Absolute Calibration of A Gravitational Wave Detector Network

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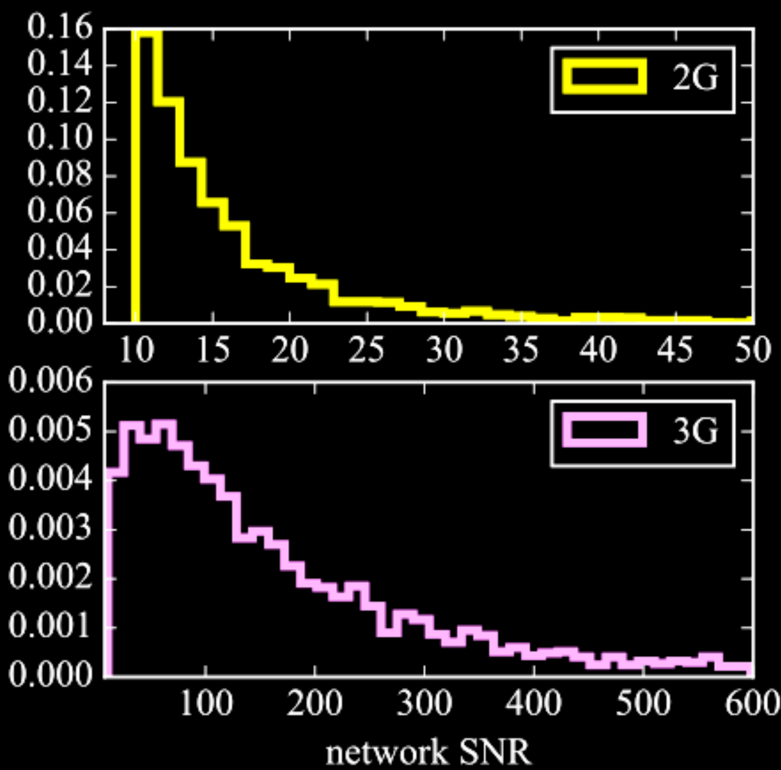
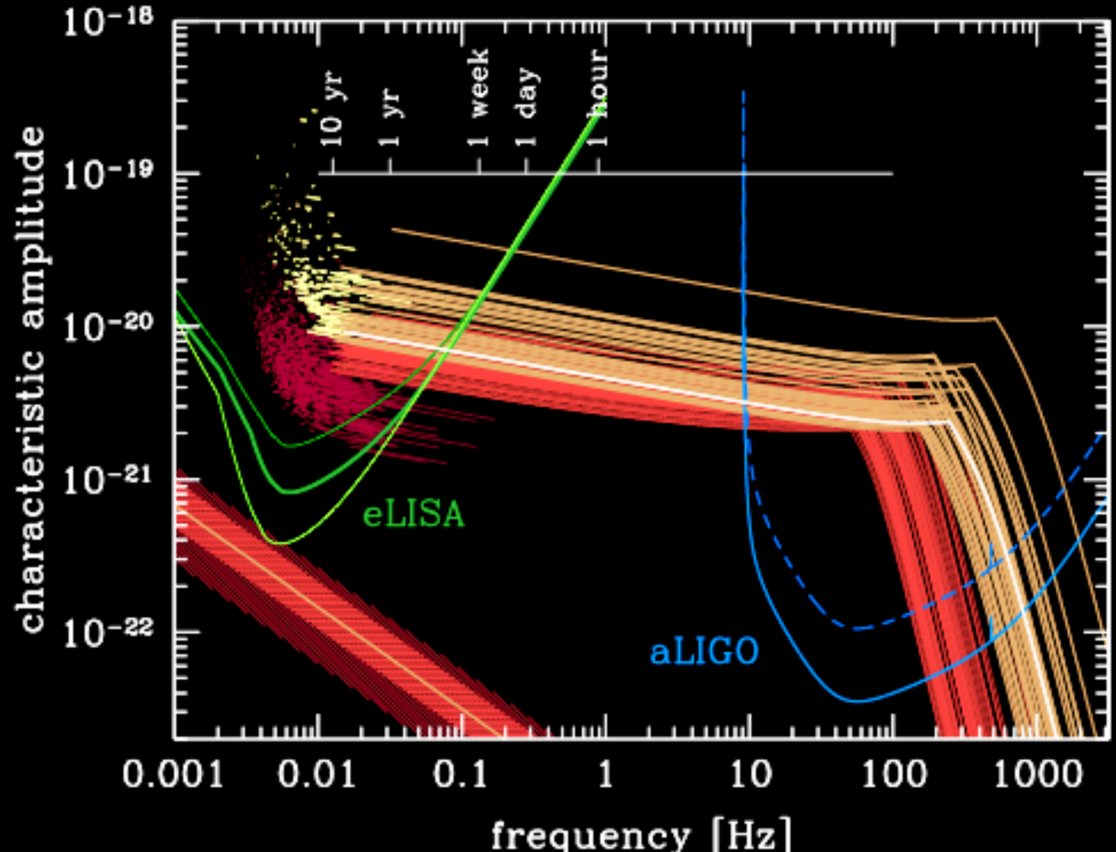
Inspiration

2G , 3G, Space, and PTAs will have events with SNRs of O(~100)…

…Detector calibration **must** get *better* than ~1%



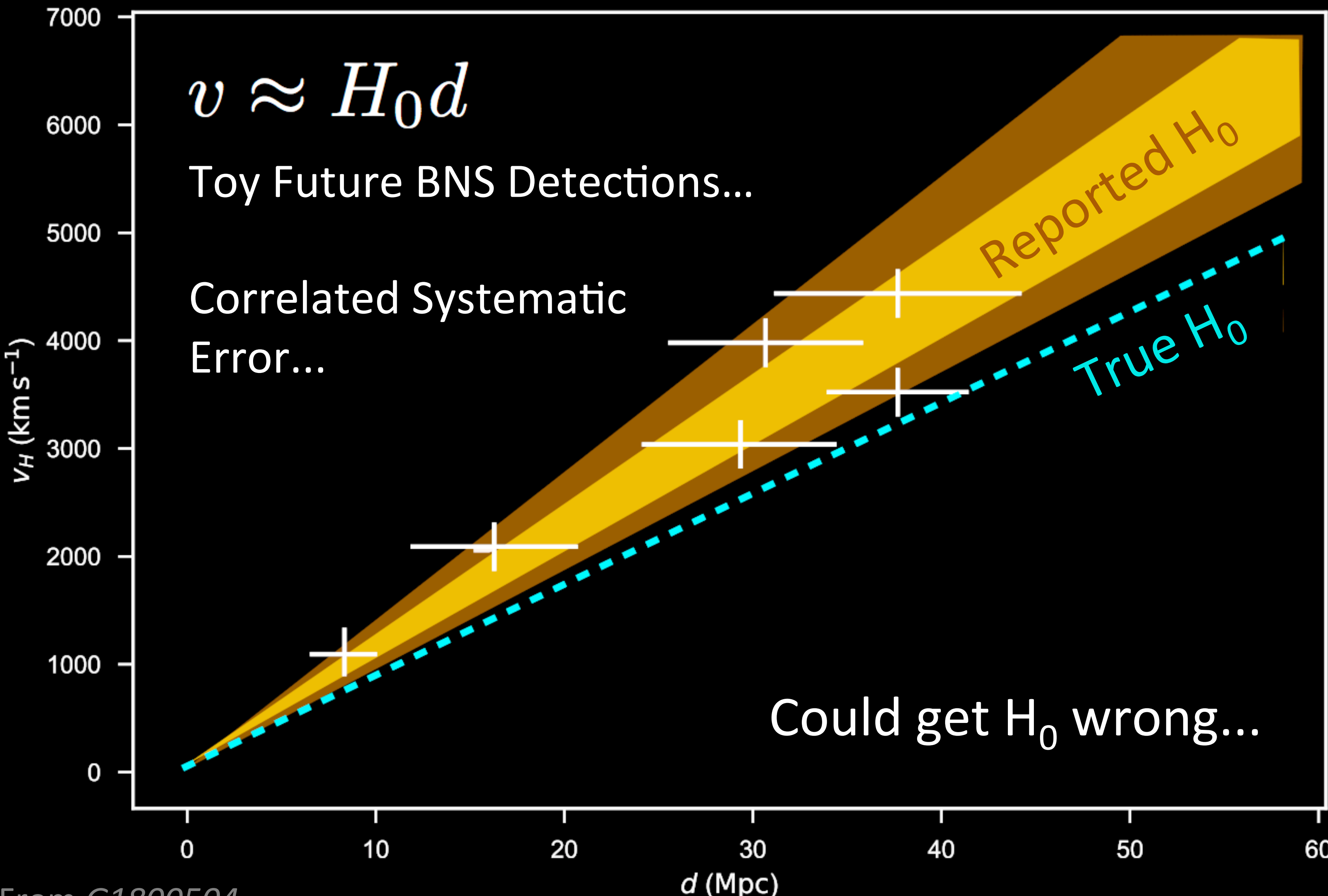


And if multi-band, we must understand each other's systematic errors.

PRD 94.12 (2016): 121501

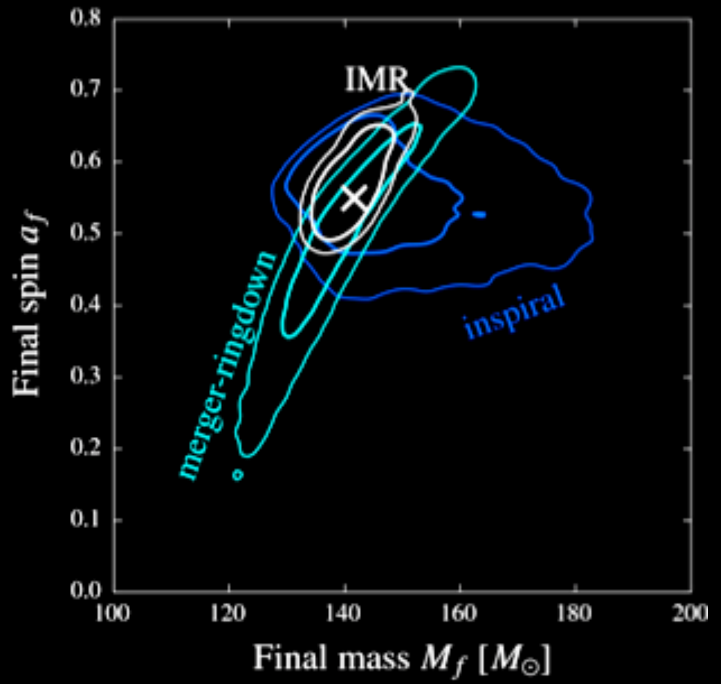
PRL 116.23 (2016): 231102

Cosmology and Correlated Systematic Errors



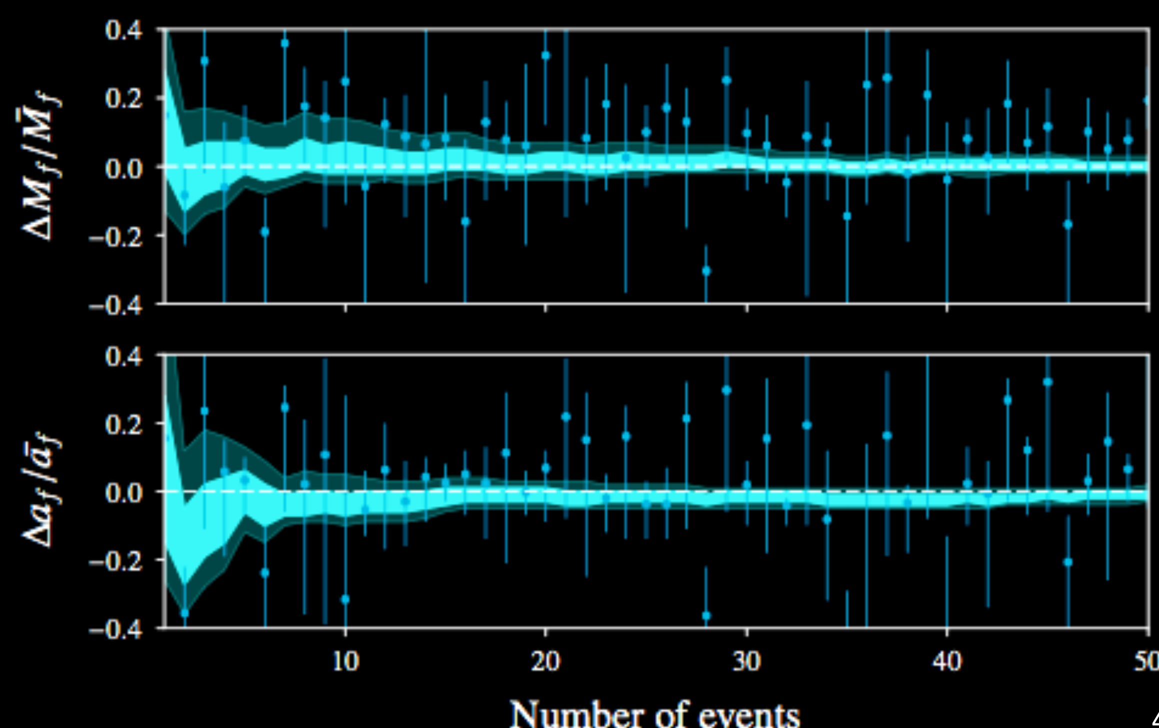
From *G1800504*

Tests of GR and Correlated Systematic Errors



Similar systematic error across events may lead you astray in GR consistency checks

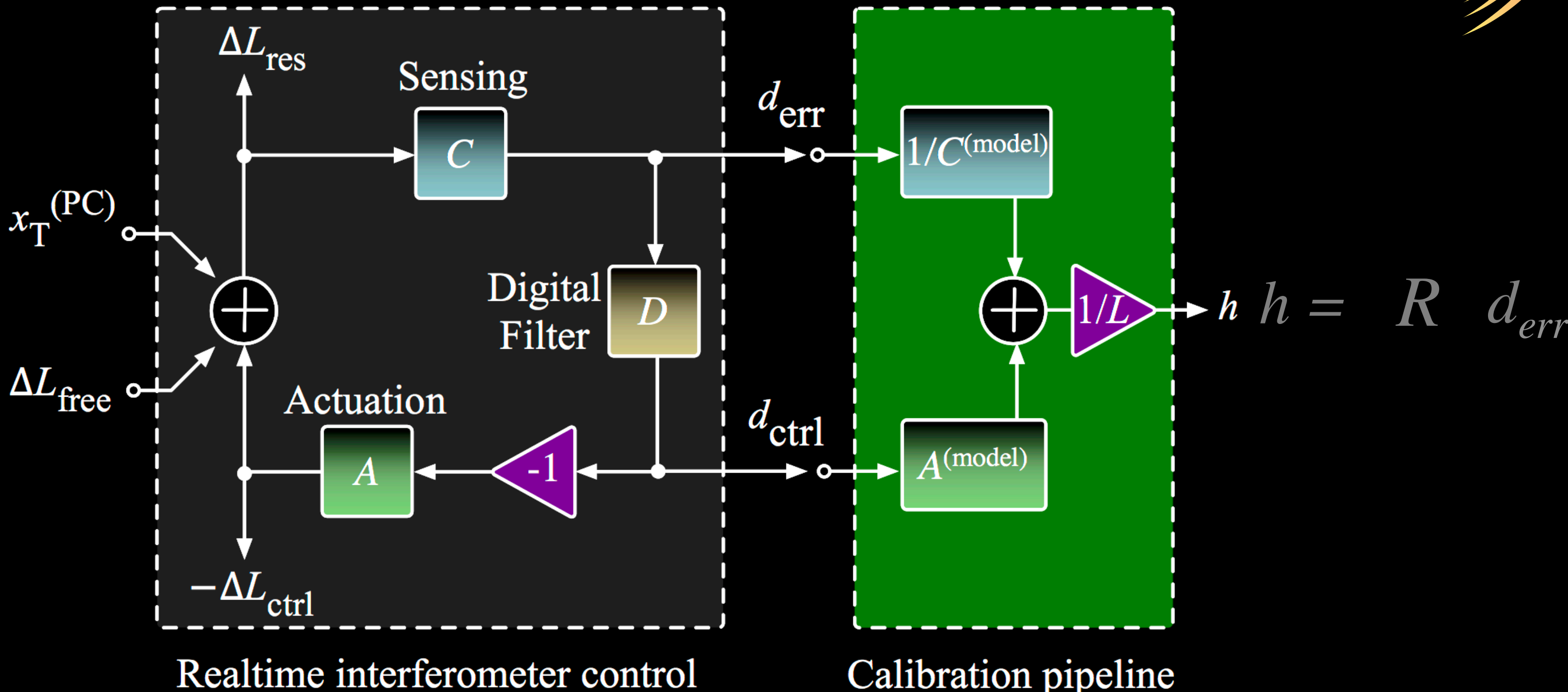
Will not get SQRT(N) improvement, because calibration's systematic errors (biases) are correlated b/w events.



Will need to consider calibration uncertainty and systematic error over several events, several observation runs as the detector hardware changes

CQG 35.1 (2017): 014002.
(and from yesterday; G1800976)

State of the Art Example: LIGO 2G



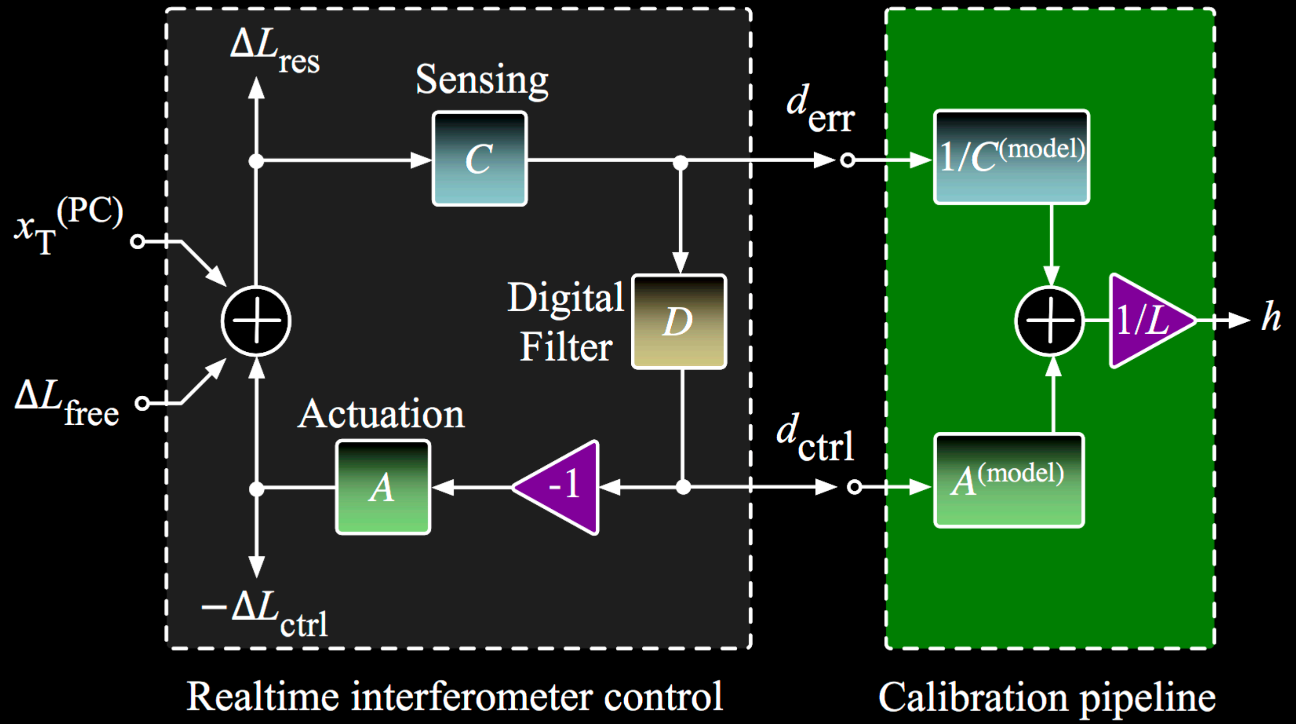
$$R = \frac{1}{L}\frac{1+G}{C} \qquad G = A\,D\,C \qquad h\,L = \frac{1}{C}\,d_{err} + A\ d_{ctrl}$$

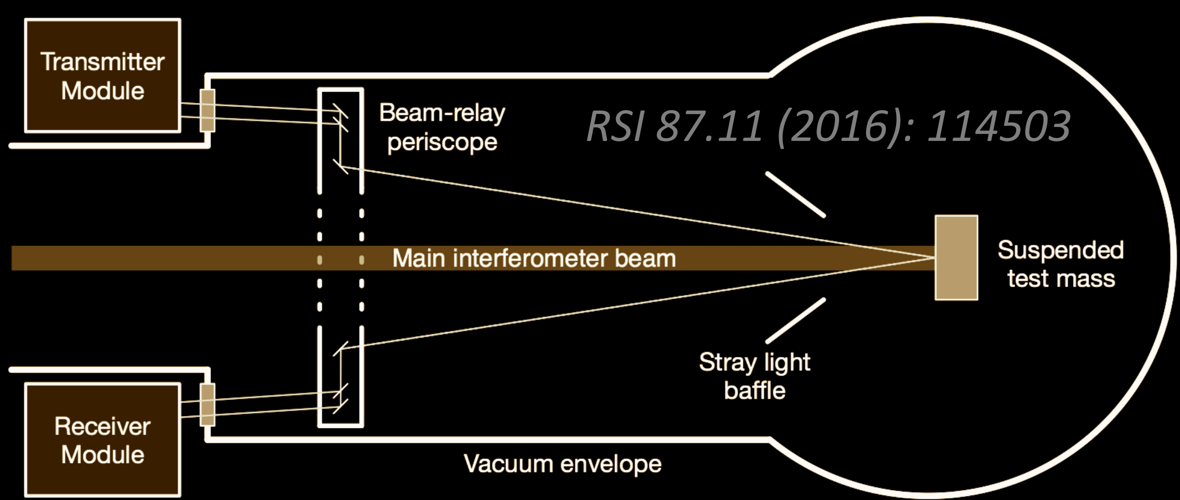
$$dR^2 = \left(\frac{1}{1+G}\right)^2\left(\frac{dC}{C}\right)^2 + \left(\frac{G}{1+G}\right)^2\left(\frac{dA}{A}\right)^2$$

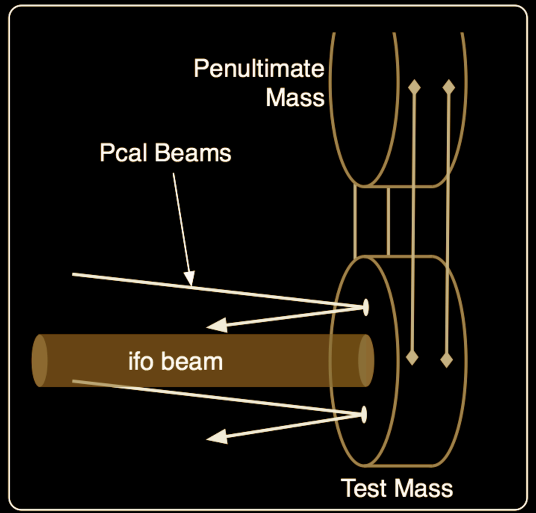
+ *Systematic Error*

PRD 95.6 (2017): 062003.

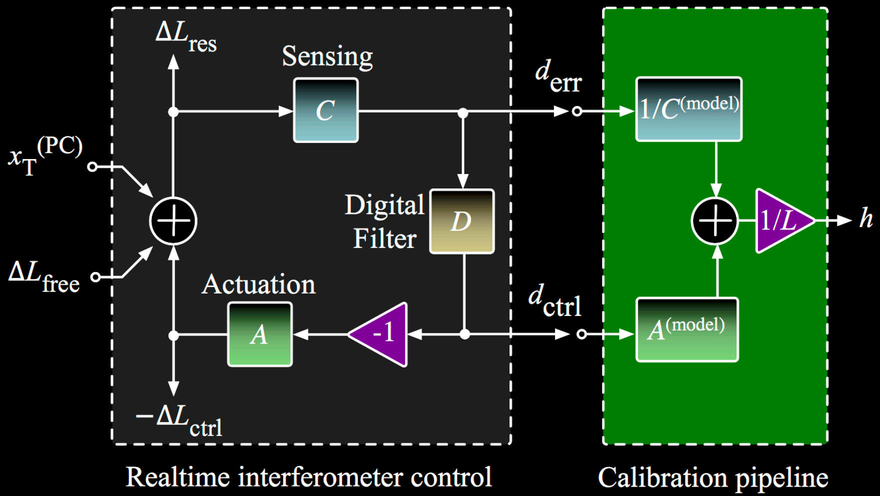
Absolute Reference: Radiation Pressure







How does LIGO Determine dC and dA

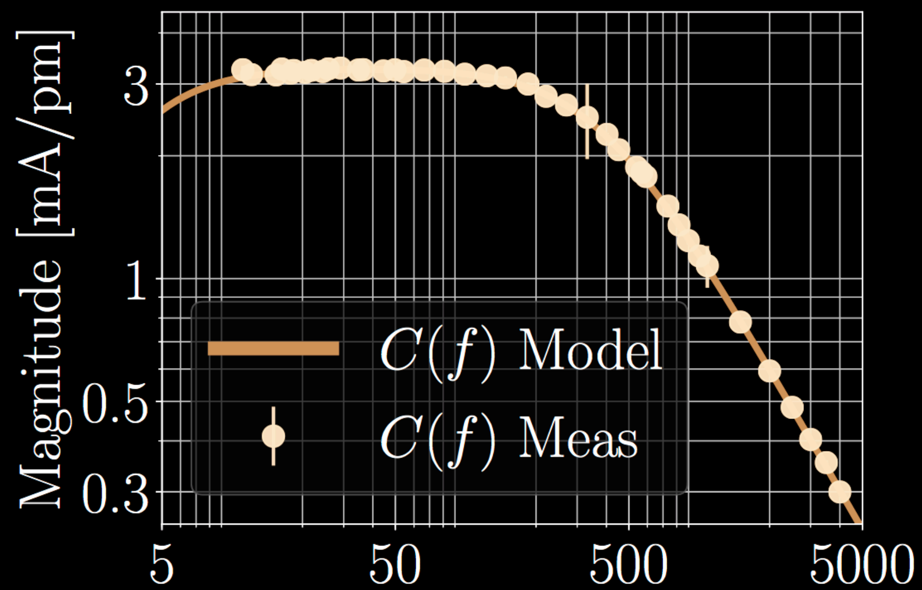


$$C = \frac{d_{exc}}{d_{IN2}} \times \frac{d_{err}}{x_{pcal}} \times \frac{x_{pcal}}{pd_{pcal}}$$

Complex TFs w/ Full IFO

Absolute Scale Factor

$$A = \frac{d_{err}}{d_{exc}} \times \frac{x_{pcal}}{d_{err}} \times \frac{pd_{pcal}}{x_{pcal}}$$

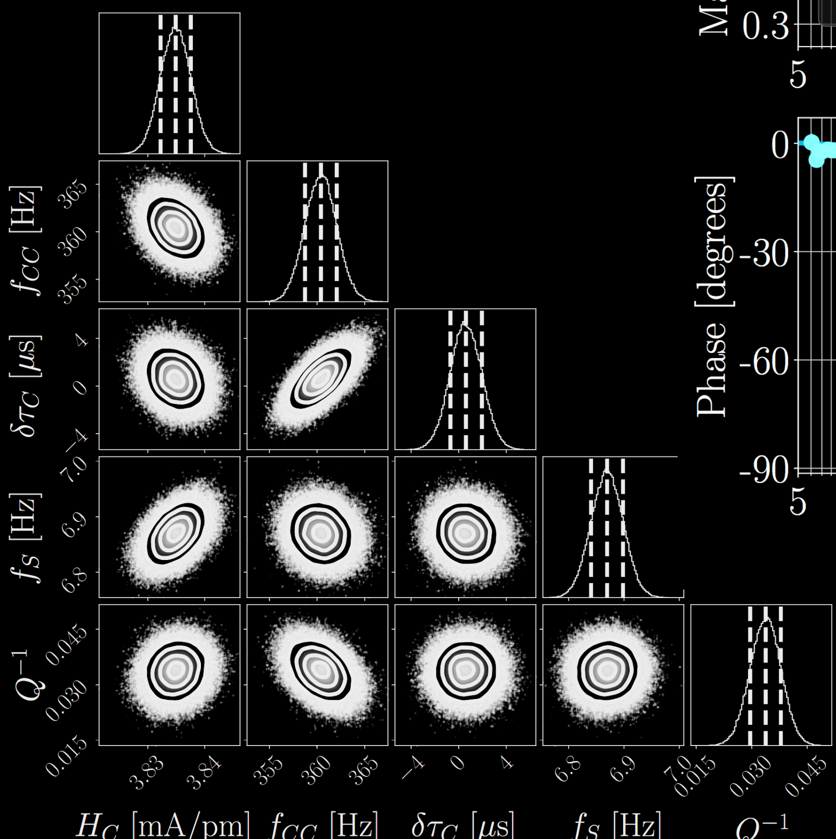


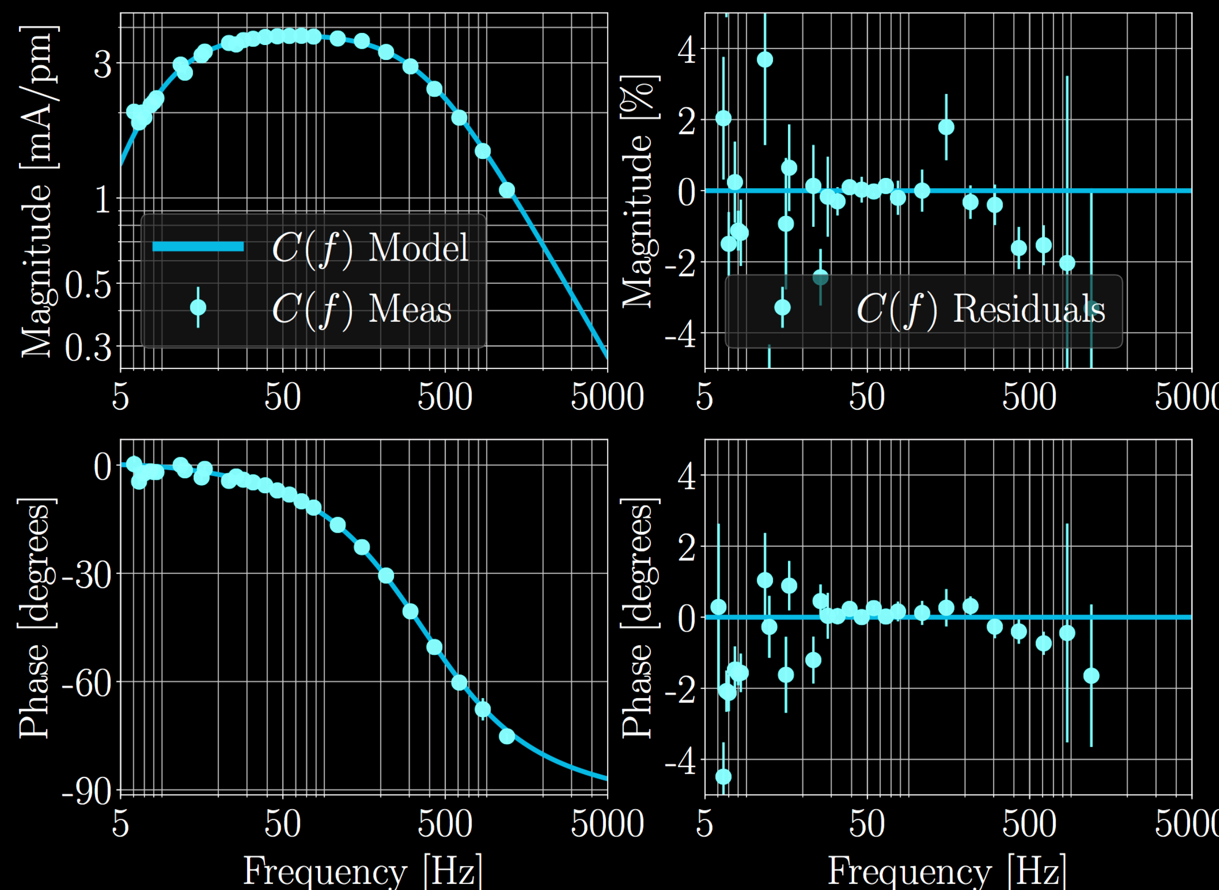
Phase uncertainty is entirely from Full IFO transfer functions, not set by absolute scale.

PRD 96.10 (2017): 102001

Systematic Error vs. Statistical Uncertainty

Statistical uncertainty: MCMC posteriors to the model parameters sampled to form a sample response function.



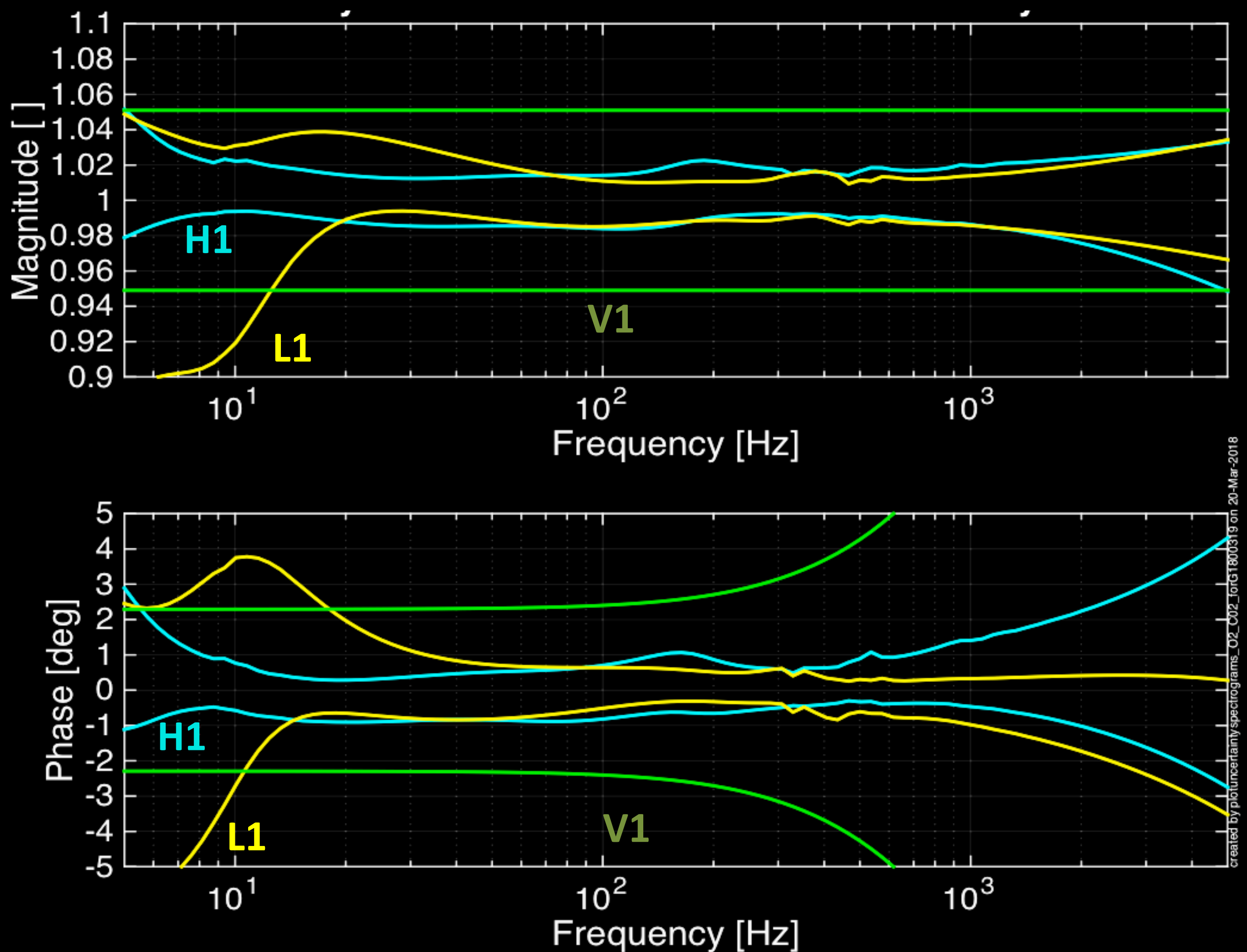


Systematic Error:

- **Any residual, statistically significant, frequency dependence**
- **Fundamental reference error**

 For the Latest IFO Model: T1800115

2G Detector (Known) Error and Uncertainty



$$dR^2 \approx \left(\frac{1}{1+G}\right)^2 \left(\frac{dC}{C}\right)^2 + \left(\frac{G}{1+G}\right)^2 \left(\frac{dA}{A}\right)^2$$

+ Systematic Error

What are the 2G limits?

- Yes… Propagation of NIST factor
  - Years of practice has this nailed down

BUT ALSO:

- PCAL Actuator Alignment
  - Will be improved for O3!
  - But can't track anymore…
- IFO Actuator Strength
  - To measure open loop gain and DARM actuator drive
- Detector Performance
  - If noise improves, SNR improves for fixed actuator
  - For detector upgrades, actuation strength will decrease

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

Complex TFs w/ Full IFO

Absolute Scale Factor

$$A = \frac{d_{err}}{d_{exc}} \times \frac{x_{pcal}}{d_{err}} \times \frac{pd_{pcal}}{x_{pcal}}$$

AND OF COURSE,

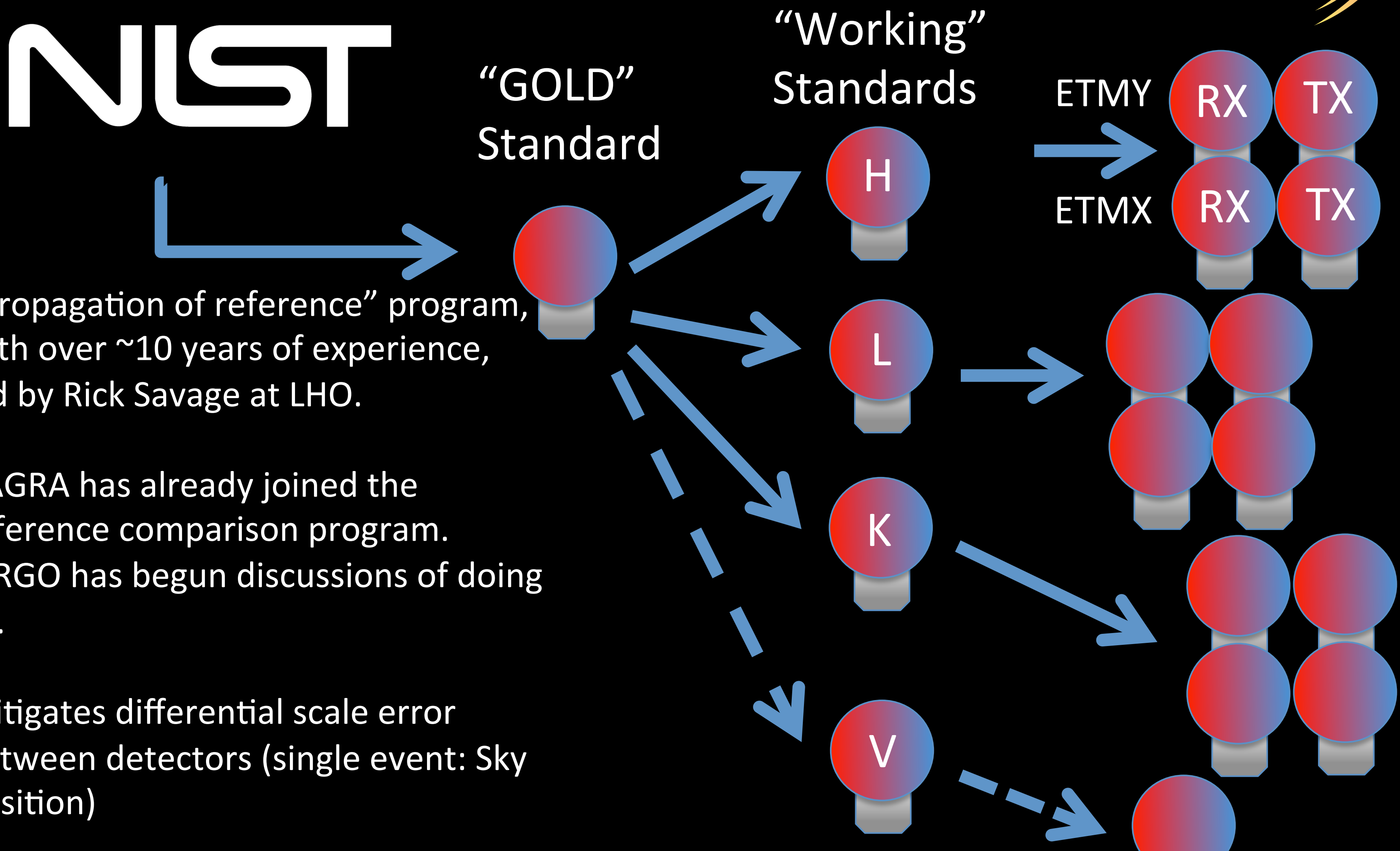
… patience

… person power

… interferometer time

(see last year's talk, G1700810)

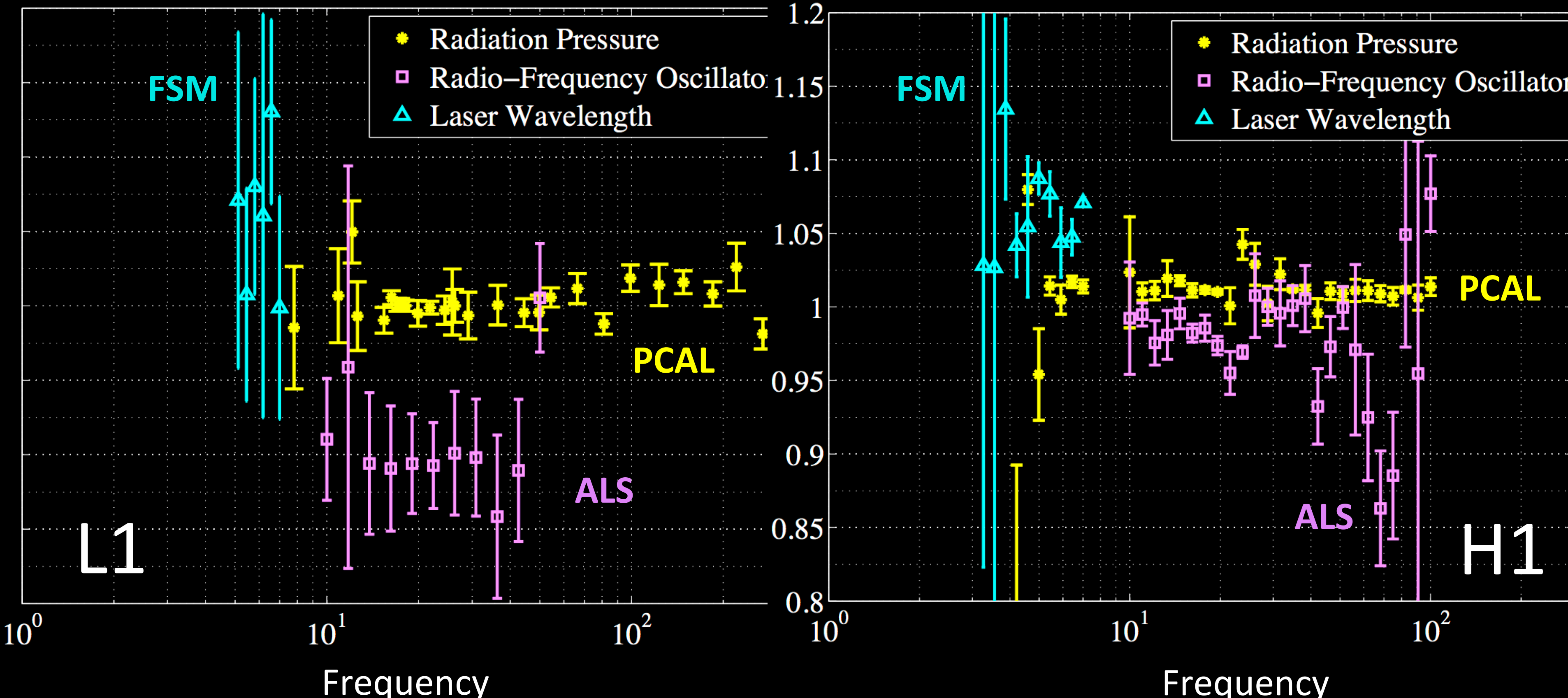
The International Reference Exchange



- "Propagation of reference" program, with over ~10 years of experience, led by Rick Savage at LHO.
- KAGRA has already joined the reference comparison program. VIRGO has begun discussions of doing so.
- Mitigates differential scale error between detectors (single event: Sky Position)
- Still leaves vulnerability to common scale error (single event: Distance)

iLIGO: *CQG 26.24 (2009): 245011.*
aLIGO: *RSI 87.11 (2016): 114503,*
T1800046, *T1800207, G1800505*

In-House PCAL Reference Check



- **Free-swinging Michelson** doesn't work well for LIGO. ITM must drive at PUM, too weak a drive.
- **Arm Length Stabilization** is too noisy, and electronics weren't well understood at the time.

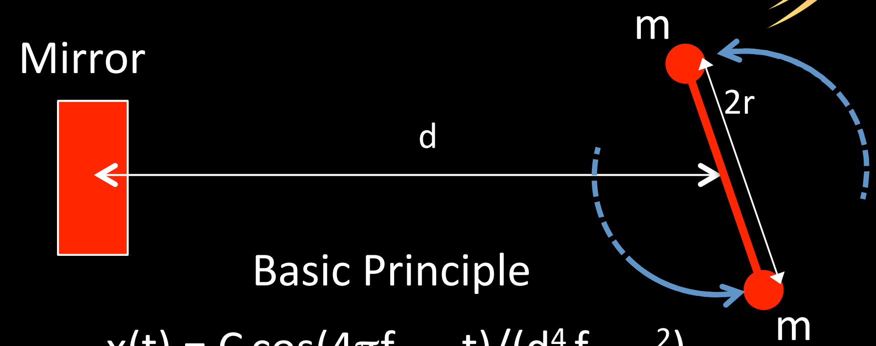
Abbott, B. P., et al. *PRD* 95.6 (2017): 062003.

Checks are not (yet?) precise.

Plans are to revisit this for O3.

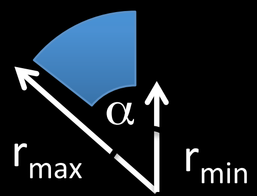
Terrestrial Detectors: The Next “New” Idea

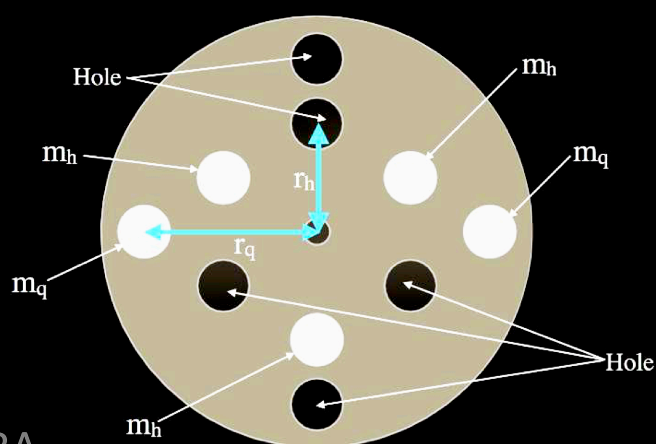
- Newtonian Gravitational Calibrators (NCAL, GCAL) have recently (re)-picked up steam
- In-theory a ~0.1% level reference
  - PCAL starts at ~0.5%
- May be ready to *corroborate* PCAL by O3



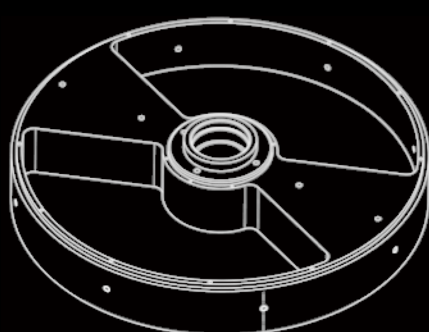
$$x(t) = C\cos(4\pi f_{rotor} t)/(d^4 f_{rotor}^2)$$

where $C = (9G/32\pi^2)(z\,\rho\,\sin(\alpha)(r_{max}^4 - r_{min}^4)/4)$

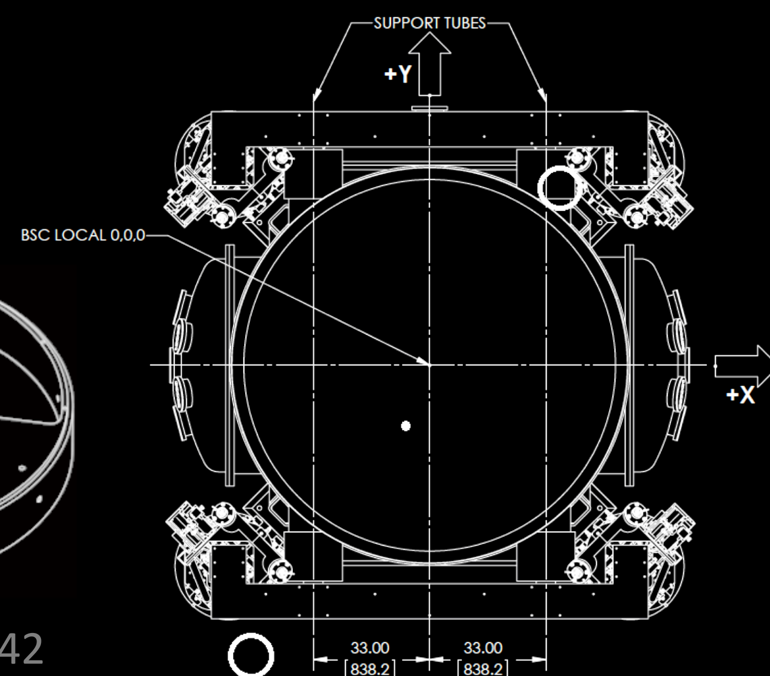




KAGRA - arXiv:1804.08249 (2018).



VIRGO - G1800442



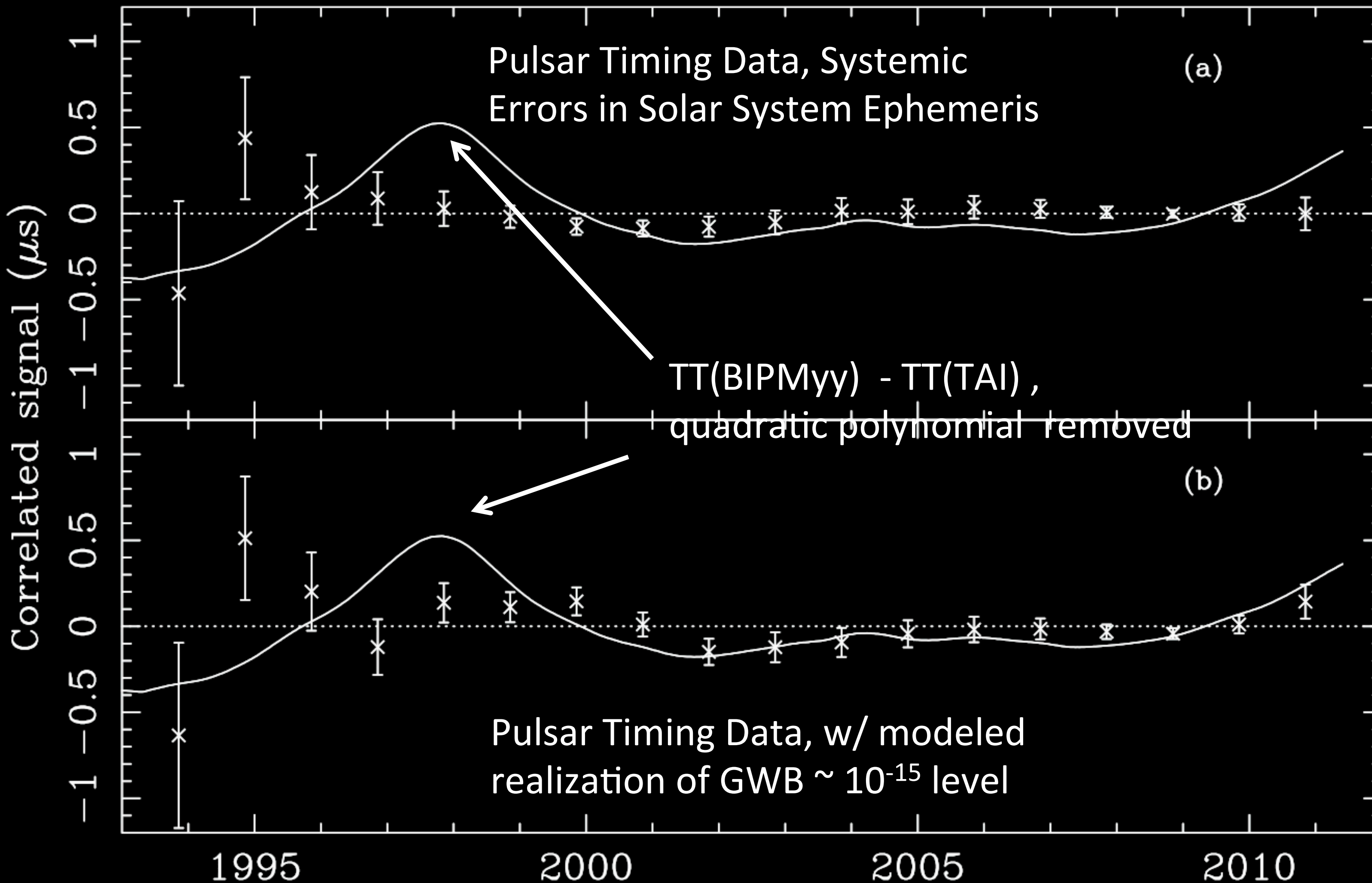
LIGO – “in prep.”

What about Space and Galactic Detectors?

- Pulsar Timing Arrays (timing systems)
  - Limited by diverse Timing Systems in Array, over Decades?
  - Everyone uses TEMPO2… (*Hobbs et. al 2006*)

- LISA (phase meters and microthrusters)
  - Time Delay Interferometry – More clocks and Frequency Refs.
    - needs to measure individual, ~1e6 m arm lengths to ~10m precision
    - needs clocks synchronized at the ~50 nsec level

Example Timing System Systematics



MNRAS **427,** 2780–2787 (2012)

TT = Terrestrial Time
BIPM = Bureau International des Poids et Mesures
TT(TAI) = International Atomic Time -> *Basis for UTC*
TT(BIPMyy) -- updates / corrections, released over time

Discussion & Questions

- Calibration is ~~service work~~ **precision engineering**

- Precision/accuracy will not linearly increase with time and costs real money, not “just” time and person power.

- We’re actively working with NIST to understand the EUROMET study – Rick @ NIST this week!
  - *(+ soon new post-doc John Cripe!)*

- Already working to make ground-based detectors internally consistent via Photon Calibrator, starting to think how to get past its limits

- Need to begin dialogue with fundamentally different GW detectors


Thank You!

Bonus Slides

Primer

Big G / (1e-11 $m^3\ kg^{-1}\ s^{-2}$)

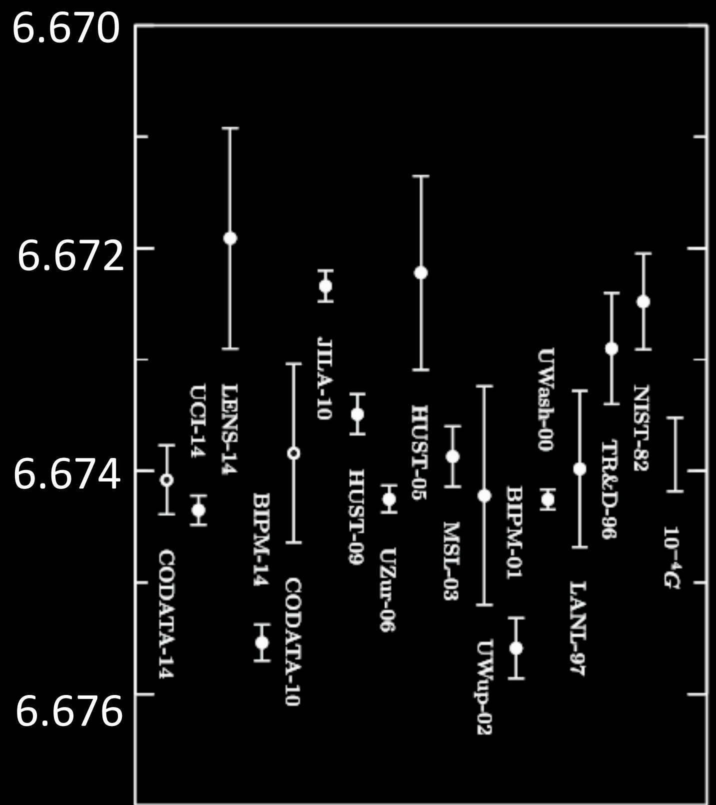


Figure 6
CODATA 2014: Mohr, Newell, and Taylor. Phys. Chem. Ref. Data 45 (2016): 043102.

Response of a Photodetector

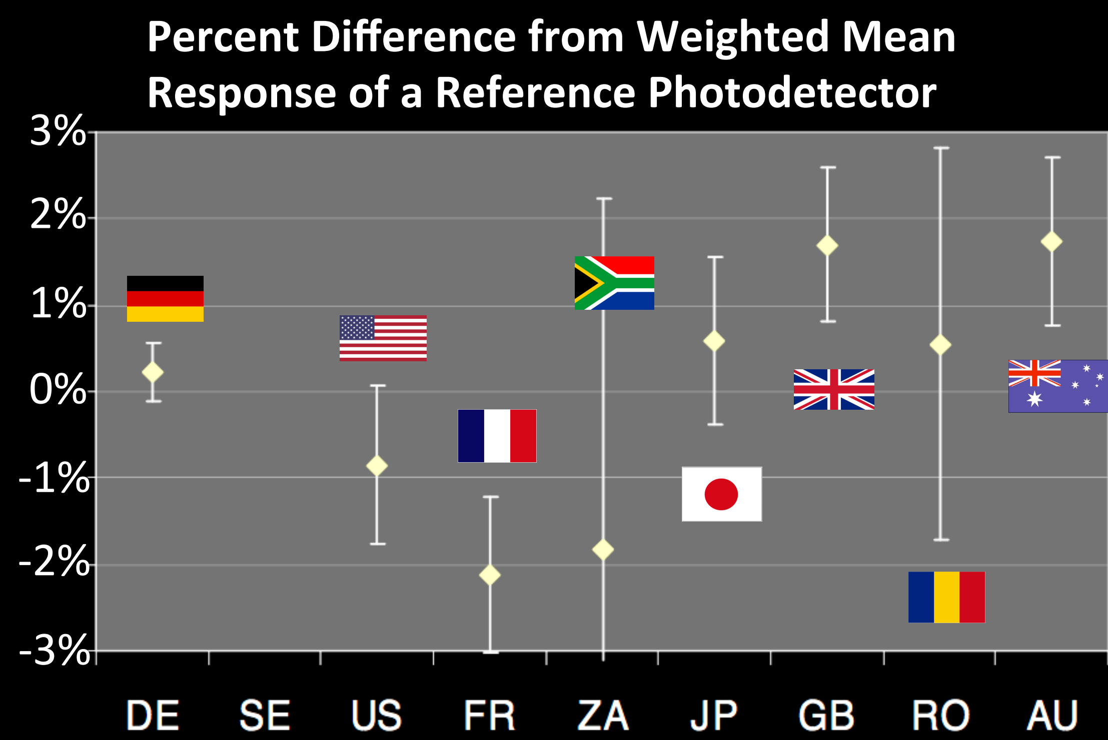
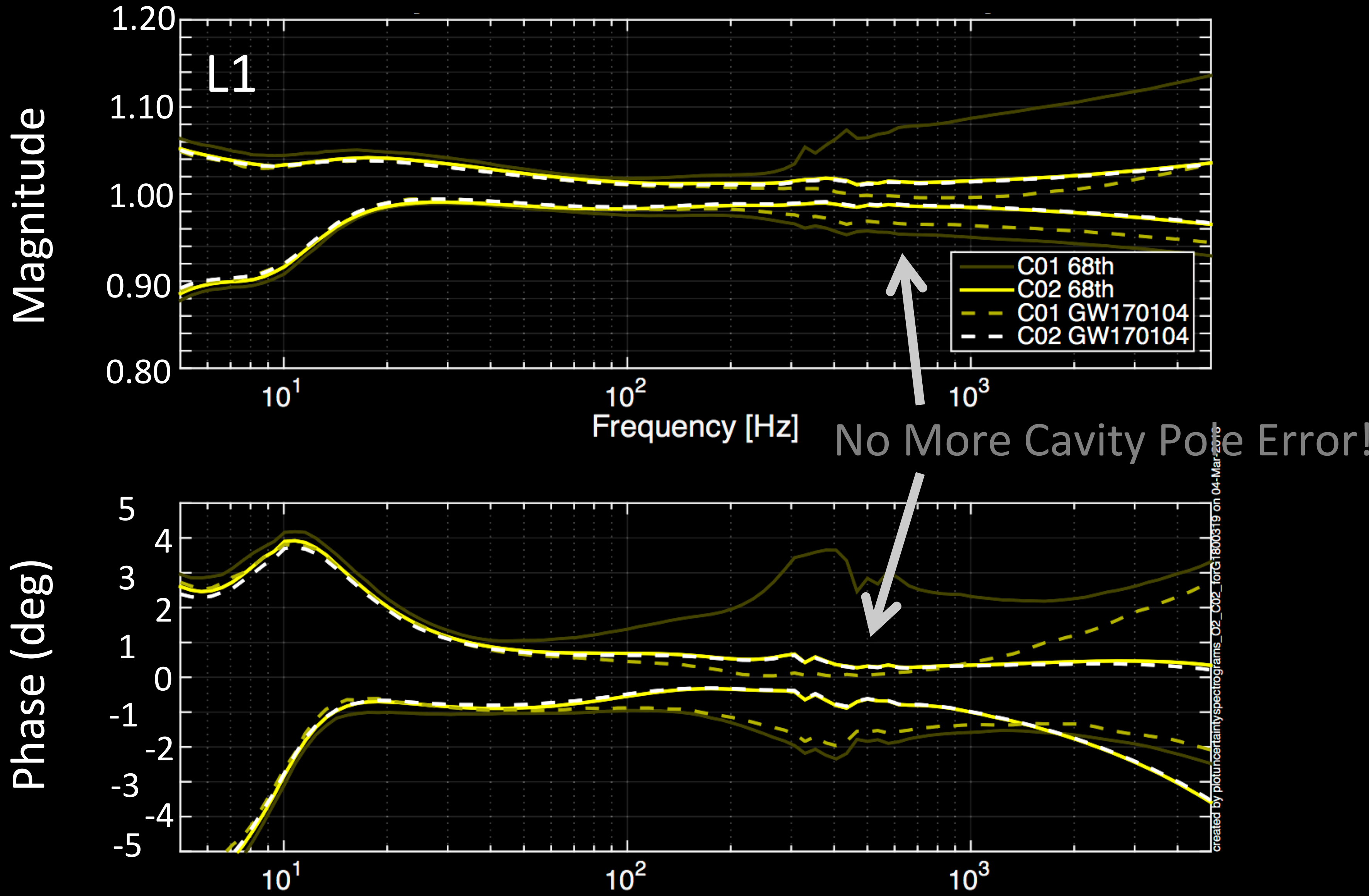


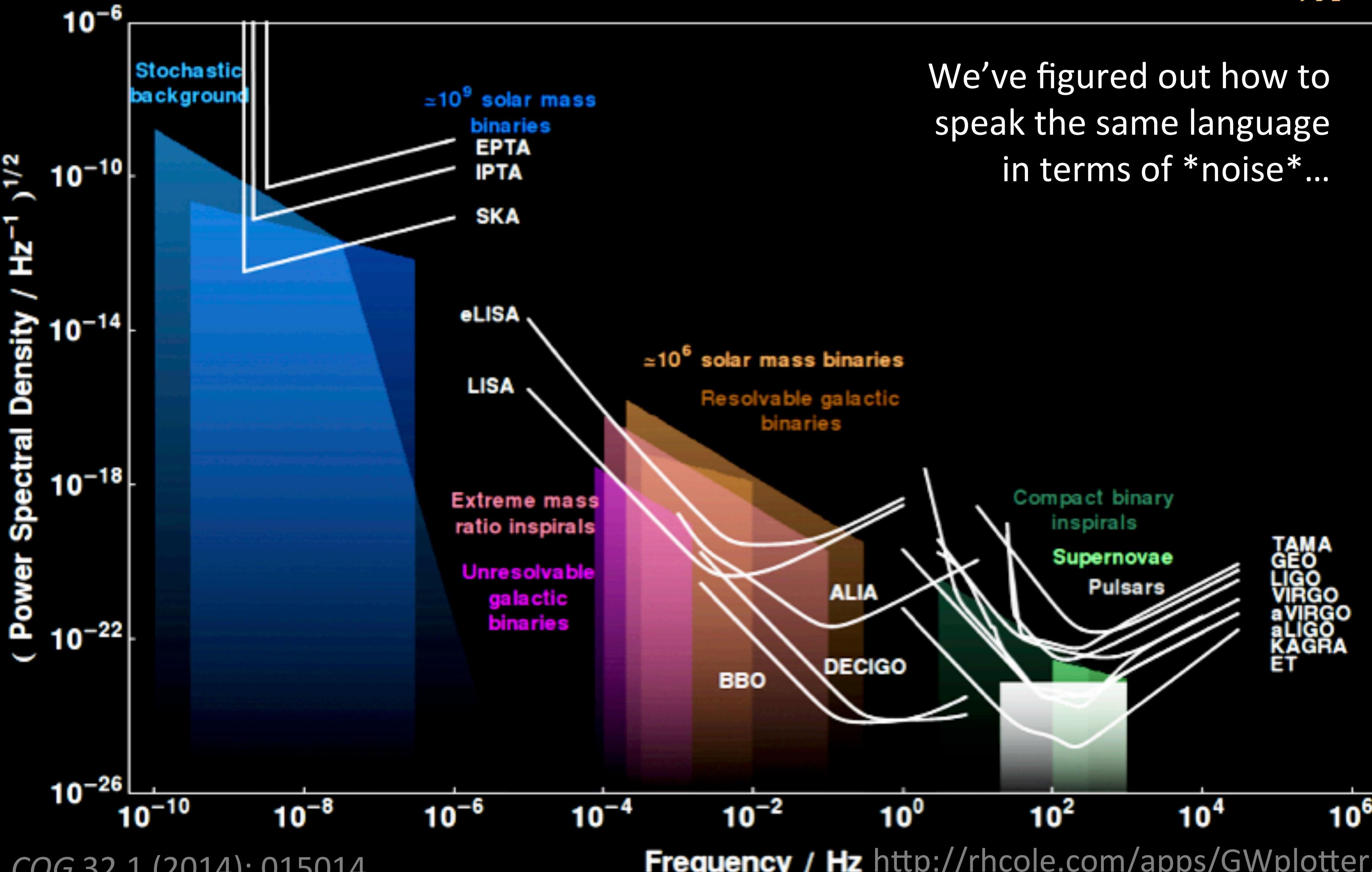
Figure 9
Kück *Metrologia* 47.1A (2010): 02003.

Bonus Slides: Removal of Systematic Error



Common Sensitivity Plot

We've figured out how to speak the same language in terms of *noise*…



CQG 32.1 (2014): 015014. http://rhcole.com/apps/GWplotter/

PTA Resolved Signal Parameter Estimation

- Current IPTA is at 49 Pulsars
  - *MNRAS* 458.2 (2016): 1267-1288
- 7 parameters – 3 for Sky Location, Amplitude, Source Inclination, Polarization Angle, Rotation Frequency
- (Distance and Mass are degenerate ☹)
- For SNR = 10, sky location uncertainty typically simulate (Fisher Matrix) to ~40 deg^2 and 30% in amplitude
  - *PRD* 81.10 (2010): 104008.
- Amplitude uncertainty scales with SNR, sky location scales with SNR^2

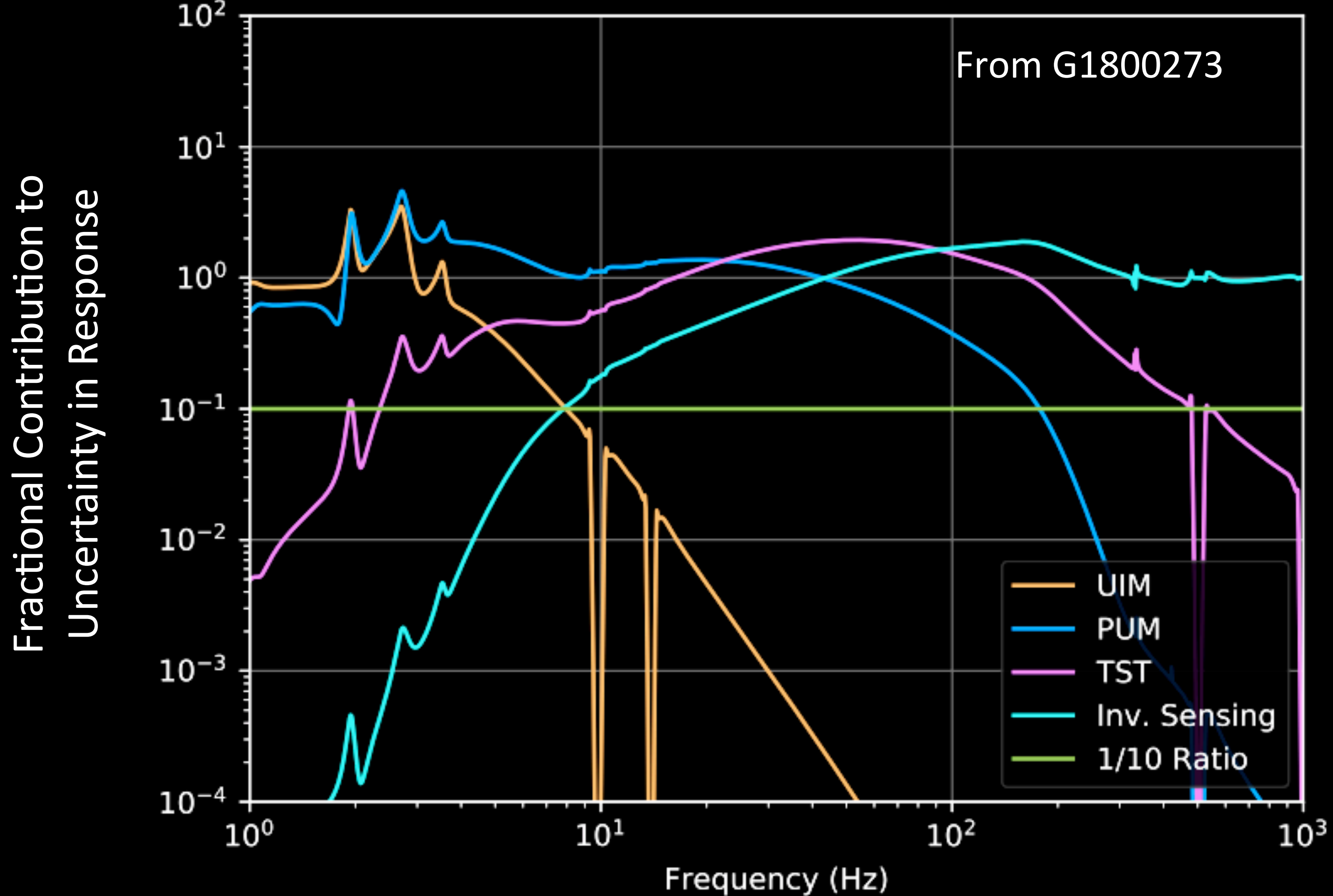
Pulsar Timing Array Papers

- Verbiest, J. P. W., et al. "Status update of the Parkes pulsar timing array." *Classical and Quantum Gravity* 27.8 (2010): 084015.
- Sesana, Alberto, and Alberto Vecchio. "Measuring the parameters of massive black hole binary systems with pulsar timing array observations of gravitational waves." *Physical Review D* 81.10 (2010): 104008.
- Arzoumanian, Z., et al. "Gravitational waves from individual supermassive black hole binaries in circular orbits: Limits from the North American Nanohertz Observatory for Gravitational Waves." *The Astrophysical Journal* 794.2 (2014): 141.
- Verbiest, J. P. W., et al. "The international pulsar timing array: first data release." *Monthly Notices of the Royal Astronomical Society* 458.2 (2016): 1267-1288.
- Hobbs, G., et al. "Development of a pulsar-based time-scale." *Monthly Notices of the Royal Astronomical Society* 427.4 (2012): 2780-2787.
- Becker, Werner, Michael Kramer, and Alberto Sesana. "Pulsar Timing and Its Application for Navigation and Gravitational Wave Detection." *Space Science Reviews* 214.1 (2018): 30.

Time Delay Interferometry Papers

- Tinto, Massimo, and Sanjeev V. Dhurandhar. "Time-delay interferometry." *Living reviews in relativity* 17.1 (2014): 6.
- Hellings, Ronald W. "Elimination of clock jitter noise in spaceborne laser interferometers." *Physical Review D* 64.2 (2001): 022002.
- Armstrong, J. W., F. B. Estabrook, and Massimo Tinto. "Time delay interferometry." *Classical and Quantum Gravity* 20.10 (2003): S283.
- Tinto, Massimo, Frank B. Estabrook, and J. W. Armstrong. "Time-delay interferometry for LISA." *Physical Review D* 65.8 (2002): 082003.

What Contributes Where?



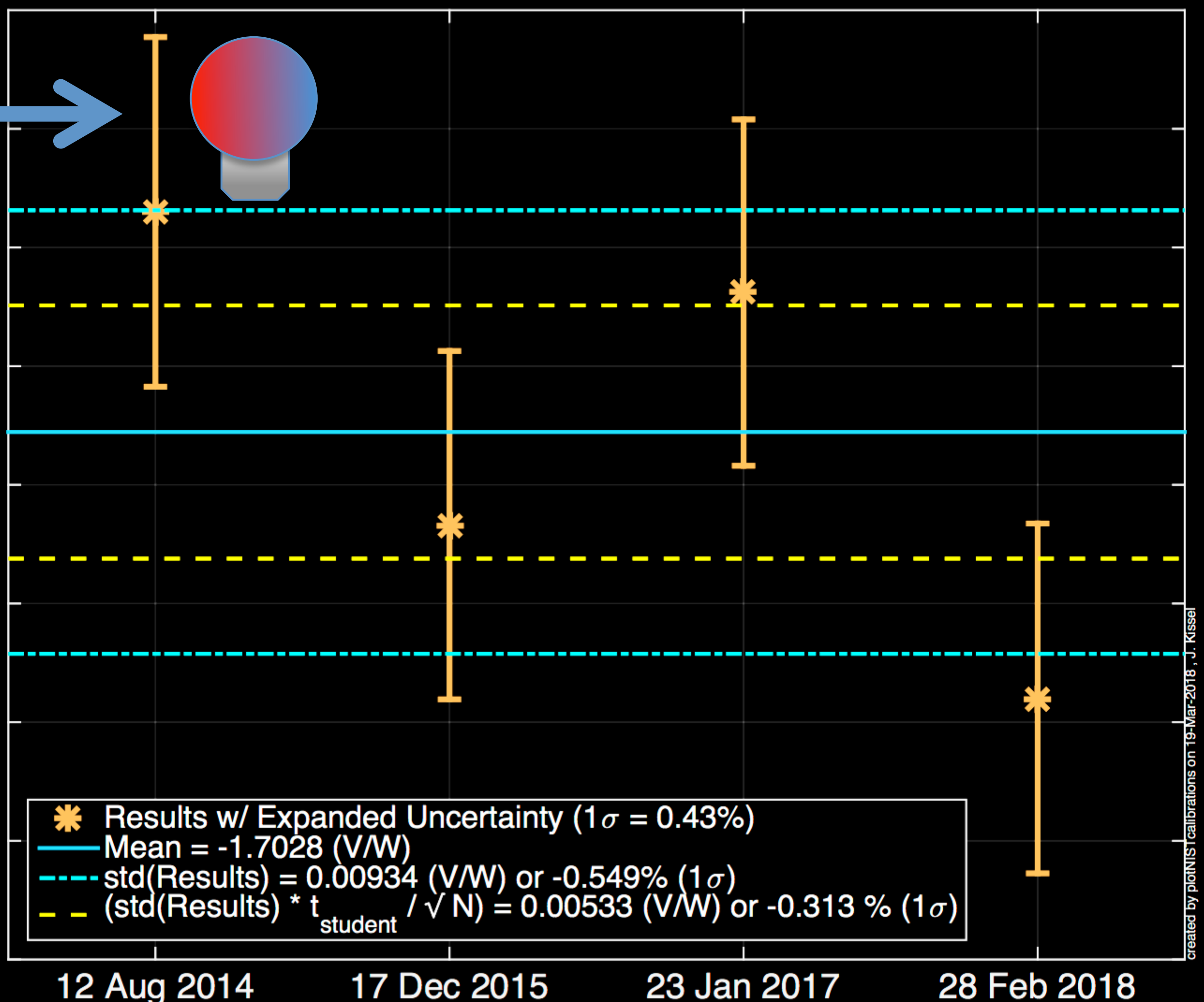
$$dR^2 = \left(\frac{1}{1+G}\right)^2 \left(\frac{dC}{C}\right)^2 + \left(\frac{G}{1+G}\right)^2 \left(\frac{dA}{A}\right)^2$$

4 Years of aLIGO NIST Data

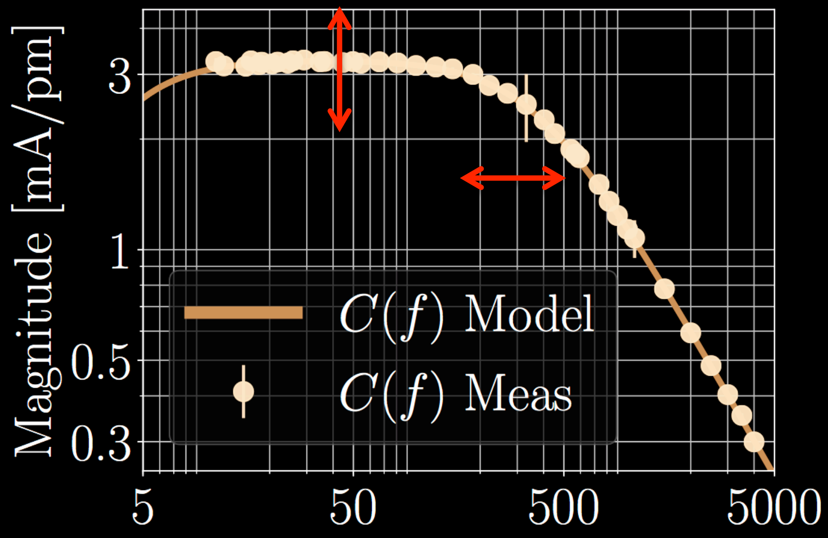
“GOLD” Standard

~$8k per calibration

T1100068

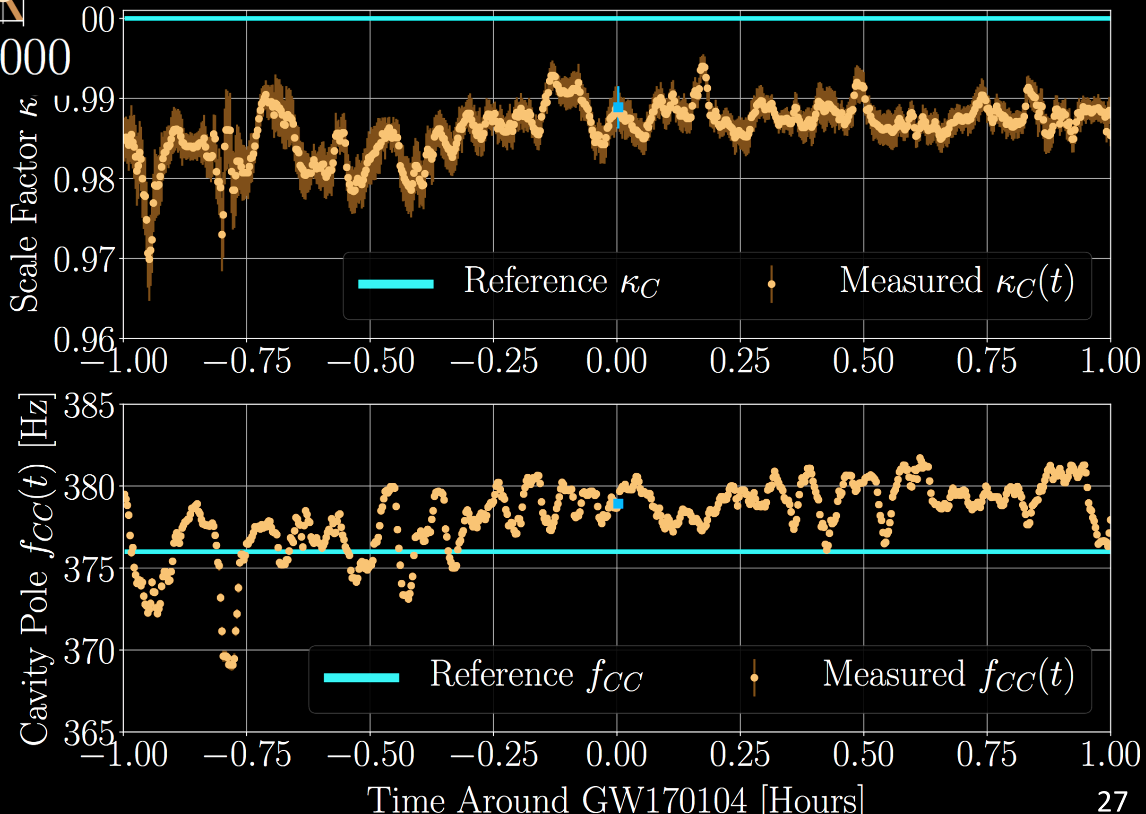


Systematic Error vs. Statistical Uncertainty



Interferometer parameters vary as a function of time.

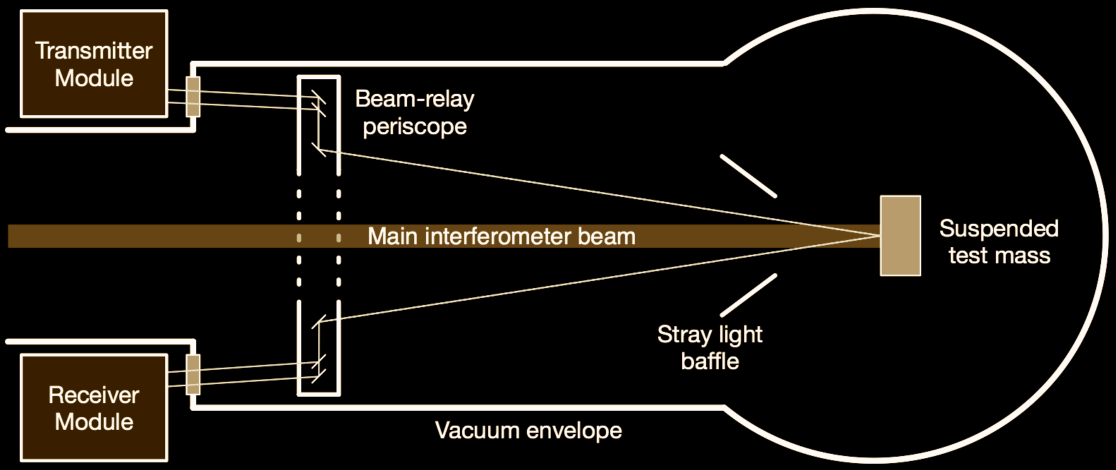
Calibration Lines > Constantly Measuring C and A at single frequencies

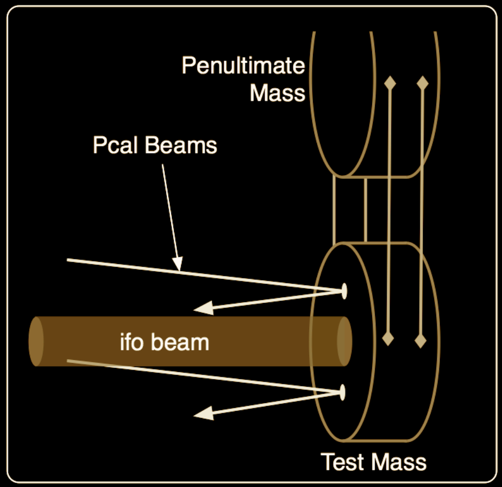


- Alignment Drifts
- Thermal Equilibrium

- Charge on the Test Mass
- Distance between Reaction Chain and Test Mass Chain

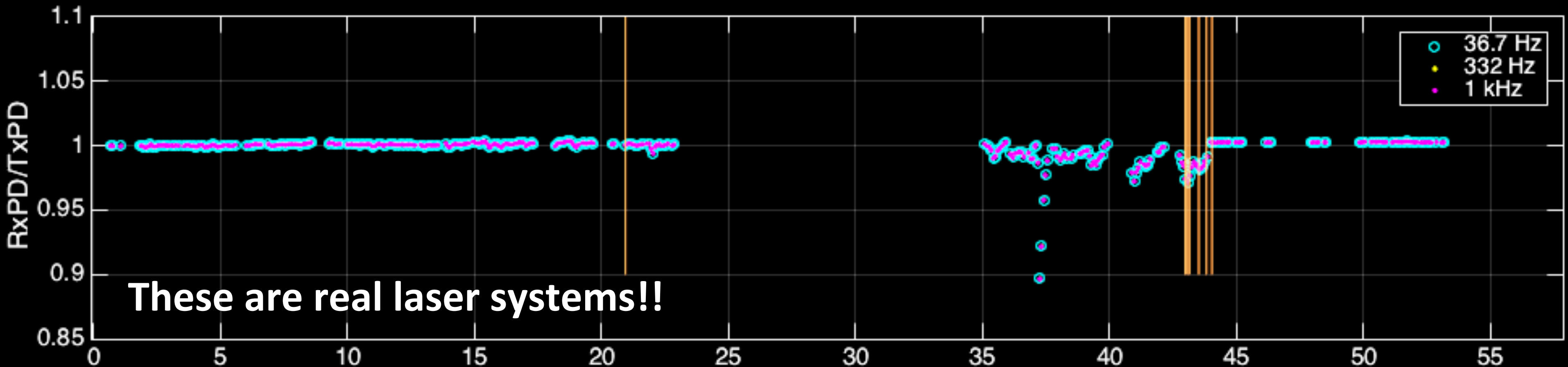
Systematic Error vs. Statistical Uncertainty





During O2 – the response of the receiver reference dropped compared the the transmitter reference

Temperature dependence of Beam Relay Periscope. Systematic error of reference!



These are real laser systems!!

In summary (From **G1700810**)

Any one can build a calibration to within a factor of 2 once.
But can you build a 1% / 1 deg calibration over ~1 year?

Seven Commandments of Calibration

1) Your **GW response** will be more complicated than you want it to be
2) You'll need to invert **it**
3) **It** will be time dependent
4) You'll be fighting your awesome isolators
5) Your reference will not be perfect
6) Your calibration will change between runs, even with the same detector
7) 1%/1 deg will be a bookkeeping nightmare