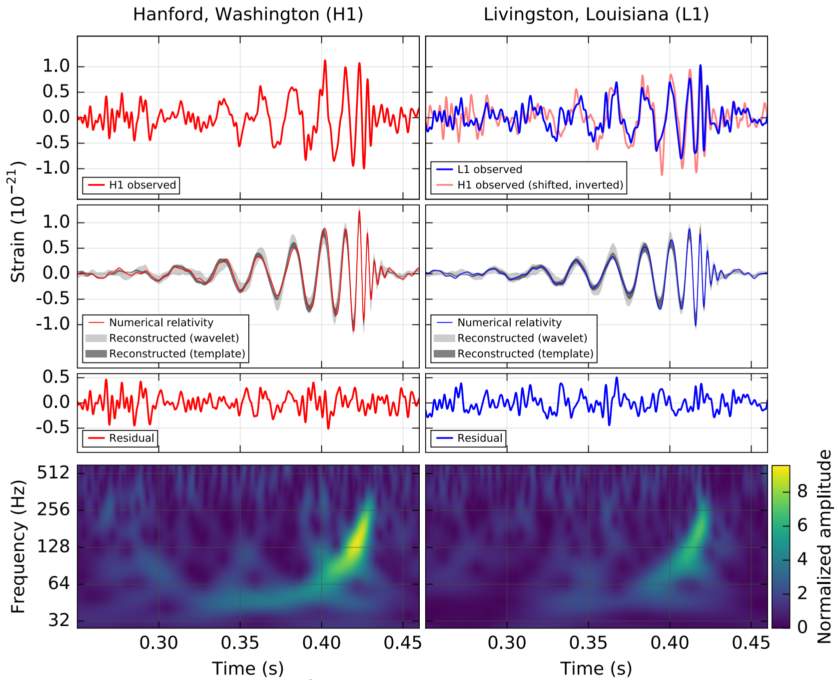
Methods for calibrating kilometer-scale interferometers

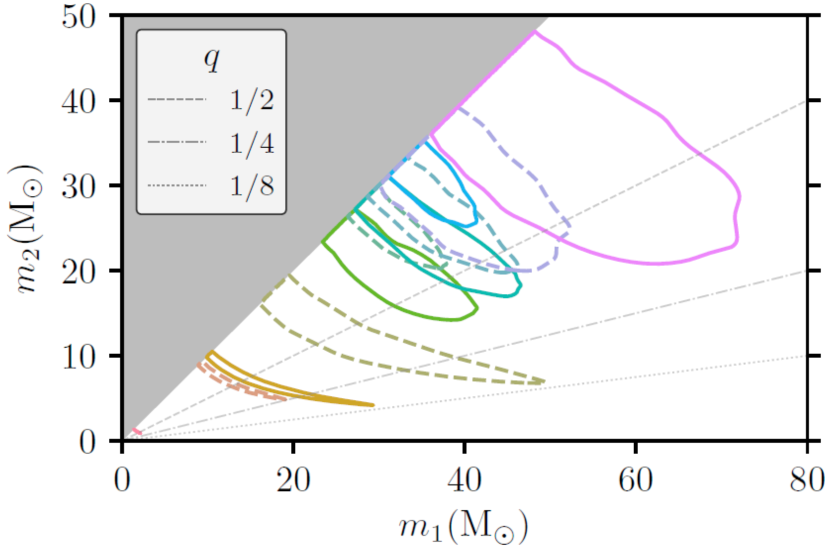
Evan Goetz
University of Michigan

Gravitational wave Metrology Workshop
NIST, Boulder, CO

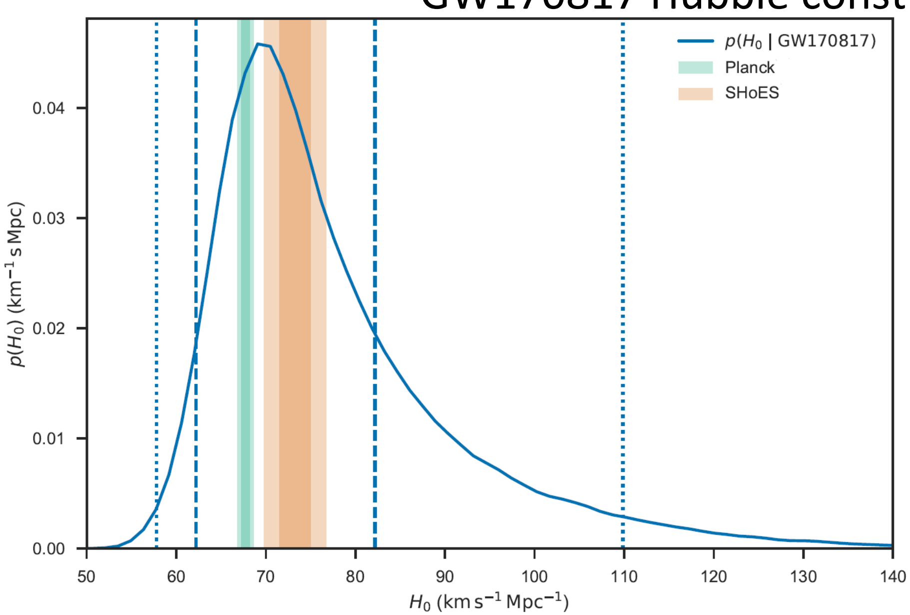


GW150914 strain

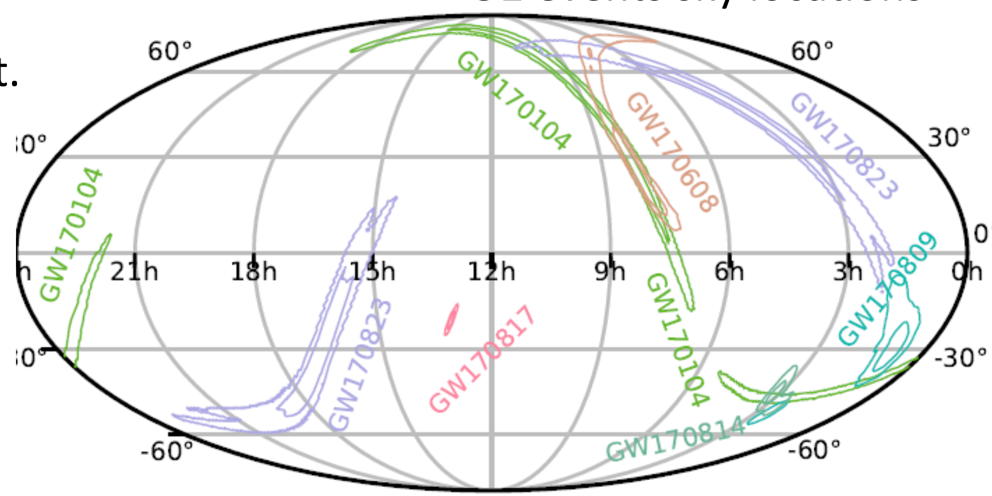
O2 events masses



GW170817 Hubble const.



O2 events sky locations

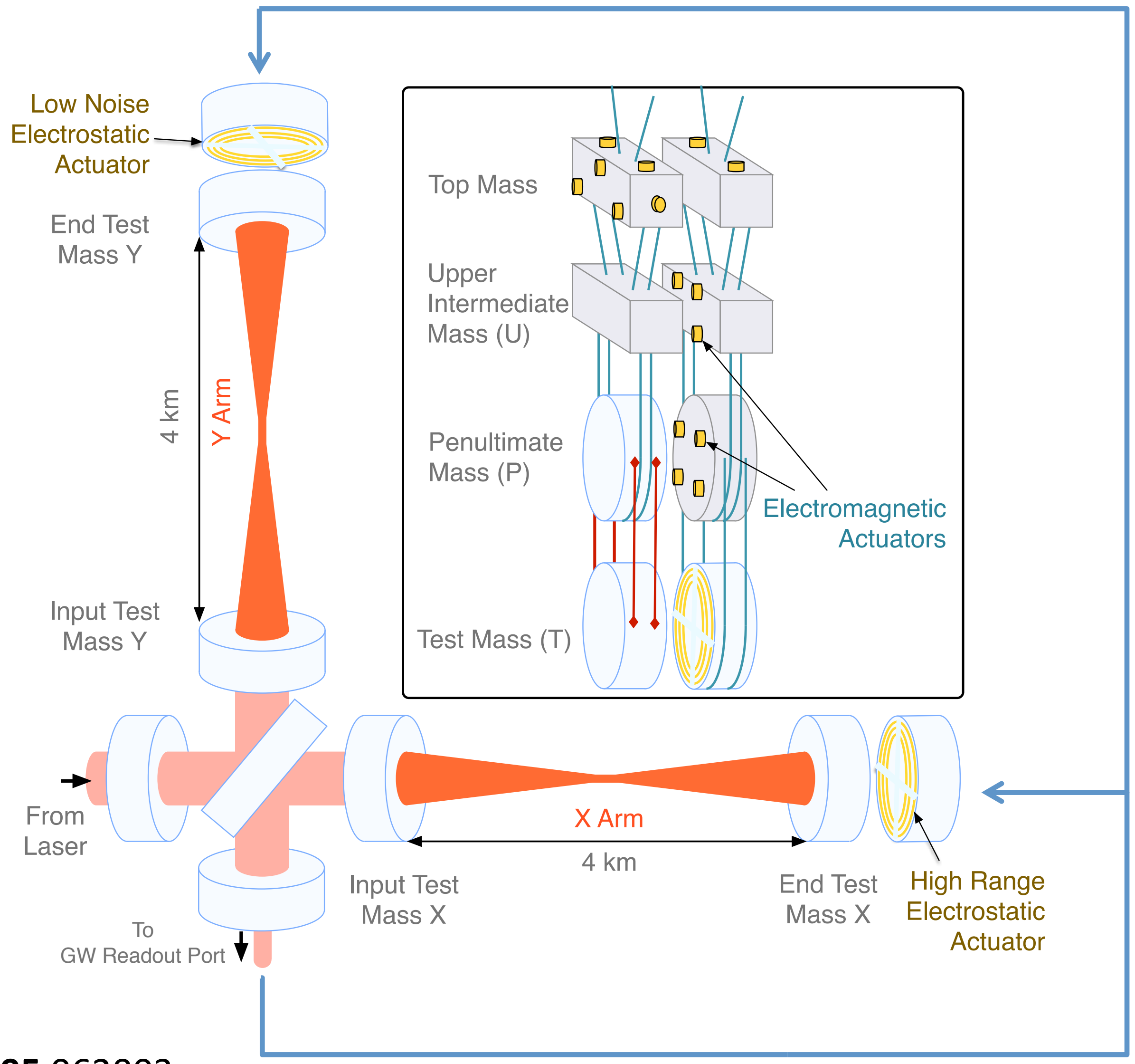


Abbott, B P, et al. PRL **116** 061102
LVC, et al. Nature **551** 85-88
arXiv:1811.12907 [astro-ph.HE]

Outline

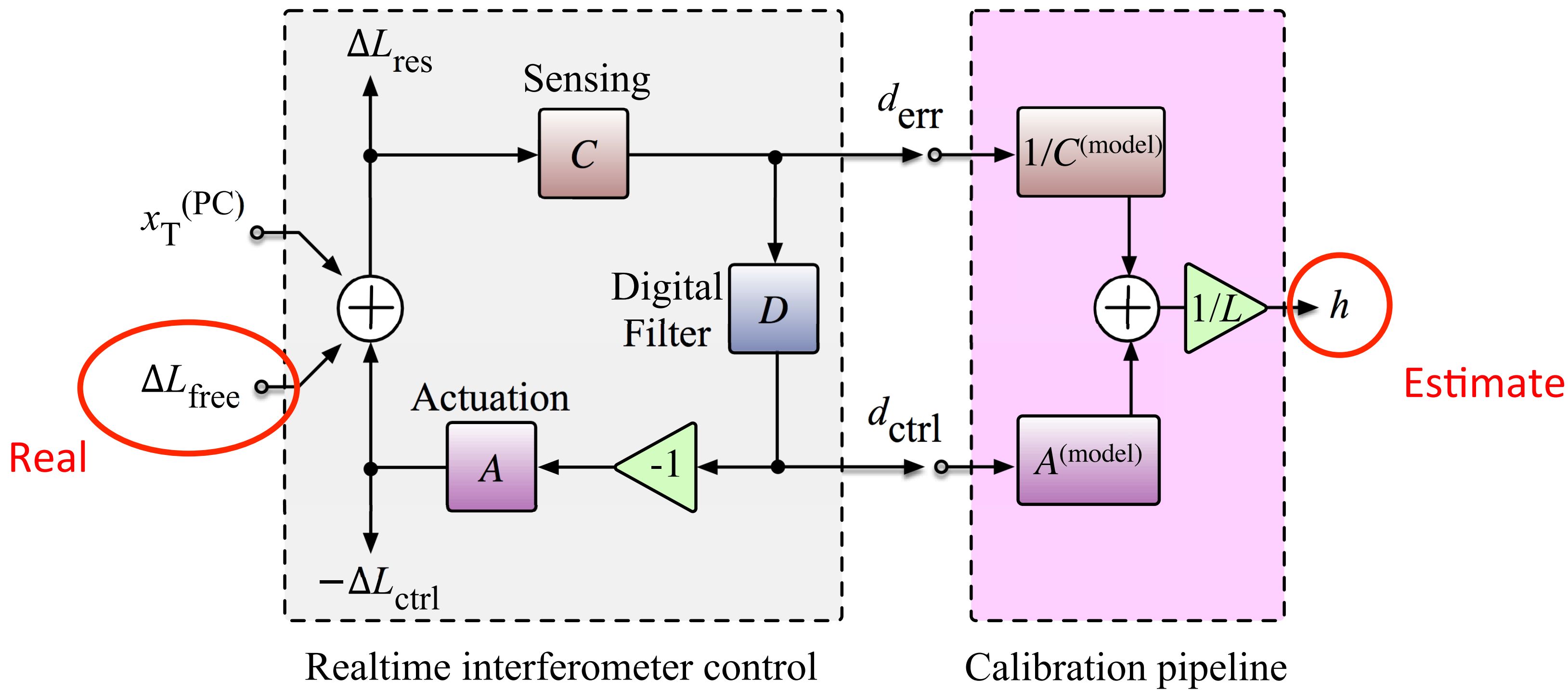
- What is GW interferometer calibration
- State-of-the-art calibration methods
  - Modeling and measurement
  - Hardware / techniques
  - Uncertainty estimation
  - Computing $h(t)$
- GW interferometer calibration challenges

Gravitational wave interferometers



Abbott, B P, et al. PRD **95** 062003

Gravitational wave measurement



Abbott, B P, et al. PRD **95** 062003

$$d_{\mathrm{err}} = \frac{\Delta L_{\mathrm{free}} C}{1 + CDA}$$

$$h(t) = \frac{\Delta L_{\mathrm{free}}(t)}{L}$$

$$d_{\mathrm{ctrl}} = D d_{\mathrm{err}}$$

$$\Rightarrow \Delta L_{\mathrm{free}} = C^{-1} d_{\mathrm{err}} + A d_{\mathrm{ctrl}}$$

Measurement of loop components

$$\Delta L_{\mathrm{free}} = C^{-1} d_{\mathrm{err}} + A d_{\mathrm{ctrl}}$$

- Measure free parameters in C and A
- Require techniques with small systematic and statistical uncertainty
- Techniques with different length fiducials are desirable

Measurement techniques

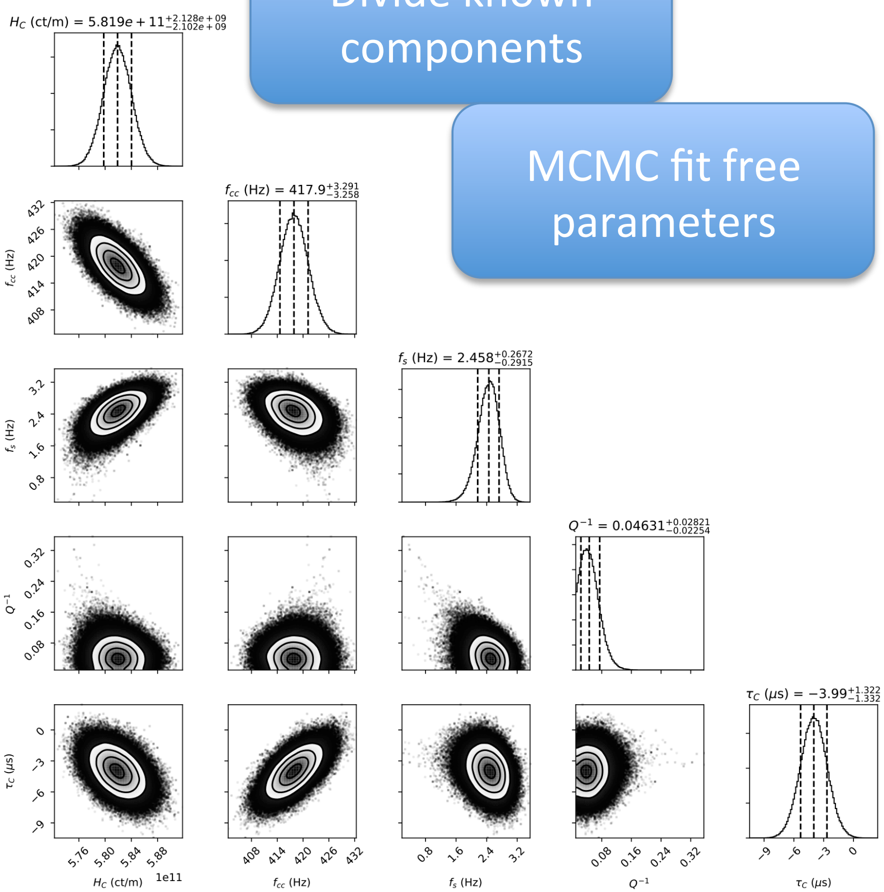
- Several methods developed over the last 20+ years
  - Laser wavelength
  - Photon radiation pressure
  - Frequency modulation
  - "Gravitational" calibration

Measurement of free parameters

Interferometer measurement

Divide known components

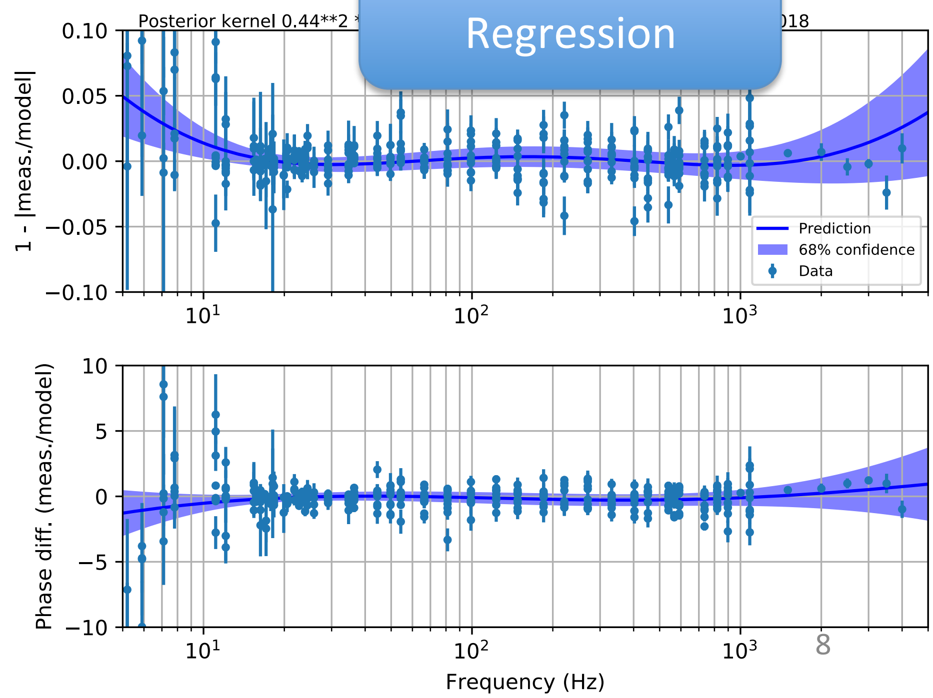
MCMC fit free parameters



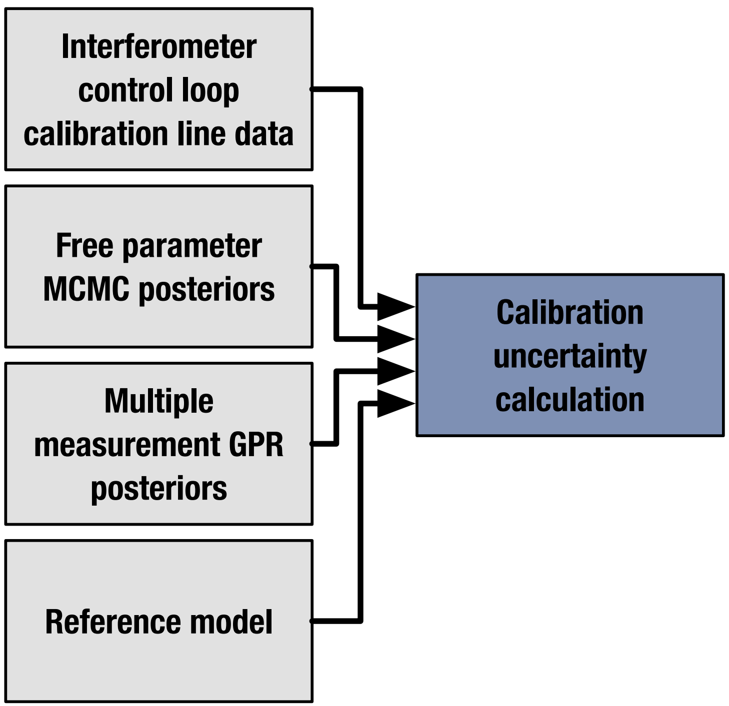
Multiple measurements

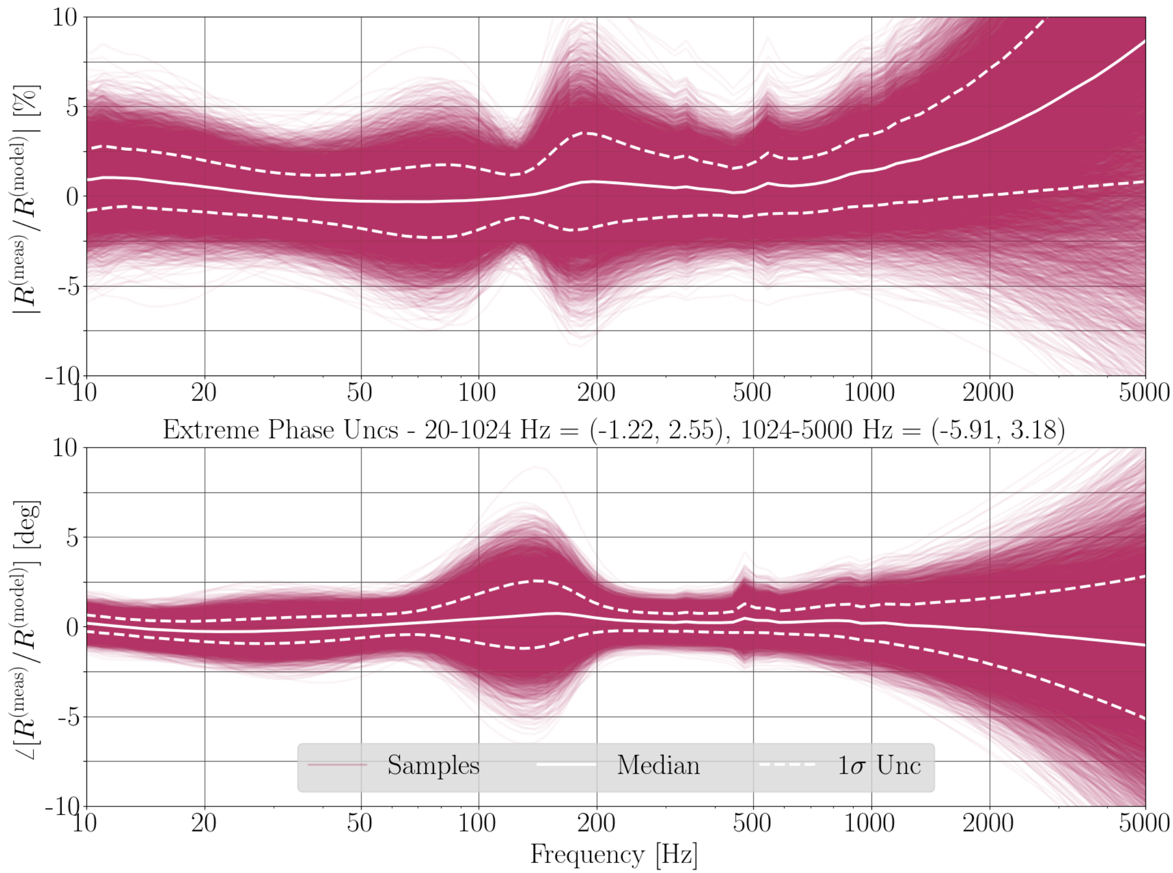
Remove known time-dependence

Gaussian Process Regression

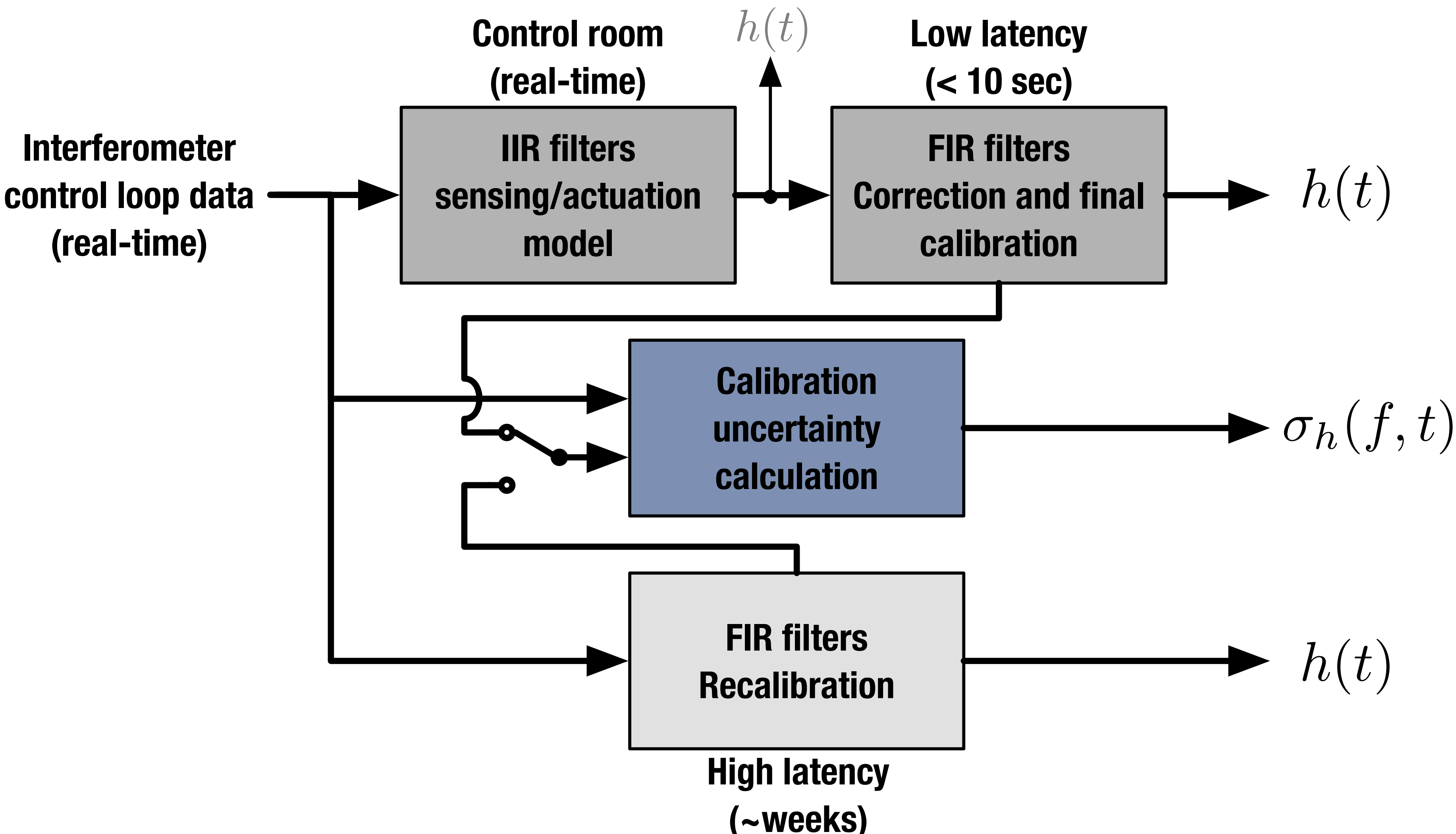


Estimating GW measurement uncertainty





Putting everything together

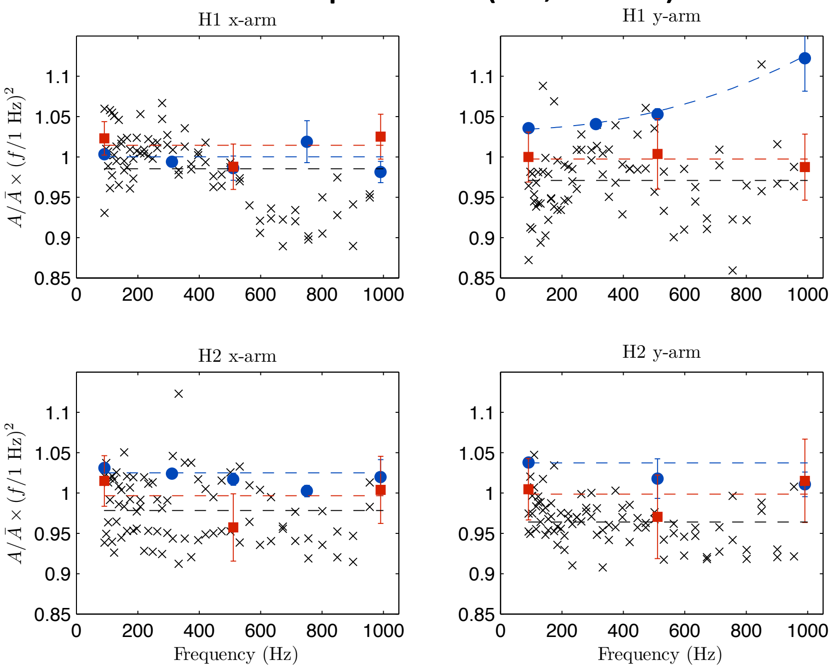


Challenges

- Time- and frequency-dependent systematic and statistical uncertainty must be estimated
- Record keeping and tracking
- Maintain calibration hardware / infrastructure
- Track a changing interferometer (purposefully or not)

Comparing fundamentally different techniques

iLIGO comparison (S5, 2007)



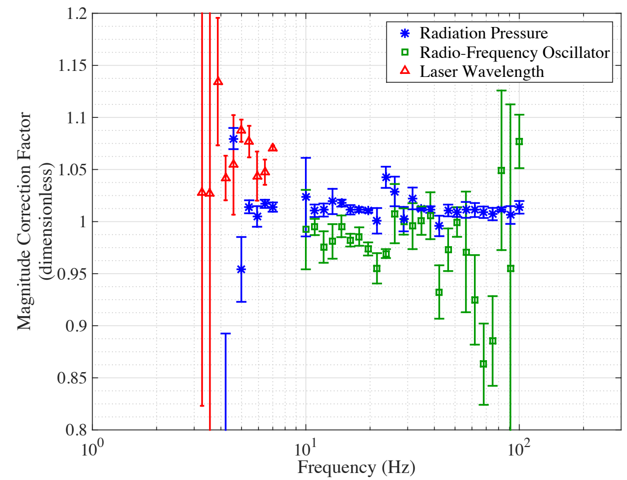
Laser wavelength

Frequency modulation

Radiation pressure

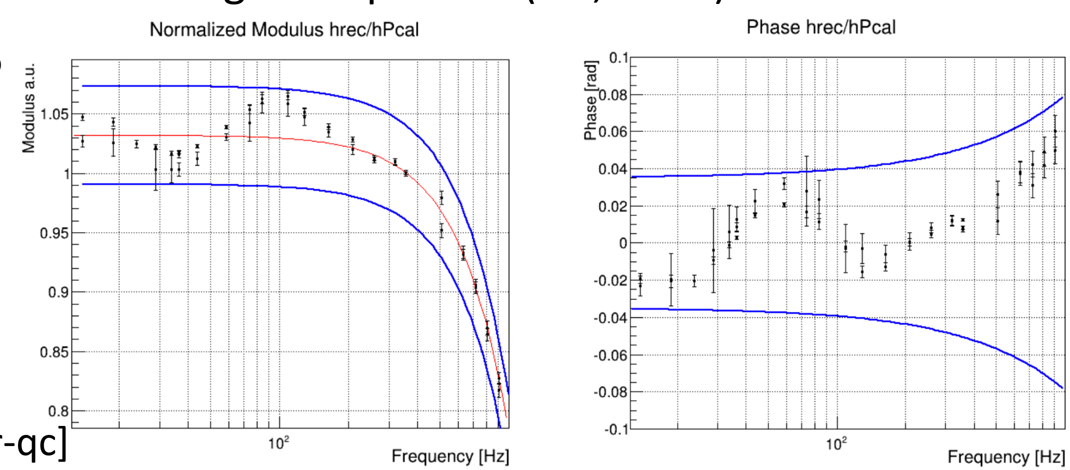
Goetz E, et al. CQG **27** 084024

aLIGO comparison (O1, 2015)



Abbott, B P, et al. PRD **95** 062003

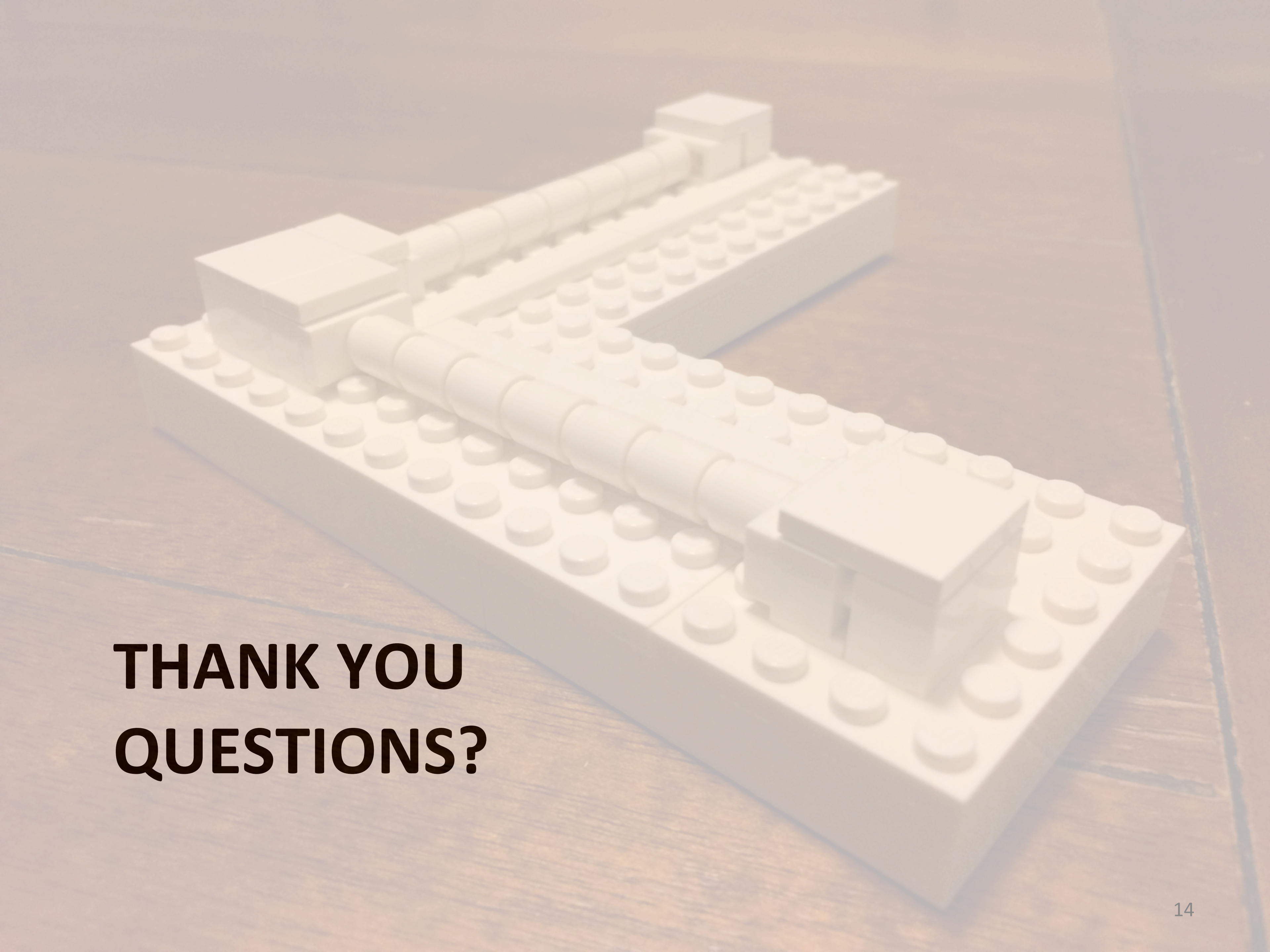
Virgo comparison (O2, 2017)



Acernese F, et al. arXiv:1807.03275 [gr-qc]

Conclusion and outlook

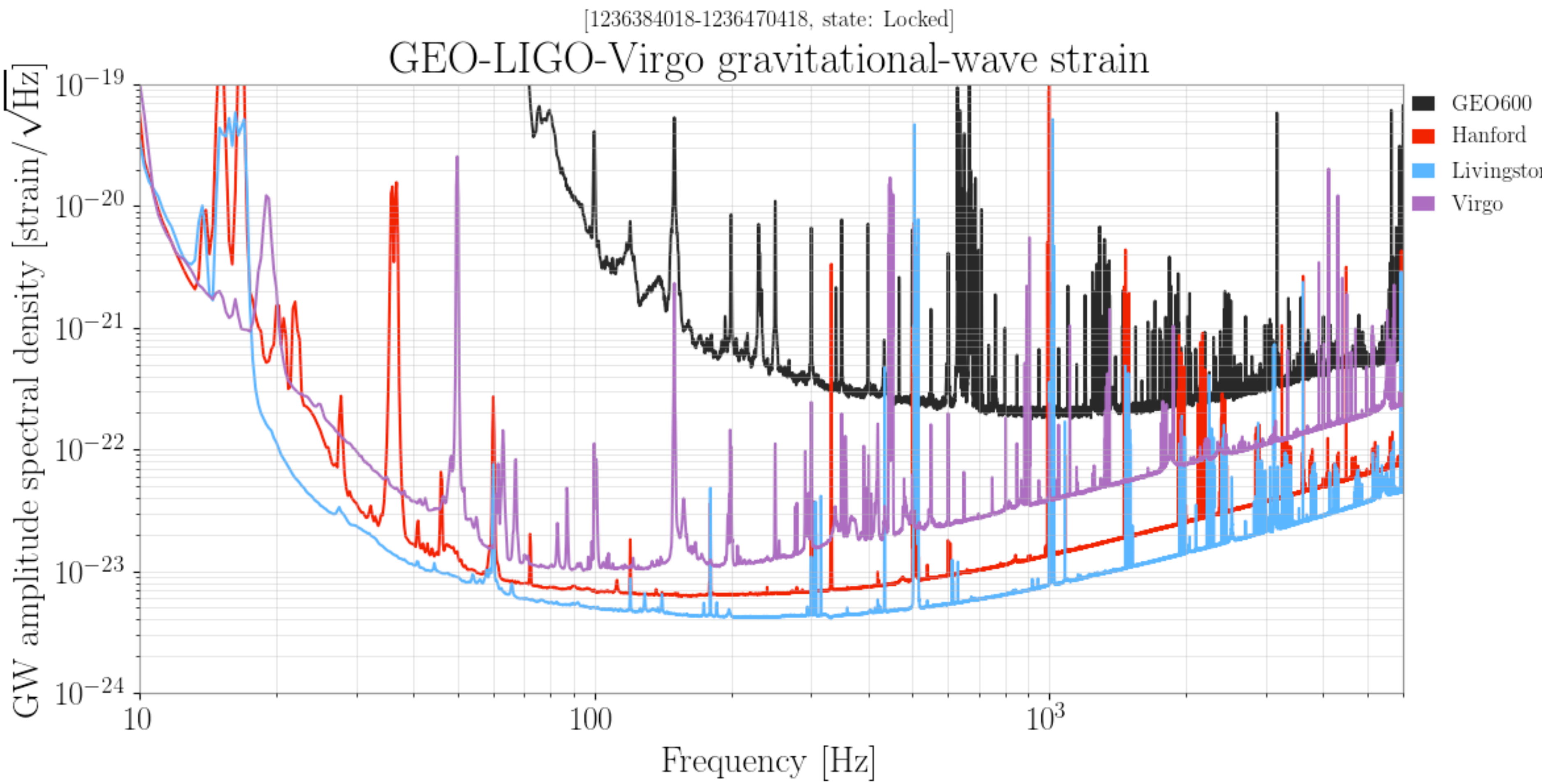
- More GW signals − the future is bright!
- Detector calibration will play increasingly important role
- Continuing characterization, maintenance, development
- Era of precision astrophysical/cosmological measurement with GWs is now



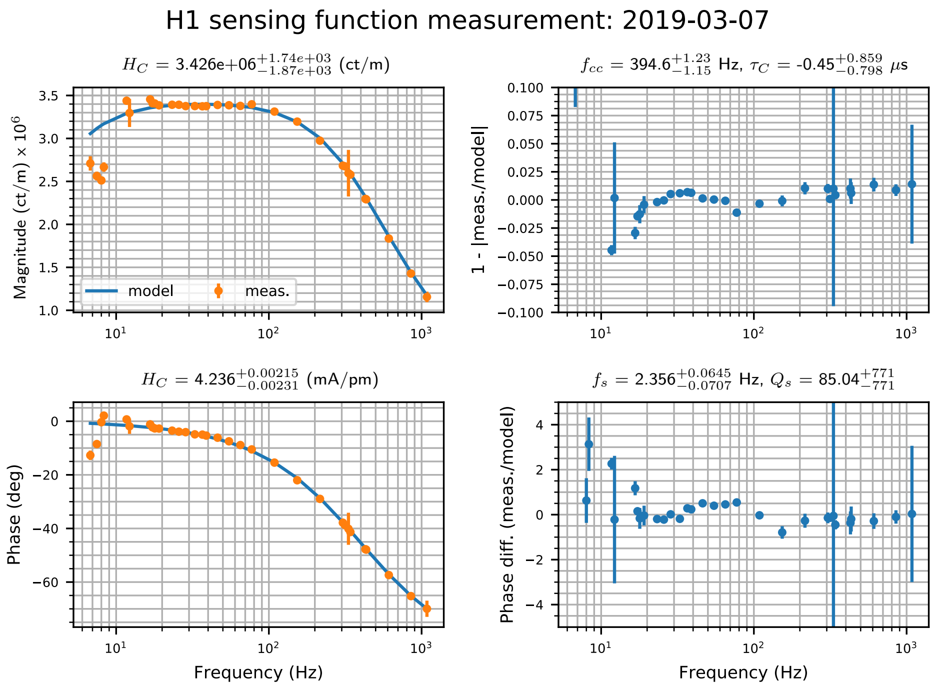
THANK YOU

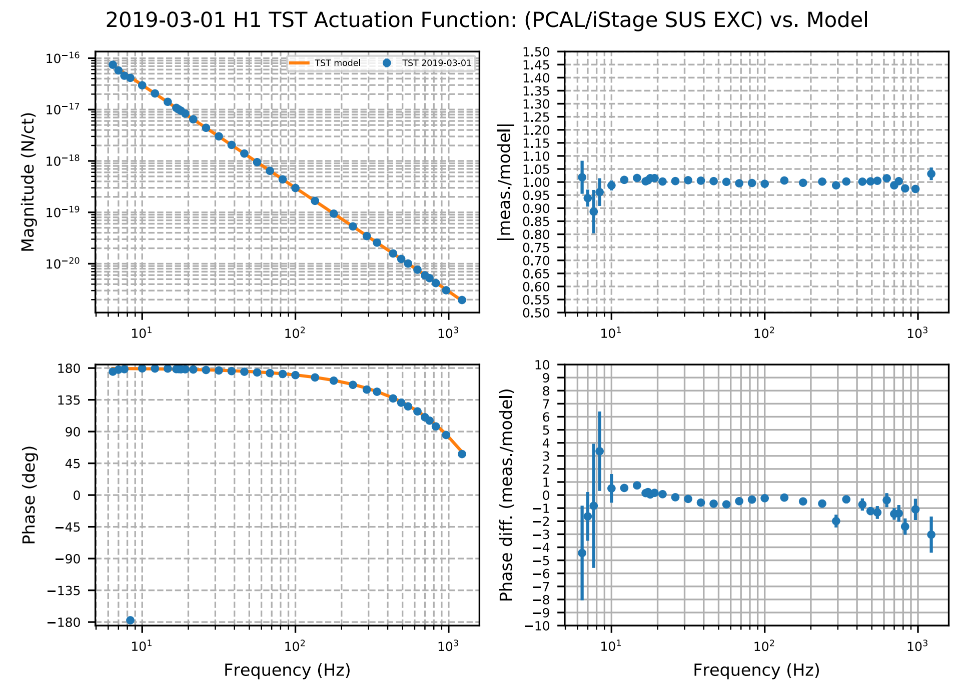
QUESTIONS?

Calibrated interferometer sensitivity



Sensing and actuation measurement examples



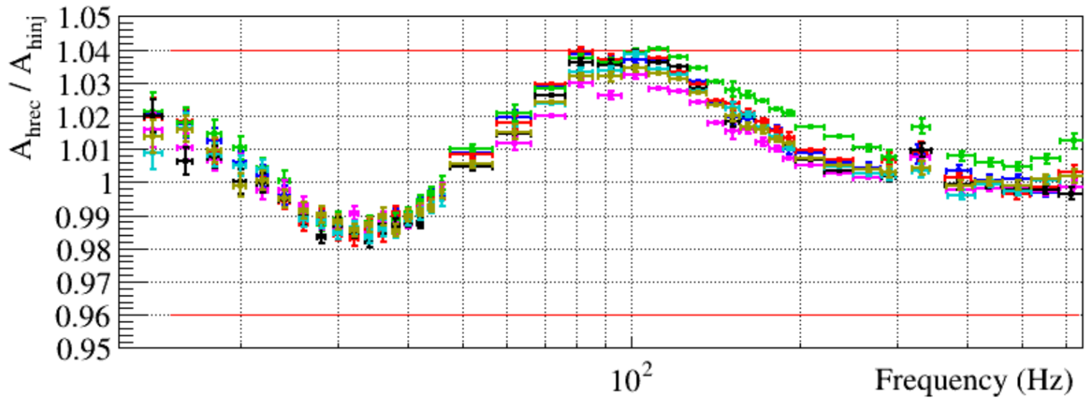


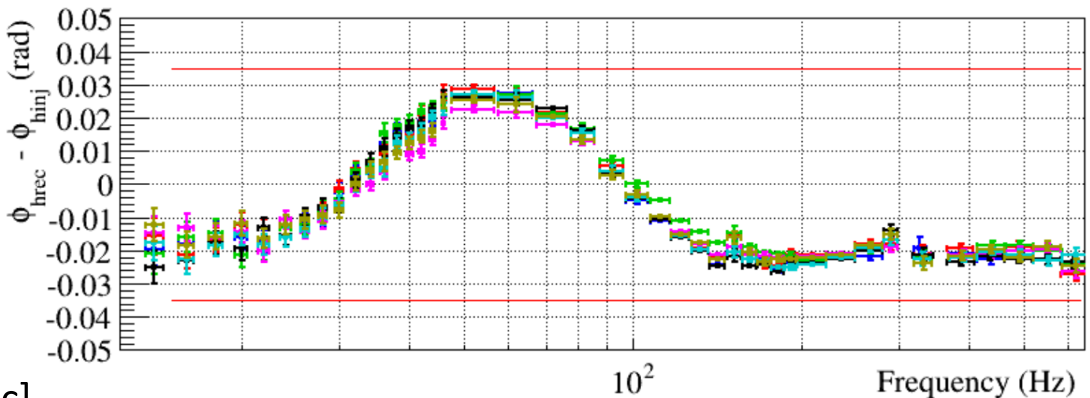
Measurement technique development

- Free-swinging Michelson (laser wavelength)
  - GEO600, iLIGO, Virgo, (aLIGO cross-check)
- Photon radiation pressure (laser power)
  - aLIGO, KAGRA, (GEO600, iLIGO, Virgo cross-checks)
- Frequency modulation (Fabry-Perot frequency-to-length transfer function)
  - (GEO600, iLIGO, aLIGO cross checks)
- Gravitational calibration (rotating masses, G)
  - (Under development: Virgo, aLIGO, KAGRA)

Virgo calibration

$h(t)$ version	Amplitude uncertainty (%)	Phase uncertainty (rad)	Timing bias
Online	$+14/-8$	$100 \times 10^{-3} + 2\pi f(20 \times 10^{-6})$	116 µs
V1O2Repro1A	± 8	$50 \times 10^{-3} + 2\pi f(20 \times 10^{-6})$	0
V1O2Repro2A	± 5.1	$40 \times 10^{-3} + 2\pi f(20 \times 10^{-6})$	0





Acernese F, et al.
arXiv:1807.03275 [gr-qc]

Many publications!

- Goetz, et al. CQG **26** 24
- Goetz, et al. CQG **27** 8
- Goetz, et al. CQG **27** 21
- Karki, et al. RSI **87** 114503
- Abadie et al NIM A **624** 1
- Tuyenbayev, et al CQG **34** 1
- Abbott, et al PRD **95** 062003
- Viets, et al. CQG **35** 9
- Leong, et al. CQG **29** 6
- Accadia, et al. JoP Conf. **228** 1
- Accadia, et al. CQG **28** 2
- Inoue, et al. PRD **98** 022005
- Adhikari, et al. CQG **20** 17
- Hewitson, et al. CQG **20** 17
- Siemens, et al. CQG **21** 20
- Landry, et al. CQG **22** 18
- Hewitson, et al. RSI **74** 4184
- Hewitson, et al. RSI **75** 4702
- Hewitson, et al. CQG **21** 20
- Mossavi, et al. PL A **353** 1
- Hewitson, et al. CQG **22** 20
- Clubley, et al. PL A **283** 1-2
- Acernese, et al. CQG **35** 20
- Yamamoto, et al. JPS Conf. **1** 013119

And more!