The Virgo experiment and the detection of Gravitational Waves

Workshop Doctorants / Post-Doctorants

Laboratoire d'Annecy de Physique des Particules

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What are Gravitational Waves (GW) ?

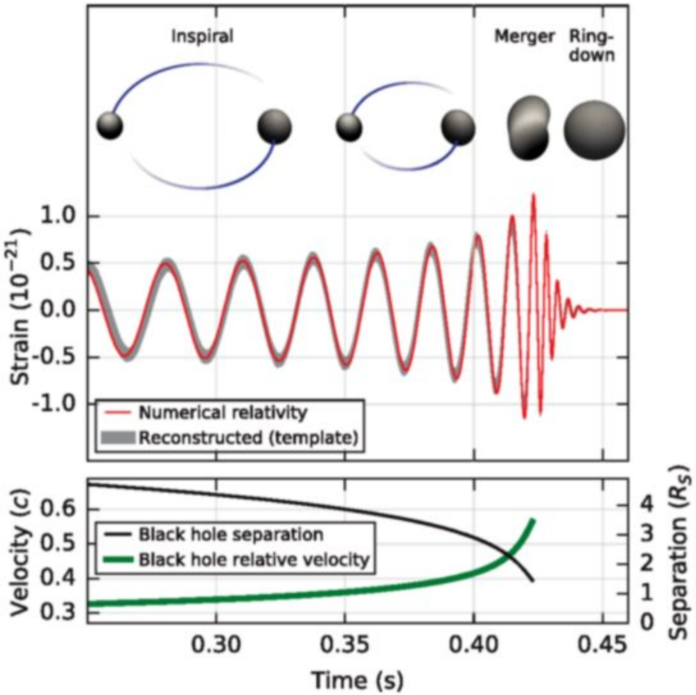
GW are deformations of space-time generated by masses in acceleration.

example: A binary system of black holes/neutron stars (dense objects).

An effect described by General Relativity:

- The system emits GW in space.
- On earth: **relative variation of distances ~ 10^{-21}**

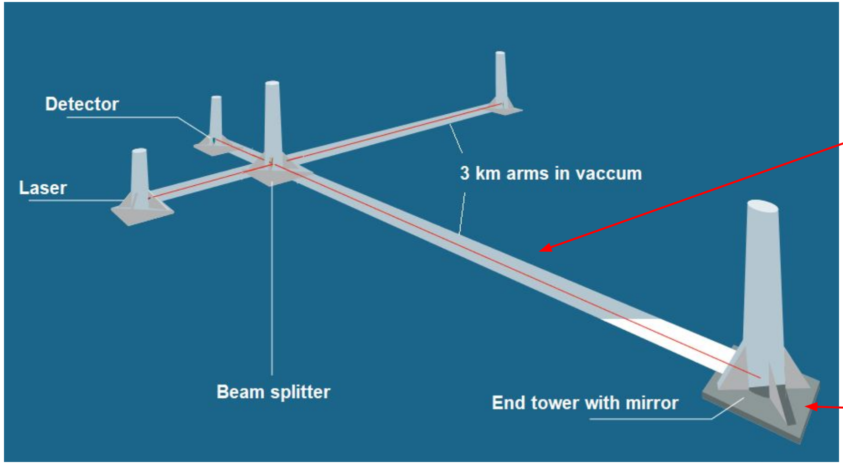
➔ First direct observation of a GW in 2015
  - With the LIGO interferometers



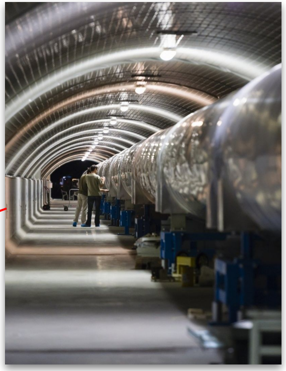
GW150914

How do we detect a GW ?

With the Virgo interferometer

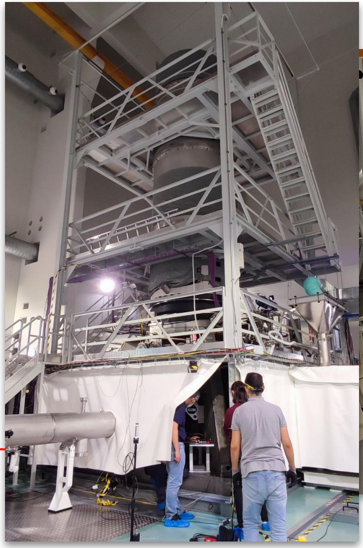


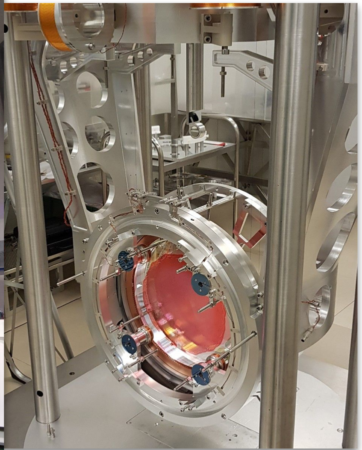
Simplified view of the Virgo interferometer (Cascina, Italie)



Virgo arms

Virgo “end tower” and 42 kg suspended mirror





35 cm of diameter and 20 cm of thickness

- Recombined beams after travelling through the 3 km arms.
- A GW travels through the interferometer (ITF) = length variation of the arms.
  - The ITF signal is correlated with the GW amplitude.

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

A network of detectors : The LIGO Virgo KAGRA collaboration

LIGO Hanford
(US)

LIGO Livingston
(US)

KAGRA (Japan)

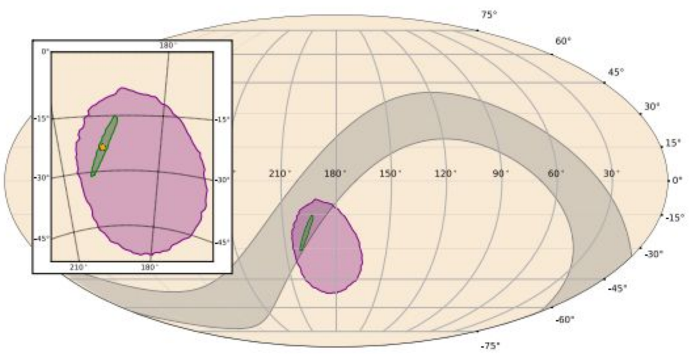
Virgo (Italy)

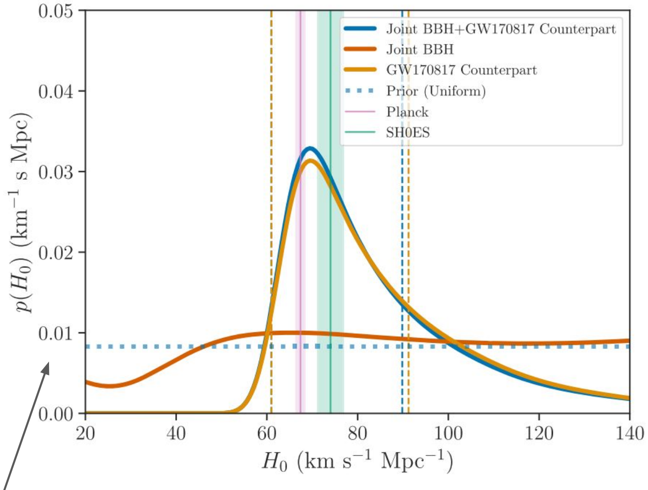
LIGO India
(in development)

The science of GW detections, an example.

Using GW signals from the detectors we can find:

- The location of sources in the sky, event rate, source parameters…

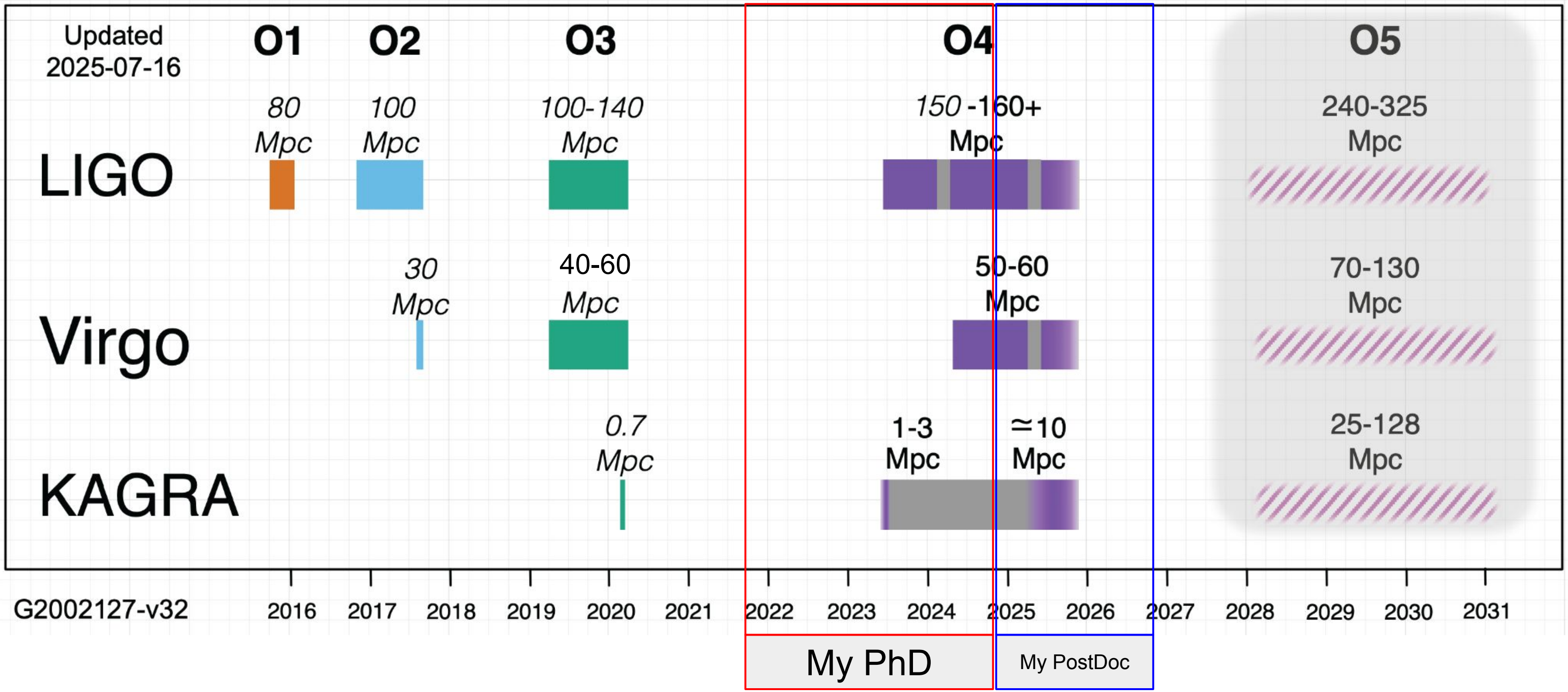




Then we can constrain cosmological parameters like the Hubble constant ($\boldsymbol{H_0 \propto d^{-1}}$)

Observing runs

- Virgo joined the detection network during the observing run O2.
- The sensitivity/detection range improves with and after each run.



My PhD work: Calibration of Virgo

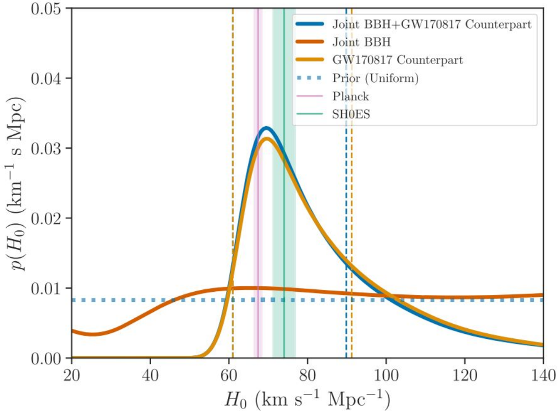
What is calibration?

The use of a reference to characterize a measurement or a tool.

Why do we need it?

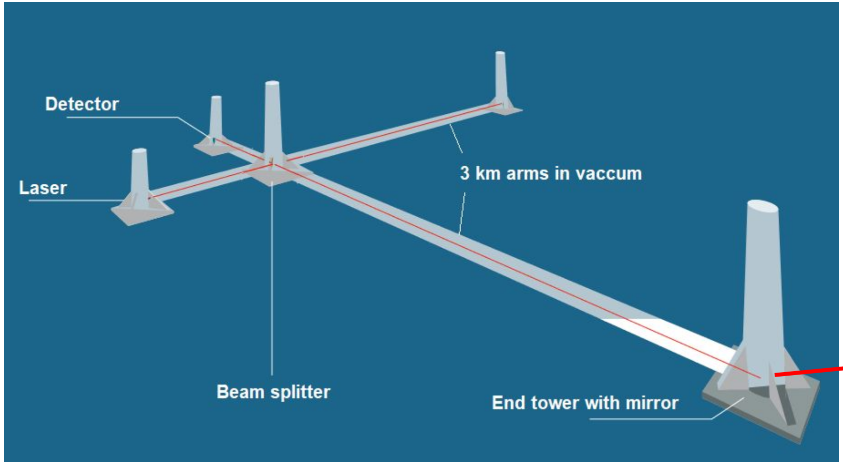
To assure precision and measurement accuracy.

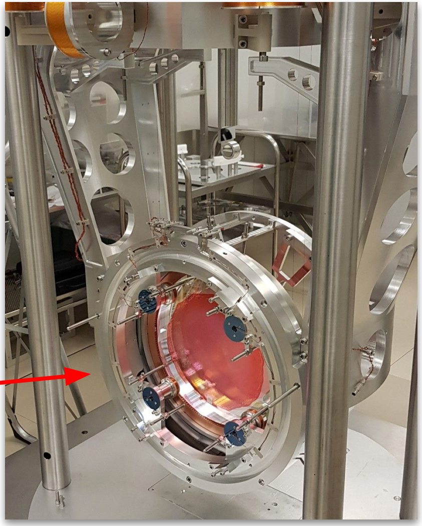
Example: Restrain cosmological parameters like H_0



How to calibrate Virgo?

Actuating on the on the mirrors to calibrate



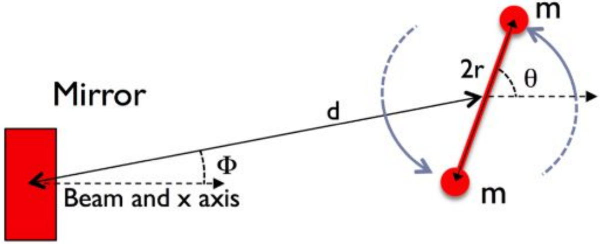


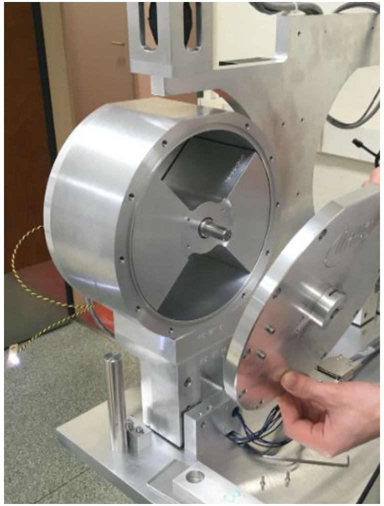
The calibration of the GW signal is done by actuating on the end mirrors

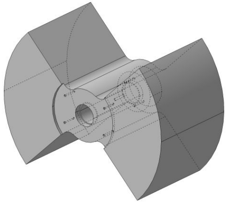
- PCal: *Photon Calibrator*, uses the radiation pressure of photon
  - Main calibrating method at LIGO,Virgo et KAGRA
- **NCal: *Newtonian Calibrator*,** uses a variating gravitational field

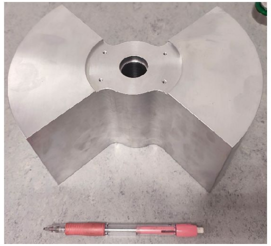
The Newtonian Calibrator (NCal)

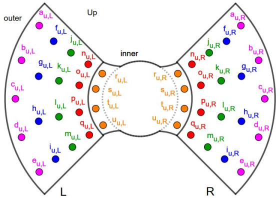
- 2 rotating masses (rotor) close to the mirror
- Use the gravitational force to move the mirror
- No direct access to the mirror is needed

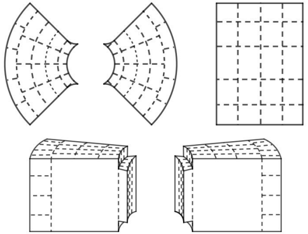


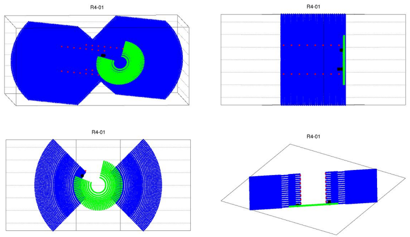








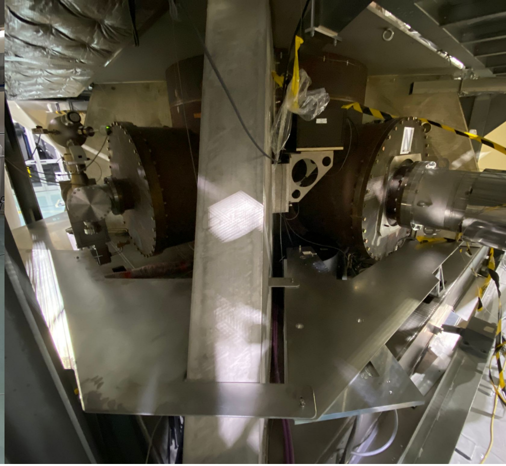
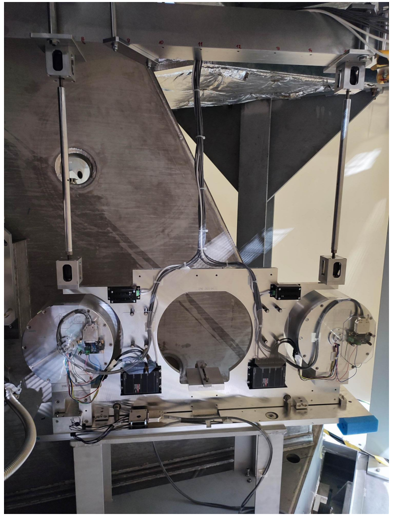


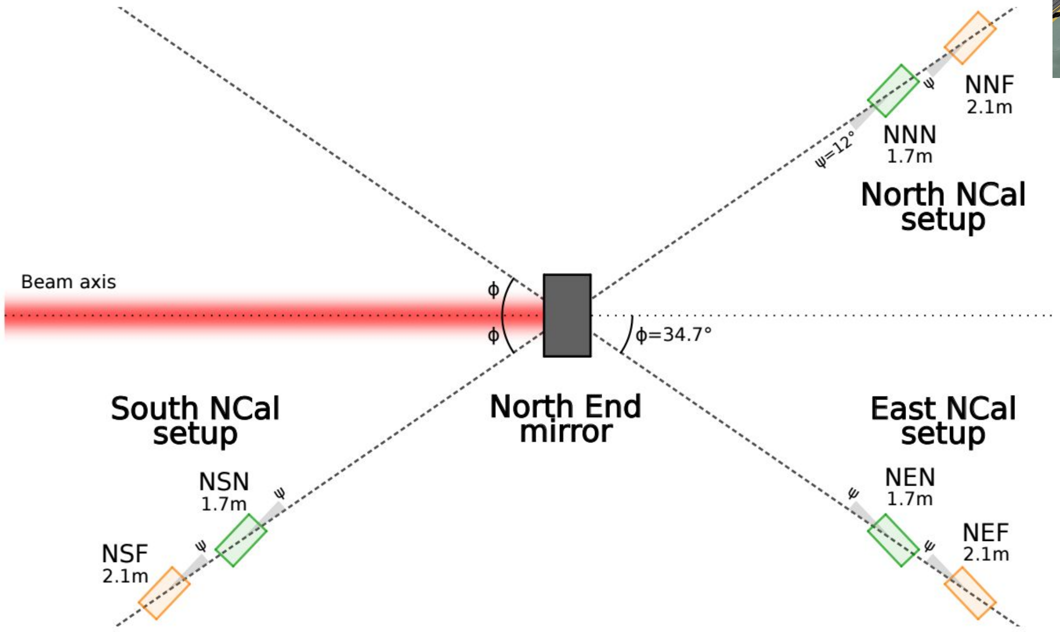


Machining -> Geometry measurements -> Simulation

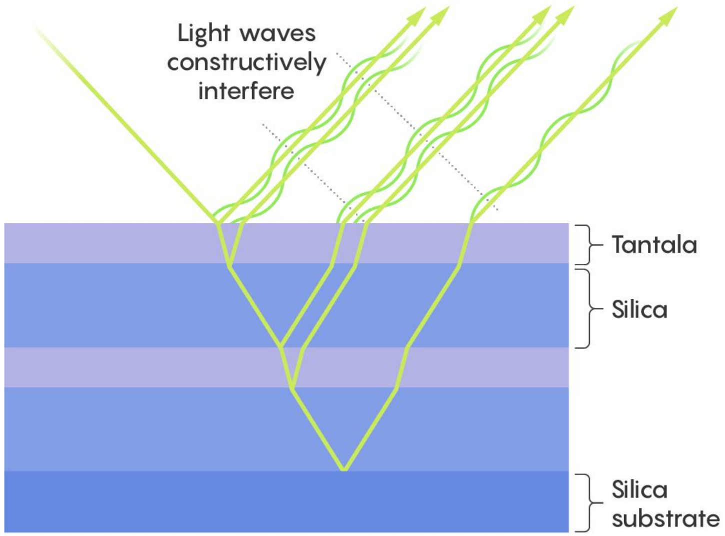
Installation work

Metrology, installation and monitoring (sensors)



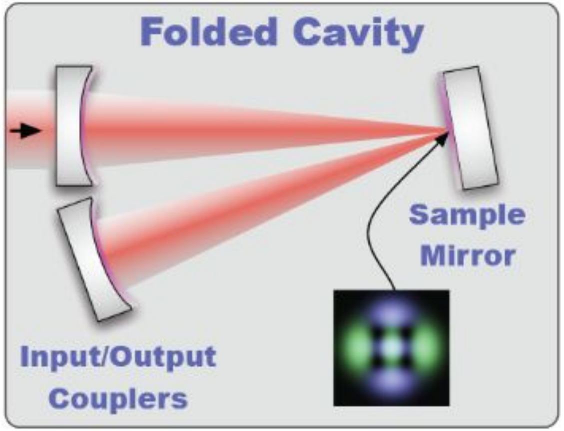
My PostDoc work: Measuring mirror coating thermal noise
MicronG



Layers of alternating High reflection and Low Reflection index materials } = Coating

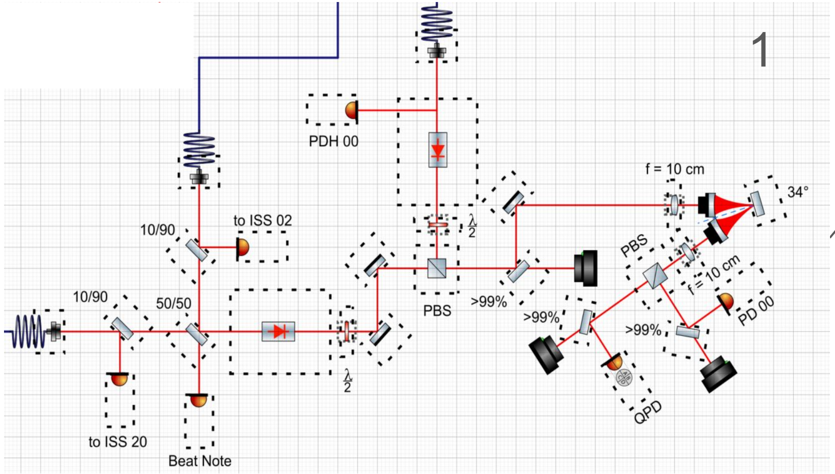
Coating thermal noise = mechanical dissipation in the coating

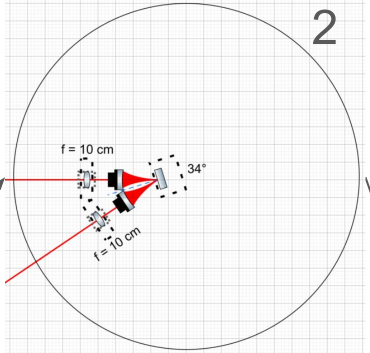
➔ How to measure it?

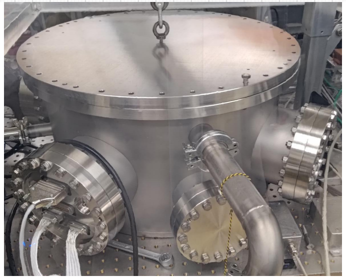


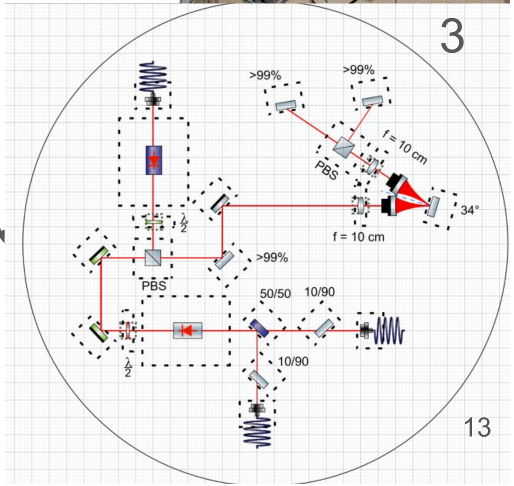
Objectifs de l’expérience MICRONG au LAPP

- Start with in-air measurement (this year).
- Moving to vacuum in 2026.





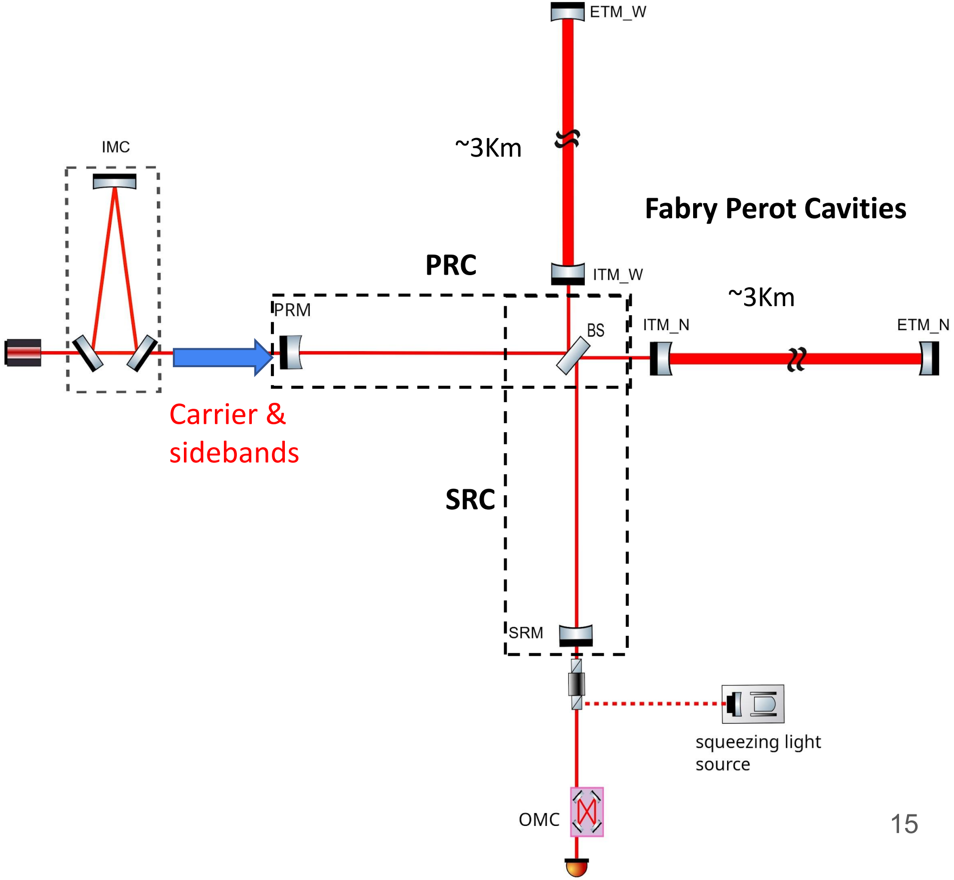




Future upgrades of Virgo (inshallah)

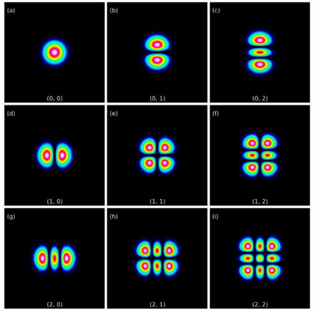
Design of Virgo gravitational waves detector

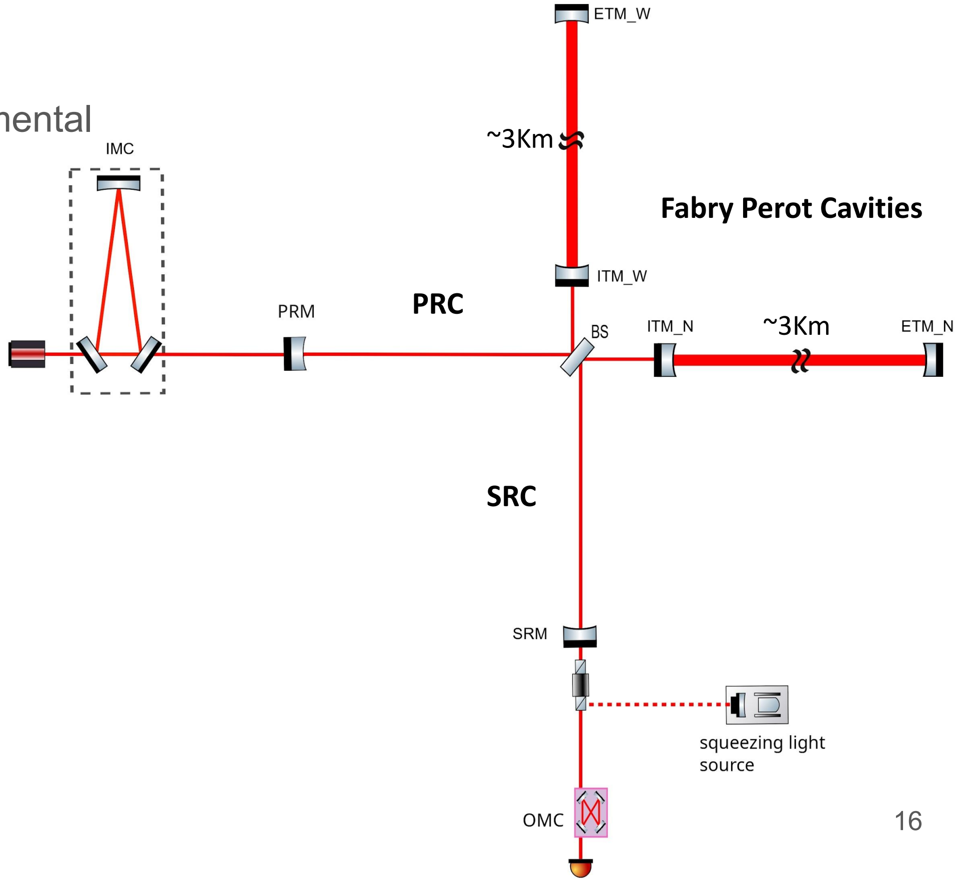
- The detection requires measuring tiny changes of length ($\Delta L \sim 10^{-18}$m).
  - Power on the output photodiode: $\delta P \propto P\_input \times \Delta L$
  - **Fabry-Perot cavities**: amplifies the beam power and optical path.
  - **Power recycling cavity (PRC)**: increase the power at the BS.
  - **Signal recycling cavity (SRC)**: increase the detection bandwidth.



Design of Virgo gravitational waves detector: Disadvantages

- Degenerate recycling cavities
  - High-order modes co-resonate with the fundamental mode.





- **Consequences:**
  - **Difficulty to control the detector.**
  - **Larger optical losses.**
  - **Increase the noise.**

Upgrade of Advanced Virgo+: stable recycling cavities

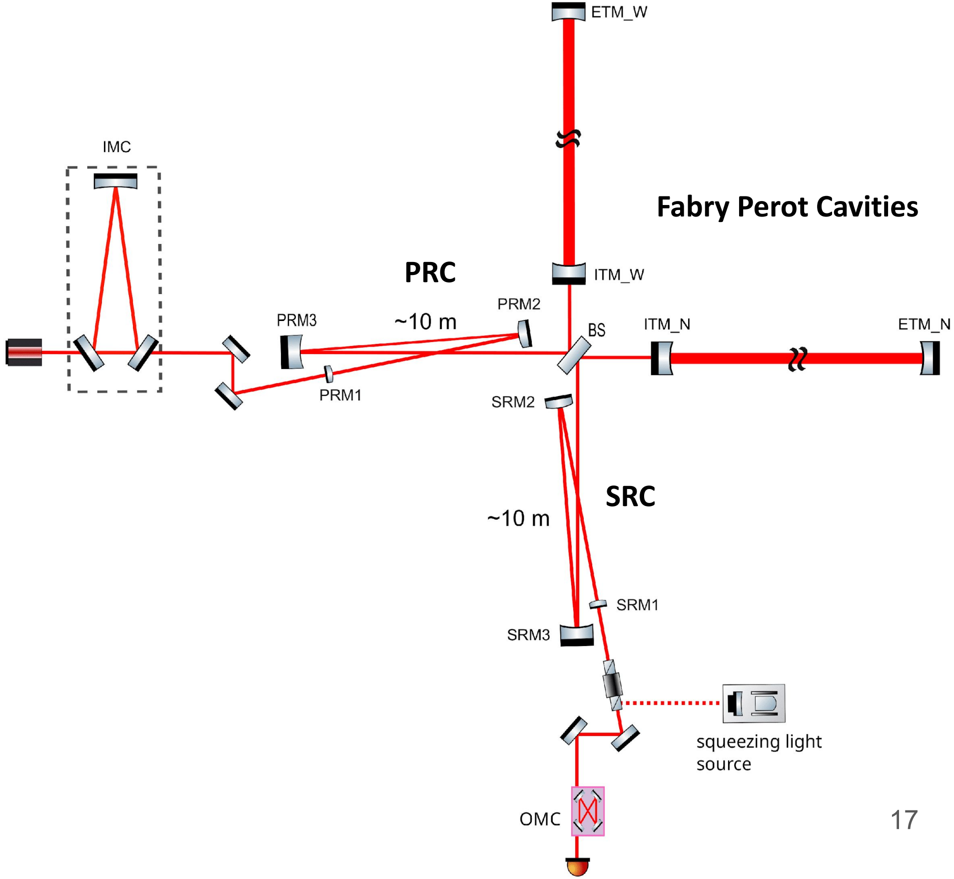
- **Solution: Use non degenerate recycling cavities**

Geometrical constraints on the stable cavities design: (limited infrastructure)

  - Short focusing telescope of the cavity
  - Angle of incidence on P/SR3 $\gtrsim 1^{o}$

Design of the cavity:

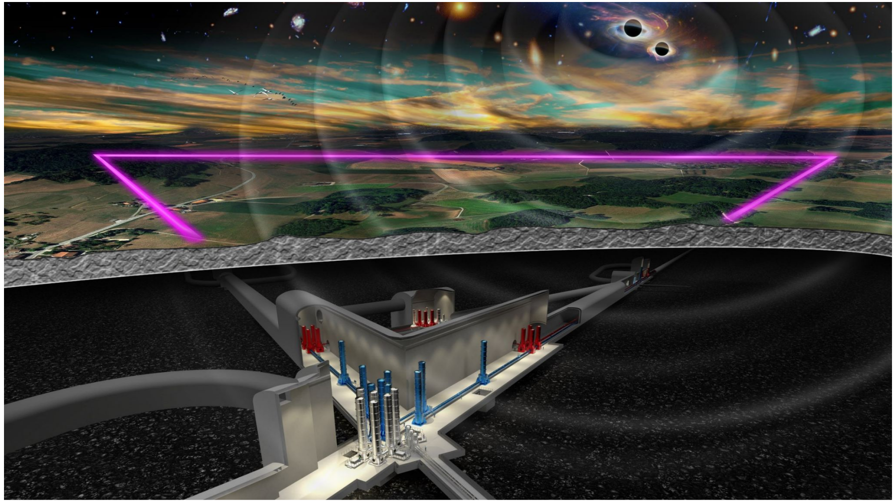
- Strongly curved mirrors ⟶ Spherical aberration losses.
- Non-negligible angles of incidence ⟶ Astigmatism losses

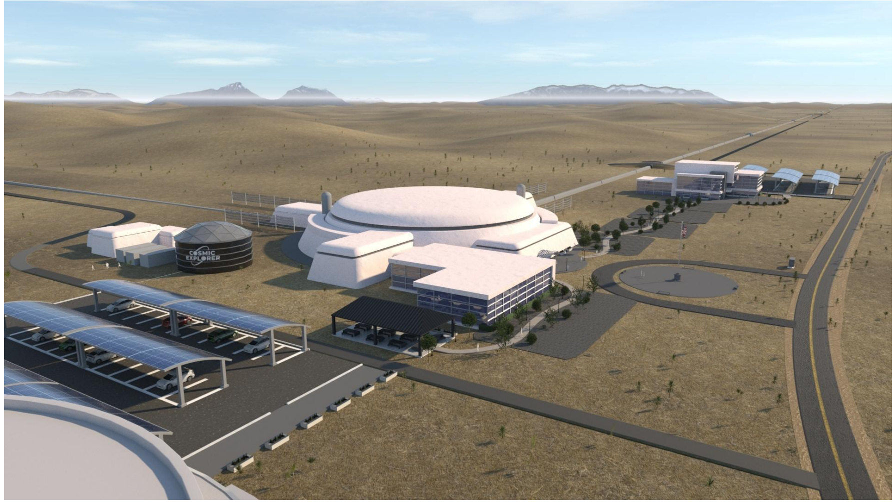


Next generation of ground-based detectors

Détecteurs de 3$^{\text{ème}}$ génération: Einstein Telescope (ET) et Cosmic Explorer (CE)

3rd generation detectors: Einstein Telescope (ET) & Cosmic Explorer (CE)






Thank you !

Le CTN dans Virgo

- Le CTN limite la sensibilité de Virgo autour de 100 Hz.
  - Zone critique pour la détection de signaux astrophysiques.
- Ce bruit dépend:
  - de la taille du faisceau sur le miroir
  - de la température du miroir
  - de l'épaisseur du revêtement
  - Des pertes mécaniques du revêtement