# Ground-based Gravitational-wave Detectors: Status and Upgrades

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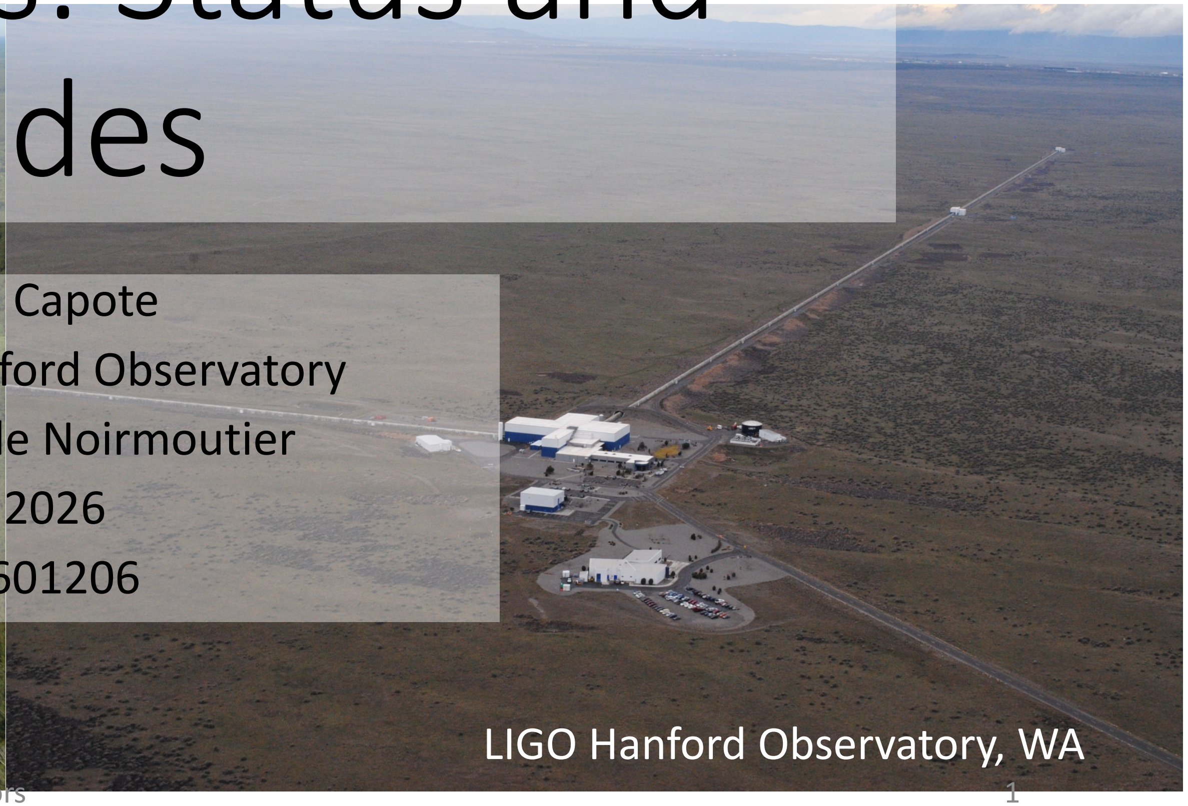


# Basics of Gravitational Wave Detection

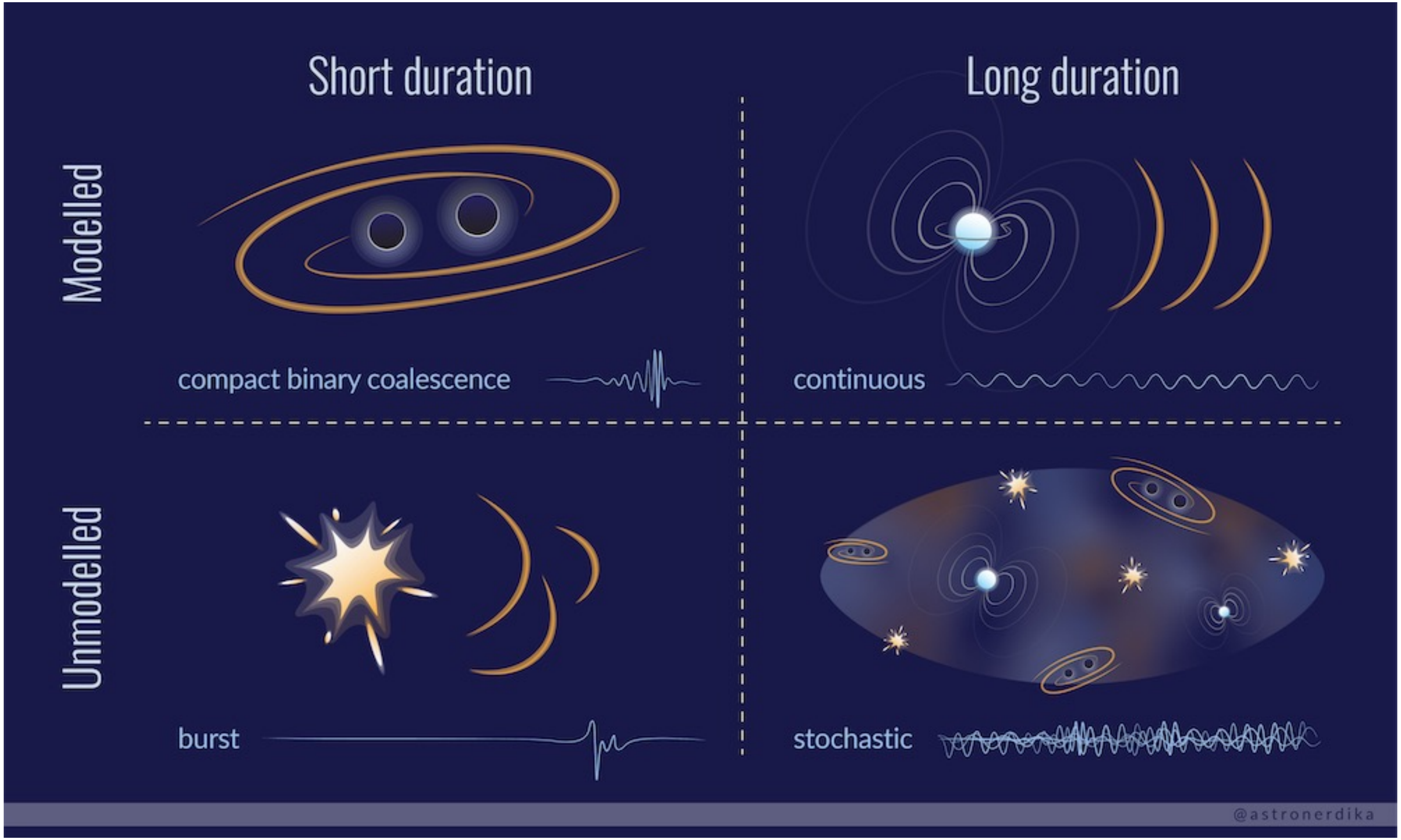
Gravitational waves are ripples in spacetime generated by accelerating masses with a non-constant quadrupole moment

$$h(t) = \frac{\Delta L}{L} \cong \frac{G}{c^2}\frac{M}{d}\left(\frac{v}{c}\right)^2$$

Gravitational wave strain (stretching and compressing of spacetime) can induce a displacement on the order of $10^{-19}$m over a km baseline

**Ground-based GW detectors use heavy test masses and a 3-4 km baseline to detect gravitational waves**

# GW Sources

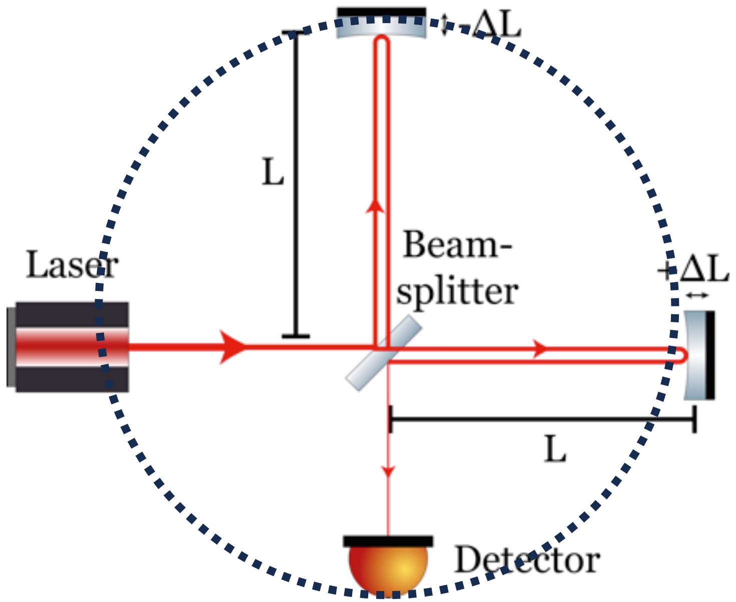

Short duration
Long duration
Modelled
Unmodelled
compact binary coalescence
continuous
burst
stochastic
@astronerdika

# Basics of Gravitational Wave Detection

Lasers allow us to measure displacement on the order of $10^{-19}$m!

Central topology: Michelson Interferometer

- ➢Operated on the dark fringe



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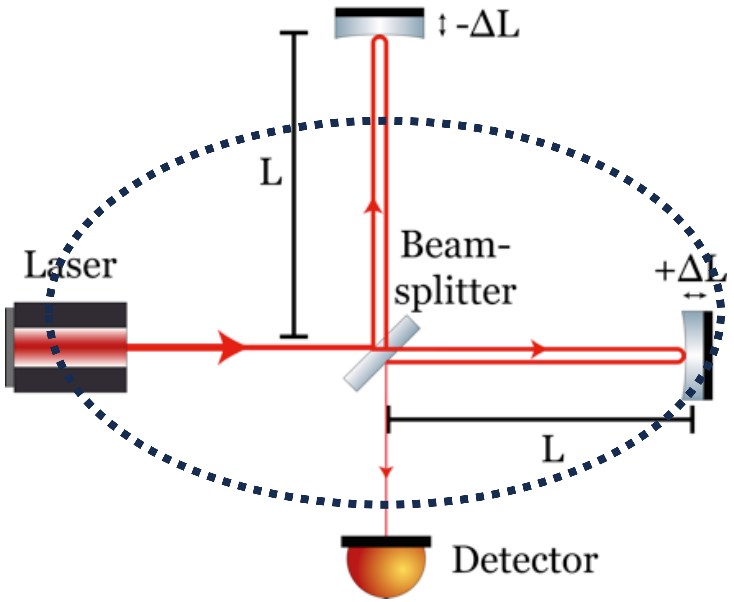

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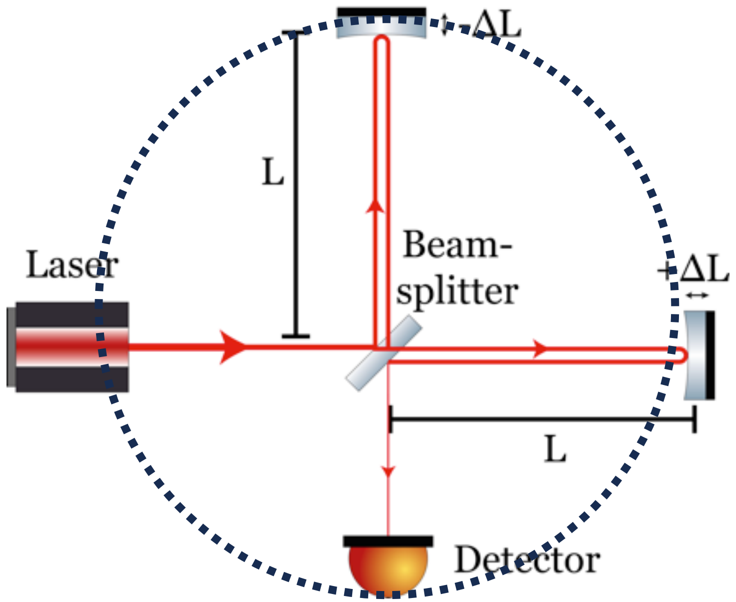

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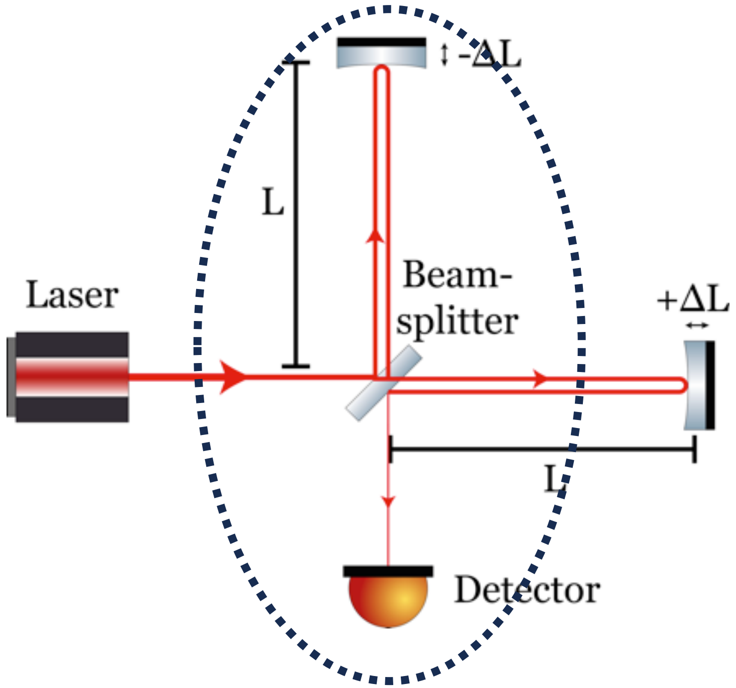

# Basics of Gravitational Wave Detection

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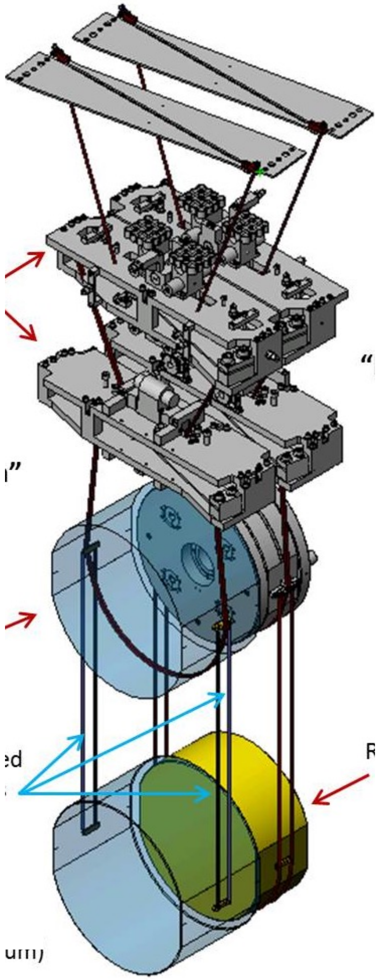
Test masses

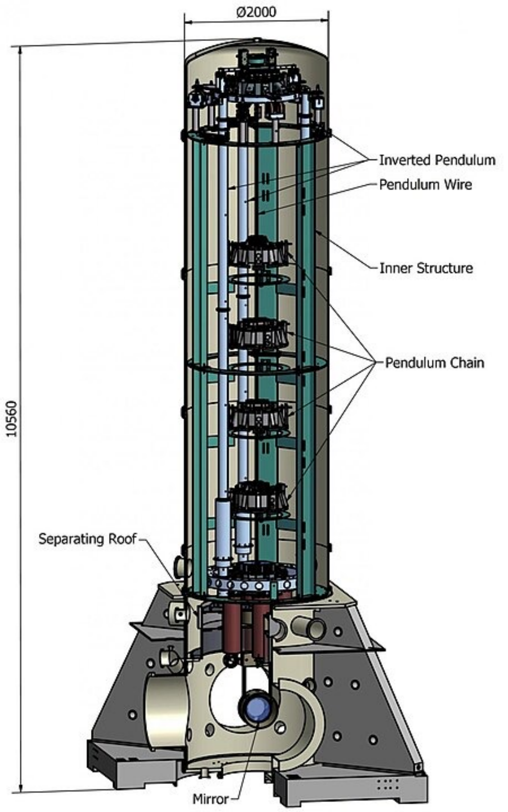
- suspended heavy mirrors (10-40 kg!)

Seismic isolation and multi-stage suspensions

- Isolate mirrors from ground motion



LIGO Quadruple Suspension

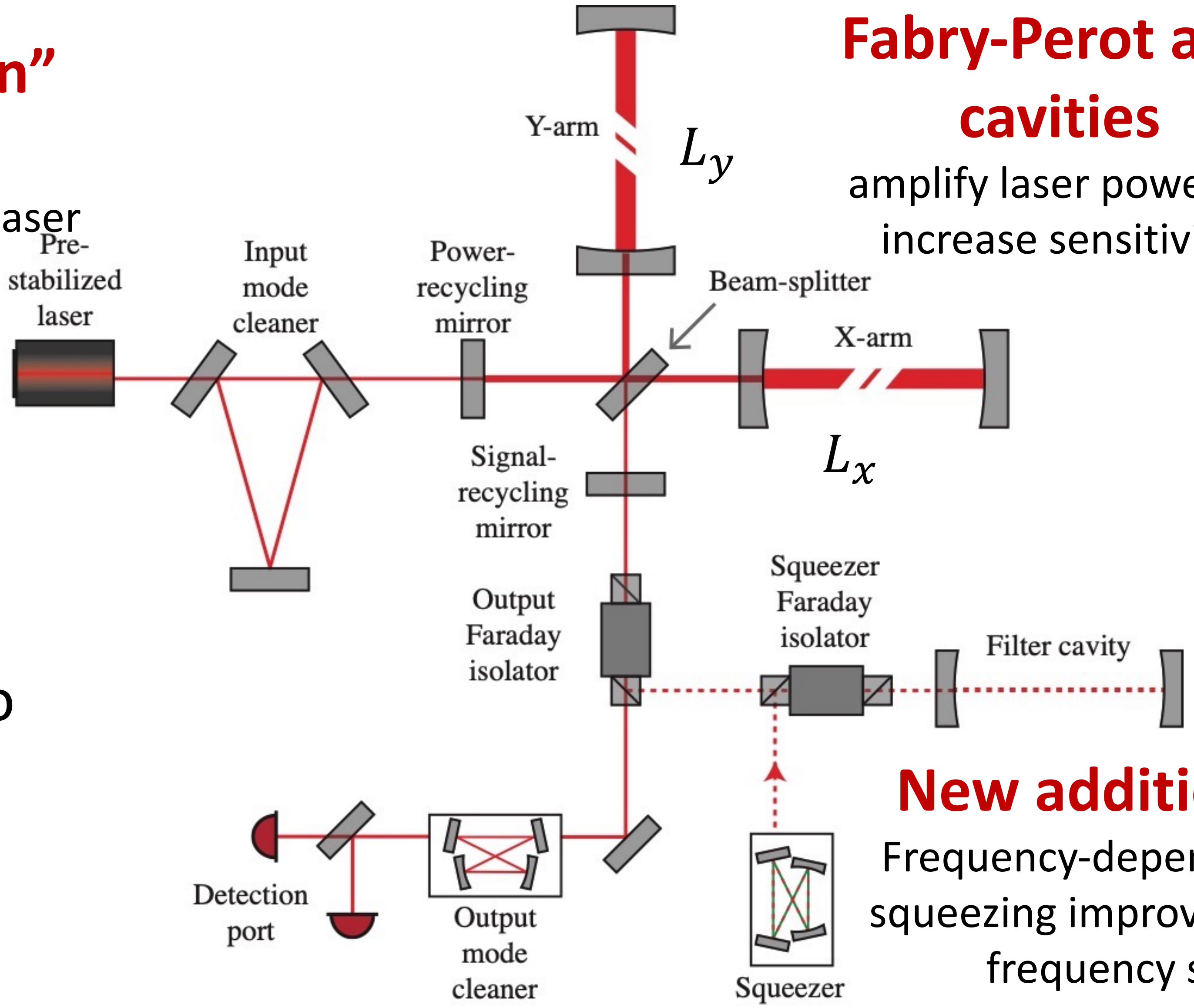



Virgo Superattenuator

# Advanced Detector Optical Layout

## "Dual-recycled Michelson" technology

Power and signal recycling increase laser power and detector bandwidth




## Fabry-Perot arm cavities

amplify laser power to increase sensitivity

GW signal couples to

## Differential Arm Length (DARM)

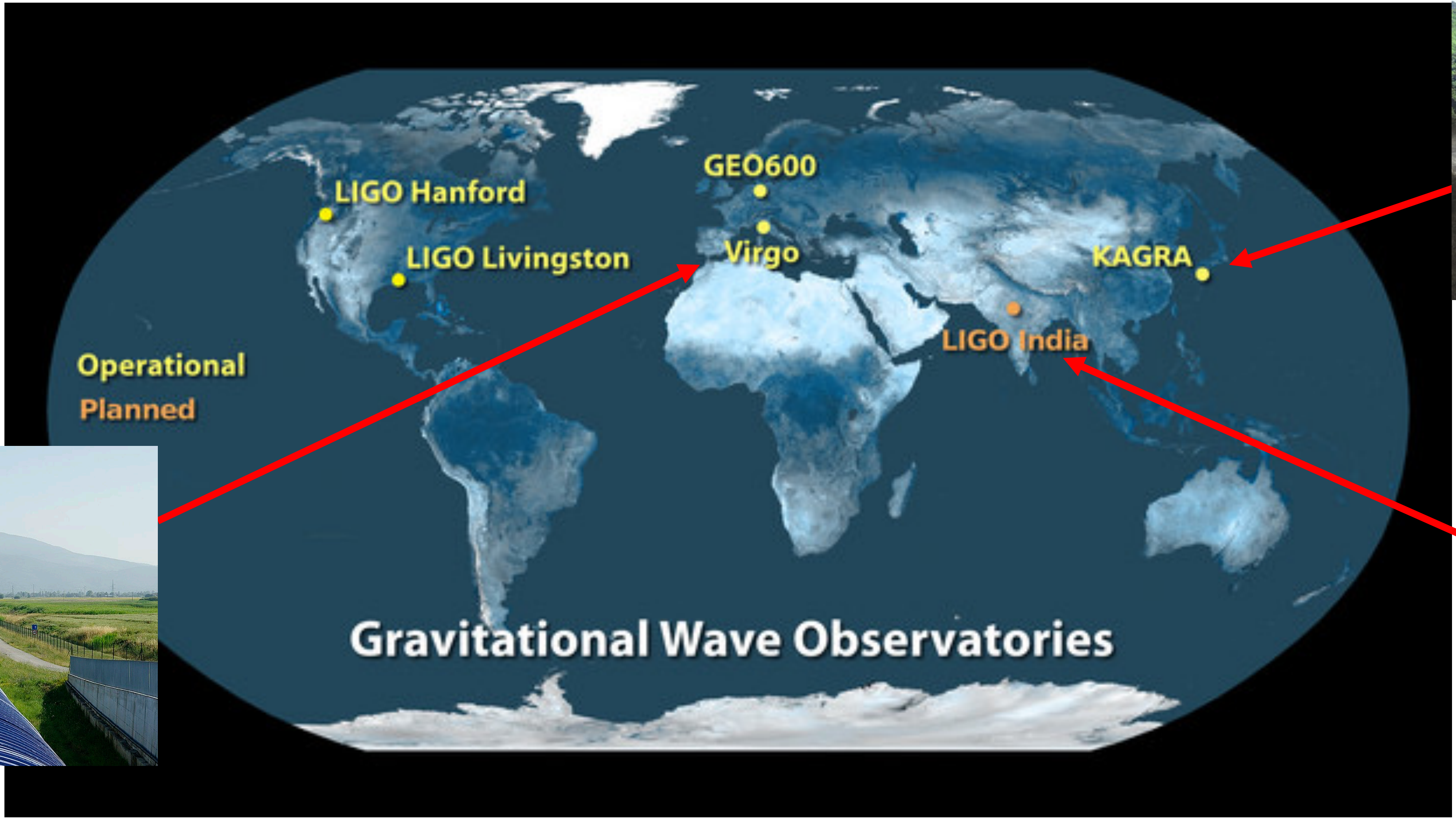
$$\Delta L = L_x - L_y$$

## New addition for O4!

Frequency-dependent quantum squeezing improves low and high frequency sensitivity

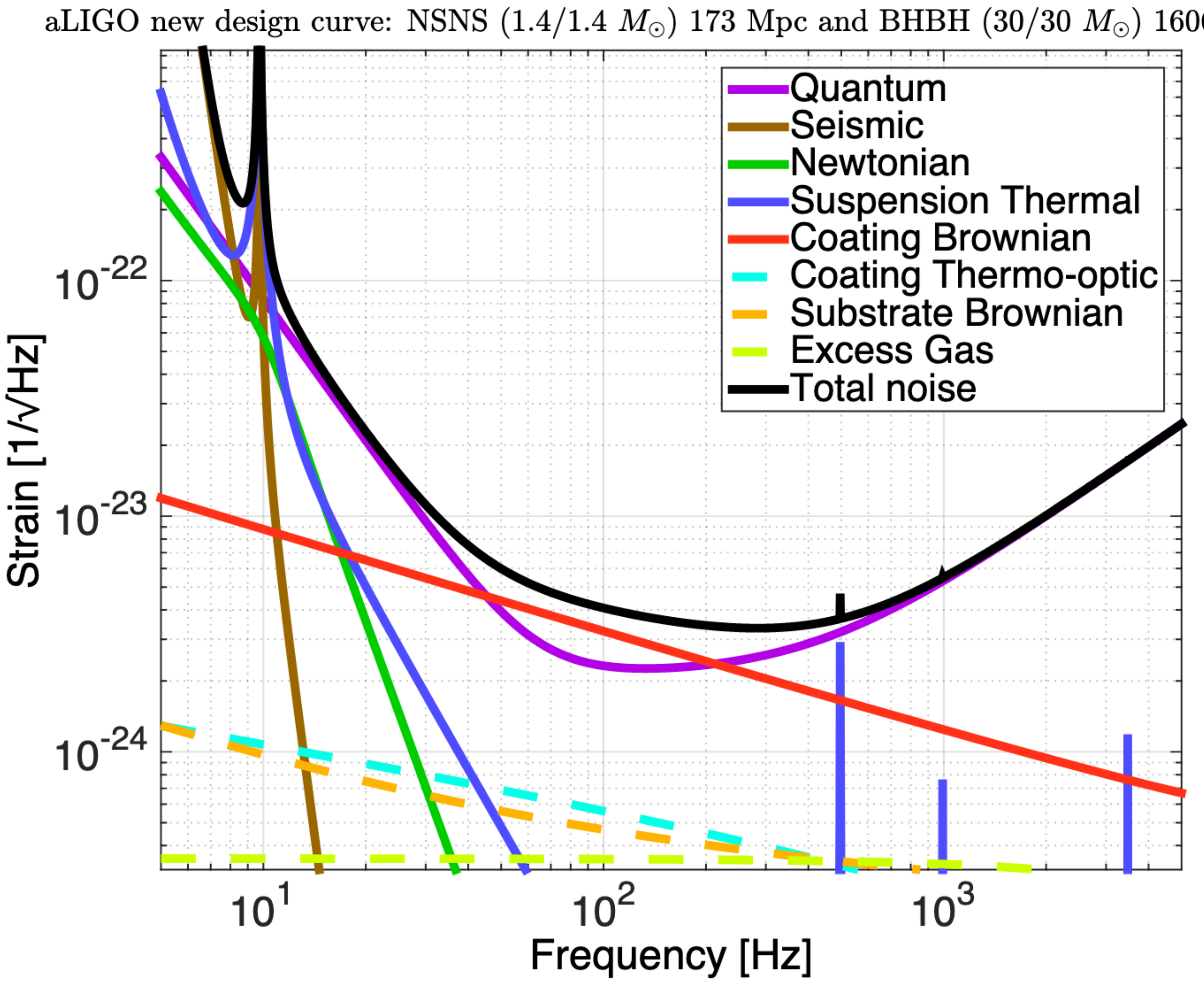
# International GW Detector Network

Cryogenic GW detector, underground!




Just broke ground for construction!

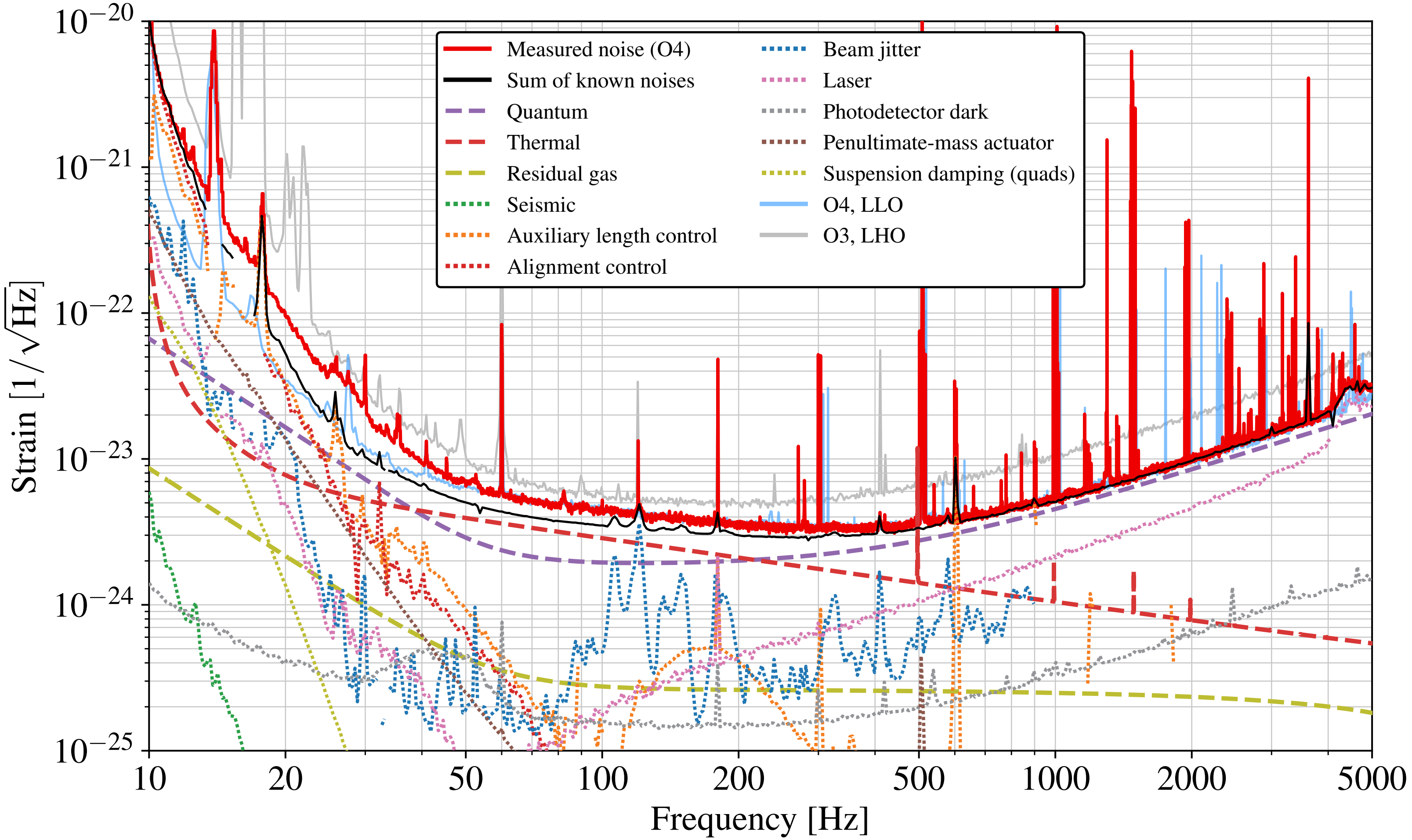
# Detector Noise: Design




"Fundamental" noise sources

- ➢ Sets the limit on what sensitivity a particular detector design can achieve

# Detector Noise: Reality




Example noise budget from LIGO Hanford

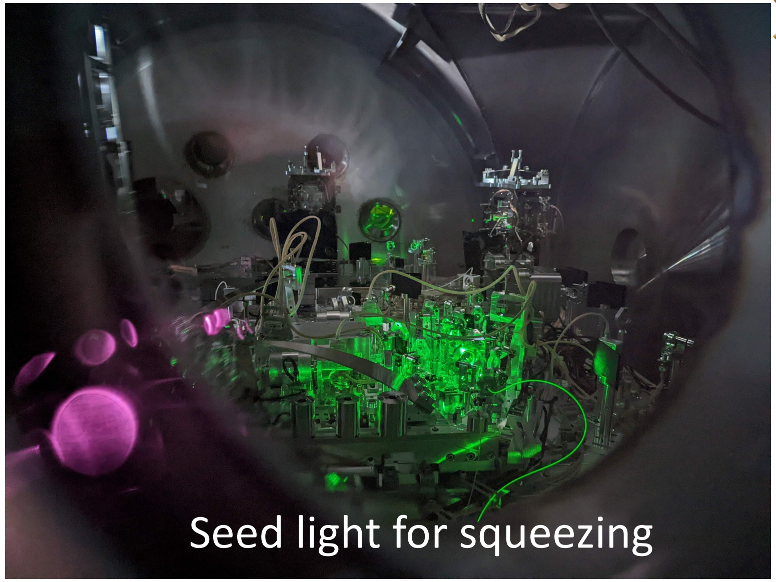
- ➢ Includes "technical" noise sources
- ➢ Not all noise sources are understood!

Capote, Jia, Aritomi, Nakano, Xu et al., Phys. Rev. D 111, 062002

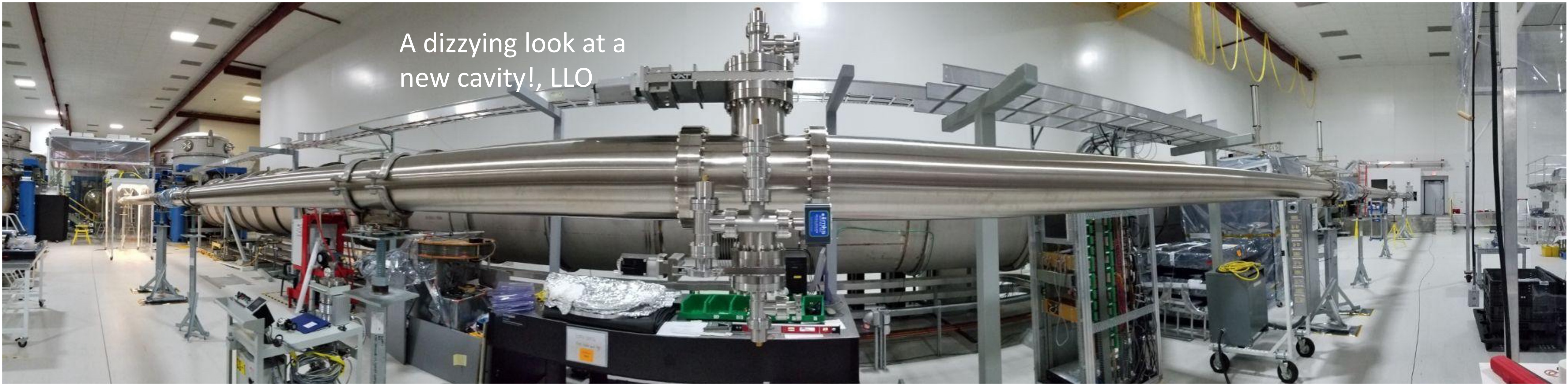
# Quantum Noise

Upgrading the laser, LLO

Quantum noise reduction is achieved through high circulating arm power and high levels of **quantum squeezing**



Seed light for squeezing



A dizzying look at a new cavity!, LLO

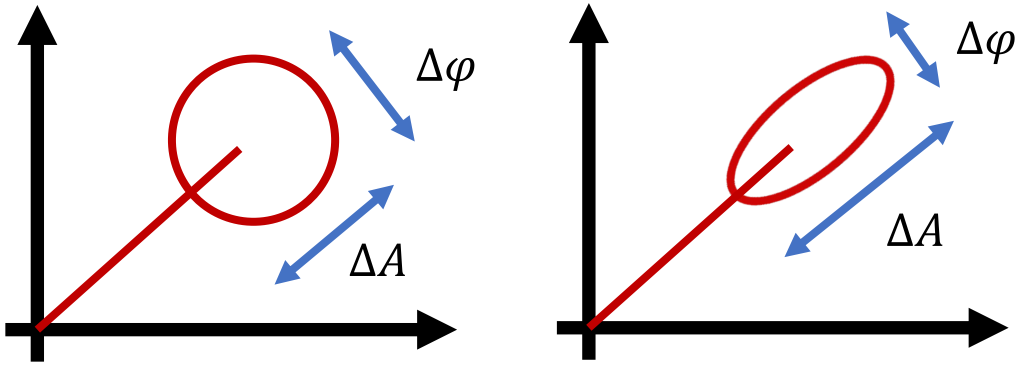
# What is Squeezing?

Quantum noise limits gravitational wave detector sensitivity

- Shot noise at high frequency (>~80 Hz)
- Radiation pressure noise (<~80 Hz)

This noise results from the phase and amplitude uncertainty of light

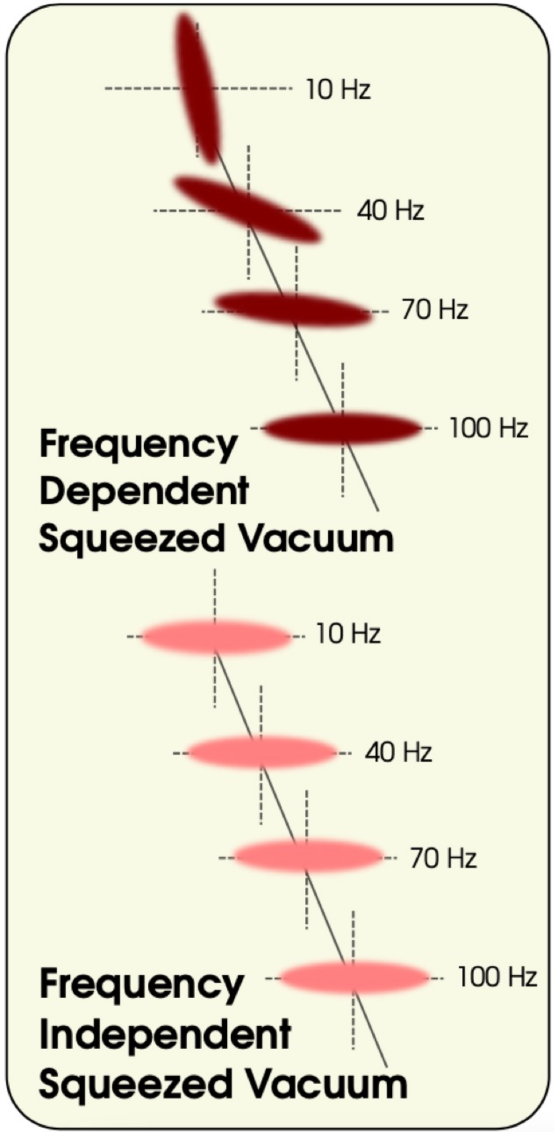
$$\Delta\varphi\Delta A \geq 1$$



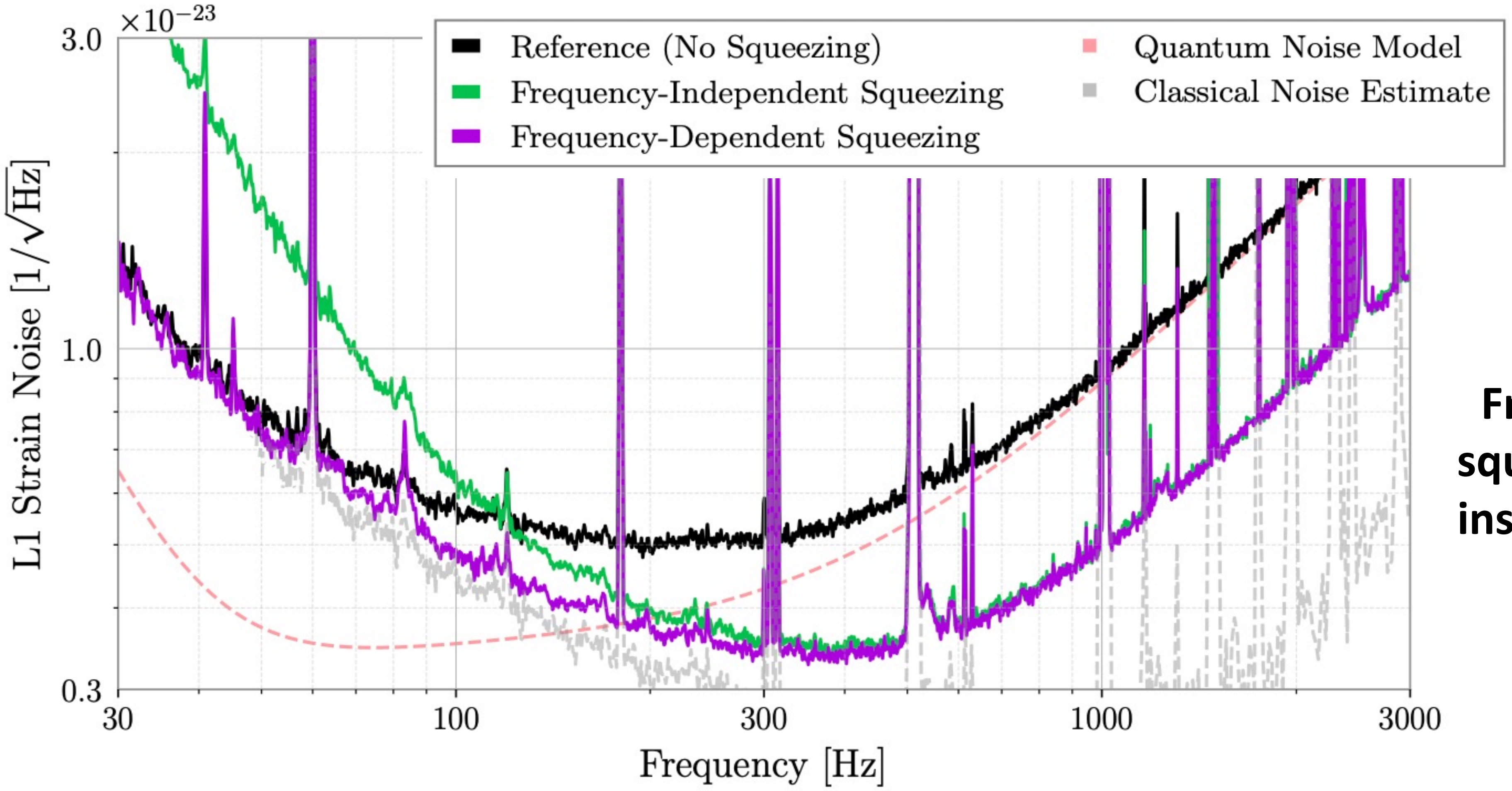

Squeezing allows us to play with the quantum nature of light in our favor

**Frequency-dependent** squeezing allows us to rotate the angle of squeezing

- ➢ We can suppress both forms of quantum noise!



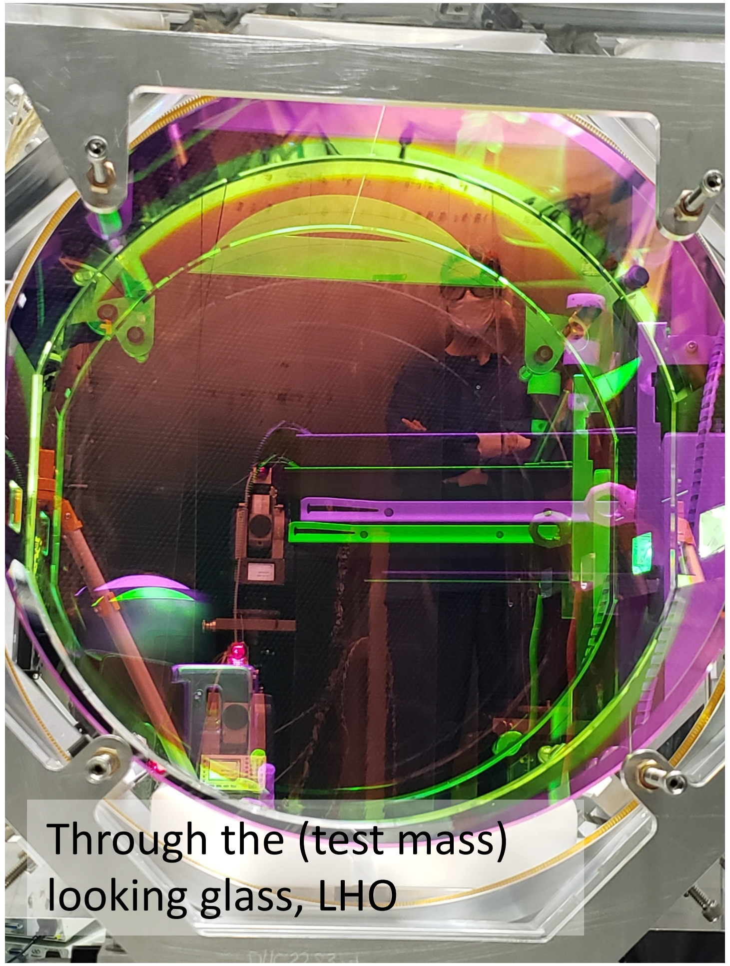
# Benefits of FDS




**Frequency-dependent squeezing increases BNS inspiral range at LIGO by 15-18%!**

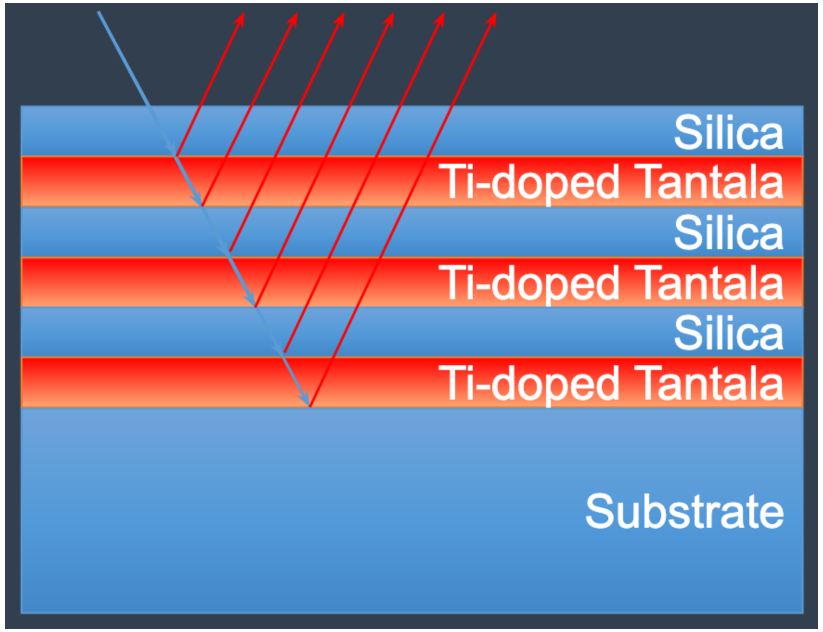
Ganapathy et al., Phys. Rev. X 13, 041021

# Coating Thermal Noise




Test mass coatings have stringent requirements for reflectivity, absorption, loss, uniformity

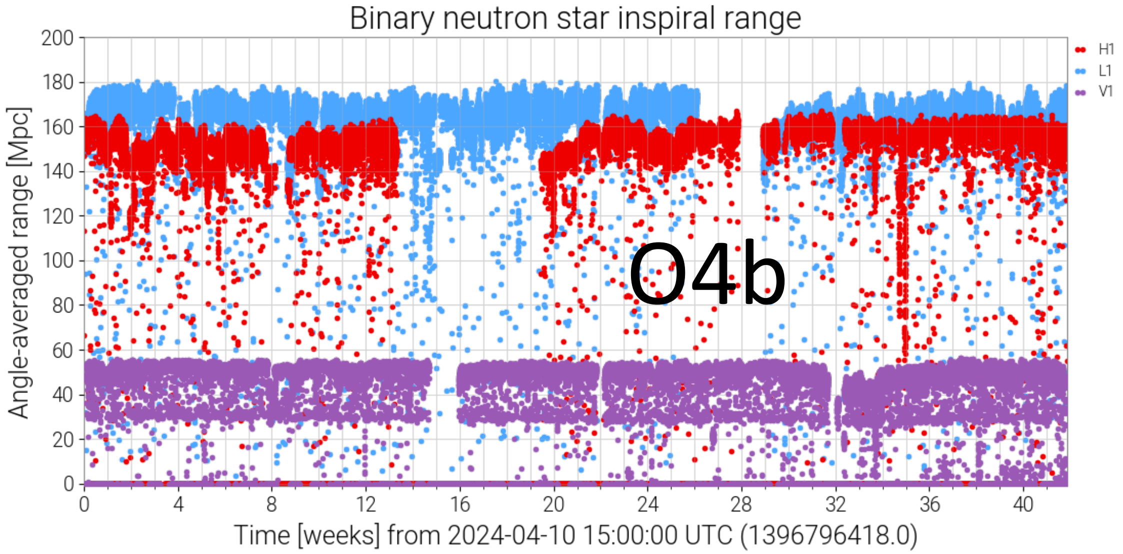
- Brownian motion in the mirror coatings is a significant limiting noise source near 100 Hz
- Future detector sensitivity heavily depends on coating properties!



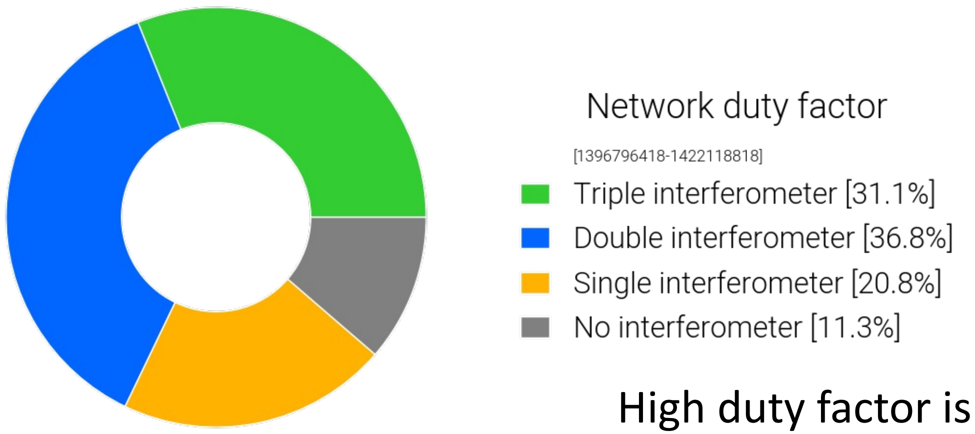

Ti-doped tantala mechanical loss is 10x greater than silica

# Detector Performance in O4

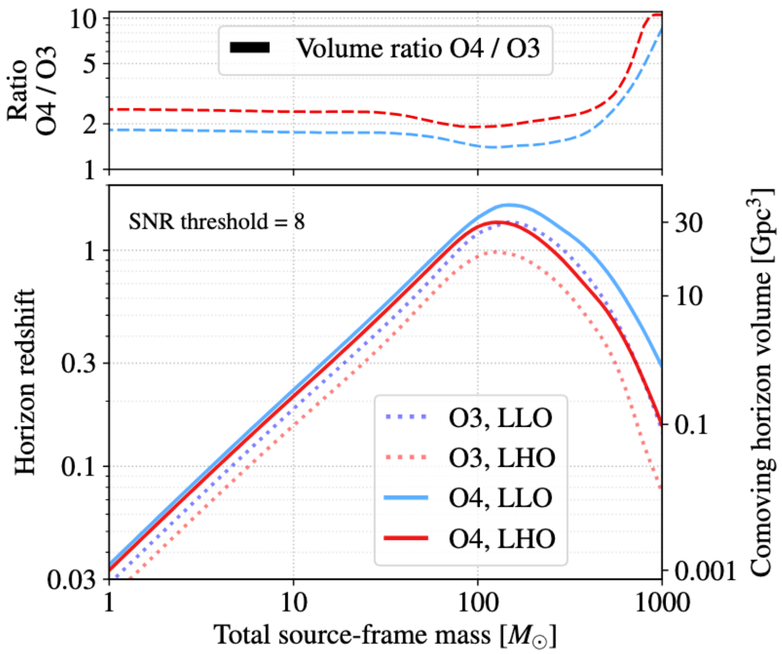
**Binary neutron star (BNS)** range provides a standard sensitivity metric to a **1.4+1.4 solar mass** binary system.




Significant improvement at low frequency increases detector sensitivity to high mass systems

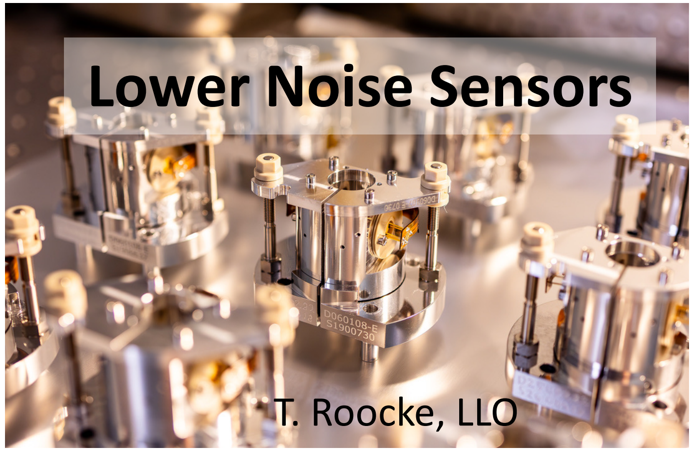


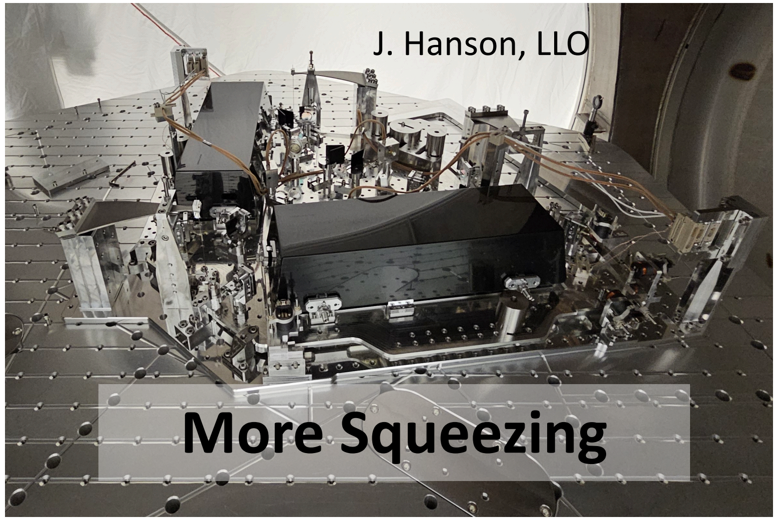

High duty factor is key- we never know when an event will occur

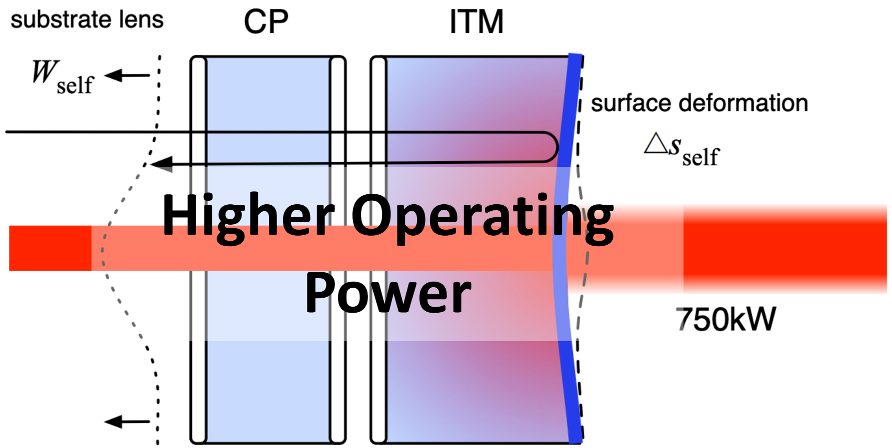



Capote, Jia, Aritomi, Nakano, Xu et al., Phys. Rev. D 111, 062002

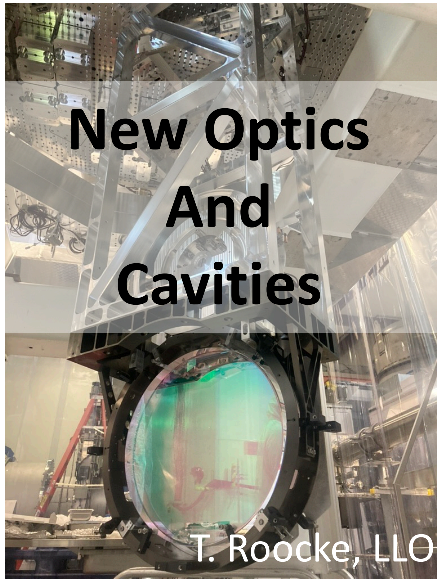
# What’s next?


A Brooks, LIGO-G2300456



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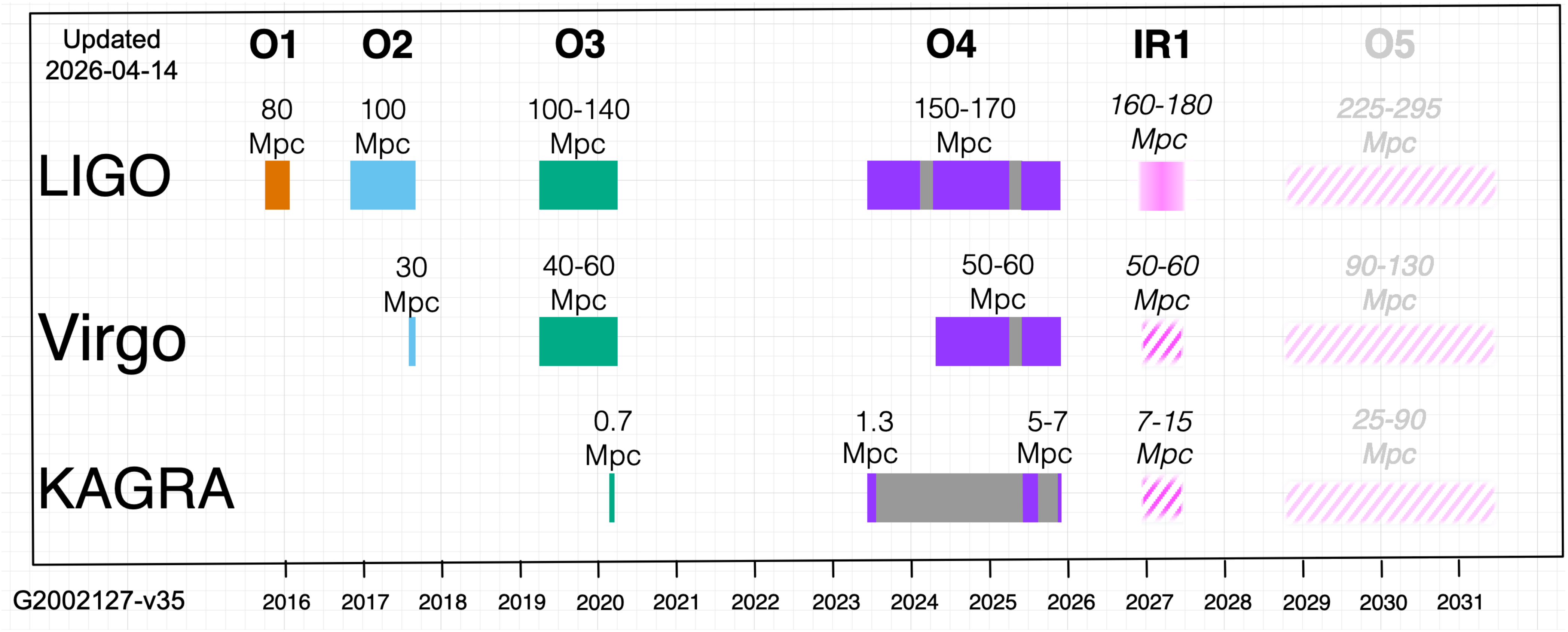
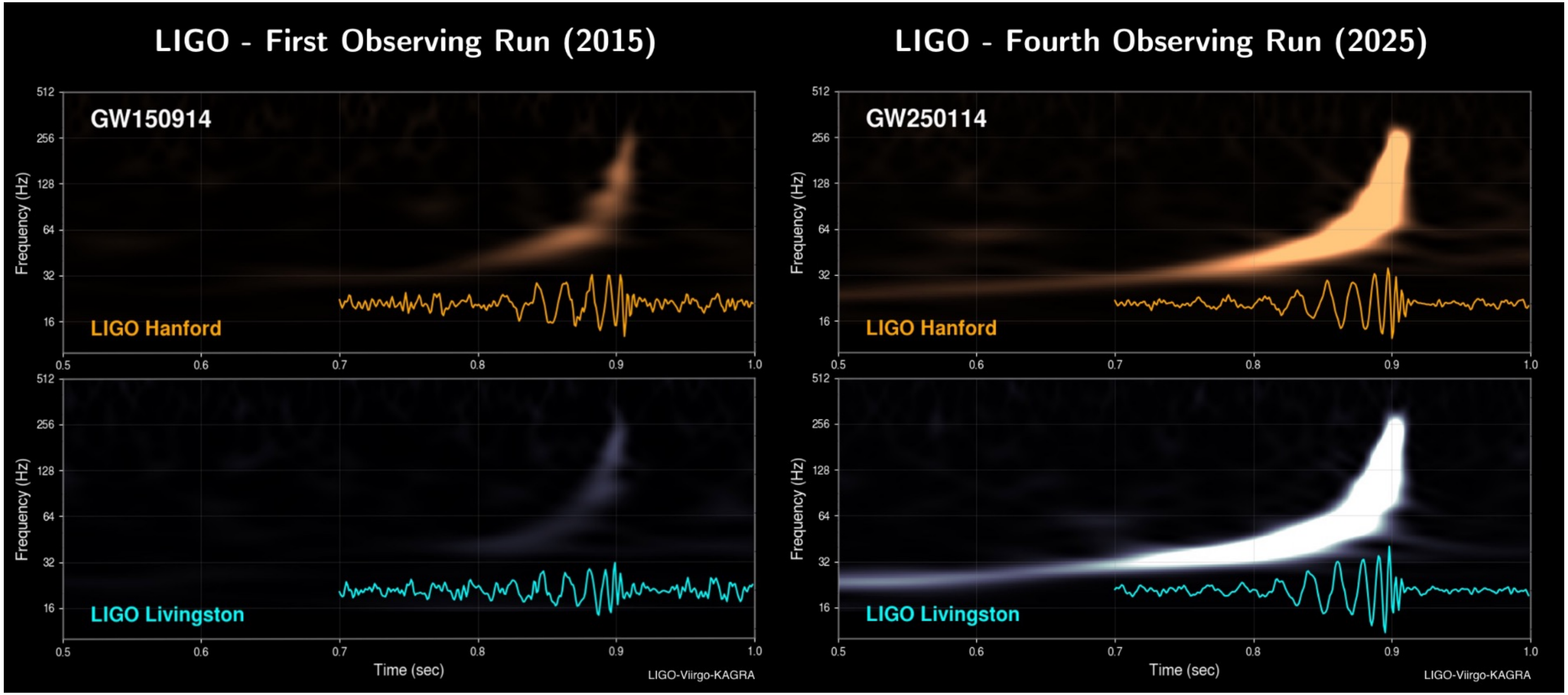



See https://observing.docs.ligo.org/plan/

# 10 Years of GW Detection!




D. Davis, University of Rhode Island