Calibrating the global network of gravitational wave observatories via laser power calibration at NIST and PTB

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with

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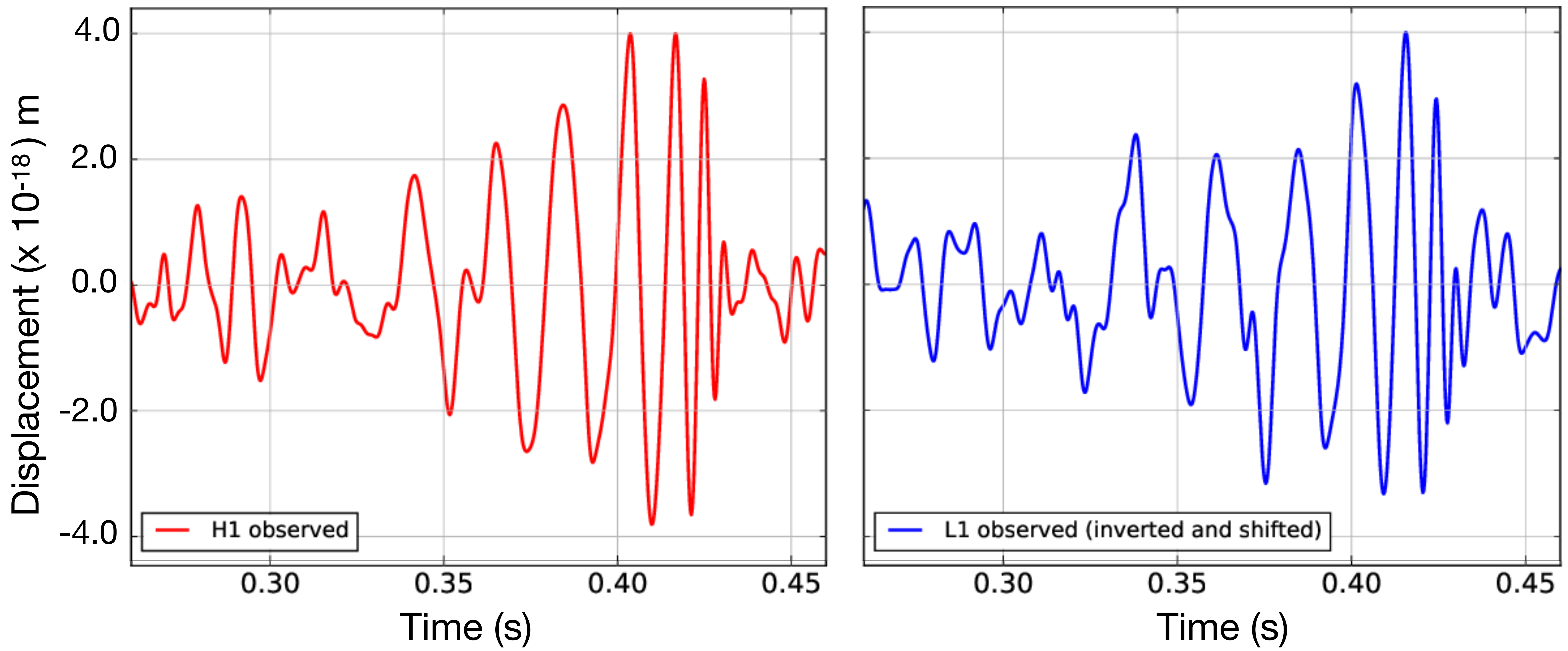
J. Lehman, M. Spidell, M. Stephens - *National Institute of Standards and Technology*

S. Kück, H. Lecher, M. López - *Physikalisch-Technische Bundesanstalt*
L. Rolland, P. Lagabbe - *Virgo Collaboration*

D. Chen, R. Bajpai, S. Fujii - *KAGRA Collaboration*

LIGO-G2300653-v8

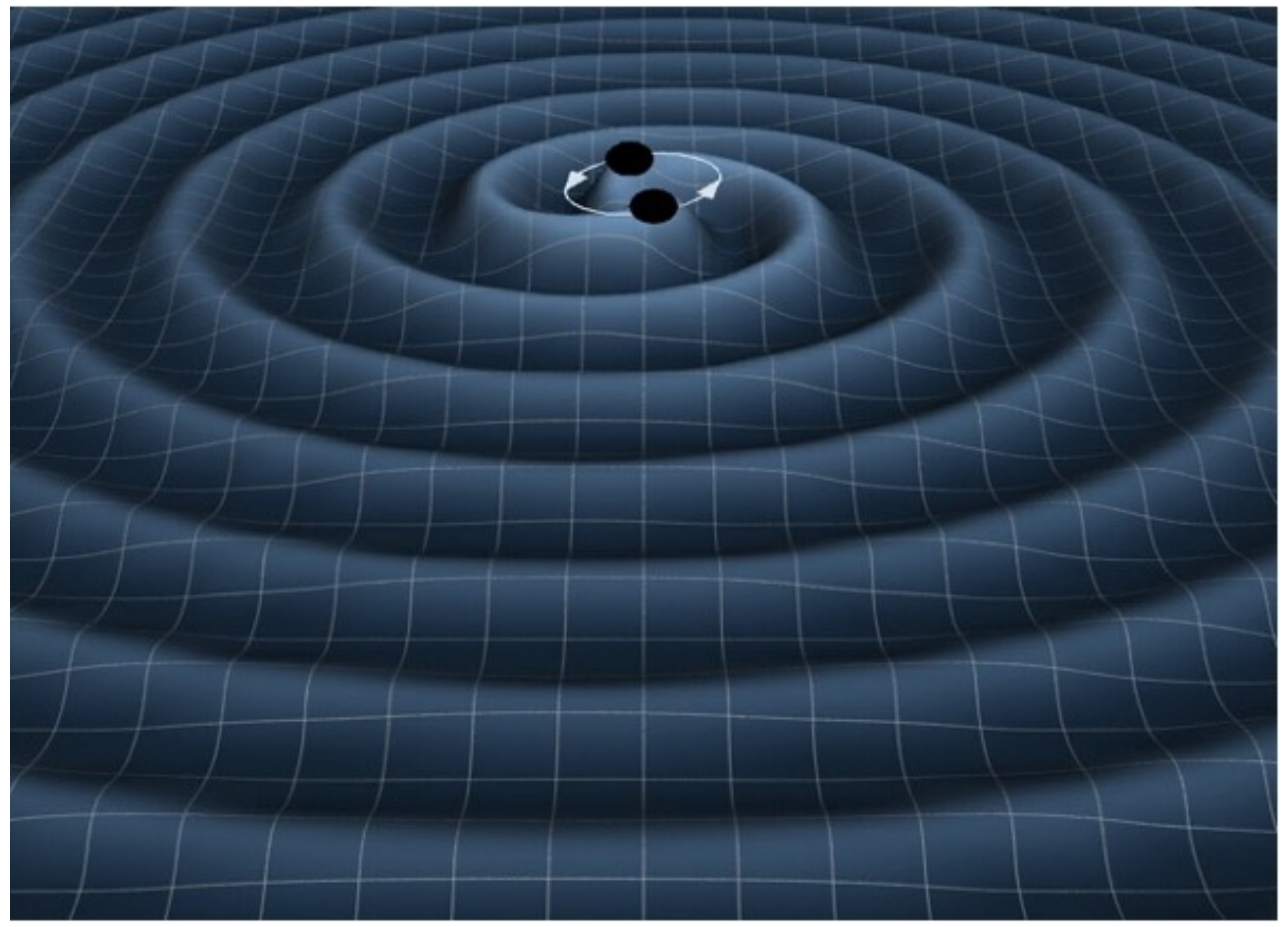
September 14, 2015 - GW150914

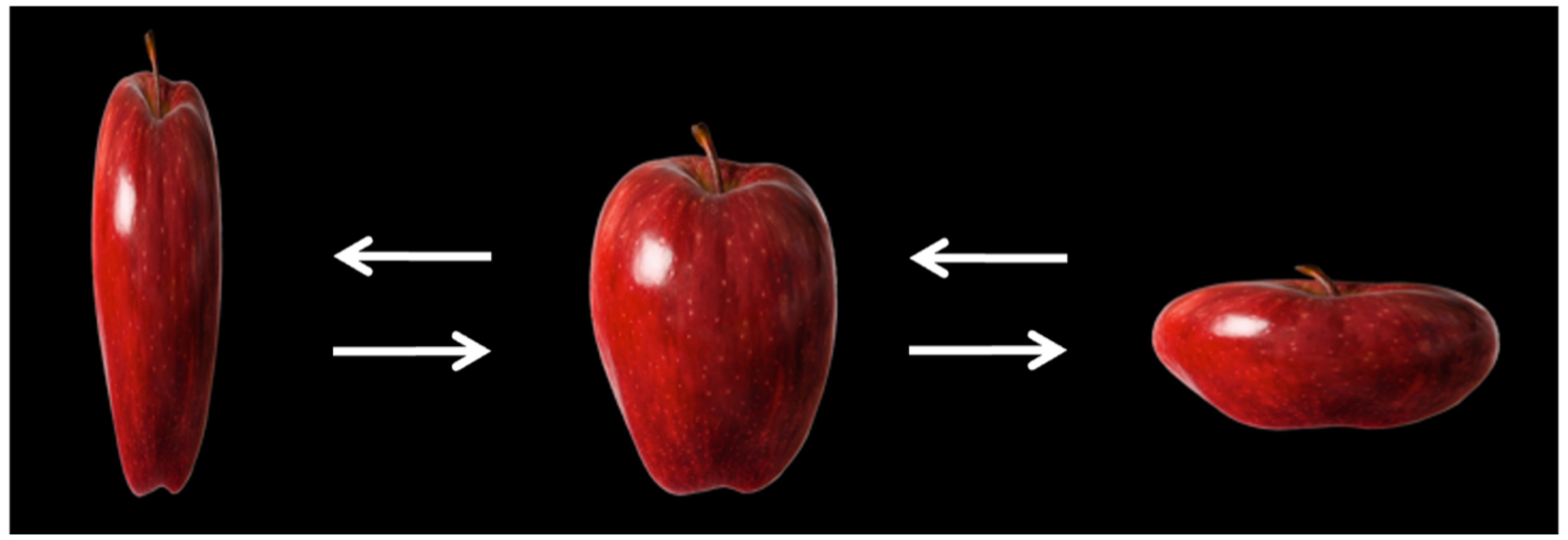


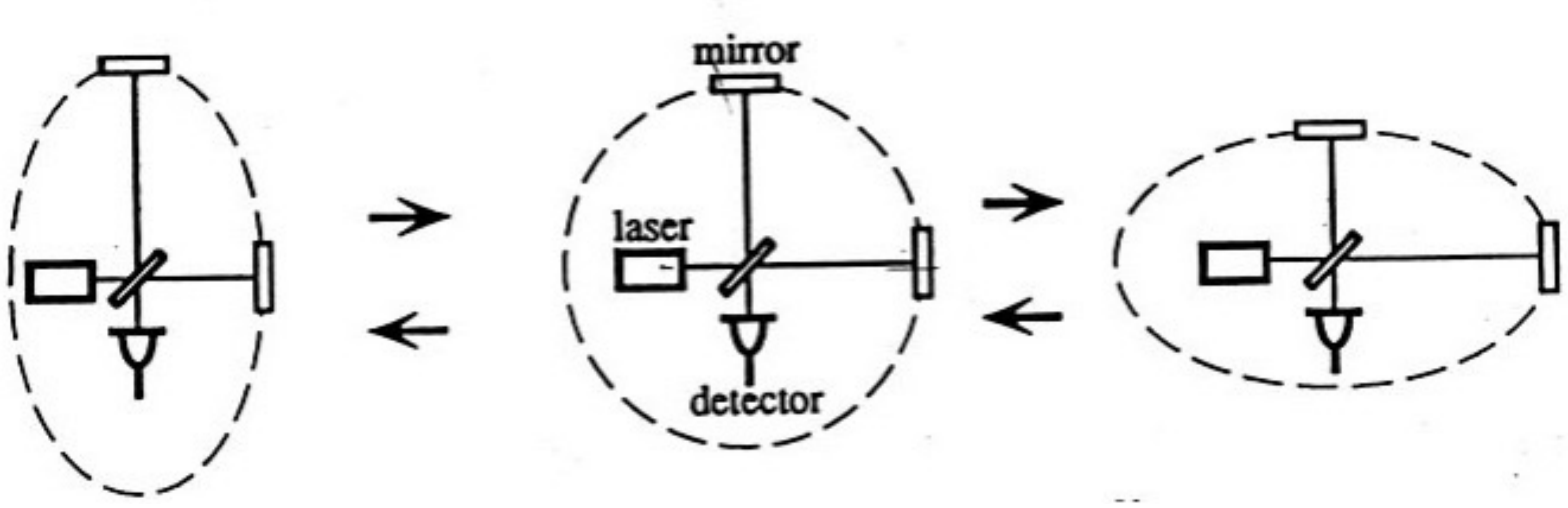
- 410 Mpc (1.34 billion light years) away
- Two black holes (BHs)
  - 36 $M_\odot$ and 29 $M_\odot$
- Formed a 62 $M_\odot$ BH
- 3 $M_\odot$ of energy radiated as gravitational waves (GWs)

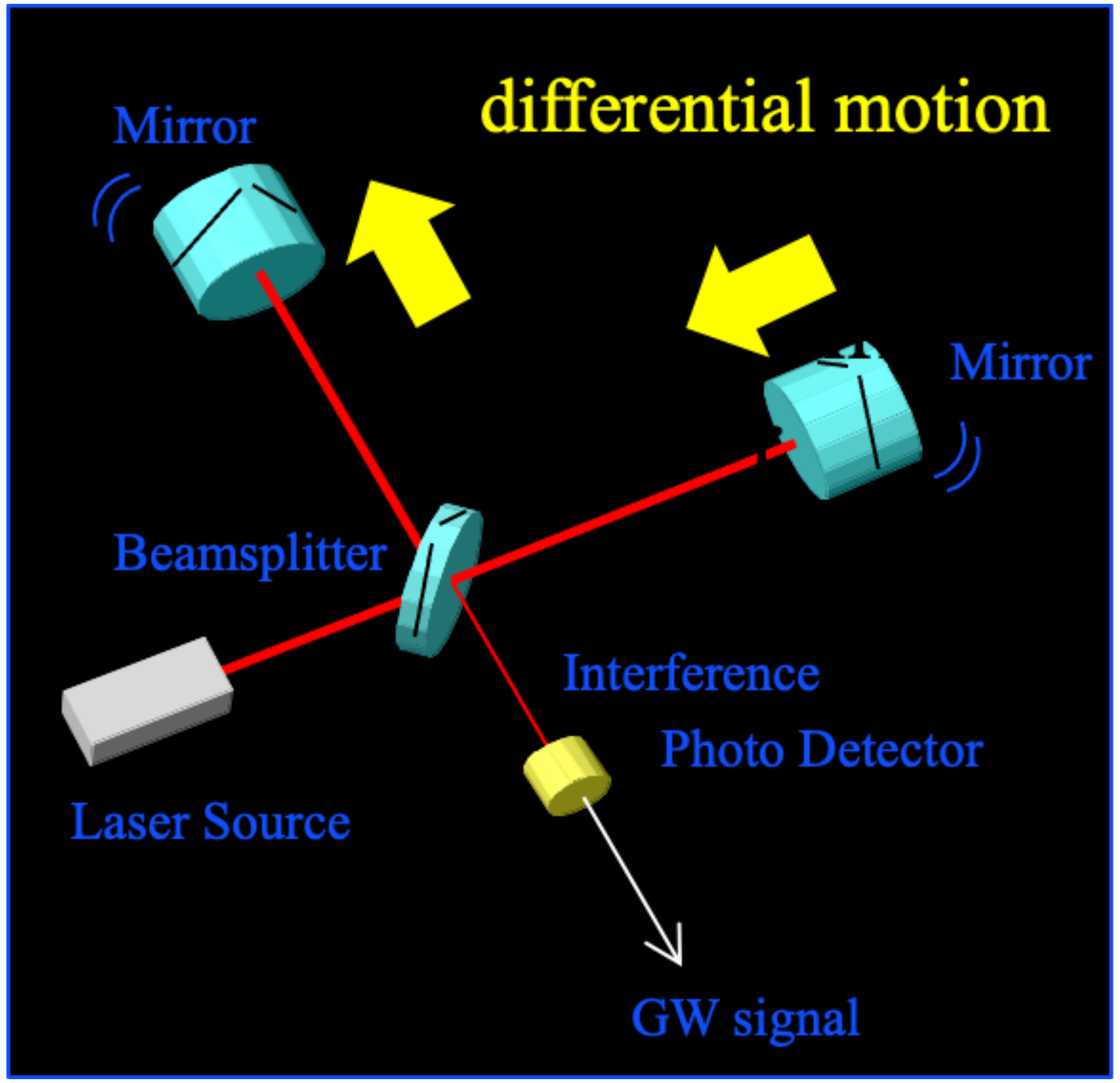
B.P. Abbott et al. (LIGO Scientific Collaboration and Virgo Collaboration) Phys. Rev. Lett. **116**, 061102

Distortion of spacetime due to coalescing binaries







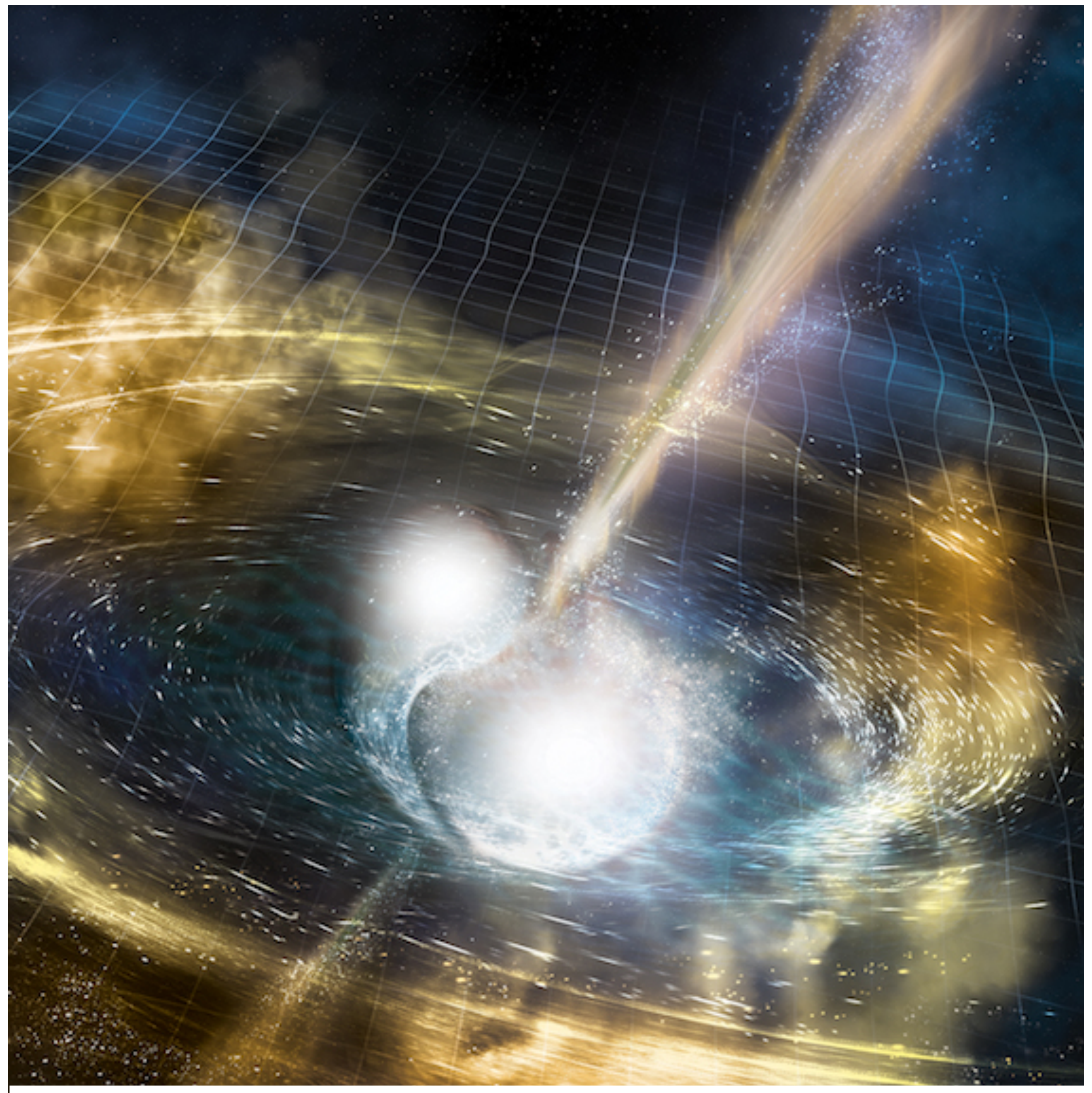


Laser interferometer is an “ideal” instrument for detecting GWs

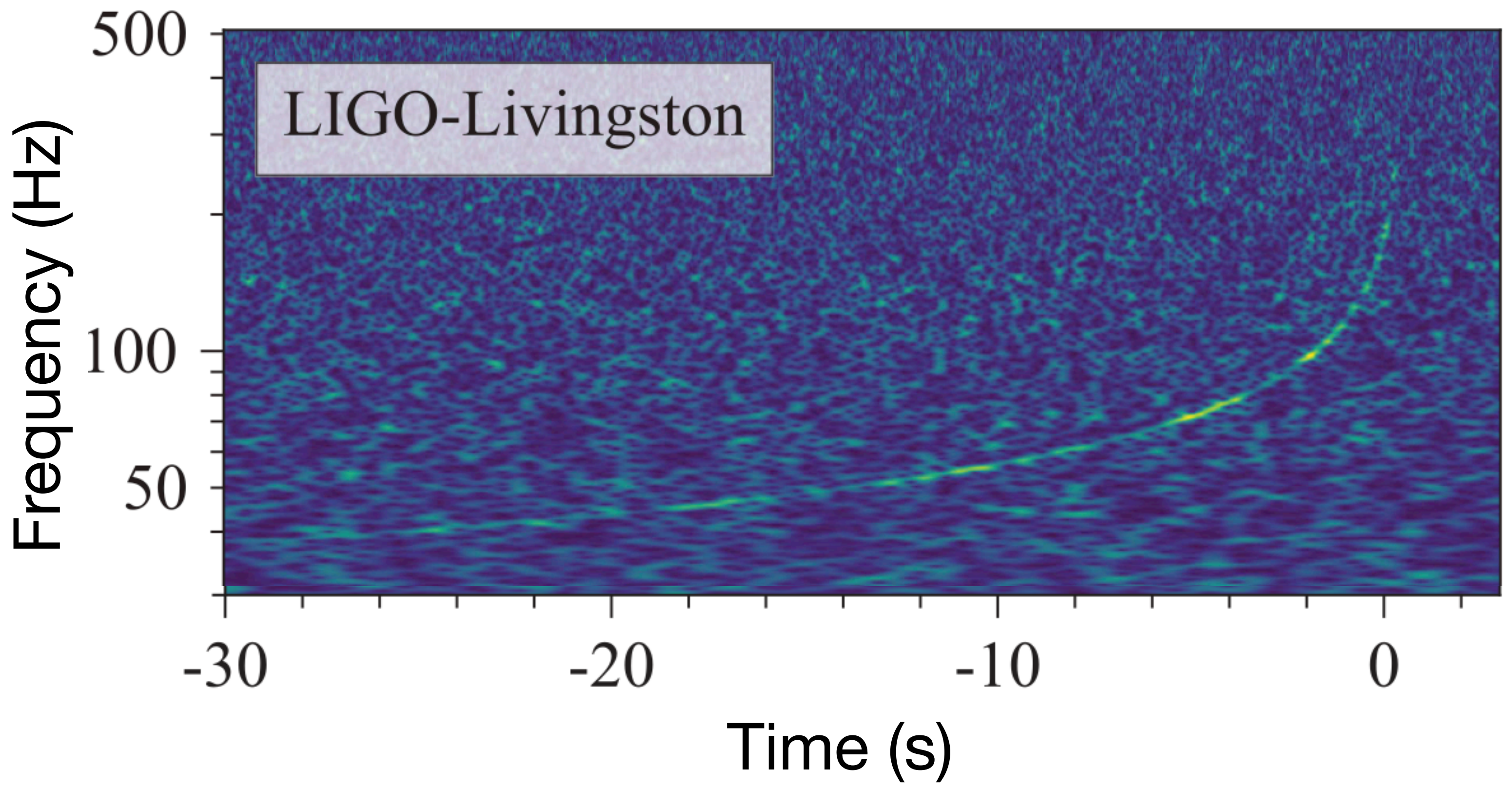
Science enabled by accurate calibration

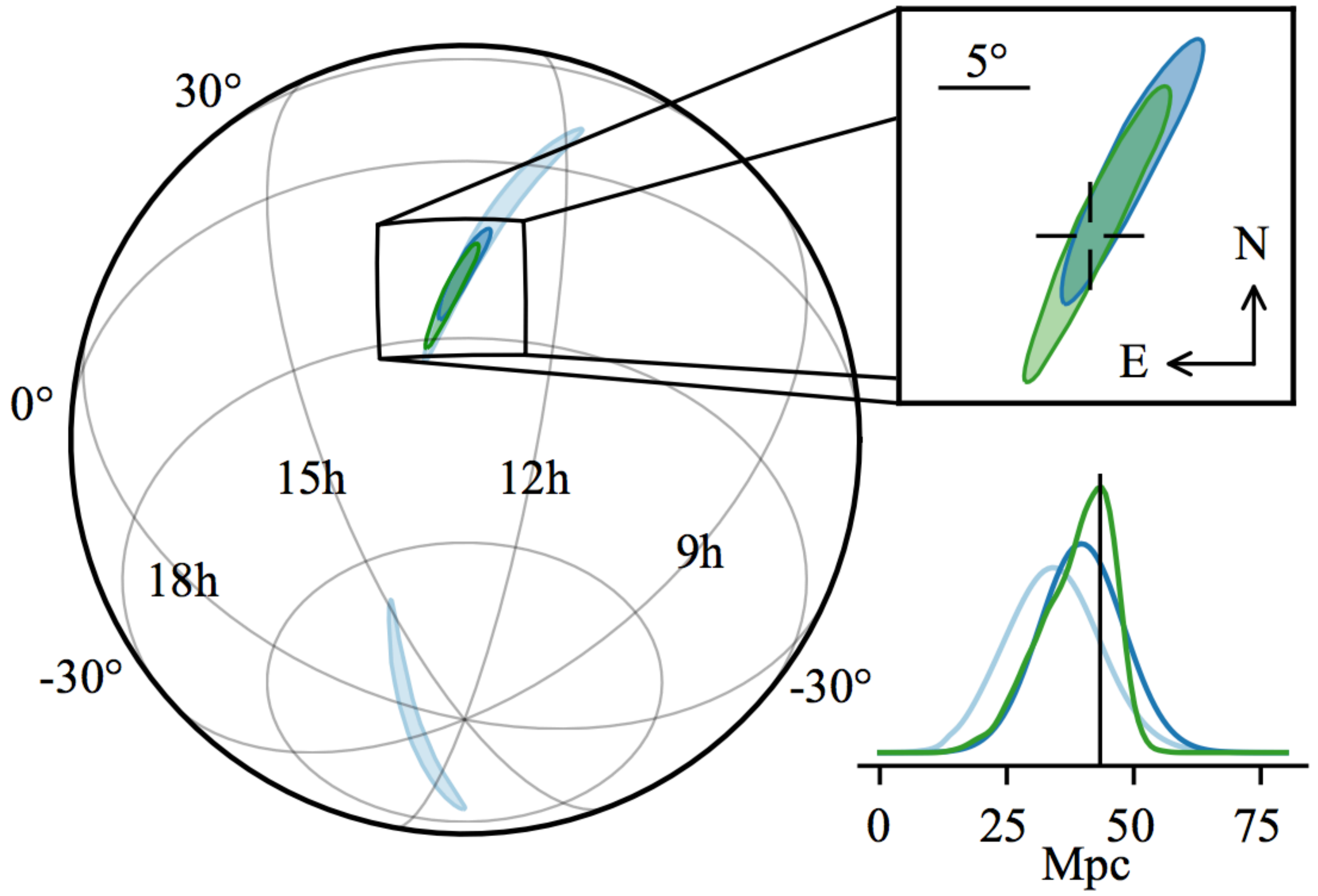
GW170817

Artist's depiction of two merging neutron stars



Credit: NSF/LIGO/Sonoma State University/ A. Simonnet



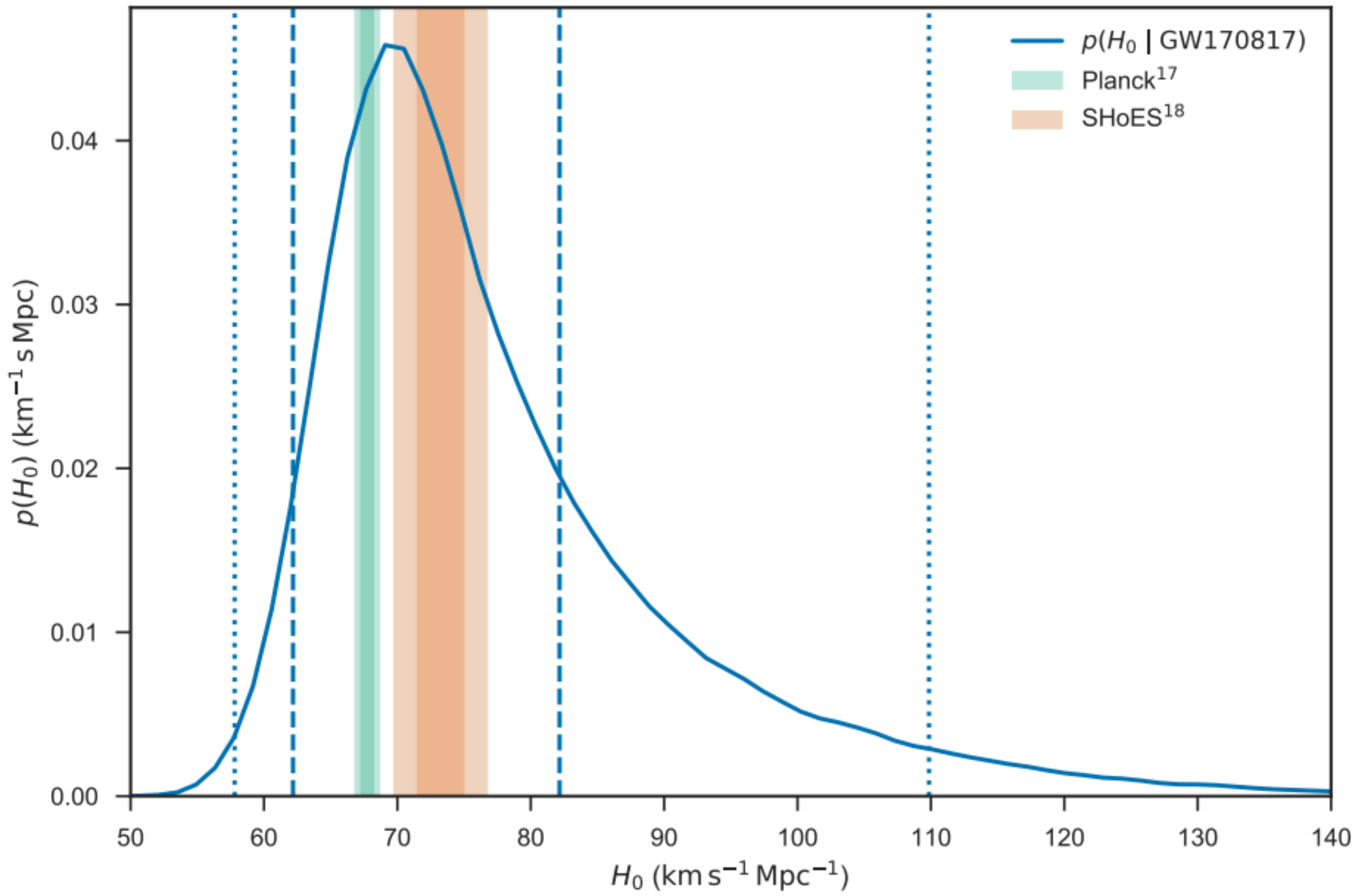


https://www.ligo.org/science/Publication-GW170817BNS/

Accurate calibration improves distance and sky localization estimates

DECam images of NGC4993 galaxy

Independent measurement of the Hubble parameter using GWs



Abbott, B et al. Nature 551 **85** (2017)

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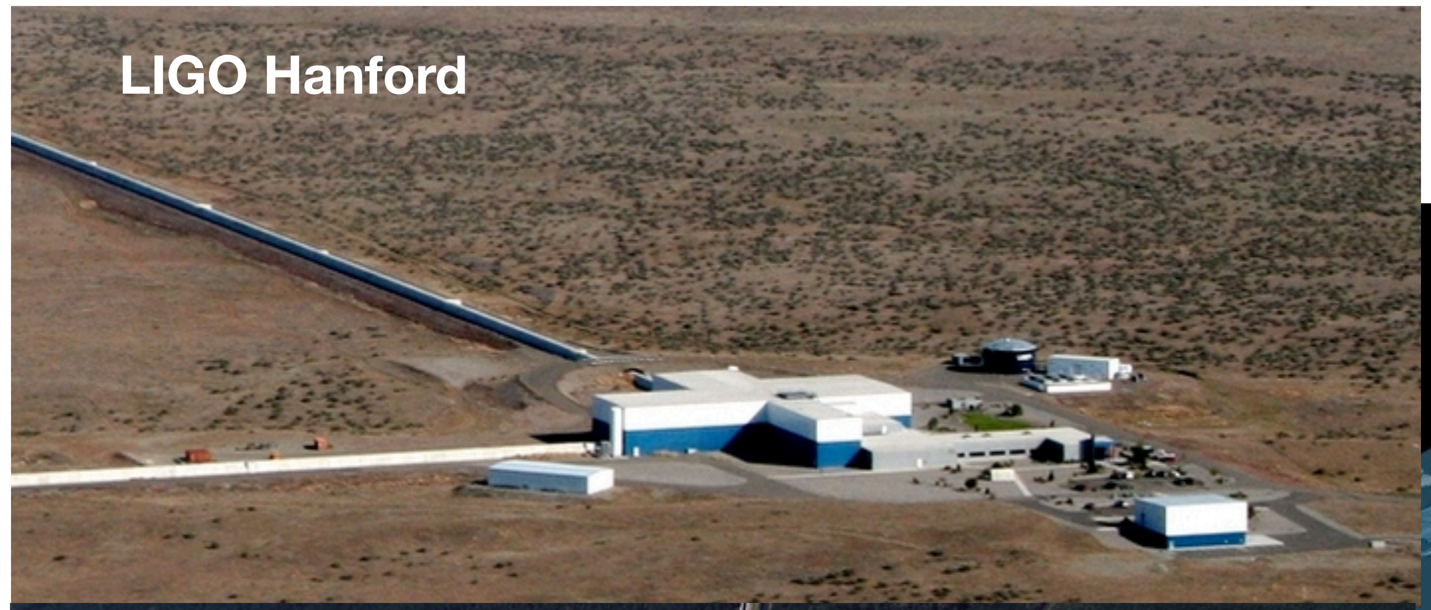
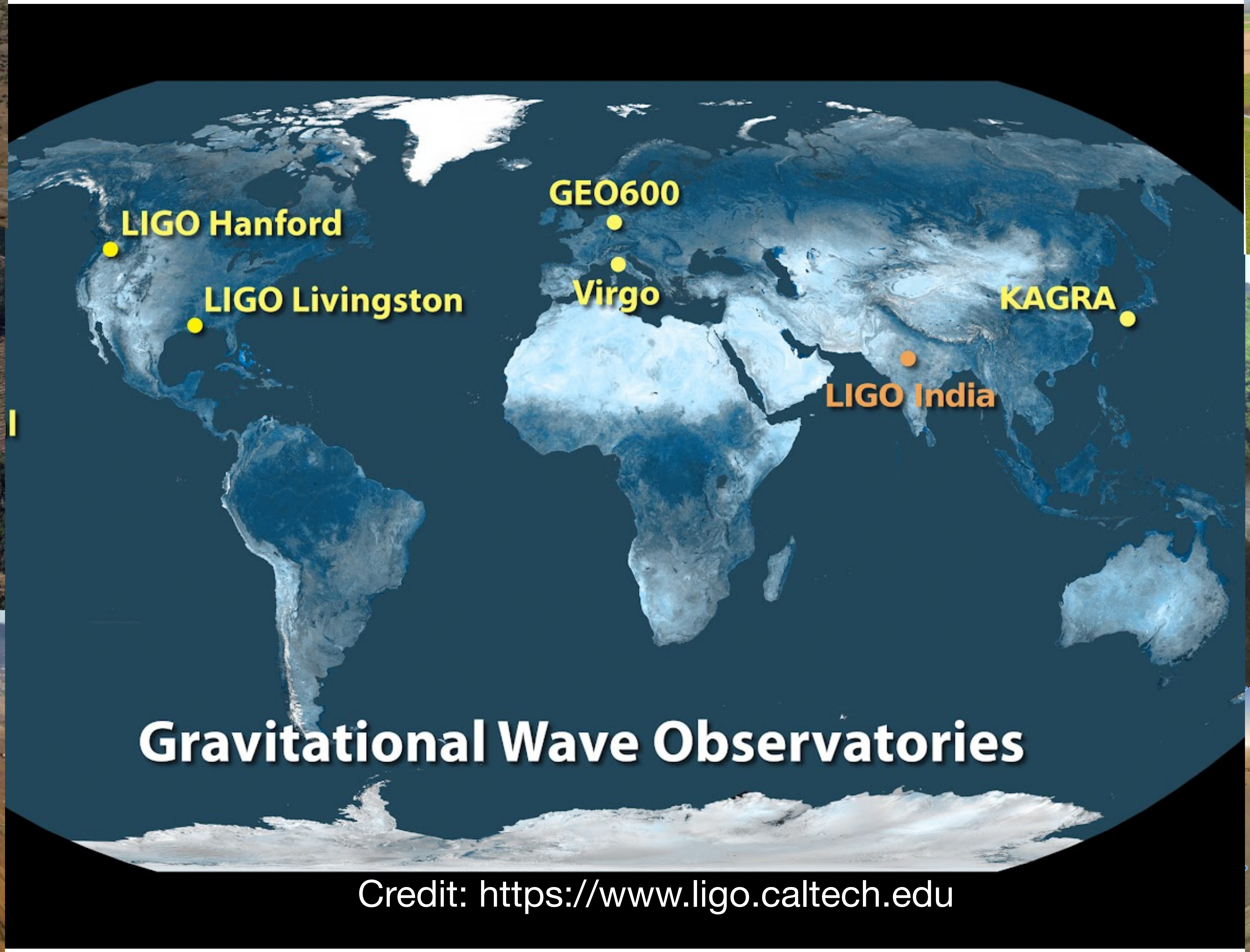
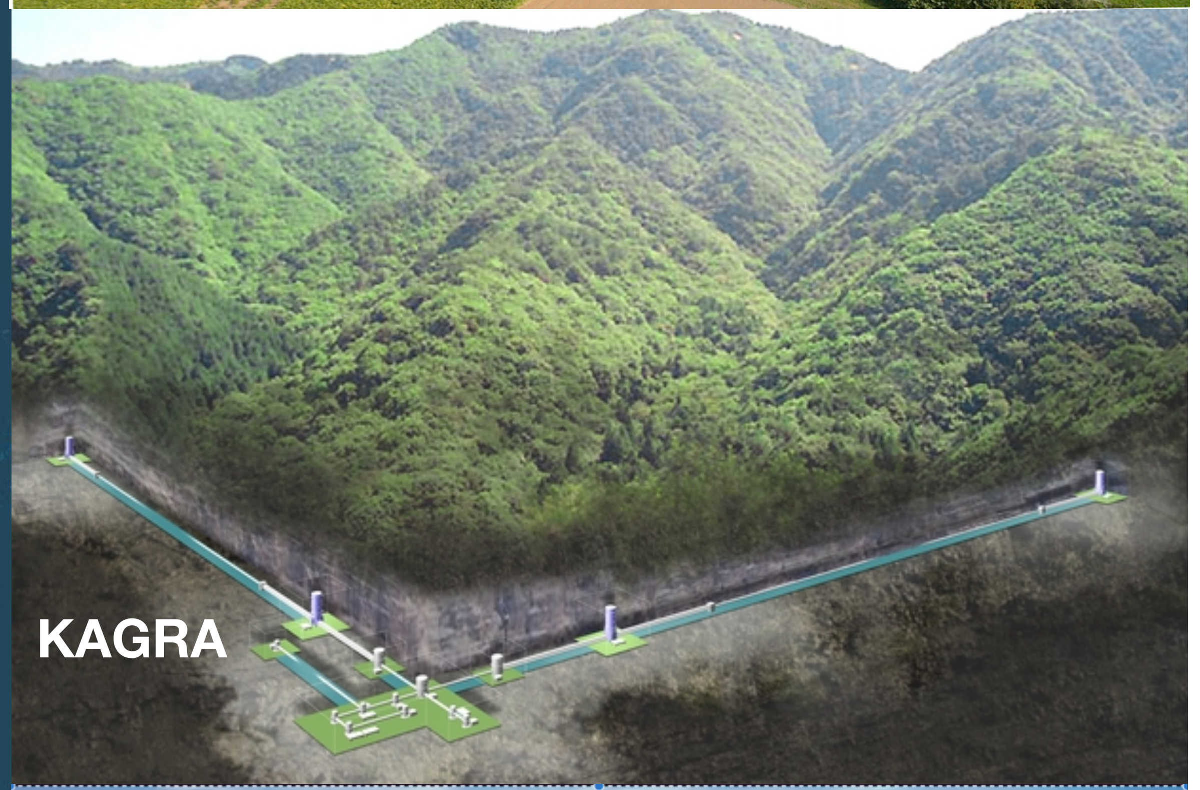
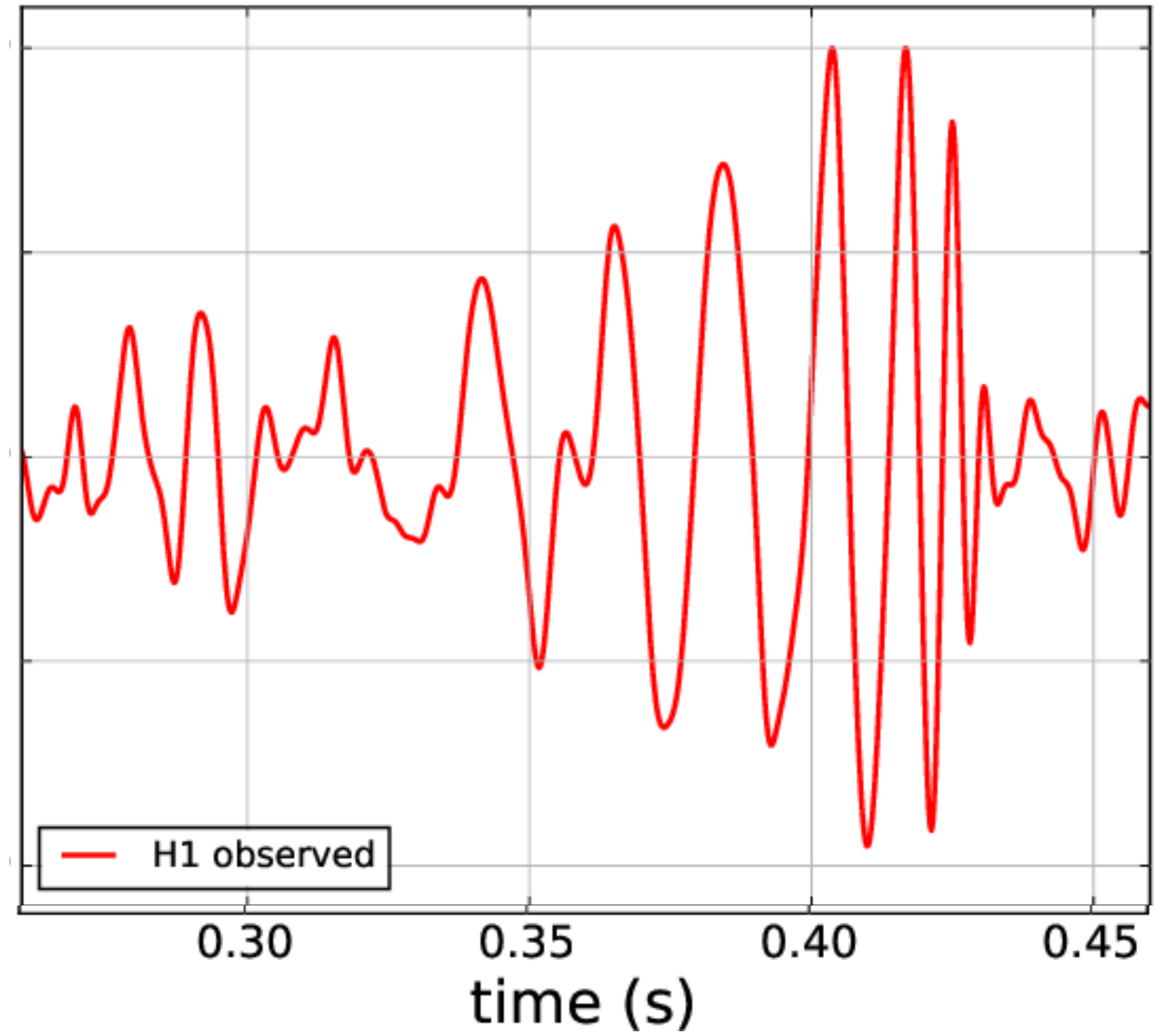
Global network of gravitational wave (GW) detectors



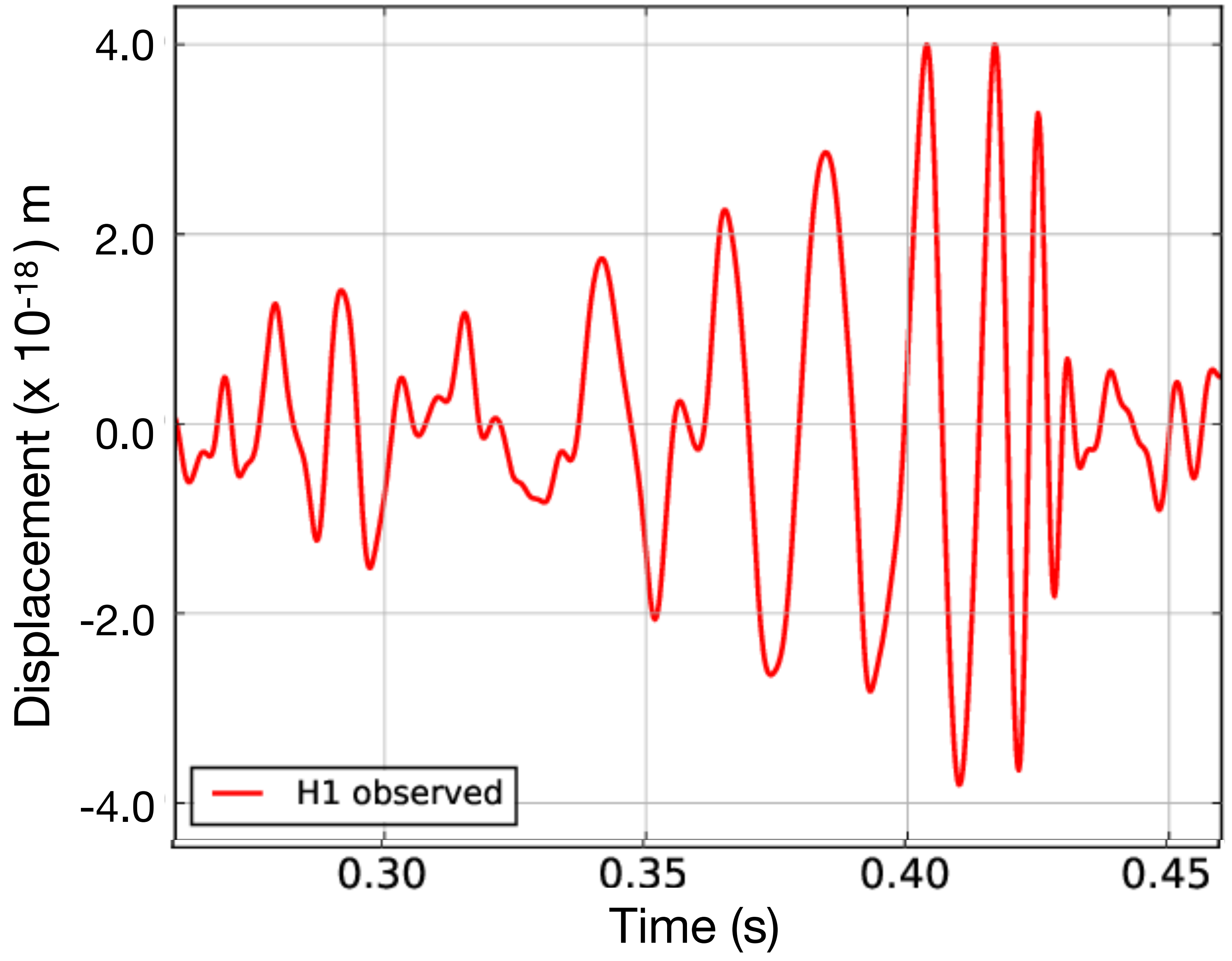




Calibration of the detected GW signals



Calibration converts the y-axis scale to meters



Accurate calibration ($\lesssim 1\,\%$) is required to optimally extract astrophysical information from GW signals

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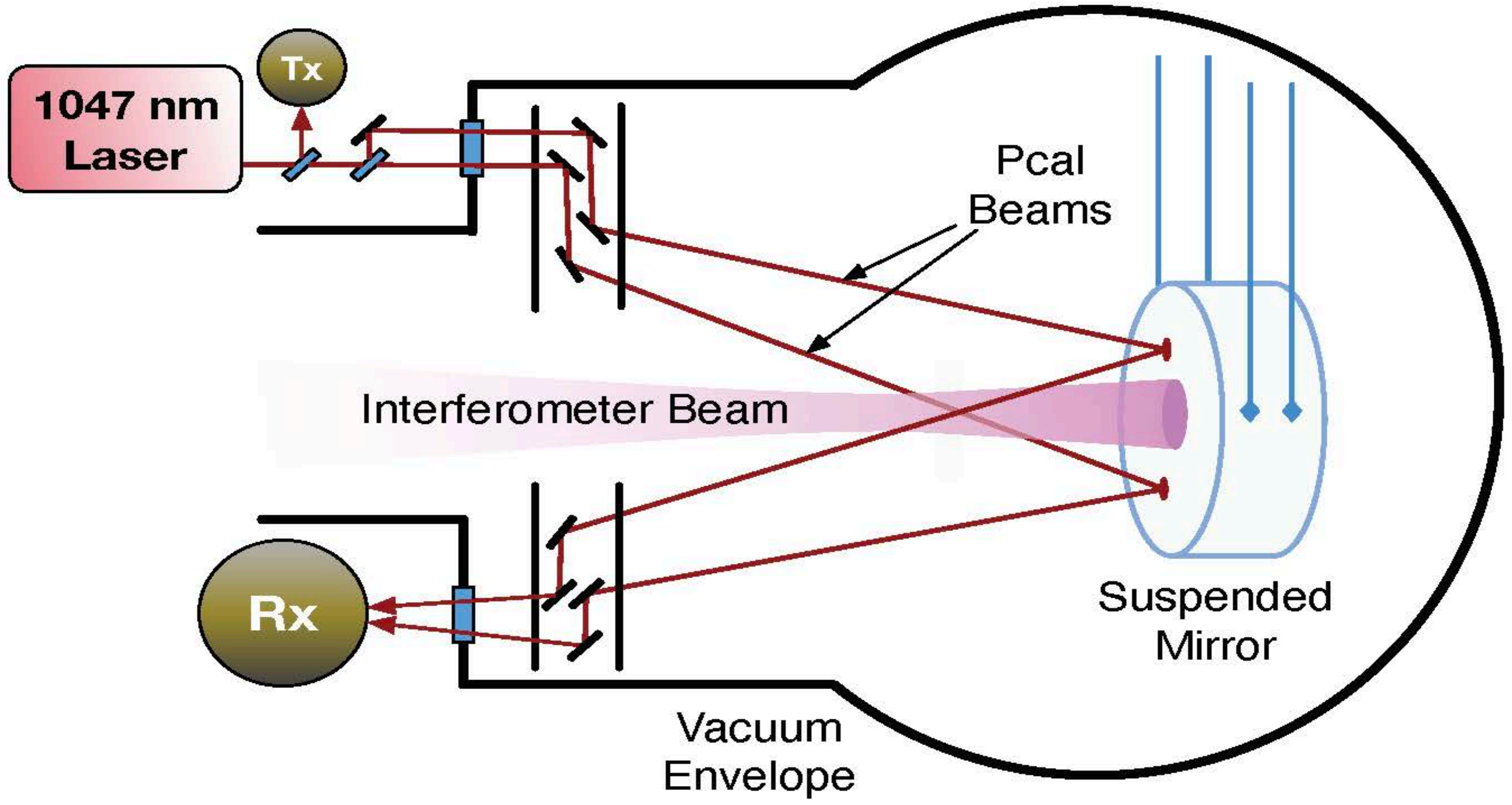
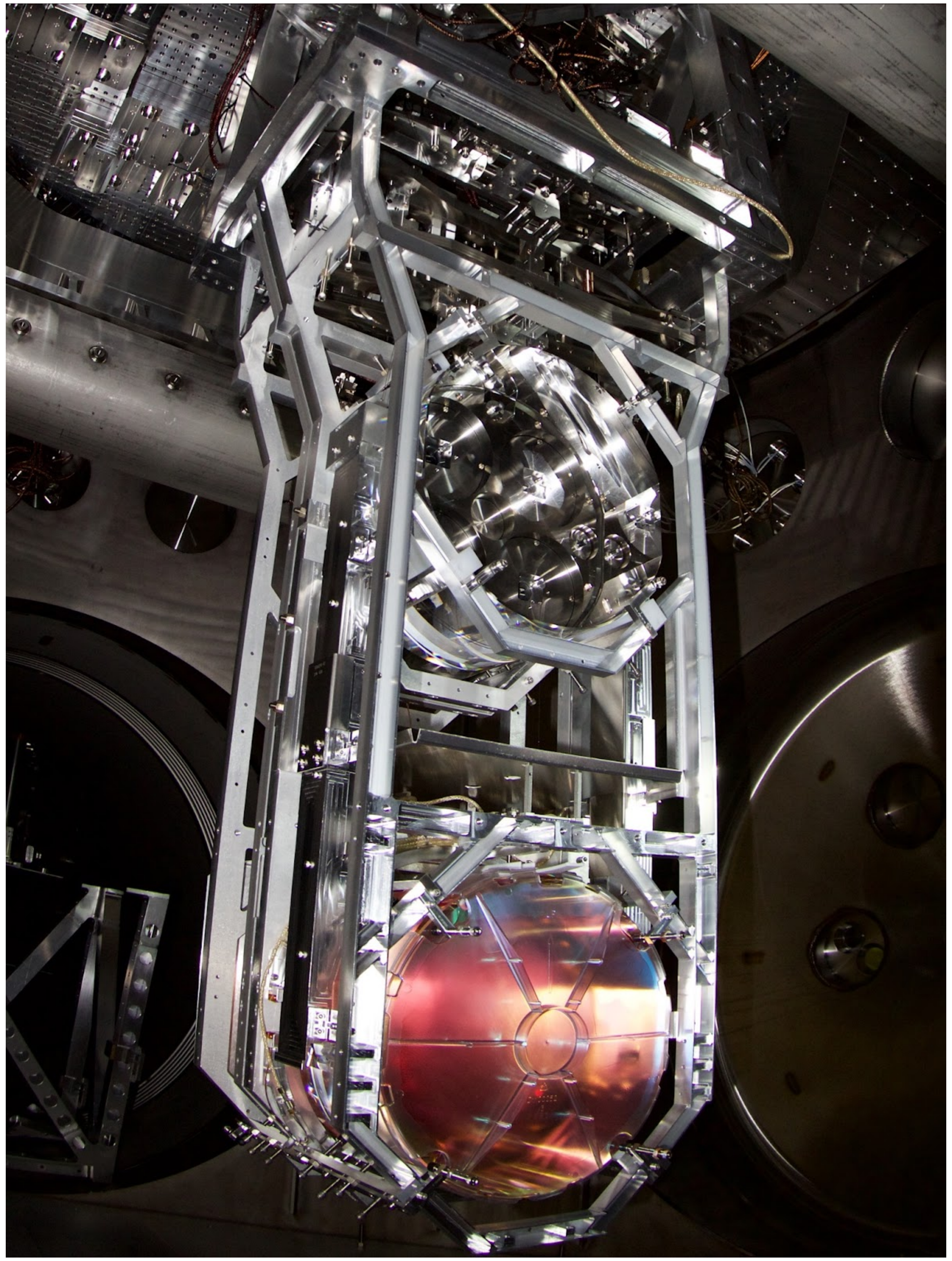
Photon calibrators - for absolute displacement calibration

Photon Calibrators (Pcals) - radiation pressure based systems to generate fiducial length variations

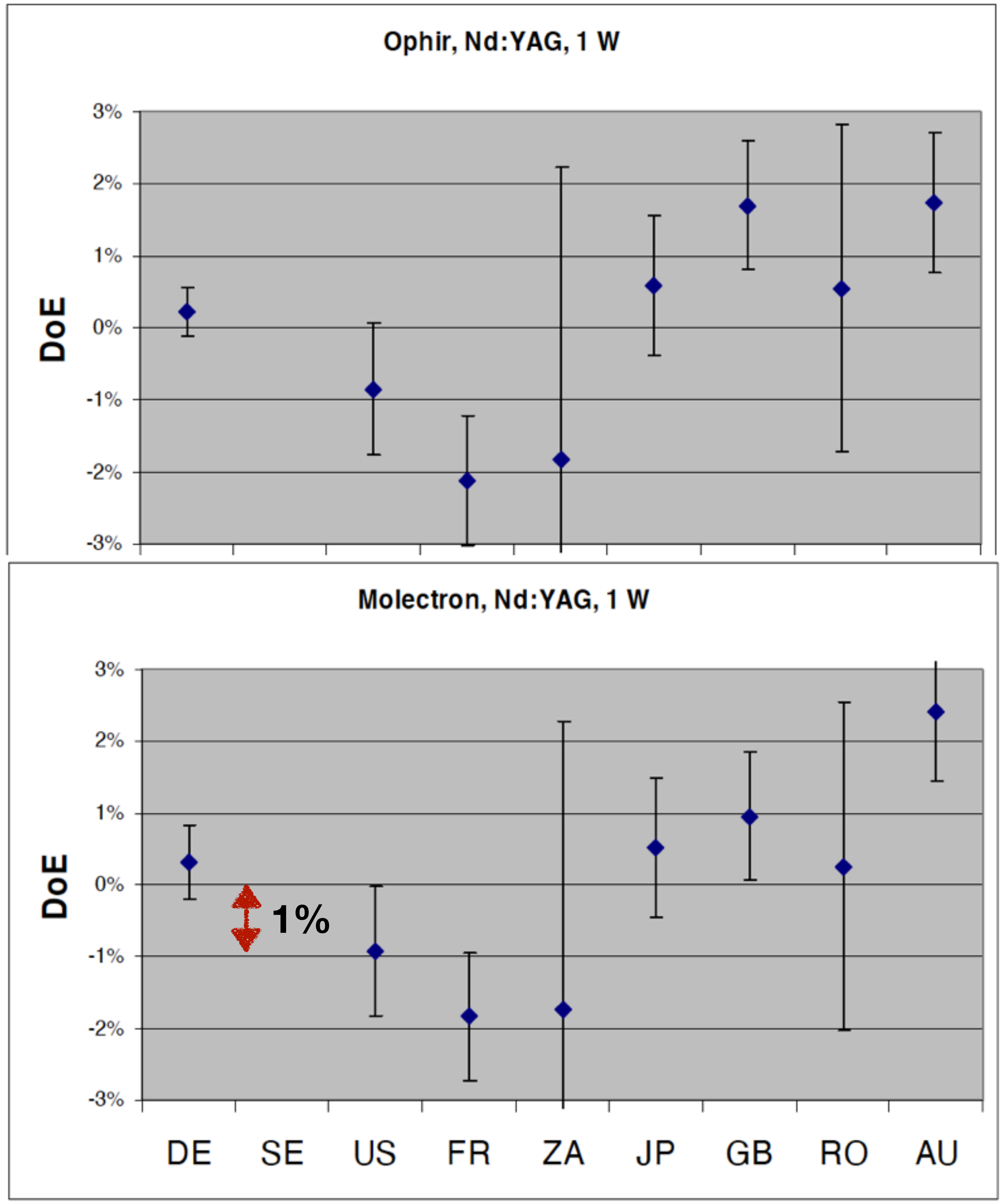


$$x(\omega) = -\frac{2\cos\theta}{M\omega^2 c}P(\omega)$$

Power reflected from the test mass inside the vacuum chamber

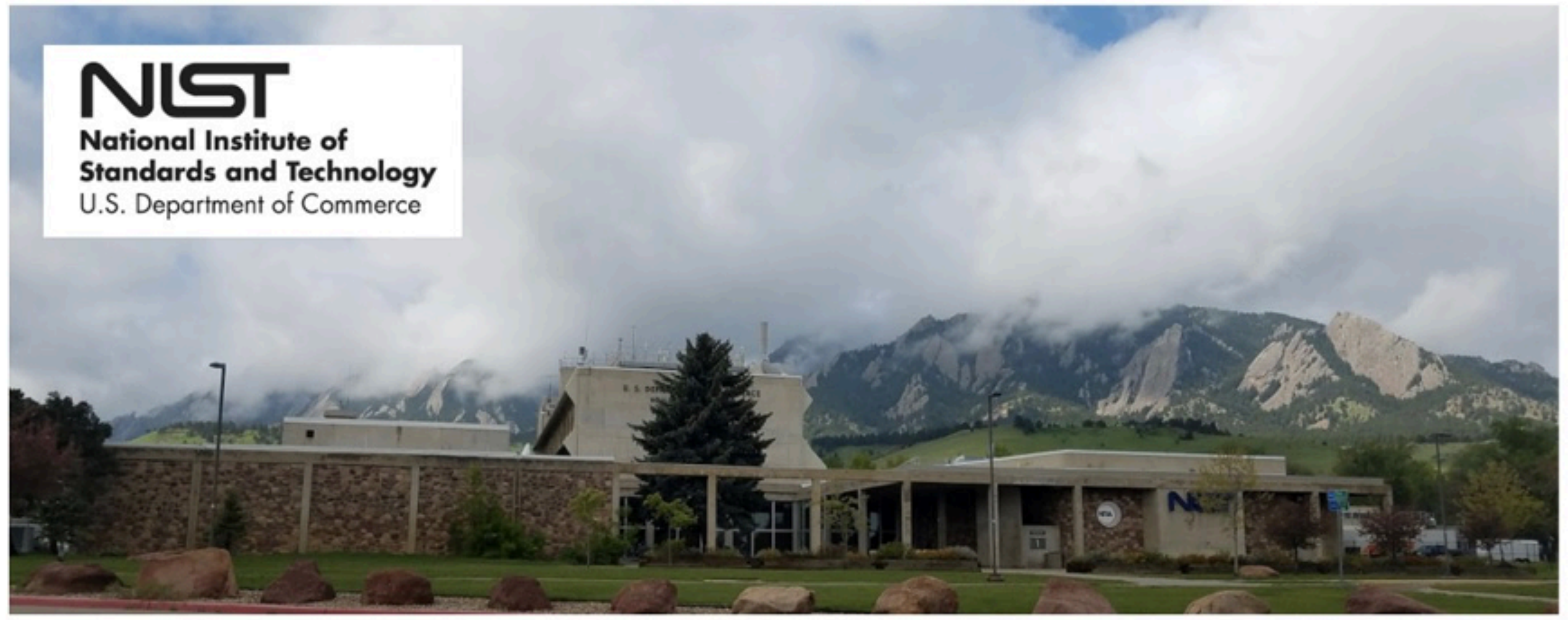


NMI radiant power calibration

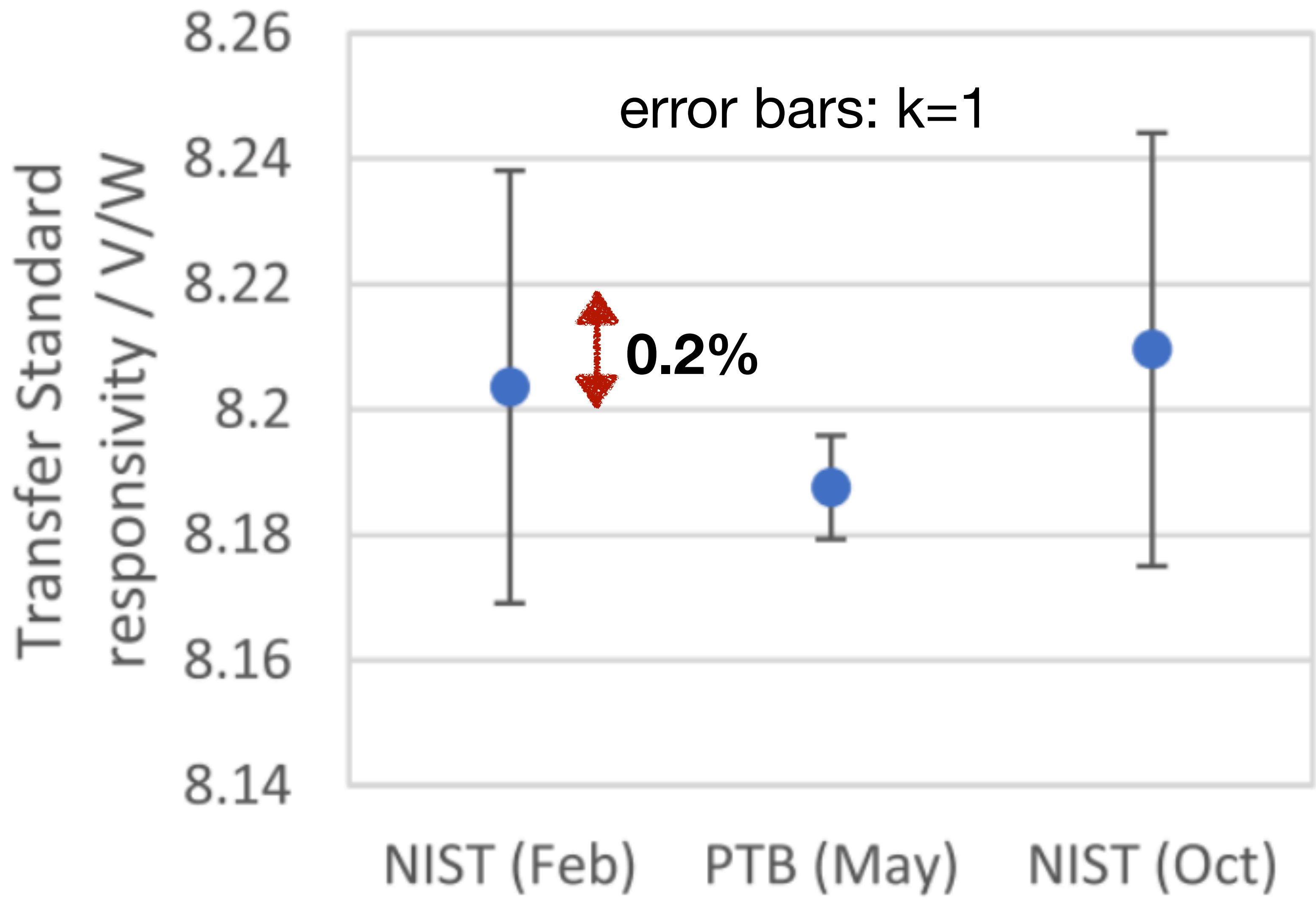


S. Kück, 2009, EUROMET Comparison, Project No. 156, EUROMET.PR-S2
Metrologia **47** 02003

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

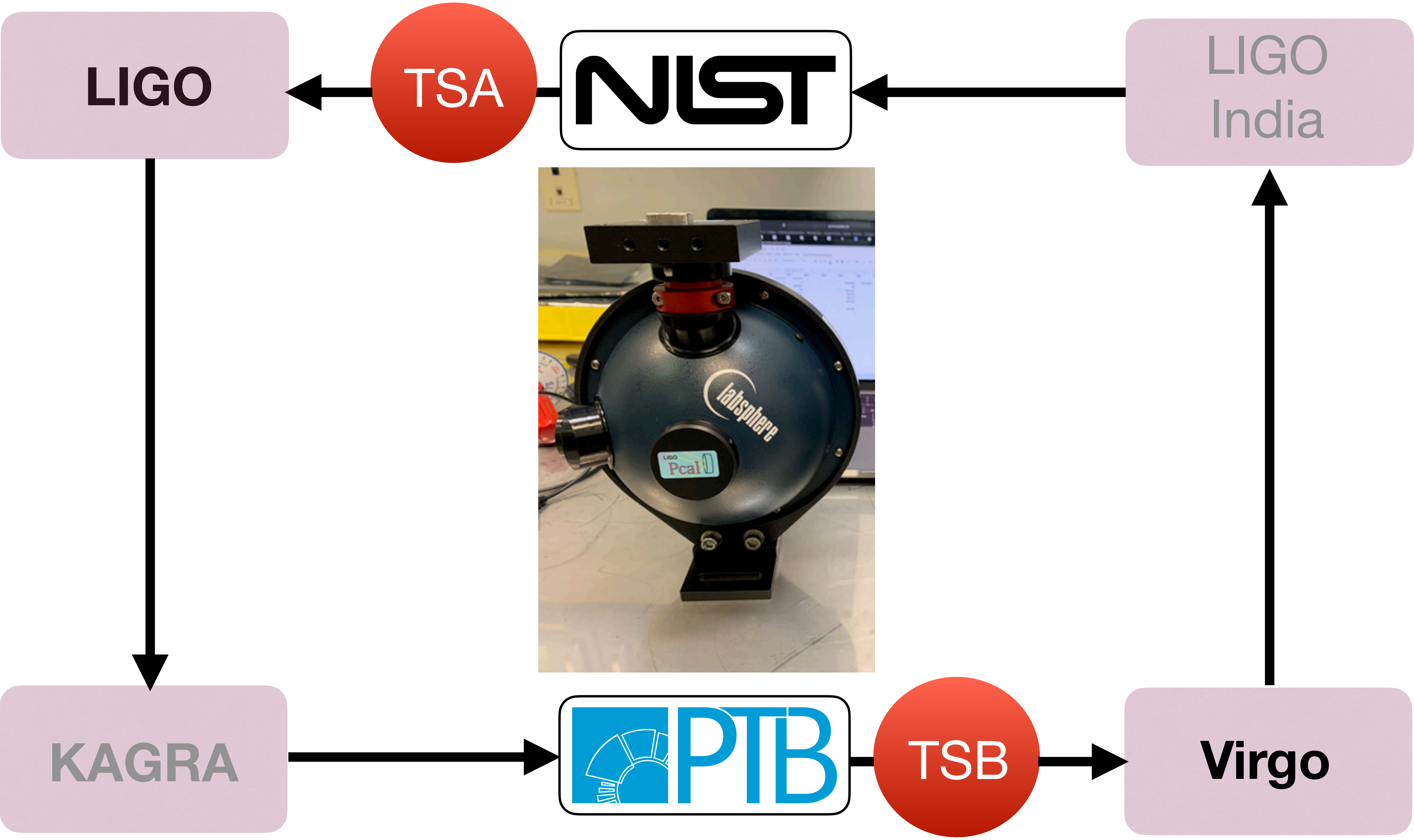


2020 NIST/PTB bilateral comparison using LIGO transfer standard



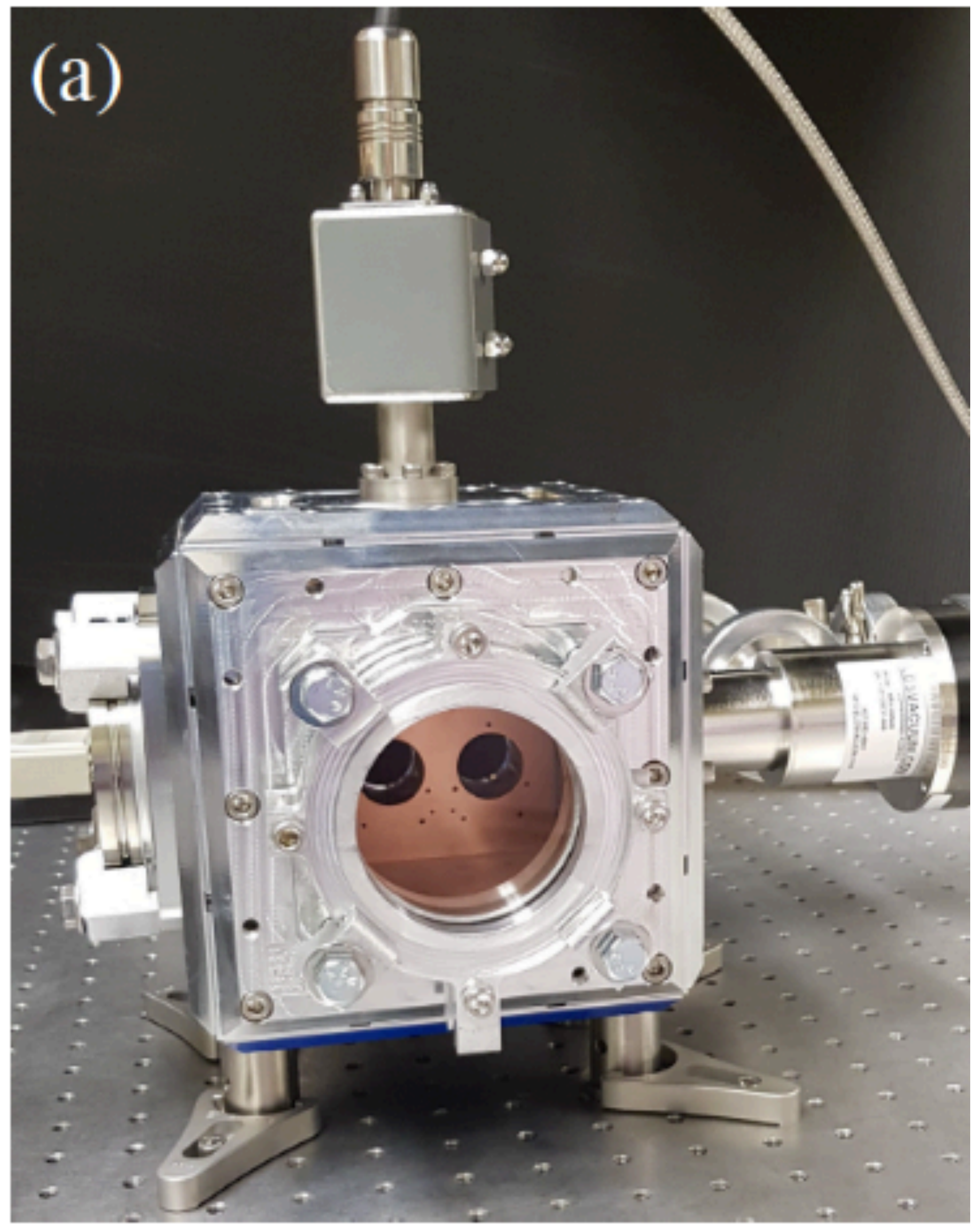
M. Spidell et al. 2021
Metrologia **58** 055011

New global calibration scheme for the ongoing O4 observing run

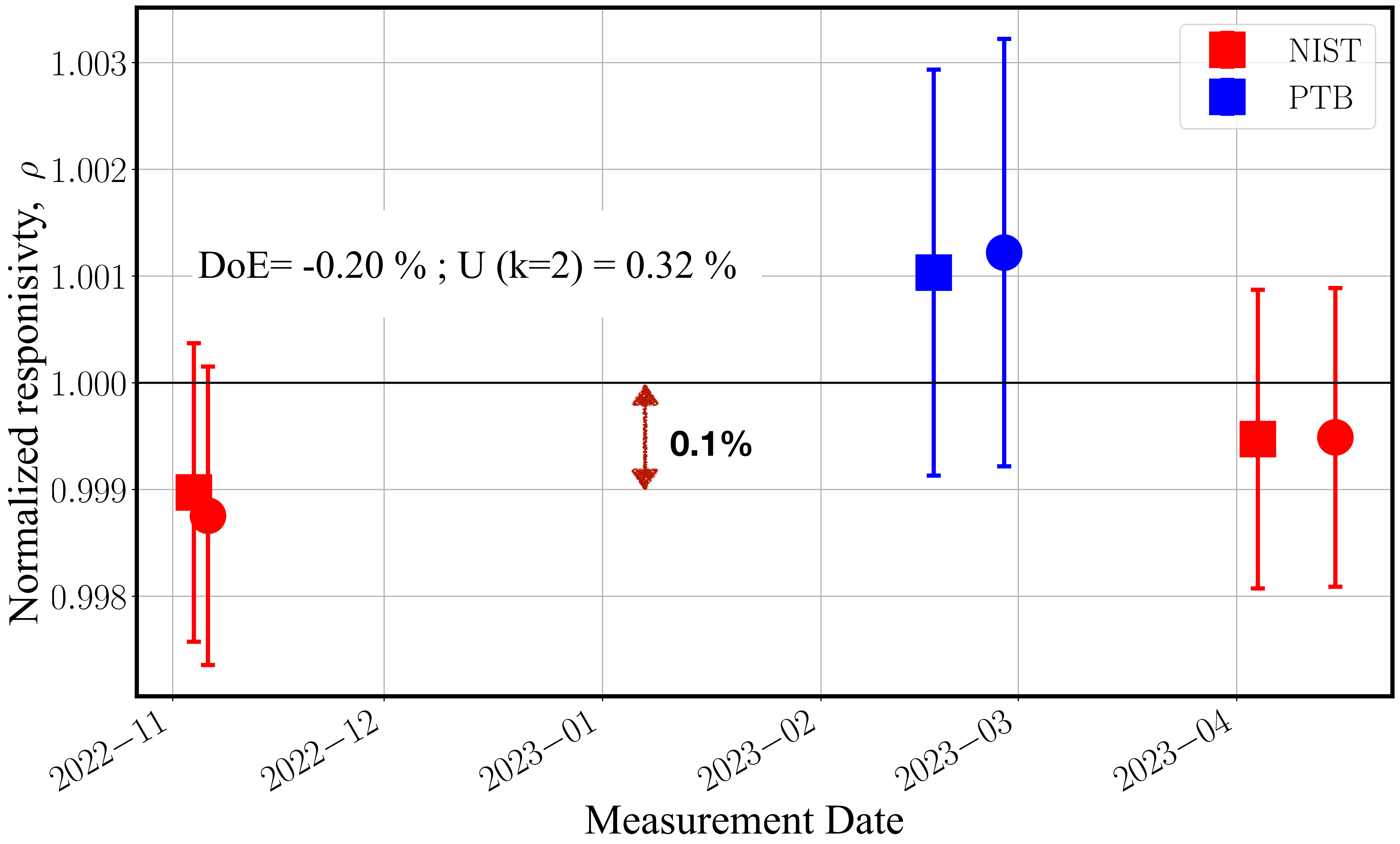


2023 NIST/PTB bilateral comparison

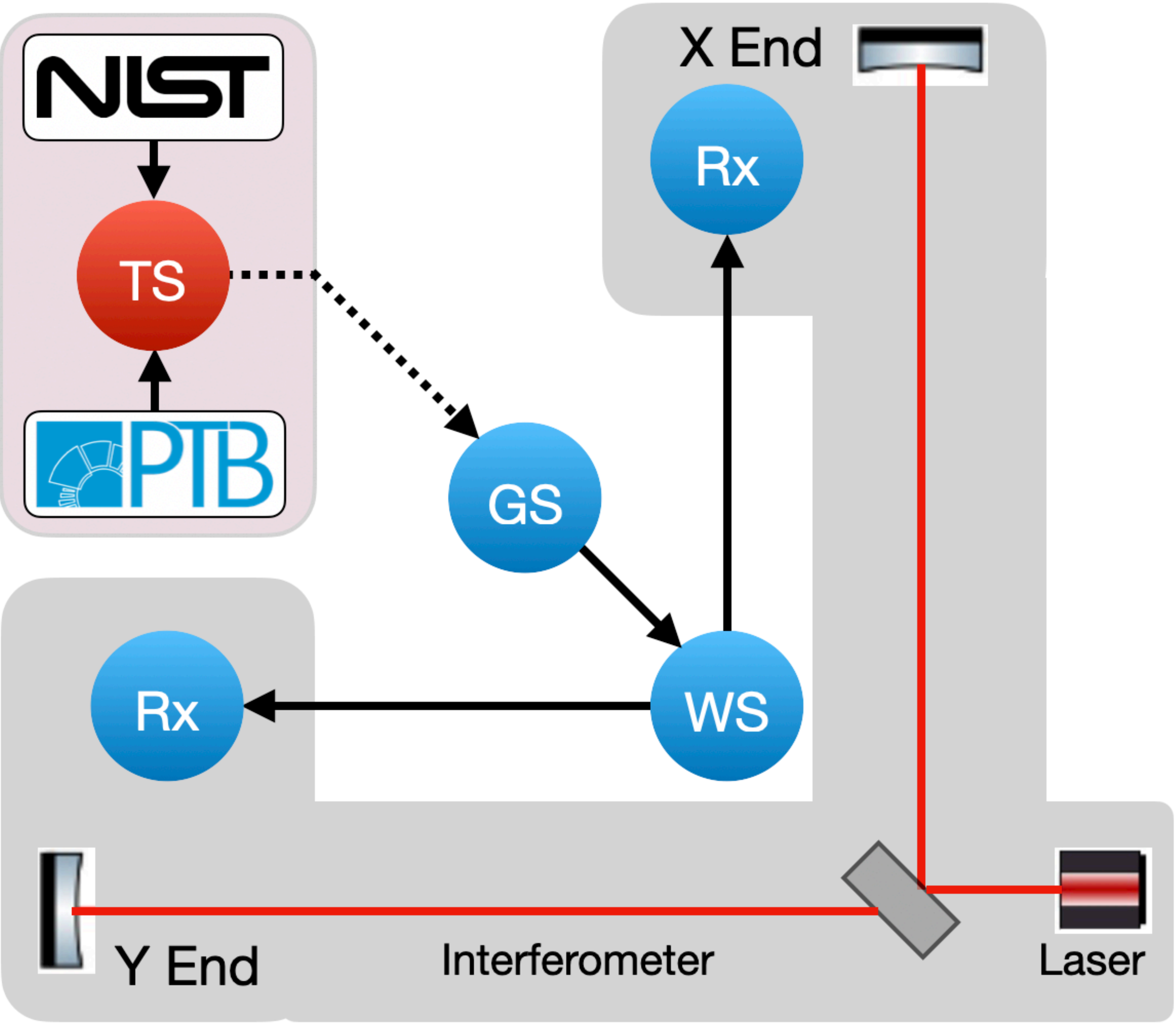
New PARRoT detector at NIST



A. Vaskuri et al. Opt. Express **29** (2021) 22533-52



Transferring the calibration to the end station sensors



$$\rho_{Rx} = \frac{\rho_{Rx}}{\rho_{WS}} \frac{\rho_{WS}}{\rho_{GS}} \frac{\rho_{GS}}{\rho_{TS}} \rho_{TS}$$

ρ : Responsivity of the power sensor

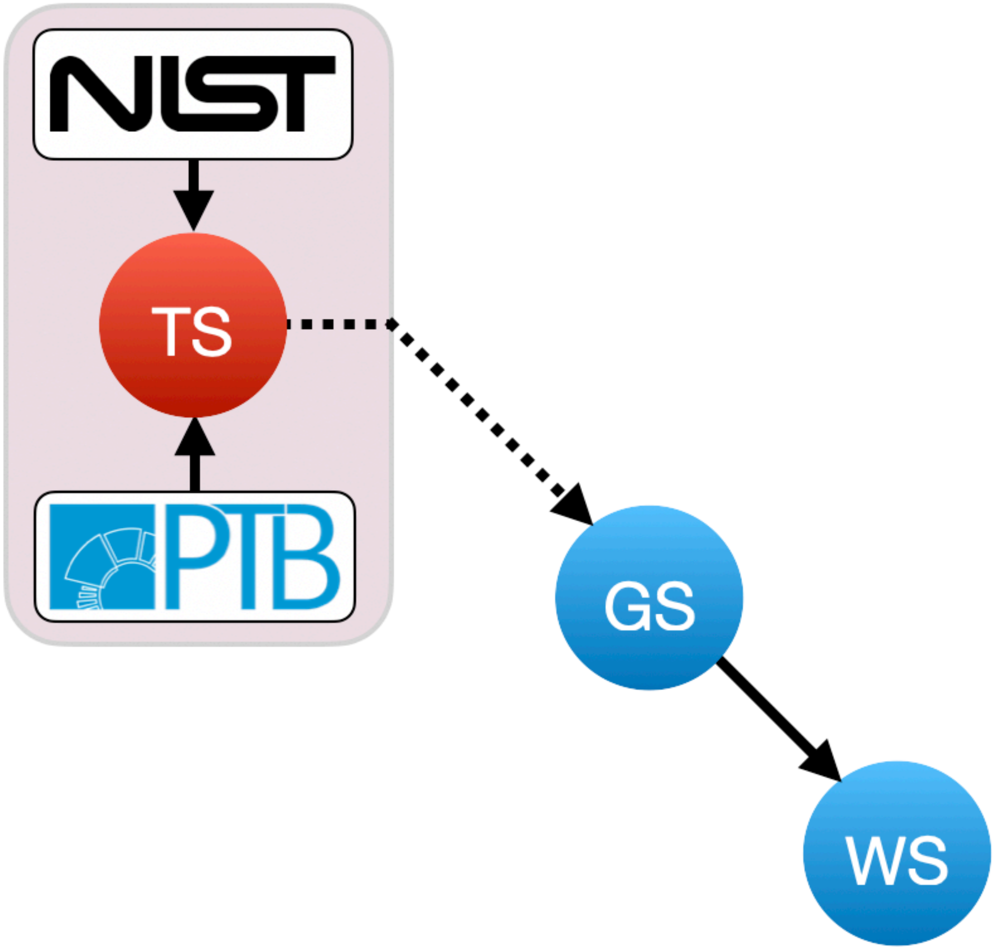
TS: Transfer standard

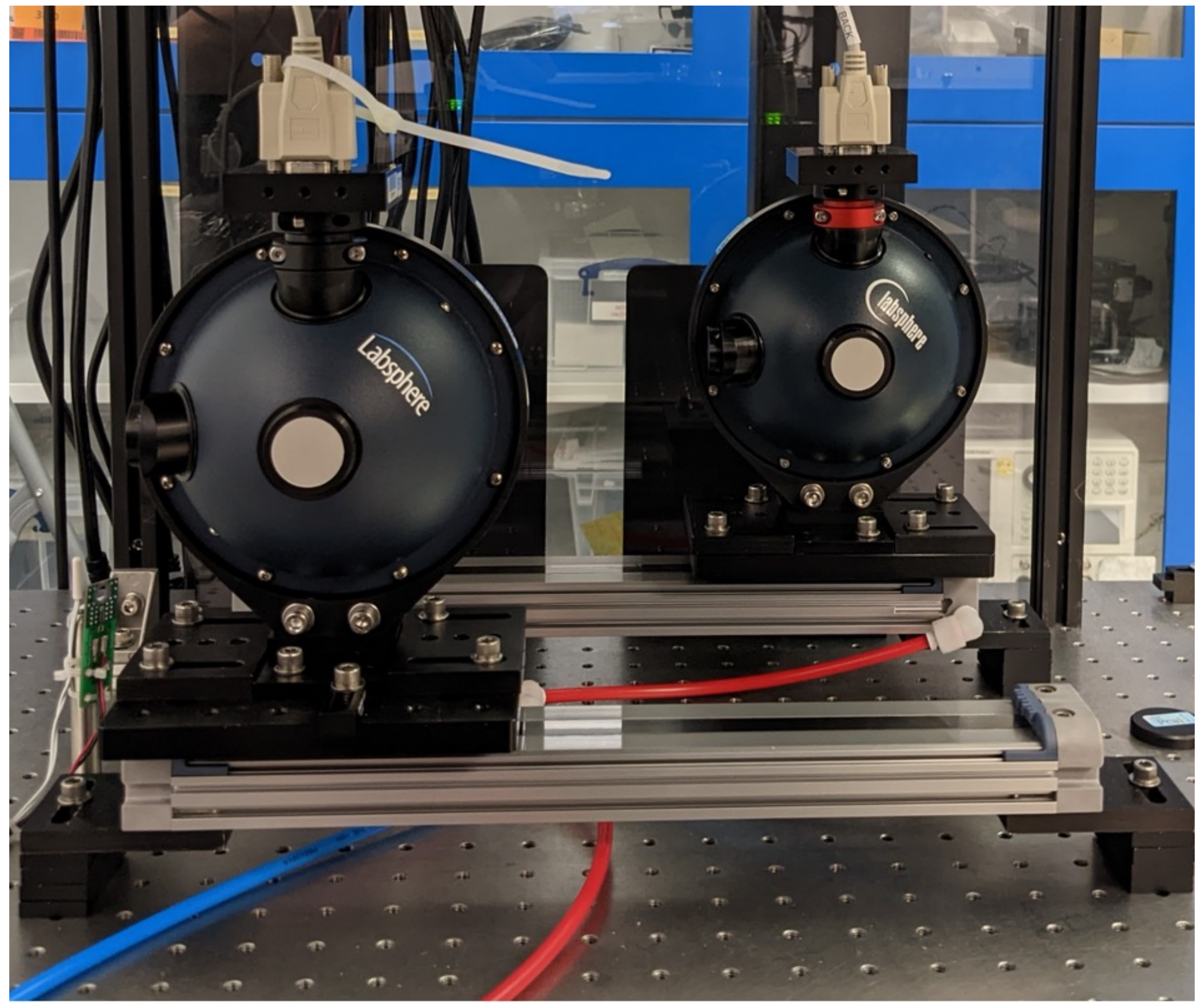
GS: Gold standard

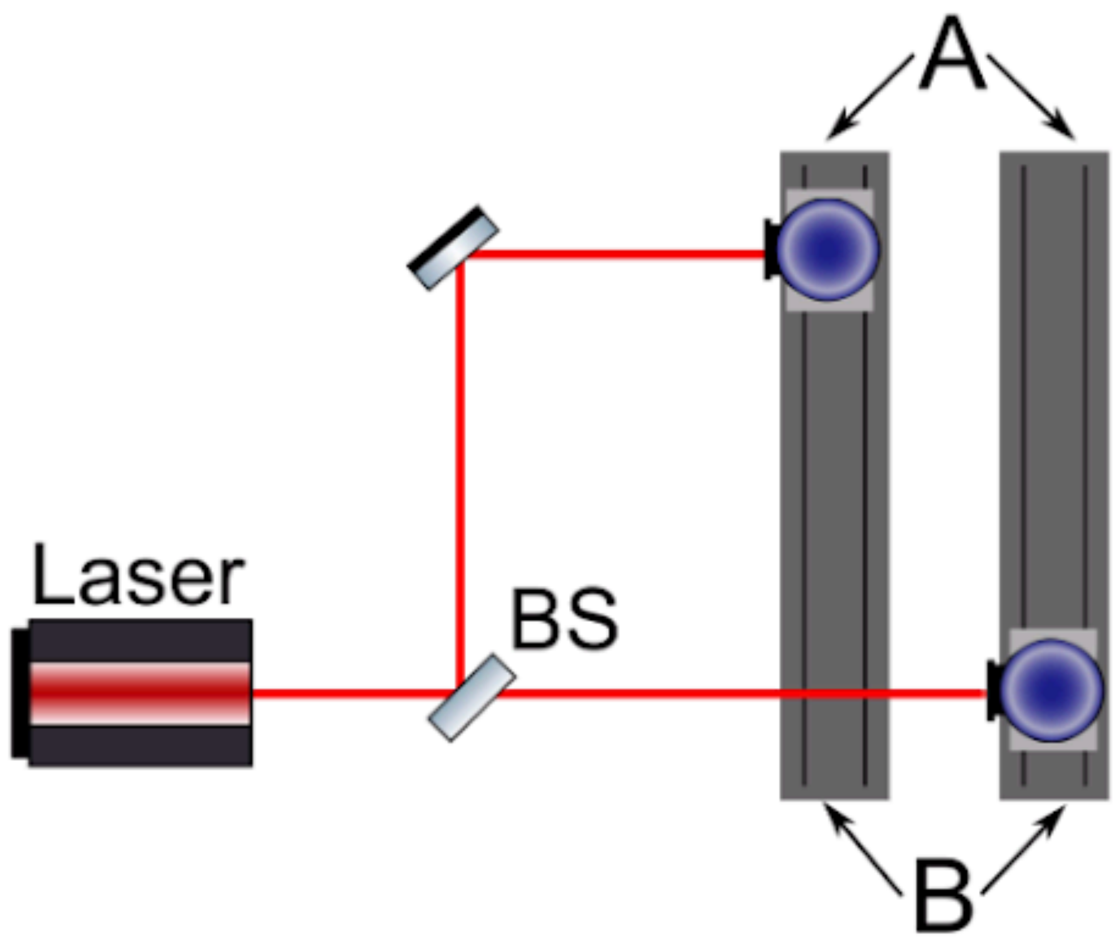
WS: Working standard

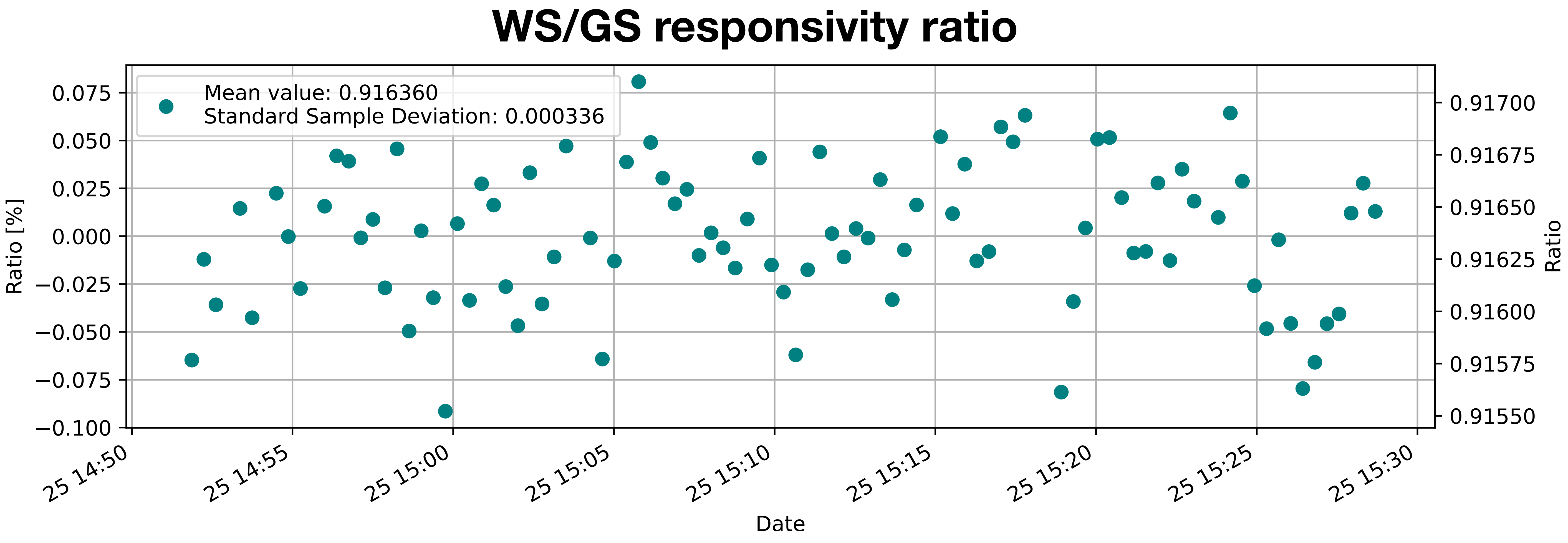
Rx: Receiver module sensor

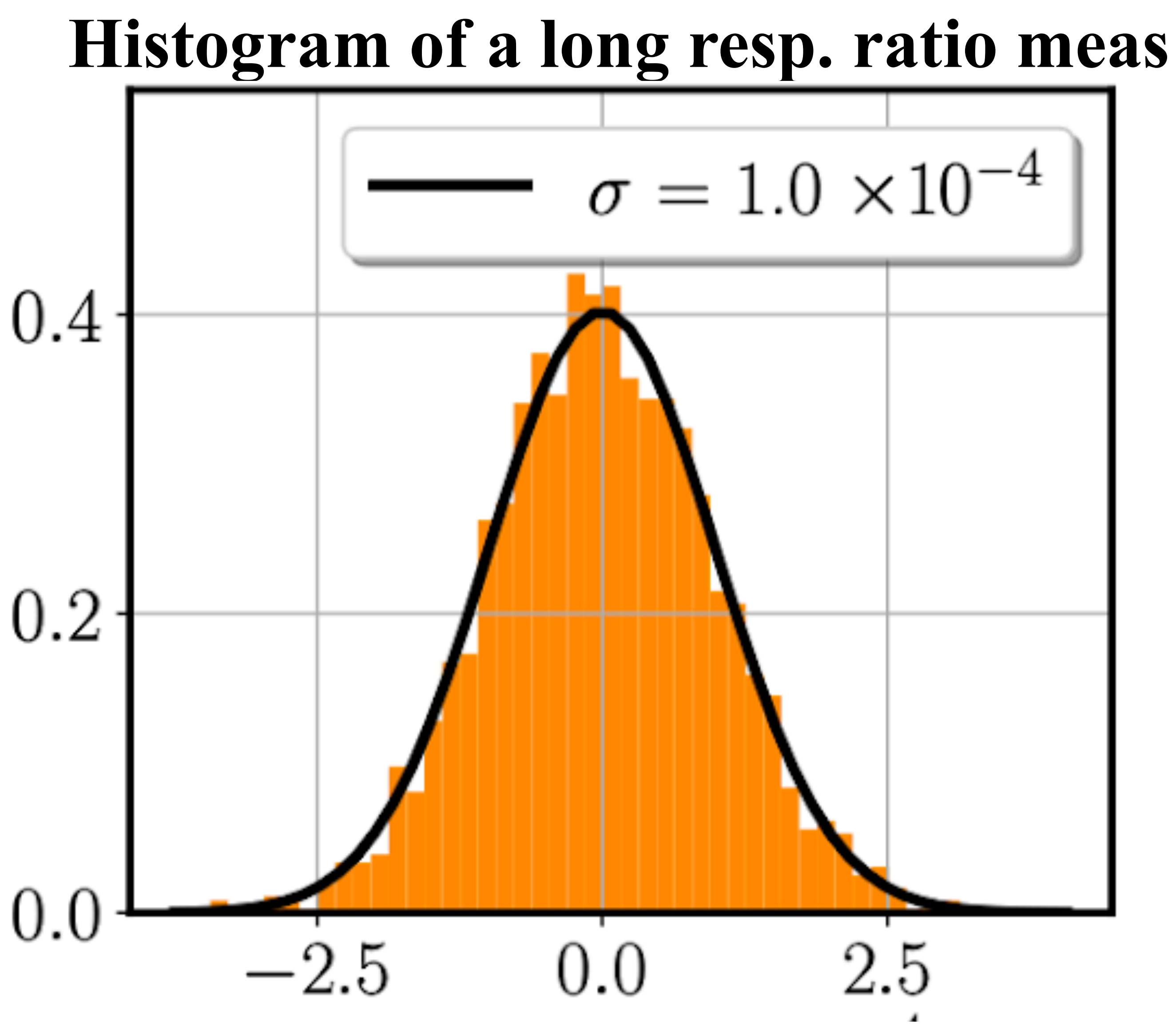
Transfer of calibration between power sensors



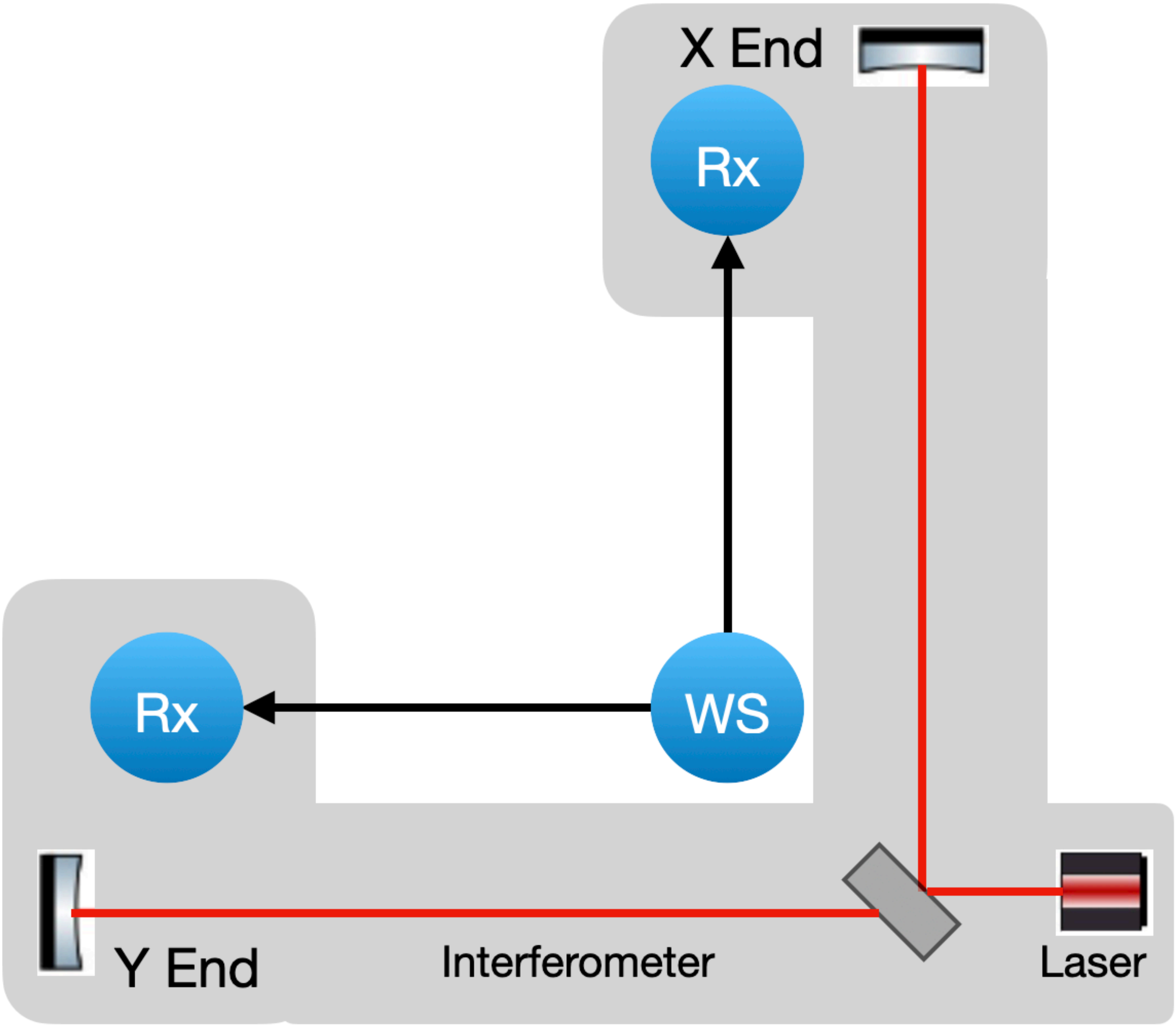


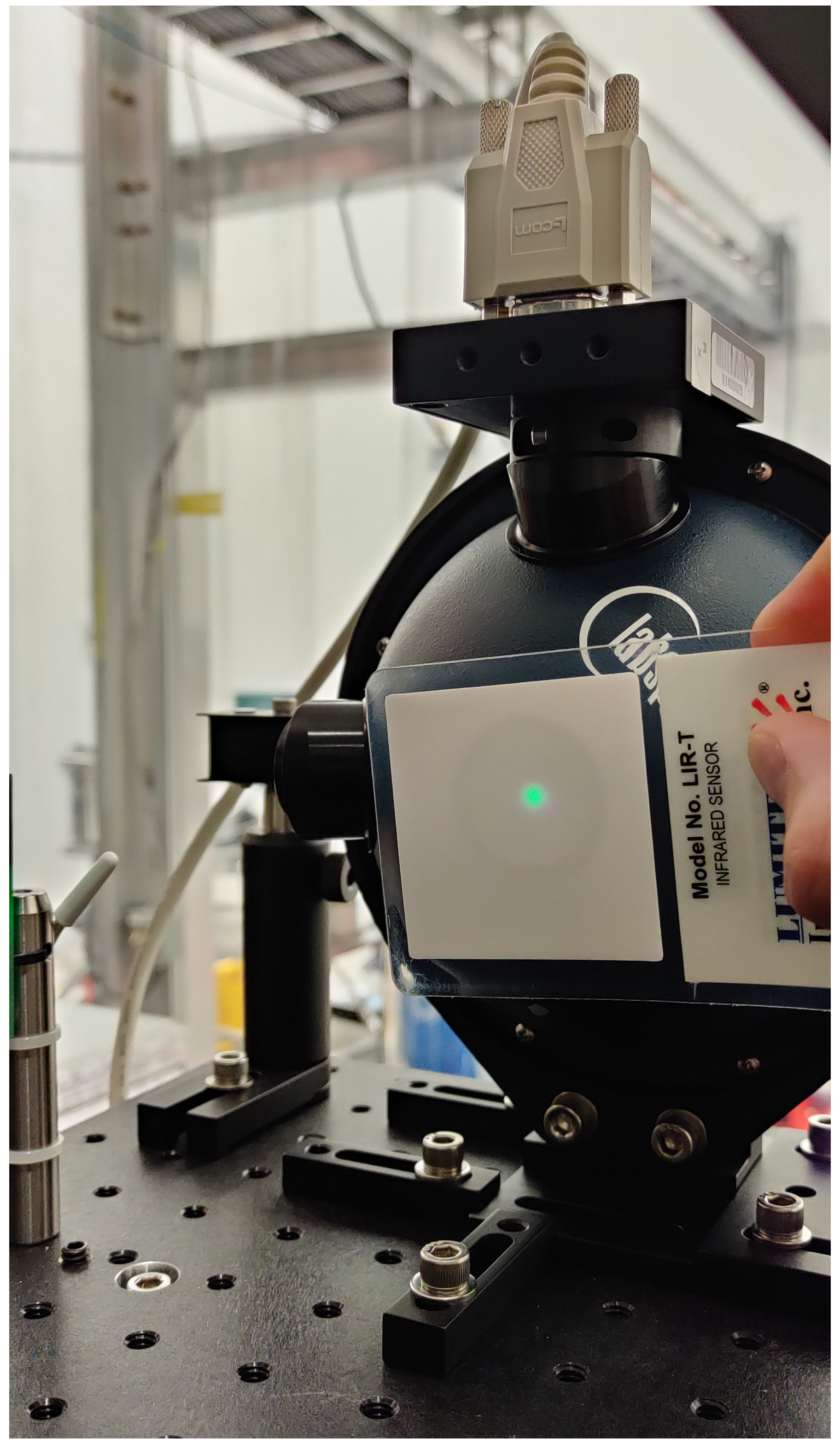


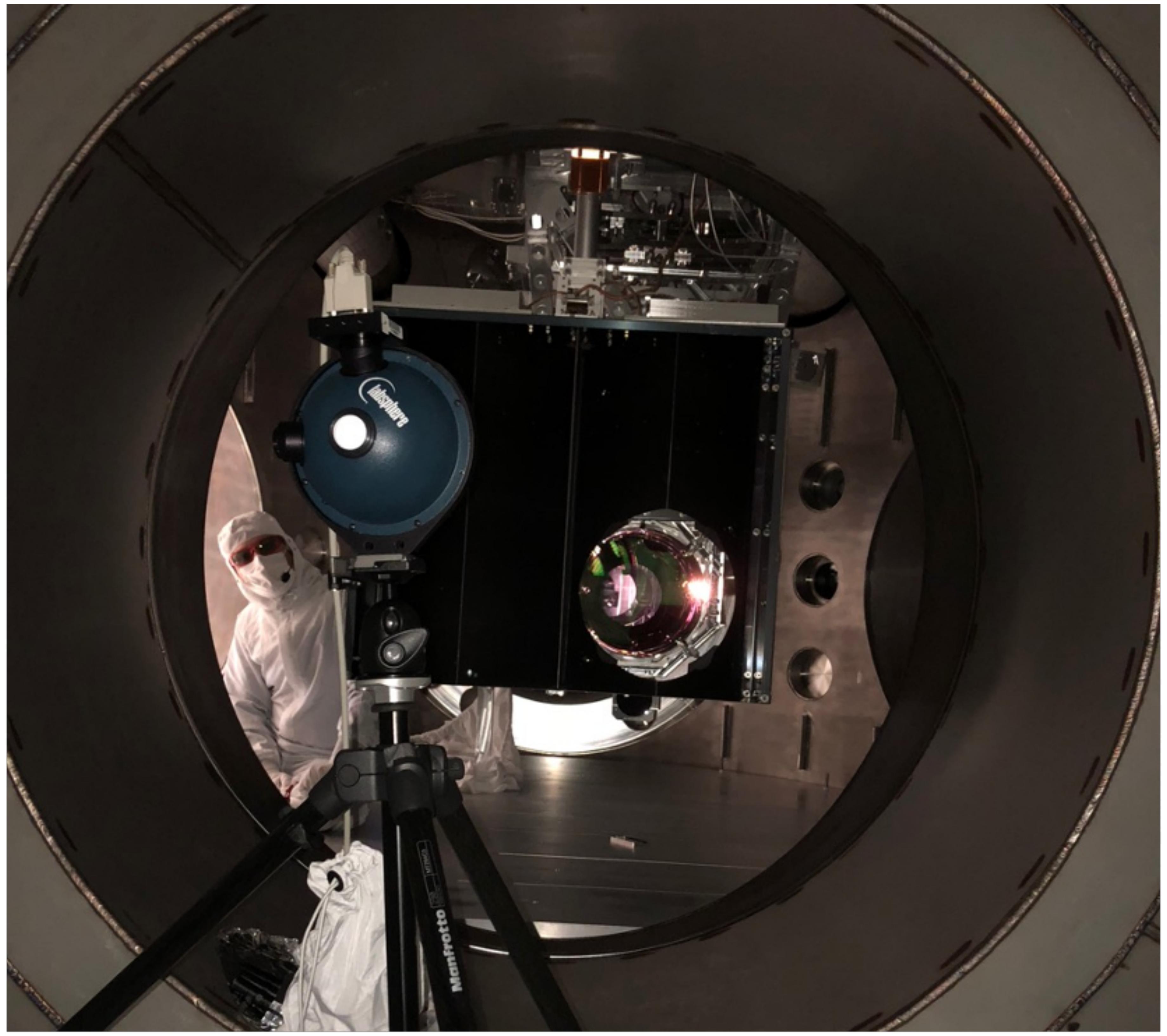




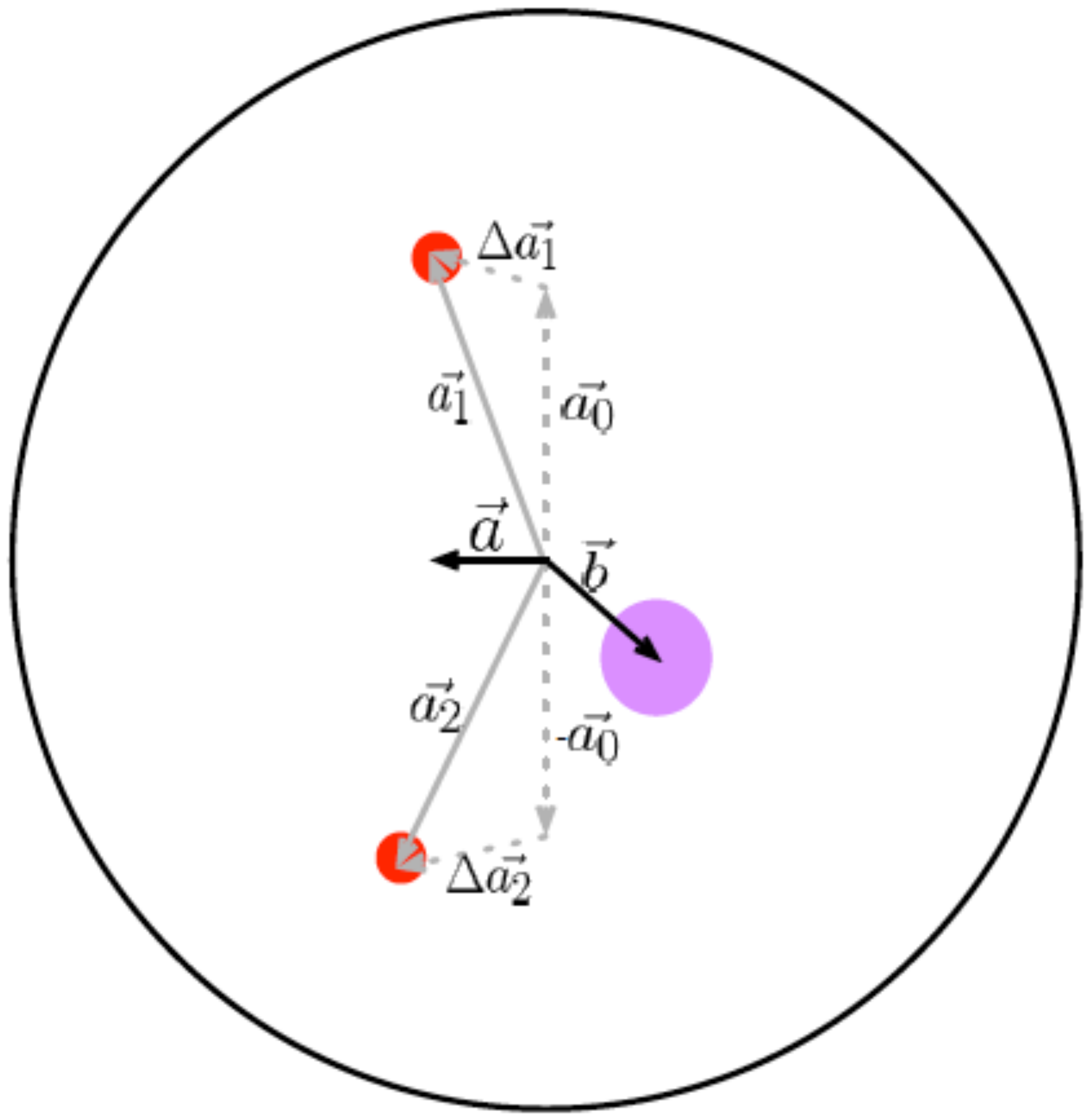
Responsivity of the Rx sensor at the end station







Unintended rotation of the mirrors

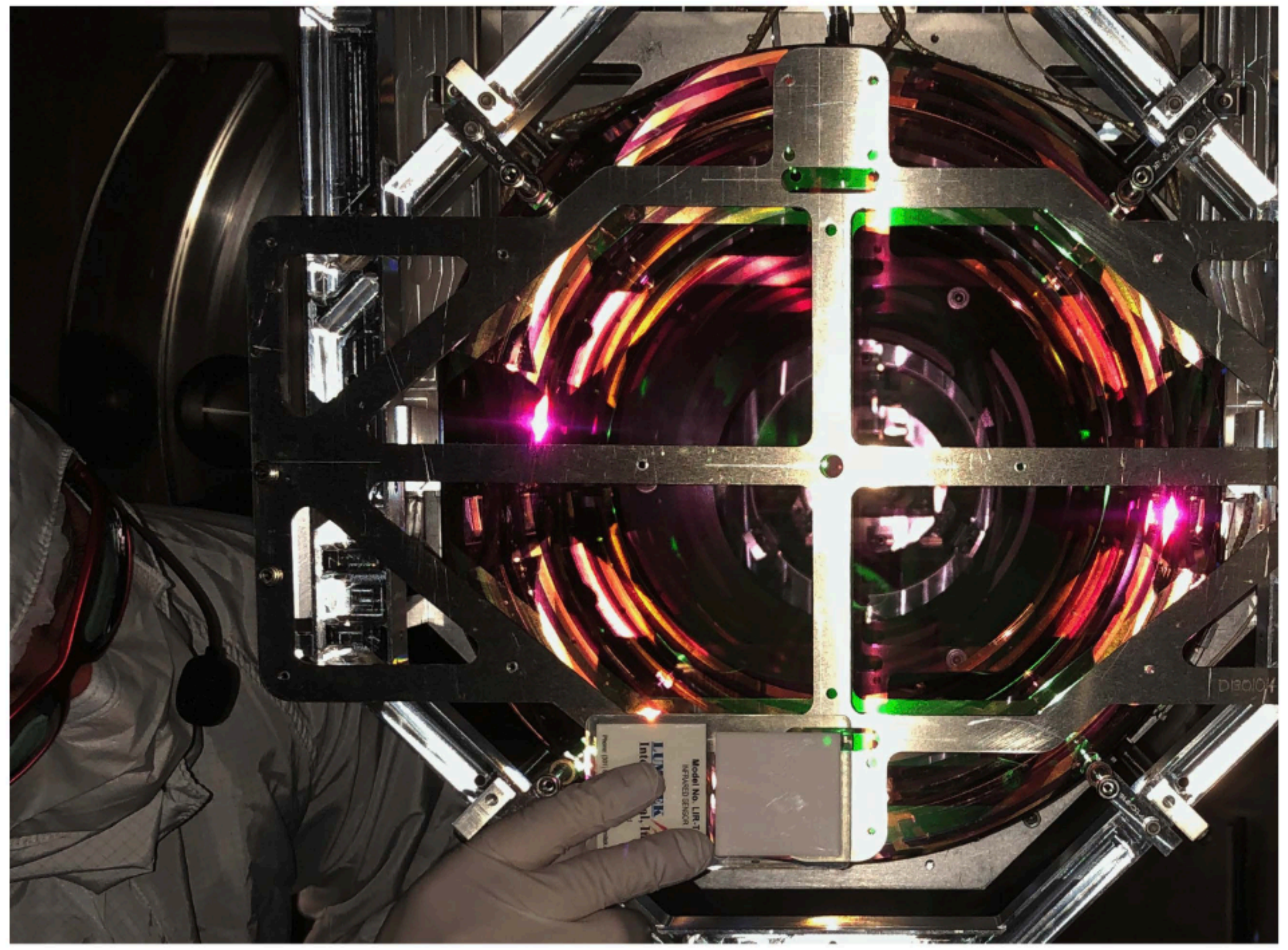


Pcal and ifo beam position offset

Unintended rotation can be caused by :

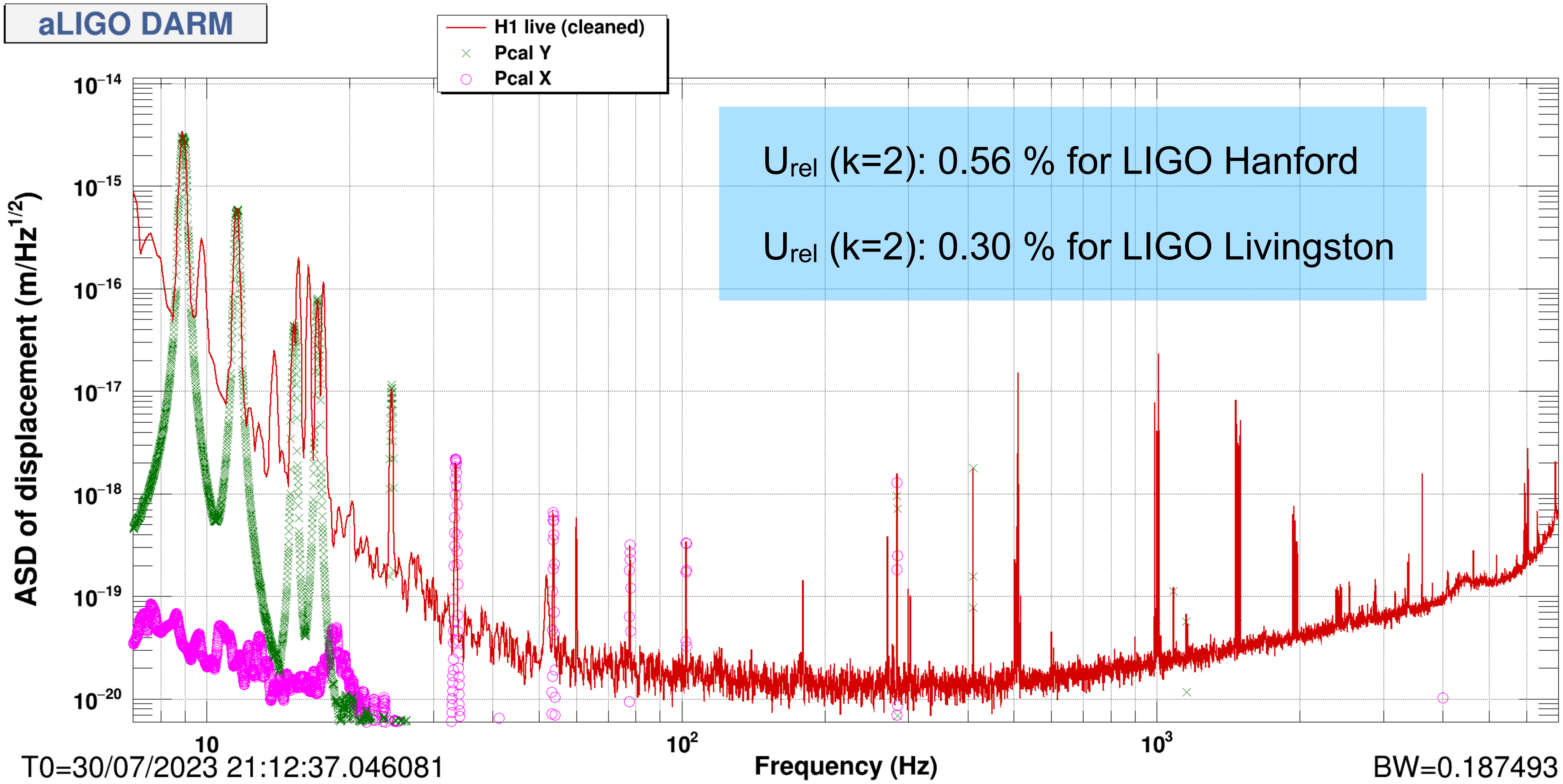
- Beam power imbalance
- Beam spot displacements

$$x(\omega) \simeq -\frac{2\cos\theta}{Mc\,\omega^2}P(\omega)\left[1+\frac{M}{I}(\vec{a}\cdot\vec{b})\right]$$



- Ifo. beam offsets at LHO10x larger than design estimate due to point absorbers

Pcal-induced calibrated displacement fiducials



U_{rel} (k=2): 0.56 % for LIGO Hanford

U_{rel} (k=2): 0.30 % for LIGO Livingston

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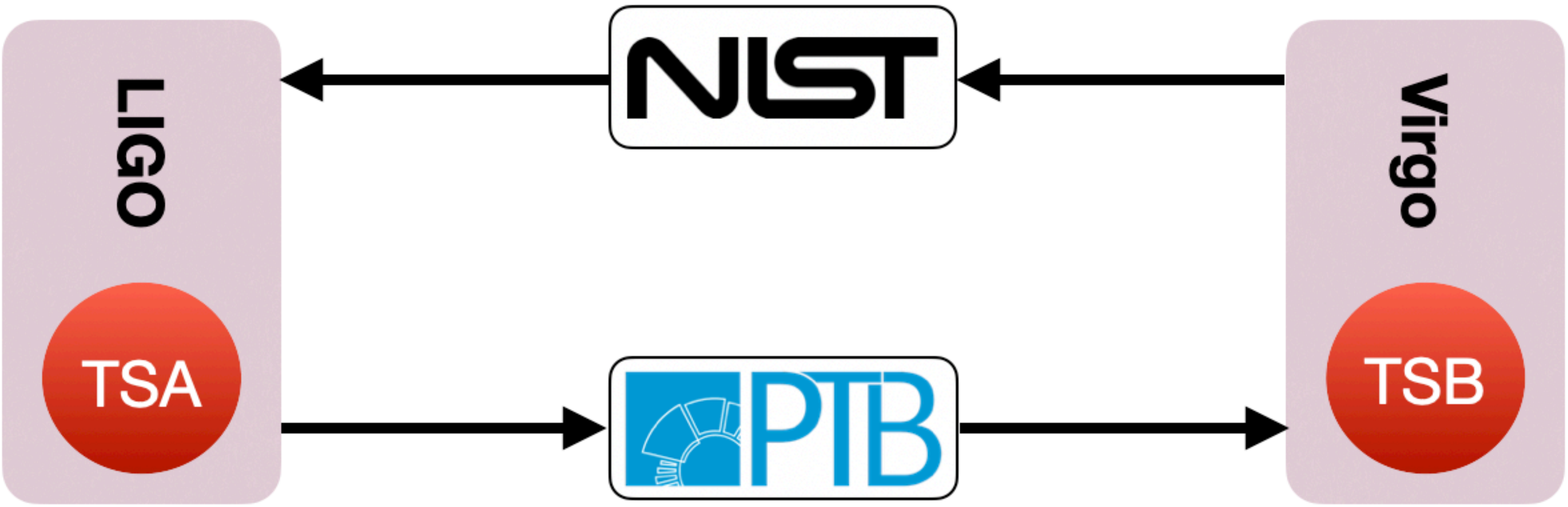
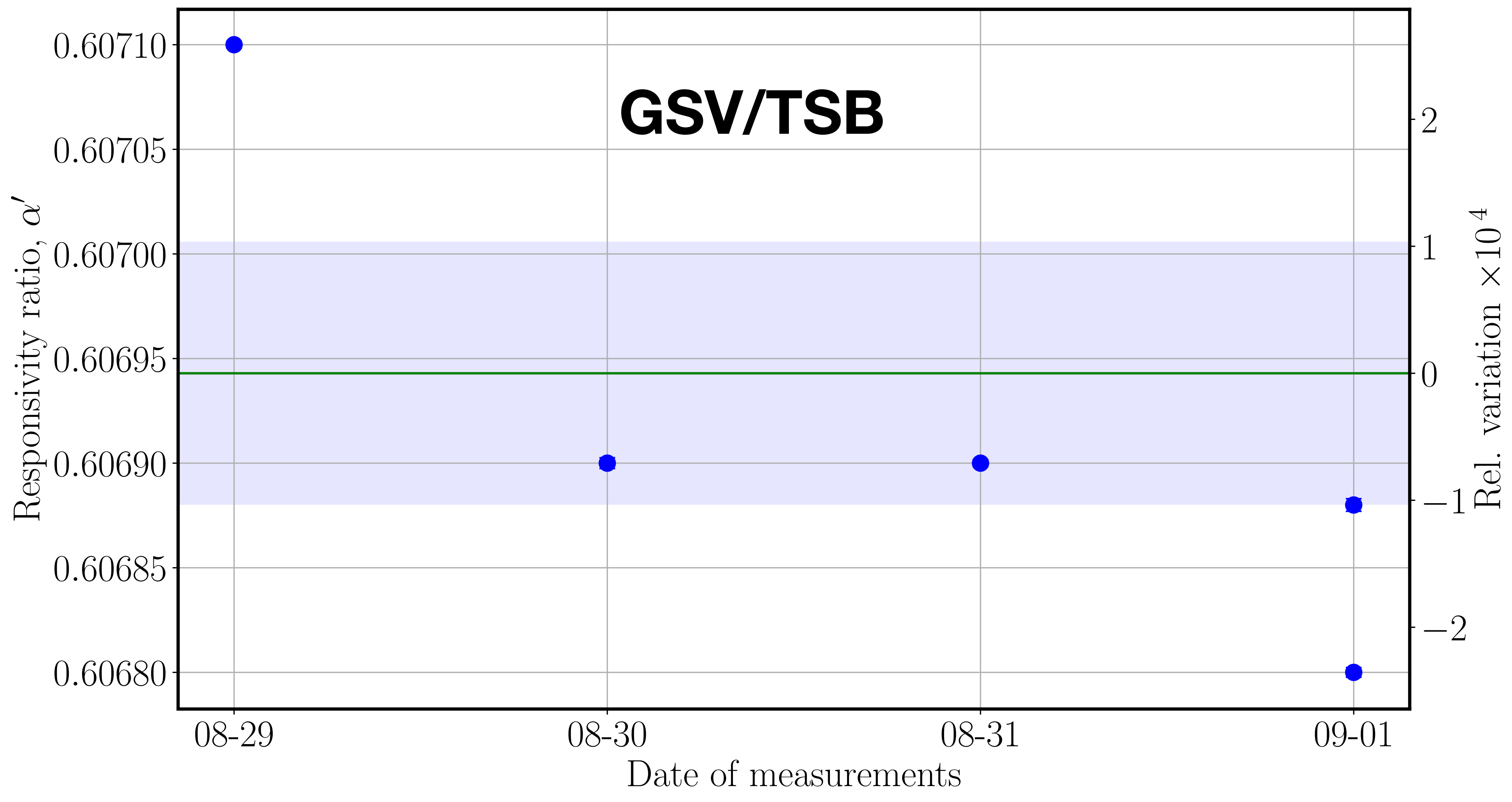
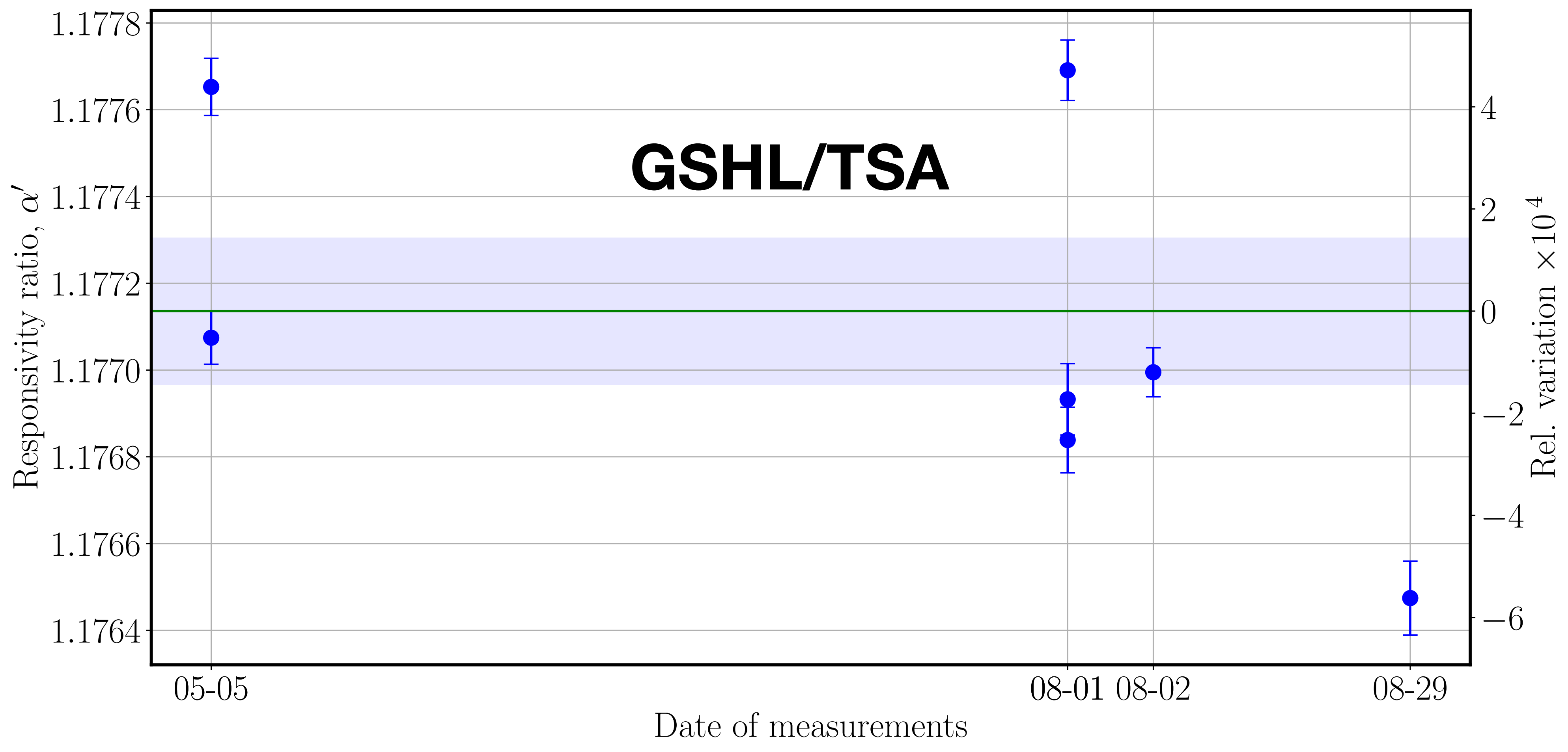
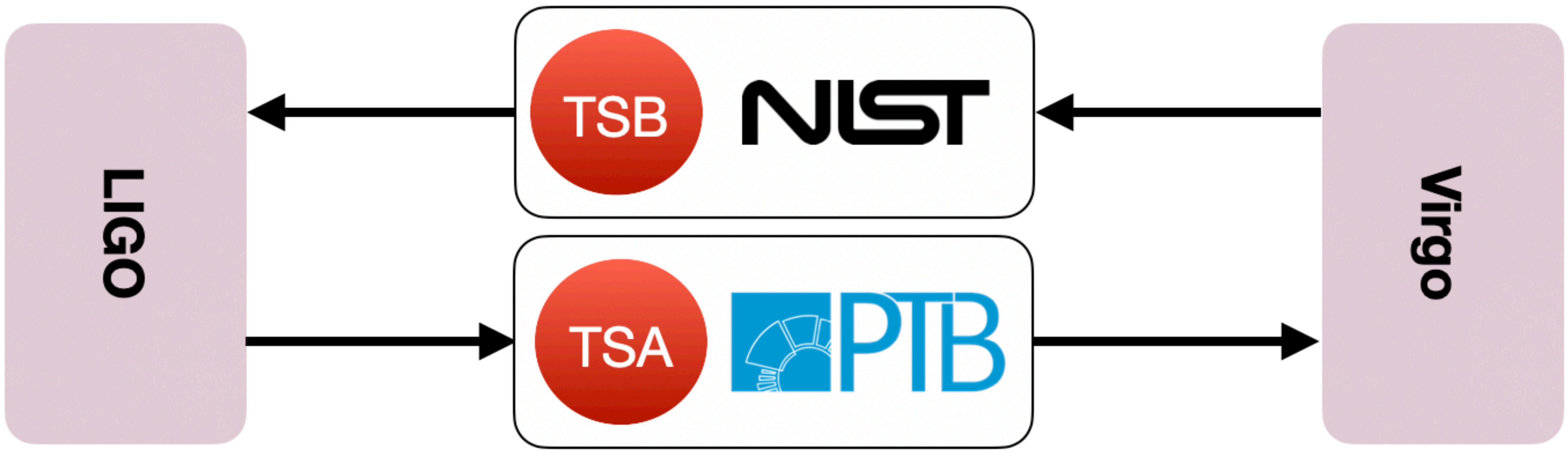
Global calibration scheme - status and next step





Credit: P. Lagabbe (Virgo)





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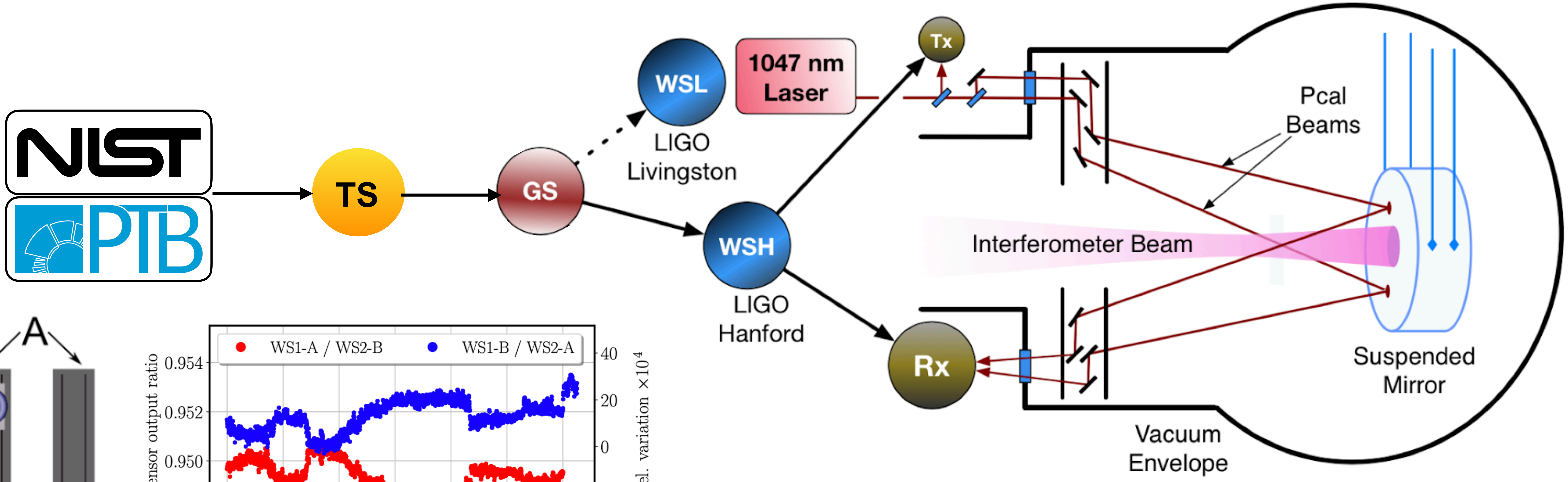
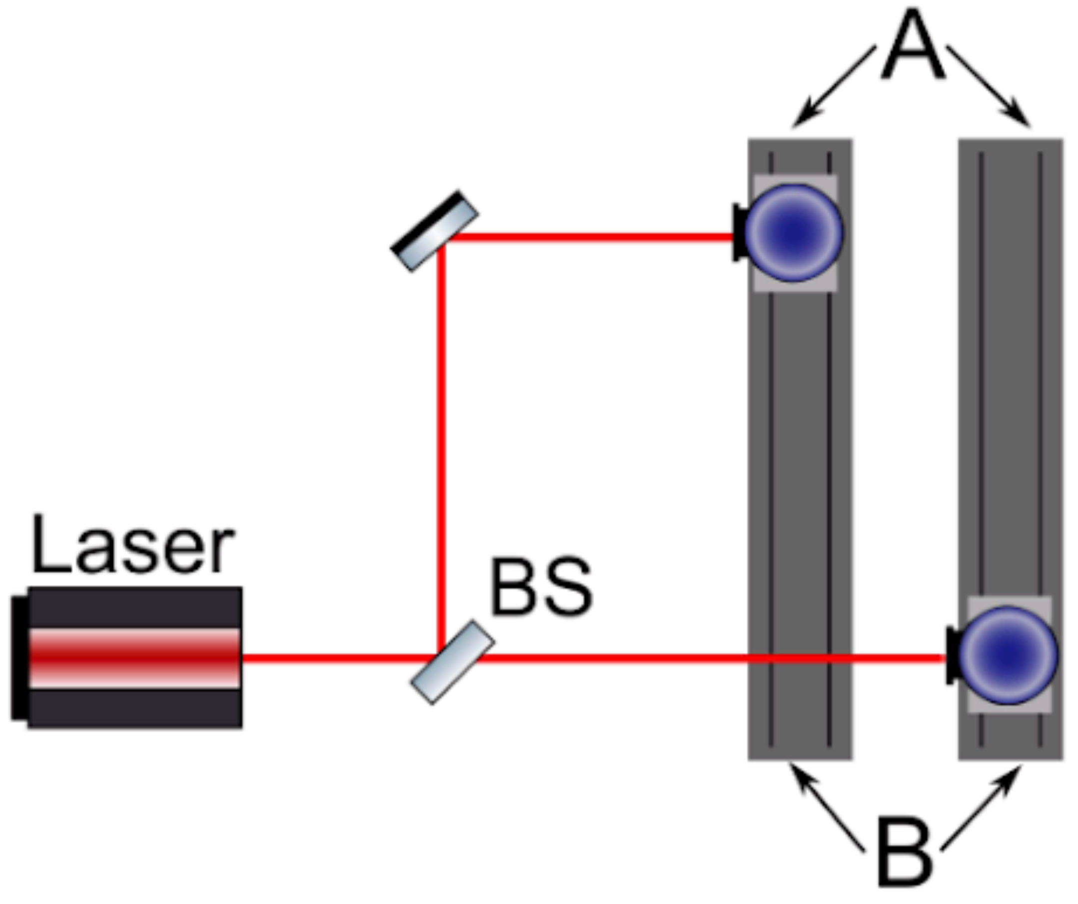
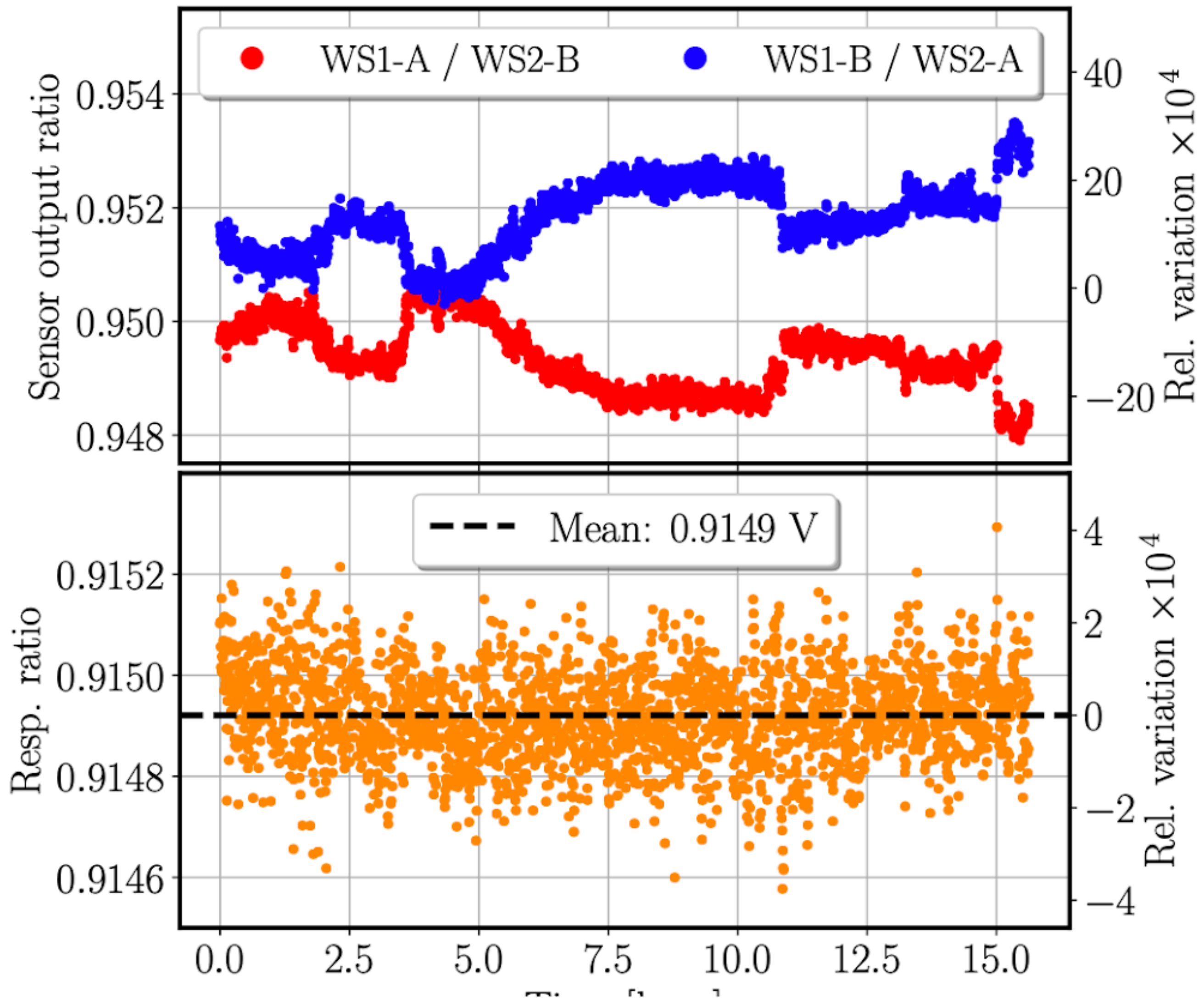
Extra

Transferring the calibration to the end station sensors







$$\sqrt{\frac{V_{WS}(\text{refl}) * V_{WS}(\text{tran})}{V_{GS}(\text{refl}) * V_{GS}(\text{tran})}} = \sqrt{\frac{\alpha_R P(t_1)\rho_{WS}\alpha_T P(t_2)\rho_{WS}}{\alpha_T P(t_2)\rho_{GS}\alpha_R P(t_1)\rho_{GS}}} = \boxed{\frac{\rho_{WS}}{\rho_{GS}}}$$

$$\rho_{Rx} = \frac{\rho_{Rx}}{\rho_{WS}}\,\frac{\rho_{WS}}{\rho_{GS}}\,\frac{\rho_{GS}}{\rho_{TS}}\,\rho_{TS}$$

TS – Transfer standard

GS – Gold standard

WS – Working standard

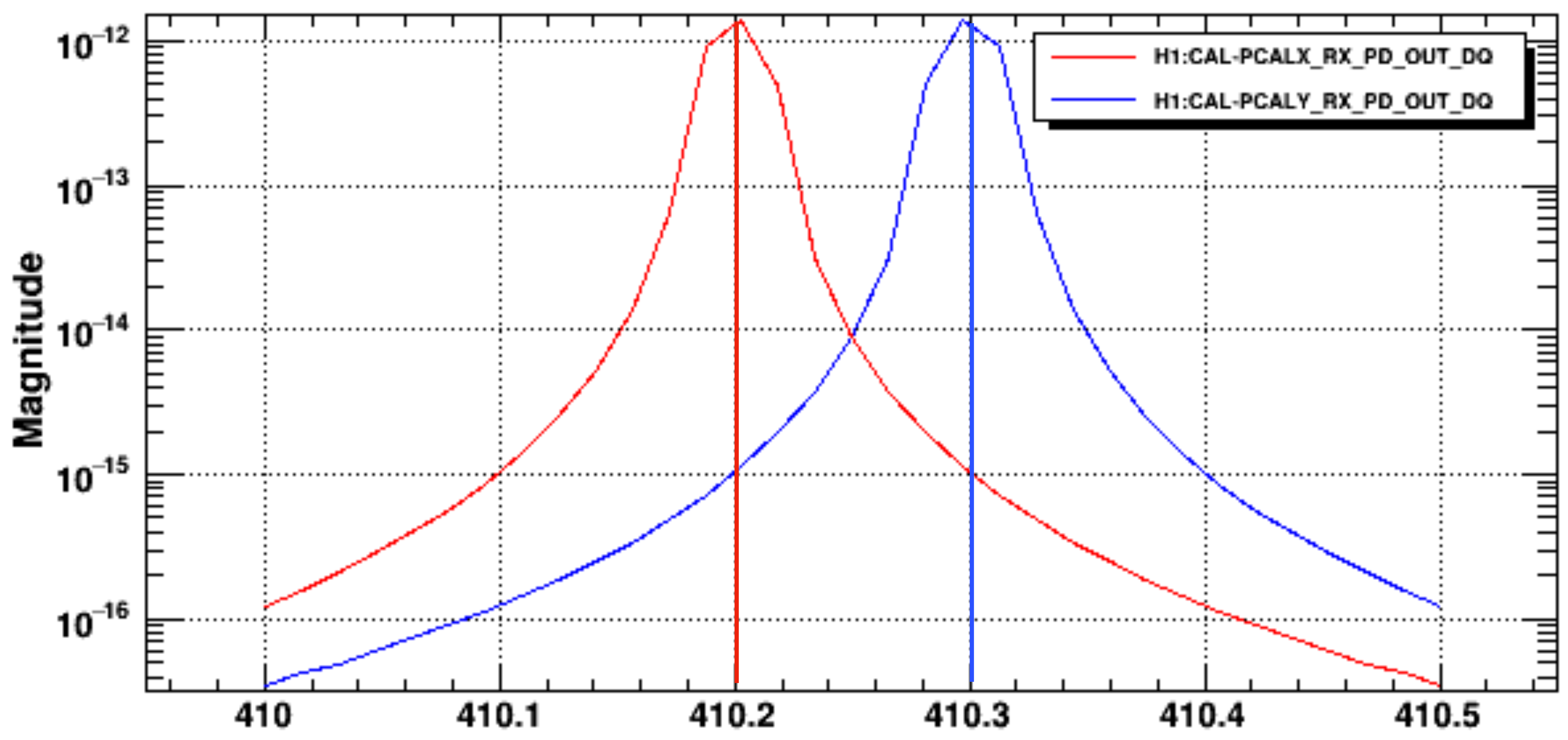
Rx – Rx sensor

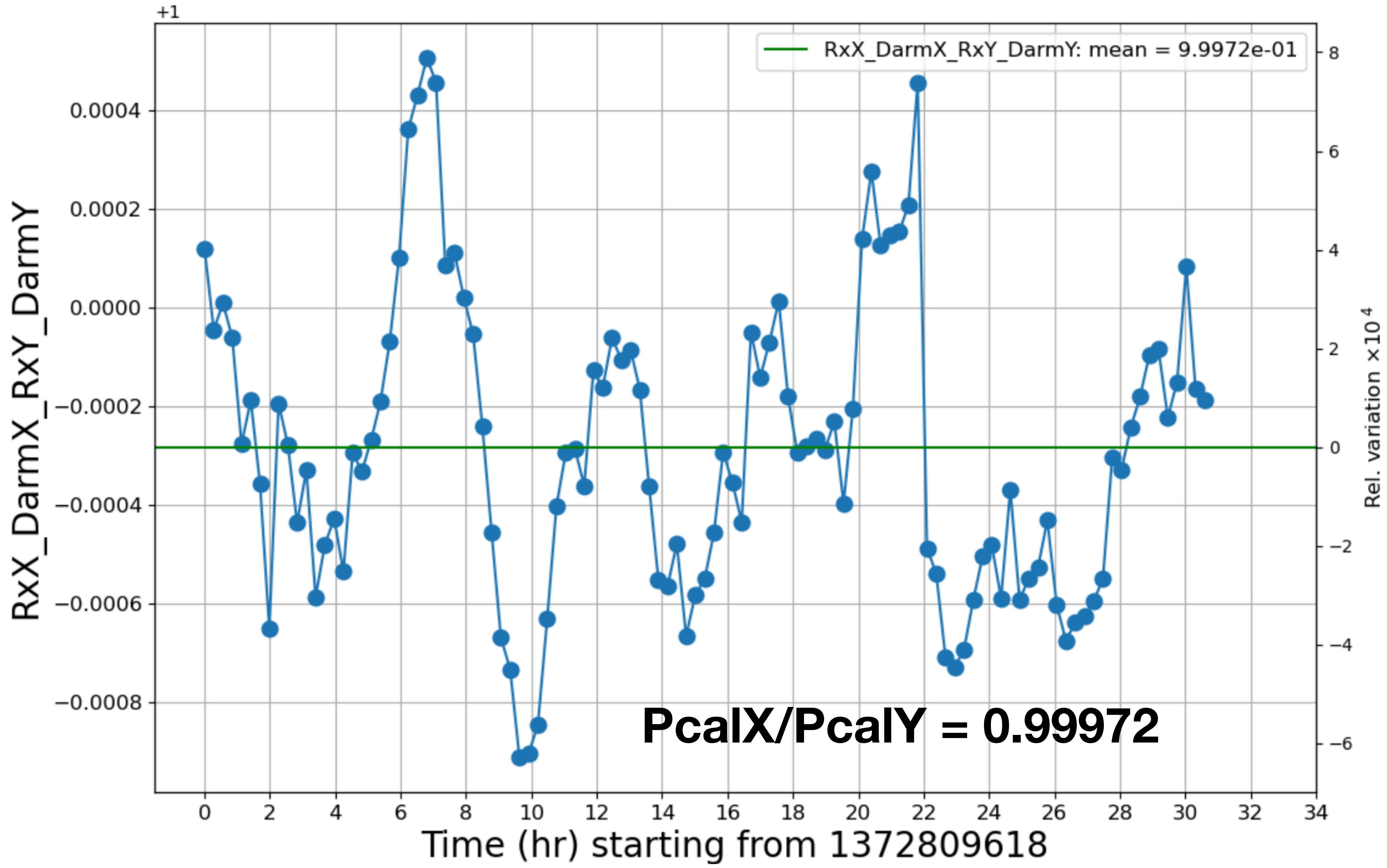
Comparison of Pcal calibrations at the two end stations

Interferometers respond equally to length variations of either arm (at 1 ppm level)

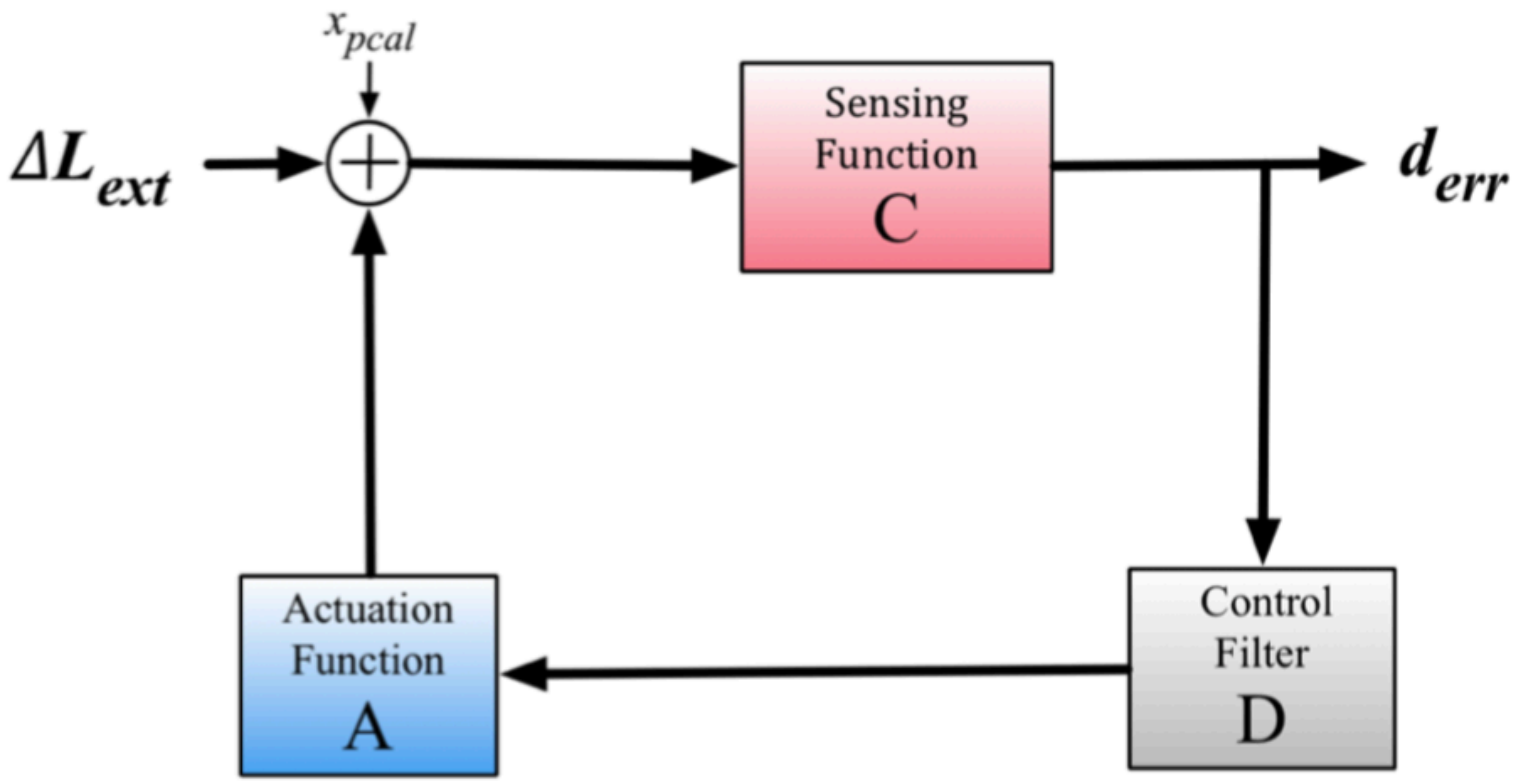
- Use this feature to compare the calibrations at the two end stations
- Further reduces uncertainty due to factors not common to the two end stations.

The Pcal calibration at the two end stations are stable



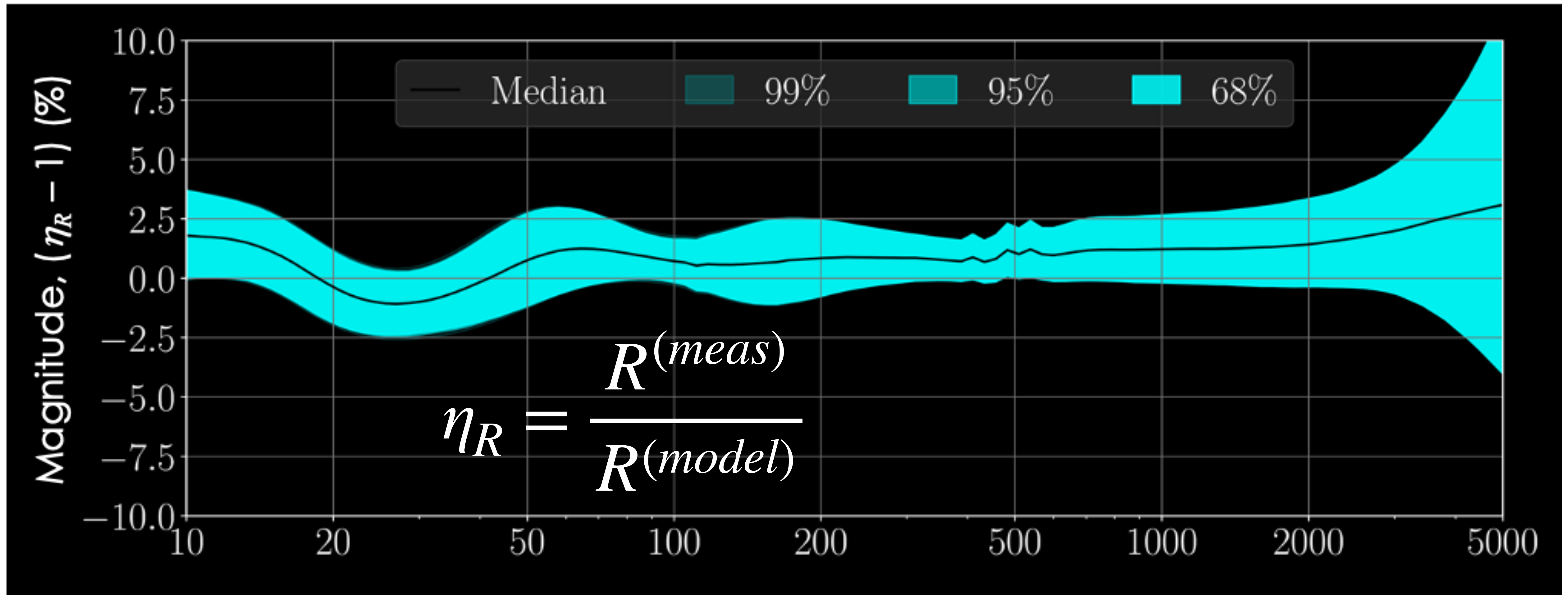


Overall interferometer calibration



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

Pcal-induced displacement fiducials are used to characterize the interferometer response functions



J. Kissel

Current overall calibration systematic error is < 2% in the sensitive frequency band region.

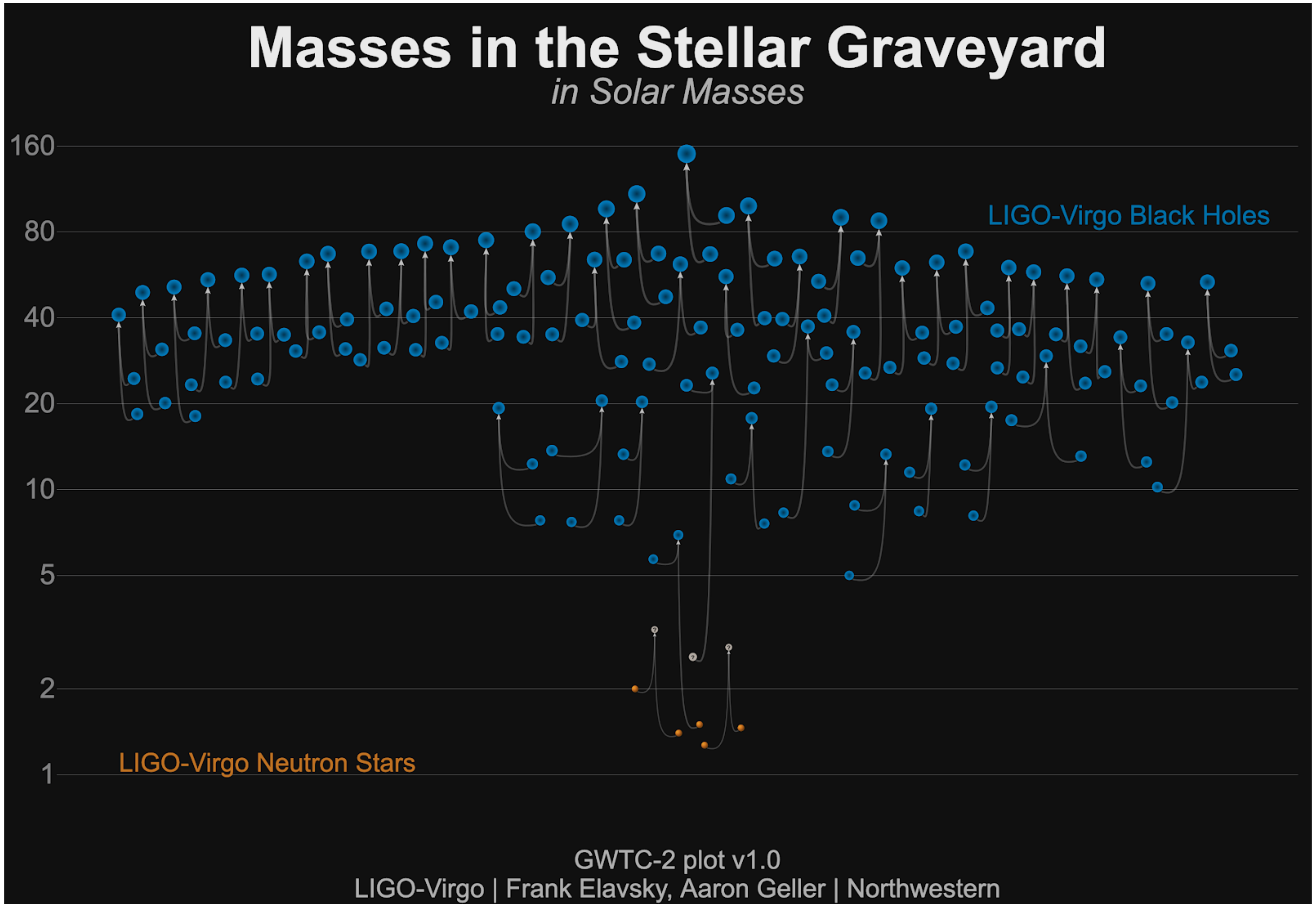
L. Sun et.al Class. Quantum Grav. 37 225008 (2020)

Overall calibration systematic error is not limited by the Pcal uncertainty

It is sufficiently small for astrophysical parameter estimation

Vitale et. al arXiv:2009.10192 (2020).
Payne et. al Phys Rev D. 102.12 (2020): 122004

Detected gravitational wave signals



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LIGO Hanford Pcal

Photo credit: J. Lewis

KAGRA Pcal

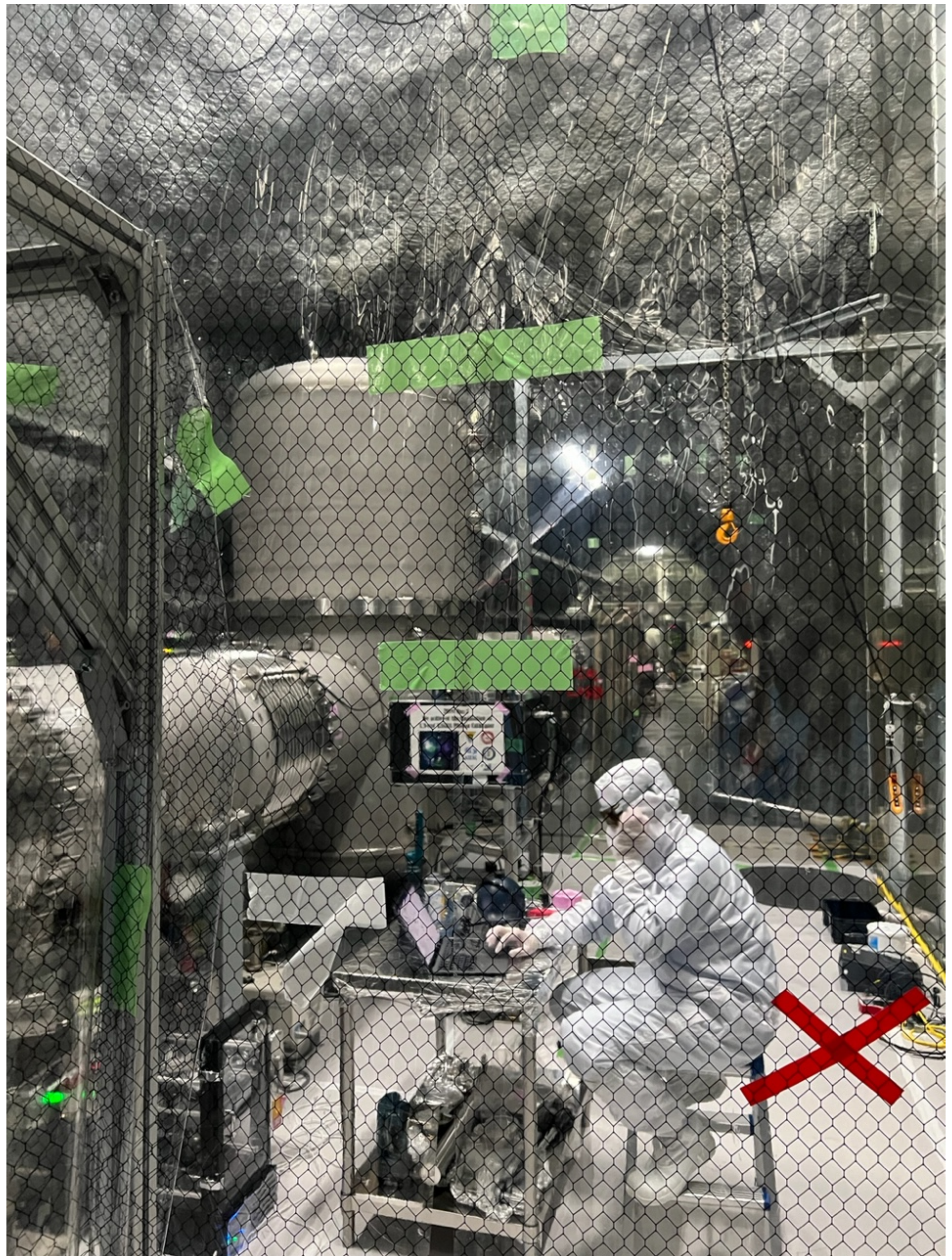

Photo credit: R. Savage

Virgo Pcal