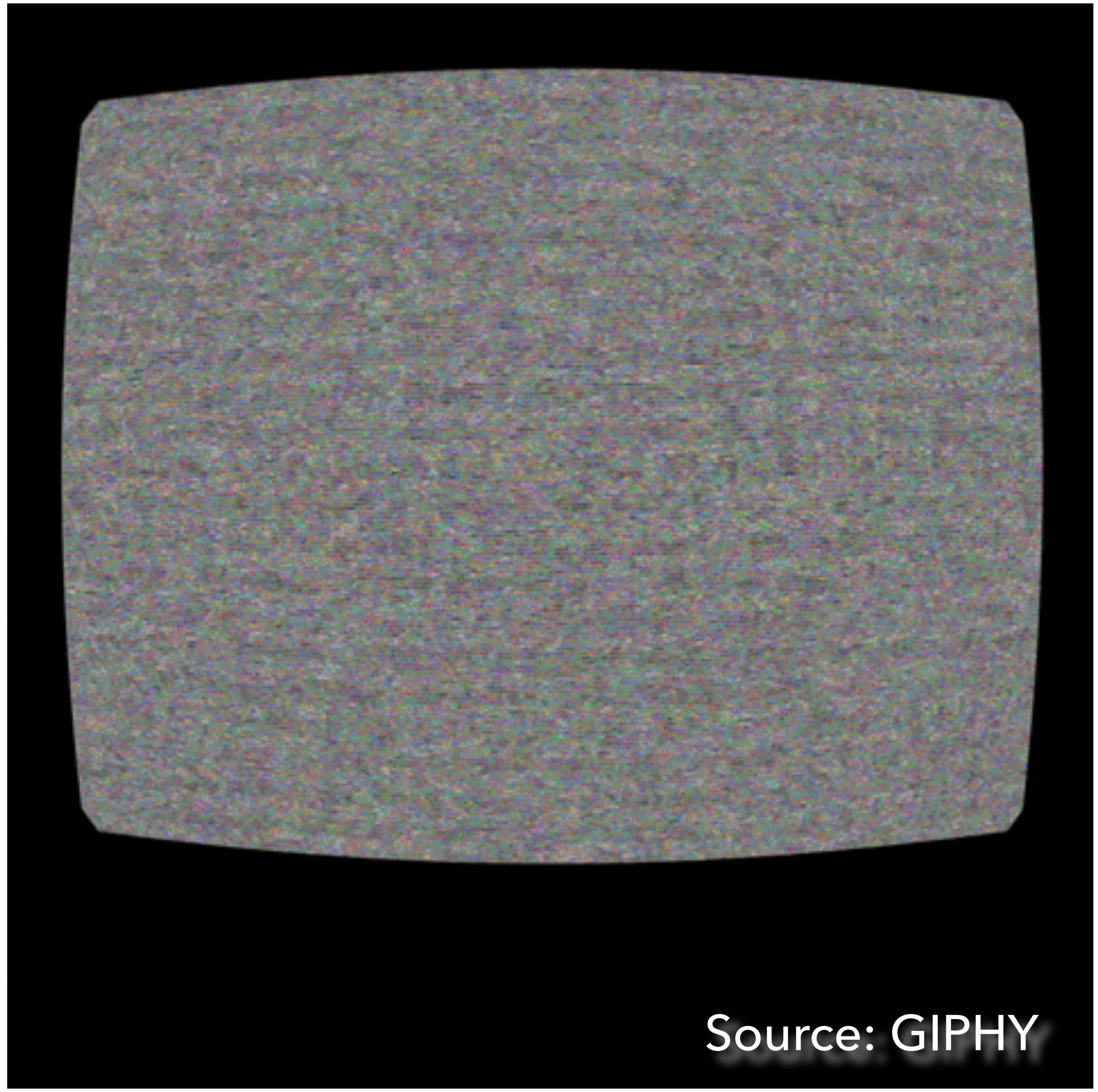
LIGO

Caltech



Advanced LIGO O3 Calibration

Ling Sun, LIGO Excellence Award Talk, Feb 2020 @ MIT

DCC-G2000234

Agenda

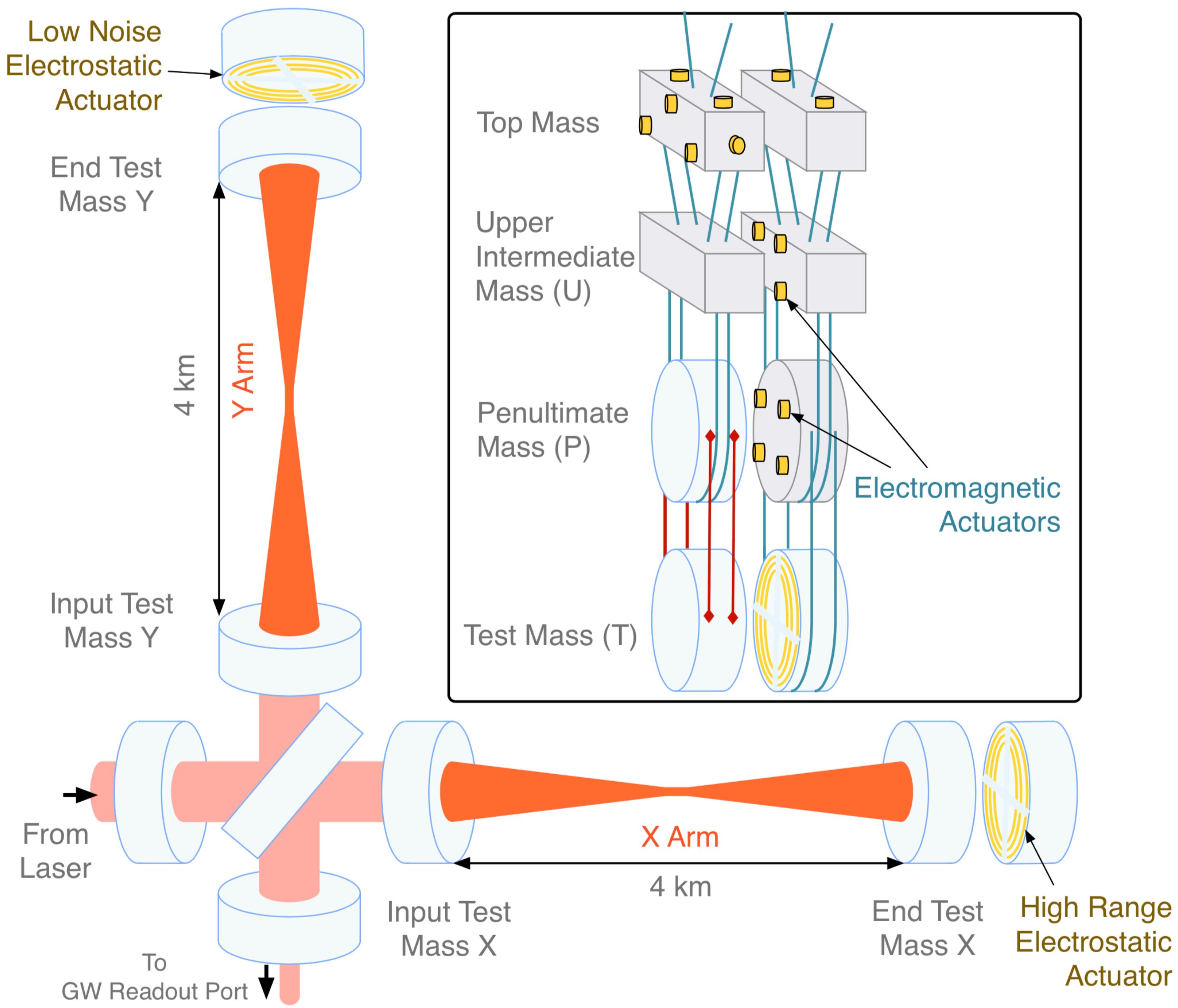
- Why is calibration important
- How does calibration work
- Understanding systematics and uncertainties
- O3 improvements and future perspectives

Agenda

- **Why is calibration important**
- How does calibration work
- Understanding systematics and uncertainties
- O3 improvements and future perspectives

Calibration pipeline produces h(t)

Differential arm (DARM) control system



C. Cahillane et al. 2017 PRD 96, 102001

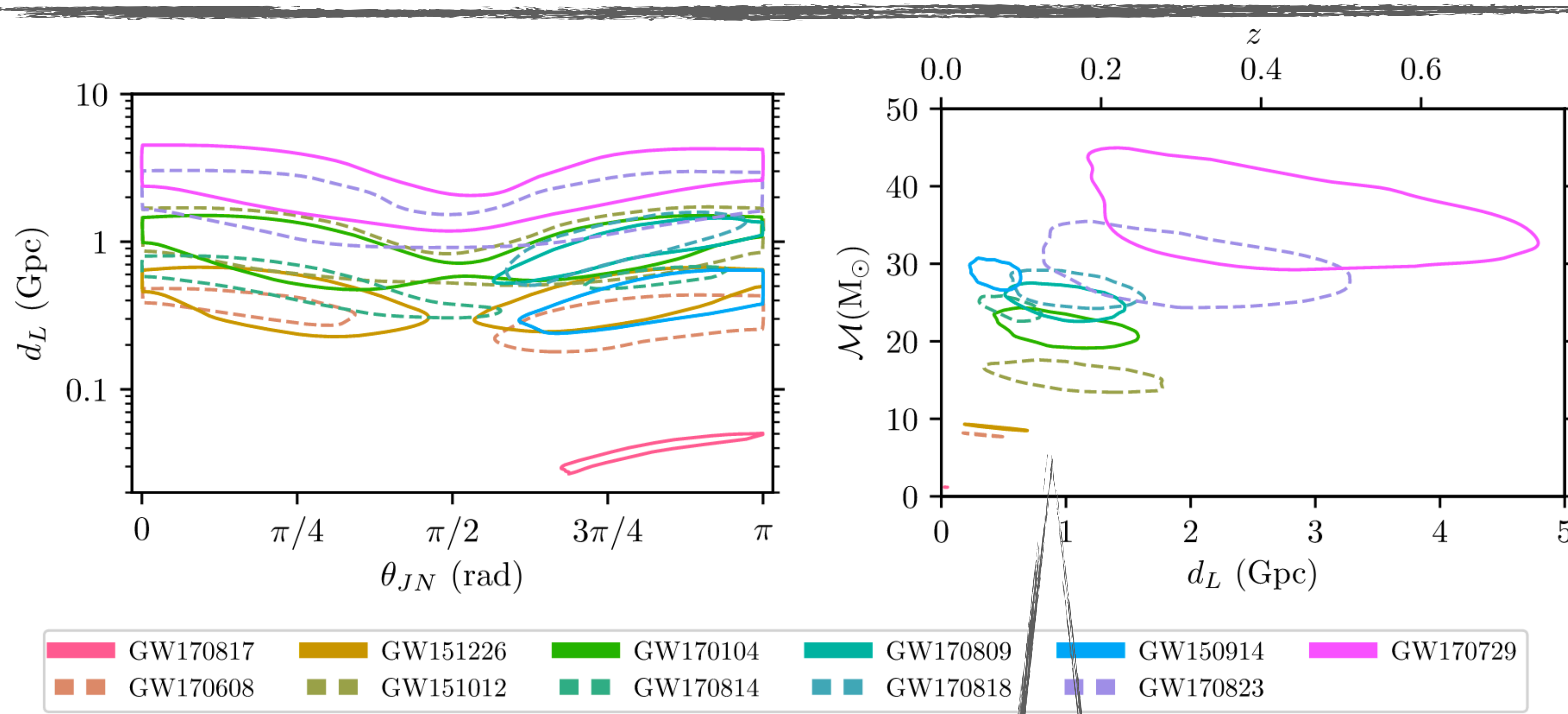
DARM displacement:

$$\Delta L_{\rm free} = \Delta L_x(t) - \Delta L_y(t)$$

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

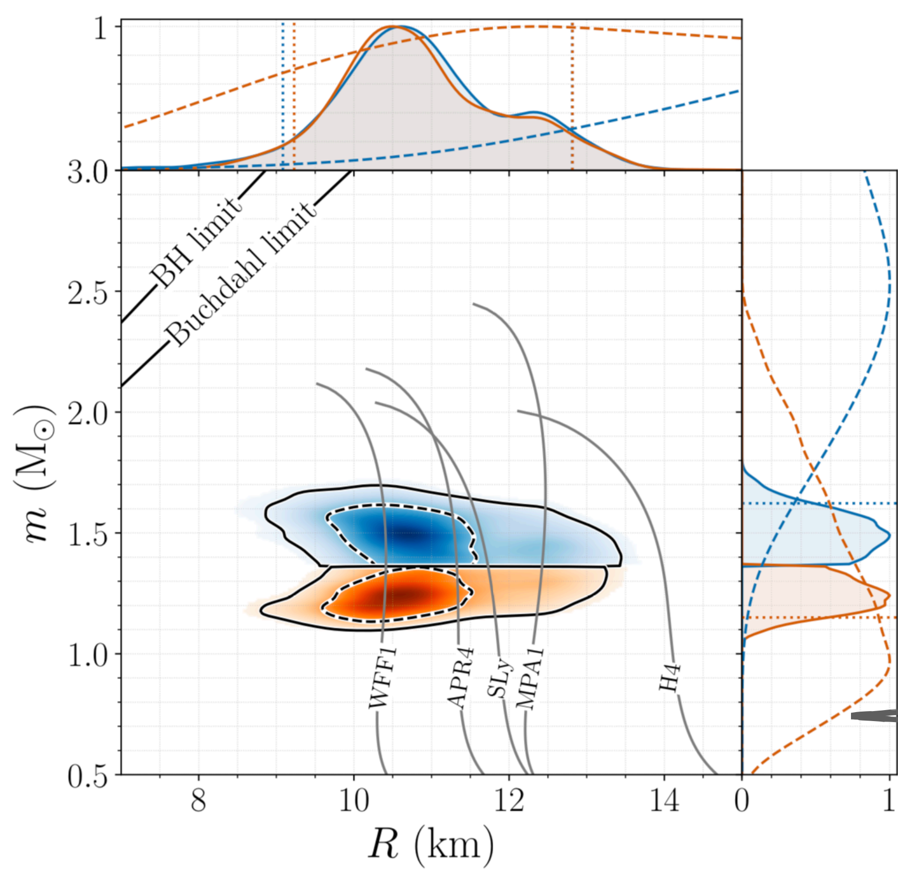
- Need to cancel the signal and keep the detector in null range
- Quadruple pendulum suspension systems
- Active seismic isolation systems
- Not enough – DARM displacement must be further controlled!

Impact on estimating source properties



Abbott et al.
PRX 9,031040 (2019)

- Calibration magnitude affects the estimation of luminosity distance
- Phase response affects the estimation of intrinsic source properties, e.g., chirp mass

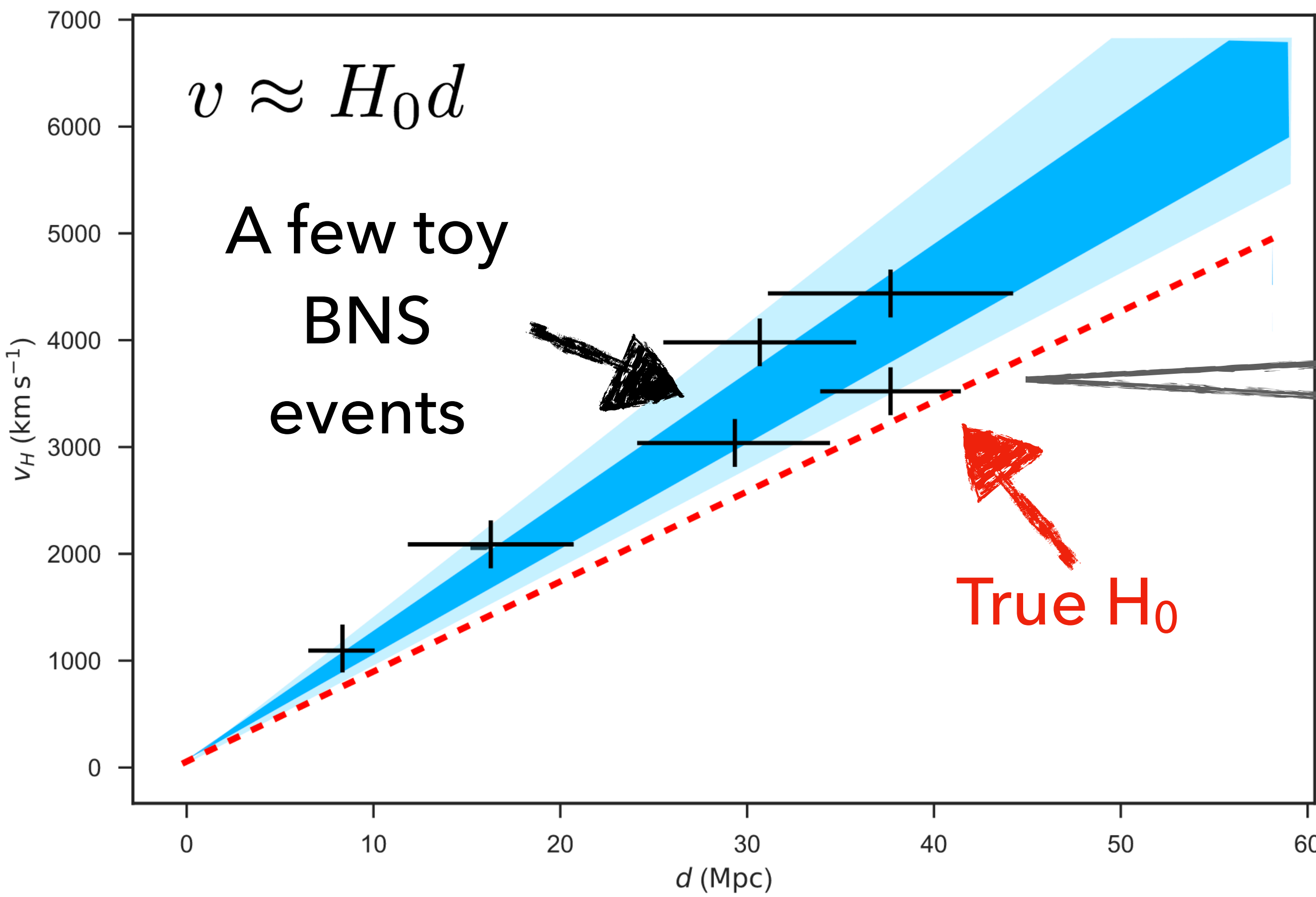


- Further improved instrumental calibration could improve constraints on NS EoS

Abbott et al. PRL 121, 161101 (2018)

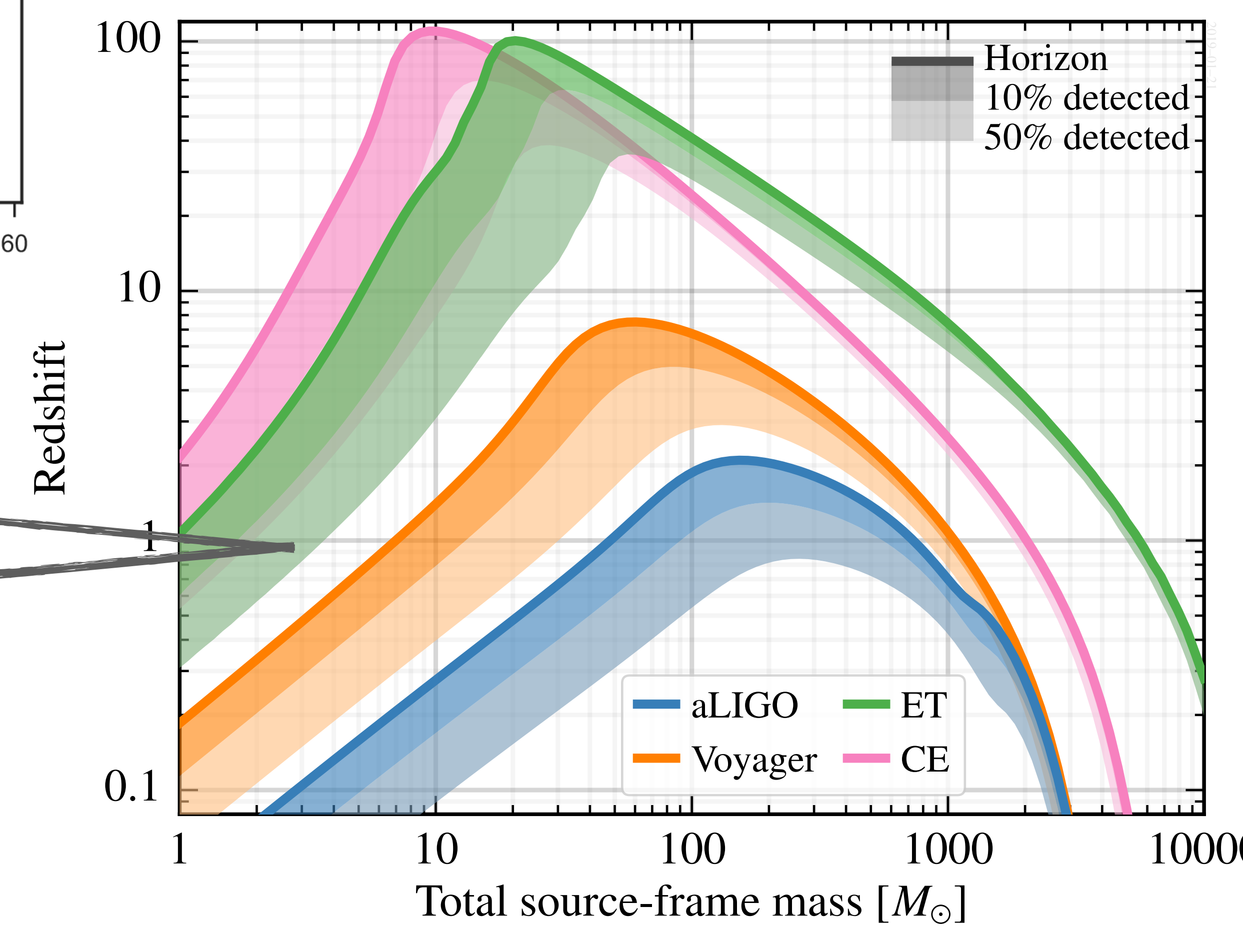
Impact on cosmology and high-redshift events

Credit: C. Messenger



- Correlated calibration systematic errors impact H_0 measurement

Credit: E. Hall



- Calibration systematic errors and statistical uncertainties impact the horizon distance, source-frame masses, rates, especially at high redshift

Agenda

- Why is calibration important
- **How does calibration work**
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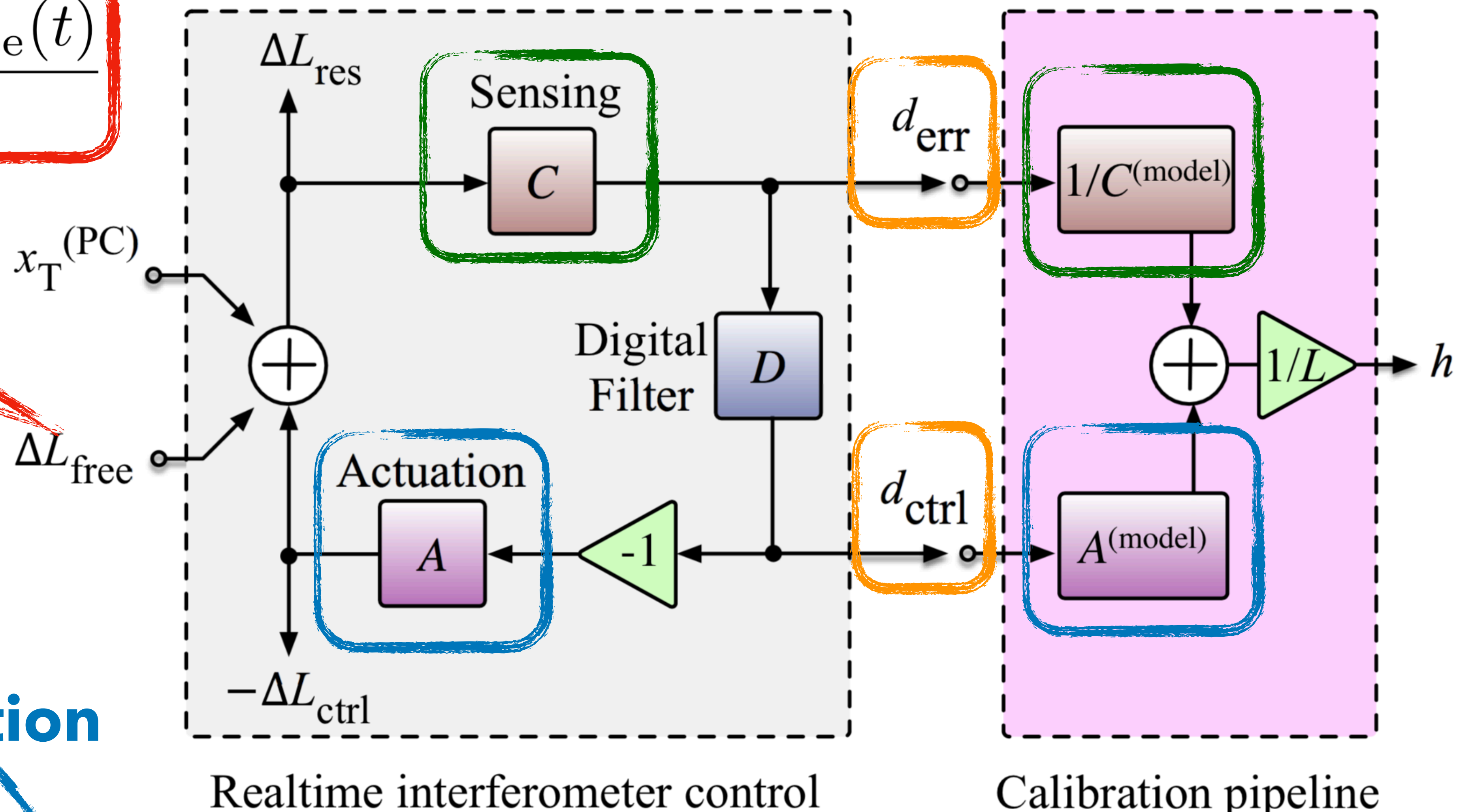
How does calibration work?

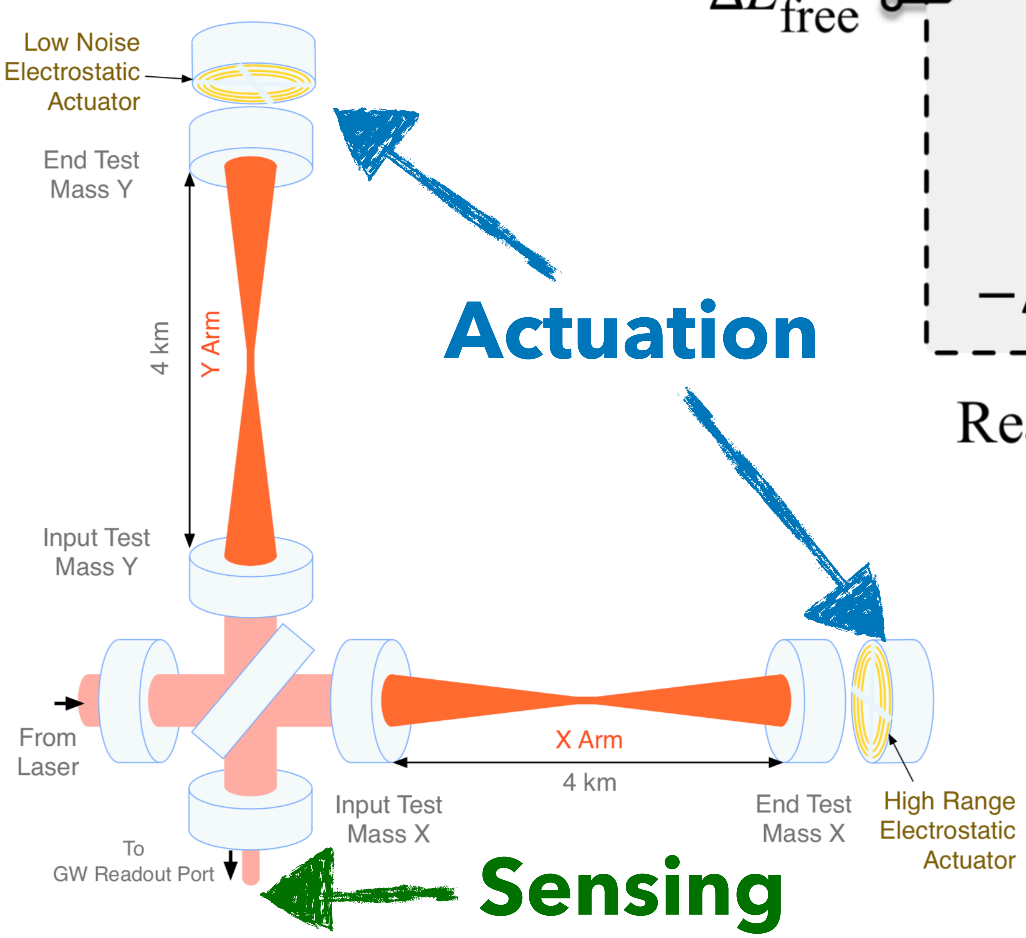
Differential arm (DARM) control loop

B. P. Abbott, et al. 2017 PRD 95 062003

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

Recover me!





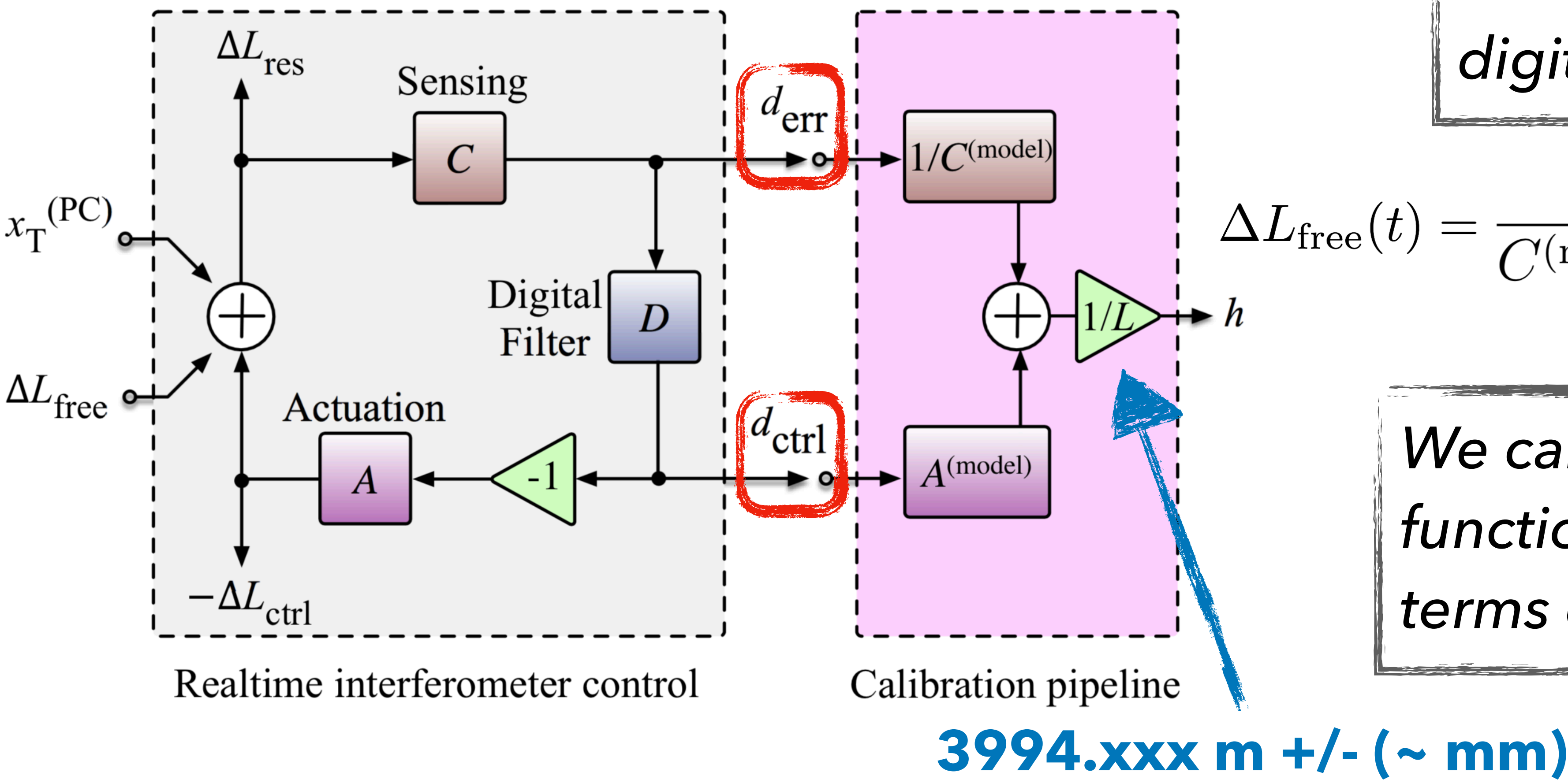
$$\Delta L_{\text{free}}(t) = \frac{1}{\mathcal{C}(t)} * d_{\text{err}}(t) + \mathcal{A}(t) * d_{\text{ctrl}}(t)$$

High freq **Low freq**

$$\Delta L_{\text{free}}(f) = \frac{1}{C(f)} d_{\text{err}}(f) + A(f) d_{\text{ctrl}}(f)$$

Detector's response function

B. P. Abbott, et al. 2017 PRD 95 062003



Calculate h(t) bypassing digital filter D

$$\Delta L_{\rm free}(t) = \frac{1}{C^{\rm (model)}} * d_{\rm err}(t) + A^{\rm (model)} * d_{\rm ctrl}(t)$$

We can define a response function by writing h(t) in terms of the error signal d_{err}

Response function

$$\Delta L_{\rm free}(t) = \frac{1}{C^{\rm (model)}} * d_{\rm err}(t) + A^{\rm (model)} * d_{\rm ctrl}(t) = R^{\rm (model)}(t) * d_{\rm err}(t)$$

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

Frequency-domain response function

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

$$h = \frac{R^{\rm (model)} * d_{\rm err}}{L}$$

Time dependent correction factors (TDCFs)

- If Sensing (C) and Actuation (A) models are perfectly known at any given time, there's no systematic error (there's still statistical uncertainty).

$$\Delta L_{\mathrm{free}} = \frac{1}{C_{\mathrm{model}}} d_{\mathrm{err}} + A_{\mathrm{model}} d_{\mathrm{ctrl}}$$

- But the model parameters are changing slightly – due to charge accumulation around the test/reaction mass, drifts of the optical alignment in the arm cavities, etc.

- Use high SNR calibration lines, track temporal variations in DARM loop model parameters, and correct them

$$\Delta L_{\mathrm{free}} = \frac{1}{\kappa_C(t) C_{\mathrm{model}}} d_{\mathrm{err}} + \kappa_A(t) A_{\mathrm{model}} d_{\mathrm{ctrl}}$$

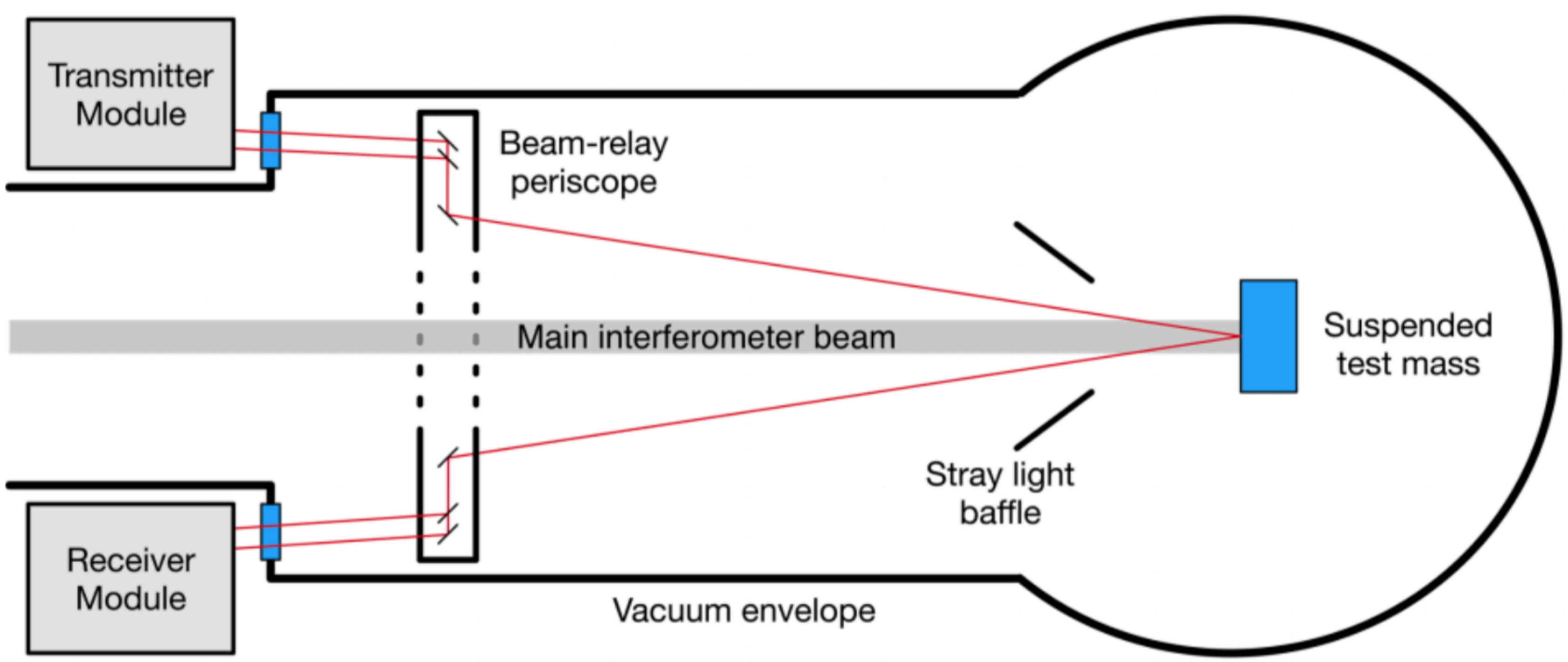
- Including factors for 3 actuation stages

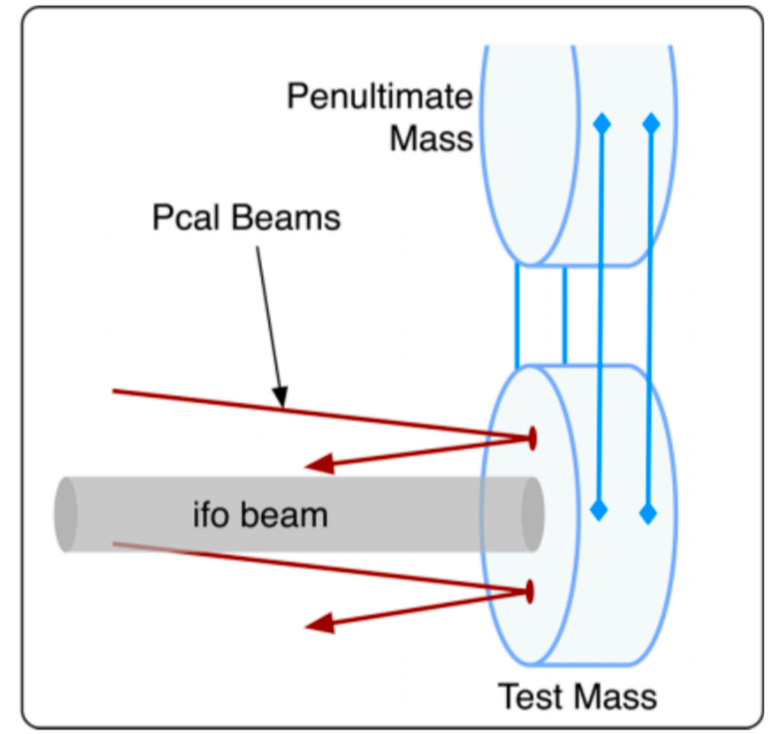
- Frequency-dependent, time-dependent factors

TDCFs

See Viets et al. 2018 (arXiv:1710.09973), T1700106

Photon calibrator (Pcal)



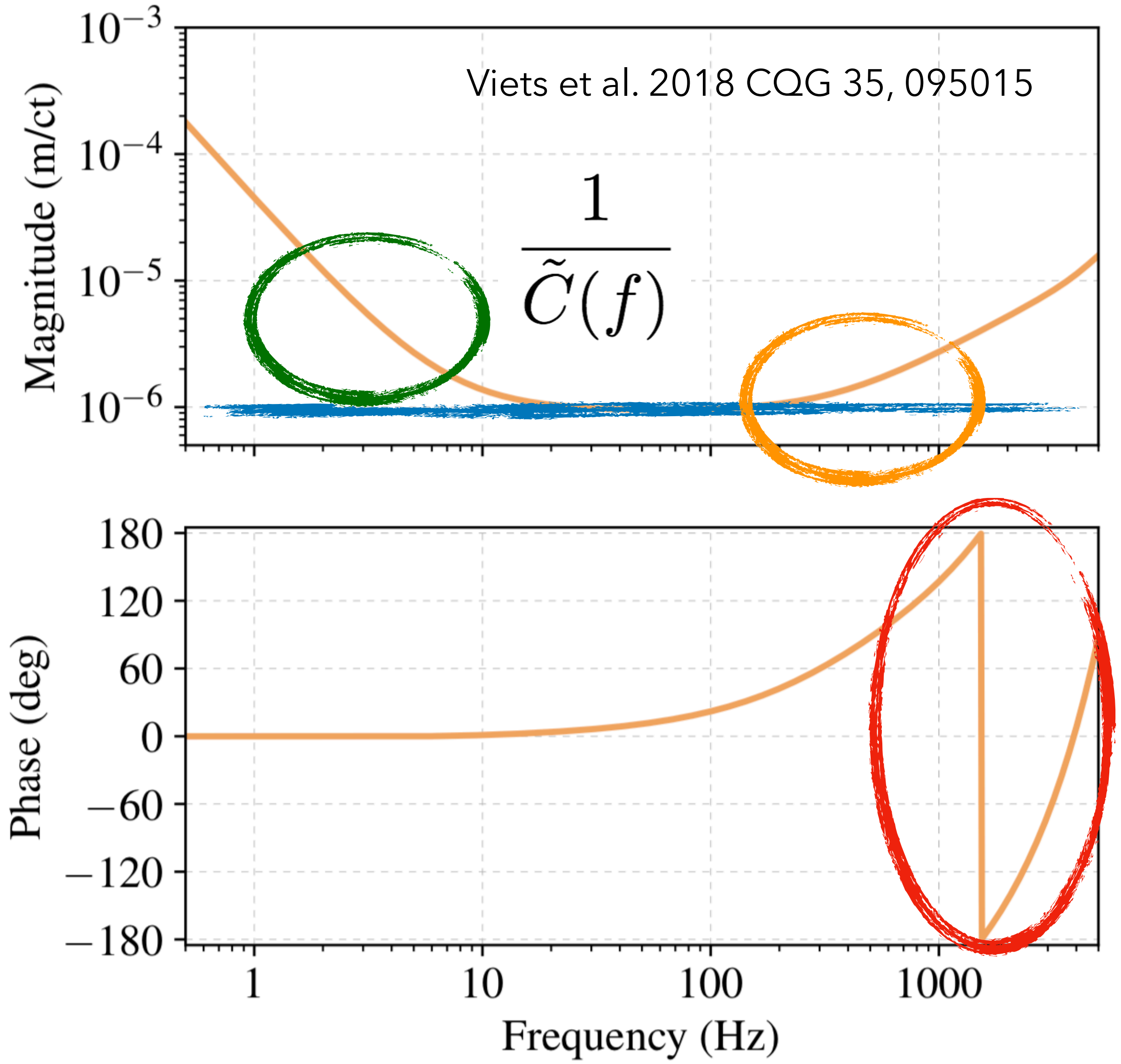


- Photon radiation pressure from auxiliary, power-modulated laser beams
- Sets absolute scale factor for calibration
- Serves as a perfect reference (with statistical uncertainty)
- Laser power, optical efficiency, incidence angle, mass of the test mass, rotation, etc.
- **Laser power** is calibrated by NIST (main contribution to overall uncertainty)

Karki et al. Review of Scientific Instruments 87, 114503 (2016)
Bhattacharjee et al. (2020) arXiv:2006.00130

- O2 Pcal uncertainty = **0.79%**
- O3 Pcal uncertainty = **0.54%**
- Only in magnitude

Sensing function (C)



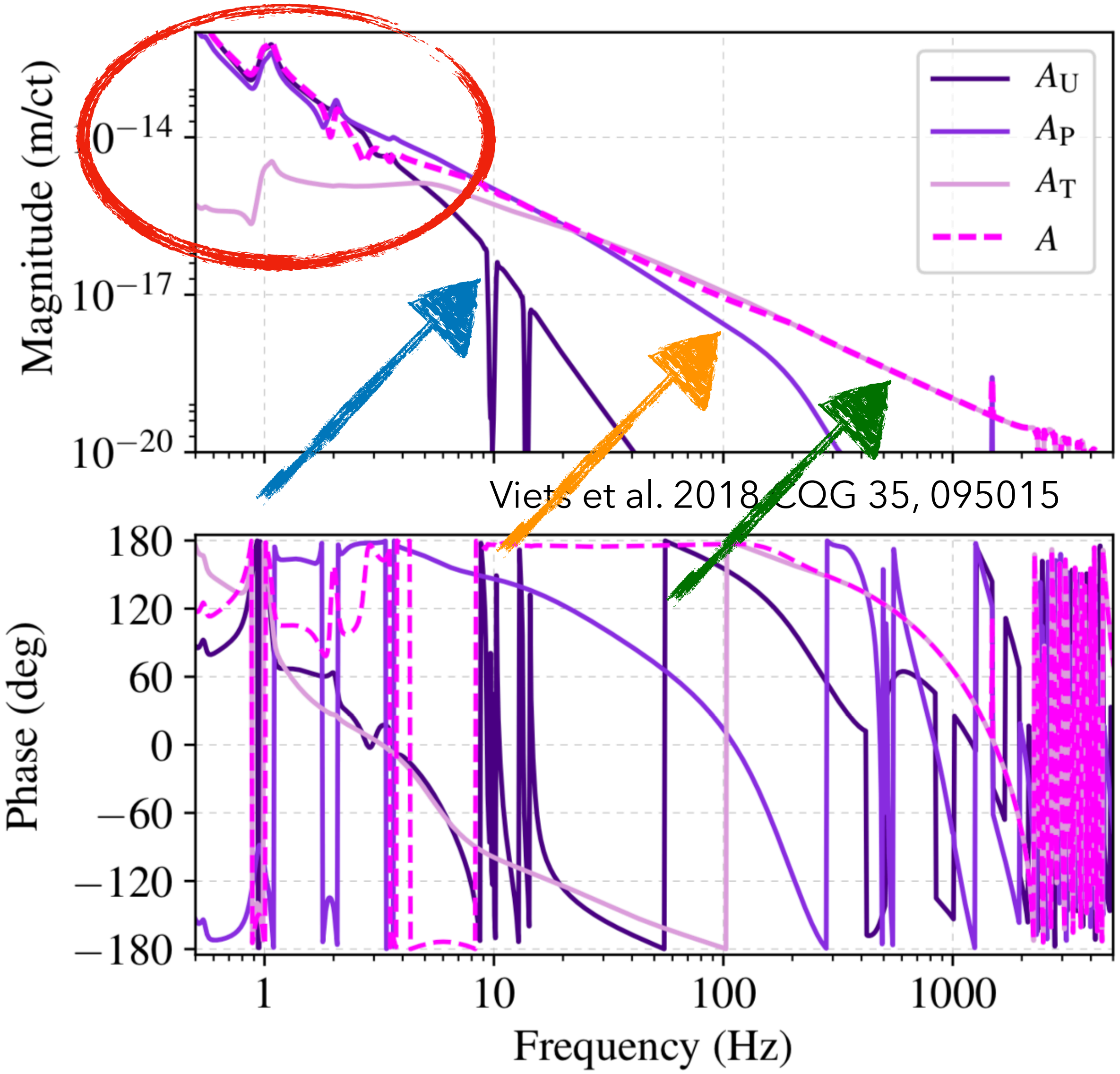
- Transfer function from the differential arm (DARM) residual displacement ΔL_{res} to digitized photodetector output signal, d_{err}
- ***Low frequency (<1kHz):*** determined by Fabry-Perot cavity response
- ***High frequency (>1kHz):*** determined by analog-to-digital conversion process

$$\tilde{C}(f;t) = \kappa_{\mathrm{C}}(t) H_C \left(\frac{1}{1 + i f f_{cc}^{-1}(t)}\right) \left(\frac{f^2}{f^2 + f_s^2(t) - i f f_s(t) Q^{-1}(t)}\right) C_R(f) \exp(-2\pi i f \tau_C)$$

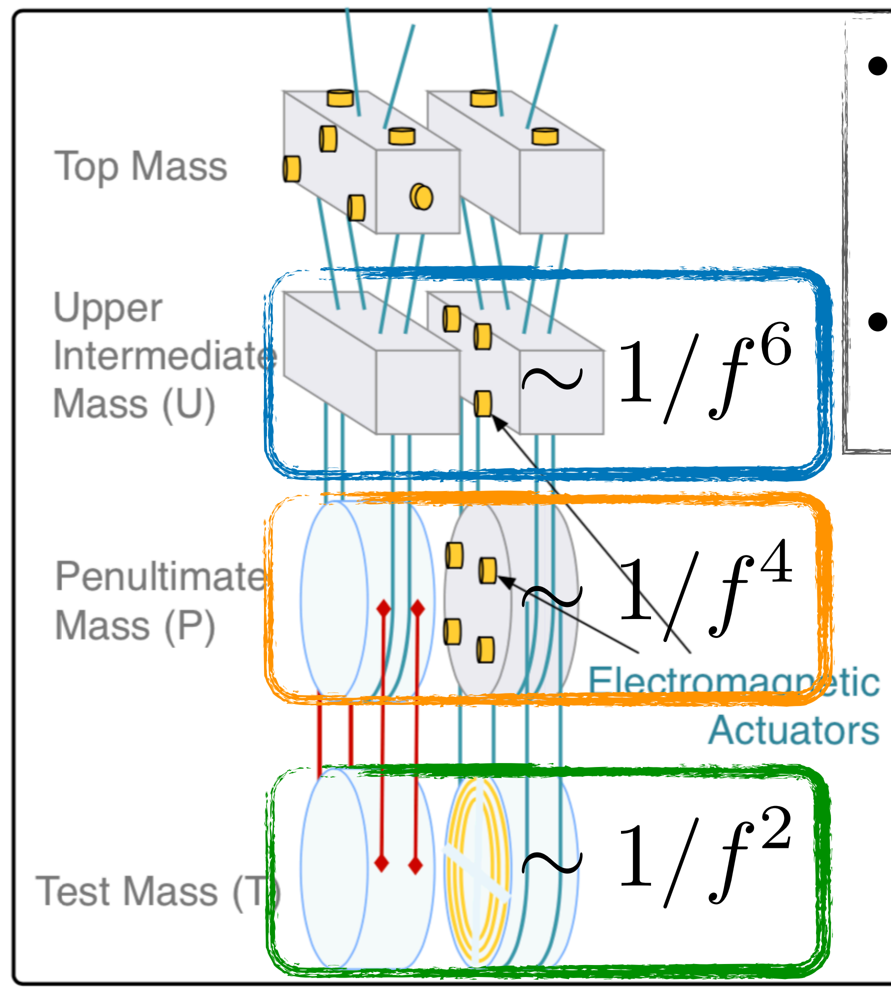
- $\kappa_{\mathrm{C}}(t) H_C$: Overall gain
- $\left(\frac{1}{1 + i f f_{cc}^{-1}(t)}\right)$: Fabry-Perot cavity response (approximated)
- $\left(\frac{f^2}{f^2 + f_s^2(t) - i f f_s(t) Q^{-1}(t)}\right)$: Optical spring from the signal recycling cavity (approximated)
- $C_R(f) \exp(-2\pi i f \tau_C)$: Electronics response and time delay

Actuation functions (A_U, A_P, A_T)

mechanical resonances



Viets et al. 2018 CQG 35, 095015



- Mechanical response of each pendulum stage
- Mainly contribute at low frequencies

$$\tilde{A}(f;t) = \left[\kappa_U(t)\tilde{A}_U(f) + \kappa_P(t)\tilde{A}_P(f) + \kappa_T(t)\tilde{A}_T(f)\right]\exp(-2\pi i f \tau_A)$$

UIM actuation response

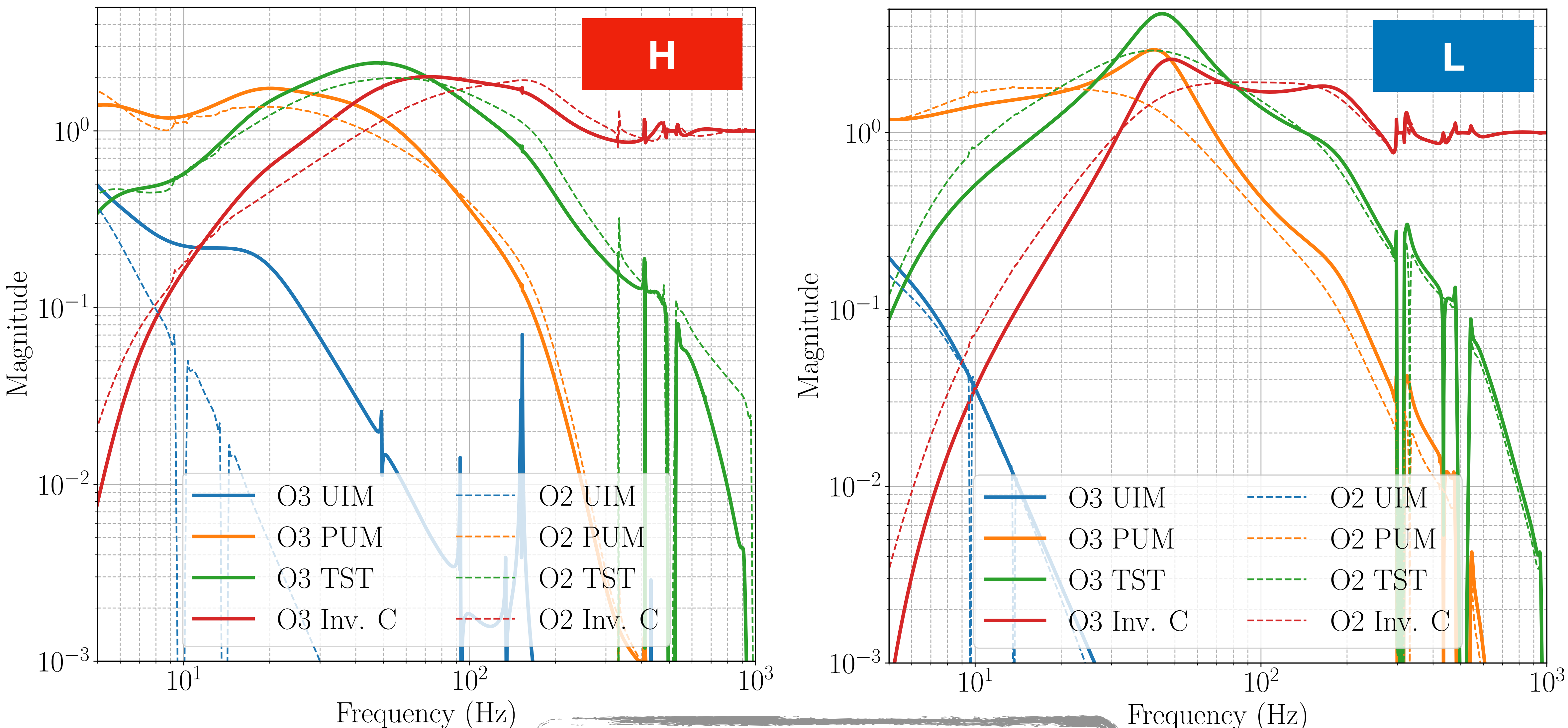
PUM actuation response

TST actuation response

Time delay

Contribution from each stage

Sun et al. (2020) arXiv:2005.02531



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

$$\frac{1/\tilde{C}^{(\mathrm{model})}(f)}{\tilde{R}^{(\mathrm{model})}(f)} \qquad \frac{\tilde{A}_U^{(\mathrm{model})}(f)\tilde{D}(f)}{\tilde{R}^{(\mathrm{model})}(f)} \qquad \frac{\tilde{A}_P^{(\mathrm{model})}(f)\tilde{D}(f)}{\tilde{R}^{(\mathrm{model})}(f)} \qquad \frac{\tilde{A}_T^{(\mathrm{model})}(f)\tilde{D}(f)}{\tilde{R}^{(\mathrm{model})}(f)}$$

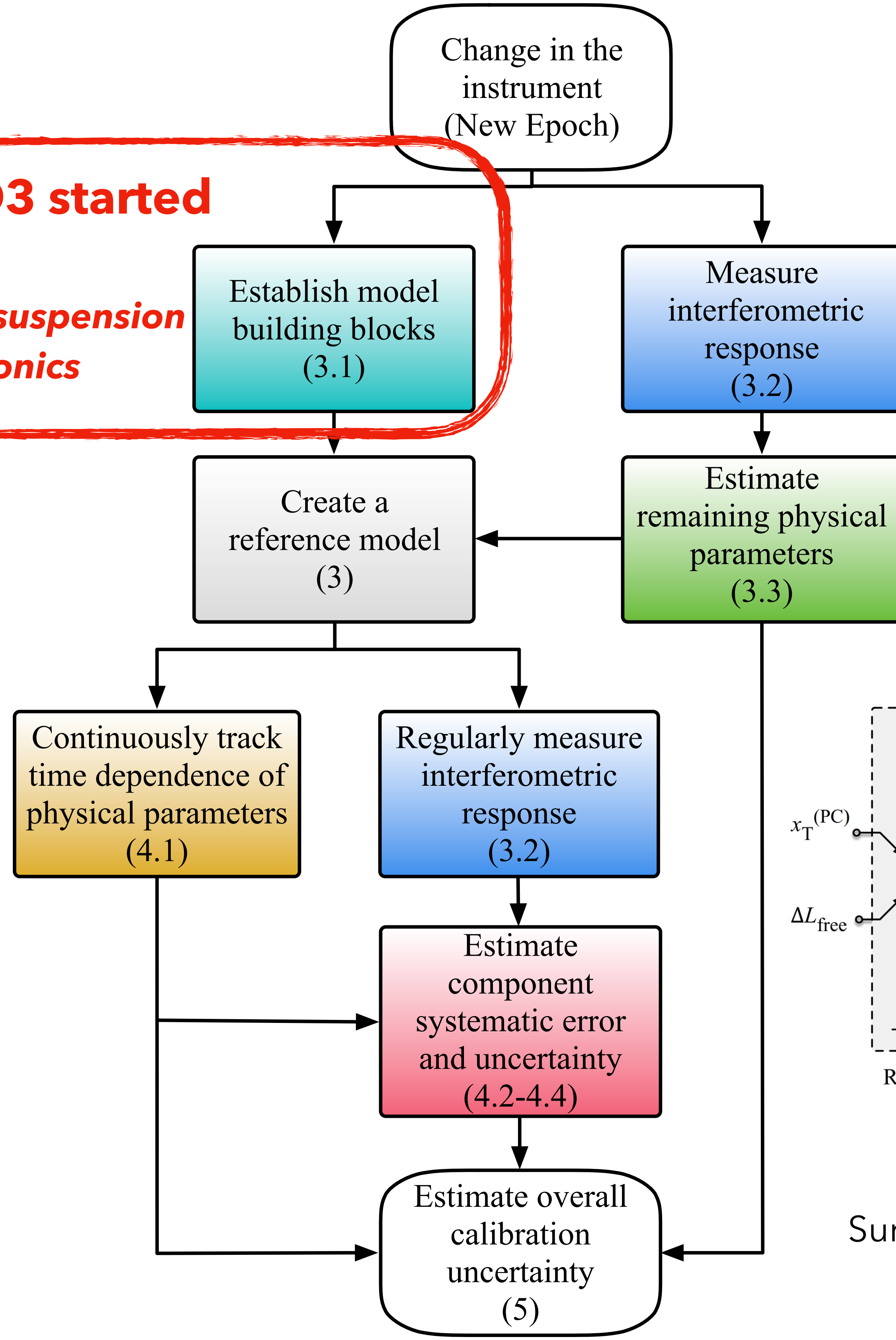
Agenda

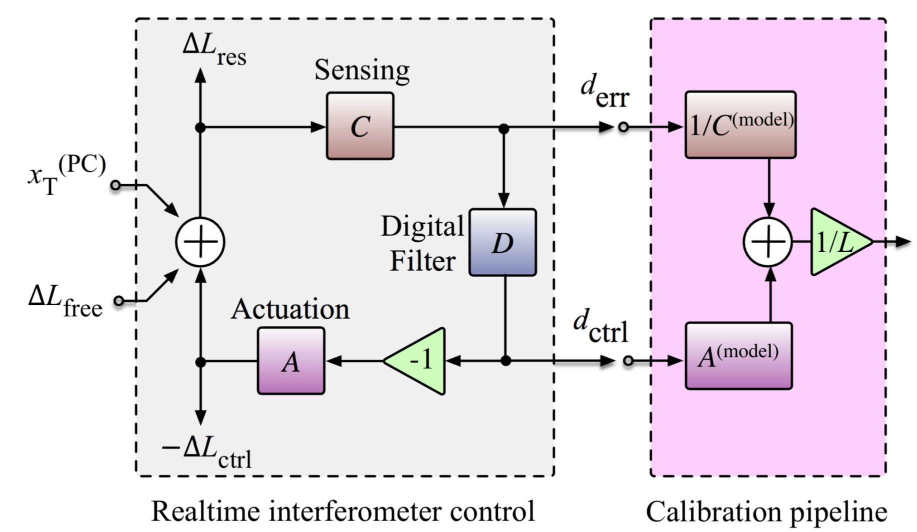
- Why is calibration important
- How does calibration work
- **Understanding systematics and uncertainties**
- O3 improvements and future perspectives

A brief flowchart of calibration procedure

1.Before O3 started

- ***Photon calibrator***
- ***Dynamics of quadruple suspension***
- ***Signal processing electronics***

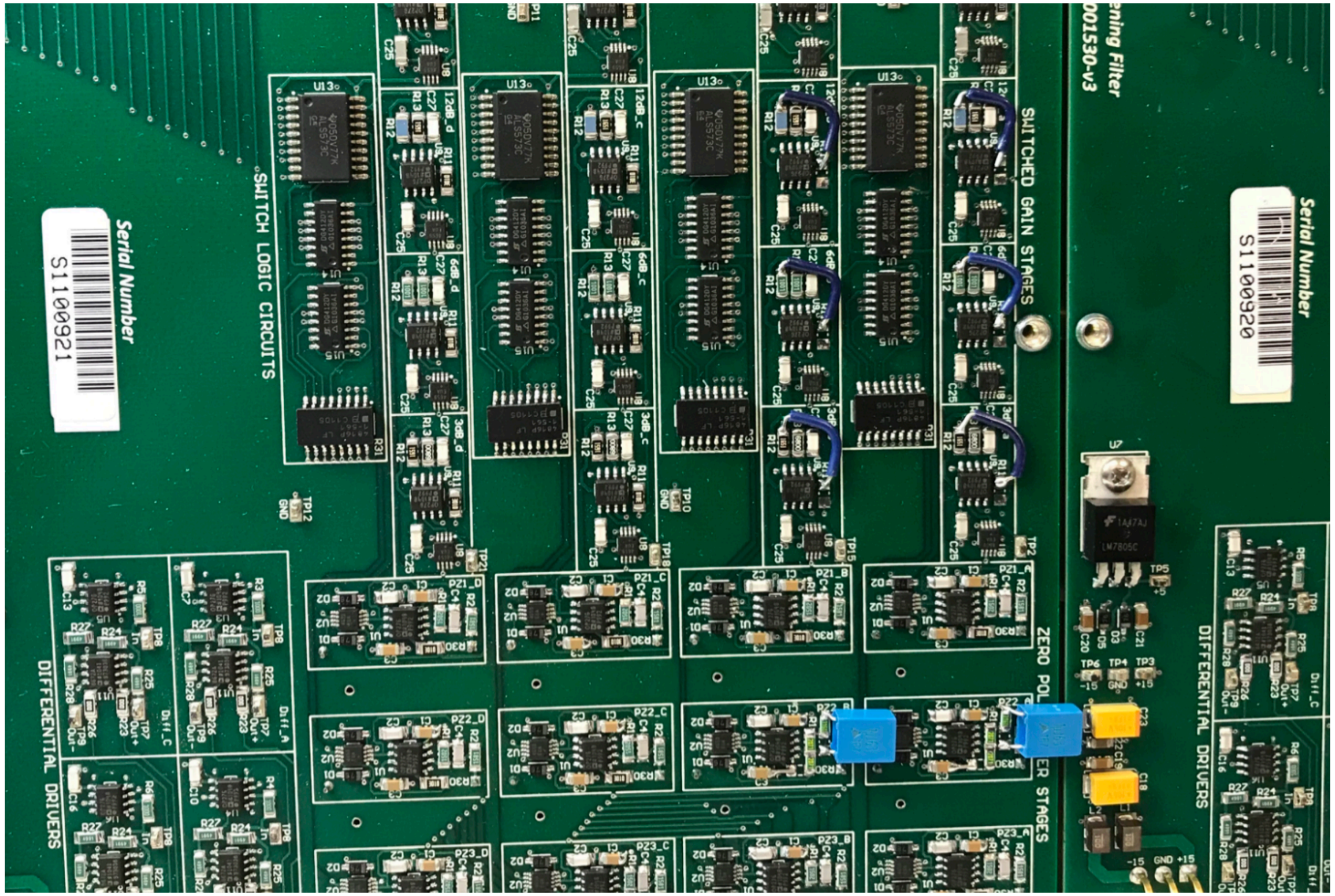




Sun et al. (2020) arXiv:2005.02531

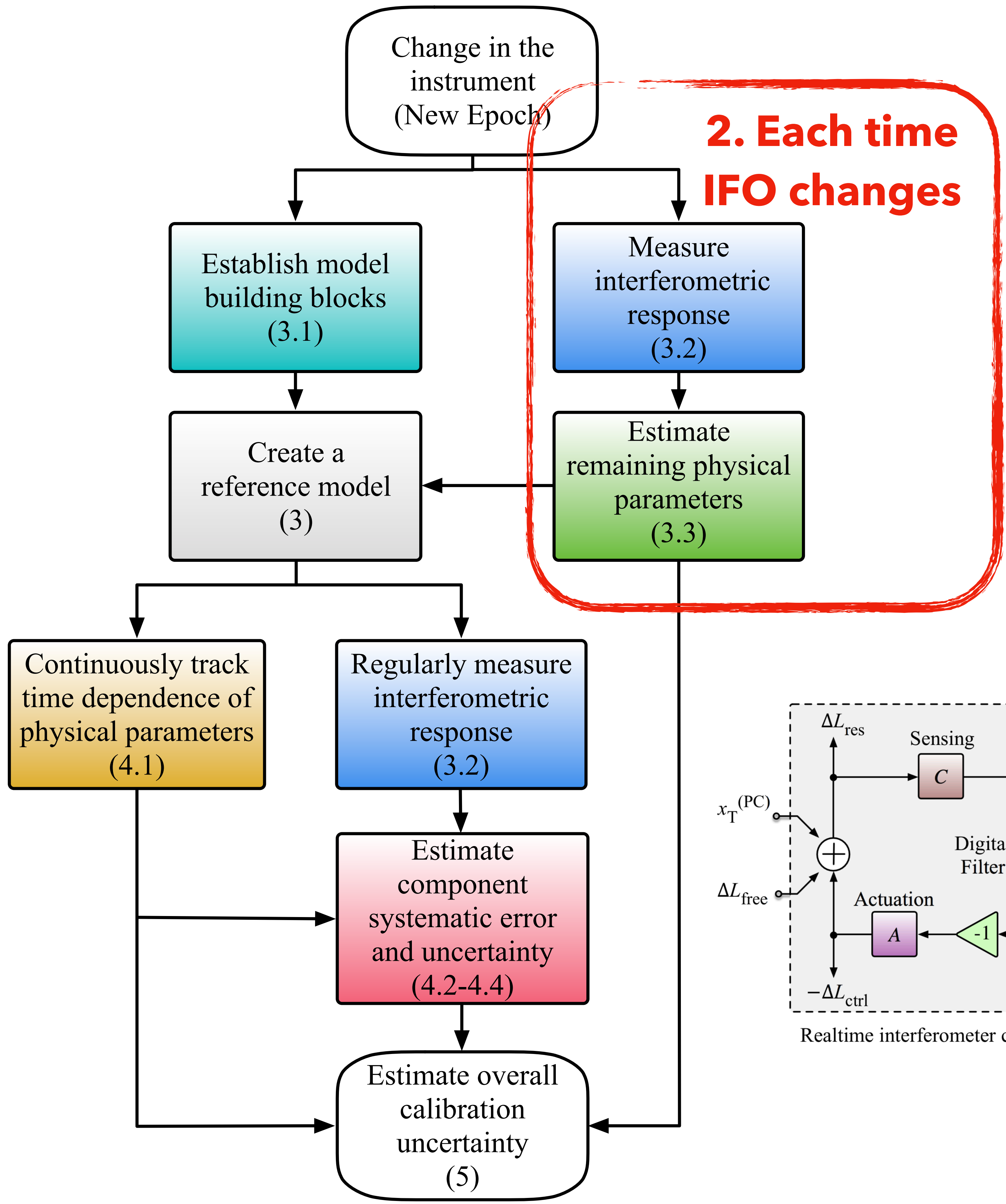
Signal processing analog electronics

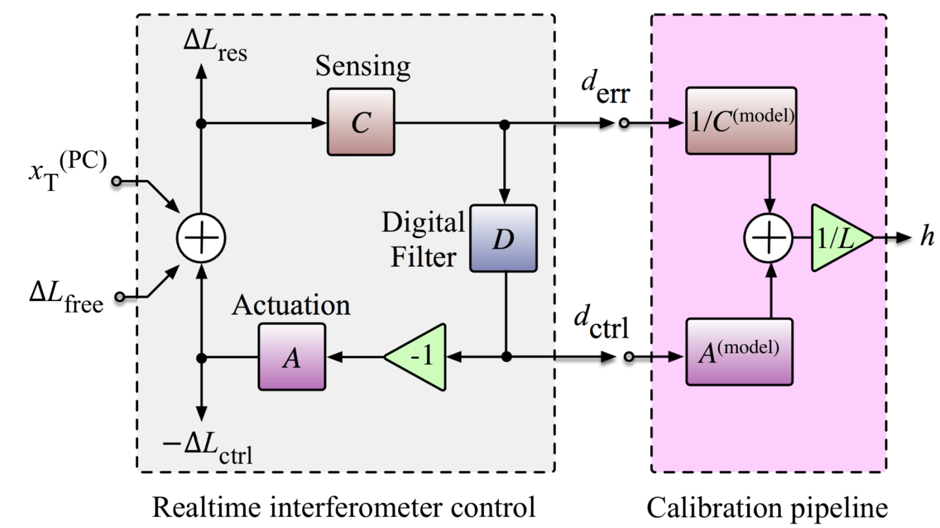
- Anti-aliasing chassis
- Anti-imaging chassis
- Coil driver chassis (UIM and PUM)
- Electro-static driver (ESD) chassis (TST)
- Whitening chassis



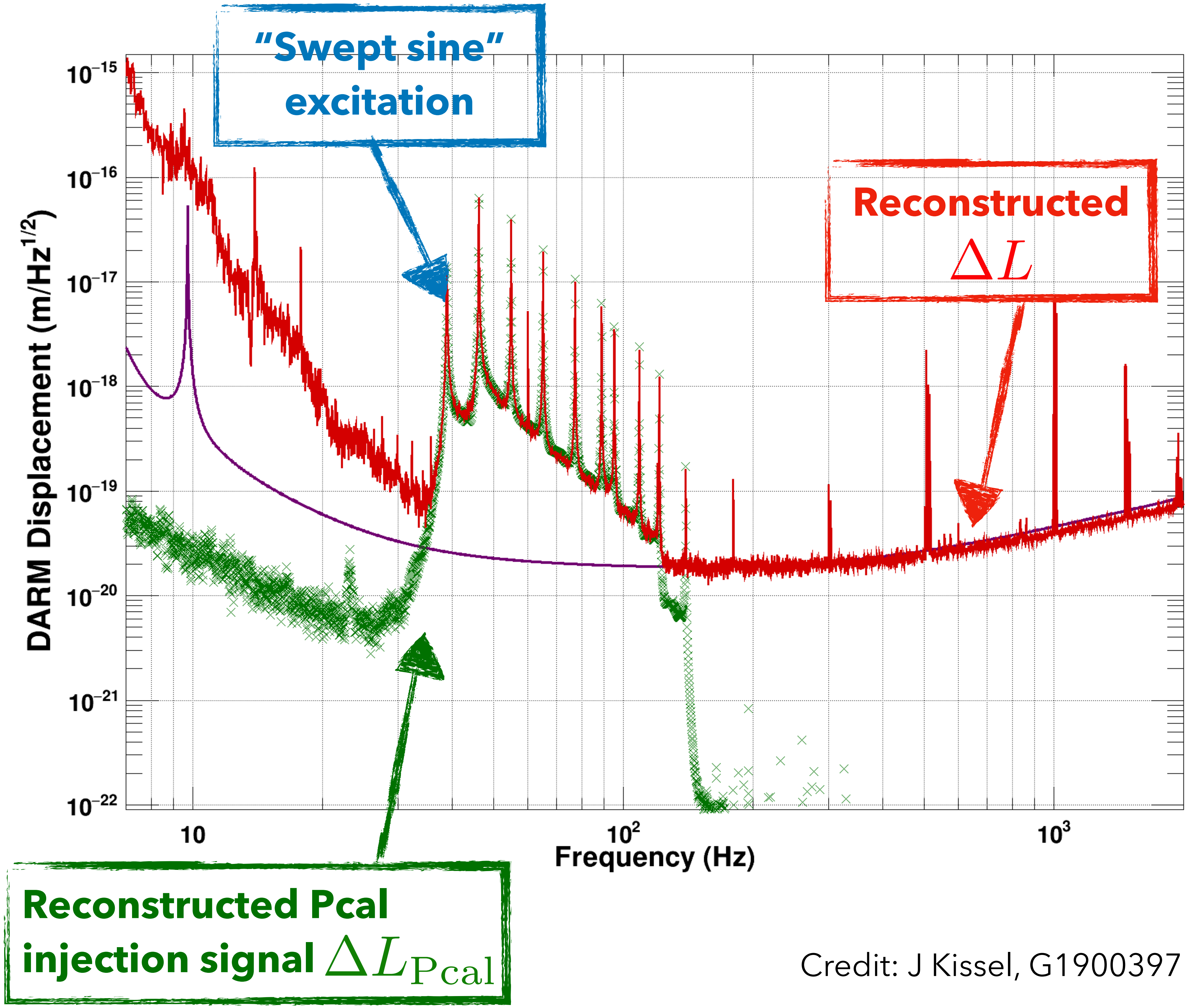
Example: OMC DCPD Whitening chassis D1002559
Rich Abbott, https://alog.ligo-wa.caltech.edu/aLOG/index.php?callRep=47254

A brief flowchart of calibration procedure





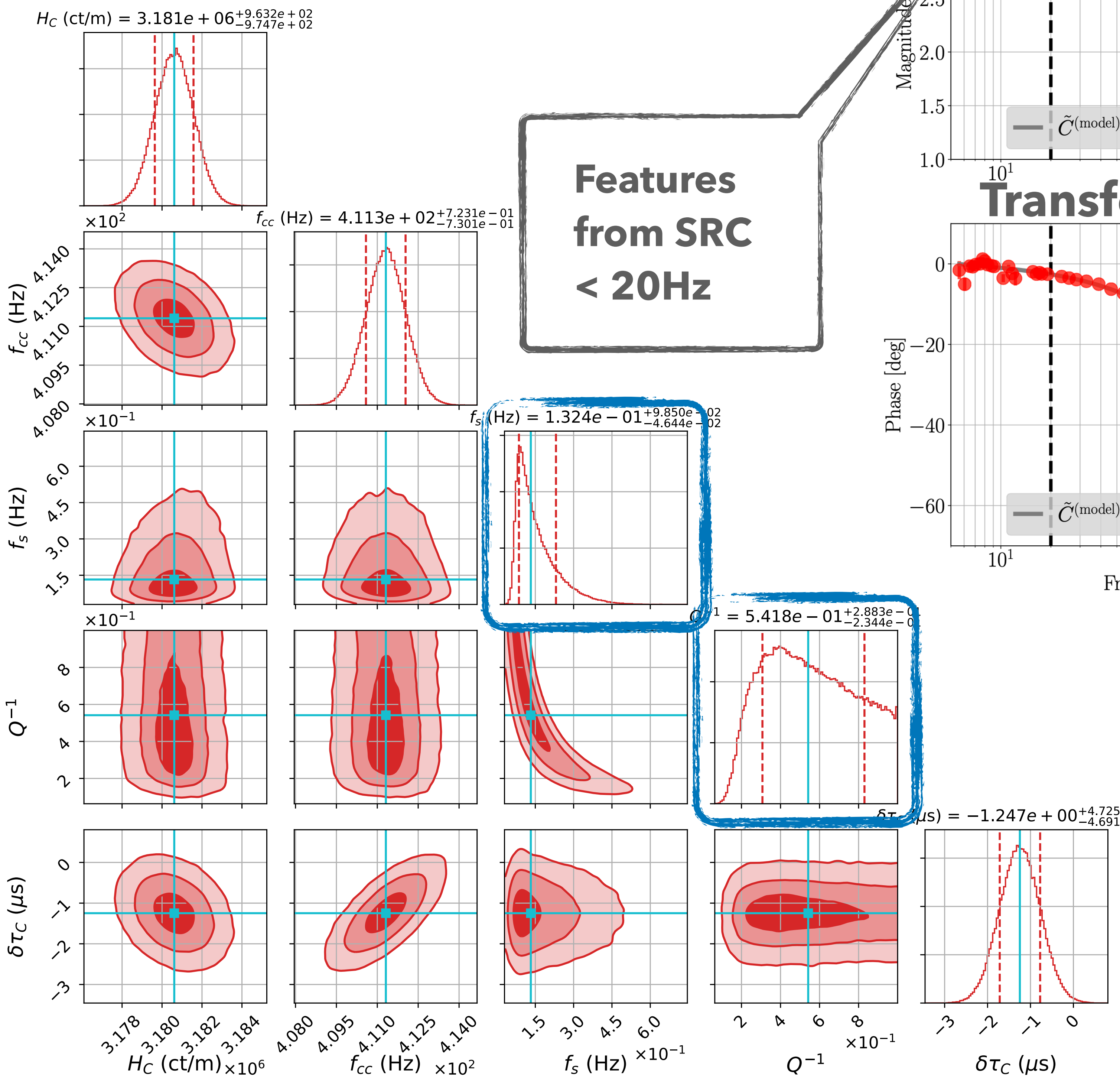
Take measurements and build the model

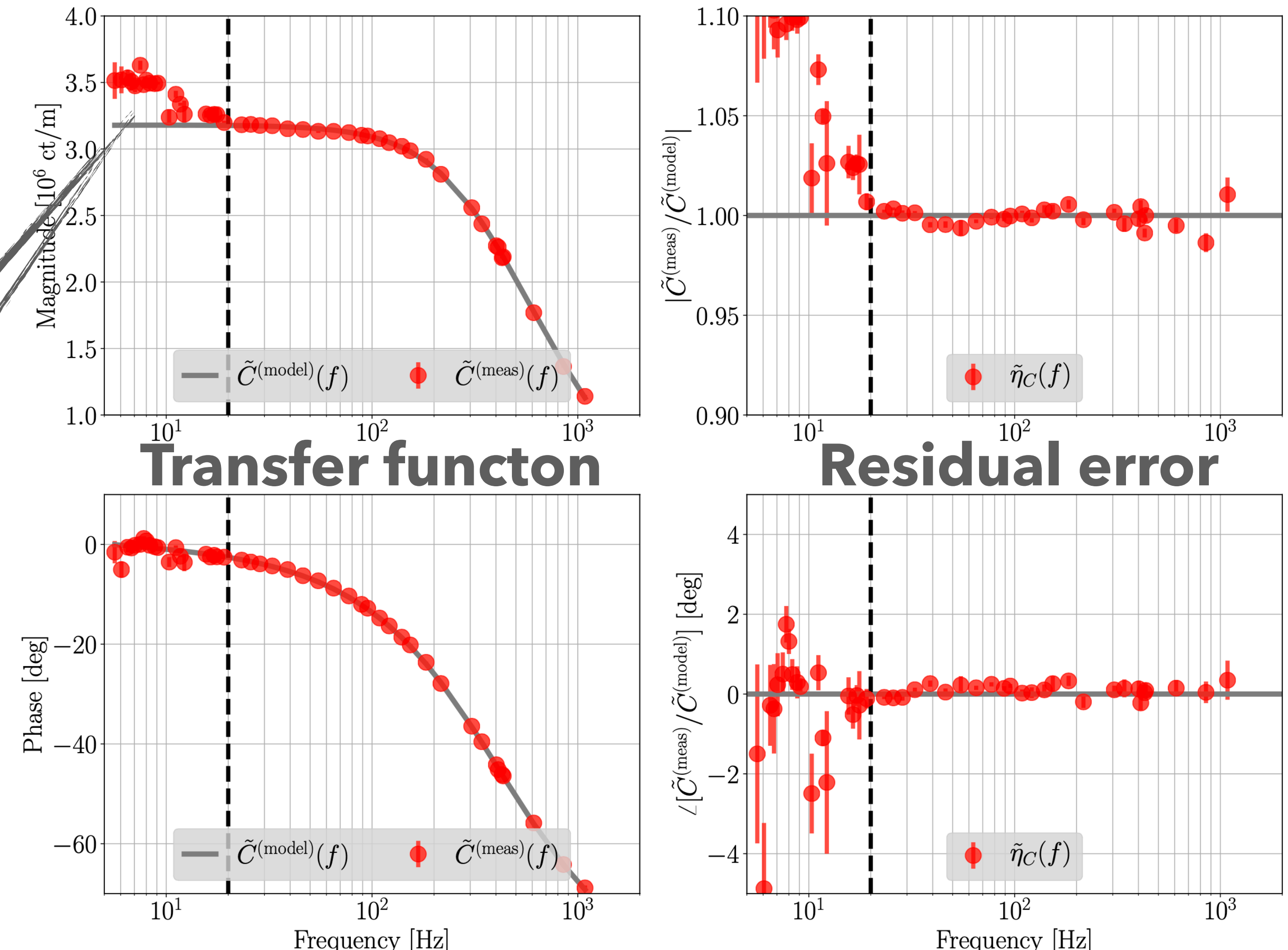


Credit: J Kissel, G1900397

Parameter estimation and build the model

H1 Sensing example; similar for 3 actuation stages





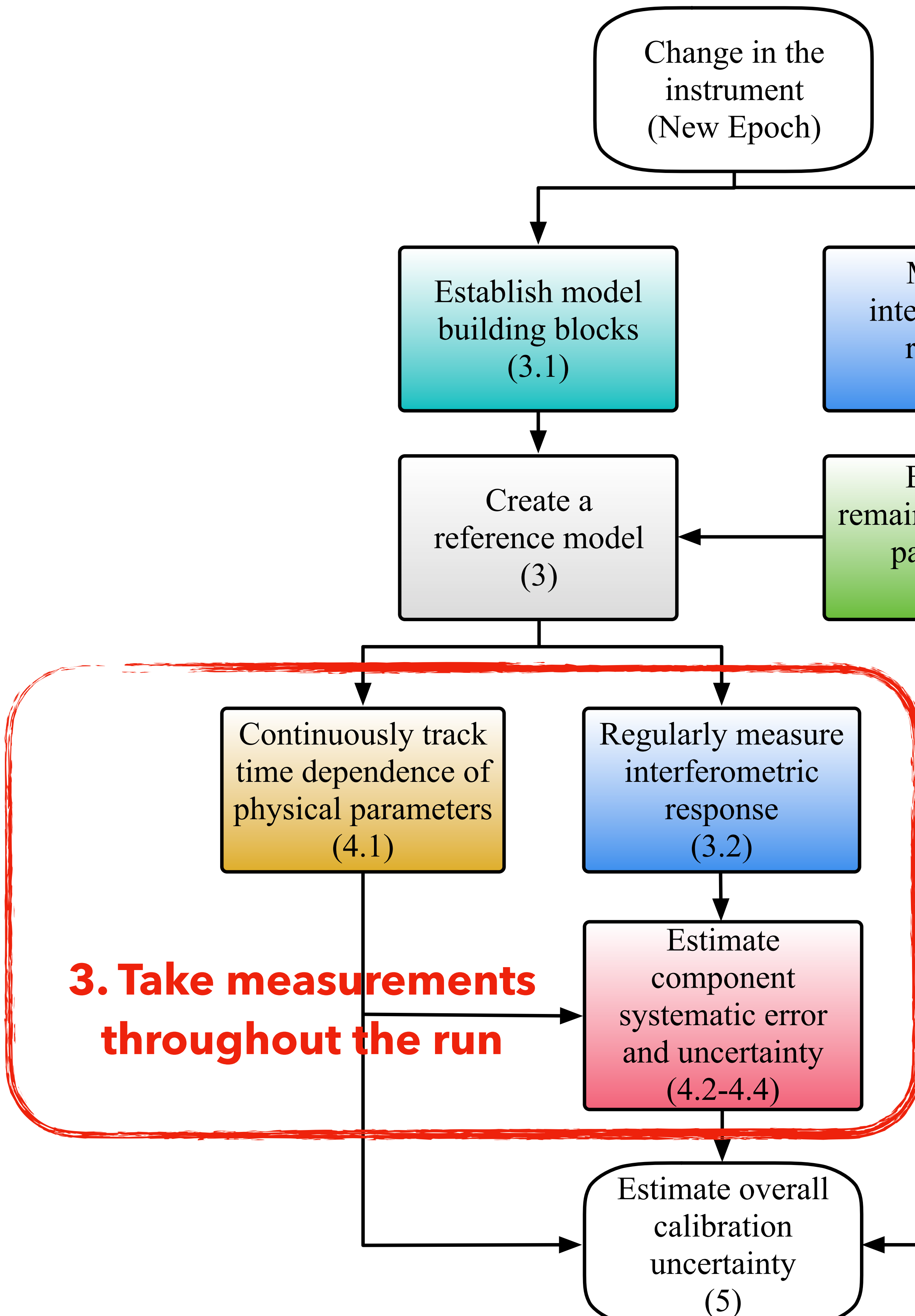
$$\tilde{C}^{\mathrm{static}}(f) = \left(\frac{H_C}{1 + if/f_{cc}}\right) \times \left(\frac{f^2}{f^2 + f_s^2 - i f f_s/Q}\right) \times C_R(f)\exp\left[-2\pi i f \tau_C\right]$$

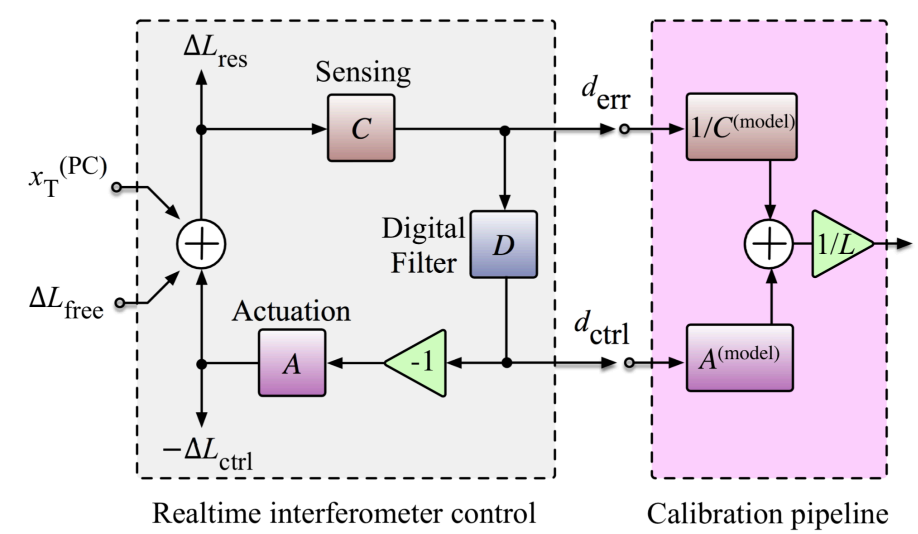
Reference model

Poorly measured

Sun et al. (2020) arXiv:2005.02531

A brief flowchart of calibration procedure

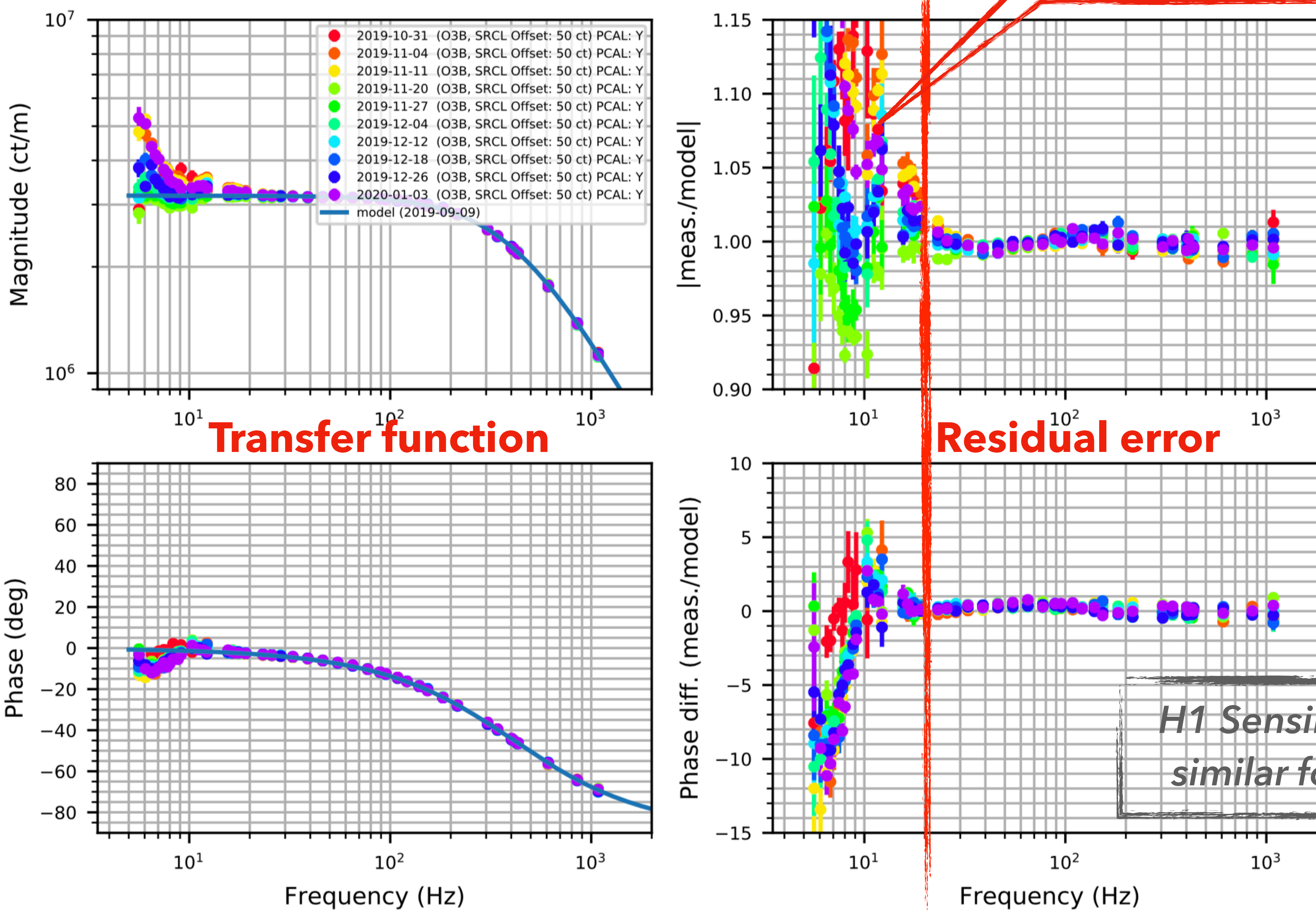




Stack multiple measurements

- Collect multiple "swept sine" measurements
- Correct for time dependence
- Stack them together to infer residual error and uncertainty

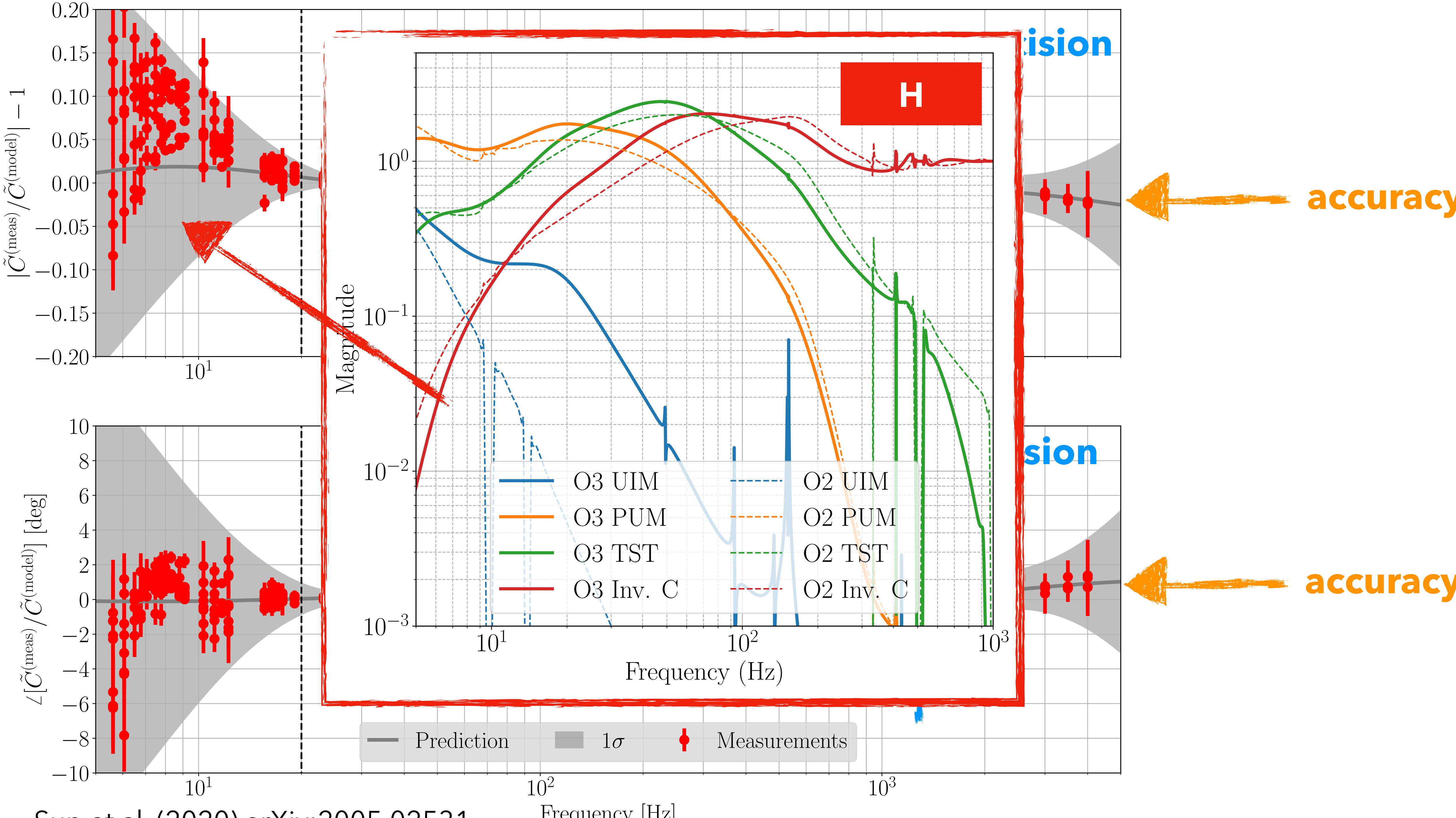
- ***What's happening < 20Hz?***
- ***How much does that contribute to the overall uncertainty?***



H1 Sensing example; similar for actuation

Estimate residual error and statistical uncertainty (GPR)

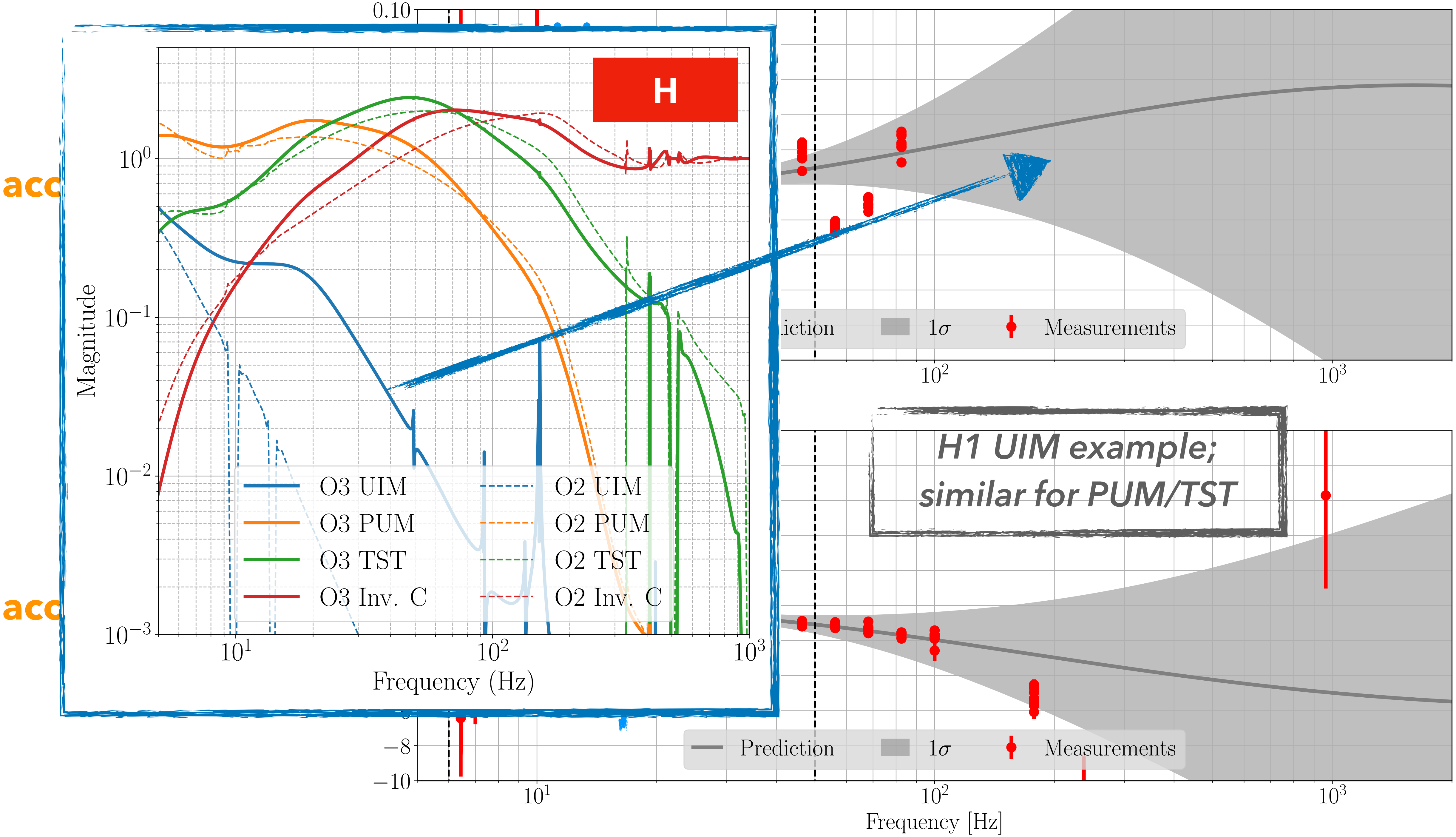
- Collect multiple "swept sine" measurements
- Correct for time dependence, and stack all measurements
- Input all the residuals (from all measurements) into **Gaussian Process Regression**



Sun et al. (2020) arXiv:2005.02531

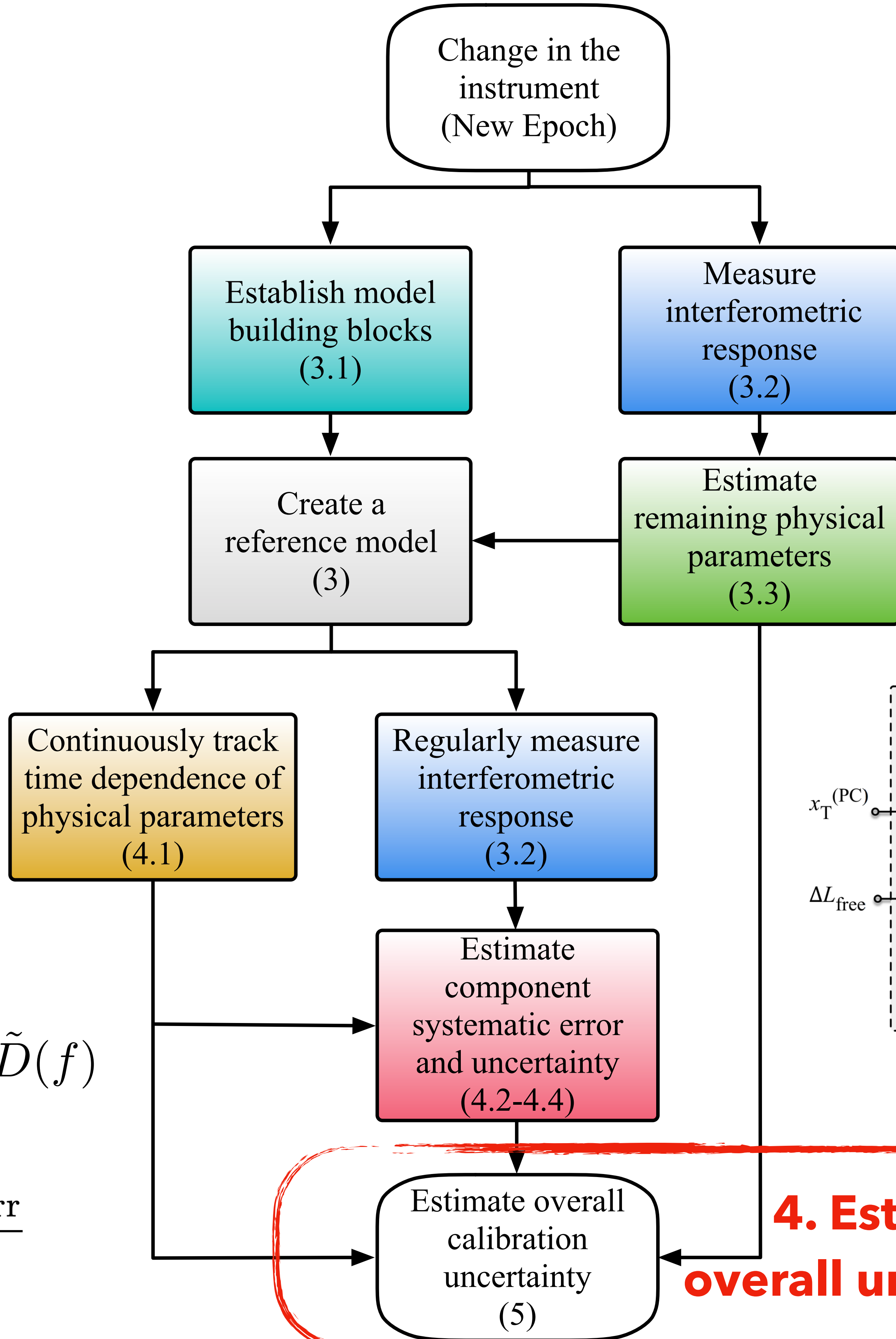
Estimate residual error and statistical uncertainty (GPR)

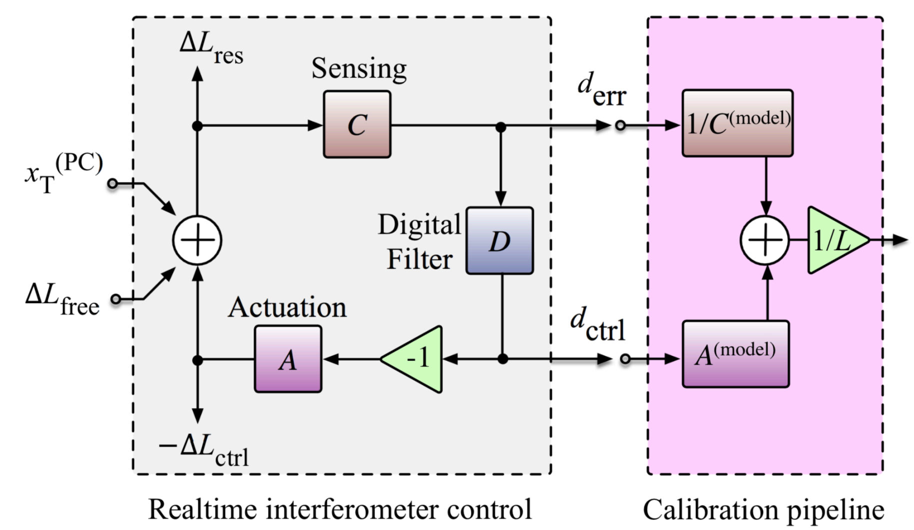
- Another example – H1 UIM actuator



Sun et al. (2020) arXiv:2005.02531

A brief flowchart of calibration procedure





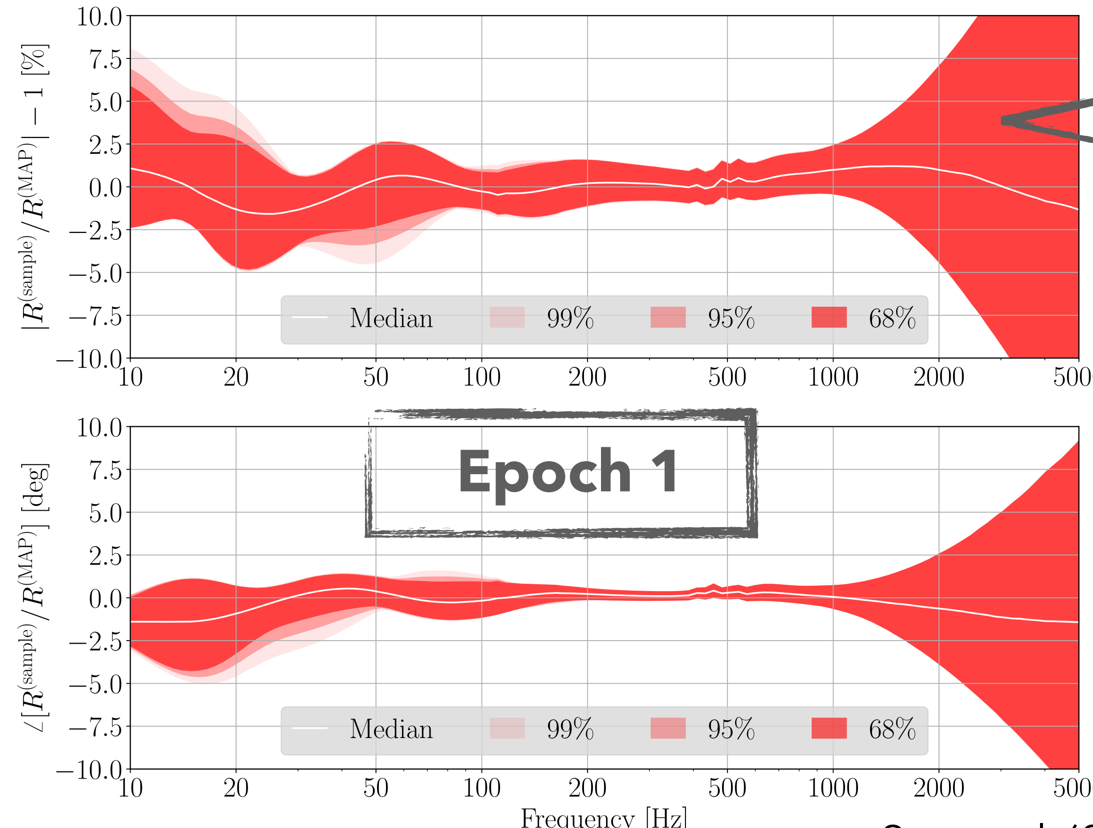
$$\tilde{R}(f) = \frac{1}{\tilde{C}(f)} + \tilde{A}(f)\tilde{D}(f)$$

$$h = \frac{R^{(\mathrm{model})} * d_{\mathrm{err}}}{L}$$

O3A final products (Hanford)

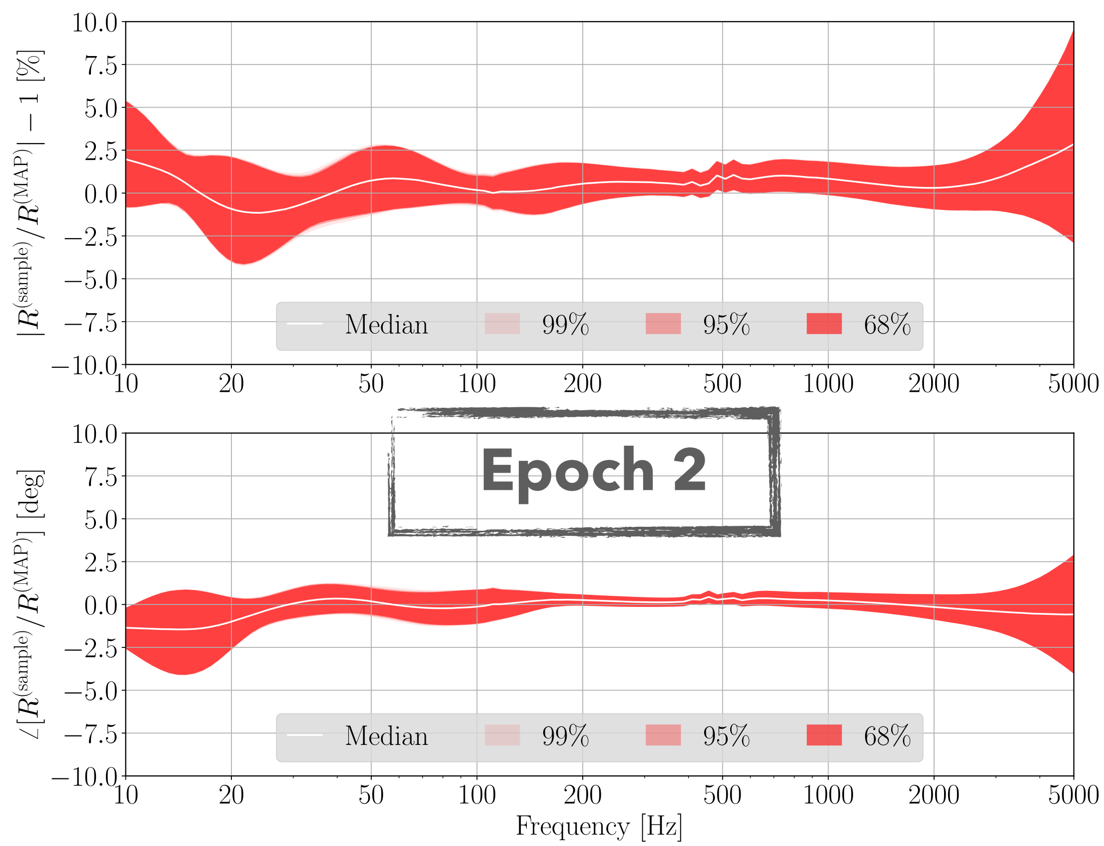
$$\tilde{R}(f) = \frac{1}{\tilde{C}(f)} + \tilde{A}(f)\tilde{D}(f)$$

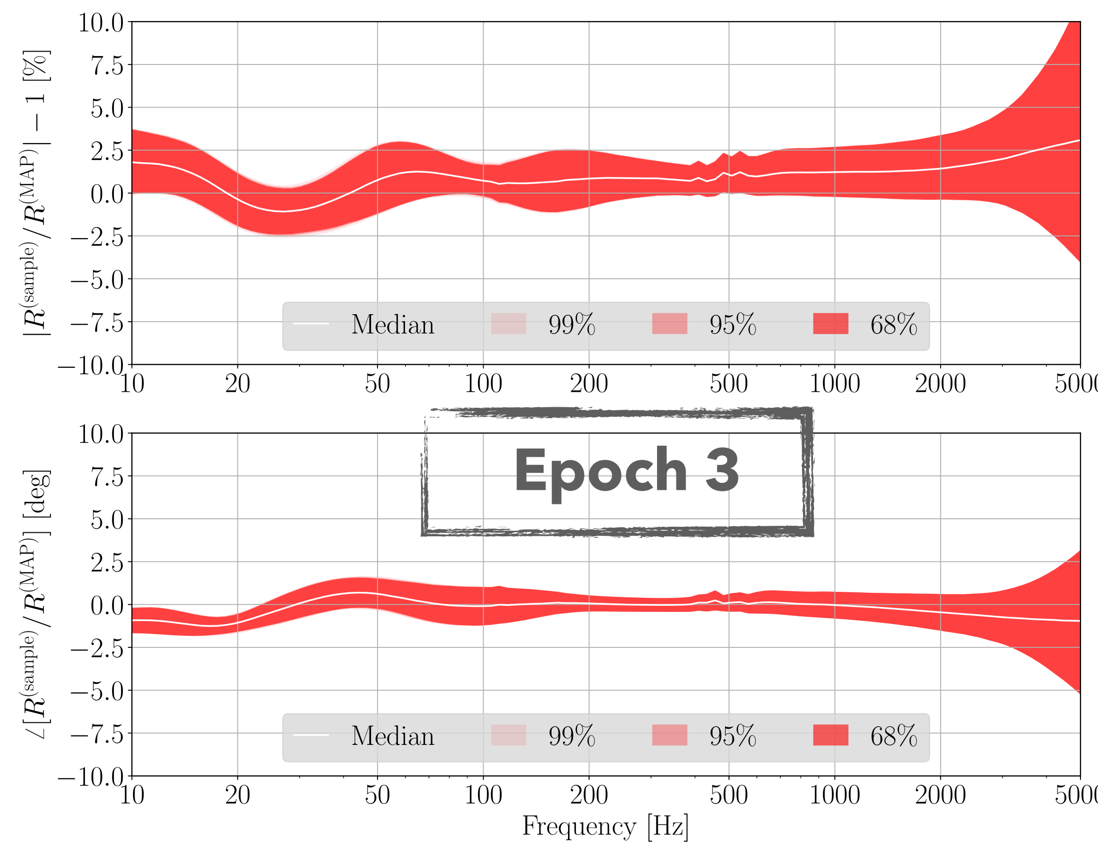
- 1-sigma limits of systematic error and associated statistical uncertainty
- Excursion from unity magnitude/zero phase



- Not yet taken high-frequency measurements

Sun et al. (2020) arXiv:2005.02531

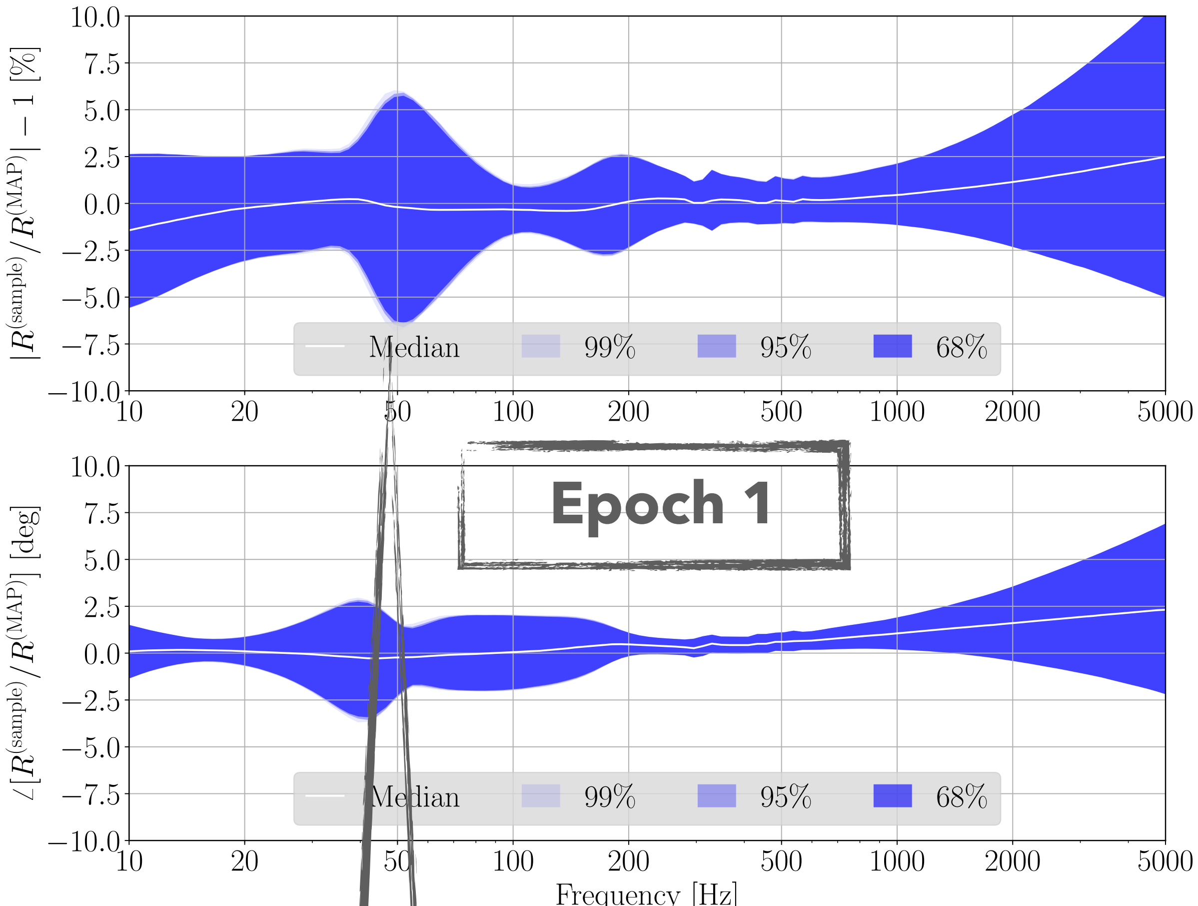




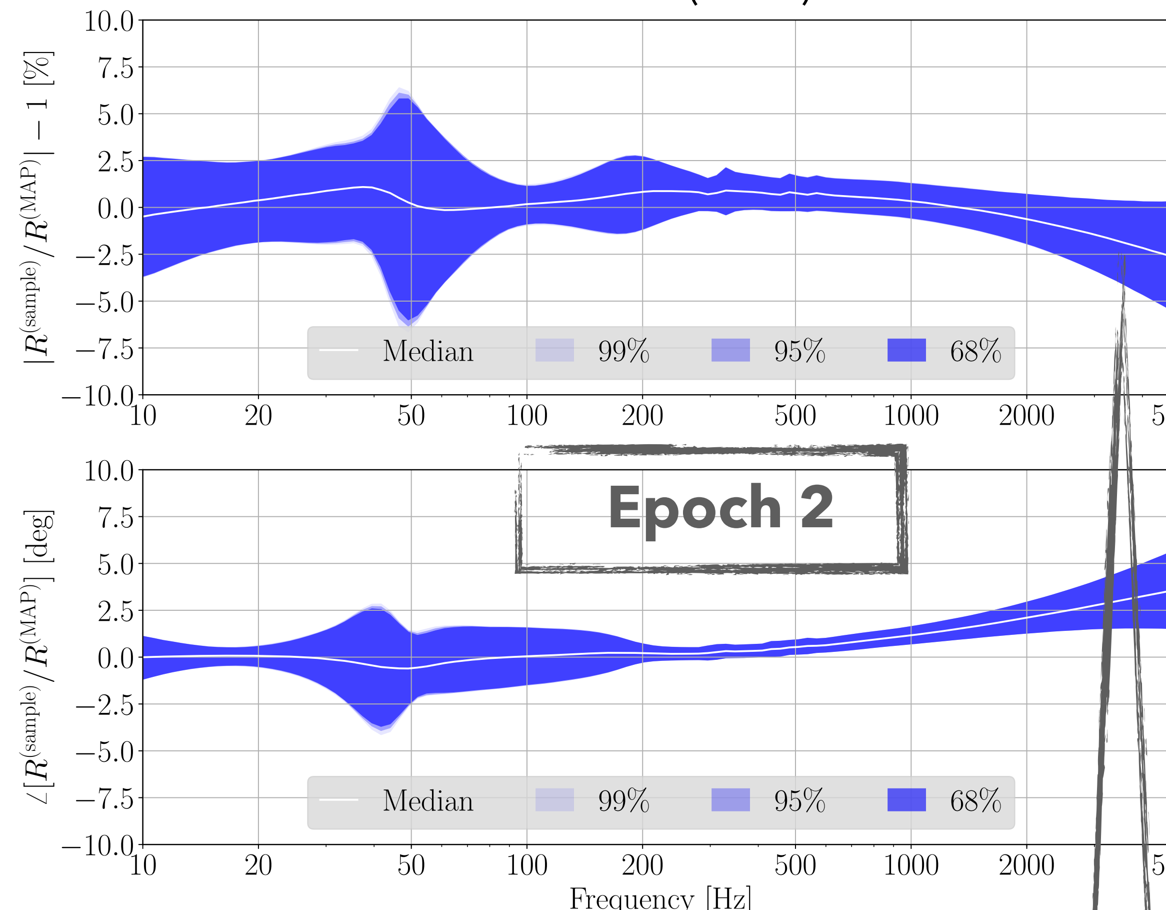
O3A final products (Livingston)

Sun et al. (2020) arXiv:2005.02531

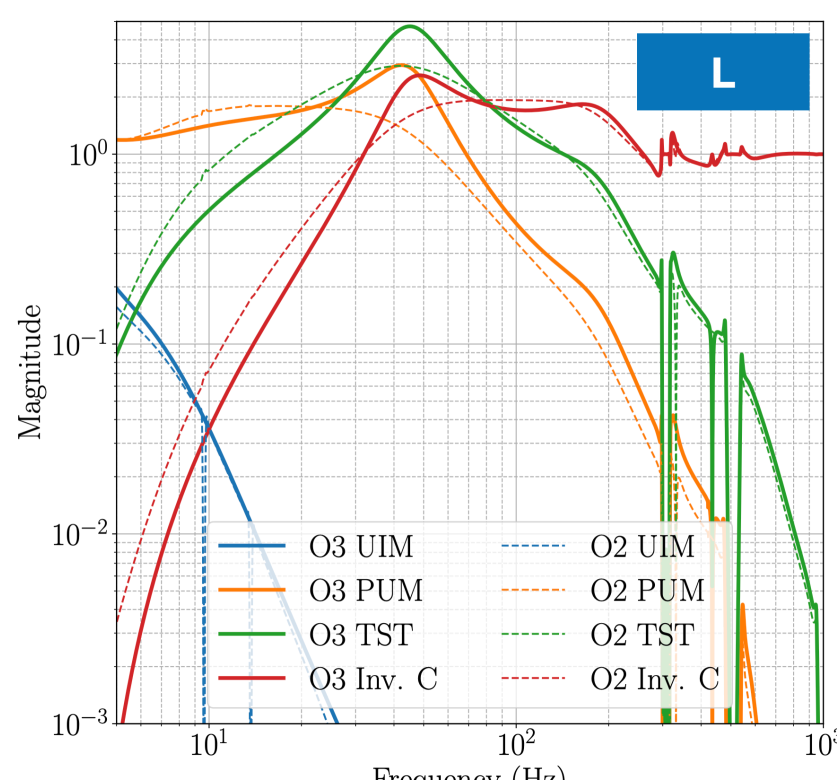
Epoch 1



Epoch 2



- Larger uncertainty due to PUM/TST actuation authority choice in Livingston
- Changed from O2 to O3



- Improved by high frequency measurements

Agenda

- Why is calibration important
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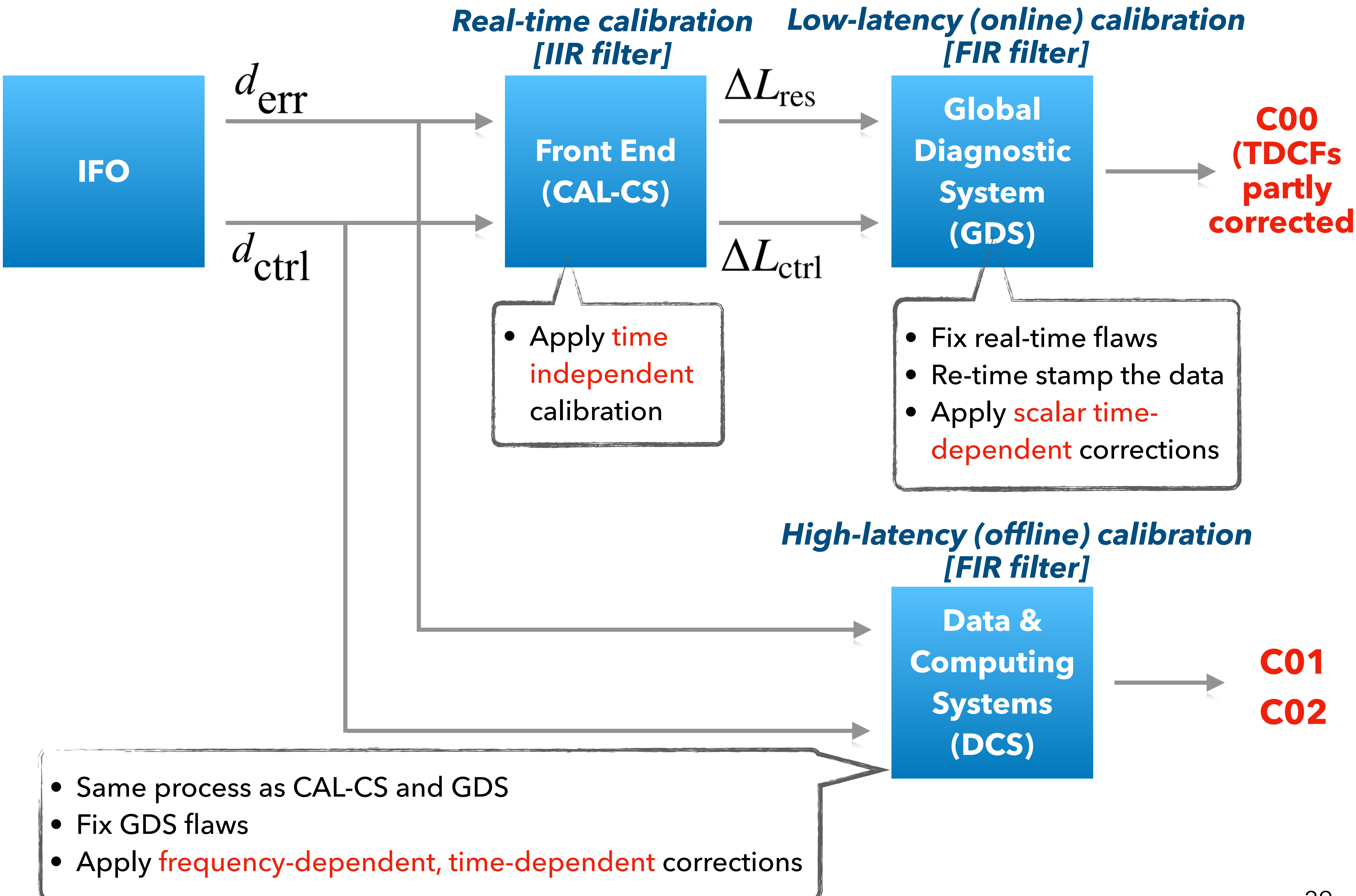
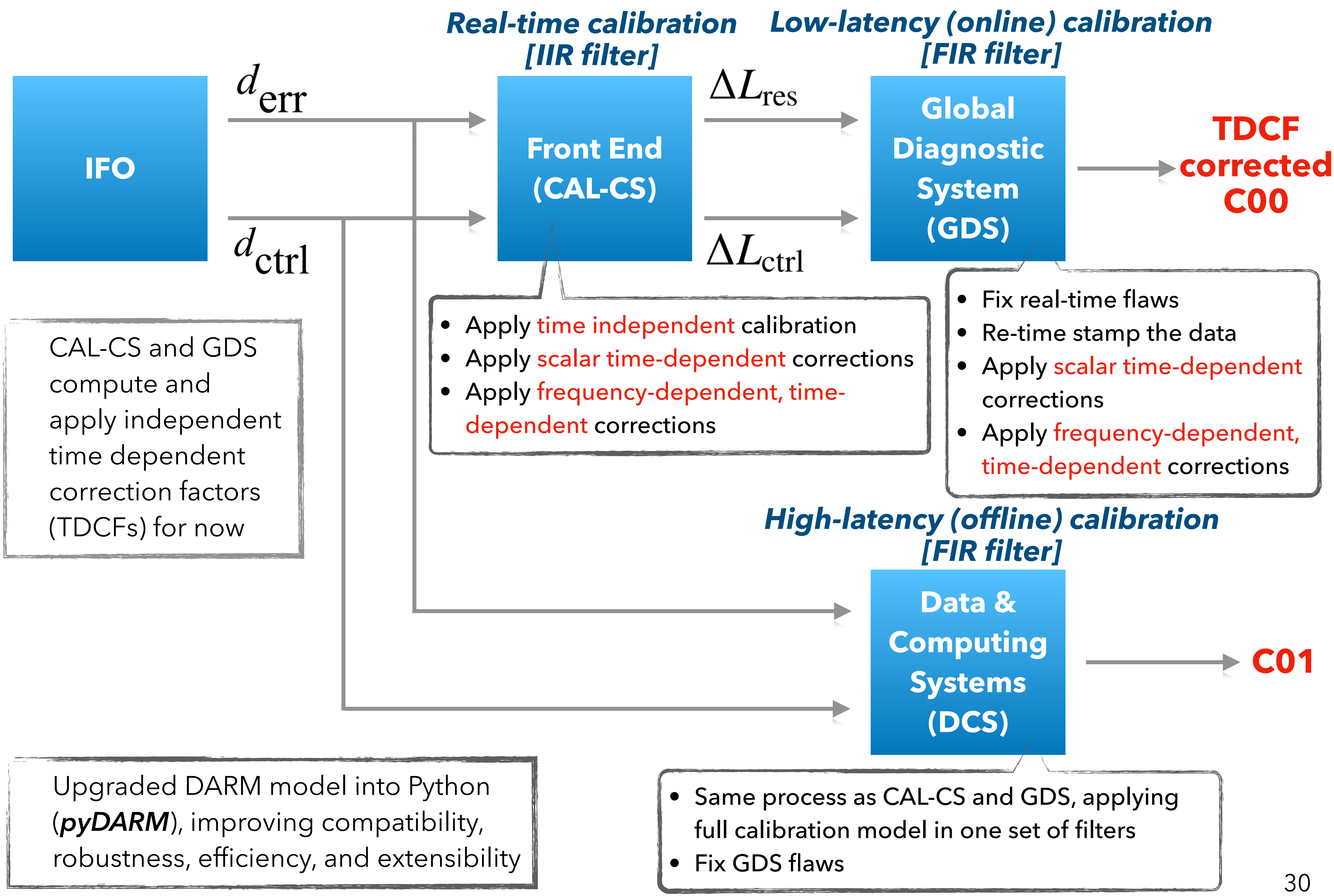
- **O3 improvements and future perspectives**

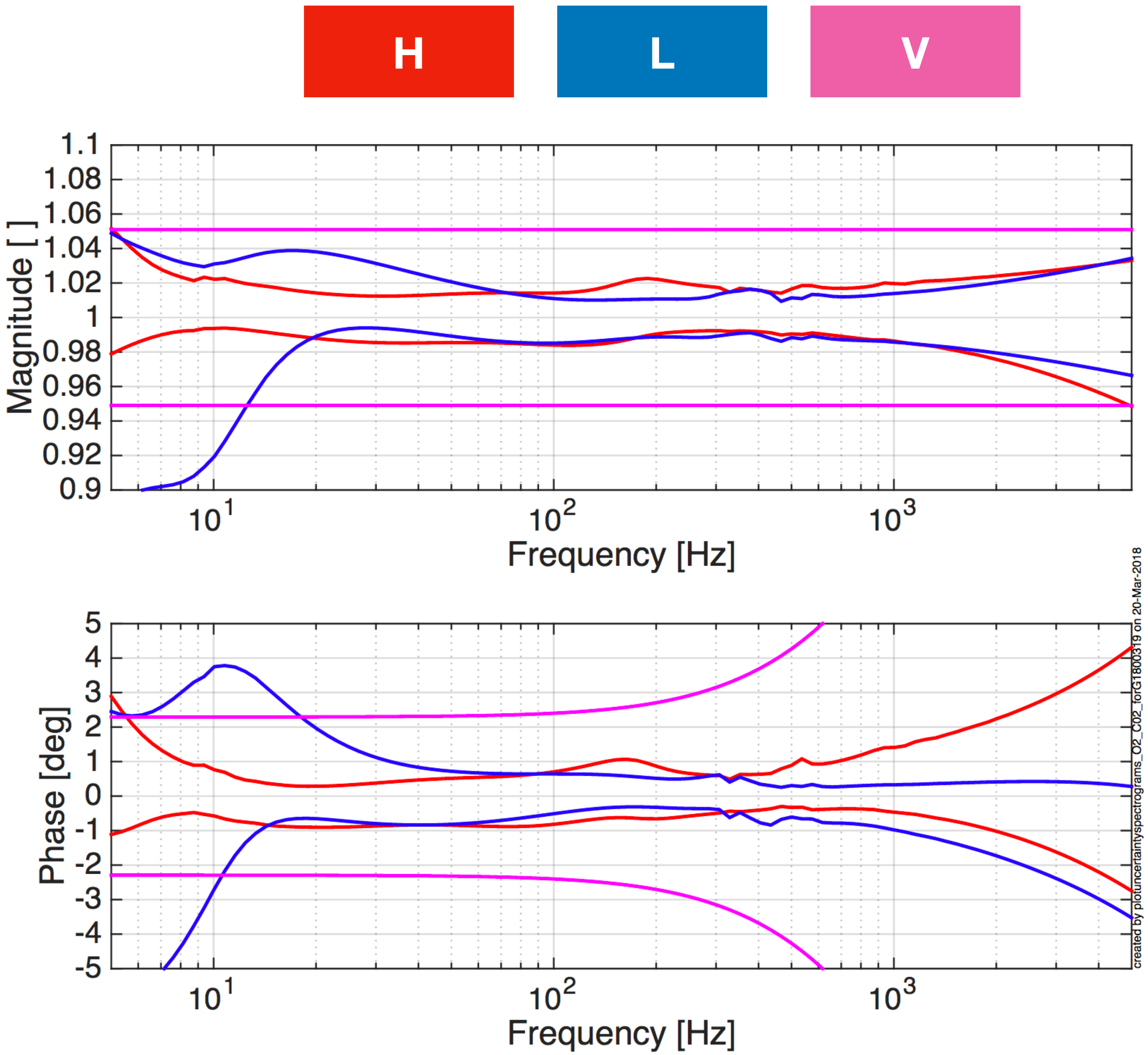
What we had in O2



What’s new in O3



Best calibration product in O2

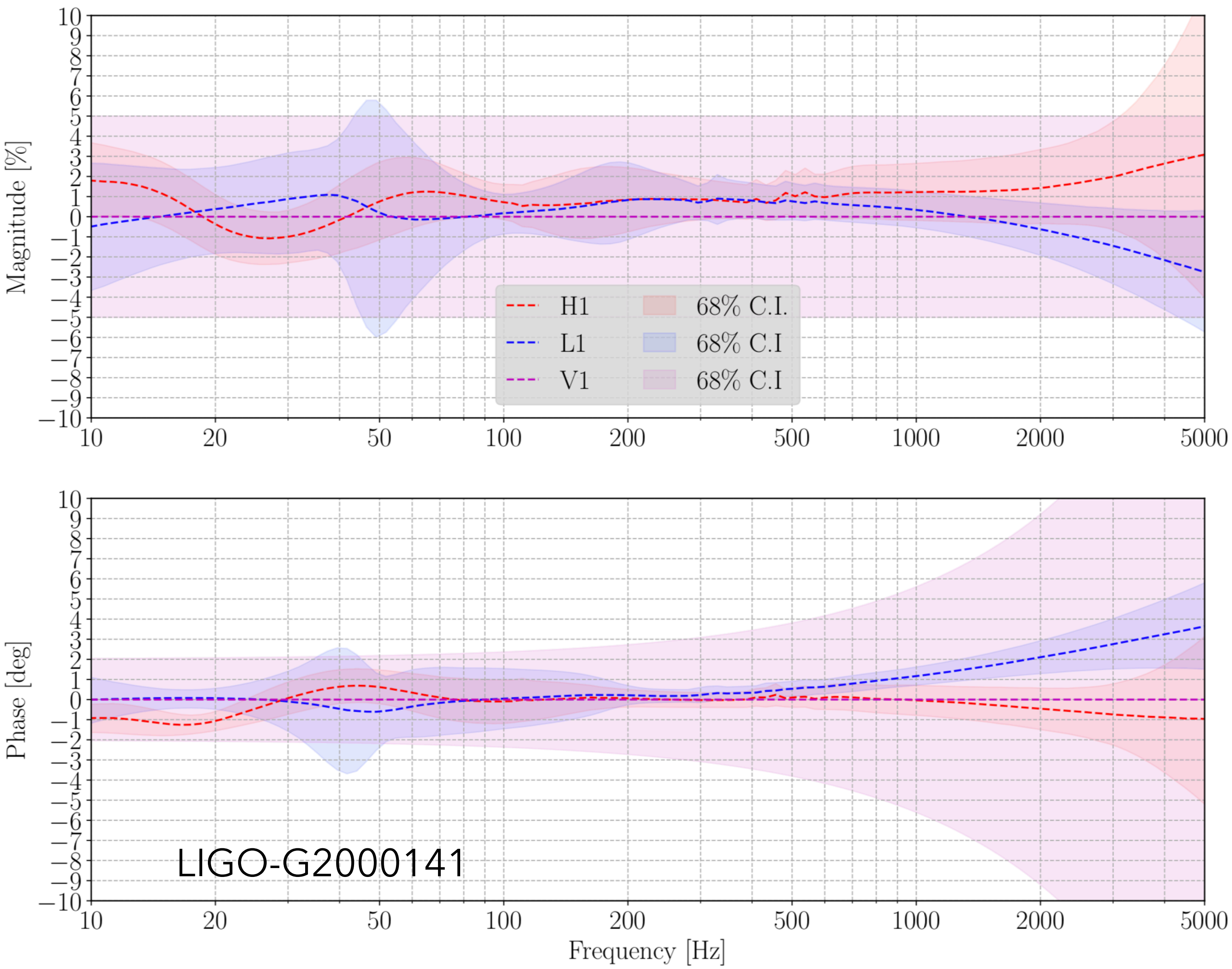


- Maximum excursion of the 1-sigma limits of systematic error and statistical uncertainty from unity magnitude/zero phase (20–1024 Hz):
  - Magnitude error: ~2-3 %
  - Phase error: ~2-3 deg
  - ~1% (mag) and ~1 deg (phase) in the most sensitive region (~100 Hz)

- Best results achieved in offline calibration (3 months after O2 ended) – time-dependent variations (TDCFs) were corrected

Calibration product in O3A

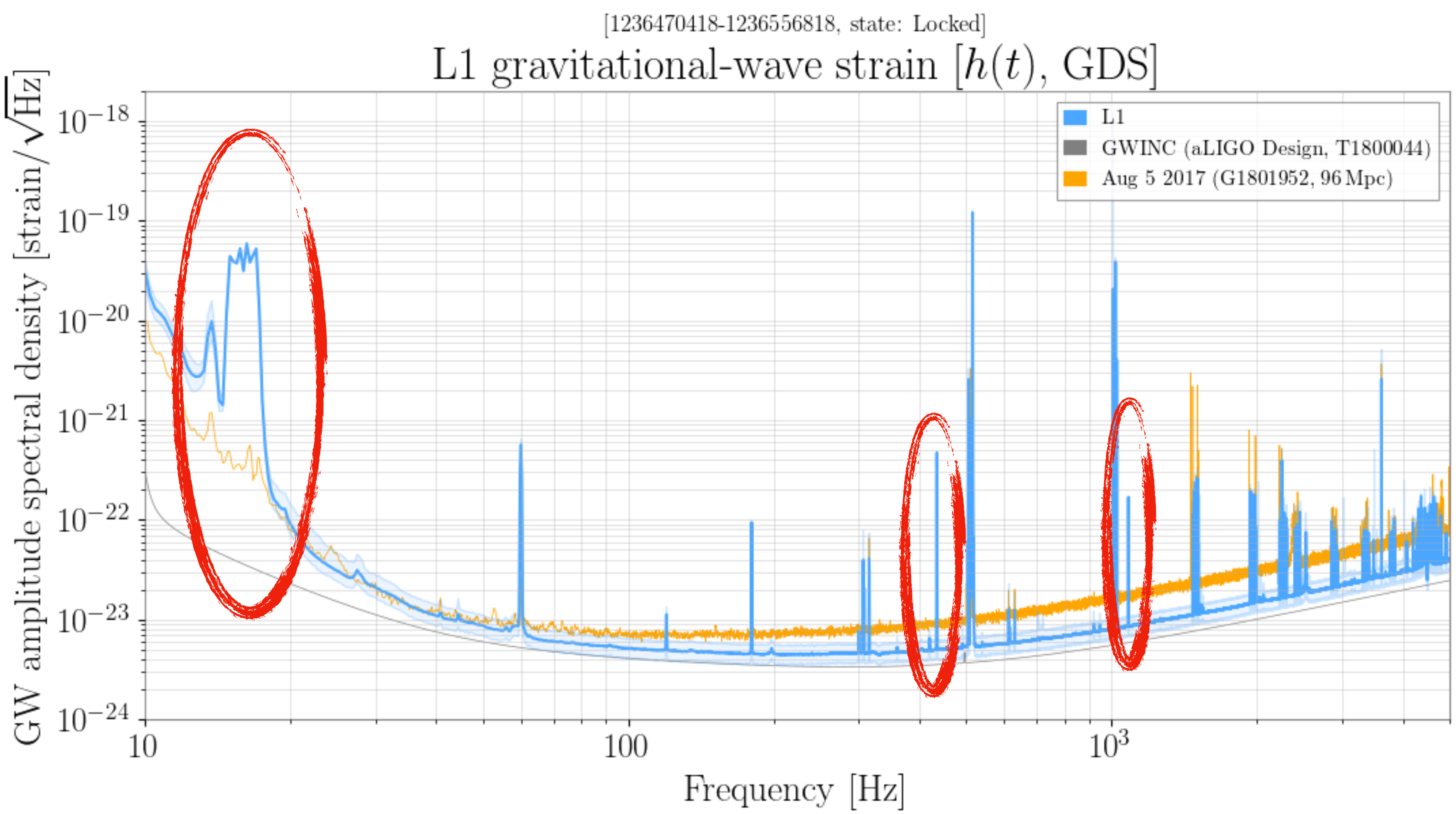
H L V



- Maximum excursion of the 1-sigma limits of systematic error and statistical uncertainty from unity magnitude/zero phase (20–1024 Hz):
  - Magnitude error: ~2-6 %
  - Phase error: ~2-3 deg
  - ~2% (mag) and ~2 deg (phase) in the most sensitive region (~100 Hz)

- Low-latency data quality has been improved (all TDCFs applied)
- Same level of precision and accuracy in the most sensitive band
- Remember that interferometers significantly changed from O2 to O3

Calibration lines moved to new frequencies

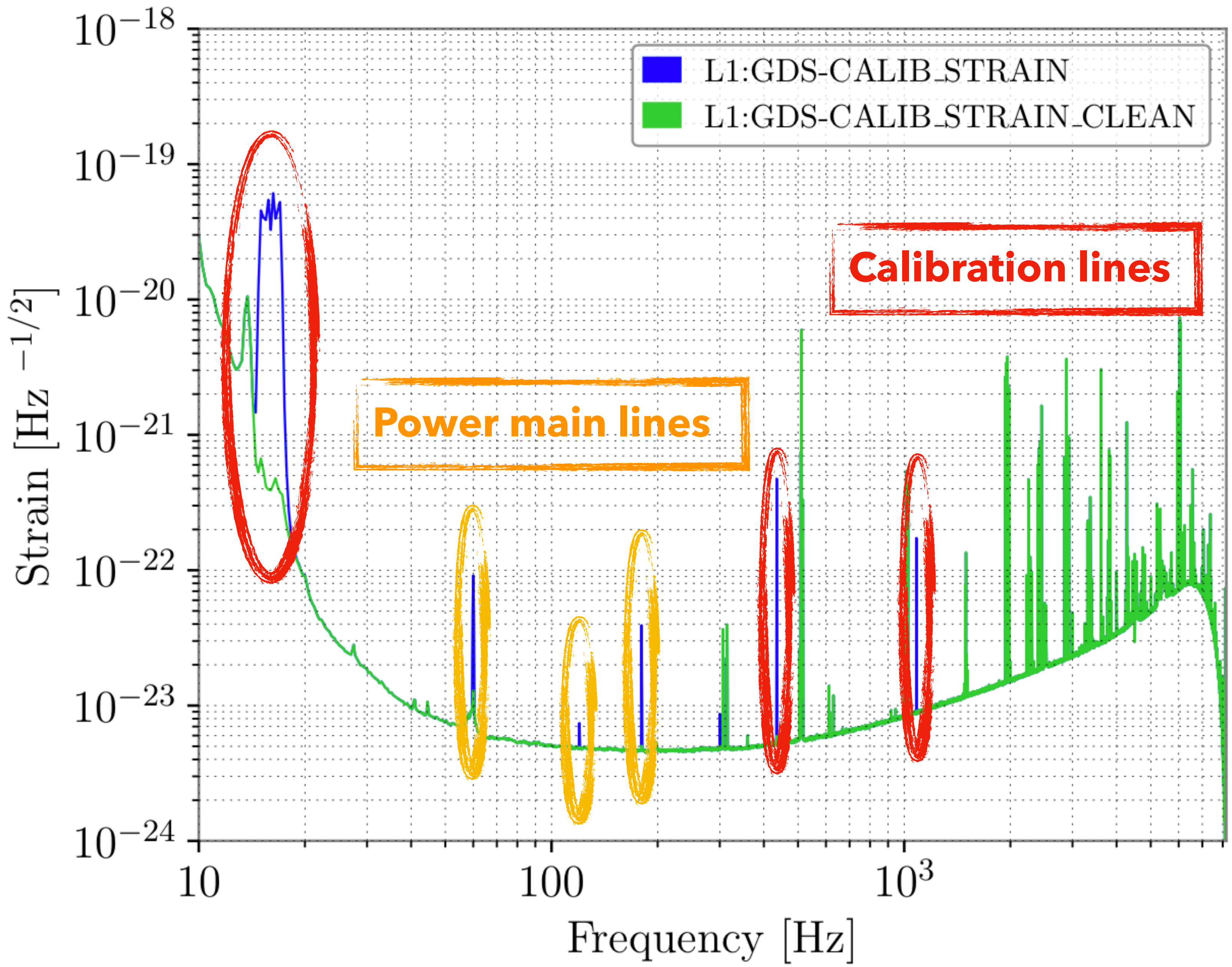


H1 Freq (Hz)	L1 Freq (Hz)
15.6	15.1
16.4	15.7
17.1	16.3
17.6	16.9
410.3	434.9
1083.7	1083.1

- Purpose:
  - Better characterize the new IFOs
  - Facilitate calculation of time-dependent correction factors
  - Move out of the most sensitive, astrophysically interesting band of the detectors
- Actuator lines (O2: H1 ~35, L1 ~15Hz) -> both IFOs to ~15 Hz for O3, out of astro-detection band
- Sensor line (O2: ~330 Hz) -> both IFOs to ~430 Hz
- Injected at different places in the DARM loop for different purposes

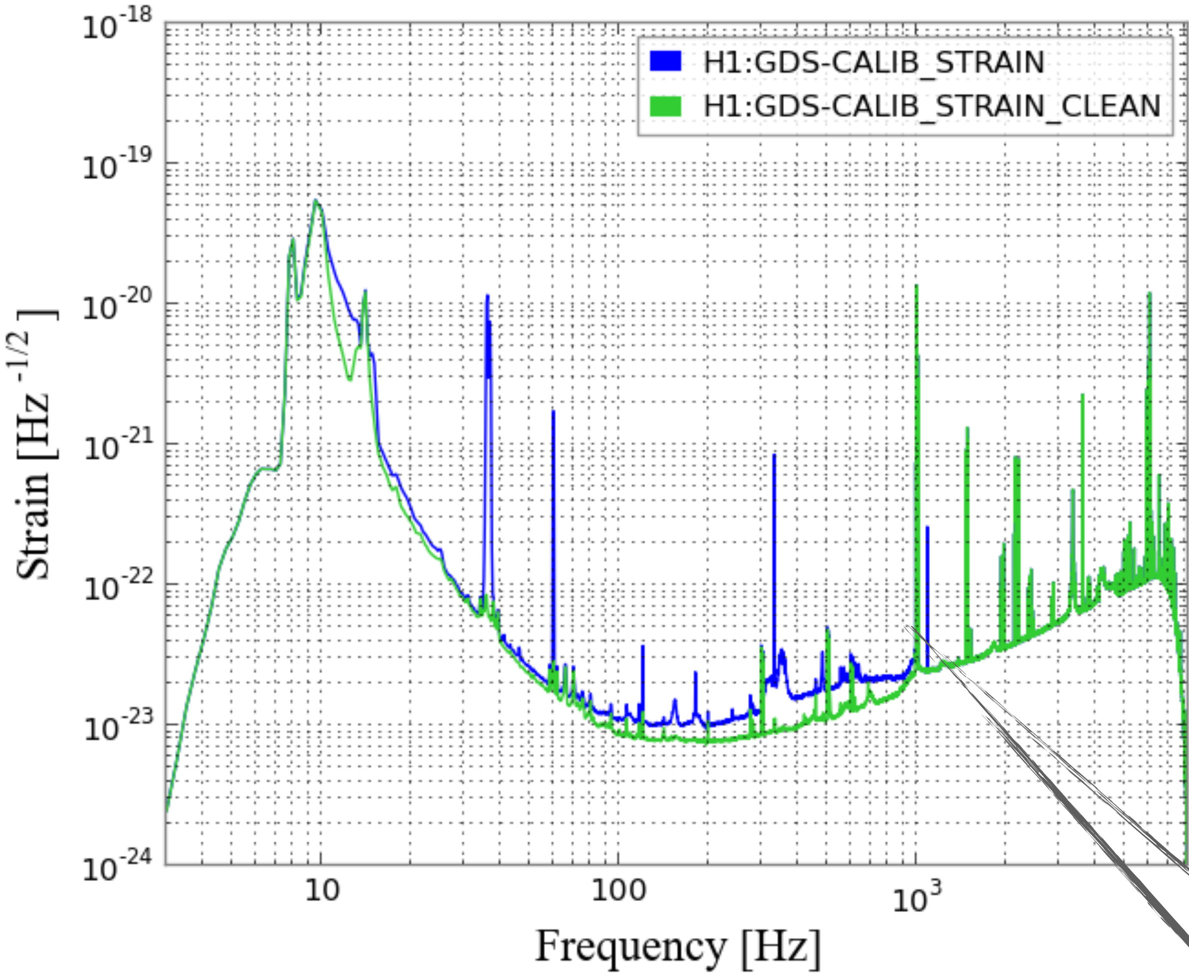
Low-latency Line Subtraction

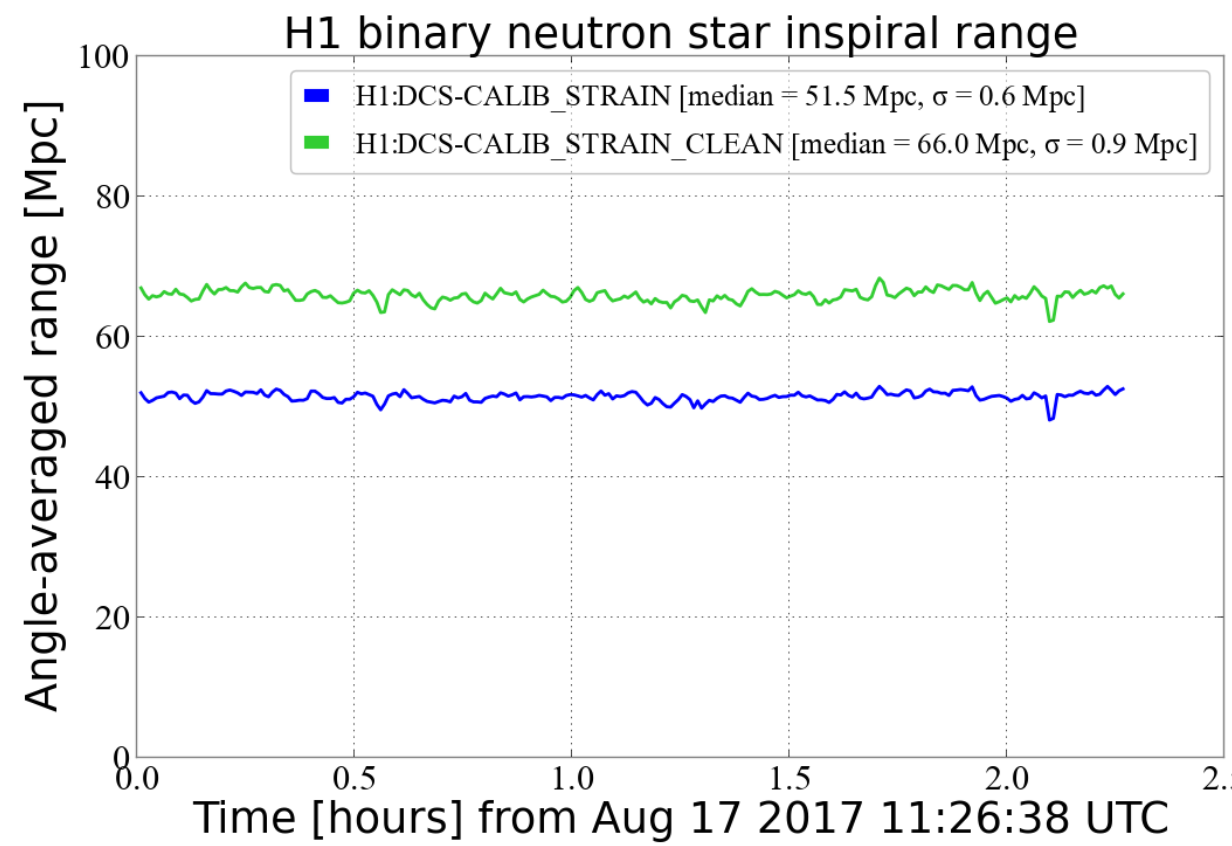
- Additional channel in C00 frames: GDS-CALIB_STRAIN_CLEAN
- Calibration lines and power main lines are subtracted (power main line subtraction is not perfect)
- Line subtraction is done in low latency
- Negligible impact on calibration latency



A. Viets, G1801495

Future: Low-latency Noise Subtraction

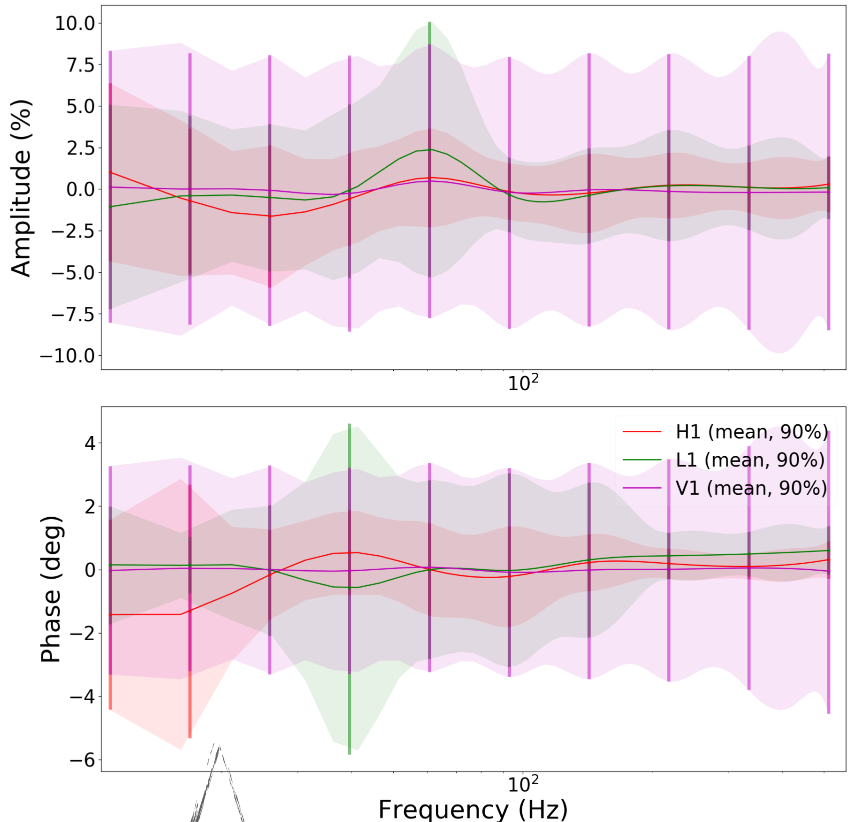




- Low-latency broadband noise subtraction – code frame available
- Similar methods to DetChar's subtraction done in O2
- Require witness channel

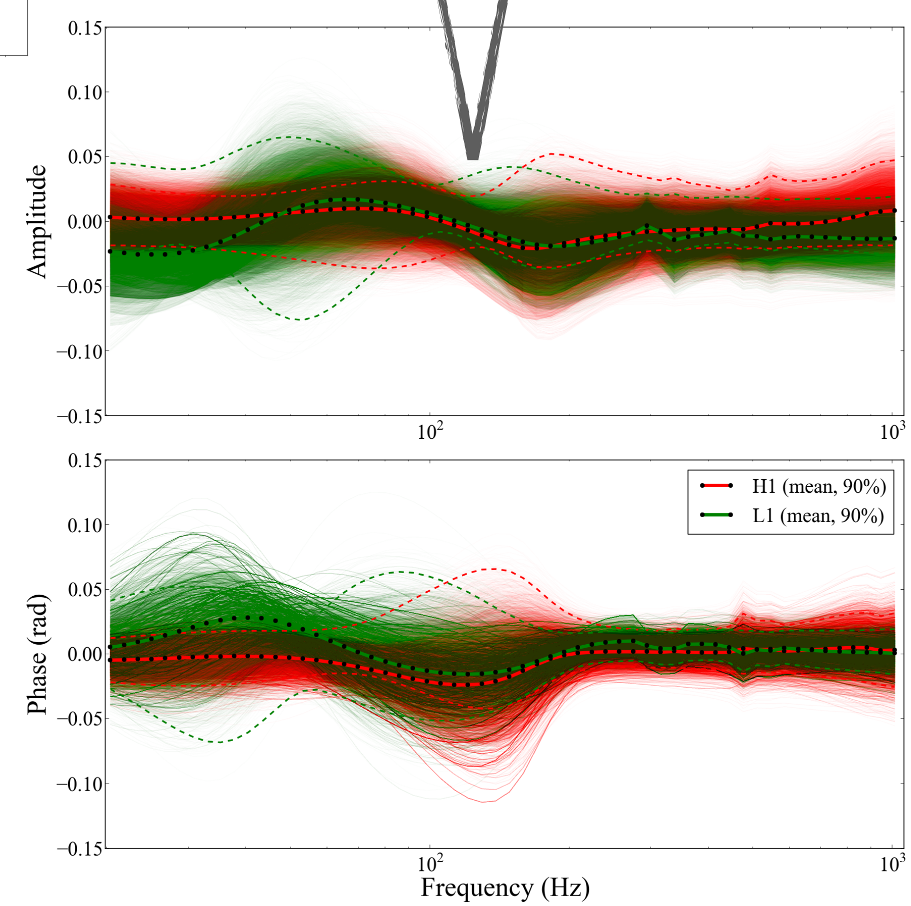
- Example: at time ~GW170817 (excess jitter noise)
- BNS range increases by 28%
- Total detectable volume increases by 110%
- In O3, impact has been small

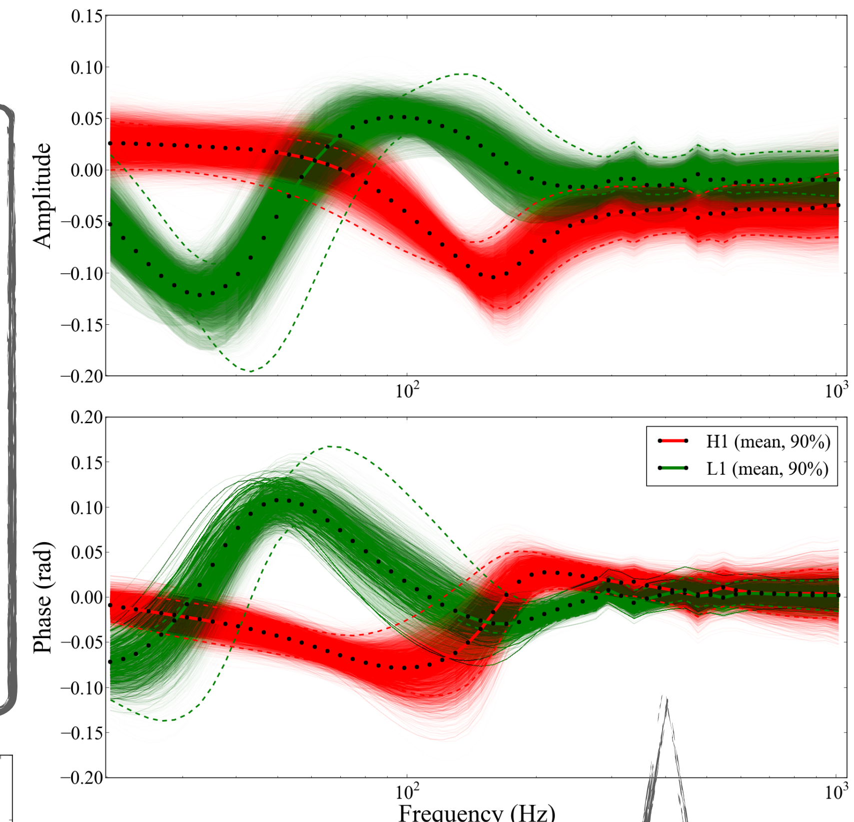
Future: Astrophysical calibration



- Have been using calibration error budget produced by calibration team as a spline in CBC parameter estimation

- Directly use the samples of detector response function (drawn from calibration parameters) as CBC PE input, estimating astrophysical and calibration parameters at the same time.





- Could larger number of loud events tell us what's wrong in our detector calibration? (assuming waveforms are correct)

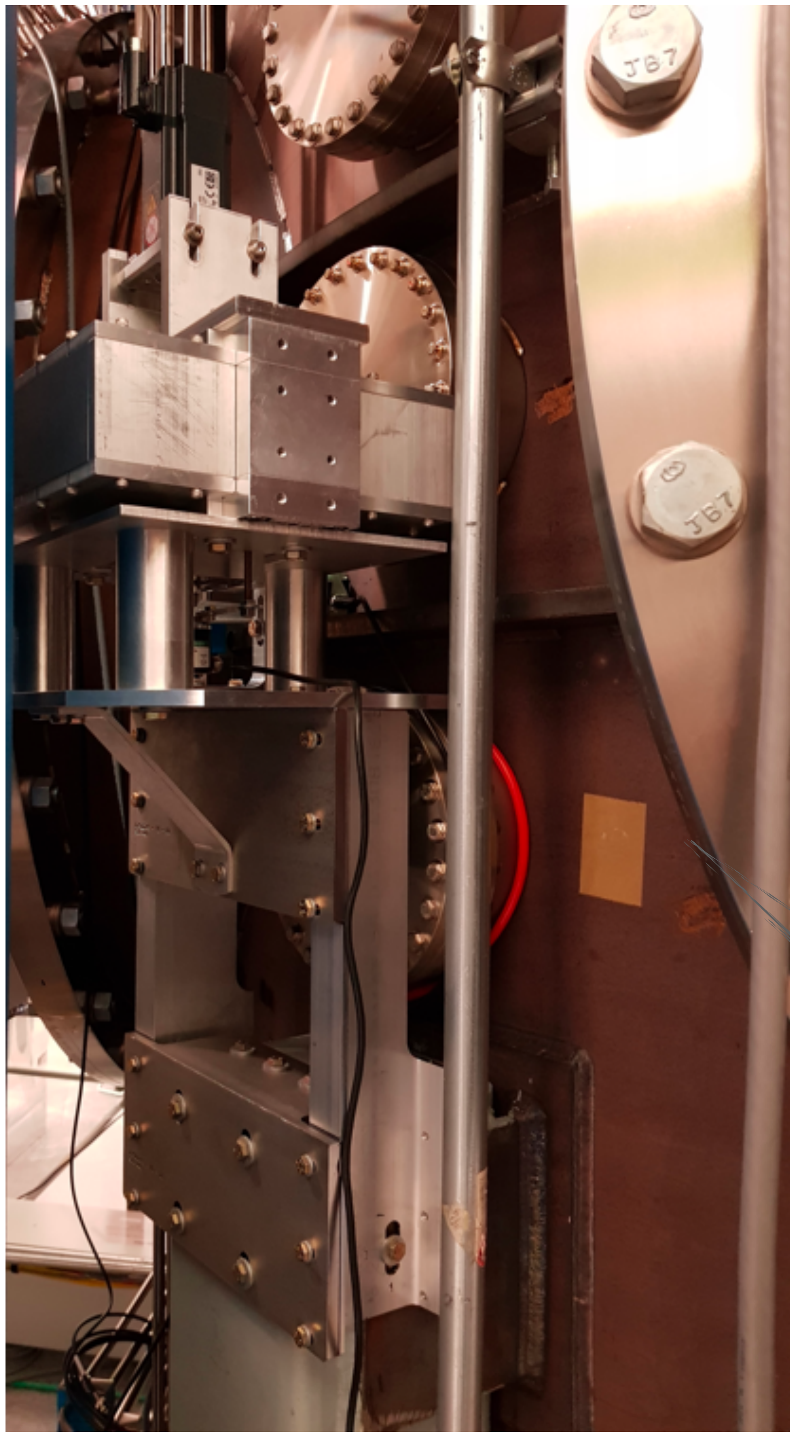
Vitale, Haster, Farr, Payne, Goetz, Hulko, Kissel, Sun

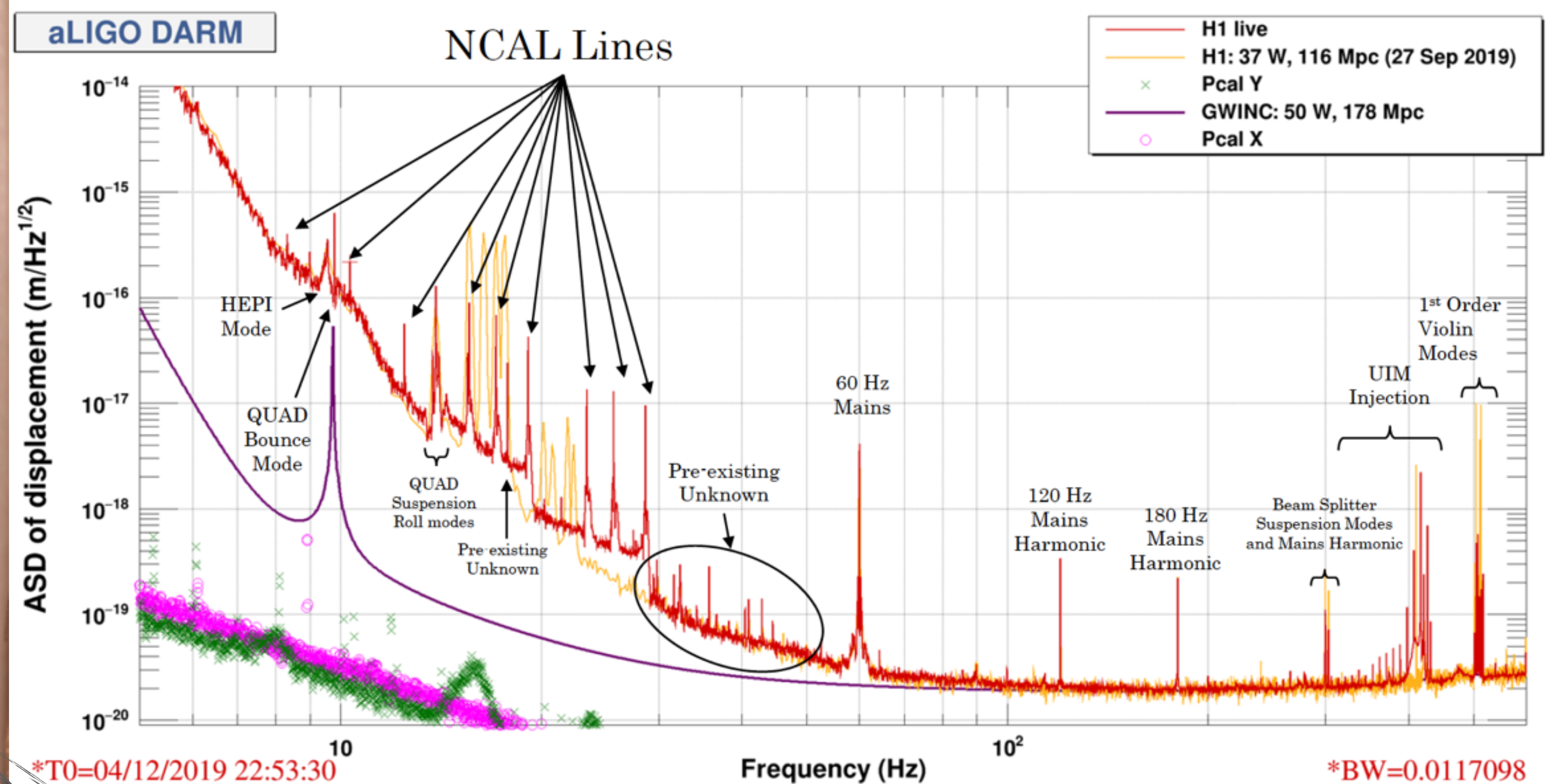
- Existing work about astrophysical calibration: Essick & Holz, CQG 36, 12, 125002 (2019)

Future: better accuracy and precision is required

- Determine the calibration accuracy and precision requirements for future generations of detector network (SNR ~100)
- Quantify the impact of calibration accuracy and precision on astrophysical interpretations, e.g., non-GR physics
- Further improve the absolute reference uncertainty of photon calibrator (already 0.54%)
- Investigate and remove sub-percent systematic errors
- Correct for the high-frequency effects (> 2kHz) caused by the approximation of the detector’s response

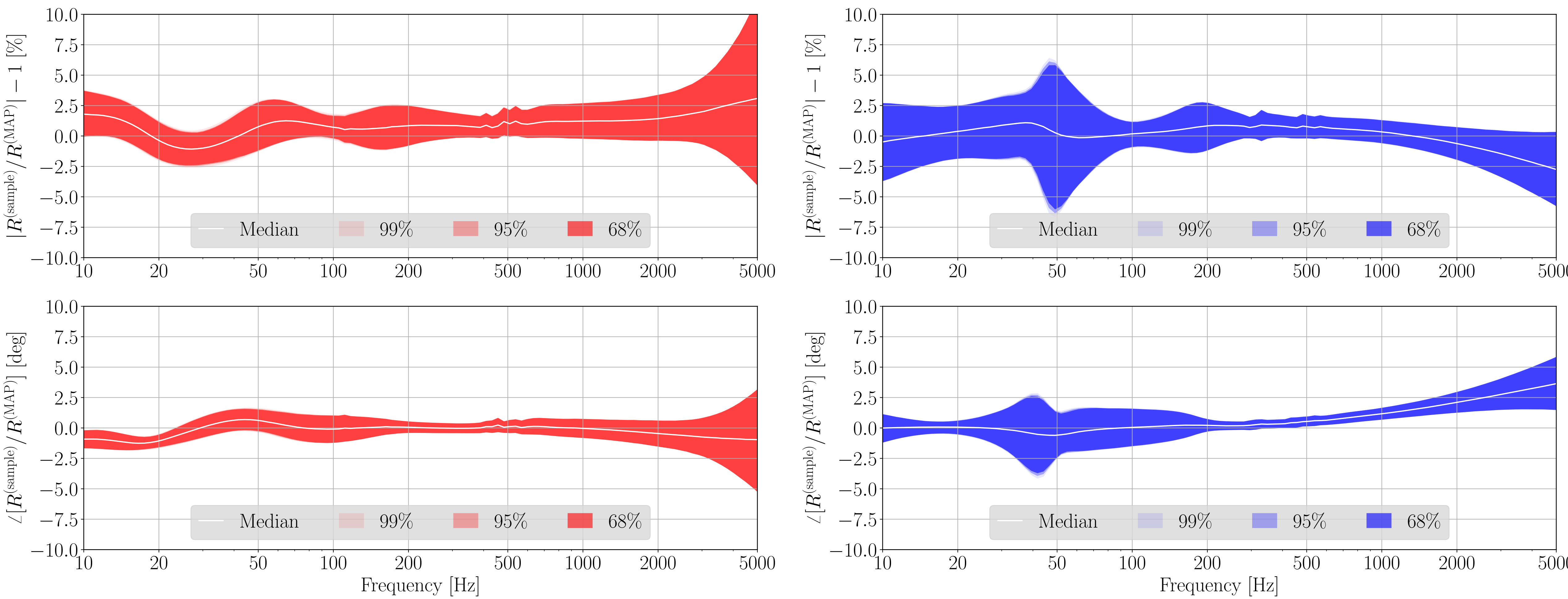
New techniques: Newtonian calibrator





- Prototype is installed and characterized at Hanford
- NCAL line sweep is seen as expected in DARM

Summary

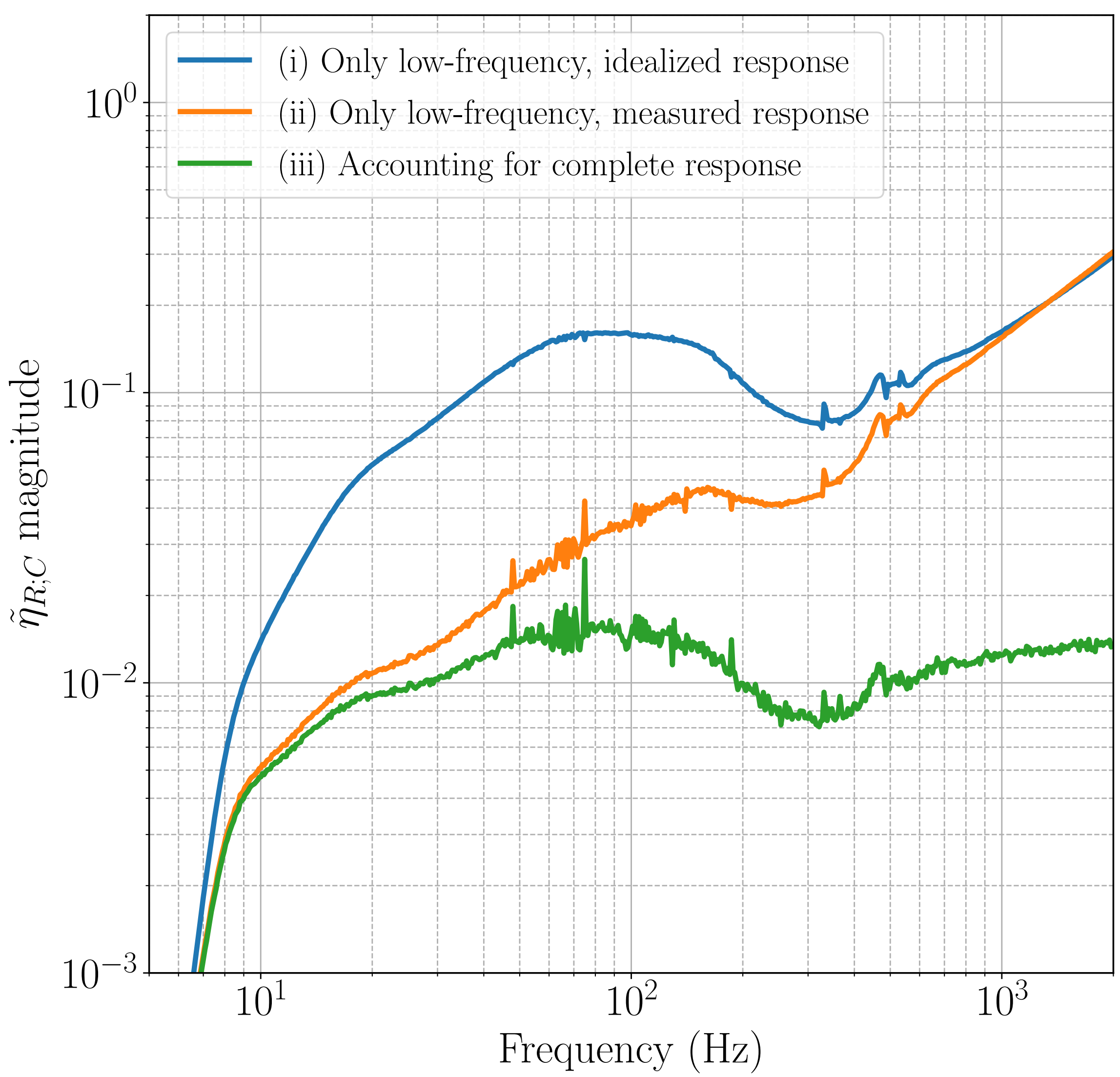


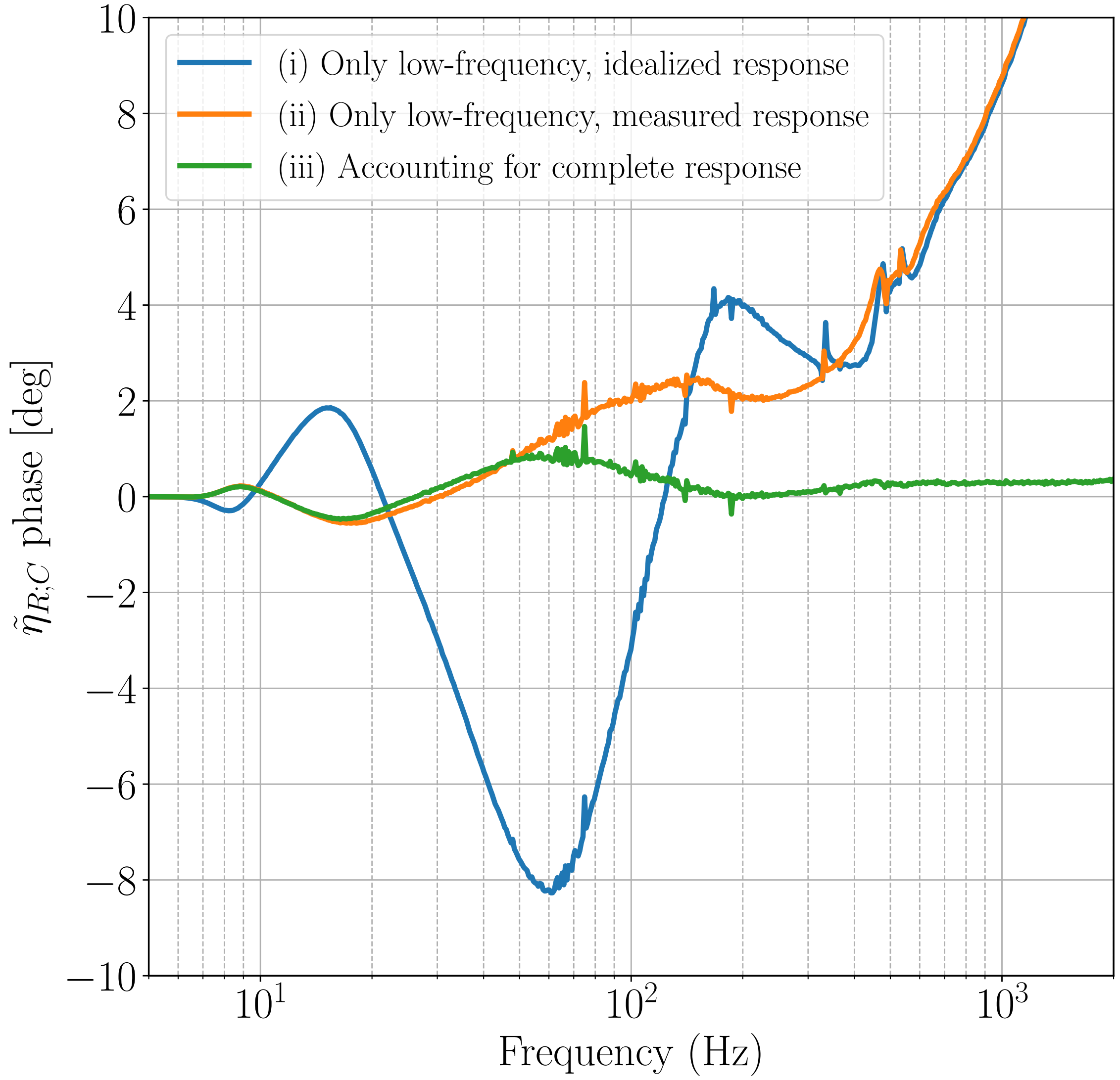
- O3a overall calibration uncertainty (20–2000 Hz):
  - < 7% in magnitude
  - < 4 deg in phase
- Systematic error alone (20–2000 Hz):
  - < 2% in magnitude
  - < 2 deg in phase

Thanks! Questions?

Backup Slides

Understanding the behavior of electronics





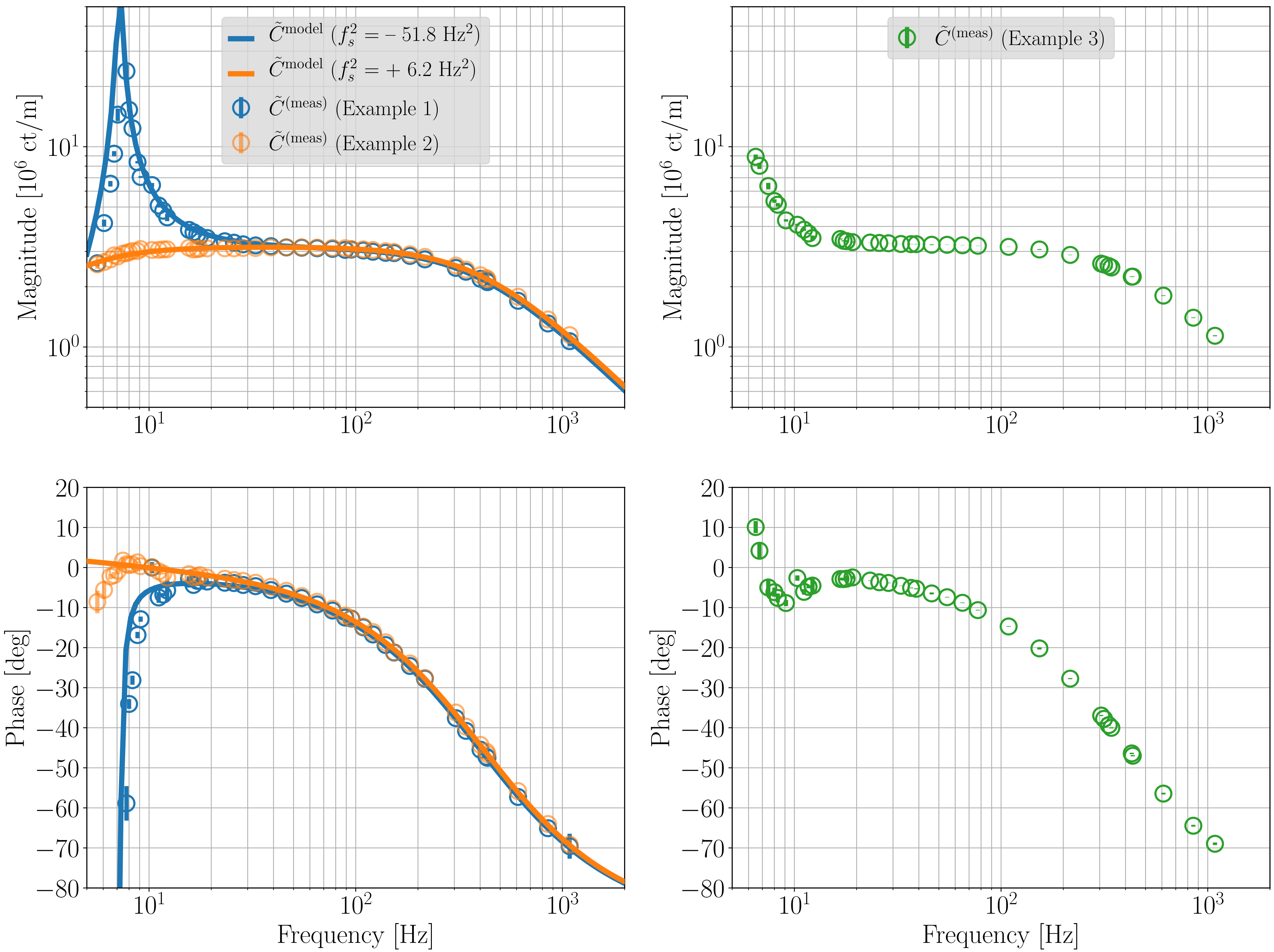
How good is good enough?

Evaluate residual contribution

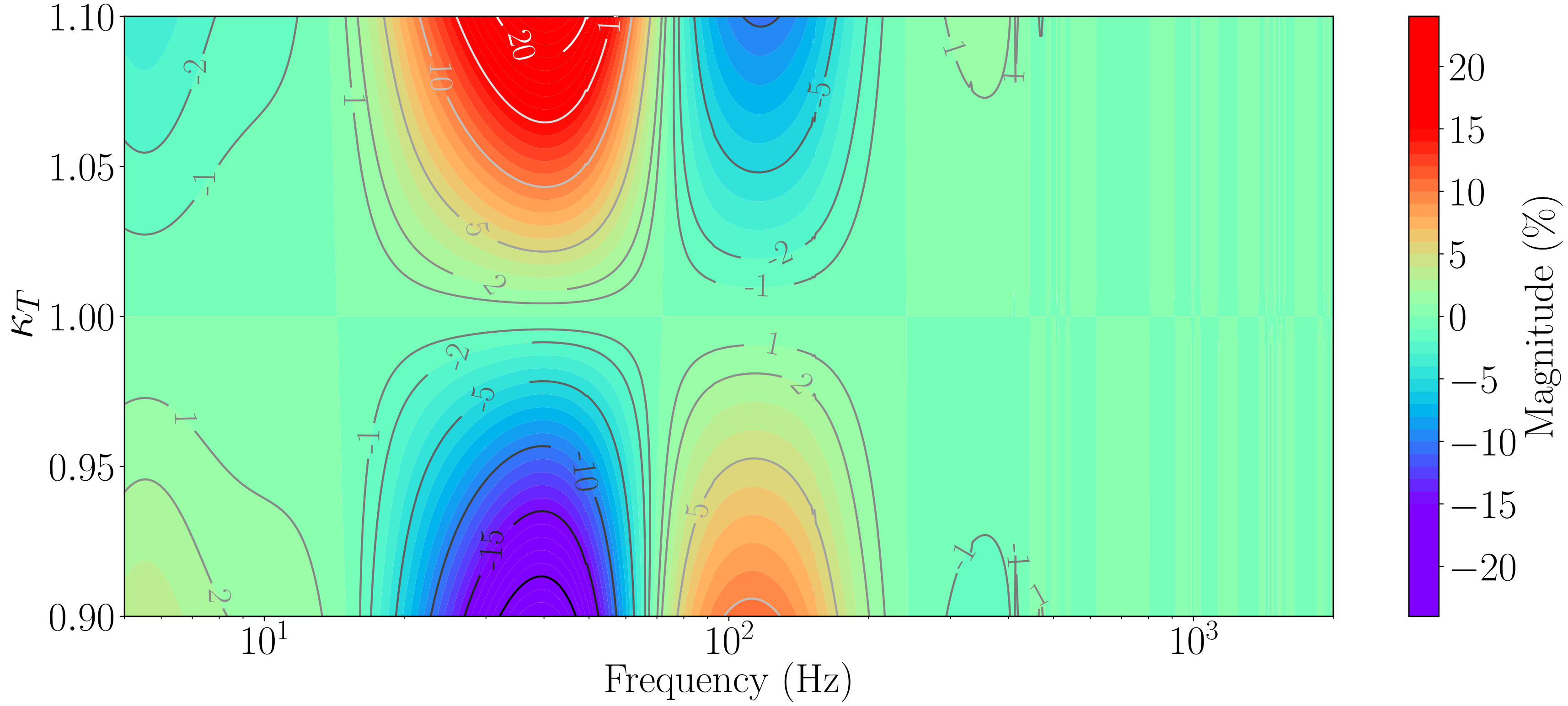
$$\tilde{R}(f) = \frac{1}{\tilde{C}(f)} + \tilde{A}(f)\tilde{D}(f)$$

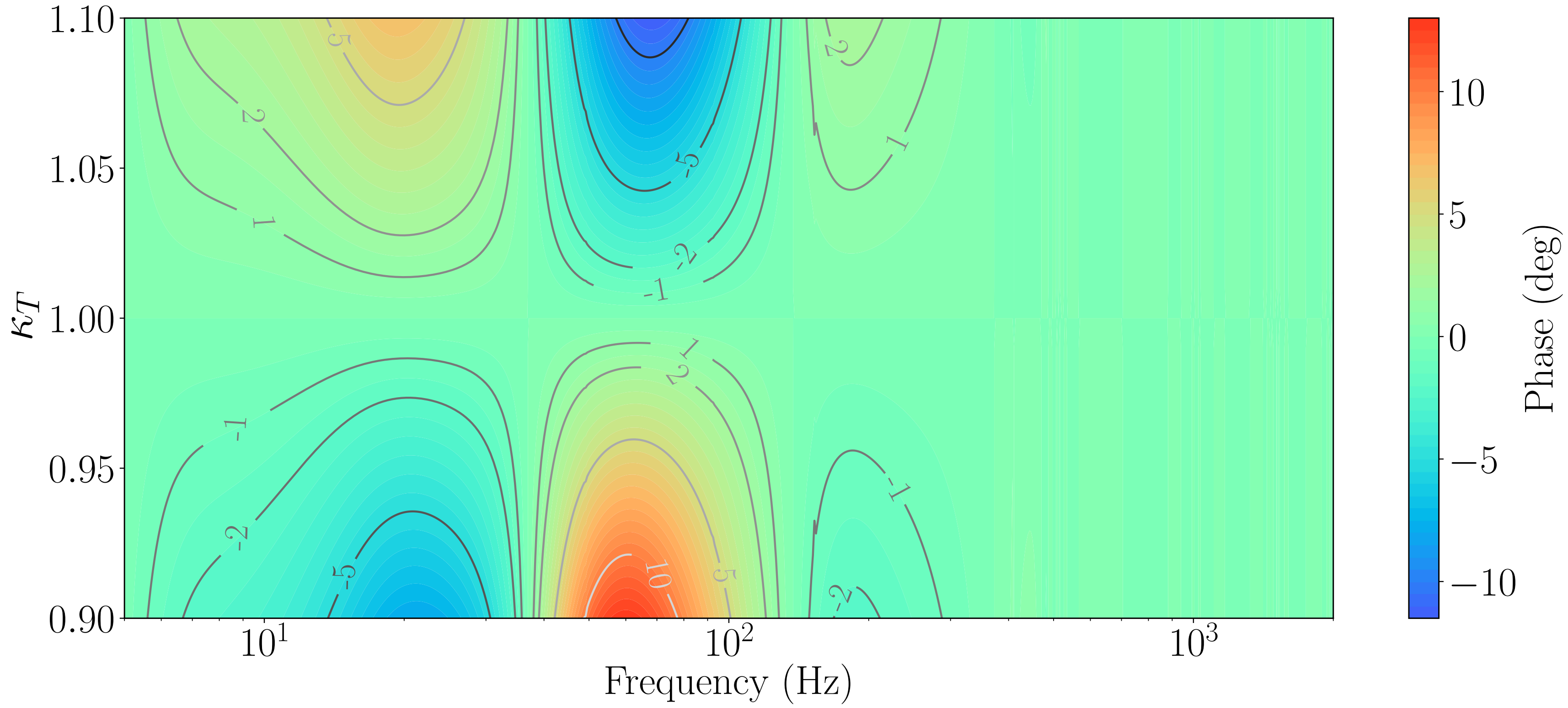
$$\tilde{\eta}_{R;C} = \frac{1}{\tilde{R}^{(\mathrm{model})}}\left[\frac{1}{\tilde{\eta}_C \tilde{C}^{(\mathrm{model})}} + \tilde{A}^{(\mathrm{model})}\tilde{D}\right]$$

O3A sensing function measurements at H1



Impact from H1 TST





Verify the uncertainty budget envelope