Virgo activities linked to cosmology at IPHC

- Calibration of GW detectors
  - ➔ Development of Newtonian Calibrators
  - ➔ Cross-calibration of the GW network using astrophysical events

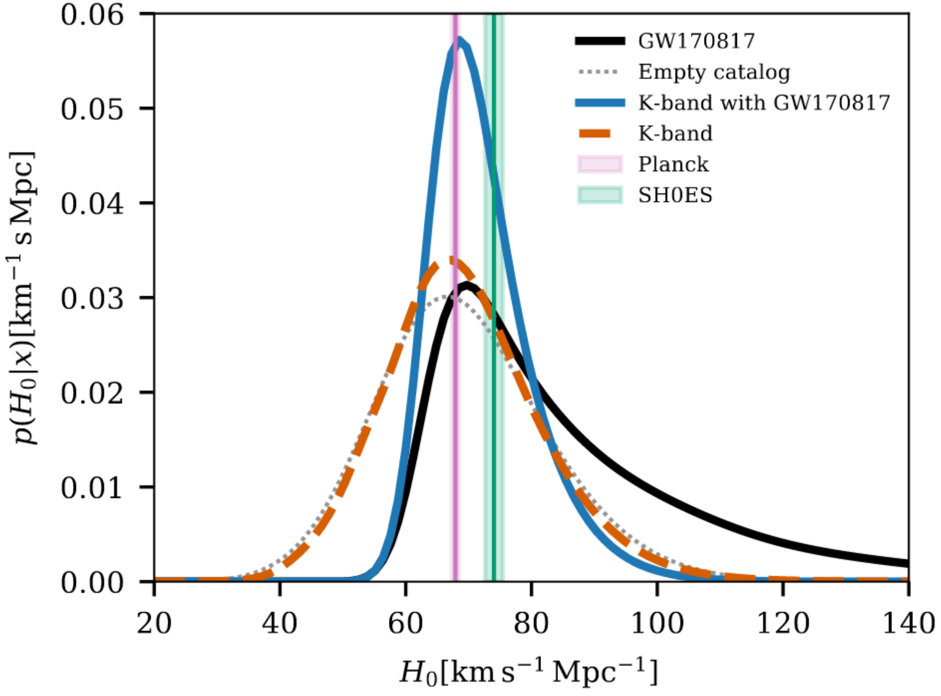
- Detection and characterization of signals with MBTA
  - ➔ Online search for EM counterpart
  - ➔ Assessing the probability of astrophysical origin and source classification

IPHC group: D. Estevez, V. Juste, B. Mours, T. Pradier, A. Syx
+ technical support

Virgo France Cosmology – June 21st 2022

Getting the Hubble constant right

LVK collaborations, 2021, arXiv:2111.03604



Accurate measurement of the luminosity distance needs accurate calibration of the GW strain

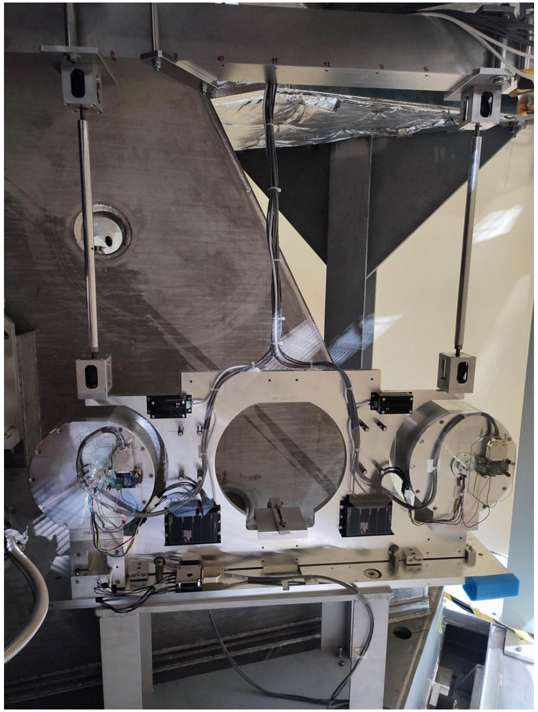
$$h \propto d_L^{-1} \qquad H_0 = \frac{cz}{d_L}, \quad z \ll 1$$

Typical calibration uncertainty on h(t) during O3:
→ between ~2% and ~7% (20Hz – 2kHz band)

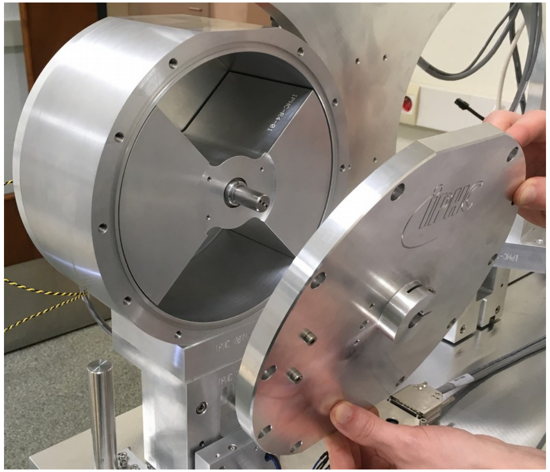
Newtonian calibrator (NCal)

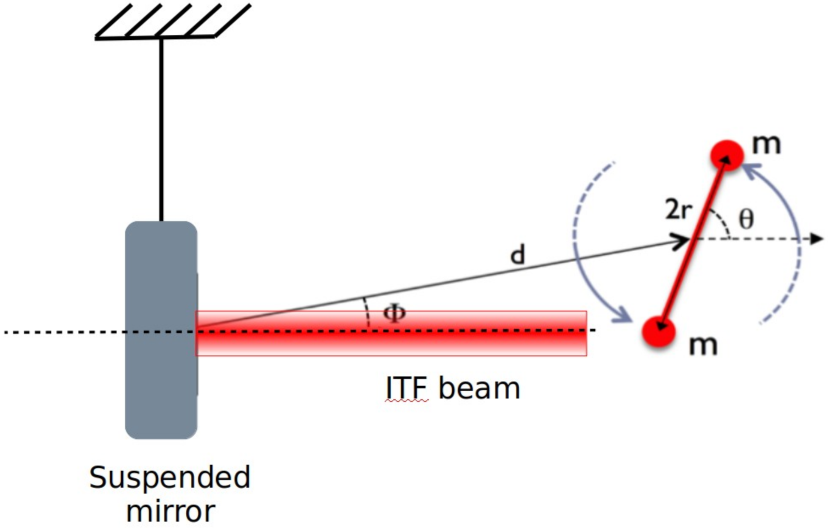
Two masses in rotation
→ Non linear effect of Newton's gravitational law
→ Displacement of the suspended mirror

Setup at Virgo



NCal rotor





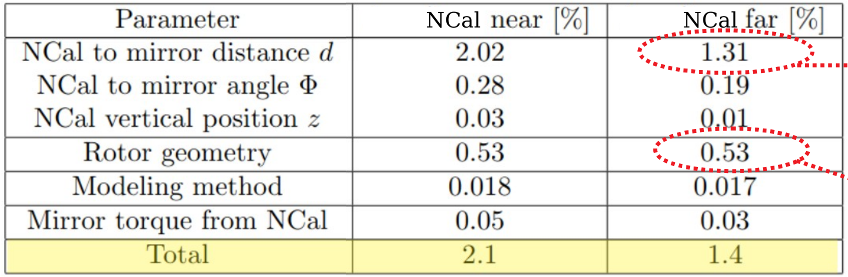
$$F(\theta) = \frac{9}{2}\frac{GMmr^2}{d^4}\cos(2\theta)$$

$$h_{NCal}(f_h) = \frac{|F(\theta)|}{M(2\pi f_h)^2} \cdot \frac{1}{L_{arm}}$$

$$f_h = 2f_{rotor}$$

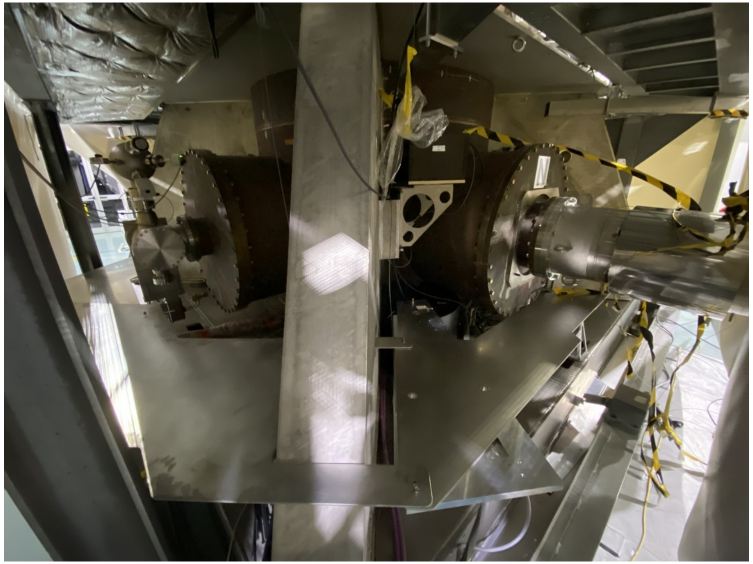
NCal uncertainties from O3 to O4

NCal strain uncertainty budget during O3



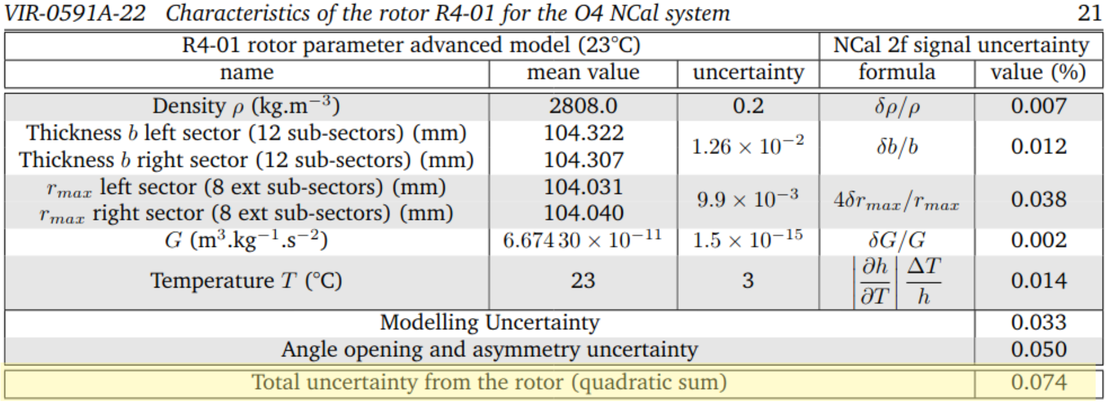
Parameter	NCal near [%]	NCal far [%]
NCal to mirror distance d	2.02	1.31
NCal to mirror angle Φ	0.28	0.19
NCal vertical position z	0.03	0.01
Rotor geometry	0.53	0.53
Modeling method	0.018	0.017
Mirror torque from NCal	0.05	0.03
Total	2.1	1.4

D. Estevez et al, 2021, CQG, 38 075012



Plan to reach a subpercent accuracy on h_{NCal} for O4:

- Reduce the contribution of the NCal-to-mirror distance
  - ➔ Installation of reference plates *(VIR-0343A-22)*
  - ➔ Distance uncertainty should be ~1 mm (0.2% at 1.7m)
- Reduce the contribution of the rotor geometry
  - ➔ Simplified geometry and better metrology *(VIR-160A-22, VIR-0591A-22)*
  - ➔ Rotor geometry uncertainty should be < 0.1%



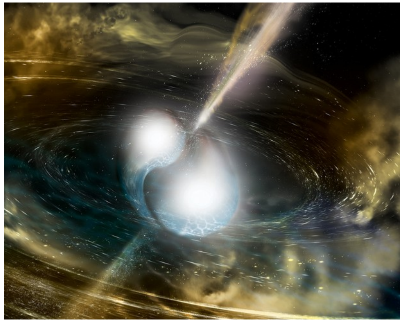
VIR-0591A-22 Characteristics of the rotor R4-01 for the O4 NCal system 21

R4-01 rotor parameter advanced model (23°C)			NCal 2f signal uncertainty	
name	mean value	uncertainty	formula	value (%)
Density ρ (kg.m^{-3})	2808.0	0.2	$\delta\rho/\rho$	0.007
Thickness b left sector (12 sub-sectors) (mm)	104.322	1.26×10^{-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	9.9×10^{-3}	$4\delta r_{max}/r_{max}$	0.038
r_{max} right sector (8 ext sub-sectors) (mm)	104.040			
G (m^3.kg^{-1}.s^{-2})	6.67430×10^{-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				0.033
Angle opening and asymmetry uncertainty				0.050
Total uncertainty from the rotor (quadratic sum)				0.074

Probability of astrophysical origin and source classification

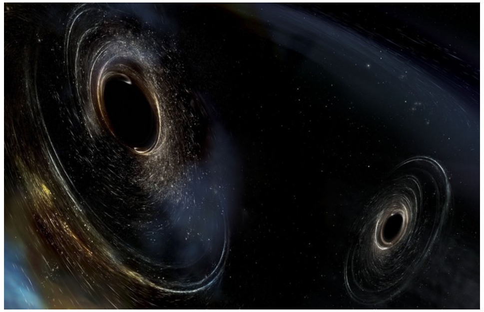
Three types of compact-binary coalescences observed:

Binary Neutron Stars (BNS)



Neutron Star Black Hole (NSBH)

Binary Black Hole (BBH)



In low-latency:

- ➔ Help astronomers to decide whether to undertake a follow-up or not of the gravitational-wave candidates

In archival data:

- ➔ Sub-threshold triggers analysis with other messengers (electromagnetic, neutrinos…)
- ➔ Compute binary merger rates of source specific compact objects

→ Requires assumptions about population models, redshift evolution...

Assessing the nature of a GW candidate: p_{BNS} , p_{NSBH} , p_{BBH}

Probability of astrophysical origin:

- Jointly estimated with source membership probabilities { p_{BNS} ; p_{NSBH} ; p_{BBH} }
- $p_{astro} = p_{BNS} + p_{NSBH} + p_{BBH} = 1 - p_{noise}$

Astrophysical foreground density for the source α

$$p_\alpha(x) = \frac{\Lambda_\alpha f_\alpha(x)}{\Lambda_0 b(x) + \vec{\Lambda}_1 \cdot \vec{f}(x)} \qquad p_{\mathrm{astro}}(x) = \sum_\alpha p_\alpha(x)$$

Background density

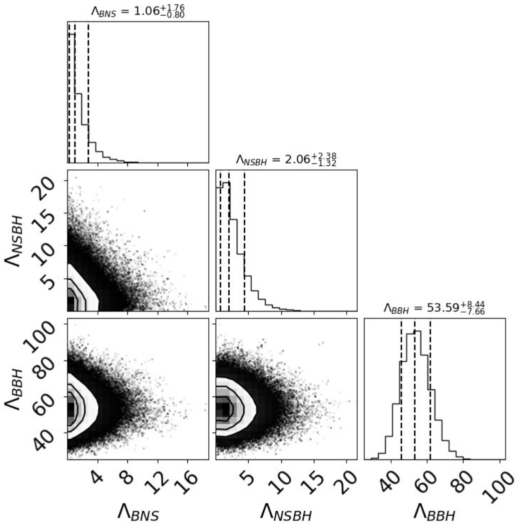
Astrophysical foreground density

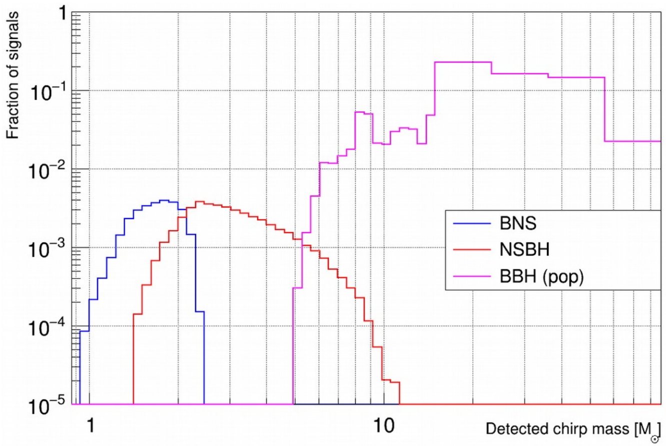
Assumed population models (MBTA example from O3)

	Mass distribution	Mass range ($M_\odot$)	Spin range	Spin orientations	Redshift evolution	Maximum redshift
BBH (pop)	Power Law + Peak	$5 < m_1 < 80$ $5 < m_2 < 80$	$\lvert\chi_{1,2}\rvert < 0.998$	isotropic	$\kappa = 0$	1.9
NSBH	$p(m_1) \propto m_1^{-2.35}$ uniform	$2.5 < m_1 < 60$ $1 < m_2 < 2.5$	$\lvert\chi_1\rvert < 0.998$ $\lvert\chi_2\rvert < 0.4$	isotropic	$\kappa = 0$	0.25
BNS	uniform	$1 < m_1 < 2.5$ $1 < m_2 < 2.5$	$\lvert\chi_{1,2}\rvert < 0.4$	isotropic	$\kappa = 0$	0.15

N. Andres et al, 2022, CQG, 39 055002

We infer the rates from the data





O4:

- Update population models
- Joint fit of the rate and redshift evolution (BBH peak?)

Remark:

- Sources near detection thresholds are far away
  → interesting for cosmology

EXTRA SLIDES

- **NCal improvements for O5 and beyond**
- **Cross-calibration of the GW network using astrophysical sources**

NCal improvements for O5 and beyond

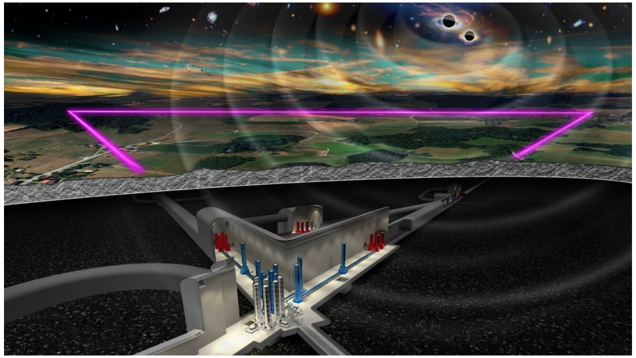
NCal improvements:

- More powerful motors to cover a large frequency range (currently: motors 70 W)
- Rotor under vacuum (currently: in air)
- Magnetic bearing (currently: classical ball bearings)
  - → Advantages: High rotor speed and reduced vibrations
  - → Drawbacks: Magnetic coupling (?) and large stress
- Upgraded suspensions if needed

ANR ACALCO: Advanced gravitational waves detector CALibration for accurate COsmology

- Joint project between IPHC (NCal) and LAPP (PCal)
- Towards a sub-percent accuracy on the reconstructed h(t)
- Current R&D is useful to prepare for third generation detectors

Einstein Telescope



Cross-calibration of the GW network using astrophysical sources

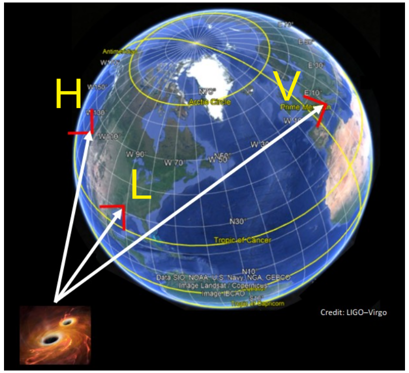
For a detector A of the network:

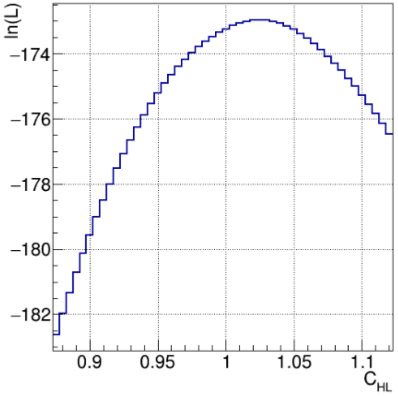
$$h_{\mathrm{A}}(f,t) = C_{\mathrm{A}}\, h_{\mathrm{A,true}}(f,t)$$

Calibrated GW signal

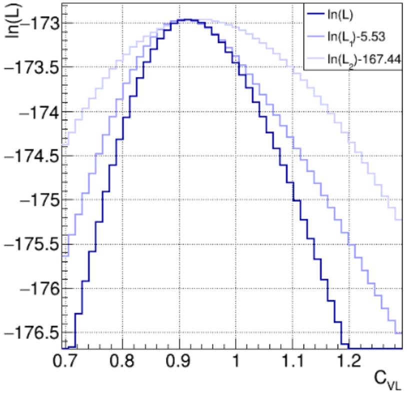
Calibration scaling

Real GW signal





$$C_{\mathrm{HL}} = 1.025 \boxed{\pm\ 0.035}$$



$$C_{\mathrm{VL}} = 0.916\boxed{^{+0.096}_{-0.084}}$$

- Building a likelihood for the relative calibration factors:
  - → For a pair of detectors AB : $C_{AB} = C_A / C_B$
  - → Simulations of astrophysical signals and Monte-Carlo study
- Using the SNR of the GW events in each pair of detectors:
  - → Sky location (+ time of flight)
- Using the fraction of GW events seen in each pair of detectors
  - → Heterogeneous sensitivities

C. Alléné et al, 2022, arXiv:2204.00337