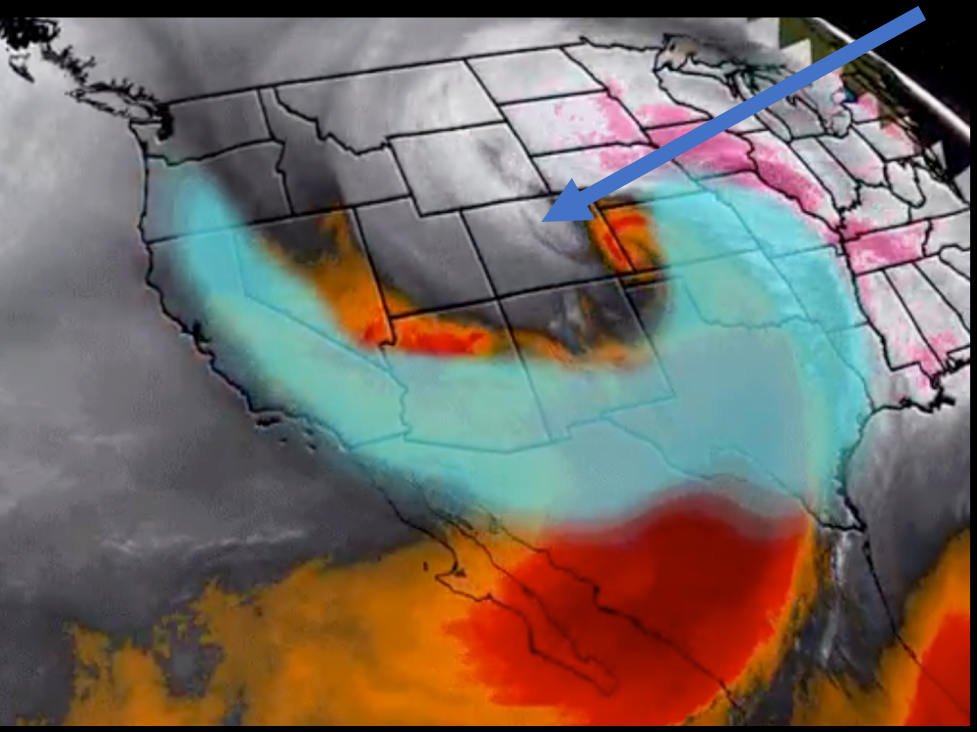
Absolute Uncertainty in the GW Detector Network:

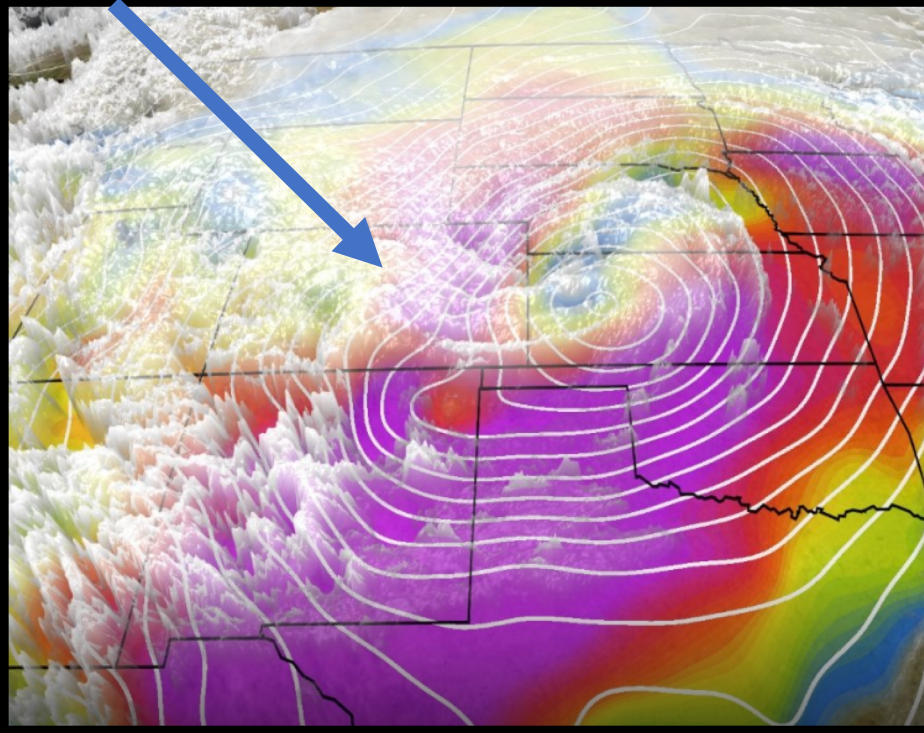
Status Update and Debrief from NIST Workshop

J. Kissel, for the World-wide collection of GW Detector Calibration Groups, the LVK, and NIST

Well… THAT Happened

Denver / Boulder





Winter Storm Ulmer destroyed all plans for attendees to fly into Denver

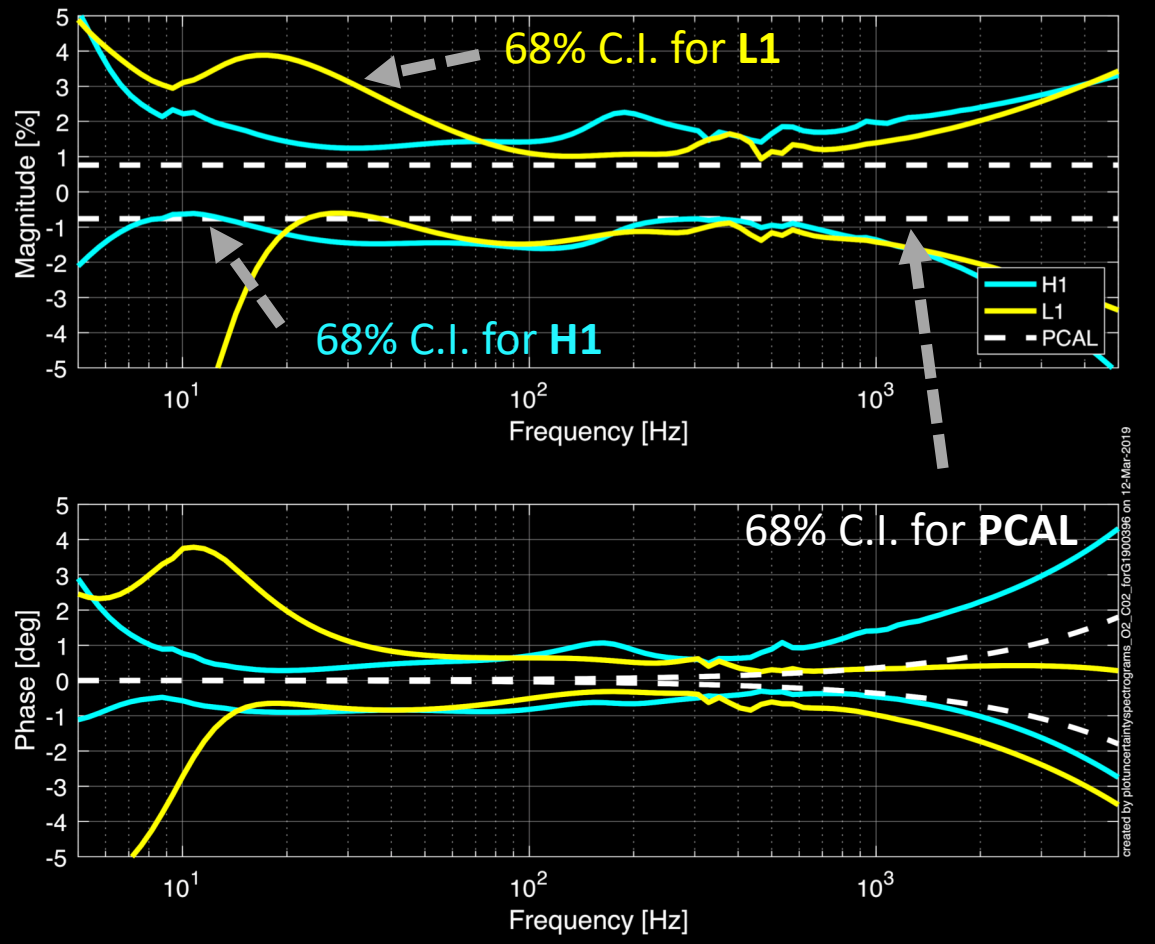
- Many attendees delayed
- Several attendees had cancel all together
- **Workshop reduced to one day** (last Friday, 2019-03-18)

Where left off in O2

The combination of

- **statistical uncertainty**
- **remaining systematic error**
- **unknown systematic error**

is numerically evaluated to form a 68% confidence interval, but roughly,

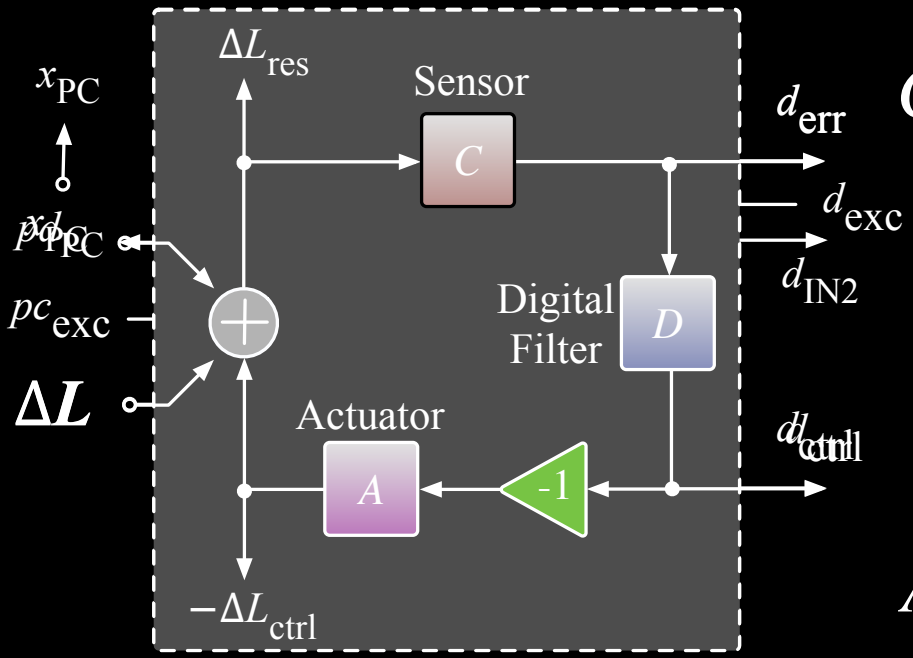


$$\partial h^2 \approx \partial R^2 \approx \left(\frac{1}{1+G}\right)^2 \left(\frac{\partial C}{C}\right)^2 + \left(\frac{G}{1+G}\right)^2 \left(\frac{\partial A}{A}\right)^2$$

+ Systematic Errors

How to Measure the DARM Loop

With all loops closed and the detector running at its best sensitivity, we request a series of **in-loop** excitations to obtain direct measurements of the sensor and actuator



$$C = \left(\frac{d_{exc}}{d_{IN2}}\right) \times \left(\frac{d_{err}}{pc_{exc}}\right) \times \frac{x_{pc}}{pd_{pc}}$$

Complex Transfer Functions w/ Full IFO

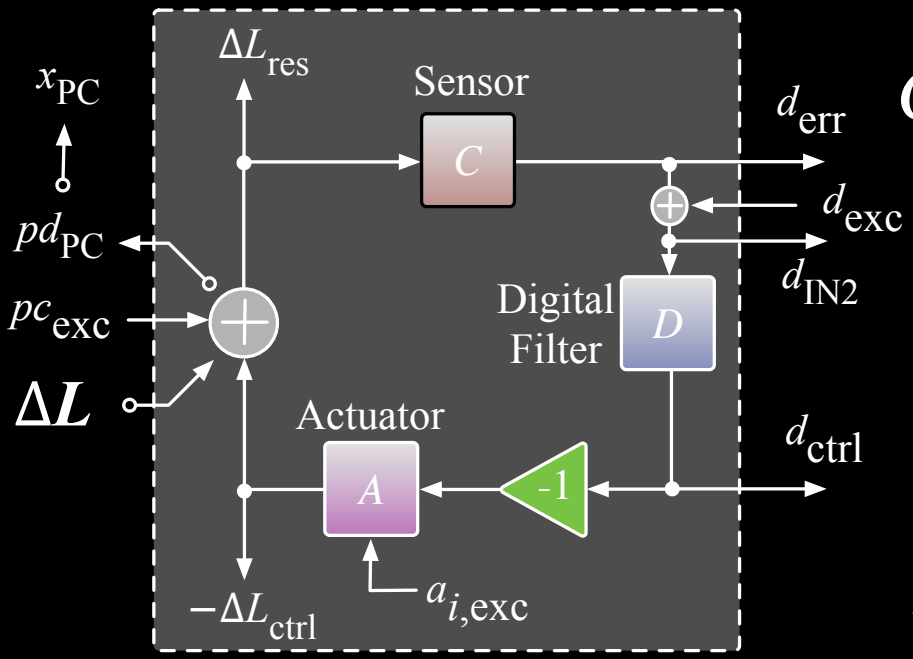
Absolute Scale Factor

$$A_i = \left(\frac{d_{err}}{a_{i,exc}}\right) \times \left(\frac{pc_{exc}}{d_{err}}\right) \times \frac{pd_{pc}}{x_{pc}}$$

Our measurements of C and A are *ratios of complex transfer functions*

*>> the **frequency-dependent, magnitude and phase** are important for uncertainty in A and C*

Focus on the IFO Measurements



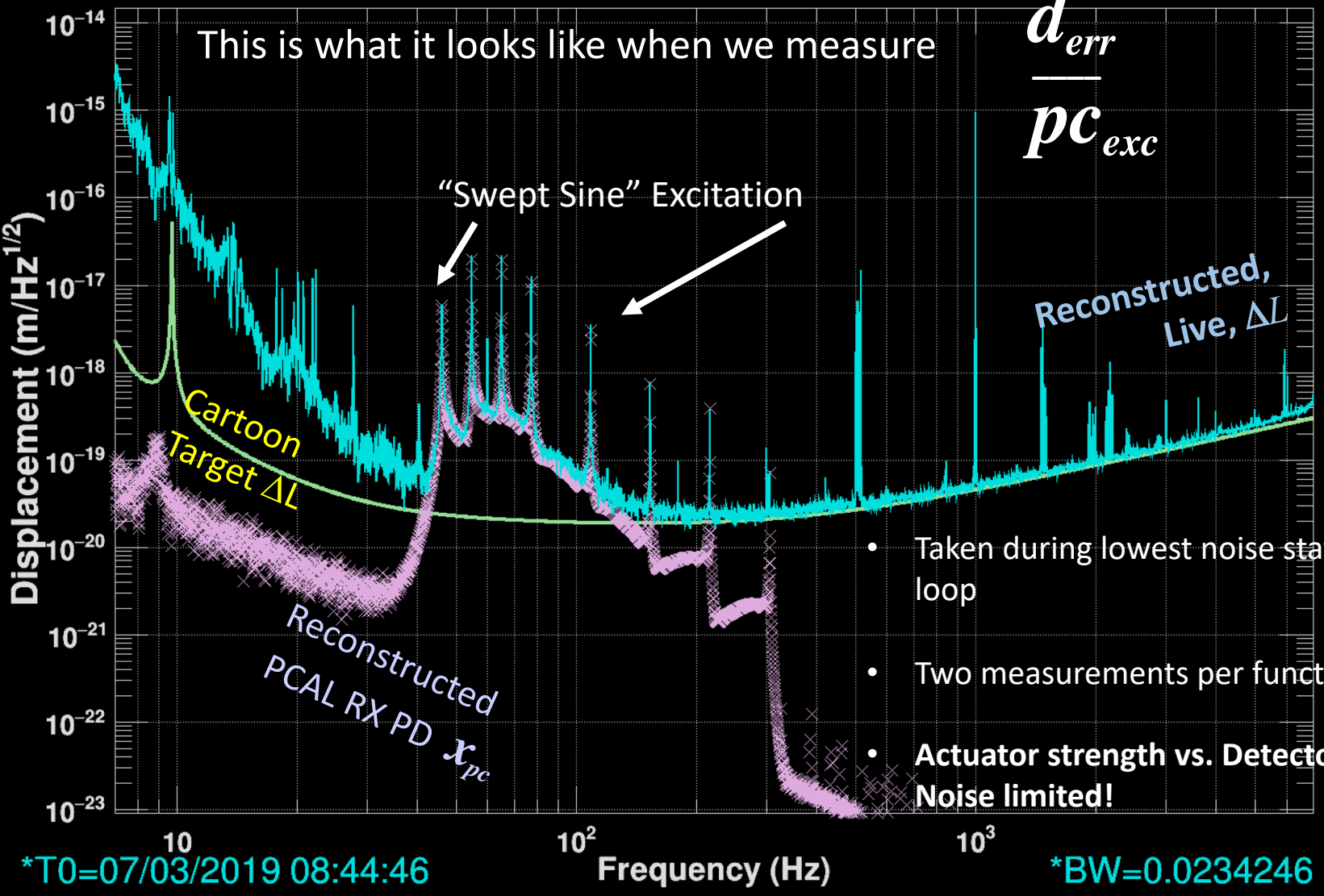
$$C = \frac{d_{exc}}{d_{IN2}} \times \frac{d_{err}}{pc_{exc}} \times \frac{x_{pc}}{pd_{pc}}$$

Complex Transfer Functions w/ Full IFO

Absolute Scale Factor

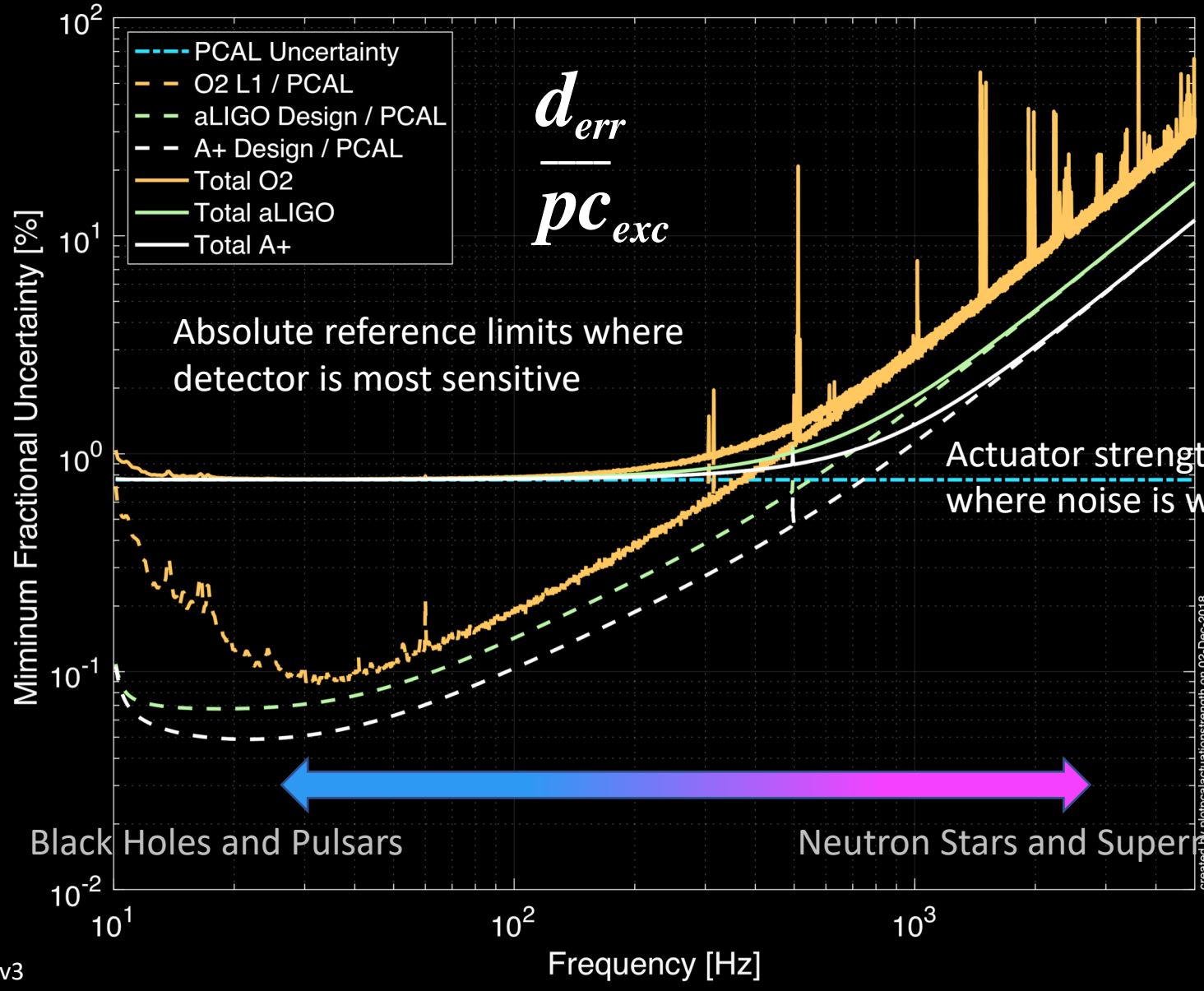
$$A = \frac{d_{err}}{a_{i,exc}} \times \frac{pc_{exc}}{d_{err}} \times \frac{pd_{pc}}{x_{pc}}$$

Example Measurement

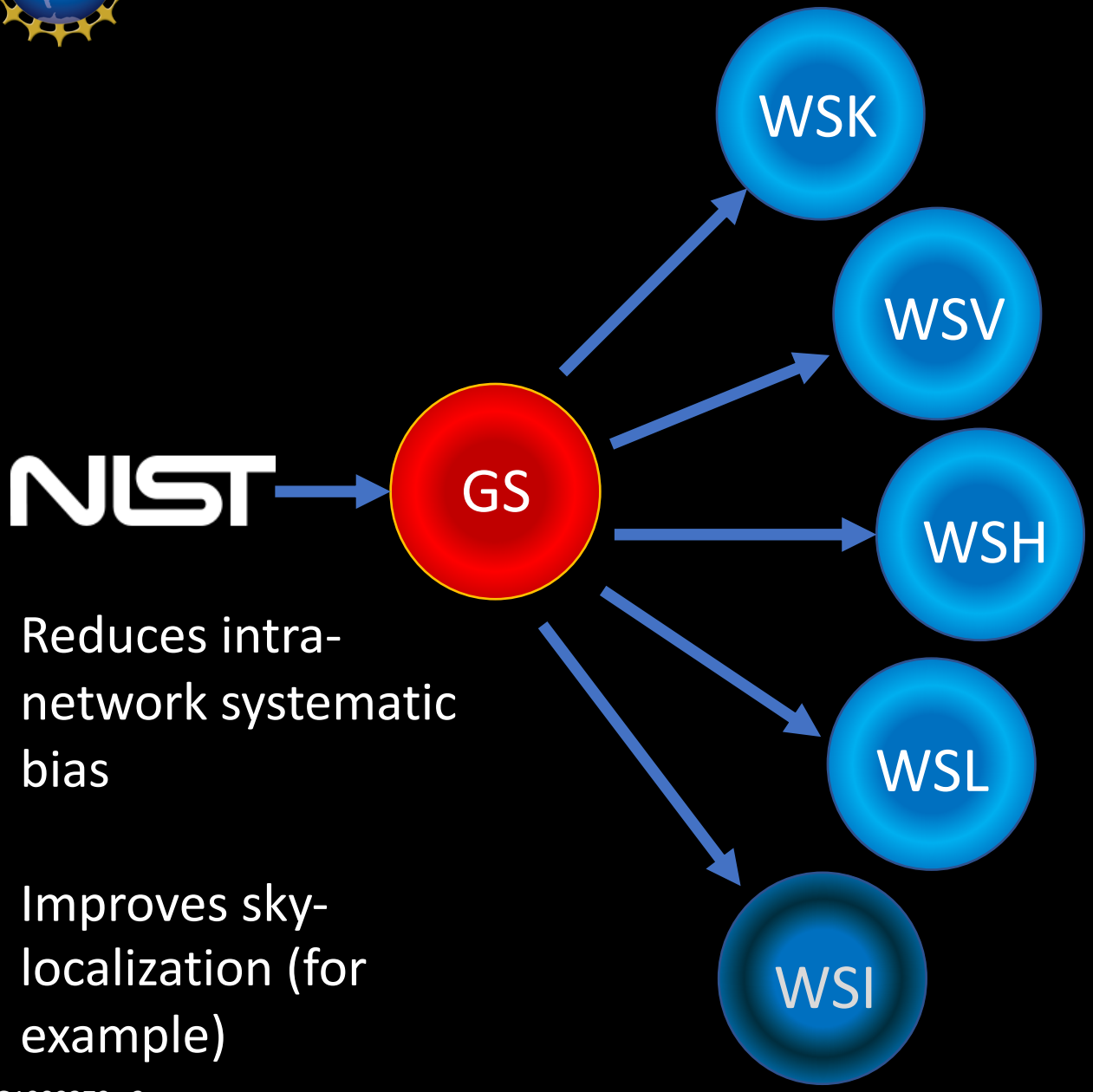


- Taken during lowest noise state, in loop
- Two measurements per function
- **Actuator strength vs. Detector Noise limited!**

Limitations (using O2 PCAL Uncertainty)



But We're Improving…



We now have built and compared

FOUR **W**orking **S**tandards

to be held at each site, all referenced to the **G**old **S**tandard and thus NIST

Reduces intra-network systematic bias

Improves sky-localization (for example)

But We're Improving...

LIGO PCAL Parameter	O2 [1]	O3 [2]	
Laser Power (NIST - GS)	**0.51**	**0.35**	★
Laser Power (GS - WS)	0.03	0.10	
Laser Power (WS - RX)	0.05	0.10	
Optical Efficiency	0.37	0.10	★
Angle of Incidence	0.07	0.07	
Mass of test mass	0.005	0.005	
Rotation	0.40	0.20	★
Total	**0.75**	**0.50**	★

Overall improved between O2 & O3!

[1] Karki, S., et al. *RSI* 87.11 (2016): 114503.
[2] Sudarshan Karki's talk from the Workshop

NIST Workshop Take-away: NMIs are *Excited*!

- Our discoveries have stimulated excitement in the *global* power standards community.
  - "New" acronym: National Metrology Institutes (NMIs)
  - EUROMET study revisited – see slides 11 and 12
- NIST reduced their standard uncertainty *for us* for O3 (special signature required!)
  - see slide 9
- On their own, current NIST reference system for laser power is old and difficult to improve; they are already planning on upgrading their systems
  - see slide 13 and 14

https://dcc.ligo.org/cgi-bin/DocDB/DisplayMeeting?conferenceid=1029

Review of EUROMET Study

Response of a Photodetector

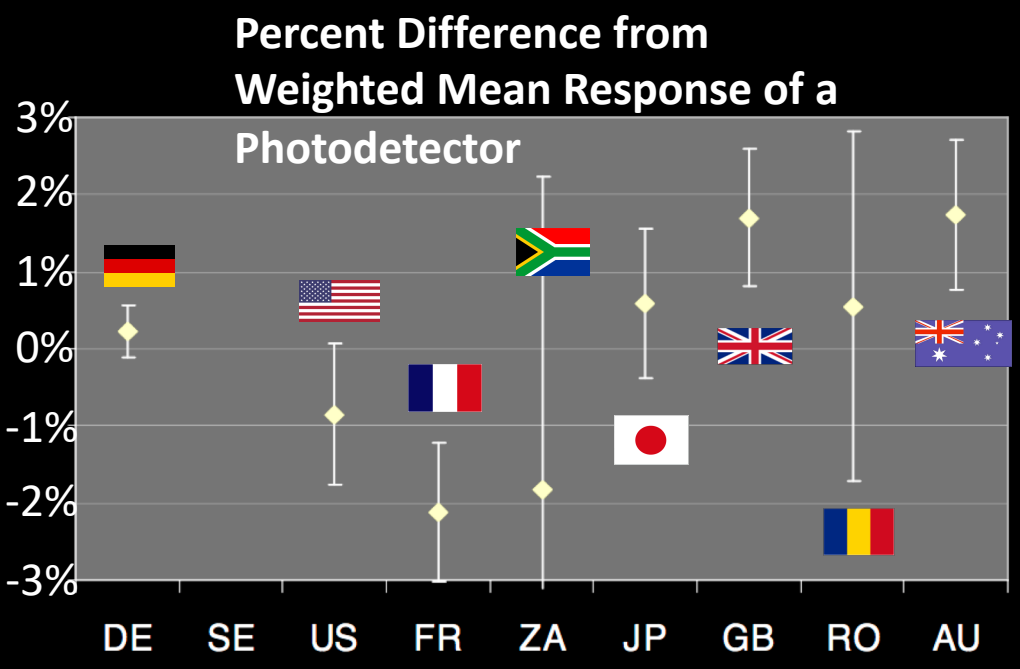


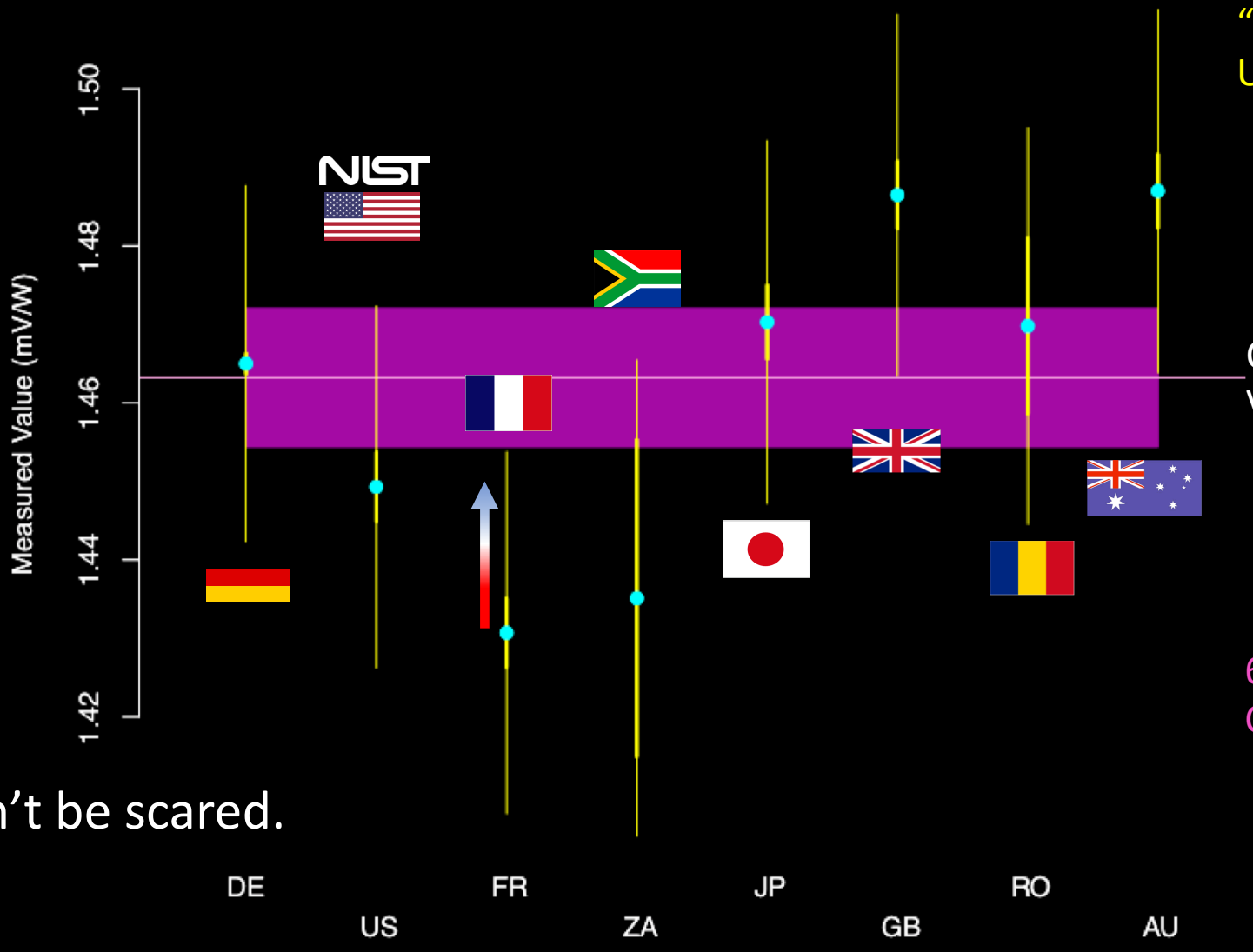
Figure 9
Kück *Metrologia* 47.1A (2010): 02003.

- NIST didn't and doesn't take it in to account
- Consensus – Initial concerns from GW community about "the plot" has been initially overblown.
- Proper statistical interpretation [3,4]:
  - NIST value and all others consistent with Consensus Estimate C.I.
  - Except France, who has since found ~2% systematic error (in the right direction)

Remember this scary plot?

[3] Amanda Koepke's Talk at NIST Workshop
[4] Jimmy Dubard's Talk at NIST Workshop

EUROMET Study Concerns Settled



"Dark" Unknown Uncertainty

Reported Value

Consensus Value

Reported Uncertainty

68% CI for Consensus

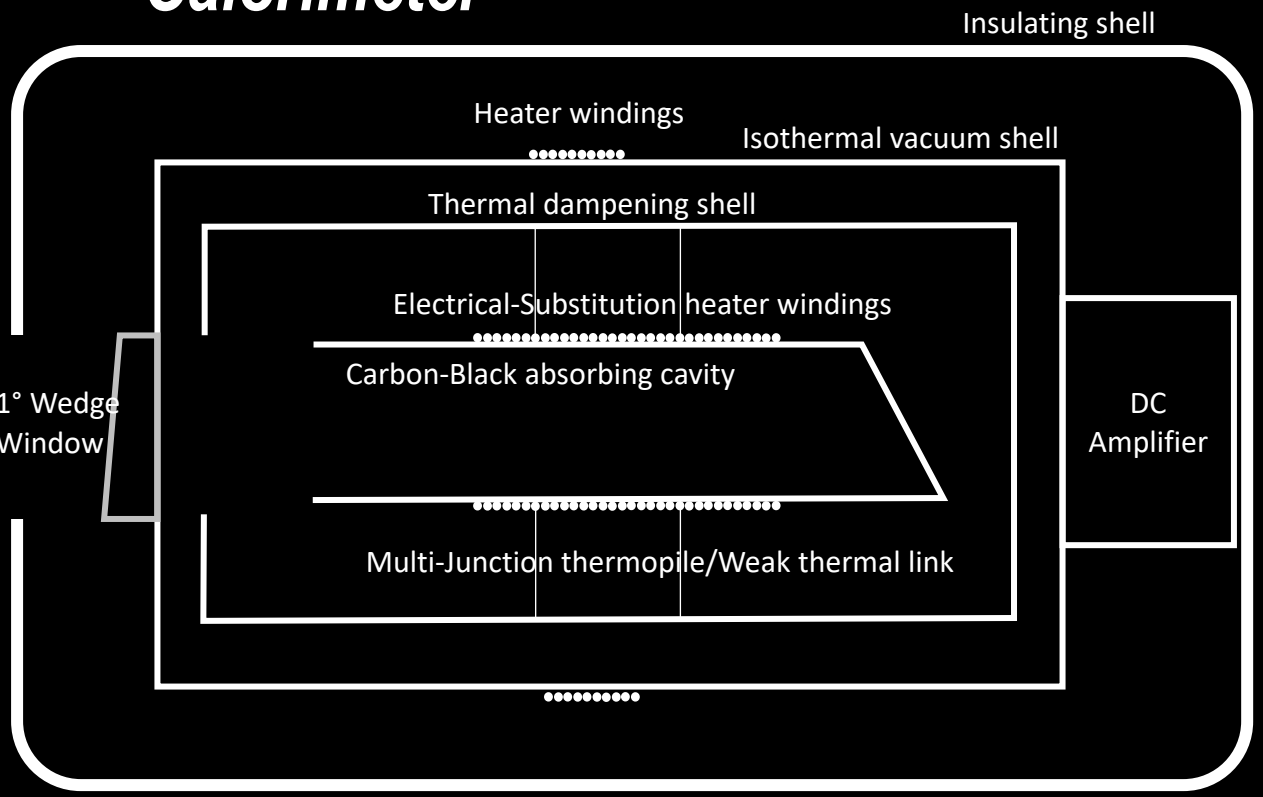
Don't be scared.

Data from Table 12, "Nd:YAG 1W" Kück *Metrologia* 47.1A (2010): 02003.

Results from consensus.nist.gov, encouraged by Amanda Koepke's Talk

The Present at NIST

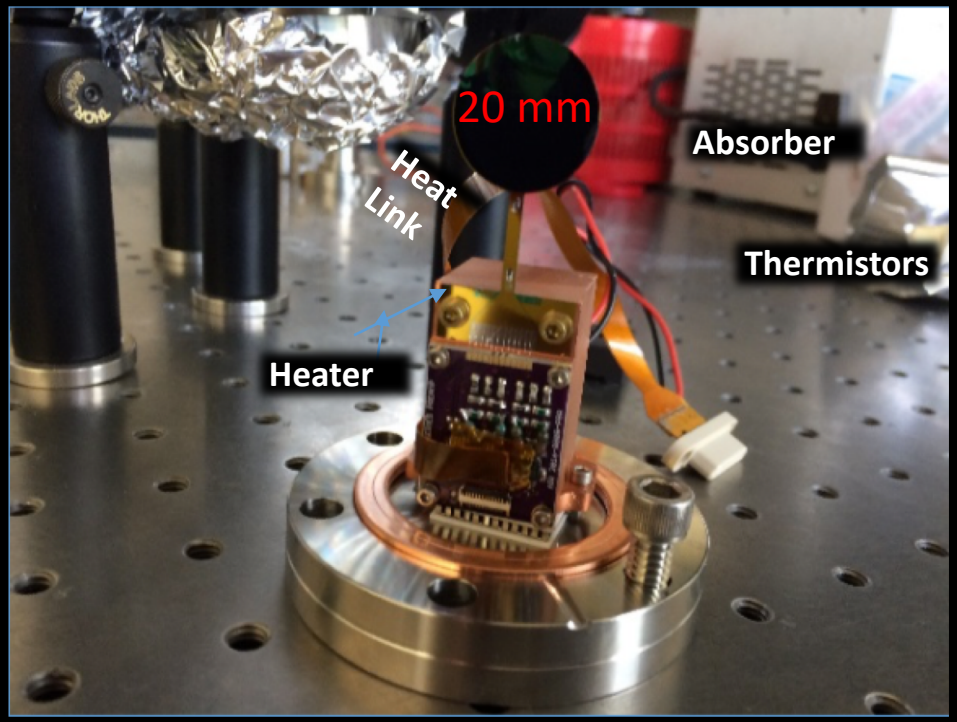
Calorimeter



- Transfer method: beam splitter compares two calorimeters, then DUT replaces one of them
- Primary calorimeter traceable to *the* kilogram (now Planck's Constant) via electrical substitution
- Some recent improvements to optical systematics of method, external to calorimeter
- Further improvements to transfer method (and thus its uncertainty) require characterization of parts internal to calorimeter

Results from Matt Spidell's Talk at Workshop

The Future at NIST



- Si substrate
- Peltier heater around perimeter
- Vertically aligned carbon nanotube absorber
- Transition edge sensor or commercial off-the-shelf thermistor or thin-film VOx for temperature measurement

Room Temperature Bolometer

Requirements:

- 2 cm beam diameter
- 100 μW – 100 mW
- 325 nm – 1.93 μm
- 2 minute time constant
- Mostly off-the-shelf

0.05% = 68% C.I. time-scale = "next few years"

Results from Michelle Stephen's Talk at Workshop

The Message: Continue As Normal

- **NIST will be implementing a new primary reference**
  - on pace with our observing runs and improved sensitivity
  - The challenge is now on us >> preserve that absolute uncertainty all the way to the end stations and through the interferometers
- **All GW interferometers now have PCAL system and all are traceable to NIST.**
- [Bonus Slides] Observatories **will continue to research new/different standards** in parallel on a "best effort" basis
  - VIRGO will continue to with Laser Wavelength reference, and move forward with improved NCAL system
  - LIGO will re-visit Laser Wavelength and RF Oscillator references, and move forward with NCAL system
  - KAGRA is pushing hard on the NCAL effort, likely will try other methods

Thank you!

BONUS SLIDES

Workshop Event on DCC

- NIST, Labsphere and other NMI attendees graciously agreed to share their talks

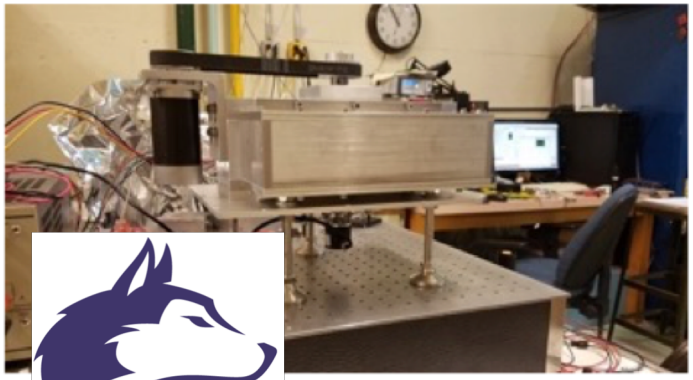
- All talks are available on DCC event page:

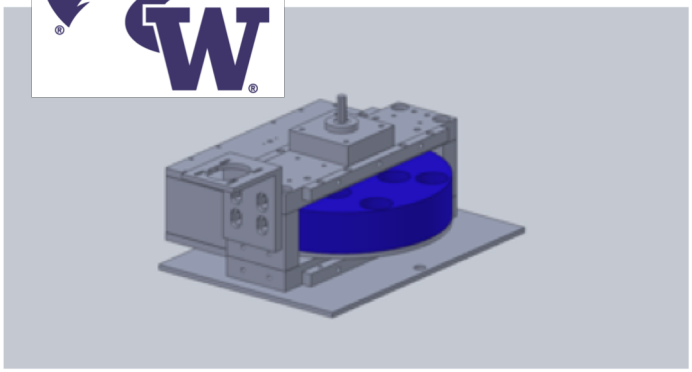
https://dcc.ligo.org/cgi-bin/DocDB/DisplayMeeting?conferenceid=1029

GCAL or NCAL

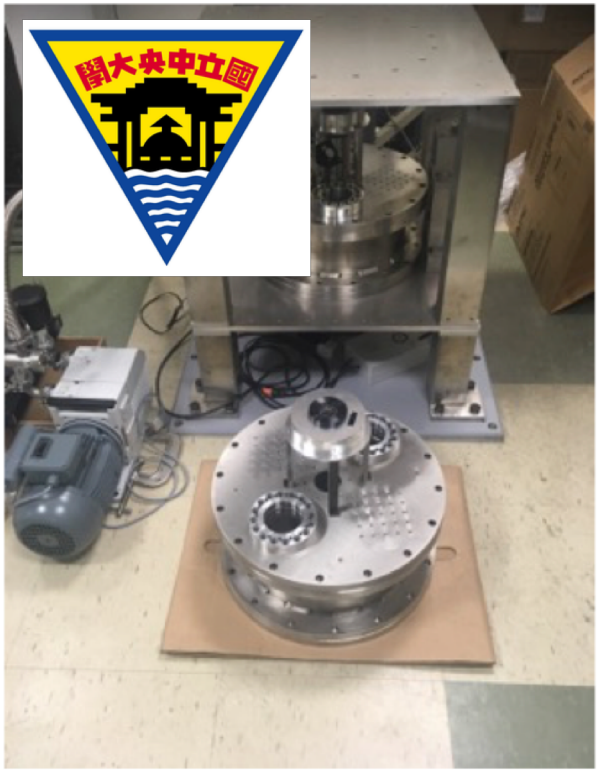
Virgo

LIGO





KAGRA



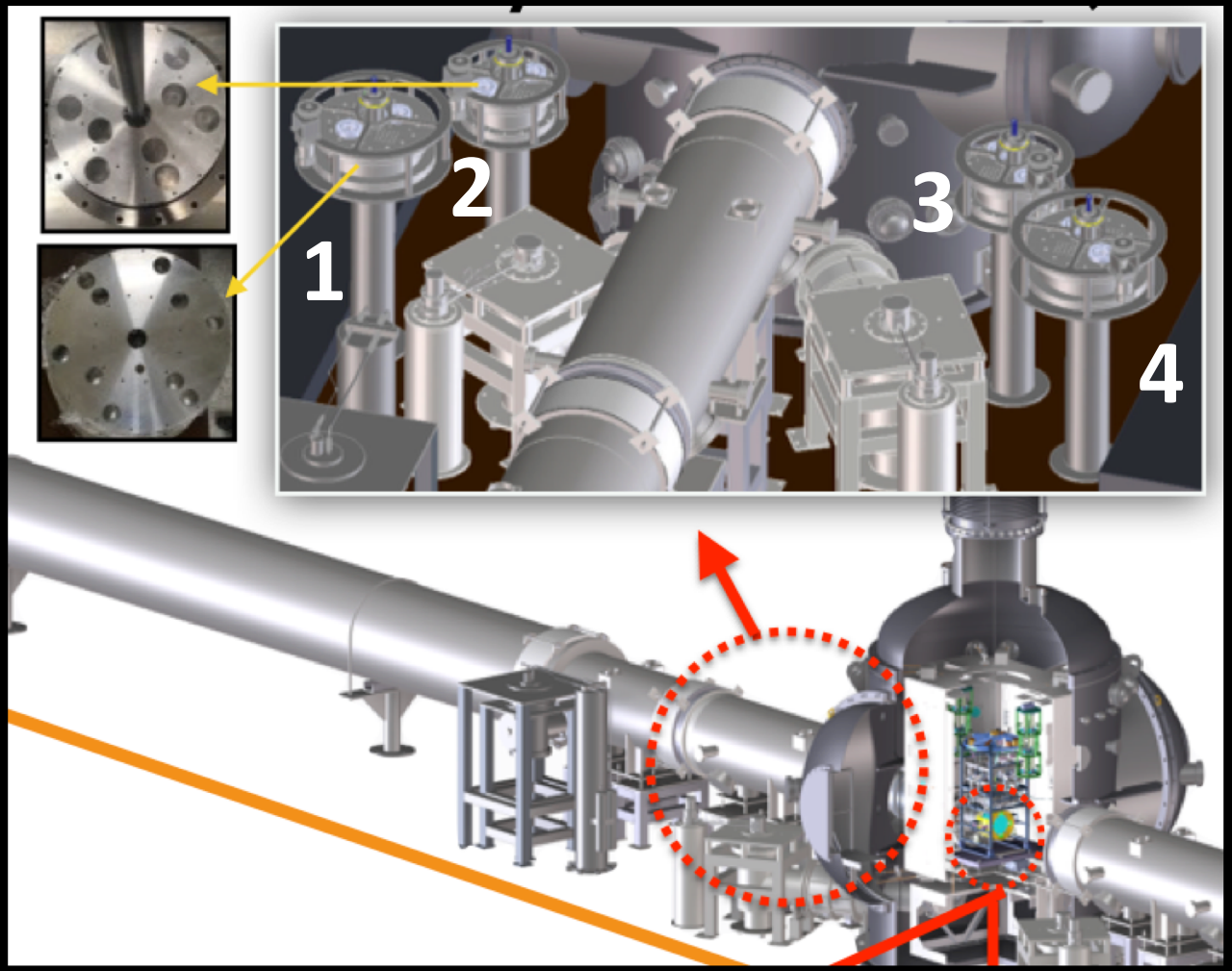
- World-wide excitement continues about Gravitational or Newtonian calibrators
- Develop on a “best effort” basis

  https://wiki.ligo.org/Calibration/NewtonianCalibrator

  ncal@ligo.org

  Search “NCAL” or “GCAL” on DCC

KAGRA Going All Out!



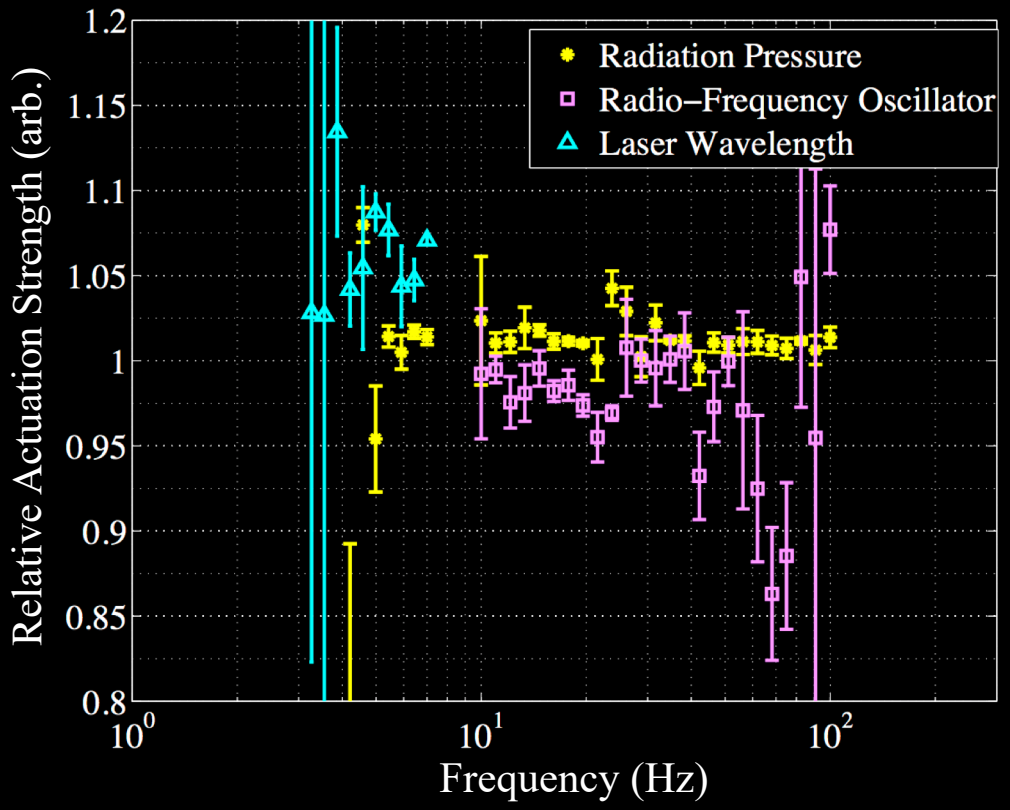
- FOUR GCALs surrounding one test mass
- In concert with photon calibrator with 20 W laser
- An almost 3G calibration setup!

Inoue, Yuki, et al. *Phys Rev D* 98.2 (2018): 022005.

See Many more details in Yuki's Workshop Talk

LSC Fellows Revive other Methods

- In GW150914 paper, LIGO published a comparison of 3 methods
  - Laser Wavelength (old standard)
  - Radio Frequency Oscillator (re-invented using ALS)
  - Radiation Pressure (PCAL)
- Now detectors are better understood and controlled
- LSC Fellows Dripta Bhattacharjee (LHO) and Rachel Gray (LLO) will support PCAL, NCAL, and resurrect the pre-O1 study, and do it more justice



Always in seek of ”The Truth,” …