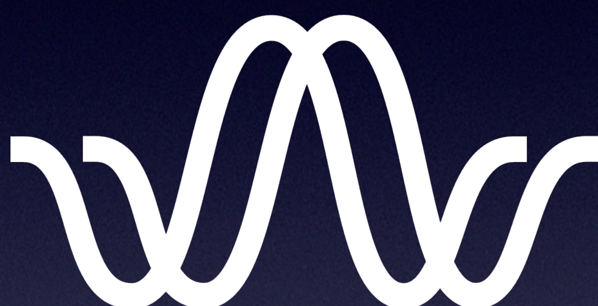
Space-base Detection of Gravitational Waves

Opening the Low-Frequency Part of the Spectrum

Jean-Baptiste Bayle

CosmoStat – CEA Saclay 2019

Let me walk you through...



Gravitational Waves, the Recap'

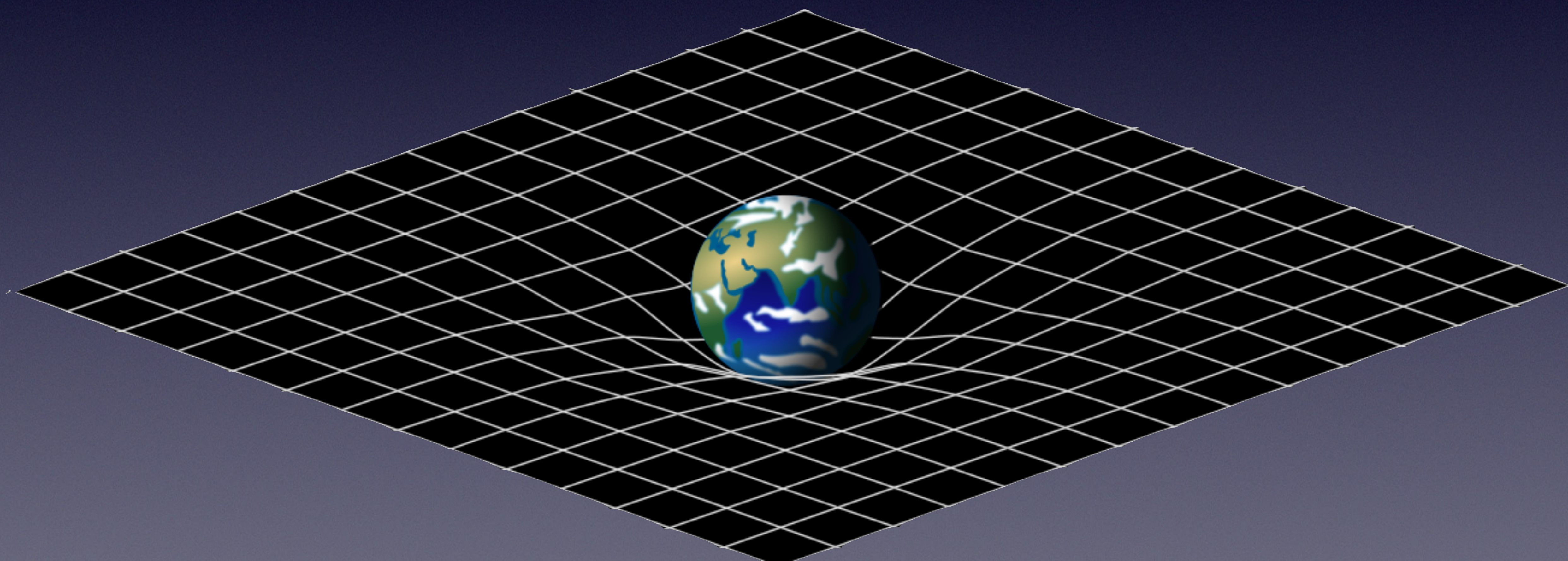
Detecting Gravitational Waves

Space-based Detection with LISA

GRAVITATIONAL WAVES,
A (BRIEF) RECAP’

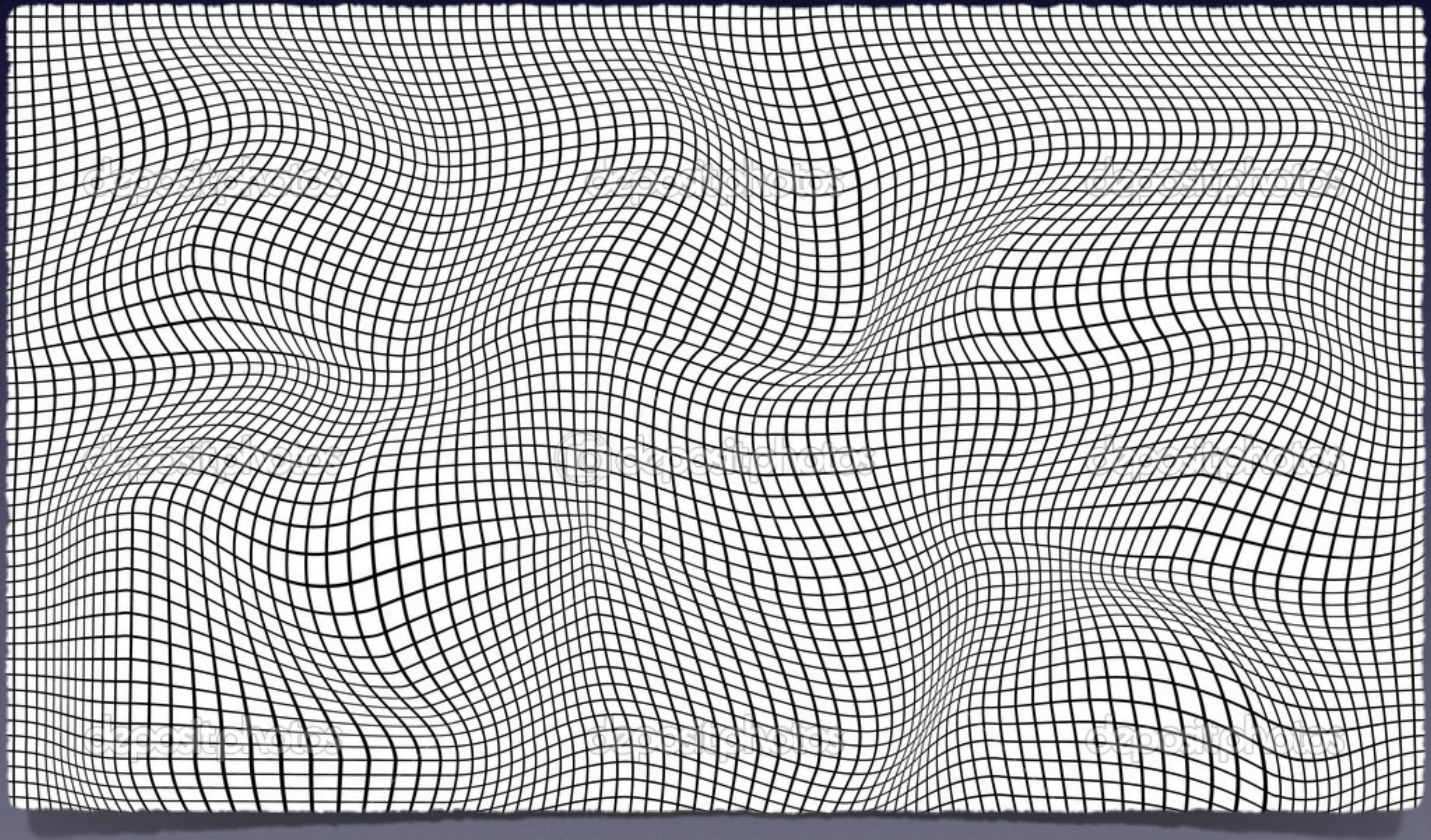
From General Relativity…

- Einstein's theory of **General Relativity** describes gravity as manifestation of curved spacetime



From General Relativity…

- Affects the **geometry of spacetime**, aka. how we measure distances and durations



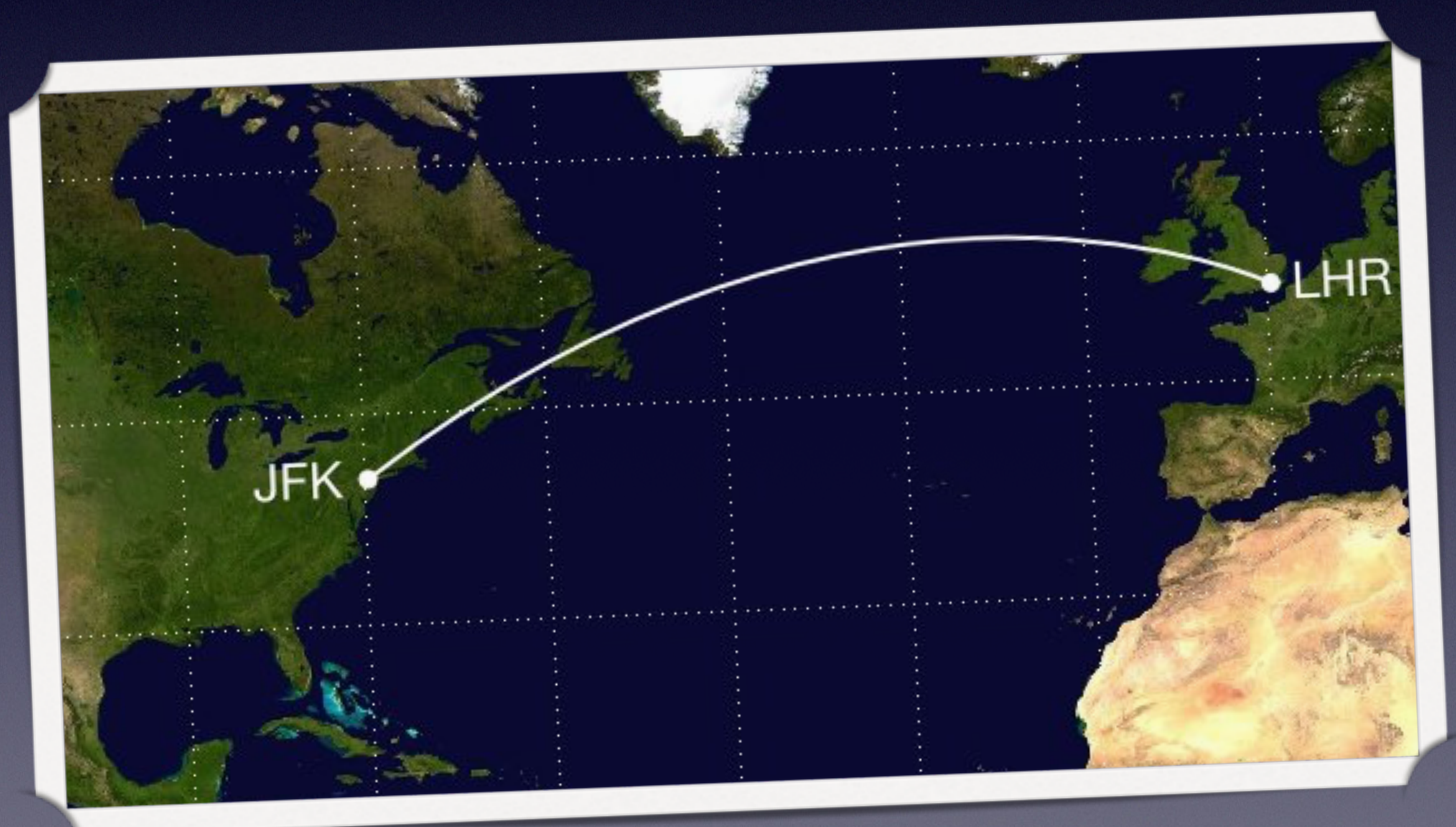
From General Relativity…

- Affects the **geometry of spacetime**, aka. how we measure distances and durations
- This is described by the **metric** tensor, related to mass-energy content by **Einstein's equation**:

$$\underbrace{R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu}}_{\text{Curvature of spacetime}} = \underbrace{\frac{8\pi G}{c^4} T_{\mu\nu}}_{\text{Mass-energy content}}$$

From General Relativity…

- Free-falling particles move along **geodesics**, which are the "lines of shortest path" in curved spacetime



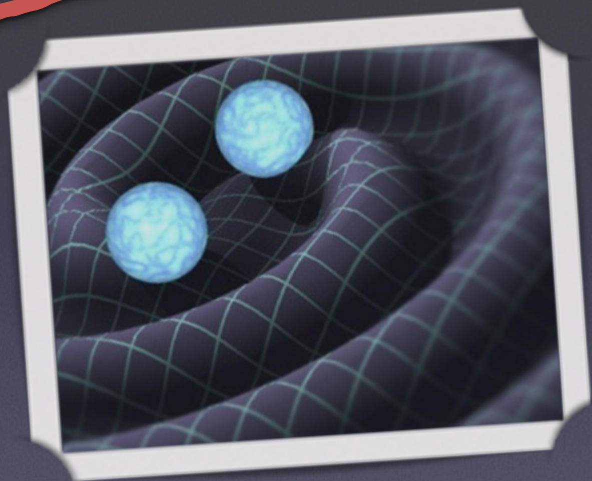
… to gravitational waves

- Analytical solutions are notoriously hard to find
- **Linearization** of Einstein's equation for small deformations ($g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$) of the metric tensor yields a **propagation equation**:

$$\eta^{\alpha\beta}\partial_\alpha\partial_\beta \bar{h}_{\mu\nu} = \frac{16\pi G}{c^4} T_{\mu\nu}$$

- This is the rise of gravitational waves moving through spacetime at the velocity of light

HARD TO DETECT!



Gravitational Wave

GOOD MESSENGER

Velocity: c

Type: transverse

Polarisation: two modes h_+ and $h_\times$

Transport: energy

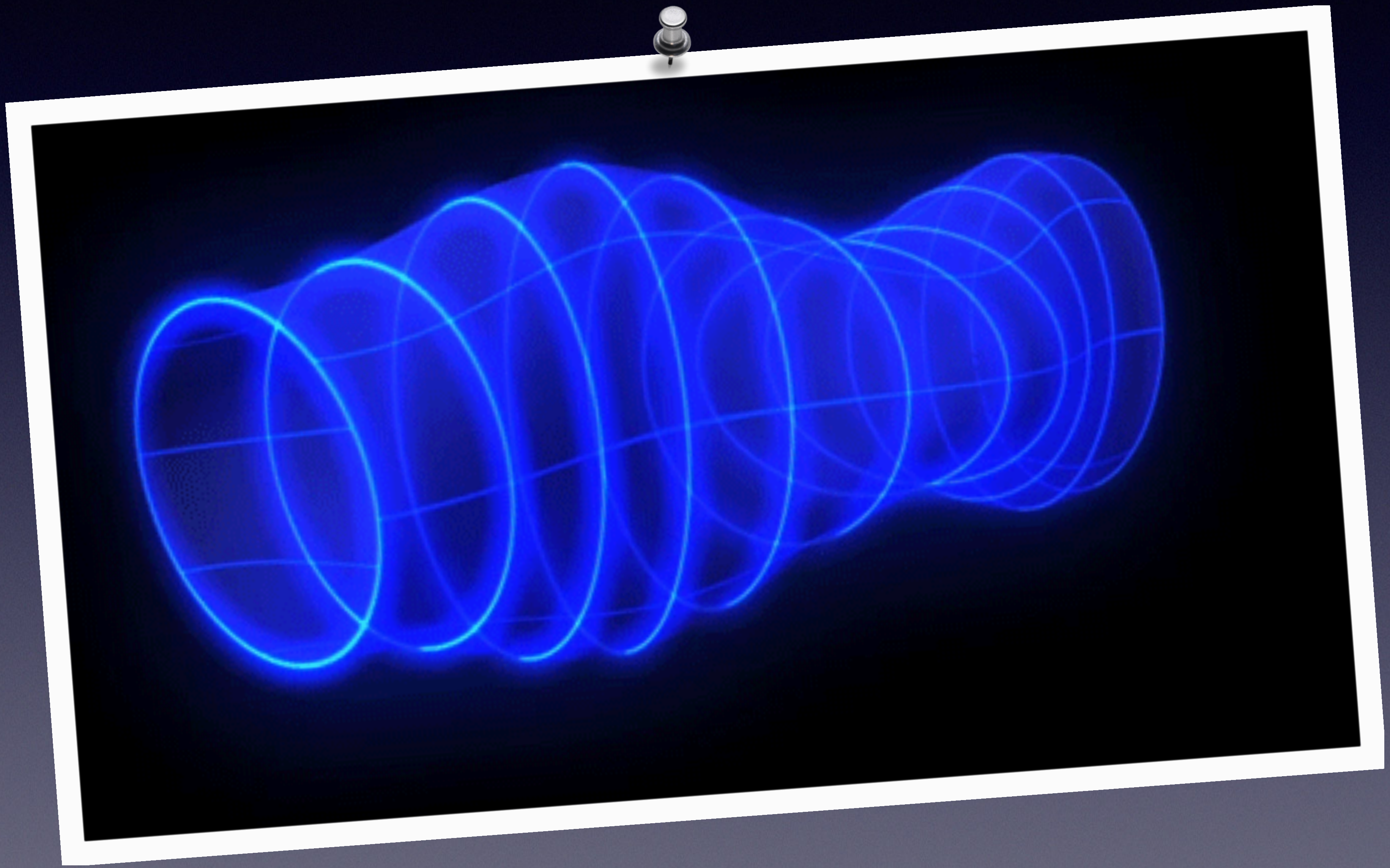
Amplitude: very small

Produced by: quadrupole moment of stress-enery tensor

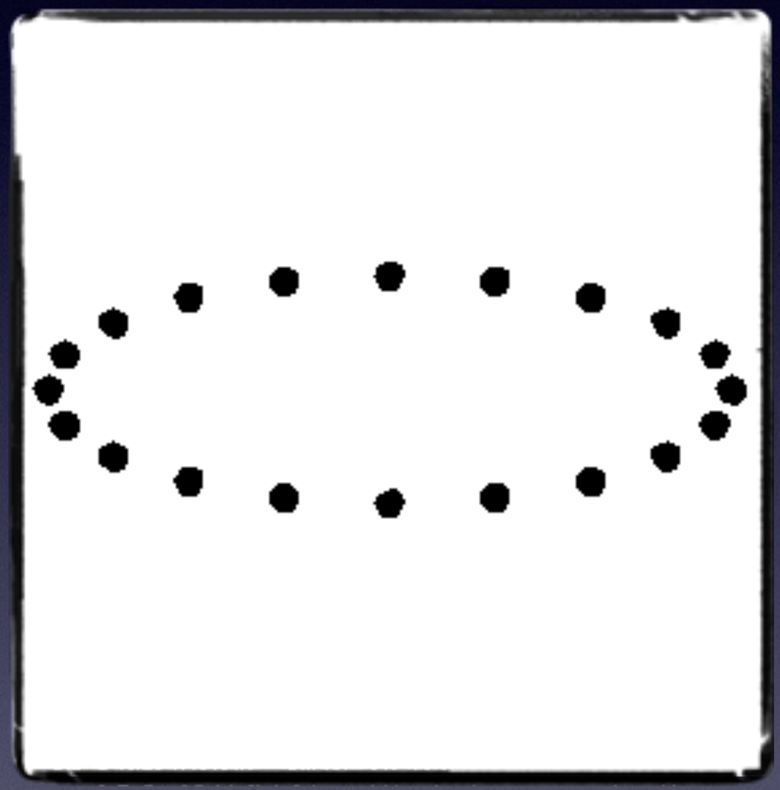
Interaction with matter: very small

DETECTING GRAVITATIONAL WAVES

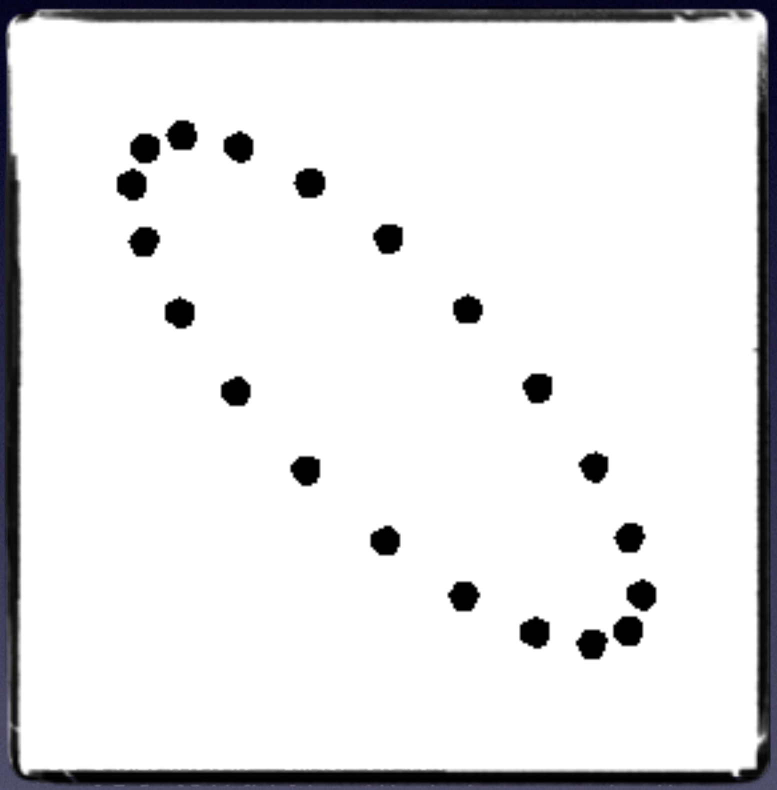
Effect of gravitational waves



Effect of gravitational waves



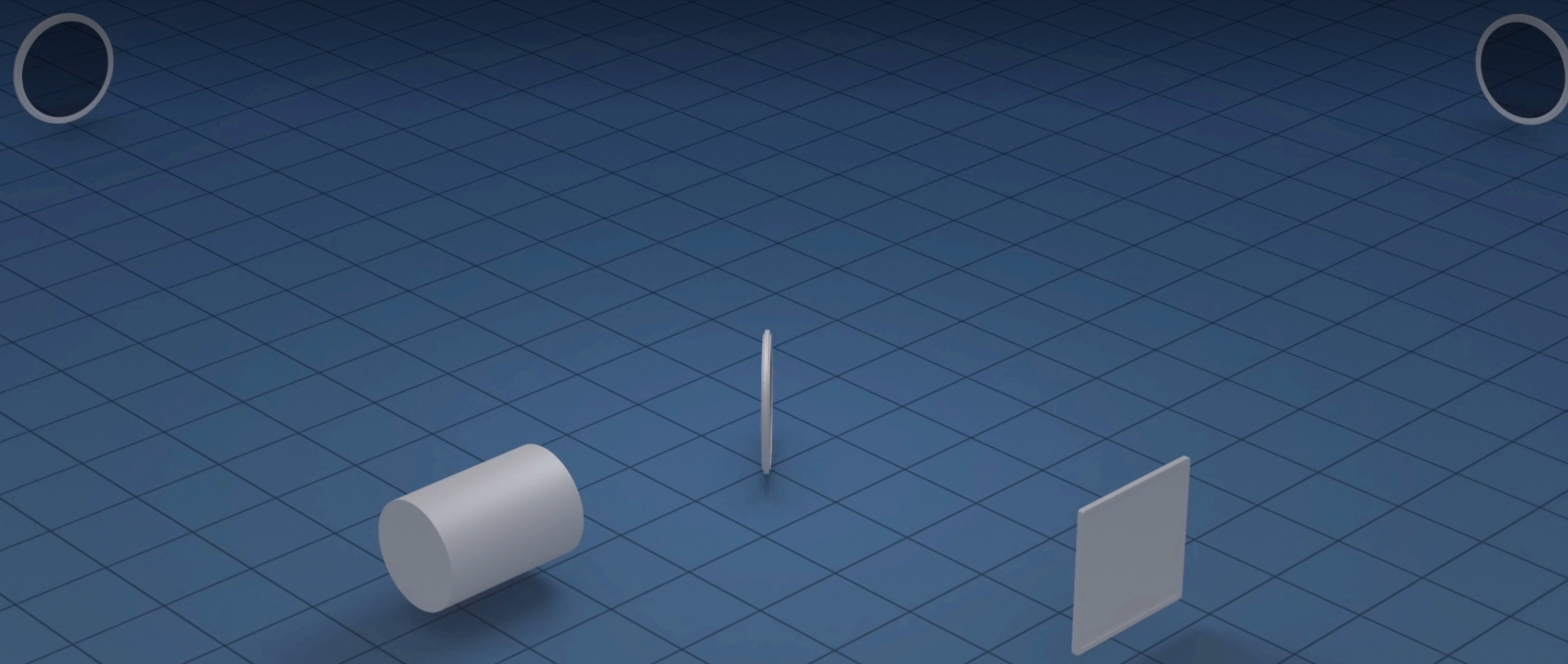
h_+



$h_\times$

Optical interferometry

- Optical **interferometry** is today's only proofed technique for gravitational wave detection ($h = \frac{\Delta l}{l}$)



Interferometric Detection

- **Light travel times** along the arms changing according to TT-view while mirror positions fixed
- Power at photodetector proportional to relative optical phase change:

$$P(t) \propto 1 + \cos(\Delta\phi)$$

- For monochromatic incident gravitational wave,

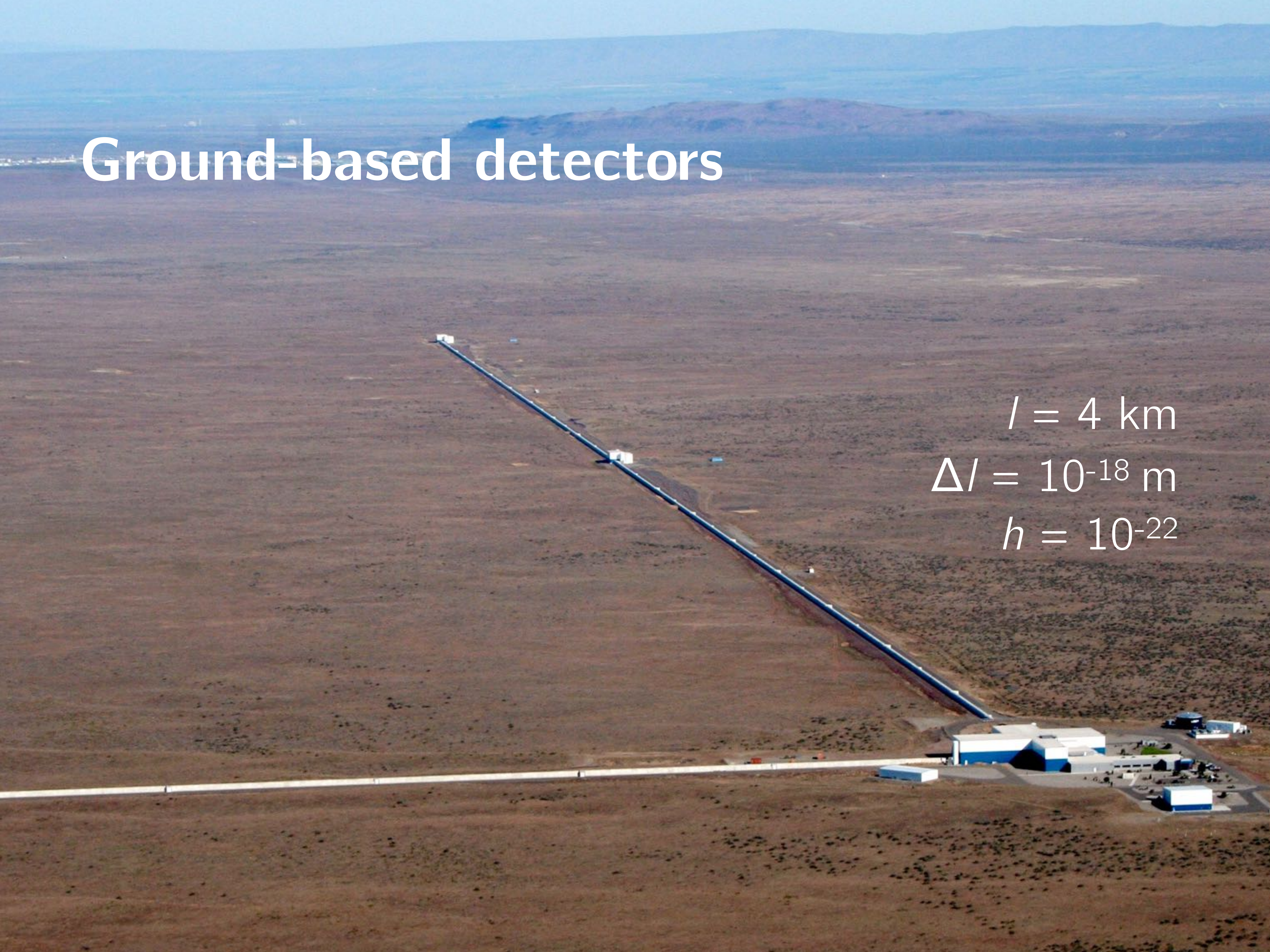
$$\Delta\phi \frac{1}{\omega_{\mathrm{GW}}} \sin\left(\frac{\omega_{\mathrm{GW}} L}{c}\right) \cos(\omega_{\mathrm{GW}} t)$$

Ground-based detectors

- 2 American detectors **LIGO** in Livingston and Hanford, third run of observation started this year
- One French-Italian detector **Virgo**, near Pisa
- German detector **GEO600** under upgrade to full sensitivity, and will be part of the world-wide network of gravitational detectors, along with:
    1. **INDIGO**, or LIGO-India
    2. **KAGRA** in Japan

Ground-based detectors

Ground-based detectors



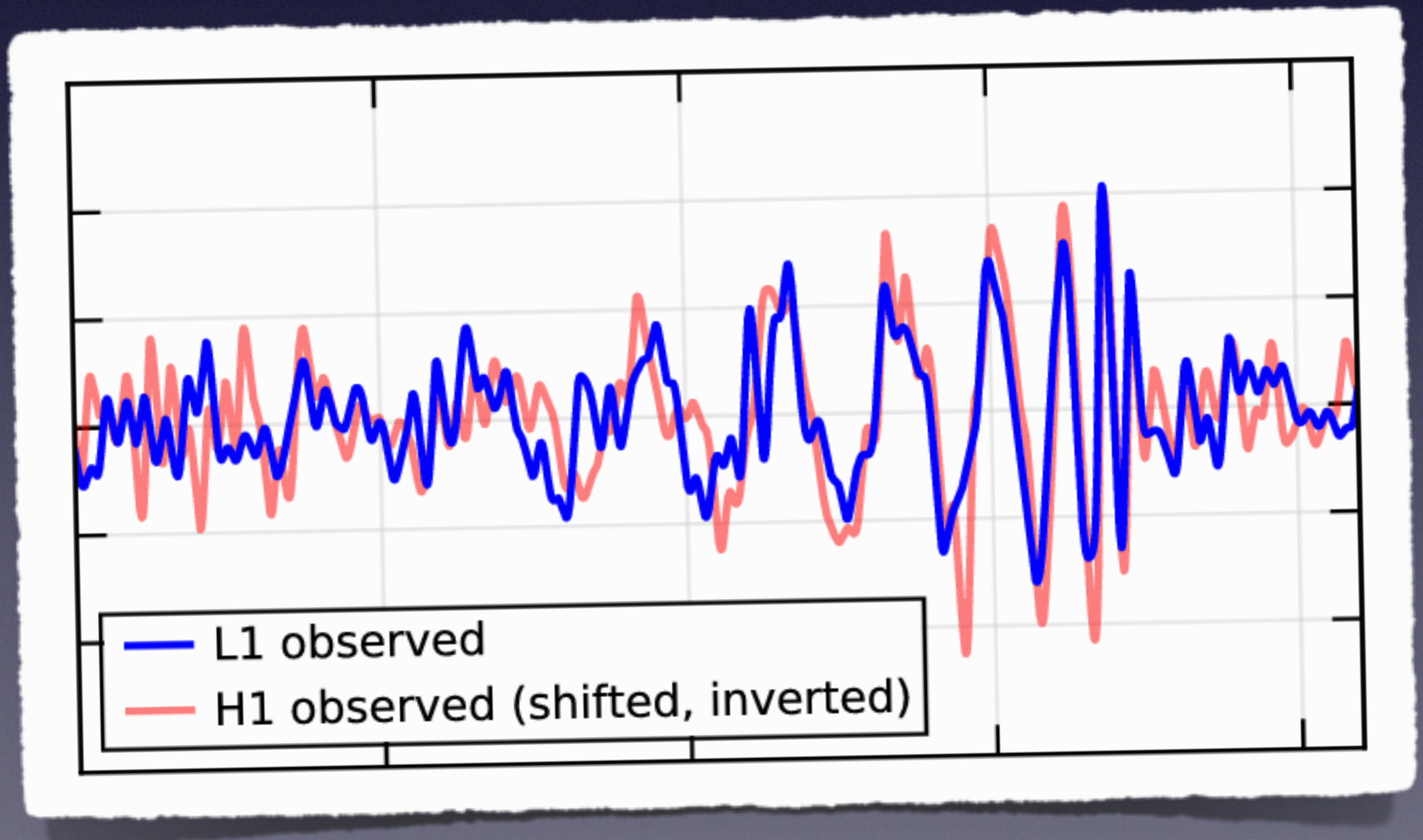
$l = 4$ km

$\Delta l = 10^{-18}$ m

$h = 10^{-22}$

GW150915

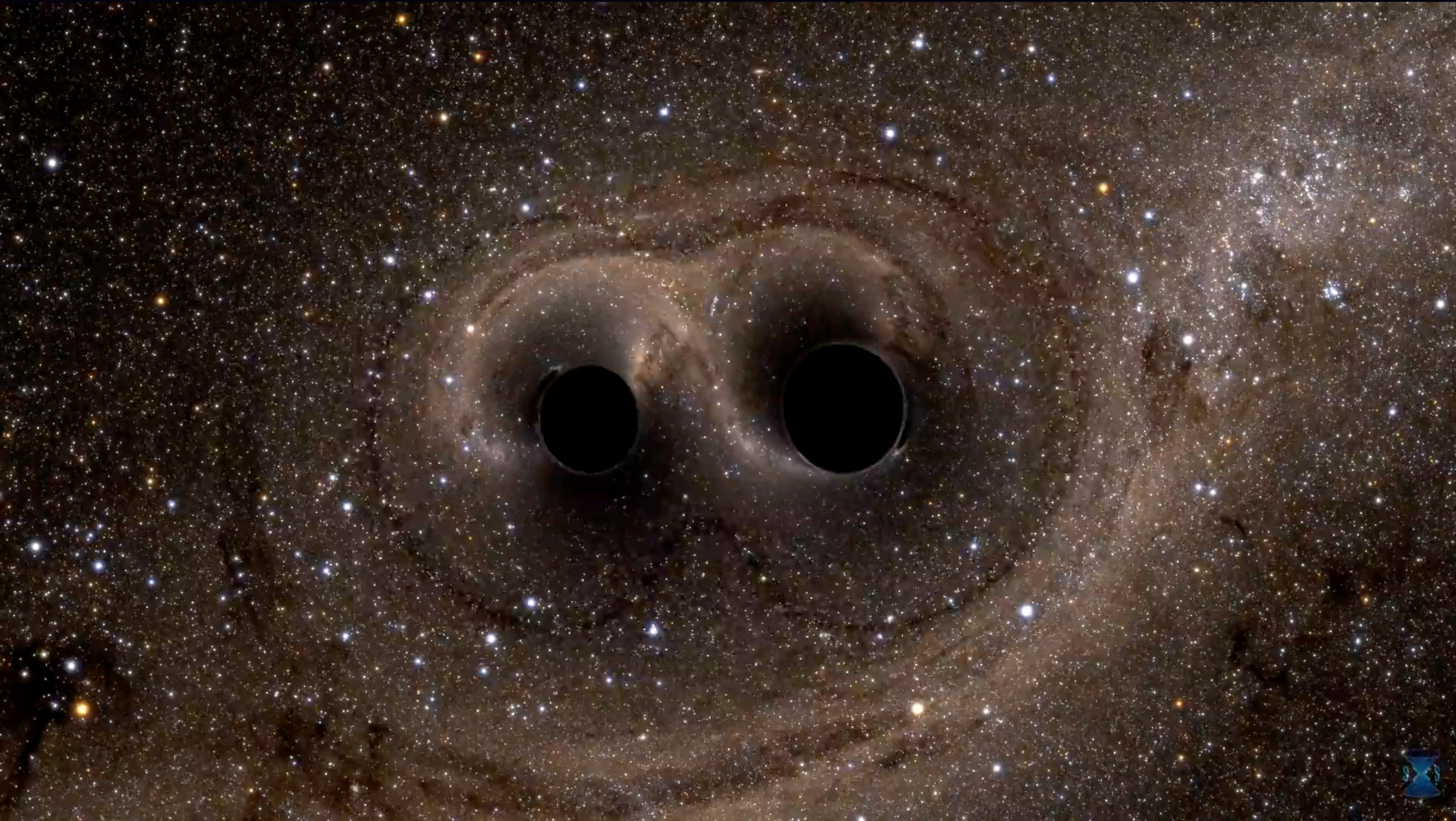
- **First direct detection** of gravitational waves announced last February by ground-based detector collaboration LIGO and Virgo



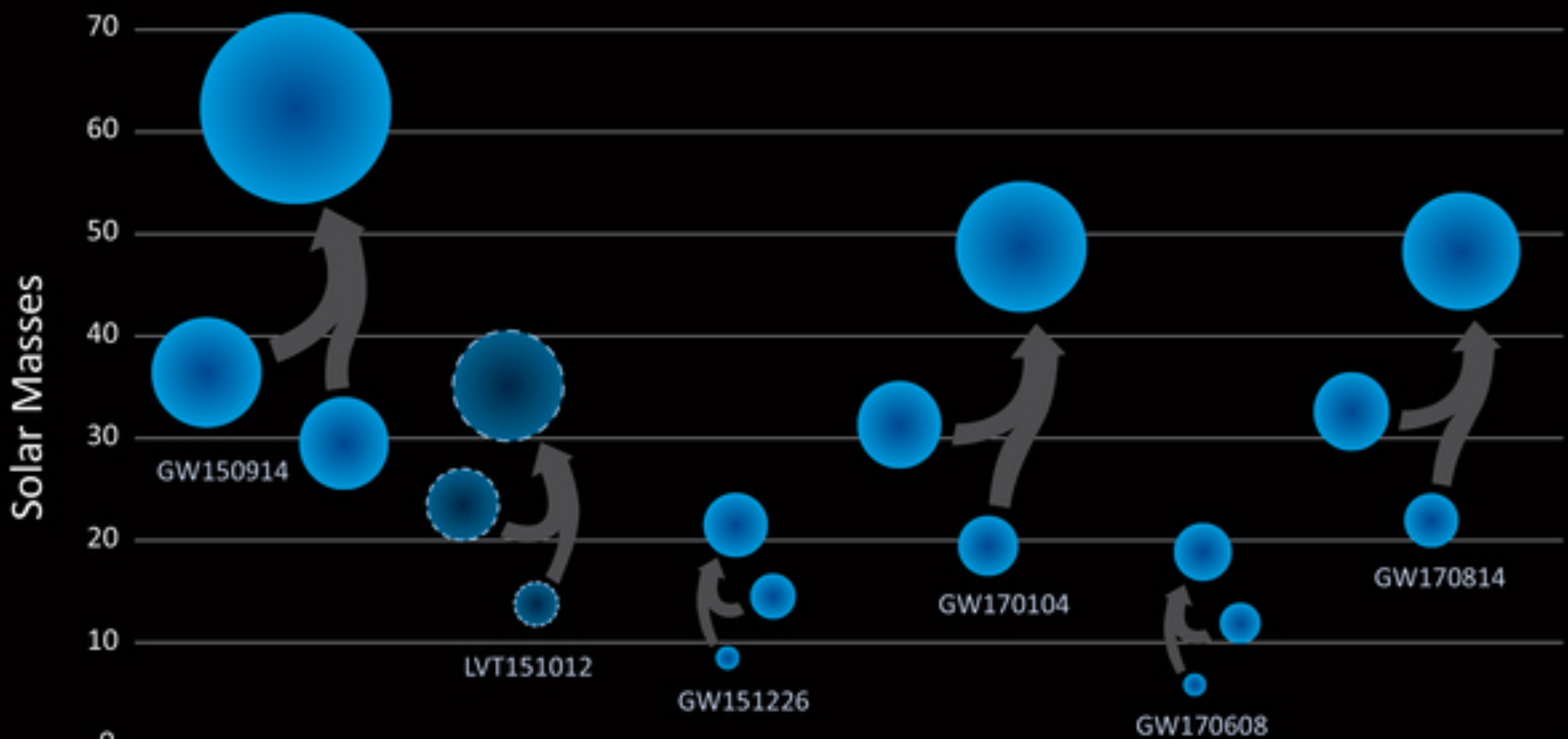
Strain from GW150914 as measured by LIGO on September, 14 2015

Physical Review Letters

GW150915



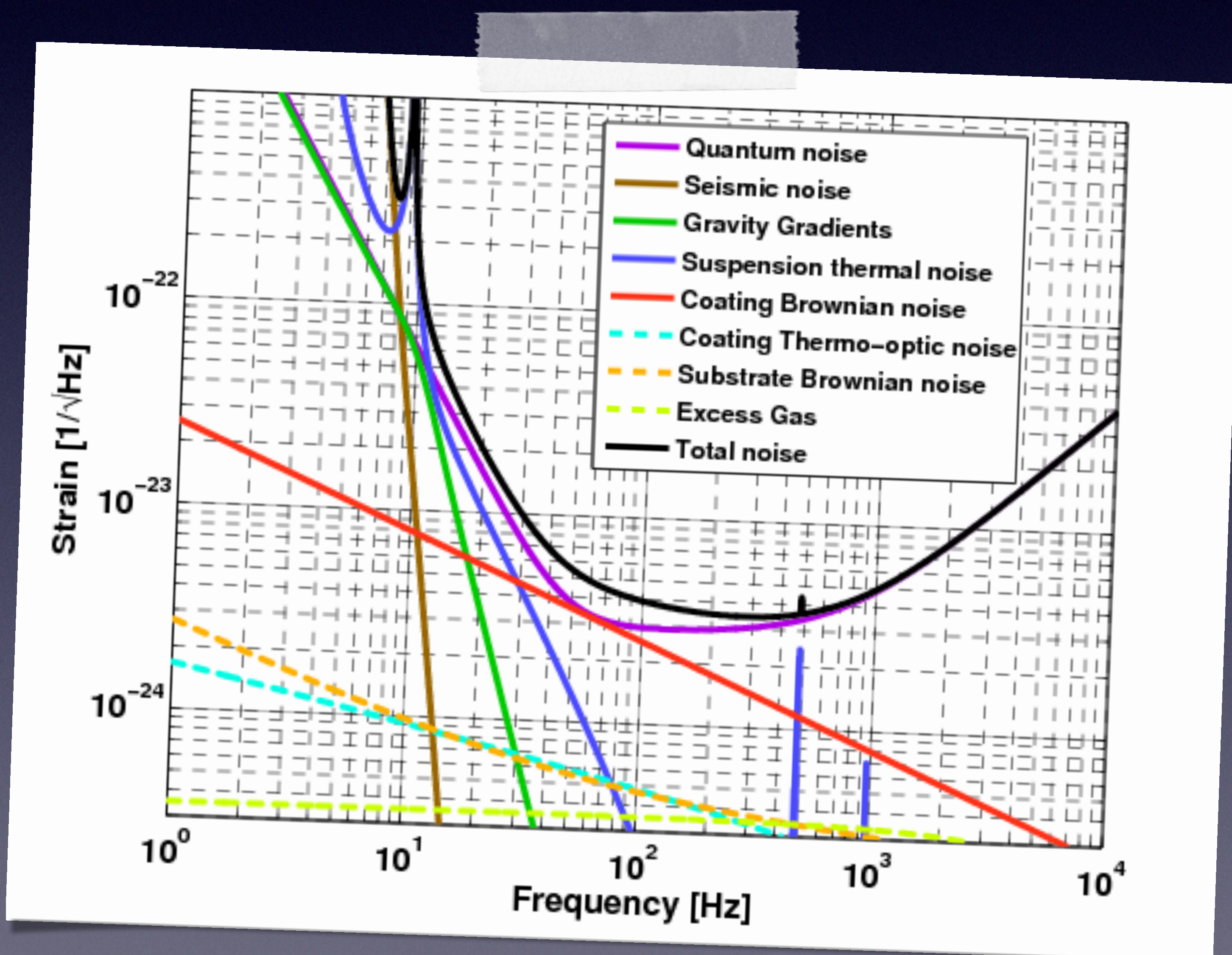
First LIGO-Virgo detections



LIGO-Virgo Collaboration

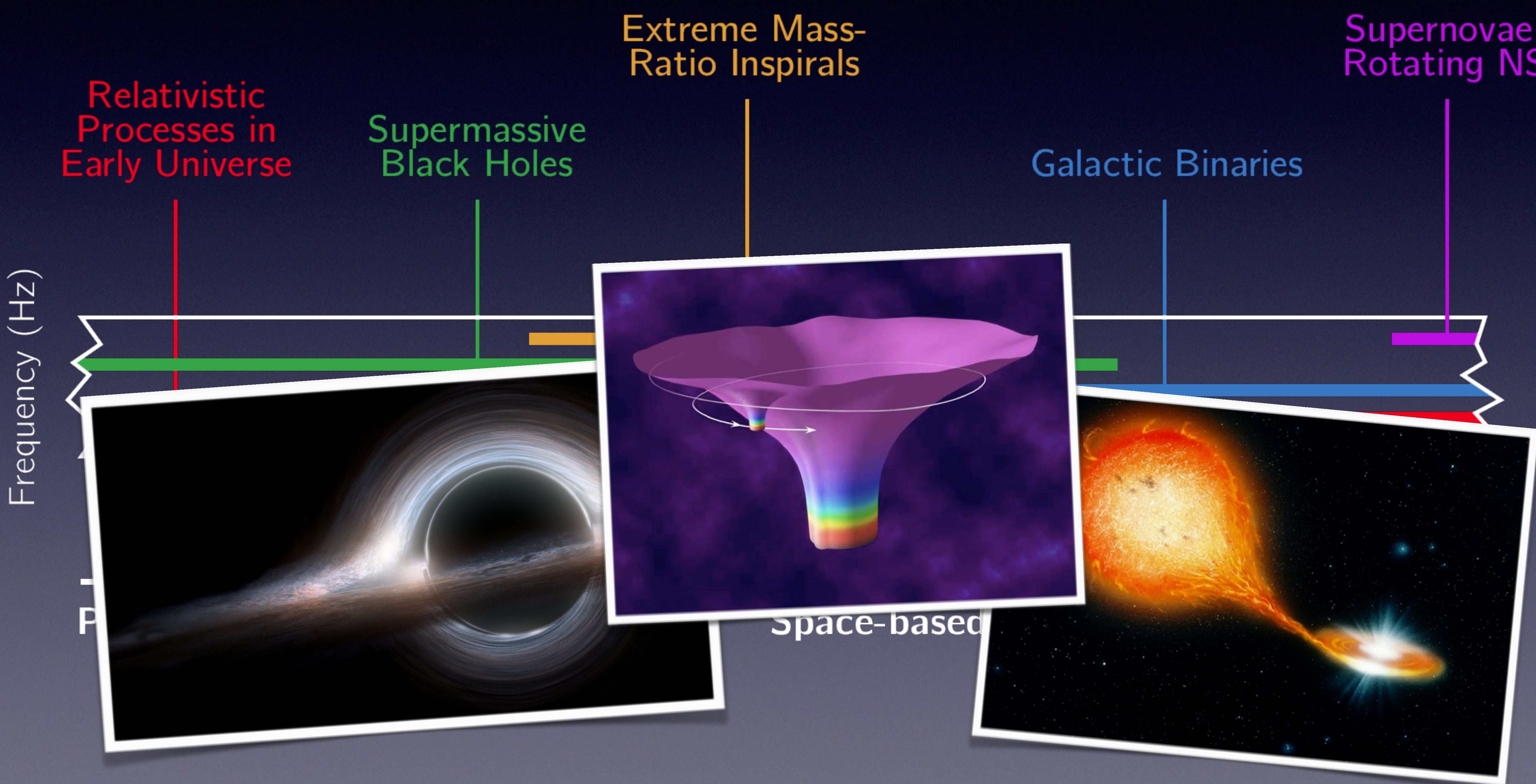
Limits in low-frequency range

- **Seismic noise** limits sensitivity to **high frequencies**

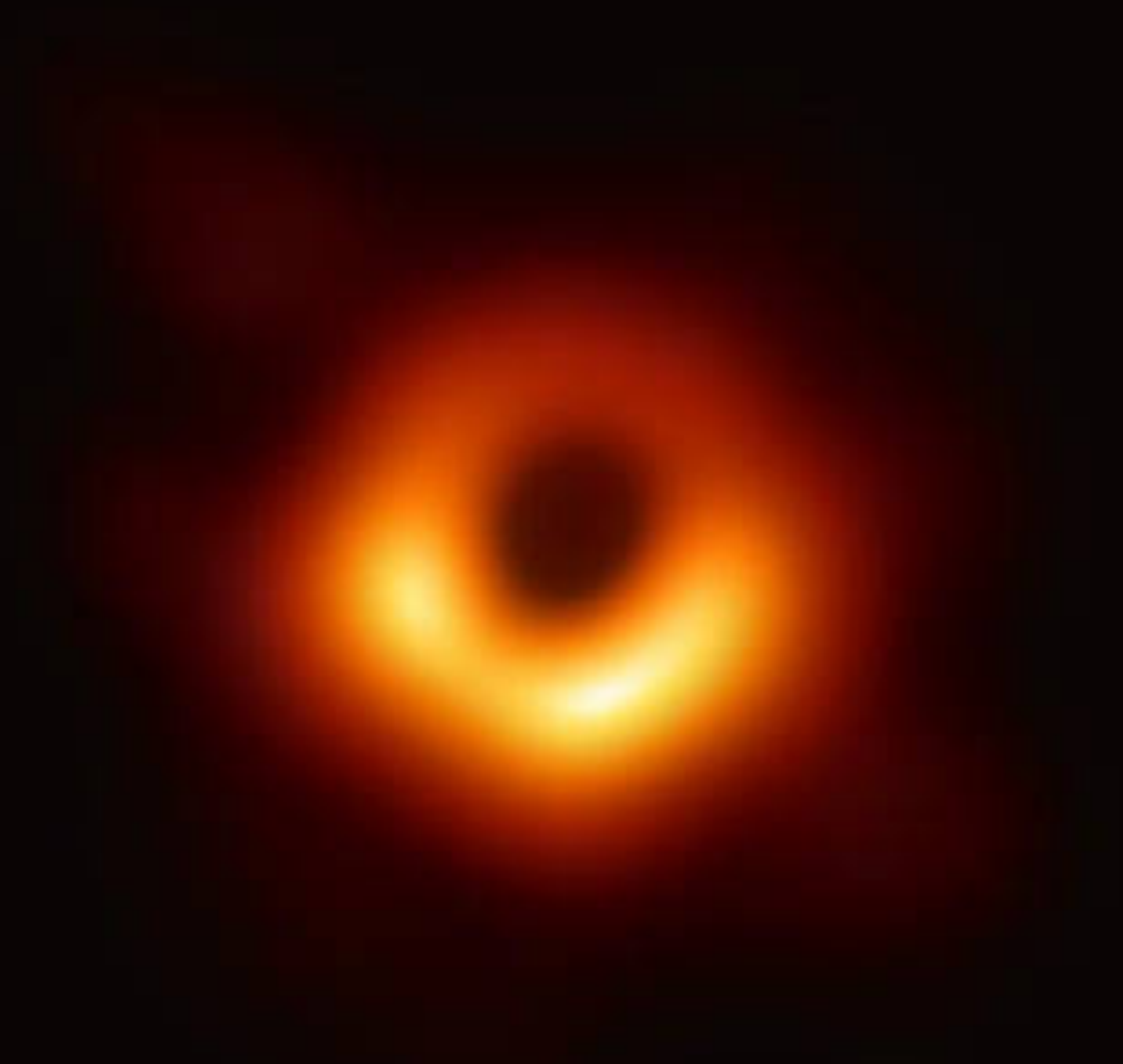


mirror motion due to ground vibrations, earthquakes, winds, ocean waves, human activities

Gravitational Spectrum

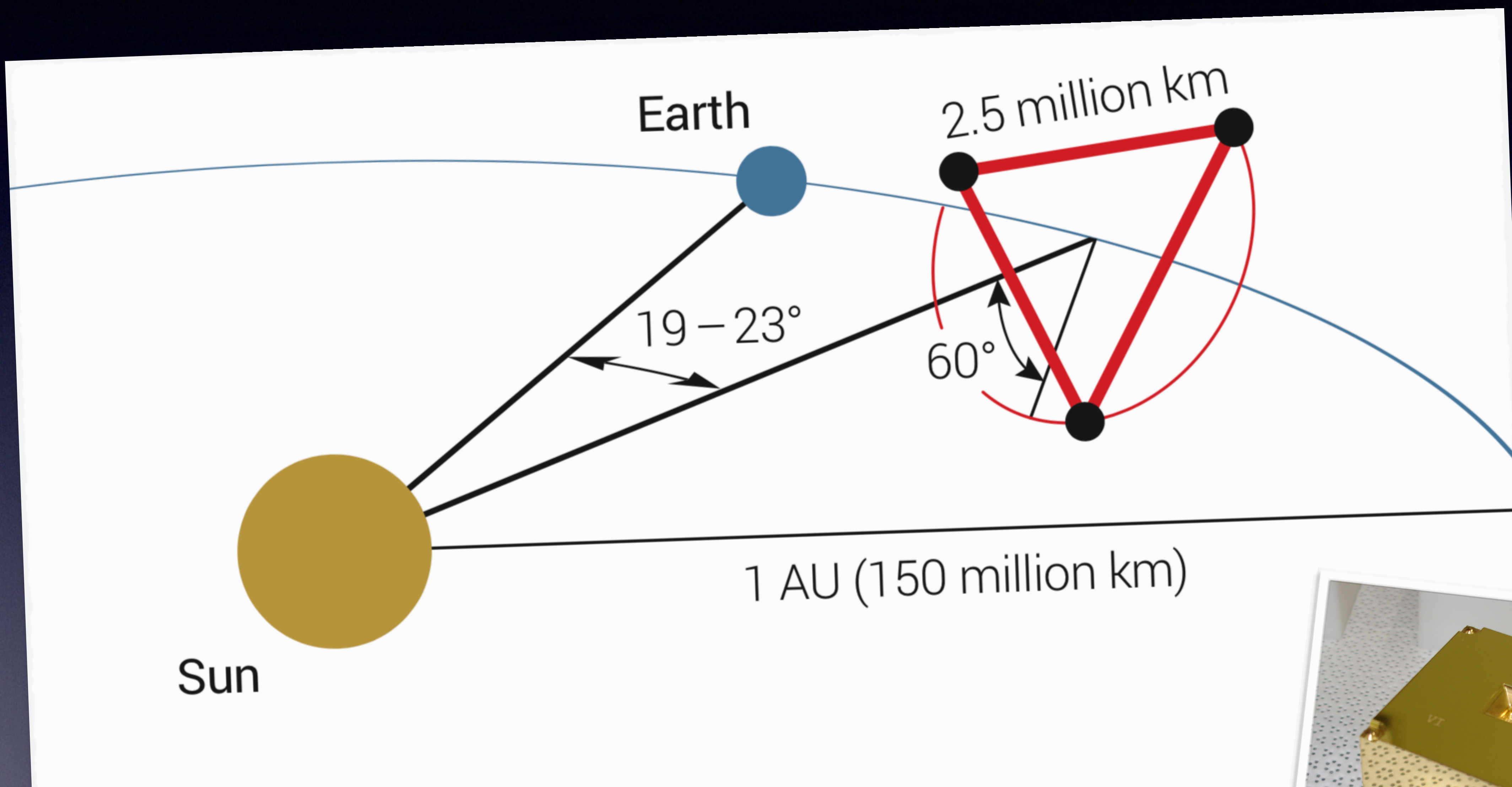


M87*

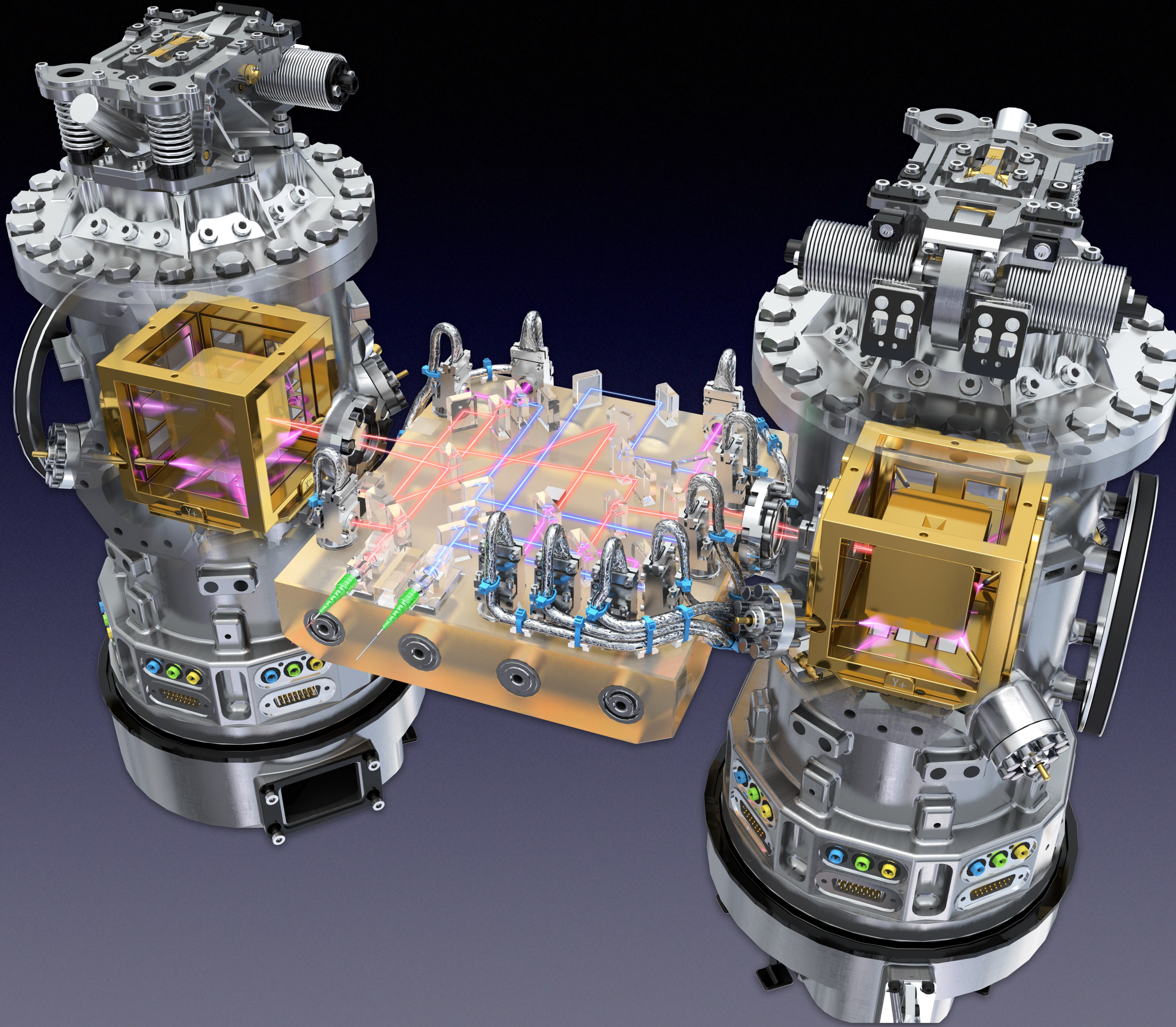


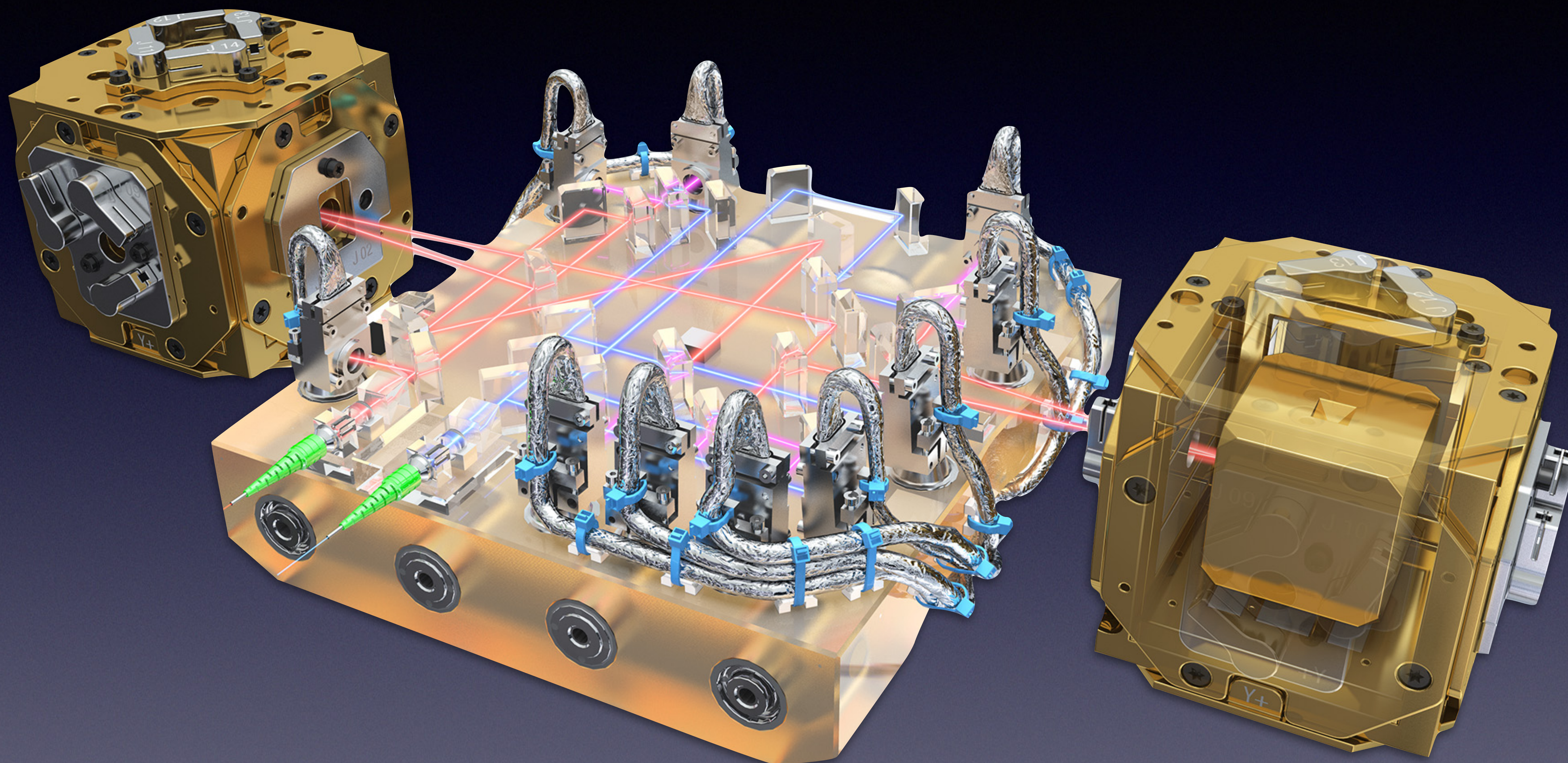
SPACE-BASED GRAVITATIONAL DETECTION

The LISA Mission



LISA Consortium (2017). *Laser Interferometer Space Antenna.*

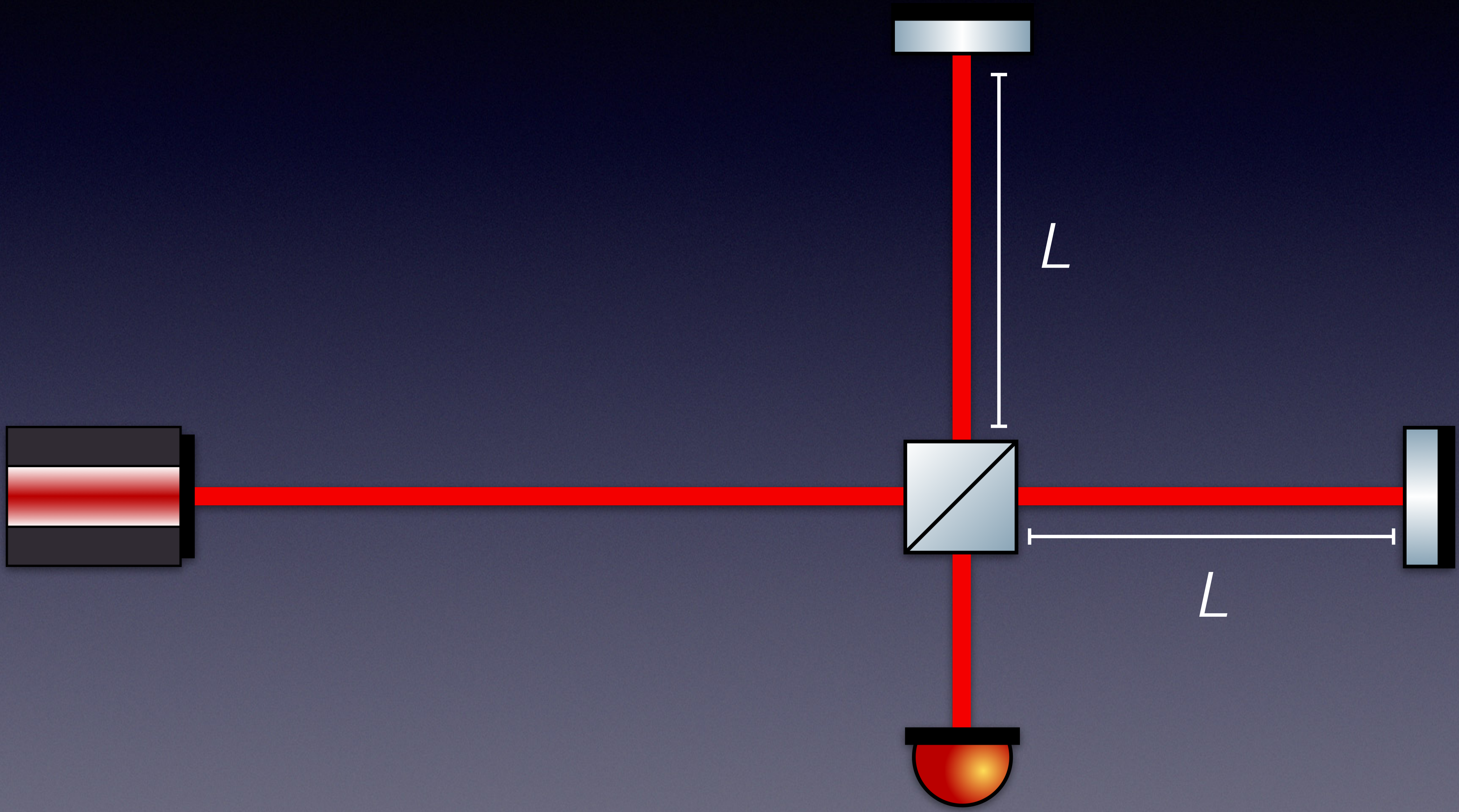



Y+
Y+

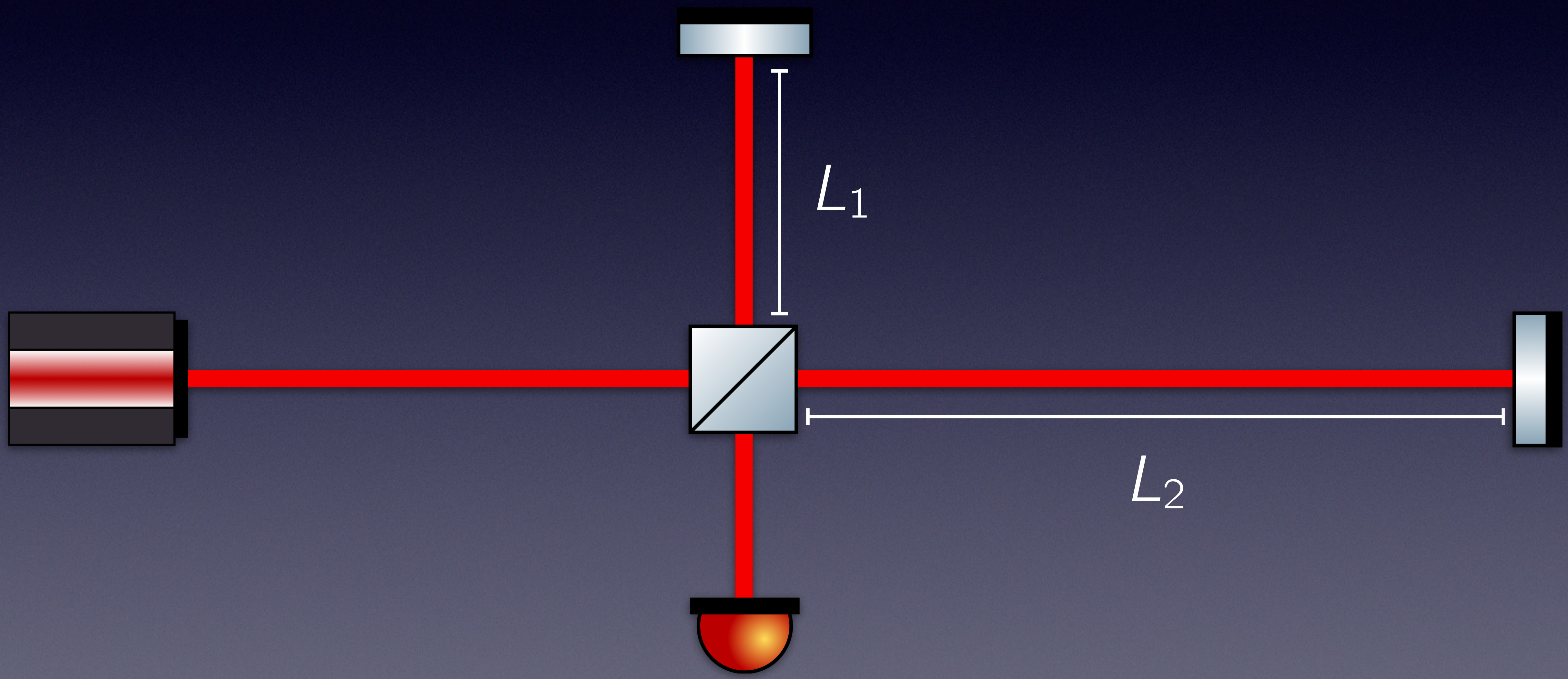
2034

Credits: ESA

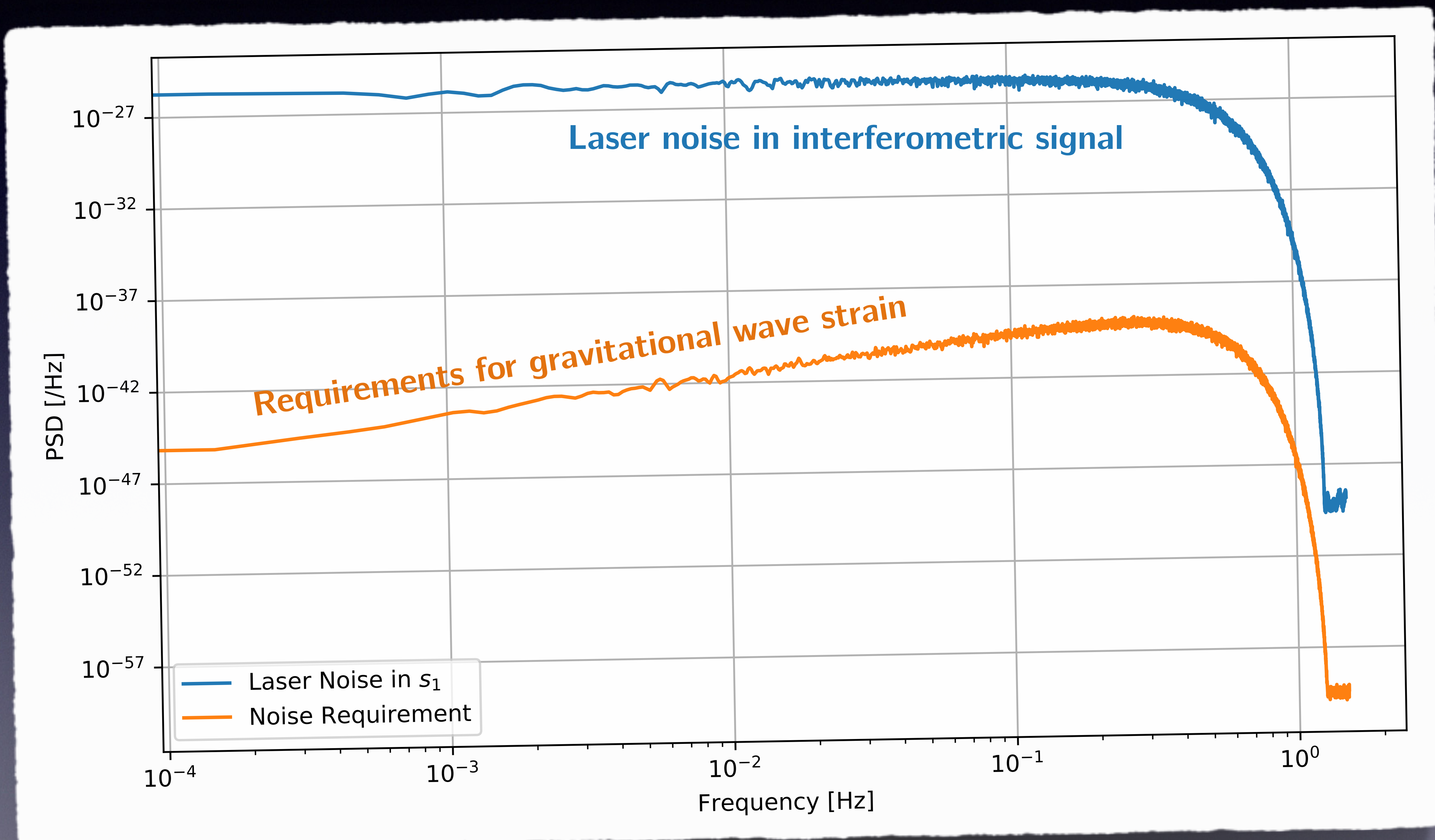
Equal-Arm Interferometry



Unequal-Arm Interferometry

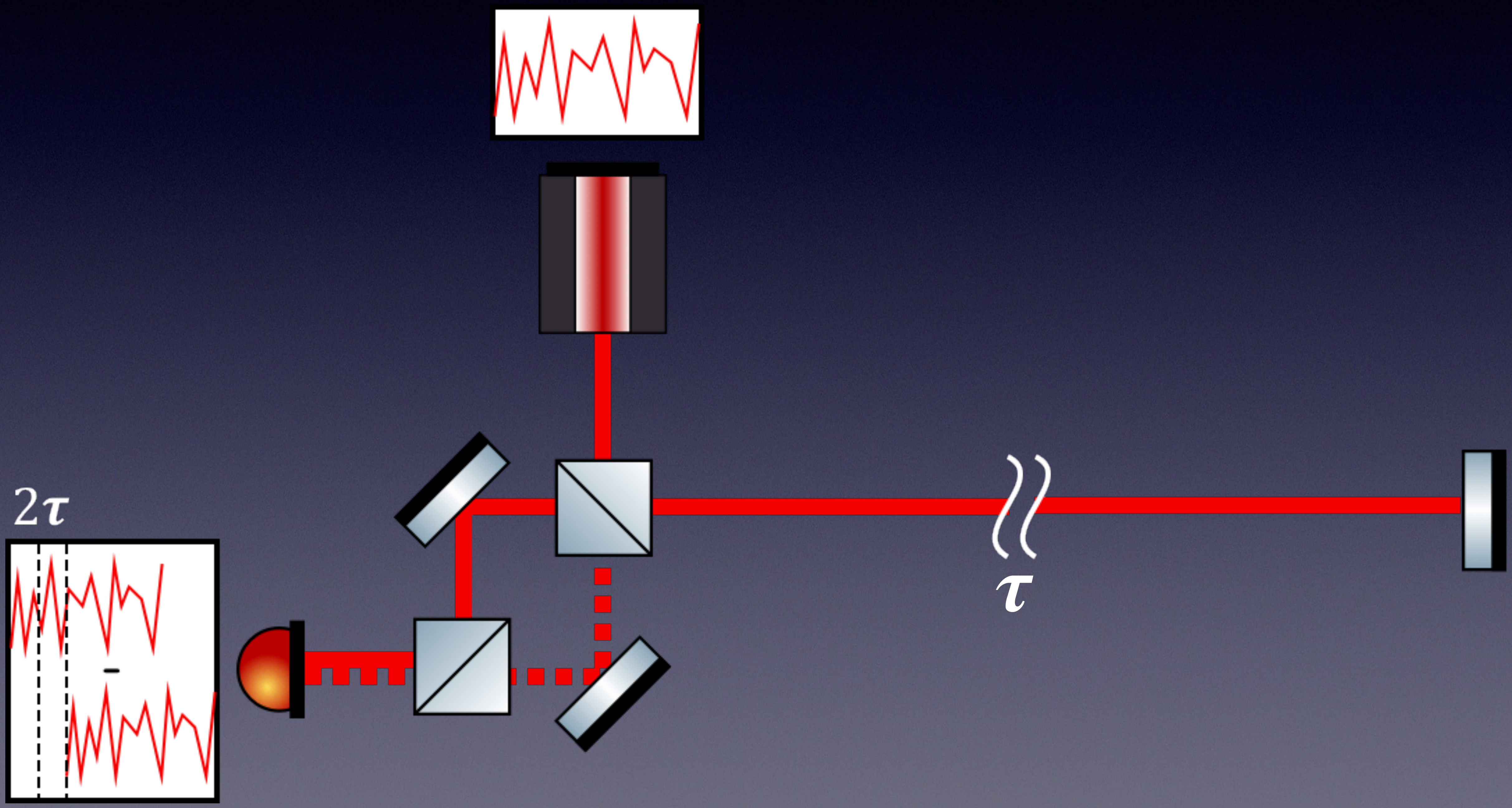


Noise Budget

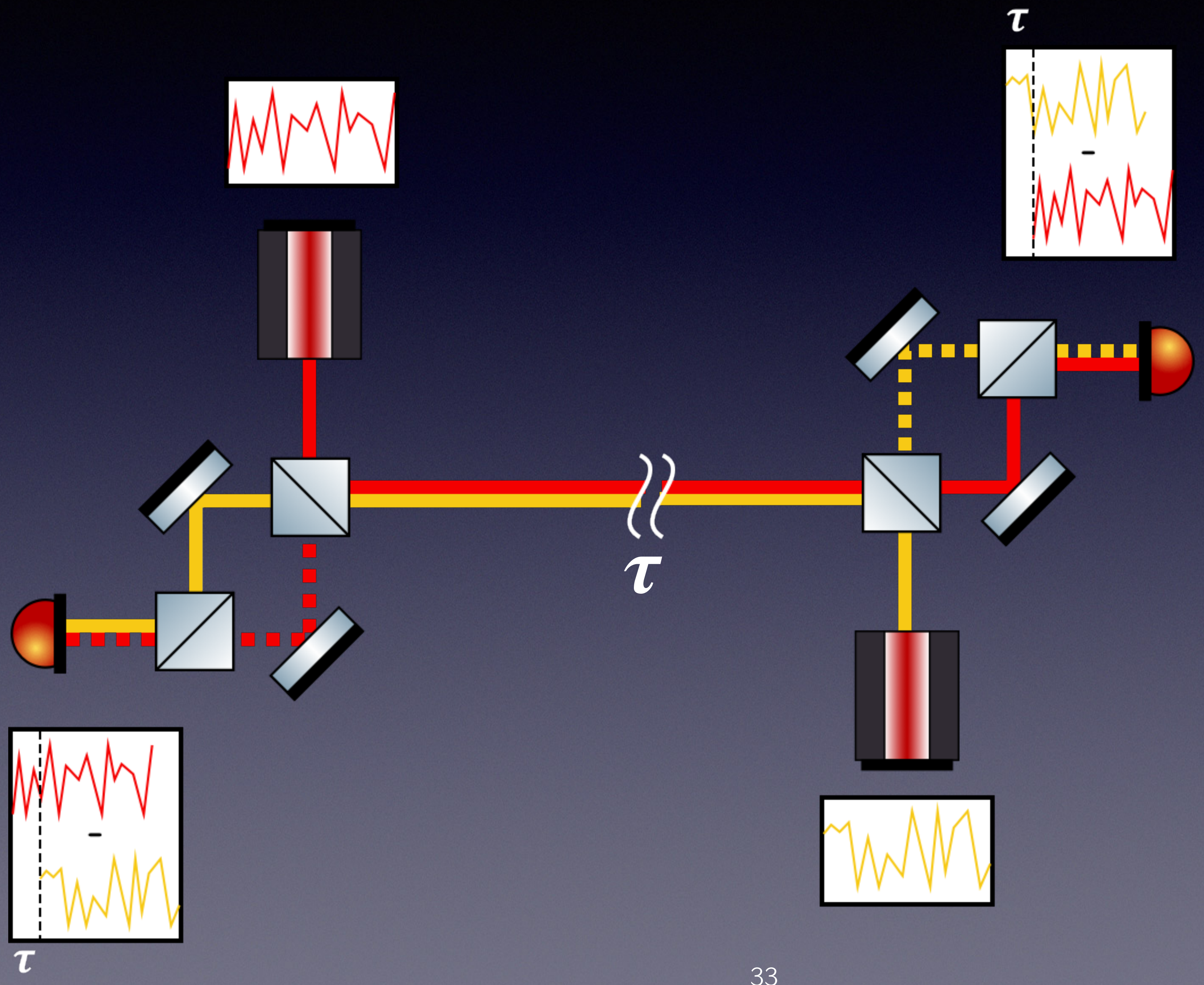


From LISANode simulations, using MRD noise levels

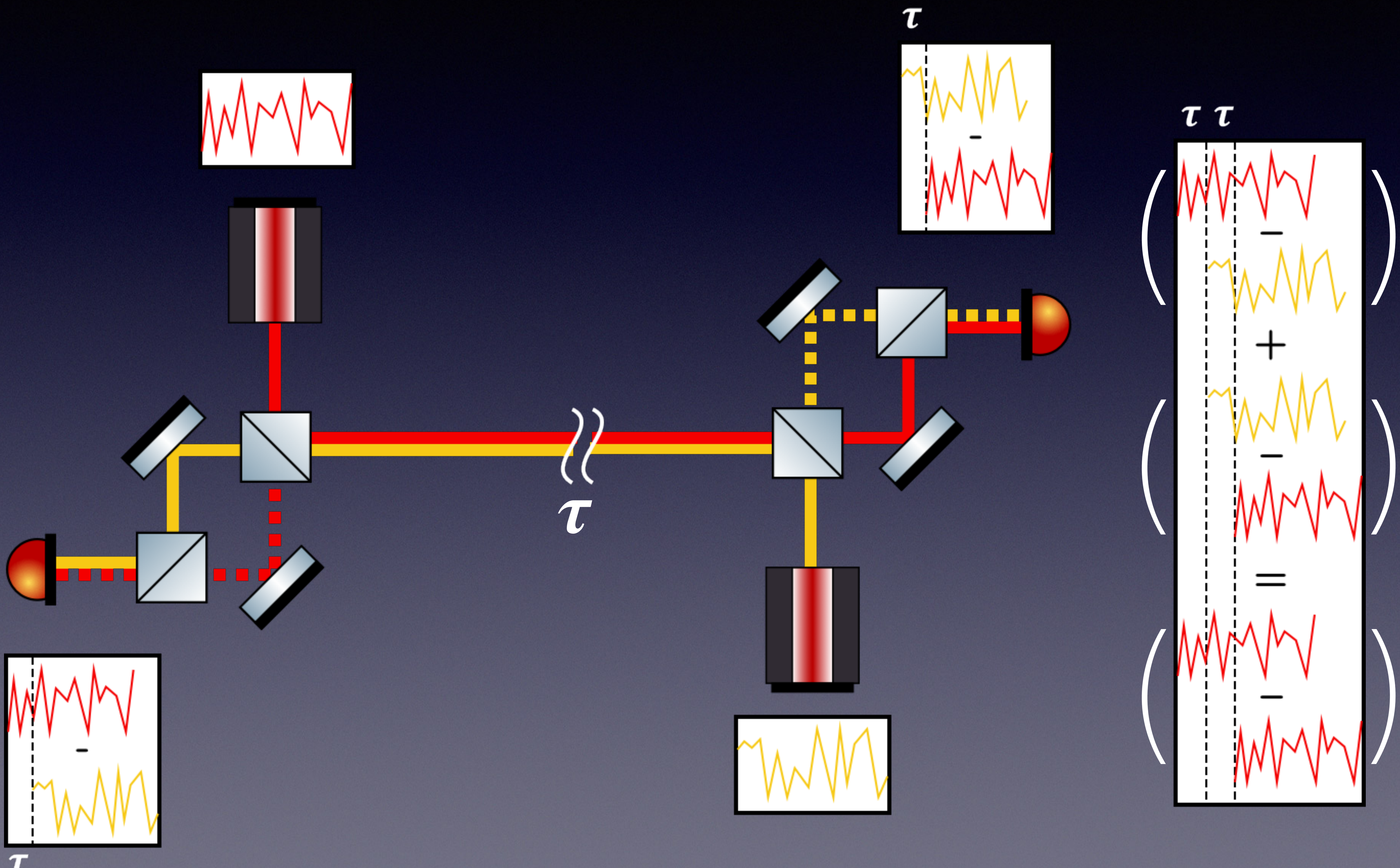
Time-Delay Interferometry



Time-Delay Interferometry



Time-Delay Interferometry

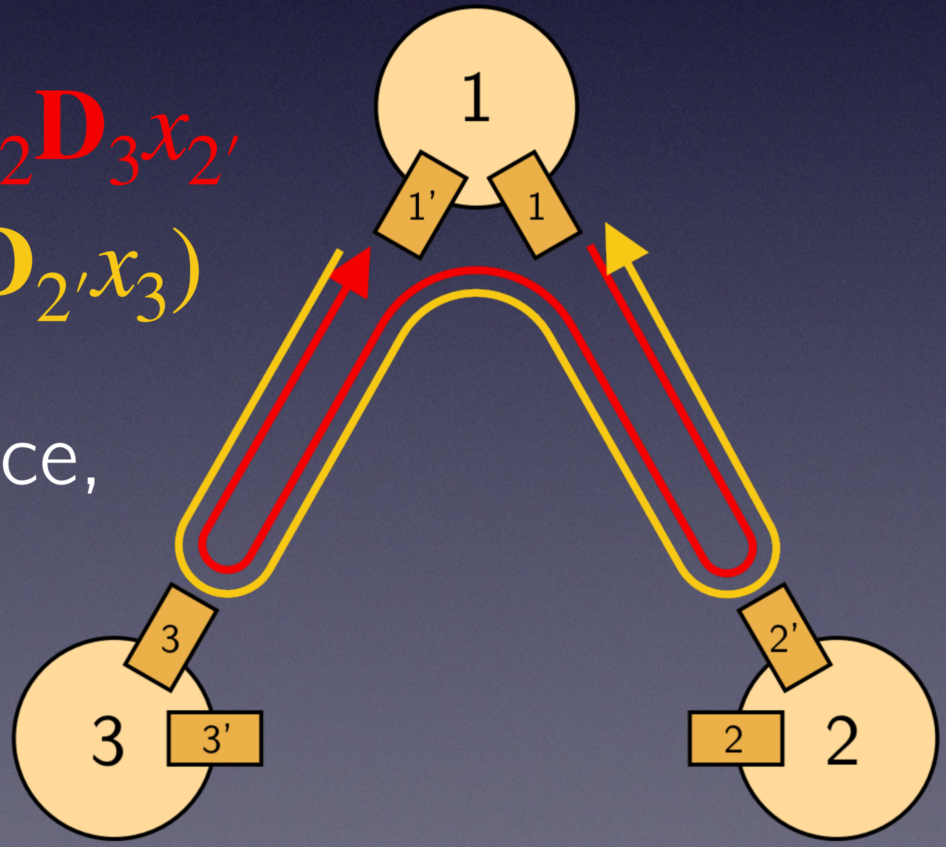


Michelson Combinations

- Synthesize three Michelson-like interferometric measurements X, Y and Z, out of which only two are independent
- First-generation X combination assumes constant armlengths (very wrong), and reads

$$X_1 = x_{1'} + \mathbf{D}_{2'}x_3 + \mathbf{D}_{2'}\mathbf{D}_2 x_1 - \mathbf{D}_{2'}\mathbf{D}_2\mathbf{D}_3 x_{2'}$$
$$-(x_1 + \mathbf{D}_3 x_{2'} + \mathbf{D}_3\mathbf{D}_{3'} x_{1'} + \mathbf{D}_3\mathbf{D}_{3'}\mathbf{D}_{2'} x_3)$$

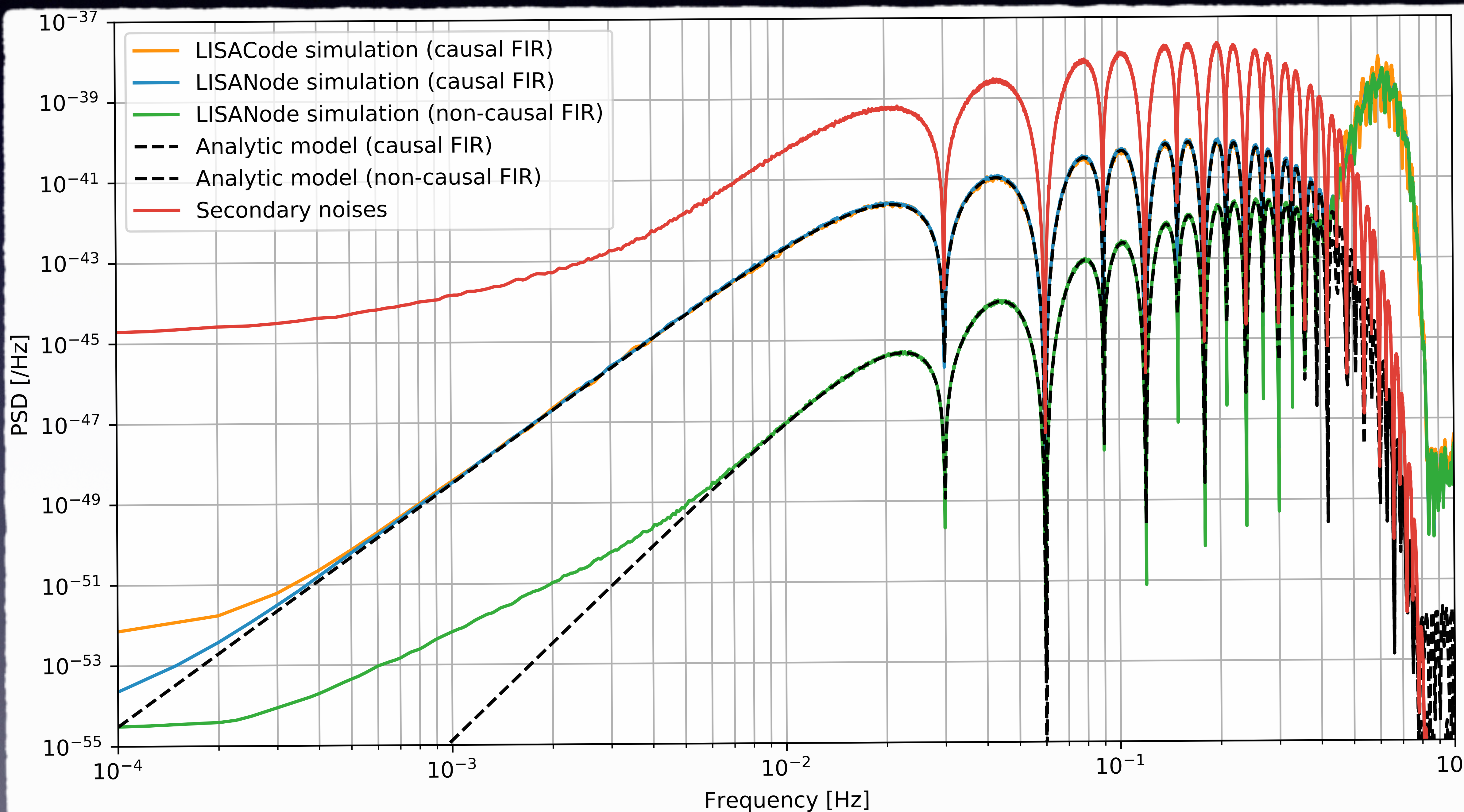
- Second generation senses each arm twice, which reduces linear changes of armlengths to first order



Simulation with LISA Node

- Model latest optical design, with various high-level instrumental noises (laser frequency noise, readout noise, optical path length noise, test-mass acceleration noise)
- Propagation of beams between spacecraft using Lagrange interpolating polynomials, linearly-varying or realistic Keplerian orbits
- **Levels of residual laser noise** not understood although cross-checked with legacy LISACode

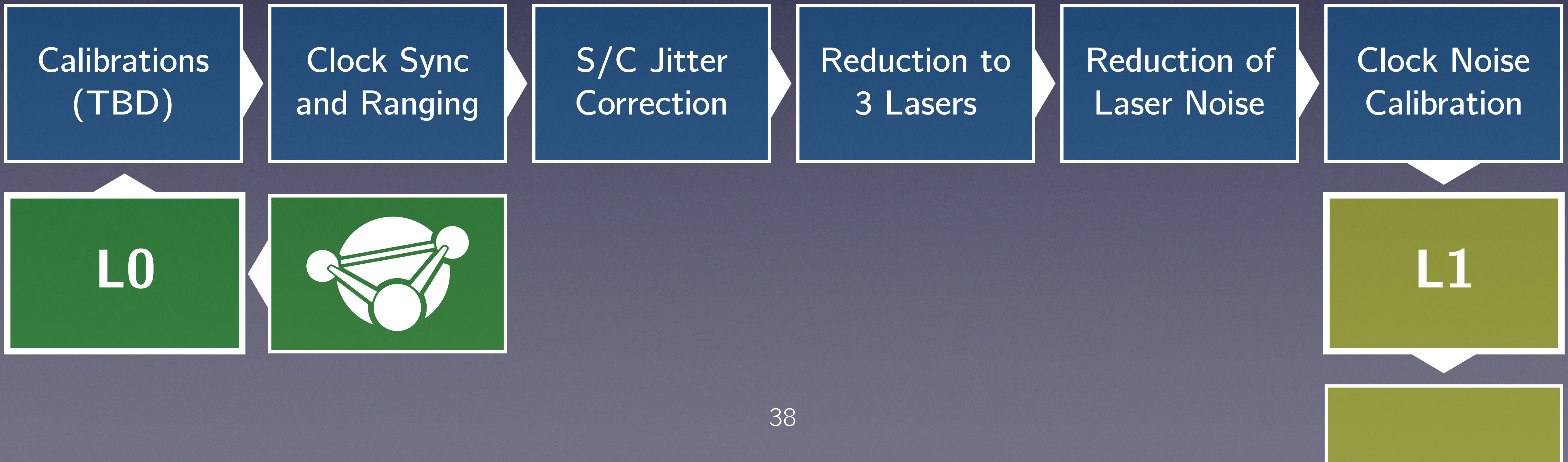
Flexing-Filtering Coupling [Bayle+19]



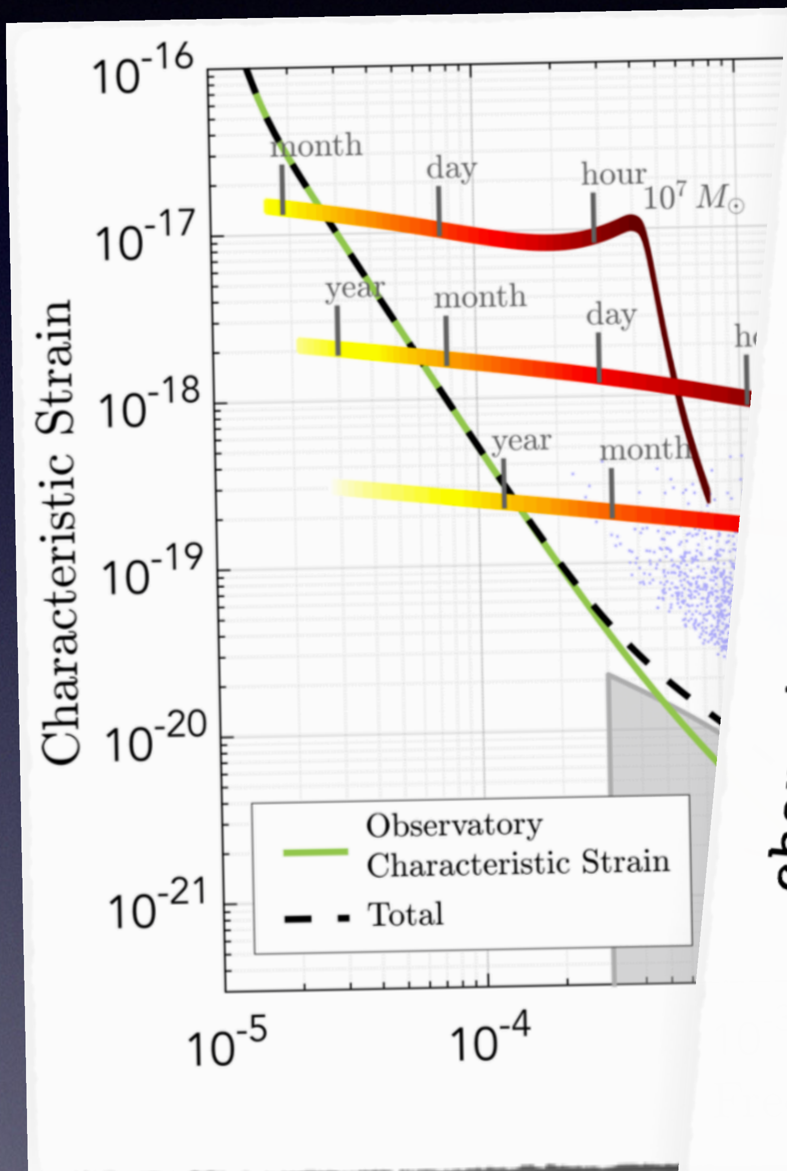
From LISACode and LISANode simulations, TDI X_2, using MRD noise levels

Conclusion

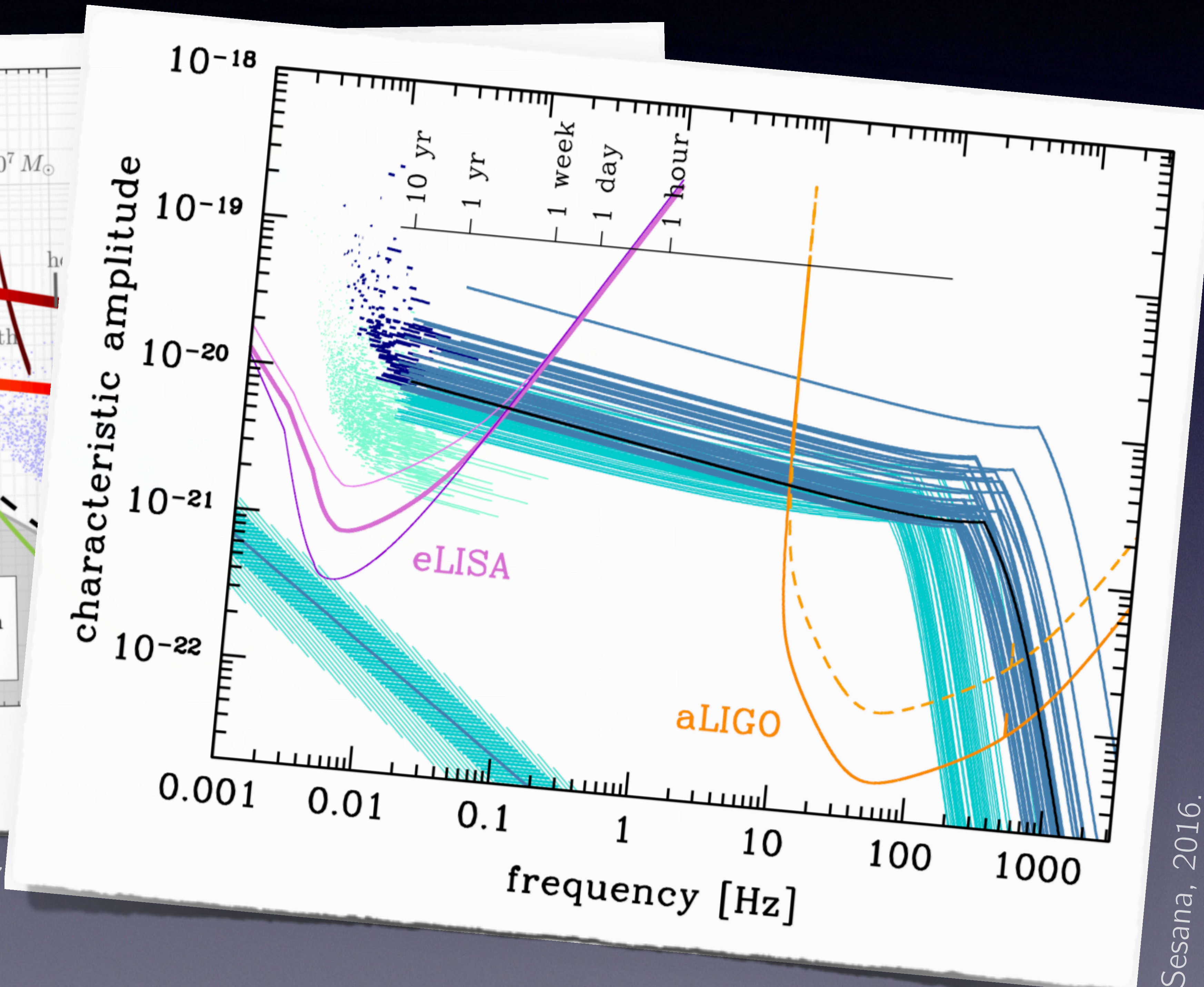
- Long way from interferometric signals to science-worthy data, with many pre-processing steps
- TDI and pre-processing algorithms' performance directly impacts **instrumental design** decisions and data analysis pipelines



Impact on Science



LISA Mission Proposal, 2017



Sesana, 2016.

Thank you.