Gravitational Waves, Experiment
Lecture 1

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08.09.2025

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Experimental gravitational wave detection

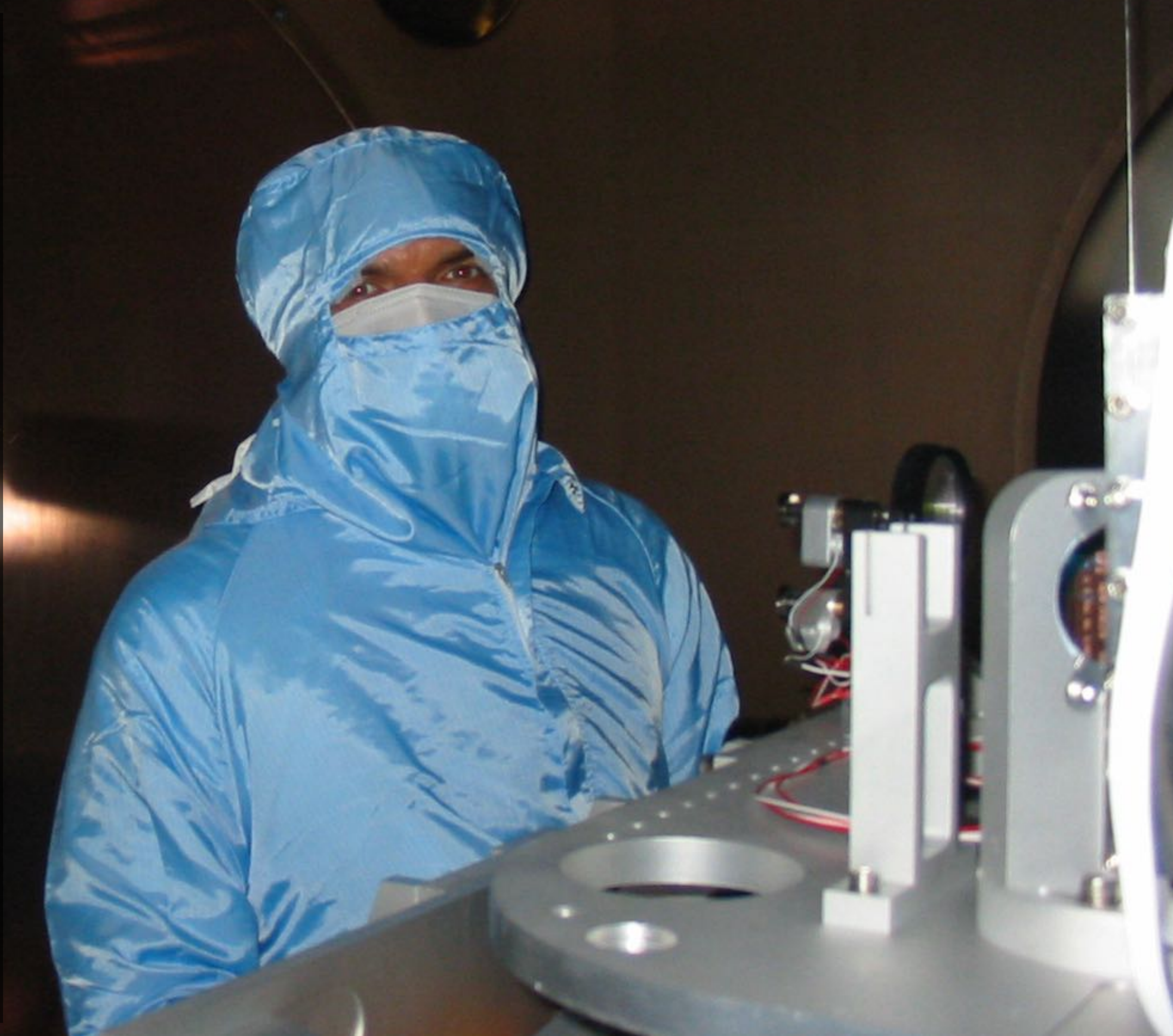
2003 PhD, Albert-Einstein Institute, Hannover, Germany

2003-2005 Post-doc, Virgo, Italy

2005-2020 Lecturer to Professor, University of Birmingham, UK

2020 Professor of Gravitational Wave Physics, Vrije Universiteit Amsterdam and Nikhef

2022 Director of the Einstein Telescope Organisation



Schedule

Lecture 1:

- Introduction to GWs
- History of ground-based GW detection
- Basics of interferometric GW detection

Lecture 2:

- Calculating optical signals in basic interferometers
- Properties of optical cavities

Lecture 3:

- Modern interferometric detectors
- Plans for future detectors
- Einstein Telescope

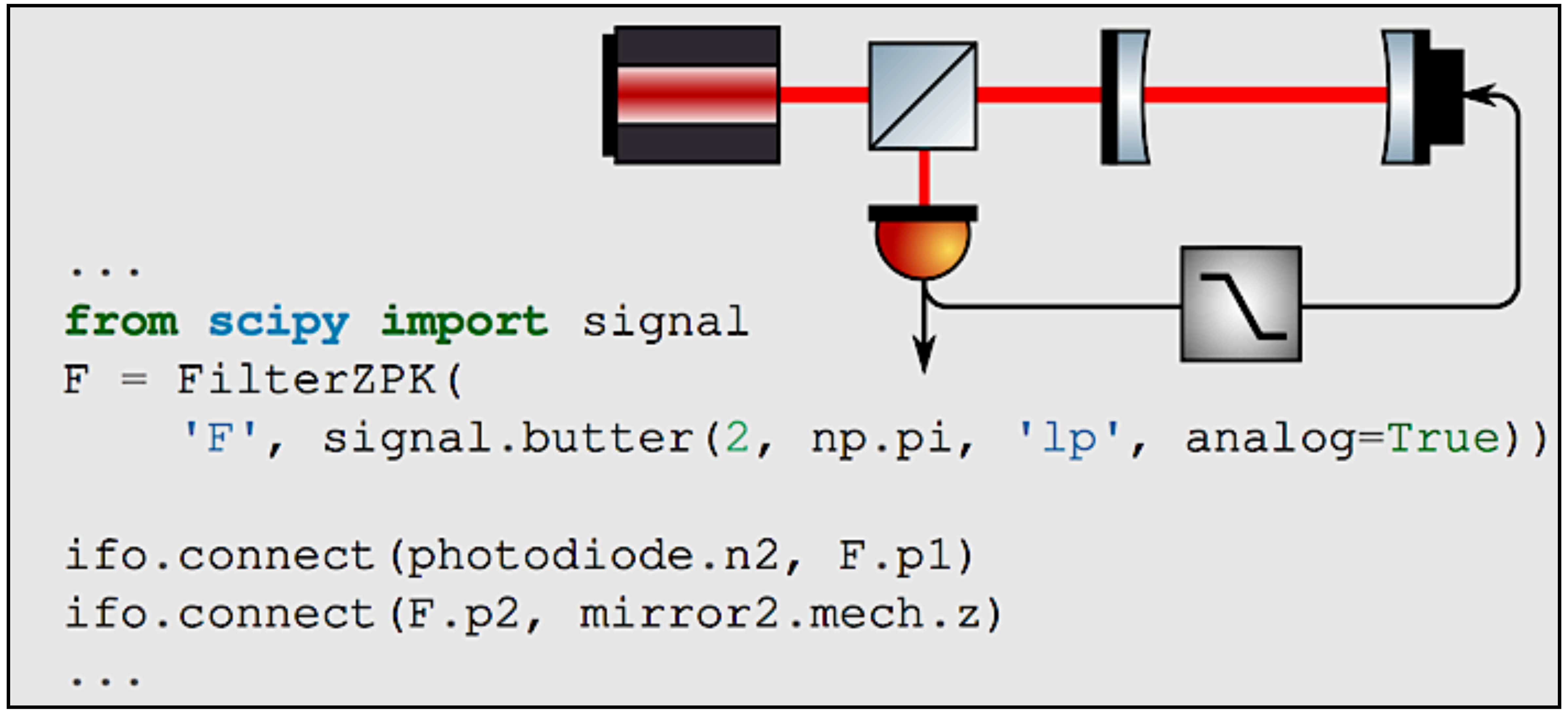
Hands-on:

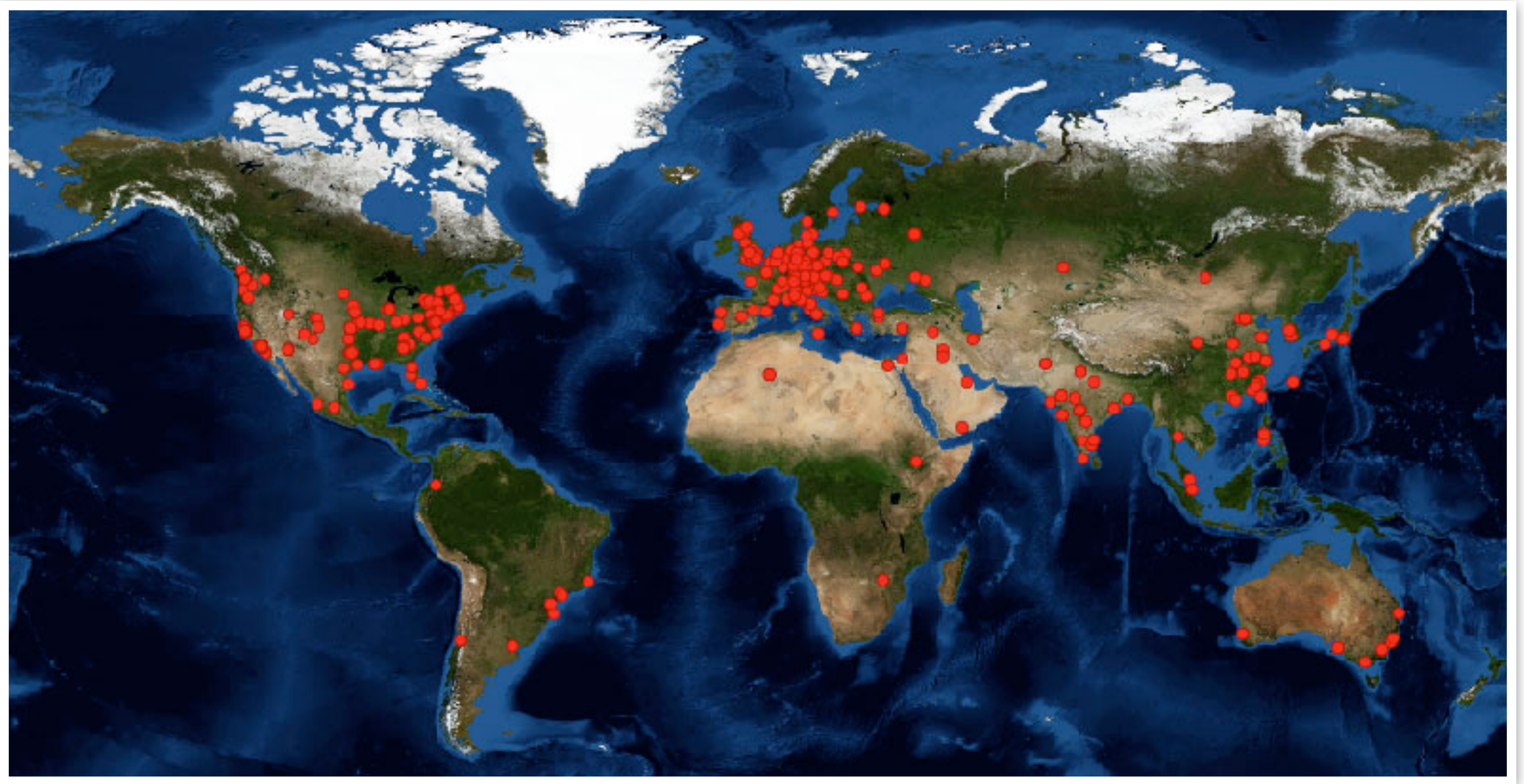
- Using the interferometer simulation Finesse
- Properties of optical cavities

FINESSE: Interferometer simulation and optical design

Hands-on session

GW detectors are unusual laser interferometers: one complex inter-connected system that couples optical fields with mechanics and electronics. We are developing and using a unique simulation software to design the next generation of detectors.



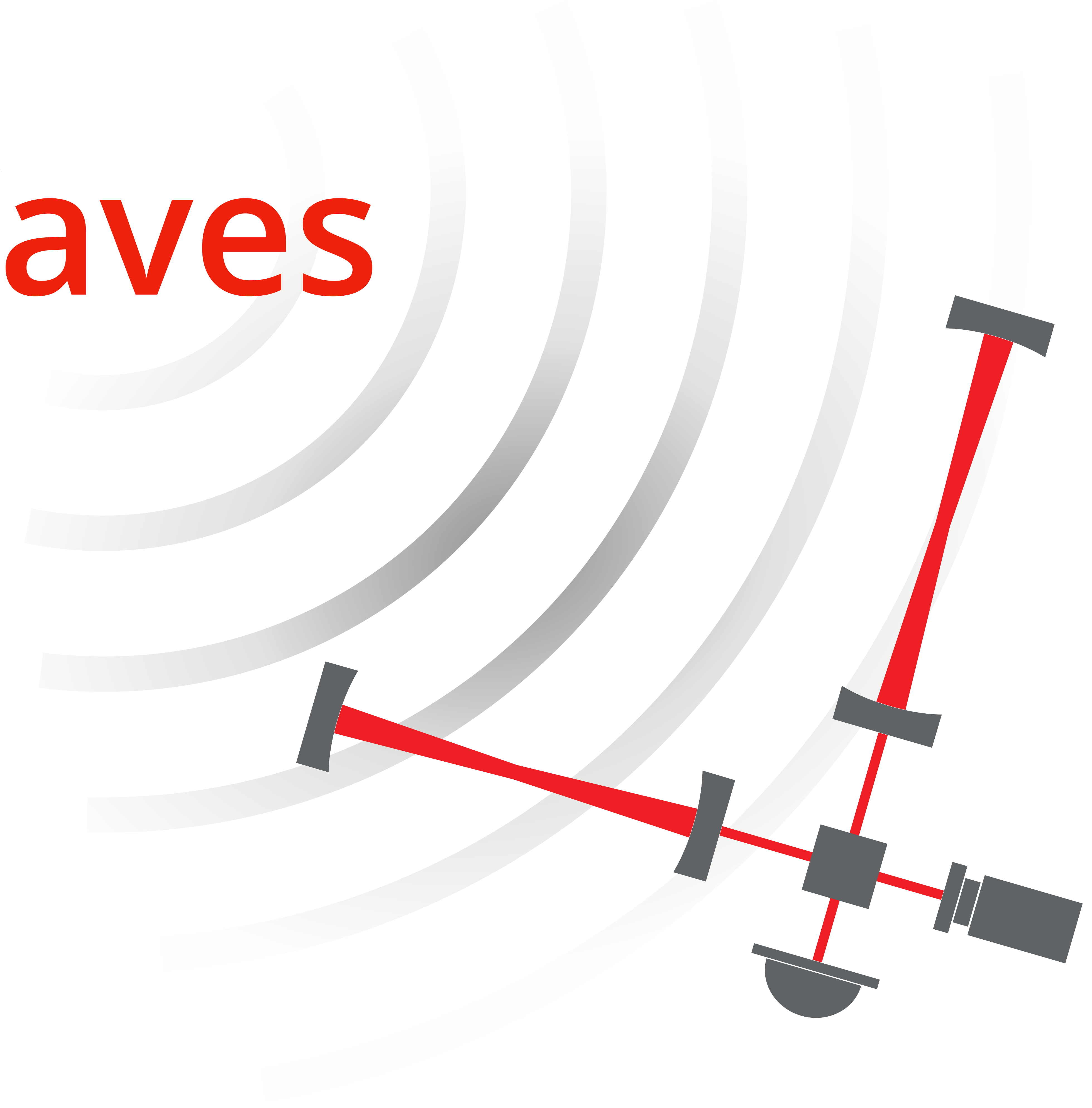


Interferometer simulation FINESSE: https://finesse.ifosim.org/

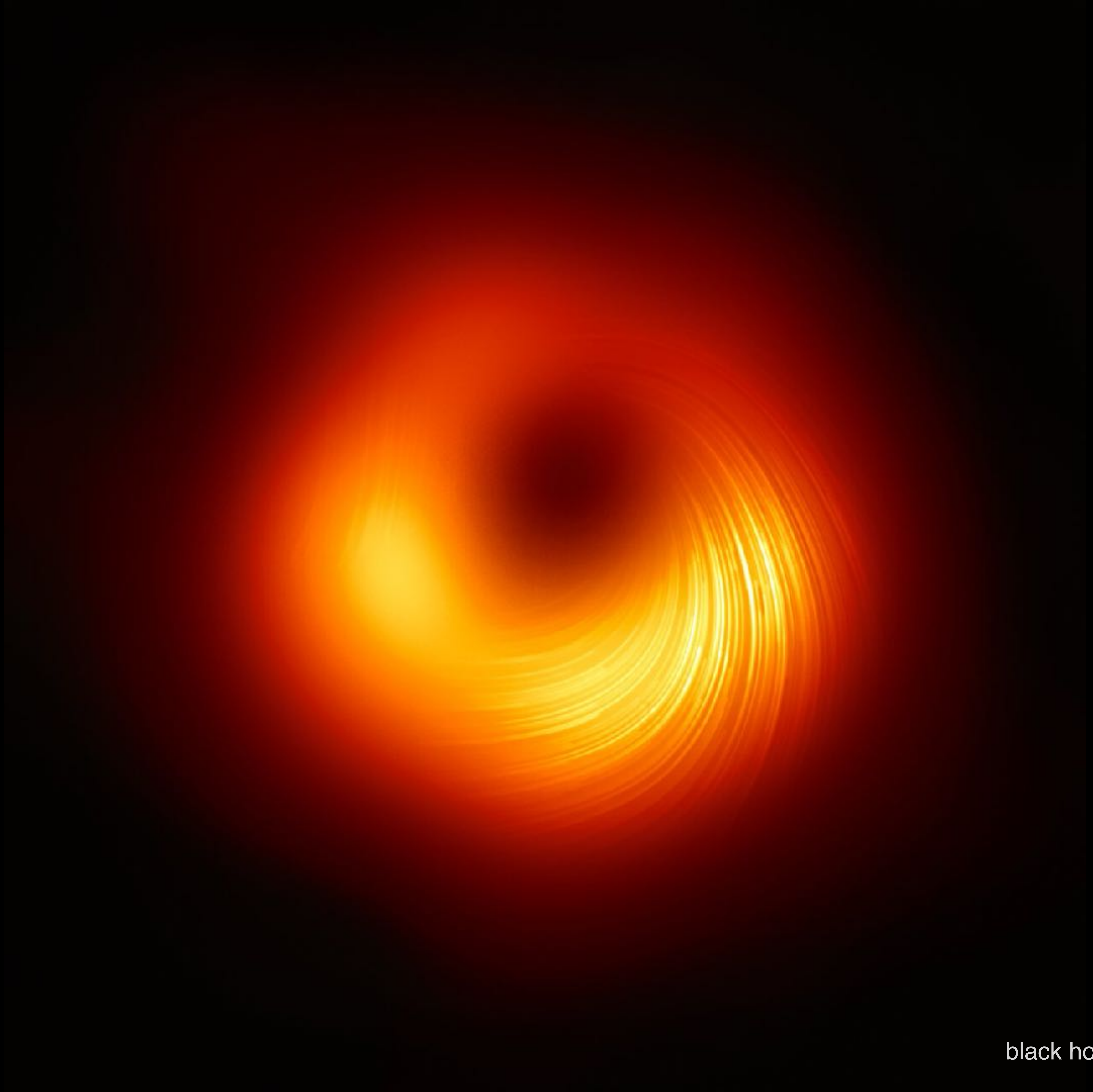
The 'textbook': Interferometer techniques for gravitational-wave detection.

Material for today: https://gitlab.com/ifosim/finesse/finesse3_getting_started

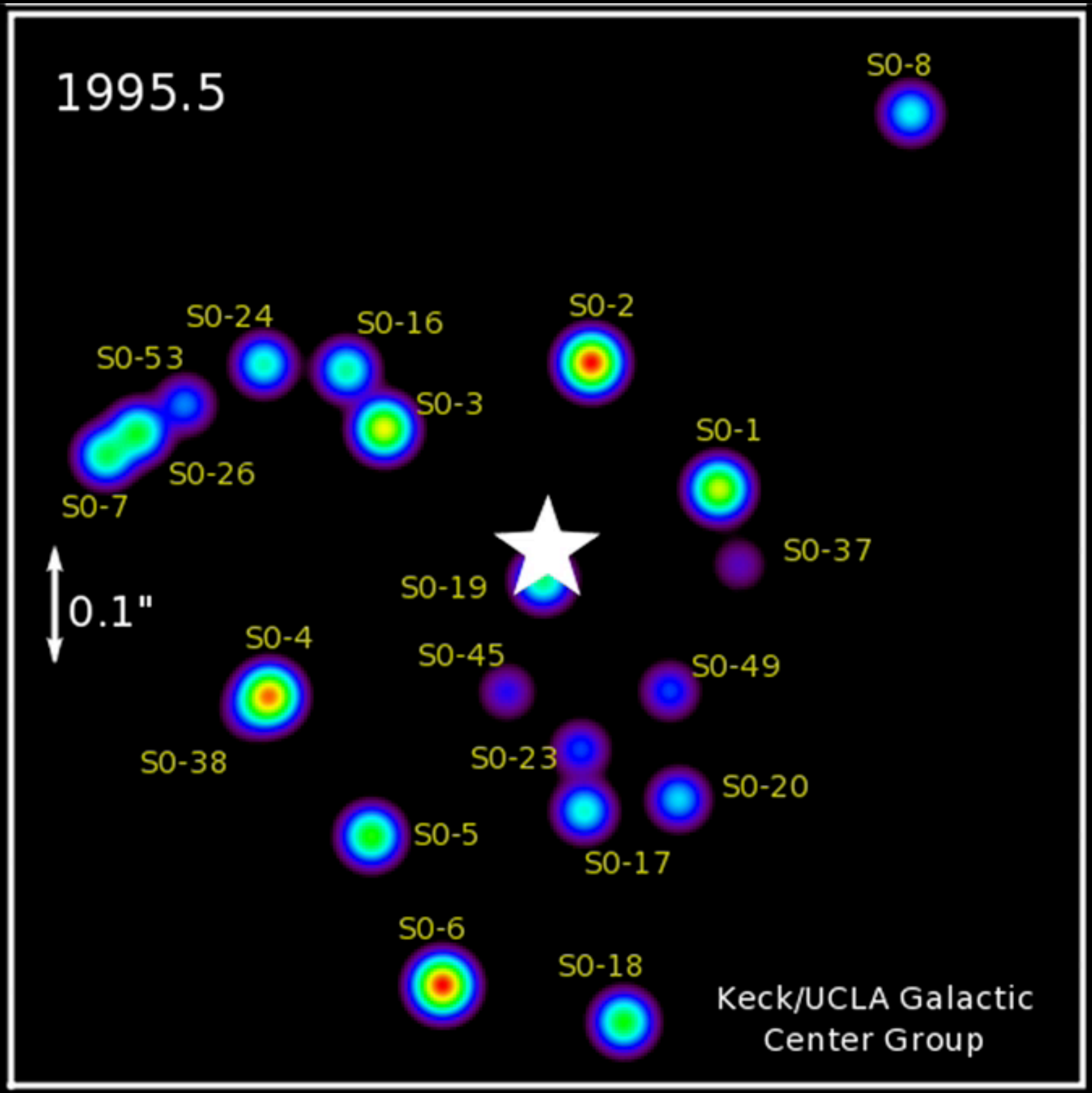
Introduction to Gravitational Waves




Gravitational Wave Astronomy
By detecting space-time vibrations on Earth we can measure black holes and explore the 'dark side' of the universe



black hole in M87, EHT Collaboration 2021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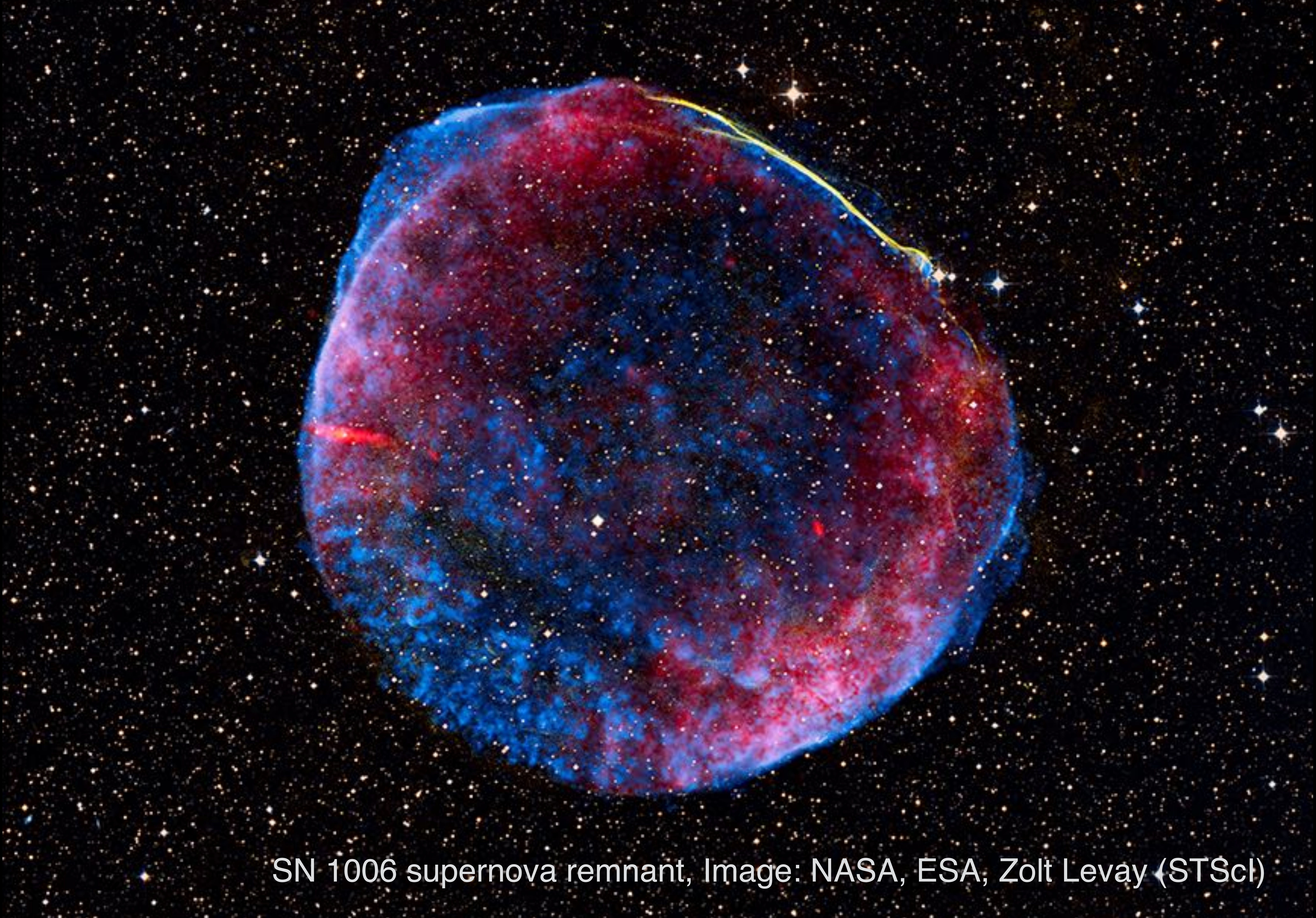
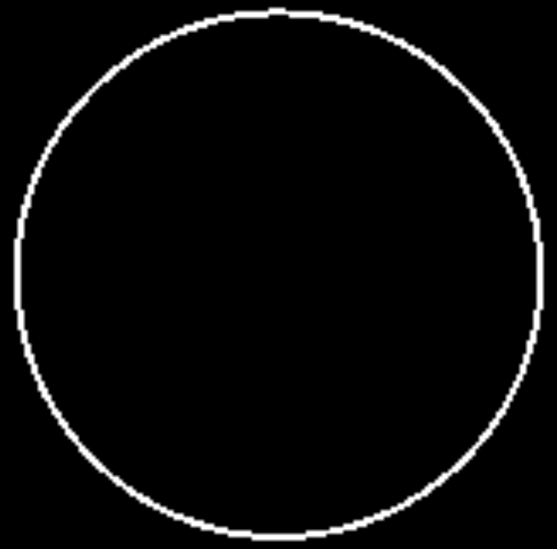
Keck/UCLA Galactic
Center Group



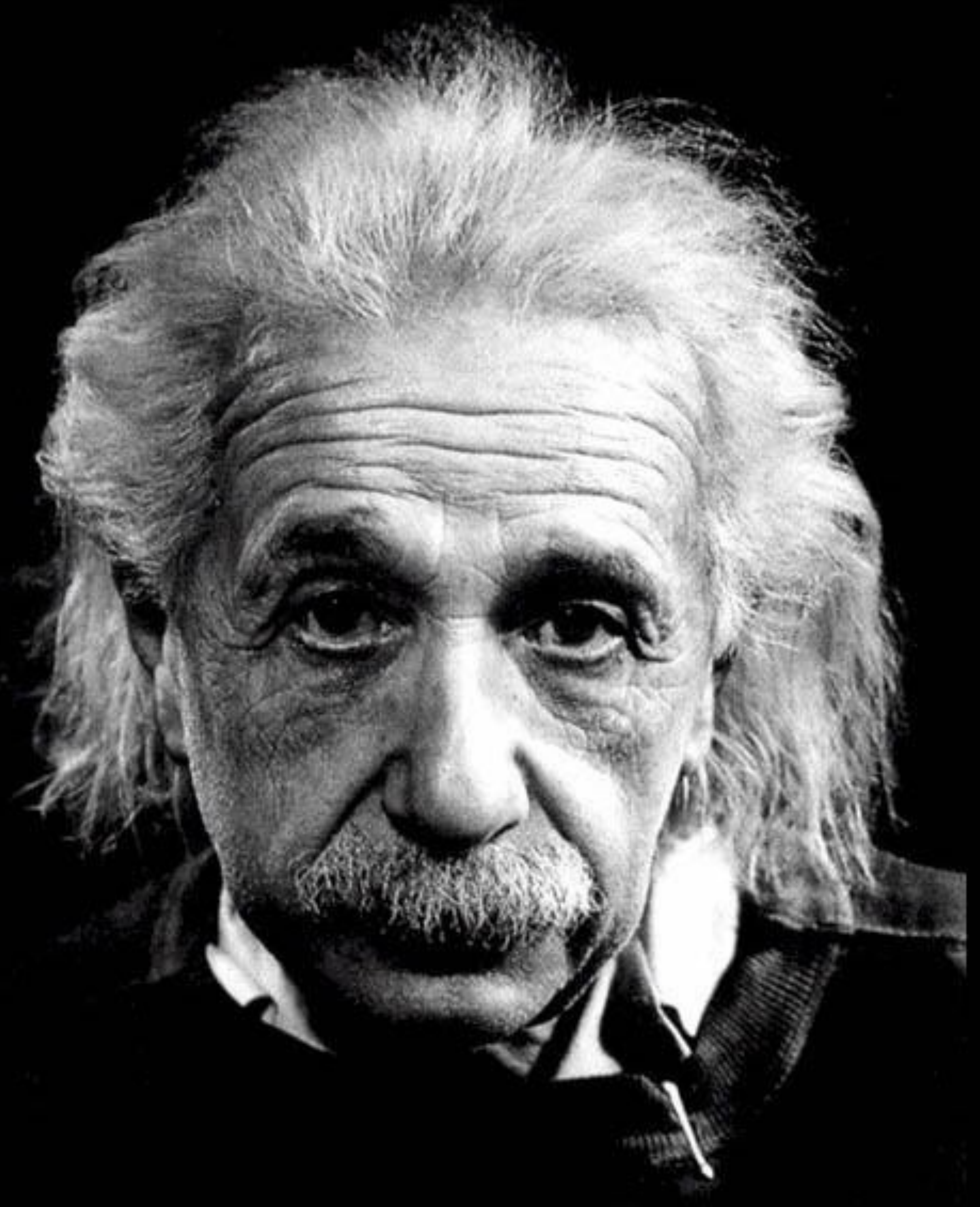
SN 1006 supernova remnant, Image: NASA, ESA, Zolt Levay (STScI)

Neutron Star



Black Hole

Amsterdam



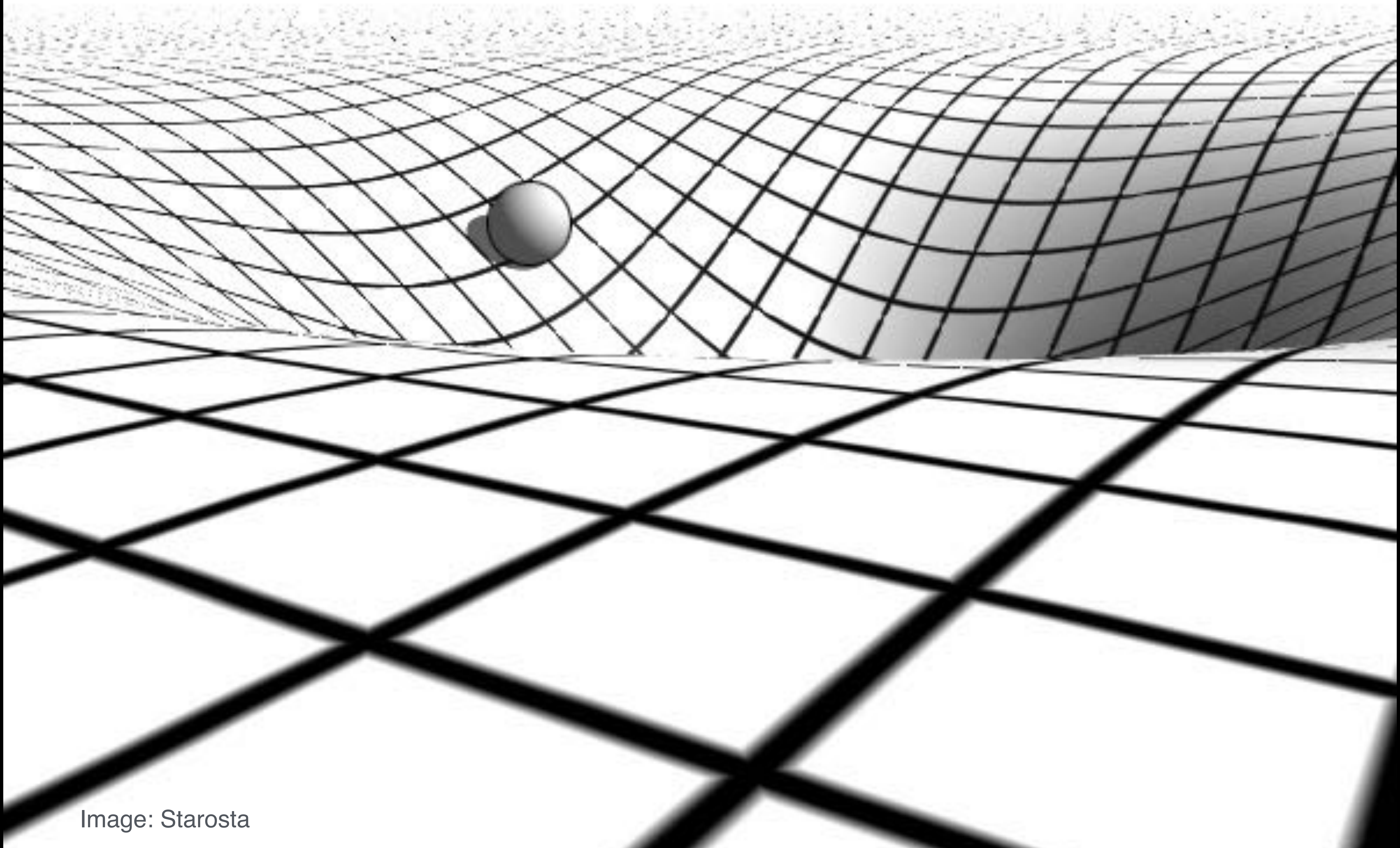
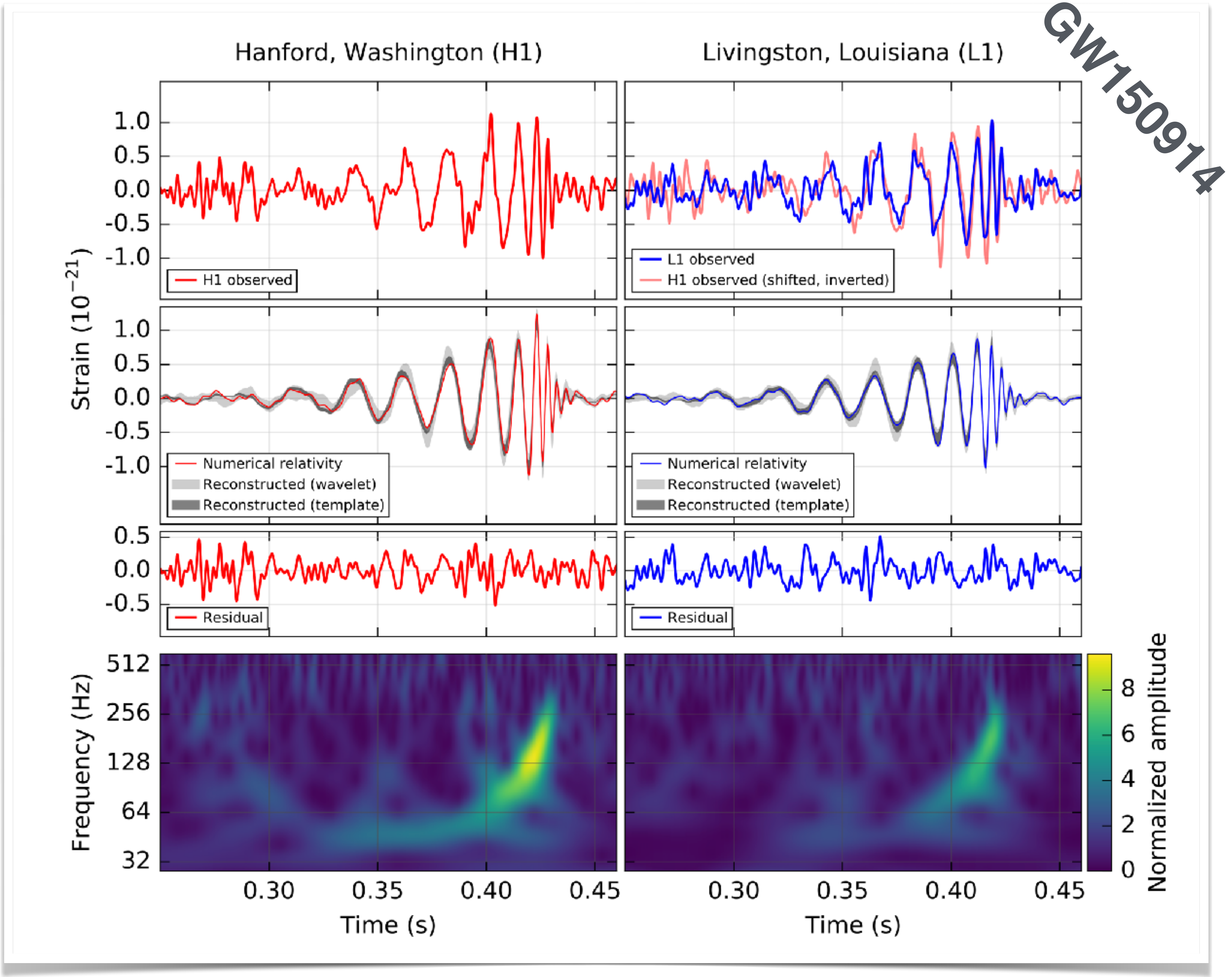


Image: Starosta

Data

… recorded by LIGO on the 14th of September 2015, at 09:50:45 UTC



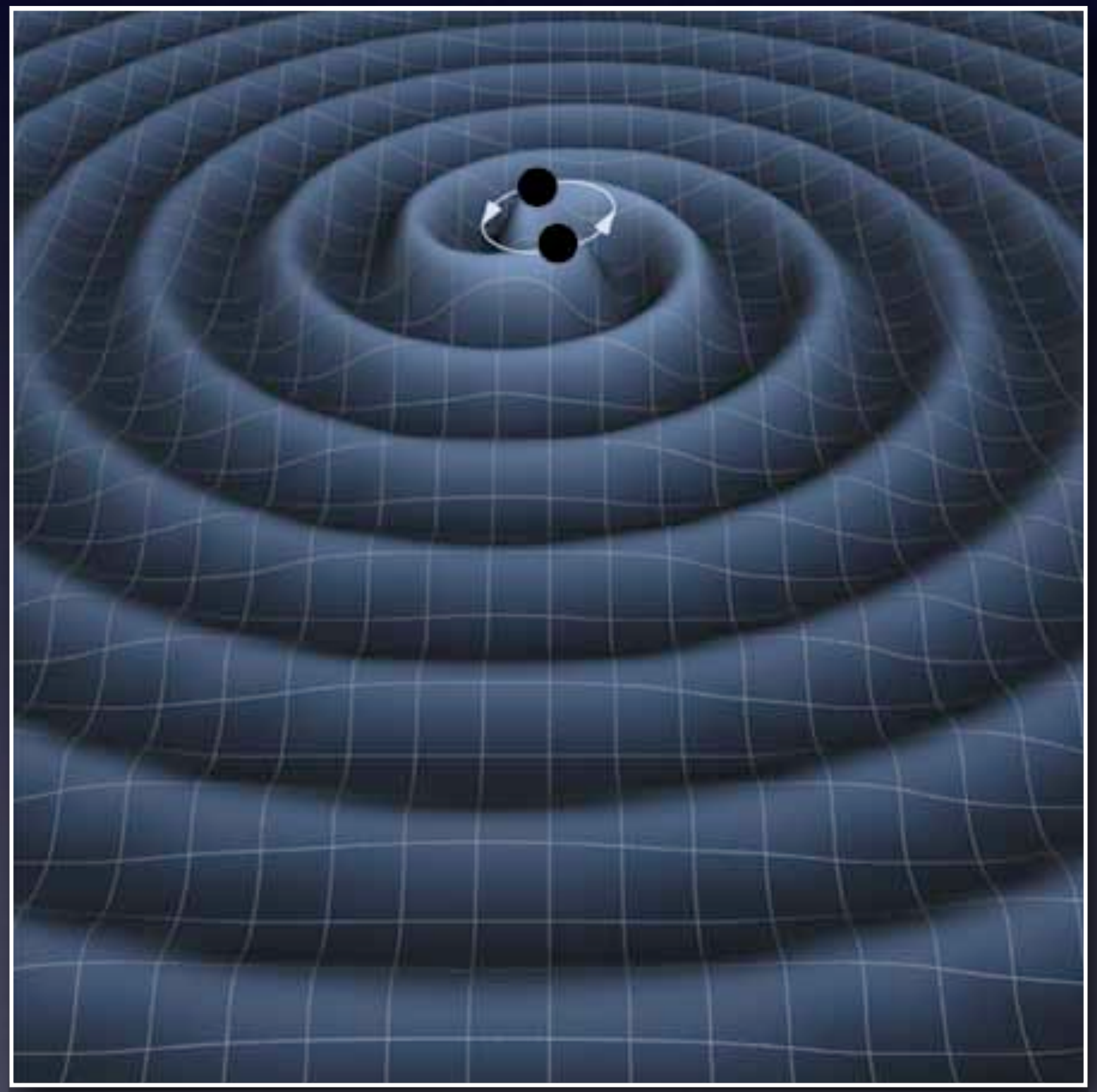
Read the timeline in the LIGO Magazine:
https://www.ligo.org/magazine/LIGO-magazine-issue-8-extended.pdf#page=8

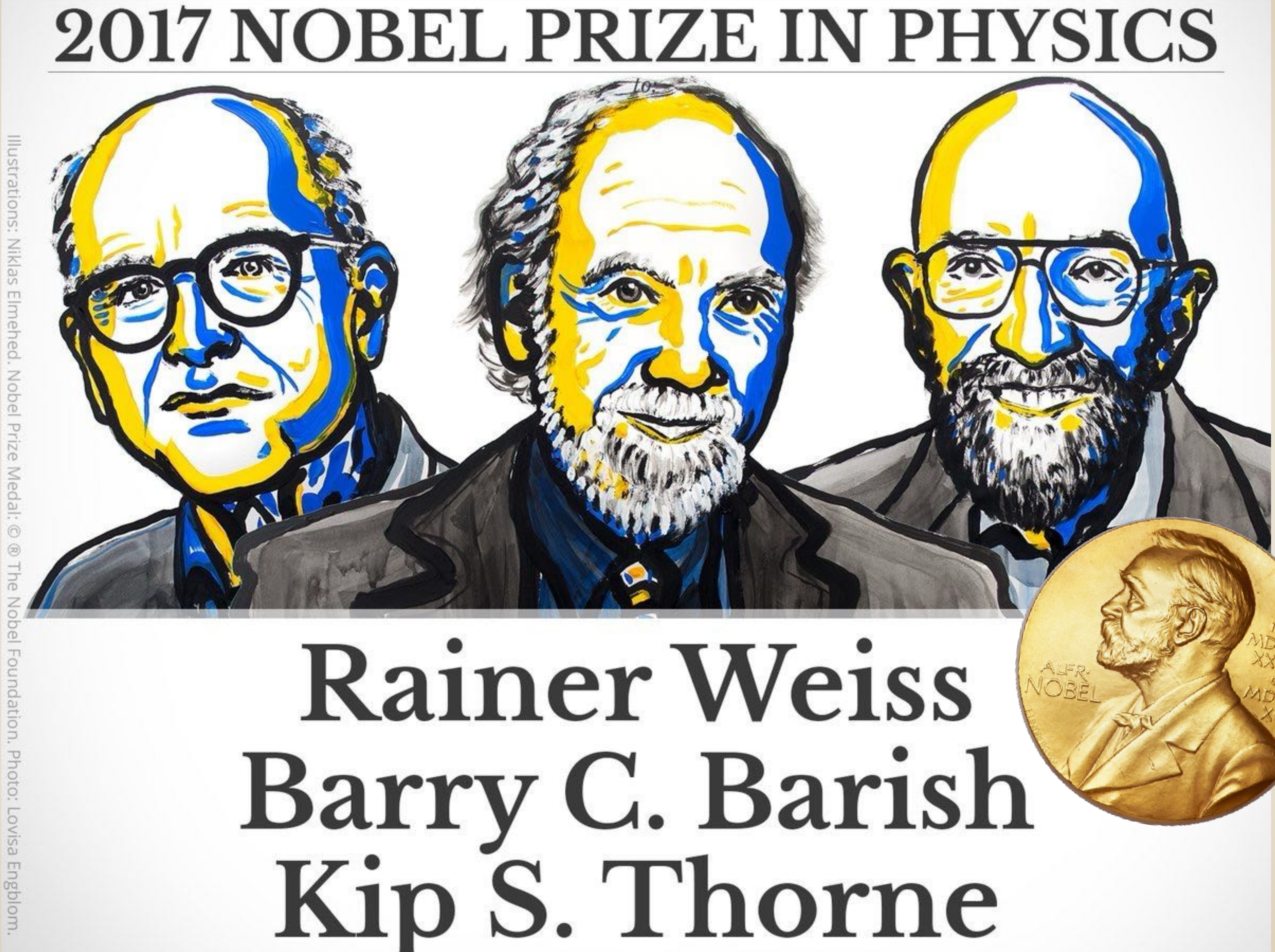

-0.76s

Fact sheet

GW150914

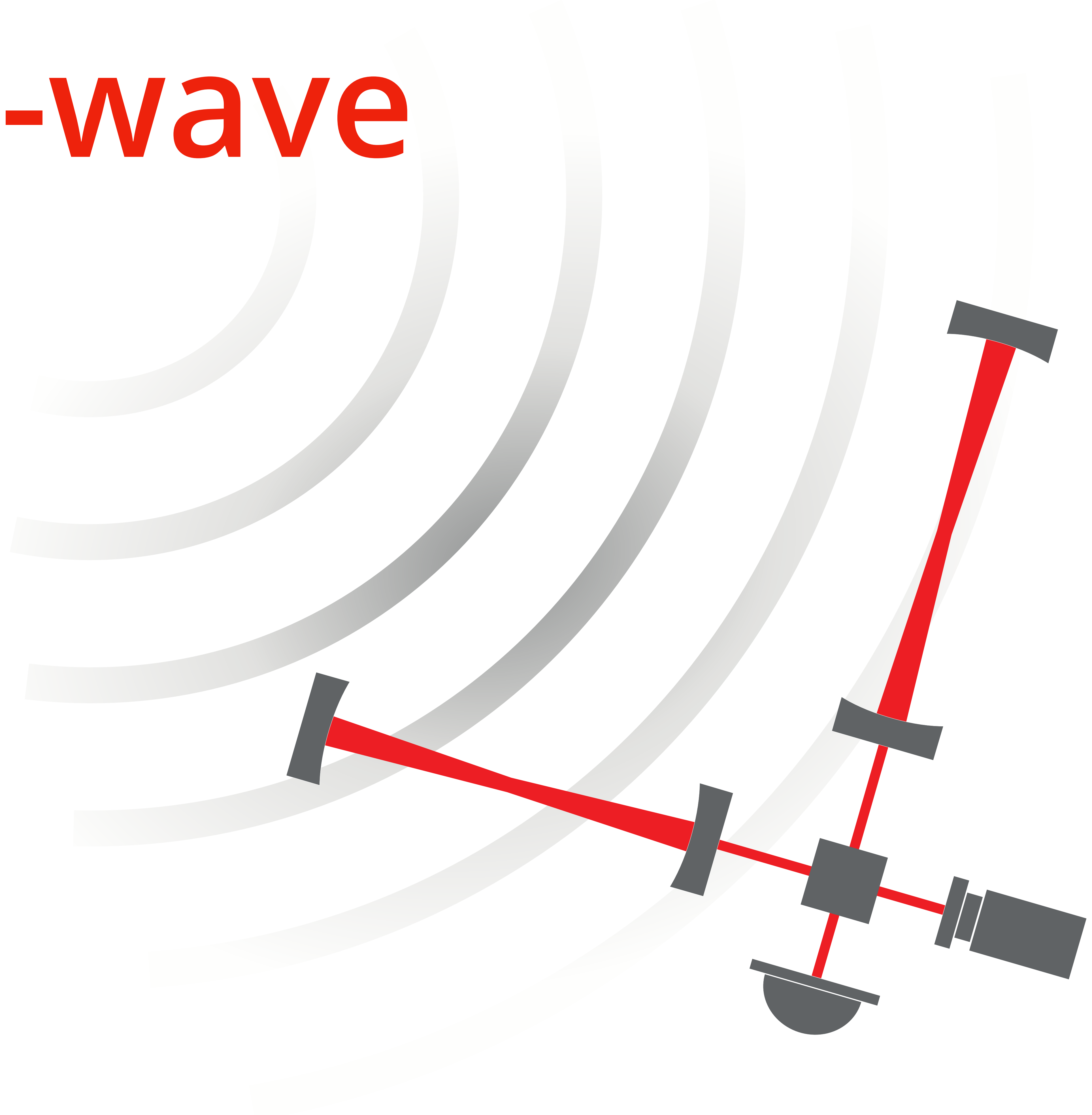
- About 1 billion years ago (1 billion light years away), two black holes merged
- Before: two black holes of 36 and 29 solar masses, after: one black hole, 62 solar masses
- **A very violent event**, rotation speed up to 200 Hz
- In 2015 the LIGO mirrors wiggled by 10^{-18} meters for 0.1 seconds




2017 NOBEL PRIZE IN PHYSICS
Rainer Weiss
Barry C. Barish
Kip S. Thorne
Illustrations: Niklas Elmehed. Nobel Prize Medal: © ® The Nobel Foundation. Photo: Lovisa Engblom.
ALFR·
NOBEL
NAT·
MDCCC
XXXIII
OB·
MDCCC
XCVI


LIGO Hanford 4km
GEO600 600m
Virgo 3km
LIGO India
(approved)
KAGRA 3km
LIGO Livingston 4km
Cosmic Explorer
(planned)
EINSTEIN TELESCOPE
Einstein Telescope
(planned)

A brief history of ground-based gravitational-wave detection



A long journey …

1915
1916

Einstein publishes new theory of gravity, predicting gravitational waves

1960s

Joseph Weber constructs resonant bar GW detectors

1970s

Rainer Weiss and Robert Forward start working on interferometric detectors

1992

LIGO is founded

1993

Nobel Prize for Hulse and Taylor, indirect proof for existence of GWs

2002 - 2010

6 scientific data taking periods with LIGO, Virgo, GEO and TAMA, **without** a detection

2008 - 2014

Upgrade of LIGO/Virgo detectors, for a 10-fold increase in sensitivity

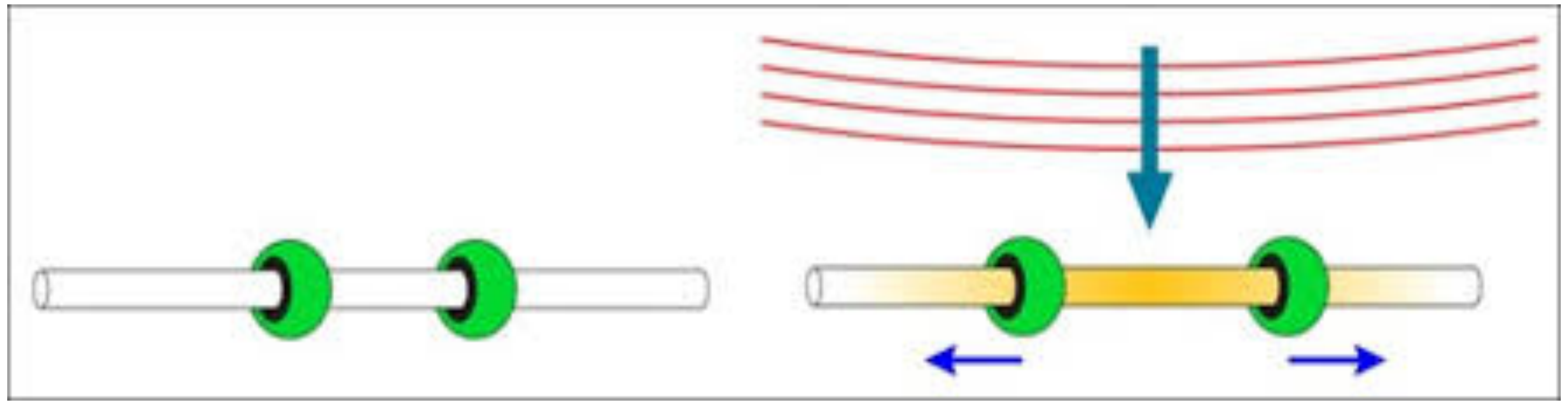
Bringing Virgo/LIGO to new design sensitivity

1915 1930 1945 1960 1975 1990 2005 2020

▲ **Today**

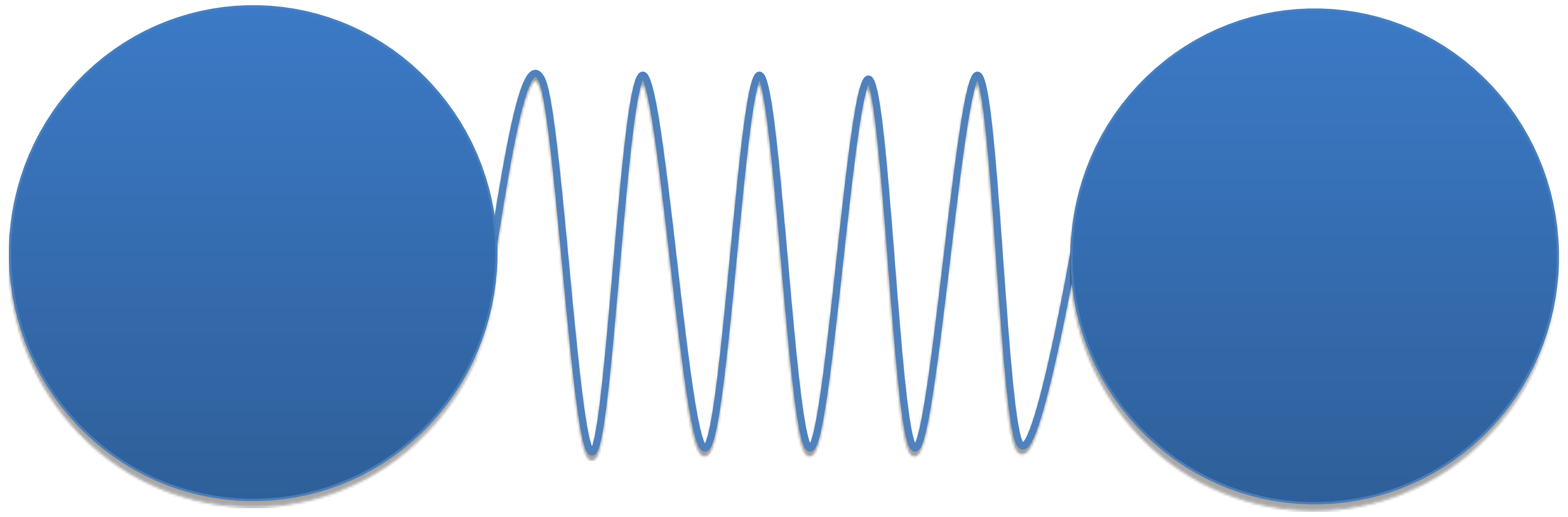
Are GWs detectable?

- Einstein: GW are so small that they can be ignored, too hard to detect
- Not a surprising idea at the time:
  - theory was not yet mature, not immediately clear if GW are observable at all, if they carry energy
  - missing observational evidence for astronomical sources of GW (black holes, neutron stars, pulsars, ...)
  - missing technology: lasers, modern electronics, ...
- **Sticky Bead Argument** (Feynman, 1957): Beads sliding with friction on a stick would generate heat due to a passing GW, so GW carries energy, can be detected.



Weber bars: a first attempt

- Passing GW will excite a mechanical resonator like a tuning fork
- First experiments around 1968 by J. Weber: resonant aluminium bar at room temperature



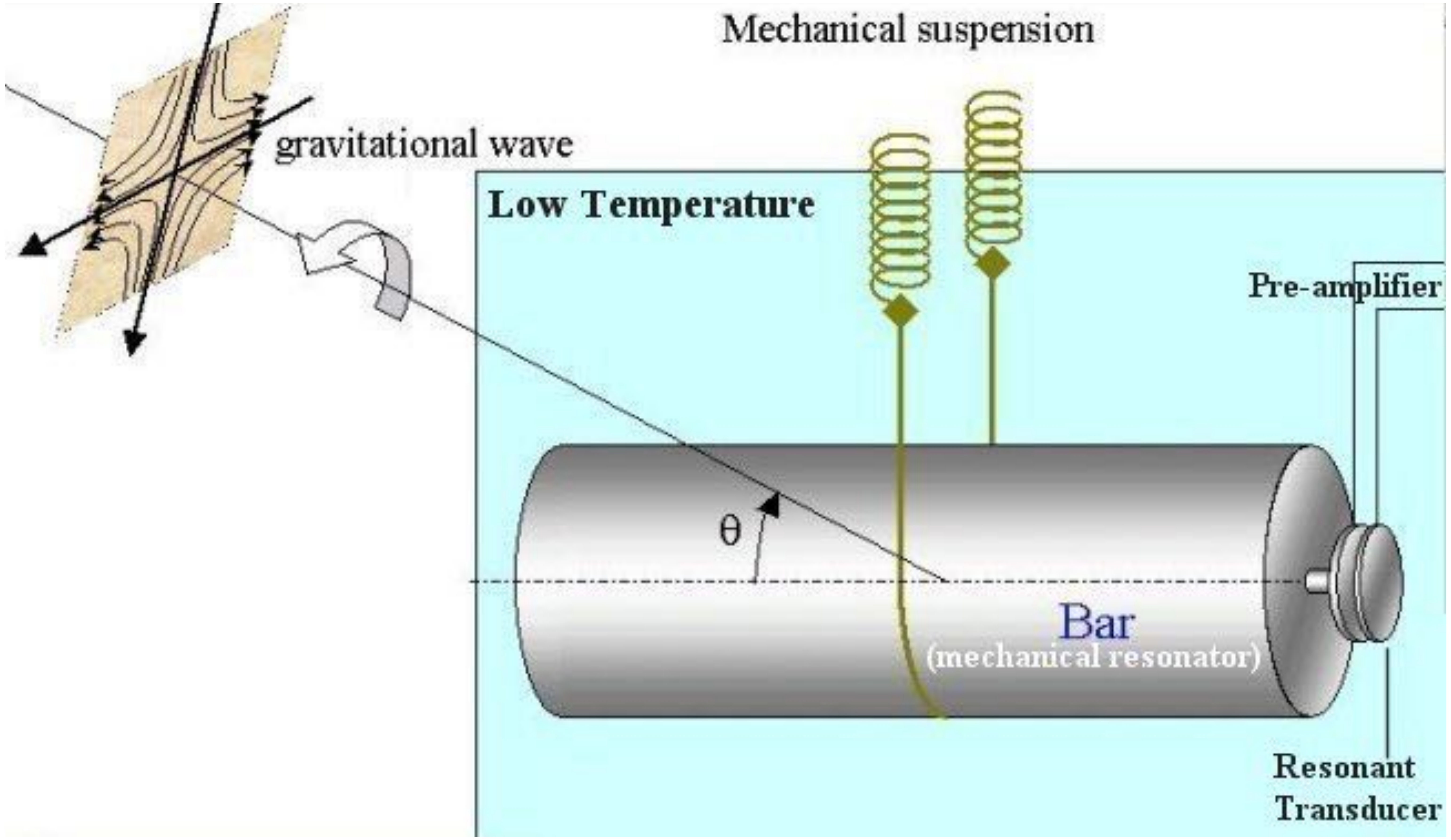
Question:

How can the stretching of space-time excite a bar detector?

Not a first detection

- Two papers in PRL by Weber, in 1969 and 1970, reported the first detections of such gravitational waves (excess correlation of signals between two separate instruments), coming apparently from the center of our galaxy.
- Detector sensitivity was limited by thermal noise at 10^{-16} m/sqrt(Hz).
- Results could not be repeated by Weber or other groups. However these papers are credited with motivating other groups to start experimental gravitational wave detection, e.g. MIT, MPG in Munich (Garching) and Glasgow (see e.g. book 'Gravity's Shadow, H. Collins).

How to amplify and detect?

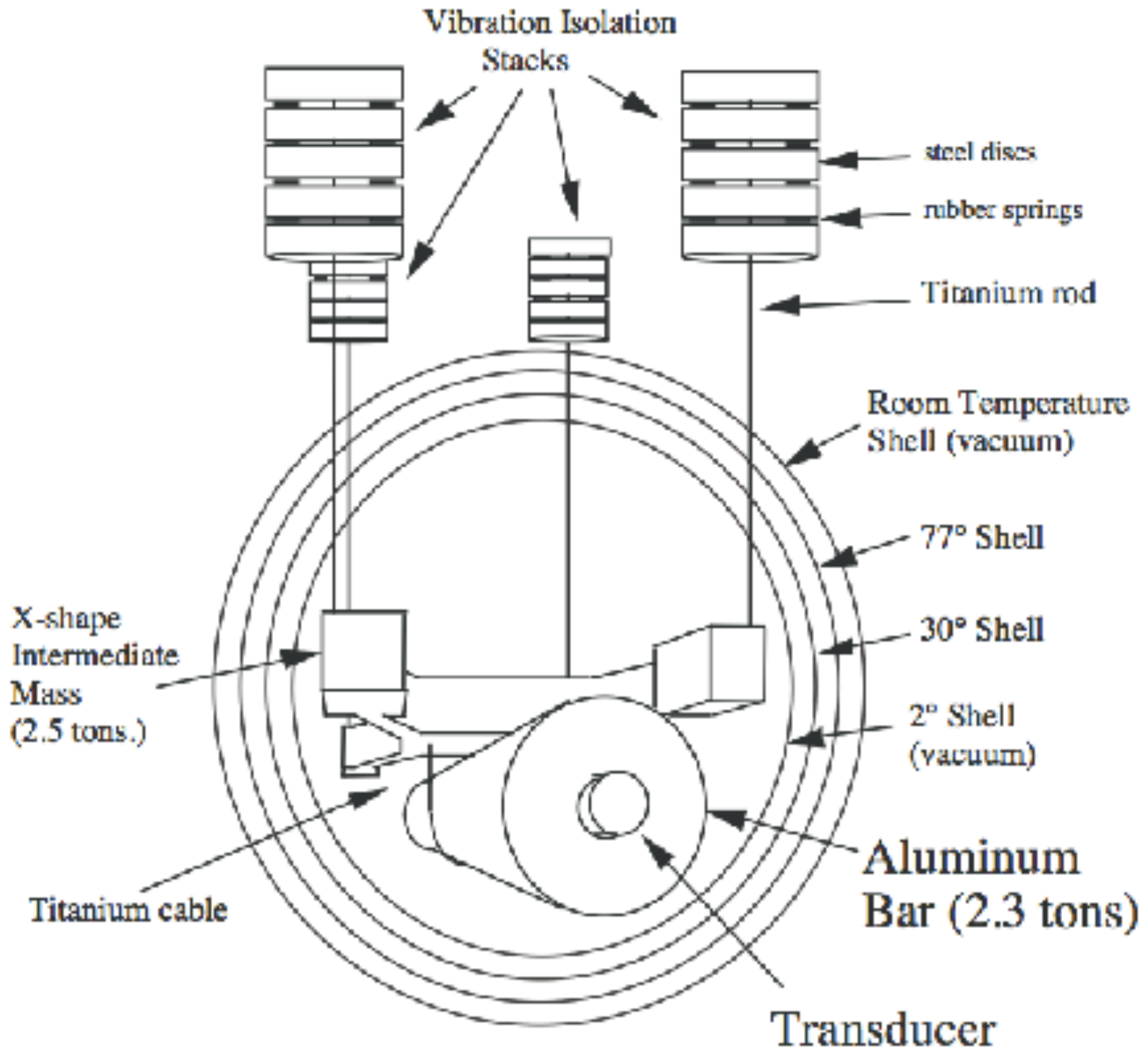


Amplification of signal by sqrt(M/m)

Modern resonant bars

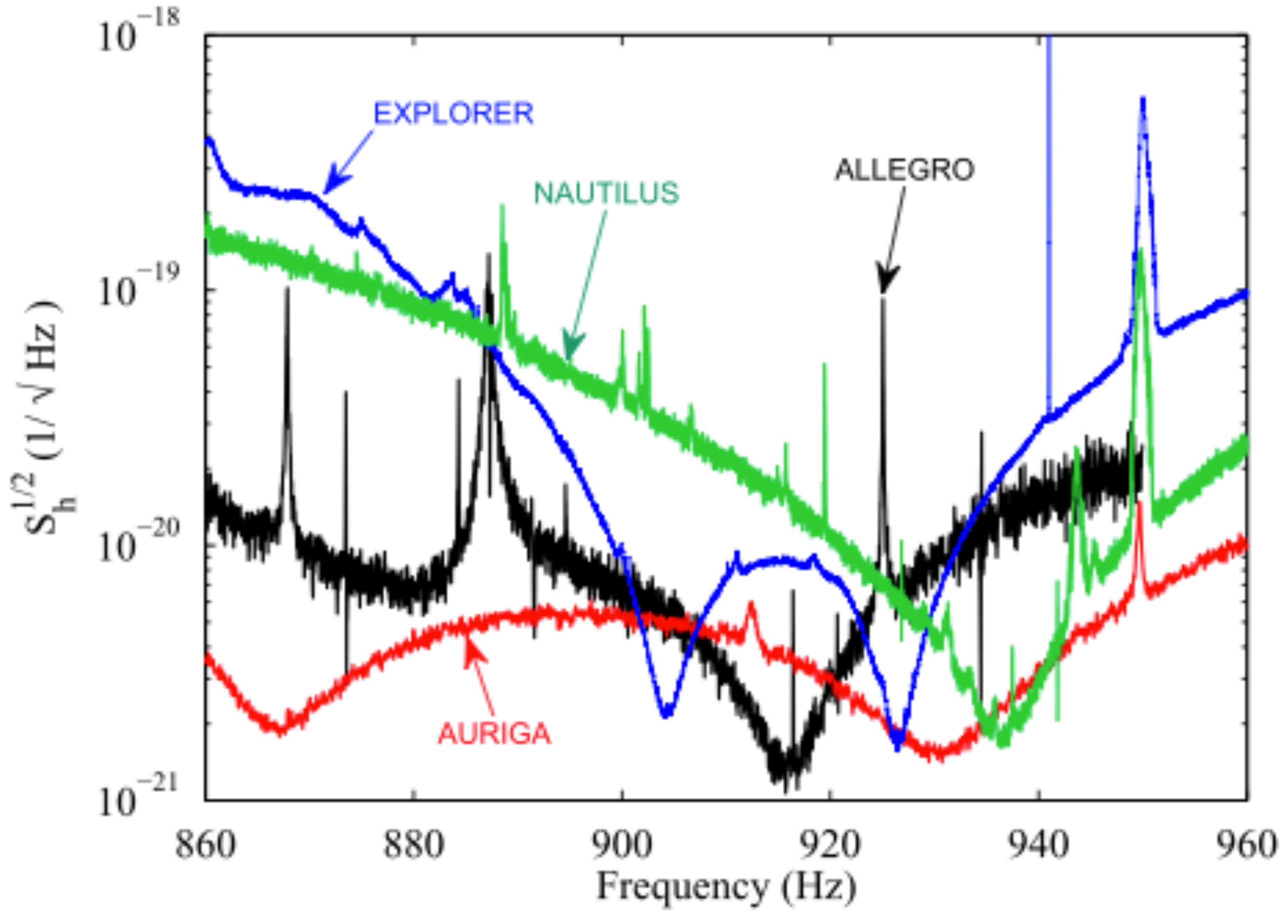
- NAUTILUS

- ALLEGRO



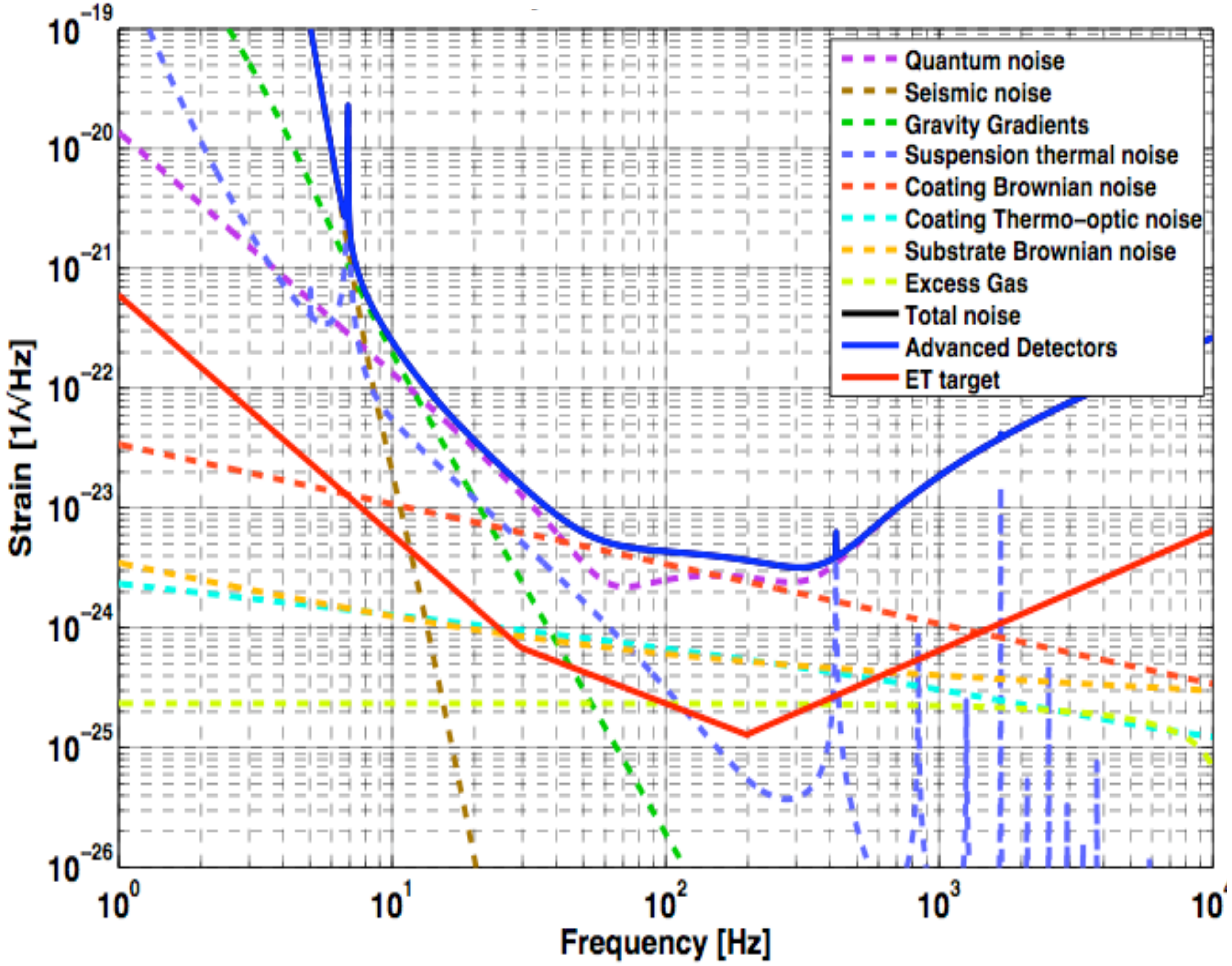
- mini-GRAIL

- Cryogenic (few mK) version of Weber bars
- Resonant bars or spheres, seismically isolated
- Position readout with capacitive or super-conducting transducers (SQUIDs), using amplification by a small mechanical resonator
- Never detected anything (one claim due to bad statistics)
- **Mostly decommissioned around 2007, since they are narrow-band, and even at resonance have lower sensitivity than interferometers**



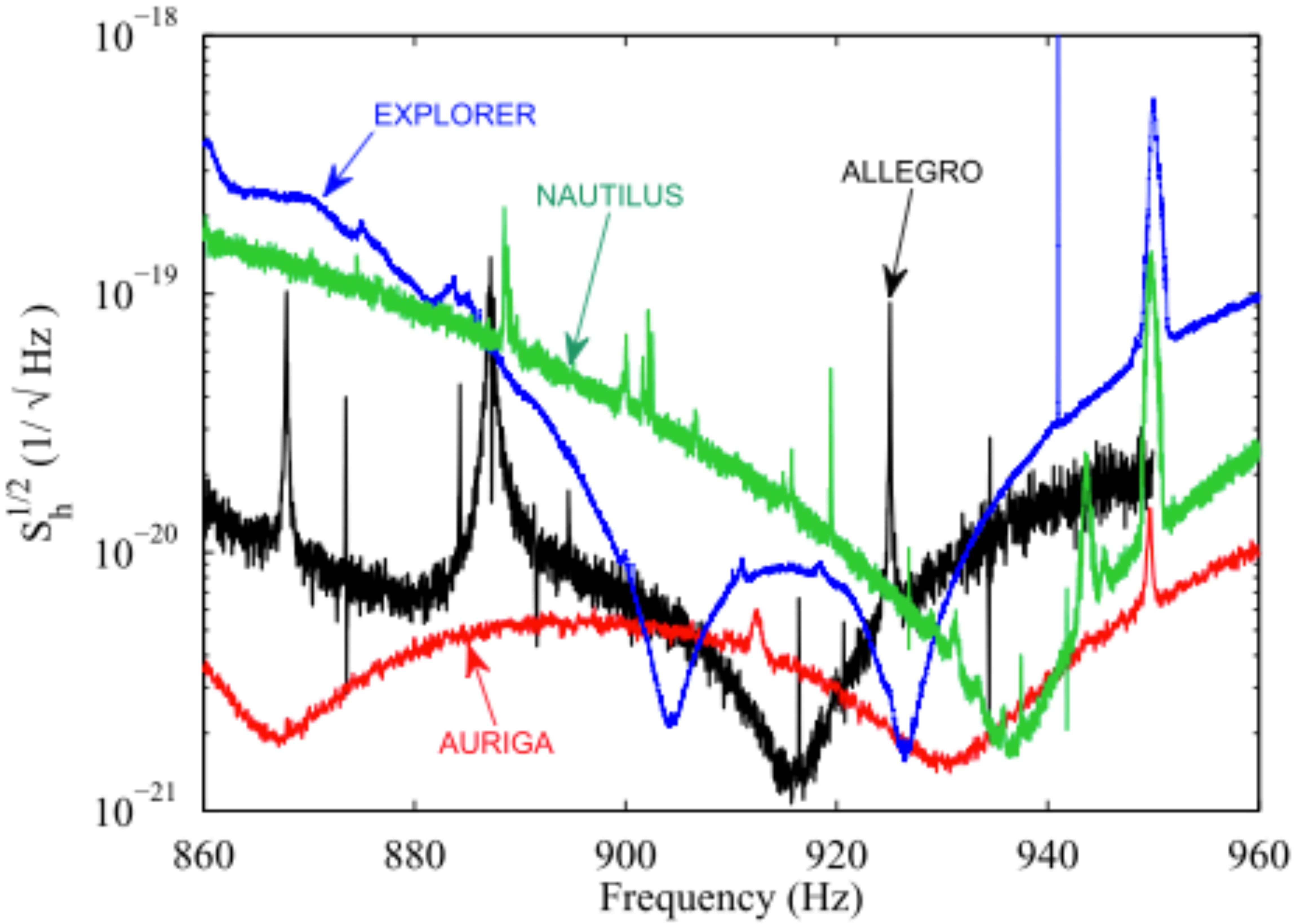
Detector sensitivity comparison

Interferometers



The unit on the y-axis is **Strain** $\Delta L/L$

Bars



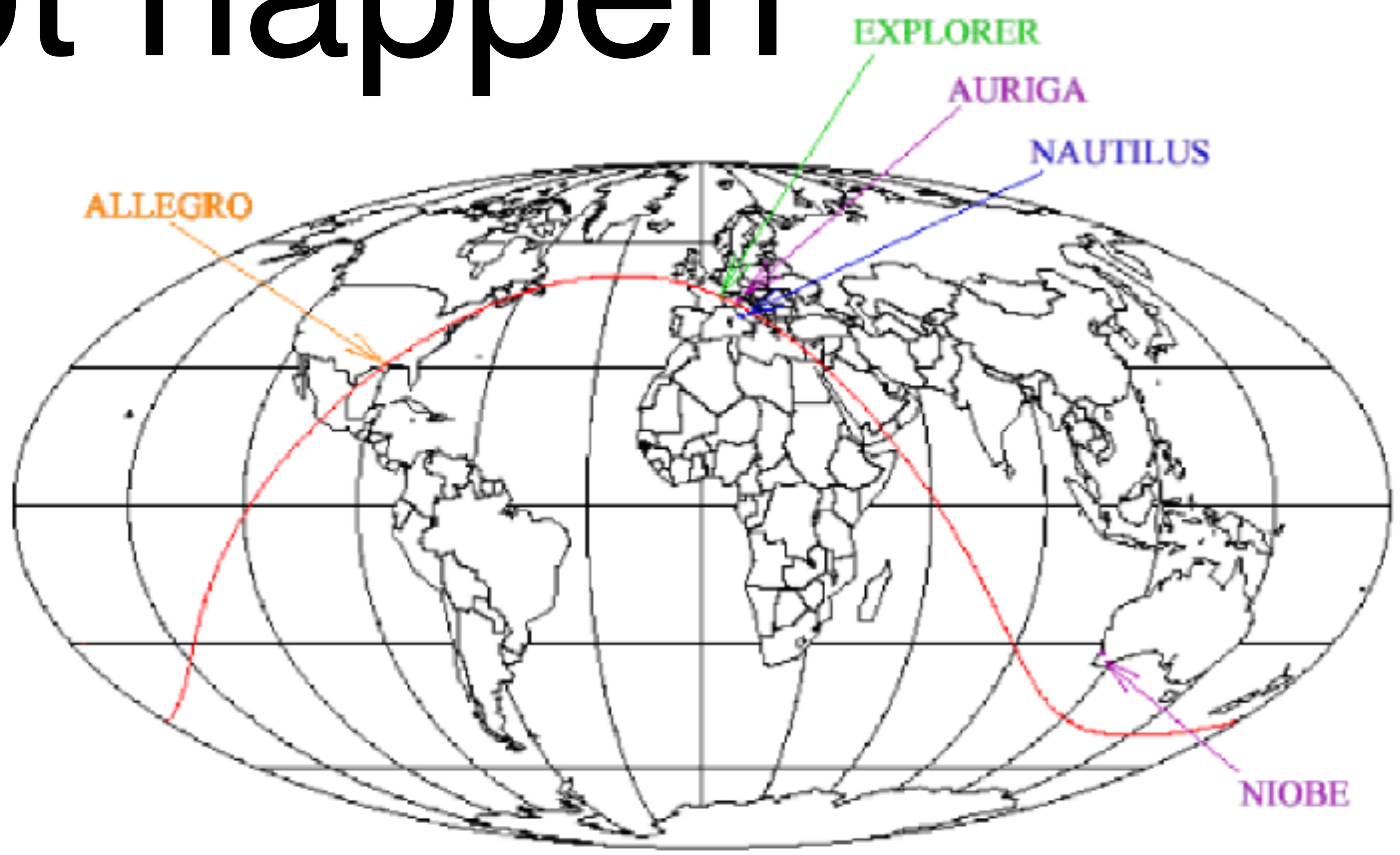
Last run of the bars

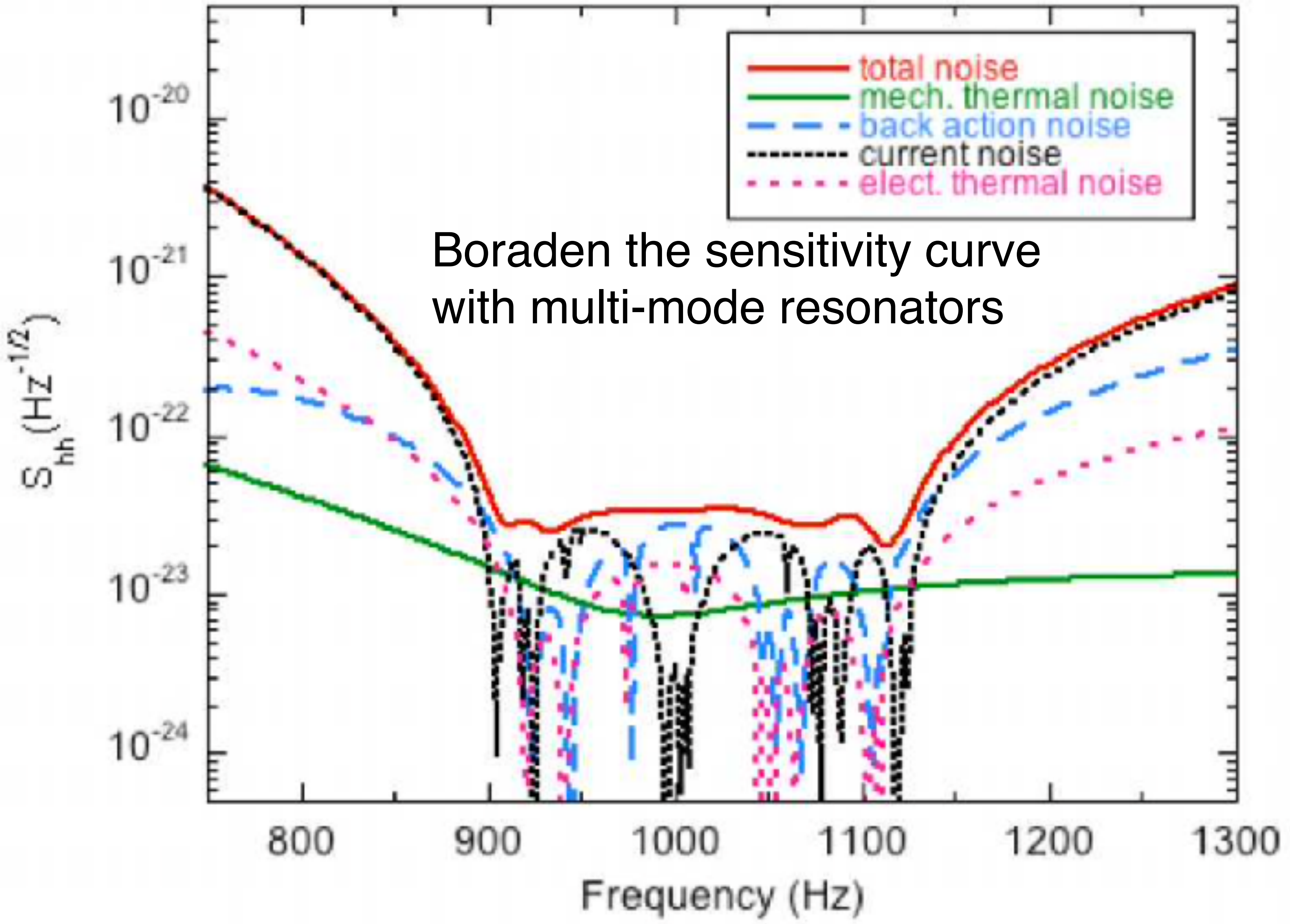
Detector	ALLEGRO	AURIGA	EXPLORER	NAUTILUS	NIOBE
Material	Al 5056	Al 5056	Al 5056	Al 5056	Nb
Mass [kg]	2296	2230	2270	2260	1500
Length [m]	3.0	2.9	3.0	3.0	2.8
+ mode [Hz]	920	930	921	924	713
- mode [Hz]	895	912	905	908	694
Temperature [K]	4.2	0.2	2.6	0.1	5.0
On time [days]	853	217	551	415	193

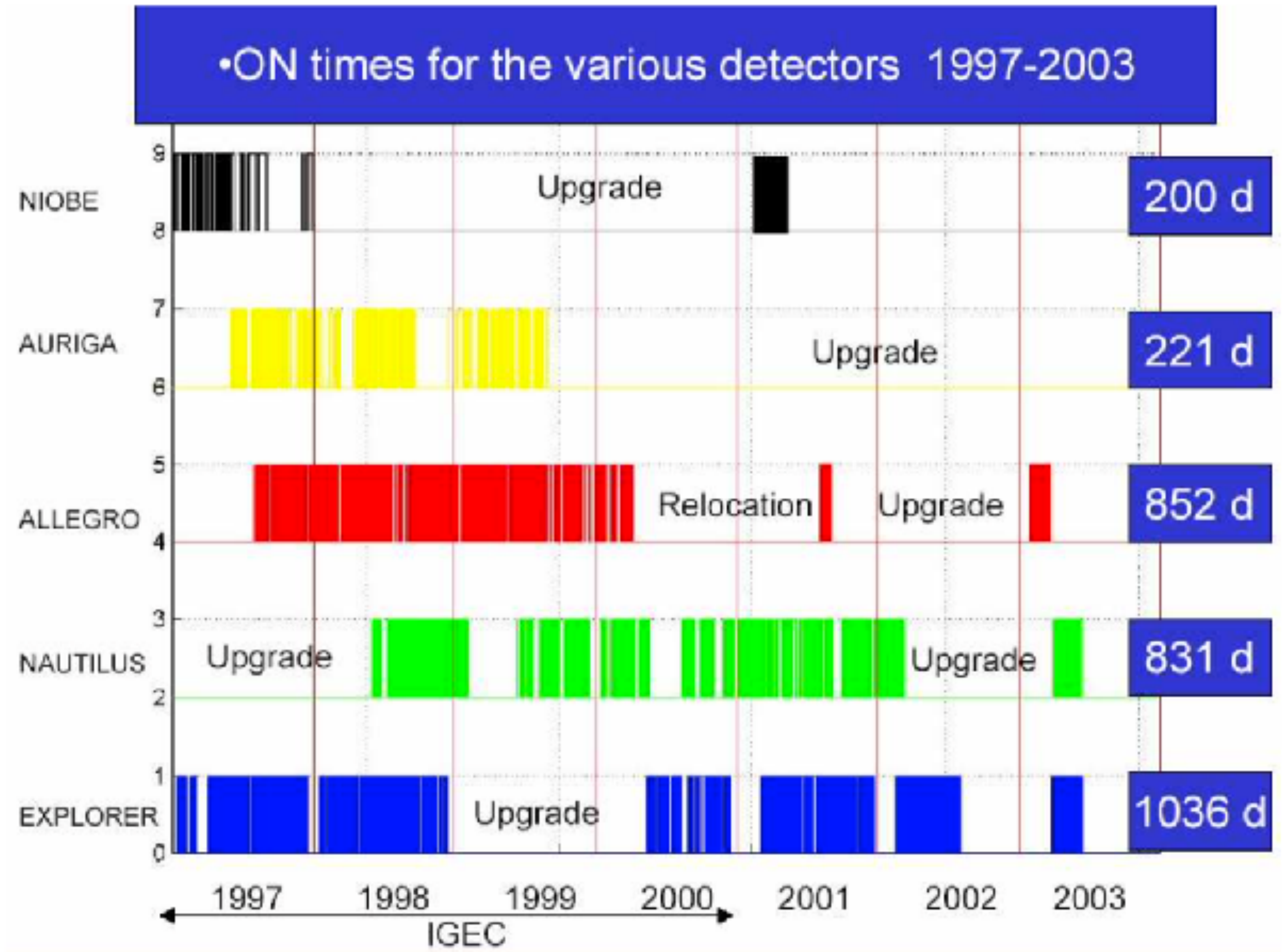
- Bar detectors participating in the 1997-2000 joint observations within the International Gravitational Event Collaboration (IGEC).
- 'Gravitational Waves: Experiments', M. Cerdonio Nuclear Physics B, 2003, https://doi.org/10.1016/S0920-5632(02)01895-9
- "The reach out will be cosmological, beyond 100 Mpc, so that the rates of gw signal will be of sev- eral/year and a true "gravitational waves astron- omy" will be borne. One dreams of a black-hole binary discovered and located in the cosmos at one time in inspiral phase by the low frequency detectors, and then predict the time at which the merging and ring-down phase will be observed by the high frequency detectors. "

A future that did not happen

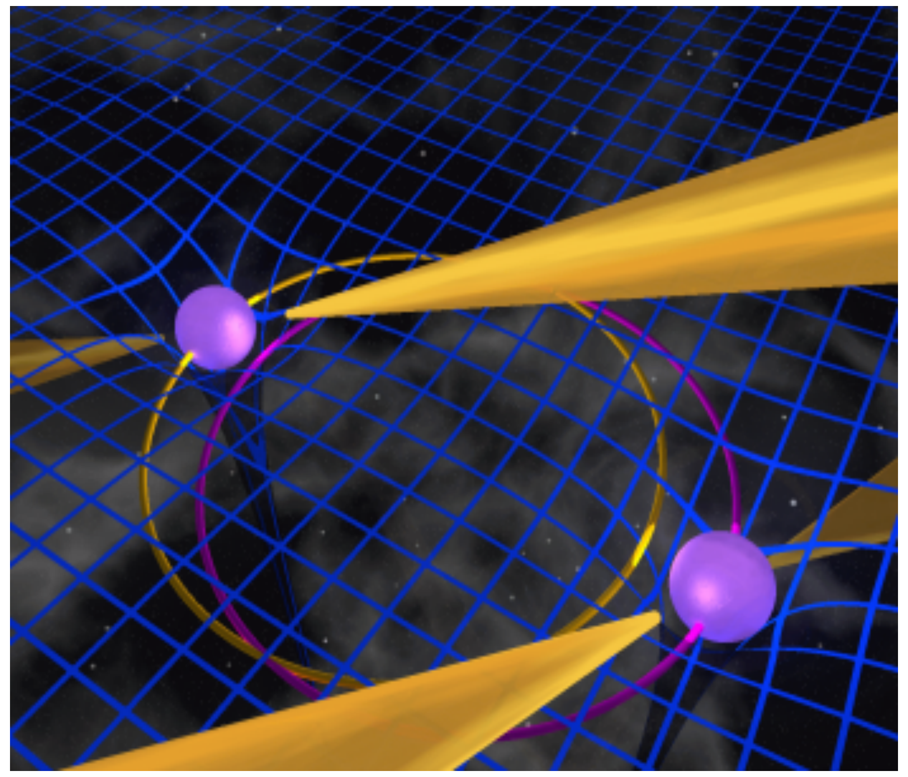
'The Past, Present and Future of the Resonant-Mass Gravitational Wave Detectors', Odylio Denys Aguiar, Res. Astron. Astrophys. 11, 1 (2011)



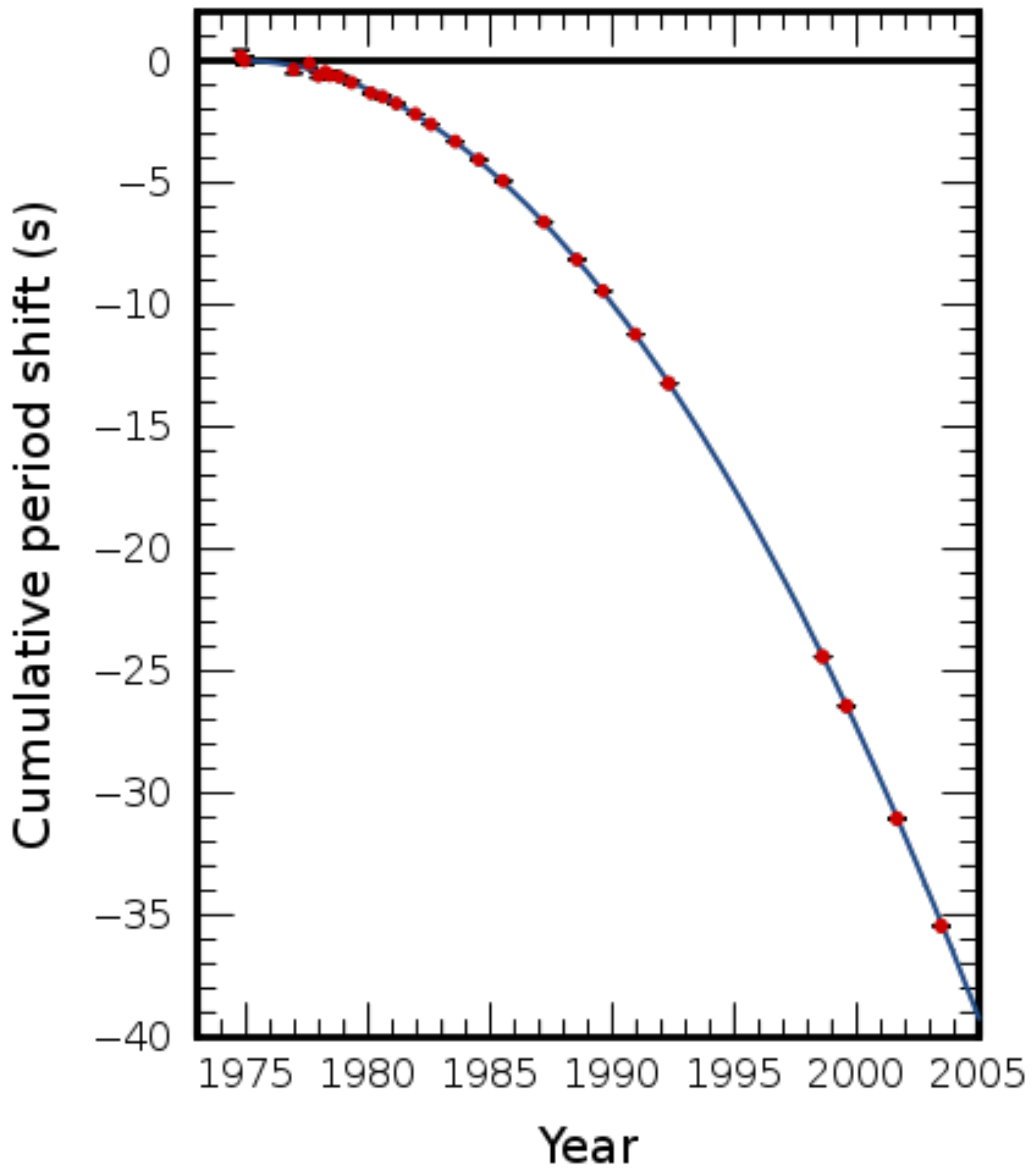




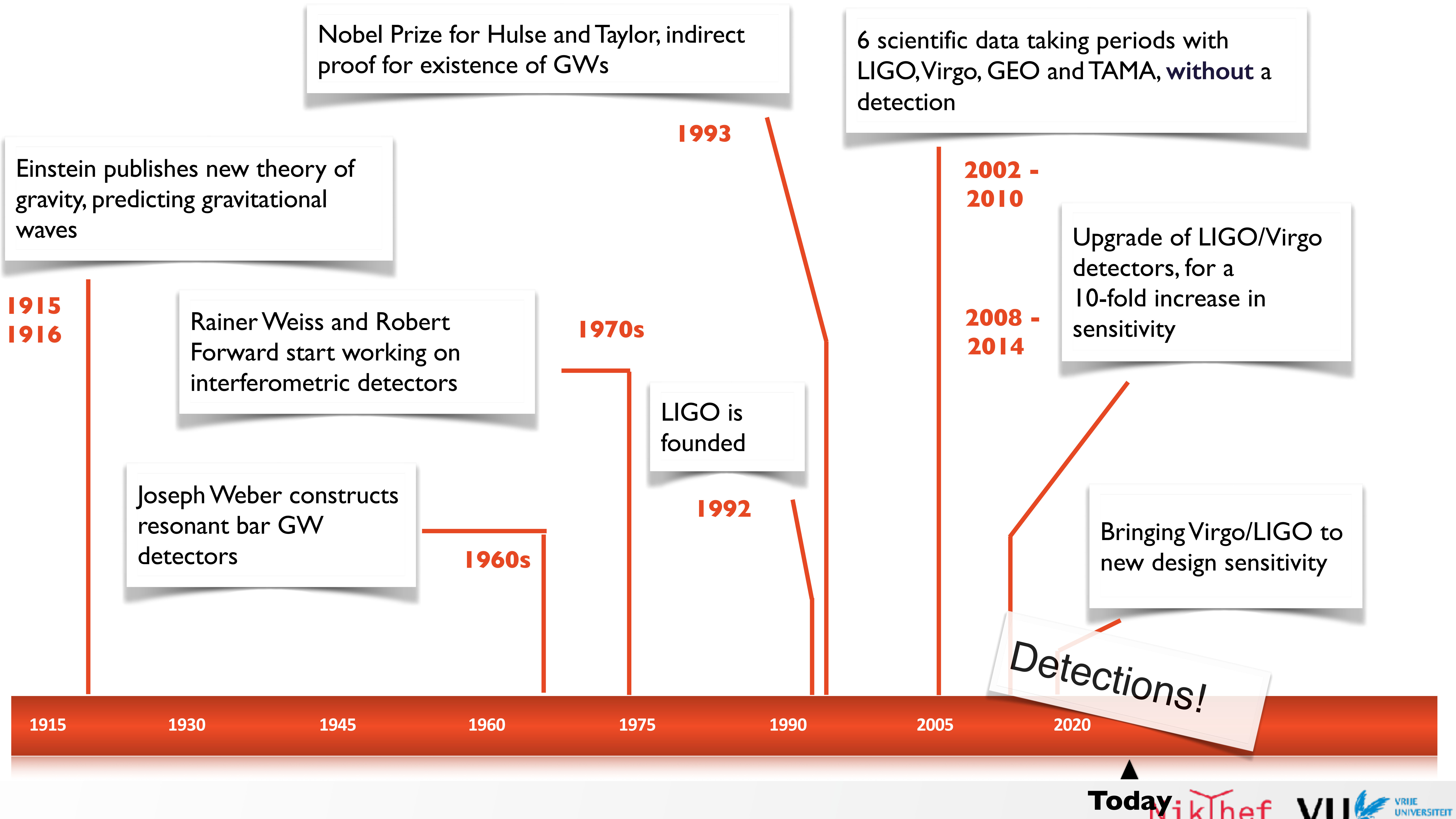
Indirect evidence for GW



- Binary system of neutron star and pulsar observed by radio telescopes (1974)
- Orbital period of 8 hours, but accurate timing over years showed that orbit gets shorter by 76 microsecond/year
- Decay perfectly predicted by loss of energy radiated away due to gravitational waves
- System will collide in 300 million years
- Nobel prize in physics for Hulse and Taylor (1993)



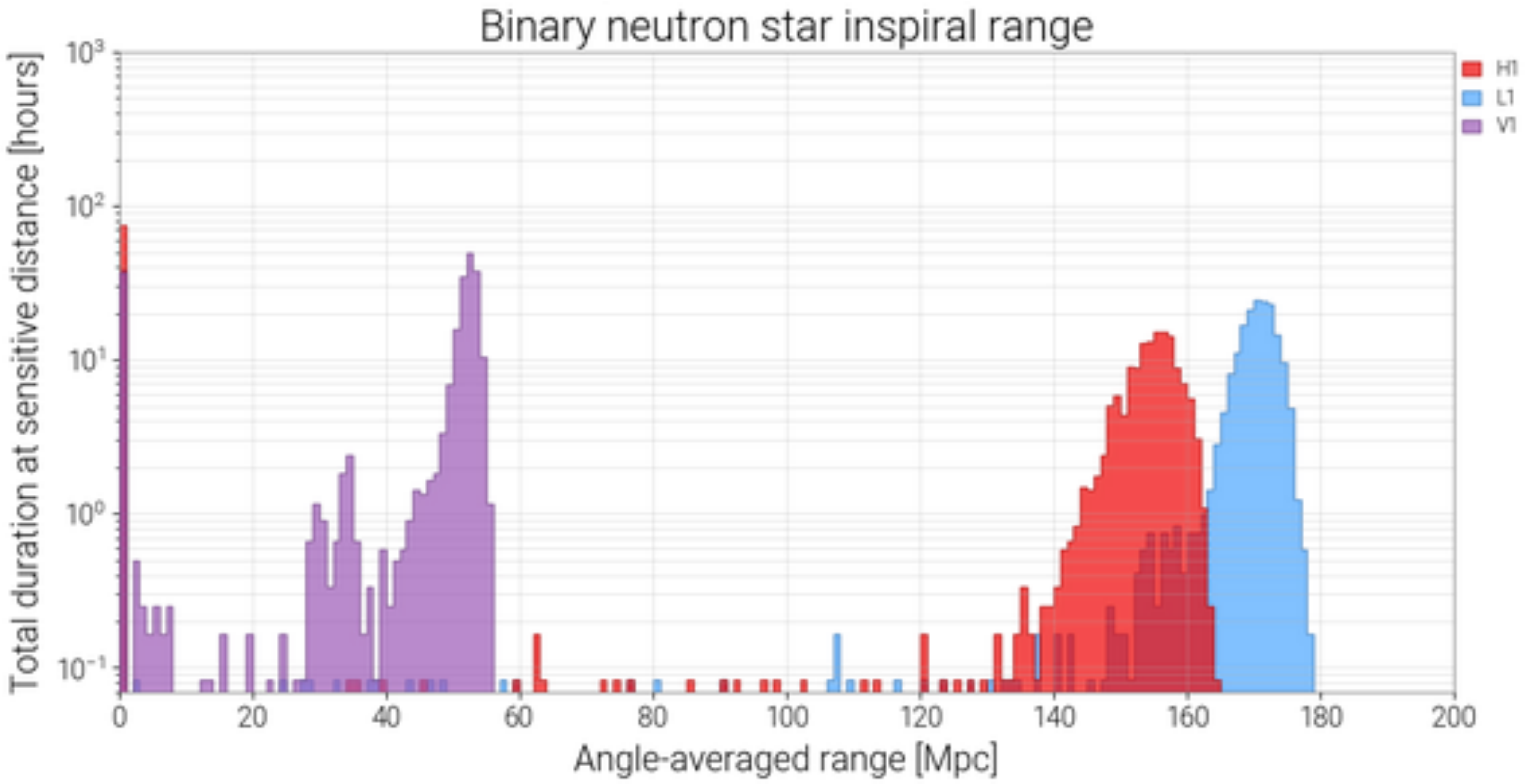
A long journey …



Social media posts of signals in current observing run (O4)

Current status of the network

We are taking data, you can see the current status here:
https://gwosc.org/detector_status/O4c/



[Data from 30.03.2025]

Hubble observation of galaxy NGC 4993

GW170817

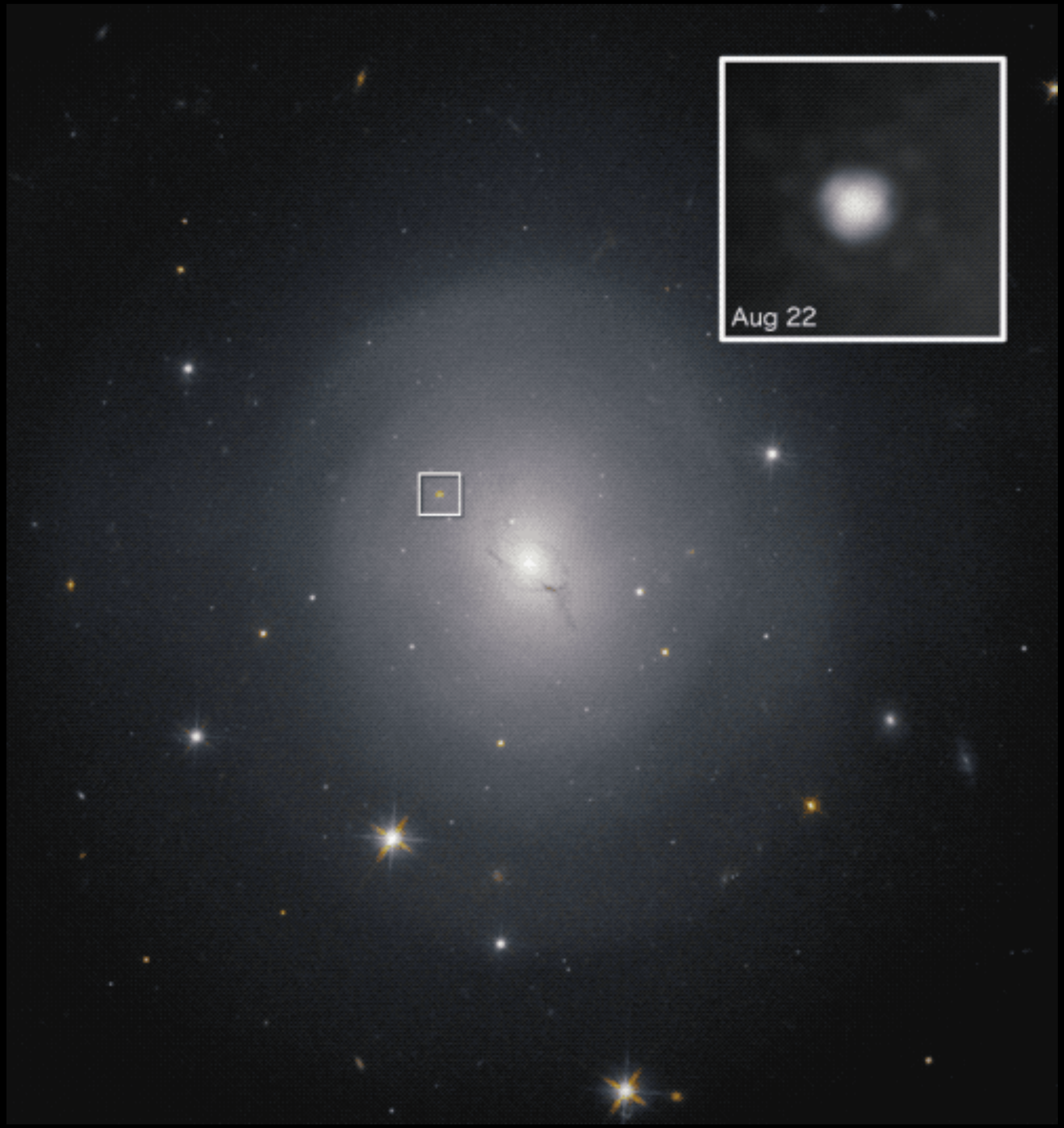
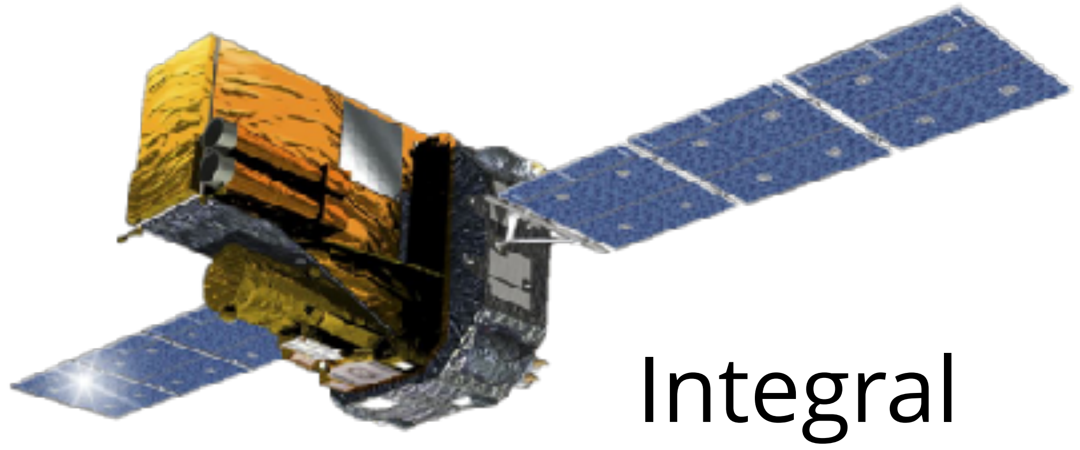


Image: NASA

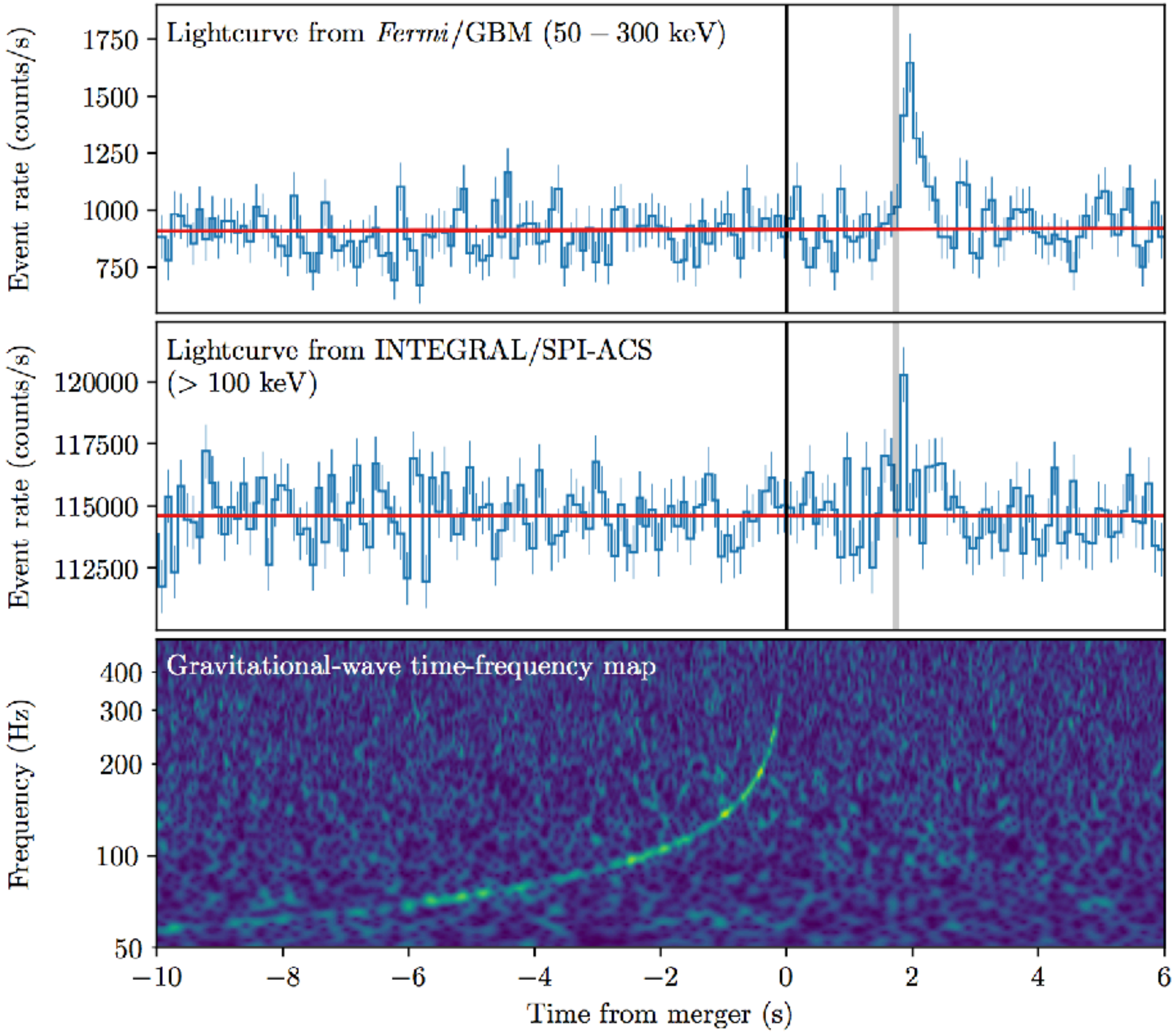
Speed of Gravity

Fermi



Integral

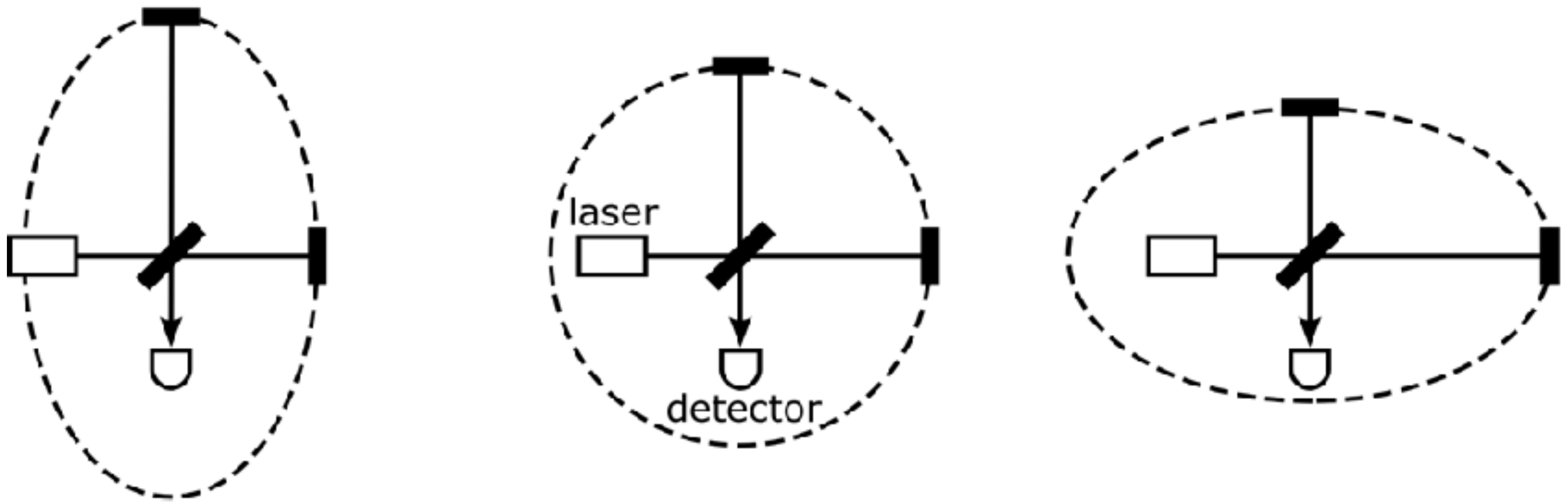
LIGO-Virgo



Difference between the speed of gravity and the speed of light: –3×10–15 to +7×10–16 times the speed of light!

Basics of Interferometric GW detection

Interferometric detection



- Michelson interferometer is a natural fit for measuring gravitational waves: GW cause a differential change of arm length

$$L_x = (1 + h/2)L$$
$$L_y = (1 - h/2)L$$
$$\Delta\phi = 2k(L_x - L_y) = 2khL$$

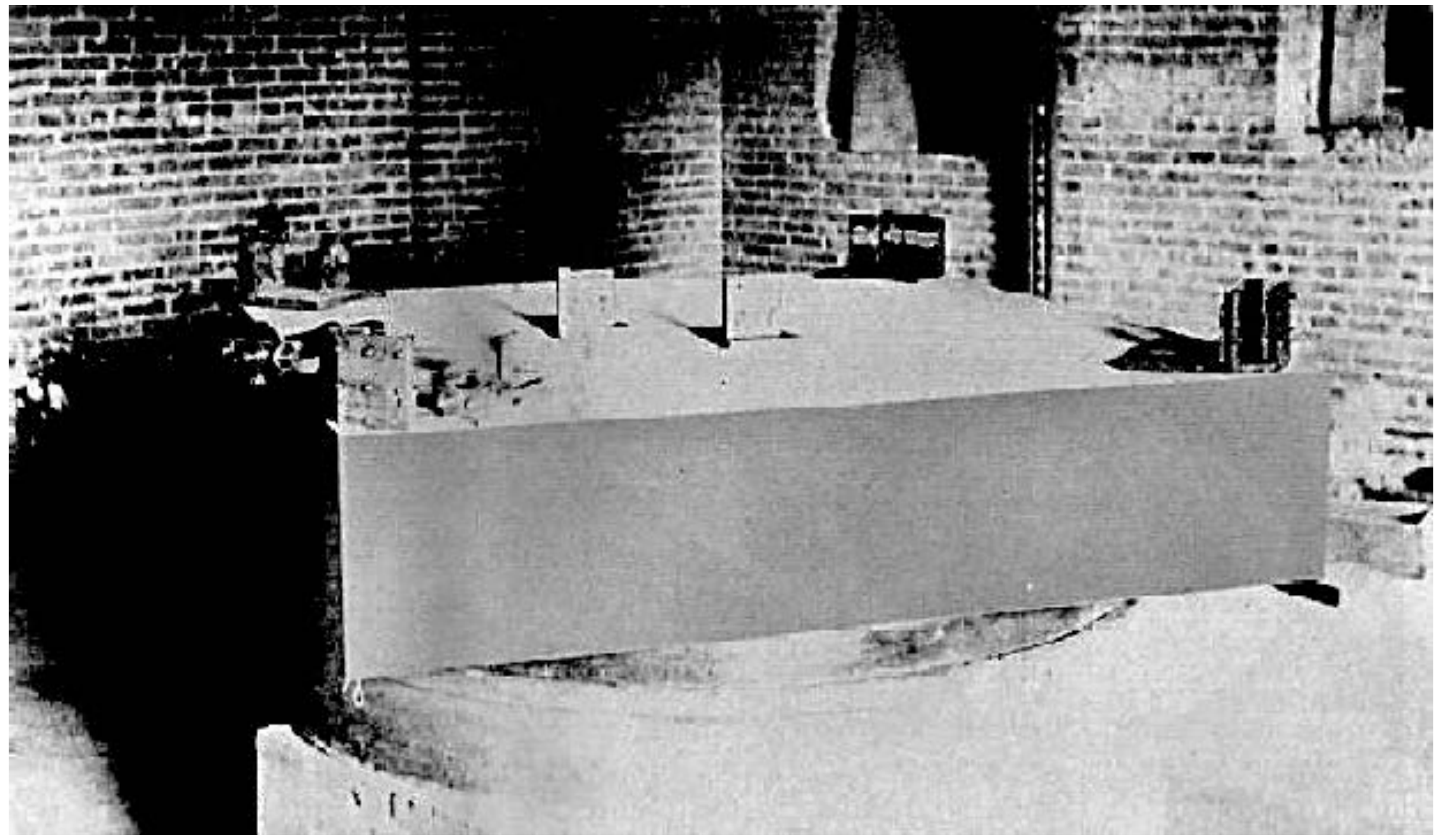
- Idea first proposed by Braginsky and others, first technical feasibility study by R. Weiss (1972)
- Note: interferometers measure the **amplitude** of the GW and not the power, so dependency on source distance is 1/R instead of 1/R^2
- A simple Michelson is not sensitive enough to detect GW, need several extra tricks …

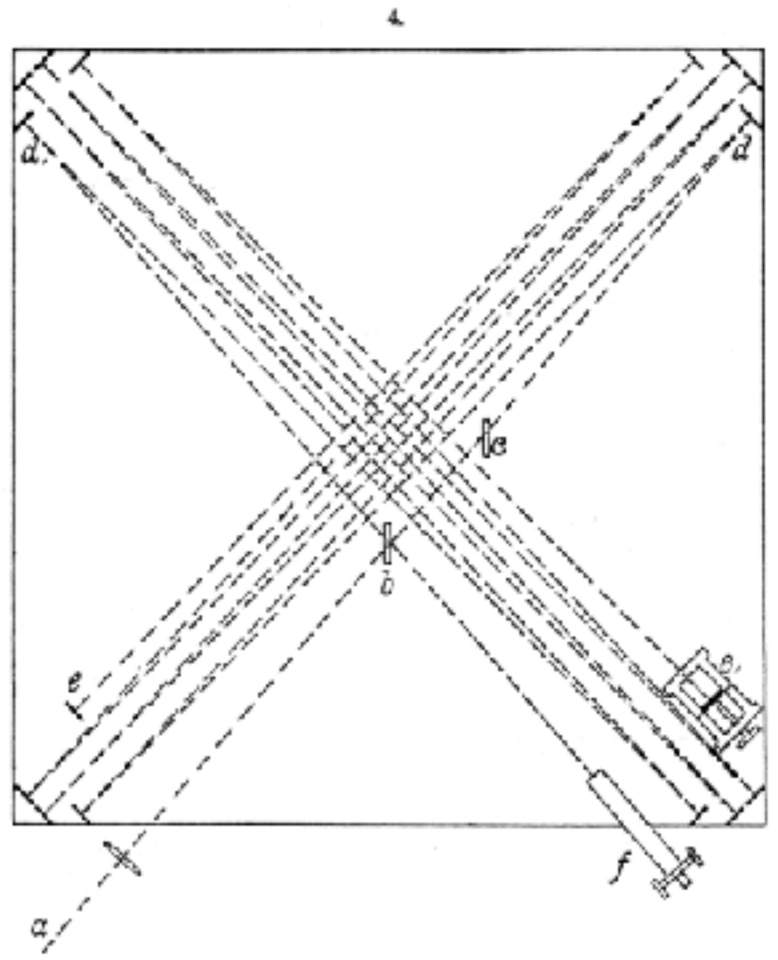
Question:

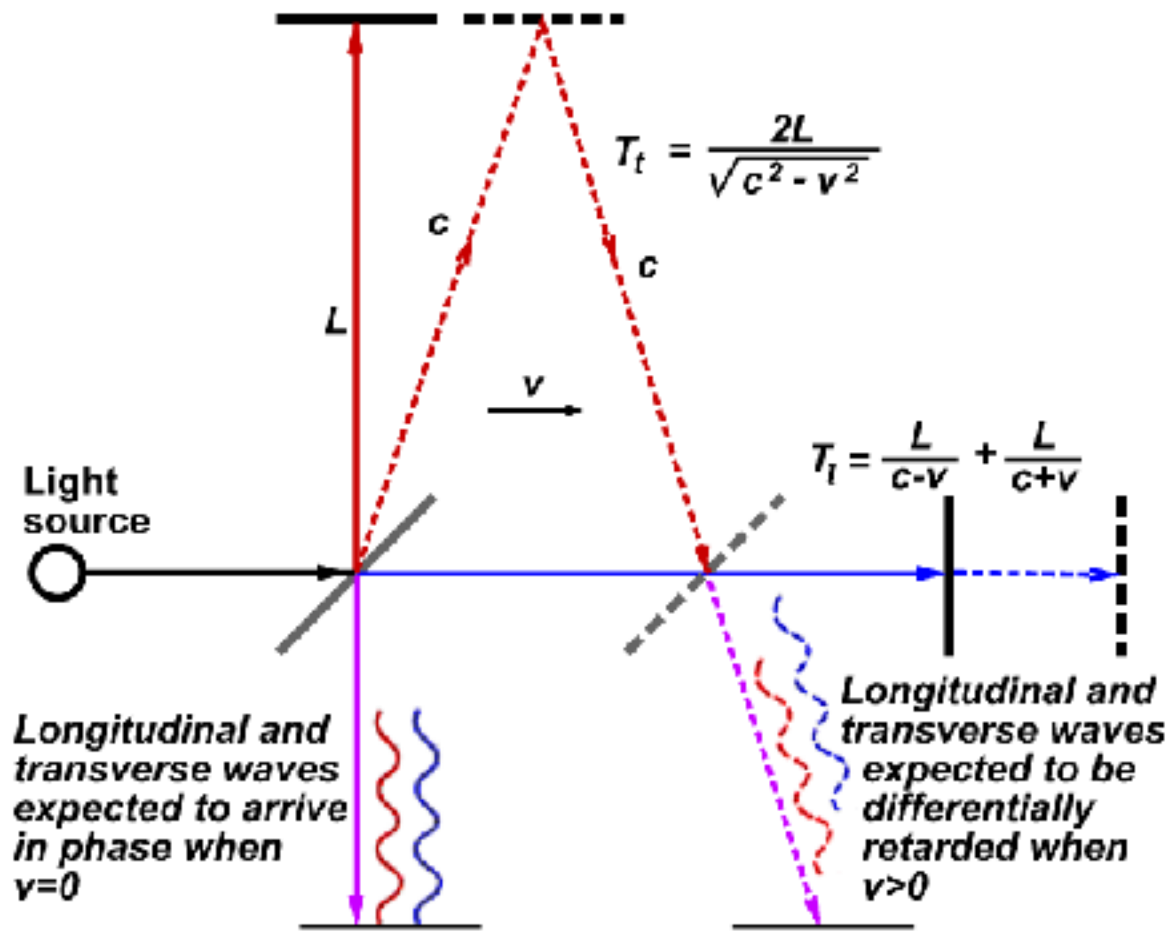
Why can we claim signal amplitudes that are 1/R while the rest of astronomy has to do with $1/R^2$?

(R being the distance between signal source and detector)

Michelson-Morley Experiment







- Old idea: if light is an oscillation in some medium (luminiferous aether), it should be possible to measure difference in the speed of light based on the direction of travel (movement of Earth around Sun)
- MM experiment (1887): white light interferometer, folded path length of 11 meter, setup could be rotated in bath of mercury
- Expected a shift of 0.4 fringe when rotating setup, observed < 0.02 fringe: one of the most famous null-results, which was at basis of Lorentz transformations, Special Relativity
- Could MM have detected GW: no, too insensitive by about 10 orders of magnitude!

Interferometry in 1887

Michelson interferometer (ca. 1887)

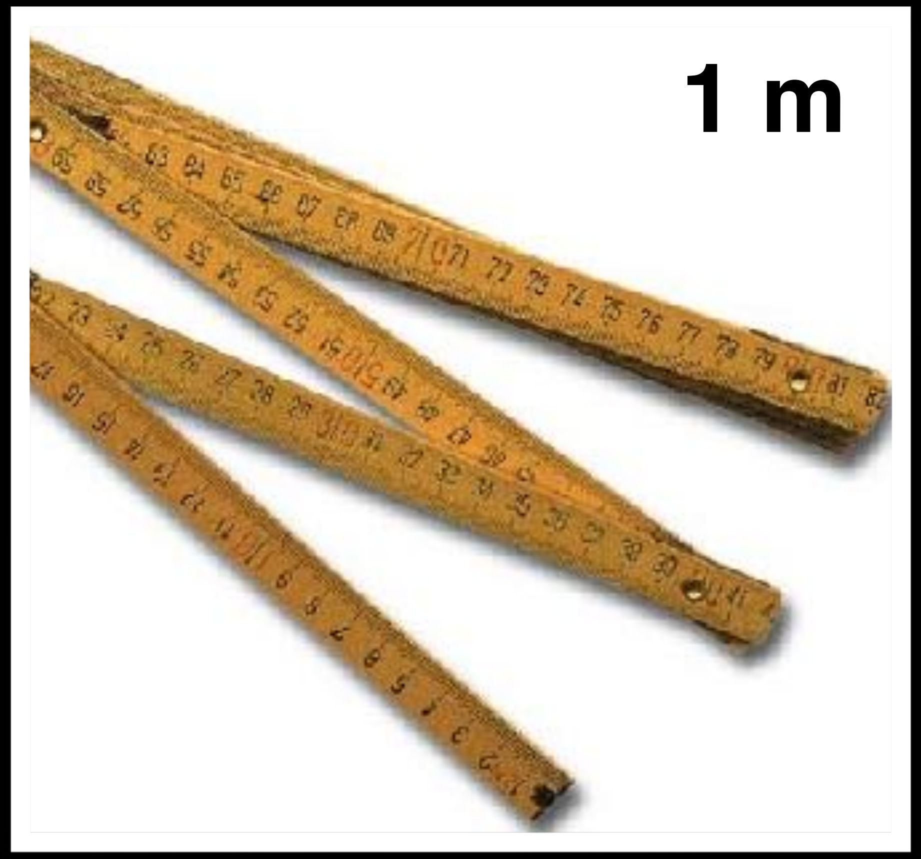
Sensitivity: 0.01 of a fringe

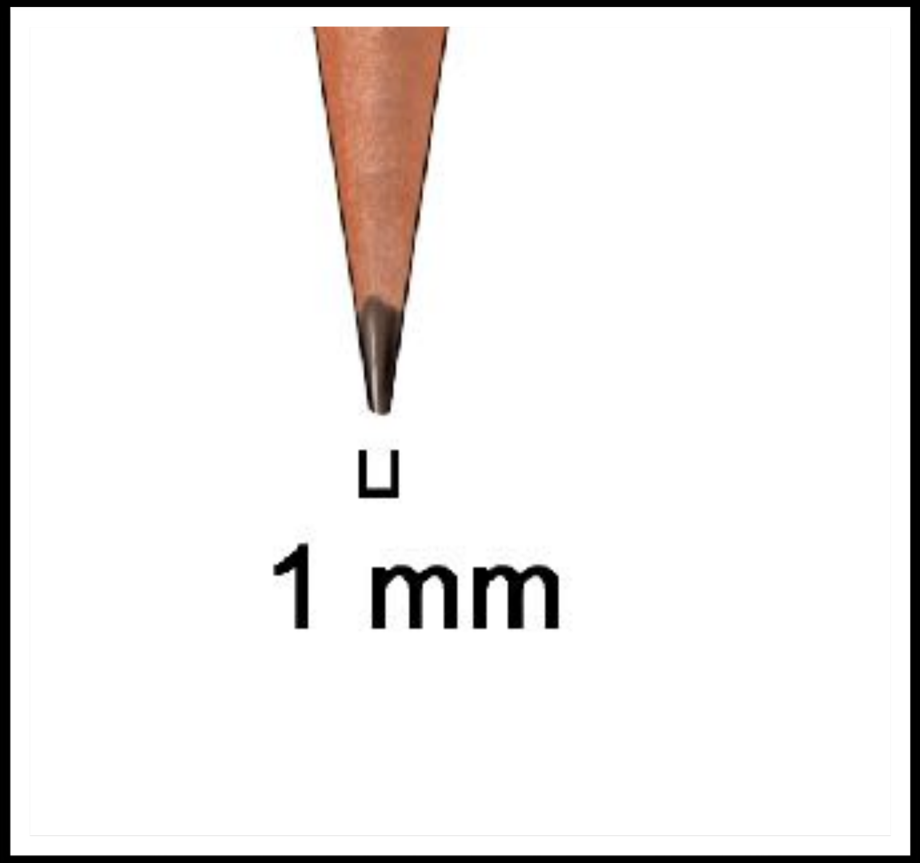
1 fringe

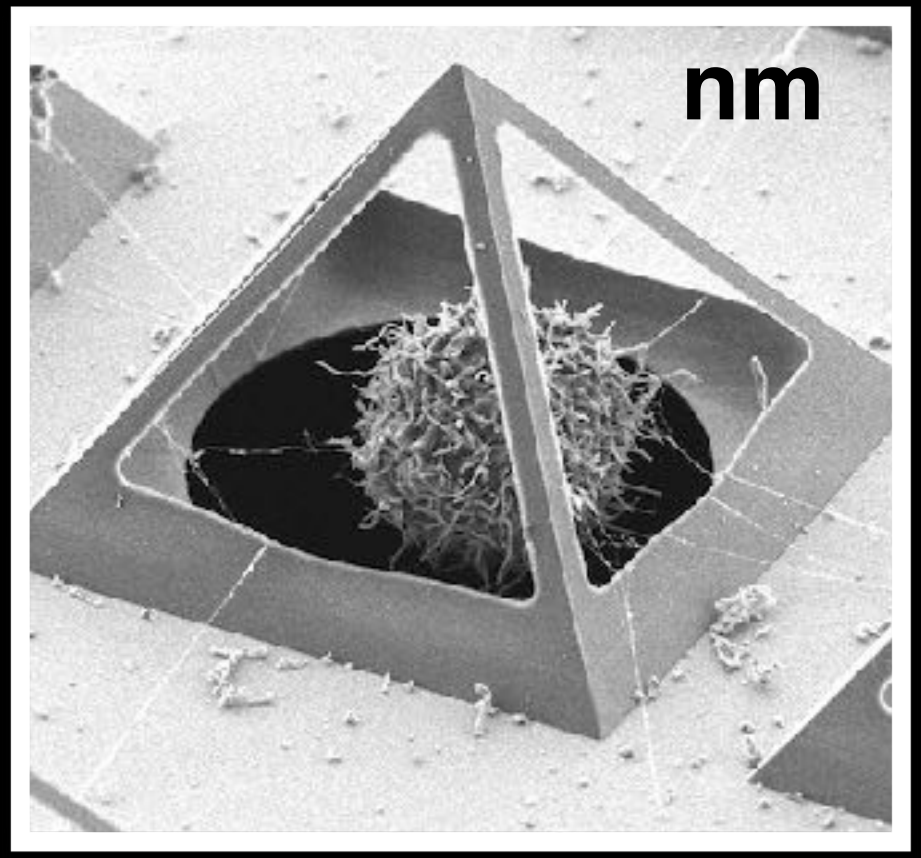
Question:

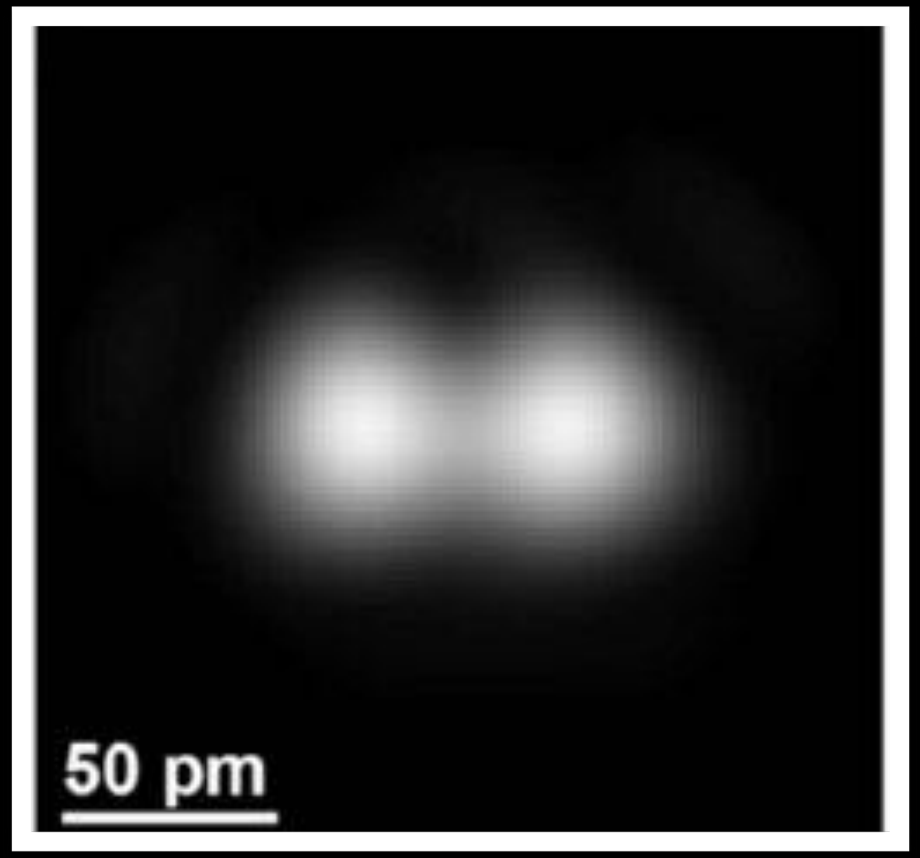
What was the sensitivity of the Michelson-Morley experiment in modern units of sensitivity (h)?

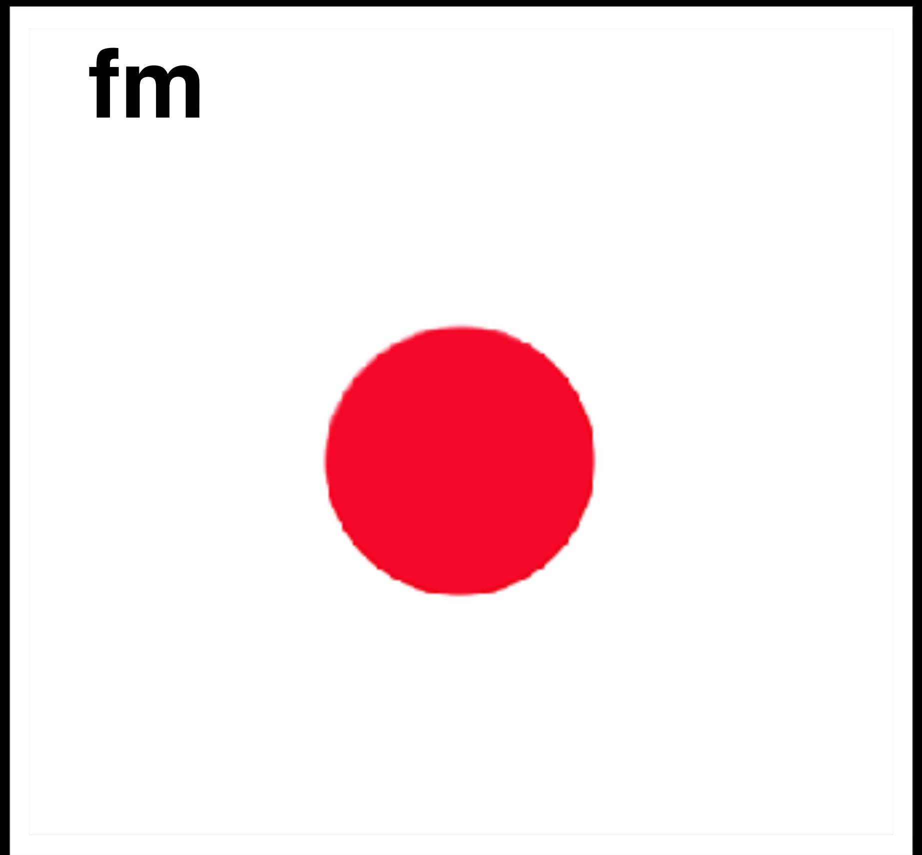
Length Scales

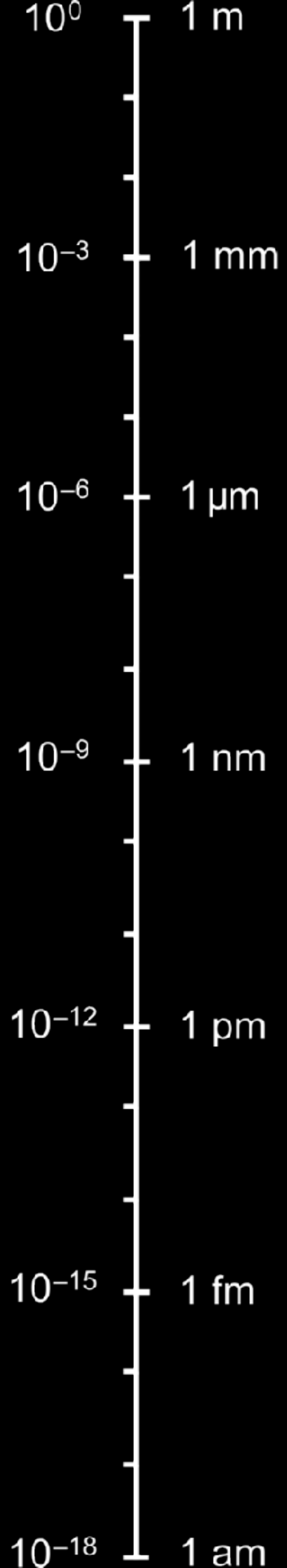




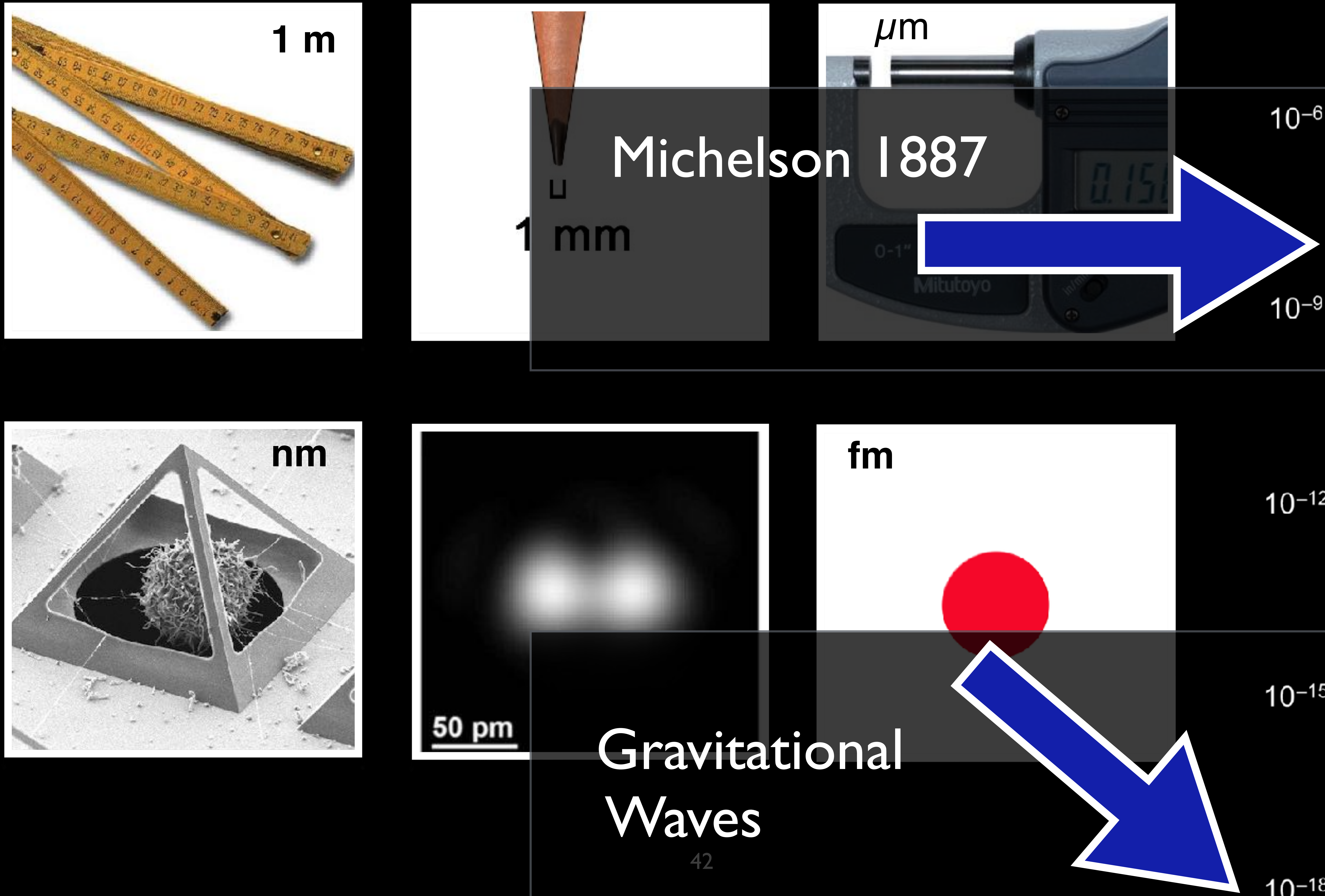






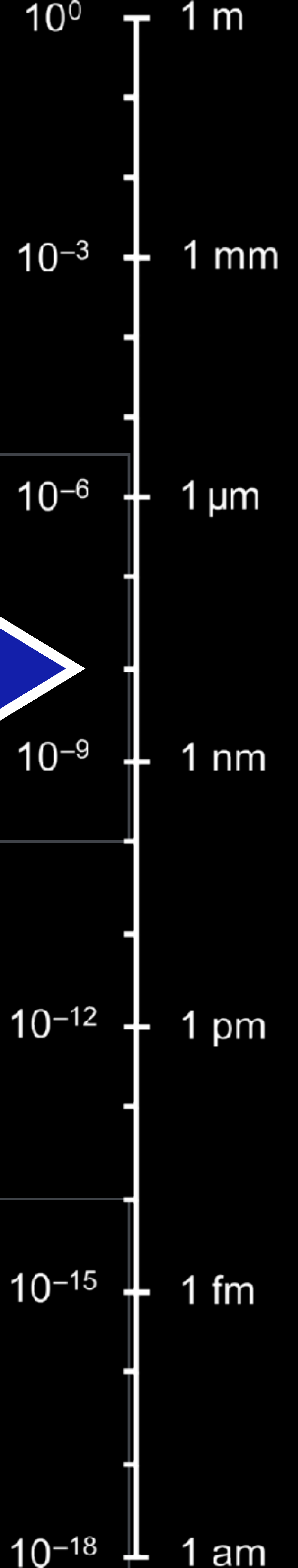


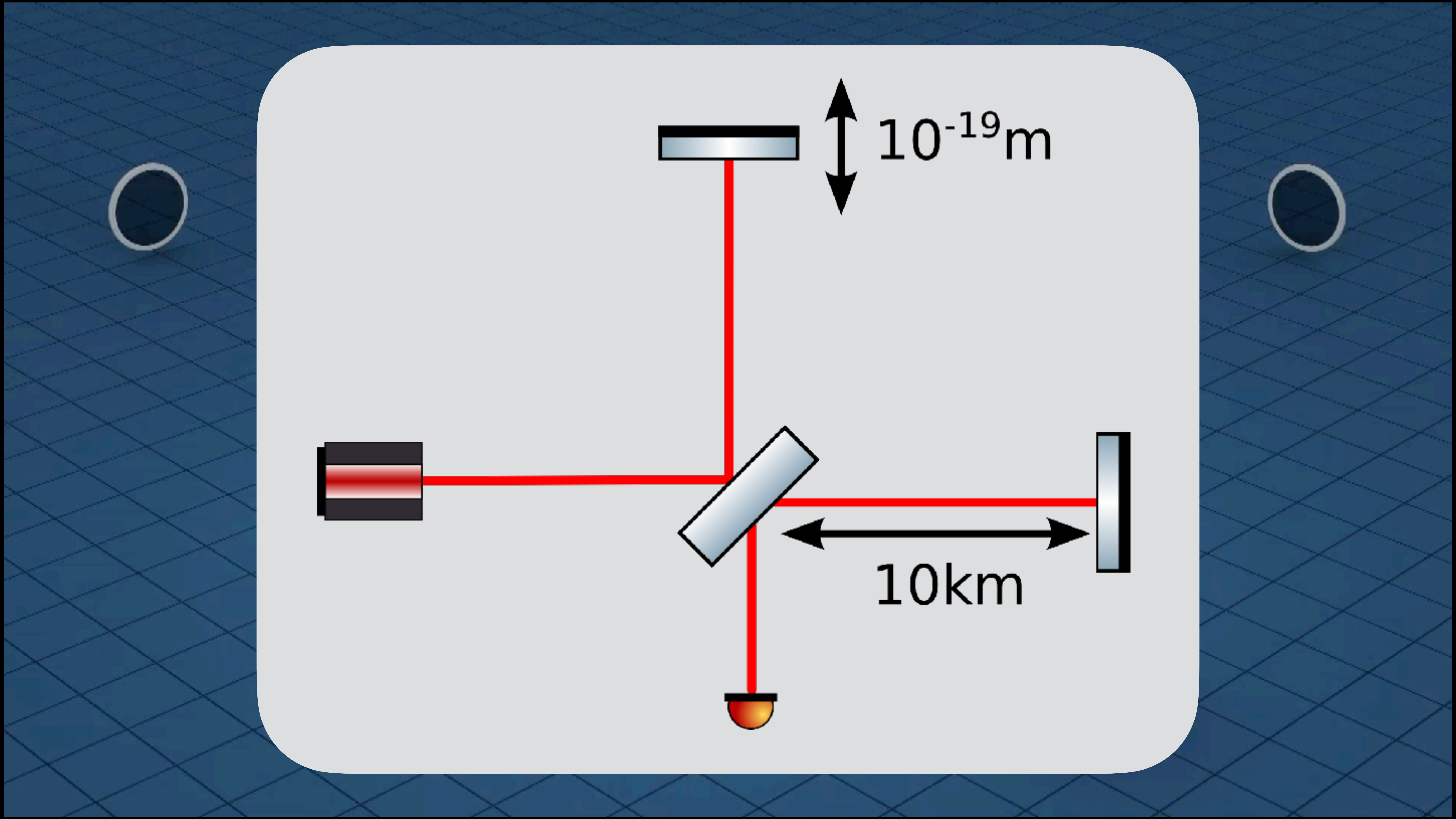
Length Scales



Michelson 1887

Gravitational Waves



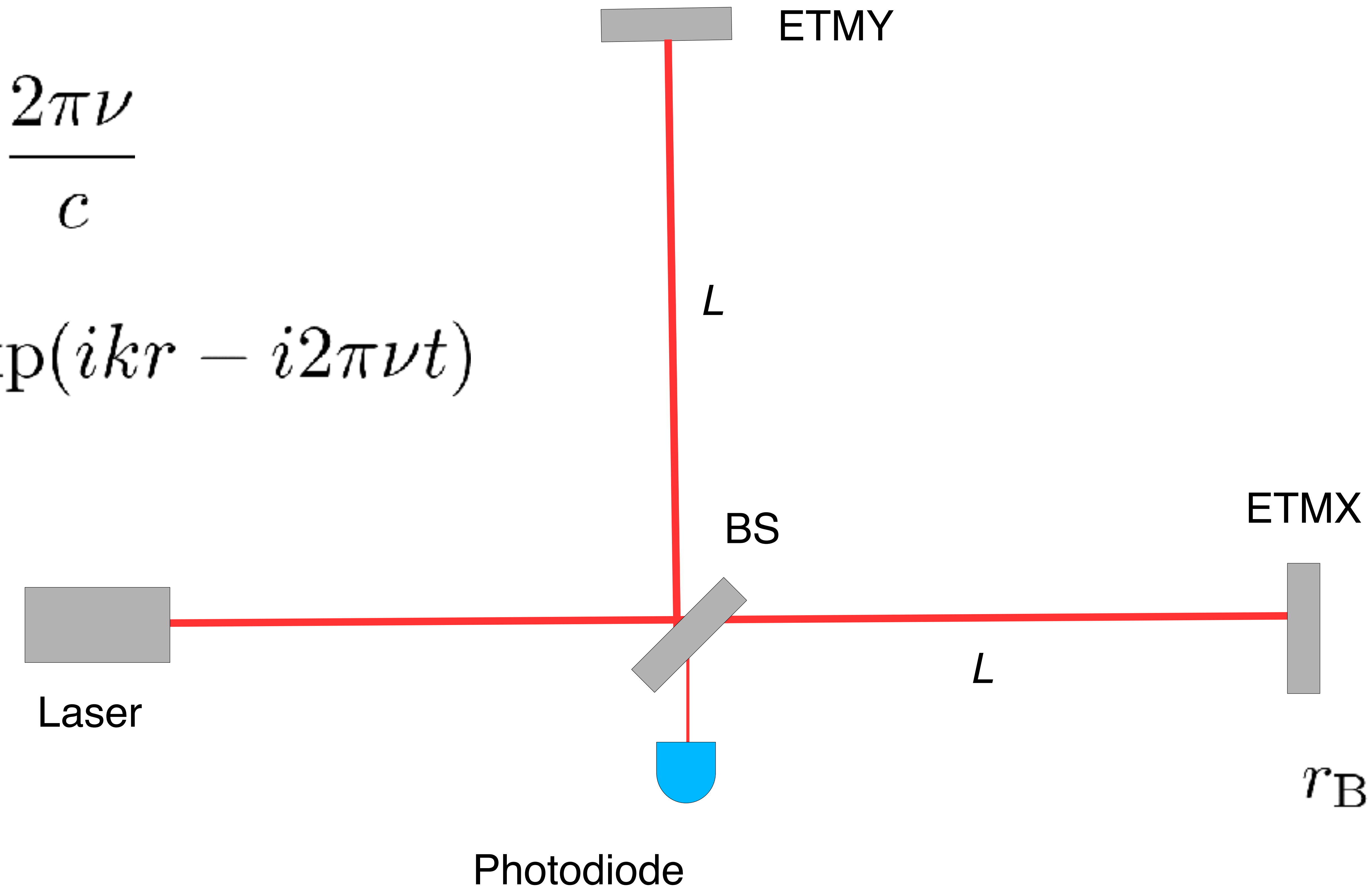


Credit: LIGO/T. Pyle

Michelson laser interferometer

$$k = \frac{2\pi}{\lambda} = \frac{2\pi\nu}{c}$$

$$E = E_0 \exp(ikr - i2\pi\nu t)$$



$$r_{\mathrm{BS}} = \pm\frac{1}{\sqrt{2}}$$

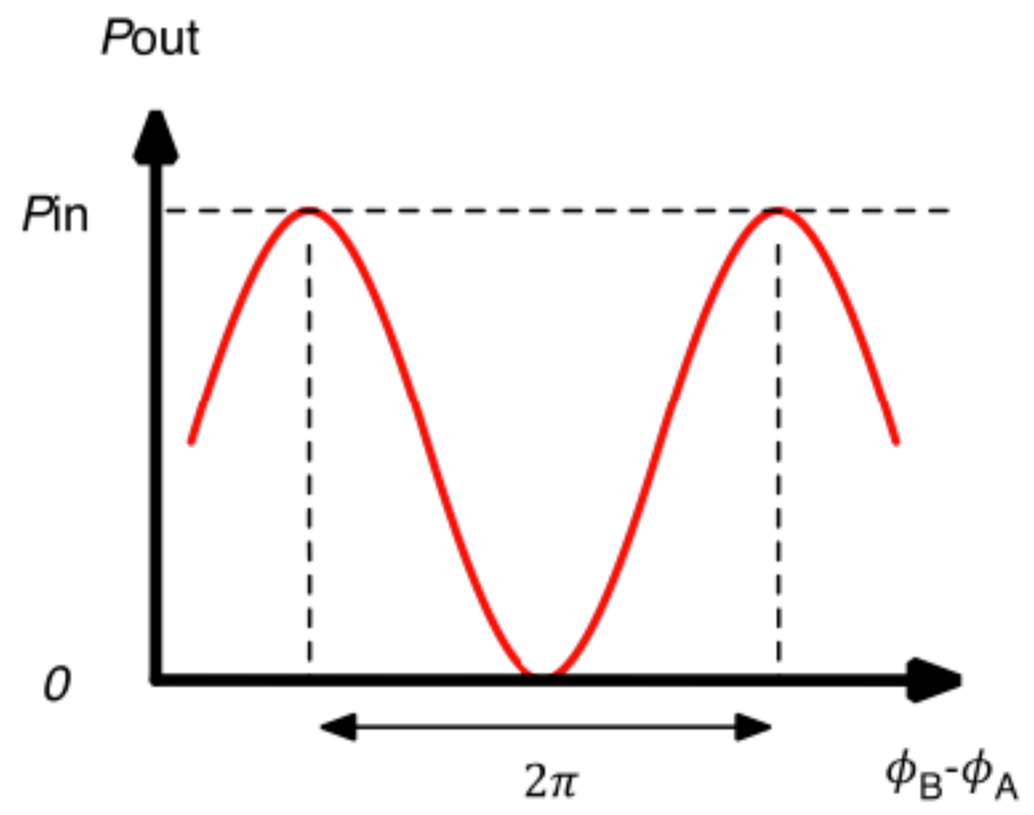
$$t_{\mathrm{BS}} = \frac{1}{\sqrt{2}}$$

$$r_{\mathrm{ETM}} = 1$$

$$P = |E|^2$$

- Monochromatic light source
- 50/50 beam-splitter
- Perfectly reflecting end-mirrors (End Test Mass):
- Light of arms interferes on photodiode, which measures power

Interferometer basics



- For a perfect interferometer:

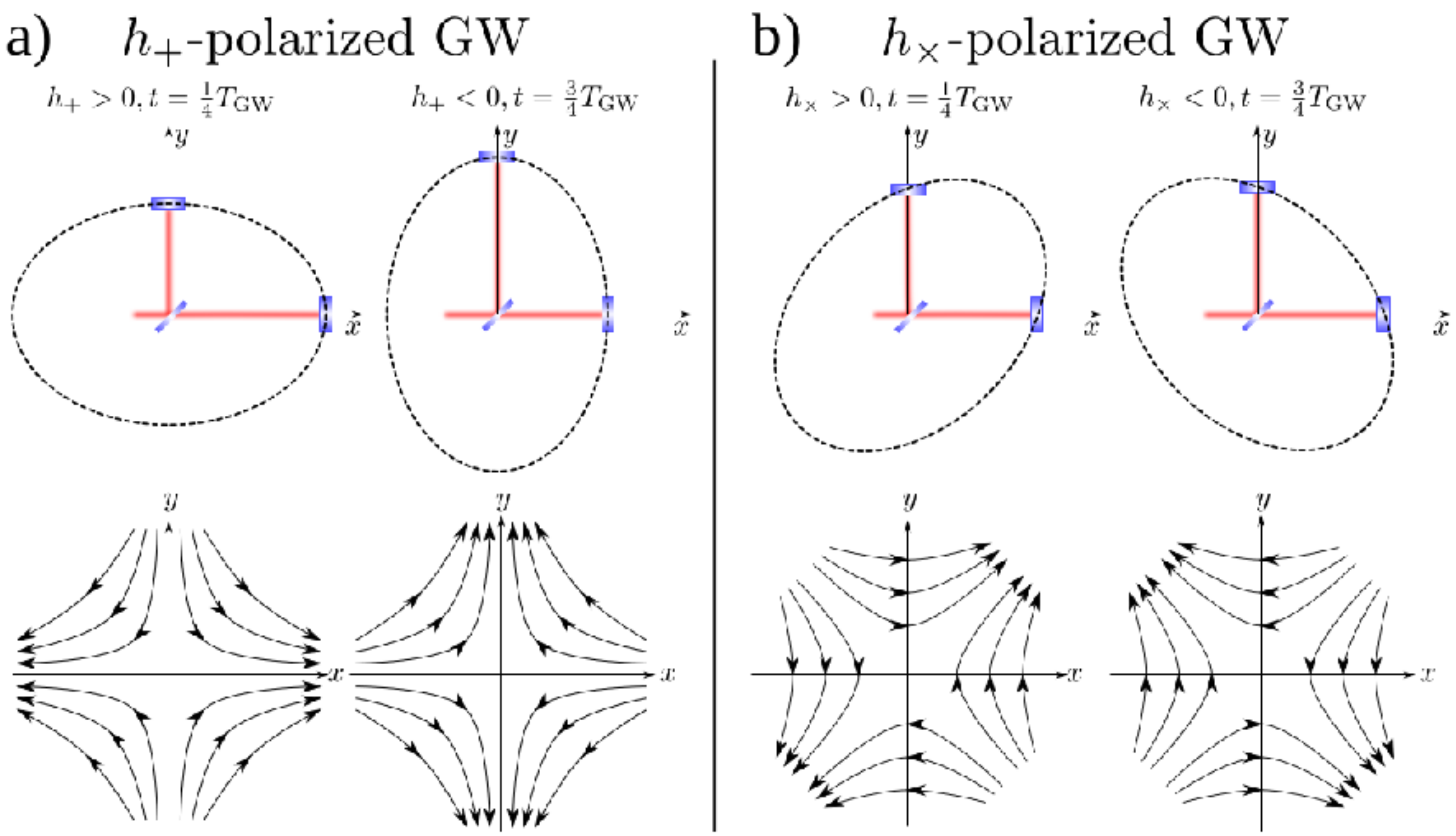
$$P = \left| E_0/2(\mathrm{e}^{ik2L_x} - \mathrm{e}^{ik2L_y}) \right|^2 = P_0/2\,(1 - \cos(\Delta\phi))$$

$$\Delta\phi = 2k(L_x - L_y)$$

- Sensitive to differential path length differences
- Maximum sensitivity (in W/m) at ‘half fringe’
- Detected power also fluctuates due to laser intensity noise (~10-8) and shot noise. To achieve the best SNR, you therefore want to be close to 'dark fringe'
- Also sensitive to laser frequency noise if arms are not equal!

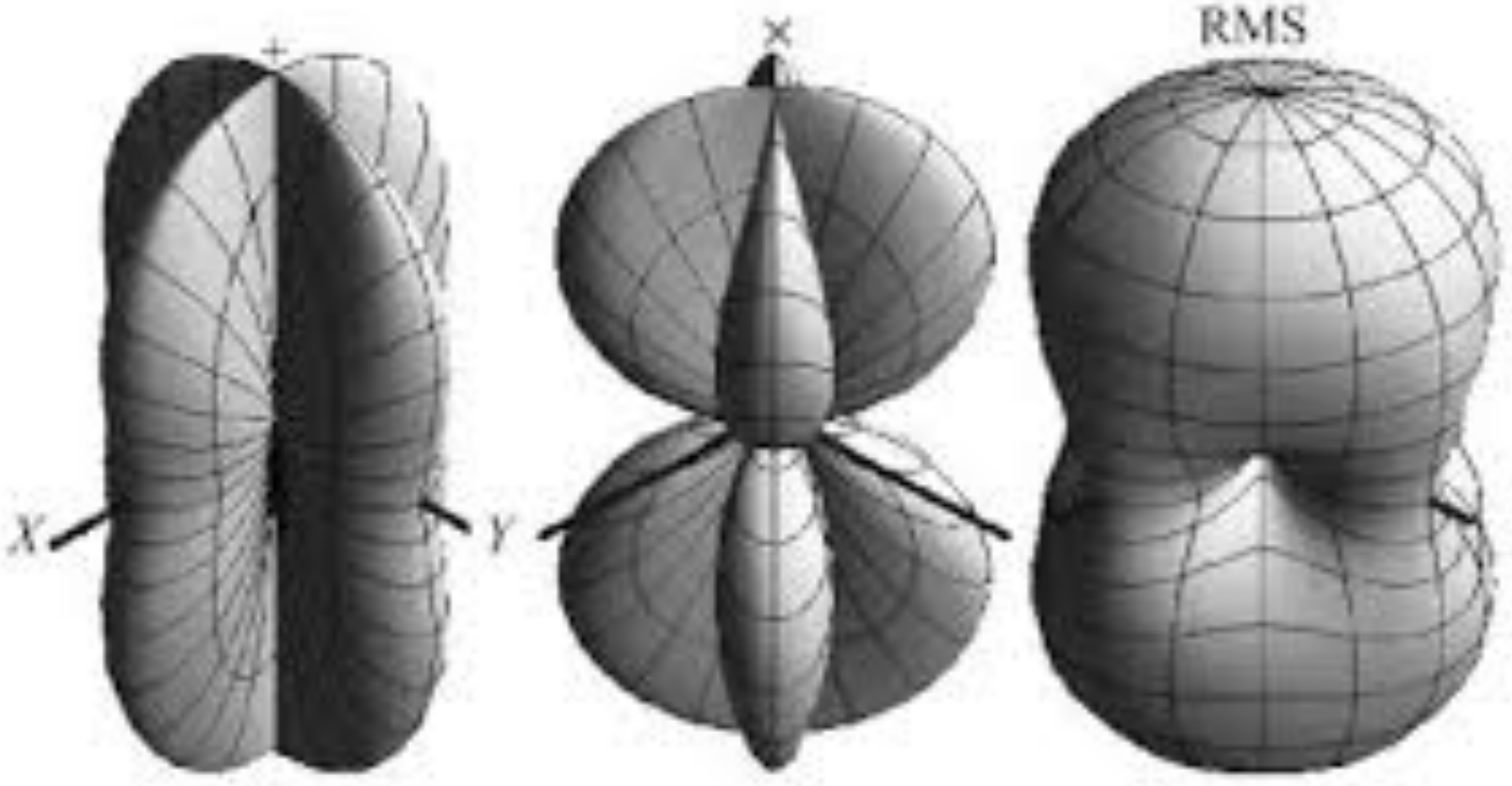
GW polarisation

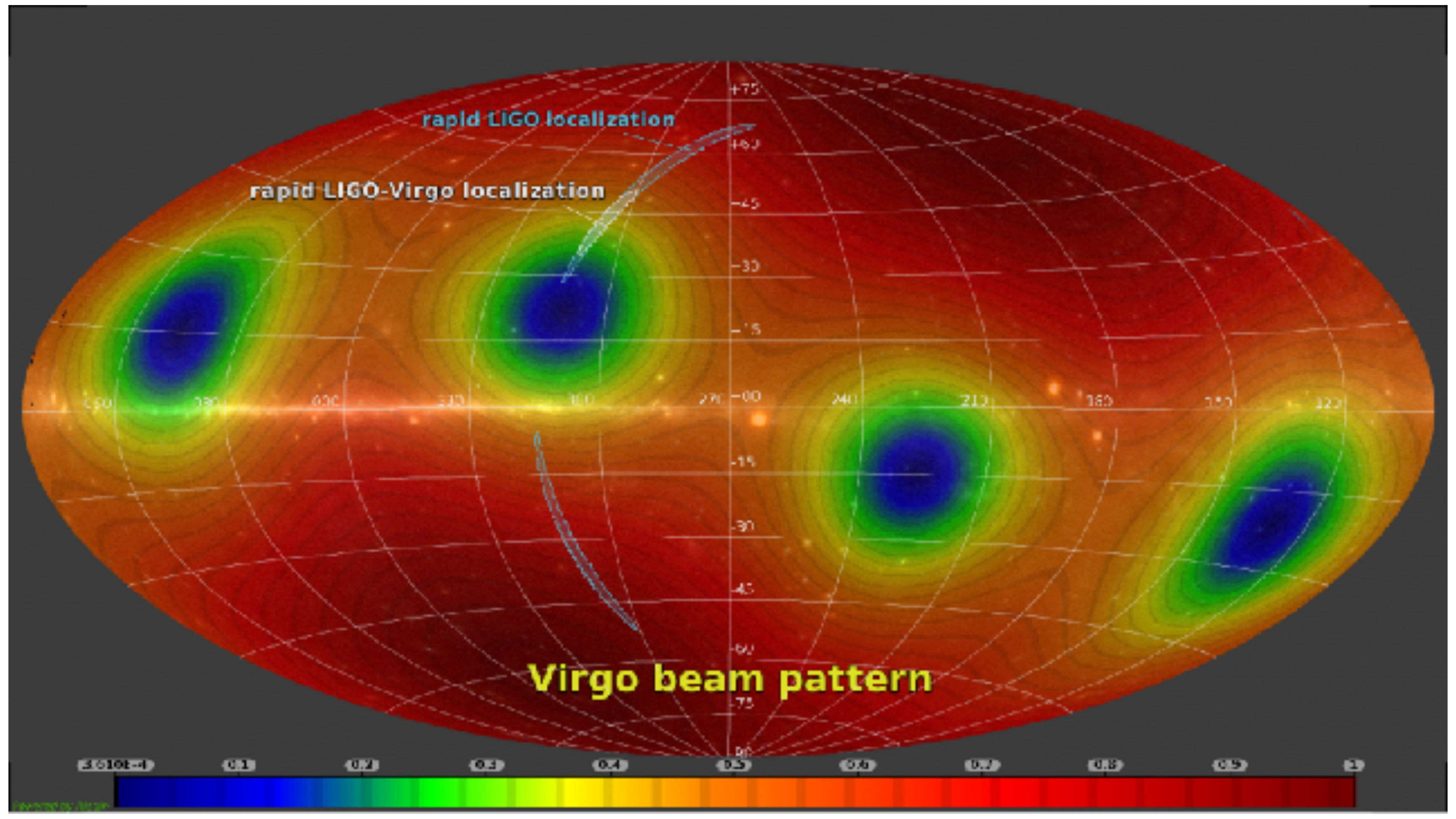
$$\delta x = \frac{1}{2}h_+ x \quad \delta y = -\frac{1}{2}h_+ y$$
$$\delta x = \frac{1}{2}h_\times y \quad \delta y = \frac{1}{2}h_\times x$$



- + polarization: $d\vec{r}_{\mathtt{ETMX}} = (h_+ L/2, 0), d\vec{r}_{\mathtt{ETMY}} = (0, -h_+ L/2)$
- x polarization: $d\vec{r}_{\mathtt{ETMX}} = (0, h_X L/2), d\vec{r}_{\mathtt{ETMY}} = (h_X L/2, 0)$
- An interferometer is only sensitive to differential changes of arm lengths, which depends on mirror movements along the optical axis
- **Perfect for detecting + polarized GW, but insensitive to X polarized GW**

Detector antenna pattern



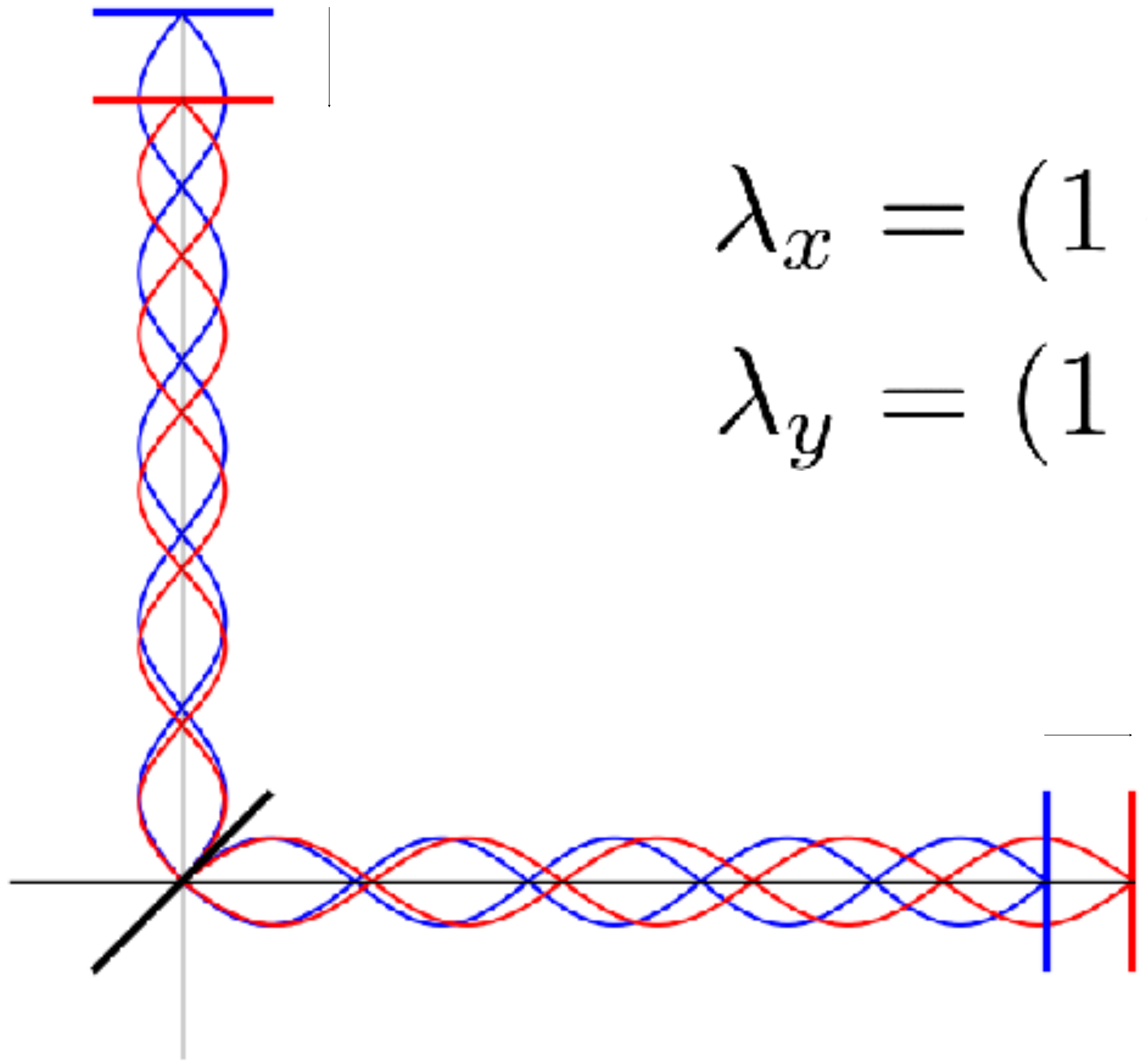


- In addition to GW polarization, the sensitivity depends also on the propagation direction of the GW: sensitive to GW traveling perpendicular to the plane, insensitive to the some directions in the plane. Leads to ‘blind spots’ (see GW170817 for Virgo)
- Argument for having multiple interferometers spread around the Earth with different orientations, if you want to observe the whole sky in both polarizations all the time (also helps with redundancy, coincident detection and sky localization)

Question:

How can the interferometer see GWs? GWs stretch space time, so why does this not also stretch the photons the same amount as the interferometer?

Stretching the interferometer and photons 1/2



$$\lambda_x = (1 + \delta h/2)\lambda_0$$
$$\lambda_y = (1 - \delta h/2)\lambda_0$$

- Valid question: we seem to use an optical wavelength as our ruler to measure distances, but doesn't the wavelength itself change by a passing GW? It does ...
- Why is the picture above not accurate?

Stretching the interferometer and photons 2/2

One of several intuitive explanations of what happens (the one I prefer):

- you don't measure GW by using the wavelength as a ruler, that picture of a continuous sinusoidal wave between two events in space time is not compatible with special or general relativity.
- Instead the detector can only measure the integrated effect of the change to the photon over the whole round-trip.
- What the interferometer measures is a difference in phase between the two arms, or in other words, the different arrival time of the wavefronts of the light/photons.
- Therefore the local stretching and shrinking of a wave-packet in the arms is not relevant, simply the integrated phase, which is given by the known equations.
- The question was valid but posed in a misleading way.

Summary

- GW detection has a 60 years long history, remains one of the most challenging projects in experimental metrology.
- For many decades GW experimentation involved pioneers who failed to succeed in the actual detection, but whose successes in science and technology made the eventual detection possible.
- Interferometric detectors provided better means of scaling the sensitivity (peak and bandwidth).