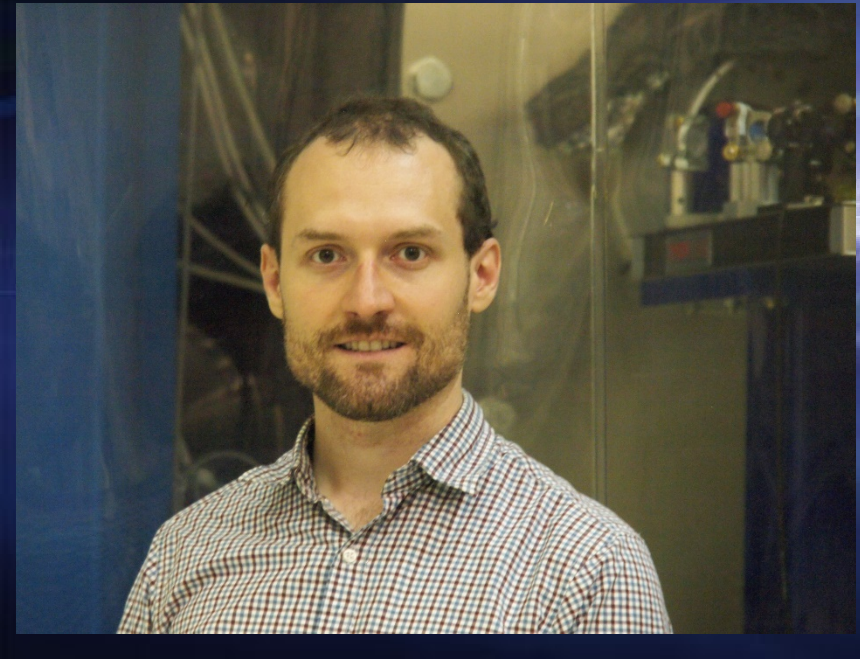
Interferometer Sensing and Control in Gravitational Wave Detectors

Speaker: Dr. Lee McCuller
MIT LiGO

OSA Webinar
Photonic Detection Group
15 October 2019
2:00 PM - 3:00 PM



OSA Photonic Detection Technical Group

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Vice Chair
Founder Banpil Photonics

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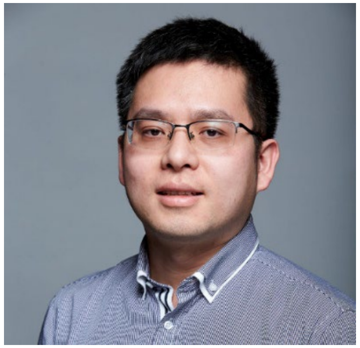

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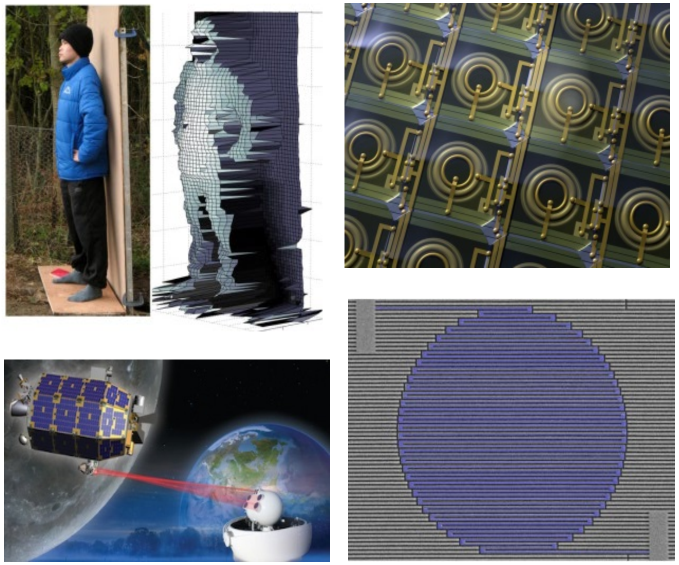
OSA
Photonic
Detection
Technical Group

OSA Photonic Detection Technical Group

About Us

The Photonic Detection technical group is part of the Photonics and Opto-Electronics Division of the Optical Society. This group focuses on the detection of photons as received from images, data links, and experimental spectroscopic studies to mention a few. Within its scope, the PD technical group is involved in the design, fabrication, and testing of single and arrayed detectors.

This group focuses on materials, architectures, and readout circuitry needed to transduce photons into electrical signals and further processing. This group's interests include: (1) the integration of lens, cold shields, and readout electronics into cameras, (2) research into higher efficiency, lower noise, and/or wavelength tunability, (3) techniques to mitigate noise and clutter sources that degrade detector performance, and (4) camera design, components, and circuitry.



Photonic Detection Technical Group

Find us online

OSA Homepage
www.osa.org/PD

LinkedIn Group
www.linkedin.com/groups/Photonic-Detection-Technical-Group-8297763/about

About OSA Awards Career Video

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hotonic Detection (PD)

Get Involved

- Technical Divisions +
  - Bio-Medical Optics
  - Fabrication, Design & Instrumentation
  - Information Acquisition, Processing & Display
  - Optical Interaction Science
  - Photonics and Opto-Electronics +
    - Fiber Optics Technology (PF)
    - Integrated Optics (PI)
    - Laser Systems (PL)
    - Optical Communications (PC)

Photonic Detection (PD)

This group involves the detection of photons as received from images, data links, and experimental spectroscopic studies to mention a few. Within its scope, it is involved in the design, fabrication, testing of single and arrayed detectors. Detector materials, structures, and readout circuitry needed to translate photons into electrical signals are considered by this group. Also included in this group is the integration of components such as lens, cold shields, and readout electronics into cameras. Research into higher efficiency, lower noise, and/or wavelength tunability is included here. Additionally, techniques to mitigate noise and clutter sources that degrade detector performance are within the purview of this group. In the imaging area, camera design, componentry, and circuitry are considered.

Announcer

Join the Photonic D
Group for their ina
Wednesday, 27 Apı

In this webinar, Dr.
describe his recent
speed quantum ke
photonic integrate
scalable quantum i
processors based
networks.

Register for the W

Technical Group Activities

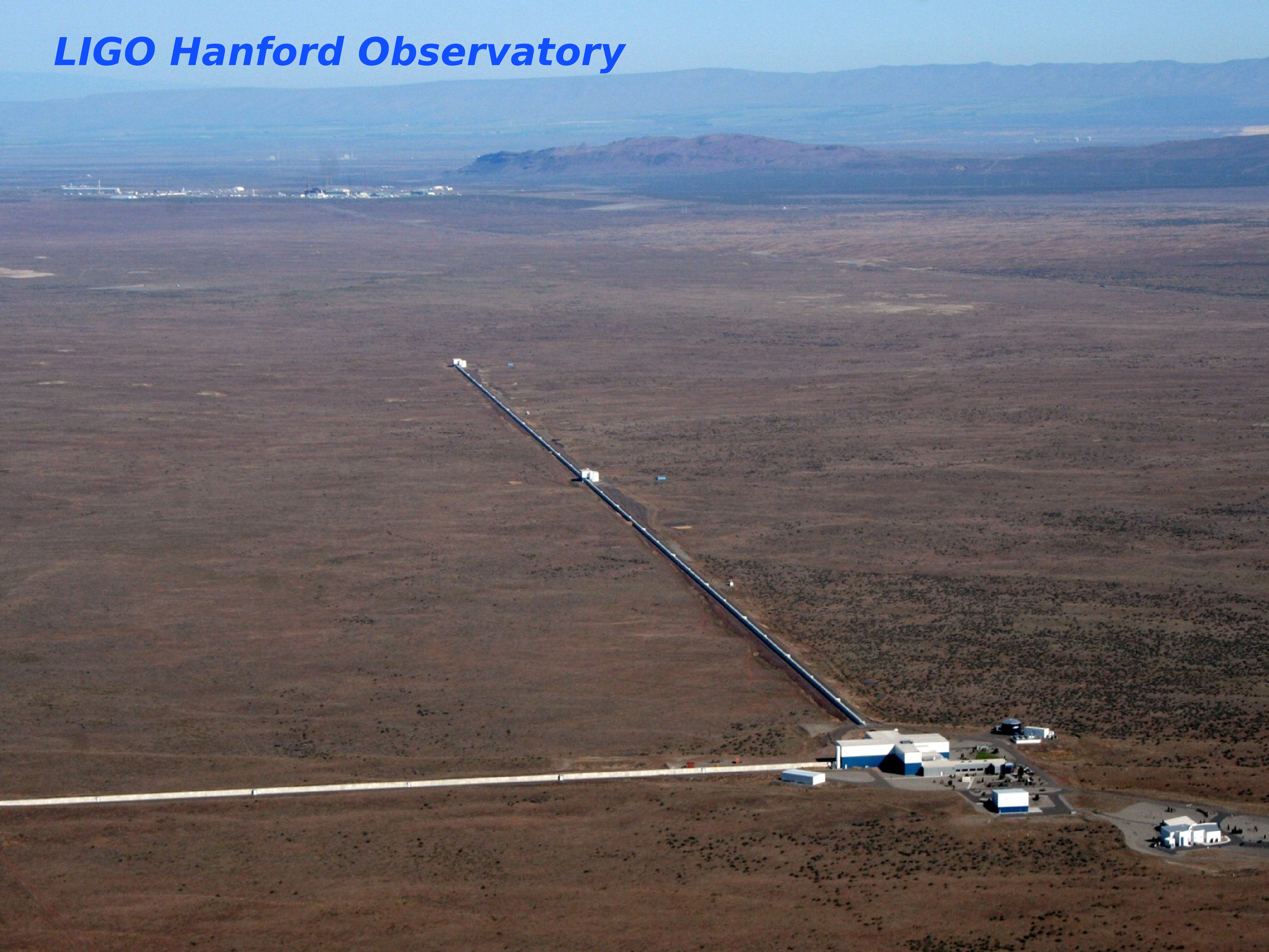
- ***Special Sessions*** at OSA conferences such as CLEO and OFC.
- ***~4 Webinars*** for this year!
- Interactions with local sections and student chapters.
- Interactive community for bringing together researchers across inter-disciplinary fields for tackling advances in photonic detection technologies.
- Example: Panel discussion on ***Silicon Photonics for LiDAR and Other Applications*** at OFC 2019 which had great turn-out and a lot of interest!

Interferometer Sensing and Control in Gravitational Wave detectors

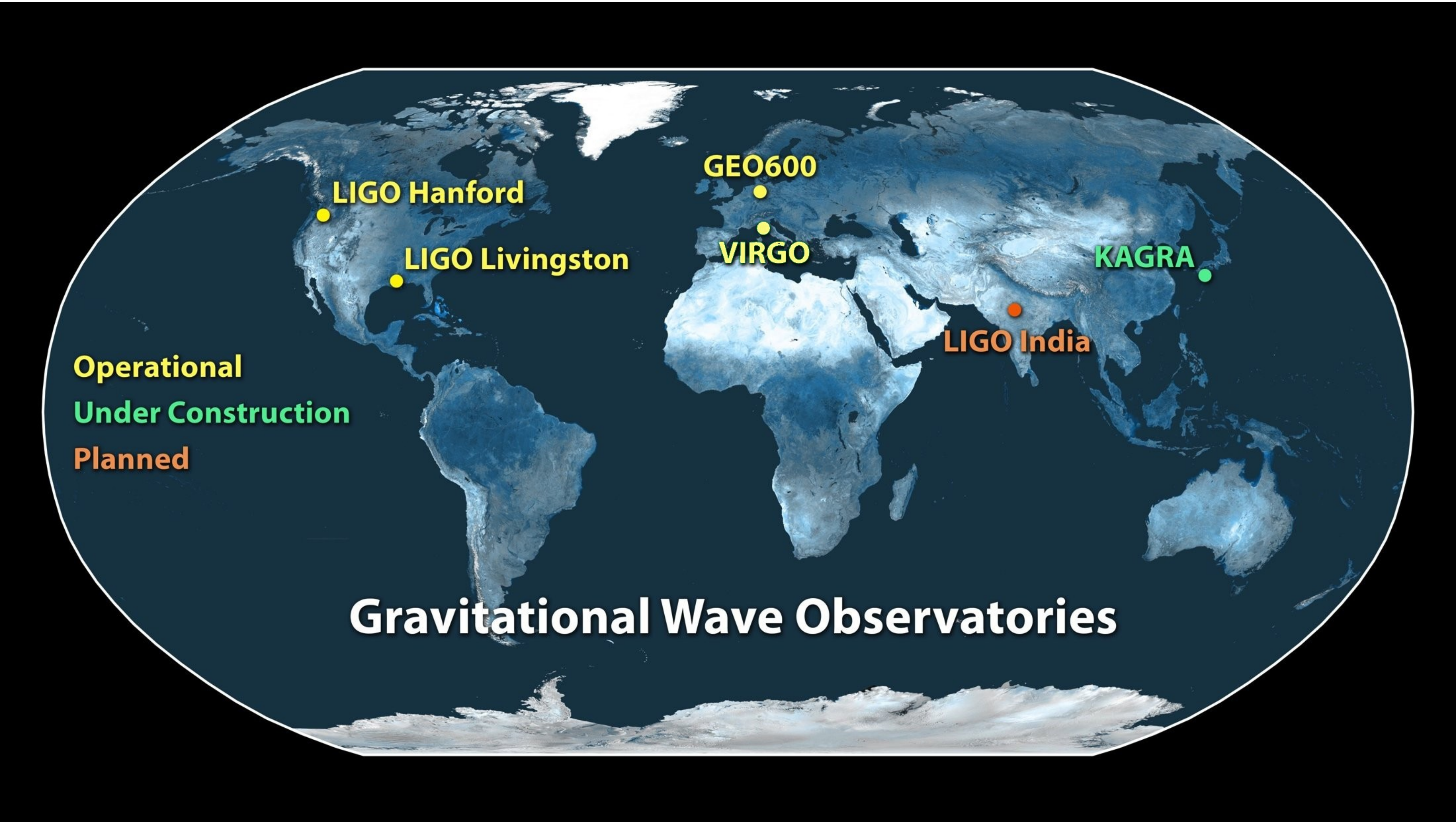
Lee McCuller, MIT
for the LIGO Laboratory
OSA Webinar

LIGO Livingston Observatory

LIGO Hanford Observatory



Observatory Network



LIGO

LIGO Scientific Collaboration

LSC

Caltech
Max-Planck-Institut für Gravitationsphysik Albert-Einstein-Institut
American University Washington, DC
Andrews University
Bard College
Bellevue College
California State University Fullerton
Cal State LA
Carleton College
Christopher Newport University
MIT
William & Mary
Colorado State University
Columbia University in the City of New York
Concordia University Wisconsin
Cornell University
Embry-Riddle Aeronautical University
Eötvös Loránd University
Georgia Tech
NASA Goddard Space Flight Center
INPE
Haverford College
Hillsdale College
Hobart & William Smith Colleges
IIP International Institute of Physics
LSU Louisiana State University
Marquette University Be The Difference.
NASA Marshall Space Flight Center
Missouri S&T
Montana State University
Montclair State University
Lomonosov Moscow State University
Tsinghua University
NCSA
Northwestern
PennState
RIT
Sonoma State University
Syracuse University
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Science & Technology Facilities Council Rutherford Appleton Laboratory
King's College London
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Stanford University
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Charles Sturt University
Monash University
University of Szeged
Texas Tech University
Trinity University
清華大學 Tsinghua University
University of the West of Scotland UWS
University of Glasgow
OzGrav
Swinburne University of Technology
University of Zurich
Berkeley University of California
Université Libre de Bruxelles
The University of Adelaide
The University of Melbourne
The University of Western Australia
Polytechnique Montréal Université d'ingénierie
The University of Arizona
USC Universidade de Santiago de Compostela
The University of Sheffield
GEO 600
The University of Rhode Island
The University of Chicago
UF University of Florida
University of Maryland
University of Michigan
University of Minnesota
University of Oregon
Leibniz Universität Hannover
University of Strathclyde Glasgow
Texas The University of Texas at Austin
UTRGV
UIB Universitat de les Illes Balears
東京大学 The University of Tokyo
University of Washington
W Bothell
UWM University of Wisconsin Milwaukee
University of Cambridge
UH Universität Hamburg Der Forschung | Der Lehre | Der Bildung
University of Southampton
IISER Kolkata
tifr
IISER Pune
Institute of Advanced Research Gandhinagar The University for Innovation
University of Southern California
Villanova University
West Virginia University
Whitman College
ICTS International Centre for Theoretical Sciences Tata Institute of Fundamental Research
CMI Chennai Mathematical Institute
Indian Institute of Technology Gandhinagar
RRI
Indian Institute of Technology Madras
NIMS National Institute for Mathematical Sciences | South Korea
서울대학교 Seoul National University
UNIST
인제대학교 INJE University
KISTI 한국과학기술정보연구원 Korea Institute of Science and Technology Information
한양대학교 Hanyang University
indigo
DCSEM
RRCAT
आई आई टी हैदराबाद IIT Hyderabad
Indian Institute of Technology Bombay
IUCAA
KASI Korea Astronomy and Space Science Institute
Pusan National University
Ewha W.U.
Korean Gravitational-Wave Group

Roadmap

- Gravitational Wave Astronomy
- Advanced LIGO Interferometer
- Fundamental Noise Sources
- Length Sensing
- Angular Sensing
- Upgrades

The Michelson Interferometer

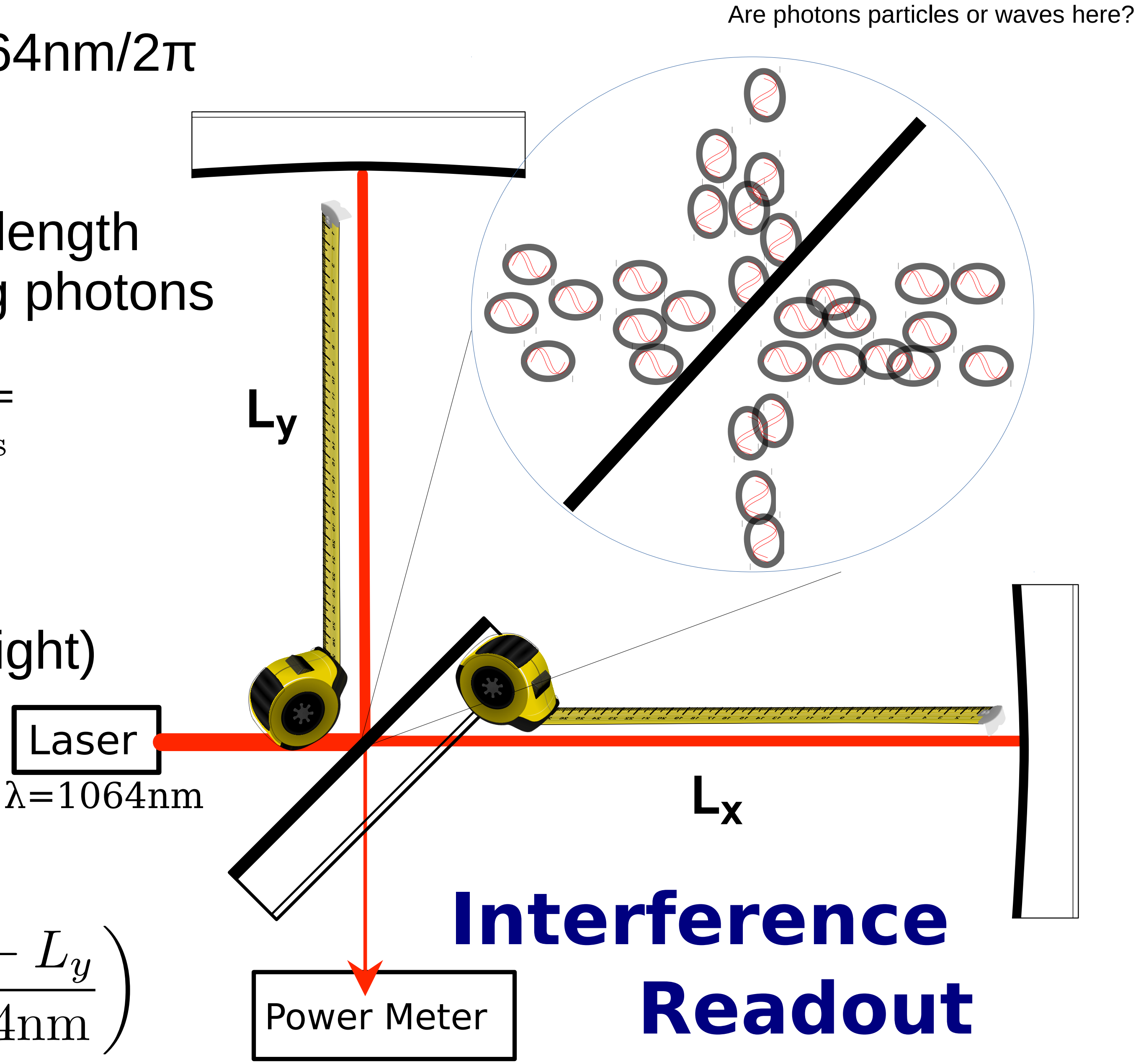
Each photon gives 1064nm/2π measurement

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)

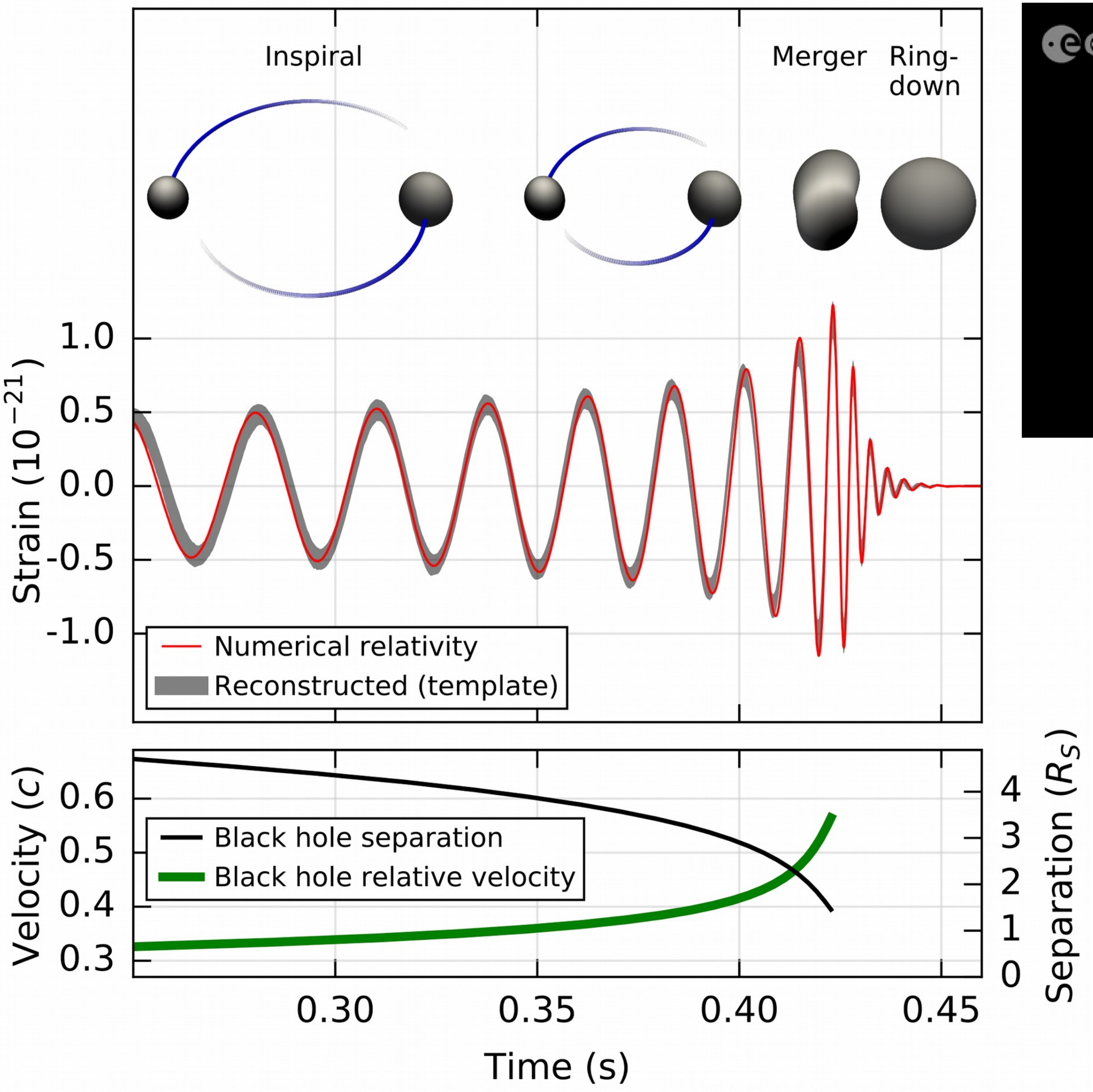
$$P \sin^2\left(2\pi \frac{L_x - L_y}{1064\text{nm}}\right)$$

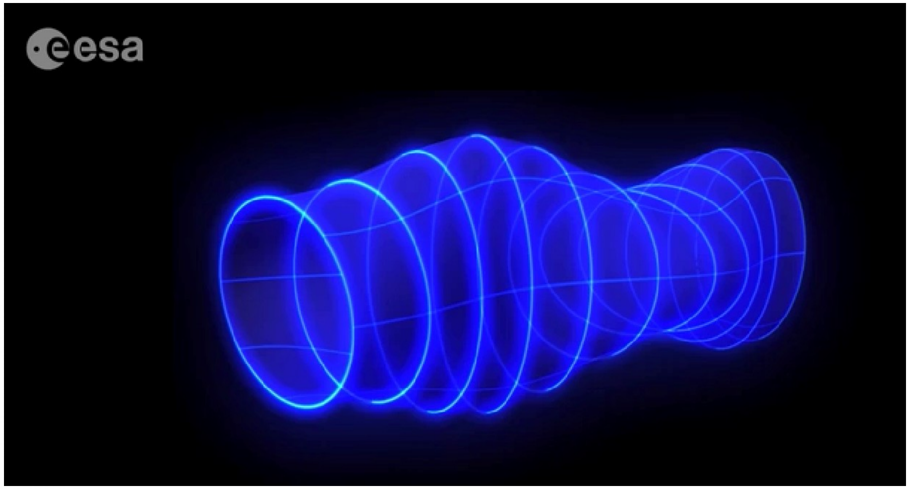


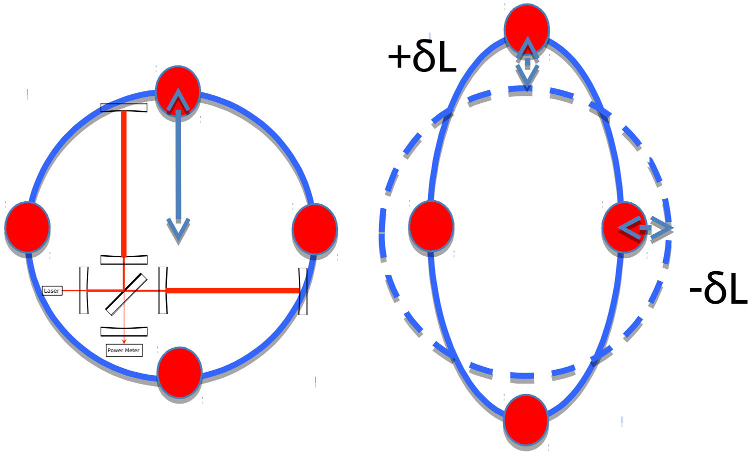
Interference Readout

Gravitational Strain Transducer

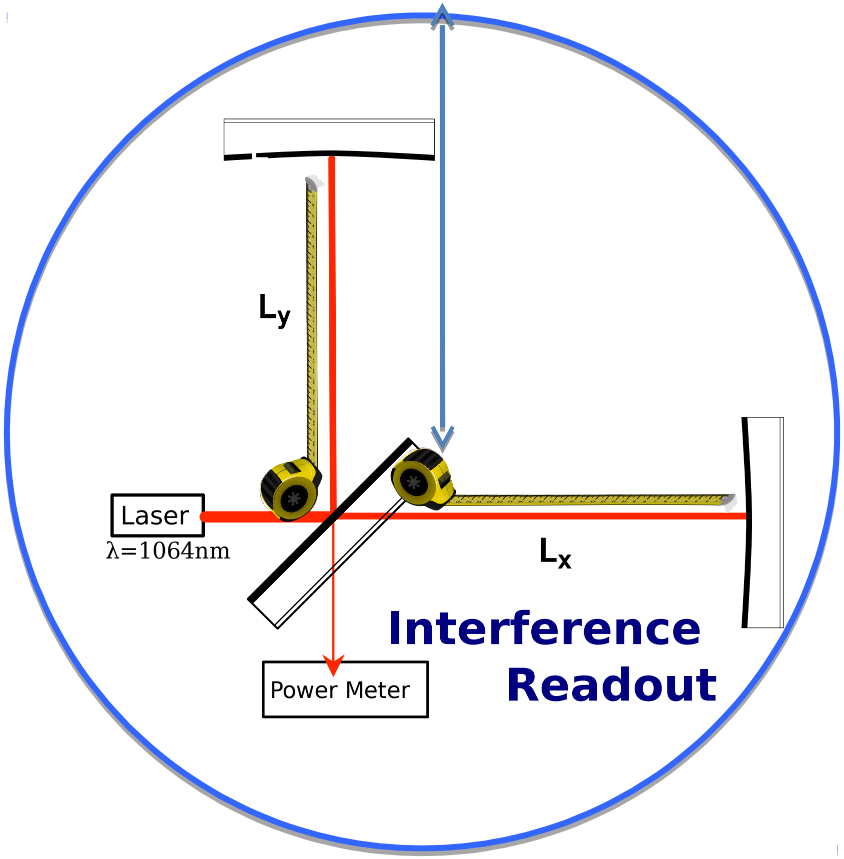
Phys. Rev. Lett. 116, 061102

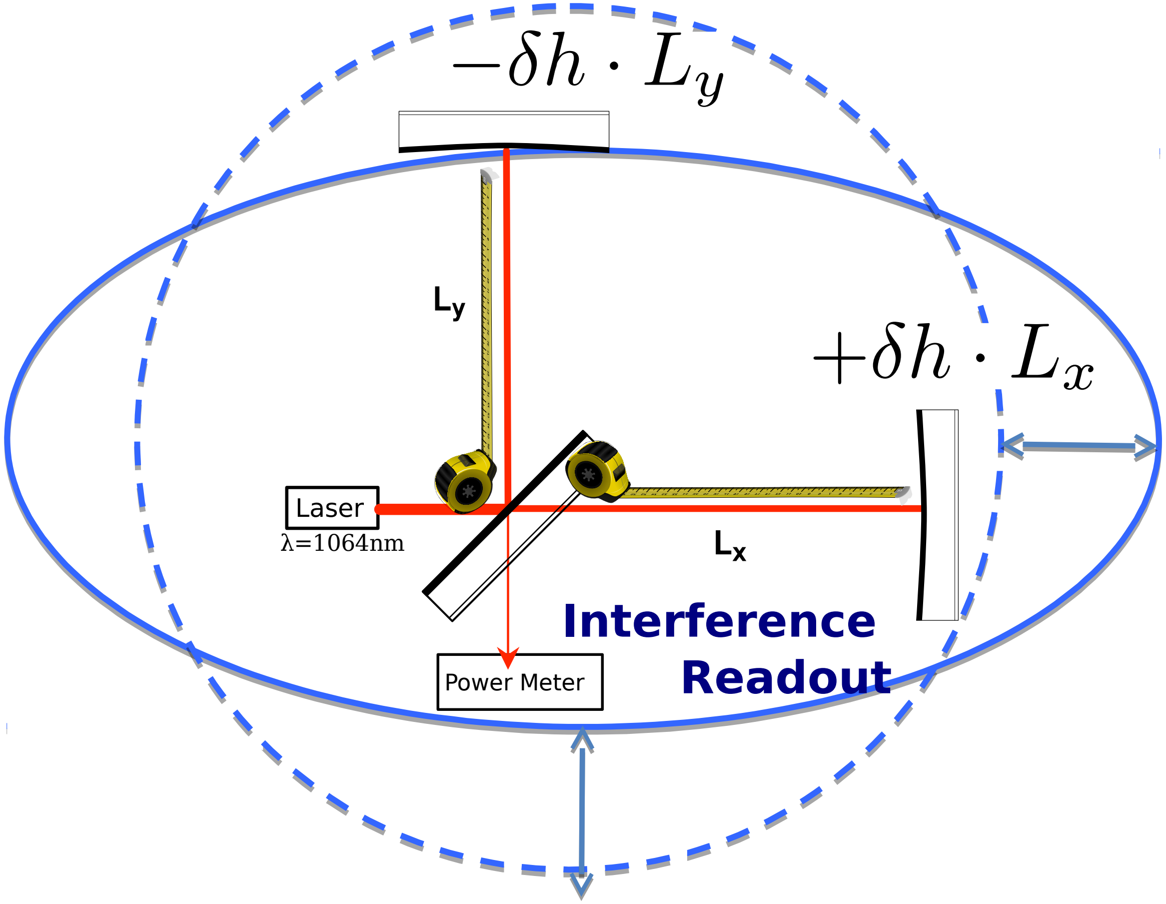






Spacetime Stretch





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

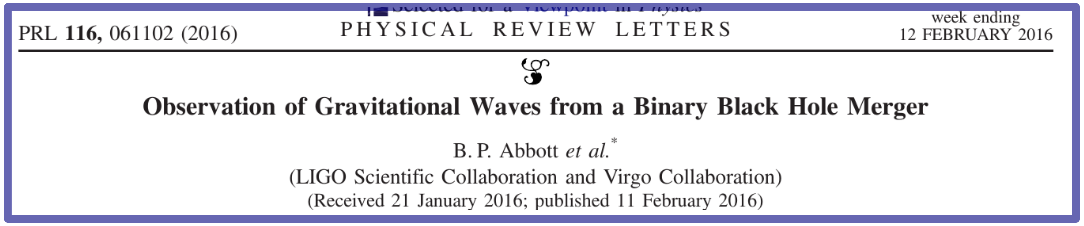
$$P\sin^2\left(2\pi\frac{L_x - L_y + \delta h L}{1064\text{nm}}\right)$$

Detection 1

- Very loud event
- Massive system (low merger freq.)

Primary black hole mass	$36^{+5}_{-4} M_\odot$
Secondary black hole mass	$29^{+4}_{-4} M_\odot$
Final black hole mass	$62^{+4}_{-4} M_\odot$
Final black hole spin	$0.67^{+0.05}_{-0.07}$
Luminosity distance	410^{+160}_{-180} Mpc
Source redshift z	$0.09^{+0.03}_{-0.04}$

- 3 solar masses radiated!
- General Relativity in strong regime



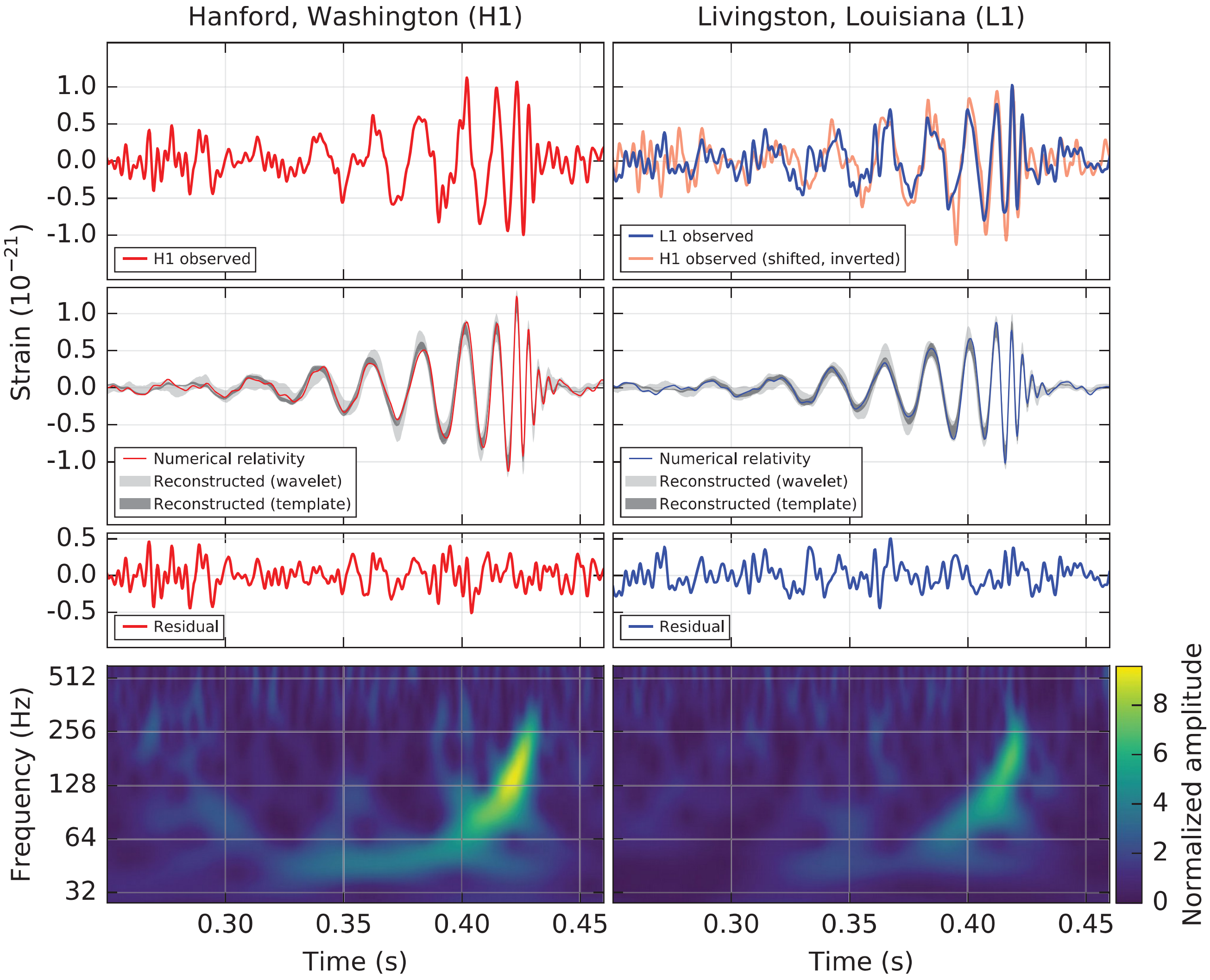
PRL **116,** 061102 (2016) PHYSICAL REVIEW LETTERS week ending 12 FEBRUARY 2016

Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.**

(LIGO Scientific Collaboration and Virgo Collaboration)

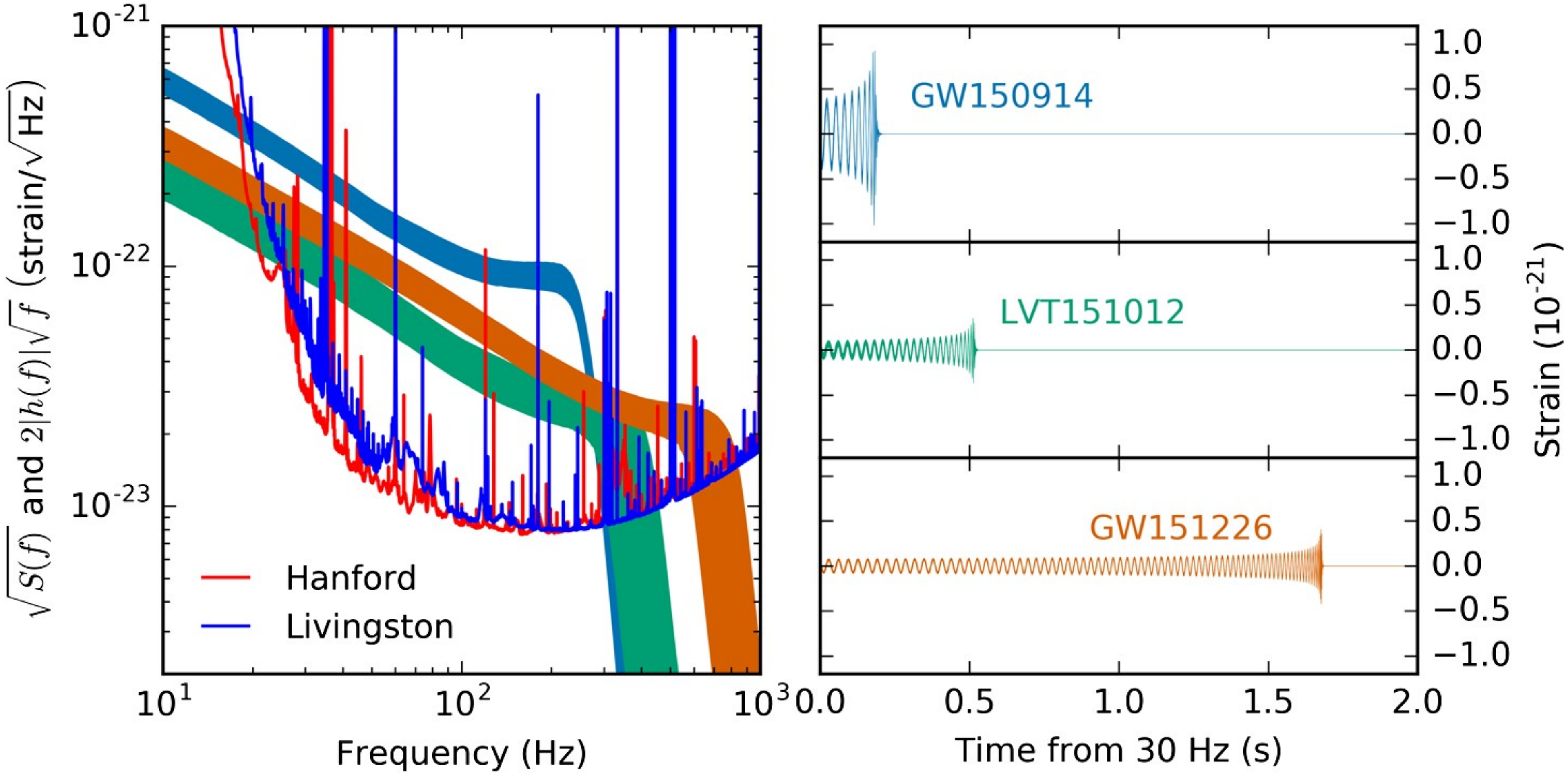
(Received 21 January 2016; published 11 February 2016)

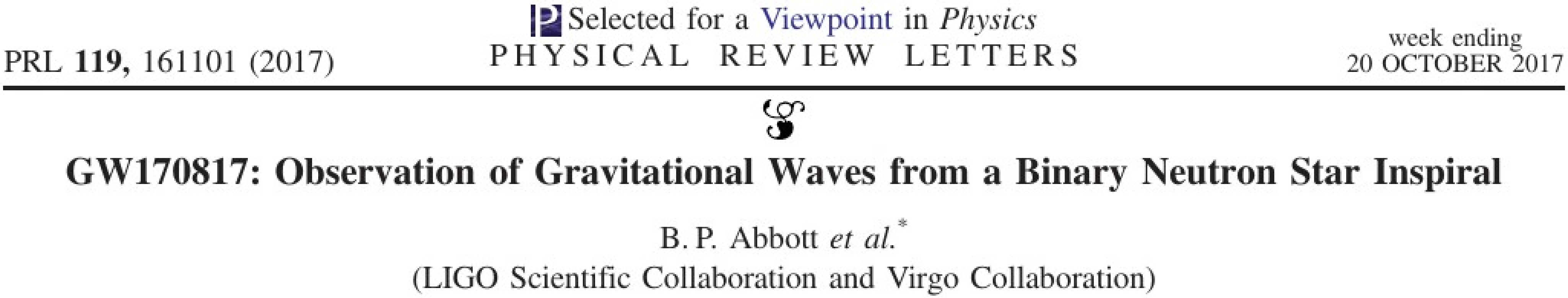


Template Spectrum Comparison

PHYSICAL REVIEW X **6,** 041015 (2016)

Binary Black Hole Mergers in the First Advanced LIGO Observing Run





Selected for a Viewpoint in *Physics*

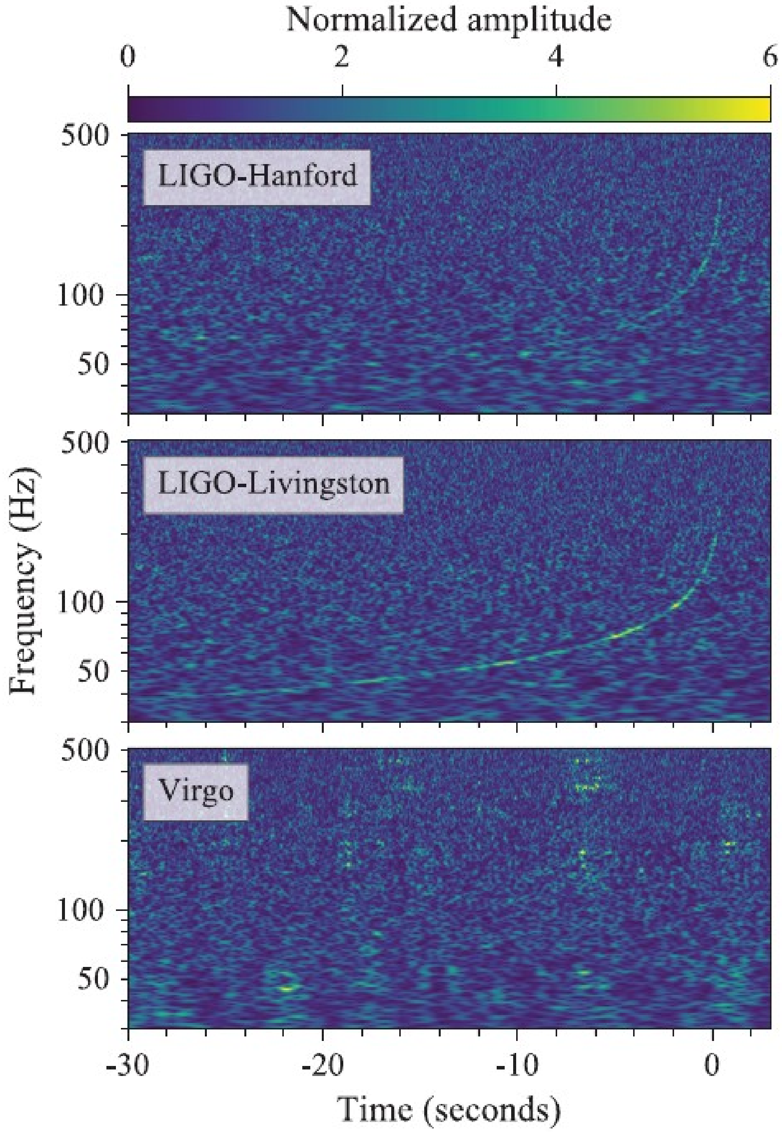
PRL **119,** 161101 (2017) PHYSICAL REVIEW LETTERS week ending 20 OCTOBER 2017

GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral

B. P. Abbott *et al.**

(LIGO Scientific Collaboration and Virgo Collaboration)

- Neutron star binary system detected!
  - Optical followup from many observatories
- Most signals not readily observable in timeseries
  - Freq-time plots show the characteristic chirp



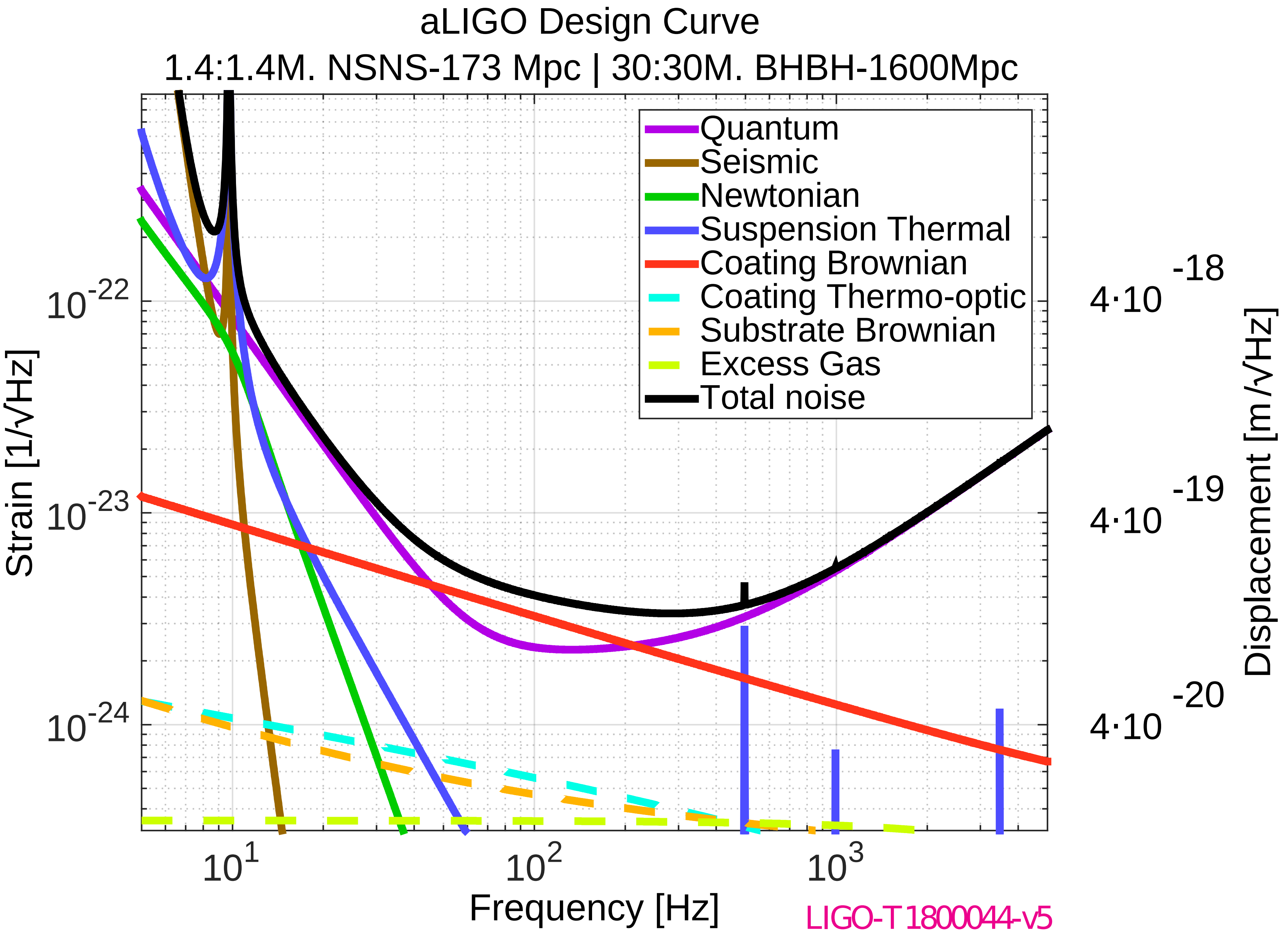
Enabling New Astrophysics

- Populations
  - Why so many heavy black-holes?
  - How do compact binary systems form
    - Dissipation mechanisms are very important in astronomy
  - What can we learn about neutron stars
    - Optical + gravitational data
    - Equation of state of dense nuclear matter
- Testing GR
  - System dynamics + general relativity → waveform characteristics
- Burst sources
  - Inner dynamics of supernova → GW emission
    - No matched templates
- Continuous Wave sources
- Stochastic Background
- Parameter estimation
  - Spin distributions
    - Useful for formation theories
  - Sky-localization, viewing angle
    - Degenerate with emission power (distance) due to antenna pattern
    - Helps observe Hubble Constant
      - New standard sirens!

Design Drivers

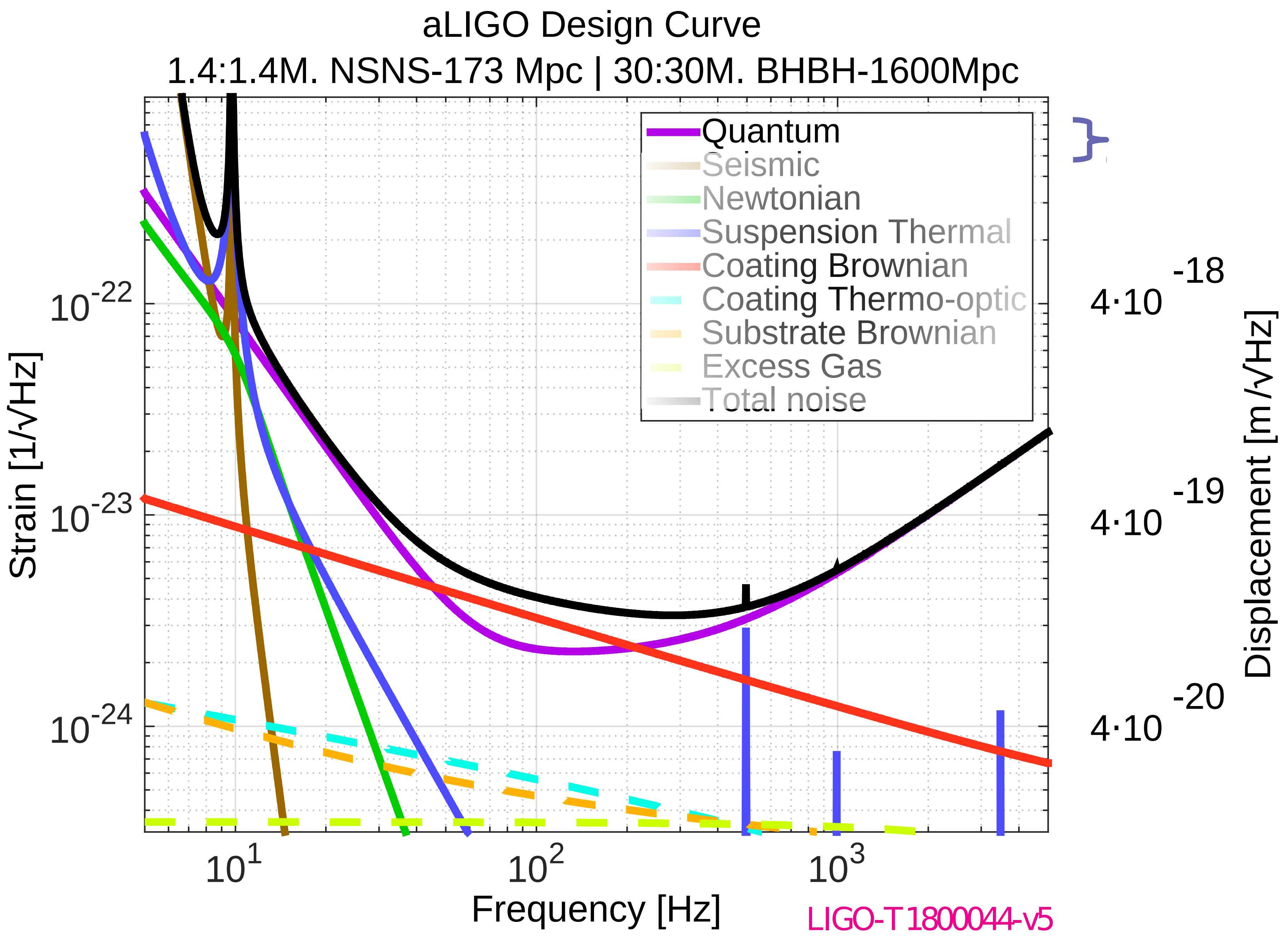
- Two factors of 10^{12} must be overcome
  - **Optical**, need <10^{-18}m sensitivity vs 10^{-6}m wavelength
    - Need a lot of photons, optical cavities, power handling
    - Need laser stability
  - **Mechanical**, need <10^{-18}m sensitivity vs $10^{-6}\frac{1}{\sqrt{\mathrm{Hz}}}$ seismic/acoustic noise
    - Need active and passive isolation from environment
    - Need to control many degrees of freedom
    - Couplings to and from interferometer also sensitive to mechanical noise (input-output optics)
  - *Optomechanical*
    - Radiation pressure both alters mechanical plant and increases *quantum noise*

Fundamental Noises

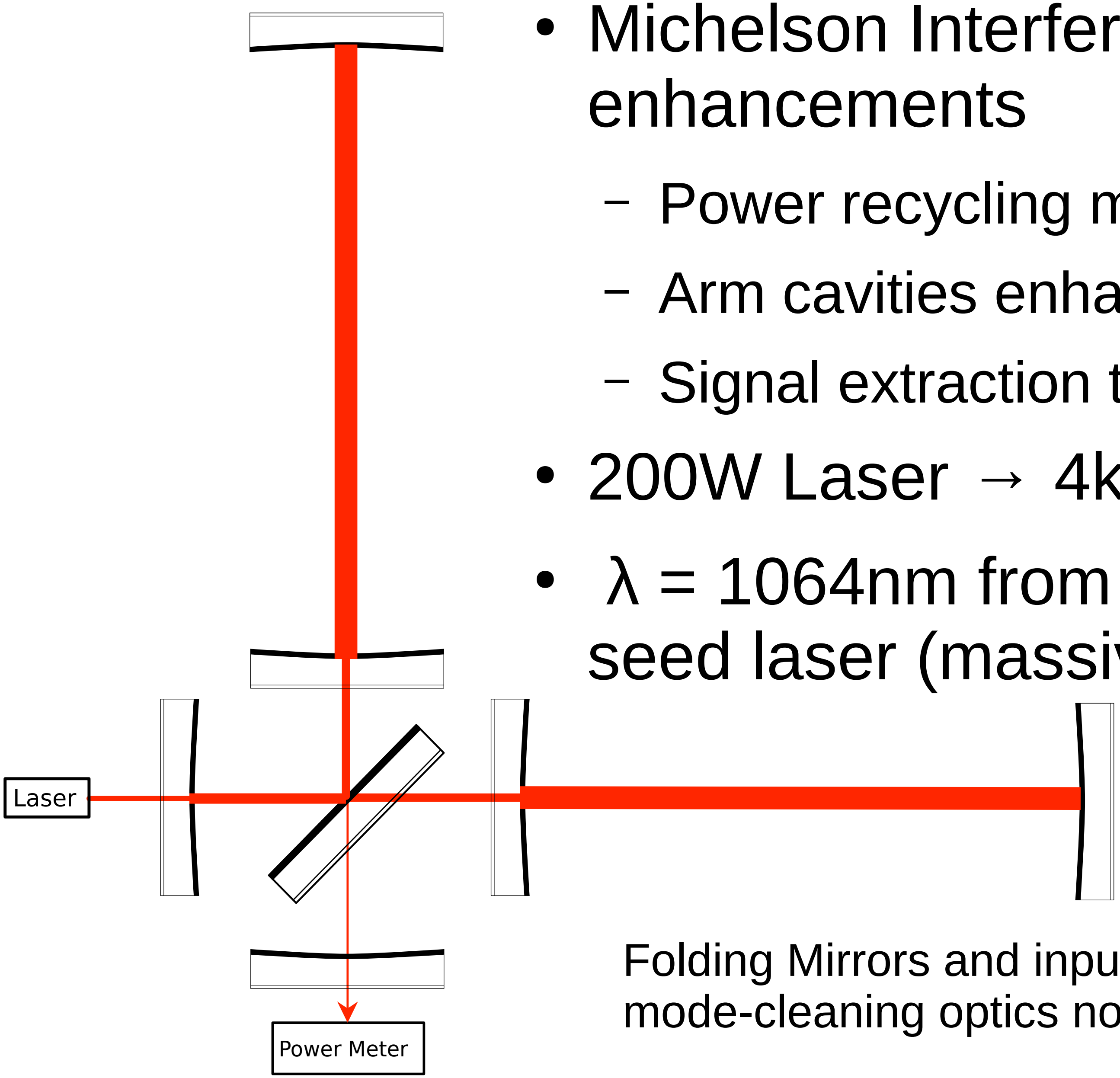


LIGO-T1800044-v5

Optical Layout



Beyond the Michelson Interferometer

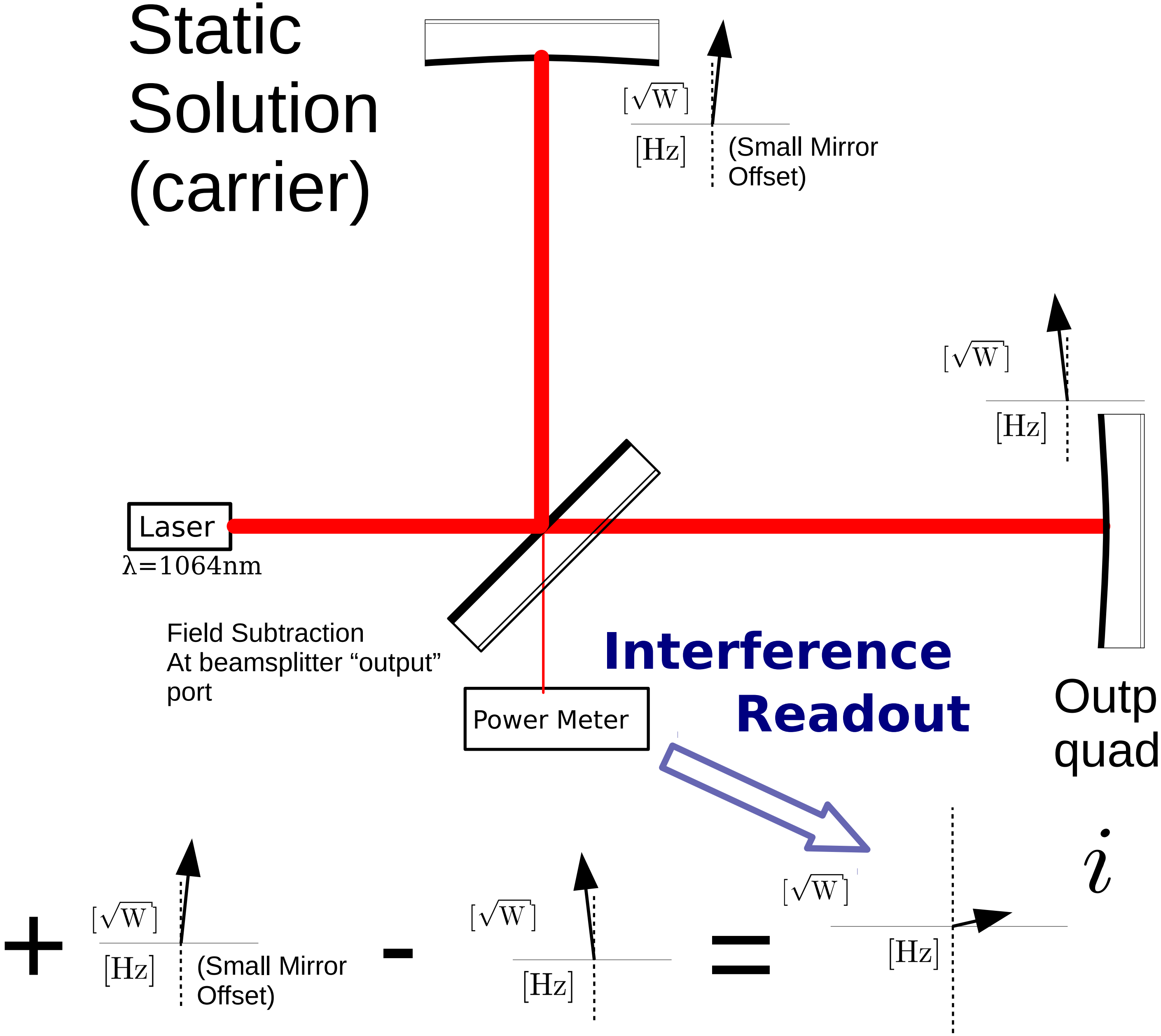


- Michelson Interferometer with cavity enhancements
  - Power recycling mirror for higher power
  - Arm cavities enhance power and signal
  - Signal extraction to enhance bandwidth
- 200W Laser → 4kW → 800kW
- λ = 1064nm from Nd:YAG NPRO seed laser (massively stabilized)

Folding Mirrors and input/output mode-cleaning optics not shown

Field Picture of the Michelson

Static Solution (carrier)



Field Subtraction
At beamsplitter “output” port

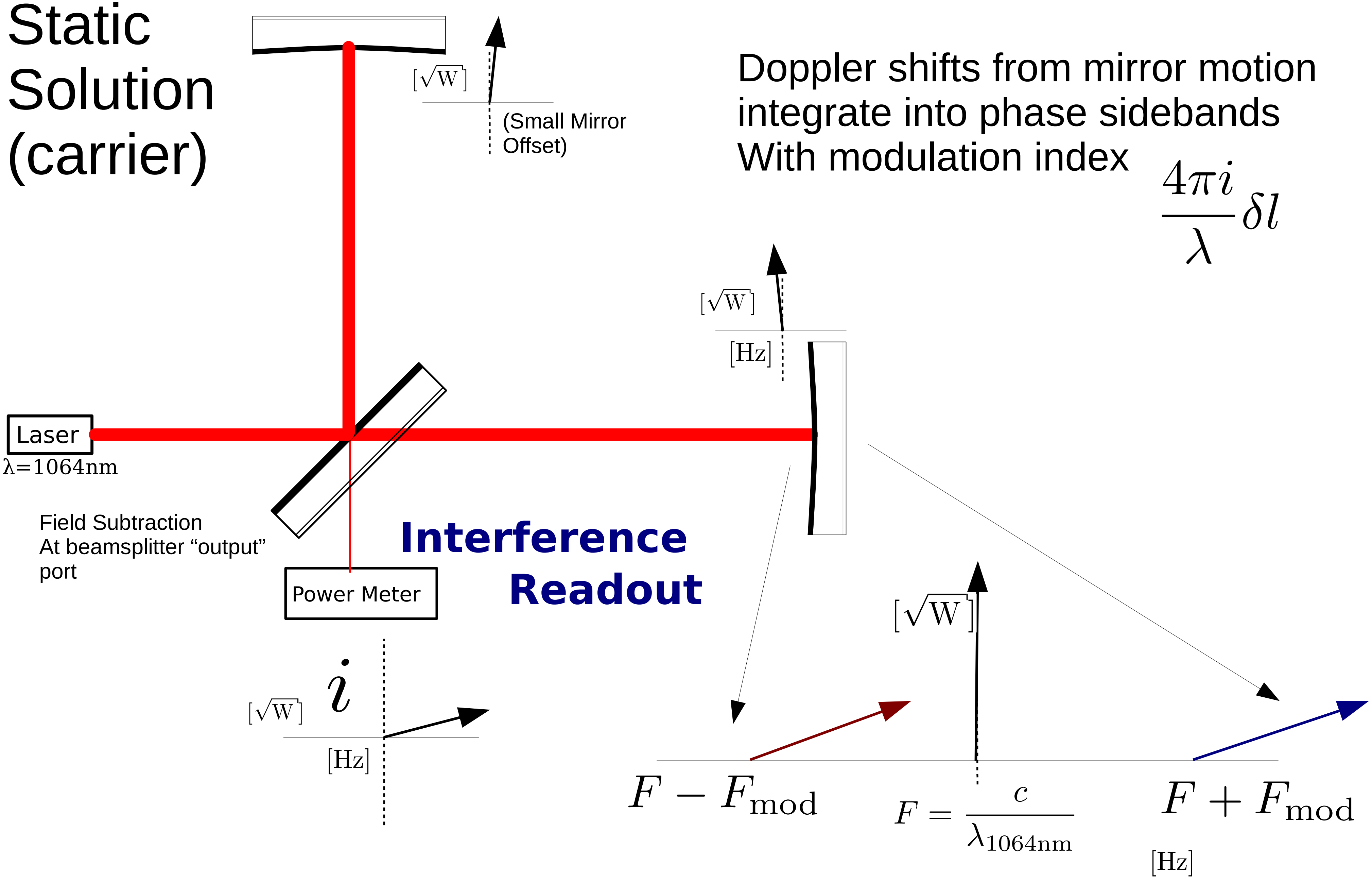
Interference Readout

Output is in “phase” quadrature

Field Picture With Modulations

Static Solution (carrier)

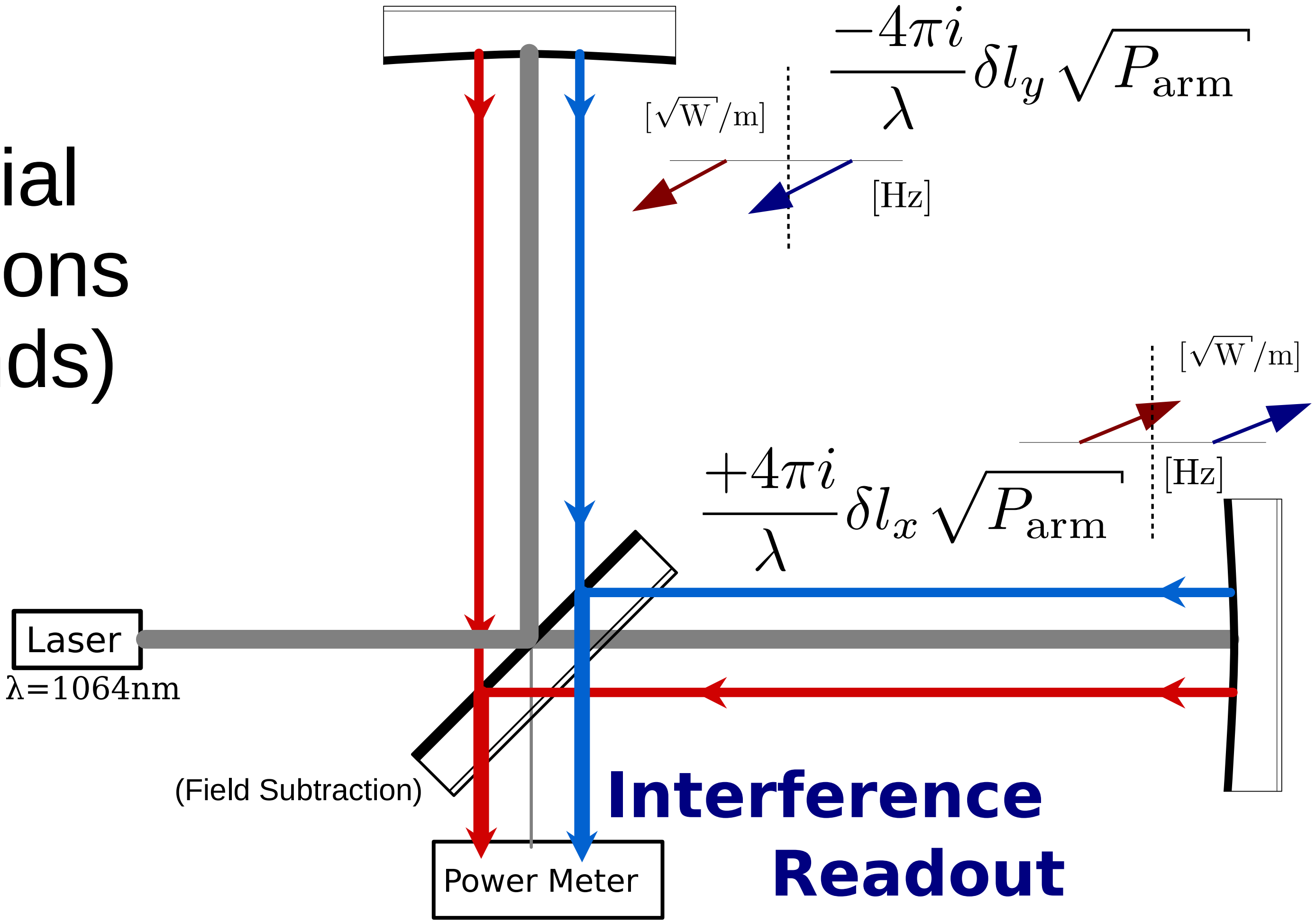
Doppler shifts from mirror motion integrate into phase sidebands With modulation index $\frac{4\pi i}{\lambda}\delta l$



Interference Readout

Sideband Picture

Differential
Modulations
(sidebands)



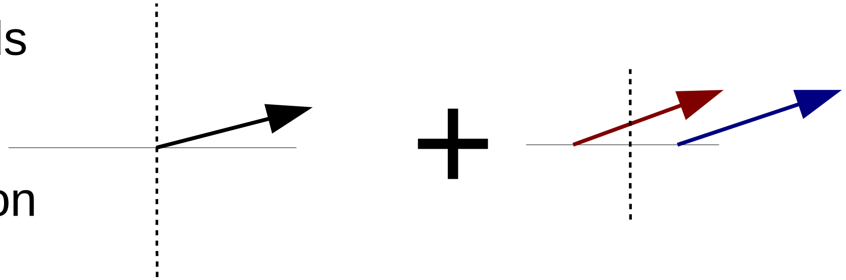
$$\frac{-4\pi i}{\lambda}\delta l_y\sqrt{P_{\text{arm}}}$$

$$\frac{+4\pi i}{\lambda}\delta l_x\sqrt{P_{\text{arm}}}$$

Interference
Readout

Output
Carrier + sidebands

Power detection
sees the modulation



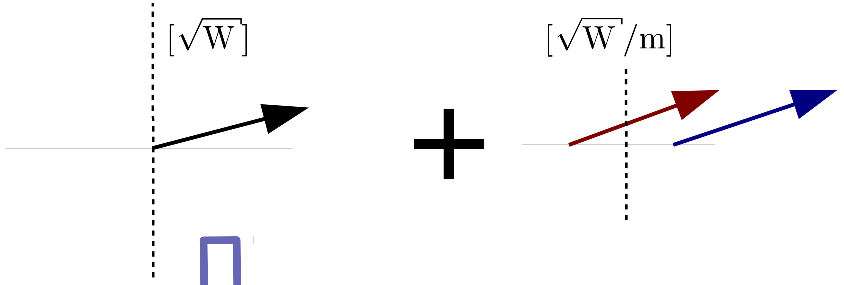
$$\frac{+4\pi i}{\lambda}\sqrt{P_{\text{arm}}}\frac{\delta l_x-\delta l_y}{\sqrt{2}}$$

Quadrature Projections

This sideband picture
Is useful to handle
Frequency dependence
Of optical cavities.
  - every frequency treated
    differently by cavities

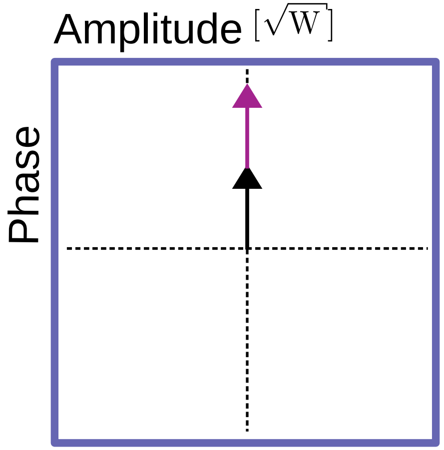
The quadrature
(phase-space) picture
Is useful for readouts and
quantum-noise

Sideband picture

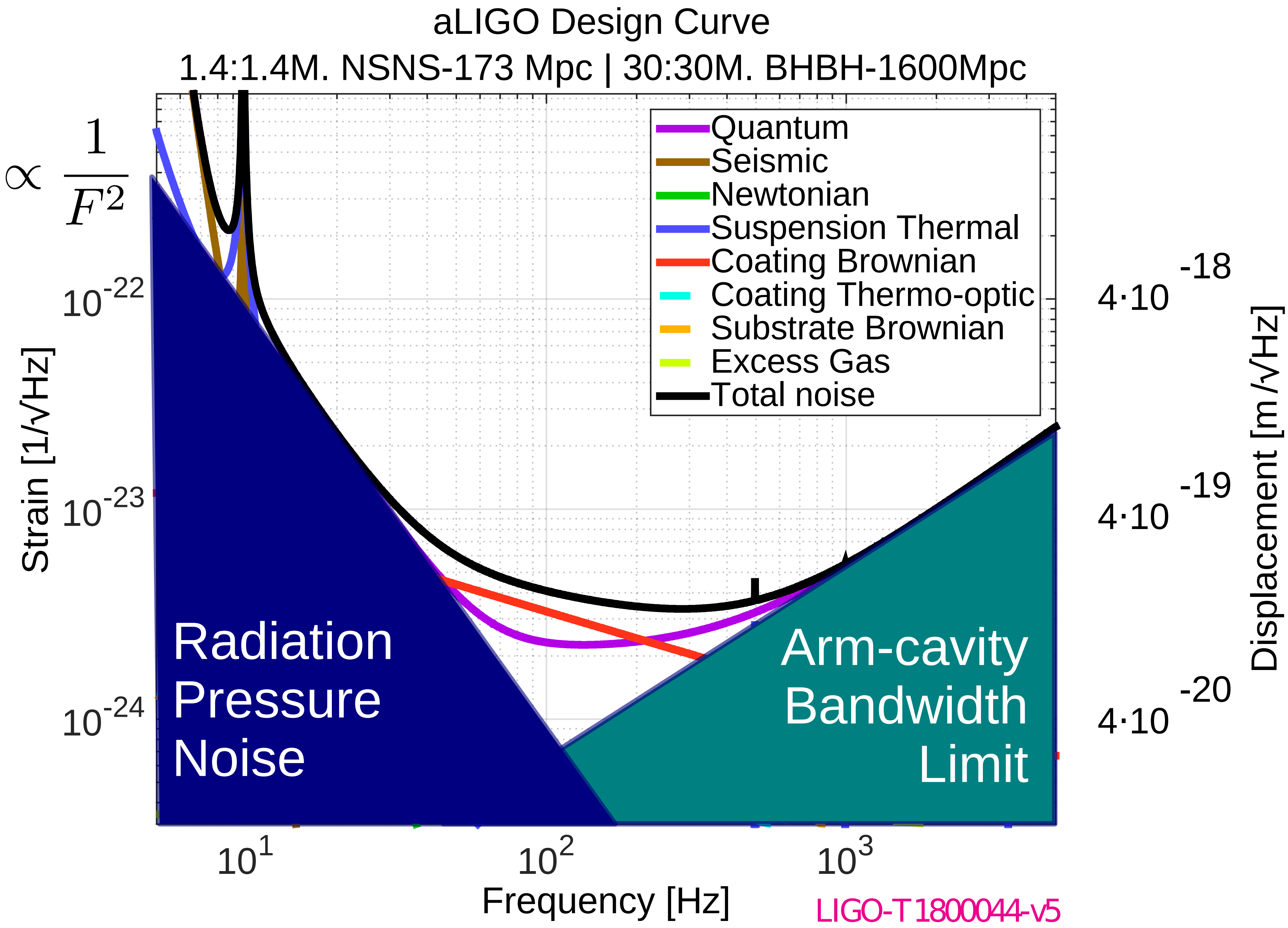


Coordinate Transformation

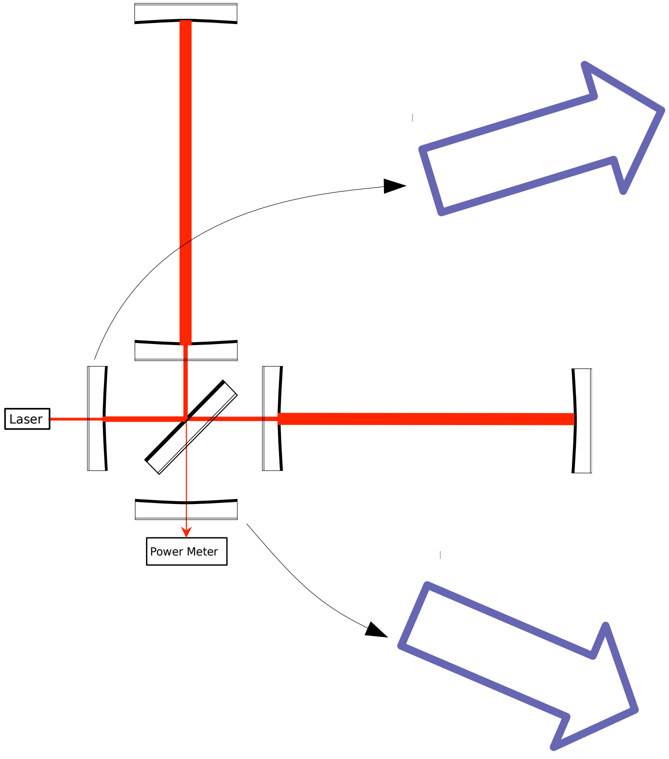
Phase-space Picture
Modulation Power [W/m]
from dot-product of
Sidebands with carrier



Quantum Noise

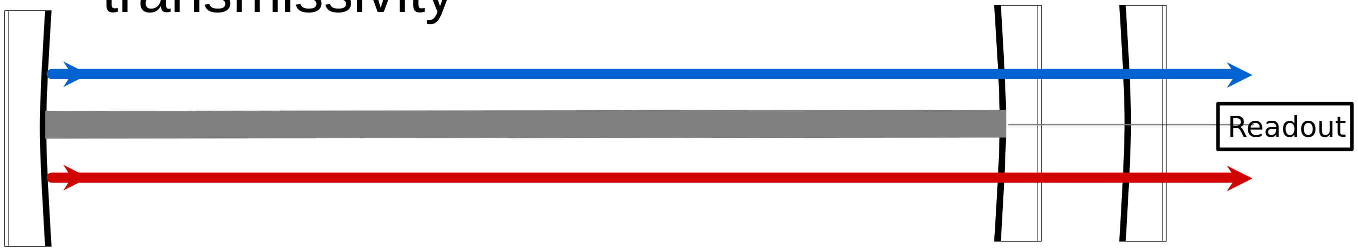


Conceptual Cavities

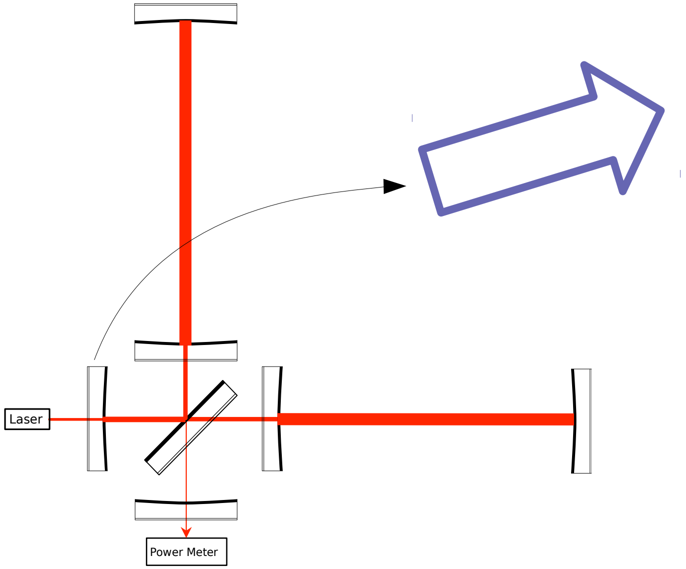


Power (carrier) Recycling.
Testmass scattering losses of 35ppm allow a power increase of ~1/70e-6 → 1MW from 160W input. Staged to put power in arms rather than optic substrates.

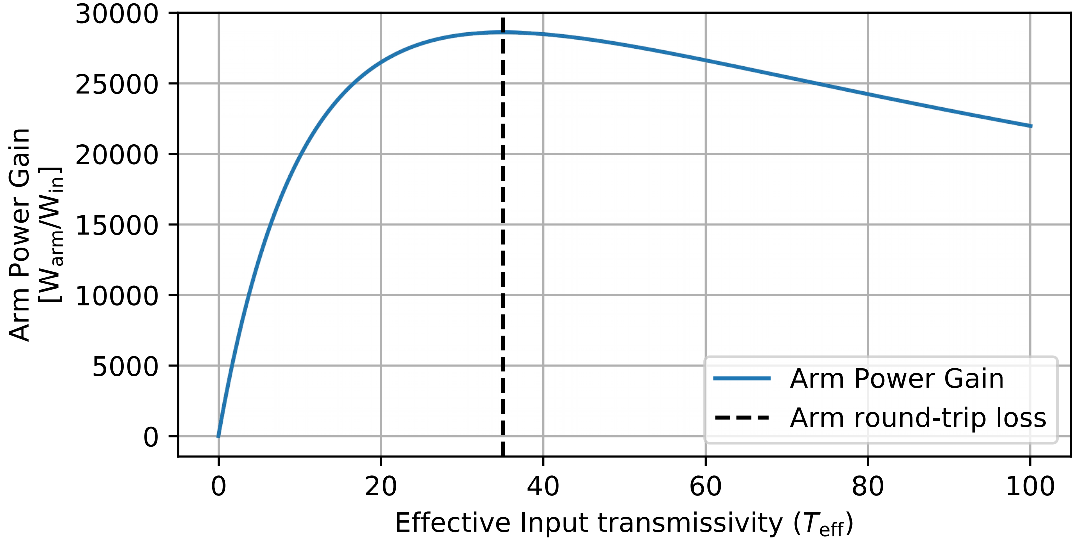
Signal ~~Recycling~~ Extraction.
Sidebands experience arm cavity circulation, enhancing them *too much,* extraction adjusts signal-sideband transmissivity



Conceptual Cavities (Power)



Power (carrier) Recycling.
Testmass scattering losses of 35ppm allow a power increase of ~1/70e-6 → 1MW from 160W input. Staged to put power in arms rather than optic substrates.

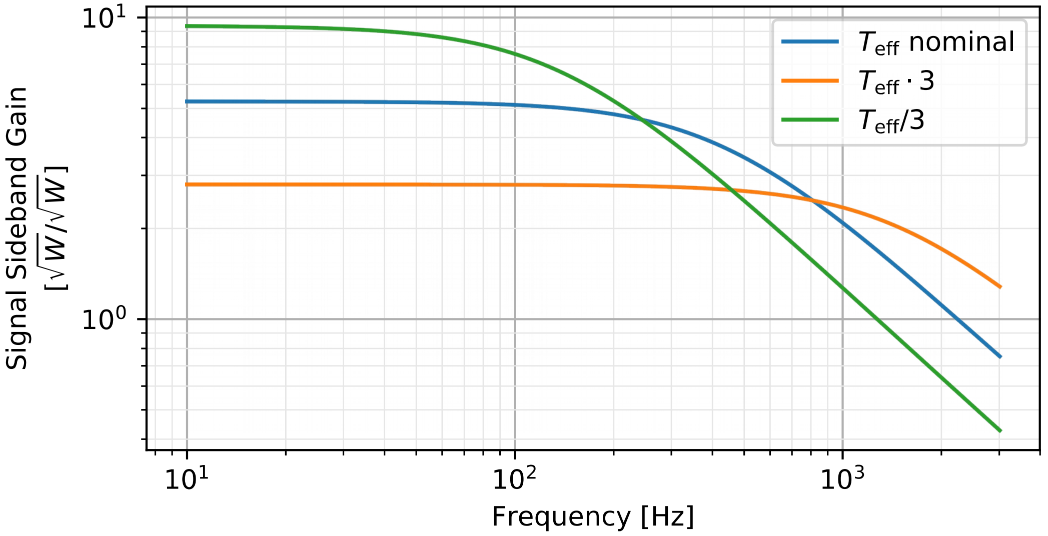


Additional mirror adjusts effective transmissivity of the arms, by storing intermediate power in the Vertex

$$P_{\mathrm{arm}} = \frac{T_{\mathrm{eff}}}{\left(1 - \sqrt{(1 - T_{\mathrm{eff}})(1 - L_{\mathrm{arm}})}\right)^2} P_{\mathrm{in}}$$

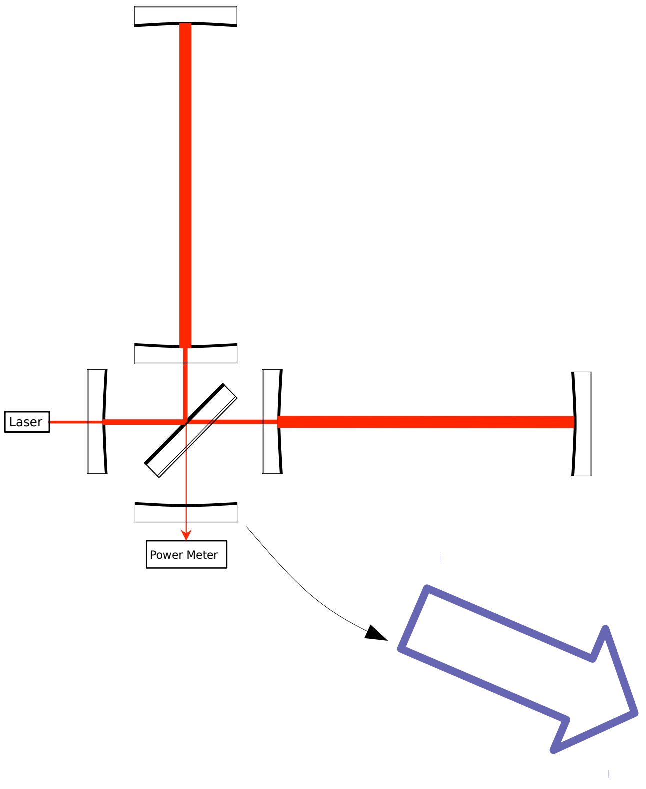
Conceptual Cavities (Signal)

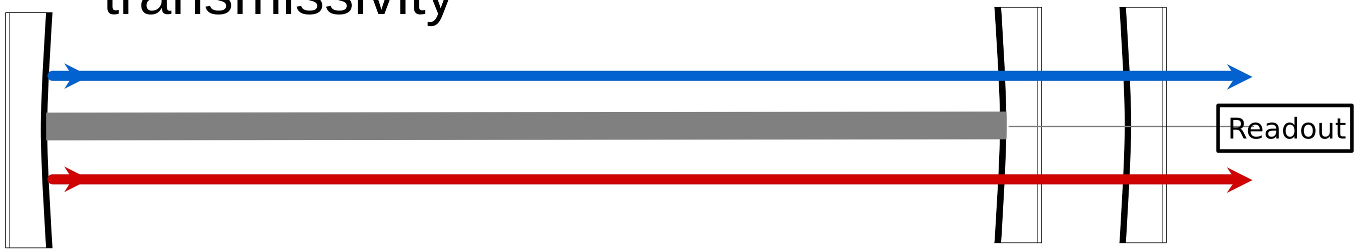
Additional mirror adjusts effective transmissivity to balance bandwidth and signal gain



$$\frac{e_\text{sig}}{\delta l_x - \delta l_y} = \frac{+2\pi i\sqrt{T_\text{eff}}\sqrt{P_\text{arm}}}{\lambda\left(1 - e^{2\pi F/37\text{kHz}}\sqrt{(1-T_\text{eff})}\right)}$$

Signal ~~Recycling~~ Extraction.
Sidebands experience arm cavity circulation, enhancing them *too much*, extraction adjusts signal-sideband transmissivity





(semiclassical) Quantum Noise

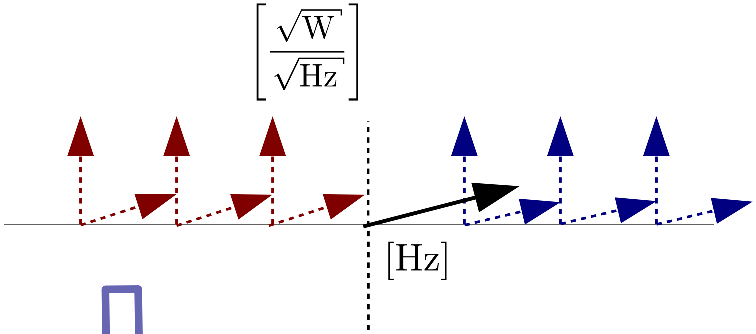
Sideband detections
Compete with $\frac{\hbar\omega}{2}$

Power spectral density
Noise at all frequencies.

Equivalent magnitude in phase-space or sideband representations

This noise is the collapse
Of the optical wave into
Photons at the detector.

Sideband picture



Coordinate Transformation

Phase-space Picture
Modulation Power $\left[\frac{\mathrm{W}}{\sqrt{\mathrm{Hz}}}\right]$
from dot-product of
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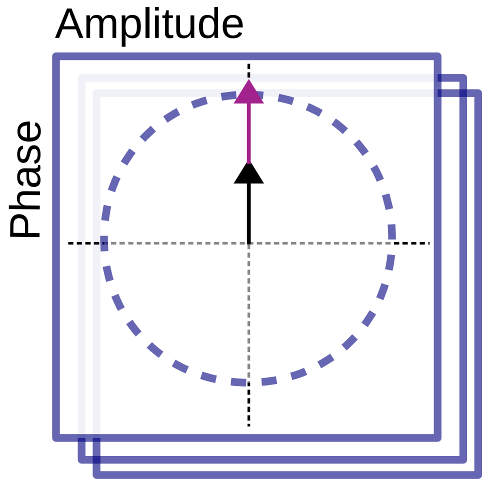
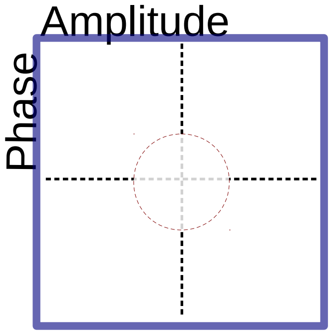


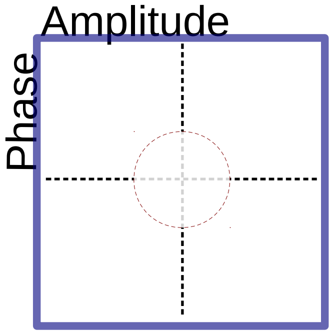
(stacked to represent
Phase space at every
measurement frequency)

Standard Quantum Limit

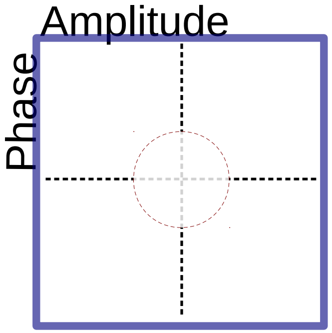
$F \ll 60\mathrm{Hz}^*$



$F = 60\mathrm{Hz}^*$

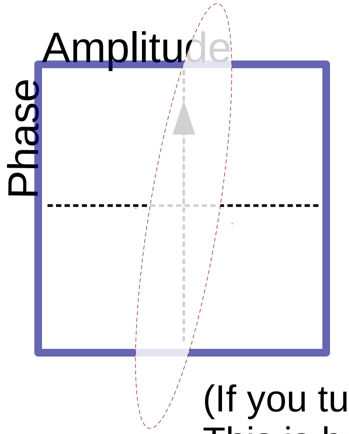


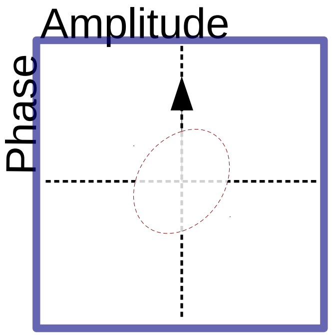
$F \gg 60\mathrm{Hz}^*$

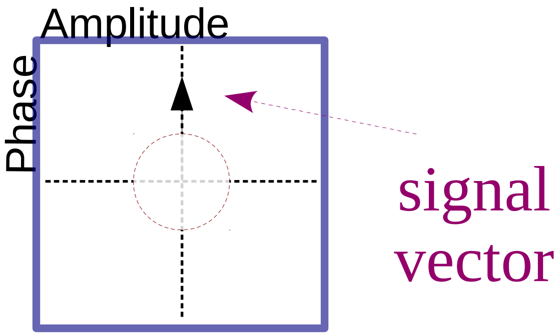


Amplitude → Force → Displacement → Phase:

Phase-space Shear $\begin{bmatrix} 1 & 0 \\ -\kappa & 1 \end{bmatrix}$





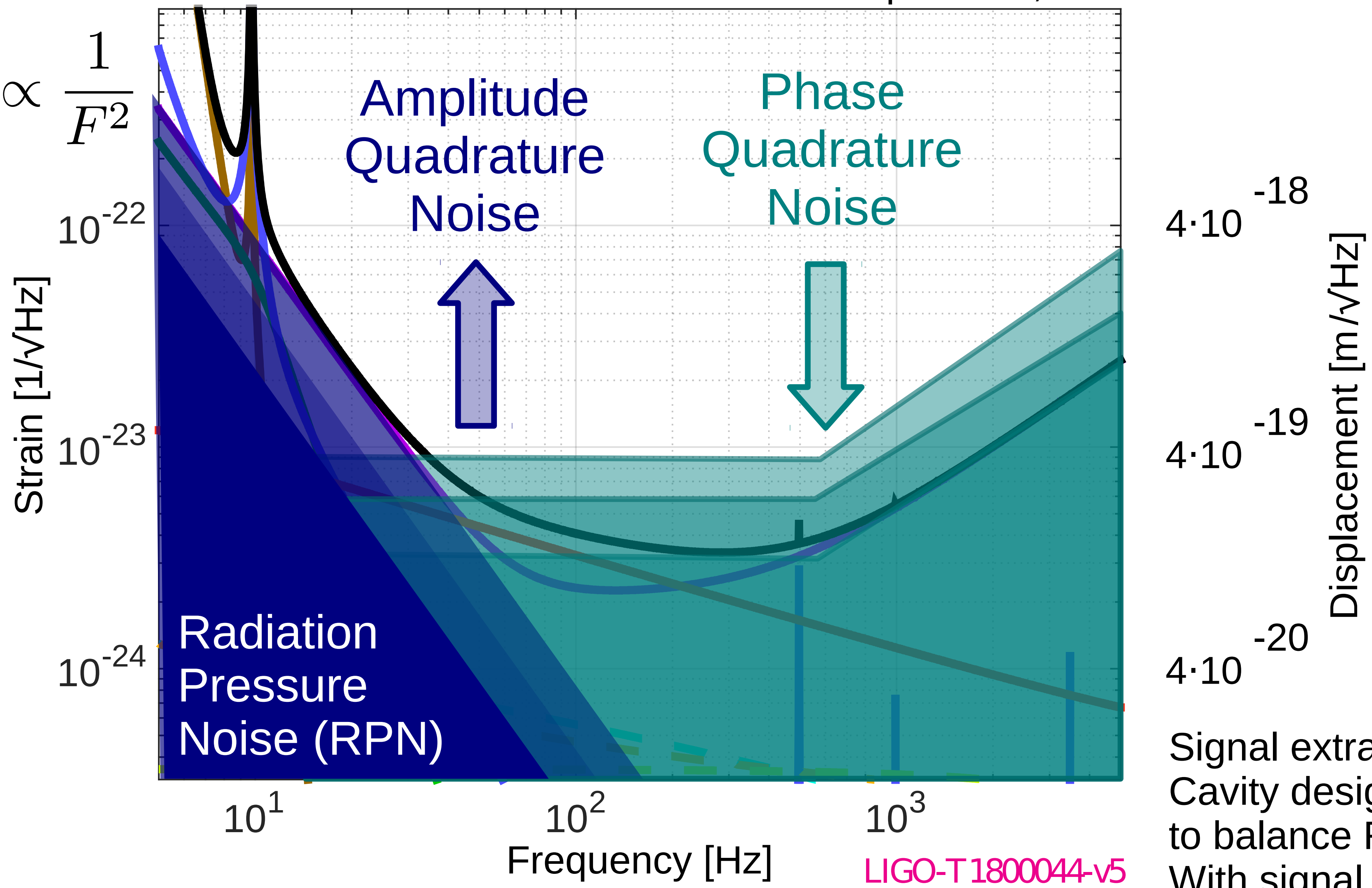


(If you turn your head – hey look squeezing!)
This is both a quantum correlation
And shot-noise observed by momentum transfer

* ~60Hz is approximate crossover only in aLIGO full power design

Power Dependence

Radiation Pressure optomechanical noise on 40kg Test-mass mirrors dominates at low frequencies,



$$\propto \frac{1}{F^2}$$

LIGO-T1800044-v5

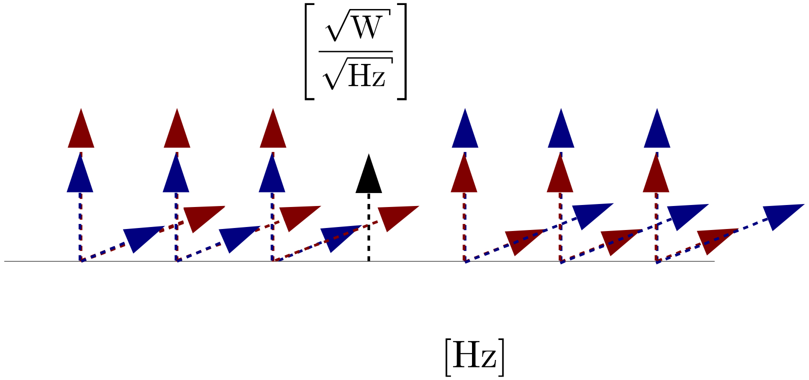
Signal extraction
Cavity designed
to balance RPN
With signal gain

Squeezed Quantum Noise

Quantum Noise may be *modified*, trading noise In one quadrature for another.

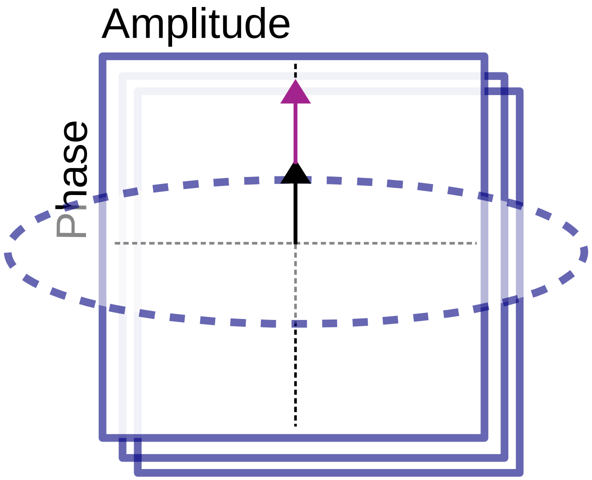
This increases the noise in sidebands, but *correlates* them, such that the noise will cancel and be suppressed!

Sideband picture



Coordinate Transformation

Phase-space Picture
Power [W]
from dot-product
with carrier

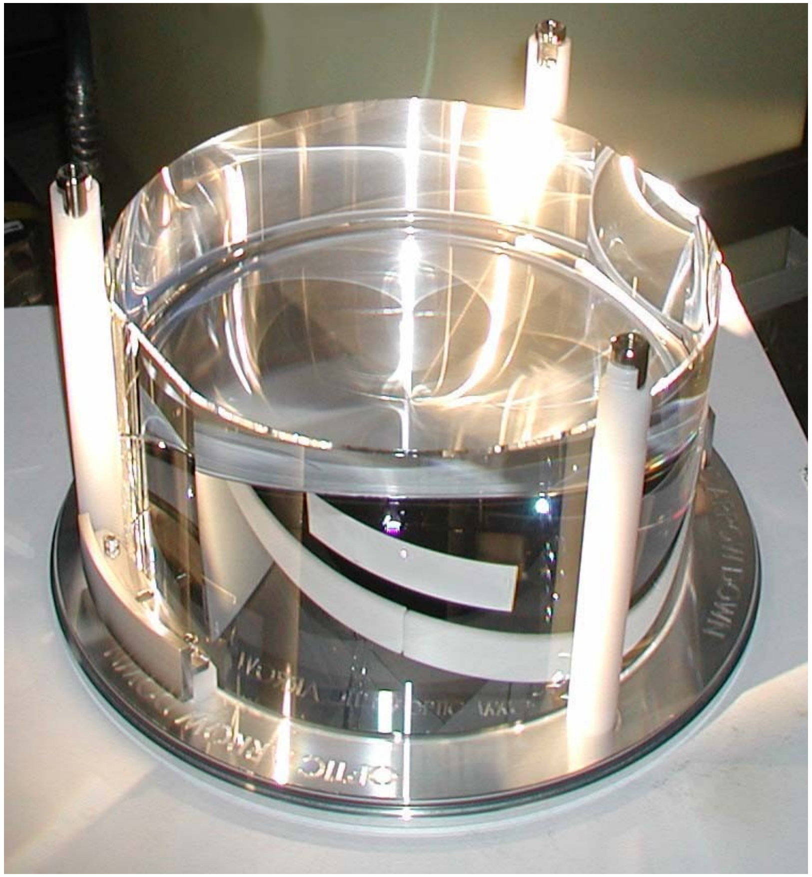


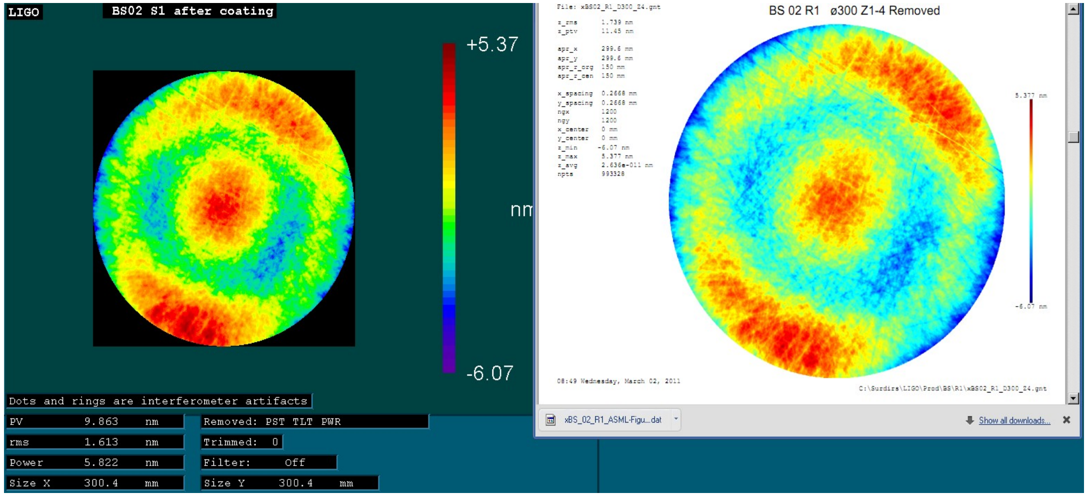
(stacked to represent Phase space at every measurement frequency)

Core Optics

Must act like a free mass in GR, must create stable matched cavities in the arms:

- Ultra-high purity fused silica
- 34 cm diameter, 20 cm thick
- 40 kg (!)
- 2240 m < ROC < 2260 m





LIGO BS02 S1 after coating

```
Dots and rings are interferometer artifacts
PV        9.863    nm     Removed:  PST  TLT  PWR
rms       1.613    nm     Trimmed:  0
Power     5.822    nm     Filter:      Off
Size X    300.4    mm     Size Y     300.4     mm
```

BS 02 R1   ø300 Z1-4 Removed

```
File: xBS02_R1_D300_Z4.gnt

z_rms       1.739 nm
z_ptv       11.45 nm

apr_x       299.6 mm
apr_y       299.6 mm
apr_r_org   150 mm
apr_r_cen   150 mm

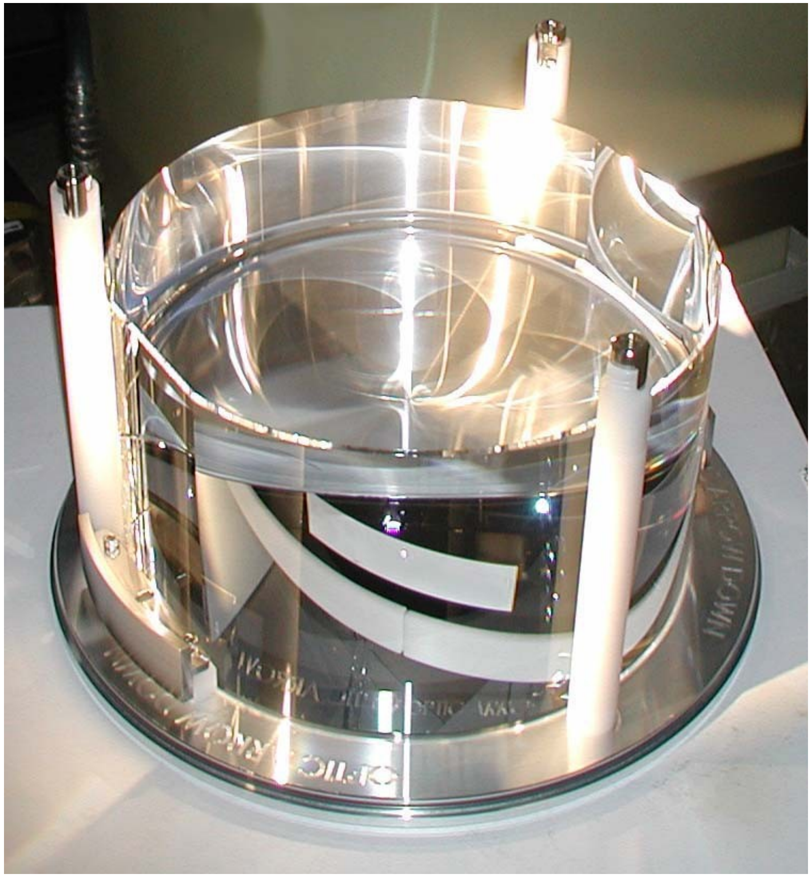
x_spacing   0.2668 mm
y_spacing   0.2668 mm
ngx         1200
ngy         1200
x_center    0 mm
y_center    0 mm
z_min      -6.07 nm
z_max       5.377 nm
z_avg       2.636e-011 nm
npts        993328

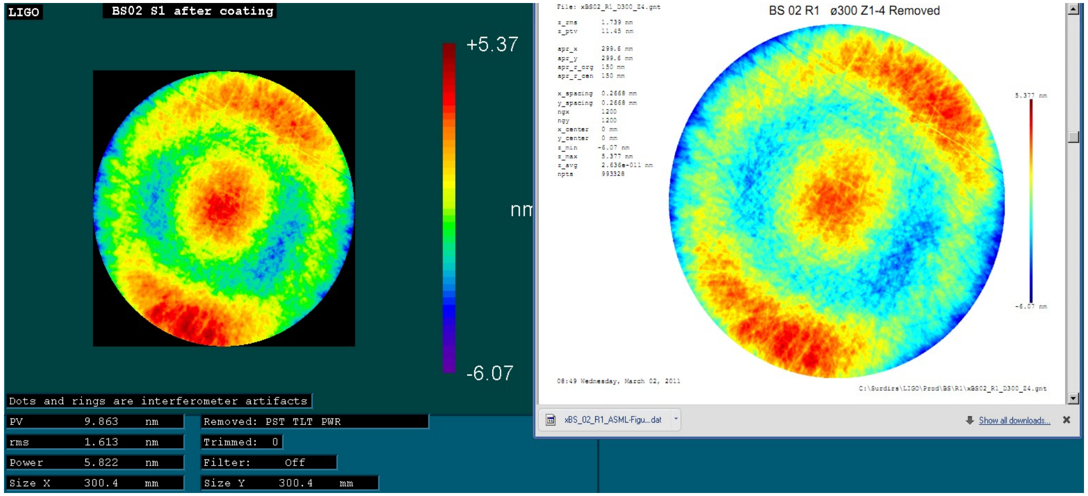
08:49 Wednesday, March 02, 2011
C:\Surdirs\LIGO\Prod\BS\R1\xBS02_R1_D300_Z4.gnt
```

Optical Quality

Minimize cavity losses:

- Spatial Freq. Band < 1 mm^{-1}
  - » Central 150 mm σ_{rms} < 0.3 nm
- Spatial Freq. Band 1- 750 mm^{-1}
  - » σ_{rms} < 0.16 nm
- R > 0.999996, T < 4 PPM
- Coating thickness uniformity $<10^{-3}$
- Total Cavity Loss < 50 (75) ppm





```
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PV       9.863   nm     Removed: PST TLT PWR
rms      1.613   nm     Trimmed:  0
Power    5.822   nm     Filter:     Off
Size X   300.4   mm     Size Y    300.4   mm
```

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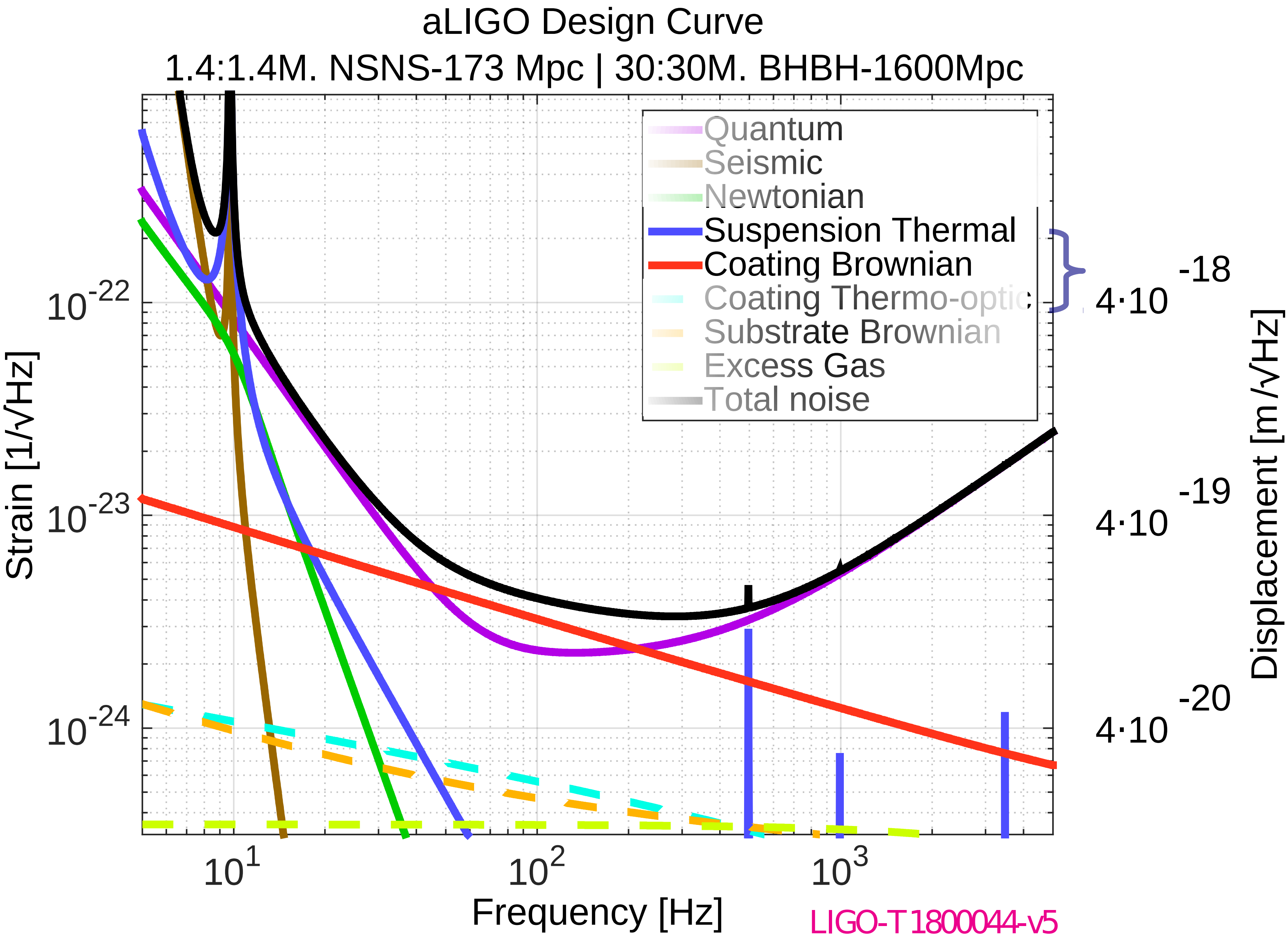
npts        993328

08:49 Wednesday, March 02, 2011
C:\Surdirs\LIGO\Prod\BS\R1\xBS02_R1_D300_Z4.gnt
```

Thermal Noise



LIGO-T1800044-v5

Thermal Noise

Fluctuation–dissipation theorem: thermally-driven fluctuations are proportional to the system's losses:

Mean-square displacement fluctuation →

$$\left\langle x^2 \right\rangle \propto \frac{T}{Q}$$

← Temperature

← Mechanical *Q*-factor

Thermal noise arises from:

Test mass coatings

Test mass substrates

Suspension fibers

How to reduce thermal noise?

Use materials with high *Q*-factors

"Dilute" couplings to lossy materials

- Suspension springs more gravitational than material

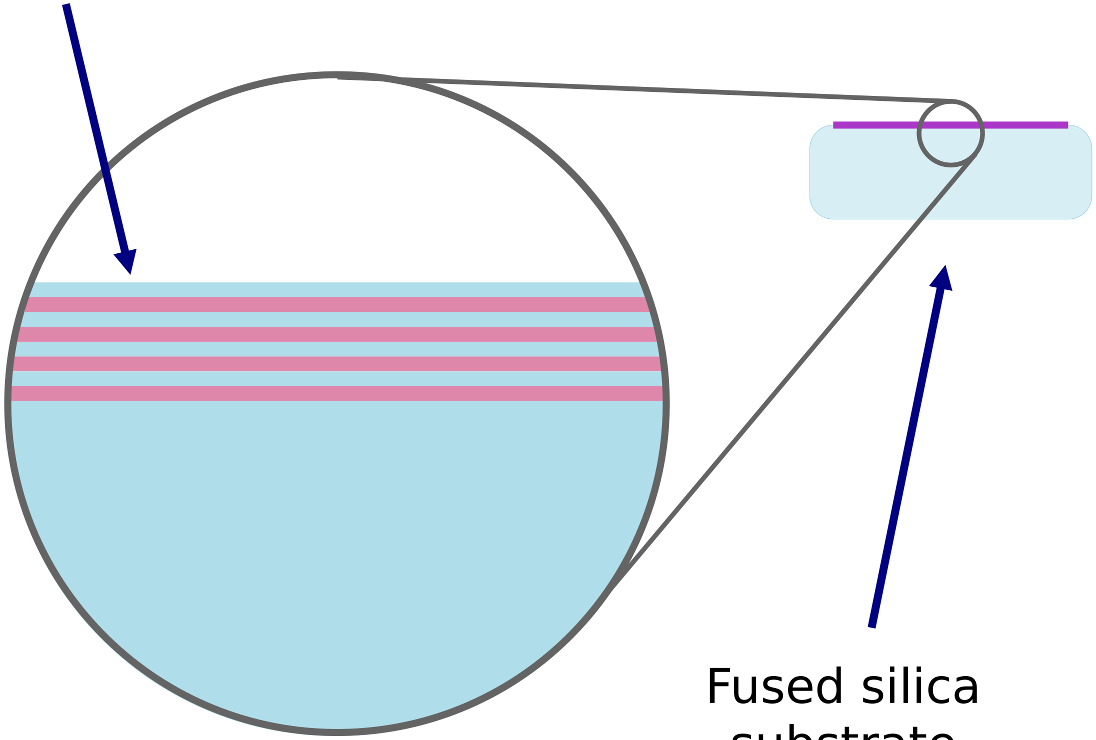
Suspension $Q \sim 10^9$

Coating Thermal Noise

Layers of

- fused silica (SiO_2) $Q \sim 10^6$
- Titania-doped tantala ($Ti{:}Ta_2O_5$) $Q \sim 10^4$

a few µm total thickness



Fused silica substrate

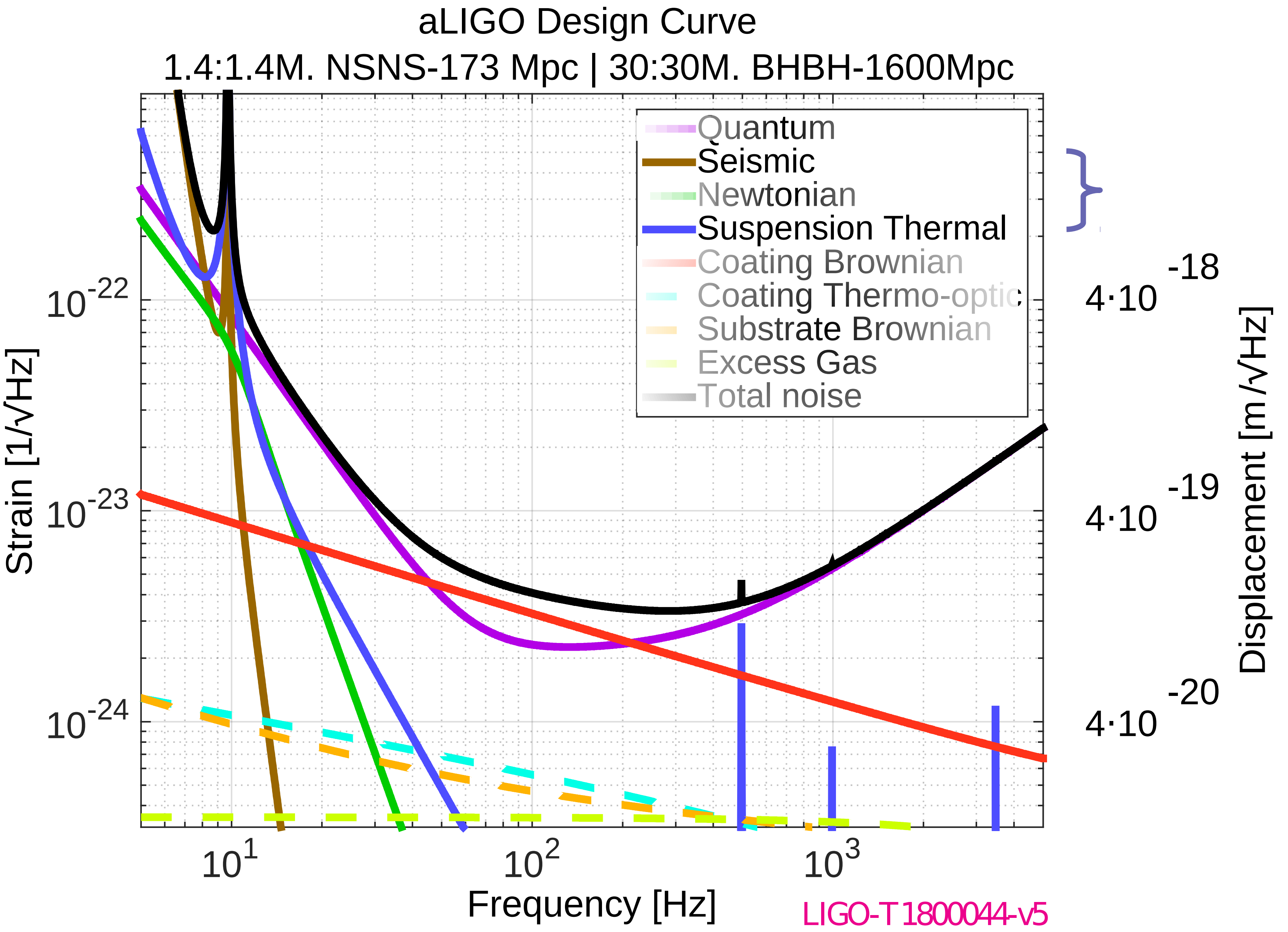
Mechanical Loss in materials cause ***phase fluctuations*** of **evanescent beam field** *stored in coating layers*.

integrates across Gaussian beam
(bigger beams average it out)

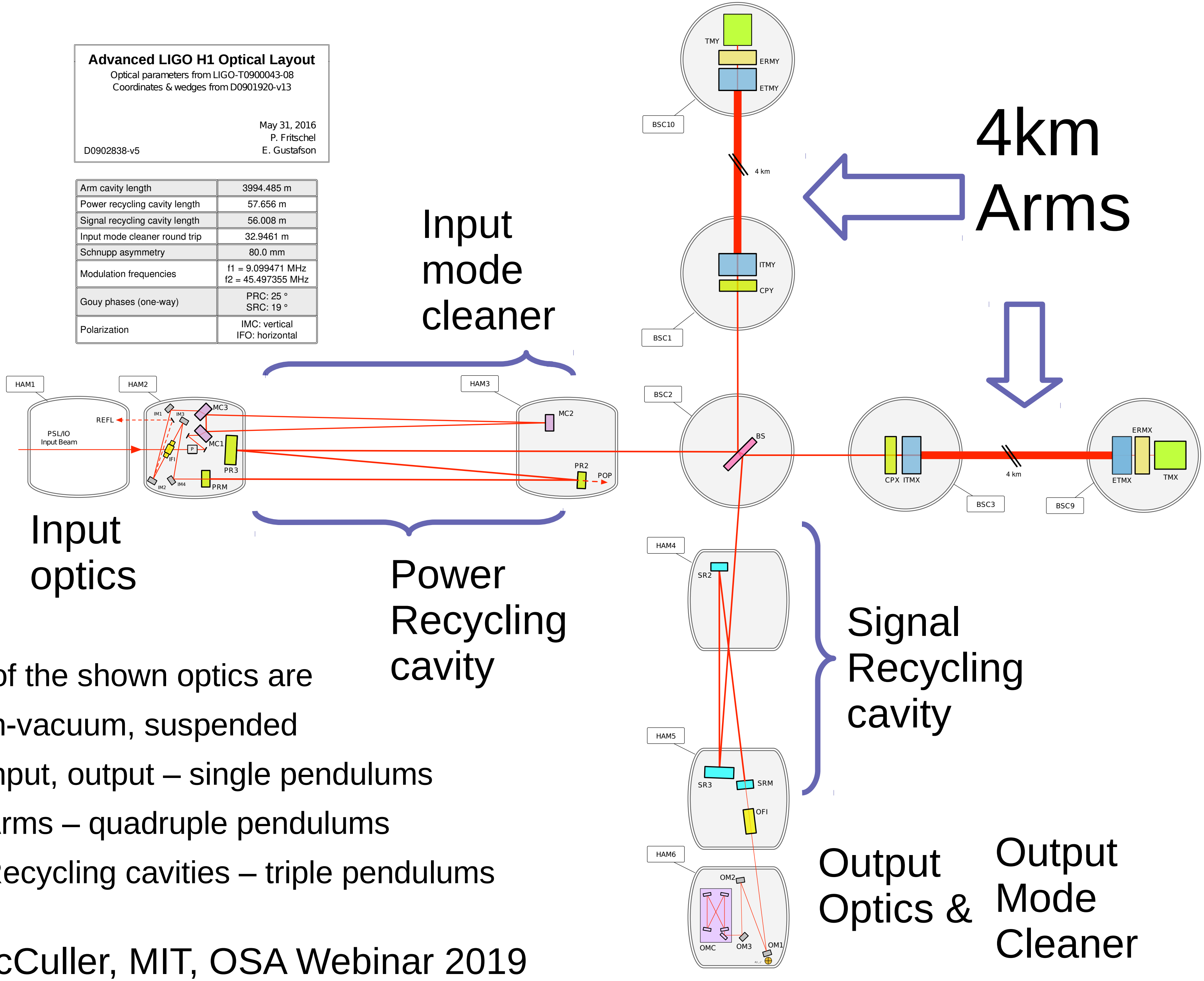
$$\langle \phi^2 \rangle \propto \frac{T}{Qw^2}$$

Difficult to find materials
low absorption, high-n and high-Q

Mechanical Layout



Suspended Optics Arrangement



Advanced LIGO H1 Optical Layout
Optical parameters from LIGO-T0900043-08
Coordinates & wedges from D0901920-v13

May 31, 2016
P. Fritschel
E. Gustafson

D0902838-v5

Arm cavity length	3994.485 m
Power recycling cavity length	57.656 m
Signal recycling cavity length	56.008 m
Input mode cleaner round trip	32.9461 m
Schnupp asymmetry	80.0 mm
Modulation frequencies	f1 = 9.099471 MHz f2 = 45.497355 MHz
Gouy phases (one-way)	PRC: 25 ° SRC: 19 °
Polarization	IMC: vertical IFO: horizontal

4km Arms

Input mode cleaner

Input optics

Power Recycling cavity

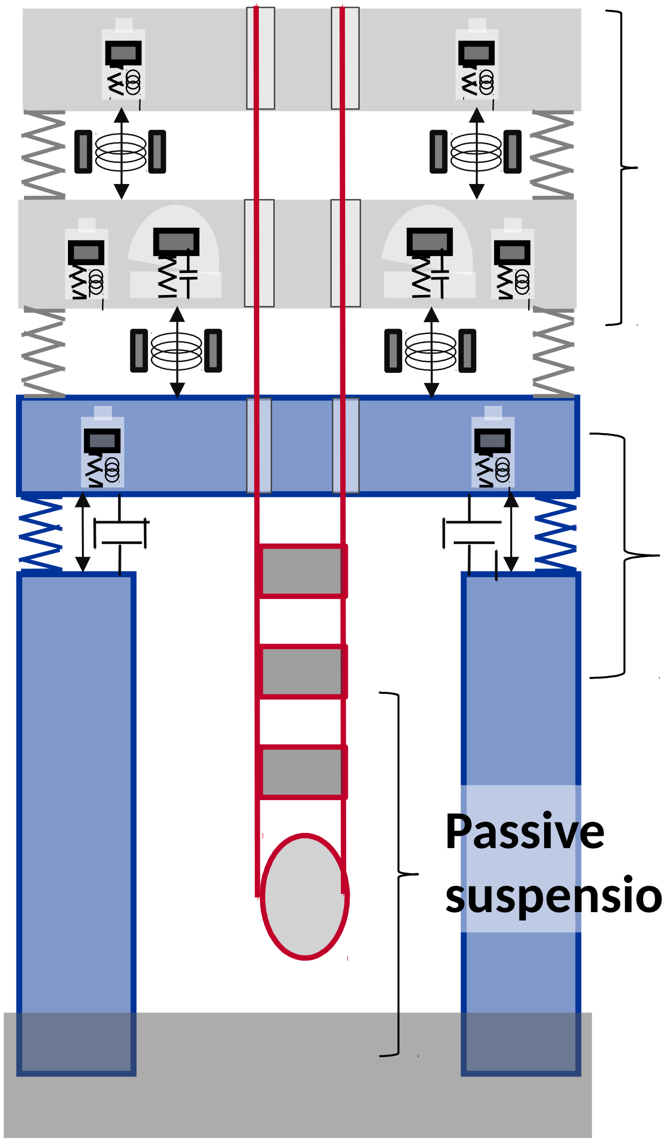
Signal Recycling cavity

Output Optics &

Output Mode Cleaner

- All of the shown optics are
  - In-vacuum, suspended
  - Input, output – single pendulums
  - Arms – quadruple pendulums
  - Recycling cavities – triple pendulums

Isolation of the core optics



Active Internal Isolator

Active Pre-Isolator

Passive suspensions

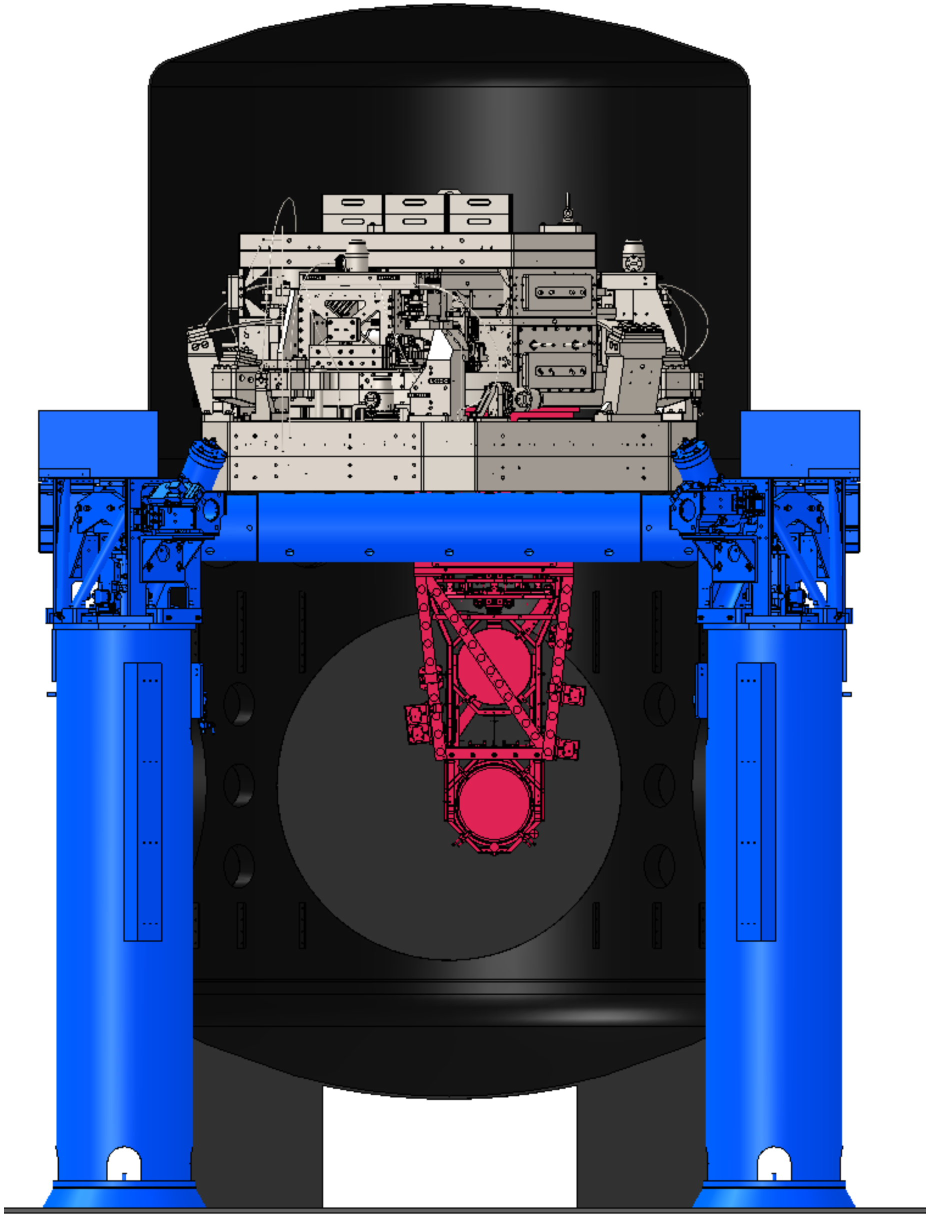
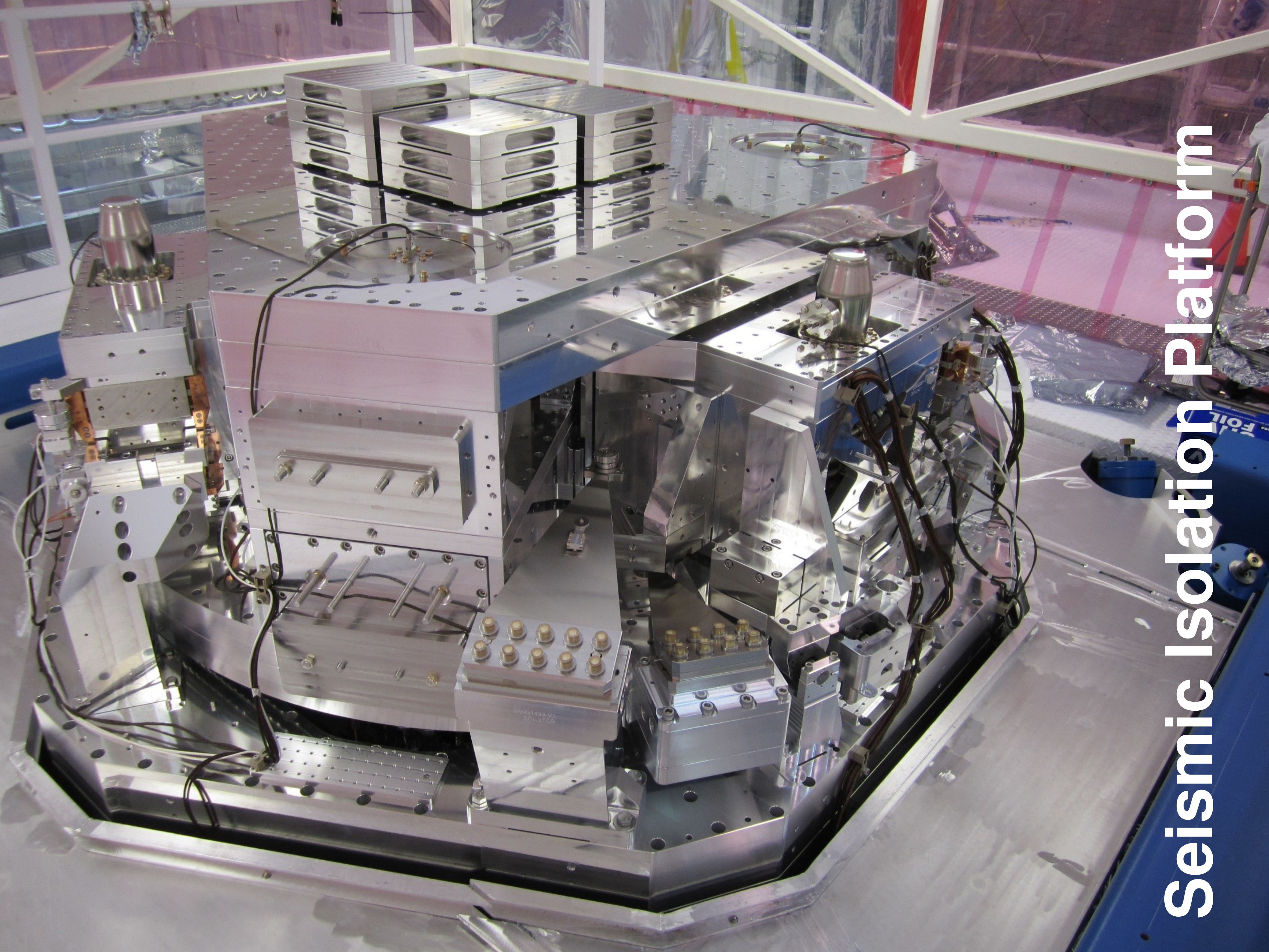
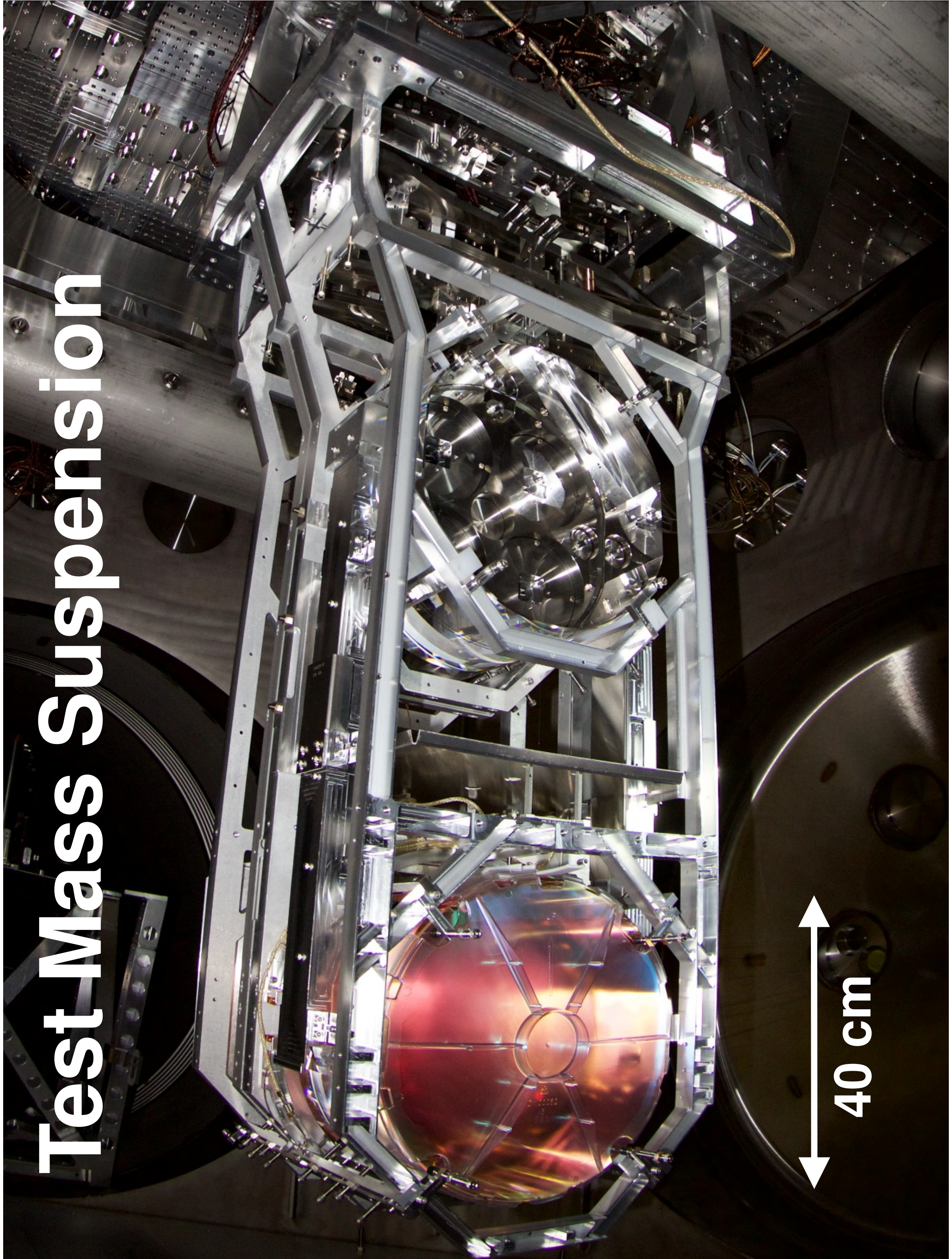


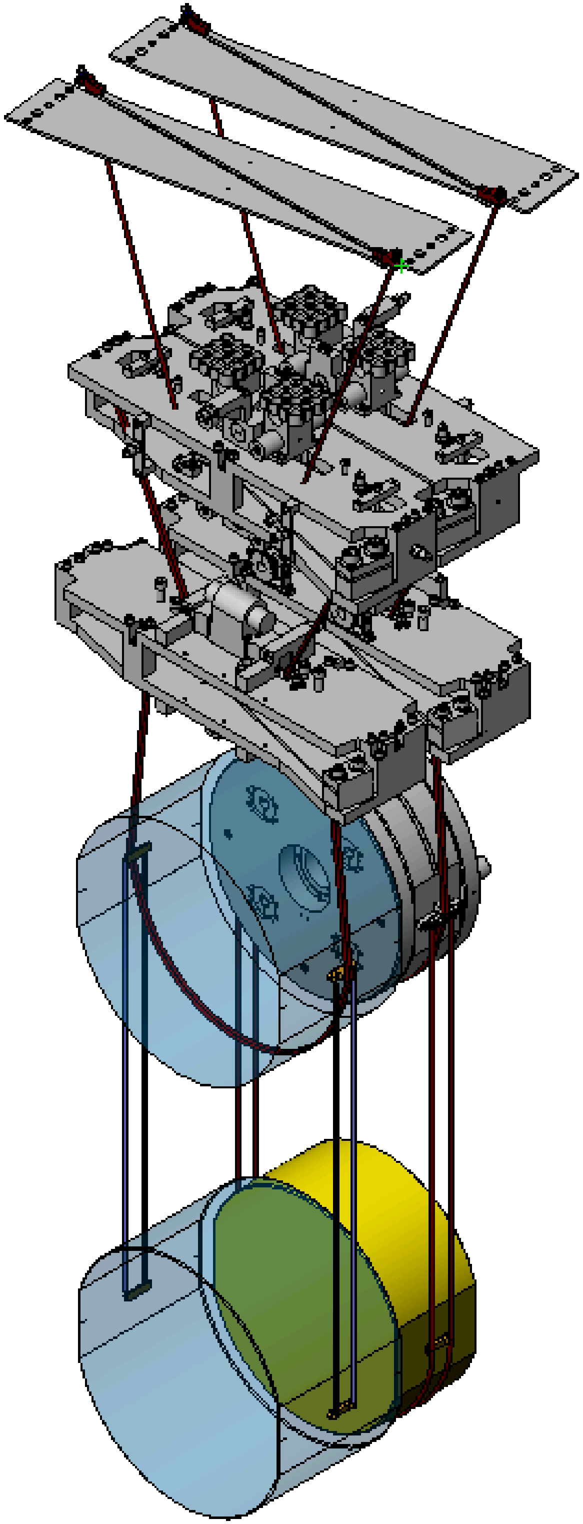
Image: F. Matichard



Seismic Isolation Platform

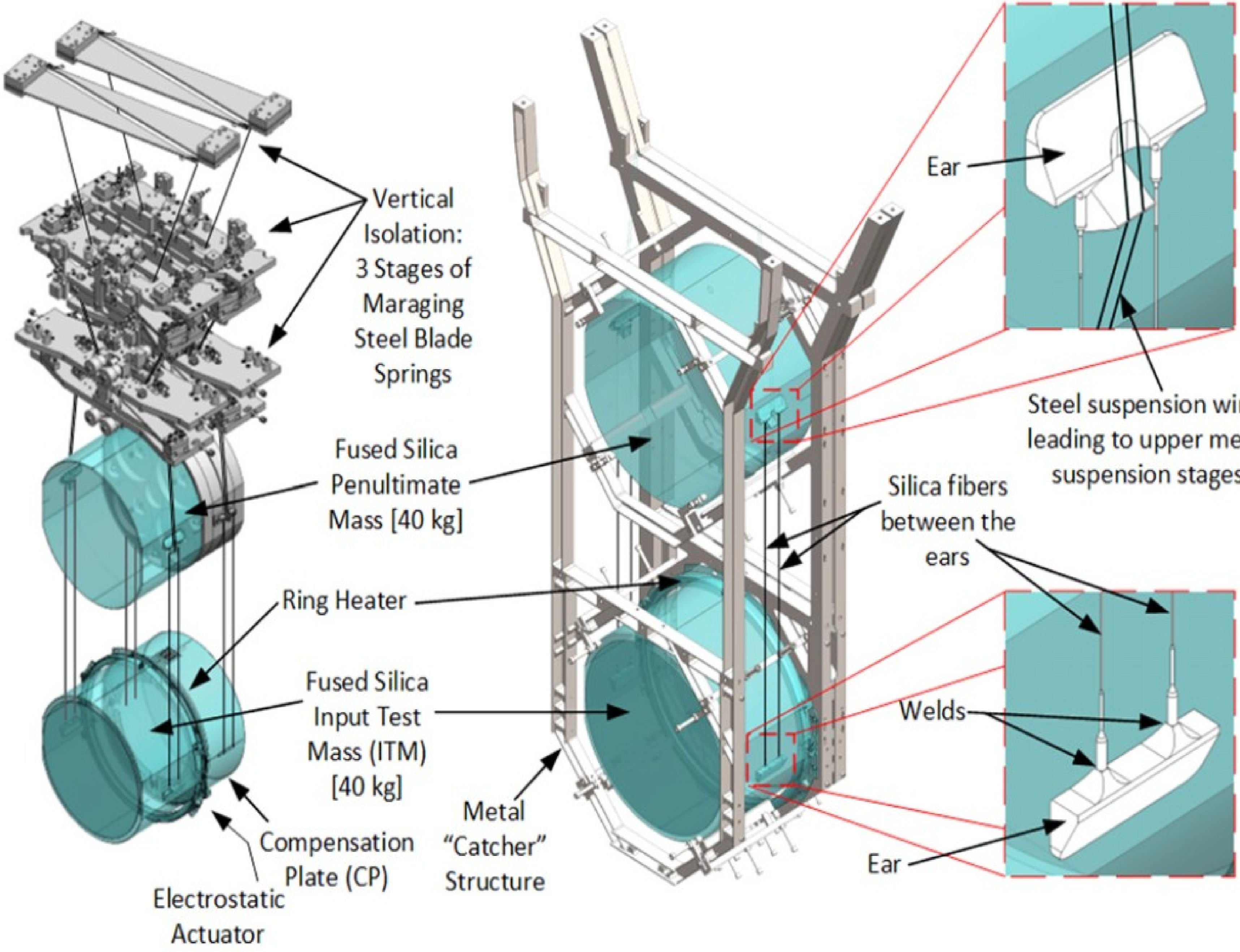
Test Mass Suspension



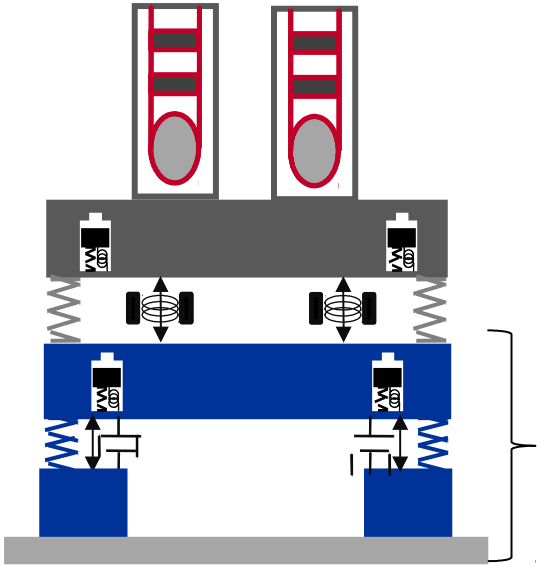


The Quadruple Pendulum

P1400177 - Advanced LIGO



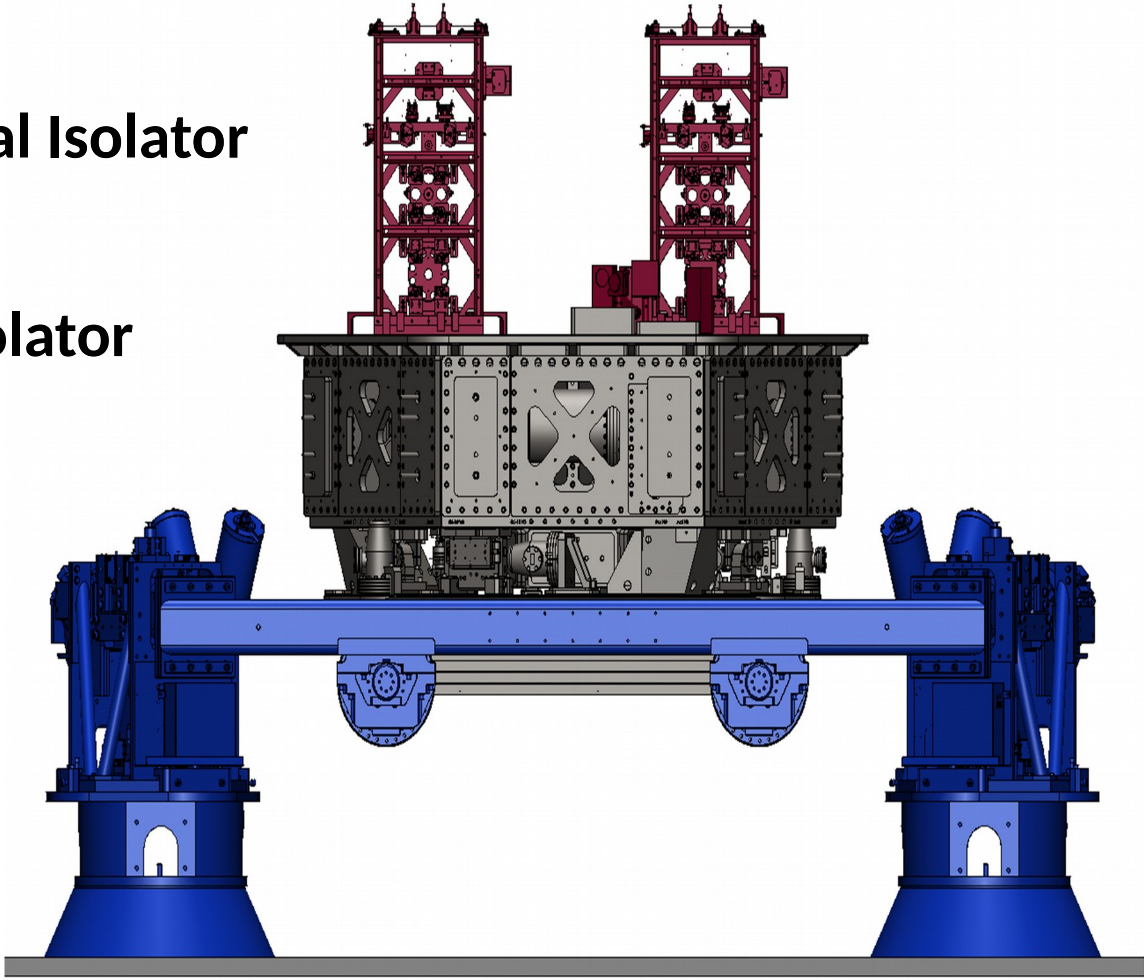
Isolation of the auxiliary optics



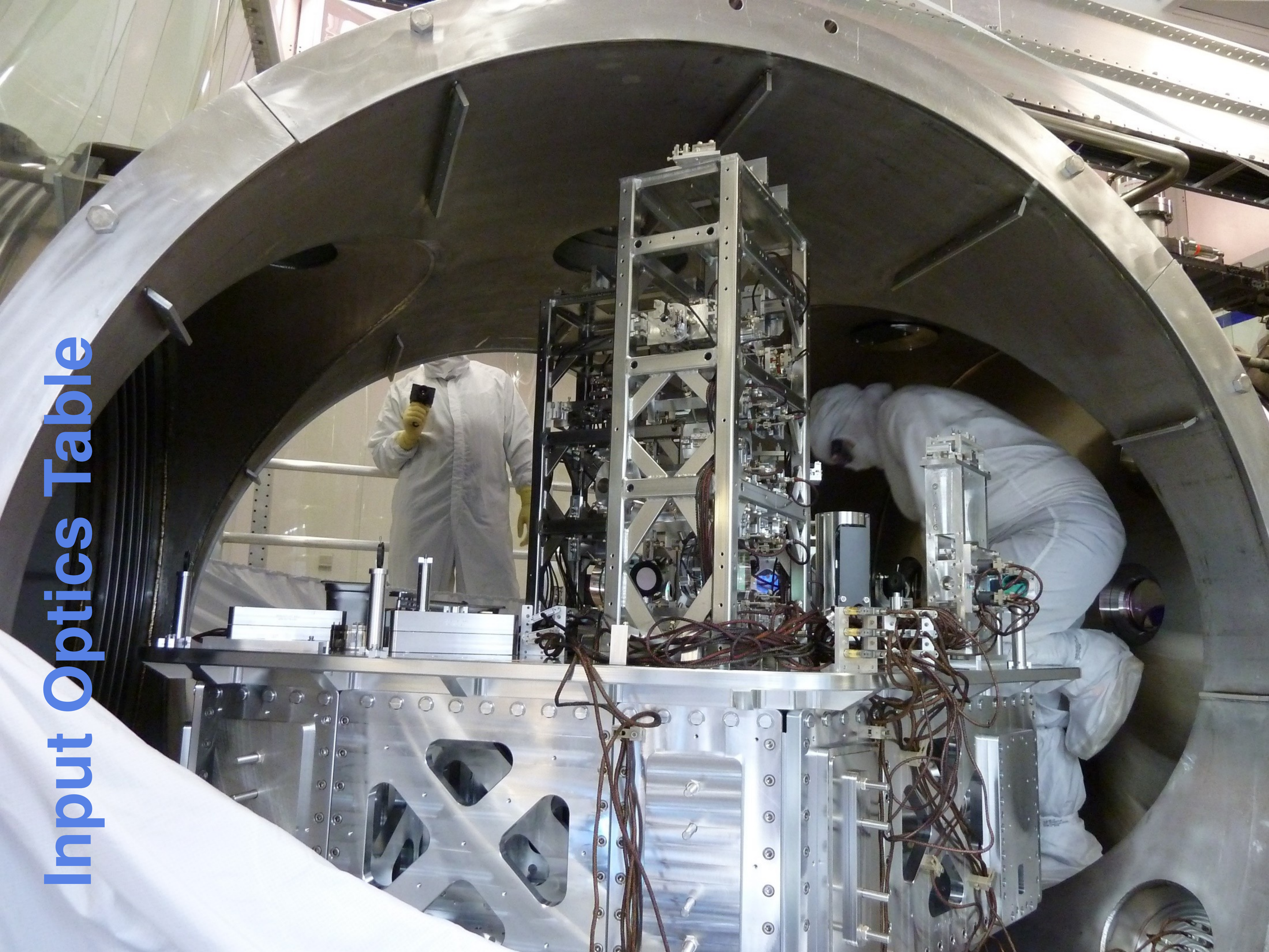
Passive suspensions

Active Internal Isolator

Active Pre-Isolator



Input Optics Table



Vacuum System Vertex

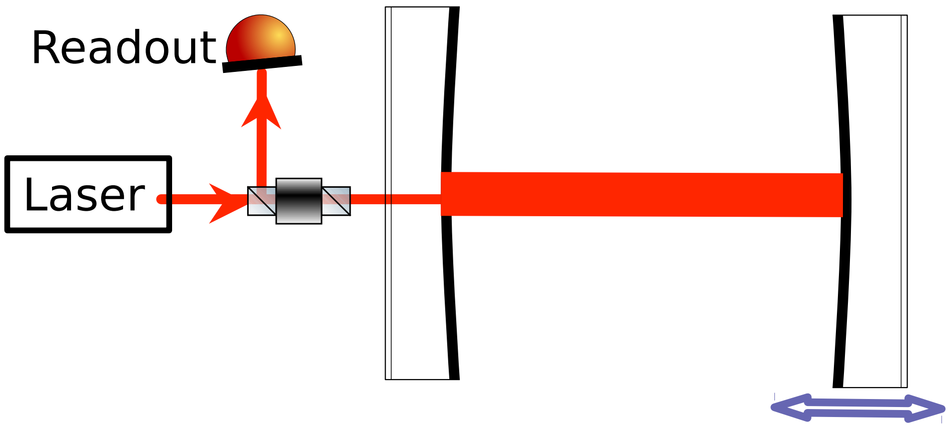
Interferometer Degrees of Freedom

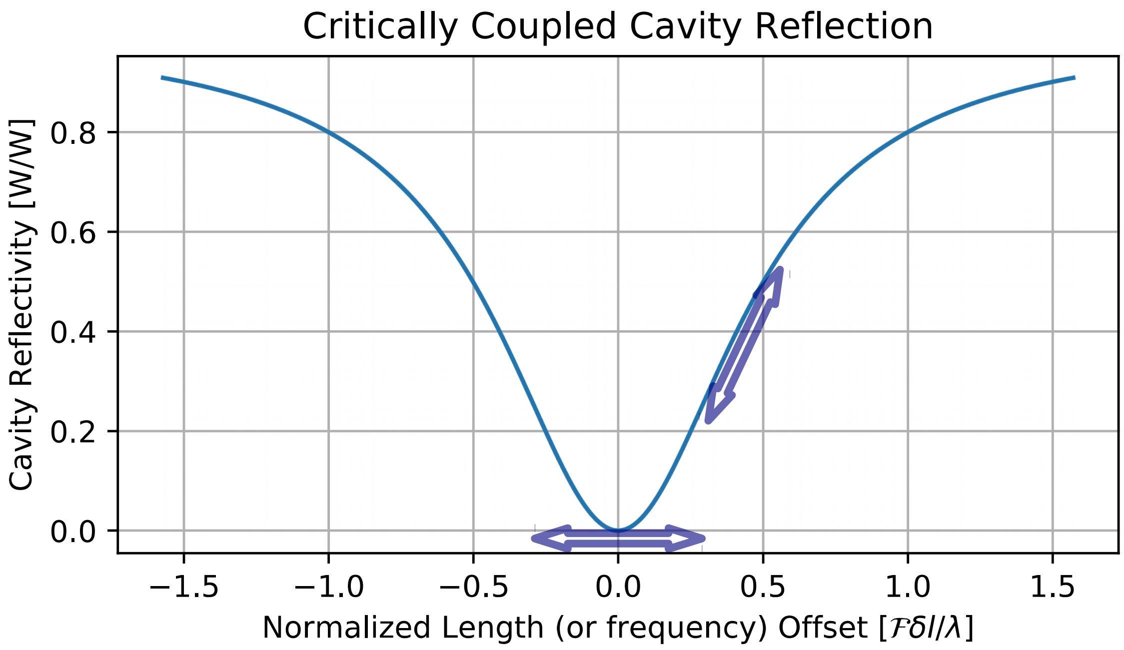
- 2 Arm cavities
  - Common arm length
  - Differential Arm length
- Beamsplitter/ Michelson
- Power Recycling Cavity
  - Laser Frequency
- Signal Recycling Cavity

- Each must be sensed and feedback controlled
- Most operate “On Resonance”
  - Signals are quadratic maximums, if measured by optical power
  - Can we measure the derivatives to generate error signals?
  - Or directly measure the optical field?

Length Sensing

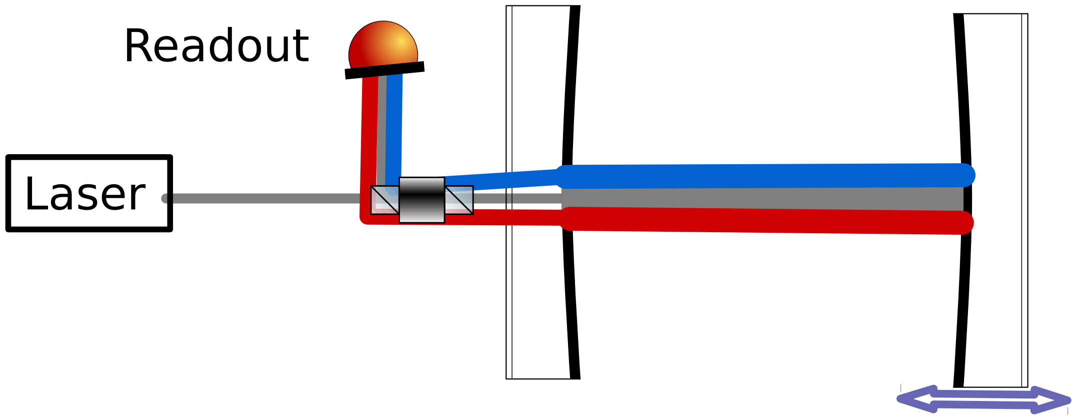
- Dither each length!
- Demodulation Measures the derivative
- Length and Frequency modulations are (mostly) indistinguishable
- Length/Frequency Modulations create *phase sidebands*

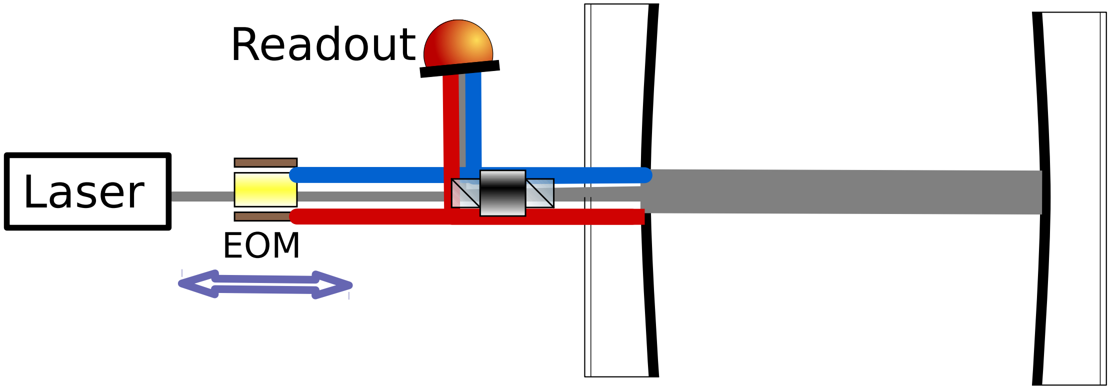


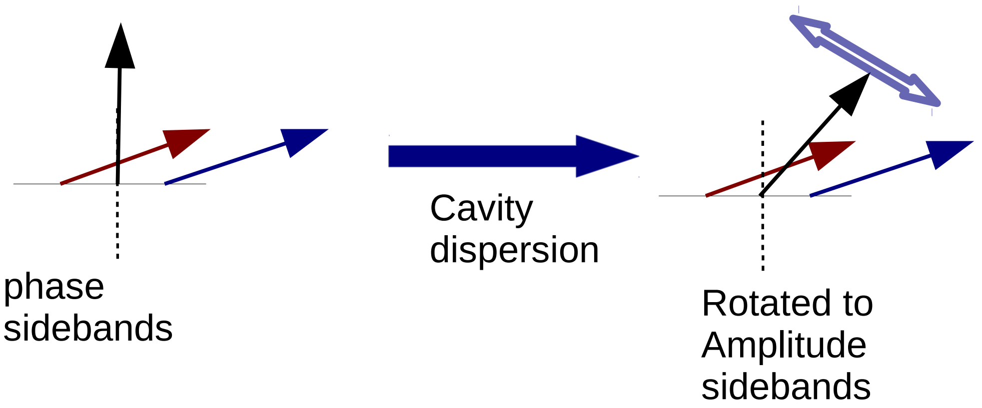


Pound-Drever-Hall Sensing

- Or…
- Directly Inject phase modulations at high frequency
- Some frequencies enter cavities, others reflect
- Dispersion causes dephasing of sidebands phase → amplitude







Interferometer Degrees of Freedom

- 2 Arm cavities
  - Common arm length
  - Differential Arm length
- Beamsplitter Michelson
- Power Recycling Cavity
  - Laser Frequency
- Signal Recycling Cavity

- RF sidebands allow direct field measurements through differential phasing
- Co-propagate with carrier allows measuring specific D.O.F’s with less contamination from others.
- RF beatnotes provide of all vertex degrees of freedom

Frequency Sensing Stages

Nested control gain hierarchy
50kHz bandwidth outer loop (reference cavity)

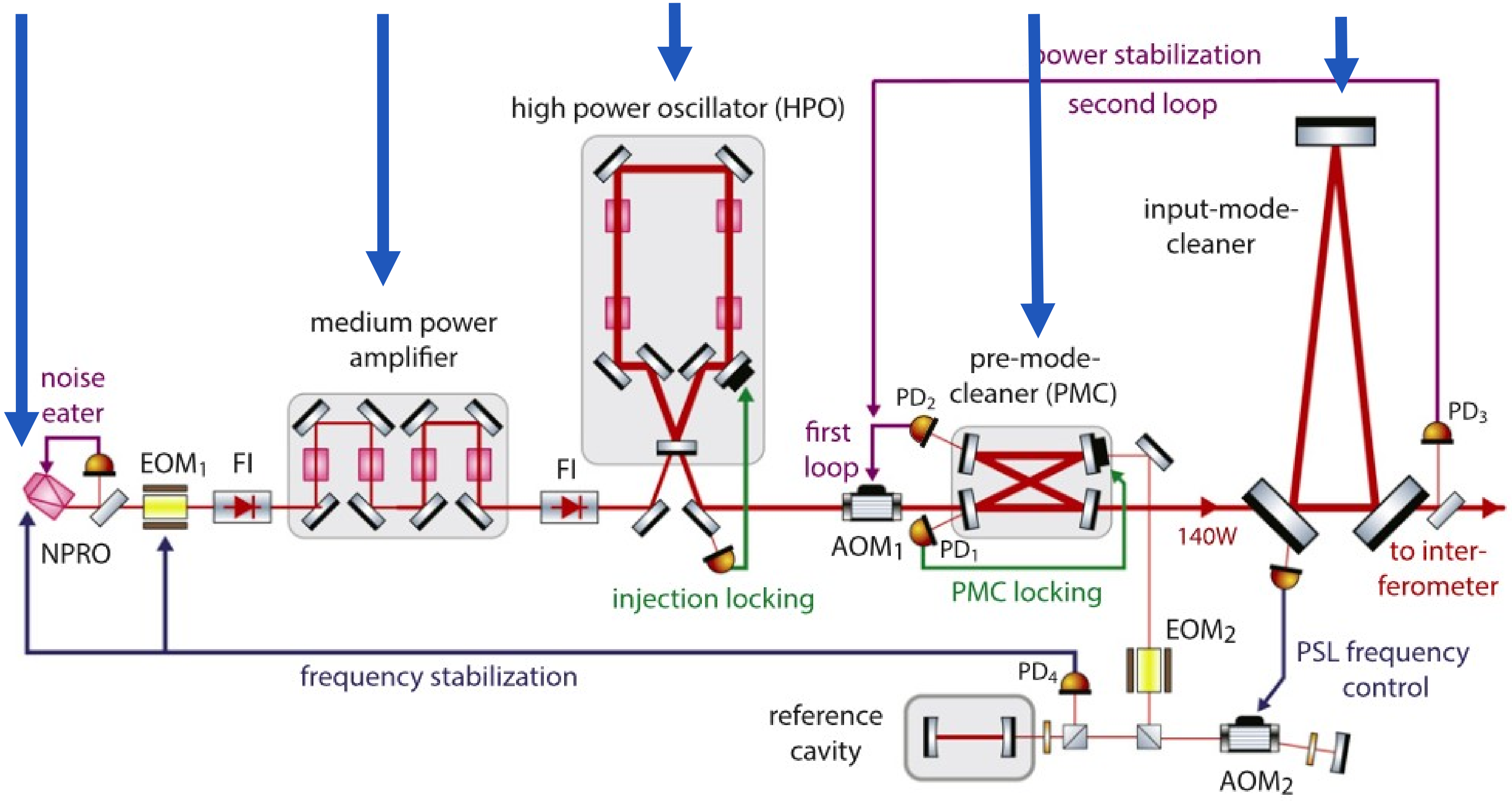
2 W seed crystal

35 W amplifier

220 W amplifier

Mode-cleaning cavity

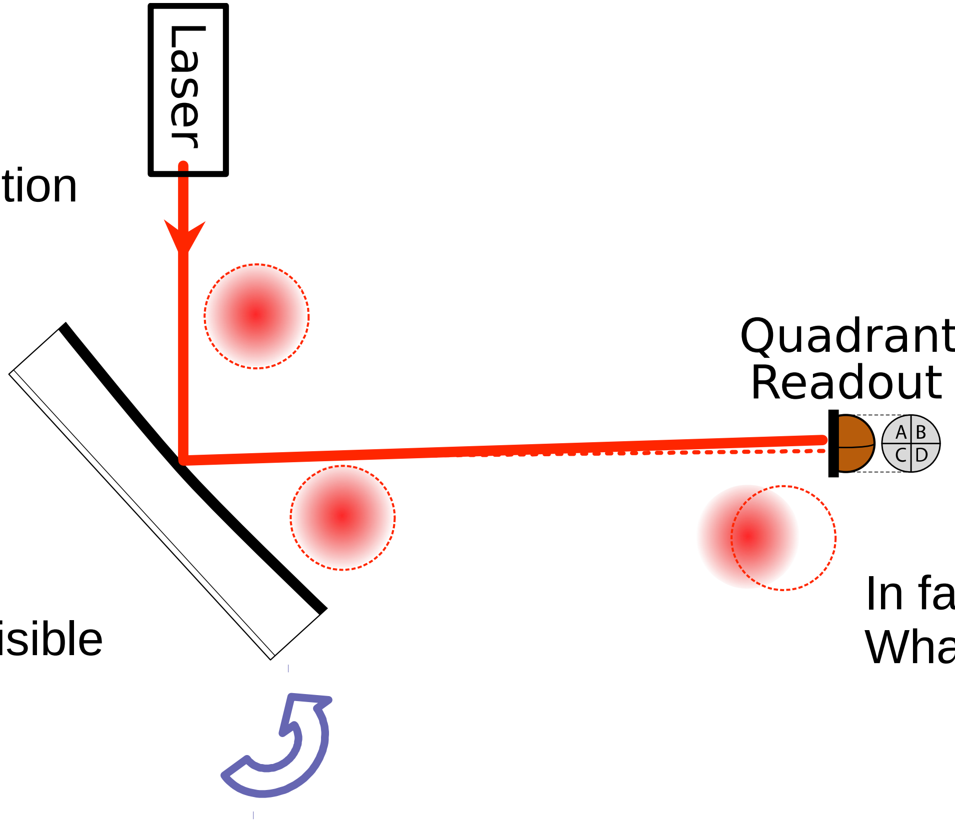
Mode-cleaning cavity



Laser frequency stabilized 10^8 to ~1 μHz/$\mathrm{Hz}^{1/2}$ at 100 Hz (~10^{-8} rad/$\mathrm{Hz}^{1/2}$)

Laser amplitude stabilized to ~10^{-8} RIN/$\mathrm{Hz}^{1/2}$ at 100 Hz

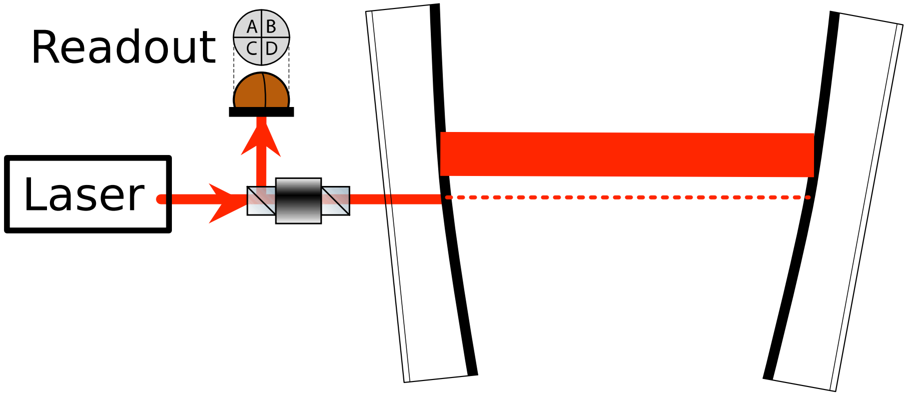
Alignment Sensing



Nominal Beam position
defined

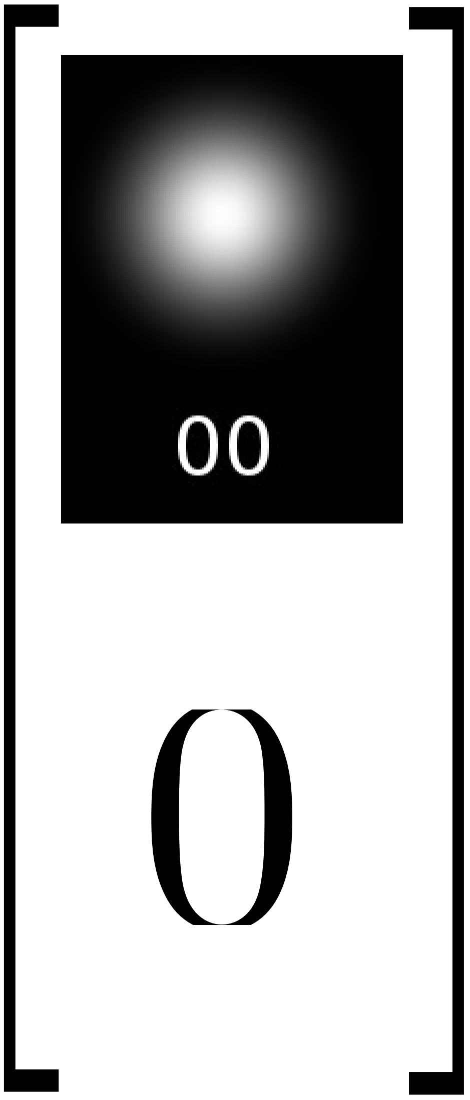
Alignment modifies
wavefront, but no visible
deflection

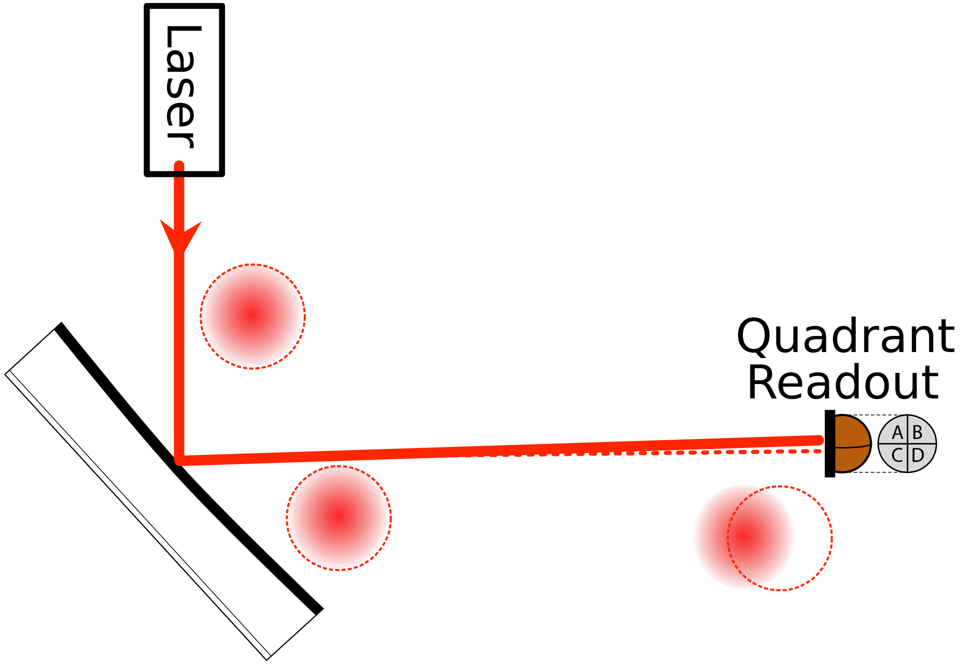
In far-field, beam deflects
What defines far-field?



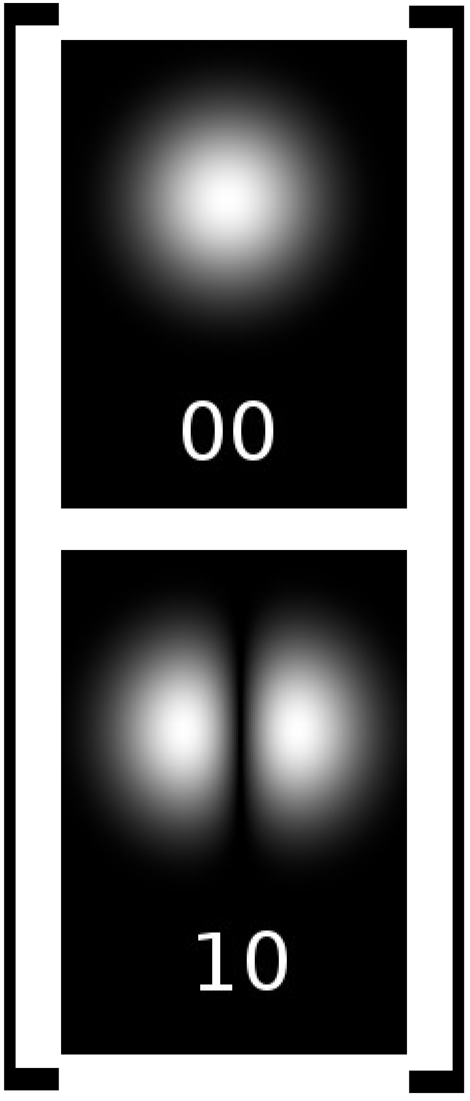
Not clear how deflection
Picture works for cavities

Alignment Sensing





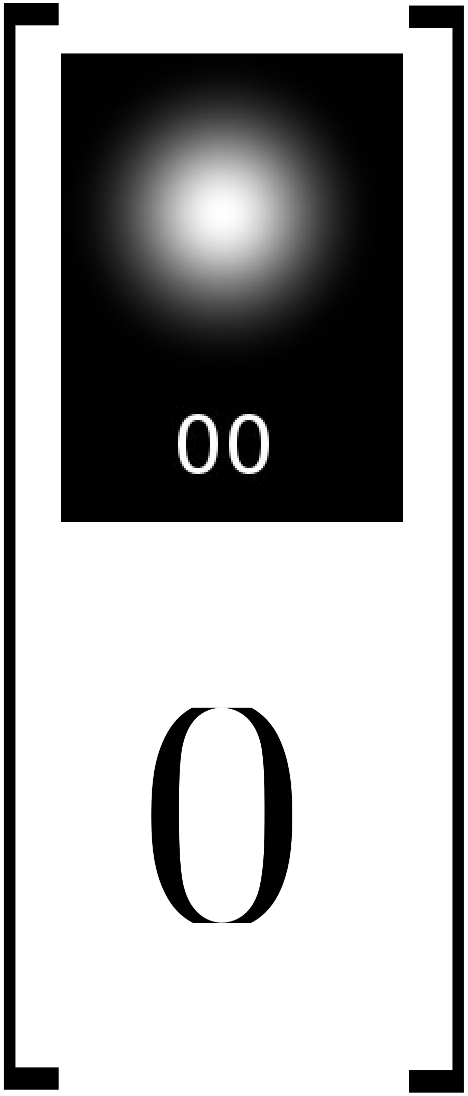
mis-alignment moves beams into higher-order modes of nominal-axis basis

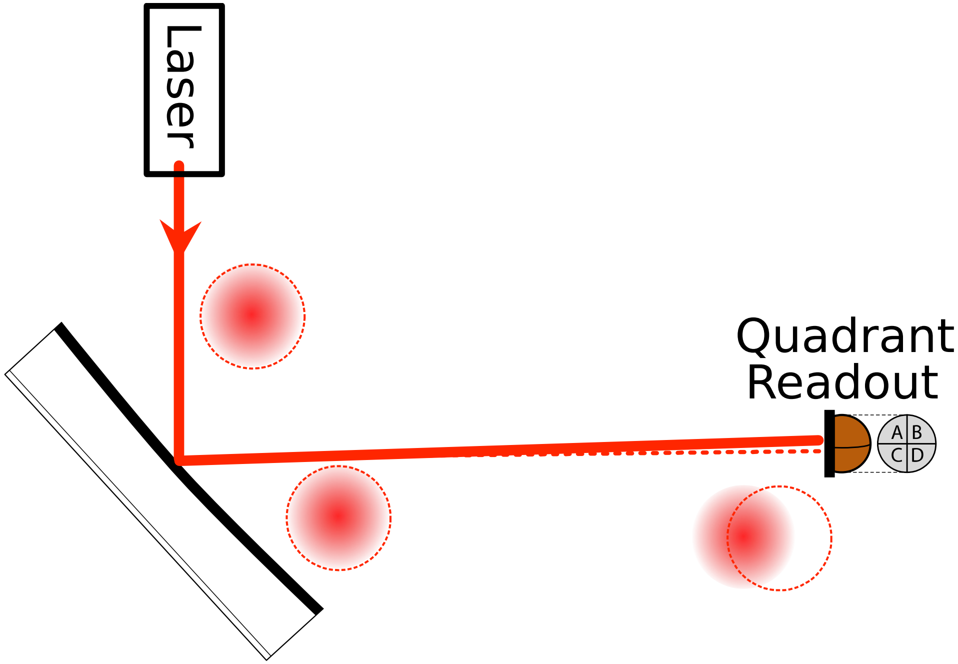


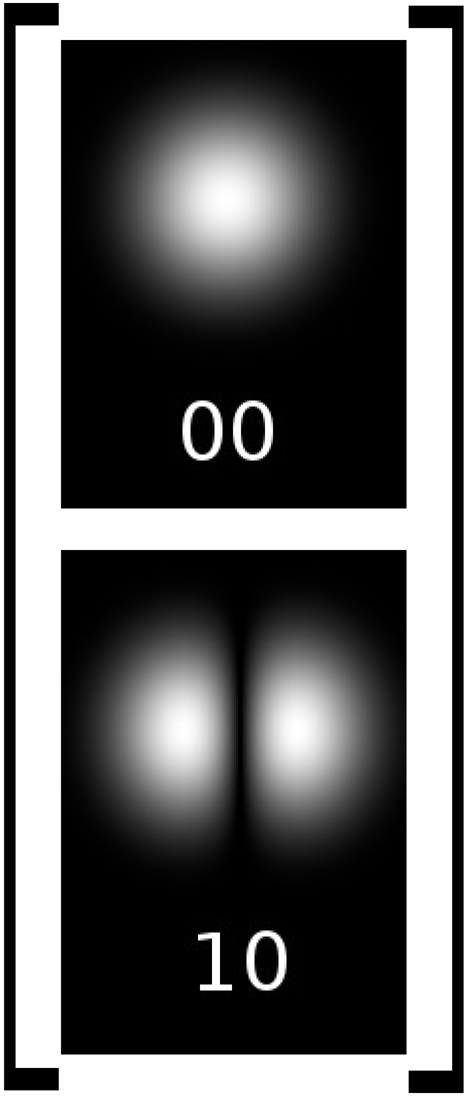
When sensing alignment to cavities, we do not (typically) using *ray propagation,* instead we use **modal decomposition**

HG images
By DrBob at English Wikipedia, CC BY-SA 3.0,
https://commons.wikimedia.org/w/index.php?curid=18064771

Alignment Sensing





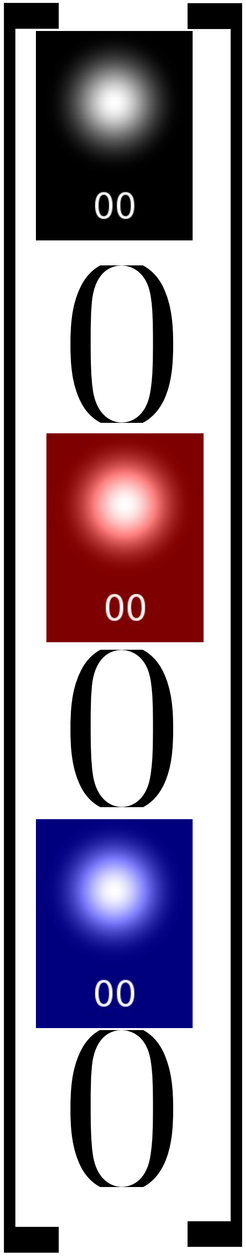


Although the deflection can be sensed best when far away, the HG01 mode coupling happened at the mirror!

Far-field: Alignment causes phase-quadrature HG01, which shifts to measurable amplitude quadrature by
Gouy phase advance

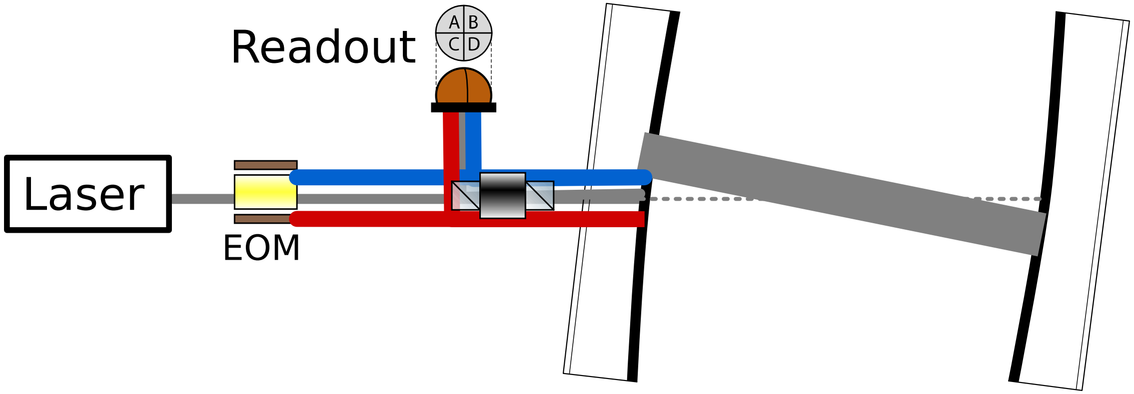
HG images
By DrBob at English Wikipedia, CC BY-SA 3.0,
https://commons.wikimedia.org/w/index.php?curid=18064771

RF Alignment Sensing

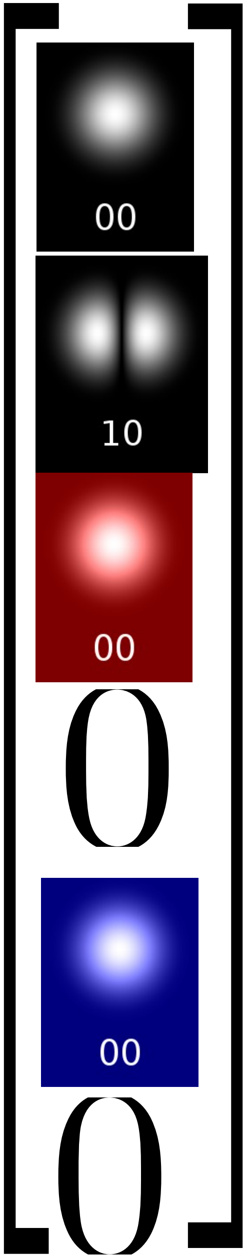


Cavity Deflection moves only some frequencies into higher-order modes

Modal-Frequency decomposition then allows shows cavity effects on RF sensitive quadrant photodetectos (wavefront sensors)



Telescope designs optimize:
Gouy phase accumulation between mirrors/detectors to actuate/measure
real and imag parts of HG01



Future Improvements and A+

Observing run 4

Continued Commissioning

- Finding/removing excess noises
  - Scattered light
- Increasing power towards design
  - Thermal compensation

Advanced LIGO+

Reduce quantum noise

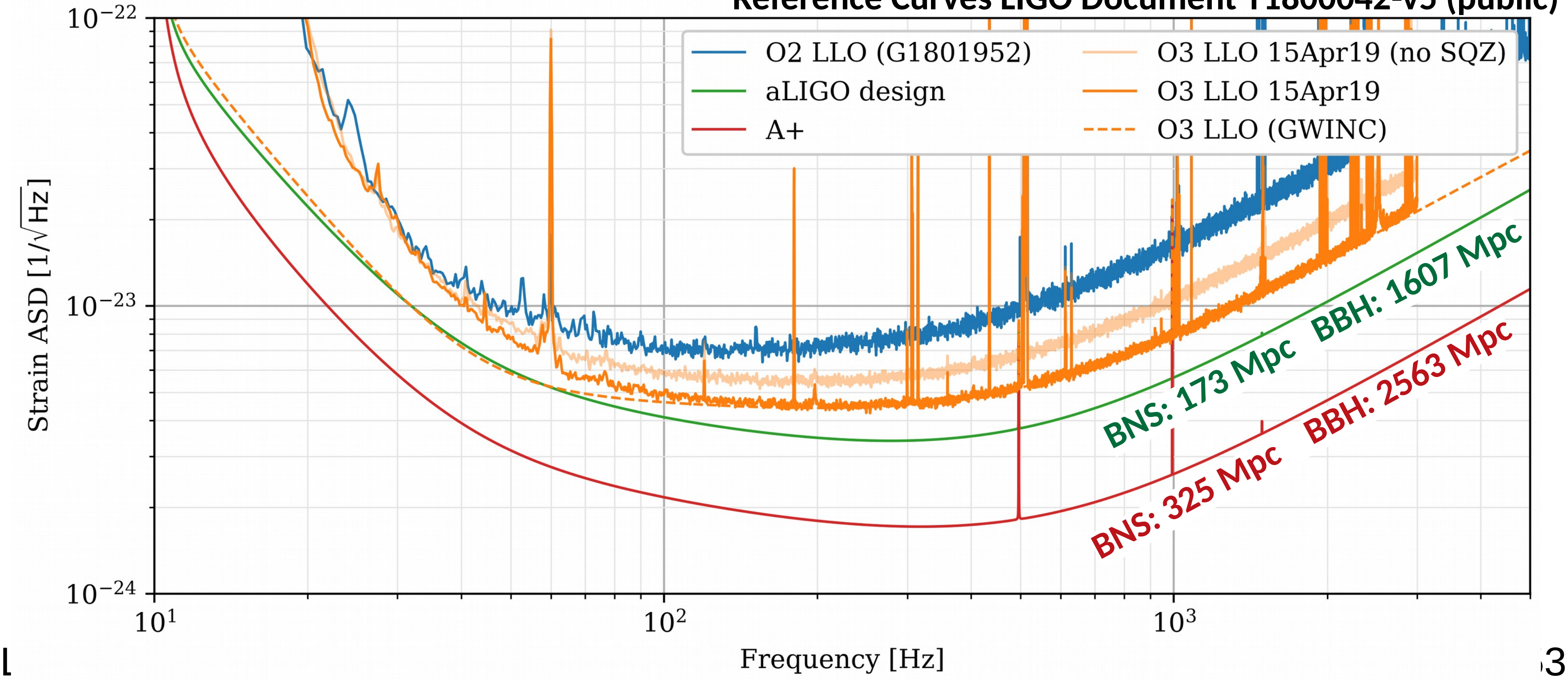
Improved optical losses

Improved readout

Frequency-Dependent Squeezing

- Reduce thermal noise
  - Improved mirror coatings

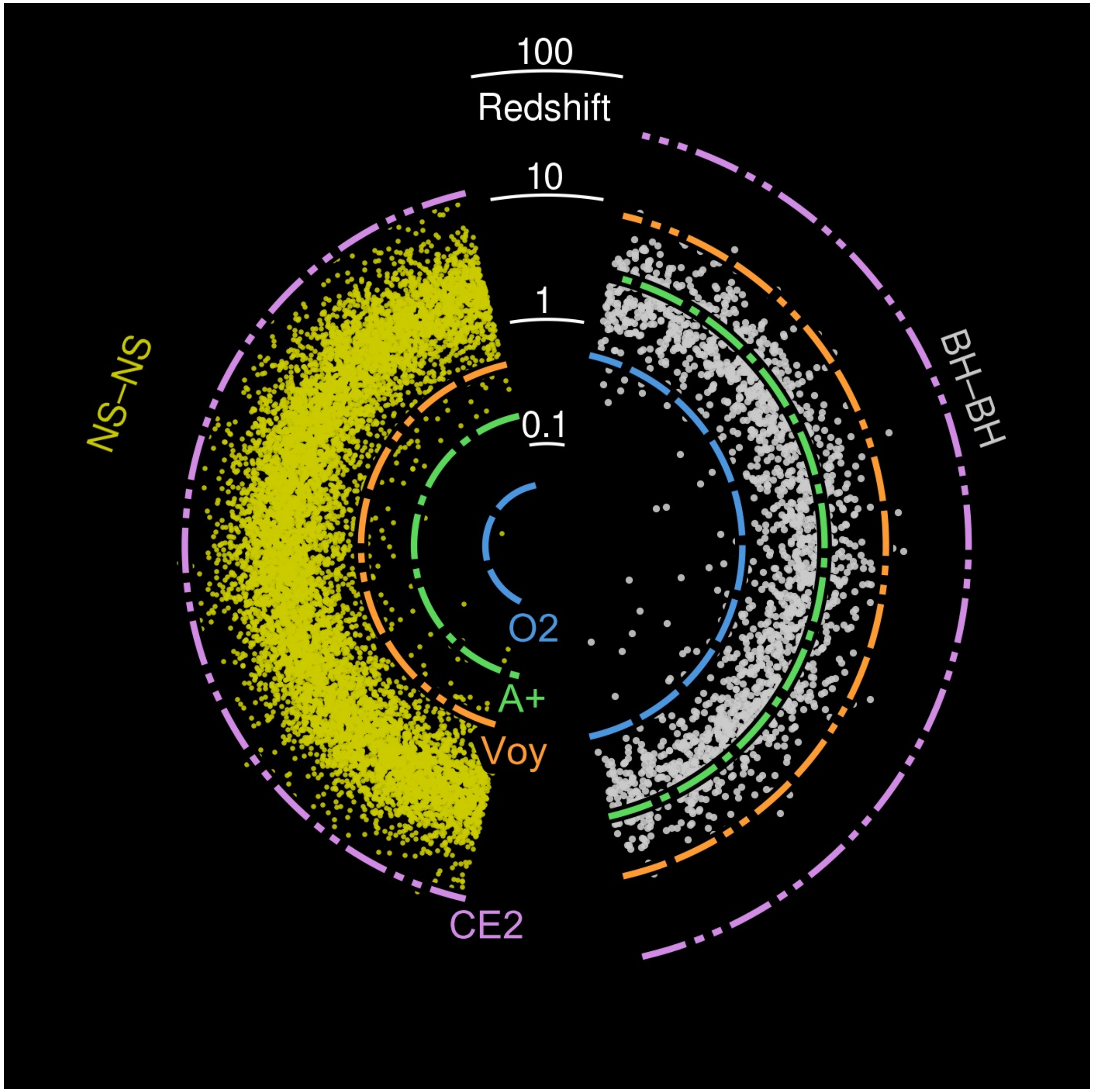
Reference Curves LIGO Document T1800042-v5 (public)



The Third Generation

- Cosmic Explorer and Einstein Telescope
  - 10-40km observatories
    (conceptual designs)
  - 10x more optical power
  - Larger suspensions

- Probe cosmological history of GW astronomy
  - High event rates
  - Extreme signal-to-noise



E. Hall/S. Vitale

Thank You

Covered Topics

- interferometer topology
- Fundamental noises
  - quantum
  - suspensions/seismic
  - coatings/thermal
- Sideband sensing
  - For length/frequency
  - For alignment

Further Topics

- Squeezed Quantum
- Calibration System
- Thermal Compensation
- Control acquisition
- Scattering
- Laser Design