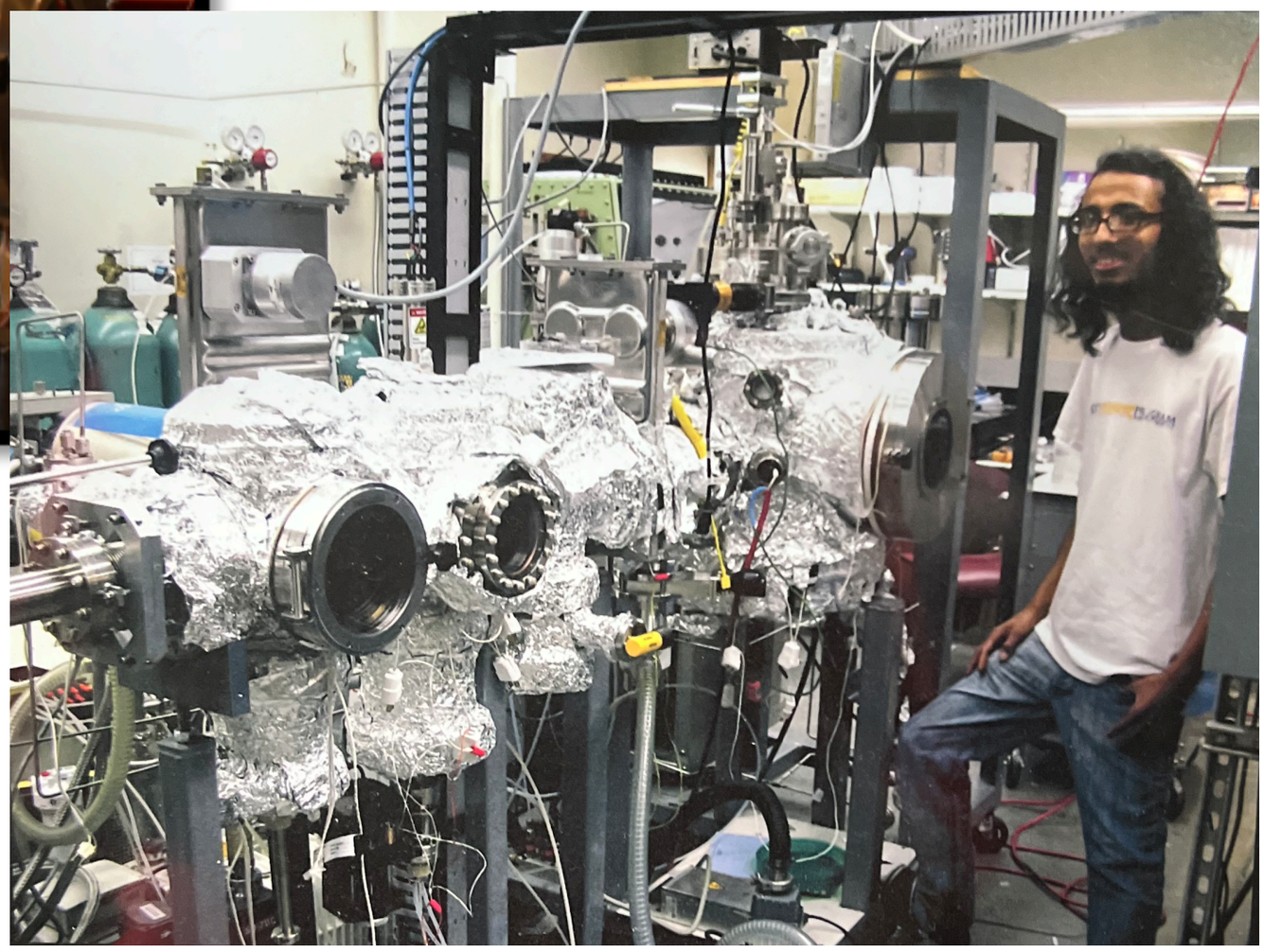
Pcals to Portland

My Journey with LIGO

Previous Life







The electronic and chemical structure of the a-B3CO0.5:Hy-to-metal interface from photoemission spectroscopy: implications for Schottky barrier heights

M Sky Driver [1], Michelle M Paquette, S Karki, B J Nordell, A N Caruso

(2008-2012)

Grad School





UNIVERSITY OF OREGON

First two years











Graduate classes and mountains

How LIGO?

Summer 2014



LIGO Fellow

Graduate Student

(2014-2019)

At First

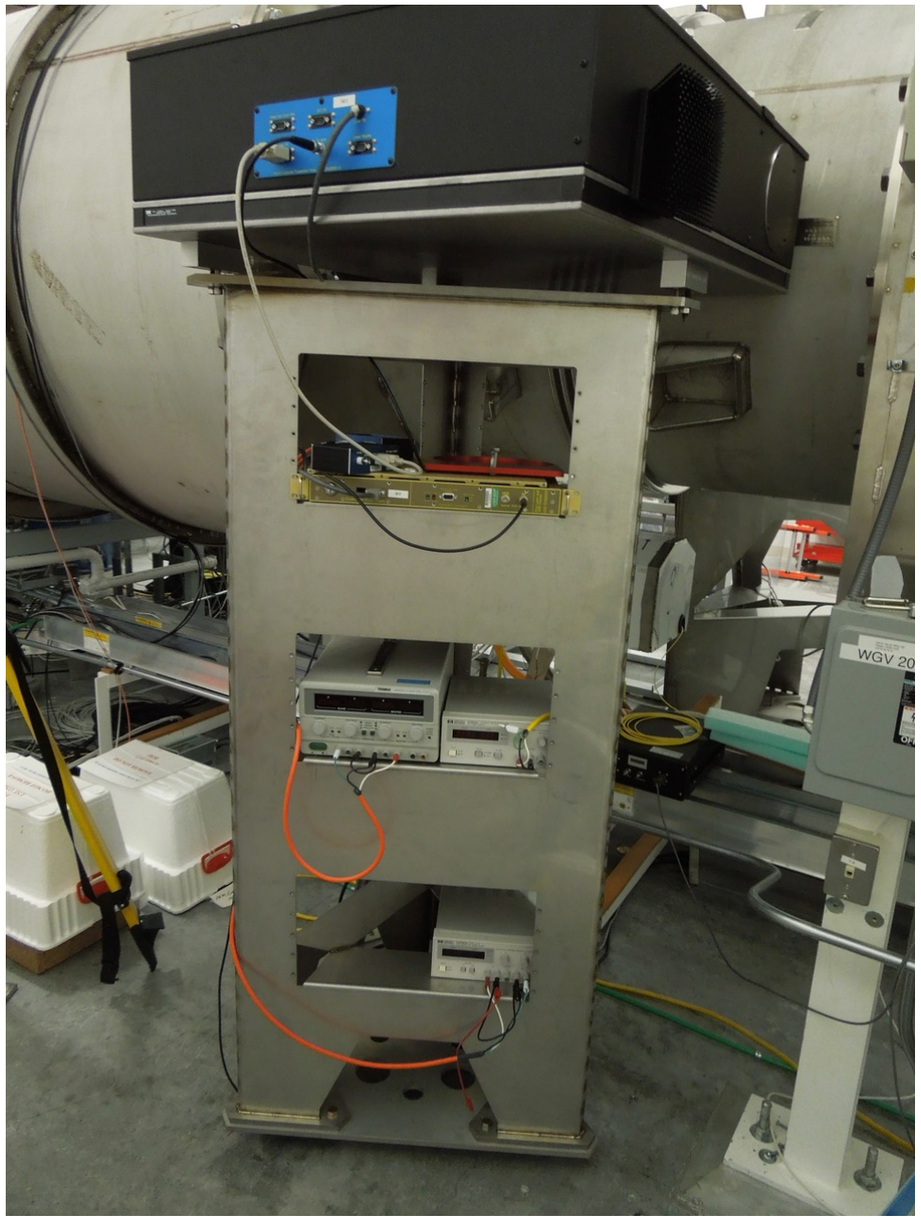
PEM WORK



Photon Calibrators

Install/Commission

LHO



LLO

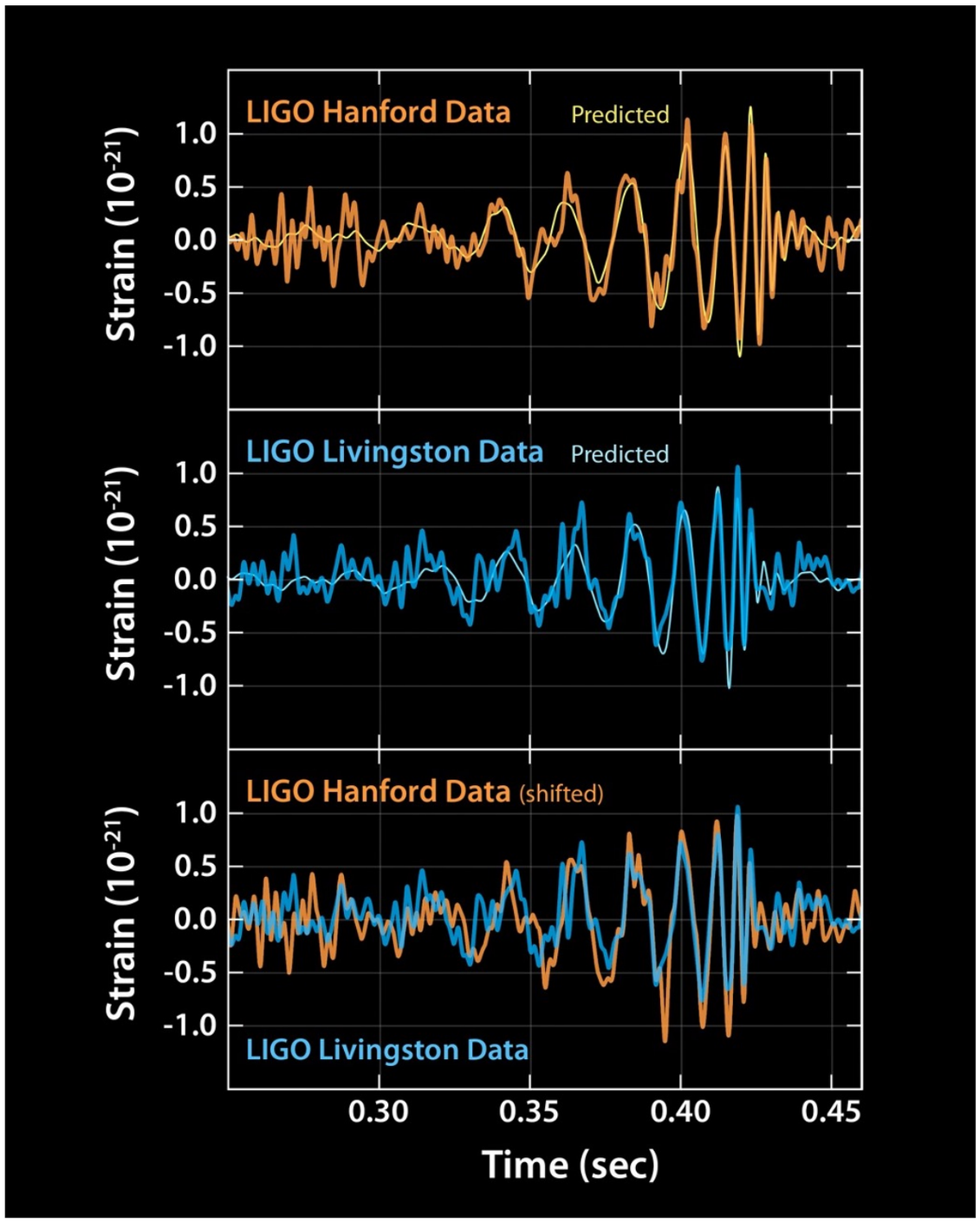


Getting Ready for O1!

LIGO India



GW150914





"All the News That's Fit to Print"

The New York Times

Late Edition
Today, some sunshine giving way to times of clouds, cold, high 28. **Tonight,** a flurry or heavier squall late, low 15. **Tomorrow,** windy, frigid, high 21. Weather map, Page A19.

VOL. CLXV . . . No. 57,140 + © 2016 The New York Times NEW YORK, FRIDAY, FEBRUARY 12, 2016 $2.50

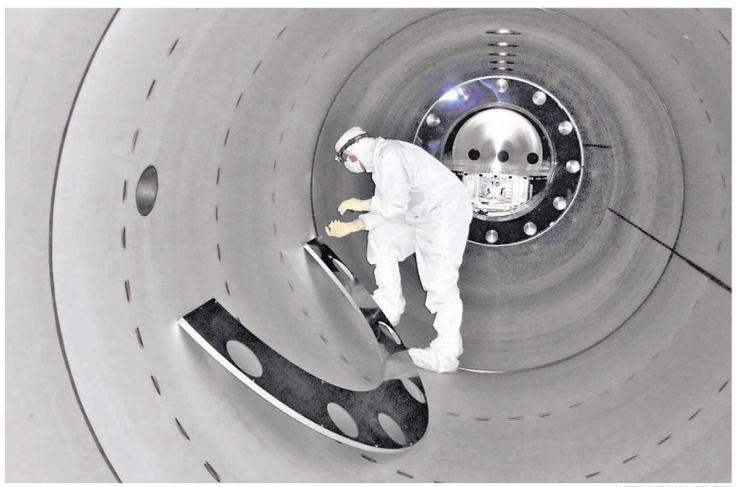
Clinton Paints Sanders Plans As Unrealistic

New Lines of Attack at Milwaukee Debate

By AMY CHOZICK and PATRICK HEALY

MILWAUKEE — Hillary Clinton, scrambling to recover from her double-digit defeat in the New Hampshire primary, repeatedly challenged the trillion-dollar policy plans of Bernie Sanders at their presidential debate on Thursday night and portrayed him as a big talker who needed to "level" with voters about the difficulty of accomplishing his agenda.

Foreign affairs also took on unusual prominence as Mrs. Clinton sought to underscore her experience and Mr. Sanders excoriated her judgment on Libya and Iraq, as well as her previous praise of former Secretary of State Henry A. Kissinger. But Mrs. Clinton was frequently on the offensive as well, seizing an opportunity to talk about leaders she admired and turning it against Mr. Sand-



CALTECH-M.I.T.-LIGO LABORATORY

A worker installed a baffle in 2010 to control light in the Laser Interferometer Gravitational-Wave Observatory in Hanford, Wash.

WITH FAINT CHIRP, SCIENTISTS PROVE EINSTEIN CORRECT

A RIPPLE IN SPACE-TIME

An Echo of Black Holes Colliding a Billion Light-Years Away

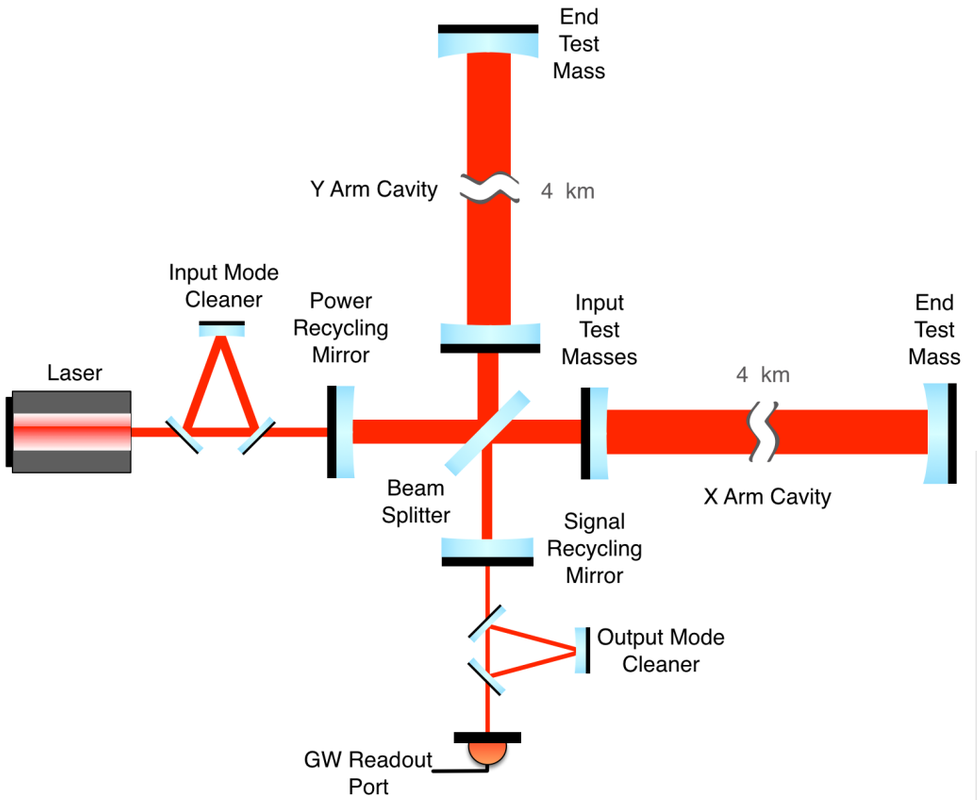
By DENNIS OVERBYE

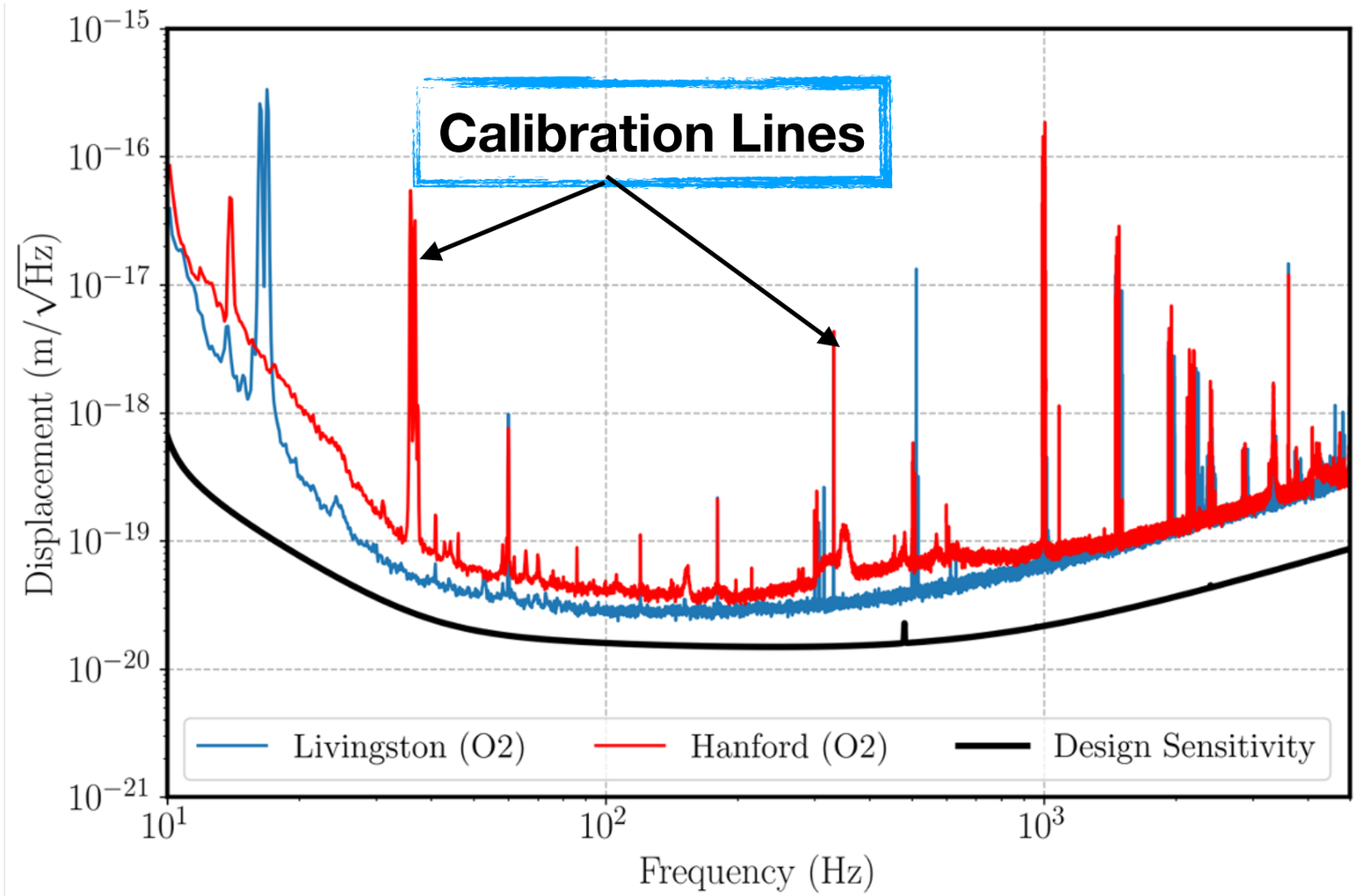
A team of scientists announced on Thursday that they had heard and recorded the sound of two black holes colliding a billion light-years away, a fleeting chirp that fulfilled the last prediction of Einstein's general theory of relativity.

That faint rising tone, physicists say, is the first direct evidence of gravitational waves, the ripples in the fabric of space-time that Einstein predicted a century ago. It completes his vision of a universe in which space and time are interwoven and dynamic, able to stretch, shrink and jiggle. And it is a ringing confirmation of

What do you do?

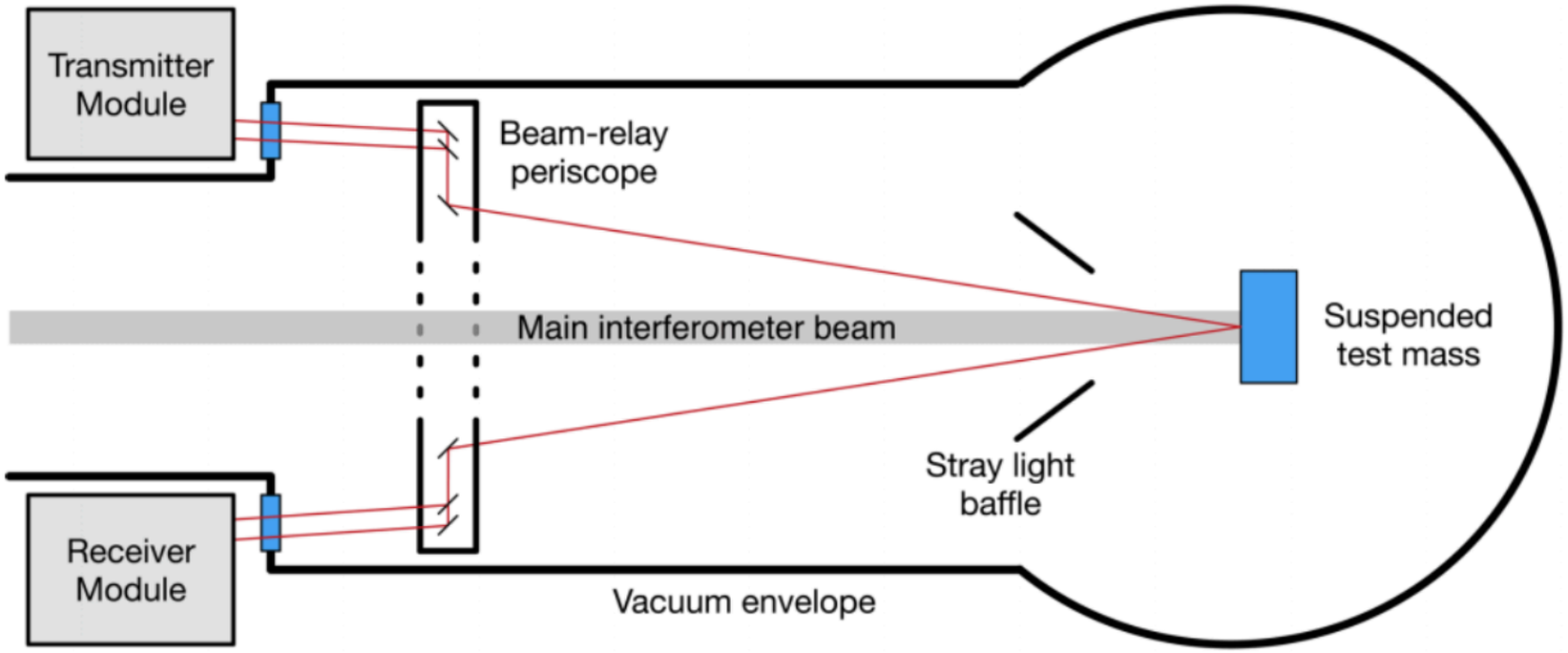
Work at LIGO and Calibrate the detector

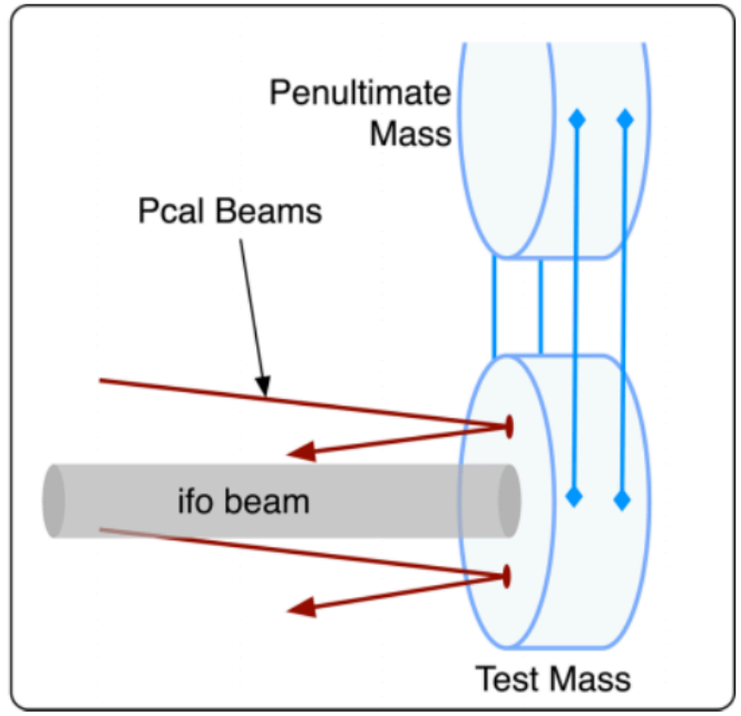




How?

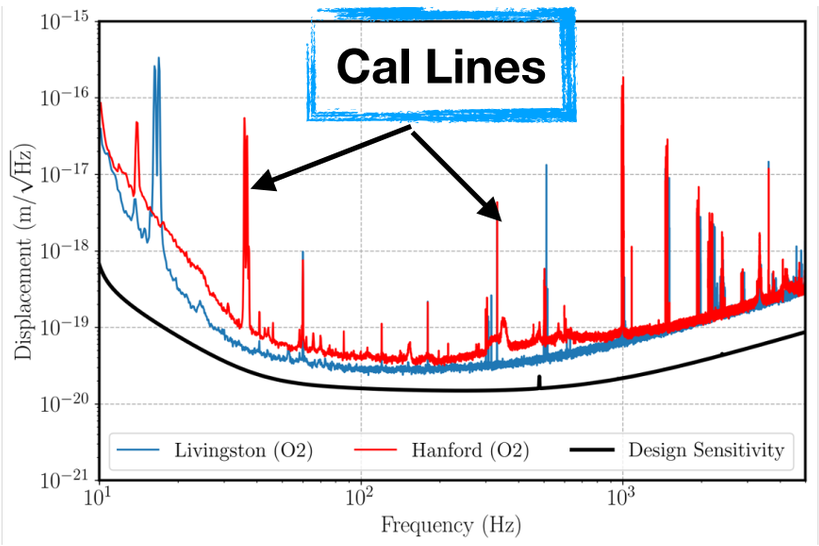
Photon calibrators “aka” Pcals





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

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



Measuring laser power



Why not use the power meter?



~ 0.42% 1-sigma

NIST calibrated Integrating-sphere-based power sensor

PHYSICAL REVIEW D **80,** 042005 (2009)

Optimal calibration accuracy for gravitational-wave detectors

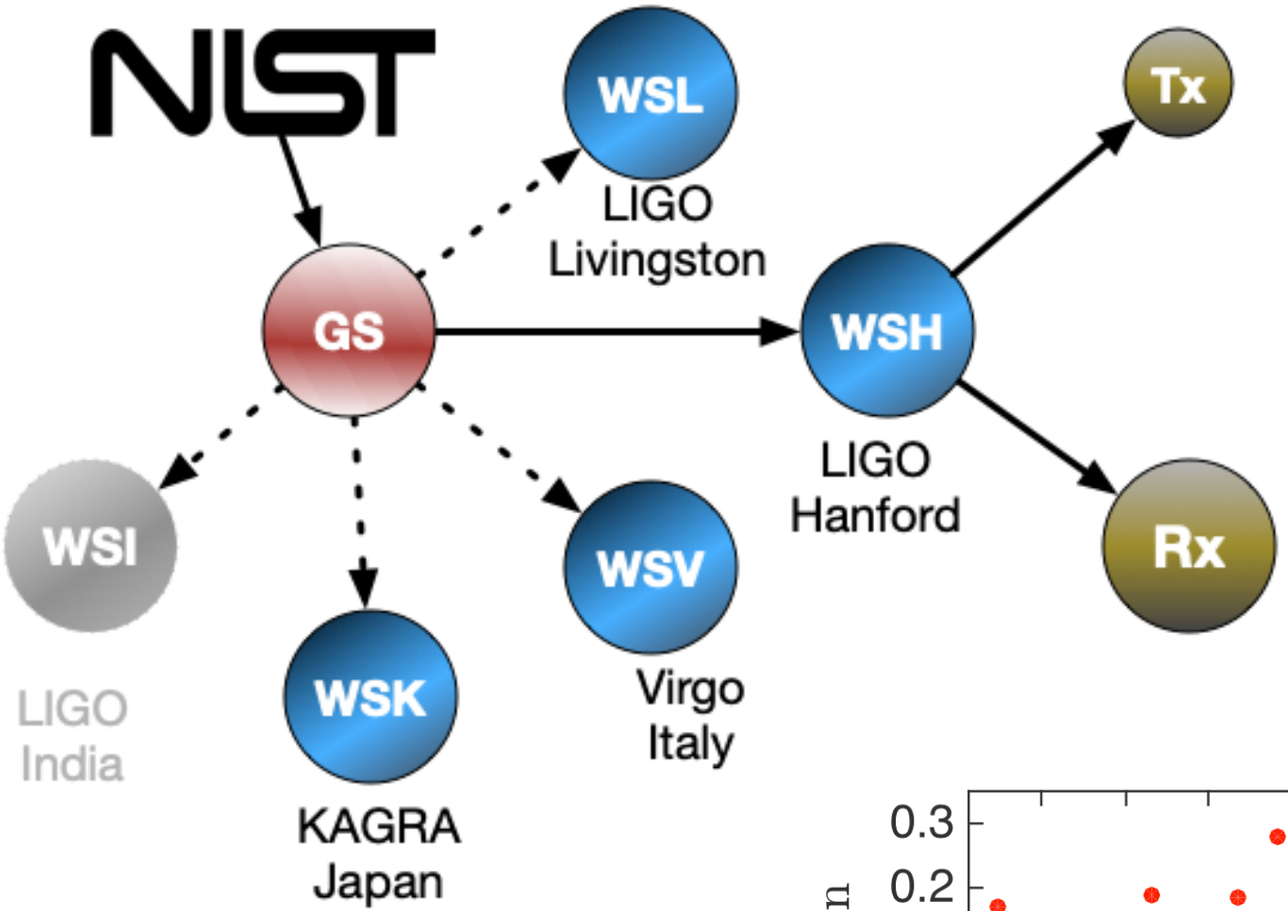
Lee Lindblom

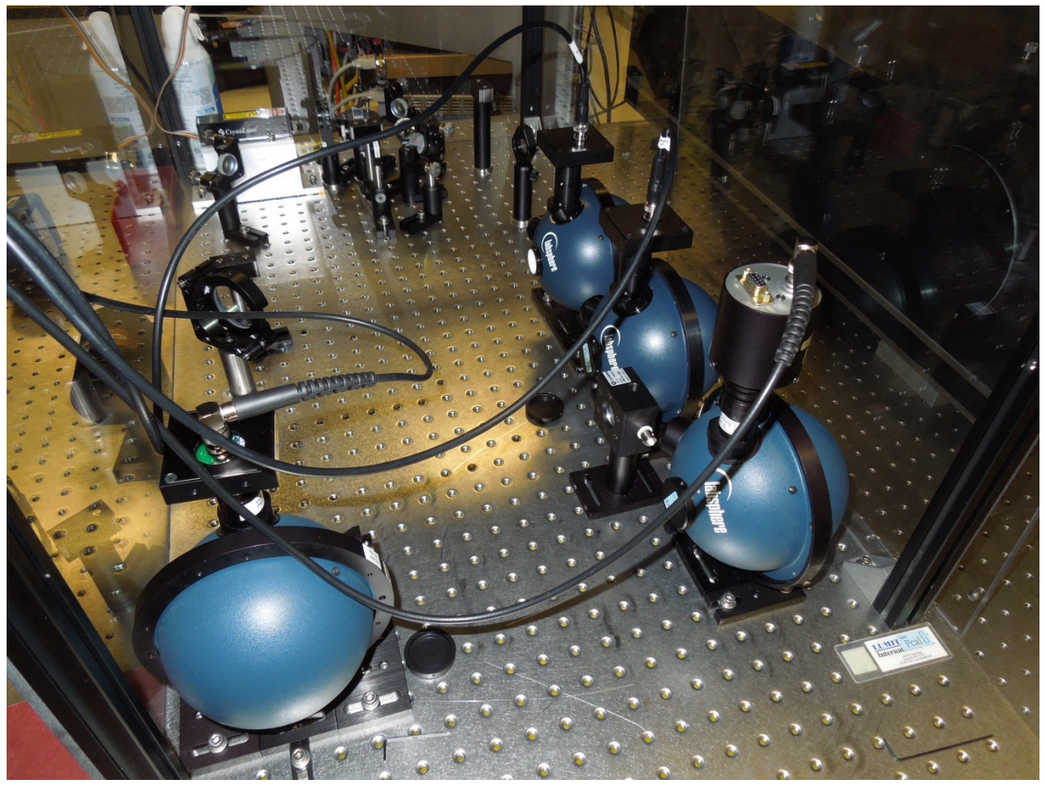
Theoretical Astrophysics 350-17, California Institute of Technology, Pasadena, California 91125, USA
(Received 28 June 2009; published 18 August 2009)

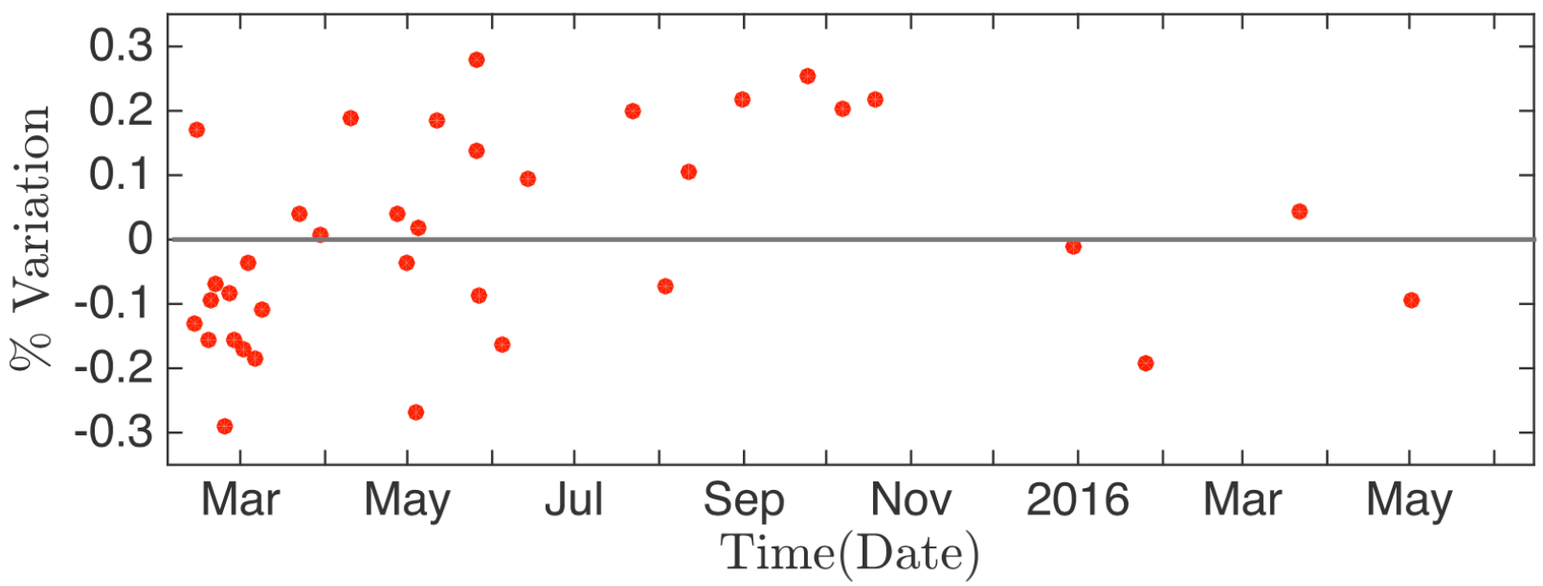
Calibration errors in the response function of a gravitational-wave detector degrade its ability to detect and then to measure the properties of any detected signals. This paper derives the needed levels of ca e th e higher accuracy would be made irrelevant by the intrinsic noise level of the detector. Calibration errors affect the data-analysis process in much the same way as errors in theoretical waveform templates. The optimal level of calibration accuracy is expressed therefore as a joint limit on modeling and calibration errors: increased accuracy in one reduces the accuracy requirement in the other.

5% for detection and 0.5% for accurate science

Calibration Transfer

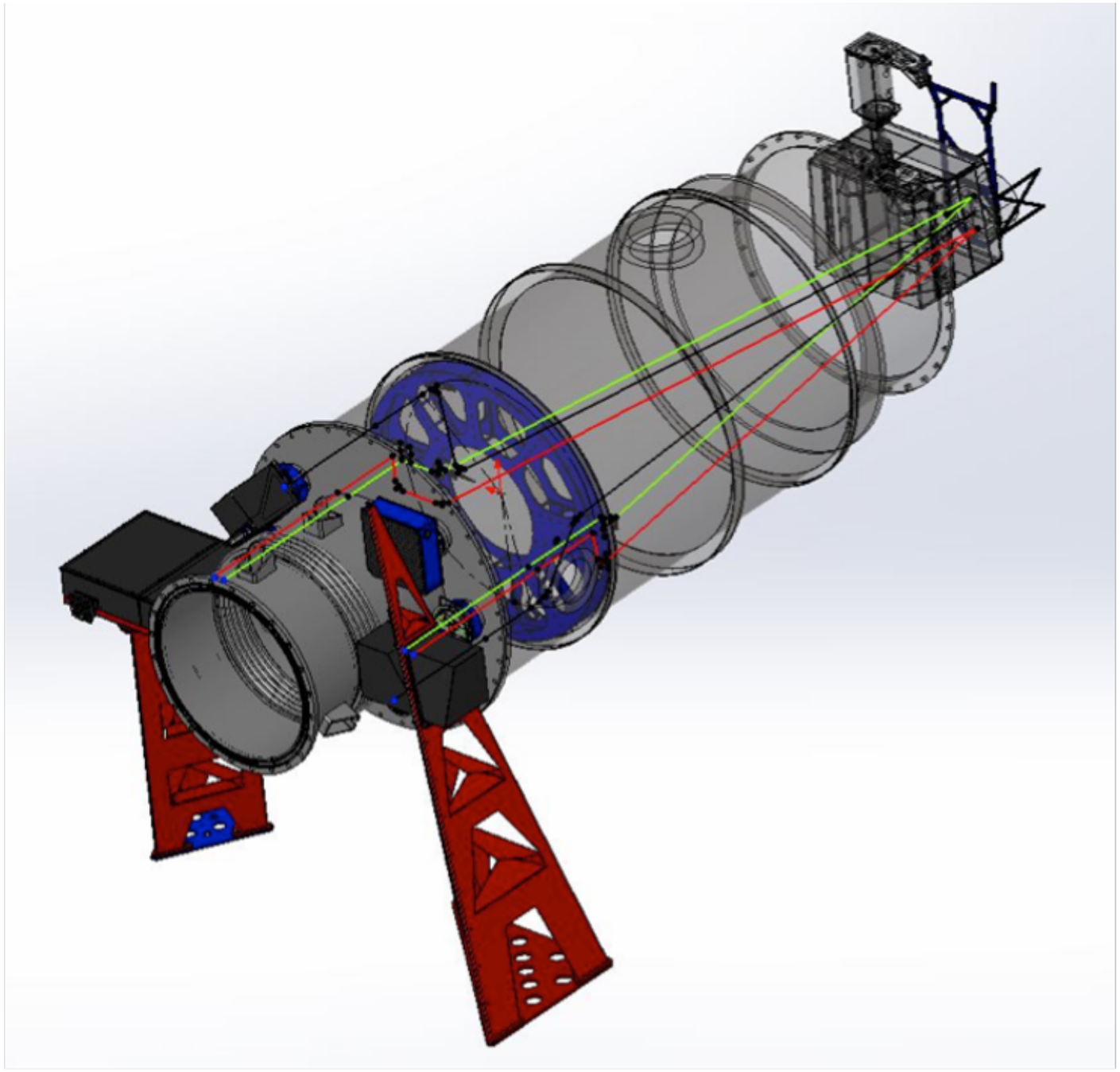






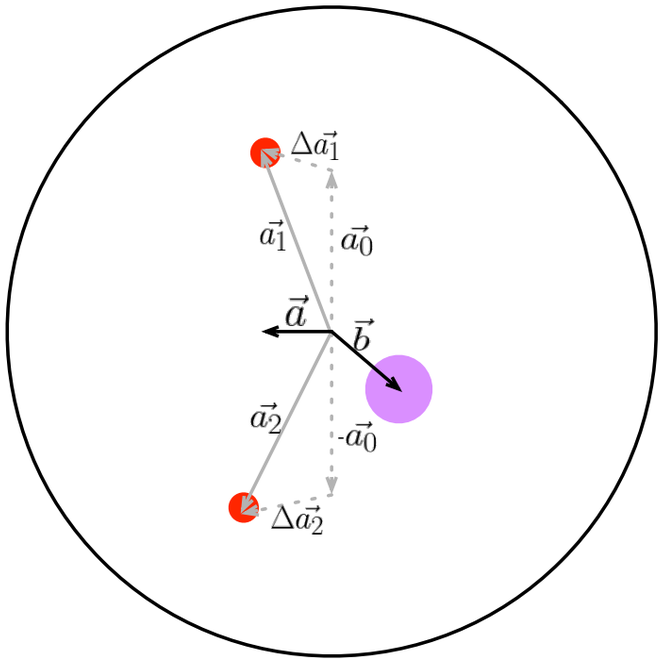
S.Karki, et al. Rev. Sci. Ins. 2016 87:11

Optical Efficiency

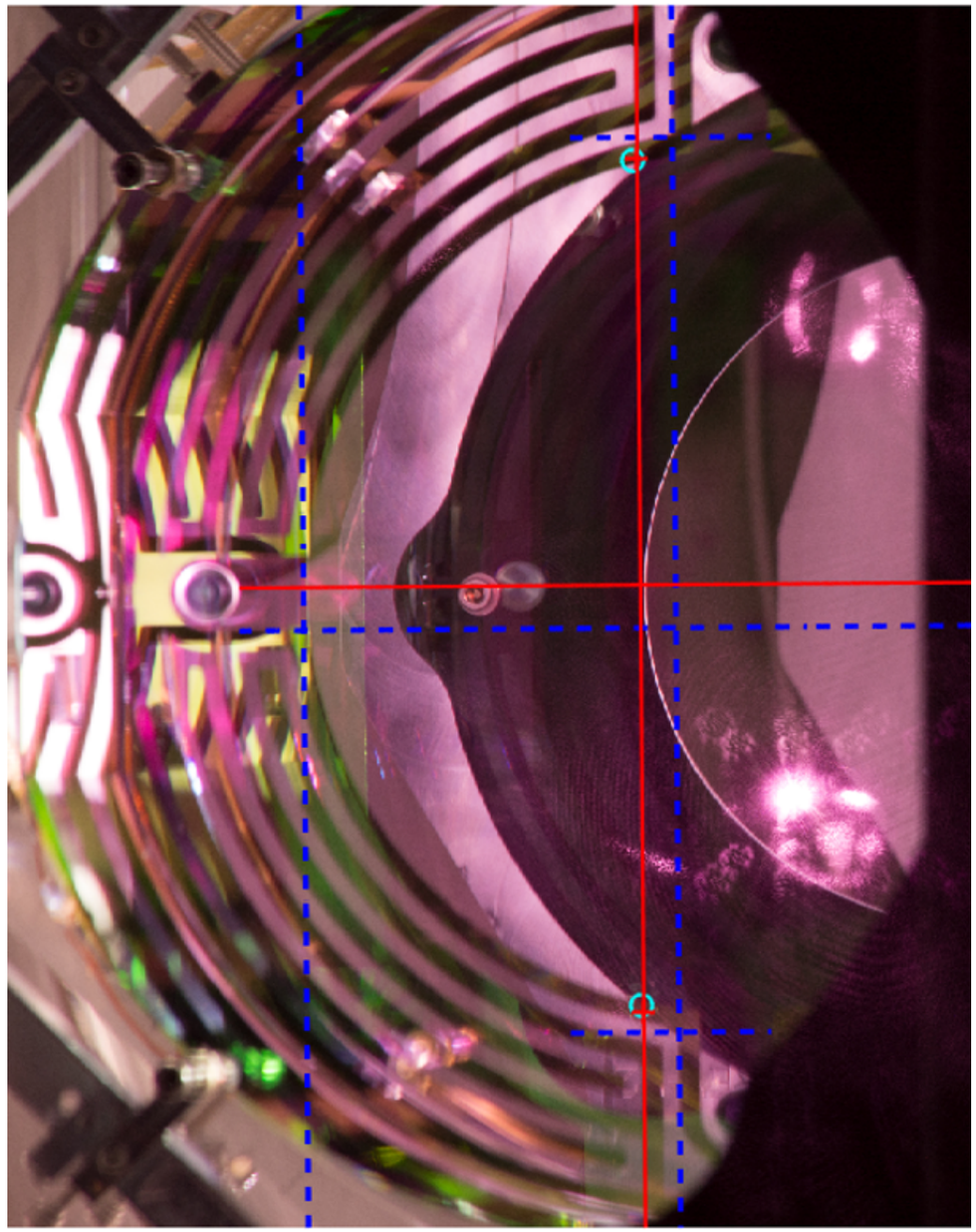


Rotation

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



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



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

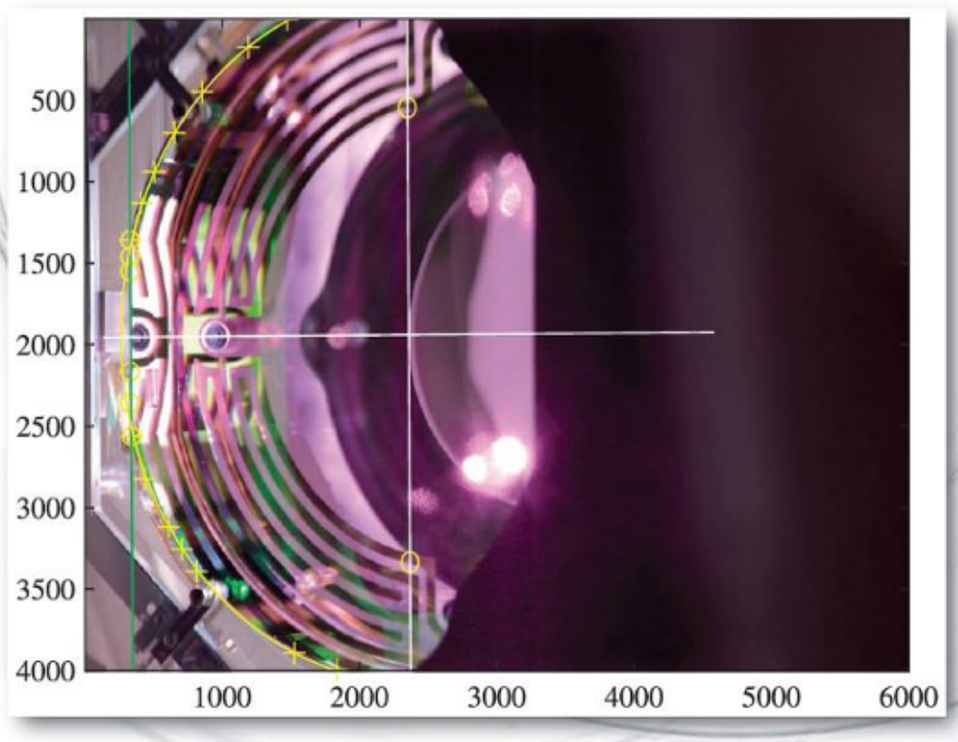
State of art in O1/O2

Parameter	**Rel. Uncer-tainty(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 %
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 %**

November 2016 Volume 87 Number 11

Part 1 of 2

AIP | Review of Scientific Instruments



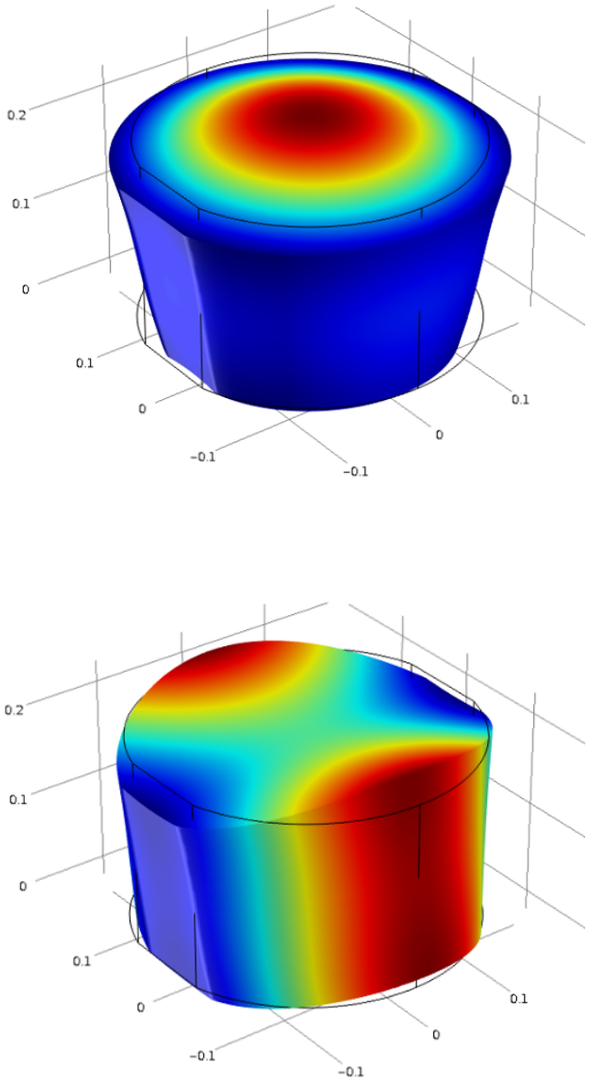
The Advanced LIGO photon calibrators

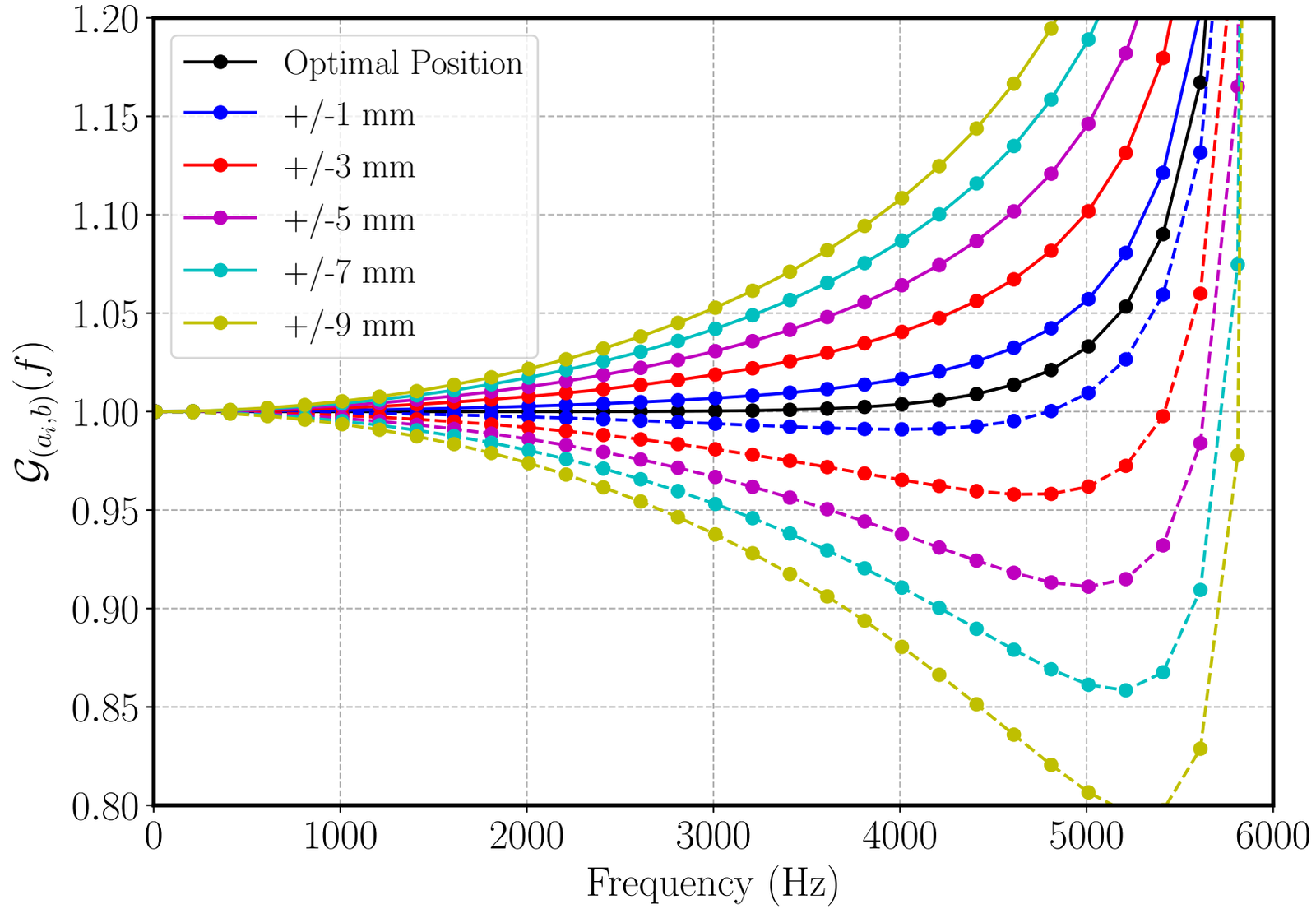
by S. Karki, D. Tuyenbayev, S. Kandhasamy *et al.*

rsi.aip.org

Test mass deformation

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

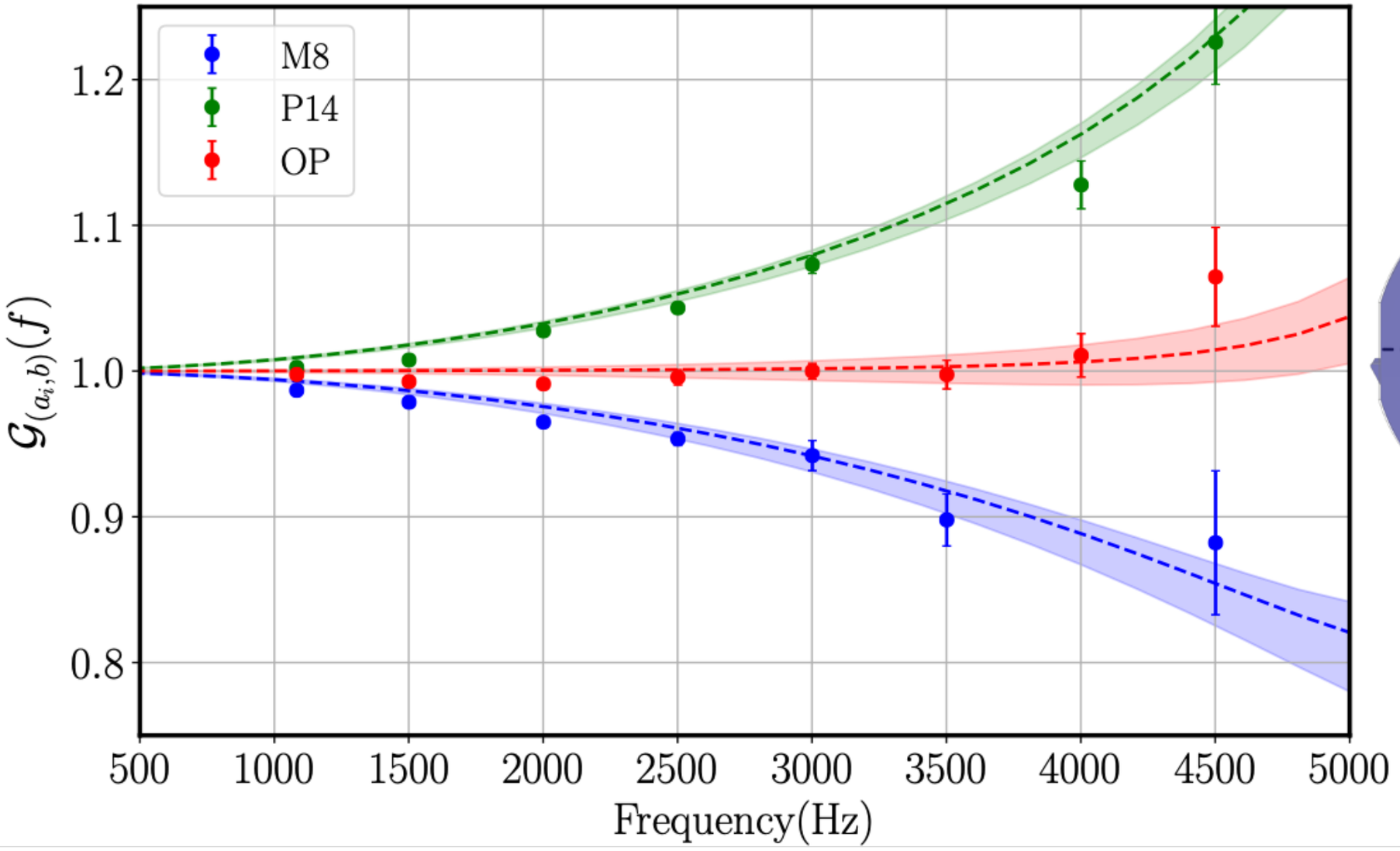


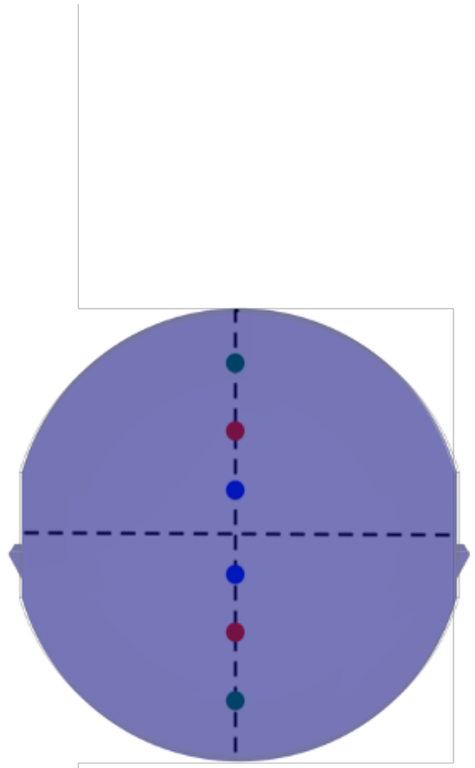


S, Karki [2019], Dissertation

Observation

“Experiment is King”

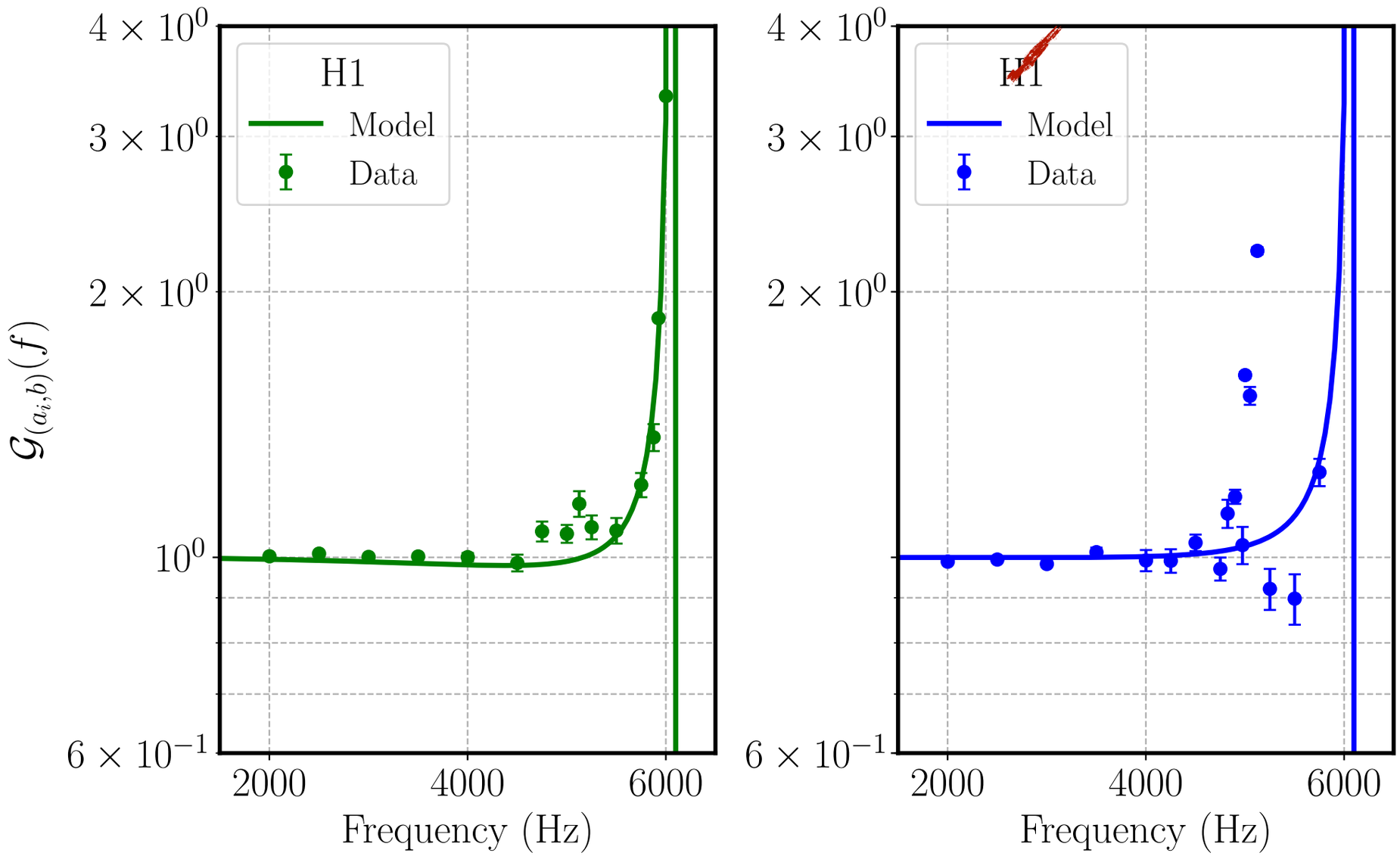




S, Karki [2019], Dissertation

Some Discrepancy

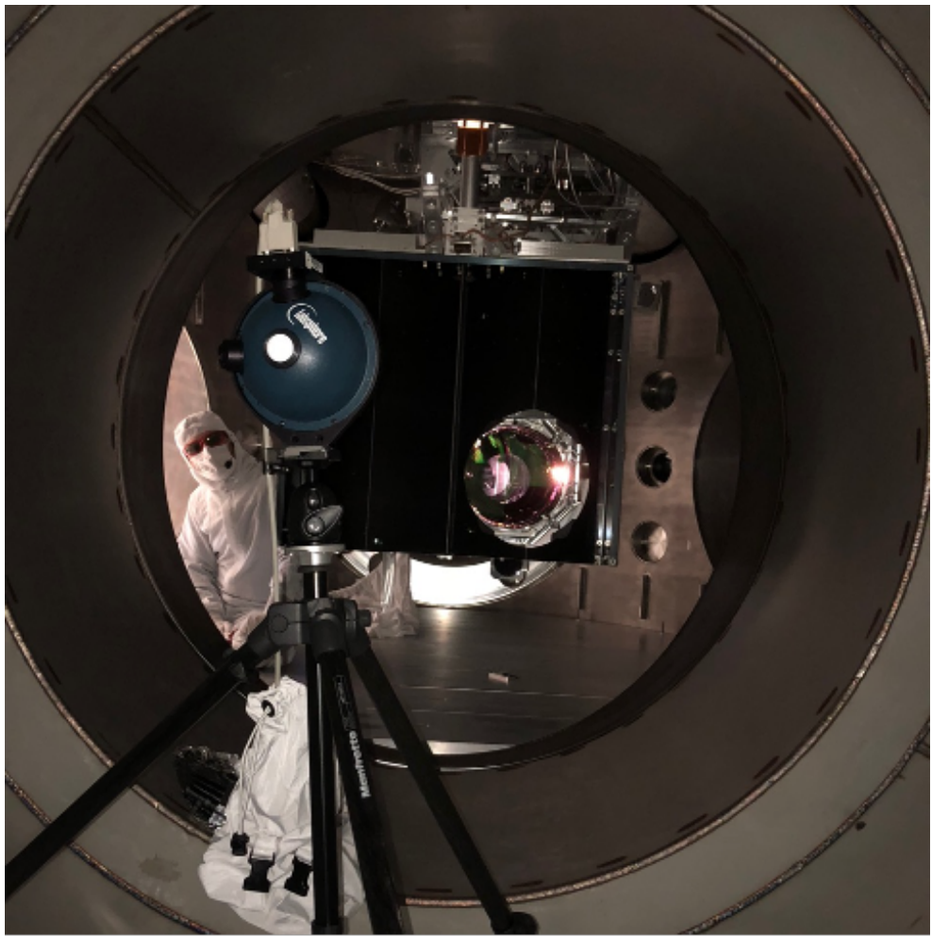
Everything is not rosy



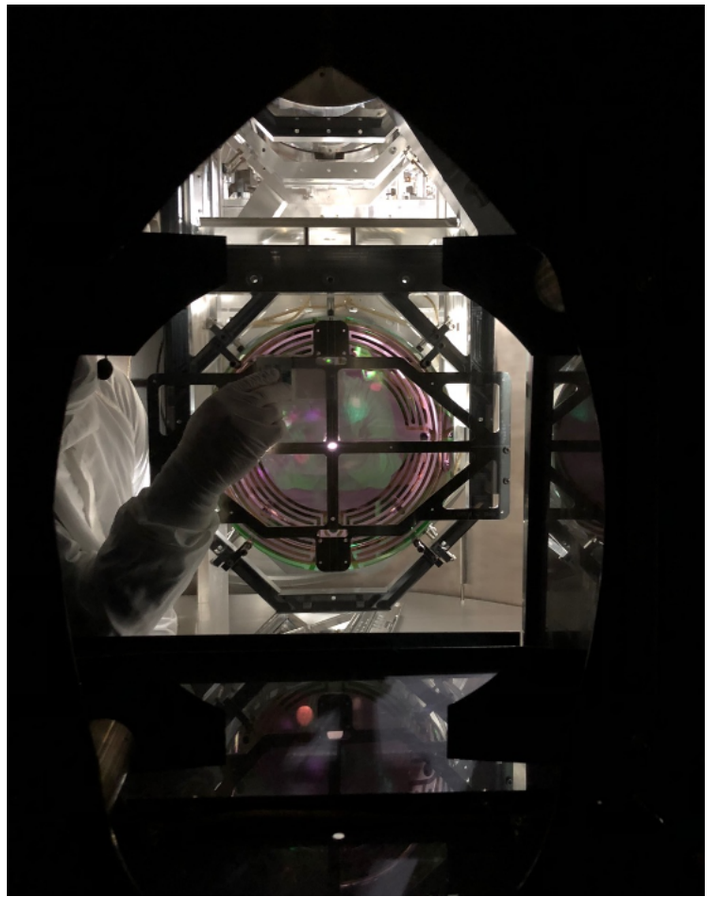
S, Karki [2019], Dissertation

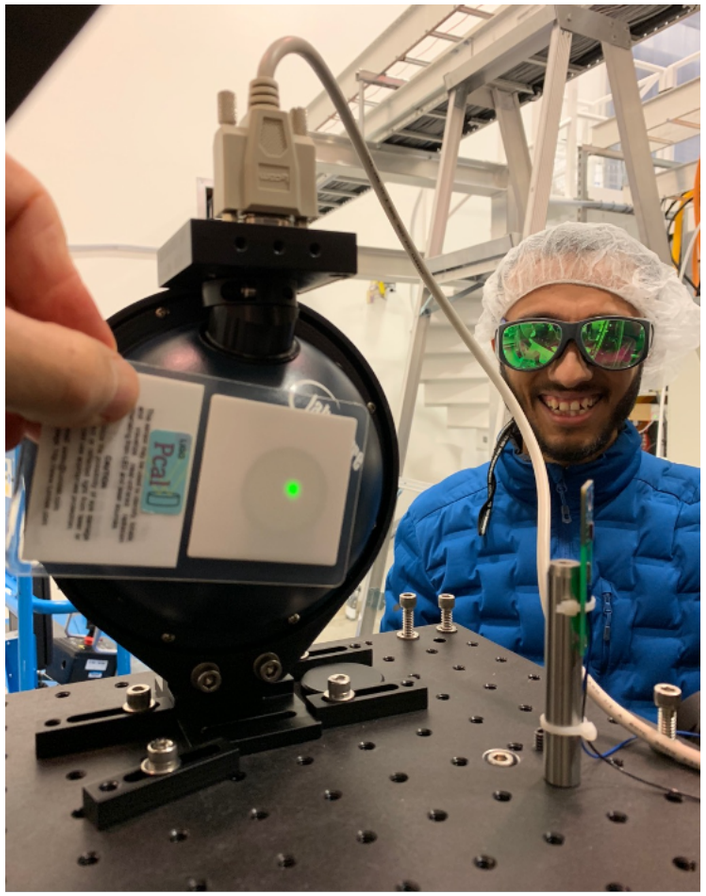
Further Improvements

In-vacuum optical efficiency measurements



0.37% ➔ 0.10%





Beam alignment using targets
Continuous monitoring using Rx aperture

0.40%➔ 0.10%

Expected in O3

Parameter	**Relative Uncertainty (Expected O3)**
NIST -> GS $[\rho_{GS}]$	$0.31\,\%$
WS/GS $[\alpha_{WG}]$	$0.03\,\%$
Rx/WS $[\alpha'_{RW}]$	$0.05\,\%$
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	$\mathbf{0.35\,\%}$

Dissertation

ACCURATE AND PRECISE CALIBRATION OF ADVANCED LIGO DETECTORS IN THE ERA OF GRAVITATIONAL WAVE ASTRONOMY

(March 2019)

by

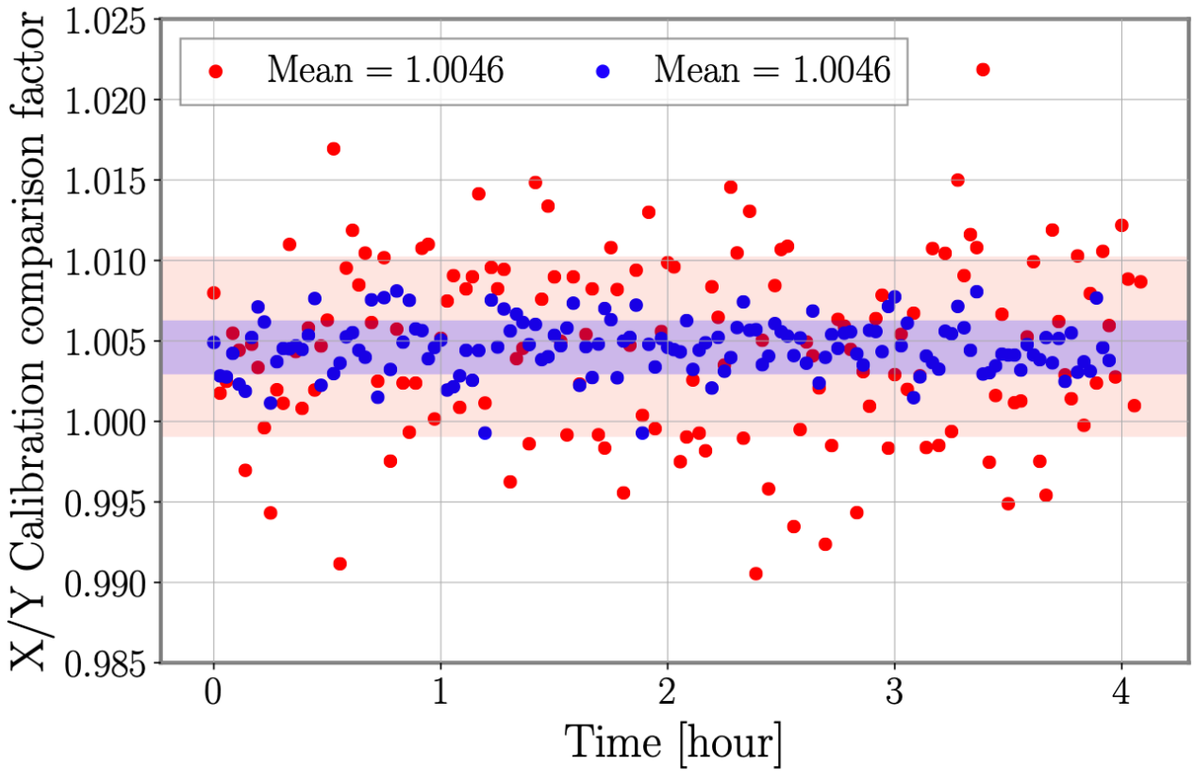
SUDARSHAN KARKI

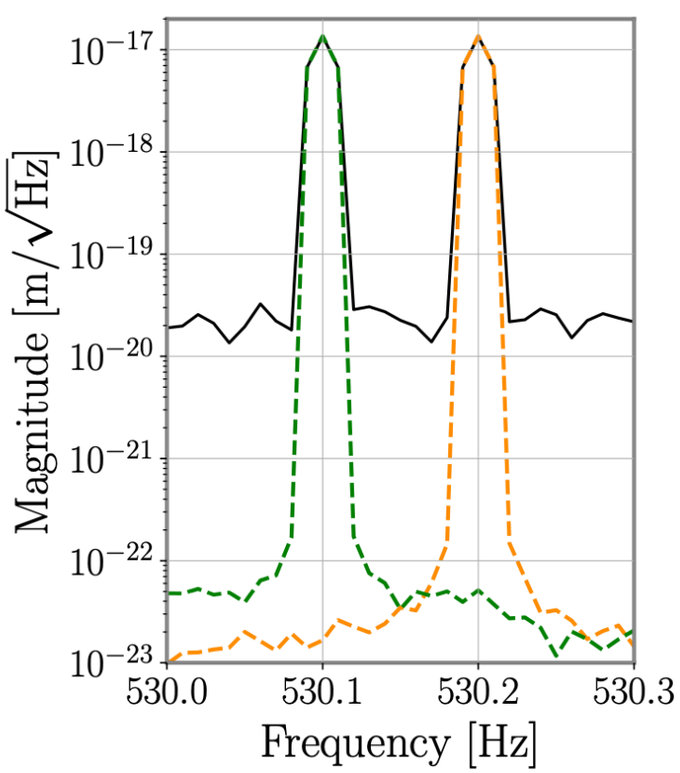
LSC Fellow PostDoc (2019-2022)

O3 Uncertainty Budget

Param	LHO X-end	
	Values	u_{rel} (%)
X_X, X_Y	1.565×10^{-14}	0.53 (0.35)
$\cos\theta$	0.9884	0.03
M	39.657	0.01
ϵ_{rot}	-	0.41 (0.10)
ρ_R	1.068×10^4	0.33
η_R	0.9942	0.04 (0.10)

Param	LHO X-end	
	Values	u_{rel} (%)
X_X^c, X_Y^c	1.561×10^{-14}	0.41
ρ_G	-8.0985	0.315
α_{WG}	1.1172	0.01 (38)
ξ_{LN}	1.0020	0.070
C_X, C_Y	1.0029	0.25

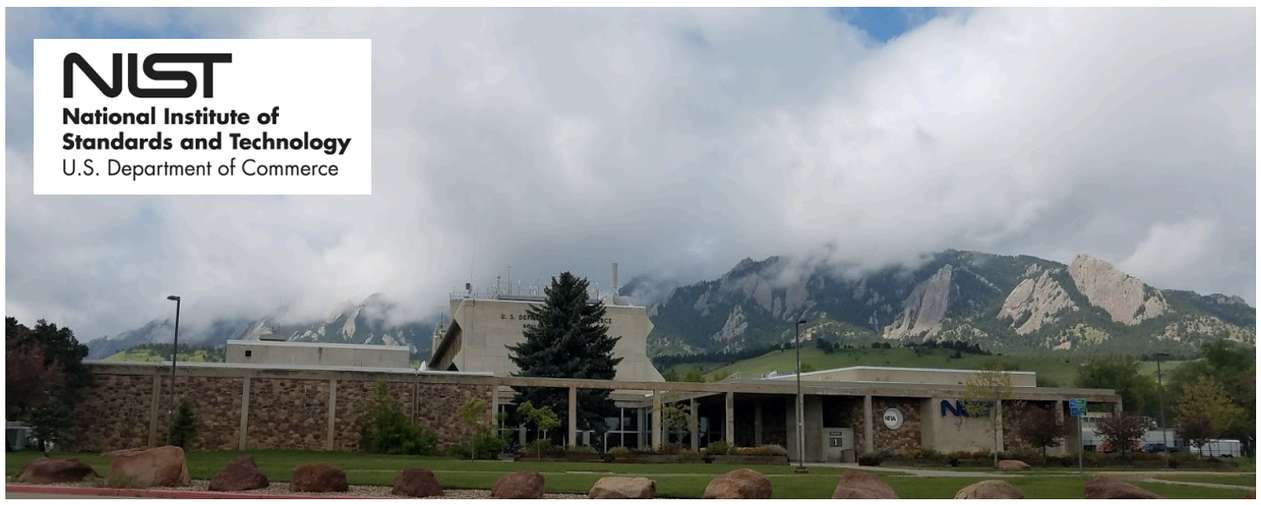




Dripta et. al. CQG, 38 (2021) 015009

In the meantime

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



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.

NIST : 0.42 %
PTB: 0.1%

IOP Publishing | Bureau International des Poids et Mesures Metrologia
Metrologia **58** (2021) 055011 (7pp) https://doi.org/10.1088/1681-7575/ac1e03

A bilateral comparison of NIST and PTB laser power standards for scale realization confidence by gravitational wave observatories

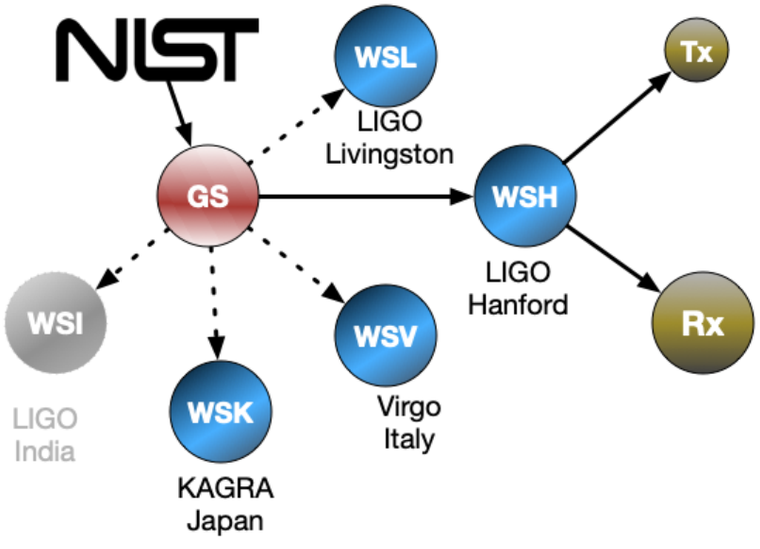
Matthew Spidell[1,*], John Lehman[1], Marco López[2], Holger Lecher[2], Stefan Kück[2], Dripta Bhattacharjee[3], Yannick Lecoeuche[3] and Richard Savage[3]

Pandemic



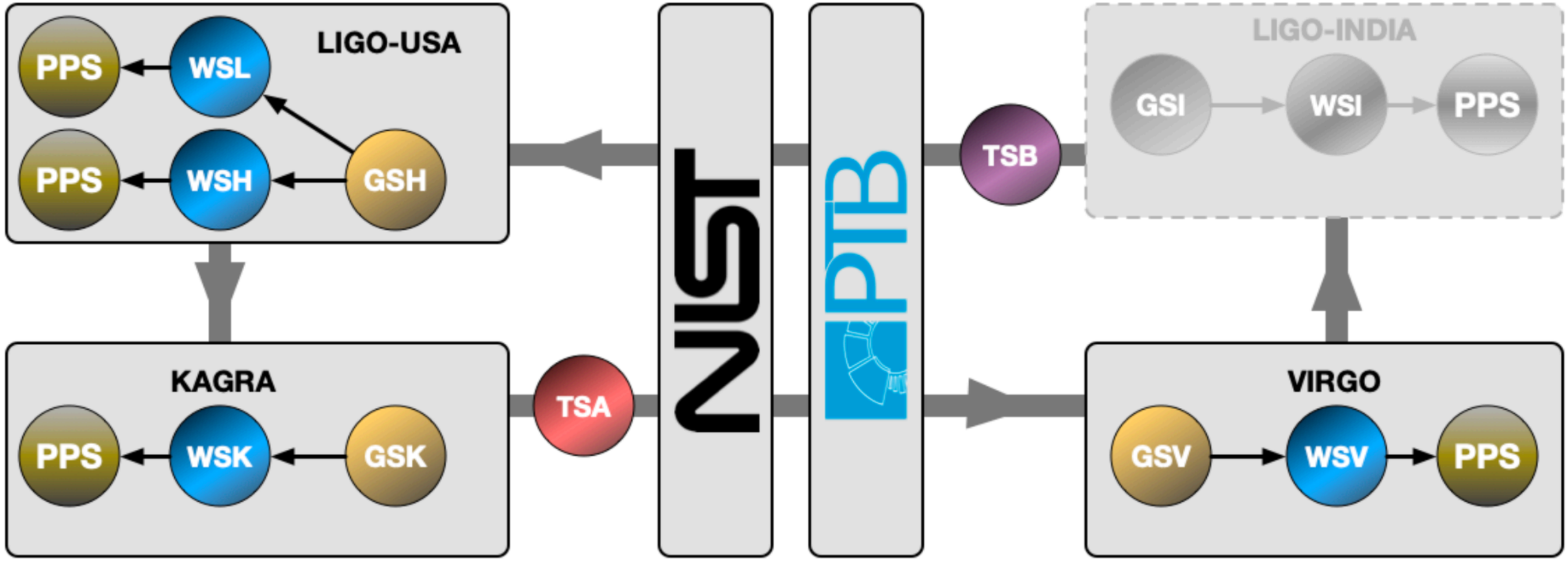
Source: Harvard Medical School Website

GW Network Calibration

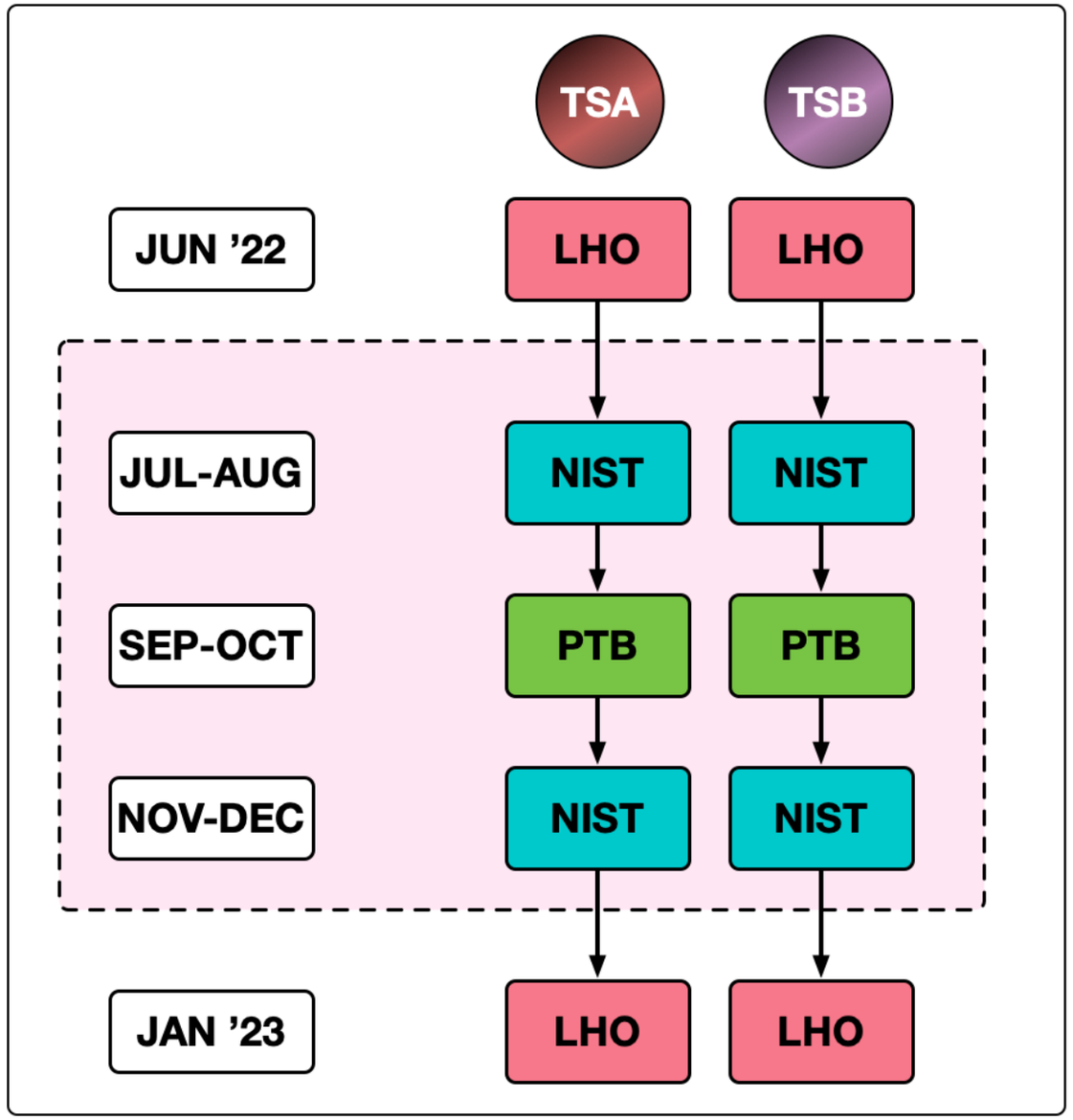


During O1, O2 and O3

S. Karki et. al. ***Galaxies***, 2022

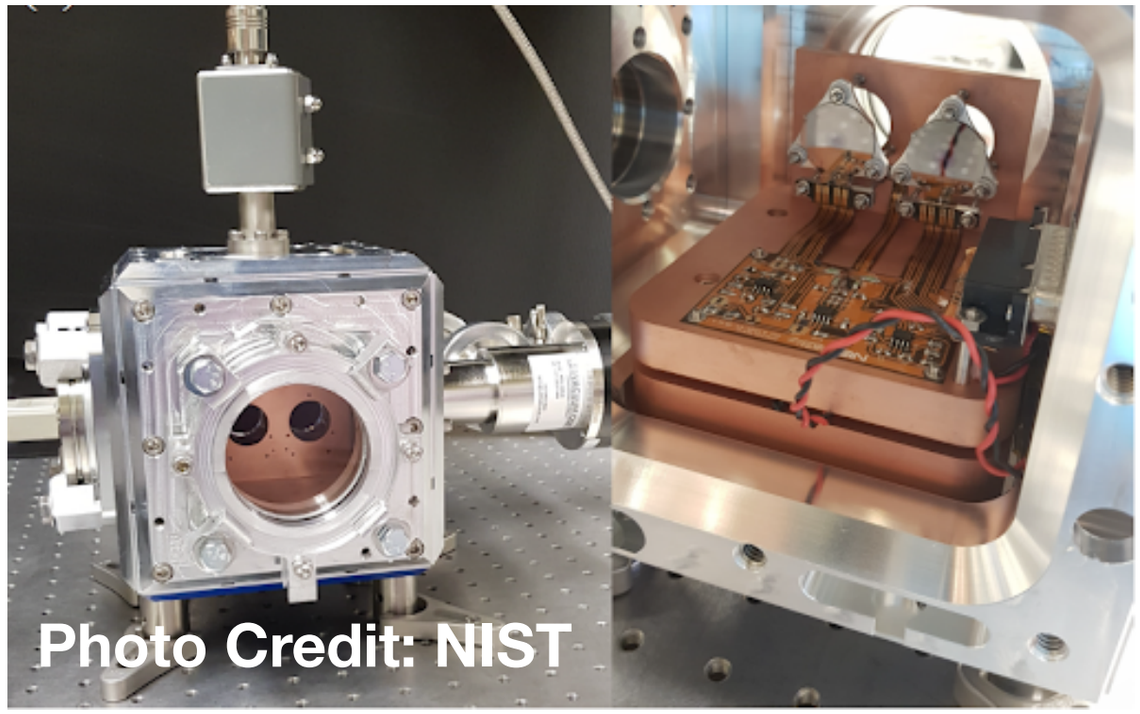


Bilateral Comparison



Bilateral Comparison

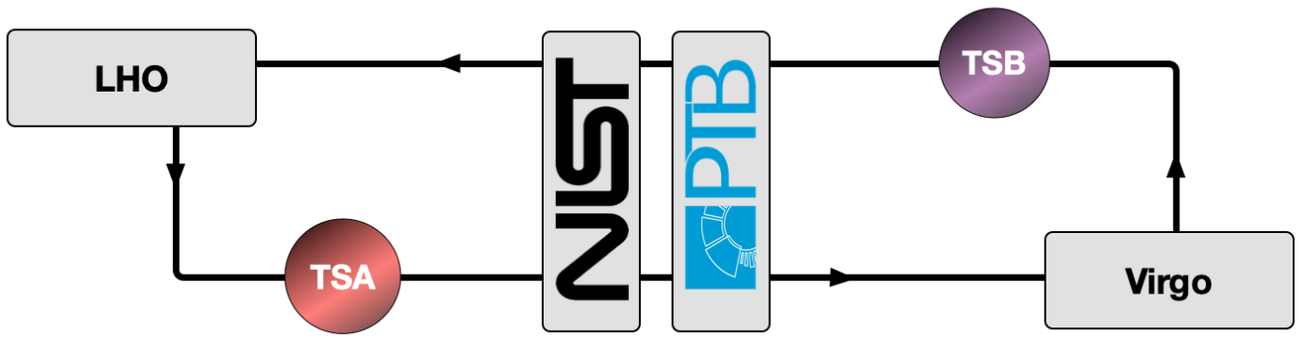
S. Karki et. al. ***Galaxies***, 2022

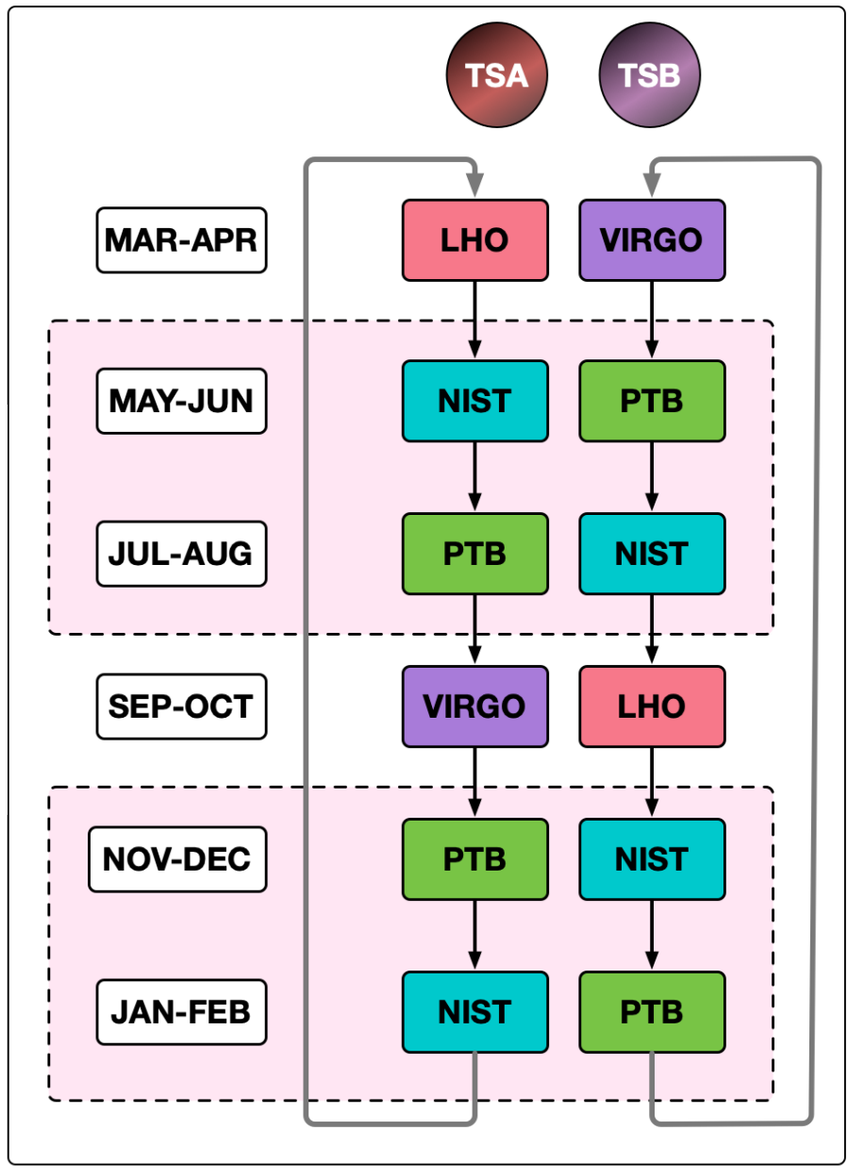


NIST's new PARRoT primary detector

0.42 % —> ~0.1%

Global Calibration effort

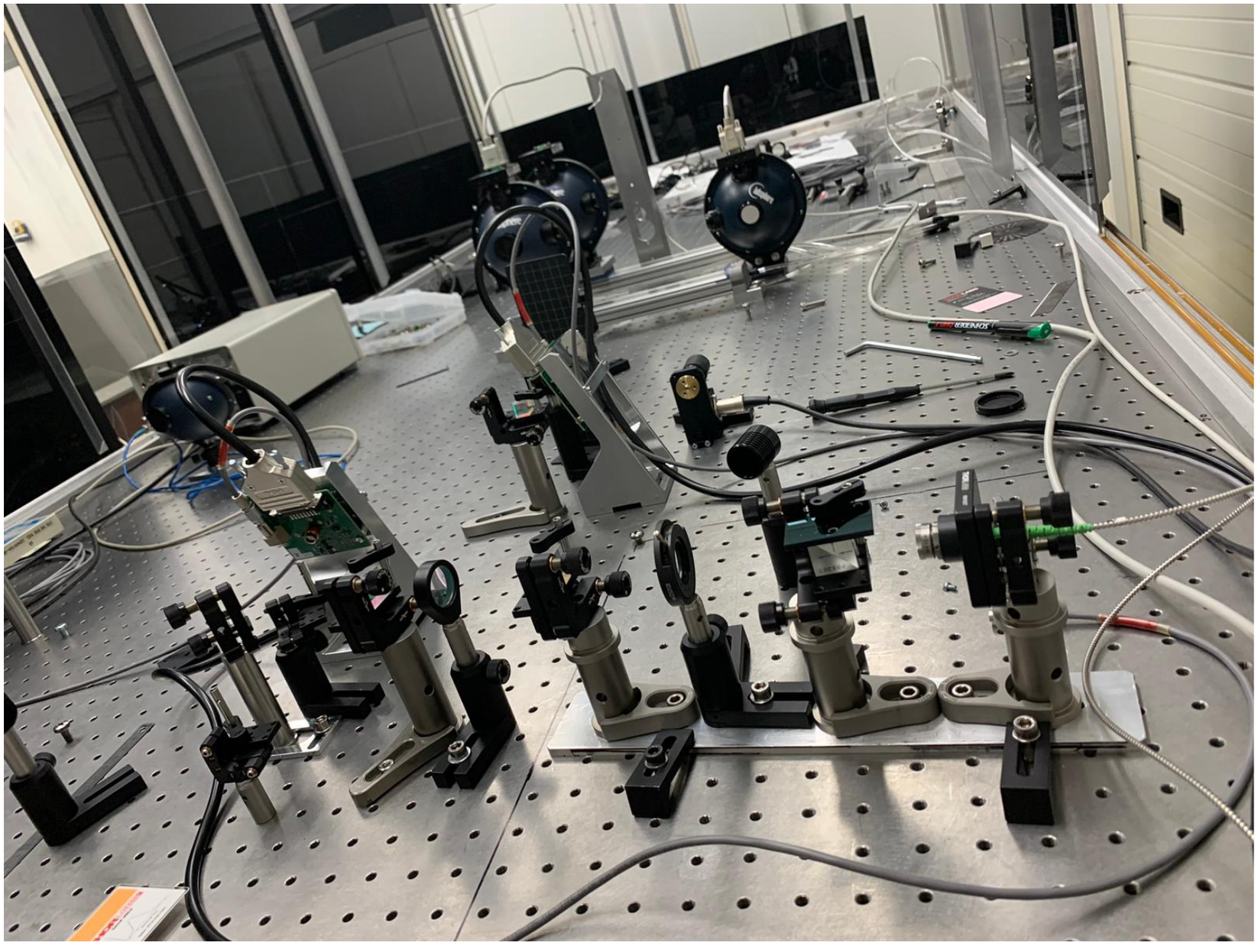




Annual Routine

S. Karki et. al. ***Galaxies***, 2022

Virgo/LAPP Visit



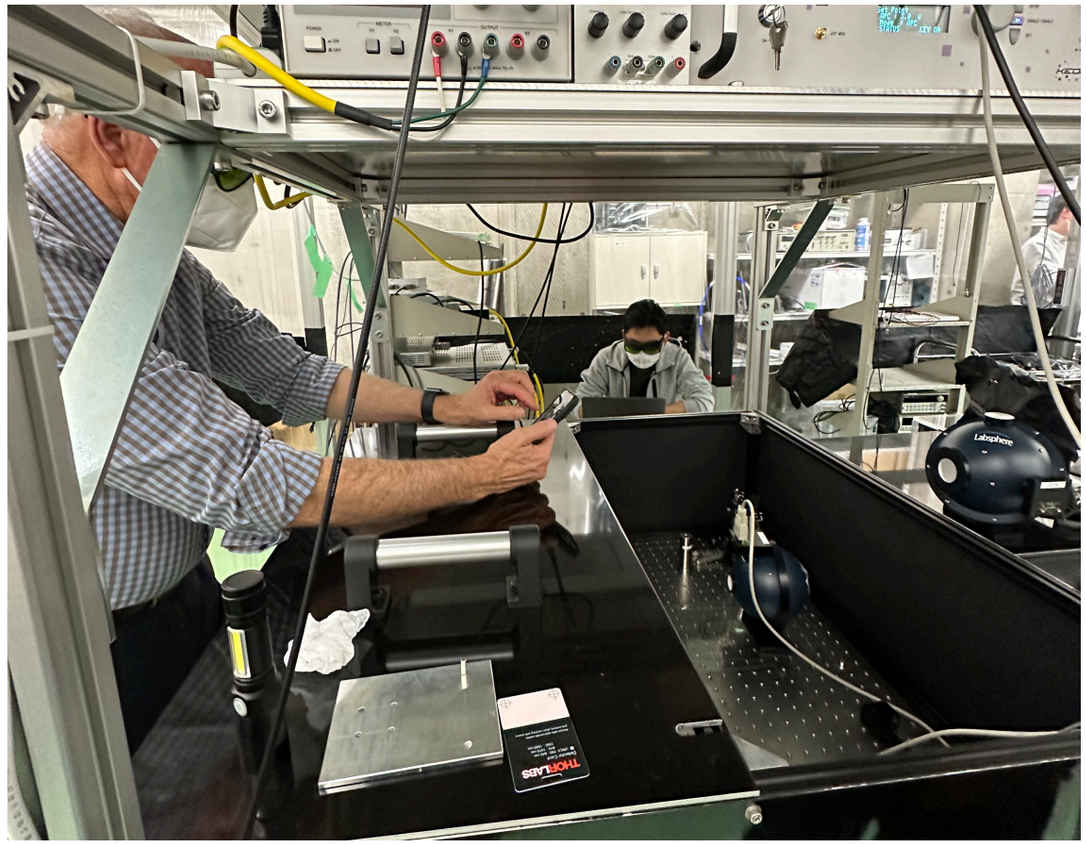
Virgo is planning to completely redesigned their Pcals for O5.

KAGRA Visit

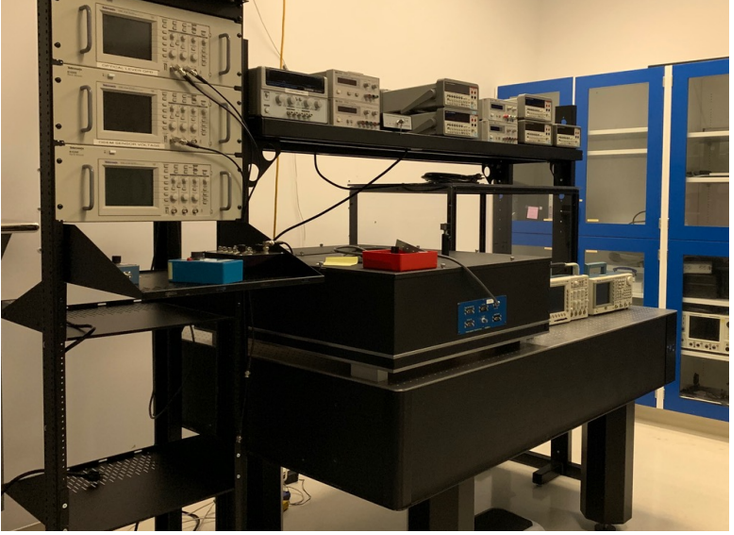




- **KAGRA Pcal is quite advanced with 20 W laser and ability to modulate two beams independently**
- **Working on implementing robust procedure to transfer calibration from Transfer Standards.**



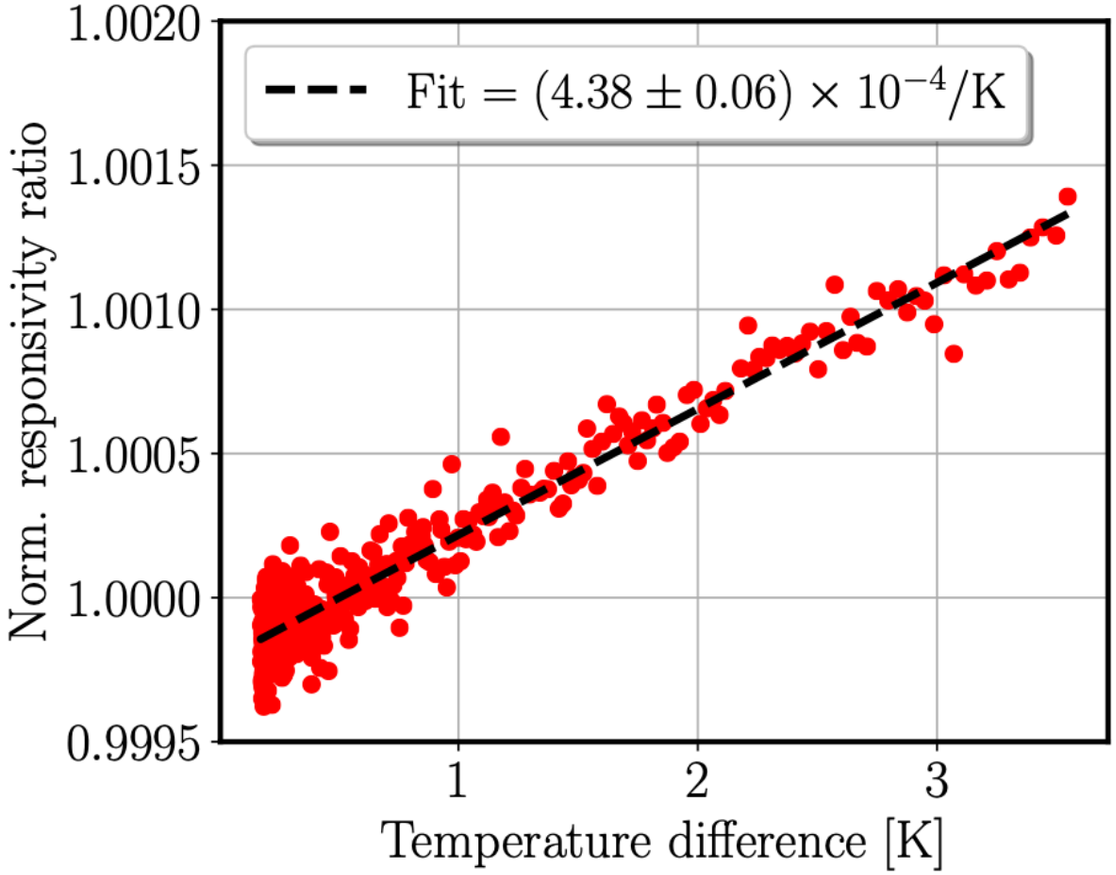
Challenges

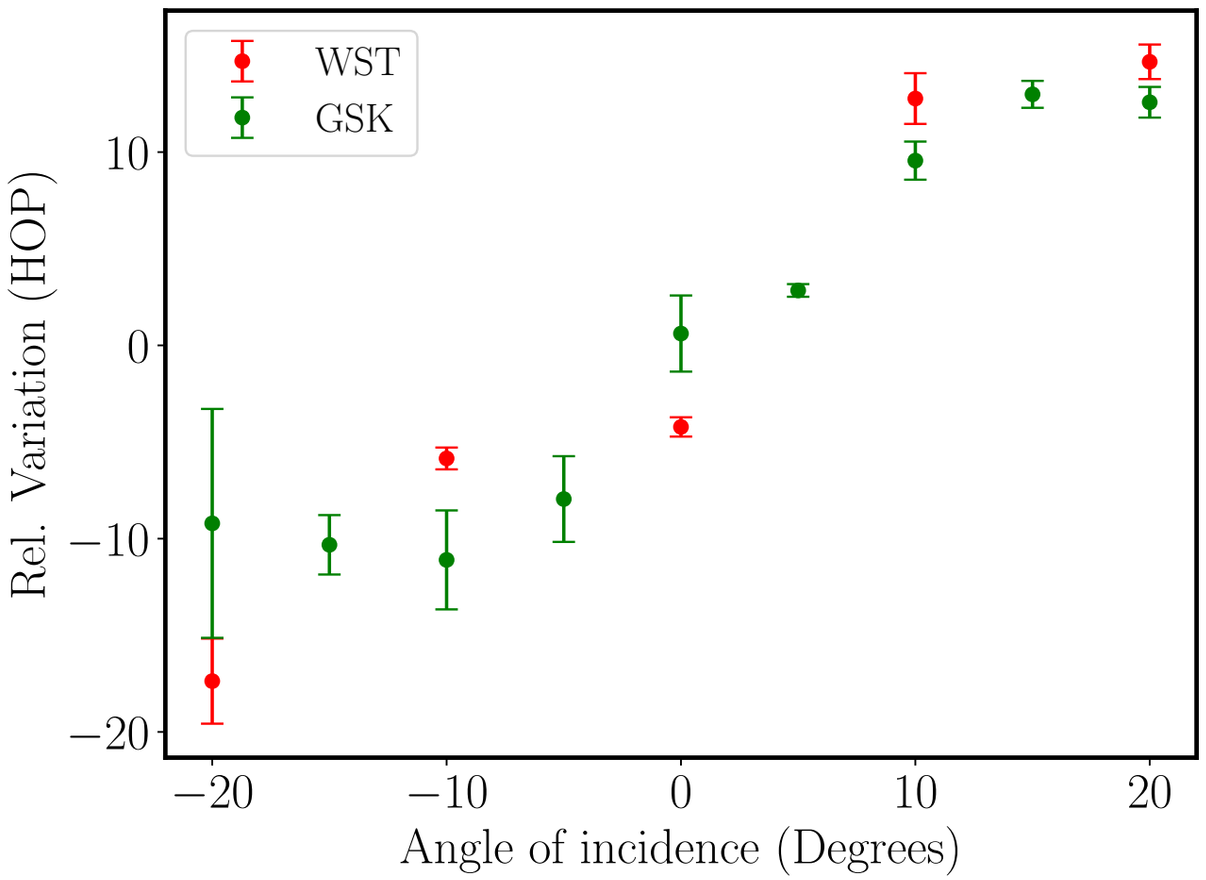


LSB —> OSB

Angular Dependence

Temperature Dependence





Dripta et. al. CQG, 38 (2021) 015009

Redesigned photodiode mount
Temperature sensor

In the end

- To summarize, I feel lucky to have been part of and come along for the ride when,
  - Pcal were realized as the primary calibration tool in LIGO.
  - Pcals are on the way to becoming the main calibration tool across global network of GW detectors.
  - Collaboration with NIST and PTB to make sure the science we do is not limited by the laser power calibration they perform.

Palouse Falls





Goat Lake





Eagle Cap Wilderness







Won’t forget all those dinners, climbing trips, wine tasting, night outs, LVK meetings

THANK YOU ALL

For making my time here thoroughly enjoyable!