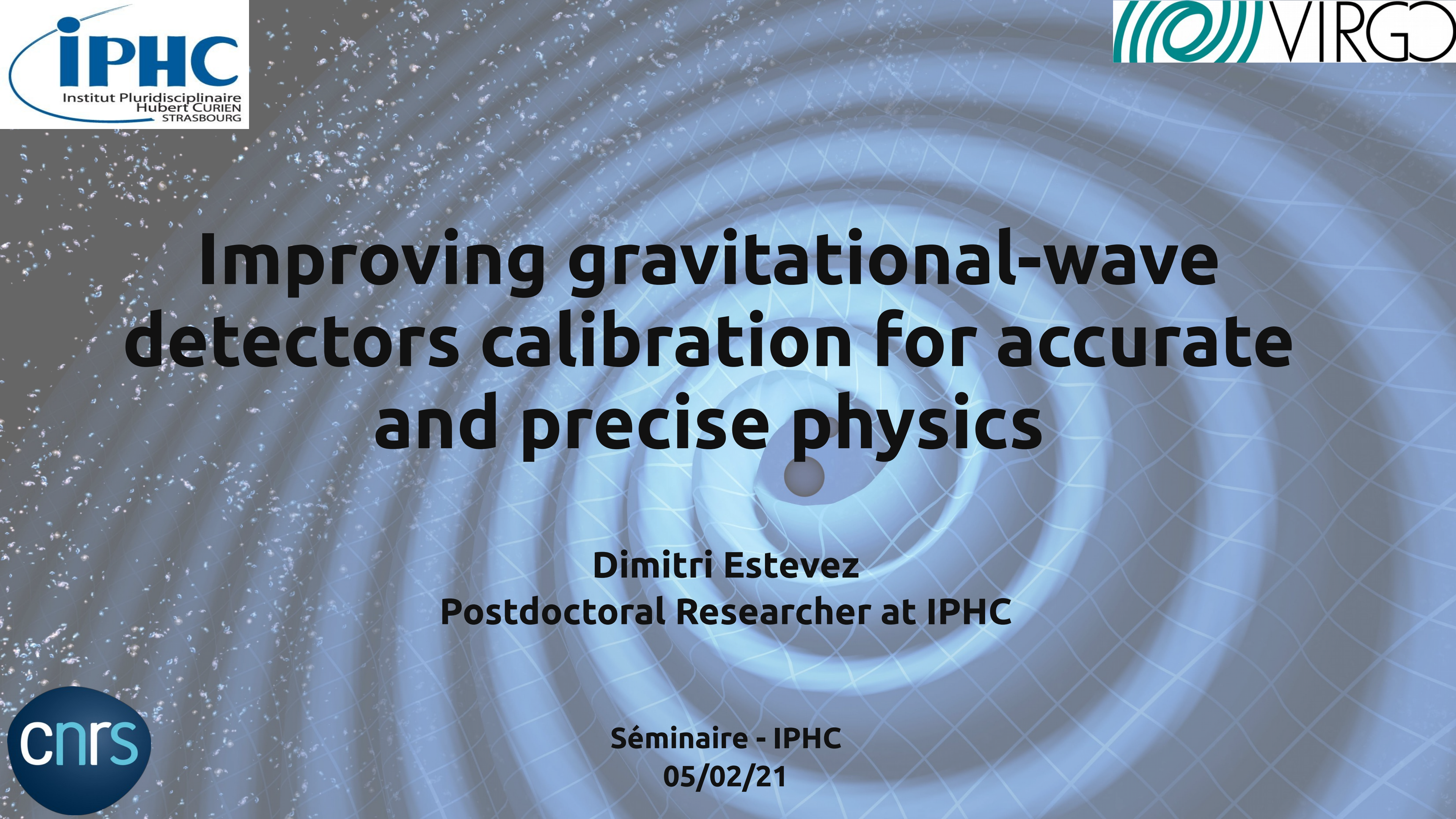


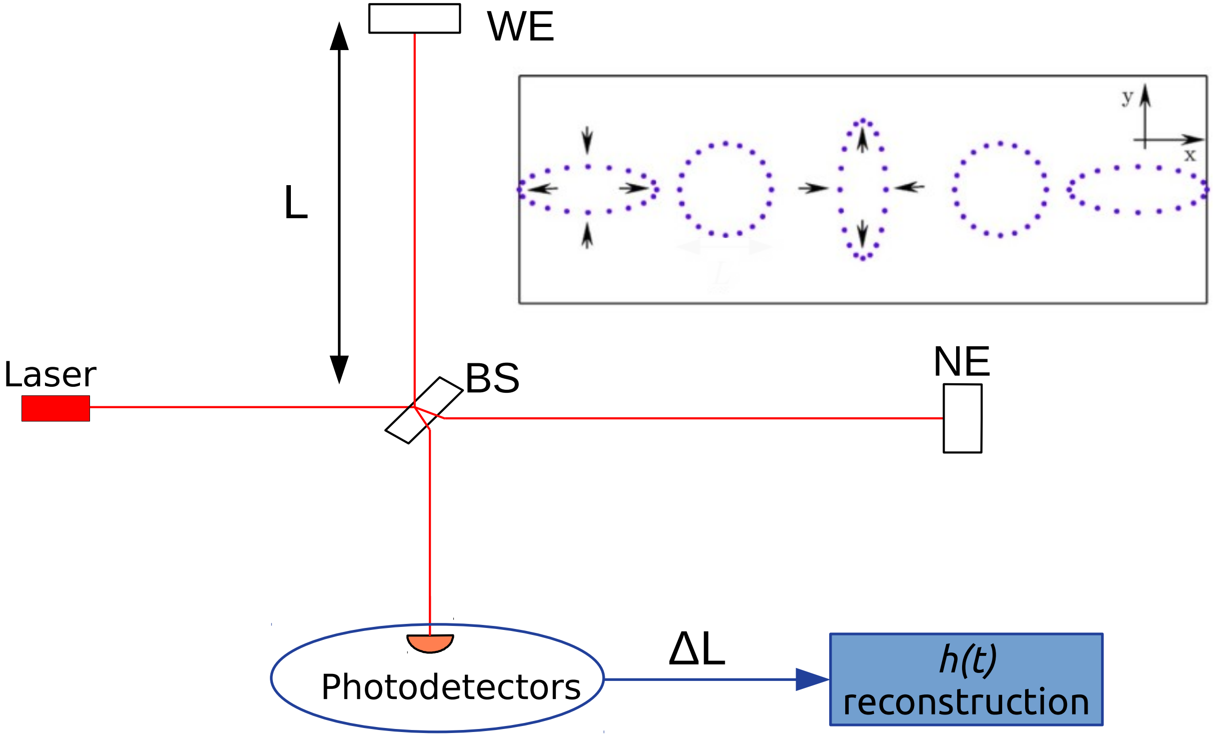
Improving gravitational-wave detectors calibration for accurate and precise physics

Dimitri Estevez
Postdoctoral Researcher at IPHC

Séminaire - IPHC
05/02/21

Gravitational waves detection

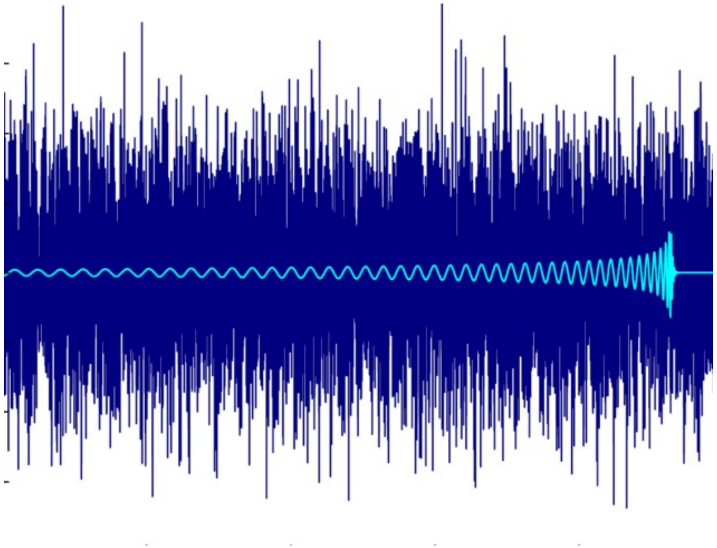
Virgo detector, Cascina, Italy



Gravitational wave amplitude: $h = \frac{\Delta L}{L}$

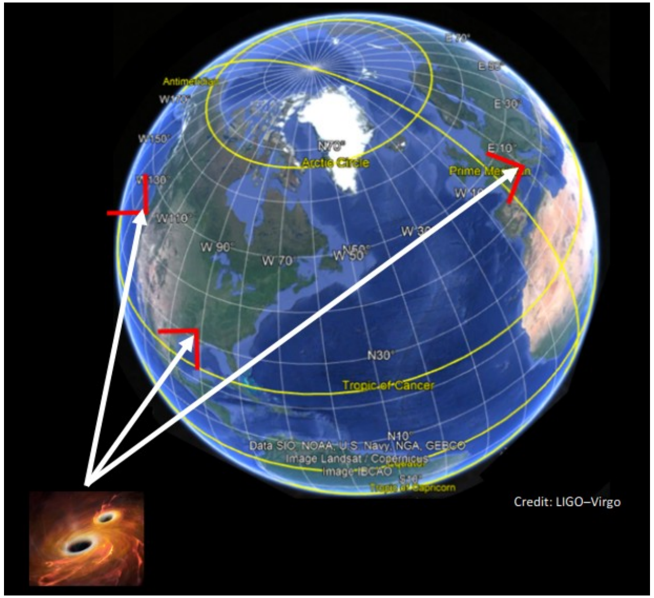
Searching for gravitational waves

Compact Binary Coalescence analysis:
Matched filtering



- Following the GW signal in time and in frequency
- Data of detectors network need to be calibrated from ~20 Hz to ~2 kHz

Sky localization



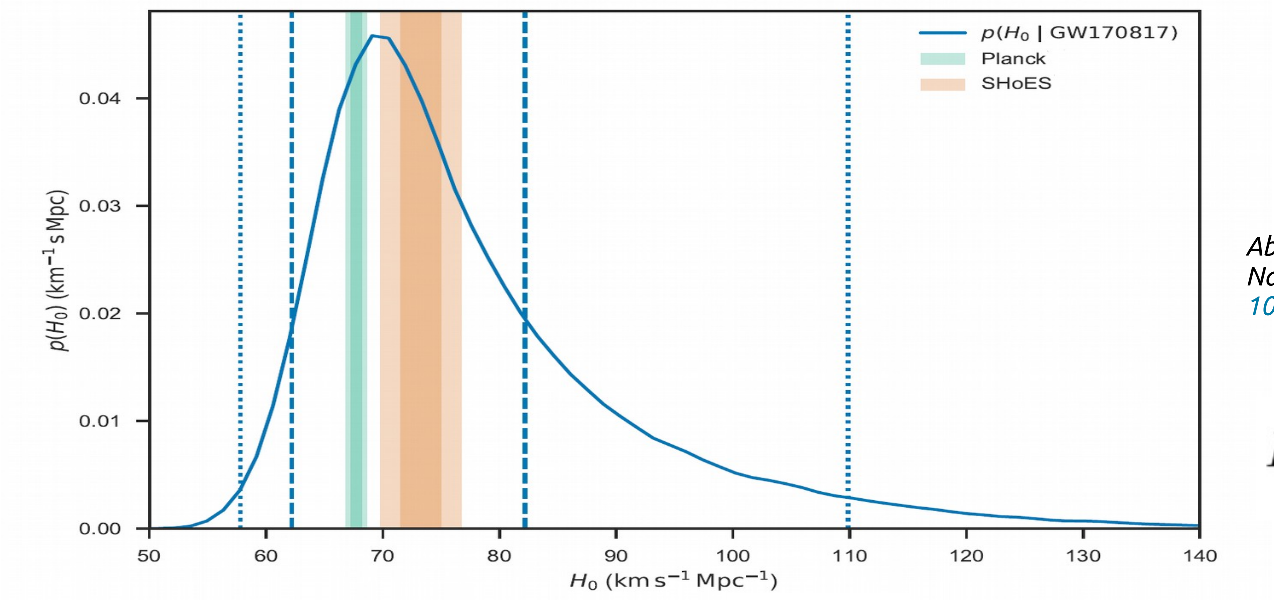
Credit: LIGO–Virgo

- Absolute intercalibration of the detectors network in amplitude
- Absolute timing reference between the detectors

Getting the Hubble constant right

Many results from GW detections, one example:

Hubble constant with GW170817



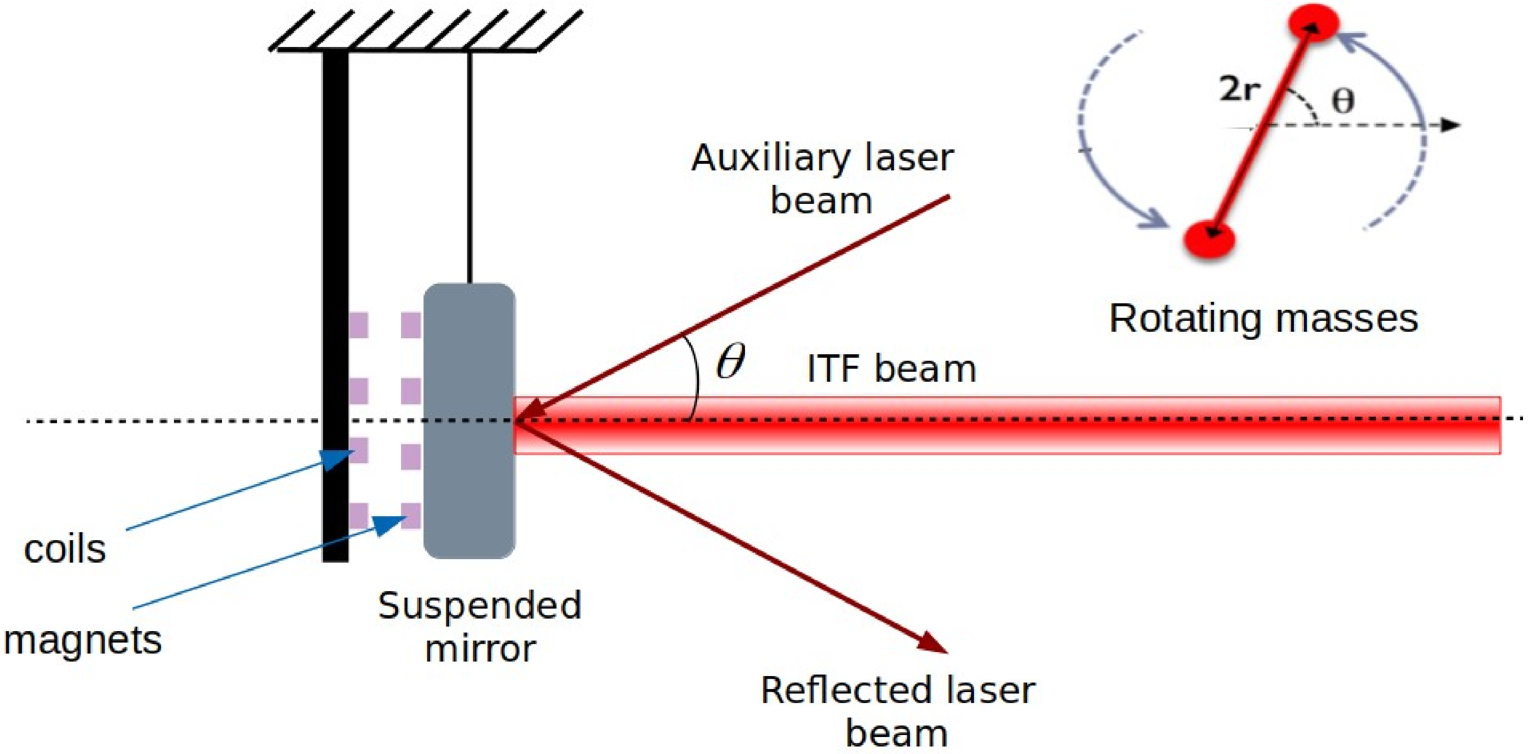
Abbott et al. 2017, Nature, *10.1038/nature24471*

$$H_0 = \frac{cz}{d_L}, \quad z \ll 1$$

- Precise measurements of the luminosity distance: $h \propto d_L^{-1}$
- Other part of my work: Classification of GW events to predict possible electromagnetic counterpart

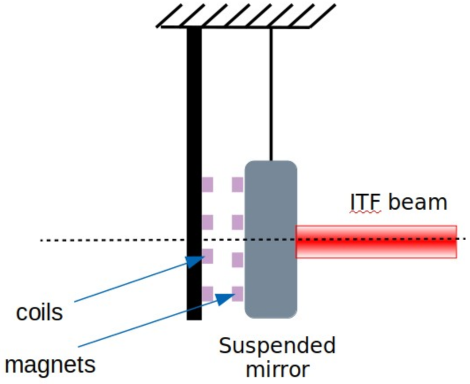
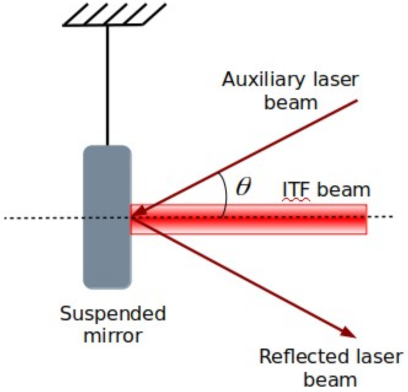
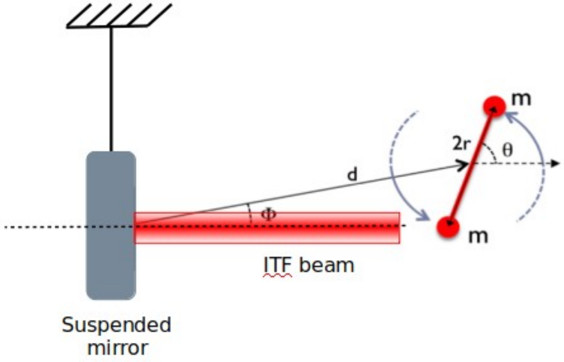
Three types of actuators to move the mirrors

Calibration method: compare a known mirror motion with the reconstructed motion



Three types of actuators to move the mirrors

Calibration method: compare a known mirror motion with the reconstructed motion

Electromagnetic actuator (EM)	**Photon calibrator** (PCal)	**Newtonian calibrator** (NCal)
		
Method: → Electromagnetic force	Method: → Radiation pressure	Method: → Variations of the local gravitational field
Calibration reference: → ITF laser wavelength	Calibration reference: → *Absolute* laser power	Calibration reference: → Gravitational Constant G
Actuation range: → ~10 Hz to ~1 kHz	Calibration range: → ~10 Hz to ~10 kHz	Calibration range: → ~10 Hz to ~200 Hz (maybe more)

Photon Calibrator (PCal)

From laser power to force:

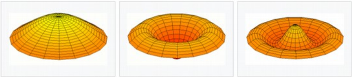
$$F(f) = \frac{2\cos(\theta)}{c} P_{ref}(f)$$

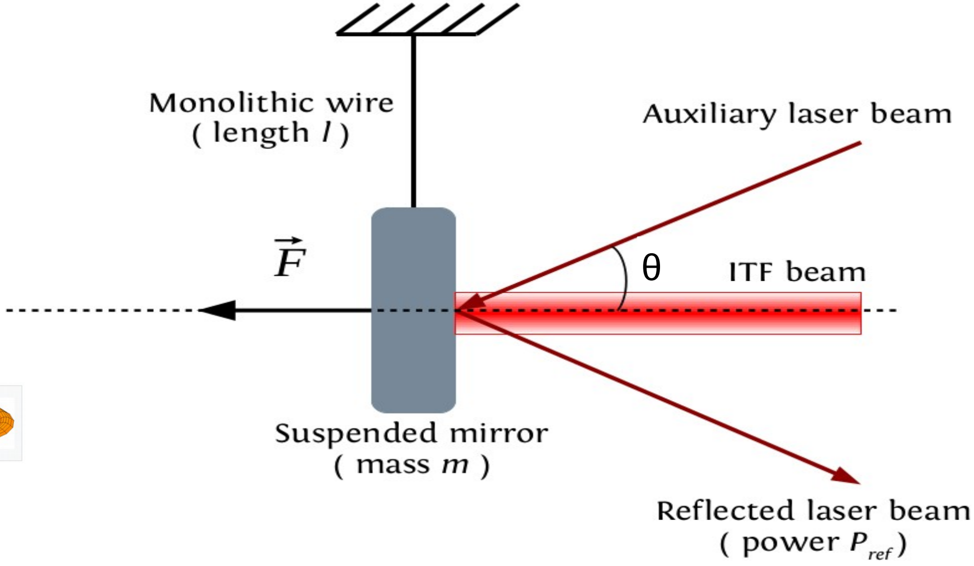
From force to mirror motion:

$$x(f) = \left[-\frac{1}{m(2\pi f)^2} + H(f) \right] . F(f)$$

Simple pendulum

Elastic deformations



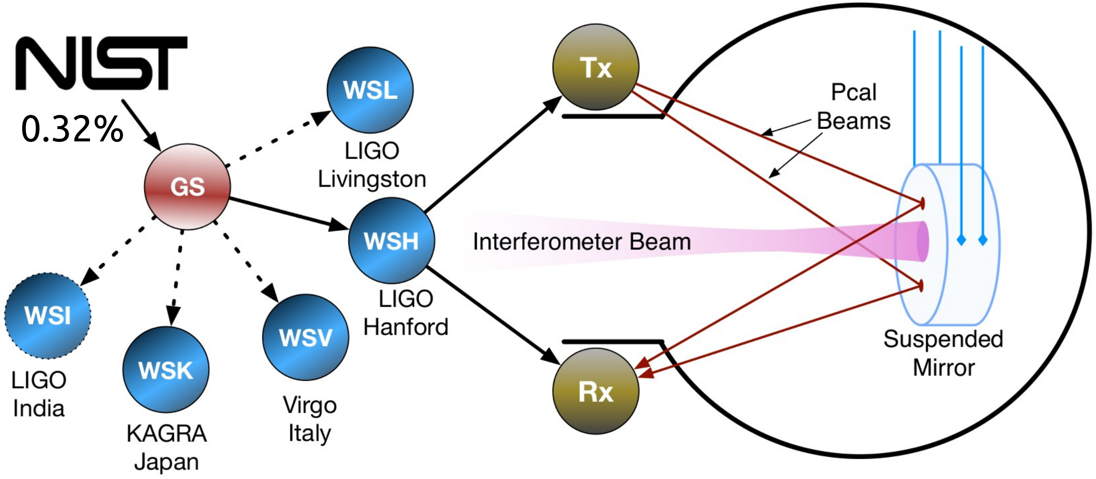


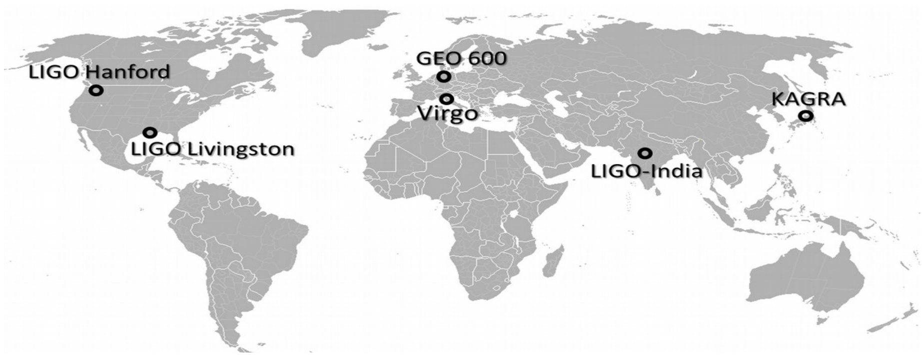
Power reflected by the mirror (~ 2W):

- Use photodiodes to read the laser power
- Photodiodes are calibrated with an integrating sphere (our reference photodetector)
- Calibration sensitive to temperature and humidity variations
- Online monitoring during O3

Does Virgo photodetector measure the same laser power as LIGO photodetectors?

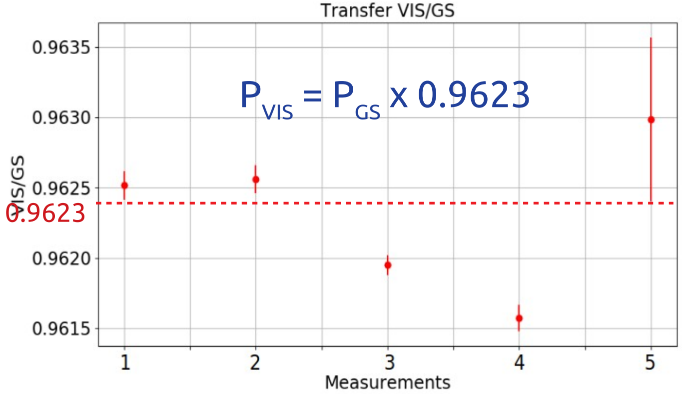
Worldwide intercalibration





Calibration transfer at LIGO Hanford between Virgo Integrating Sphere and Gold Standard

P_{VIS} has to be corrected by +3.92%



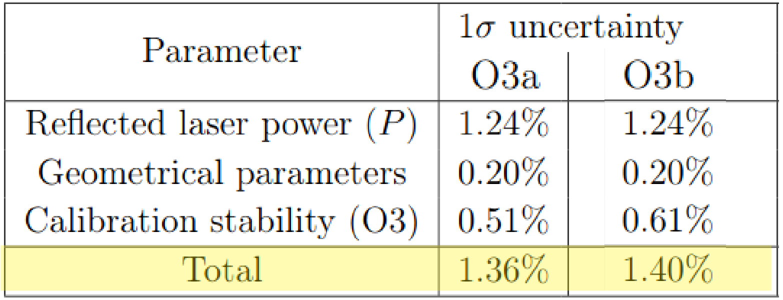
$P_{VIS} = P_{GS} \times 0.9623$

0.2%

Only stat. errors

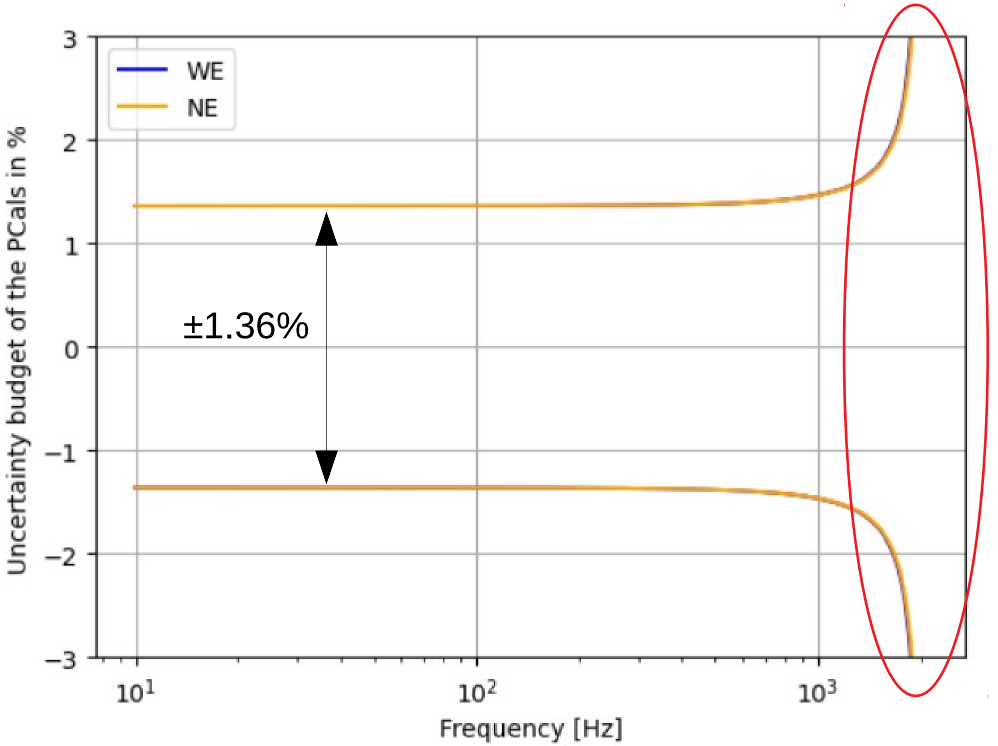
Uncertainty on PCal-induced mirror motion

Estevez et al., 2021, The Advanced Virgo Photon Calibrators, accepted in *Classical and Quantum Gravity*, DOI: 10.1088/1361-6382/abe2db



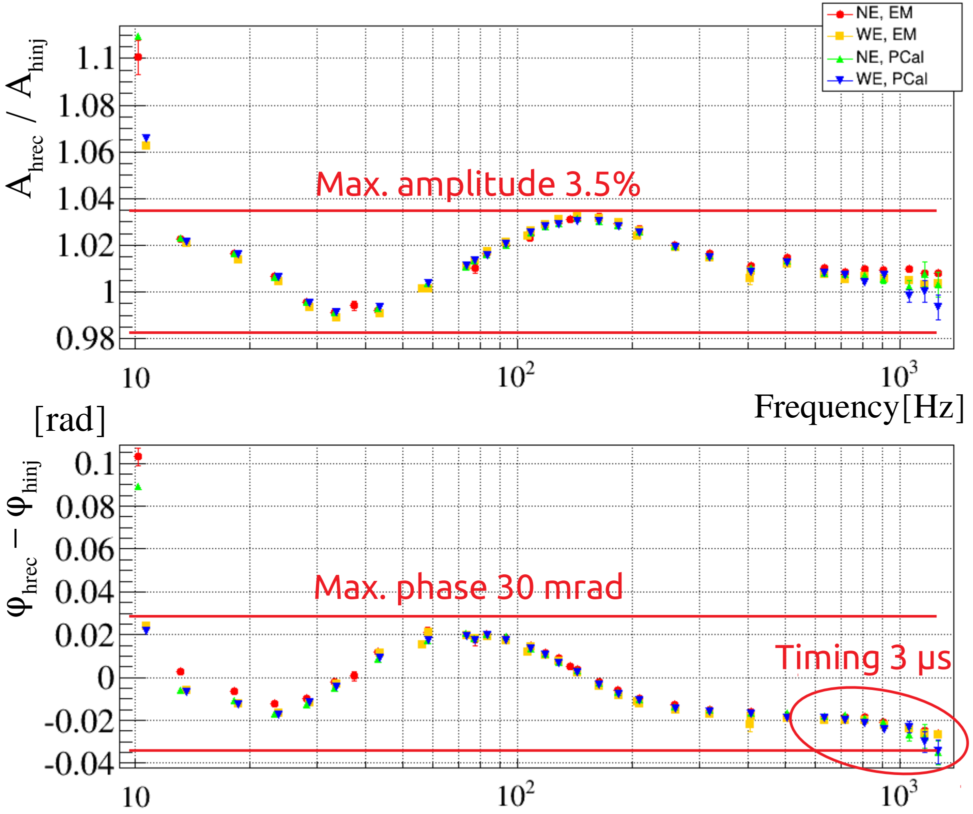
Parameter	1σ uncertainty	
	O3a	O3b
Reflected laser power (P)	1.24%	1.24%
Geometrical parameters	0.20%	0.20%
Calibration stability (O3)	0.51%	0.61%
Total	1.36%	1.40%

From 10 Hz to 1 kHz



Elastic deformations effect

Checking the reconstructed *h(t)*



Max. amplitude 3.5%

Max. phase 30 mrad

Timing 3 µs

Paper in preparation on behalf of Virgo collaboration

Adding uncertainty from calibration steps:

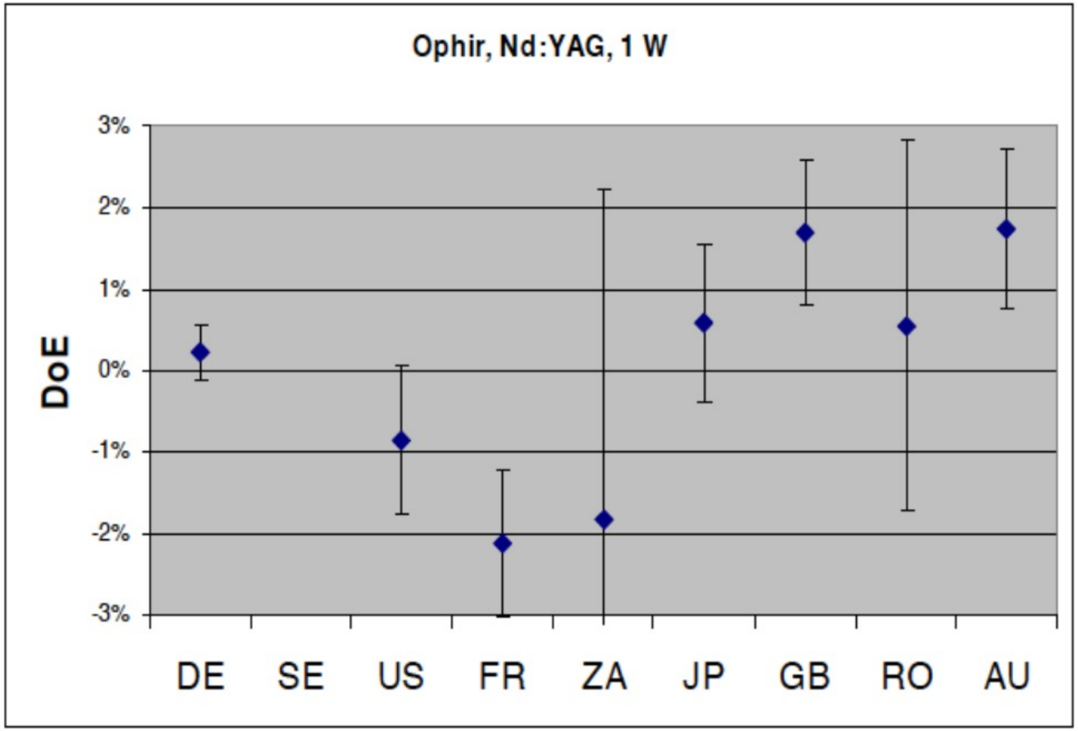
- Amplitude uncertainty → **δA = ±5%**
- Phase uncertainty → **δΦ = ±35 mrad**
- Timing uncertainty → **δτ = ±10 µs**

Uncertainties provided on online *h(t)* during O3 are good:

- **SNR events in Virgo < 8**
- **Uncertainty from the searches scales as $(SNR)^{-1}$**

Absolute laser power calibration?

1 Watt in France = 1 Watt in the US?



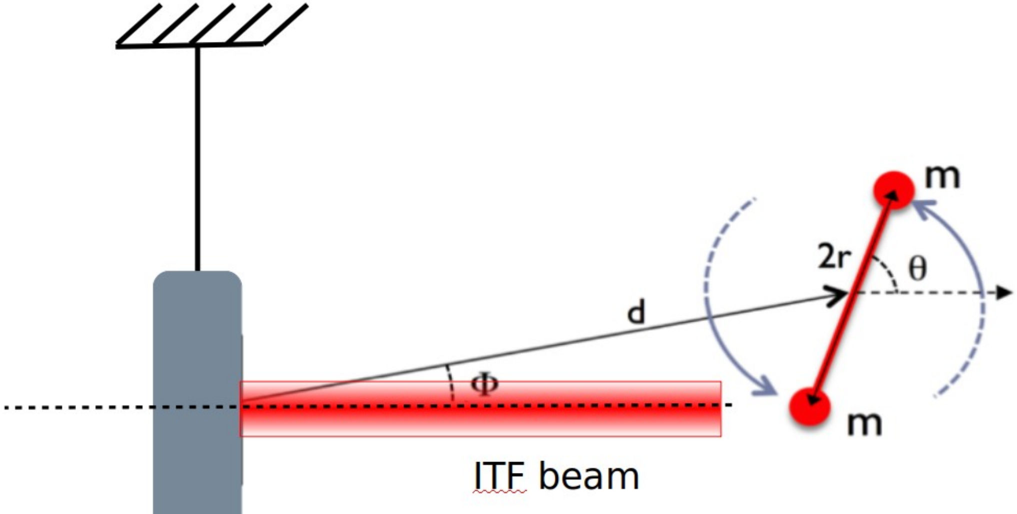
(2009 EUROMET comparison)

LIGO-Virgo reference:
Gold Standard calibrated by NIST at the level of 0.32%...

Need another calibration method to check the absolute calibration
→ Newtonian Calibrator (NCal)

Newtonian Calibrator (NCal)

Estevez et al., 2018, First tests of a Newtonian calibrator on an interferometric gravitational-wave detector,
Classical and Quantum Gravity 35 235009
DOI: 10.1088/1361-6382/aae95f

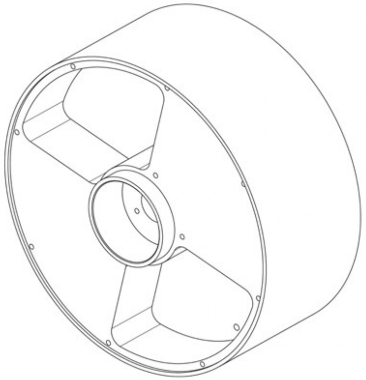


Point mass approximation:

$$F(\theta) = \frac{9}{2}\frac{G M_r m r^2}{d^4}\cos(2\theta)$$

$$x(\theta, f_h) = \frac{F(\theta)}{m(2\pi f_h)^2} \qquad f_h = 2 f_{rotor}$$

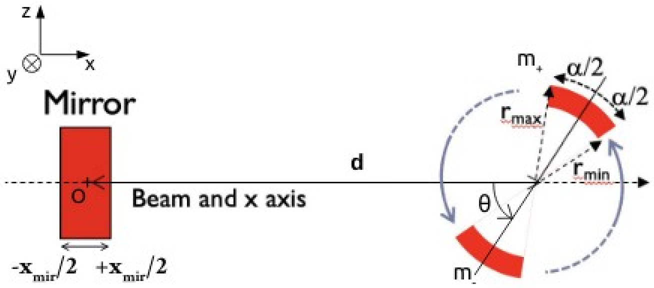
In reality:



Improvements on the modeling

Analytical model:

- Parametrization of the extended mirror and the extended rotor

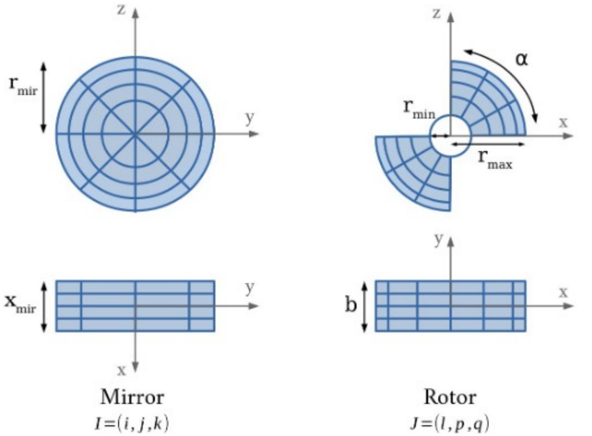


$$F_x \approx \frac{9G}{8d^4}\rho_{rot} b(r_{max}^4 - r_{min}^4)\sin(\alpha)\rho_{mir}\pi r_{mir}^2 x_{mir}\cos(\phi)\Bigg[\Bigg(1 + \frac{25}{54d^2}\frac{r_{max}^6 - r_{min}^6}{r_{max}^4 - r_{min}^4} + \left(\frac{45}{8}\sin^2(\phi) - \frac{5}{2}\right)\left(\frac{r_{mir}}{d}\right)^2 + \left(\frac{15}{8}\cos^2(\phi) - \frac{25}{24}\right)\left(\frac{x_{mir}}{d}\right)^2 - \frac{25}{72}\left(\frac{b}{d}\right)^2 - \frac{35}{6}\left(\frac{z}{d}\right)^2\Bigg)\cos(2\theta) + \frac{8}{3}\frac{z}{d}\sin(2\theta)\Bigg]$$

- Difference of ~3% with the point mass force

Numerical model:

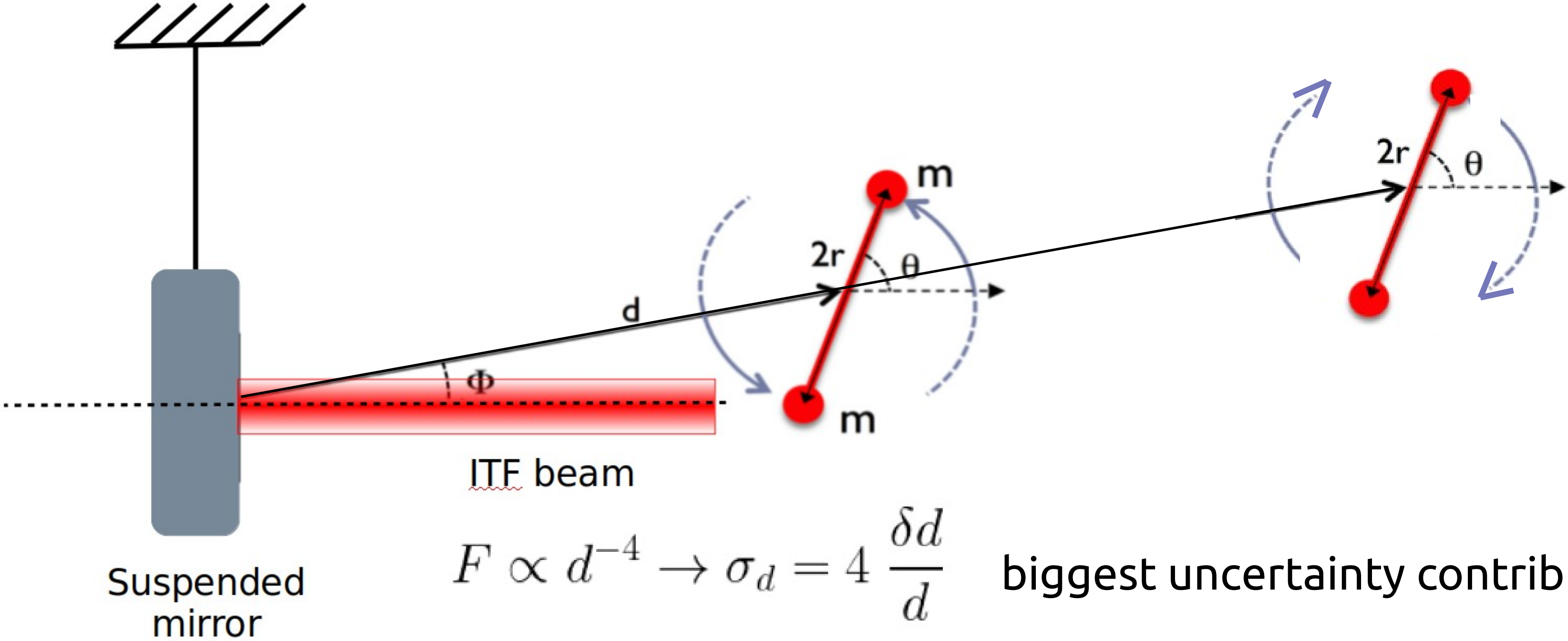
- FROMAGE: Finite element analysis of ROtating MAsses for Gravitational Effects



$$\vec{F} = G\sum_I\sum_J \frac{m_{mir,I}\; m_{rot,J}}{d_{I,J}^2}\vec{u}_{I,J}$$

Agreement on the NCal-induced mirror motion between both models better than 0.02%

Reducing the uncertainty with two NCals



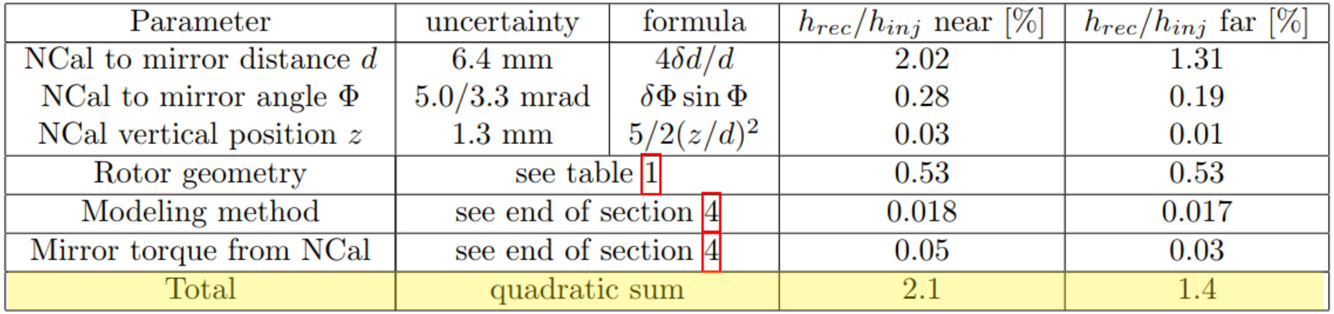
$F \propto d^{-4} \rightarrow \sigma_d = 4\,\frac{\delta d}{d}$ biggest uncertainty contribution

- No direct measurement of the distance (mirror in vacuum chamber)
  - ➔ Comparing the NCal signals amplitude allows to measure the distance

- No direct measurement of the vertical offset (w.r.t plane of the interferometer)
  - ➔ Comparing the NCal signals phase allows to measure the vertical offset

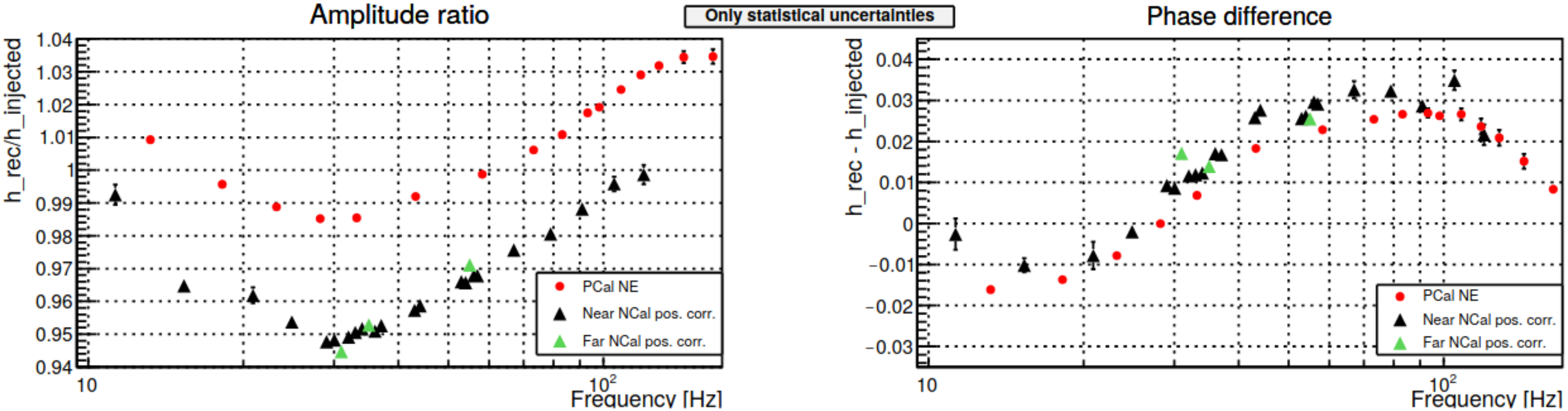
NCal tests during O3

Estevez et al., 2021, Newtonian calibrator tests during the Virgo O3 data taking, accepted in *Classical and Quantum Gravity*
DOI: 10.1088/1361-6382/abe2da



Parameter	uncertainty	formula	h_{rec}/h_{inj} near [%]	h_{rec}/h_{inj} far [%]
NCal to mirror distance d	6.4 mm	$4\delta d/d$	2.02	1.31
NCal to mirror angle Φ	5.0/3.3 mrad	$\delta\Phi \sin\Phi$	0.28	0.19
NCal vertical position z	1.3 mm	$5/2(z/d)^2$	0.03	0.01
Rotor geometry	see table 1		0.53	0.53
Modeling method	see end of section 4		0.018	0.017
Mirror torque from NCal	see end of section 4		0.05	0.03
Total	quadratic sum		2.1	1.4

Verification of *h(t)* reconstruction:



Not incompatible with the PCal systematic uncertainty

Toward a sub-percent calibration

- Which precision to reach?
  - Next observing runs will improve the GW events statistics: hope to reach 1% or less on *h(t)* systematic uncertainty
  - Third generations detectors (Einstein Telescope, Cosmic Explorer) events with SNR ~ 1000: calibration uncertainty smaller than 1/SNR = 0.1% for one event

- Photon Calibrators are the current reference calibration tools for the detectors network:
  - Intercalibration on a common "Gold Standard" calibrated by NIST
  - Measurement of laser power is not that simple, dependence on temperature, humidity etc…

- An independent method for relative and absolute calibration of GW detectors:
  - Newtonian Calibrators with "simpler" parameters to control (distance and geometry)
  - Difficult to check the reconstructed *h(t)* at high frequency (limitations on the rotor speed)
  - Calibrate the PCals at low frequency with the NCal signals and extend the calibration of the GW detectors at high frequency with the PCals

- Using astrophysical sources to make a relative calibration of the detectors network