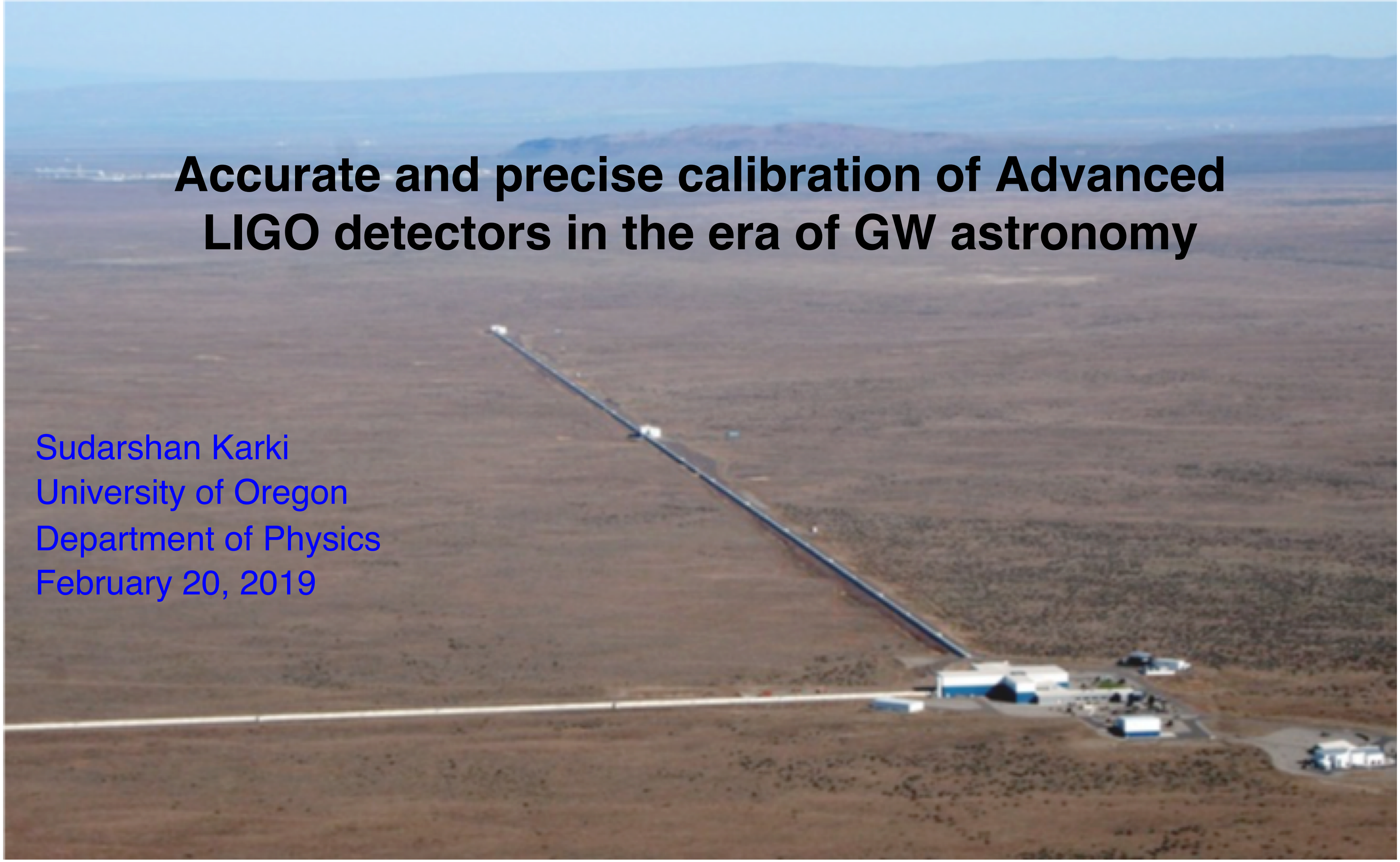


Accurate and precise calibration of Advanced LIGO detectors in the era of GW astronomy

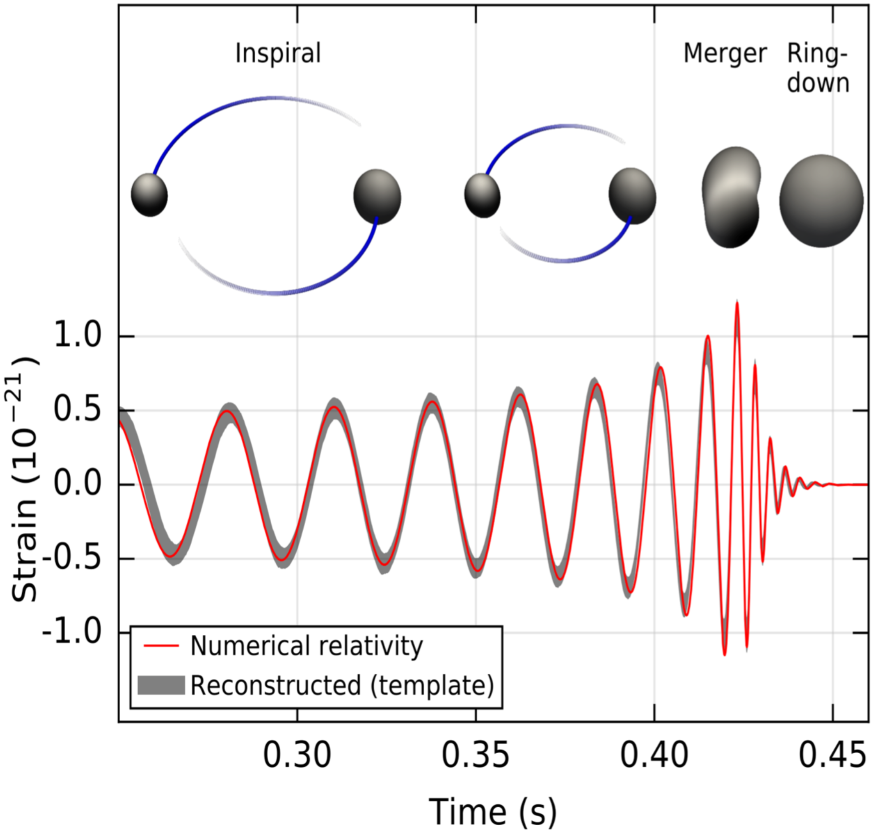
Sudarshan Karki
University of Oregon
Department of Physics
February 20, 2019

OVERVIEW

Realization of sub 1% calibration on aLIGO Pcals

- LIGO’s detections and their astrophysical implications.
- LIGO detectors and what it means to calibrate them.
- Radiation pressure based calibration tool called Photon calibrators.
- Issues with trying to use the Photon calibrator at high frequencies where NS post merger GW emission are expected to occur.
- Conclusions and Outlook

GW150914: First Direct GW Detection



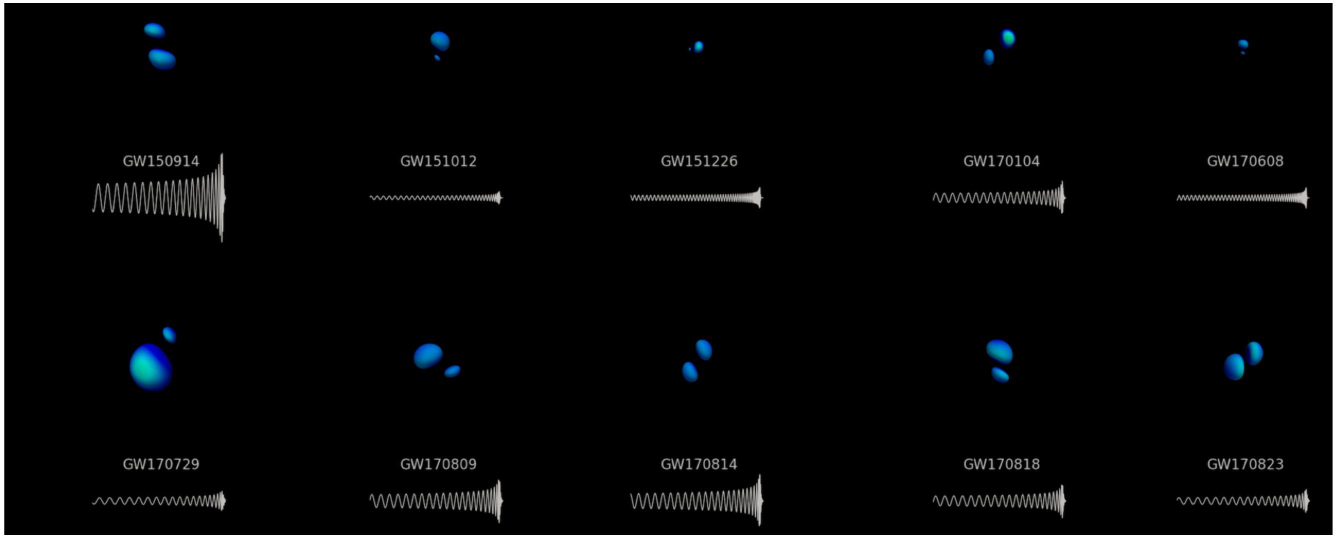
- First direct observation of gravitational waves.
- 1.3 billion light years away
- 36 and 29 solar mass binary black hole merger
- Final black hole = 62 solar mass
- 3 solar masses converted into gravitational waves in 0.2 s.

Phys. Rev. Lett. **116**, 061102 (2016)

GW ASTROPHYSICS
What can we learn from these detections?

Increased detections and accurate parameter estimation will provide:

- Better estimate of the rates of these events.
- Insights into formation process of these binary black holes.



Source Parameters: (are impacted by calibration)

- Masses, Spin, Sky location, Distance (D)

$$h \approx \left(\frac{4\pi^2 G}{c^4}\right) \frac{M(R\, f_{orb})^2}{D}$$

Calibration requirements became 10 times more stringent

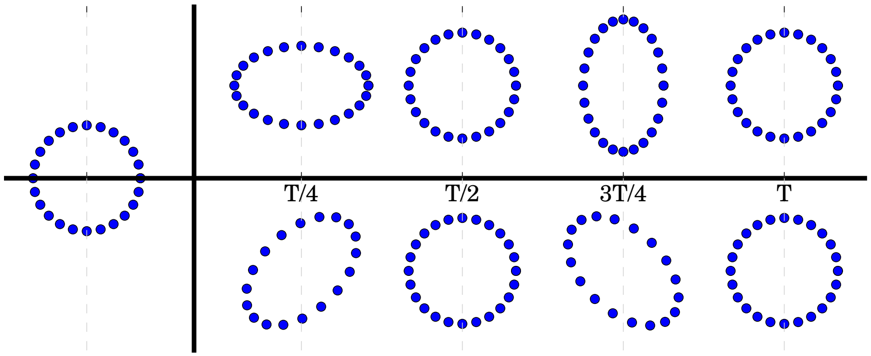
10 % for detection ➔ 1 % to optimize scientific reach of LIGO

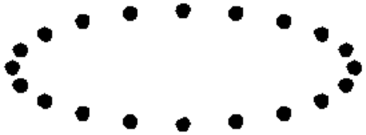
Advanced LIGO detectors and their calibration

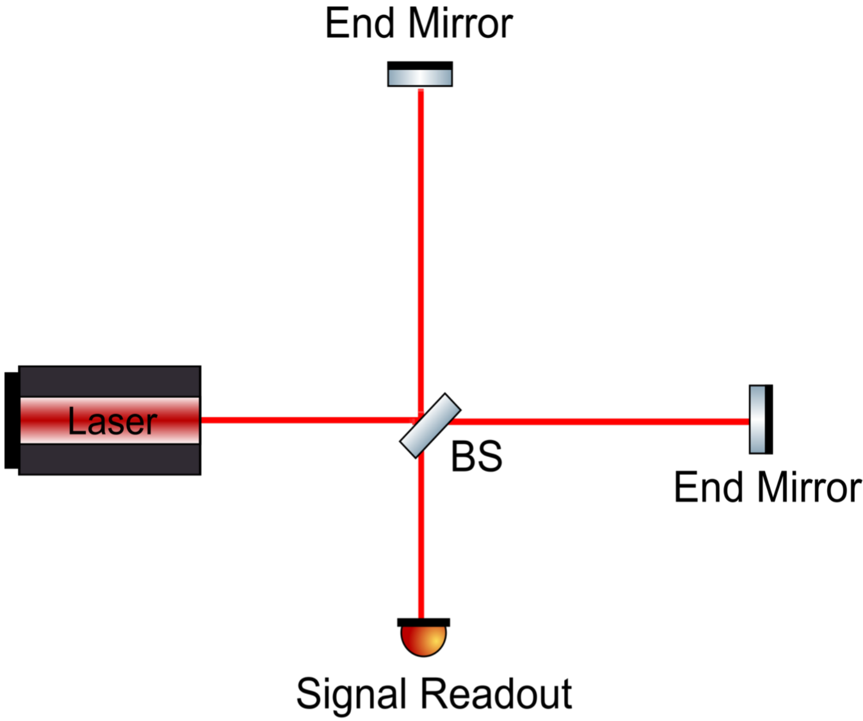
How LIGO detectors work and what it means to calibrate them.

LIGO

Gravitational Waves and Interferometer



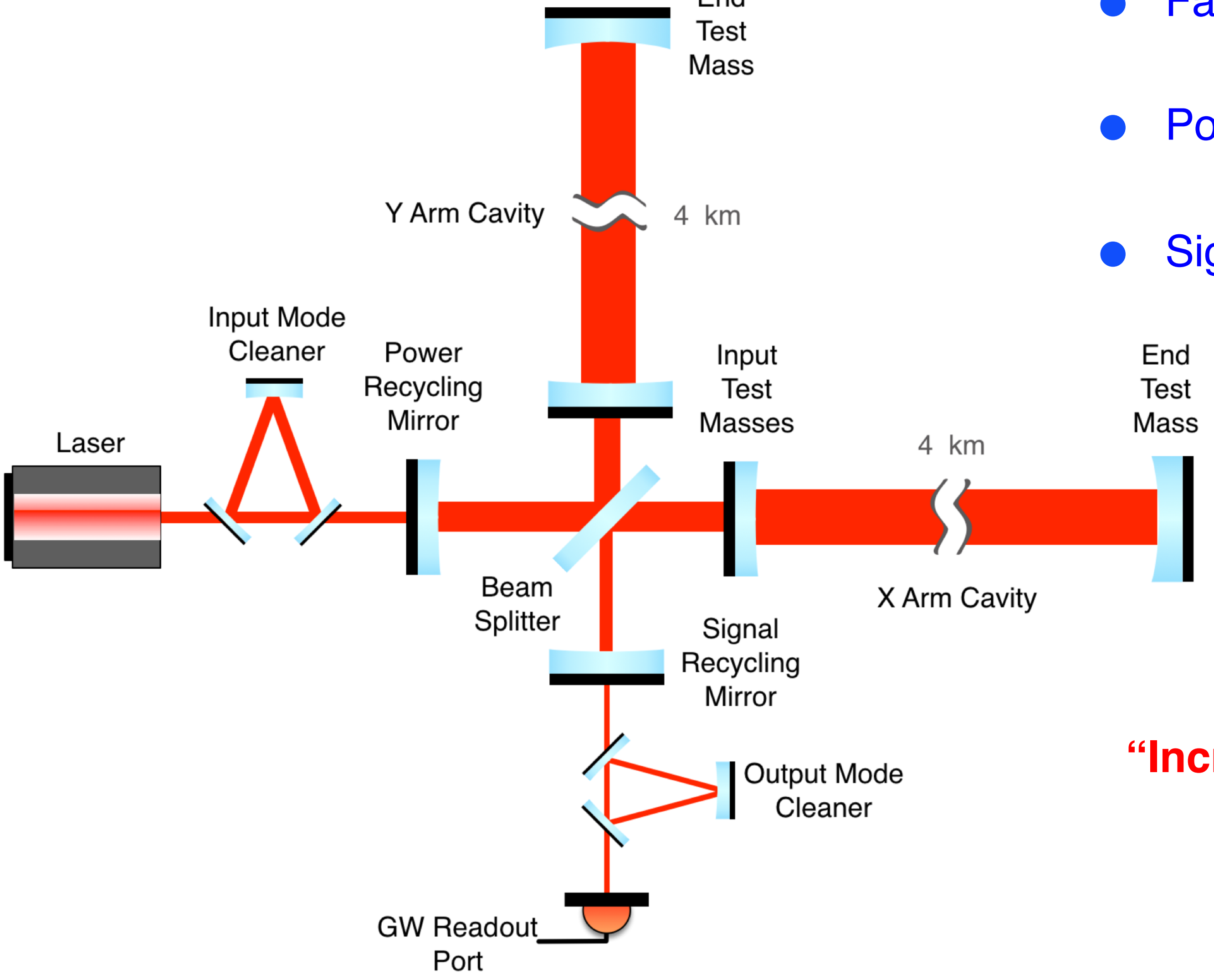




$$\Delta L = \underset{\boxed{10^{-21}}}{h} \times \underset{\boxed{10^{3}}}{L}$$

$$\Delta L = \boxed{10^{-18}\ \mathrm{m}}$$

Advanced LIGO Optical Layout

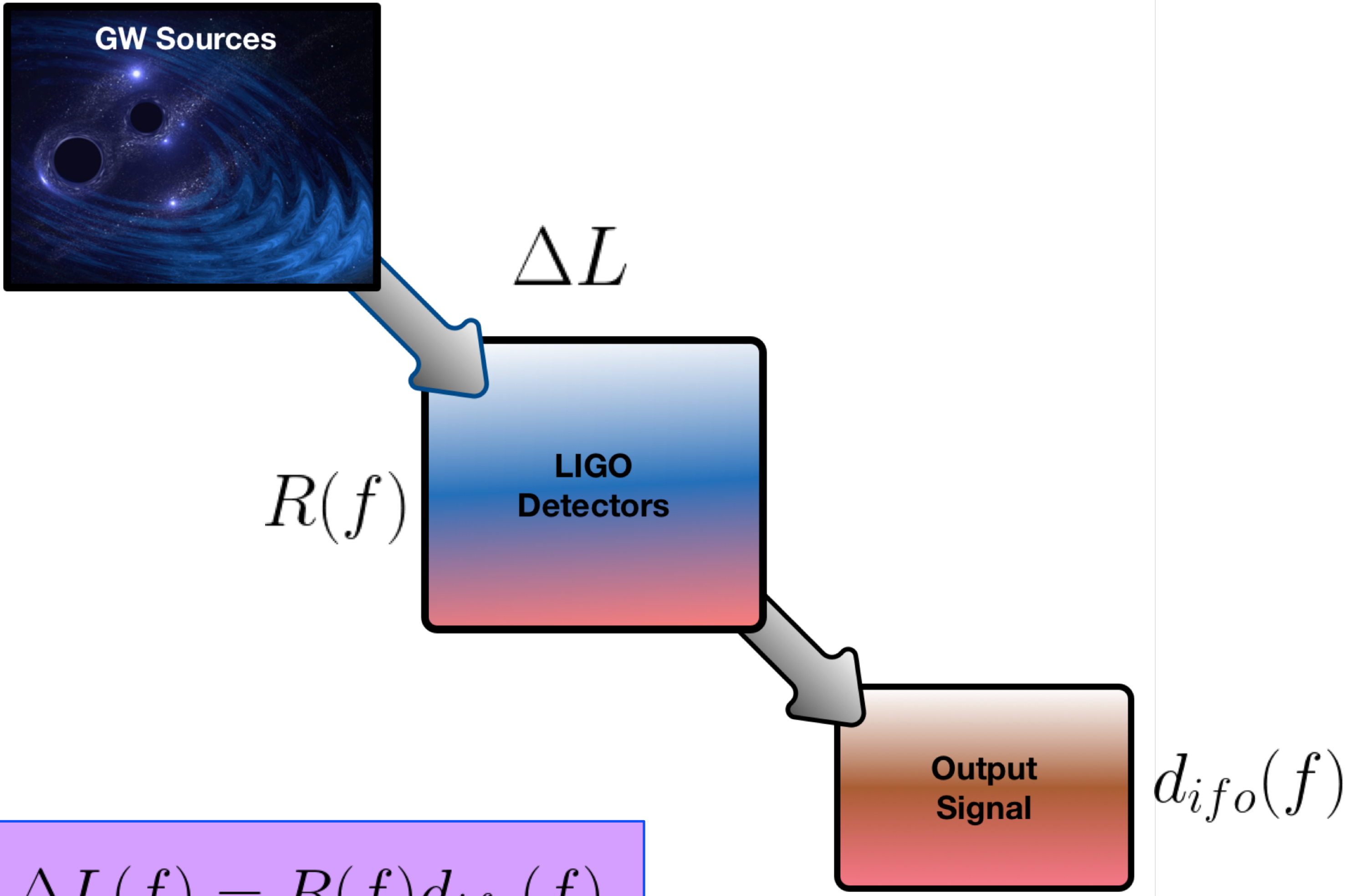


- Fabry-Perot Cavities
- Power Recycling
- Signal Recycling

“Increase Sensitivity”

“Complexity”

CALIBRATION
What is Calibration?



GW Sources

ΔL

$R(f)$

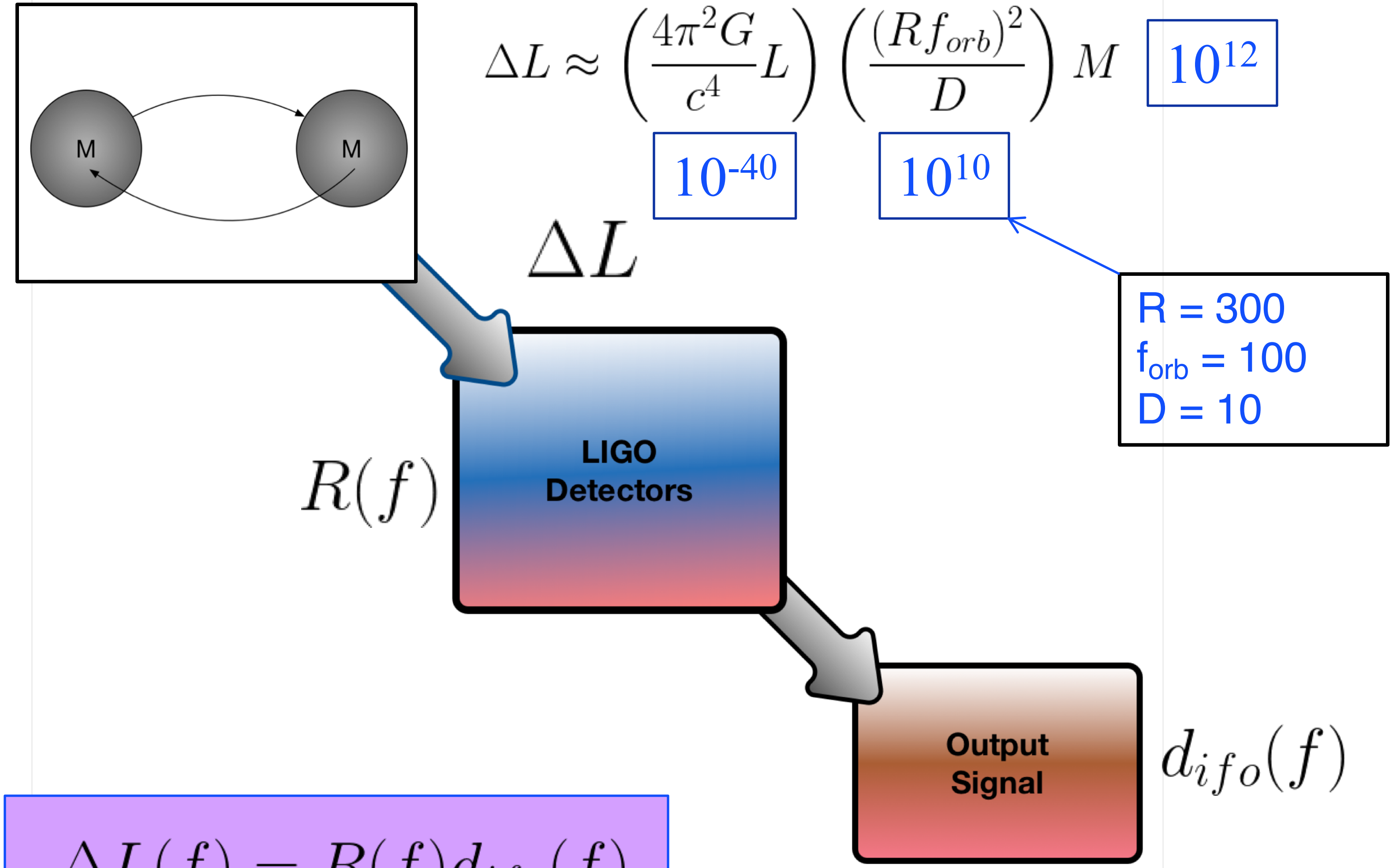
LIGO Detectors

Output Signal

$d_{ifo}(f)$

$$\Delta L(f) = R(f)d_{ifo}(f)$$

CALIBRATION
How can we calibrate?



$$\Delta L \approx \left(\frac{4\pi^2 G}{c^4} L\right)\left(\frac{(R f_{orb})^2}{D}\right) M$$

$\boxed{10^{-40}}$ $\boxed{10^{10}}$ $\boxed{10^{12}}$

$R = 300$
$f_{orb} = 100$
$D = 10$

ΔL

$R(f)$

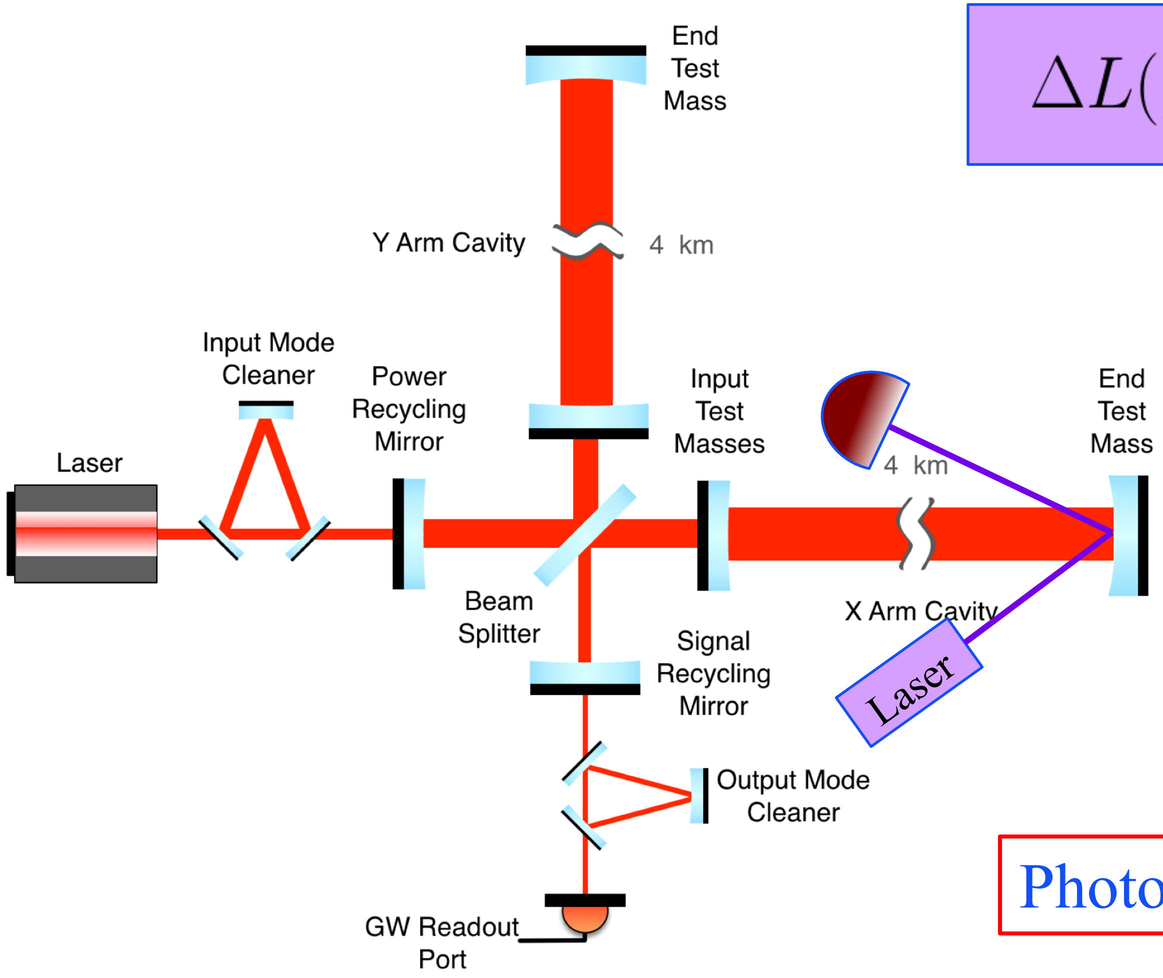
LIGO Detectors

Output Signal

$d_{ifo}(f)$

$$\Delta L(f) = R(f) d_{ifo}(f)$$

CALIBRATION
Using radiation pressure



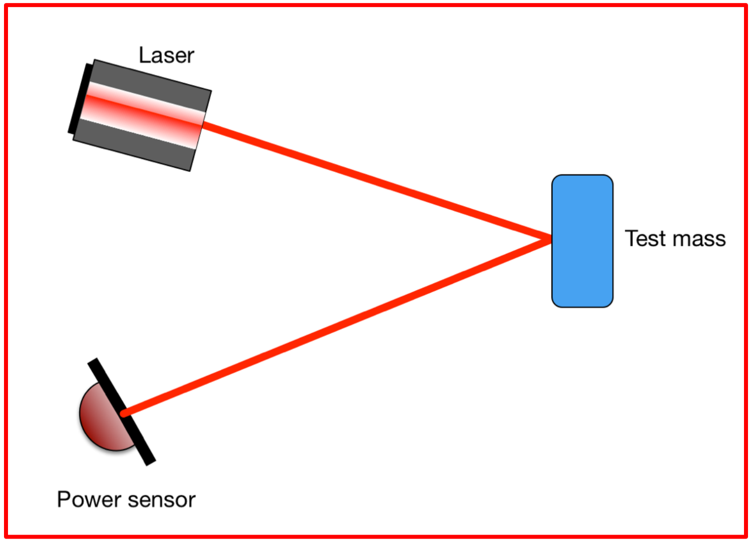
$$\Delta L(f) = R(f) d_{ifo}(f)$$

Photon calibrators (Pcals)

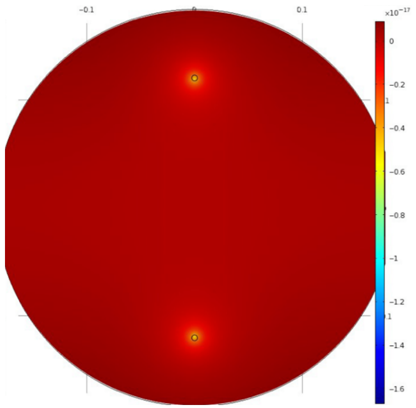
PHOTON CALIBRATORS

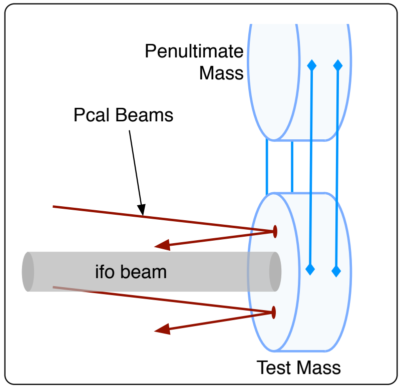
How we produce displacement fiducials at the level of 10^{-18} m with accuracy of better than 1%.

PHOTON CALIBRATORS
Working Principle

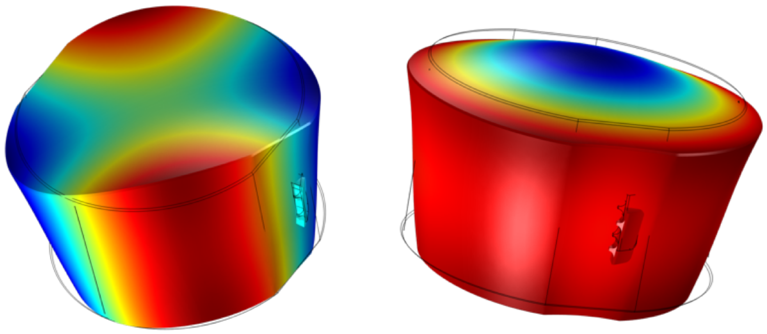


Local Elastic Deformation + Rotation



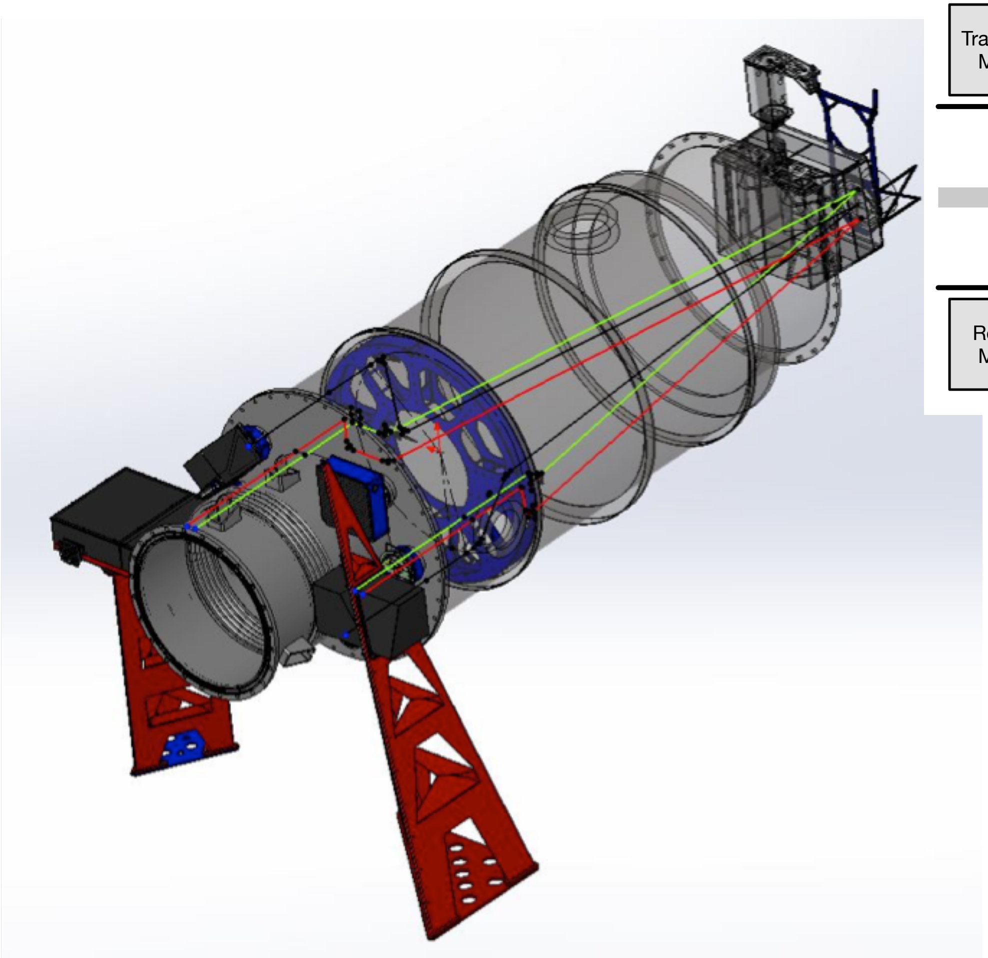


Bulk Elastic Deformation

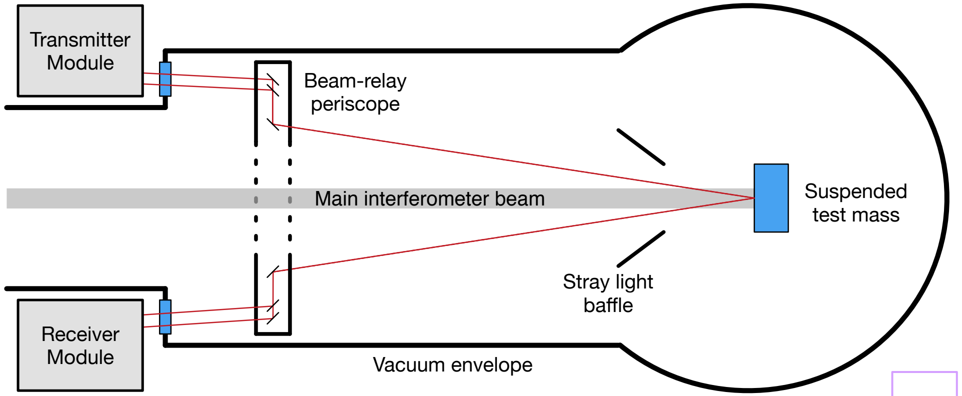


$$x(f) = -\frac{2\cos(\theta)}{Mc(2\pi f)^2}\, P(f)\, \mathcal{R}\, \mathcal{G}(f)$$

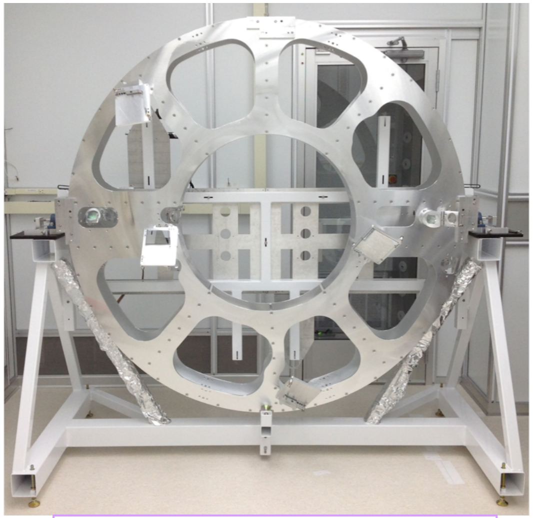
PHOTON CALIBRATORS
Hardware Configuration



Bird-eye view of the layout of Photon calibrator as installed.



Schematic Layout of Photon calibrator

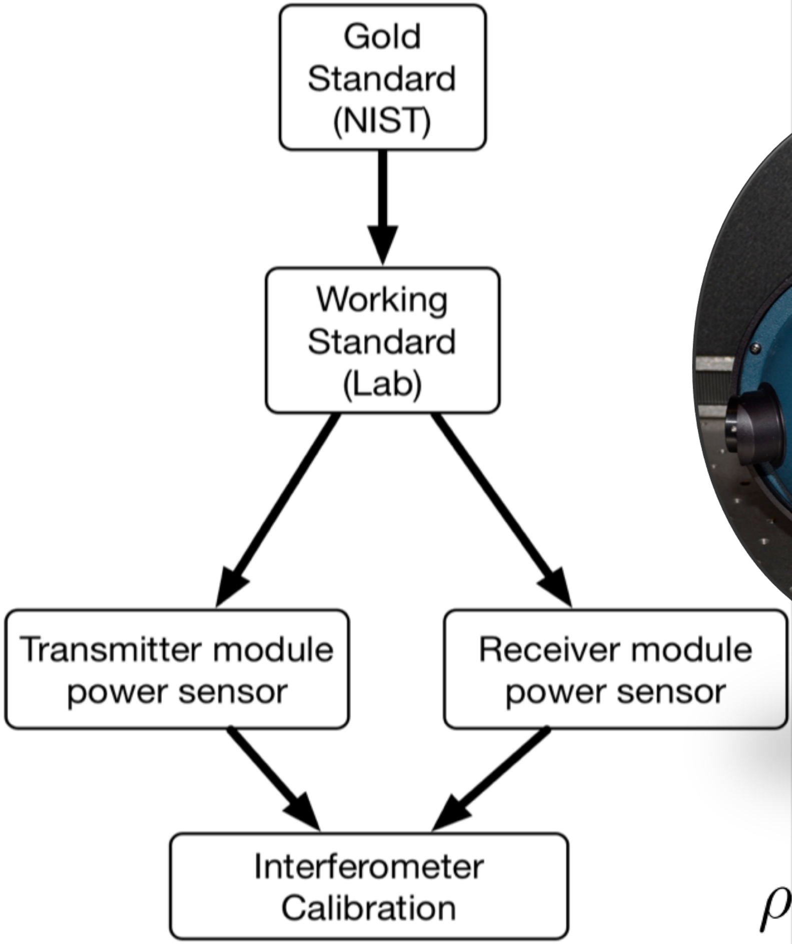


Pcal persicope structure

S.Karki, et al. Rev. Sci. Ins. 2016 87:11

POWER CALIBRATION
Calibration Transfer

$$x(f) = -\frac{2\cos(\theta)}{Mc(2\pi f)^2}\,P(f)$$


Gold Standard (NIST)

Working Standard (Lab)

Transmitter module power sensor

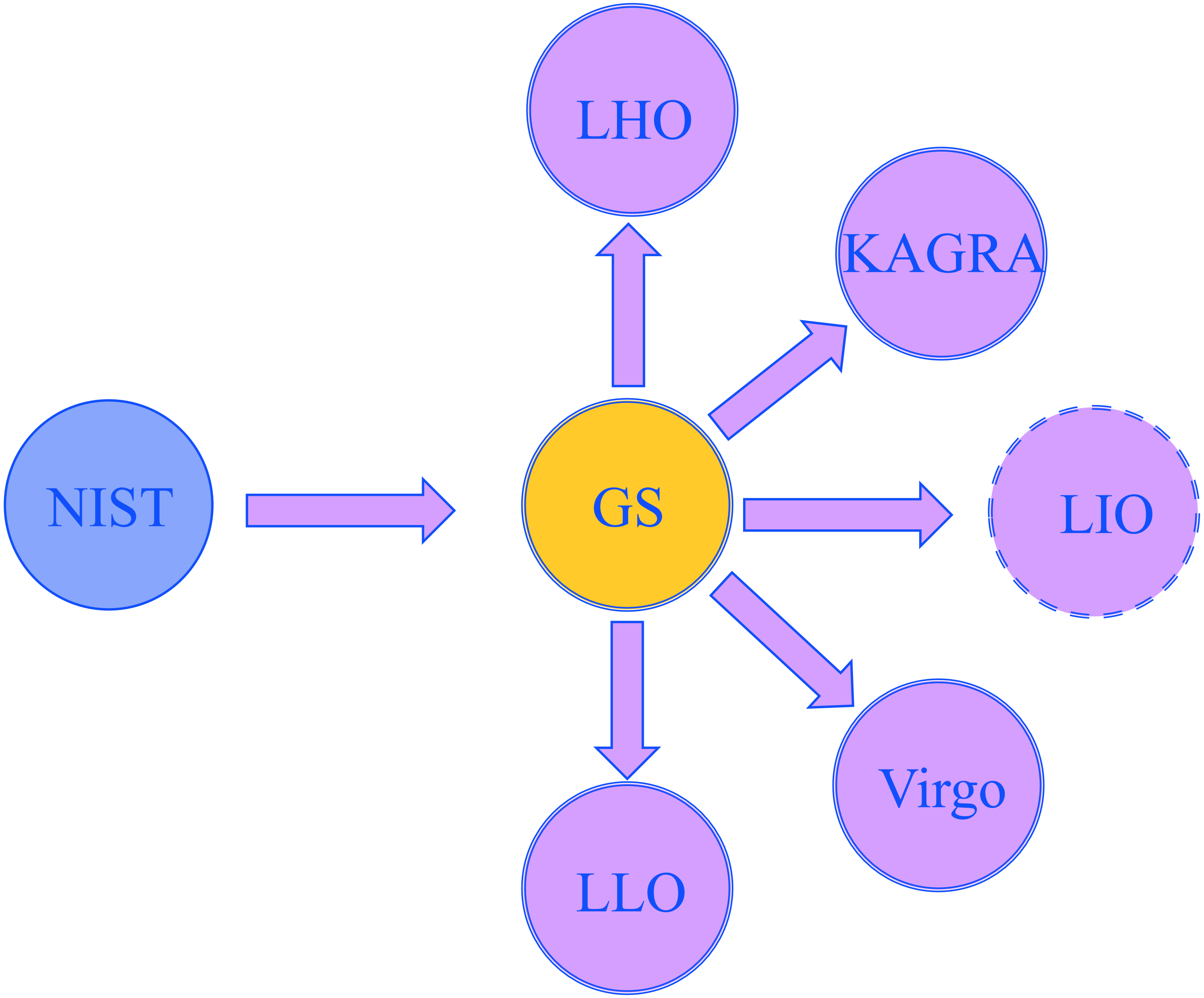
Receiver module power sensor

Interferometer Calibration

- Gold Standard (GS) calibrated at NIST
  - One single standard used for both LIGO detectors
- Working Standard (WS) calibrated against GS.
  - WS -> One for each detector
- Pcal power sensors (Tx and Rx) at each end station calibrated against WS.

$$\rho_R = \alpha_{RW} \times \alpha_{WG} \times \rho_G$$

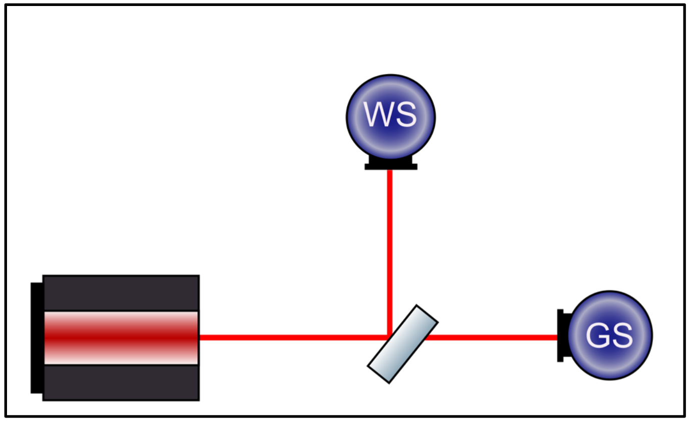
RELATIVE CALIBRATION
Sharing Gold Standard Calibration

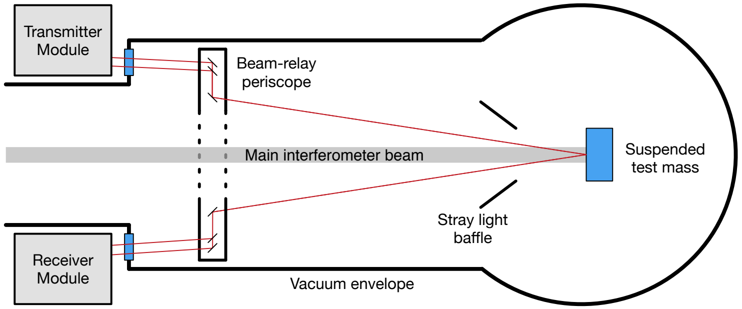


- KAGRA is already sending out its WS to be calibrated at LIGO.
- Just shipped WSV to Virgo after calibration.

POWER CALIBRATION
Uncertainty Budget (O1 and O2)

- Each NIST measurement has uncertainty of 0.44%.
- Calibration transfer measurement are well understood and the uncertainty associated with these measurements are at the level of 0.1%.





Uncertainty due to power loss

$$\frac{1.3\%}{2\sqrt{3}} \approx 0.37\%$$

Parameter	**Relative Uncertainty (O2)**
NIST -> GS $[\rho_{GS}]$	0.51 %
WS/GS $[\alpha_{WG}]$	0.03 %
Rx/WS $[\alpha_{RW}]$	0.05 %
Optical efficiency $[\mathcal{E}_T]$	0.37 %
Overall	**0.63 %**

CALIBRATION
Pcal Uncertainty Budget (O1 and O2)

$$x(f) = -\frac{2\cos(\theta)}{Mc(2\pi f)^2} P(f)\,\mathcal{R}$$

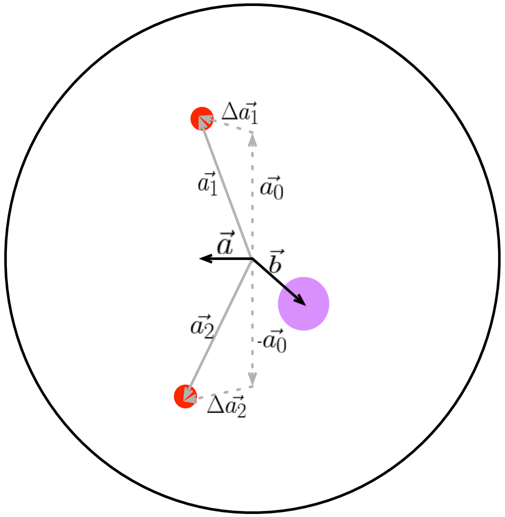
Parameter	Relative Uncertainty (O2)
NIST -> GS [ρ_{GS}]	0.51 %
WS/GS [α_{WG}]	0.03 %
Rx/WS [α_{RW}]	0.05 %
Optical efficiency [$\mathcal{E}_T$]	0.37 %
Angle of incidence [$\cos\theta$]	0.07 %
Mass of test mass [M]	0.005 %
Rotation [$\mathcal{R}$]	0.40 %
Overall	**0.75 %**

POWER CALIBRATION

S.Karki, et al. Rev. Sci. Ins. 2016 87:11

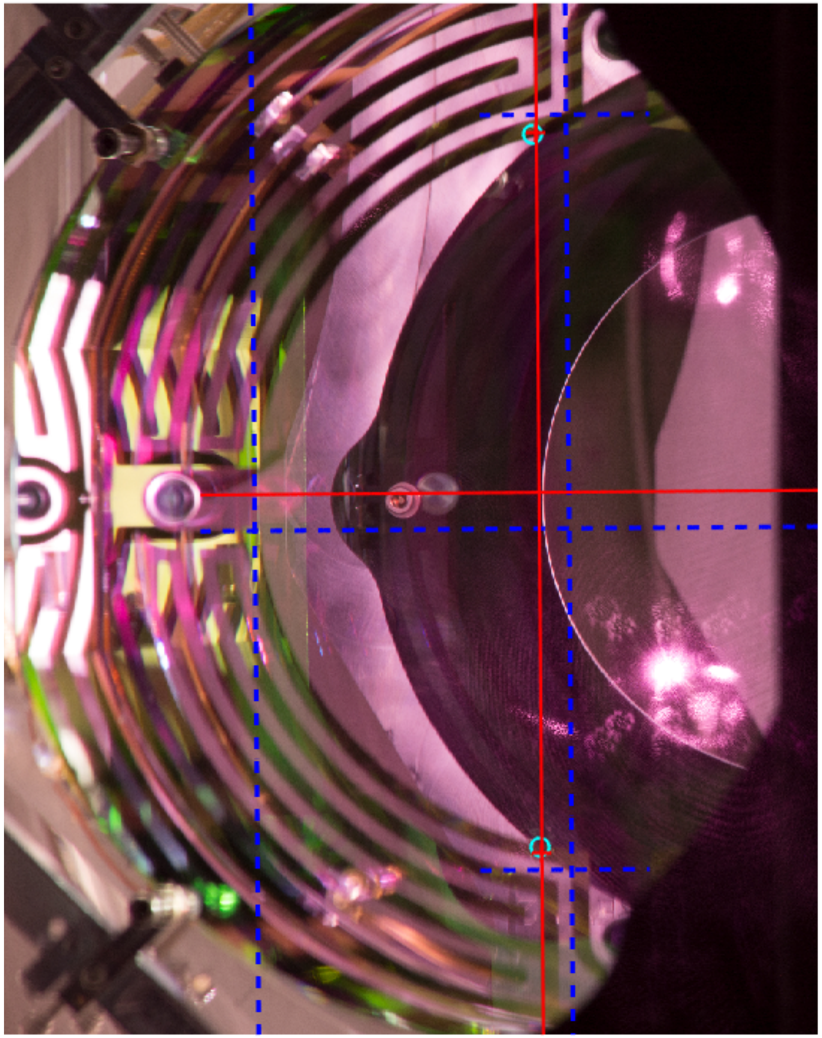
CALIBRATION
Error due to Rotation

- Unintended Rotational effect
  - Poor localization of the beams
  - Power imbalance between the beams



$$\vec{a} = \frac{\beta\vec{a}_1 + \vec{a}_2}{\beta + 1}$$

$$\boxed{\mathcal{R}(a,b) = \left[1 + \frac{M}{I}\vec{a}\cdot\vec{b}\right]}$$



CALIBRATION
Pcal Uncertainty Budget (O1 and O2)

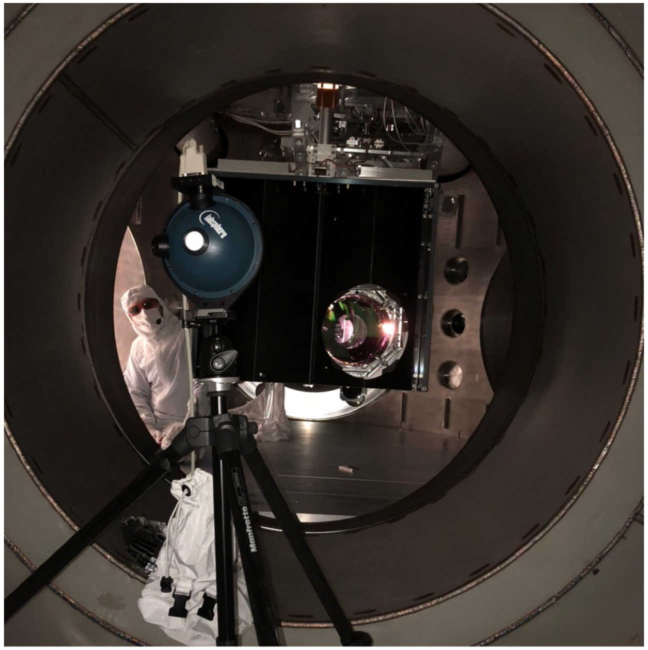
Parameter	**Rel. Uncertainty(O2)**
NIST -> GS [ρ_{GS}]	0.51 %
WS/GS [α_{WG}]	0.03 %
Rx/WS [α'_{RW}]	0.05 %
Optical efficiency [$\mathcal{E}_T$]	0.37 %
Angle of incidence [$\cos\theta$]	0.07 %
Mass of test mass [M]	0.005 %
Rotation [$(\vec{a}\cdot\vec{b})M/I$]	0.40 %
Overall	**0.75 %**

S.Karki, et al. Rev. Sci. Ins. 2016 87:11

This is the accuracy of calibration on the displacement fiducials.

CALIBRATION
Improvements over O2

Optical Efficiency



- In vacuum measurements at all 4 end stations
  - Allows us to apportion the losses between the input and output path

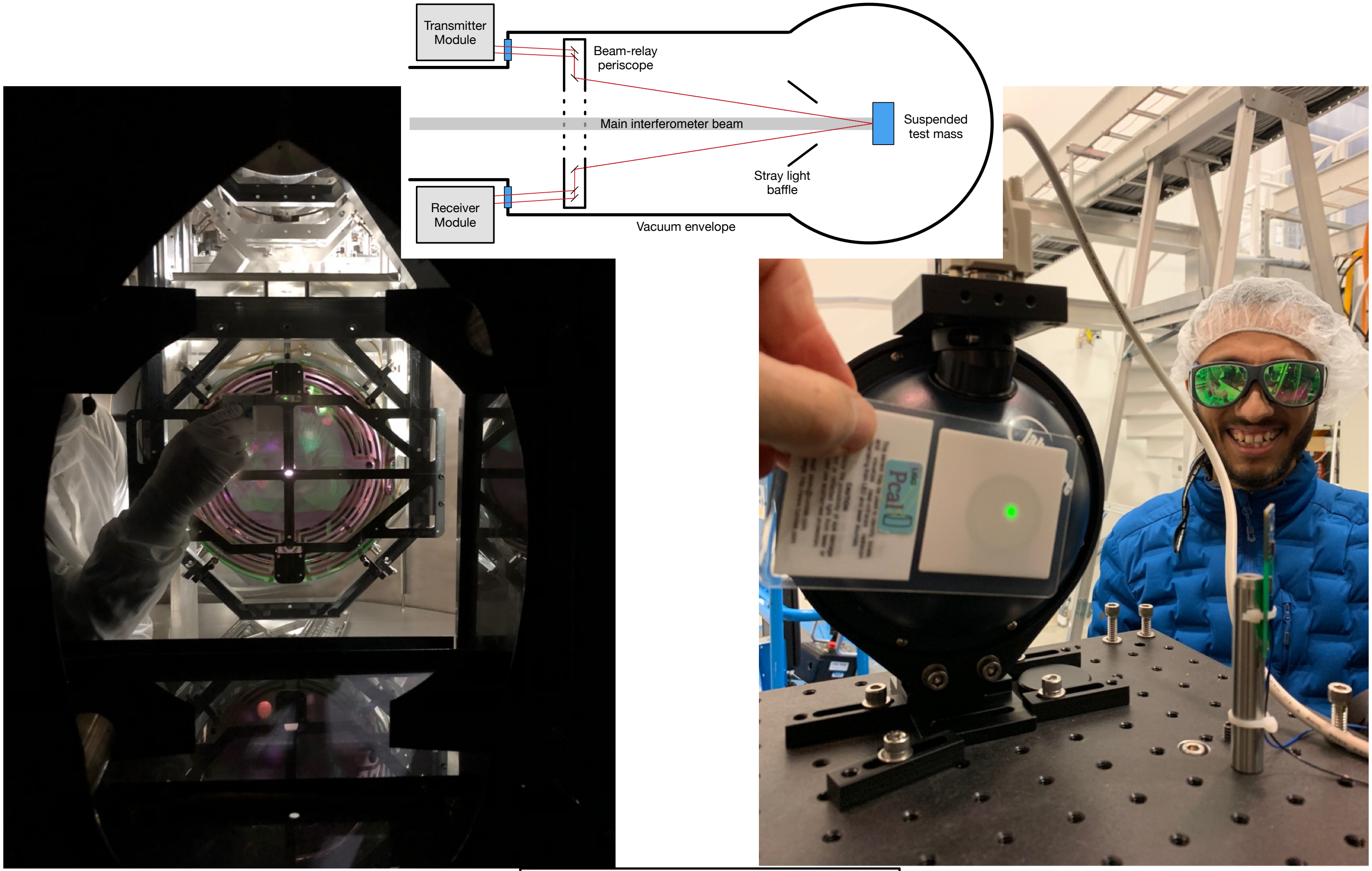
0.37% ➔ 0.10%

NIST Calibration Uncertainty

- NIST carried out additional measurements.

0.44%➔ 0.31%

CALIBRATION
Improvements over O2



0.40%➔ 0.10%

CALIBRATION
Expected Pcal Uncertainty (O3)

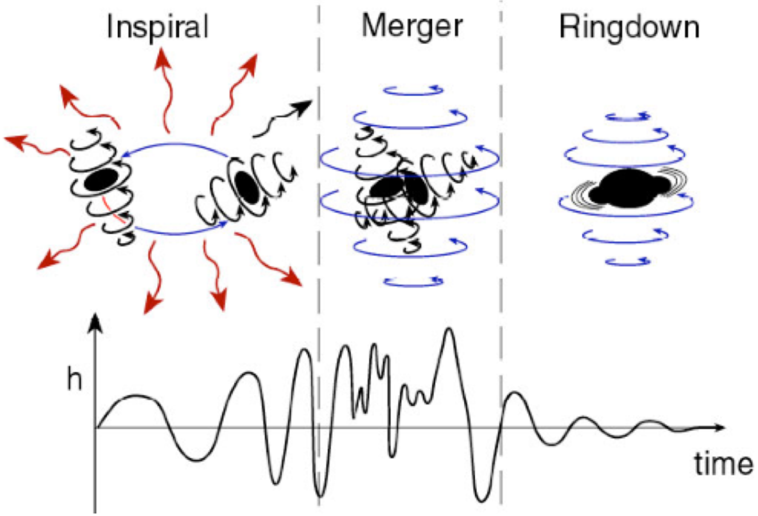
Parameter	**Relative Uncertainty (Expected O3)**
NIST -> GS [ρ_{GS}]	0.31 %
WS/GS [α_{WG}]	0.03 %
Rx/WS [α'_{RW}]	0.05 %
Optical efficiency [$\mathcal{E}_T$]	0.10 %
Angle of incidence [$\cos\theta$]	0.07 %
Mass of test mass [M]	0.005 %
Rotation [$(\vec{a}\cdot\vec{b})M/I$]	0.10 %
Overall	**0.35 %**

Calibration at High Frequencies

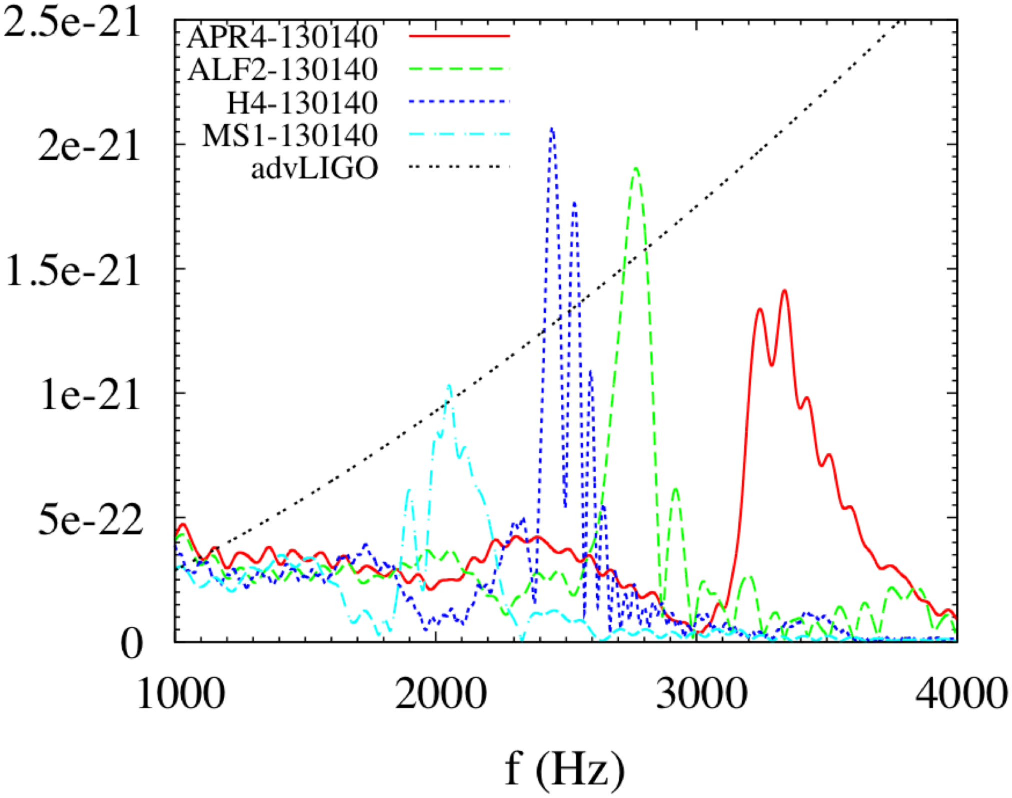
Challenges that arise when calibrating at frequencies near and above 1 kHz.

CALIBRATION AT HIGHER FREQUENCIES
Motivation

- Millisecond pulsars
- Compact Binary merger and ringdown.
- Post merger binary neutron star.



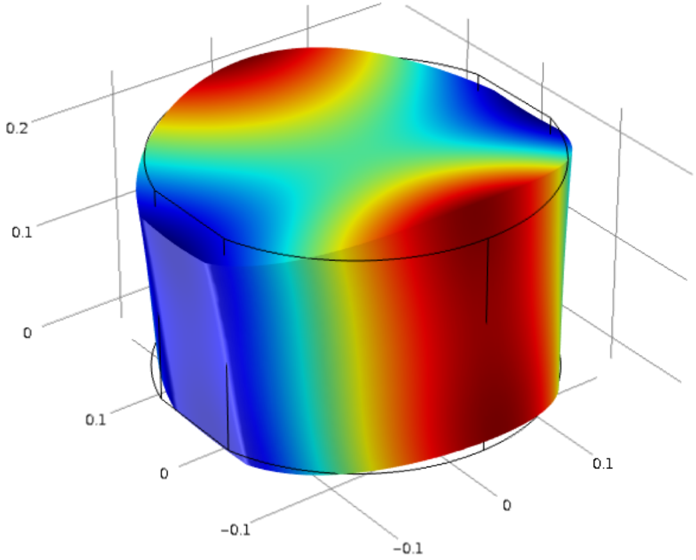
Credit: K. Thorne



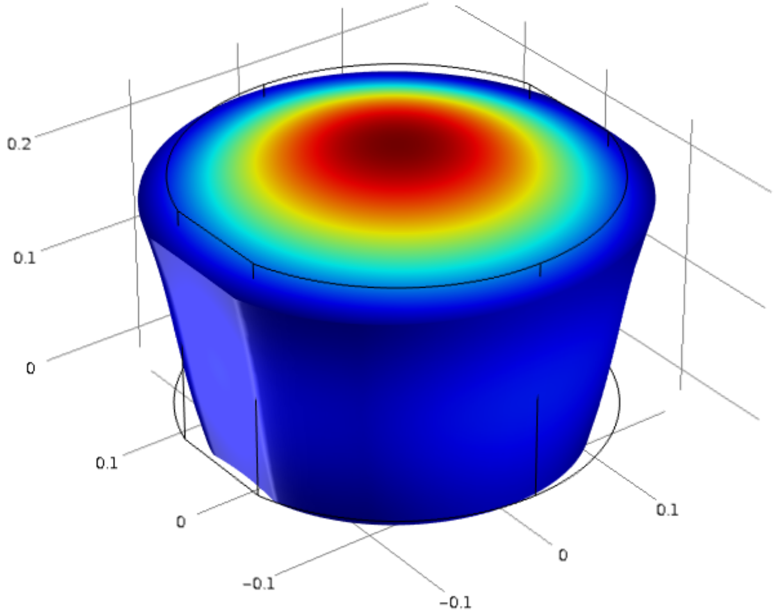
Physical Review D, vol. 87, Issue 2

CALIBRATION AT HIGHER FREQUENCIES

Bulk Elastic Deformation



Butterfly Mode
5953 Hz

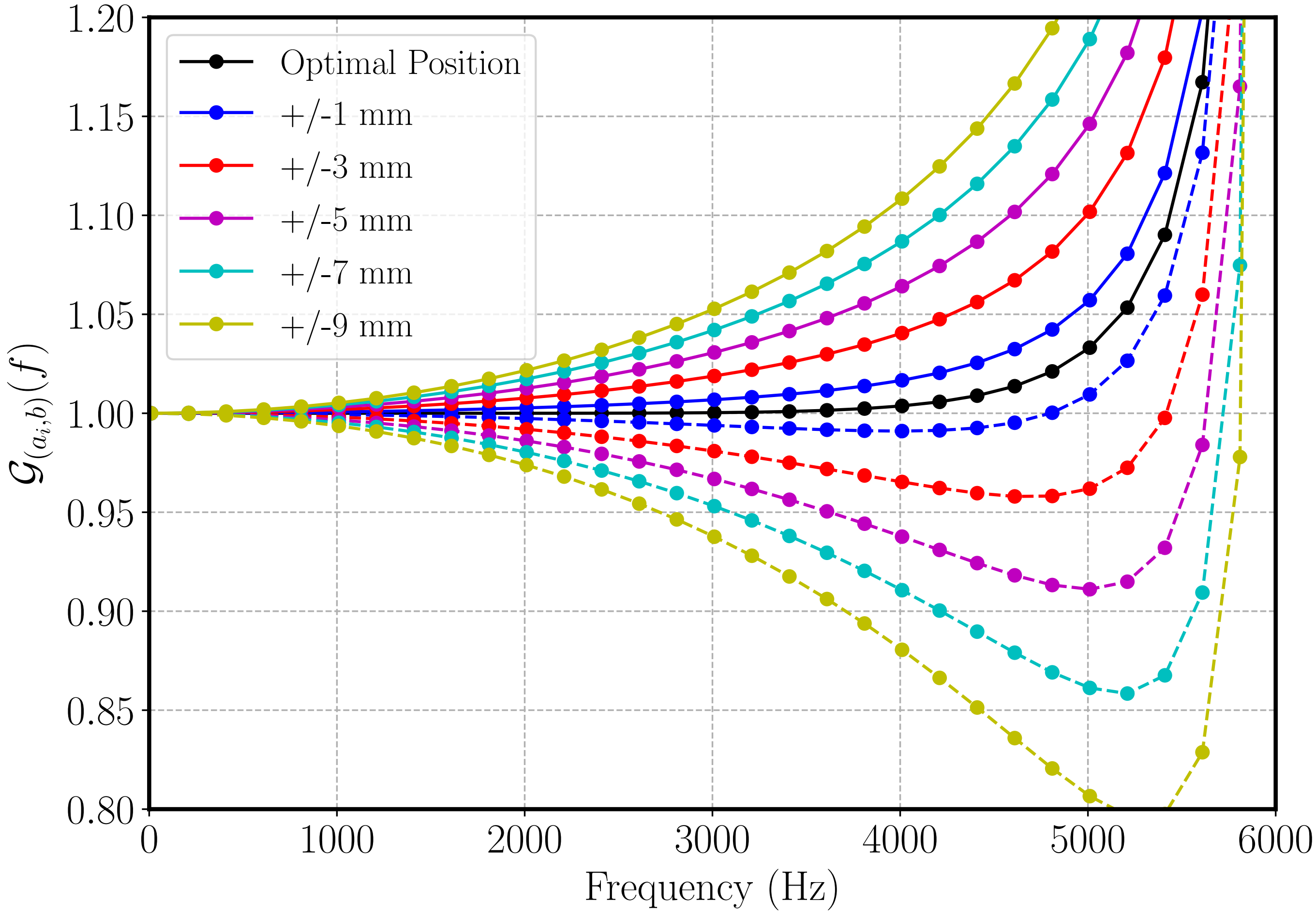


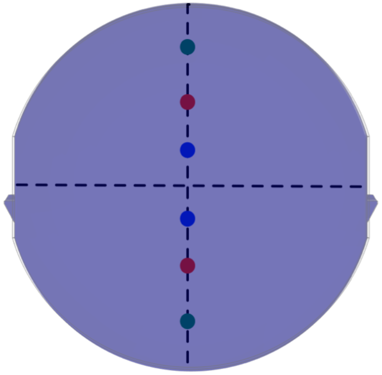
Drumhead Mode
8151 Hz

ETM motion deviates from their rigid body approximation due to the excitation of the natural modes by applied forces

$$x(f) = -\frac{2\cos(\theta)}{Mc(2\pi f)^2}\, P(f)\, \mathcal{R}\mathcal{G}(f)$$

CALIBRATION AT HIGHER FREQUENCIES
FEA (COMSOL) Results



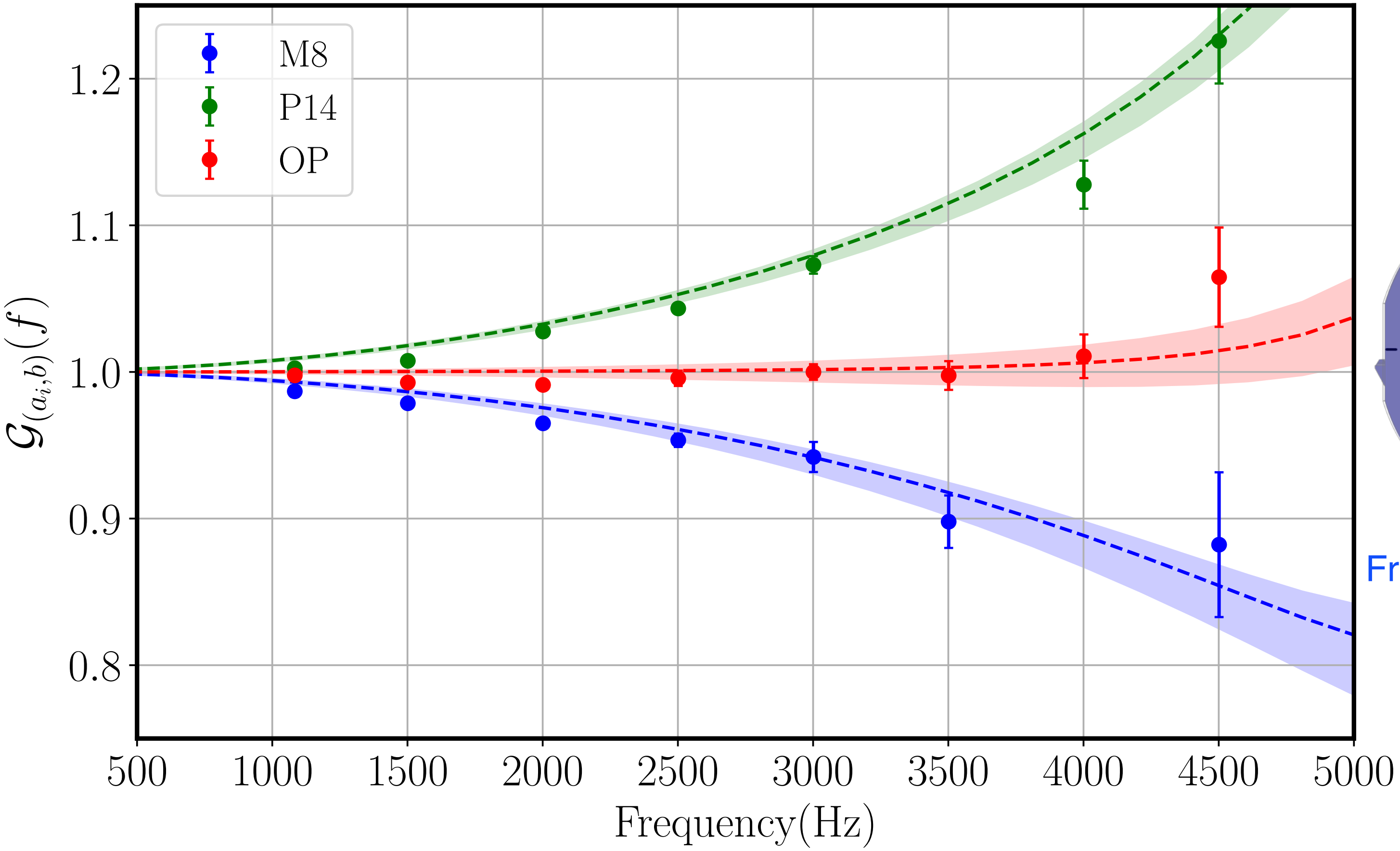


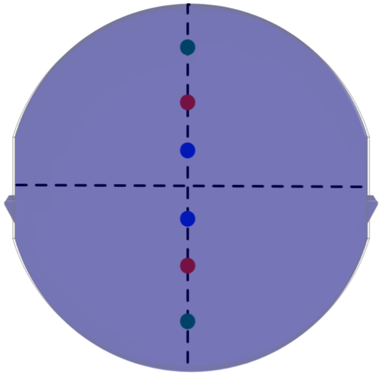
Front face of the test mass

CALIBRATION AT HIGHER FREQUENCIES

Experimental Results

Experimental confirmation of the results estimated from FEA.





Front face of the test mass

Enable better calibration at high frequencies.

SUMMARY
Advanced LIGO Pcals

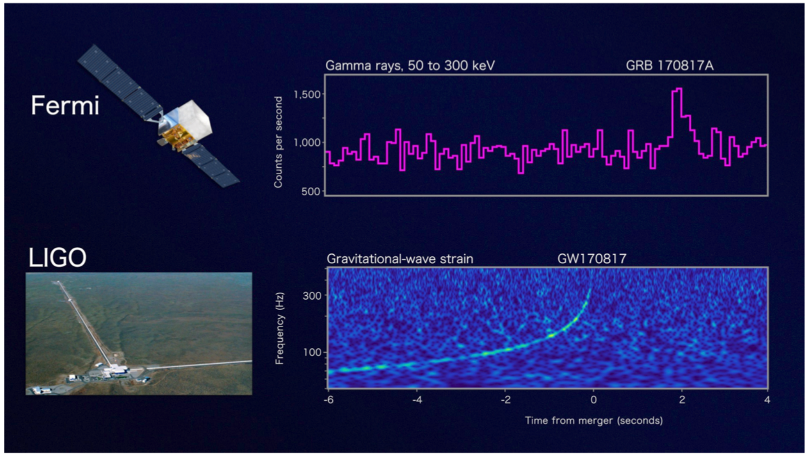
- aLIGO Photon calibrators have achieved the ability to introduce fiducial displacements with accuracies better than 1%.
  - » This enables calibration of the interferometers at 1% level required to maximize scientific benefit.

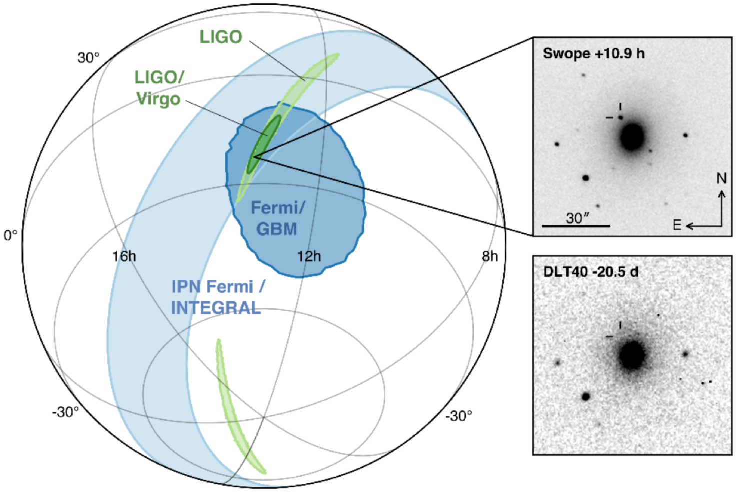
- Bulk elastic deformation due to calibration forces at higher frequencies, estimated using finite element analysis, has been confirmed experimentally.
  - » Compensating for this effect is possible but will be challenging.

OUTLOOK

Hubble Parameter with improved calibration

GW170817: Binary neutron star merger



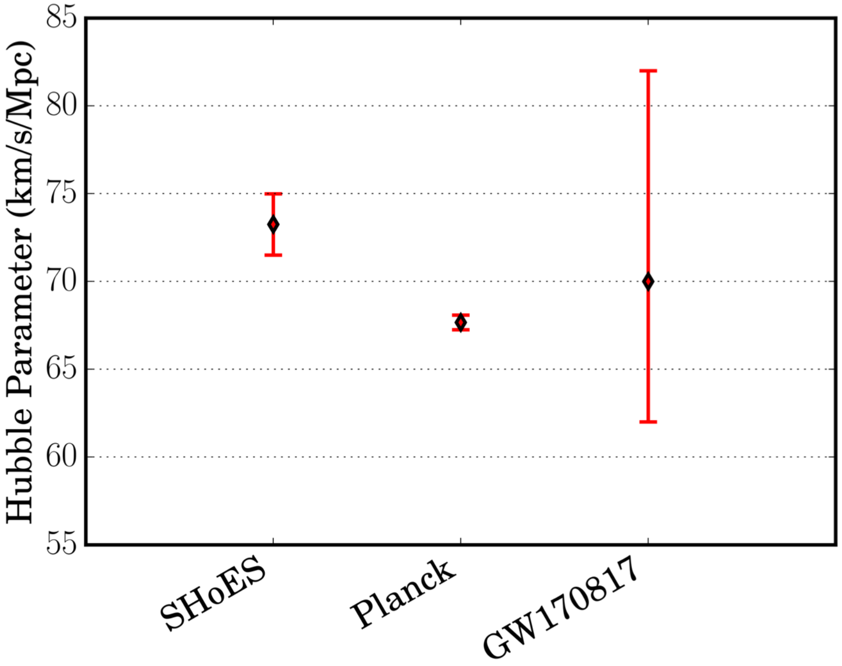


Measurement of Hubble parameter

$$v_H = H_0 d$$

Redshift
EM signal

Distance
GW signal



OUTLOOK
Pushing the Envelope

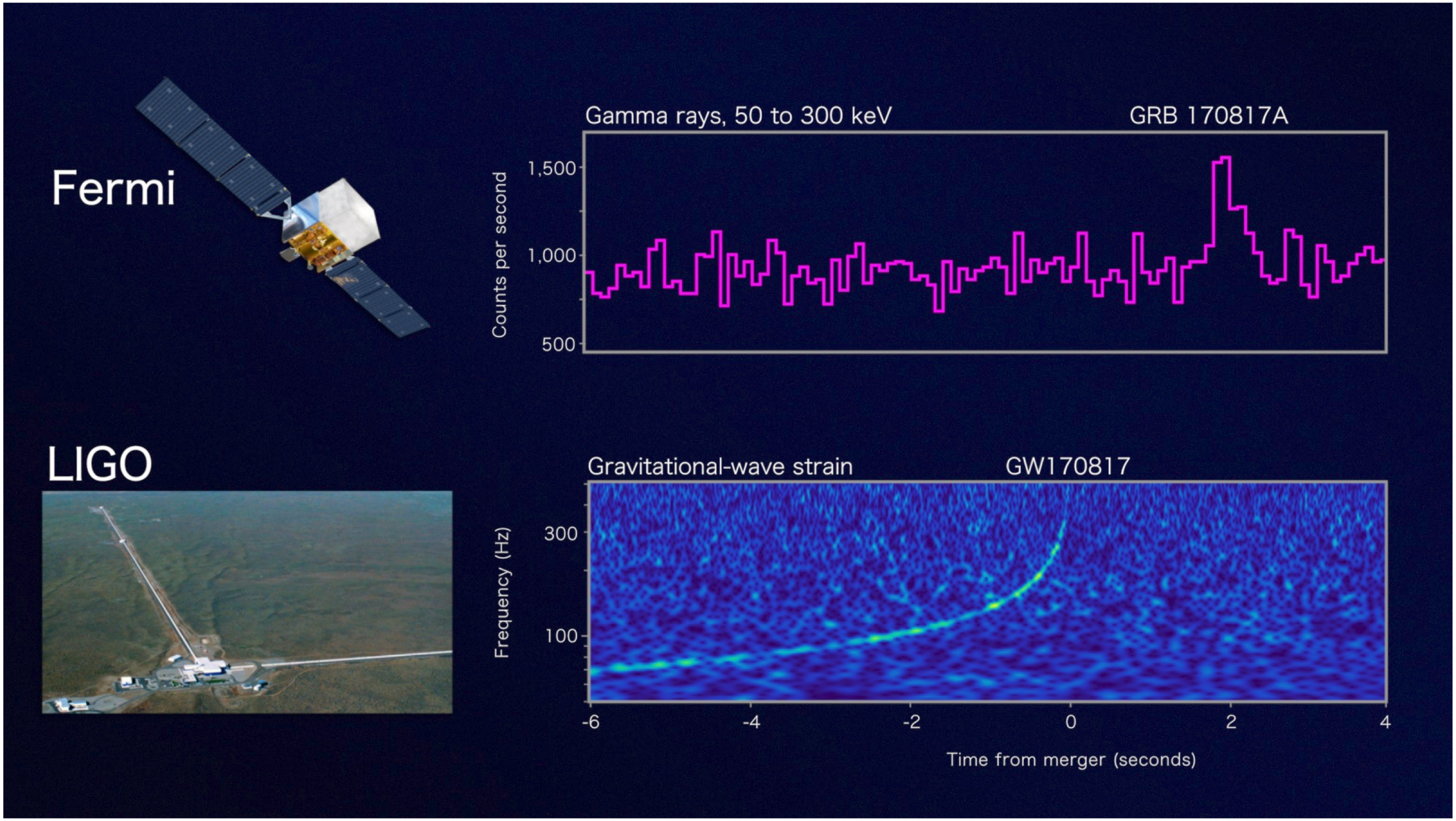
GW (Gravitational Wave) Metrology Workshop
March 14, 15, 2019
NIST, Boulder, Colorado, USA

- 30 min. LIGO Photon Calibrators and global GW network calibration - Sudarshan Karki (Univ. Oregon)

Justification and Purpose: The purpose of the Workshop is to bring together researchers and metrologists in scientific areas related to the observation of gravitational waves by interferometry. The primary interest of the metrology is laser-detector measurements and related optics. The goal of the workshop is twofold: (1) to improve the ability of gravitational wave observatories to identify events, and (2) to improve our ability to extract source parameters such as the distance from Earth from the gravitational wave signals.

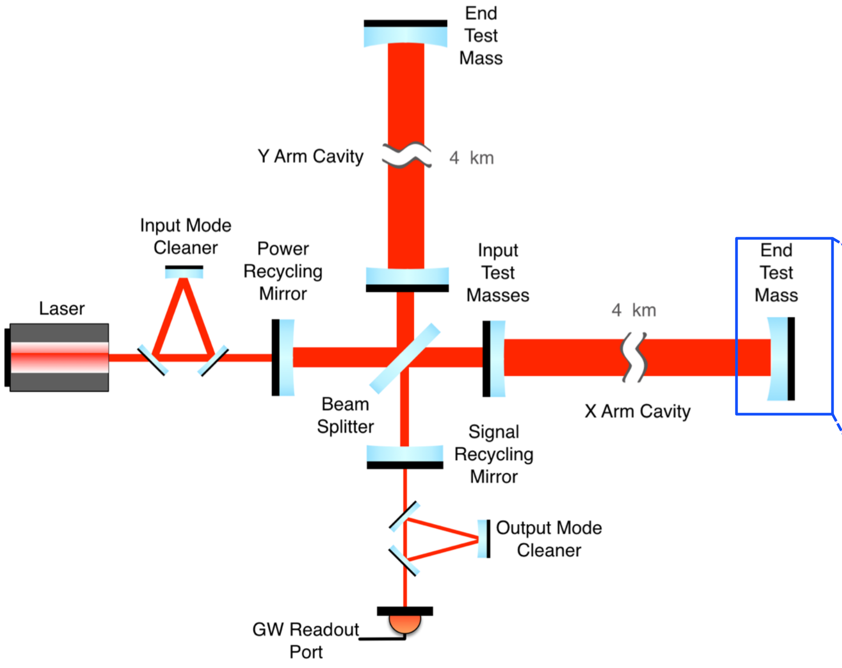
EXTRA SLIDES

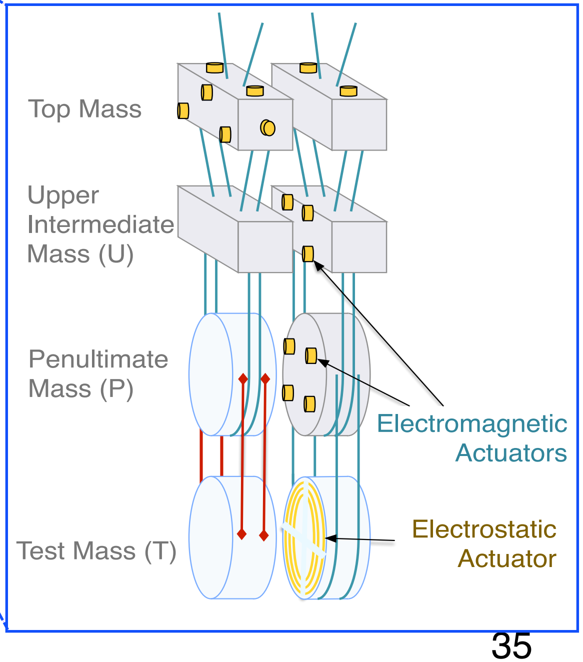
GW170817: BINARY NS
Multi-messenger Astronomy



Advanced LIGO
Test mass Pendulum

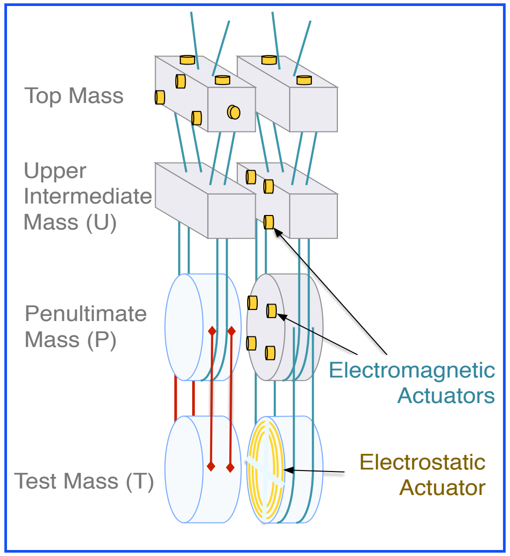
- Four stage (quadruple) pendulum.
- Reduces the effect of seismic noise.



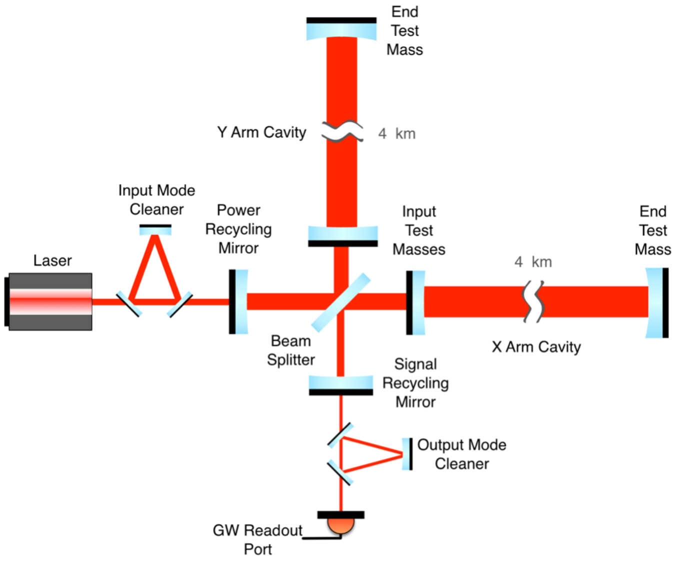


CALIBRATION
Actuation and Sensing Function

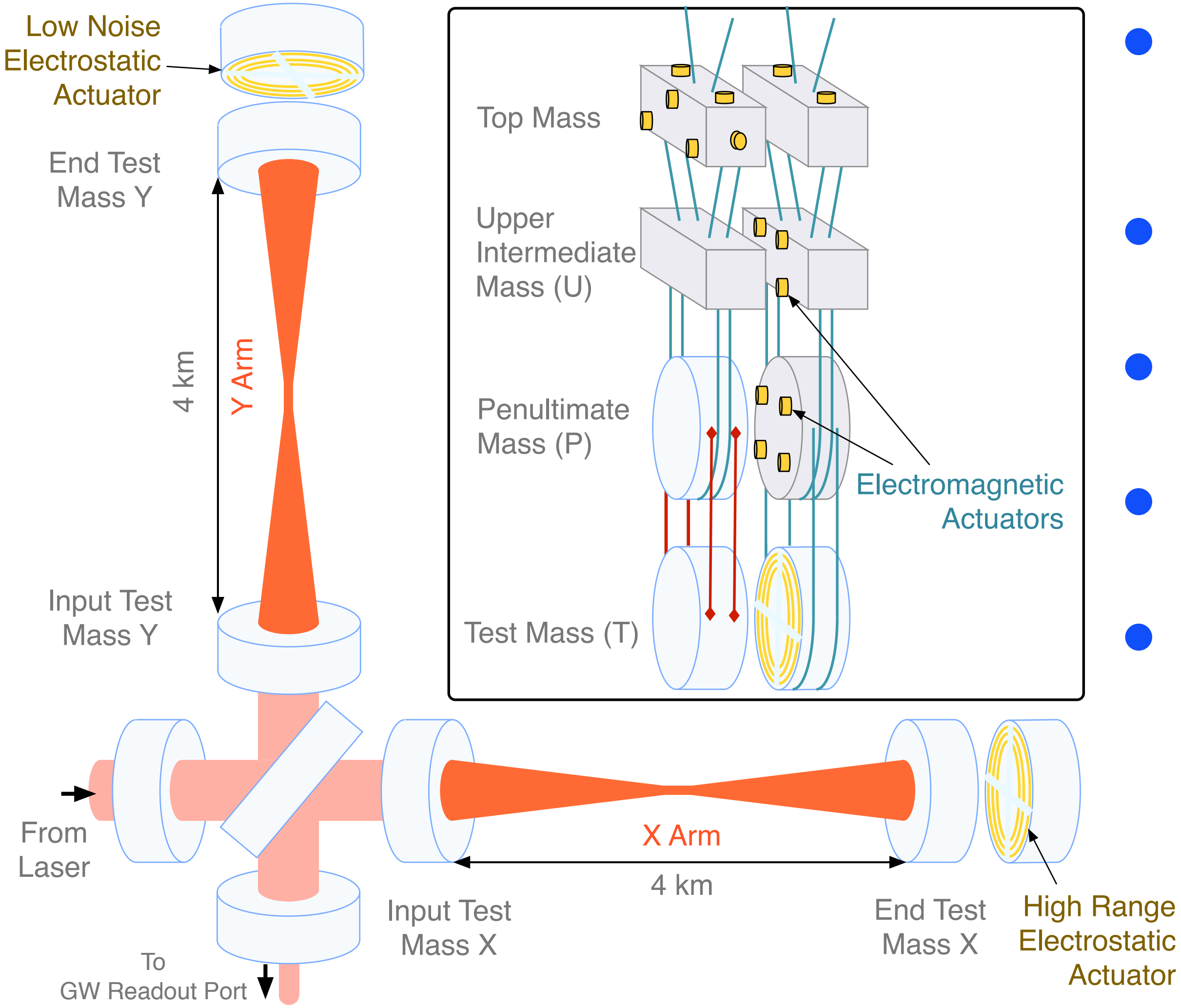
- Actuation Function (A)
  - LIGO suspension response to the requested drive
  - consists of mechanical response of the suspended test mass, time delay and effects of drive electronics transfer functions.



- Sensing function (C)
  - interferometer response to the differential arm displacement
  - includes IFO Cavity response and detector photodiodes and electronics.

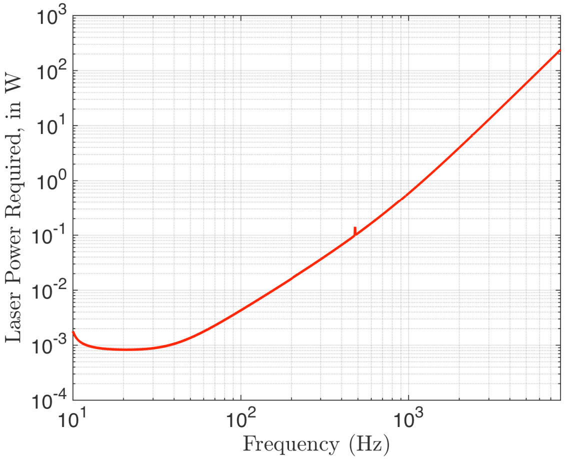


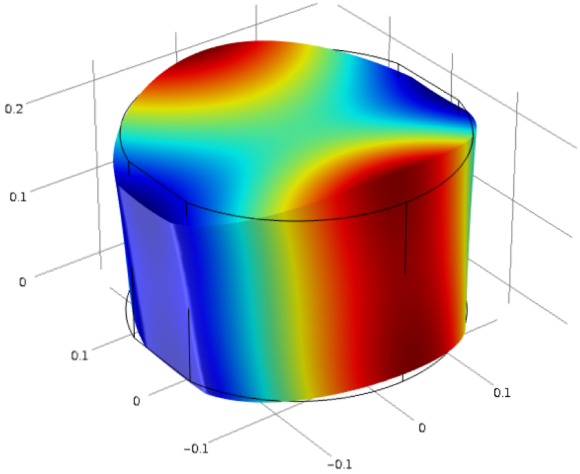
LIGO
Detection Technique

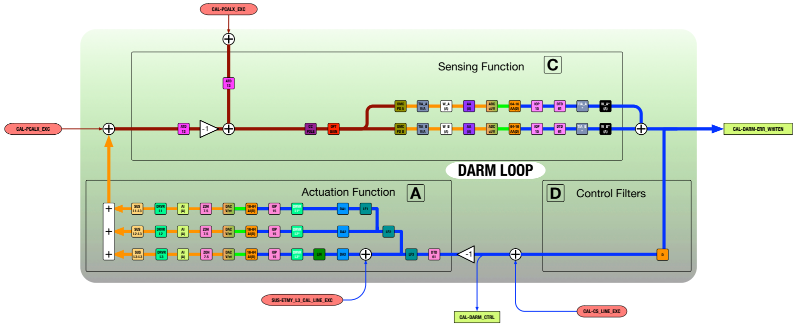


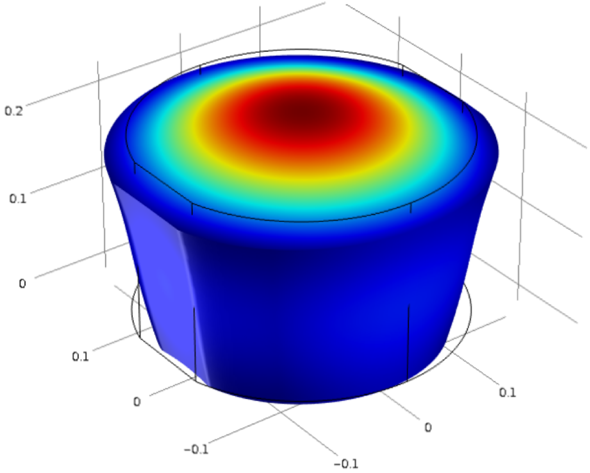
- Modified Michelson Interferometer
- Fabry-Perot Cavities
- Power Recycling
- Signal Recycling
- Suspended Quadruple Pendulum

CALIBRATION AT HIGHER FREQUENCIES
Challenges









$$\mathcal{G}_{(a_i;b)}(f)$$

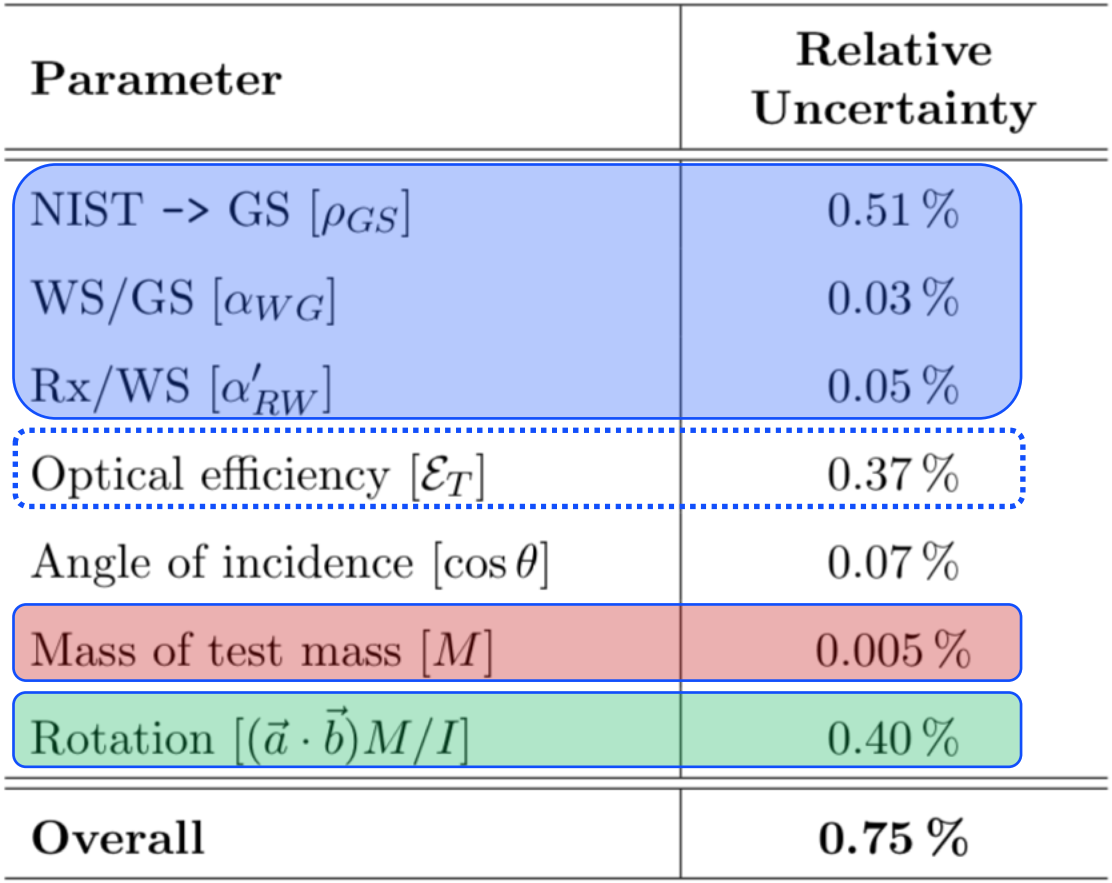
PCAL UNCERTAINTY BUDGET
O2 (through 2017)

Parameter	**Relative Uncertainty**
NIST -> GS [ρ_{GS}]	0.51 %
WS/GS [α_{WG}]	0.03 %
Rx/WS [α'_{RW}]	0.05 %
Optical efficiency [$\mathcal{E}_T$]	0.37 %
Angle of incidence [$\cos\theta$]	0.07 %
Mass of test mass [M]	0.005 %
Rotation [$(\vec{a}\cdot\vec{b})M/I$]	0.40 %
Overall	**0.75 %**

- Laser Power Calibration

- Suspension TF
- Rotation effect

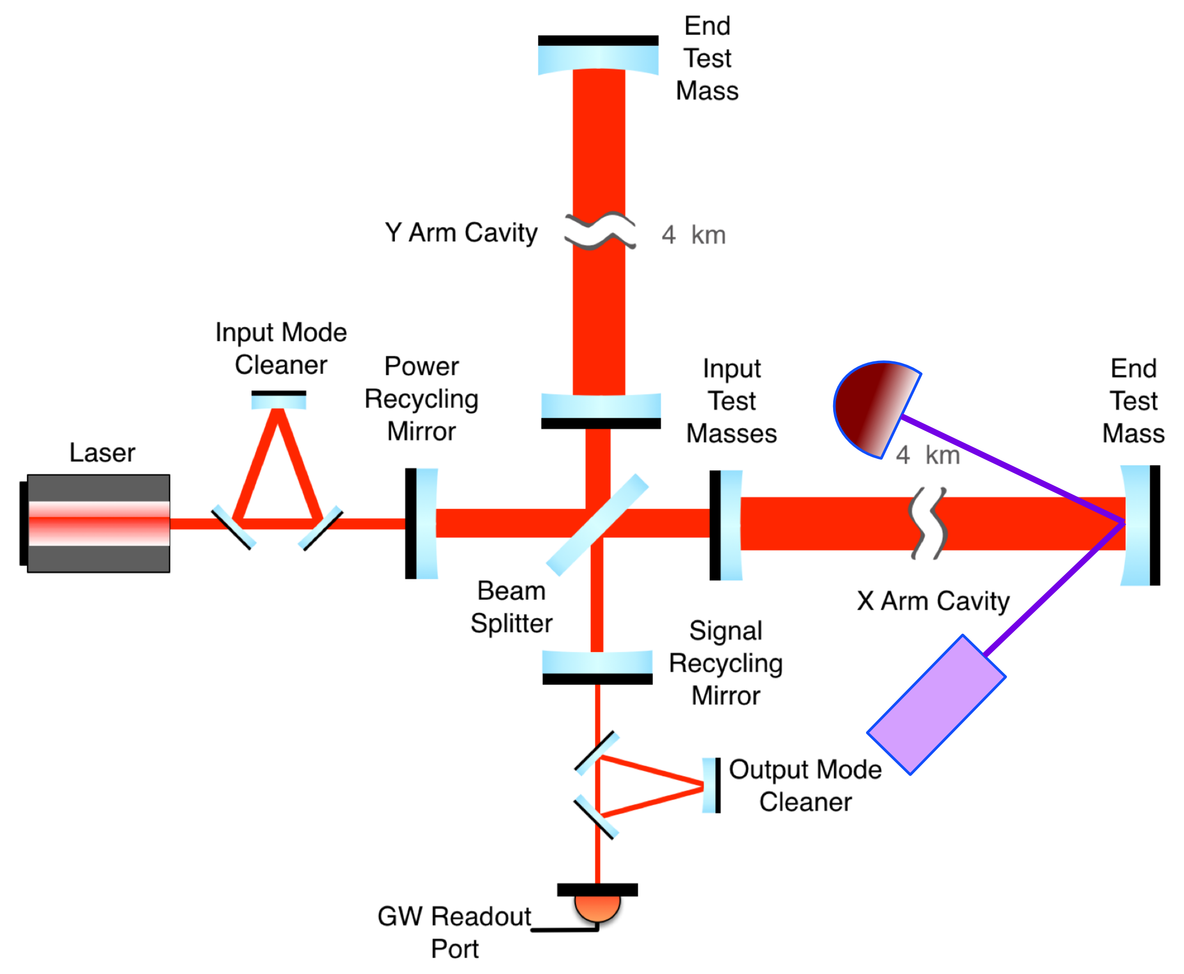
PCAL UNCERTAINTY BUDGET
O2 (through 2017)



Parameter	Relative Uncertainty
NIST -> GS [ρ_{GS}]	0.51 %
WS/GS [α_{WG}]	0.03 %
Rx/WS [α'_{RW}]	0.05 %
Optical efficiency [$\mathcal{E}_T$]	0.37 %
Angle of incidence [$\cos\theta$]	0.07 %
Mass of test mass [M]	0.005 %
Rotation [$(\vec{a}\cdot\vec{b})M/I$]	0.40 %
Overall	**0.75 %**

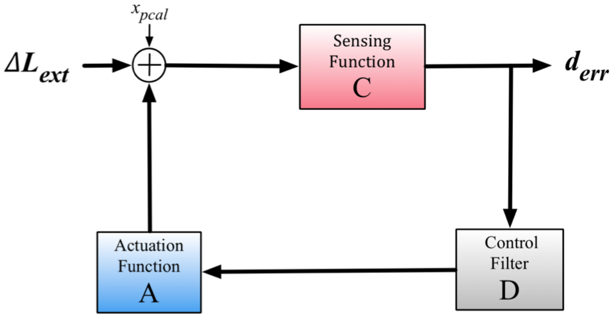
- Laser Power Calibration
  - Dominated by NIST GS calibration
  - Uncertainty due to optical efficiency can be reduced by making in-vacuum measurements.
  - This has been done at one of the site and the uncertainty can be improved by a factor by 5.
- Suspension TF
  - We know suspension transfer with greater accuracy.
- Rotation effect
  - Preliminary numbers from worst estimate.
  - We can reduce this significantly for future observing runs.

CALIBRATION
Using radiation pressure



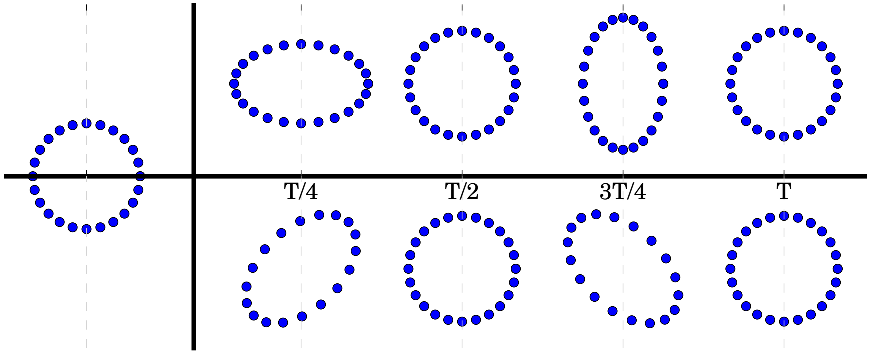
$$F = \frac{dp}{dt} = m\ddot{x}$$

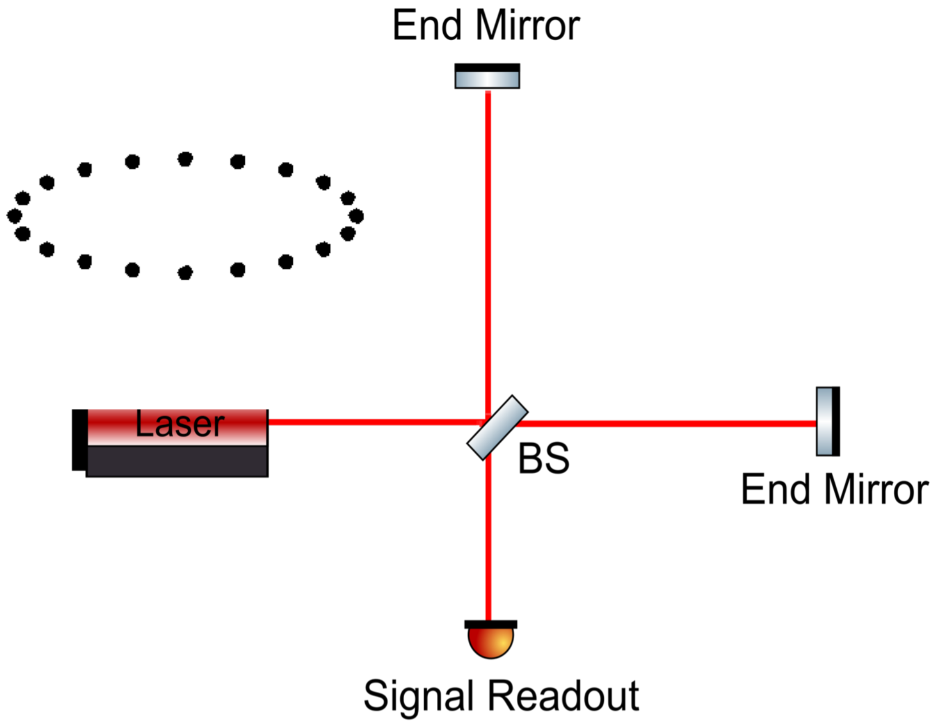
$$\frac{dp}{dt} = \frac{2\cos\theta}{c}P$$



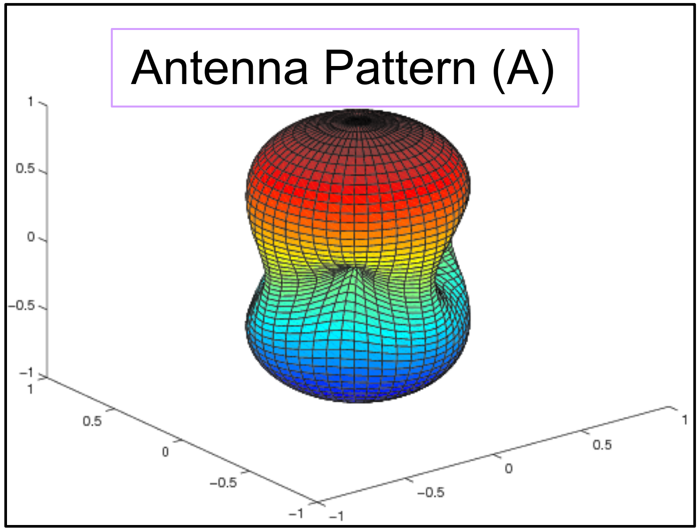
$$R(f) = \left(\frac{1 + A(f)D(f)C(f)}{C(f)}\right)$$

LIGO
Gravitational Waves and Interferometer





$$h = h_{GW} \times A$$


Antenna Pattern (A)

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$$\Delta L = \underset{\boxed{10^{-21}}}{h} \times \underset{\boxed{10^{3}}}{L}$$

$$\Delta L = \boxed{10^{-18}\text{ m}}$$