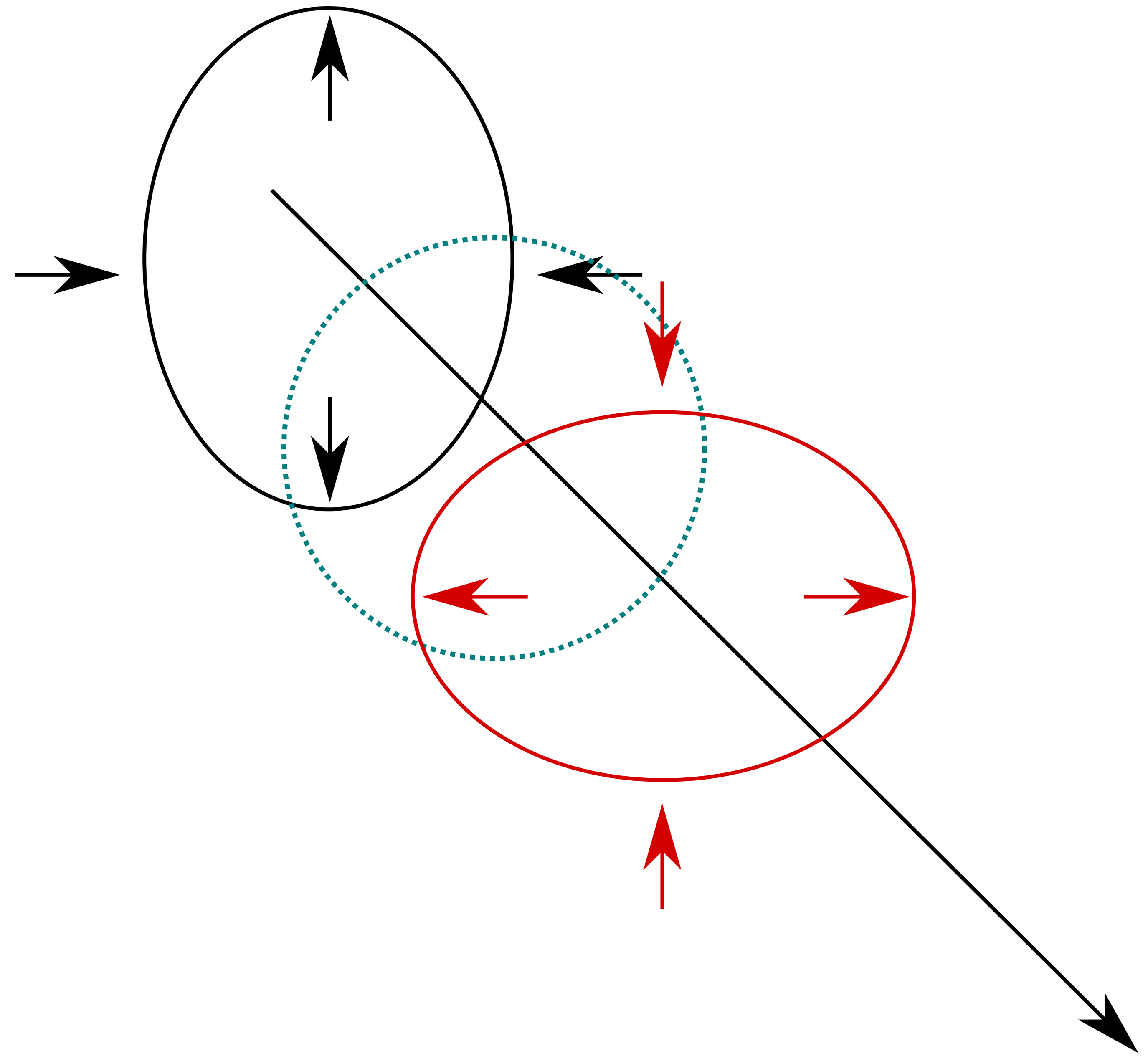

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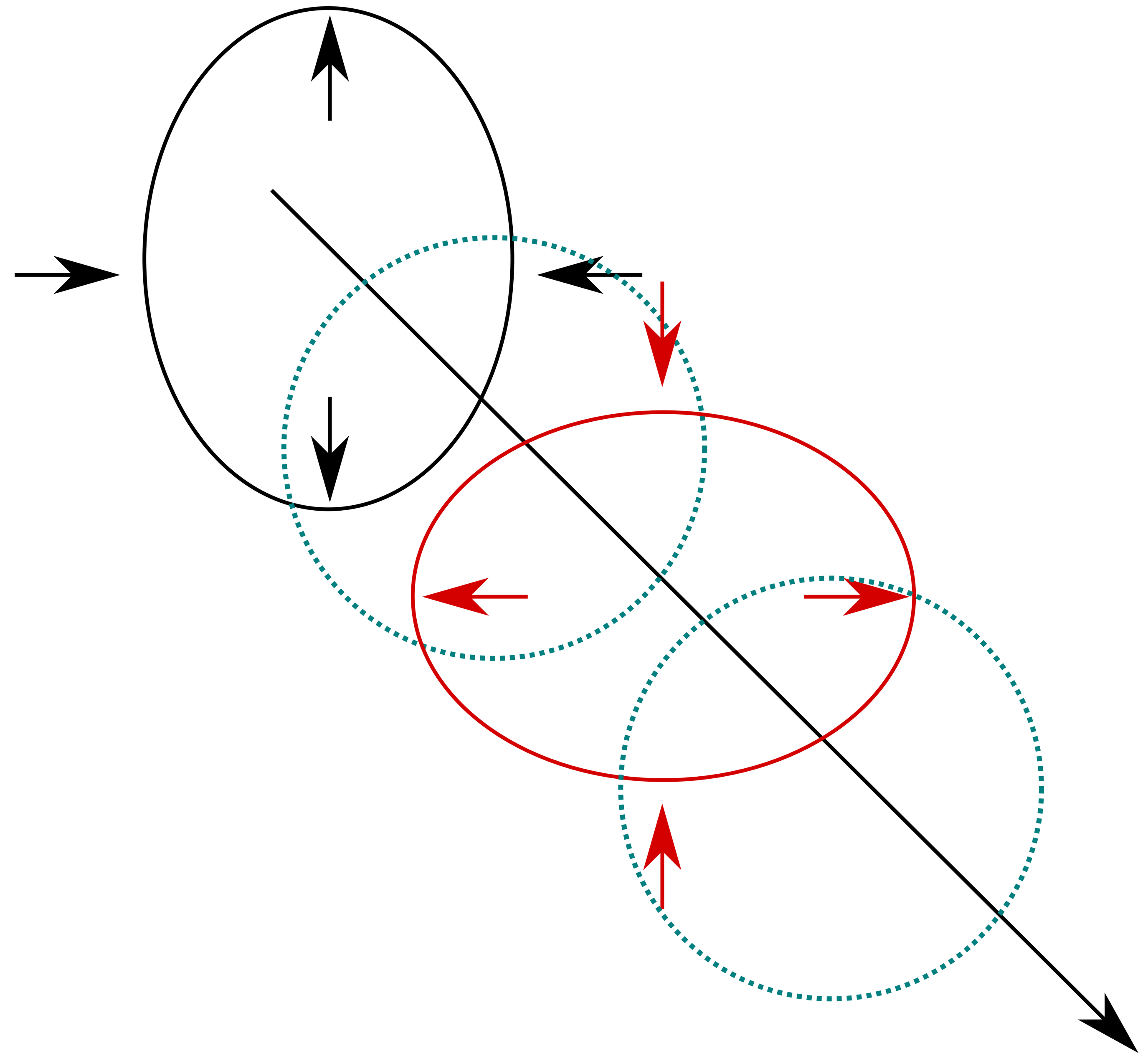

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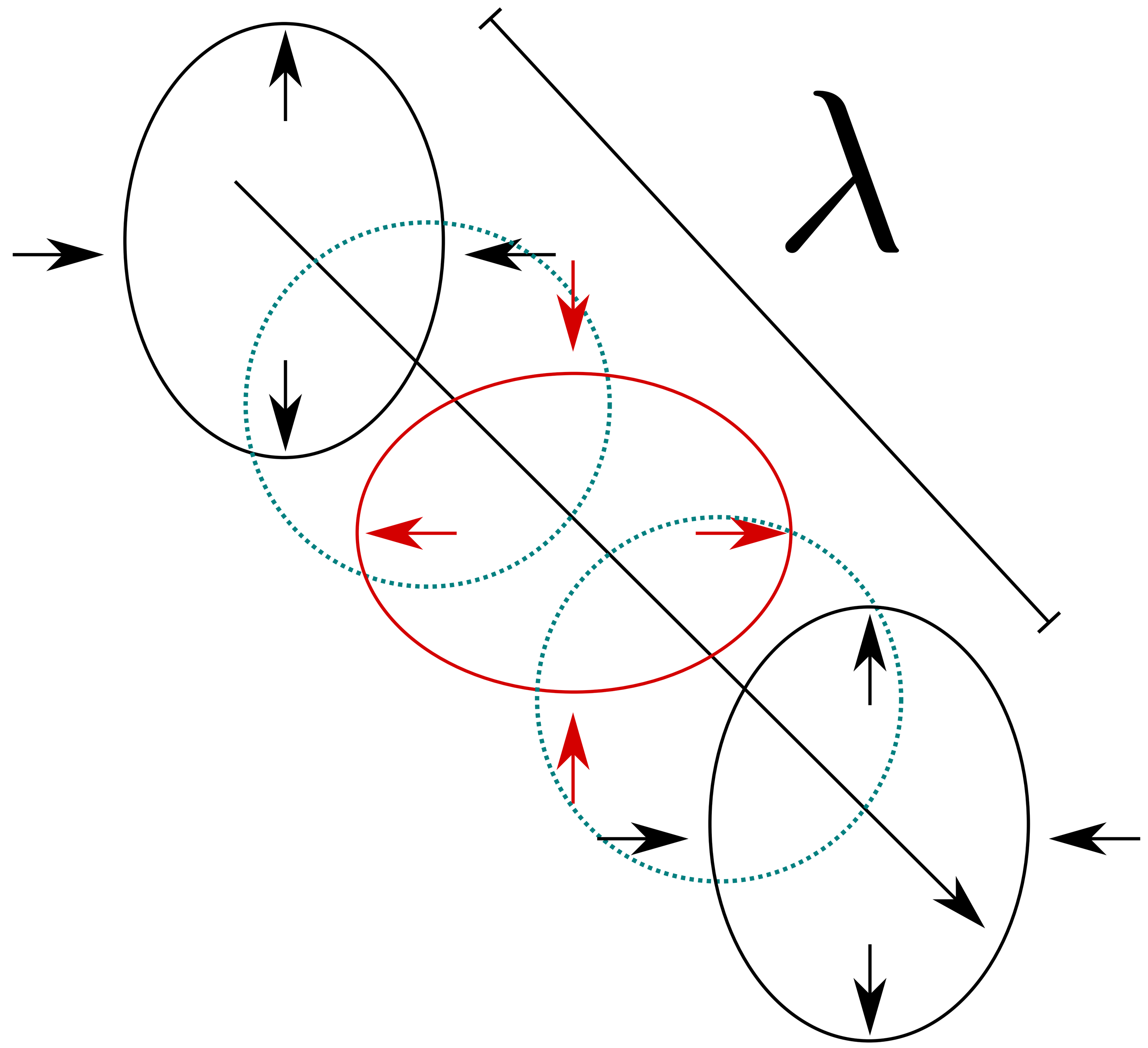

Basic properties of GWs

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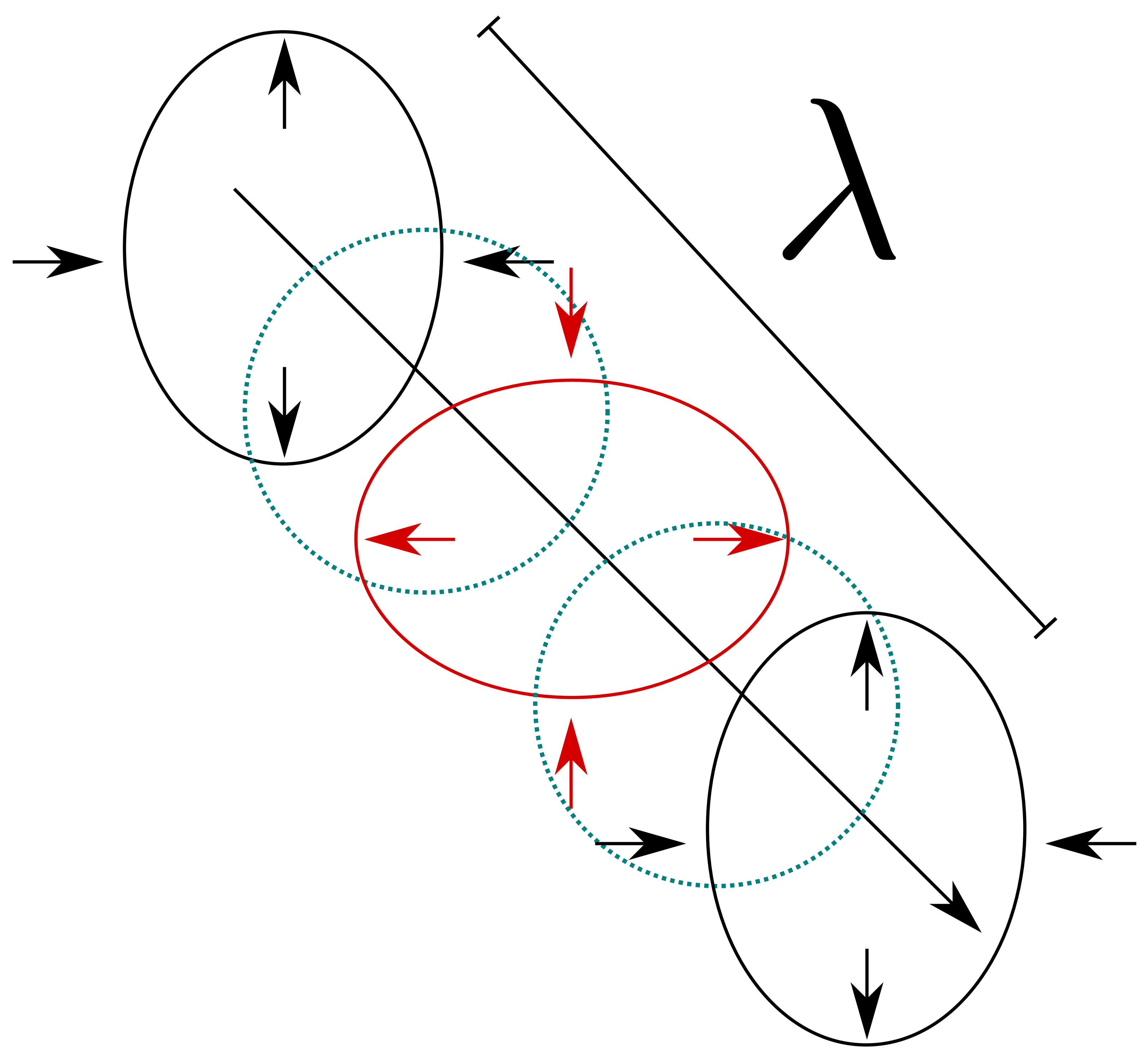
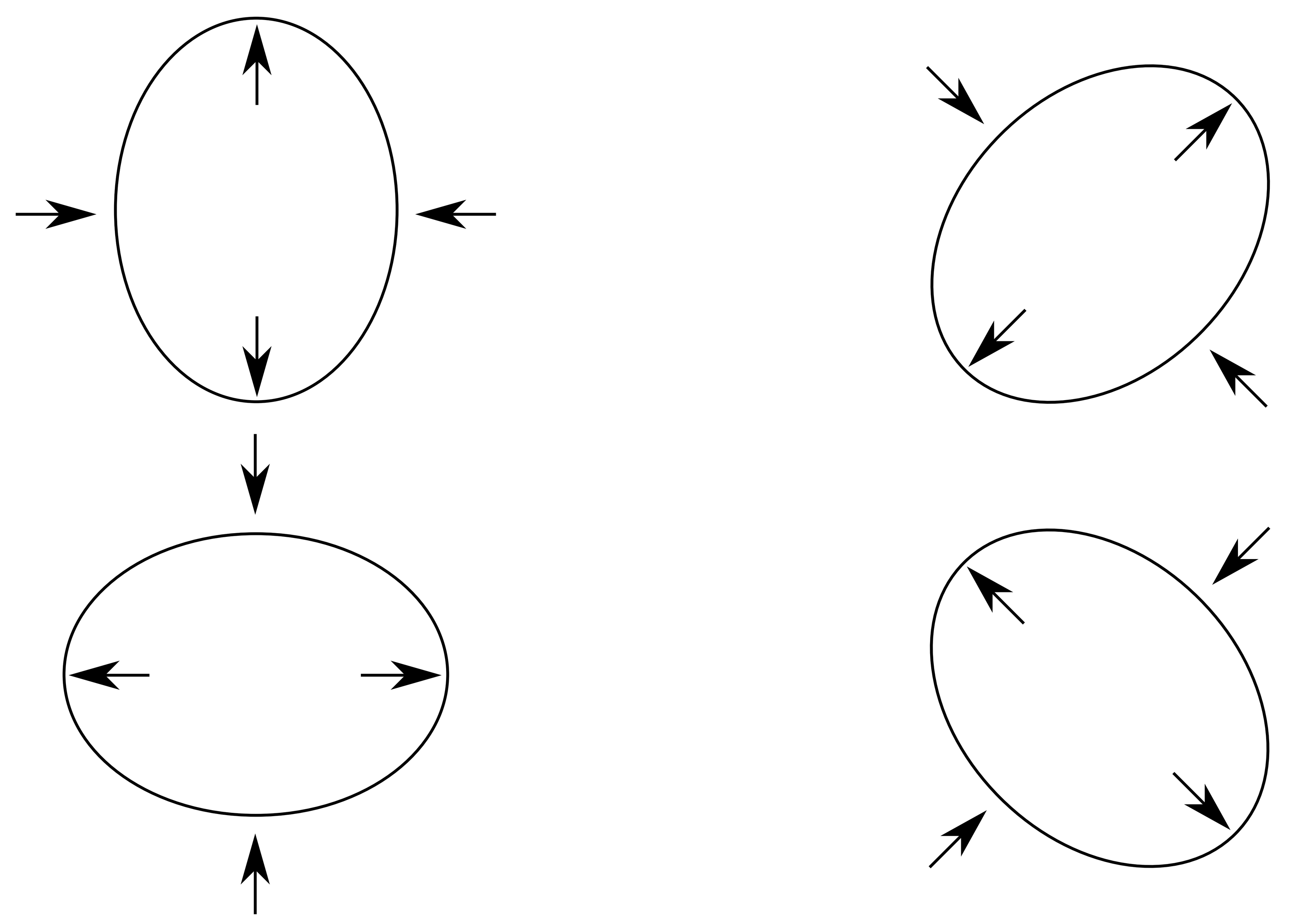
- Two polarization states, commonly separated in **"plus"** and **"cross"** components.



+ polarization **x polarization**



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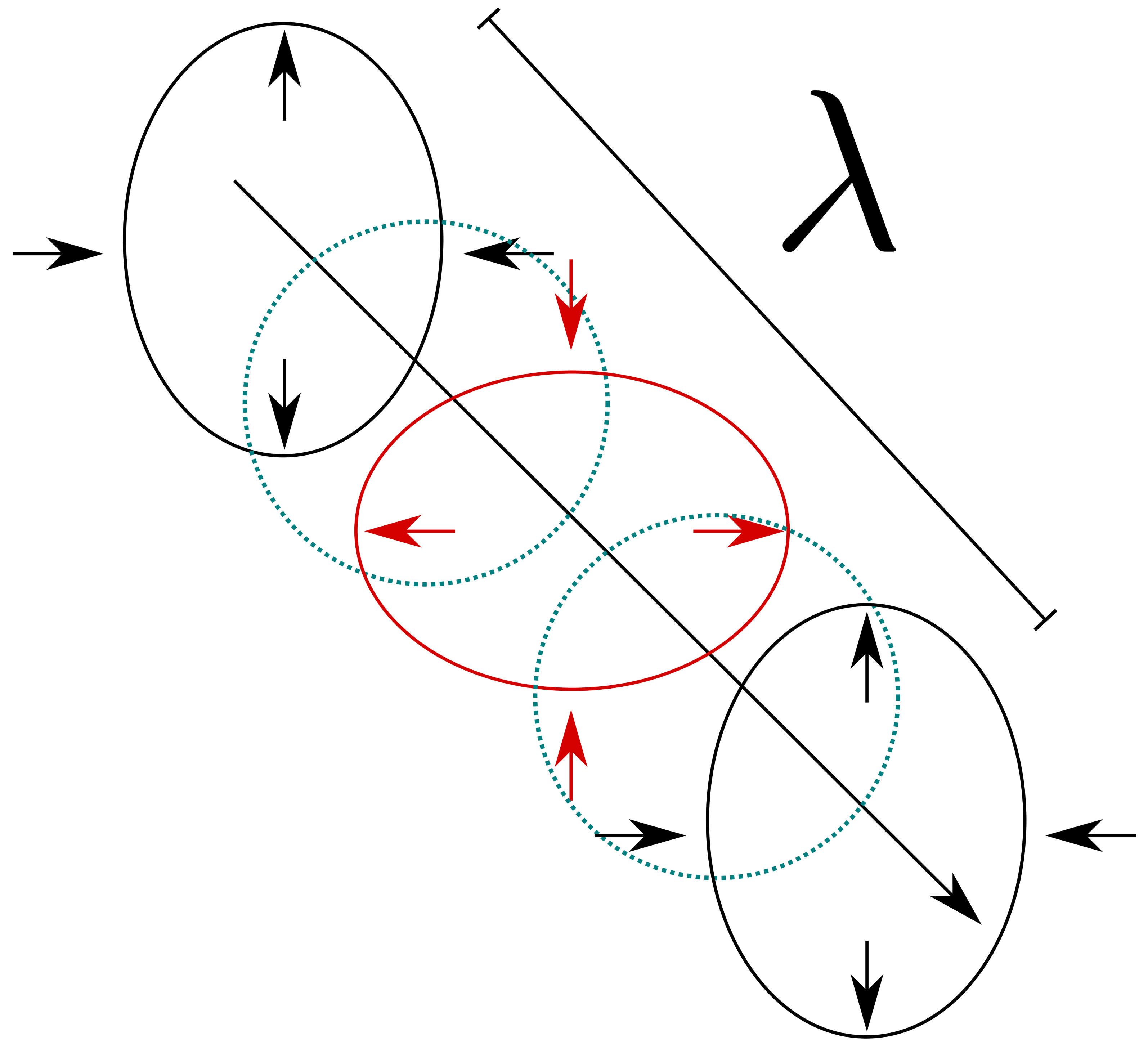

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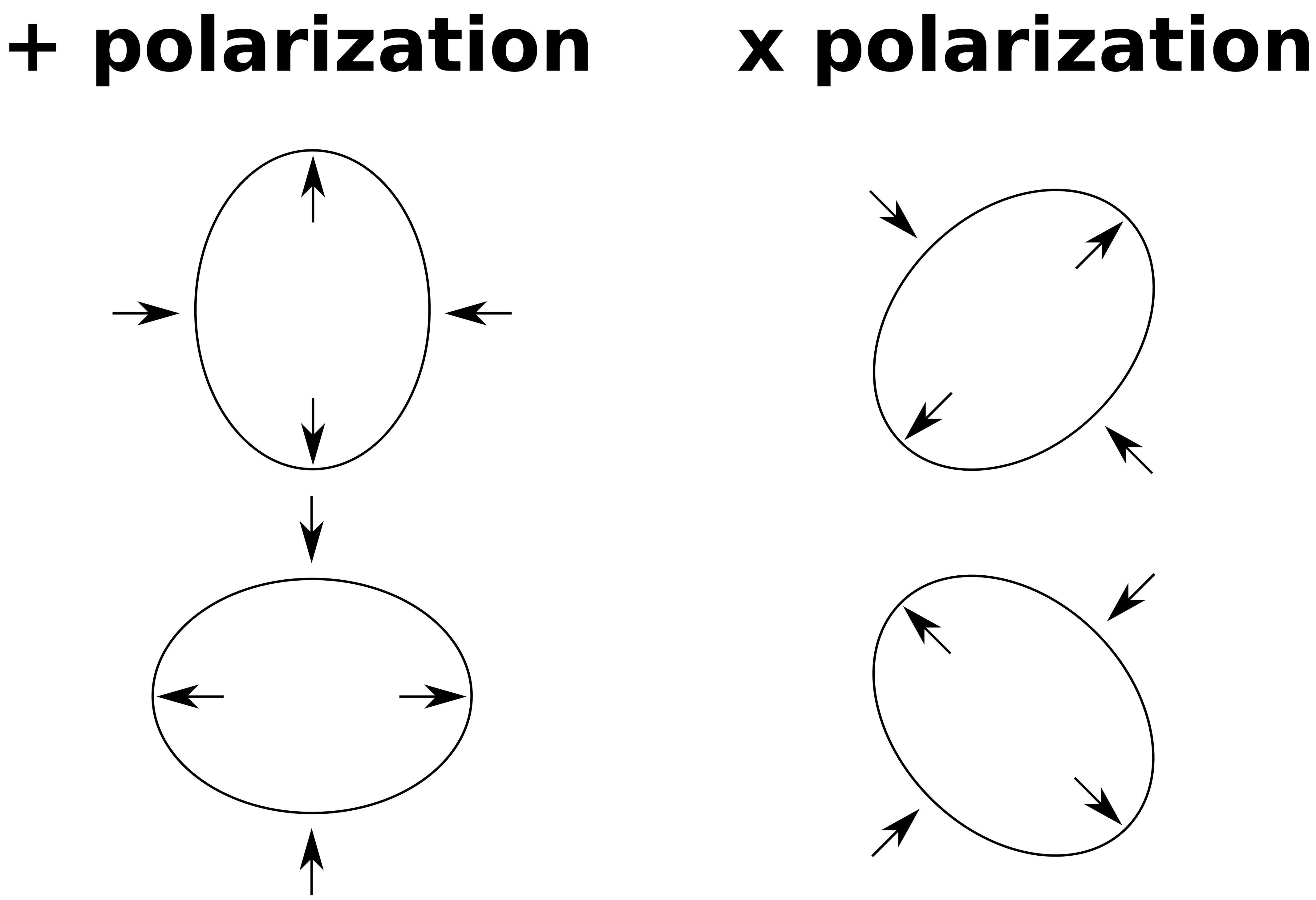


- Energy flux proportional to the square of the strain

$$F \simeq \frac{\pi}{4}\frac{c^3}{G} f^2 h^2 \simeq 0.01\ [\mathrm{W\ m^{-2}}] \left(\frac{f}{200\ [\mathrm{Hz}]}\right)^2 \left(\frac{h}{10^{-21}}\right)^2$$

Early History

- 1893: Pre-SR, Olivier Heaviside, inverse square law could suggest the existence of GWs.

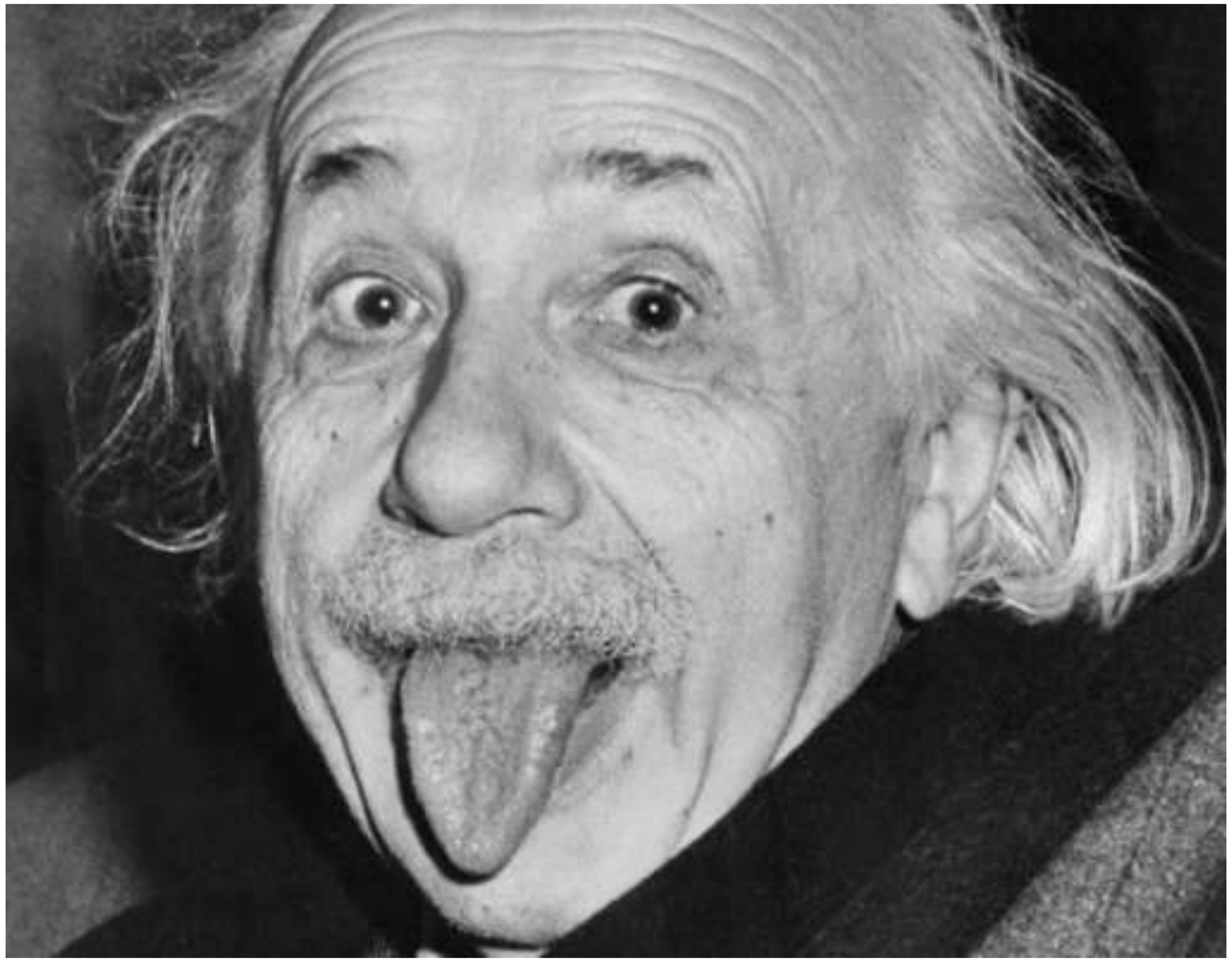
- 1905: Pre-GR, Henri Poincaré, GWs expected from accelerating masses.

- 1915: Einstein presents his theory of general relativity. Later conjectures the existence of three types of waves.

- 1922: Eddington shows two of those types of waves are coordinate artifacts.

- 1936: Einstein & Rosen submit a paper claiming GWs do not exist, retract it angrily because it was sent to a referee who pointed out errors.

- 1937: After being convinced that his conclusions were erroneous, Einstein published a modified version of his paper with Rosen with an opposite conclusion.



Cervantes-Cota et al. (2016), arXiv:1609.09400

Weber bars, first claim of detection

- 1957: Joseph Weber, an engineer, becomes interested in the possibility of directly measuring GWs.

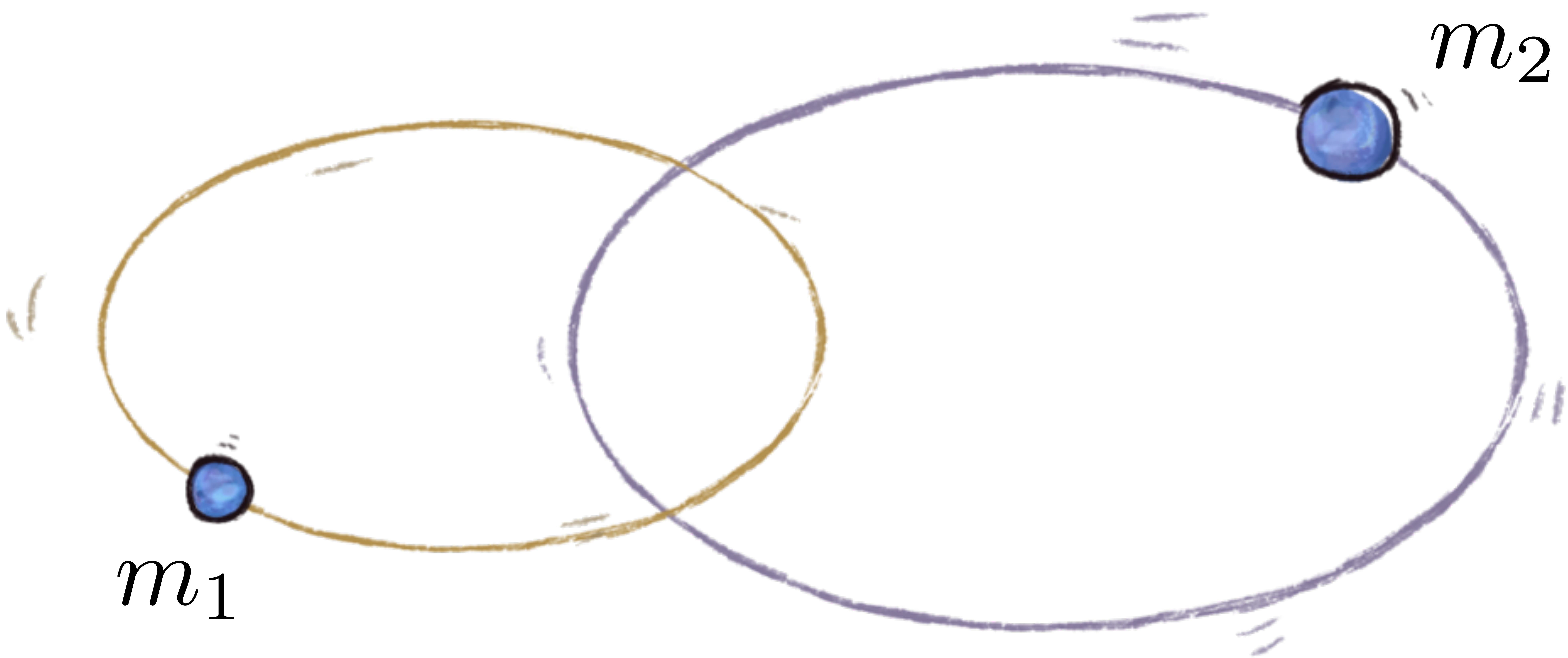
- 1960: Proposal of bar detectors (referred to as Weber bars by some).

- 1969: First claim of detection of GWs.

- Following years: Result discredited by astrophysical arguments, as well as independent groups with more sensitive instruments.

- Joseph Weber kept claiming multiple detections (including from SN1987a). Despite his claims being disproven by the community, he is seen as a pioneer in the field.

Radiation from orbiting point masses



$$a\,,e$$

$$v_{\mathrm{orb}} \ll c$$

Radiation from orbiting point masses

PHYSICAL REVIEW VOLUME 131, NUMBER 1 1 JULY 1963

Gravitational Radiation from Point Masses in a Keplerian Orbit

P. C. Peters* and J. Mathews
California Institute of Technology, Pasadena, California
(Received 18 January 1963)

The gravitational radiation from two point masses going around each other under their mutual gravitational influence is calculated. Two different methods are outlined; one involves a multipole expansion of the radiation field, while the other uses the inertia tensor of the source. The calculations apply for arbitrary eccentricity of the relative orbit, but assume orbital velocities are small. The total rate, angular distribution, and polarization of the radiated energy are discussed.

PHYSICAL REVIEW VOLUME 136, NUMBER 4B 23 NOVEMBER 1964

Gravitational Radiation and the Motion of Two Point Masses

P. C. Peters*†
California Institute of Technology, Pasadena, California
(Received 2 July 1964)

The expansion of the field equations of general relativity in powers of the gravitational coupling constant yields conservation laws of energy, momentum, and angular momentum. From these, the loss of energy and angular momentum of a system due to the radiation of gravitational waves is found. Two techniques, radiation reaction and flux across a large sphere, are used in these calculations and are shown to be in agreement over a time average. In the nonrelativistic limit, the energy and angular momentum radiation and angular distributions are expressed in terms of time derivatives of the quadrupole tensor Q_{ij}. These results are then applied to a bound system of two point masses moving in elliptical orbits. The secular decays of the semimajor axis and eccentricity are found as functions of time, and are integrated to specify the decay by gravitational radiation of such systems as functions of their initial conditions.

Radiation from orbiting point masses

Peters & Mathews 1963

$$\left\langle \frac{dE}{dt} \right\rangle = -\frac{32}{5}\frac{G^4 m_1^2 m_2^2 (m_1+m_2)}{c^5 a^5 (1-e^2)^{7/2}} \left(1 + \frac{73}{24}e^2 + \frac{37}{96}e^4\right)$$

Peters 1964

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$$a = -\frac{G m_1 m_2}{2E}$$

$$L^2 = \frac{G m_1^2 m_2^2 a (1-e^2)}{m_1+m_2}$$

$$\rightarrow \left\langle \frac{da}{dt} \right\rangle, \left\langle \frac{de}{dt} \right\rangle$$

Radiation from orbiting point masses

For an eccentric orbit, the time to merger can be computed from an integral expression. For a circular orbit the result is analytical:

$$t_d = \frac{a^4}{4\beta},\ \beta \equiv \frac{64}{5}\frac{G^3 m_1 m_2 (m_1 + m_2)}{c^5}$$

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Using Kepler's third law, this can be expressed in terms of the orbital period and a combination of the masses called the chirp mass

$$t_d = 7.4\ [\mathrm{Gyr}] \left(\frac{P}{12\ [\mathrm{h}]}\right)^{8/3} \left(\frac{\mathcal{M}}{M_\odot}\right)^{-5/3},\ \mathcal{M} \equiv \frac{(m_1 m_2)^{3/5}}{(m_1+m_2)^{1/5}}$$

$$\text{for } m_1 = m_2,\ \mathcal{M} \simeq 0.87 m_1$$

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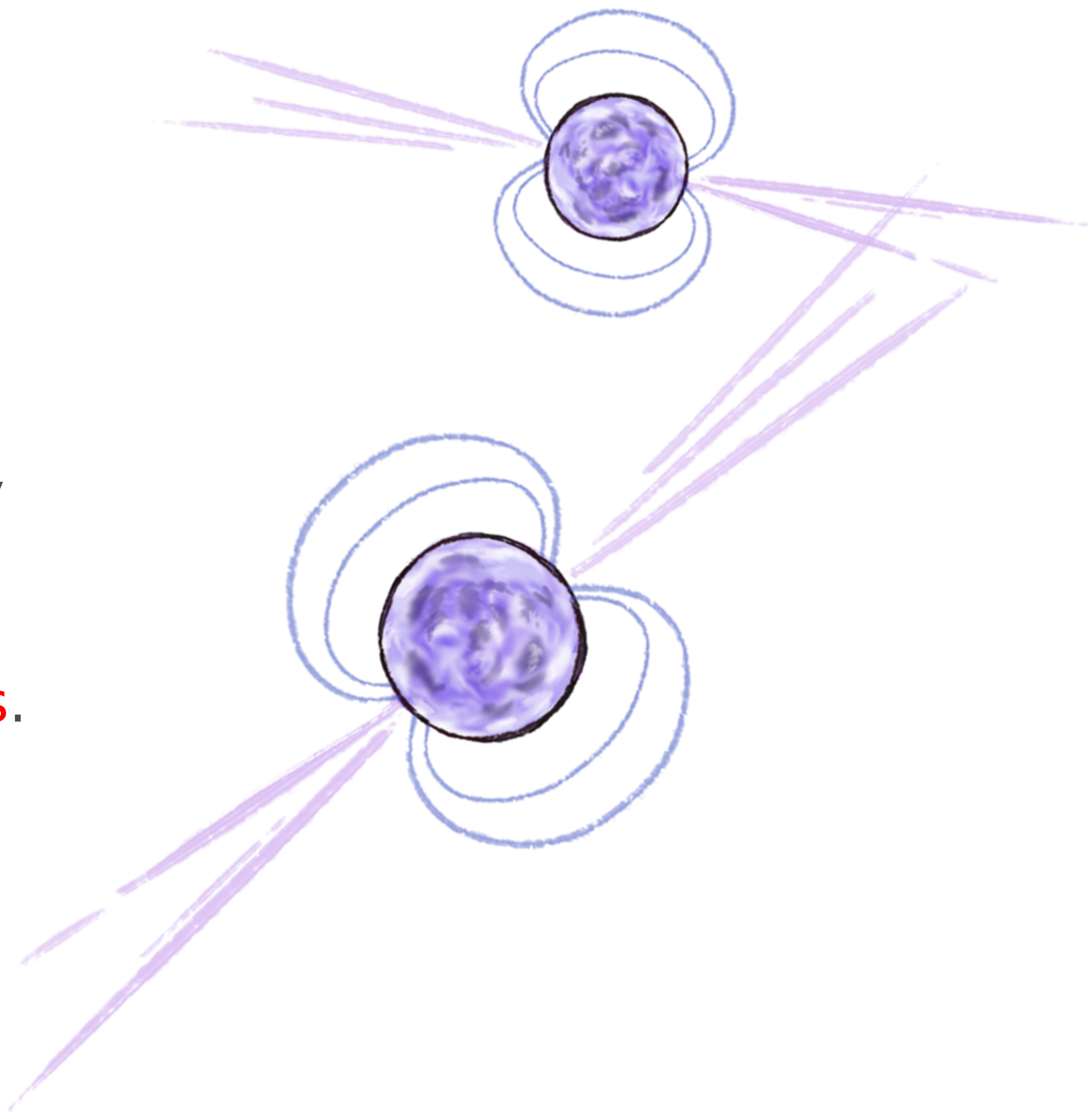
Does nature provide such massive and compact binaries?

The Hulse-Taylor binary

- Pulsars are rapidly rotating neutron stars that can be used as extremely accurate clocks.

- 1975: Hulse & Taylor report the discovery of the first pulsar in a binary system.

- Expected time to merger of 300 Myrs. orbital decay on the order of 80 microseconds a year.



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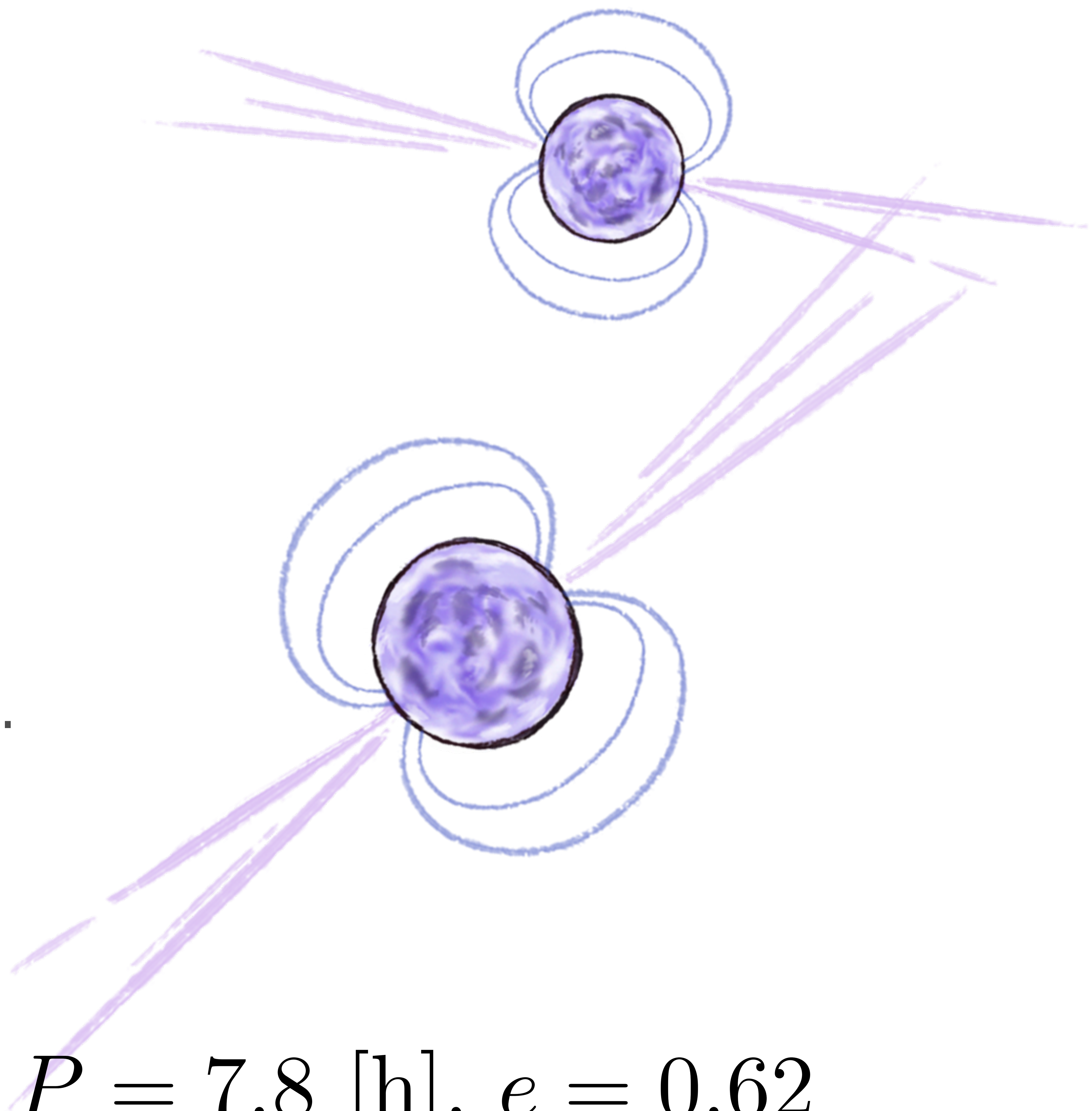

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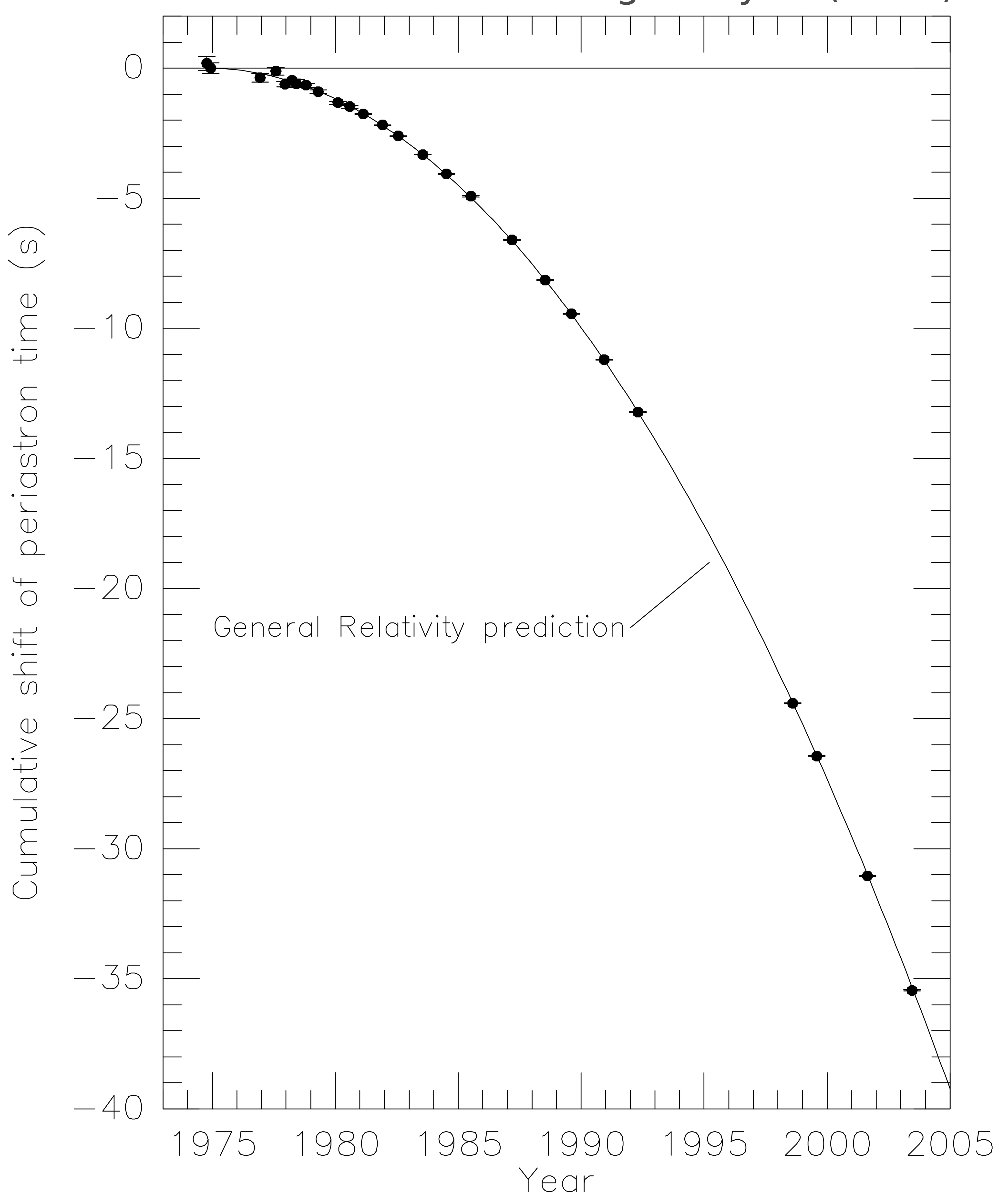

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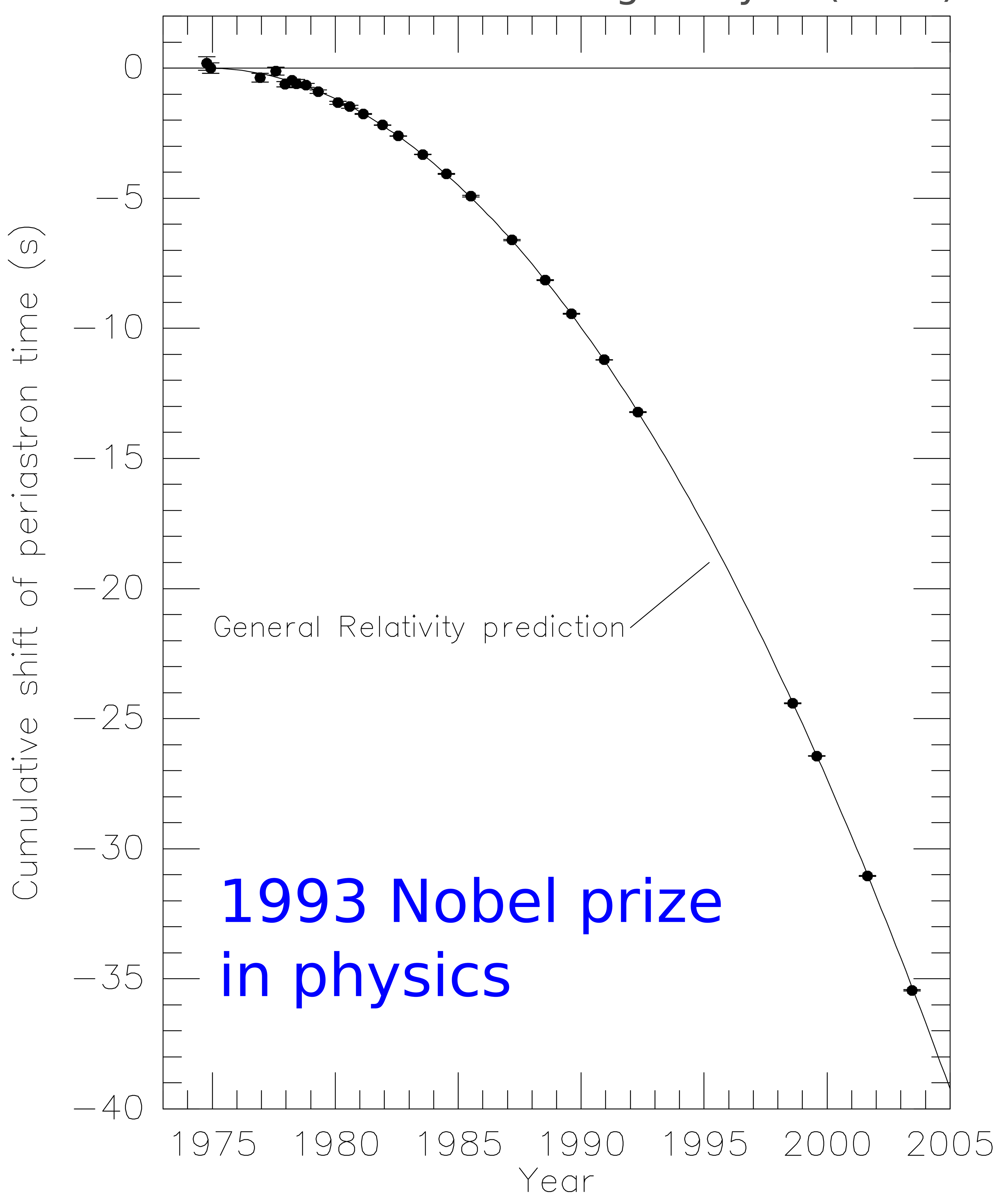

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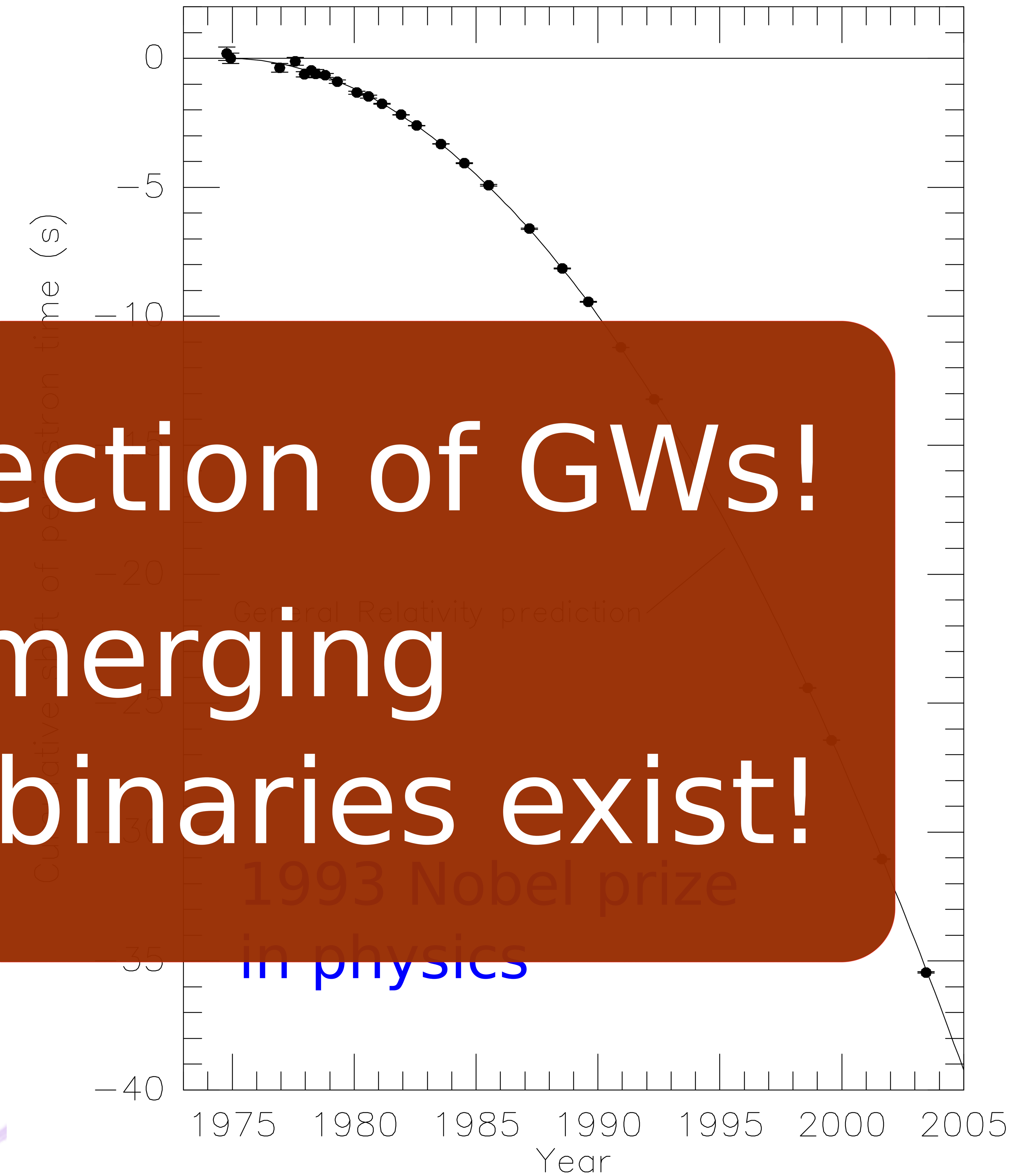

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Not a direct detection of GWs!

But shows that merging compact object binaries exist!

$$m_1 \sim m_2 \sim 1.4 M_\odot,\ P = 7.8\ [\mathrm{h}],\ e = 0.62$$

LIGO and Virgo very simplified history!

- 60s-70s: Rainer Weiss (among others) studies concept of interferometers for high frequency (~10-1000 Hz) detectors.

- 1968: Kip Thorne creates the Caltech research group dedicated to the theory of GW sources and their detection.

- 90s: LIGO is funded, Barry Barish appointed as principal investigator. Virgo is funded.

- 2000s: Operation of initial detectors.

https://www.ligo.caltech.edu/system/media_files/binaries/386/original/LIGOHistory.pdf

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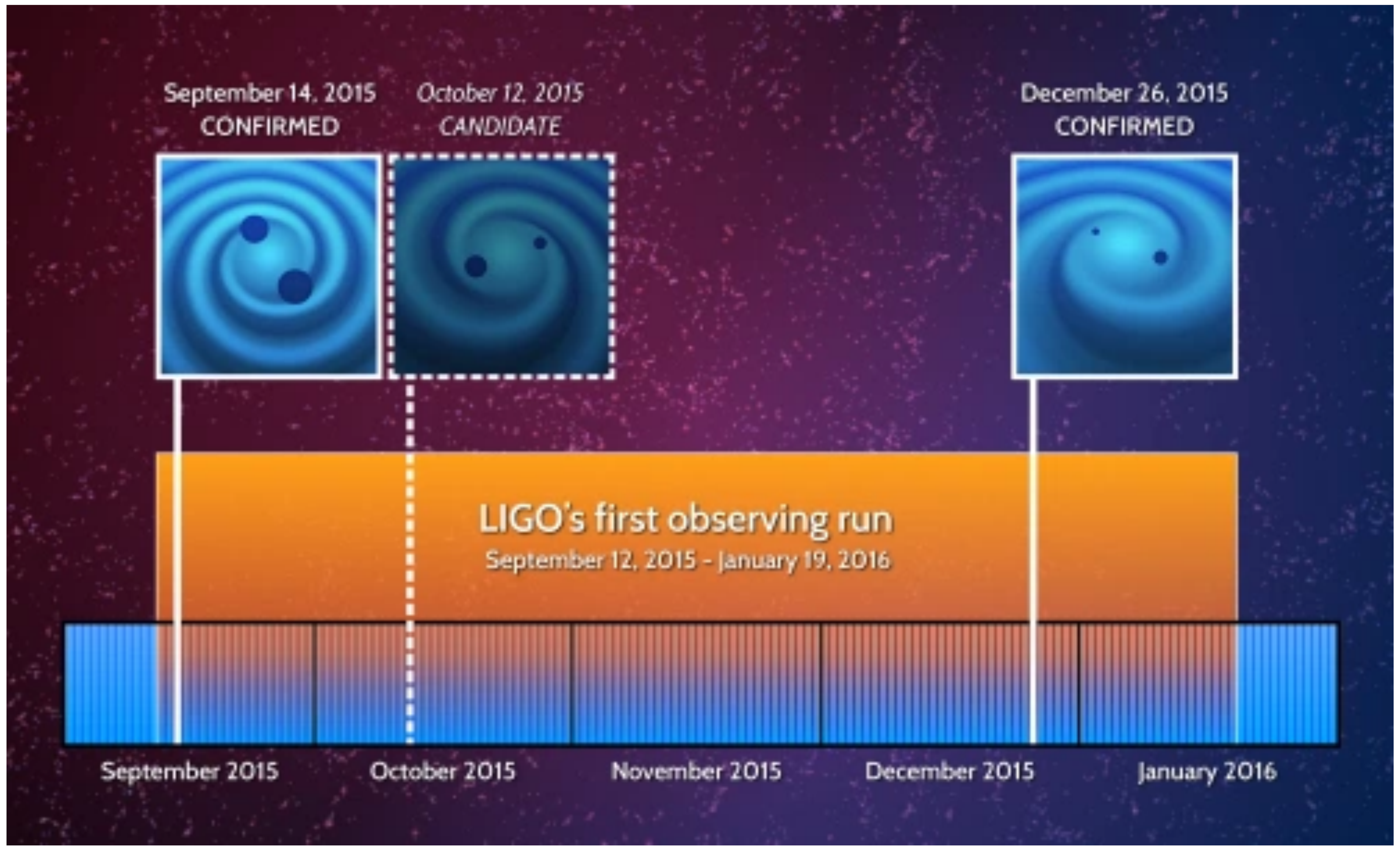
Over a thousand members in the joing LIGO-Virgo collaboration!

LIGO and VIRGO



Credit: LIGO collaboration

Credit: Soares-Santos et al. and DES collaboration

- 2015: First observing run (O1) of LIGO, GW150914 detected within the first month.

- 2016-2017: Second observing run (02), advanced Virgo detector joins the run.

- 2017: Nobel prize awarded to Weiss, Thorne & Barish.

- August 2017: First NS+NS detection, succesful electromagnetic identification making it the first multimessenger source with GWs.

Sources observed to date

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O1	GWTC-1	GWTC-2
3 BH+BH	10 BH+BH, 1 NS+NS	46 BH+BH, 2 NS+NS, 2 ?
astro-ph 1606.04856	astro-ph 2010.14527	astro-ph 2010.14527

Sources observed to date

Real data is messier!

O1	GWTC-1	GWTC-2
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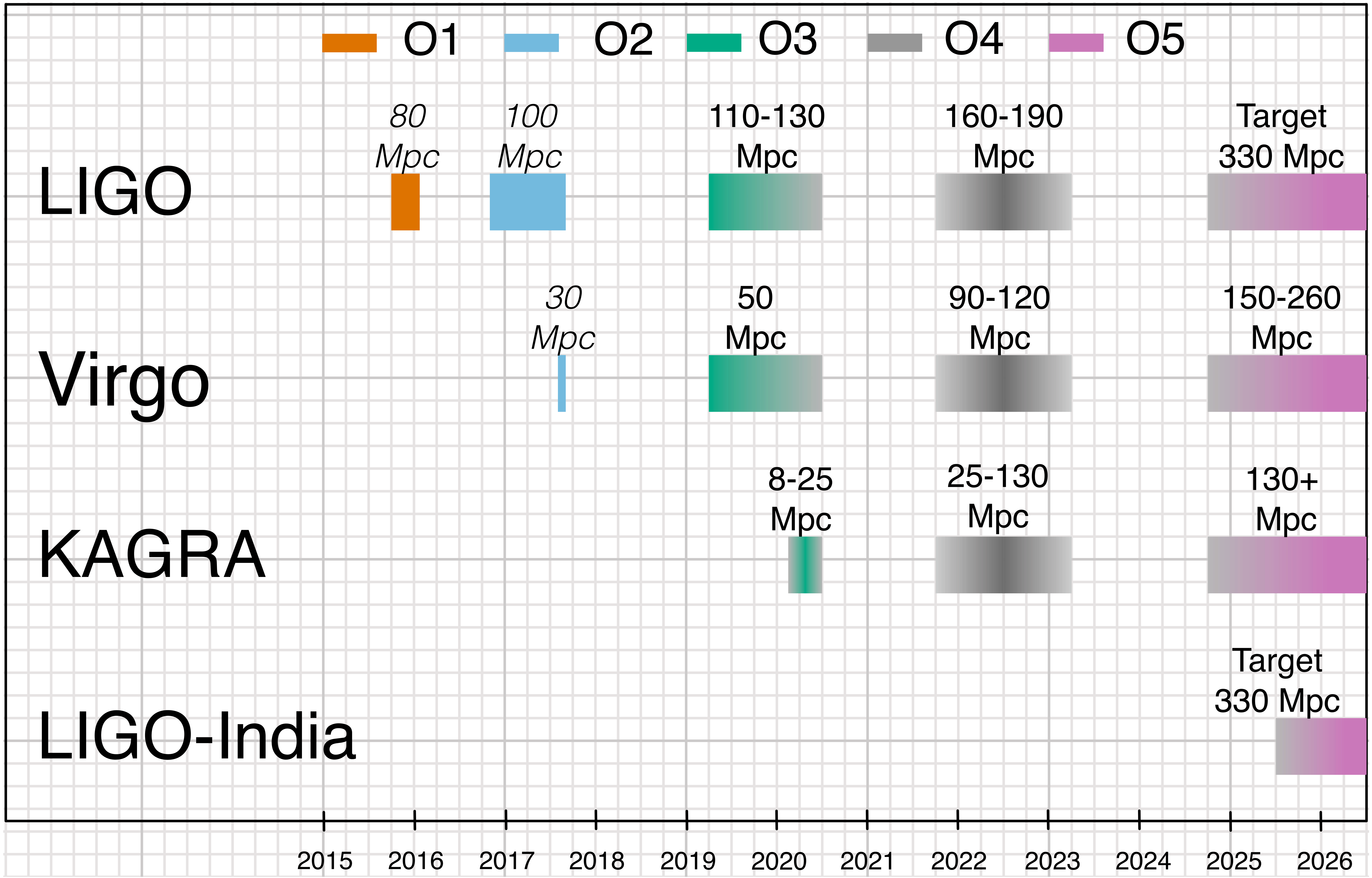
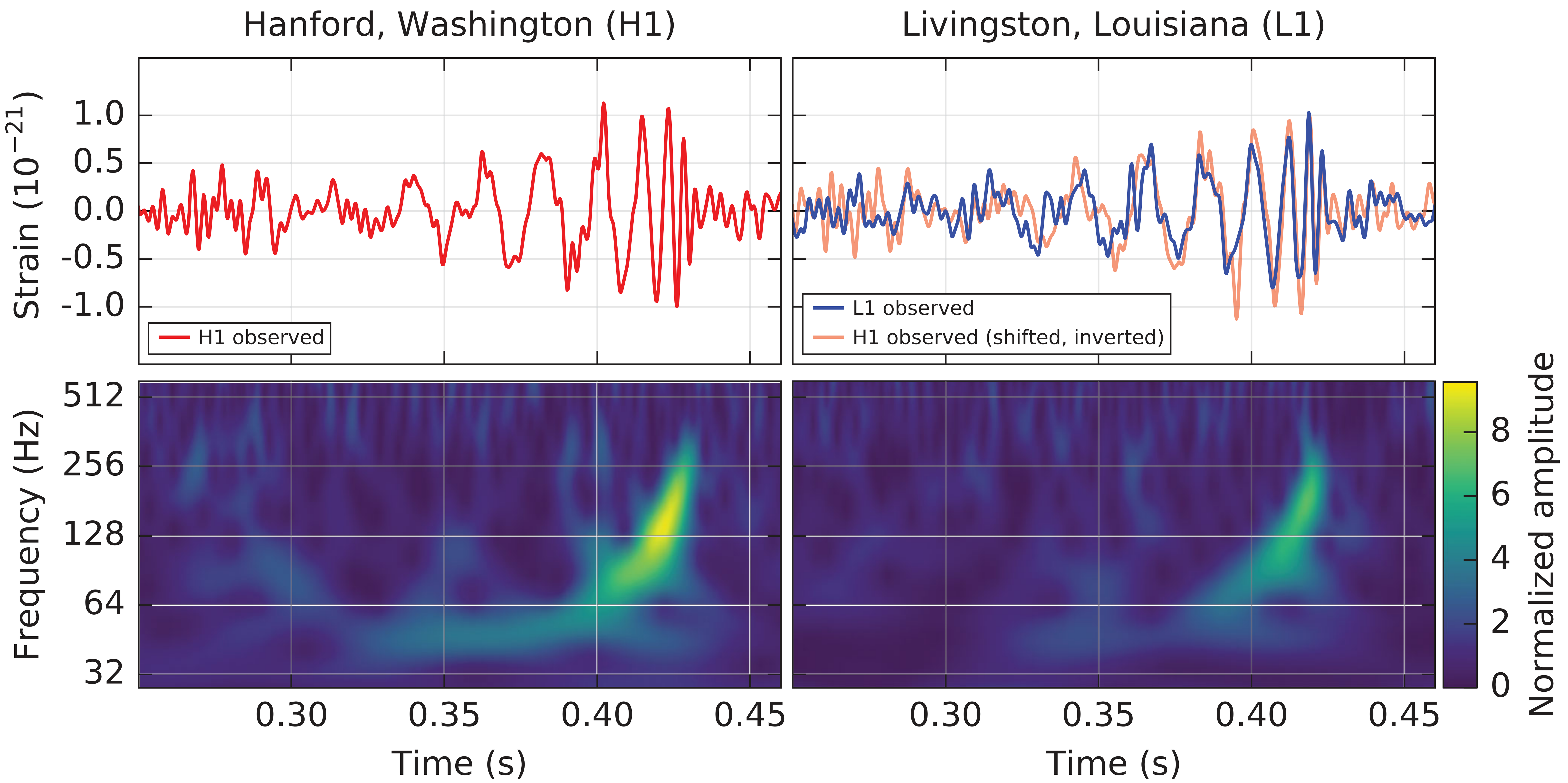
Timeline for the coming years



astro-ph 1304.0670

GW spectrum



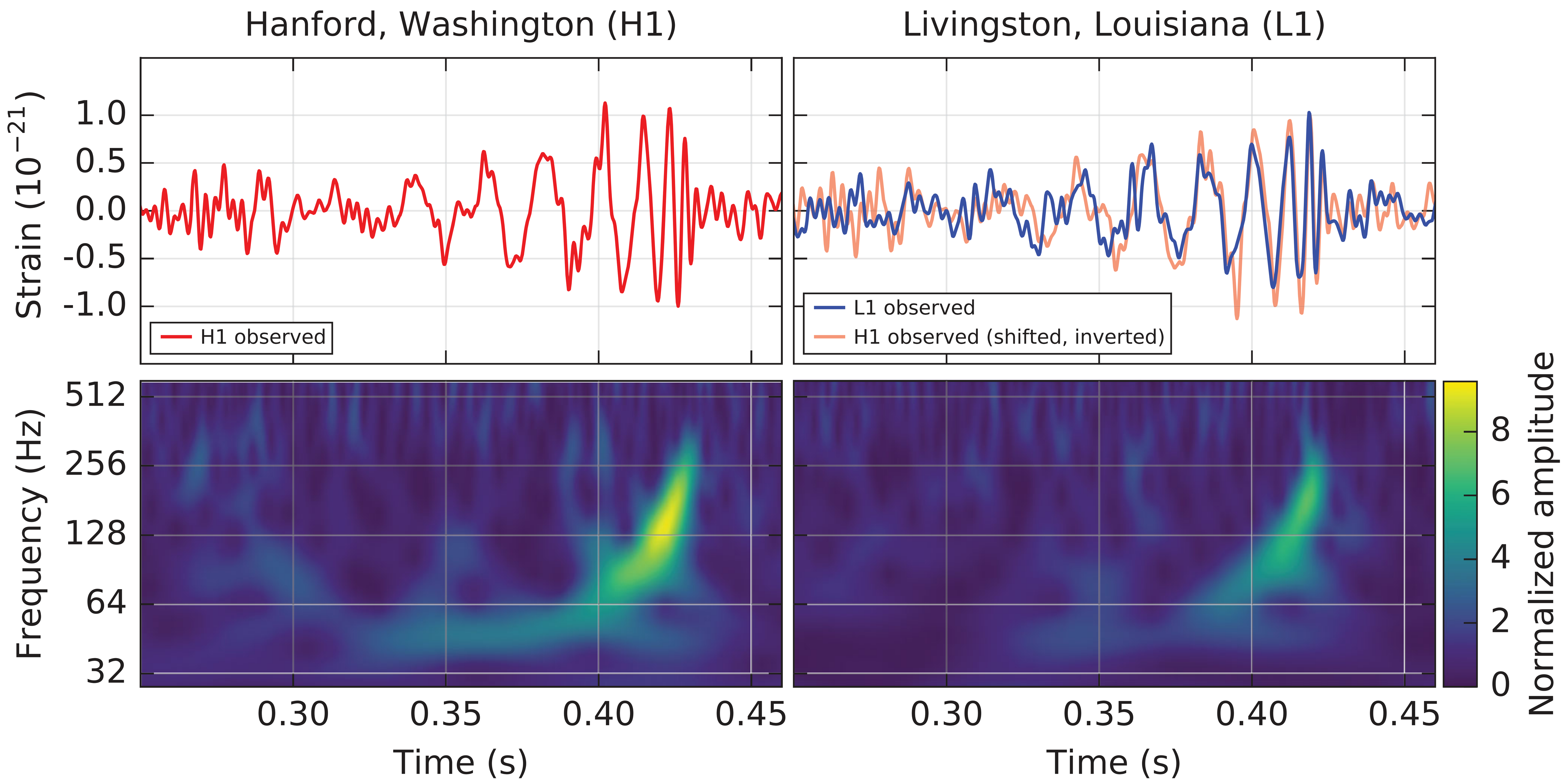
Physical Review Letters 116, 061102 (2016)

Binary black holes observed by LIGO/Virgo merge at a frequency of order ~ 200 Hz.

What about more massive BHs?

$$m_1' = \alpha m_1, \, m_2' = \alpha m_2$$

GW spectrum



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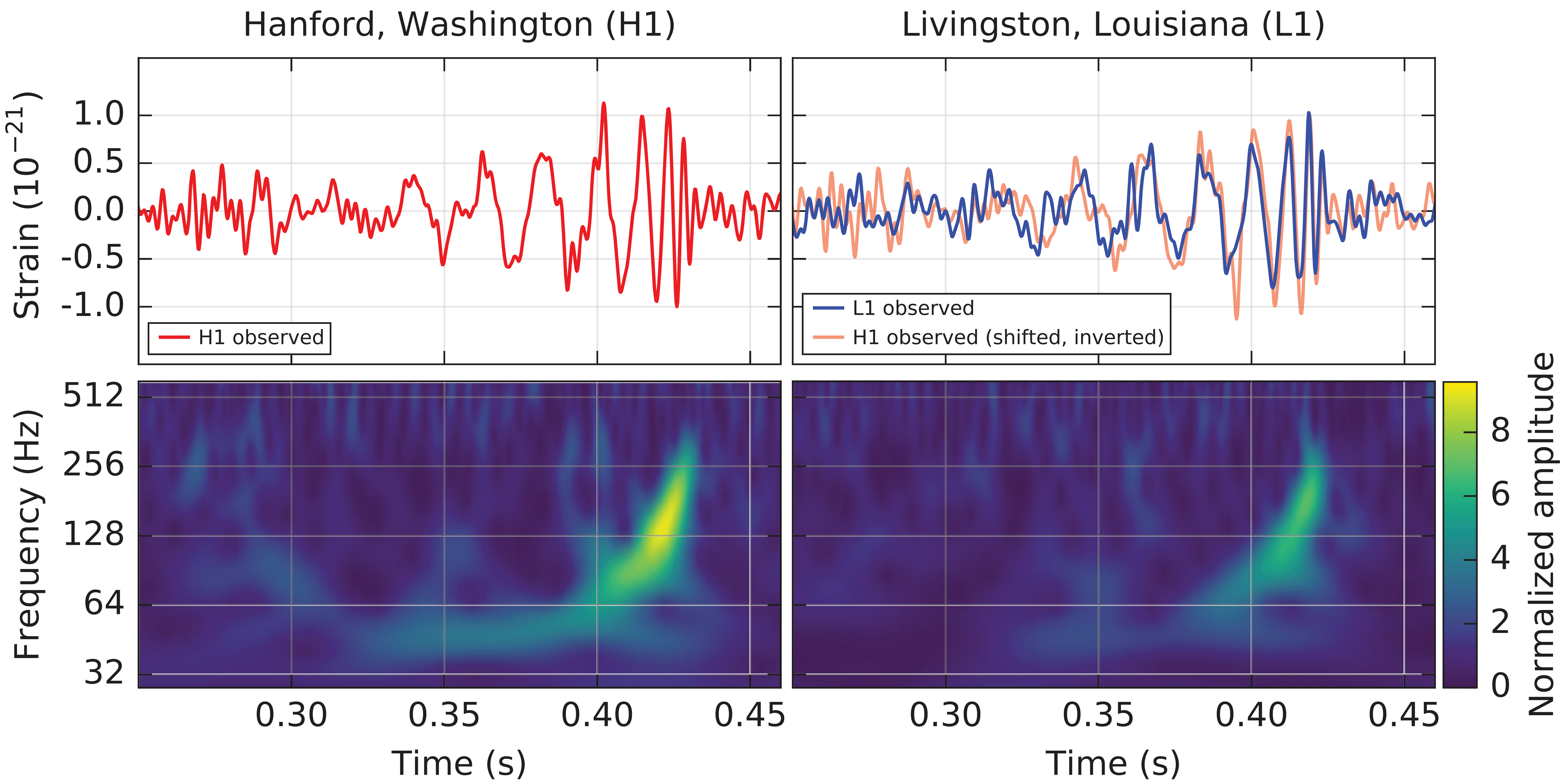

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What about more massive BHs?

$$m'_1 = \alpha m_1,\ m'_2 = \alpha m_2$$

$$f'_{\rm m} = \alpha^{-1} f_{\rm m}$$

More massive black holes merge outside LIGO's sensitivity band

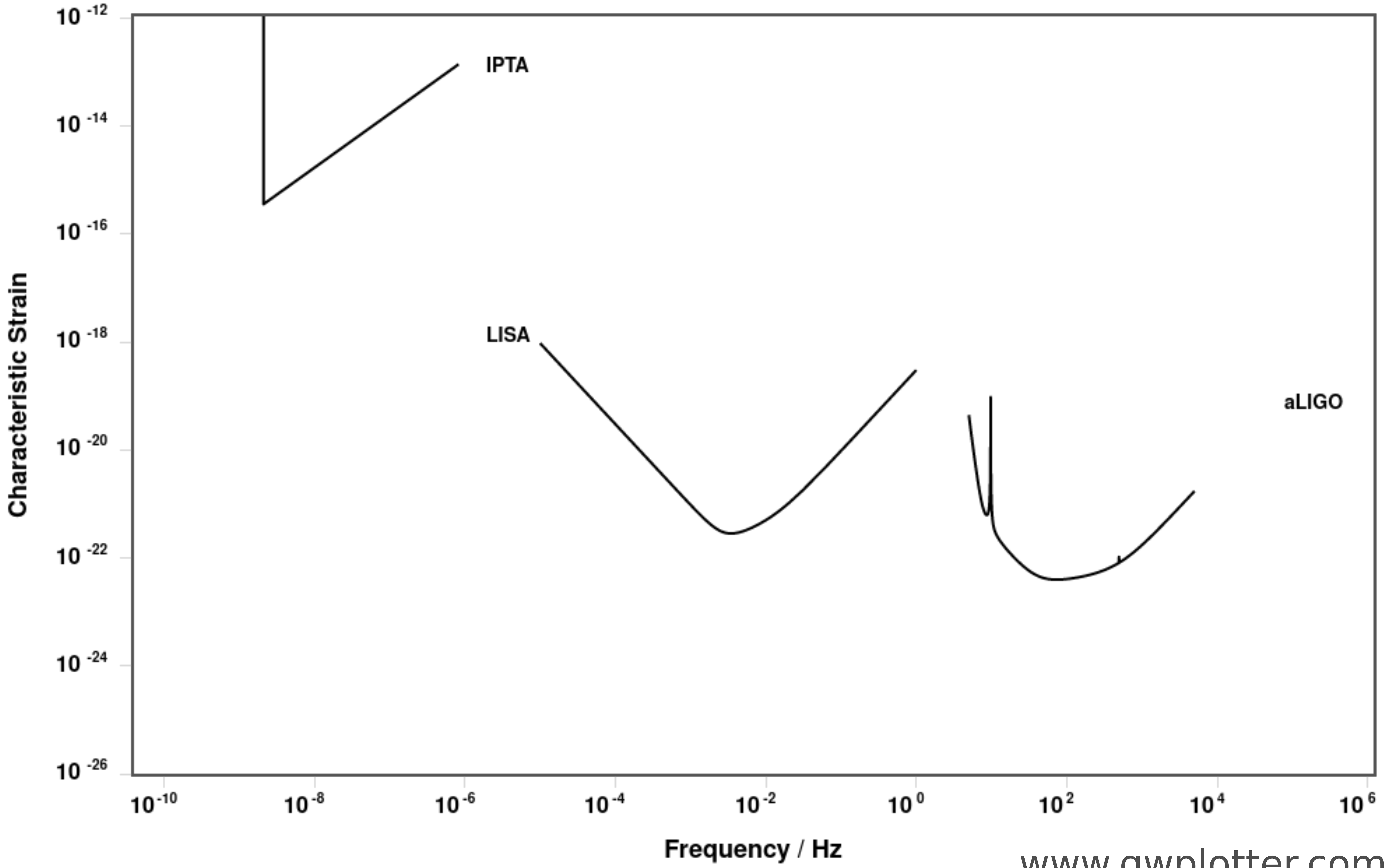
$$3 \times 10^4 M_\odot \rightarrow f_m \sim 0.2\ [\rm Hz]$$

$$3 \times 10^9 M_\odot \rightarrow f_m \sim 2 \times 10^{-6}\ [\rm Hz]$$

GW spectrum

www.gwplotter.com

GW spectrum



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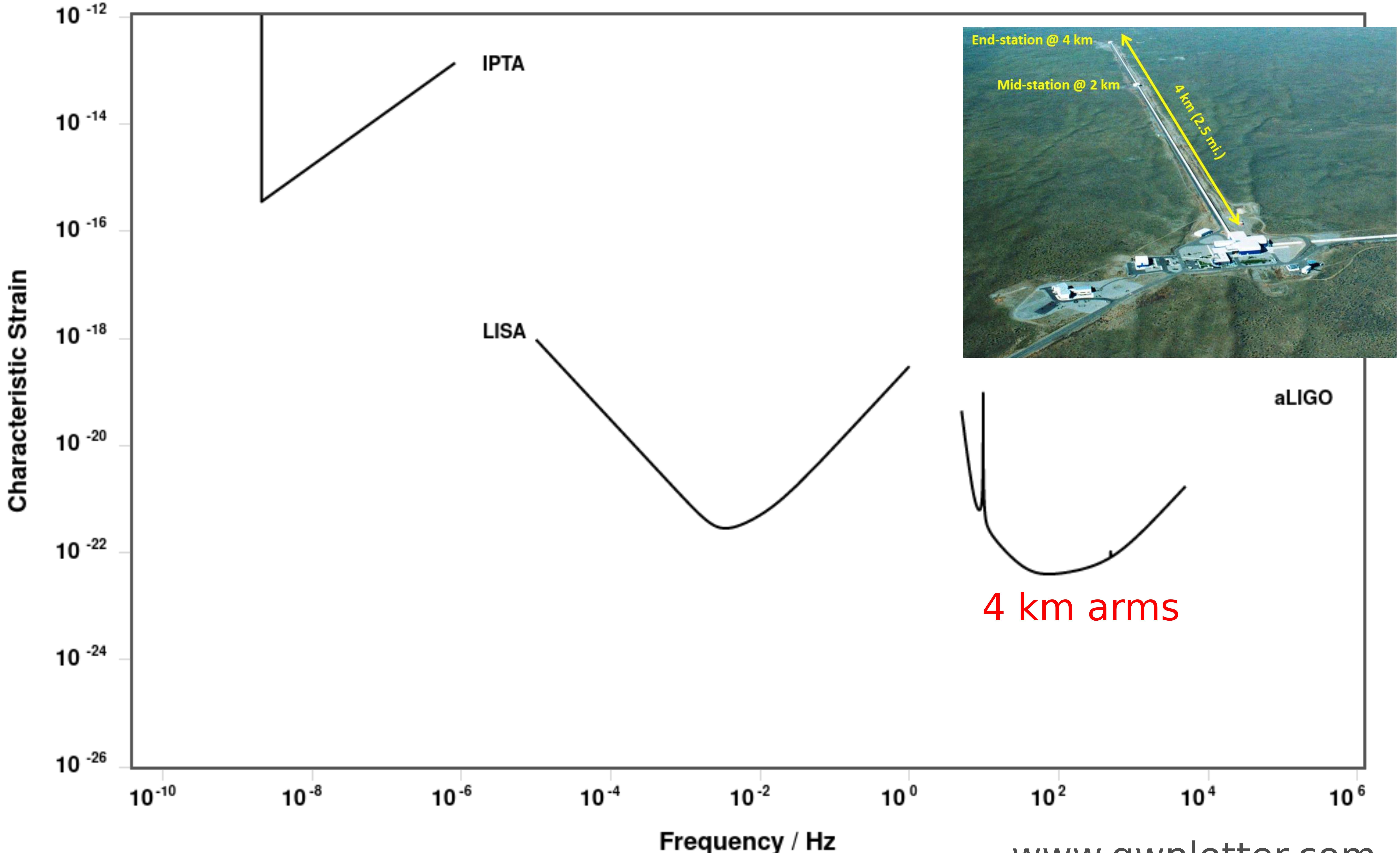
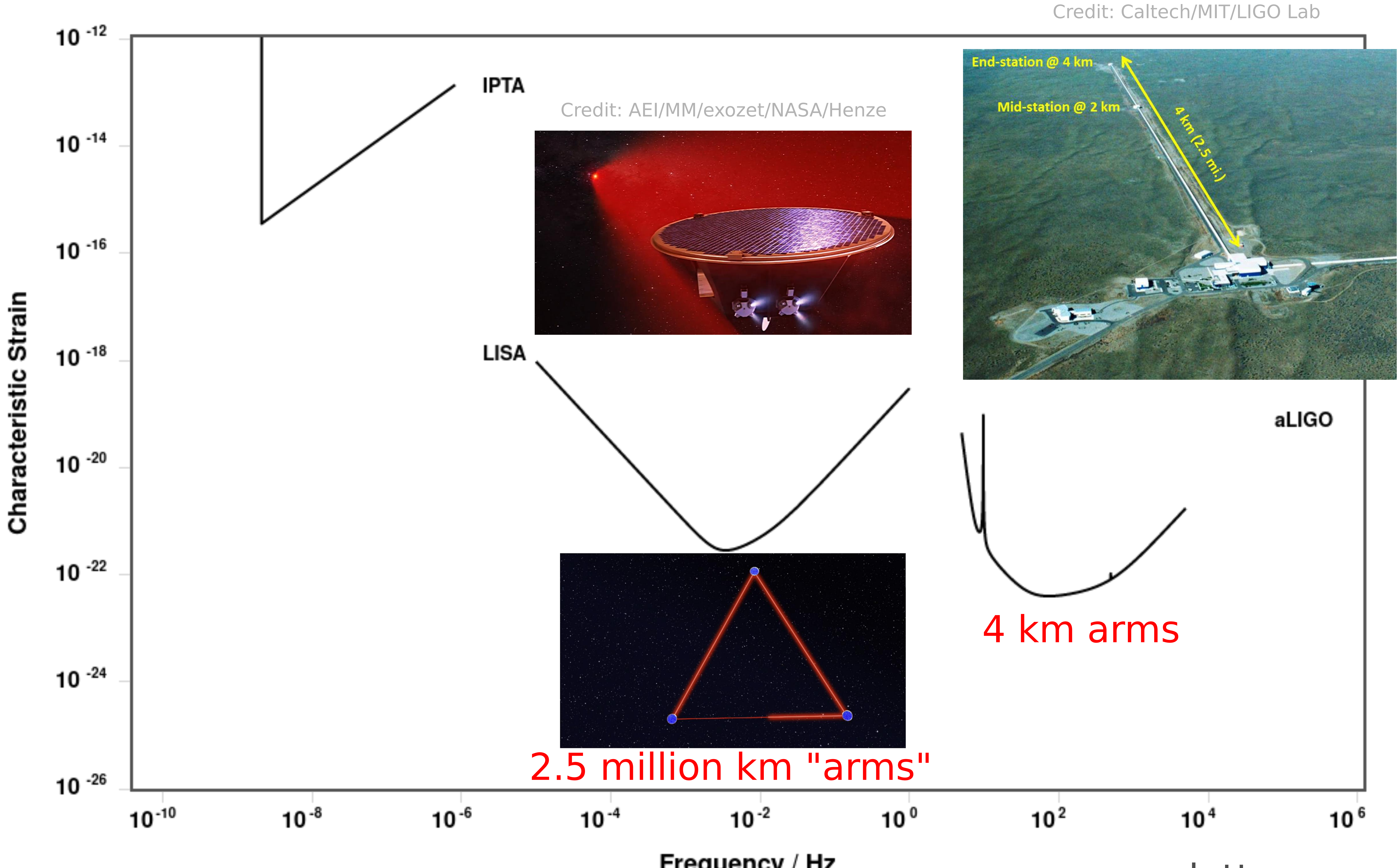
GW spectrum

Credit: Caltech/MIT/LIGO Lab



www.gwplotter.com

GW spectrum



Credit: Max Planck Institute for Gravitational Physics /
Milde Marketing Science Communication / Exozet Effects

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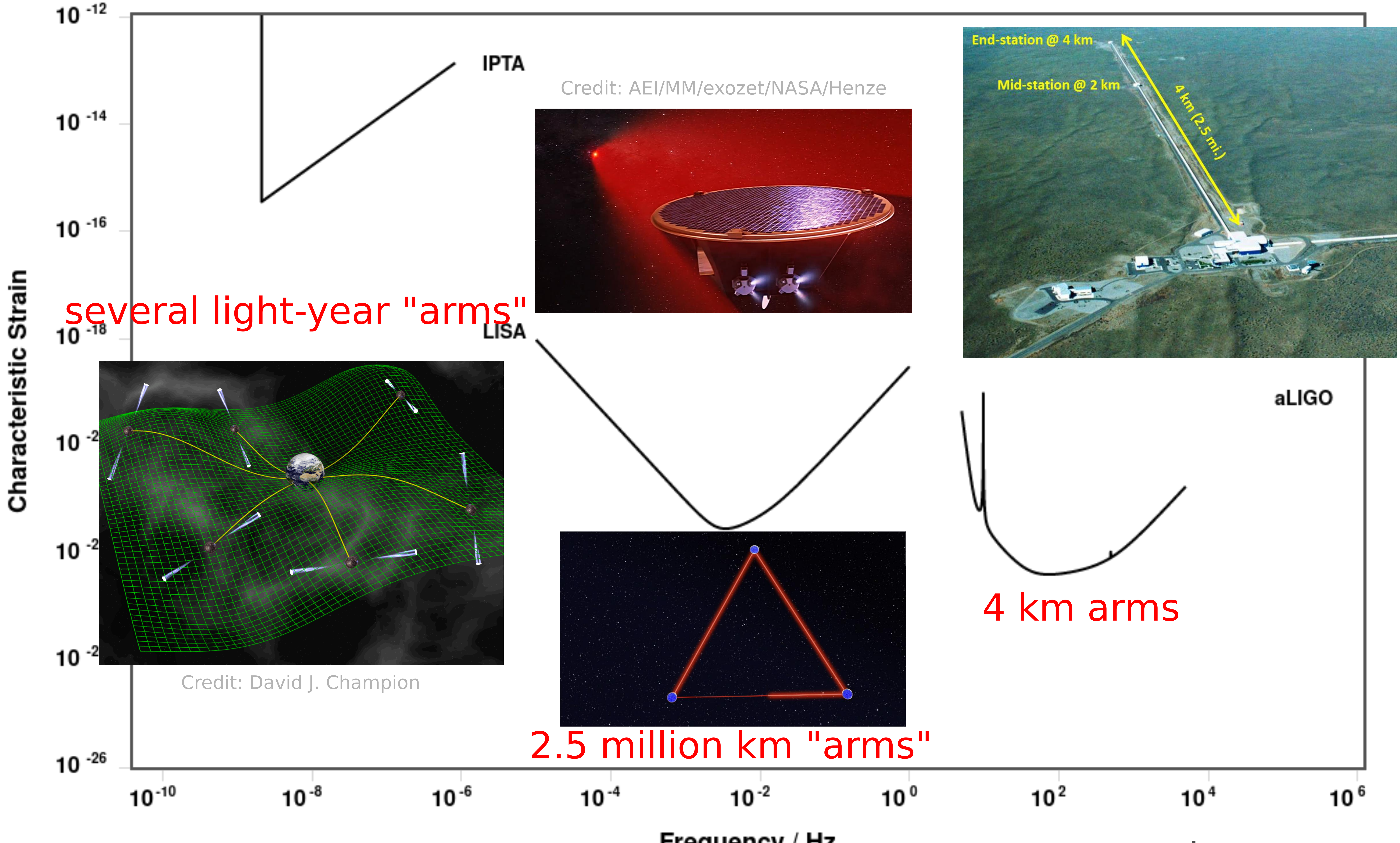

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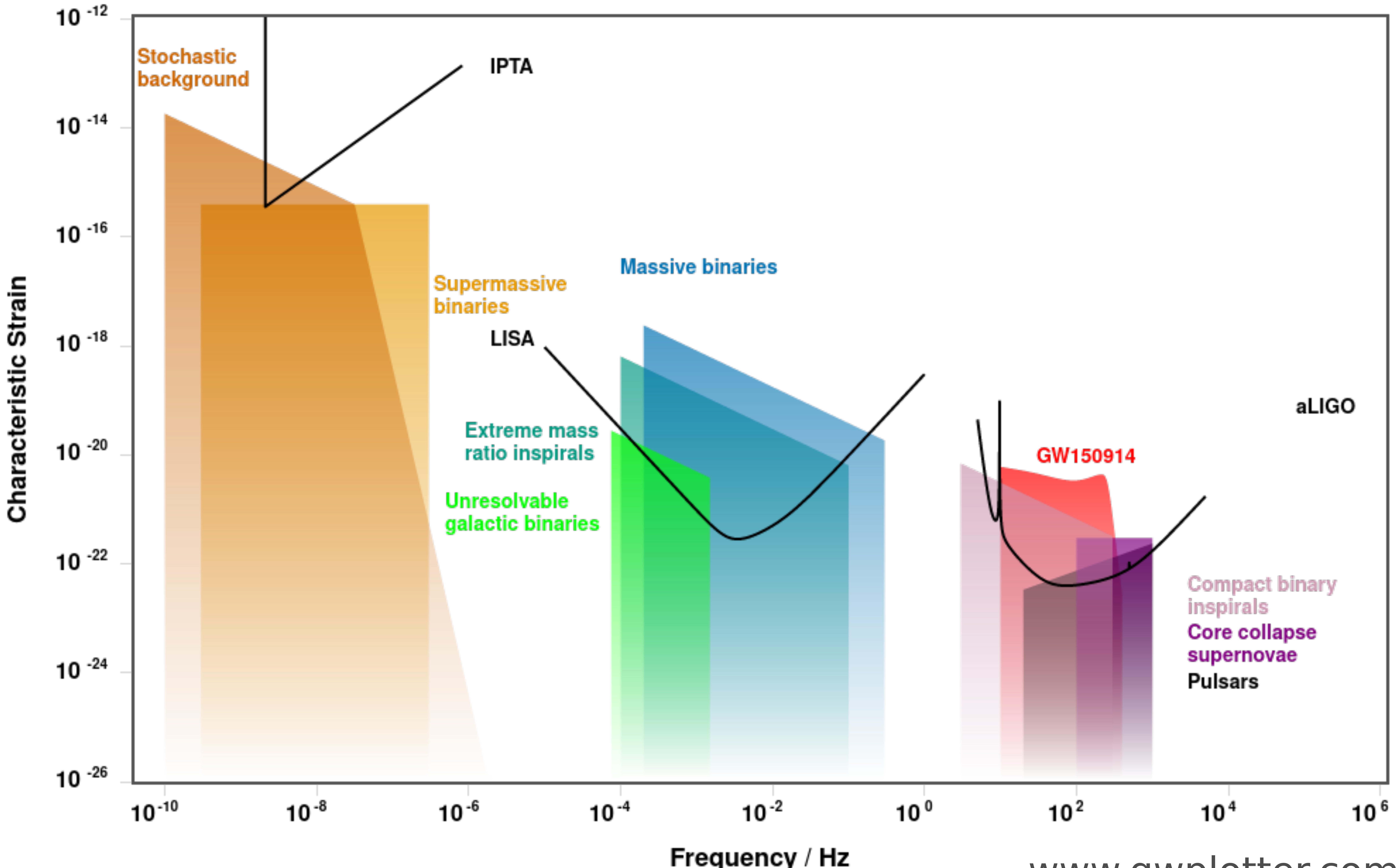

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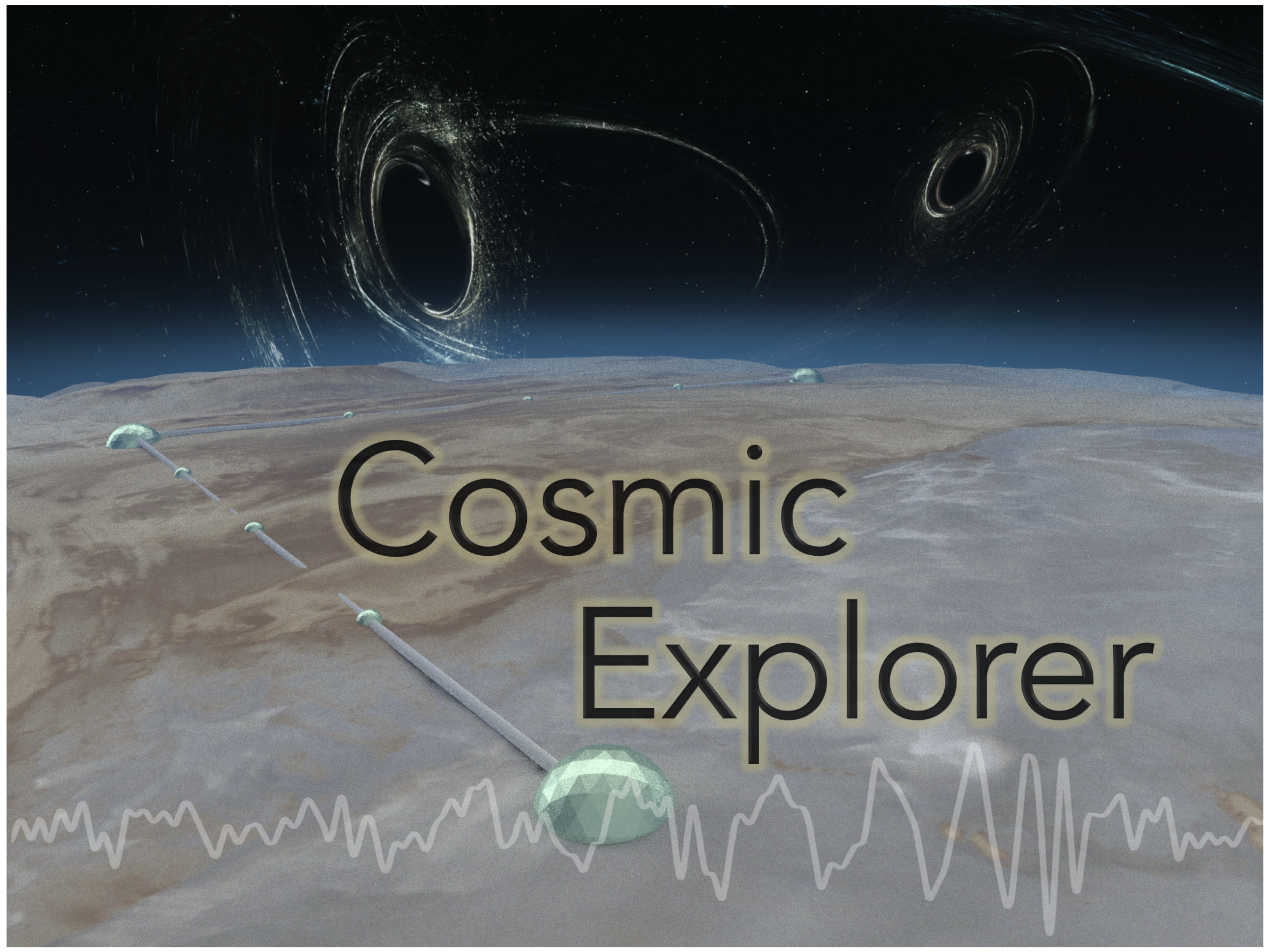
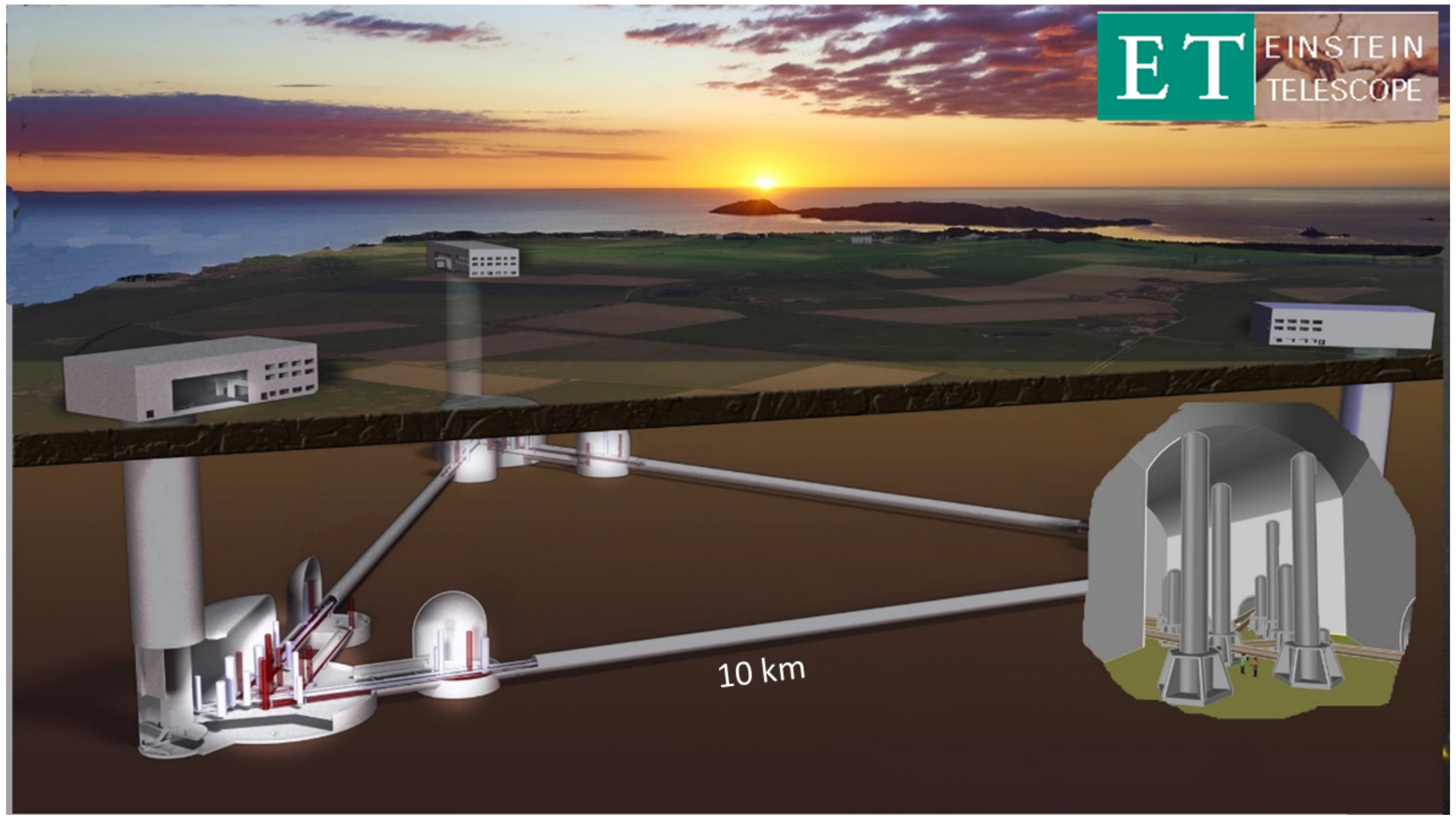
3rd generation detectors



Cosmic Explorer

Succesor to LIGO. Interferometer with 40 km arm length.

Reitze et al. 2019,
astro-ph 1907.04833

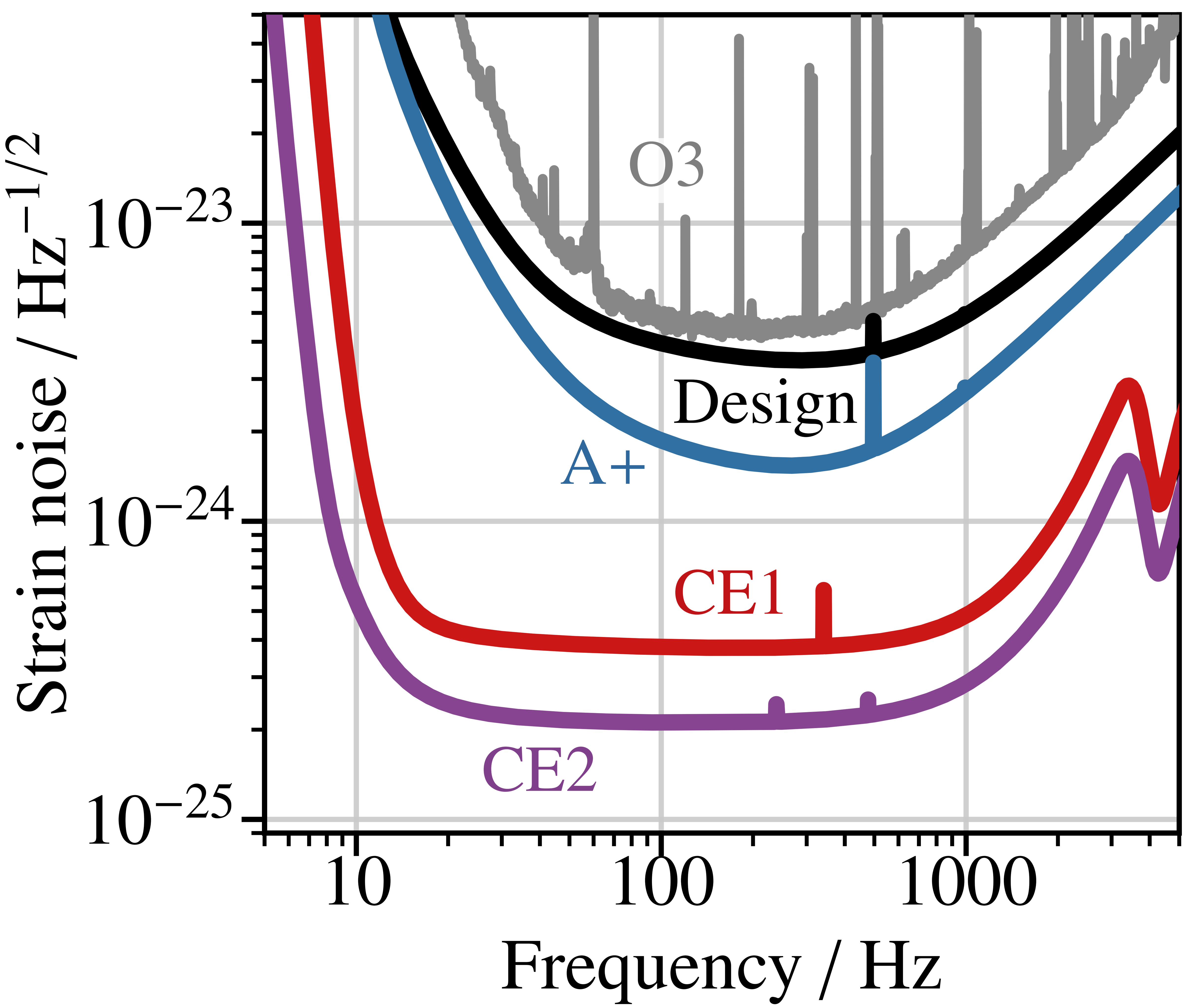


Einstein Telescope

European 3rd generation detector. Three 10 km arms in triangular configuration.

Punturo et al. (2010)
Maggiore et al. (2020)

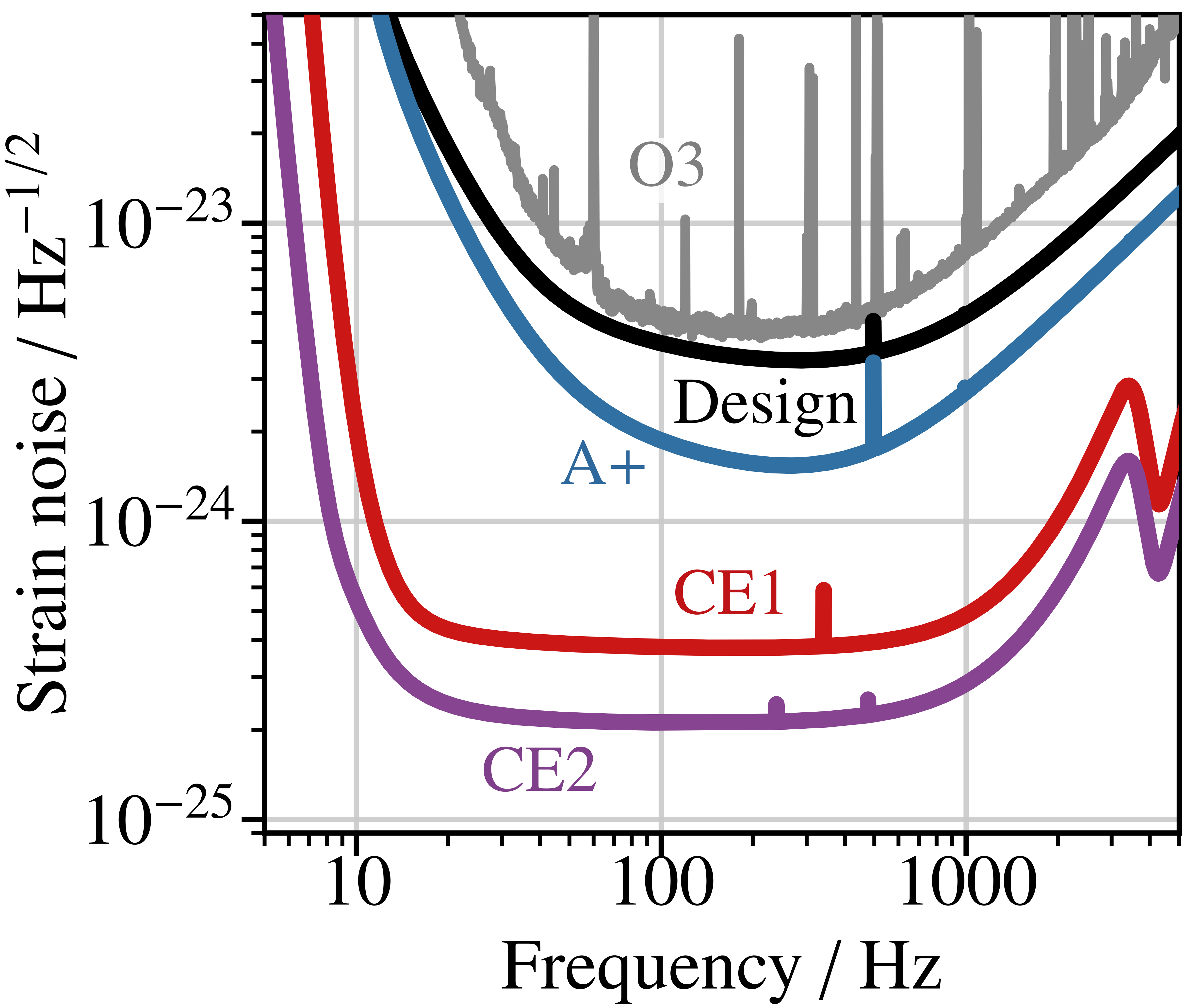
3rd generation detectors



Reitze et al. (2019)

Order of magnitude increase in sensitivity!

3rd generation detectors

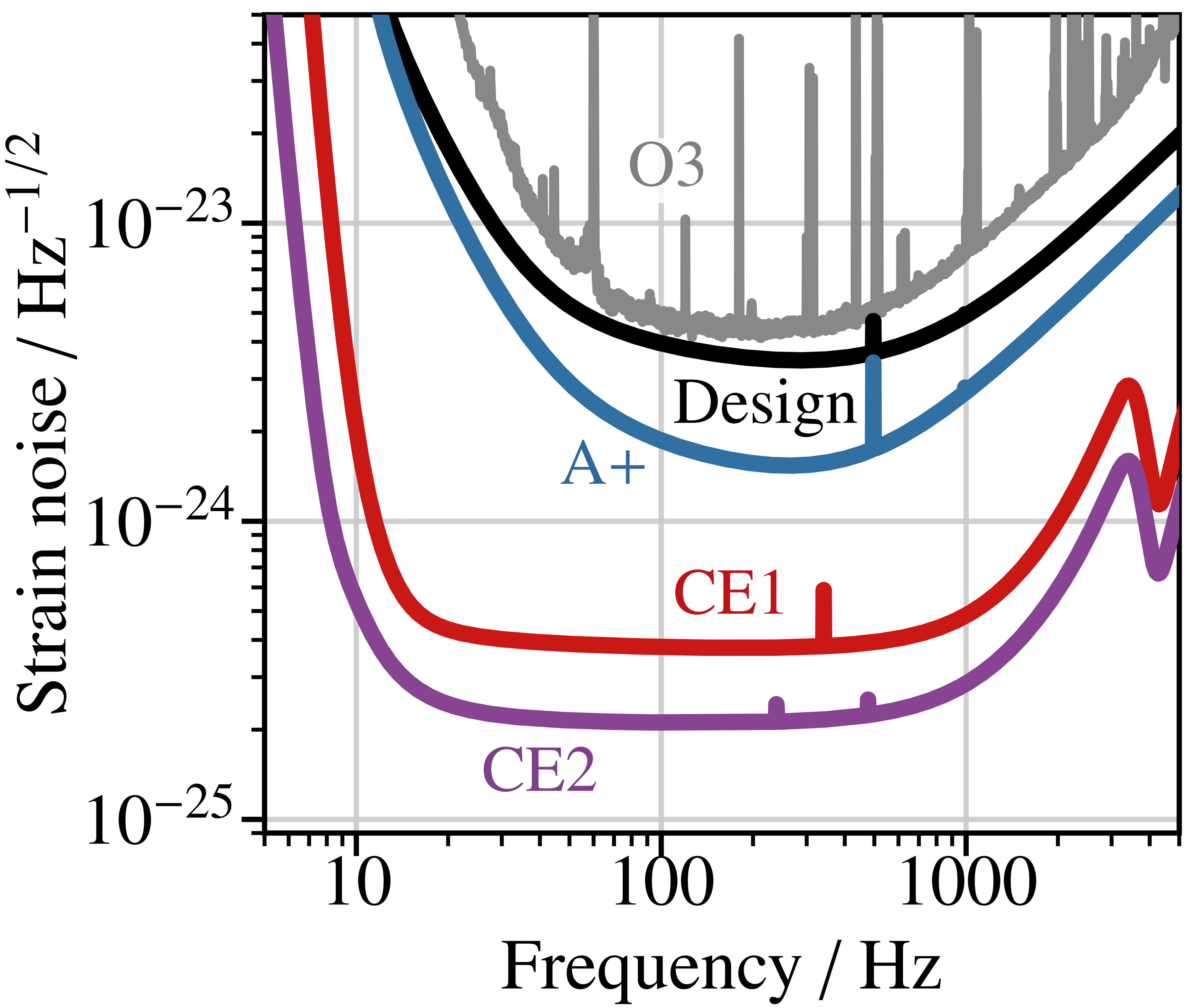


Reitze et al. (2019)

Order of magnitude increase in sensitivity!

$$h \propto \sqrt{F} \propto D_L^{-1}$$

3rd generation detectors



Reitze et al. (2019)

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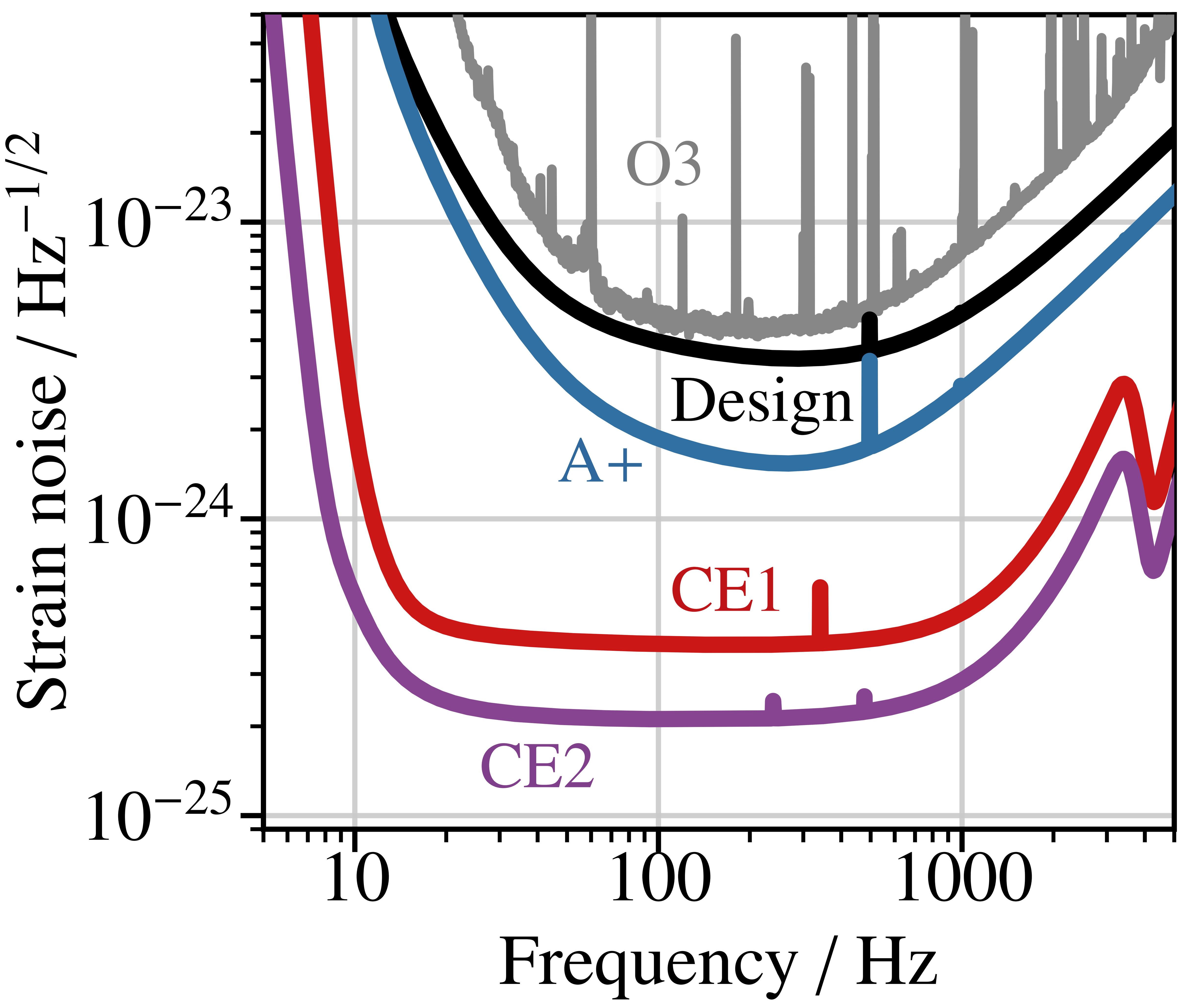
10 fold increase in horizon distance translates to 1000 fold increase in sensitive volume

3rd generation detectors



Reitze et al. (2019)

Order of magnitude increase in sensitivity!

$$h \propto \sqrt{F} \propto D_L^{-1}$$

10 fold increase in horizon distance translates to 1000 fold increase in sensitive volume

Compare with EM radiation, order of magnitude improvement in flux gives ~30 fold increase in sensitive volume.

3rd generation detectors

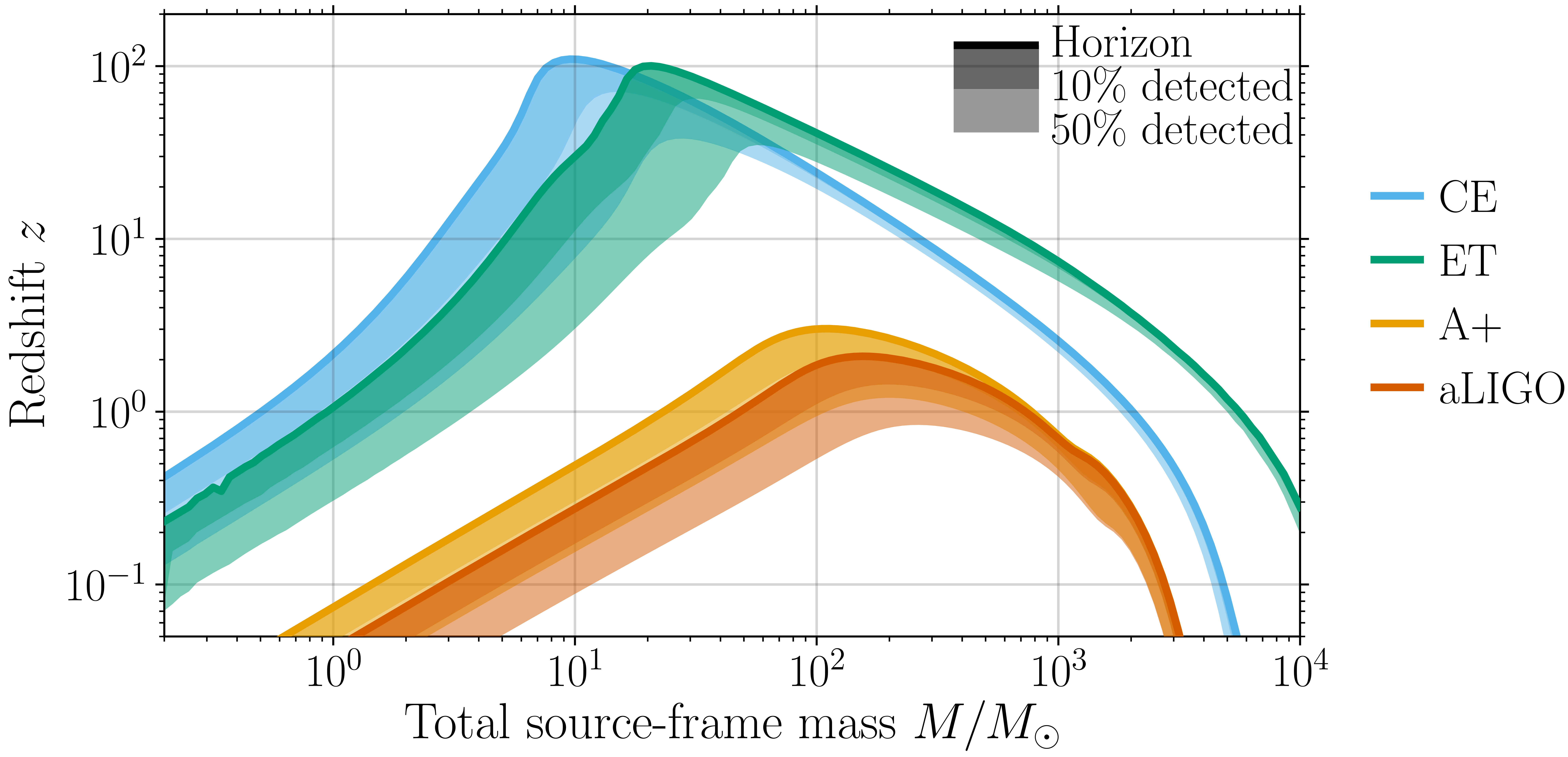
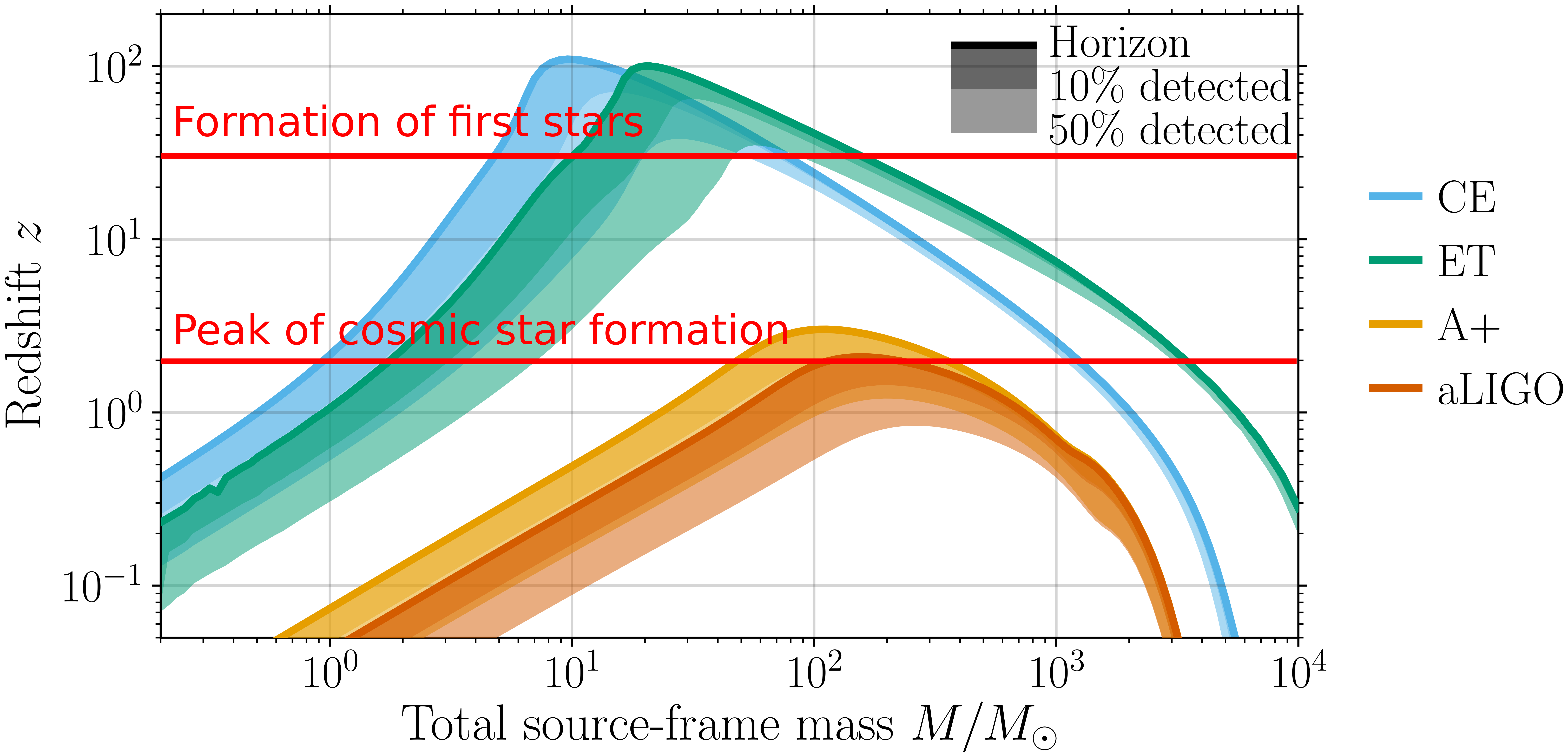


Figure courtesy of Christopher P. L. Berry, based on the calculations of Hall & Evans 2019 (1902.09485)

3rd generation detectors



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