Gravitational-wave Observations and Detector Improvements

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The 6th KMI International Symposium

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- Introduction
- Summary of GW observations far
- Gravitational Waves Detectors
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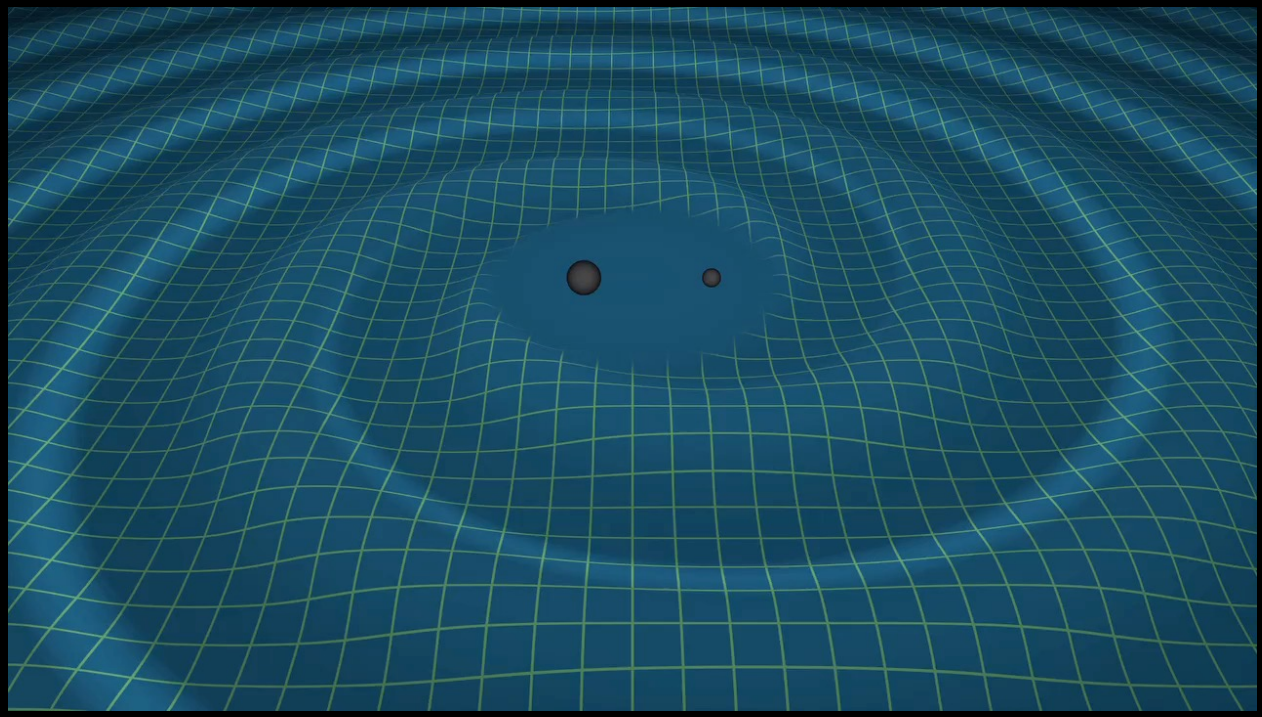
Gravitational Waves

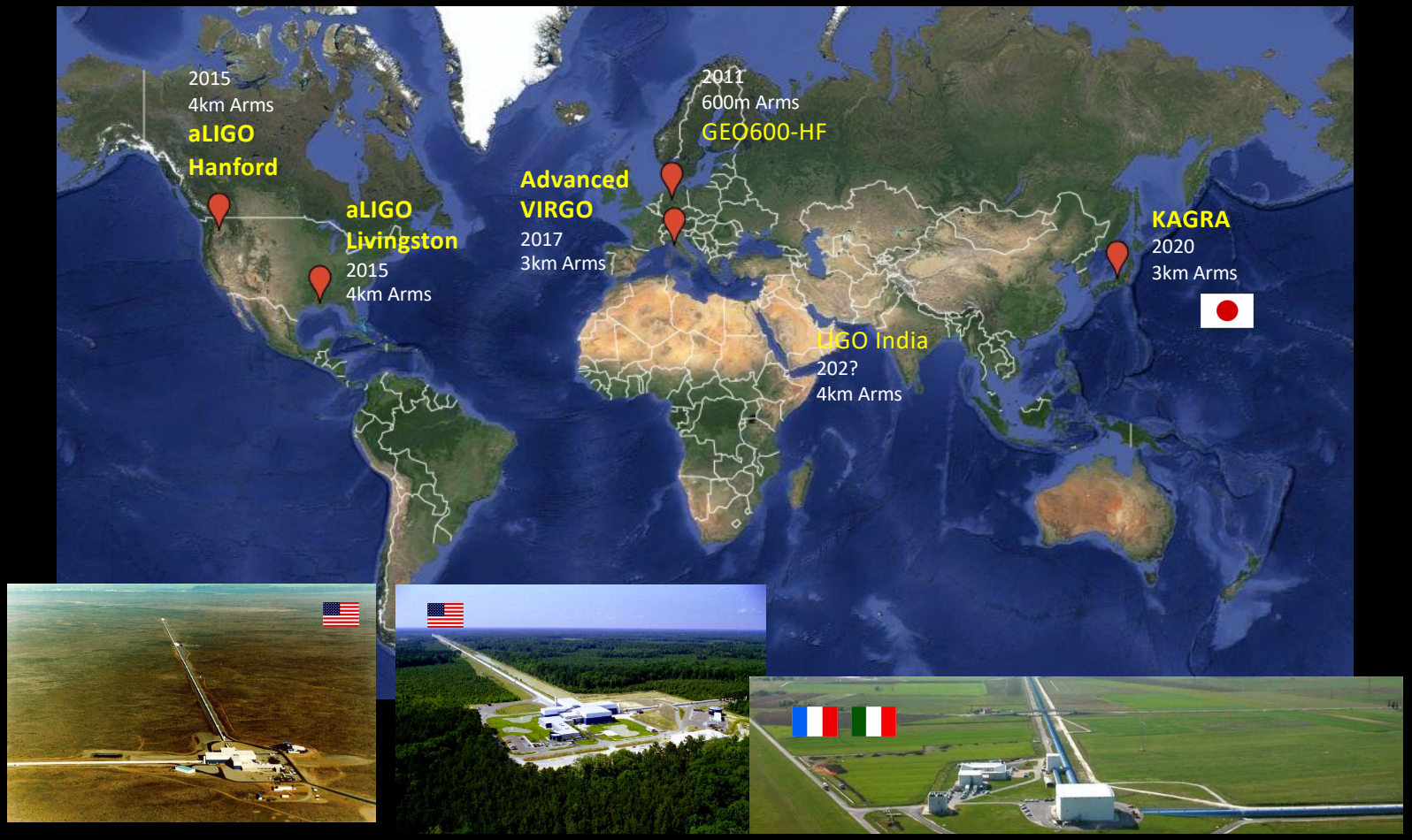
Dynamic distortions of the spacetime

- Emitted when heavy masses move at accelerated speed
- Propagates at the speed of light
- The distortion of the space-time is extremely tiny
- (so it took **100 years** to detect)

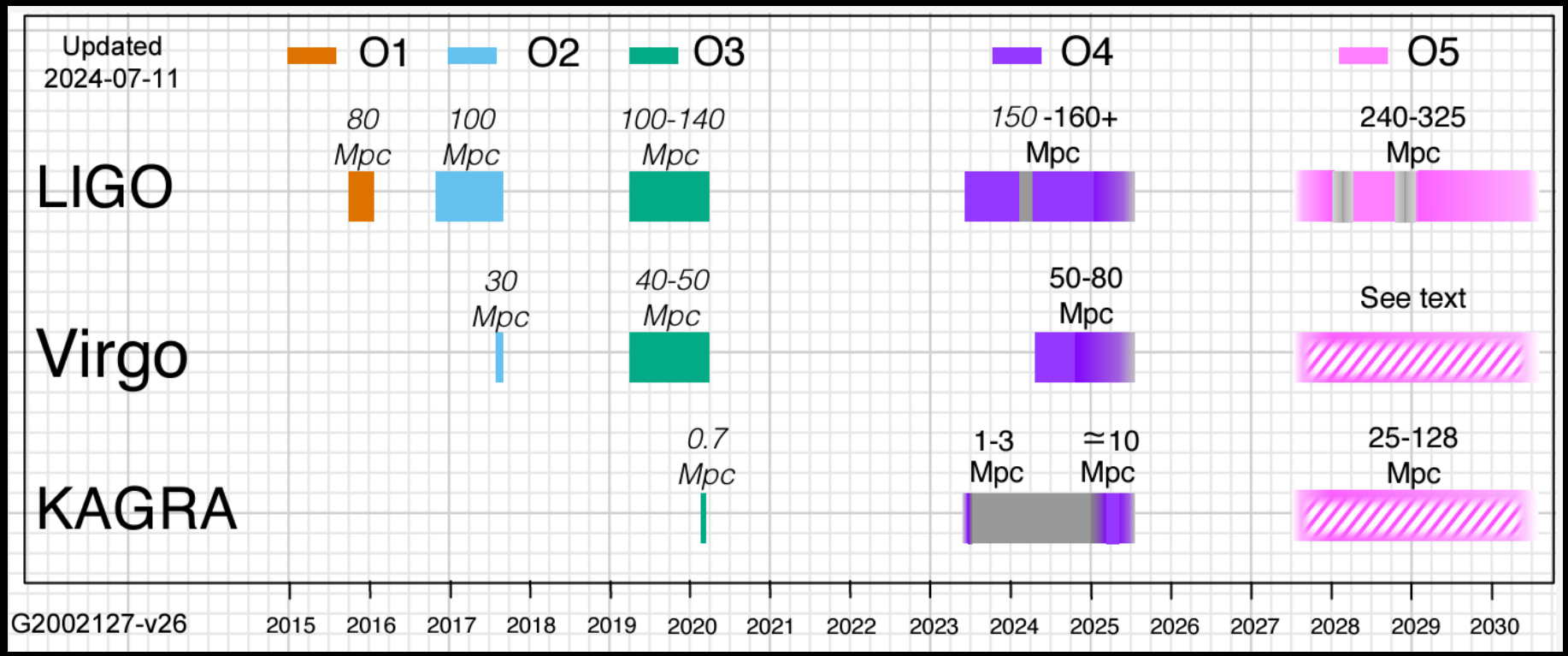


Video Credit: LIGO-VIRGO

Worldwide Detector Network



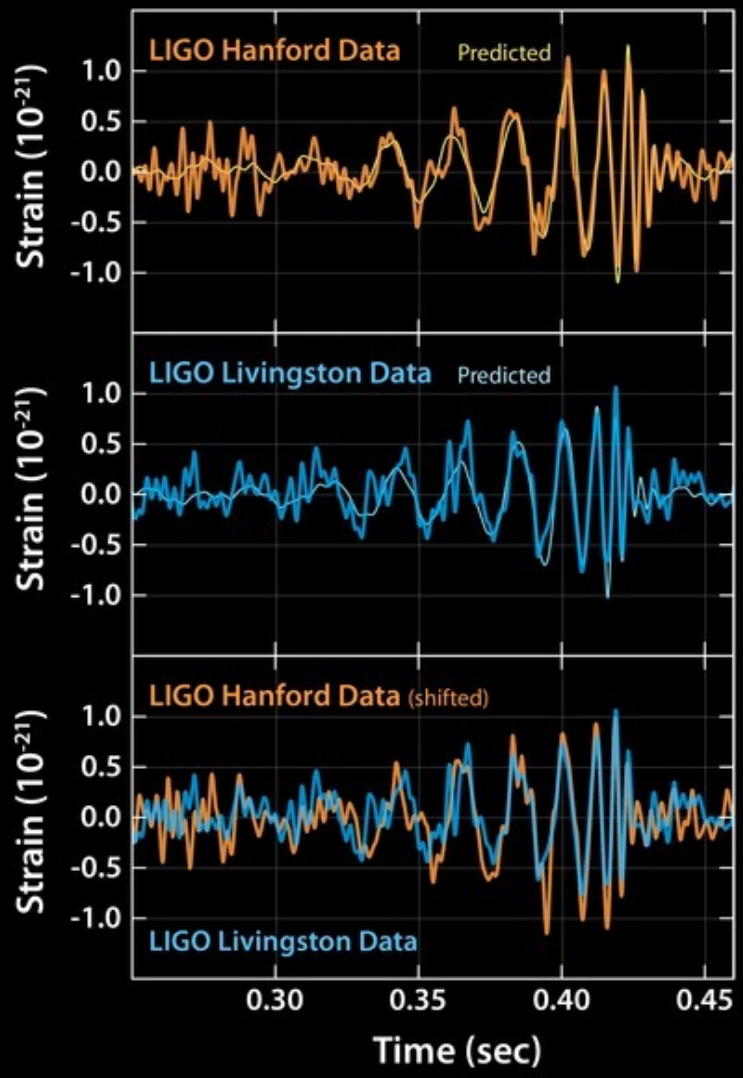
Observation Timeline



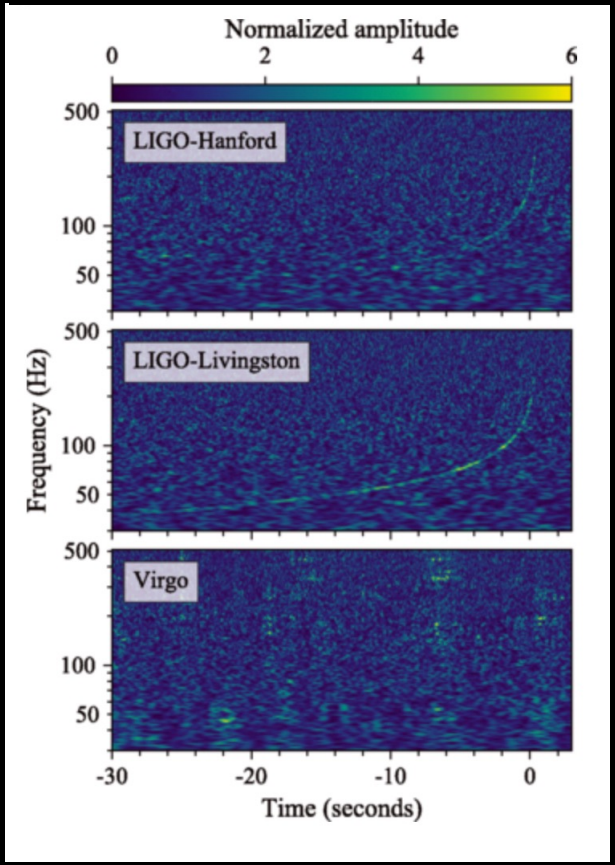
The First Detection

- First gravitational-wave observation
- Waveform did not contradict with General Relativity (even under the strong gravity of BHs)
- First observation of a binary black holes
- First observation of a binary black hole merger
- First confirmation of the existence of 30 $M_\odot$ black hole

Figures: Caltech/MIT/LIGO Lab



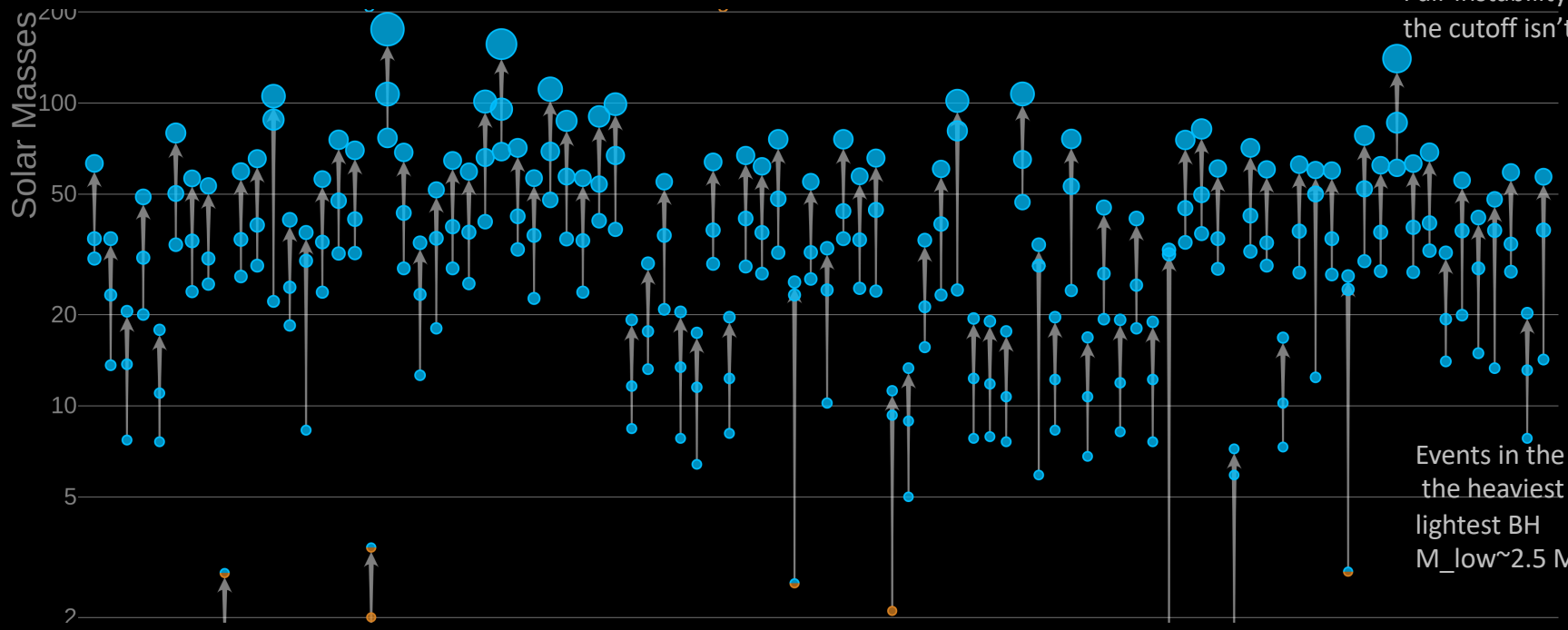
Observing Run 2



- GW170817 (1.1 - 1.6 Msol, 40 Mpc)
- The first NS merger observed by the GW
- The EM counterpart confirmed a connection between the NS merger, kilonova and gamma-ray burst
- The speeds of the GW and light agreed (supporting General Relativity, ruling out some alternative gravity theories)
- Provided an independent Hubble parameter measurement (70^{+12}_{-8} kms^{-1}Mpc^{-1})

Figure: Phys. Rev. Lett. 119, 161101 (2017)

Observing Run 3



Less events due to Pair instability? But the cutoff isn't significant

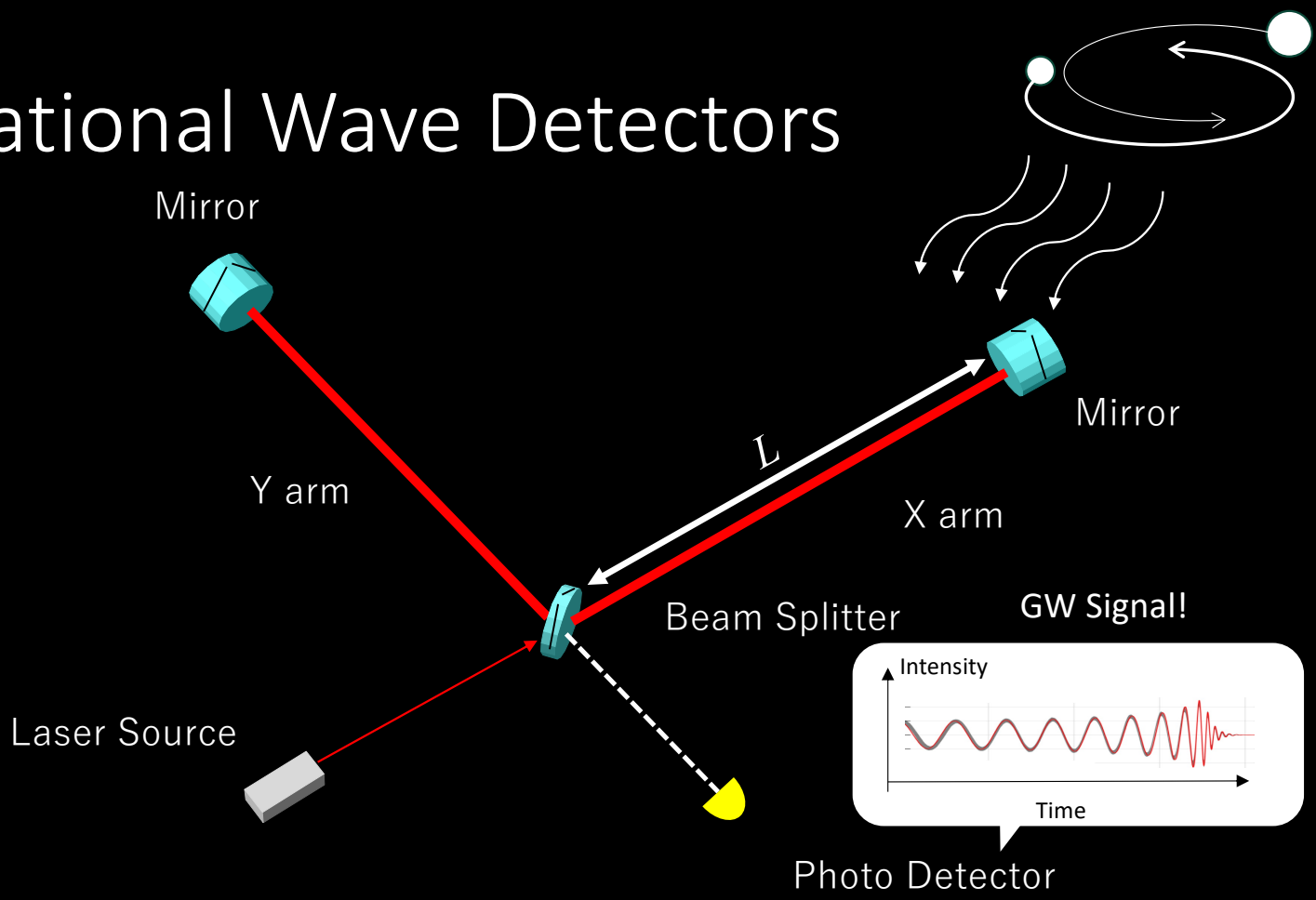
Events in the gap between the heaviest NS and lightest BH
M_low~2.5 Msol

- Broader NS mass distribution
- NS-BH binary
- NSs at the mass gap
- Masses not clear whether NS or BH
- Asymmetry mass binary (1:30)
- Misaligned spin (one's spin vector is on the plane of the orbit)
- Mass ~ 120 Msol (not allowed by a normal stellar evolution)

O4 is Running Now (planned total 22 months)

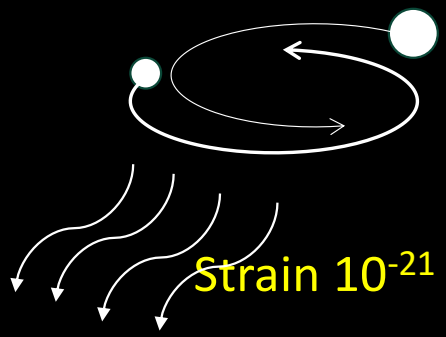
- O4a : 2023/5/24 – 2024/1/16
- O4b: 2024/4/10 – planned 2025/6
- The number of public alerts so far is ~200, getting a candidate every 2-3 days!
- Advanced VIRGO is running at ~80 Mpc
- KAGRA detector plans to join the last few months of O4 at 10 Mpc

Gravitational Wave Detectors

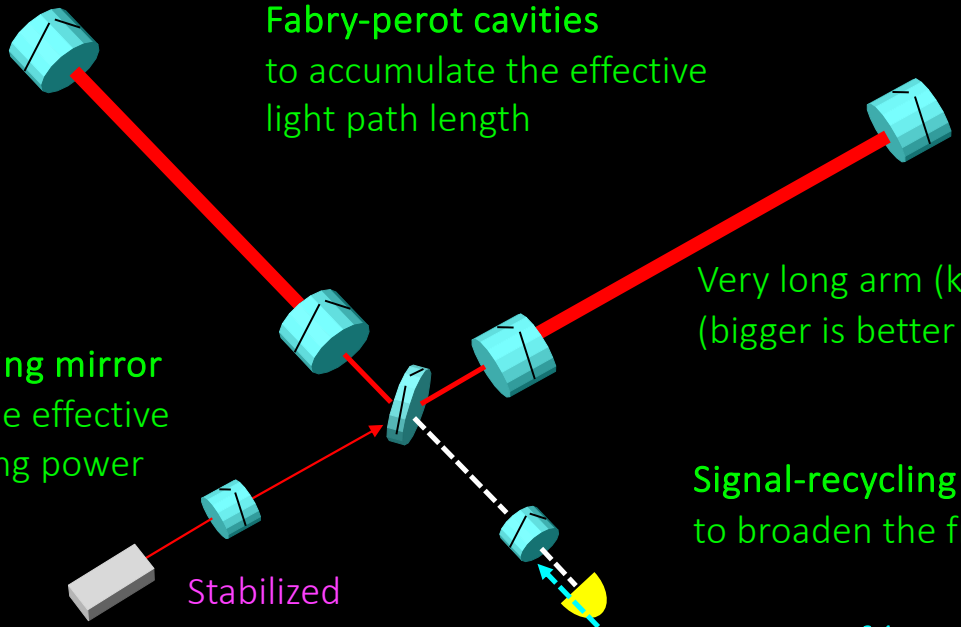


Optical sensor detecting the length difference between X and Y arms
The length difference is the order of 10^{-21} m per m

Actual “Advanced” Detectors



Strain 10^{-21} m/m



Fabry-perot cavities
to accumulate the effective light path length

Very long arm (km)
(bigger is better!)

Power-recycling mirror
to enhance the effective laser circulating power

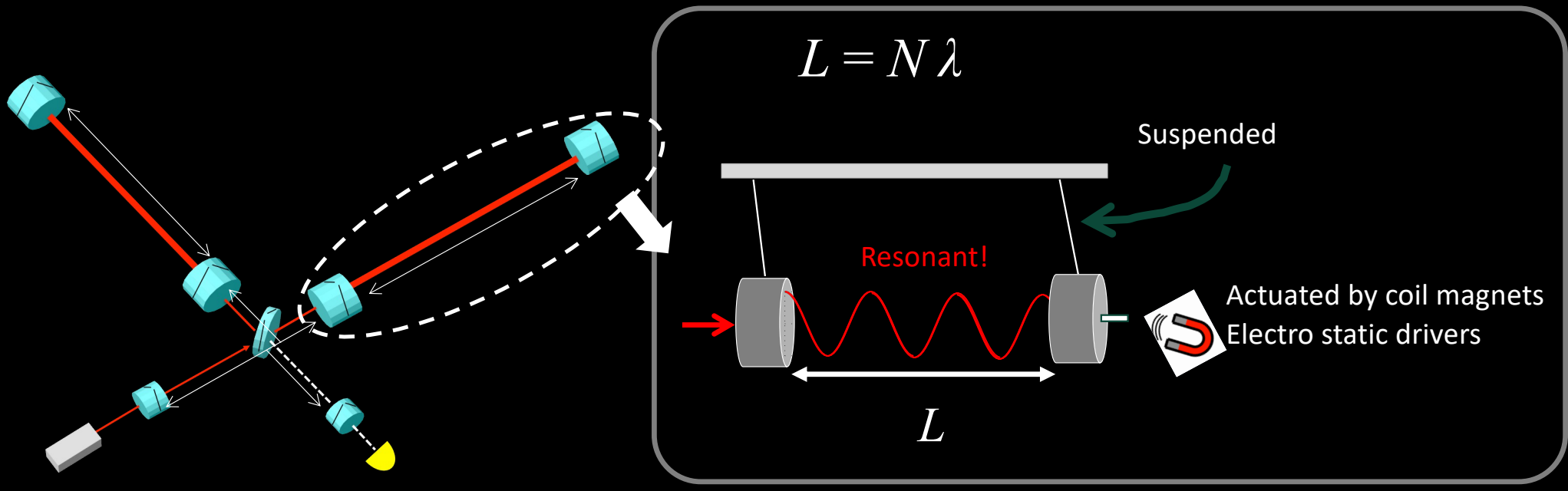
Signal-recycling mirror
to broaden the frequency response to the GW

Stabilized
Laser
order of 100W

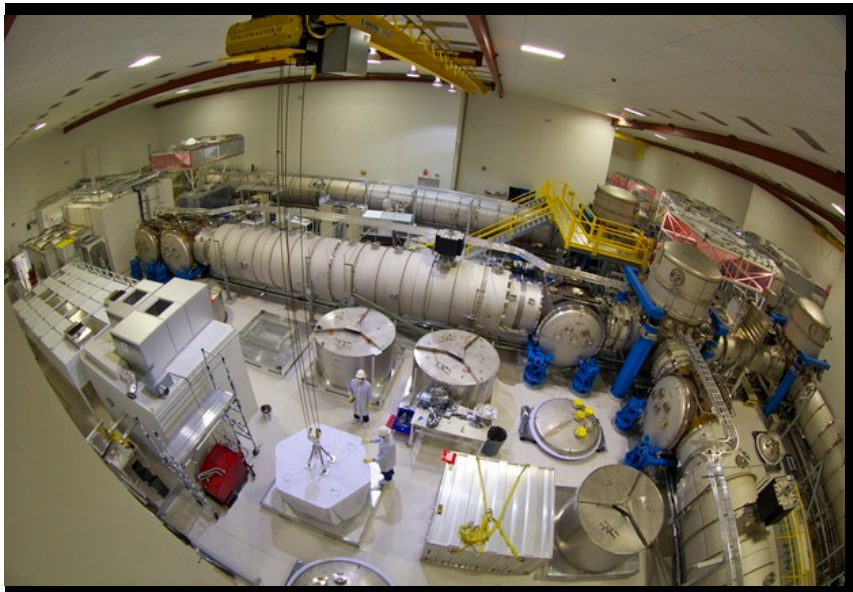
Injection of ‘squeezed vacuum’
to reduce the quantum noise

Key to Operation: Interferometer Control

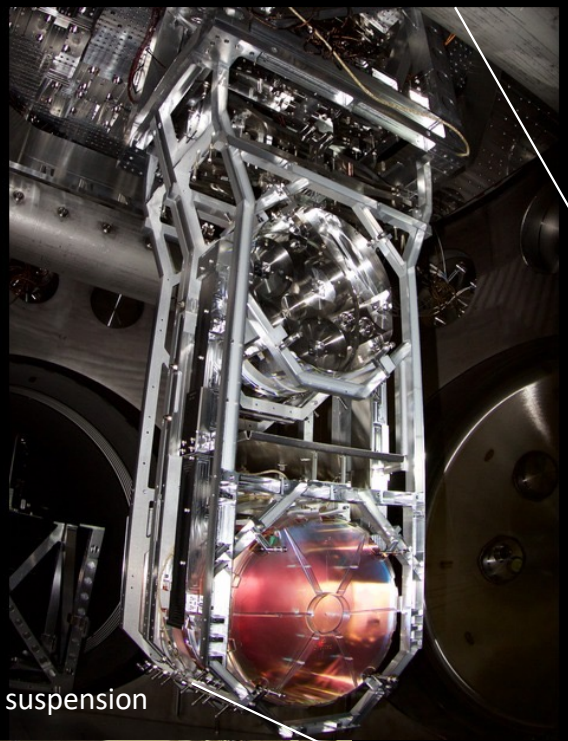
Distances between the mirrors must be controlled so that the laser light resonates in the cavity. We control them in the order of the laser wevelength (1064nm)



First stable operation was accomplished in 2014

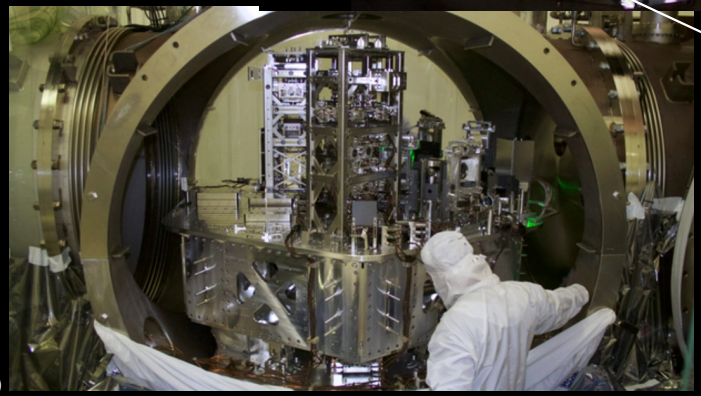


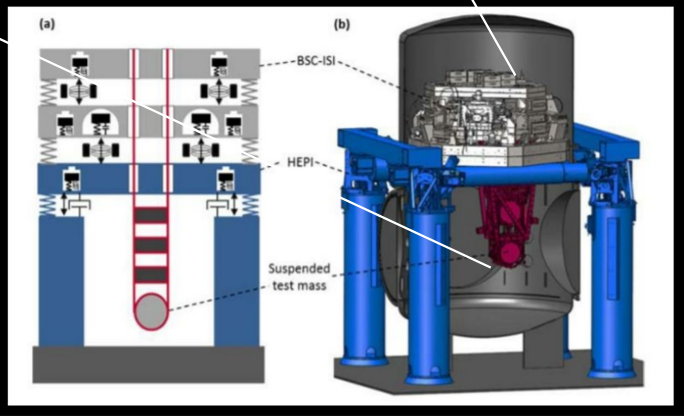
Electronics for detector control and data acquisition



Quadruple suspension

Seismic isolation stage





all photo credit: Caltech/MIT/LIGO Lab

Cycles of Detector Upgrades

image credit: LIGO/Virgo/KAGRA

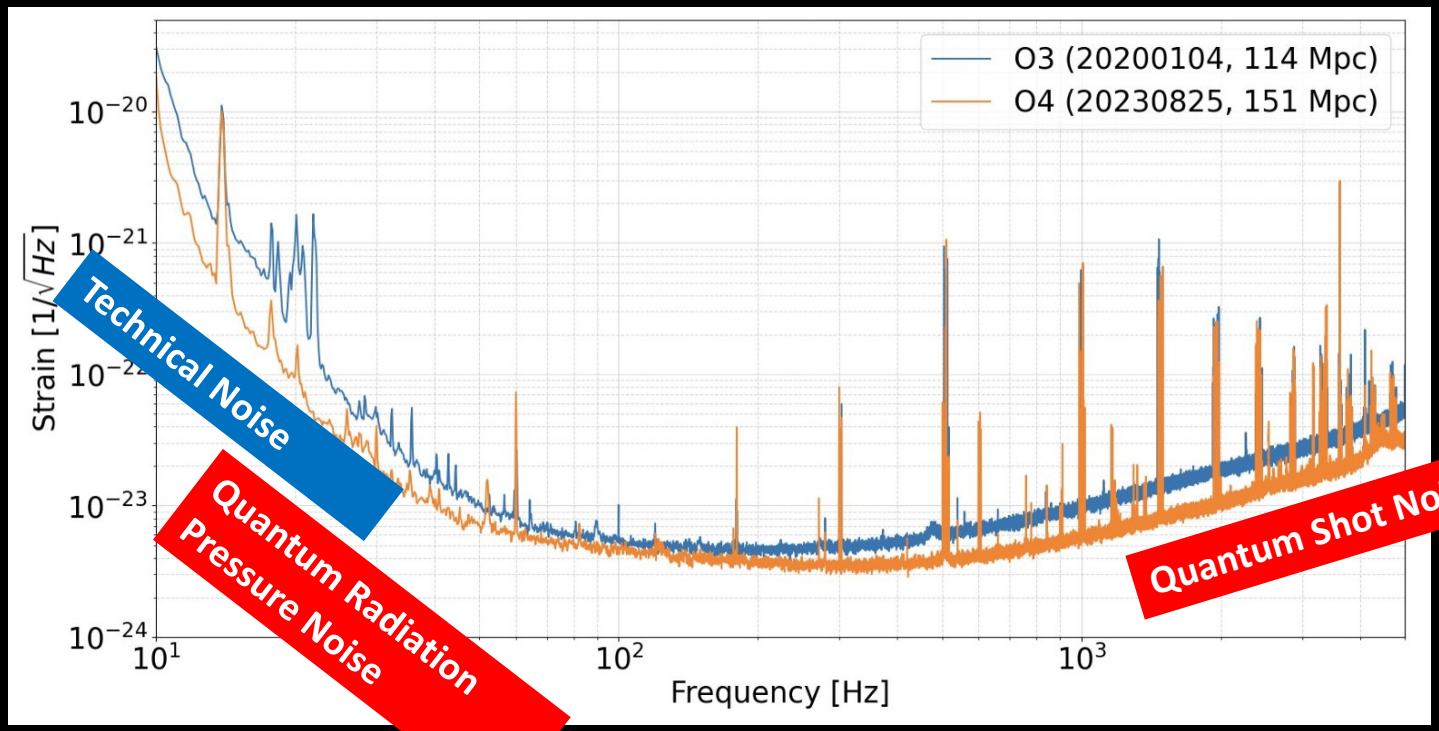
Detector Sensitivity (O3 to O4)

BAD

Sensitivity

Good

A Effler, LIGO-G2301945 (Hanford example)

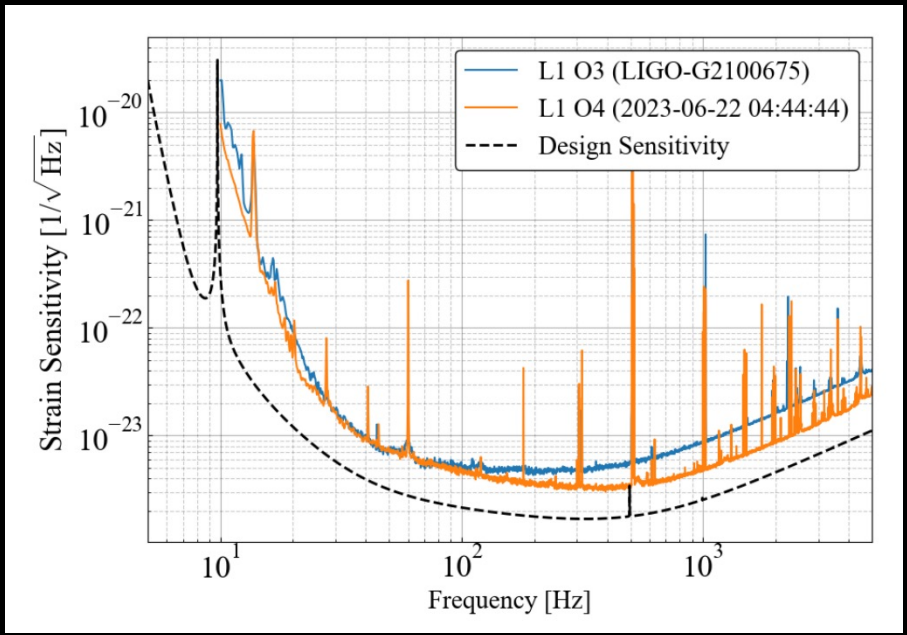


Heavier sources

Lighter sources

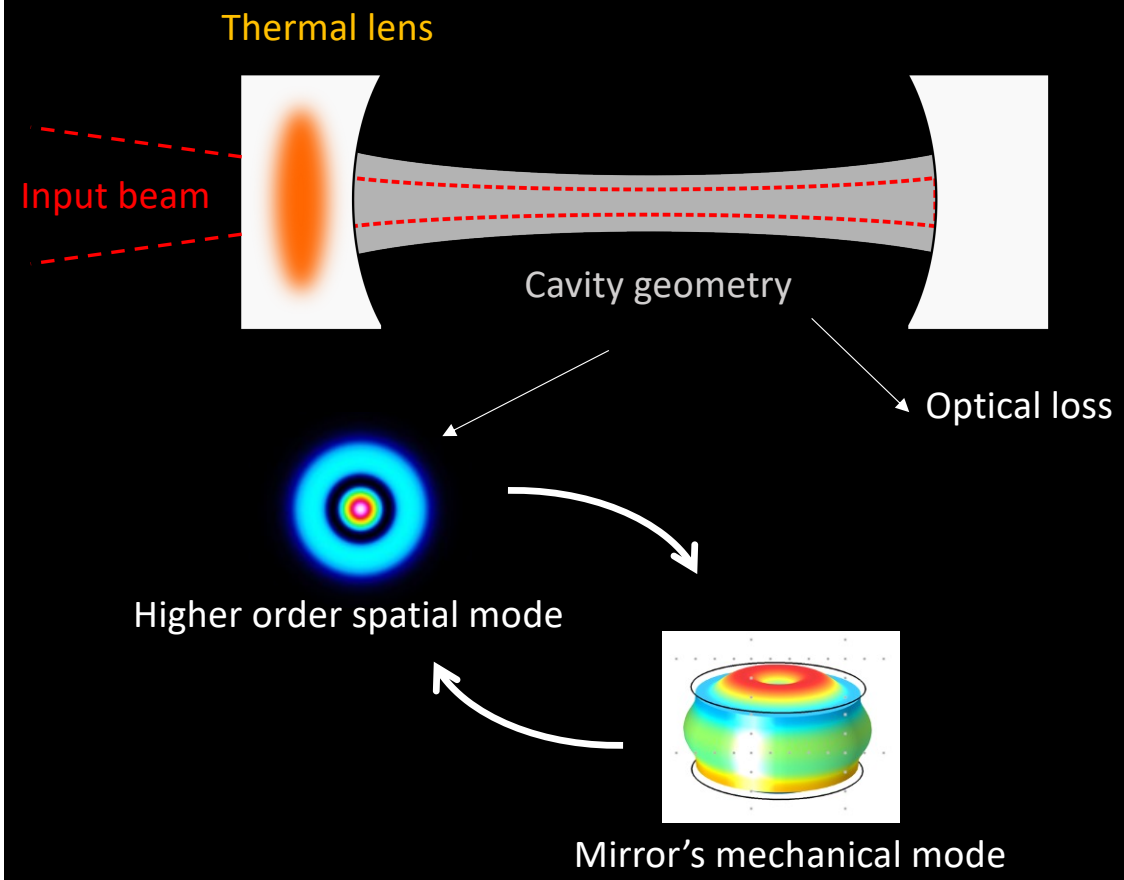
Planned Detector Commissioning for O5

- Period: from later 2025 (likely from 2026) for about 2 years
- The design sensitivity will be achieved
- Higher laser power (Max 750 kW), Test mass replacements (new coating), Balanced homodyne readout scheme
- Expected sensitivity approx. 300 Mpc for BNS mergers
- Advanced VIRGO will also be upgraded



K Tsuji, NU master thesis (2025)
L Barsotti, LIGO-T1800042-v5
E Goetz LIGO-G2100675

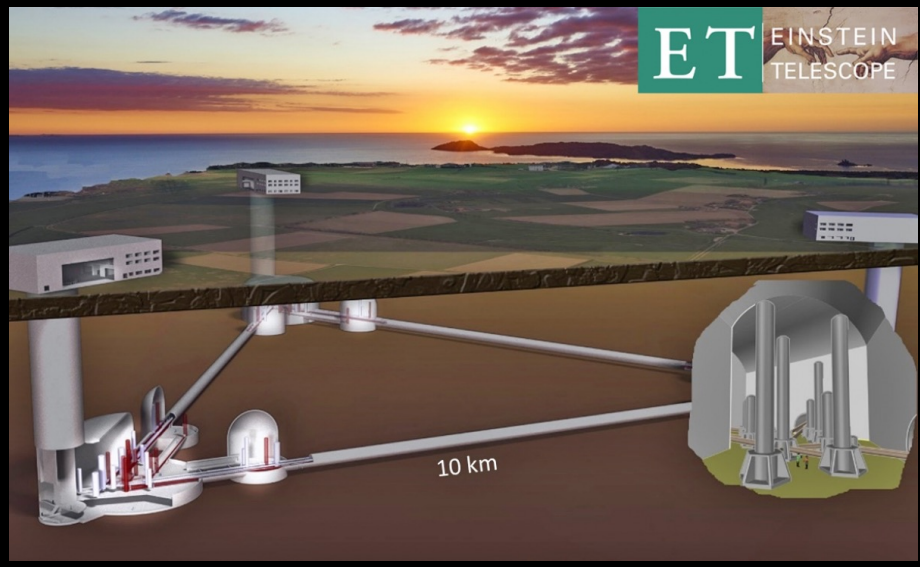
Thermalized Interferometer (Nagoya research)



- Thermal lens is formed inside the mirror substrate and changes the cavity geometry
- The interferometer control is disabled as the interferometer mirrors are warmed up.
- Working on the ifo model to be able to tune the controls, incl. thermal actuators

K Tsuji, NU master thesis (2025)

Next-gen Ground-based Detectors



40 km, large masses, higher power

10 km, a pair of detectors with a high power one and low power and cryogenic one

x10 sensitivity at all frequencies, enabling the observation beyond the local universe
R&Ds are funded in the US, UK, and elsewhere; Prototype in Netherland
Also, LIGO India (copy of aLIGO) is funded and to be constructed