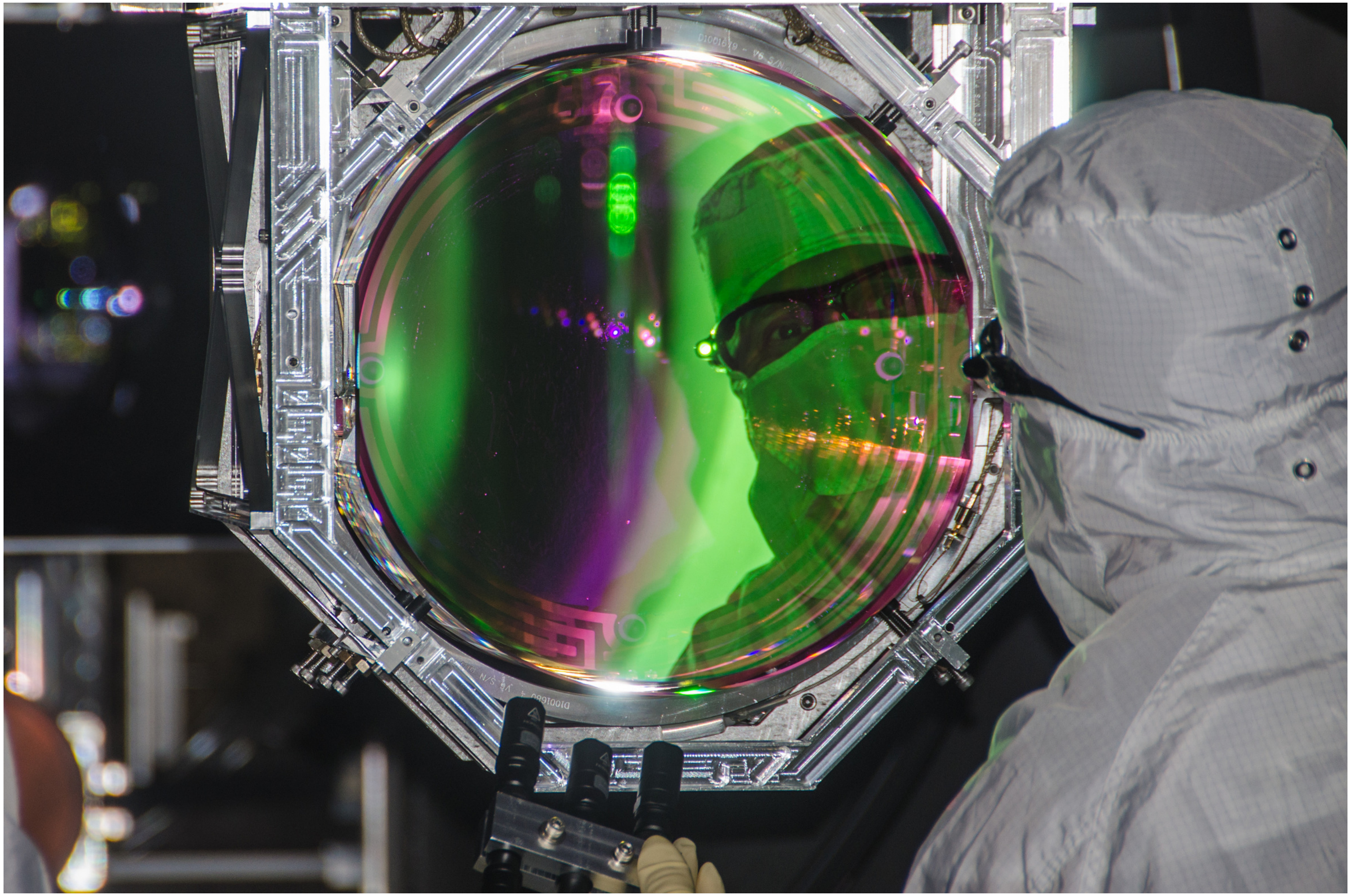
The Instruments Behind Gravitational Wave Detection



Dr. Lee McCuller for the
LIGO Scientific Collaboration
Apr 2015

LIGO
G1600903

Massachusetts Institute of Technology

Introductory Video

https://www.ligo.caltech.edu/video/ligo20160211v1

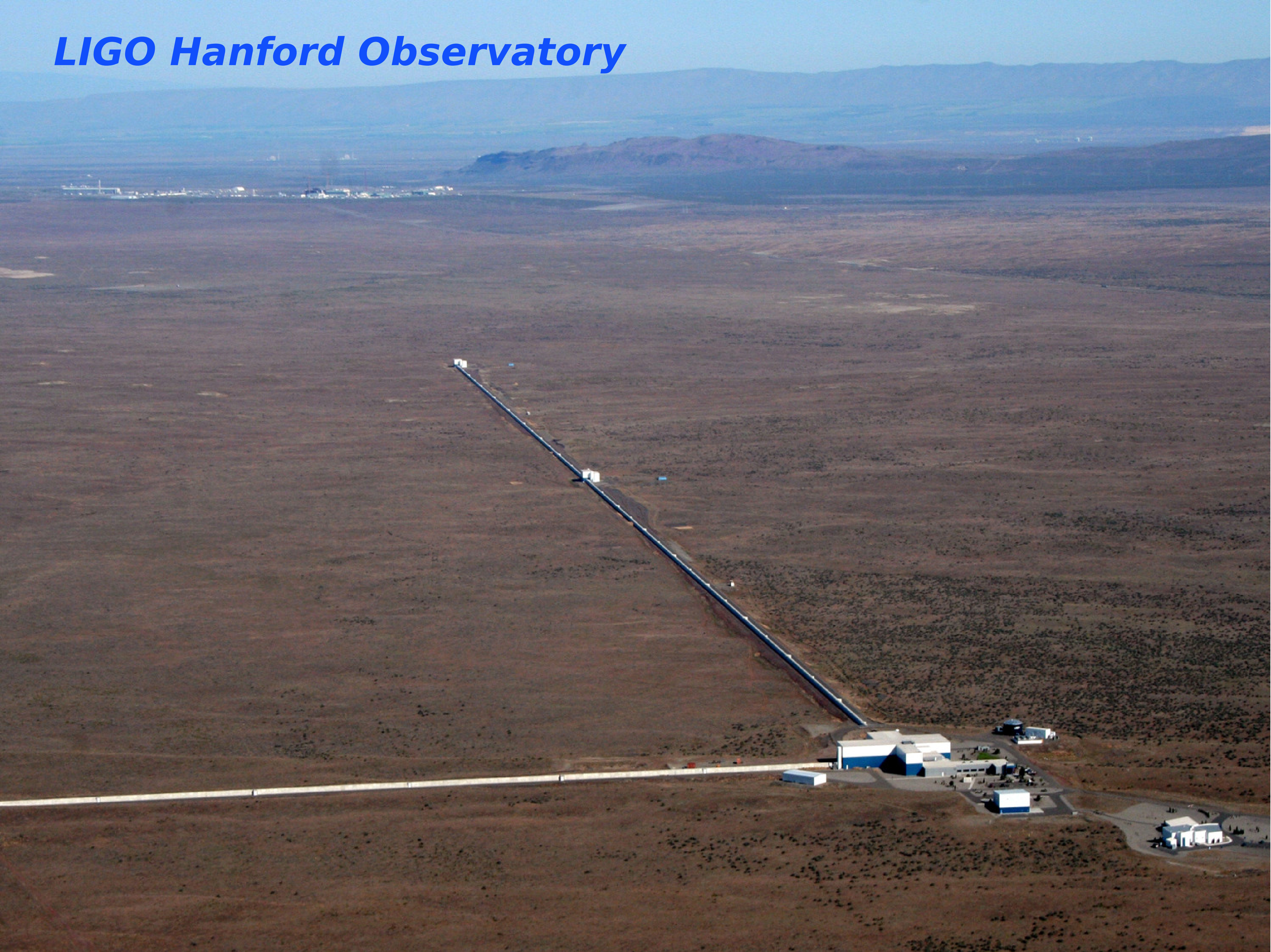
Credit LIGO/SXS/R.Hurt and T. Pyle

Overview

- Gravitational Waves – their scale on earth
- Overview of the Instrument
  - Spacetime -> light
- The limits of physical measurements
  - Examples for light and sound
- The LIGO Detector
  - Design
  - Limits
  - Effect on data
- Possibilities for the future

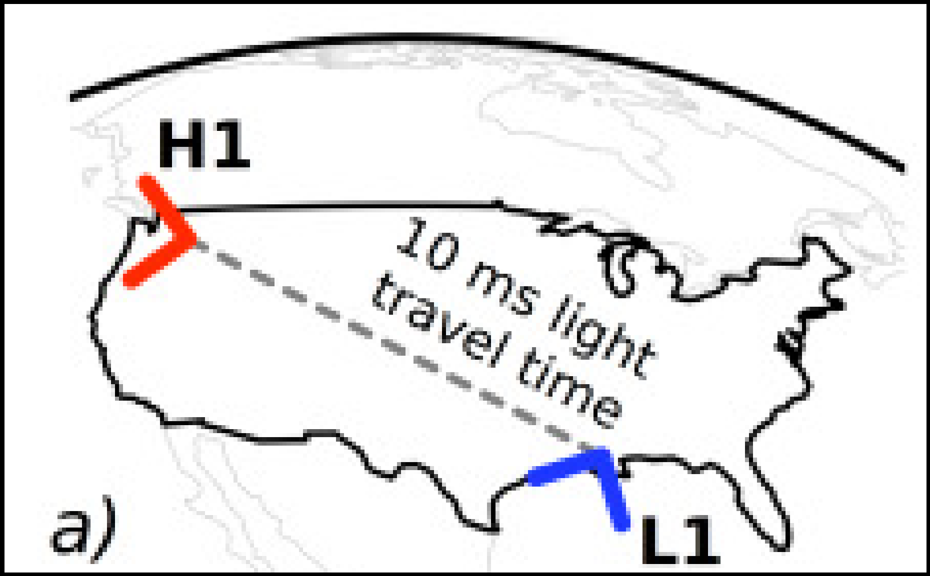

LIGO Livingston Observatory

LIGO Hanford Observatory

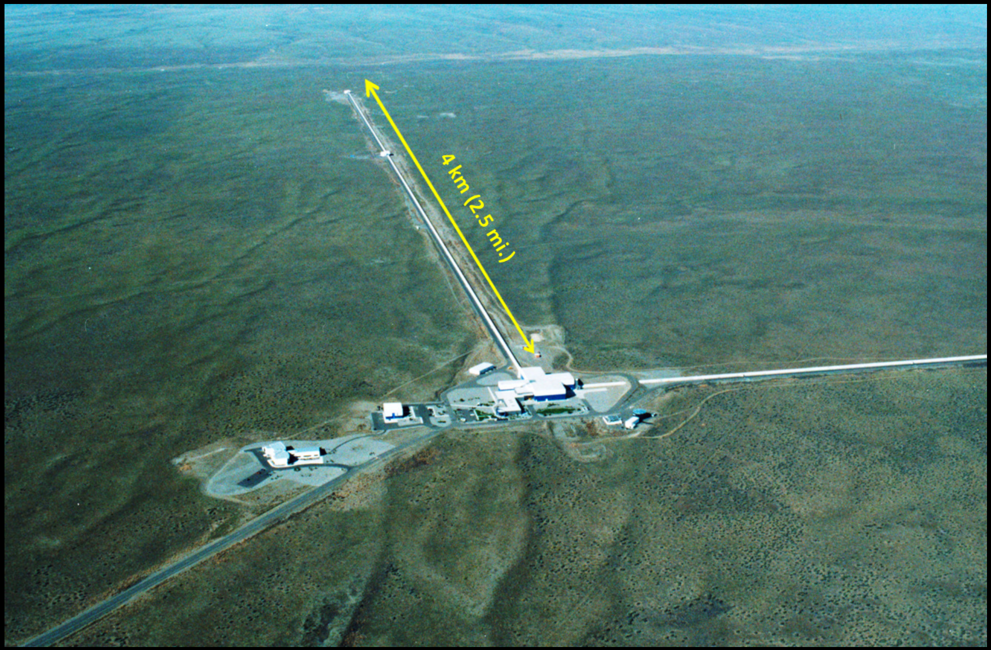


2 LIGO Observatories, each with one laser interferometer with 4 km arms

L

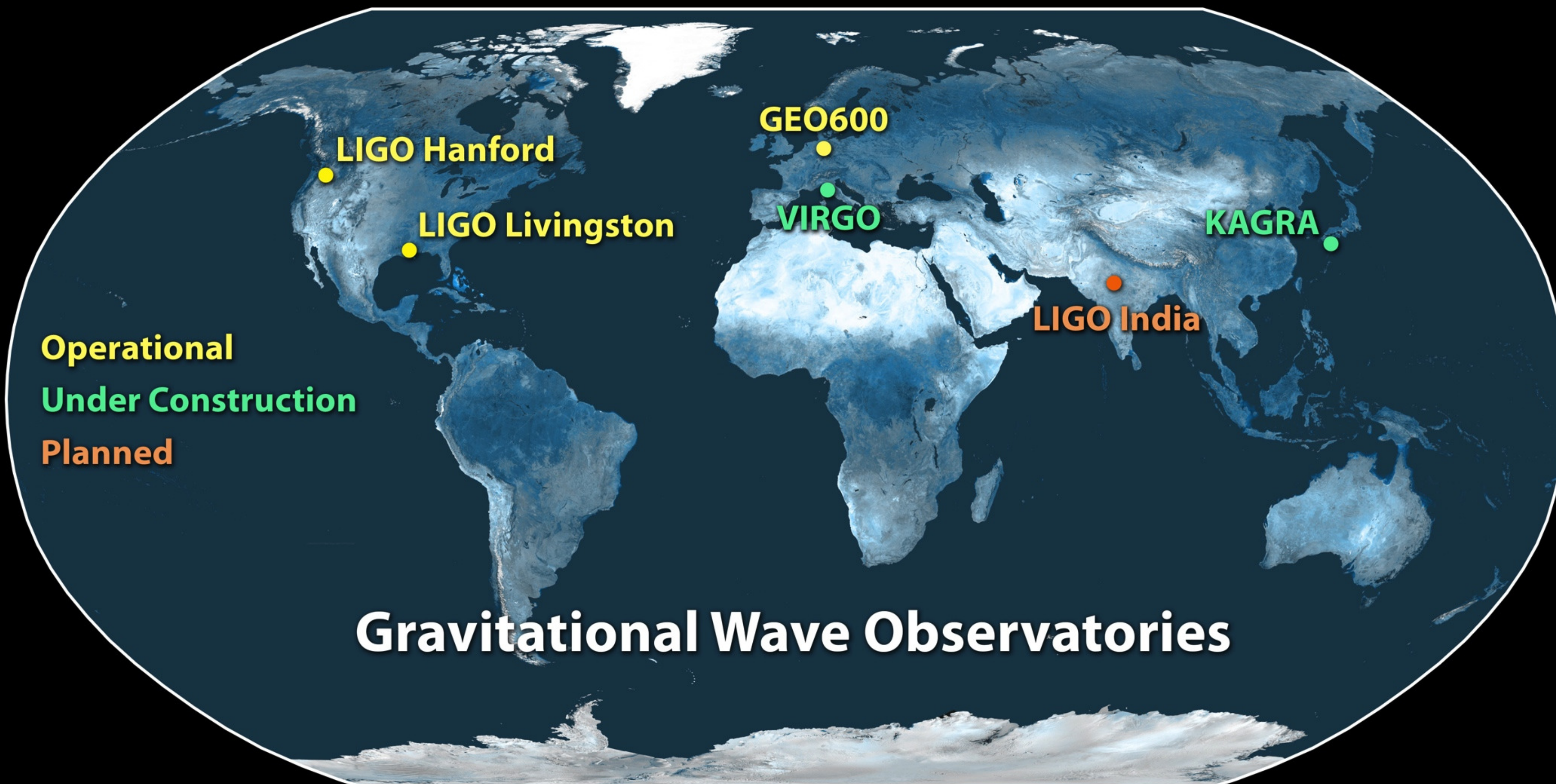


LIGO Hanford Observatory (Washington State)

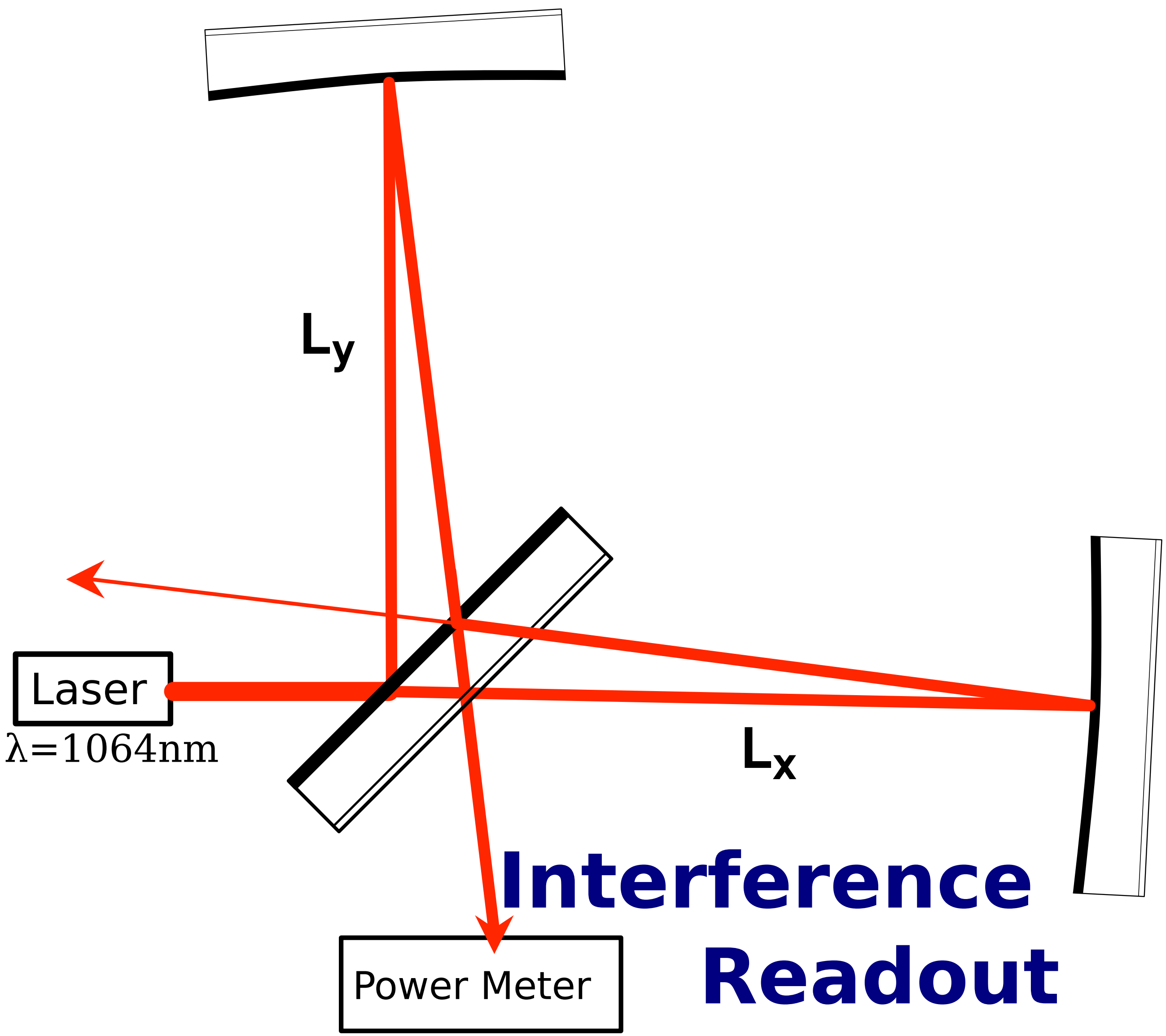


LIGO Livingston Observatory (Louisiana)

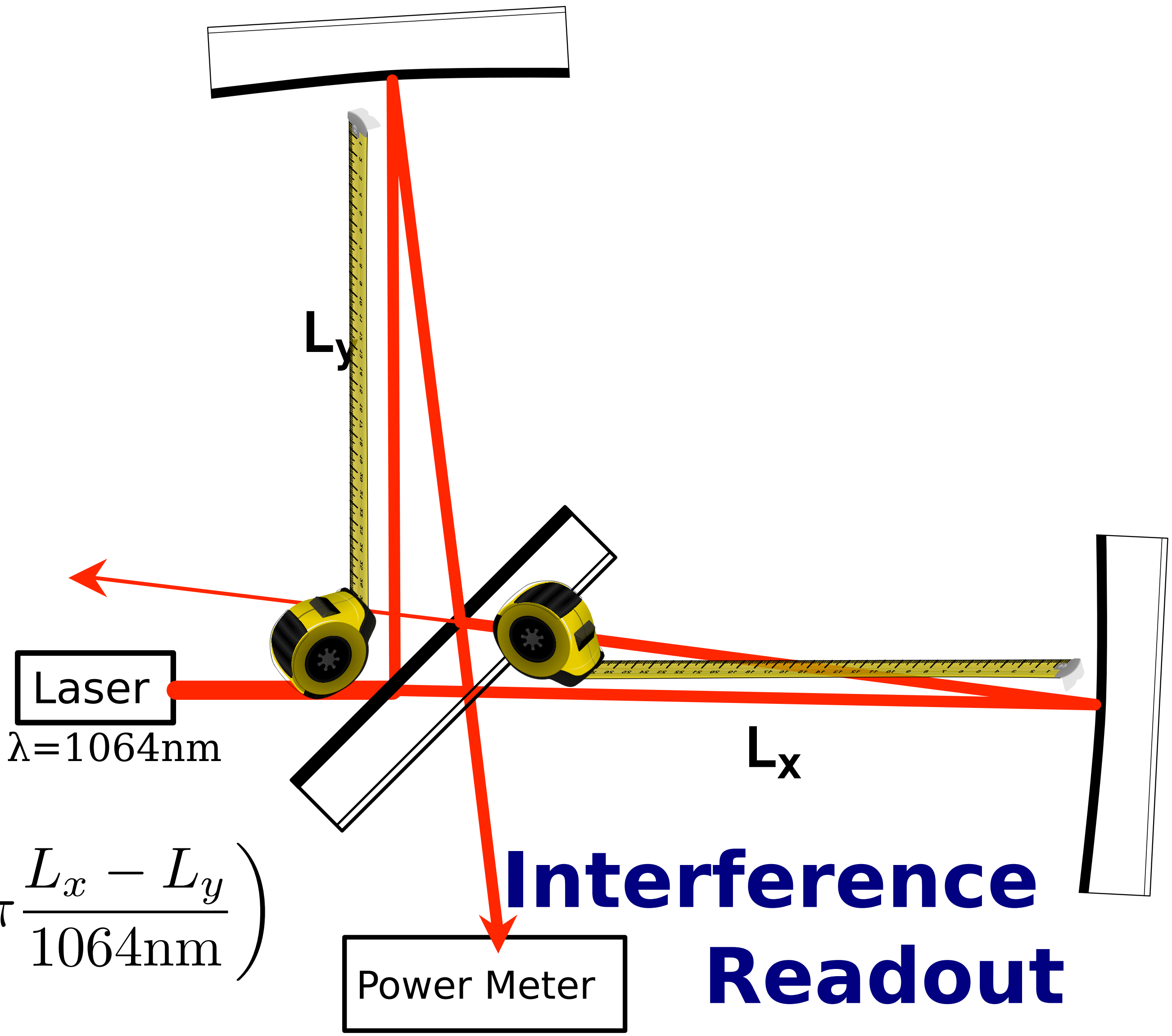
Observatory Network



The Michelson Interferometer



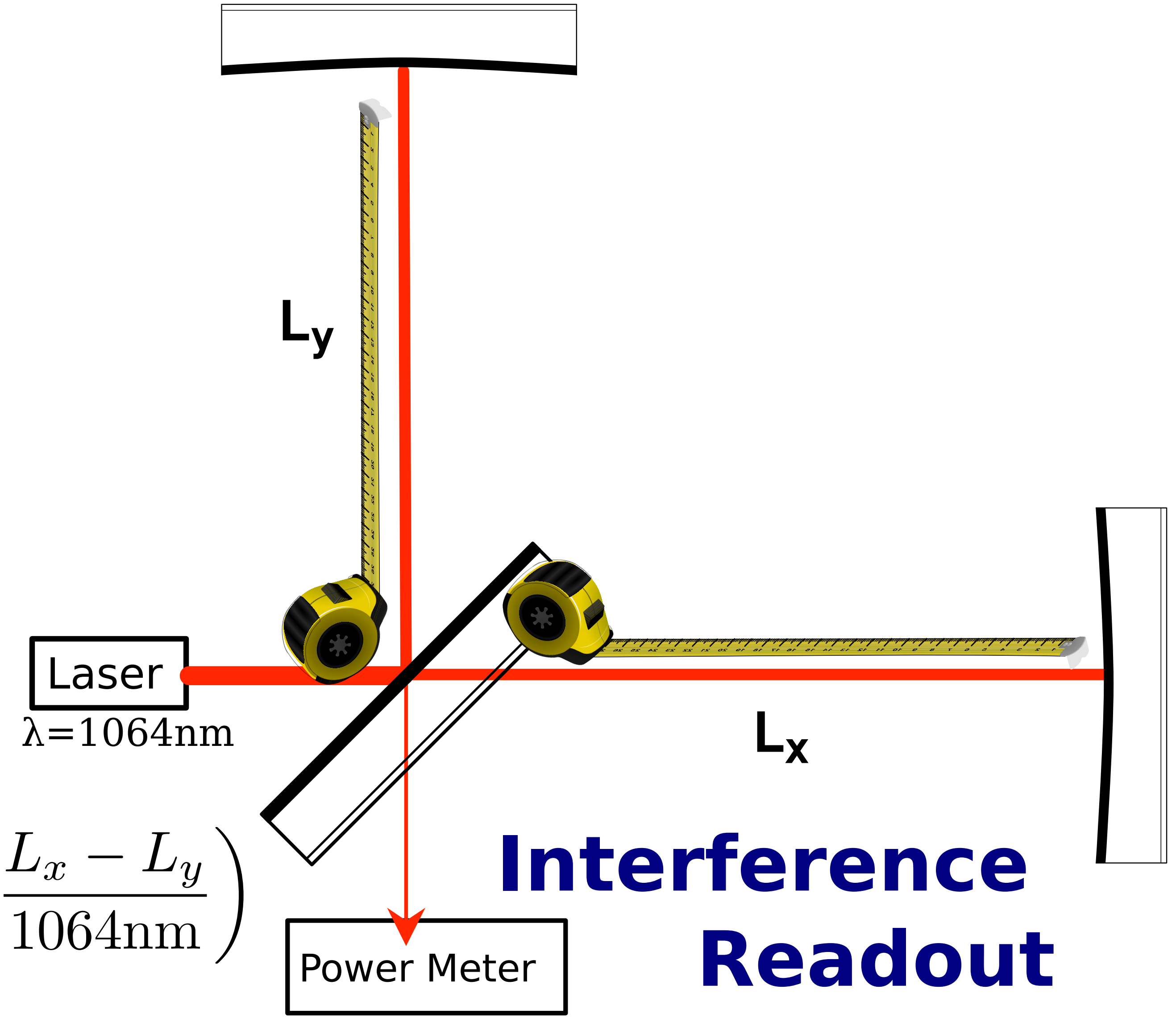
The Michelson Interferometer



$$P \sin^2\left(2\pi \frac{L_x - L_y}{1064\text{nm}}\right)$$

Interference Readout

The Michelson Interferometer



$$P\sin^2\left(2\pi\frac{L_x - L_y}{1064\text{nm}}\right)$$

Interference Readout

Michelson Video

Video

C:\Users\mcculler\Desktop\Presentation\ligo20160211v6.m4v

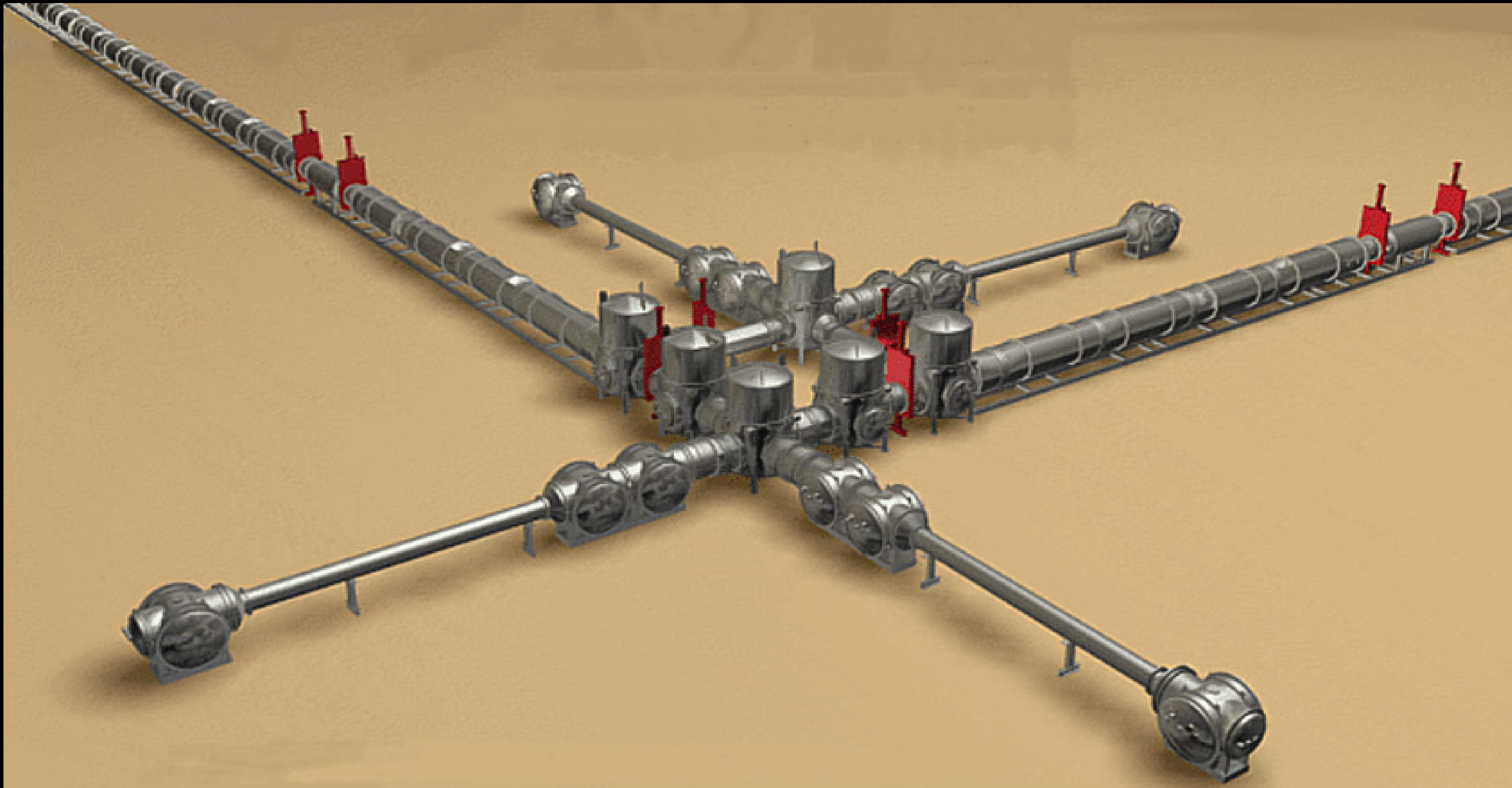
https://www.ligo.caltech.edu/video/ligo20160211v6

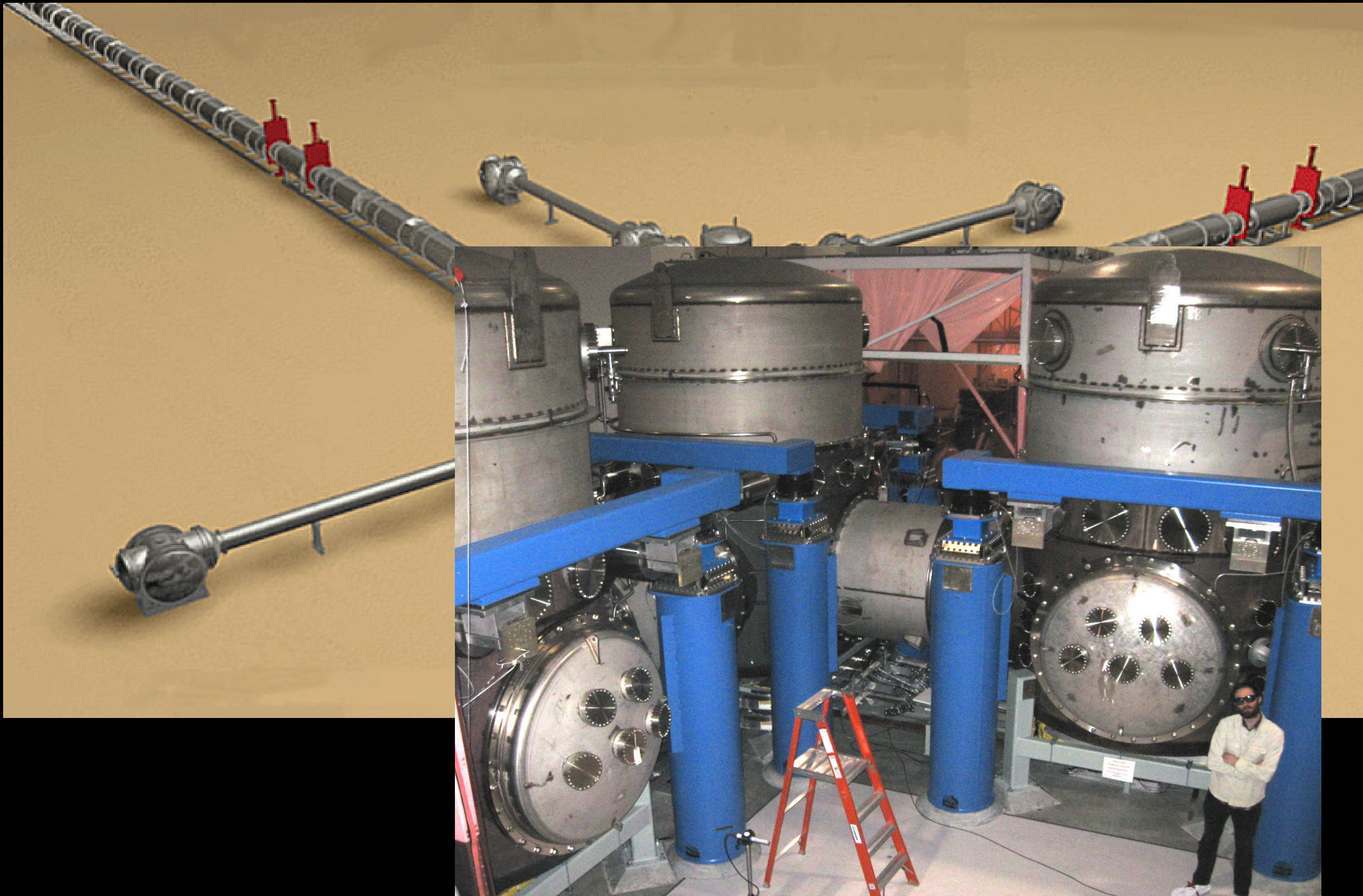
Credit: LIGO/T. Pyle

Michelson Video

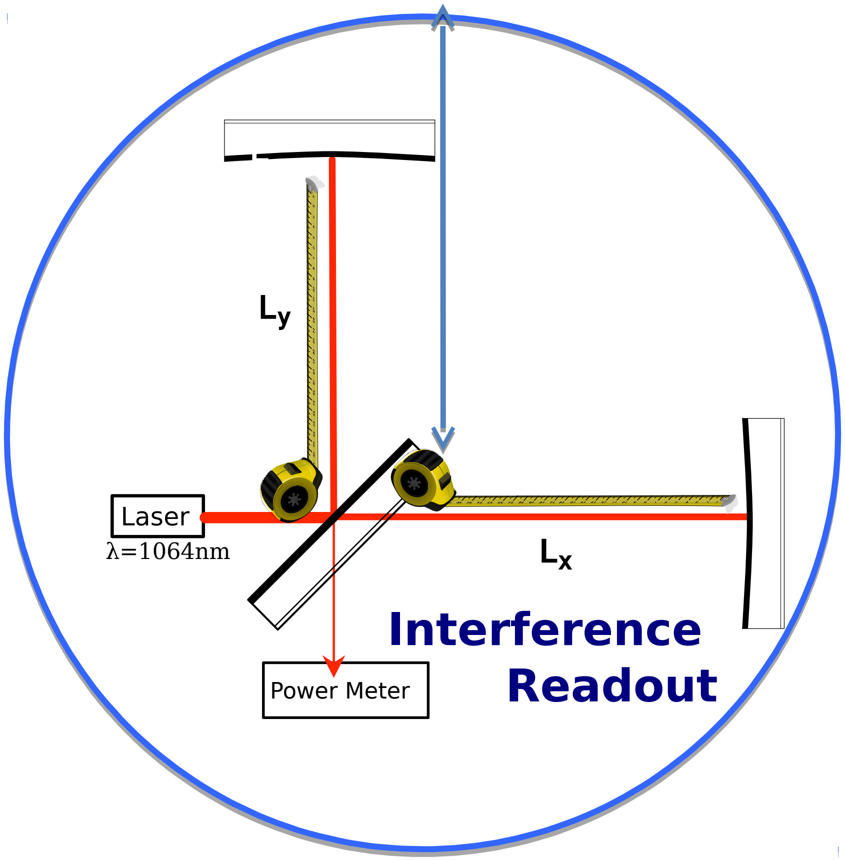
https://www.ligo.caltech.edu/video/ligo20160211v6

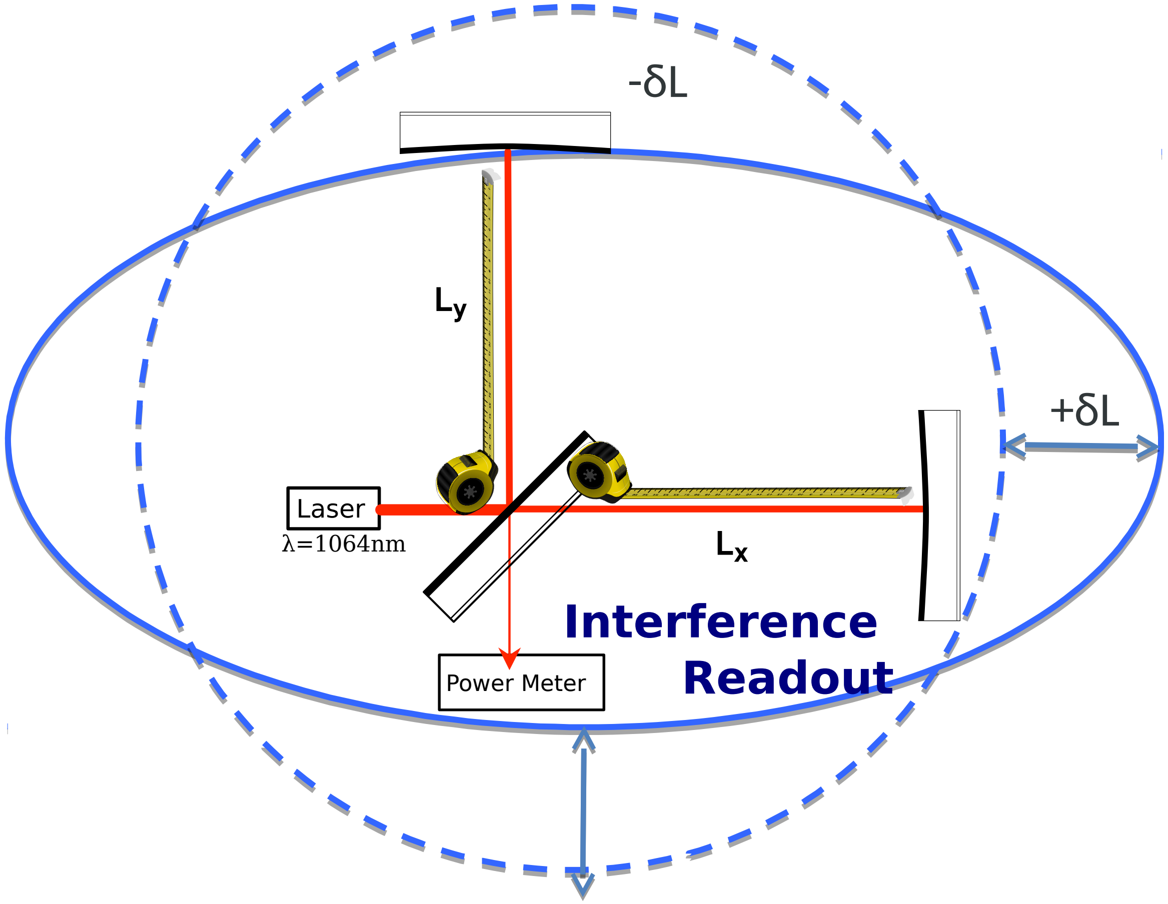
Credit: LIGO/T. Pyle





Spacetime Stretch

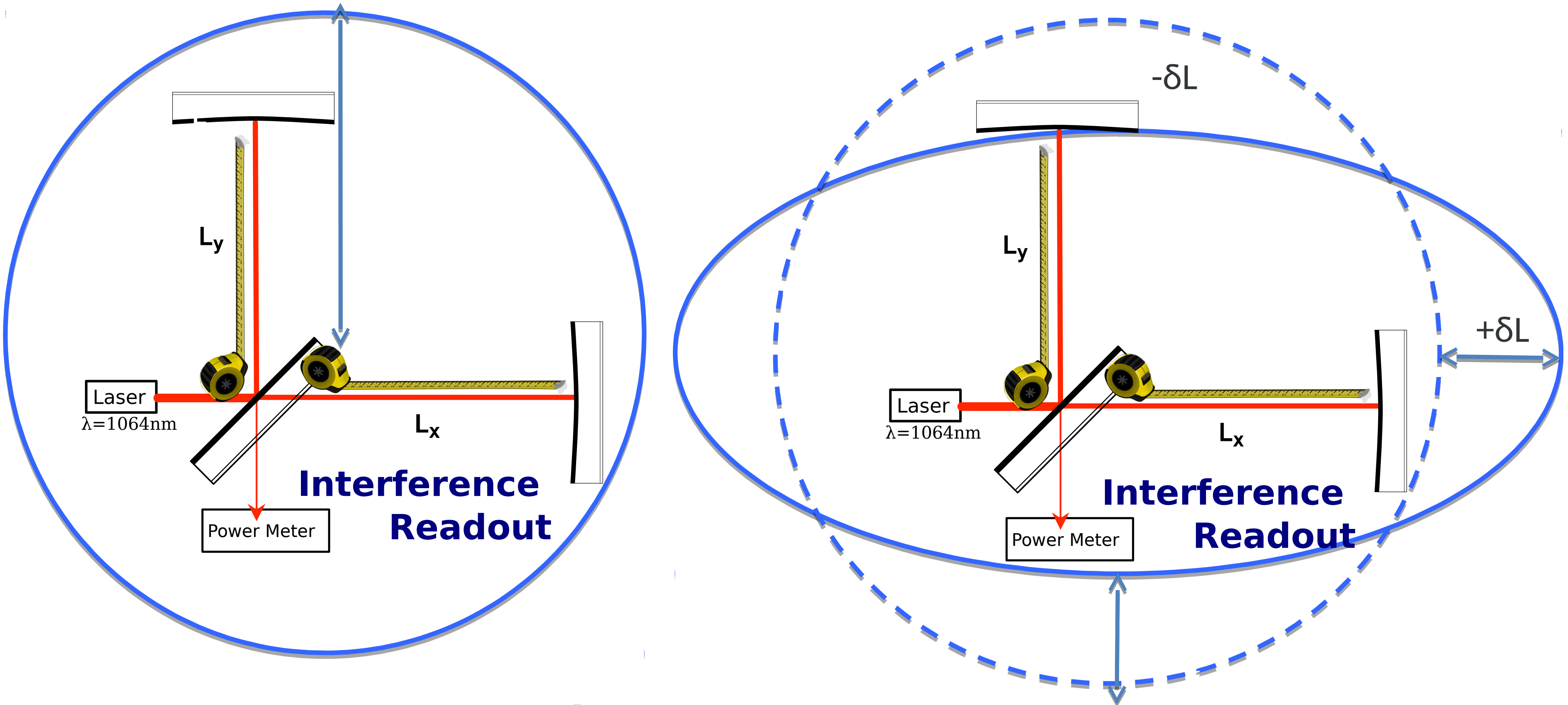




$$P \sin^2\left(2\pi \frac{L_x - L_y}{1064\text{nm}}\right)$$

$$P \sin^2\left(2\pi \frac{L_x - L_y + 2\delta L}{1064\text{nm}}\right)$$

Spacetime Strain

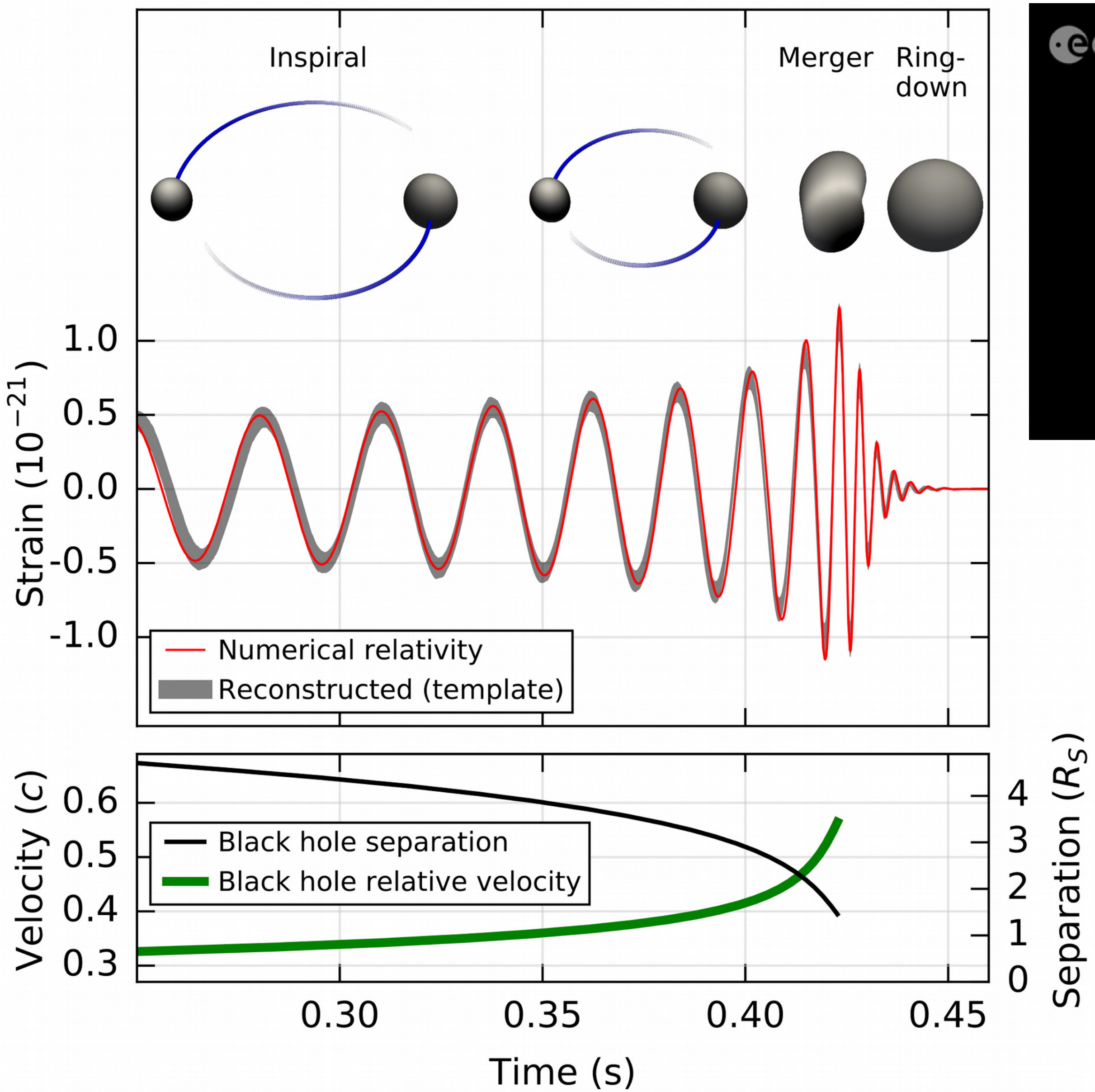


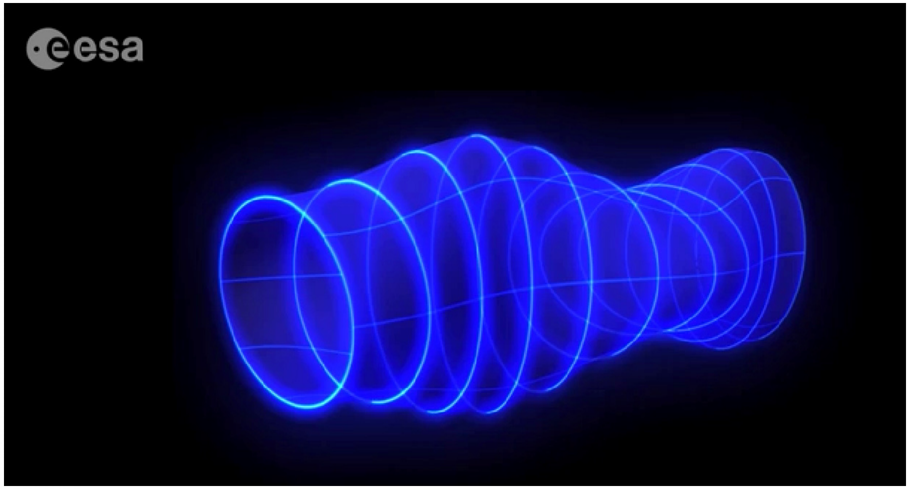
Strain

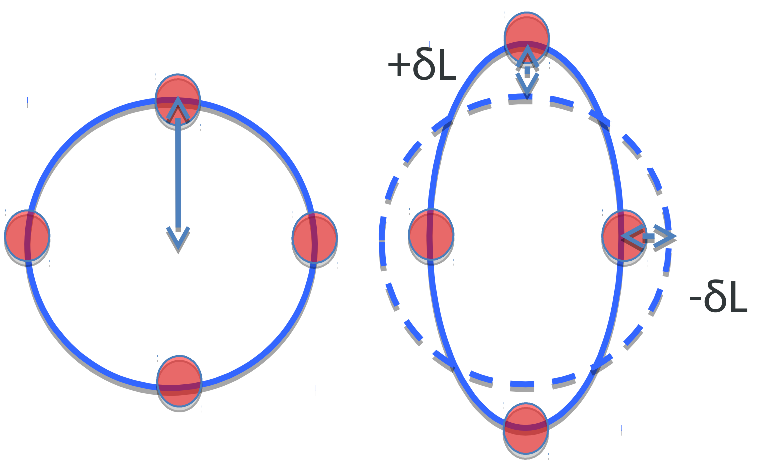
$$\delta L = hL_{\text{baseline}}$$

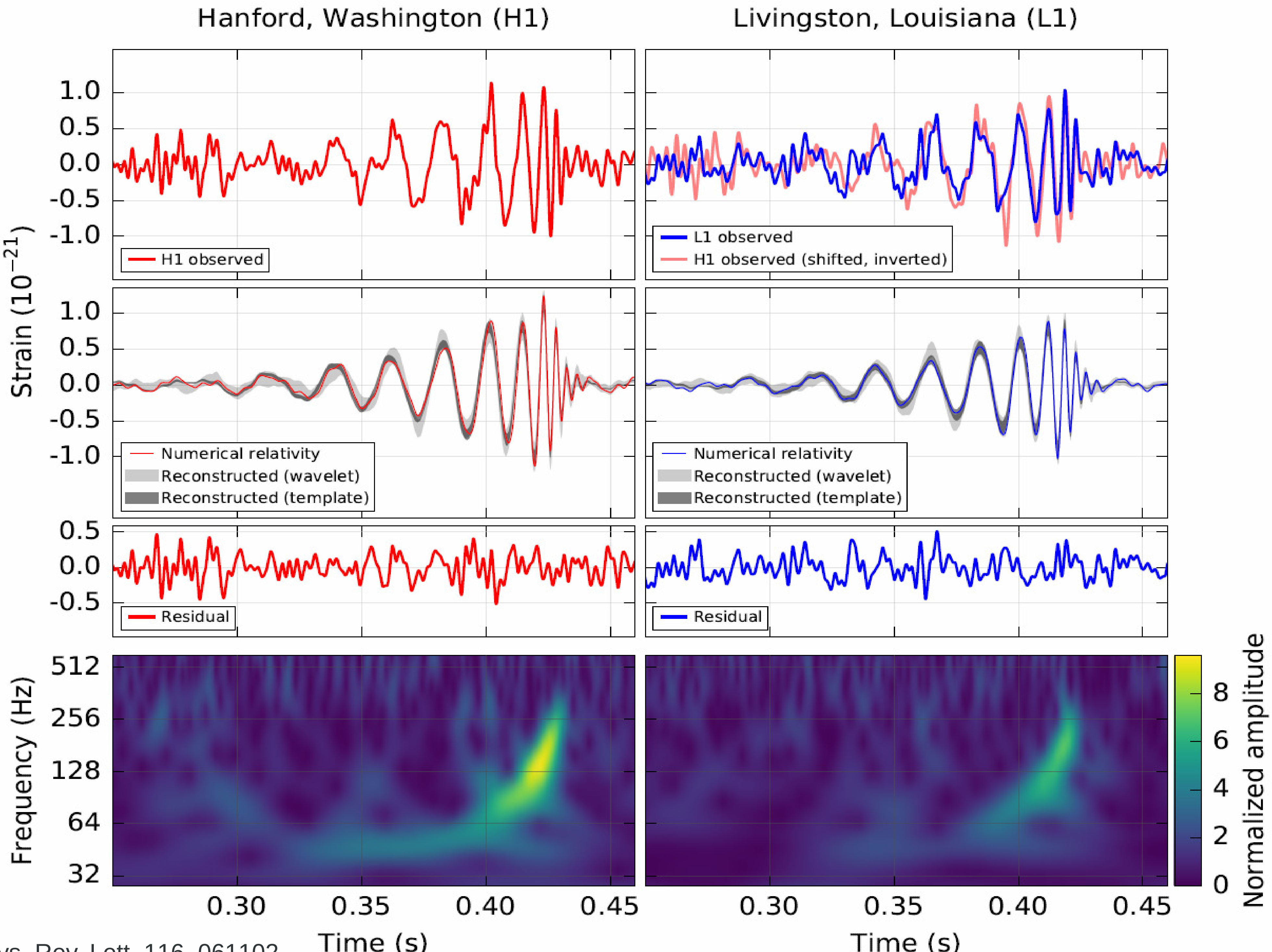
Strain Waveforms

Phys. Rev. Lett. 116, 061102







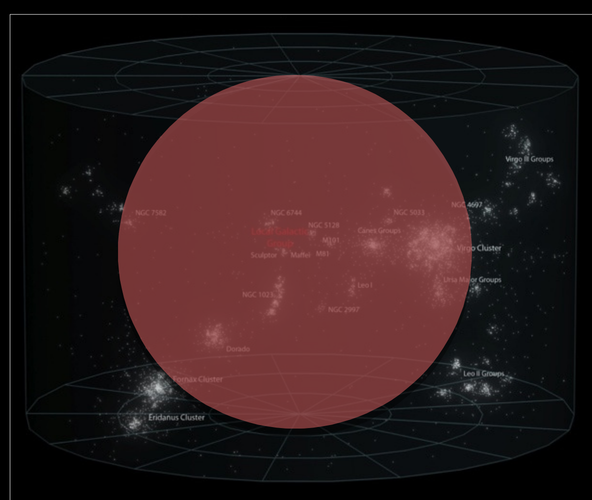


Phys. Rev. Lett. 116, 061102

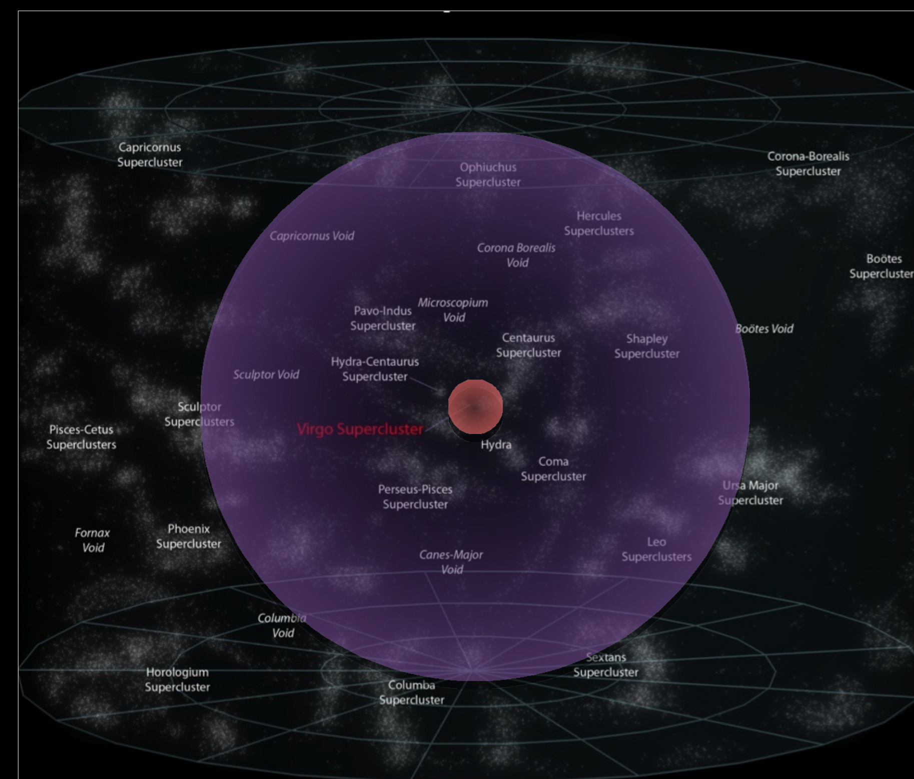
Advanced LIGO Sensitive Volume

- Rate 2-400 BBH mergers each year in a volume of 1 Gpc^3 ApJL 818:L22 (2016)
- About 10 million galaxies per Gpc^3
- Advanced LIGO range now ~ 0.1 to 1 Gpc, depending on system mass

Assuming representative rates for this event:
~5 or more BBH events in the next observing run (due to start later this year).



Initial Range



Advanced Range

On Measurement

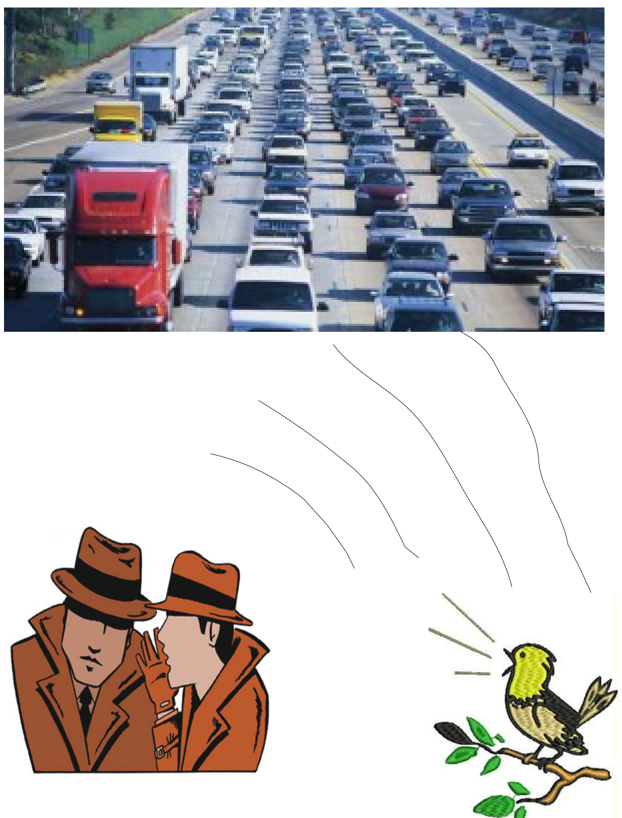
Zoom! Enhance?

Roadside Guitars - Flickr: Tascam M-520

How far can you go?

On Measurement

Backgrounds

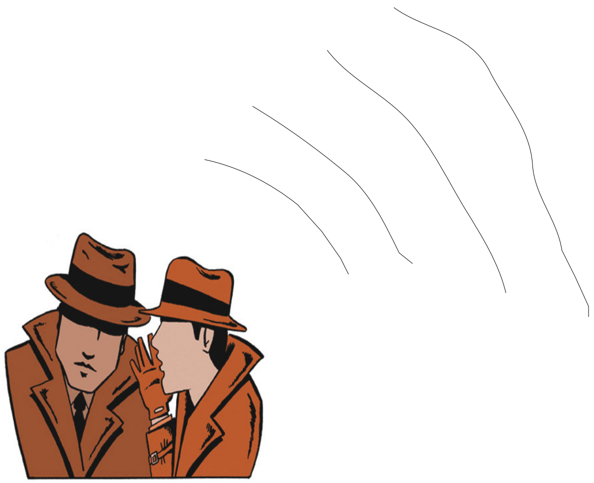


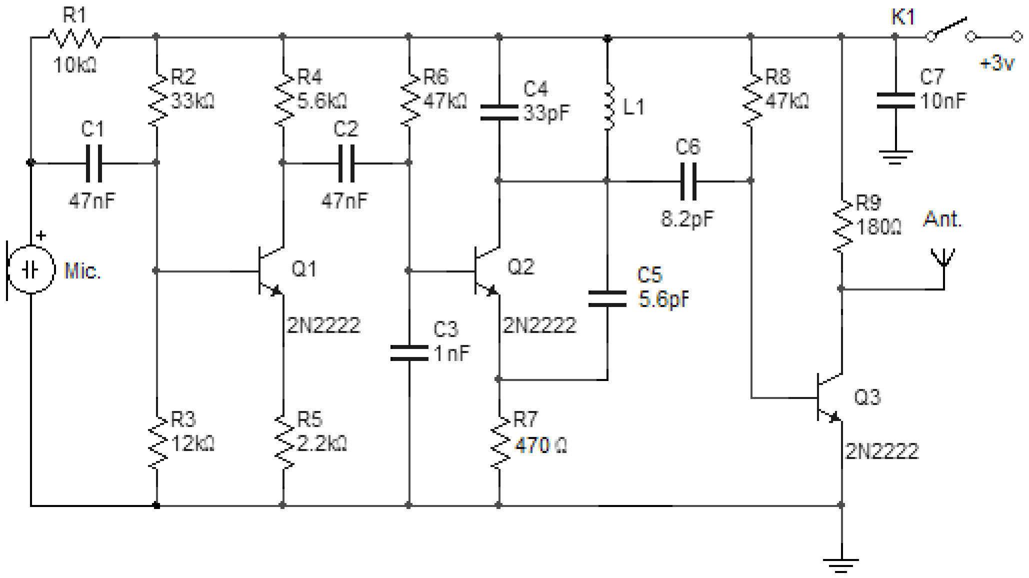
On Measurement

Sensor Noise

Turning up The volume only
Overcomes the sensor limits
of your ear

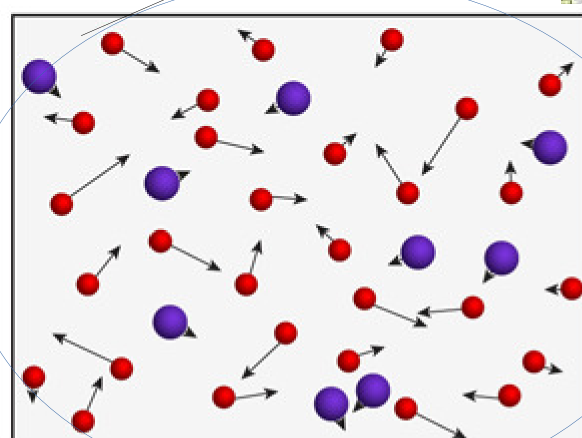
What about the limits of the machine?





On Measurement

Fundamental
Noise



http://atomsinmotion.com

The Michelson Interferometer

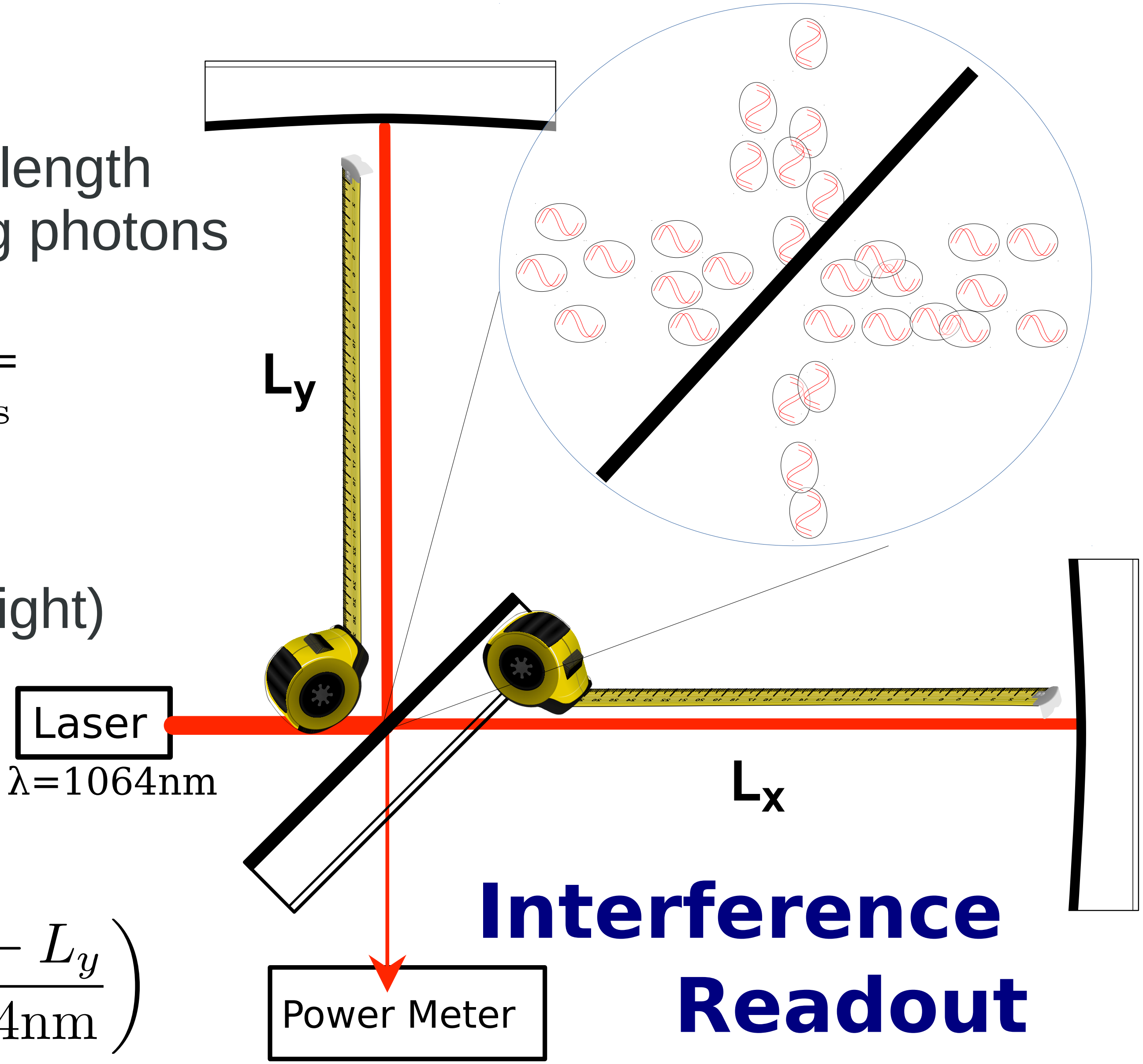
Each Photon gives 1064nm/2π measurement

minimum measurable length variance from counting photons

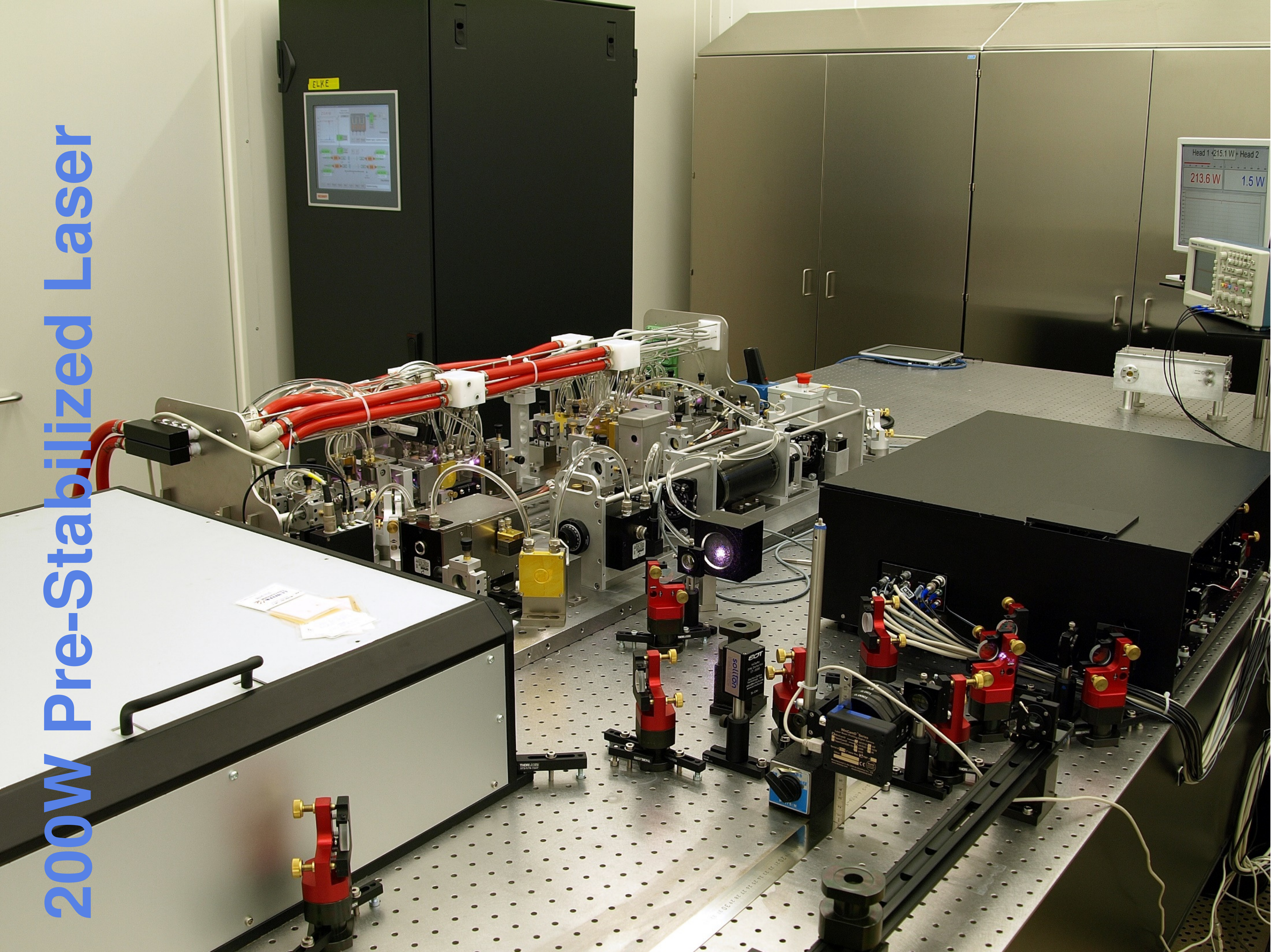
$$\sigma_{\Delta L} \propto \frac{1}{\sqrt{N_{\text{photons}}}}$$

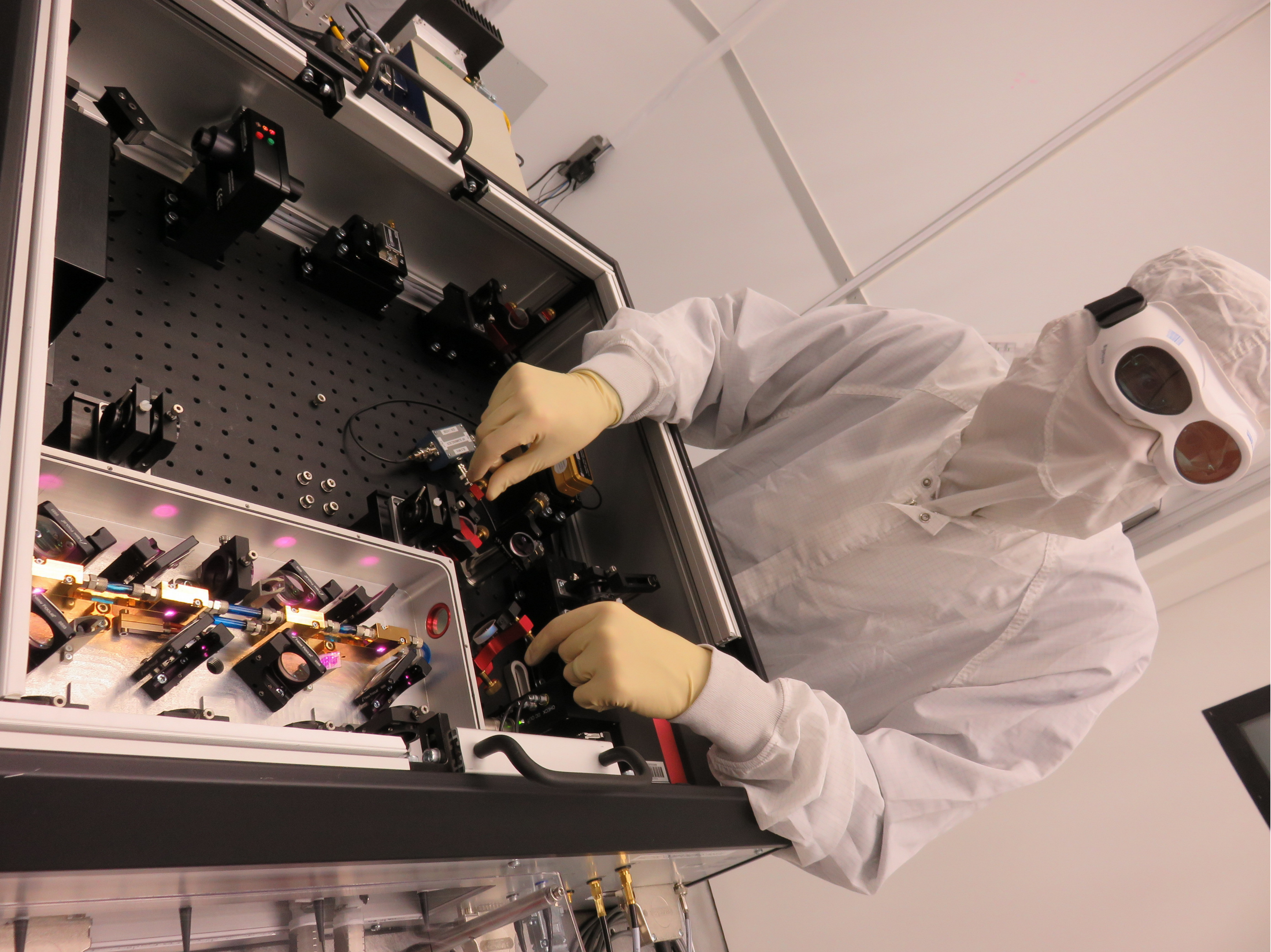
~10^19 photons/s in
1 Watt (of 1064nm light)

$$P \sin^2\left(2\pi \frac{L_x - L_y}{1064\text{nm}}\right)$$

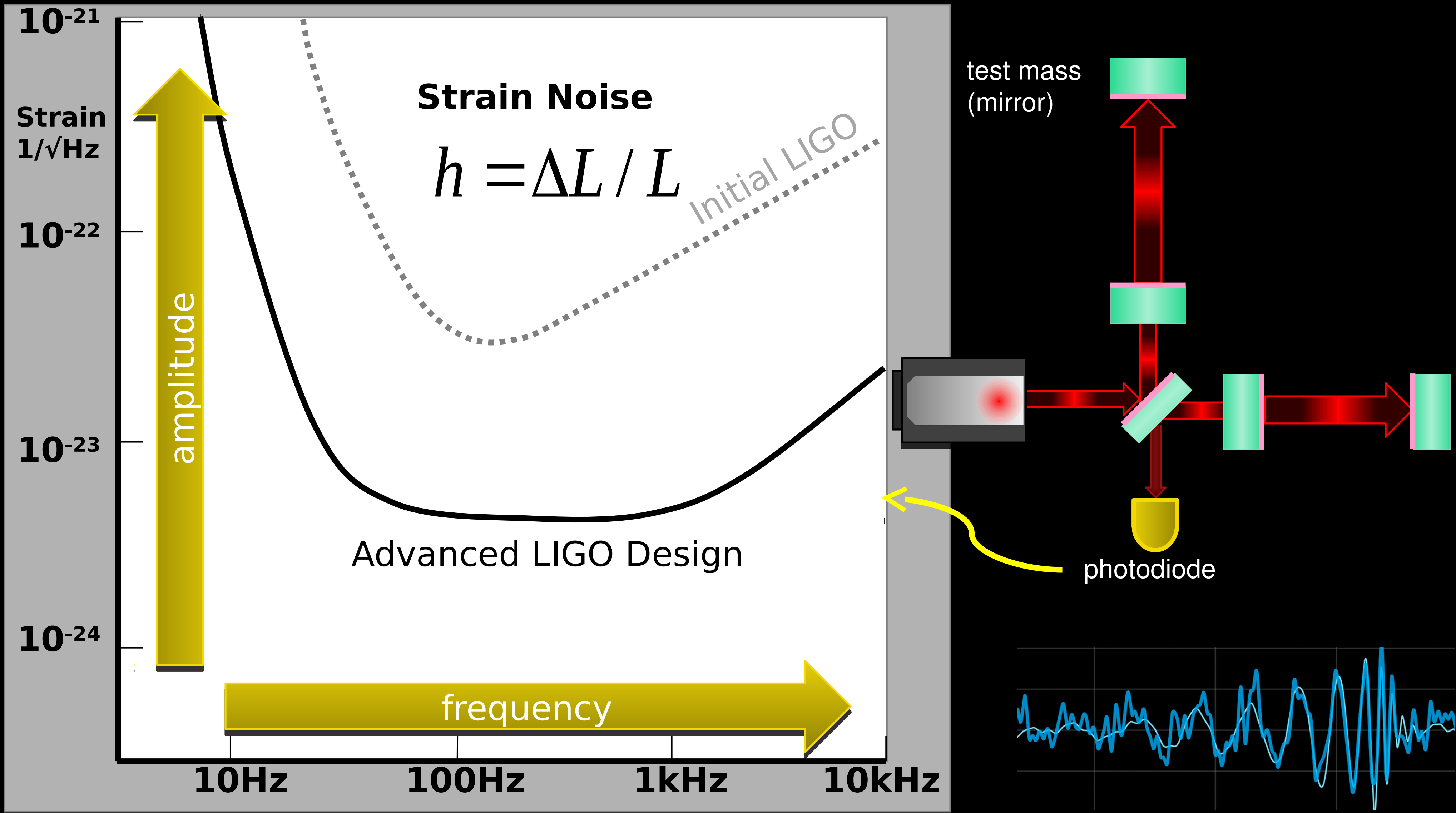


200W Pre-Stabilized Laser





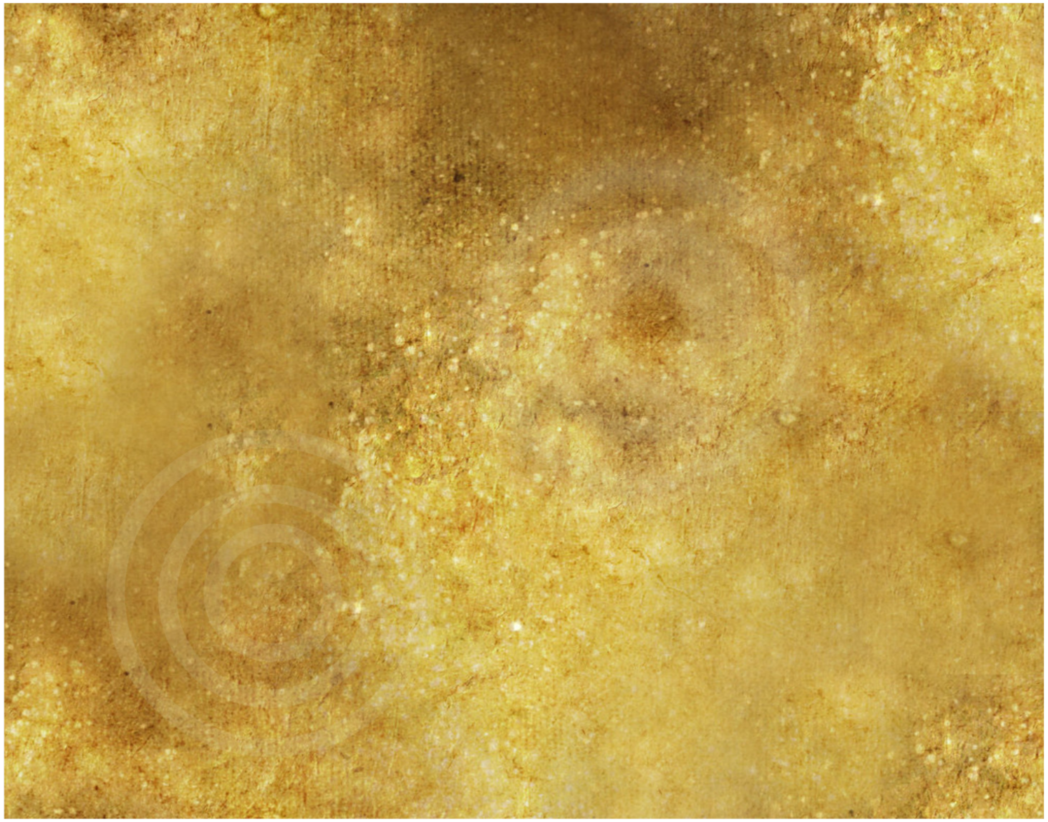
Advanced LIGO Noise

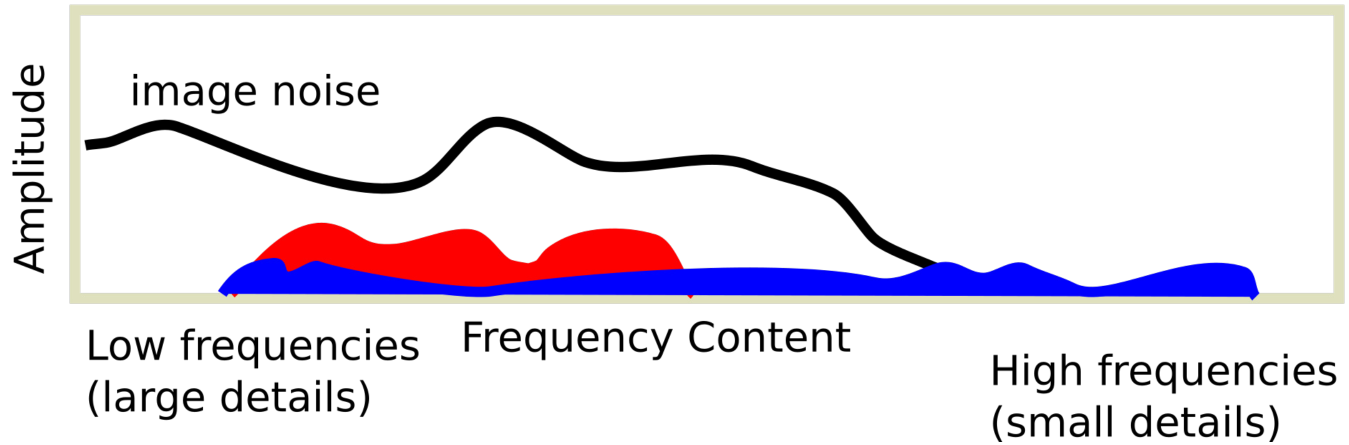


Frequency Dependence

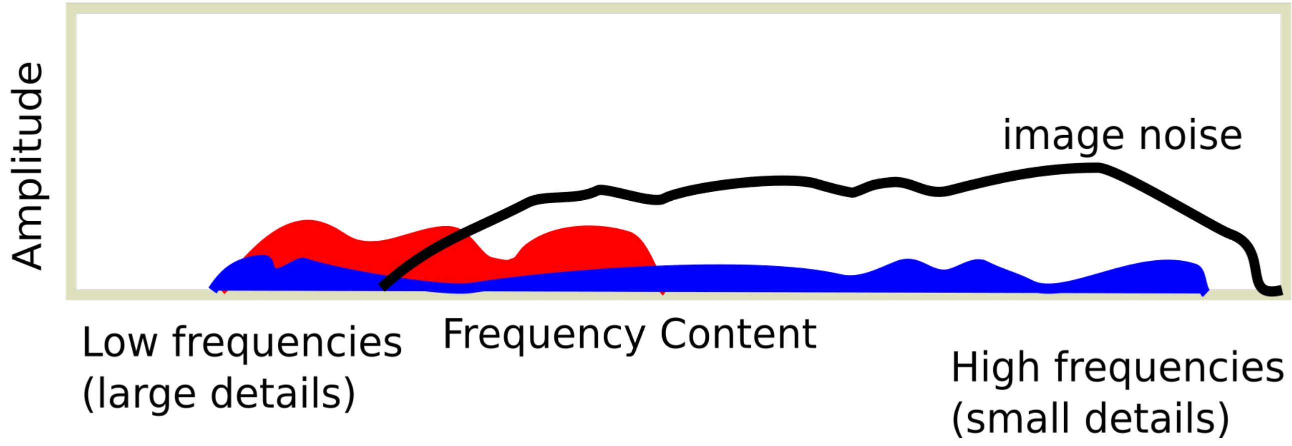
A

B

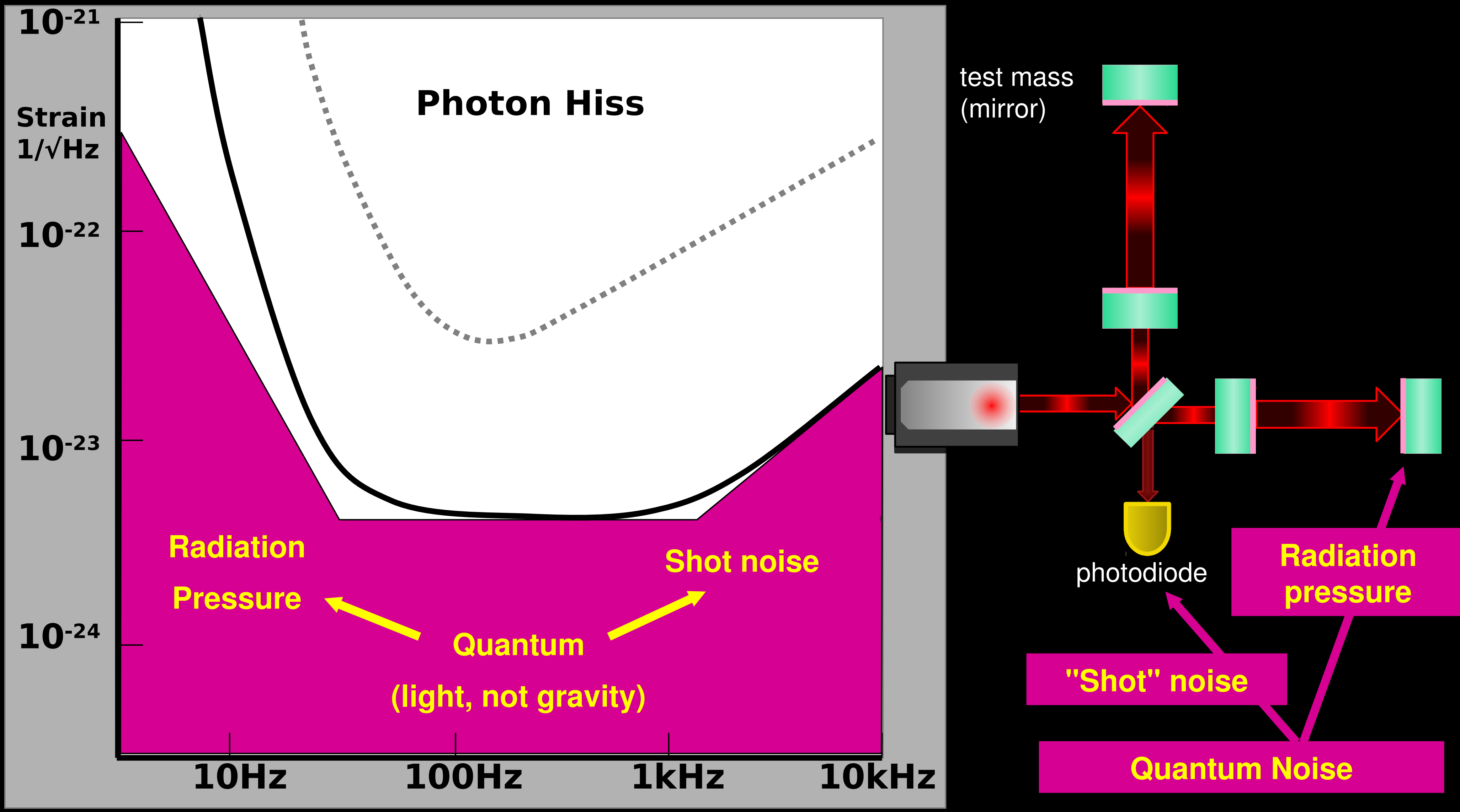




Frequency Dependence



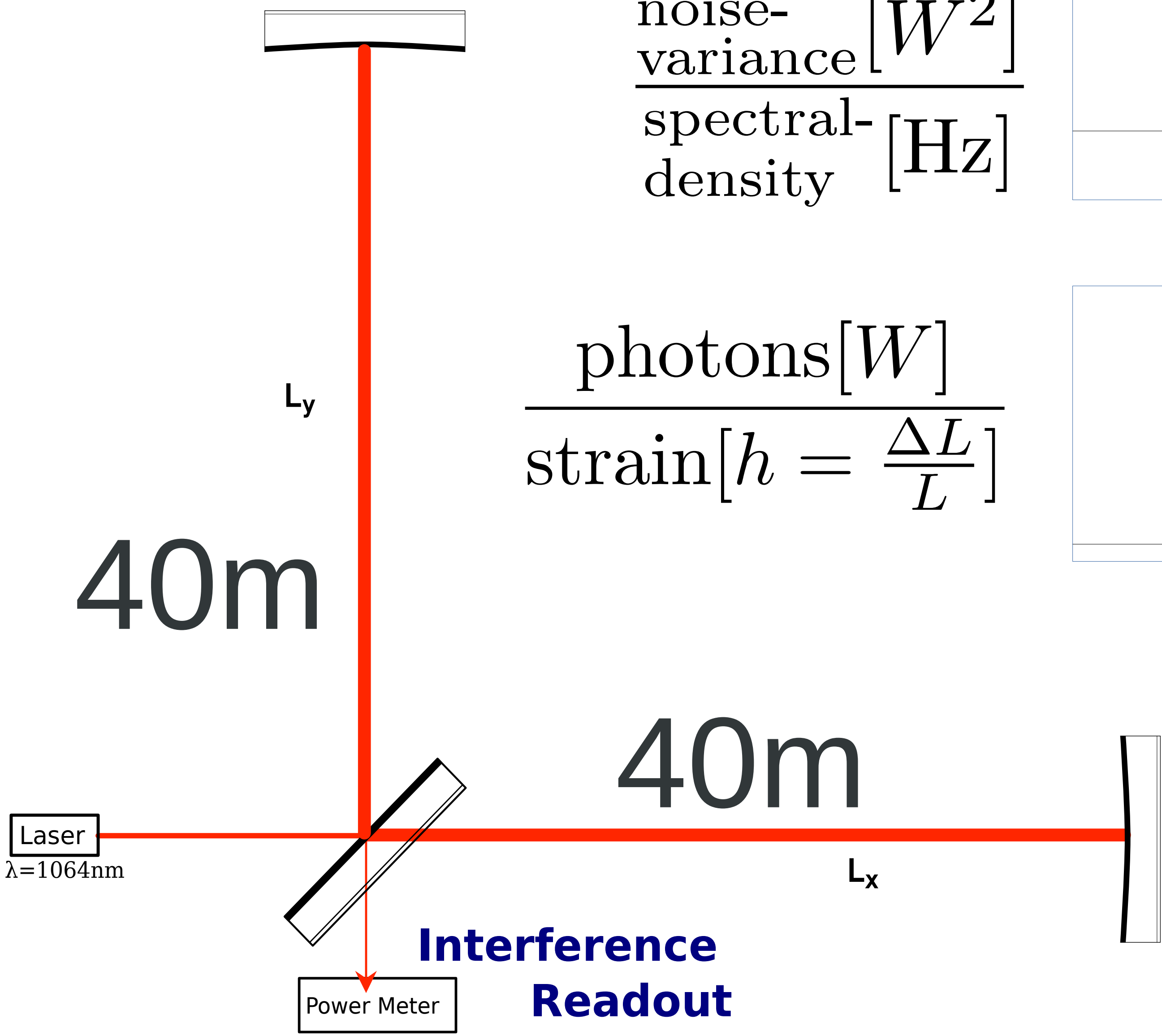
Advanced LIGO Noise



Optical Layouts

$$\frac{\text{noise-variance}[W^2]}{\text{spectral-density}[\text{Hz}]}$$

$$\frac{\text{photons}[W]}{\text{strain}[h = \frac{\Delta L}{L}]}$$



Optical Layouts

$$\frac{\text{noise-variance}[W^2]}{\text{spectral-density}[\text{Hz}]}$$

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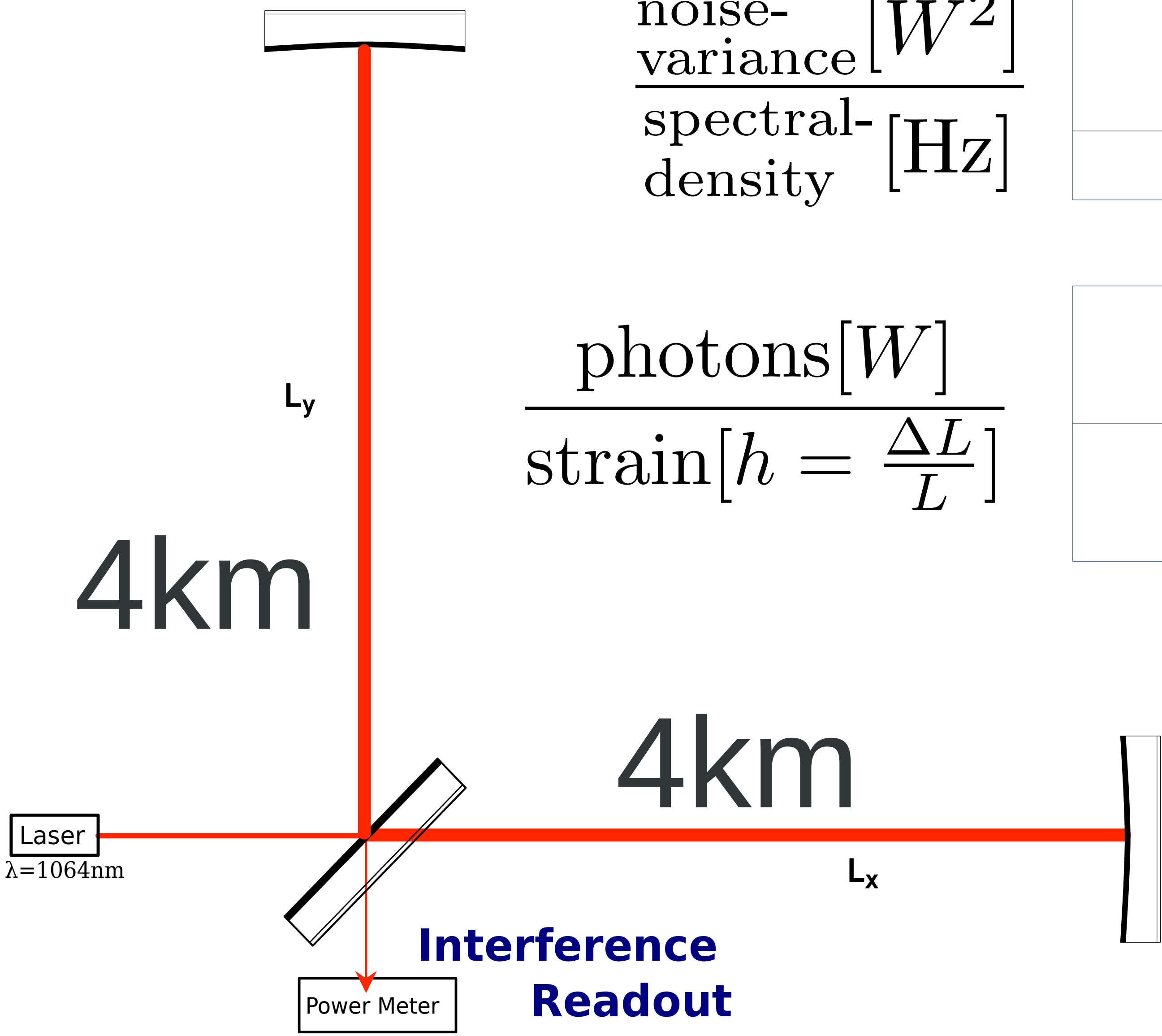
$\text{Frequency}[\text{Hz}]$

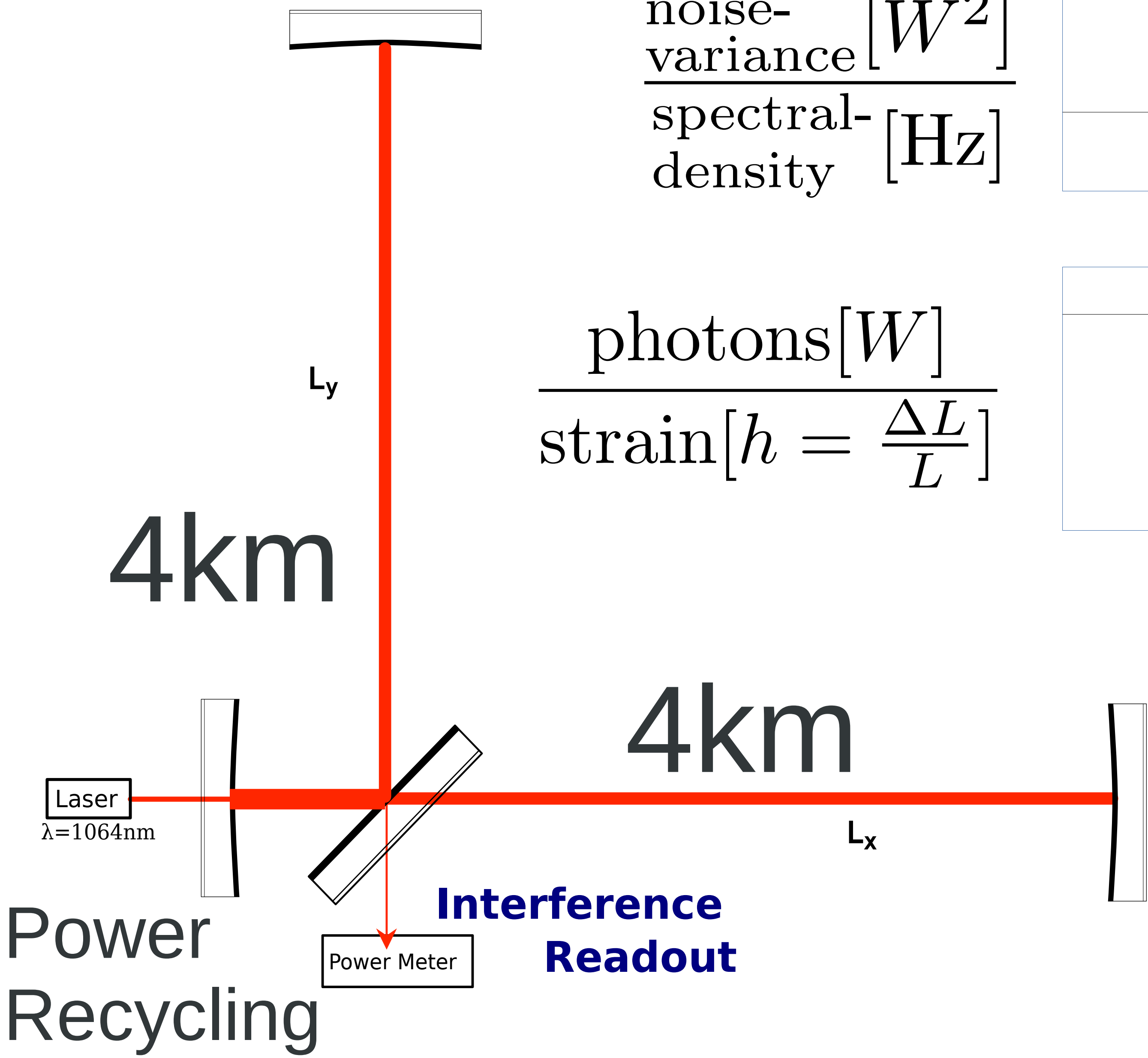


Optical Layouts

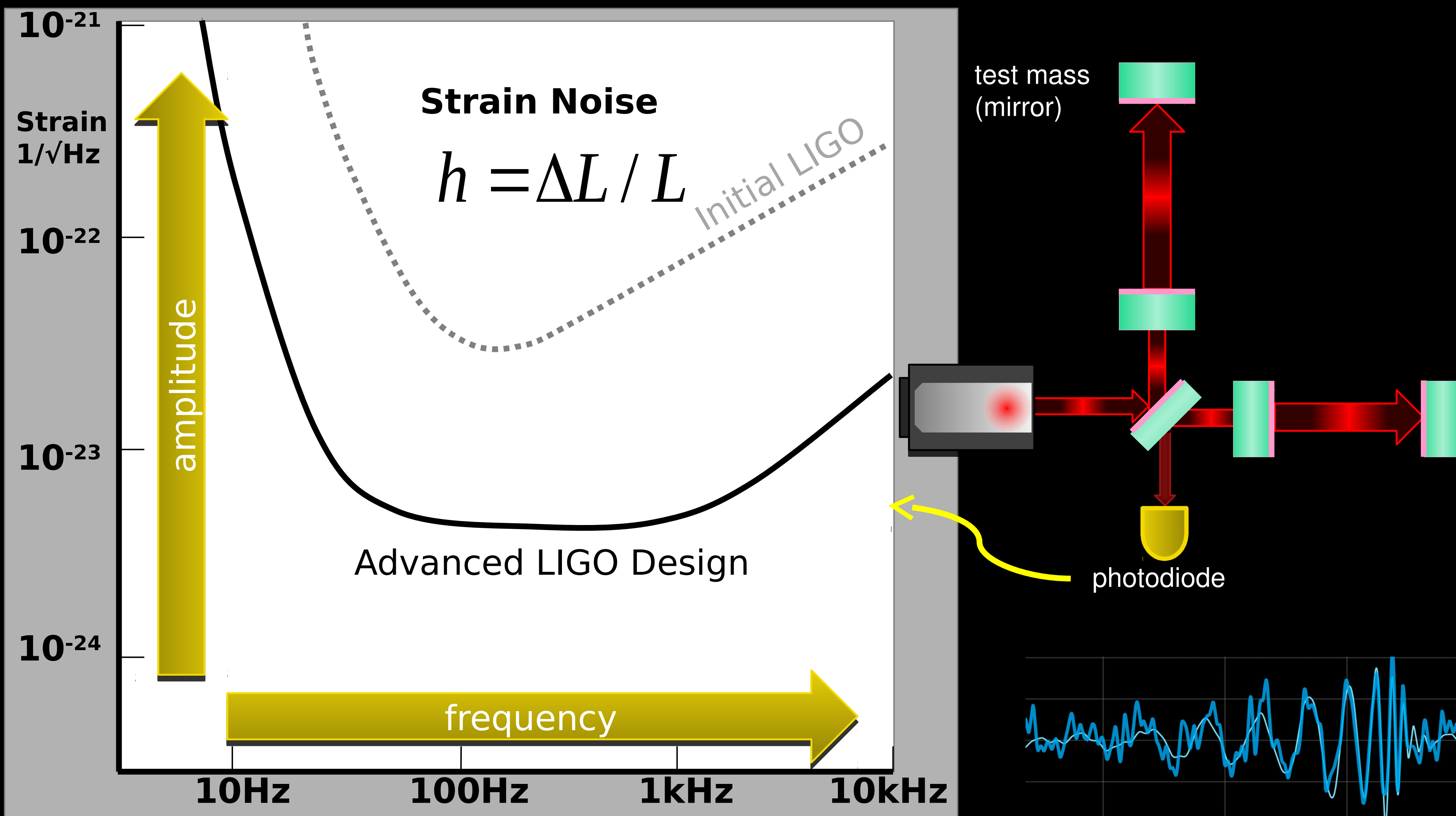
$$\frac{\text{noise-variance}\,[W^2]}{\text{spectral-density}\,[\mathrm{Hz}]}$$

$$\frac{\text{photons}[W]}{\text{strain}[h = \frac{\Delta L}{L}]}$$

$\text{Frequency}[\mathrm{Hz}]$

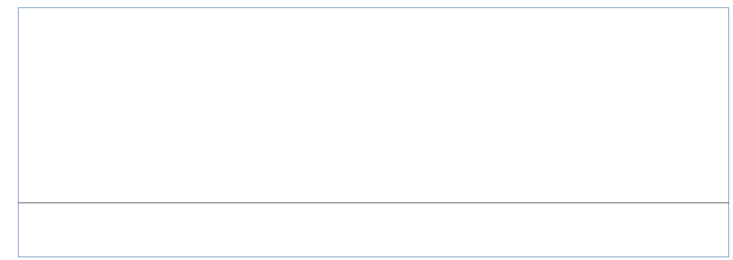


Advanced LIGO Noise

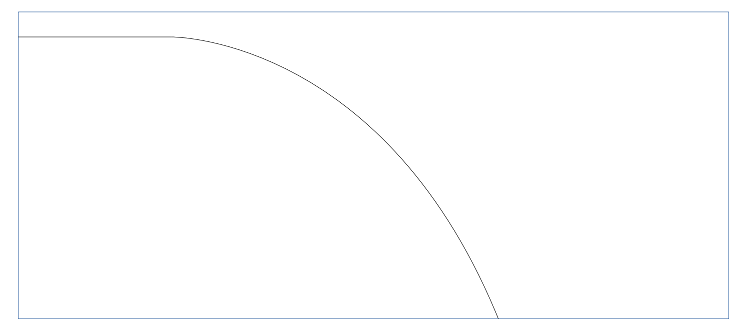


Optical Layouts

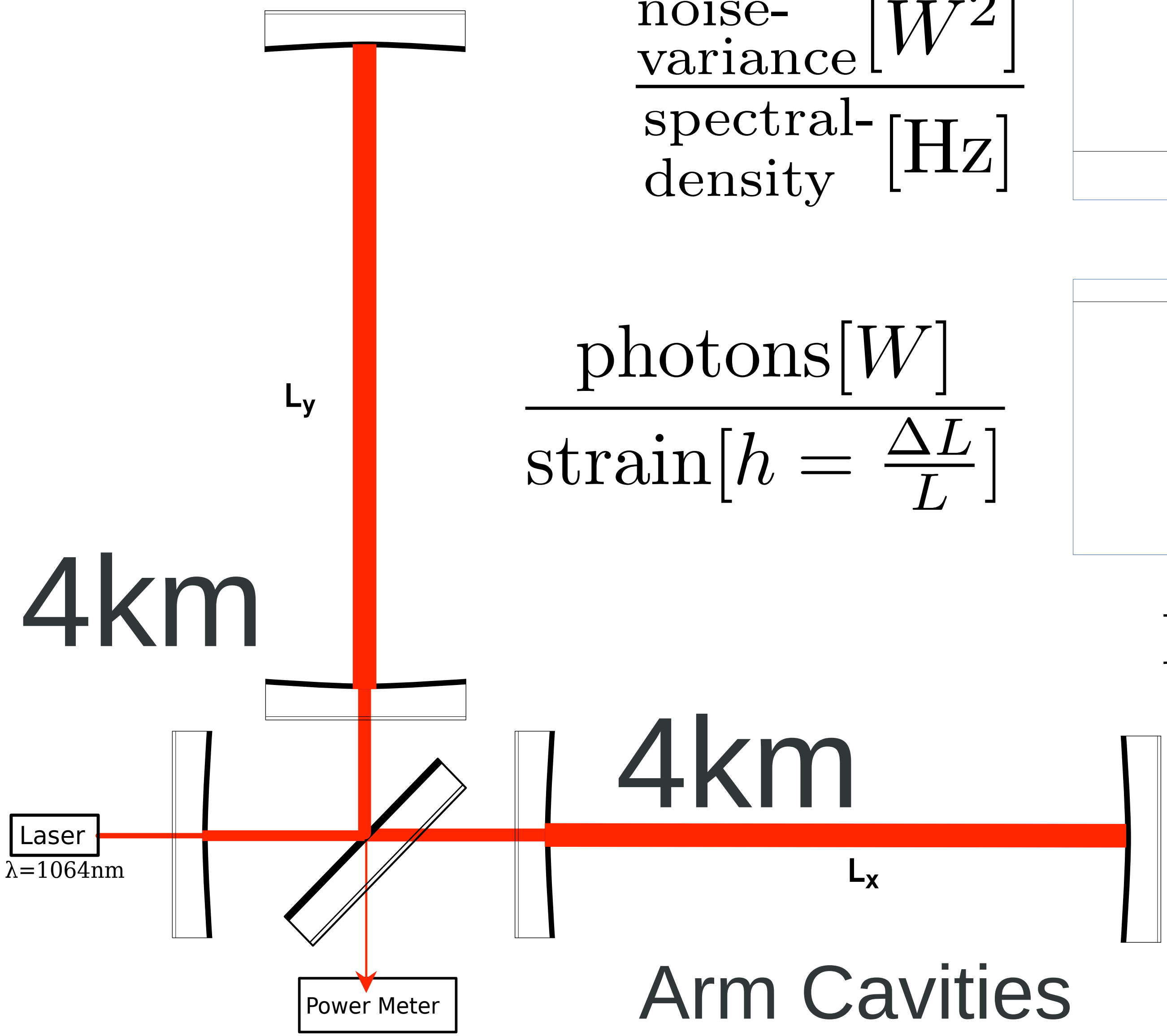
$$\frac{\text{noise-variance}\,[W^2]}{\text{spectral-density}\,[\mathrm{Hz}]}$$



$$\frac{\text{photons}[W]}{\text{strain}[h = \frac{\Delta L}{L}]}$$

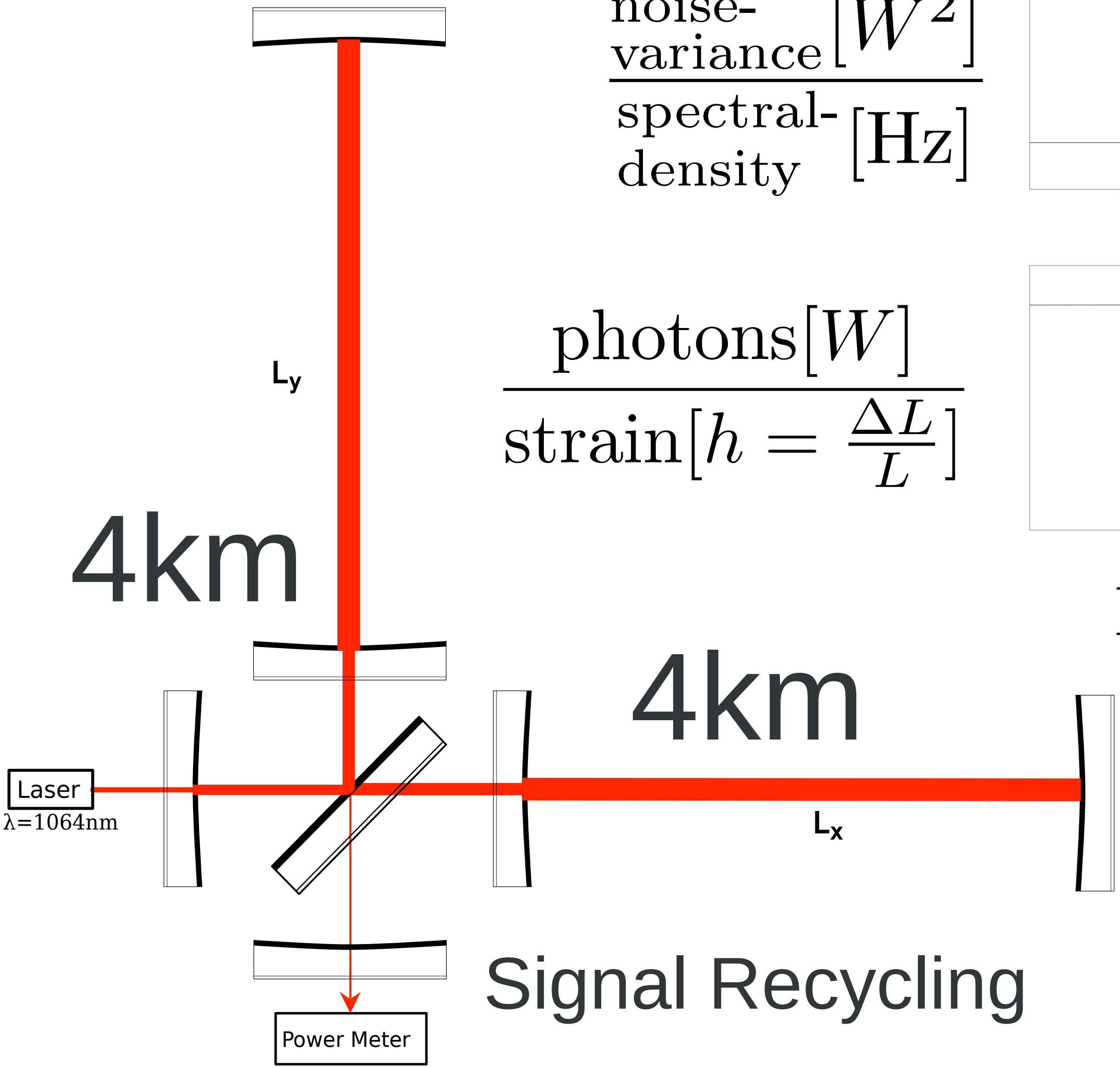


$\text{Frequency}[\mathrm{Hz}]$



Arm Cavities

Optical Layouts



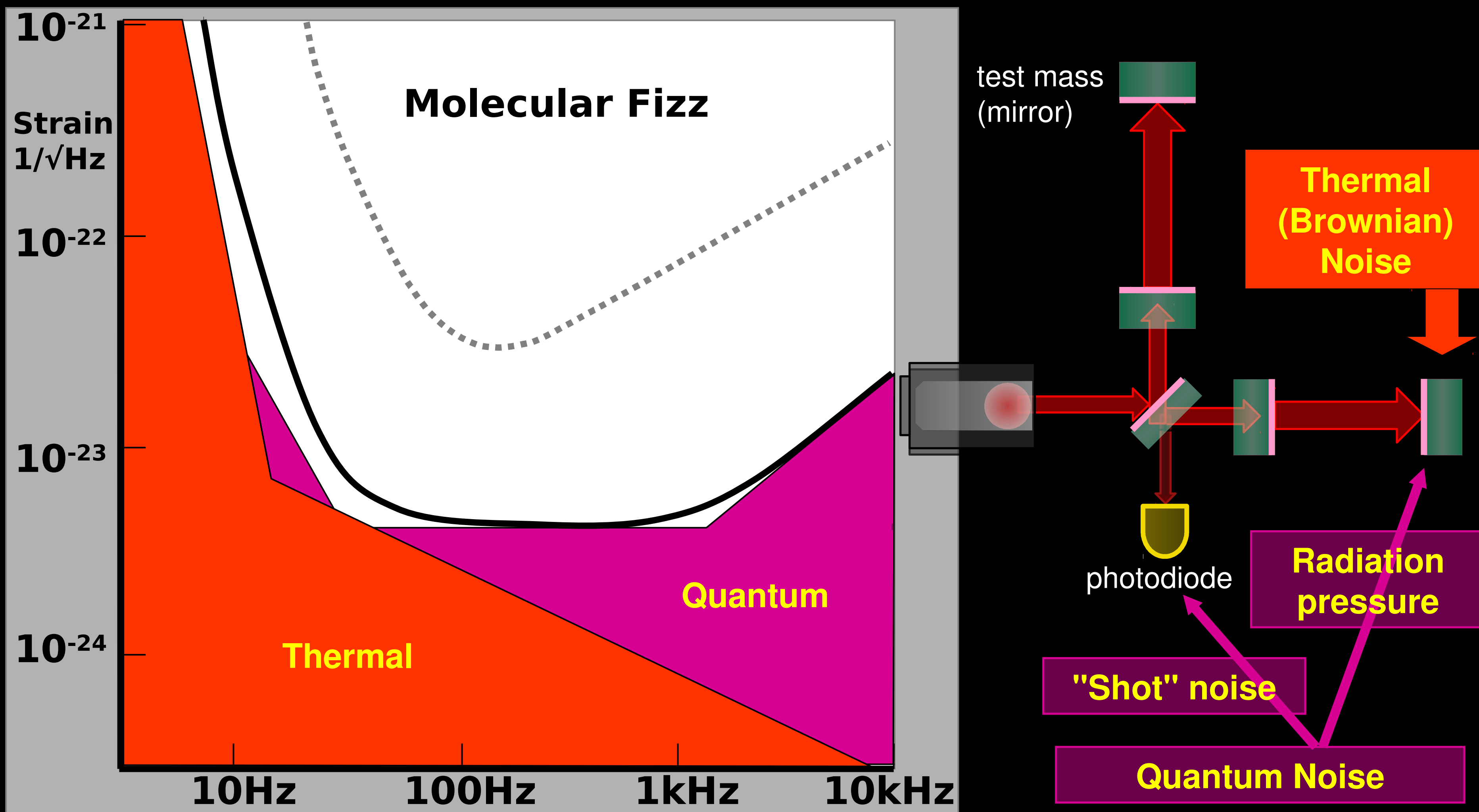
$$\frac{\text{noise-variance}\,[W^2]}{\text{spectral-density}\,[\text{Hz}]}$$

$$\frac{\text{photons}[W]}{\text{strain}[h = \frac{\Delta L}{L}]}$$

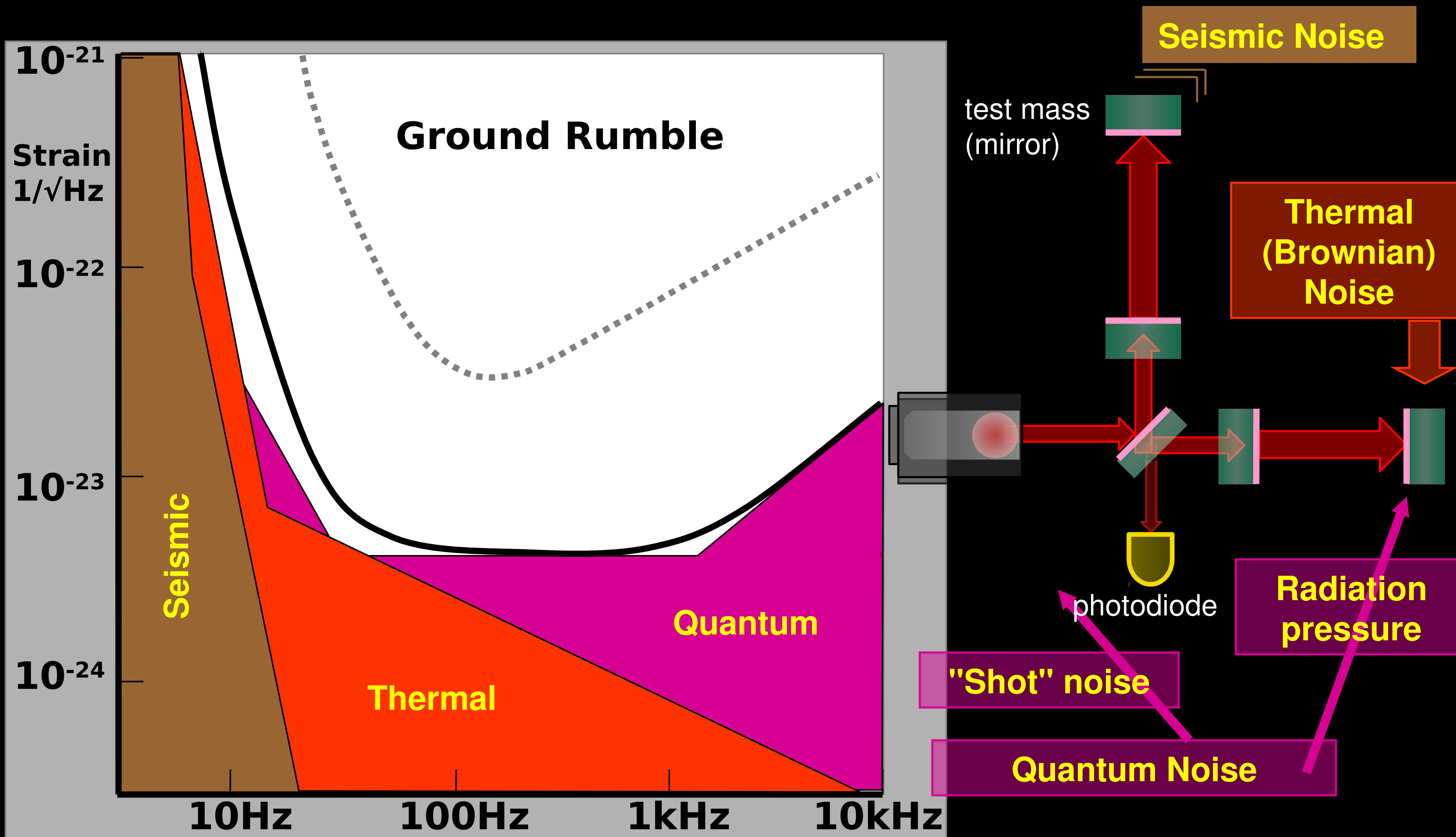
Frequency[Hz]

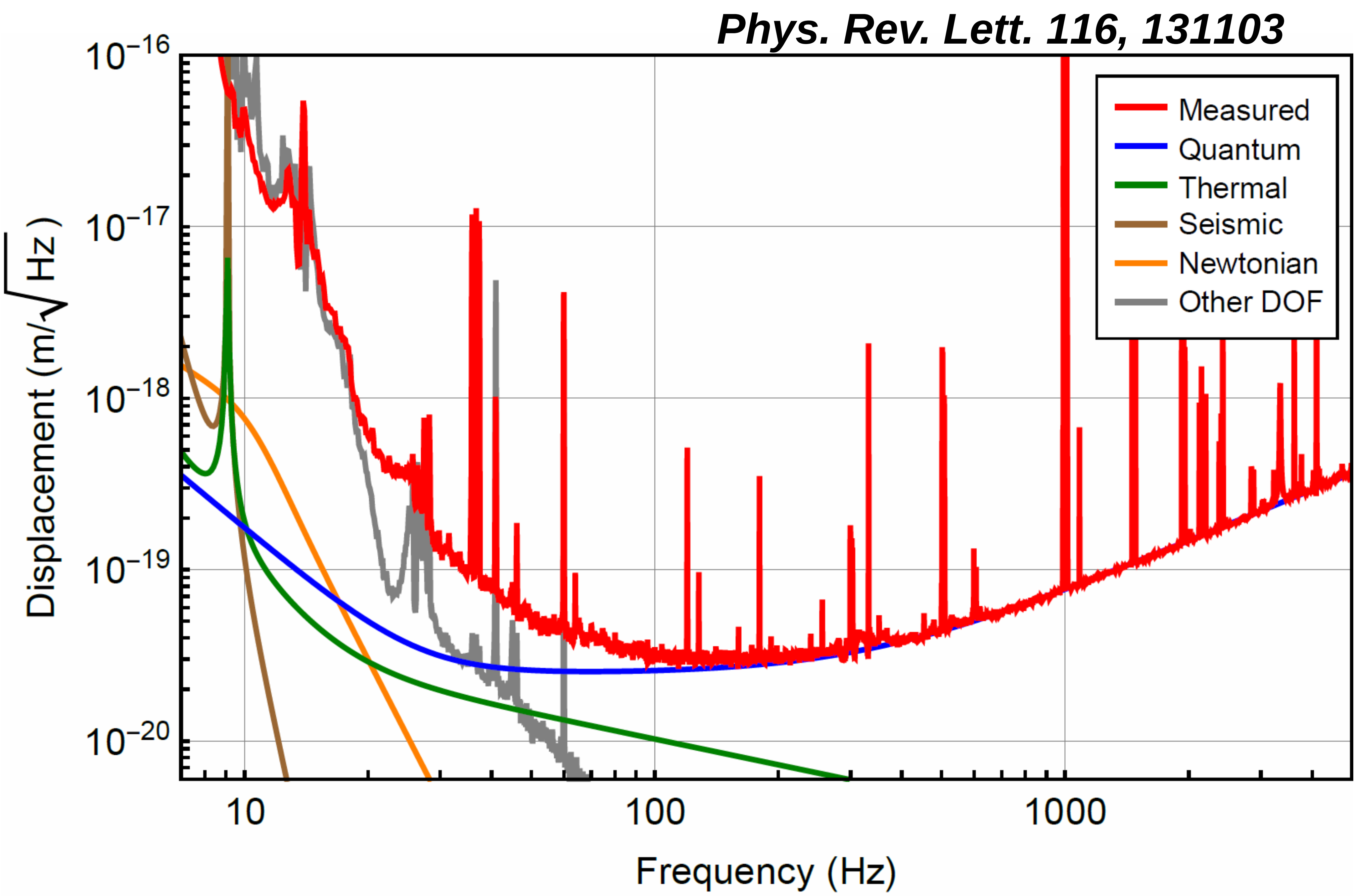
Signal Recycling

Advanced LIGO Noise



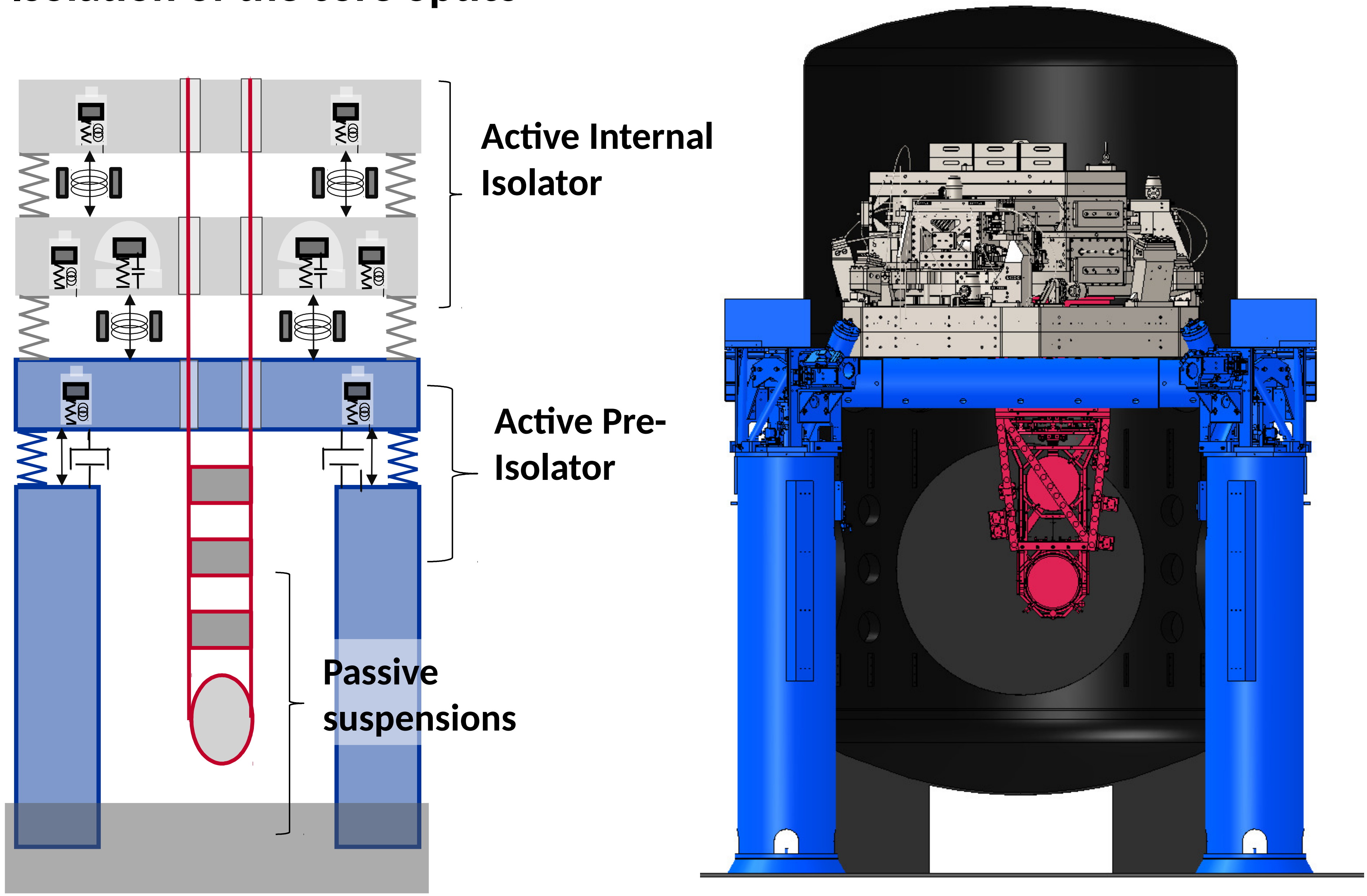
Advanced LIGO Noise

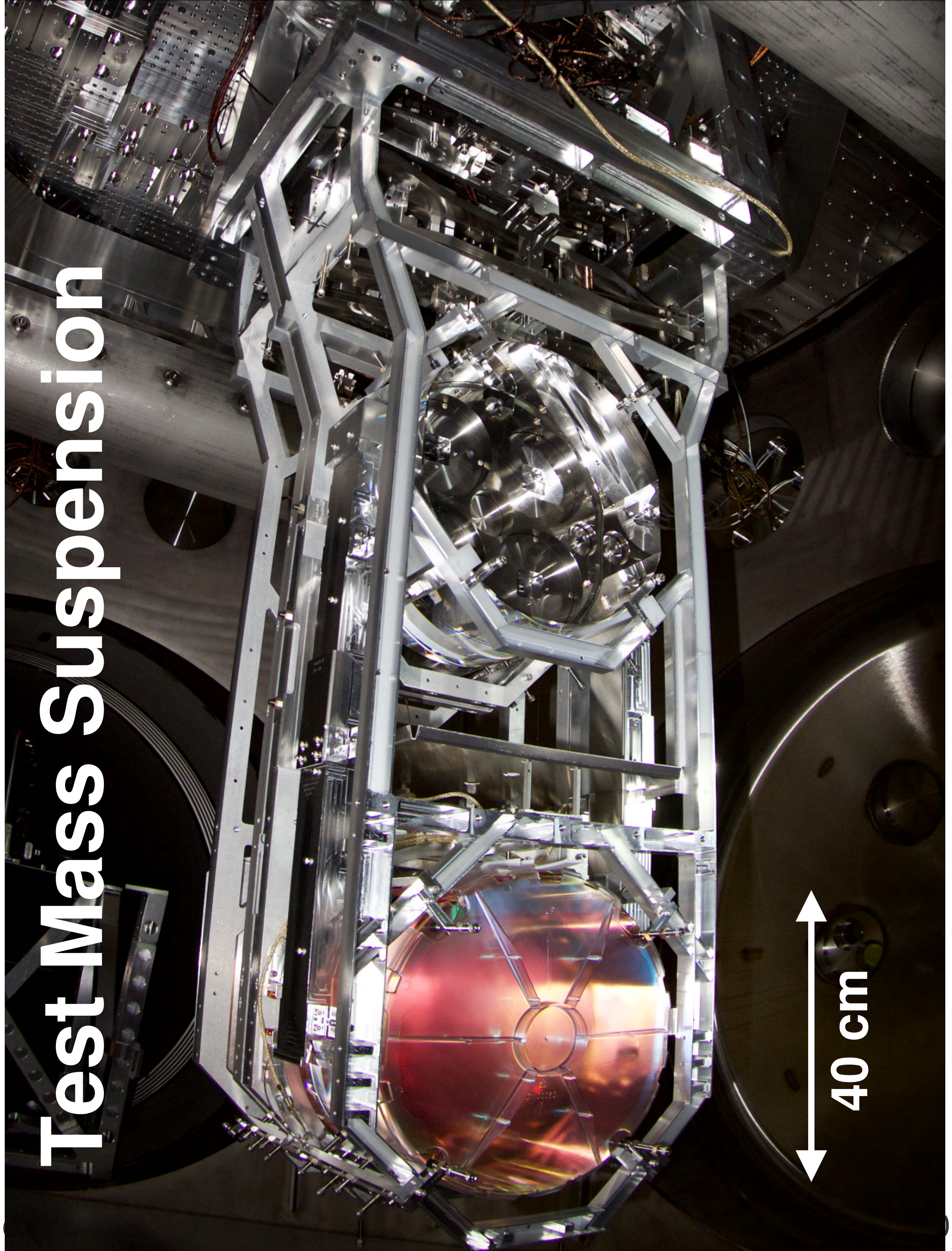


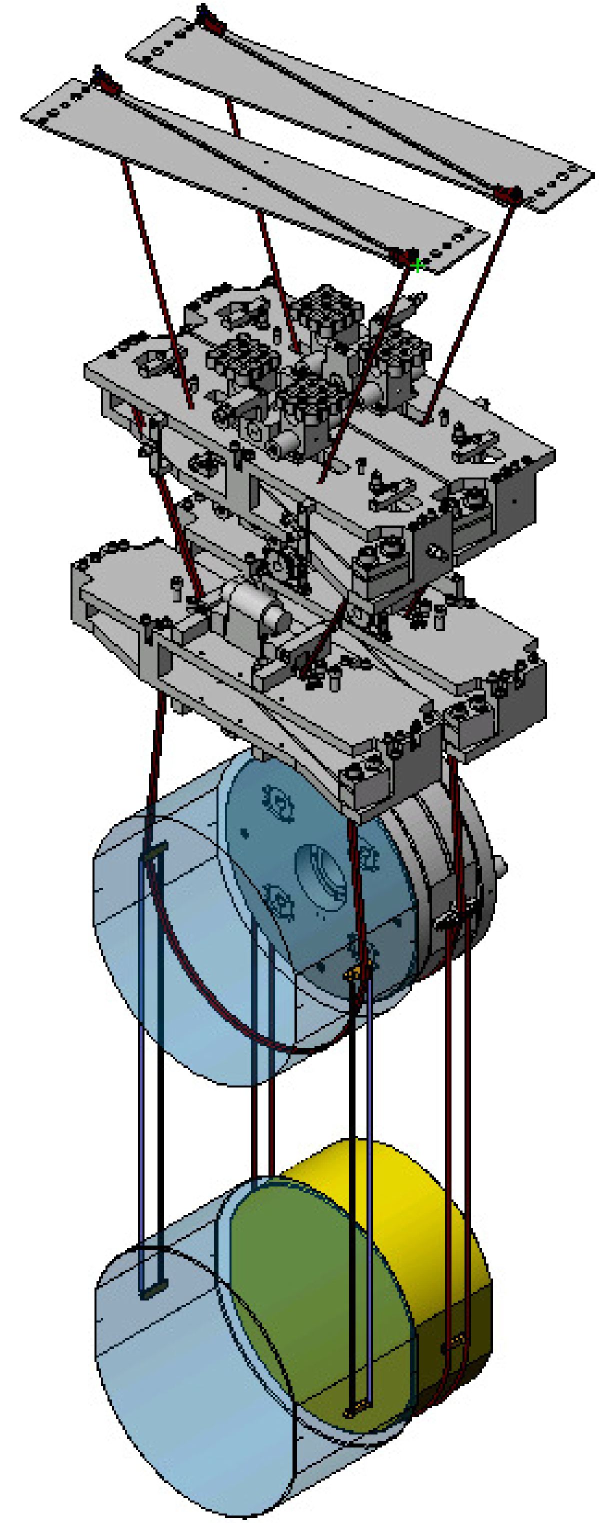

Phys. Rev. Lett. 116, 131103
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
Displacement (m/$\sqrt{\text{Hz}}$)
10
100
1000
Frequency (Hz)
Measured
Quantum
Thermal
Seismic
Newtonian
Other DOF


Vacuum System Vertex

Isolation of the core optics

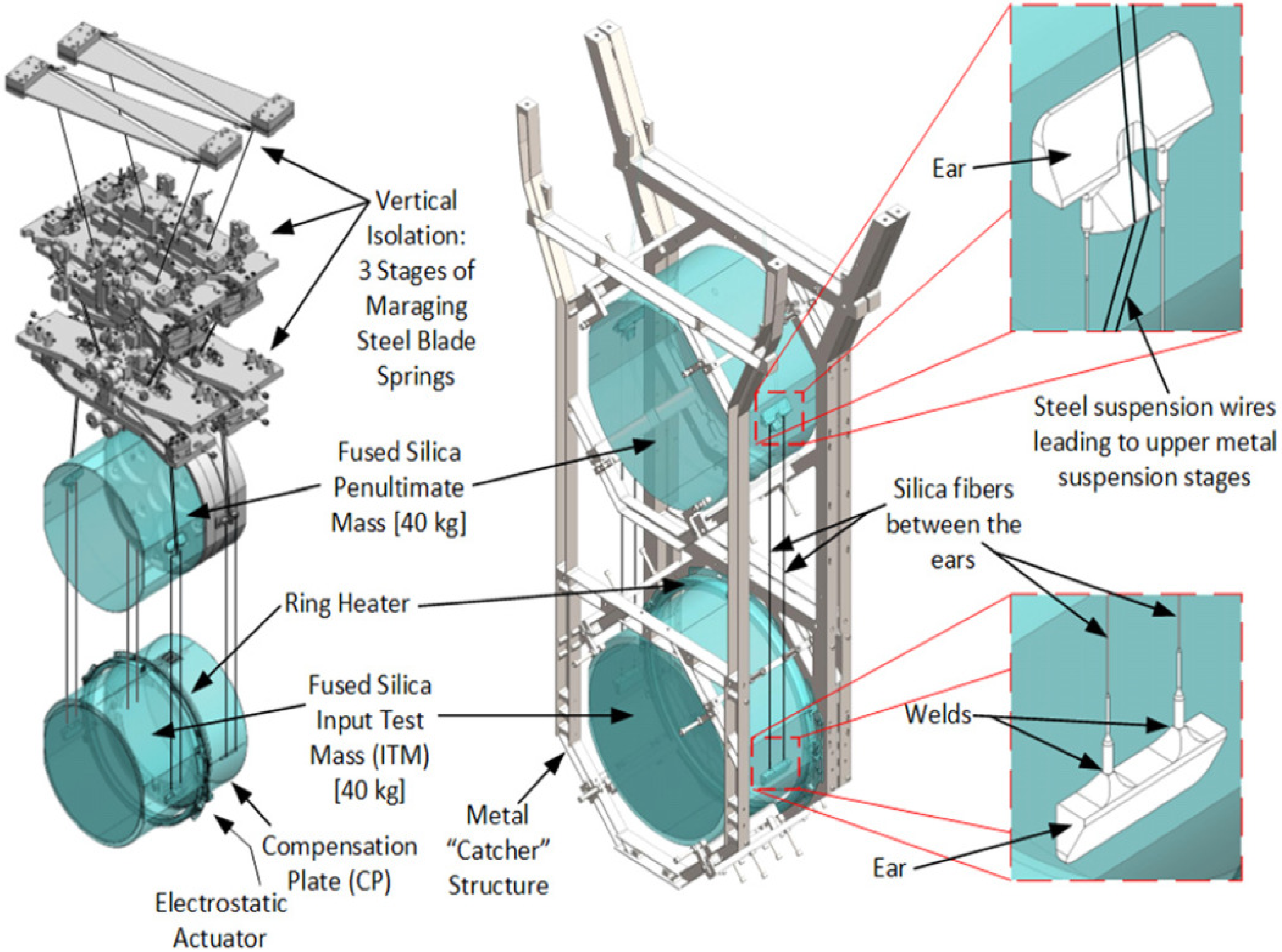



Test Mass Suspension
40 cm

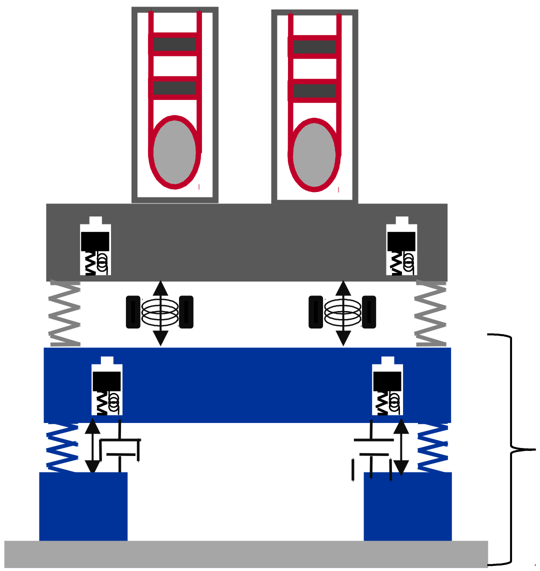


The Quadruple Pendulum

P1400177 - Advanced LIGO



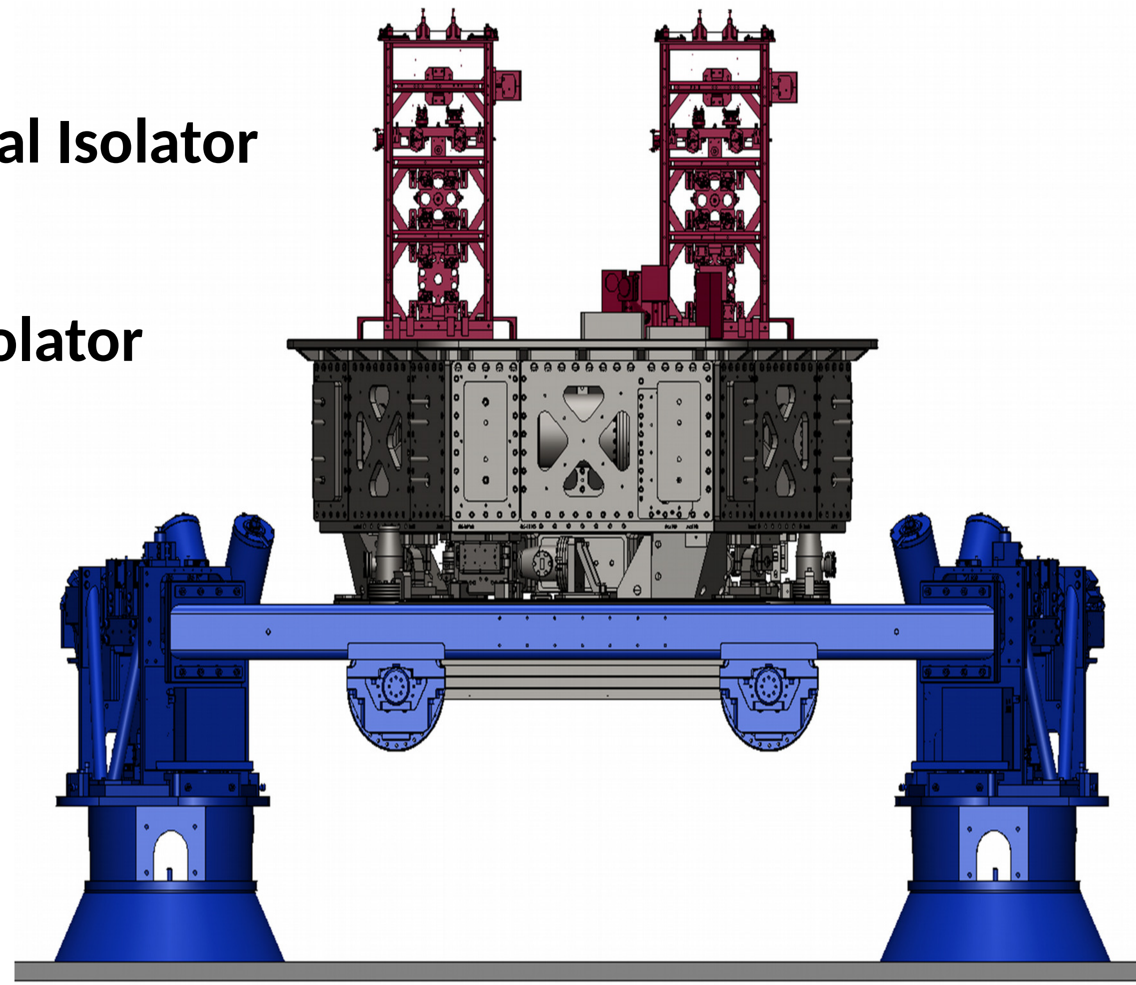
Isolation of the auxiliary optics

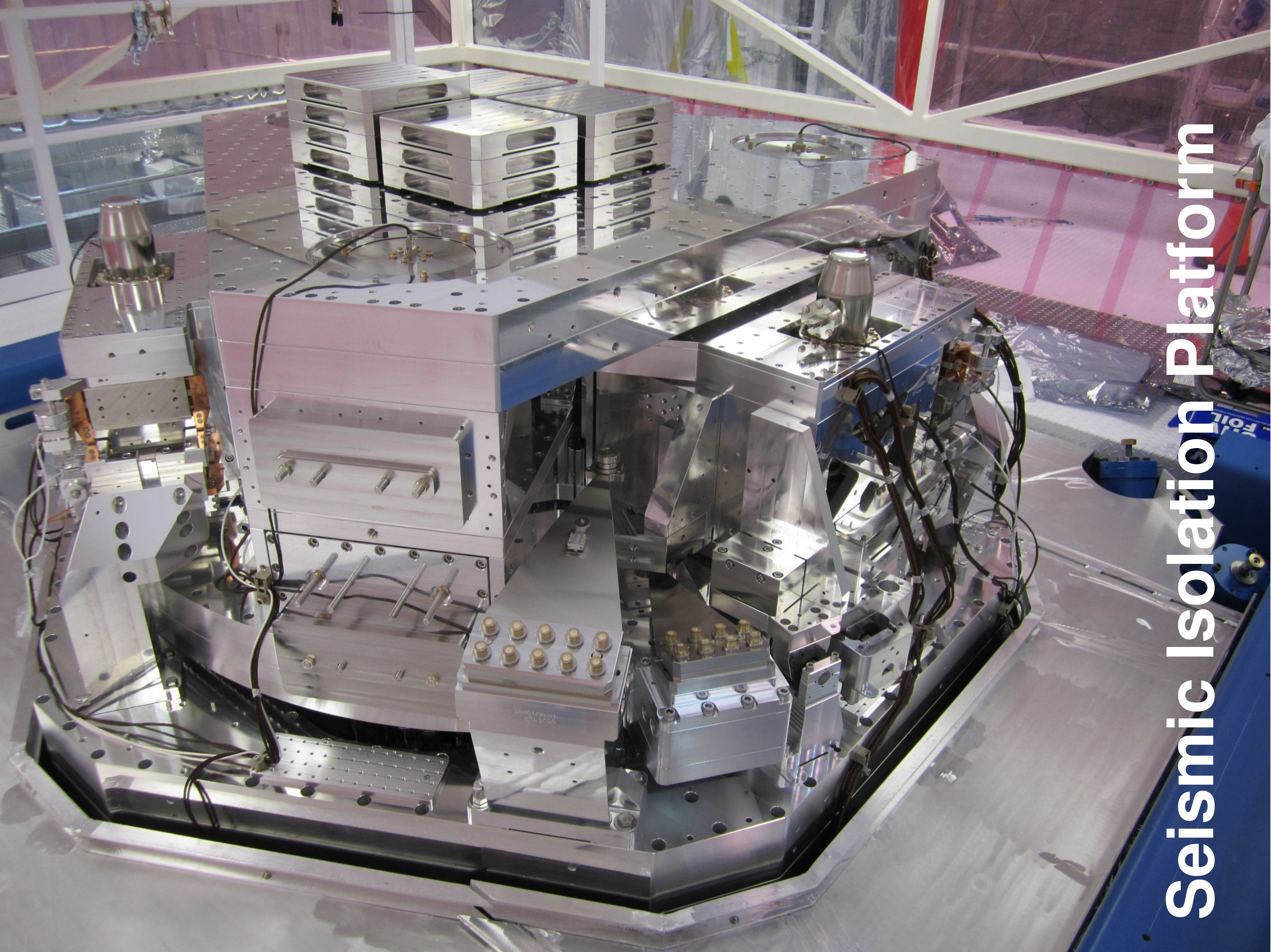


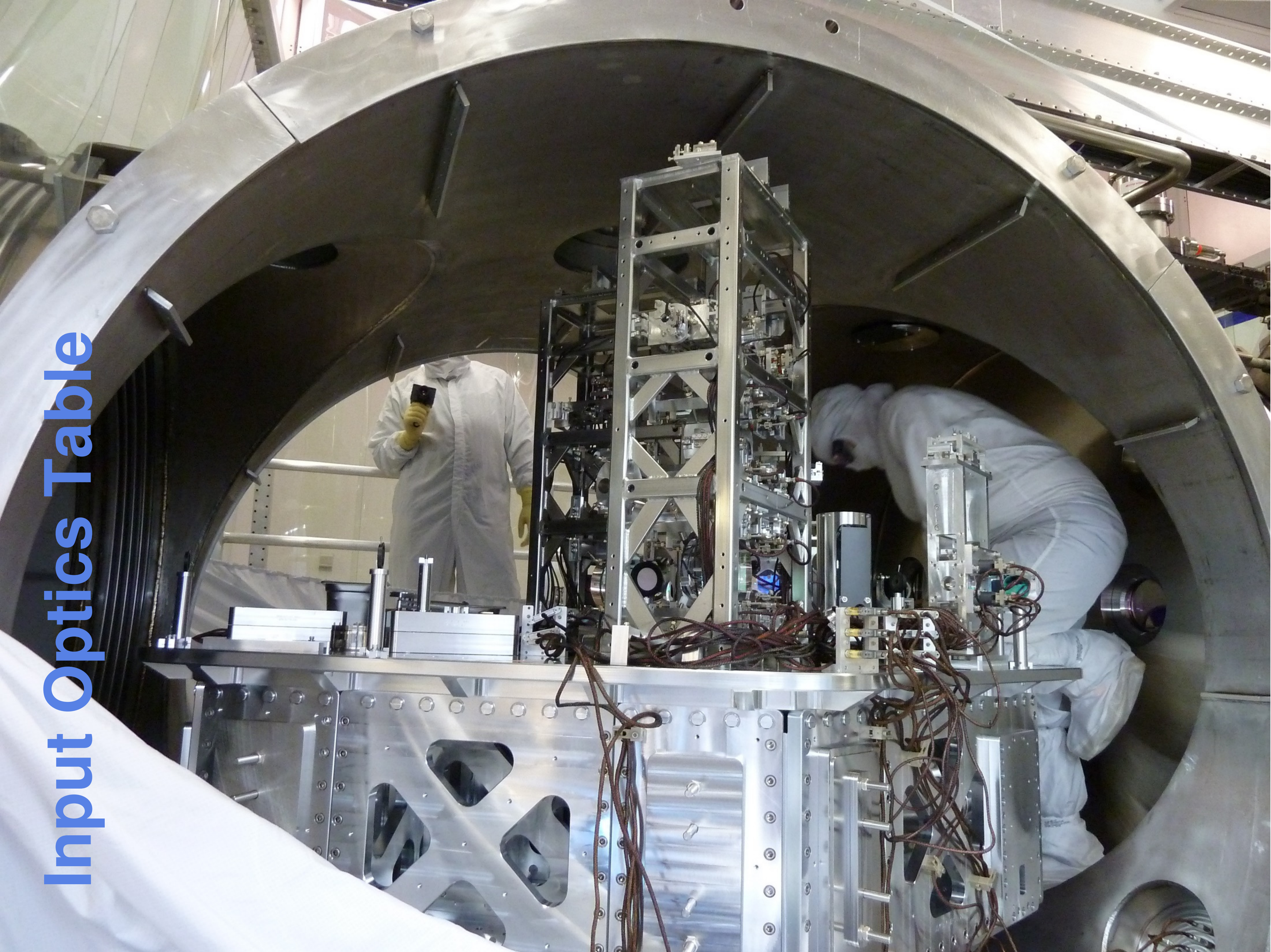
Passive suspensions

Active
Internal Isolator

Active
Pre-Isolator

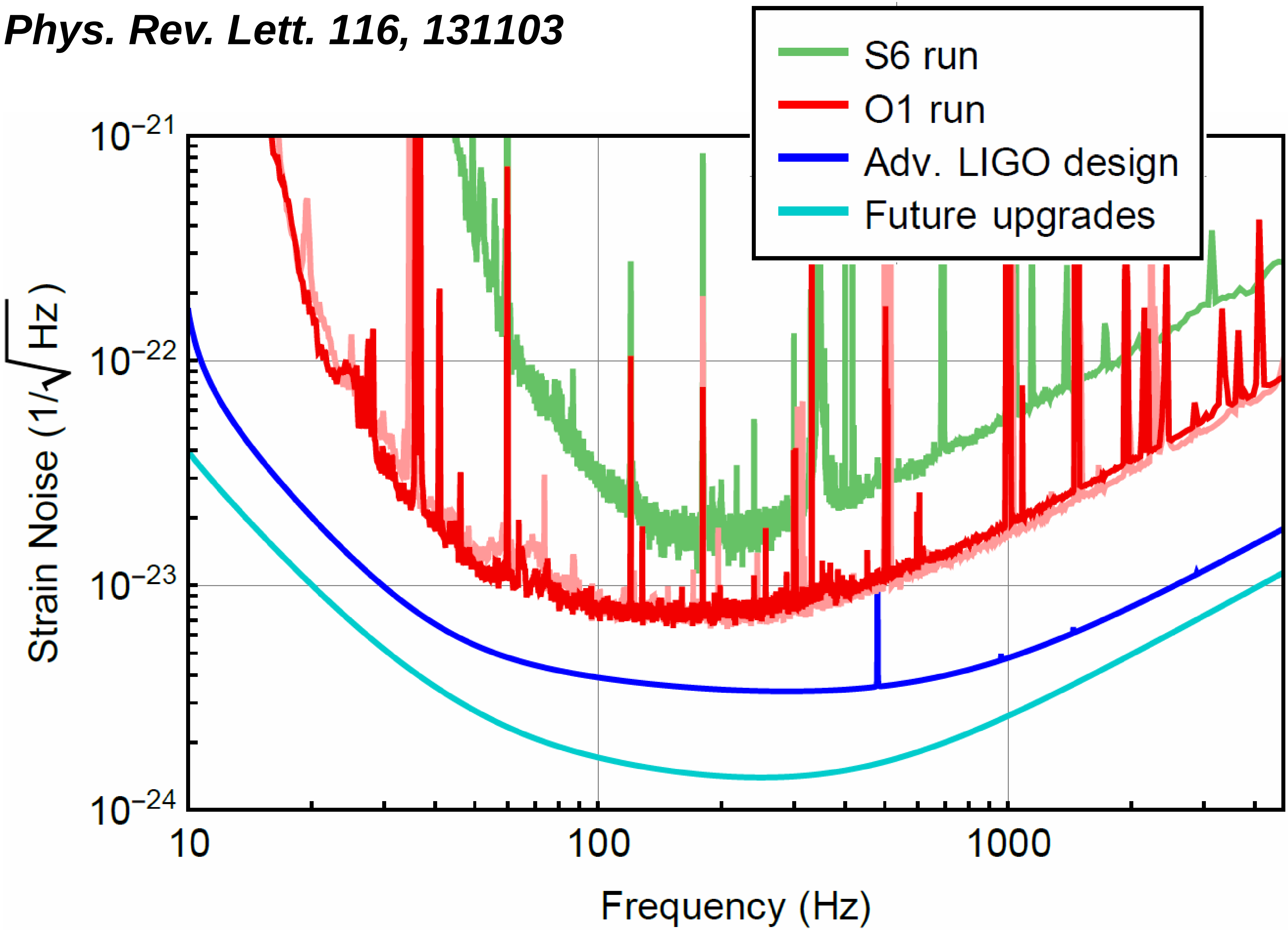



Seismic Isolation Platform


Input Optics Table

Control Room in Hanford

Phys. Rev. Lett. 116, 131103



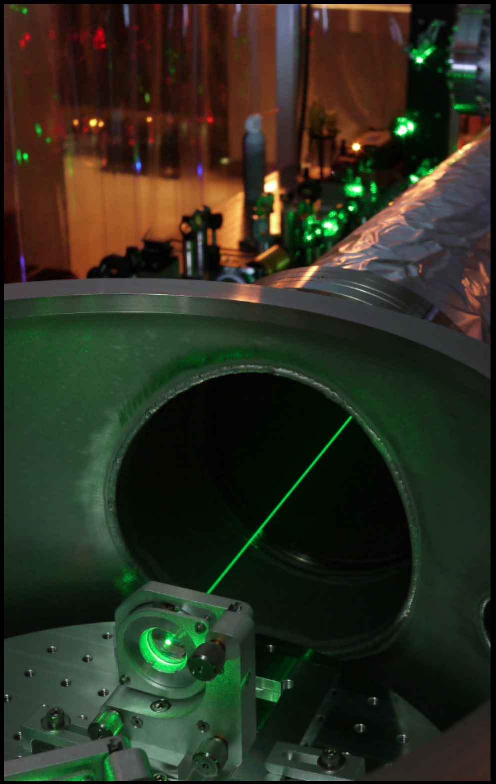
Advanced LIGO: ways to do better?

- Mature technologies available to reduce quantum noise and improve aLIGO sensitivity by ~35% beyond design $x1.35^3$=2.5 in rate
  - Squeezed light

A gravitational wave observatory operating beyond the quantum shot-noise limit
Nature Physics 7, 962–965 (2011)
Enhanced sensitivity of the LIGO gravitational wave detector by using squeezed states of light
Nature Photonics 7, 613–619 (2013)
Audio-Band Frequency-Dependent Squeezing for Gravitational-Wave Detectors
Phys. Rev. Lett. 116, 041102 (2016)

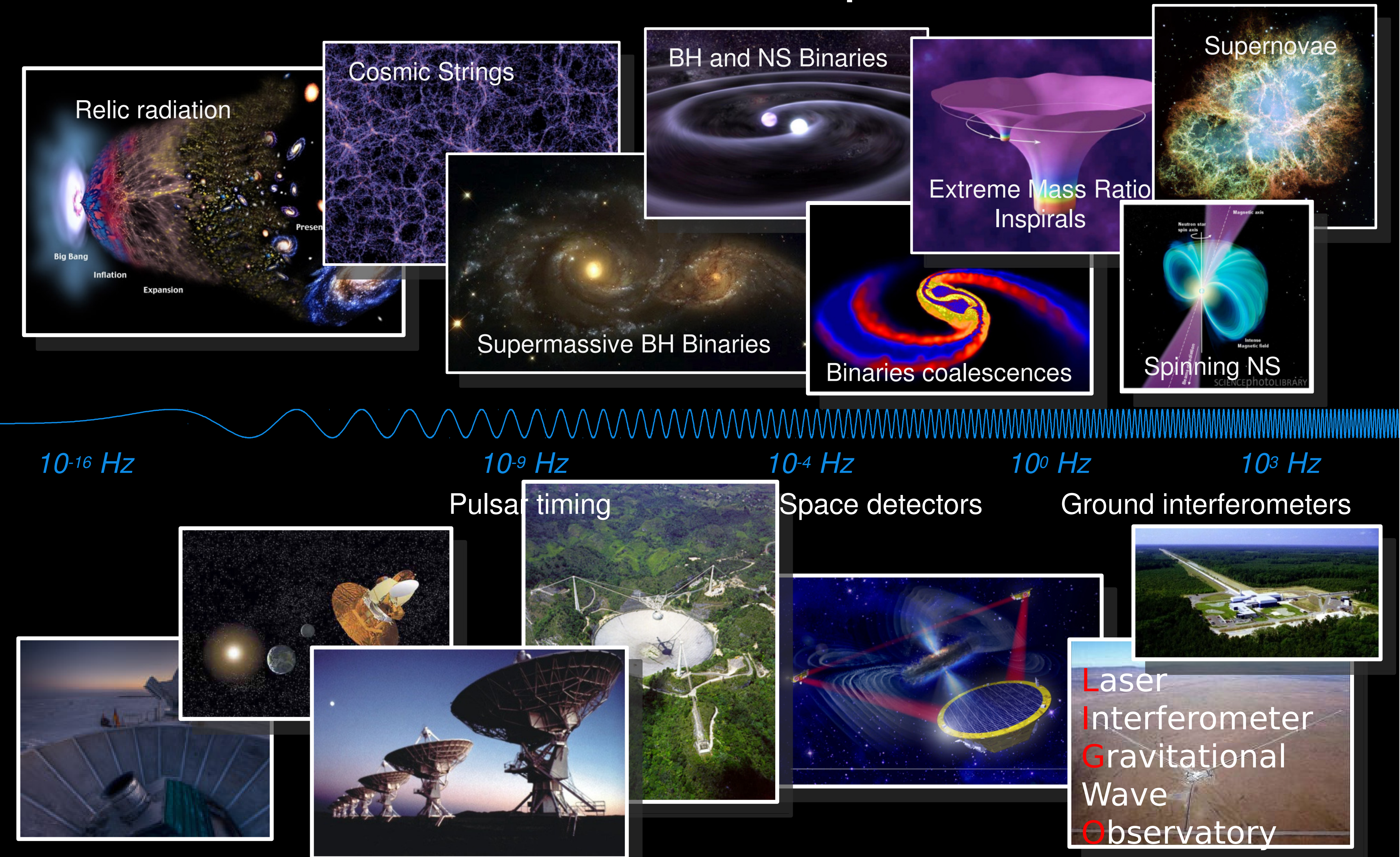
- Need to reduce other noise sources for maximal benefit:
  - Reducing coating thermal noise as well can lead to a reduction in the noise by a factor of 2

$x2^3$ = 8 in rate!



2 m prototype quantum filter cavity @ MIT for frequency dependent squeezing

The Gravitational Wave Spectrum



Thanks to:

www.ligo.org

LIGO
LASER INTERFEROMETER GRAVITATIONAL-WAVE OBSERVATORY

LIGO VIRGO