Journées de Rencontres Jeunes Chercheurs 2022

Calibration of the Virgo gravitational waves detector using a Newtonian Calibrator

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VIRGO

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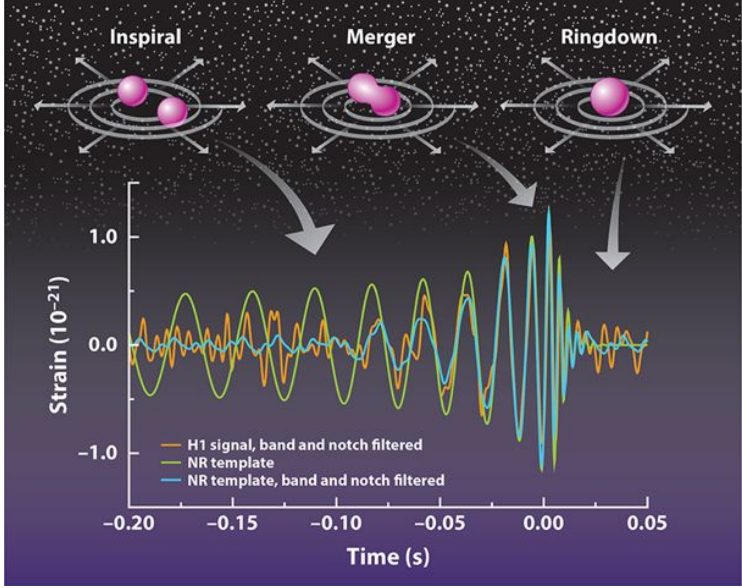
Gravitational Wave (GW) ?

GW are space-time deformations generated by accelerated masses (ex: orbital binary mogettes), according to general relativity:

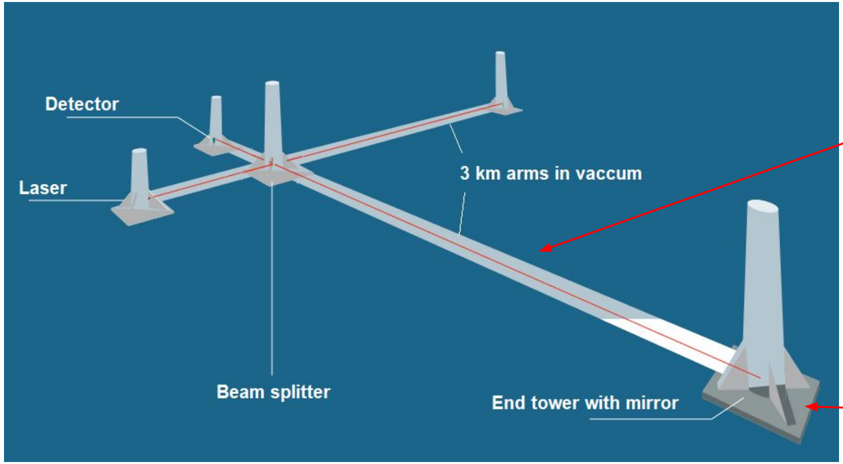
- System loses energy in space
- Emission as waves travelling at speed of light
- On earth: **GW strain** up to **~ 10^{-21}** (compact objects in binary systems)

➔ First direct observation in 2015 (by LIGO interferometers)



How to detect GW ?

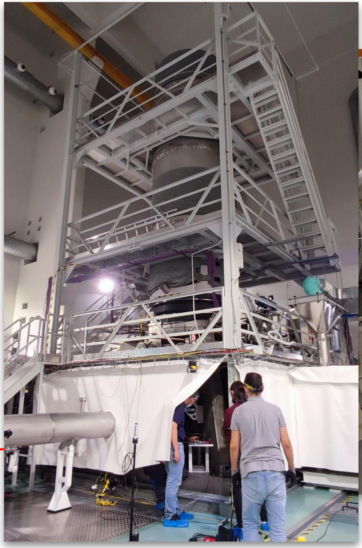
With Virgo interferometer

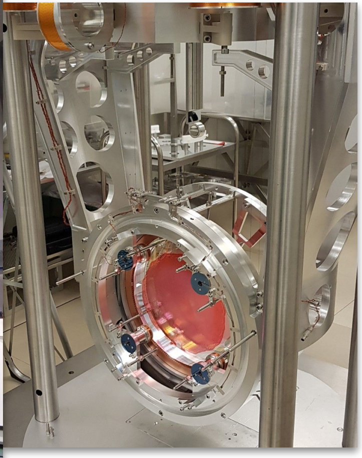


Simple layout of the Virgo Interferometer (Cascina, Italia)

Virgo arm

Virgo end tower and 42 kg suspended mirror





35 cm diameter and 20 cm thickness

- Beams recombined after travelling through the 3 km arms
- A GW crosses the interferometer = infinitesimal arms length (L) variation
  - Interferometer signal correlated to the amplitude of the GW

Signal $h = \delta L/L$ with L=3km

See Virgo website for more information

The LIGO Virgo Kagra network

GW travel through everything

LIGO Hanford
(US)

LIGO Livingston
(US)

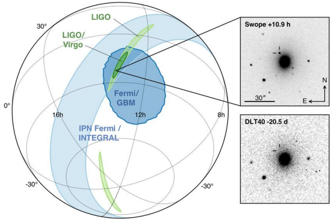
KAGRA (Japan)

Virgo (Italia)

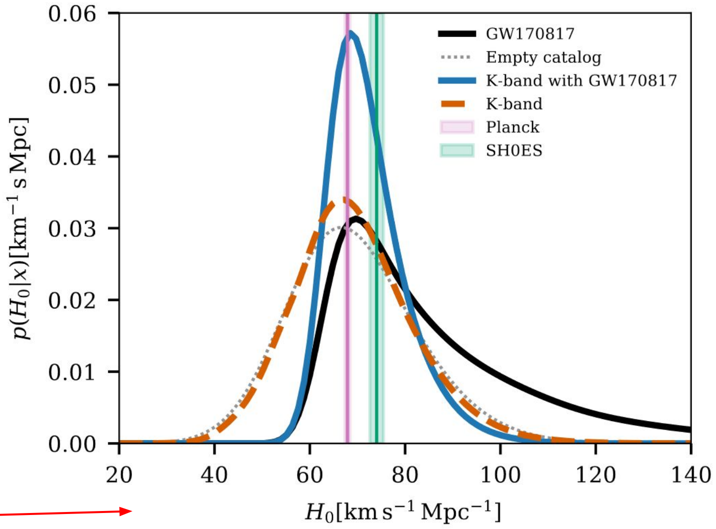
Purpose of the calibration

h calibration impacts key measurements:

Sky localization, rates, H_0…



Ex: Hubble constant $\boldsymbol{H_0 \propto d^{-1}}$



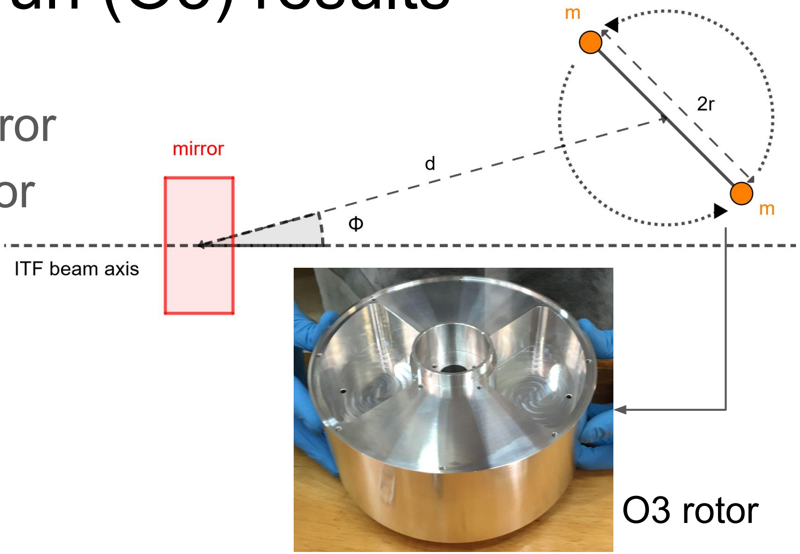
- The distance is inversely proportional to the amplitude of the GW
- Calibration errors induce a bias on H_0

h calibration is done by moving a mirror by a well known amount:

- PCal: Photon Calibrator using the photons radiation pressure
  - main calibration at LIGO,Virgo and KAGRA
- **NCal: Newtonian Calibrator** using gravitation to move the mirror

NCal principle and last observing run (O3) results

- Two rotating masses (rotor) close to the mirror
- Use the gravitational force to move the mirror
- No direct access to the mirror required



O3 rotor

Point mass approximation:

$$F_{\text{beam axis}} \approx \frac{9GmMr^2}{2d^{\boxed{4}}}\cos(\Phi)\cos(2(\theta+\psi))$$

- The distance d is the main source of uncertainty followed by the rotor geometry

Parameter	NCal error [%]
NCal to mirror distance d	1.31
NCal to mirror angle Φ	0.19
NCal vertical position z	0.01
Rotor geometry	0.53
Modeling method	0.017
Mirror torque from NCal	0.03
Total	1.4

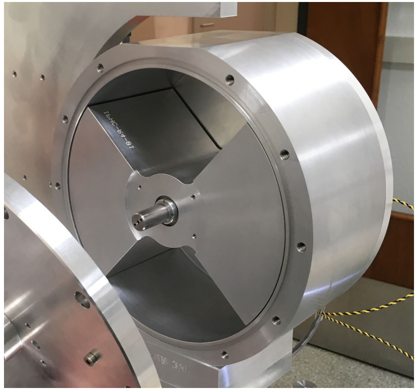
➔ O3 NCal uncertainties (D Estevez *et al* 2021 *Class. Quantum Grav.* **38** 075012)

NCal for O4

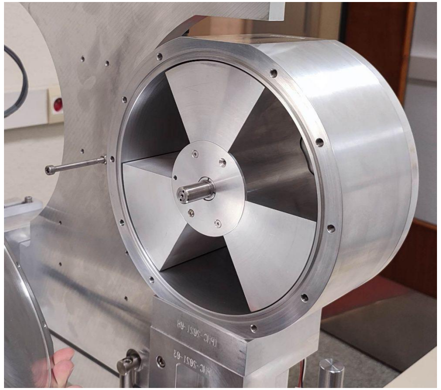
6 NCals installed around the end mirror from October 2021 to July 2022:

- 5 NCals at 2f 🟩 🟦 🟪
  - 3 at same distance and 2 further away
- 1 NCal at 3f 🟥
  - Closest to the mirror

➔ Finding the mirror position using NCals signal

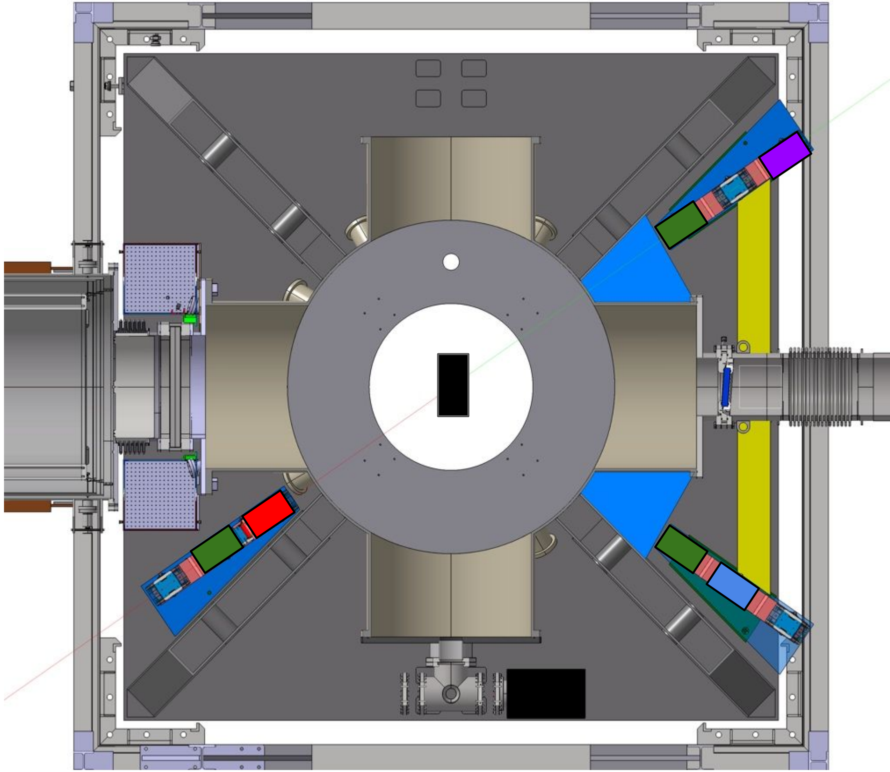


NCal for signal at $2f_{rotor}$



NCal for signal at $3f_{rotor}$

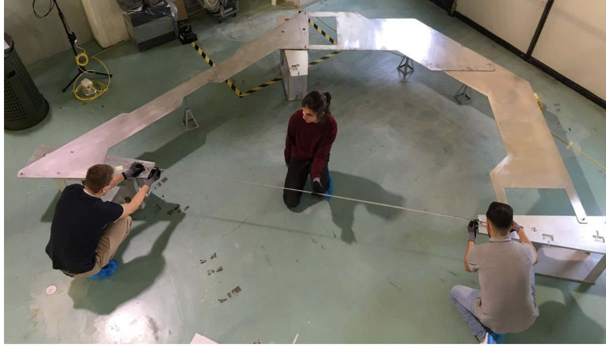
Top view of vacuum chamber



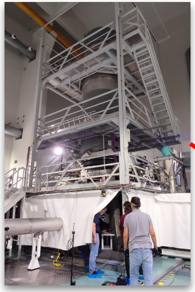
NCal installation

Pairs of NCals mounted on 3 suspended frames around the vacuum chamber:

- Monitoring of the position with position sensors on reference plates
- Reference plates position uncertainty from 0.4 mm to 0.9 mm



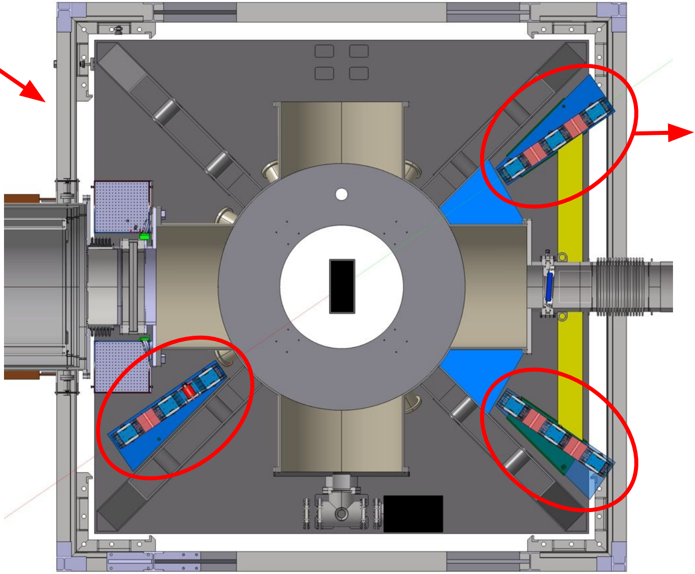
Template used for installation



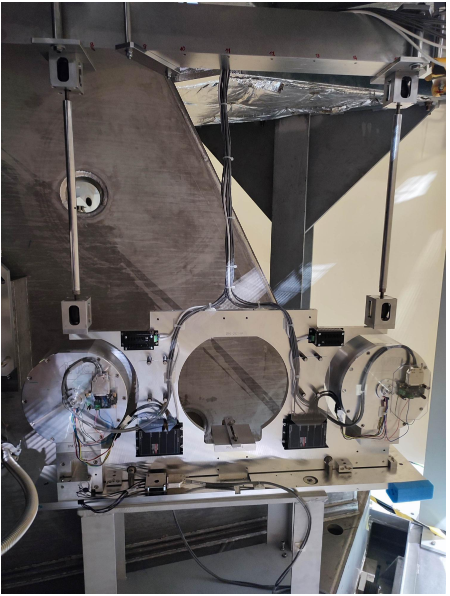
Vacuum chamber

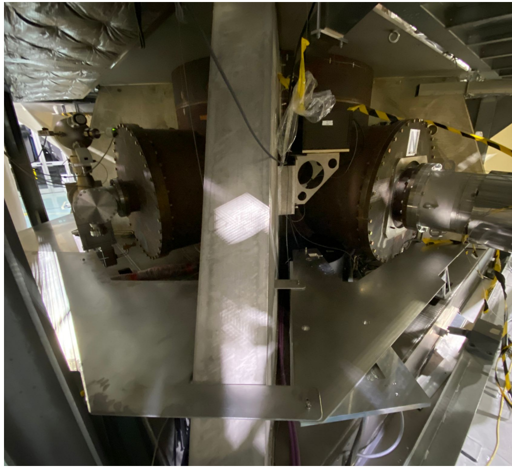
Main beam

Top view of end vacuum chamber

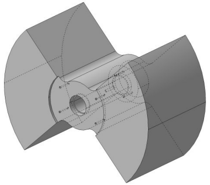


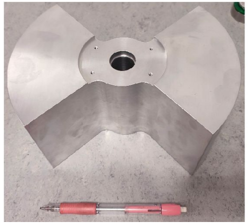
NCal setup



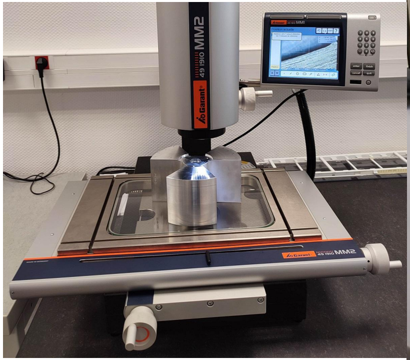


Rotors careful productions and metrology





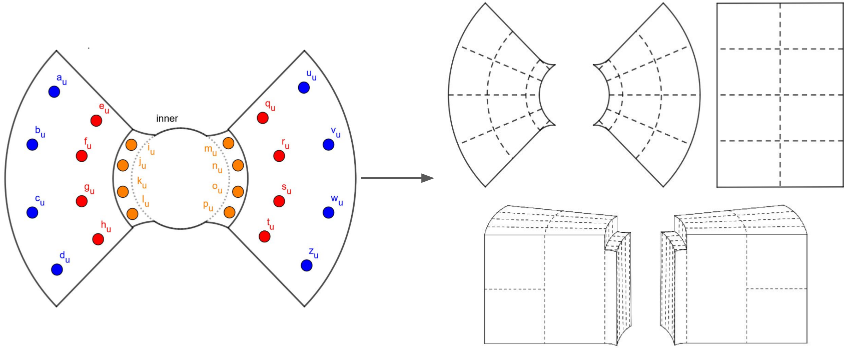
Design, machining and metrology of 7+1 rotors at IPHC using Al7075



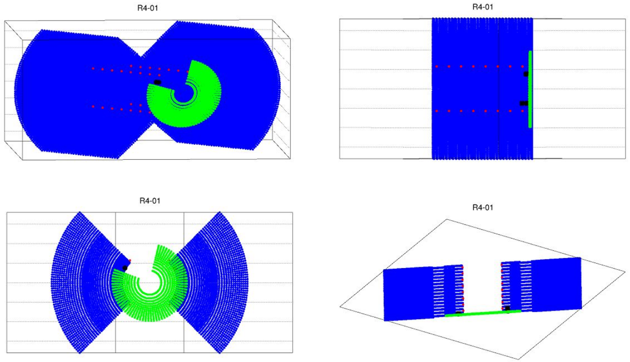
Rotors: predicting the signal

- ➔ Measure the geometry of each rotor to predict the signal induced in the interferometer using FEA with **MOGETTES*** software (density, radius, thickness, opening angle and asymmetry of the sectors)

***M**assive **O**rbital and **G**ravitational **E**ffects **T**hrough **T**he **E**xperimental **S**oftware



Measurements to FROMAGE layout:
each element simulated with a 8x17x14 grid

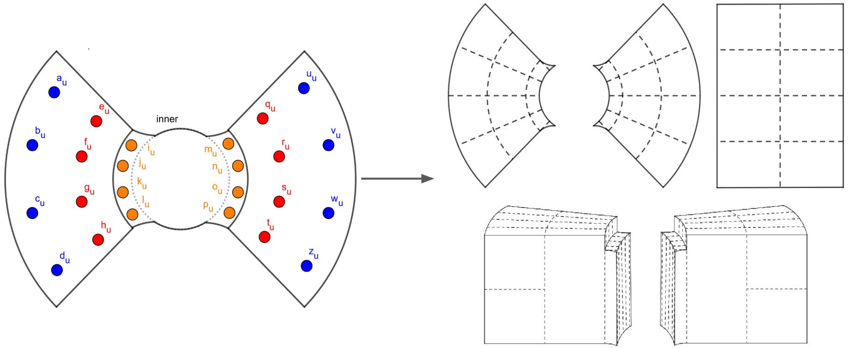


Cloud of points extracted from FROMAGE simulation using a 16x65x40 grid

➔ **$h(2f) = 2.121e\text{-}18/(2f^2) \pm 0.001$**

Rotors: predicting the signal

- ➔ Measure the geometry of each rotor to predict the signal induced in the interferometer using FEA with **FROMAGE*** (density, radius, thickness, opening angle and asymmetry of the sectors)



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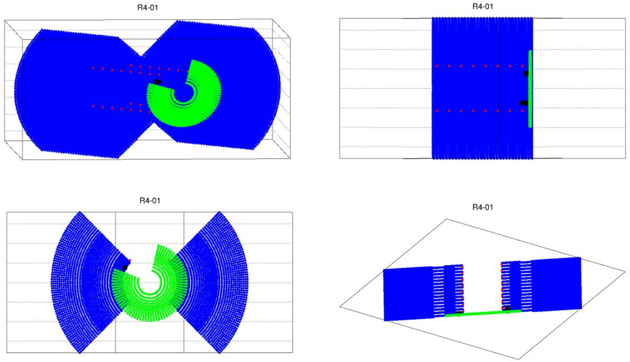
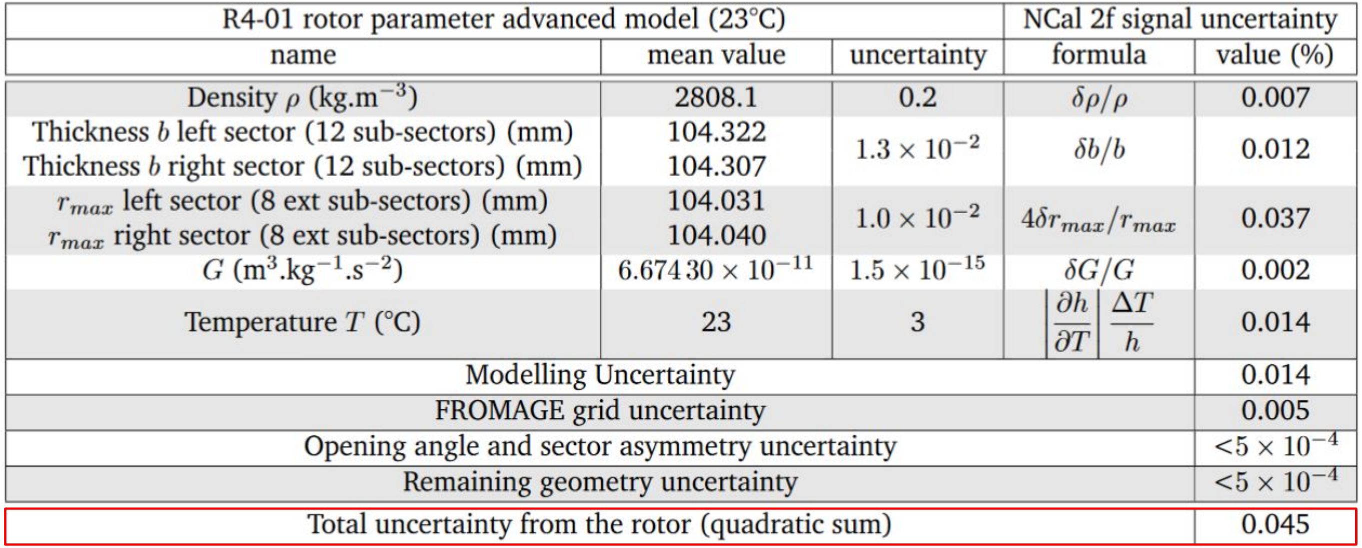


Cloud of points extracted from FROMAGE simulation using a 16x65x40 grid

➔ **$h(2f) = 2.121e{-18}/(2f^2) \pm 0.001$**

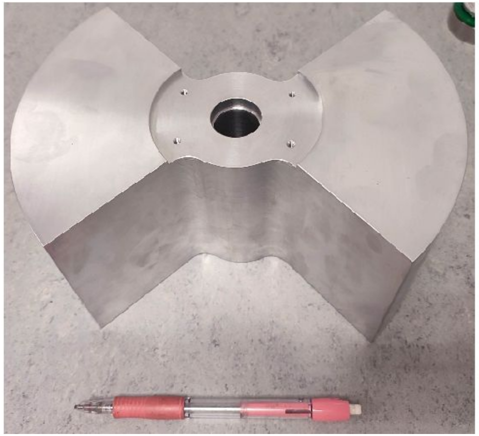
***F**inite element analysis of **RO**tating **MA**sses for **G**ravitational **E**ffects

NCal rotor uncertainty



R4-01 rotor parameter advanced model (23°C)			NCal 2f signal uncertainty	
name	mean value	uncertainty	formula	value (%)
Density ρ (kg.m^{-3})	2808.1	0.2	$\delta\rho/\rho$	0.007
Thickness b left sector (12 sub-sectors) (mm)	104.322	1.3×10^{-2}	$\delta b/b$	0.012
Thickness b right sector (12 sub-sectors) (mm)	104.307			
r_{max} left sector (8 ext sub-sectors) (mm)	104.031	1.0×10^{-2}	$4\delta r_{max}/r_{max}$	0.037
r_{max} right sector (8 ext sub-sectors) (mm)	104.040			
G (m^3.kg^{-1}.s^{-2})	$6.674\,30 \times 10^{-11}$	1.5×10^{-15}	$\delta G/G$	0.002
Temperature T (°C)	23	3	$\left\lvert\frac{\partial h}{\partial T}\right\rvert \frac{\Delta T}{h}$	0.014
Modelling Uncertainty				0.014
FROMAGE grid uncertainty				0.005
Opening angle and sector asymmetry uncertainty				$<5 \times 10^{-4}$
Remaining geometry uncertainty				$<5 \times 10^{-4}$
Total uncertainty from the rotor (quadratic sum)				0.045

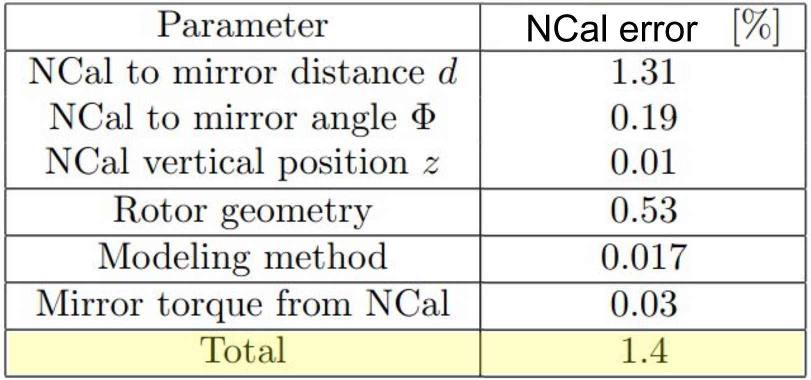
➔ Done for 7+1 rotors



NCal overall estimated uncertainty for next observing run (O4)

O3

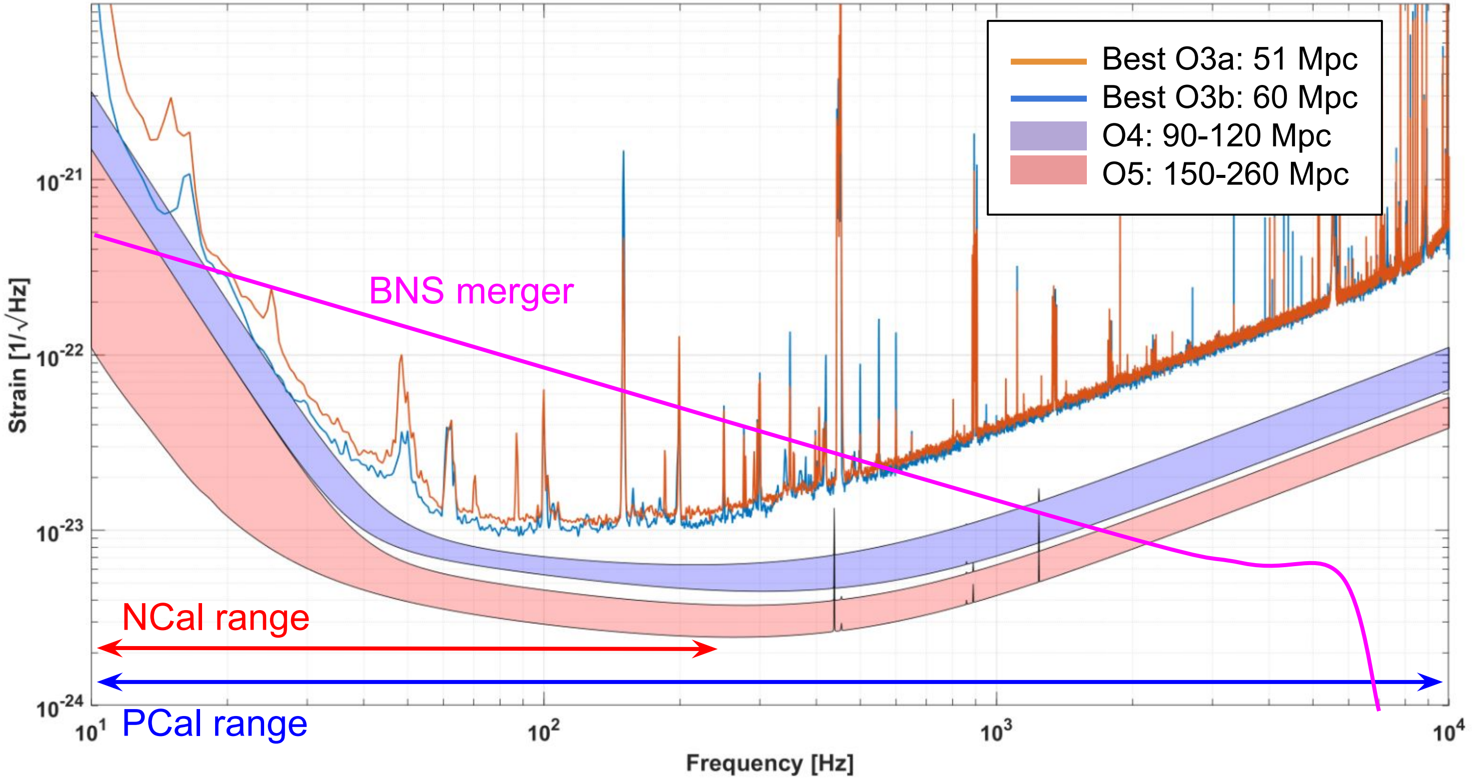
O4 expectations



Parameter	NCal error [%]	O4 expectations
NCal to mirror distance d	1.31	< 0.4%
NCal to mirror angle Φ	0.19	< 0.1%
NCal vertical position z	0.01	
Rotor geometry	0.53	< 0.1%
Modeling method	0.017	
Mirror torque from NCal	0.03	
Total	1.4	< 0.5%

NCal frequency range and Virgo sensitivity

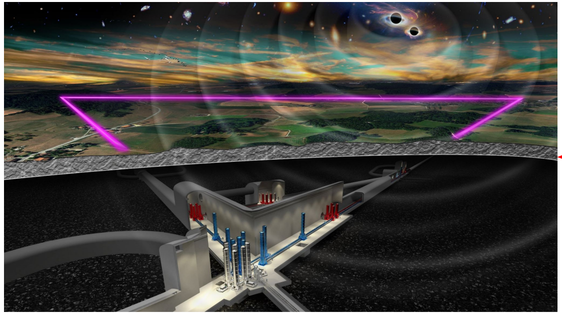
NCals rotation: up to 80 Hz -> signal up to 160 or 240 Hz

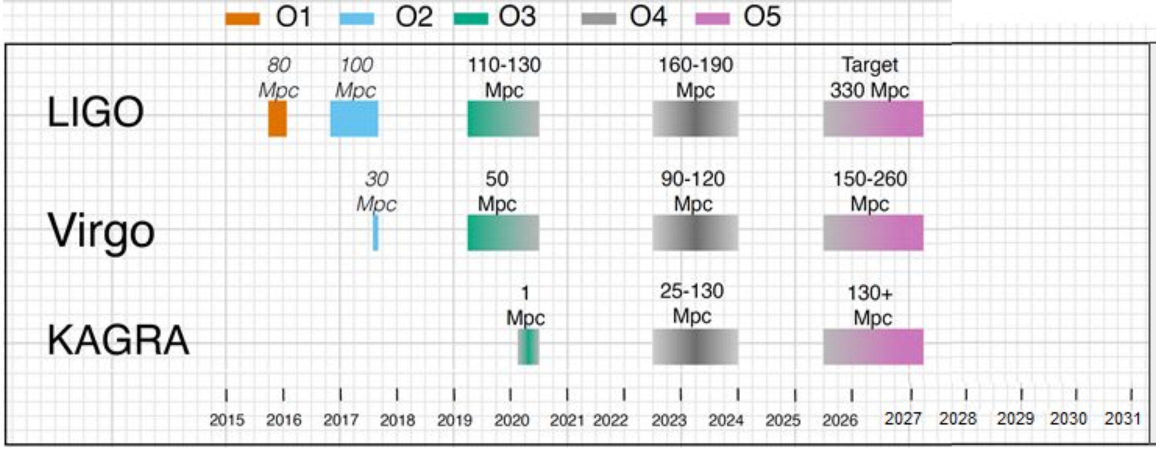


Conclusion and perspectives

- NCal system ready for O4 run (starting march 2023)
- Expected accuracy of the injected NCal signal below 0.5 %
- … Start preparing O5 setup soon

Calibration will be even more challenging in the future





3rd Generation telescopes

Einstein Telescope (ET) >2035

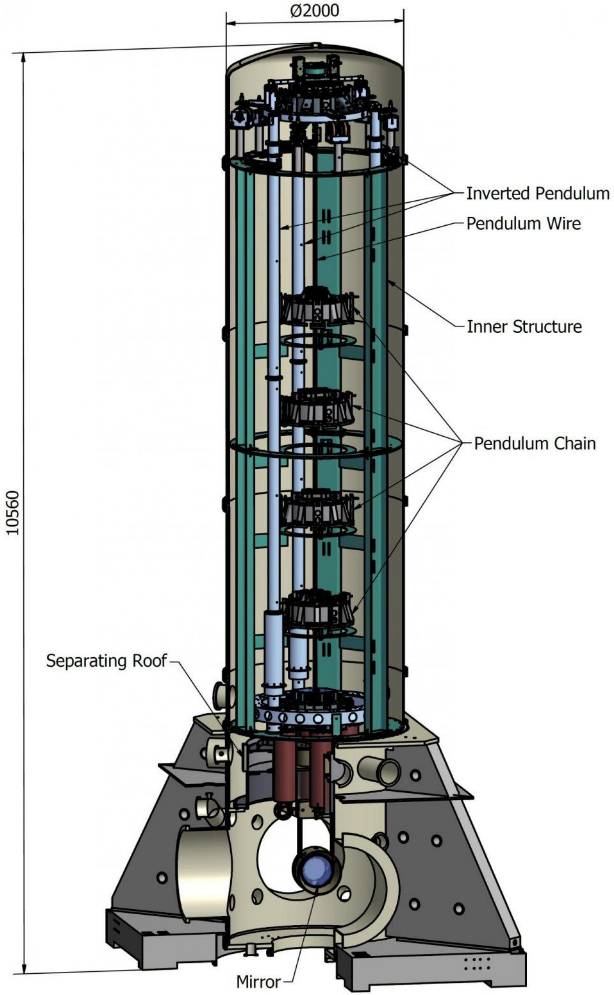
Range of detection of interferometers for different operating runs (see https://emfollow.docs.ligo.org/userguide/capabilities.html#sensitivity)

Thank you !

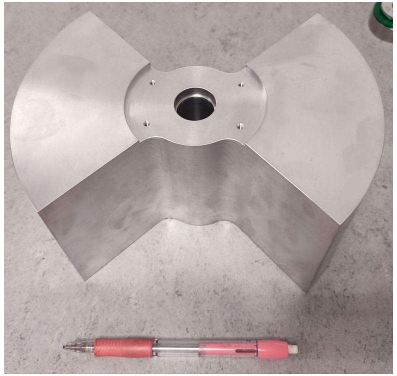
Backup

Mirrors suspensions

Elements of a suspension

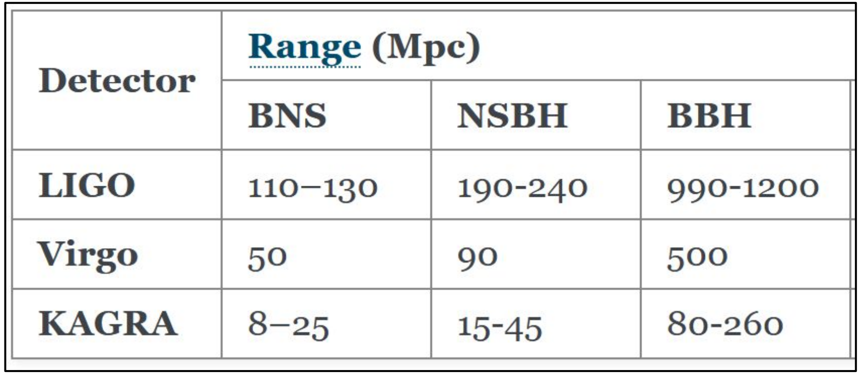


Amplitude of a rotor at 2f

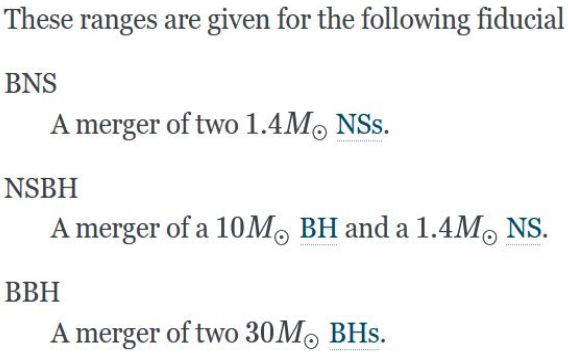


$$a(f_{2rot}) = \frac{9G\rho_{rot}\ b\ \sin(\alpha)(r_{max}^4 - r_{min}^4)}{32\pi^2 f_{2rot}^2 d^4}\cos(\phi)\Big[1 + \frac{25}{54d^2}\frac{(r_{max}^6 - r_{min}^6)}{(r_{max}^4 - r_{min}^4)} + \Big(\frac{45}{8}\sin^2(\phi) - \frac{5}{2}\Big)\Big(\frac{r_{mir}}{d}\Big)^2 + \Big(\frac{15}{8}\cos^2(\phi) - \frac{25}{24}\Big)\Big(\frac{x_{mir}}{d}\Big)^2 - \frac{25}{72}\Big(\frac{b}{d}\Big)^2\Big] \qquad (42)$$

Detectors range and units



Detector	Range (Mpc)		
	BNS	NSBH	BBH
LIGO	110–130	190-240	990-1200
Virgo	50	90	500
KAGRA	8–25	15-45	80-260



These ranges are given for the following fiducial signals:

BNS

A merger of two $1.4 M_\odot$ NSs.

NSBH

A merger of a $10 M_\odot$ BH and a $1.4 M_\odot$ NS.

BBH

A merger of two $30 M_\odot$ BHs.

Units conversion:

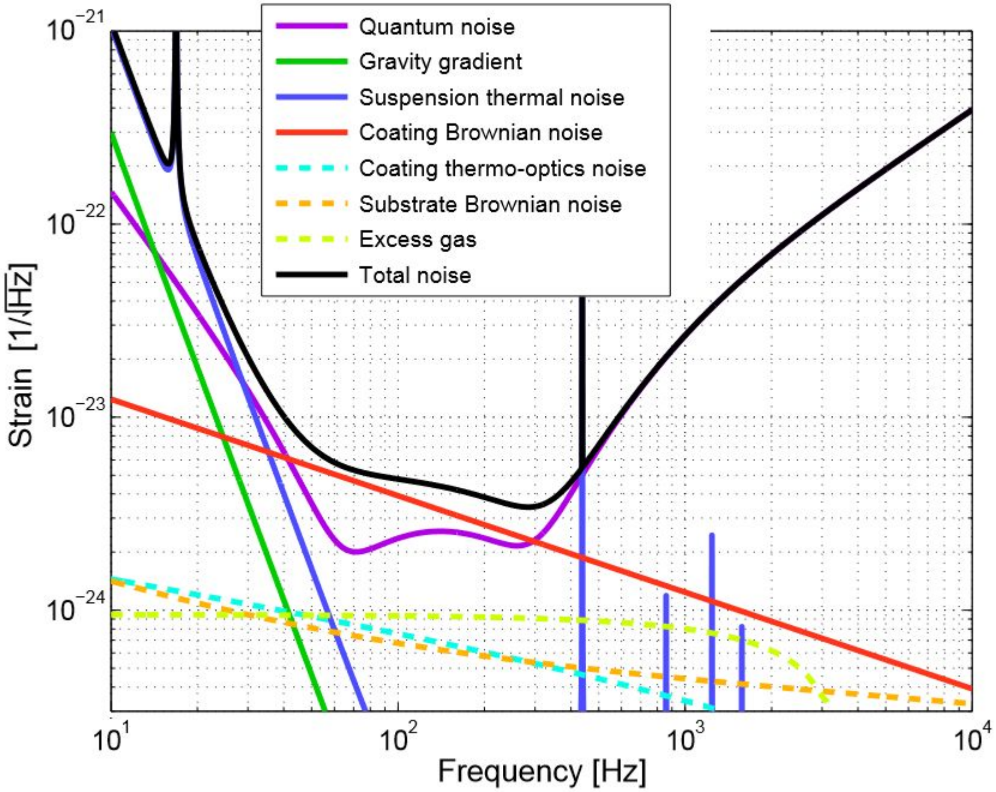
Mpc = Megaparsec
Ly = light year

1 Mpc = 3.262e+6 ly = 3.086e+22 m

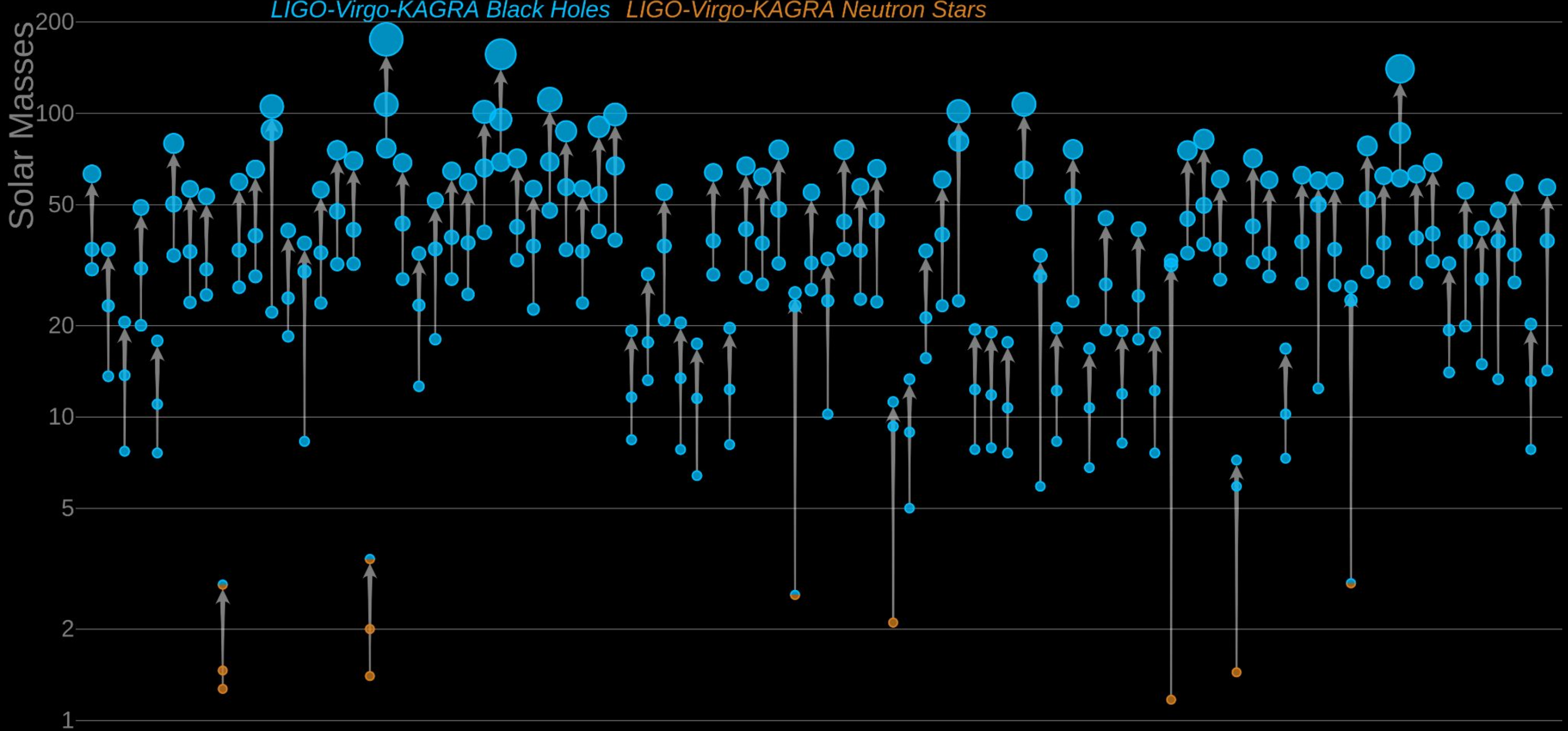
The Milky Way is 10e+5 ly wide (0.03 Mpc)
The Andromeda galaxy is 0.765 Mpc away

See https://emfollow.docs.ligo.org/userguide/capabilities.html#sensitivity

Virgo sensitivity curve noise



Masses in the Stellar Graveyard



LIGO-Virgo-KAGRA | Aaron Geller | Northwestern