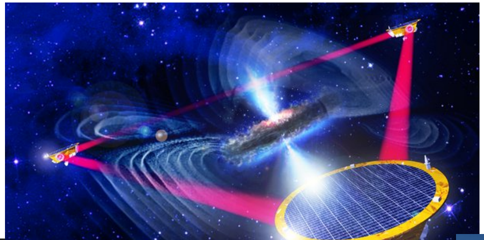
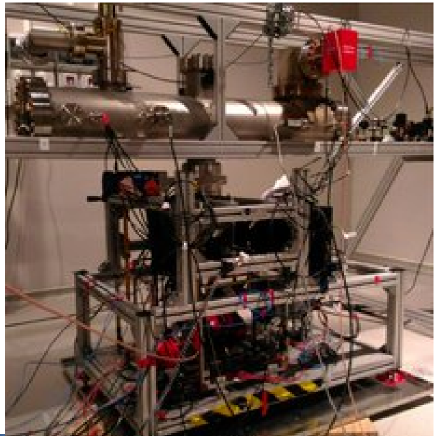
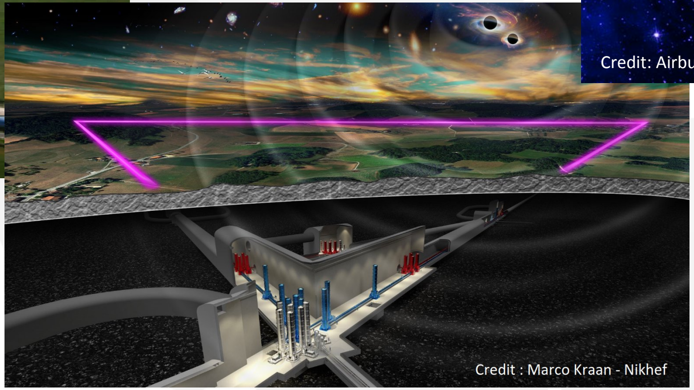
Gravitational wave detectors instrumental developments

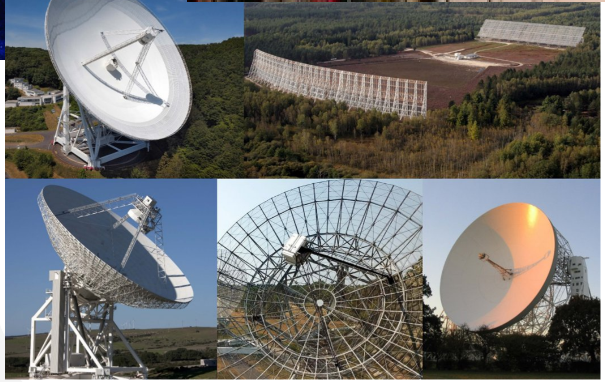


Credit: Airbus





Credit : Marco Kraan - Nikhef

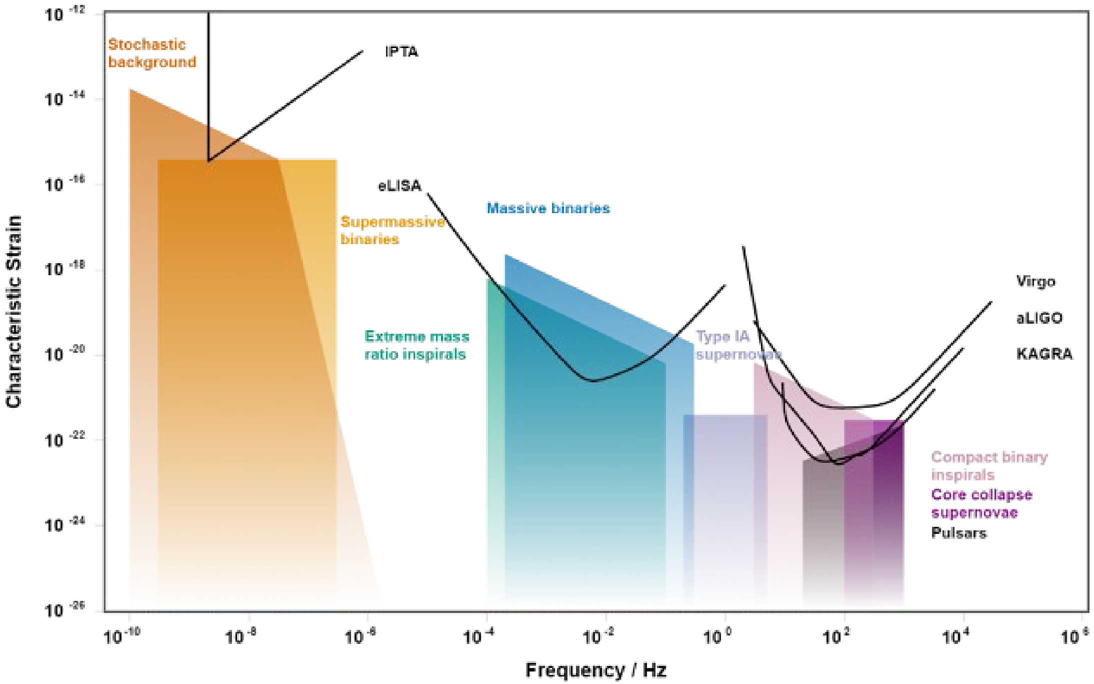


Angélique Lartaux

Short introduction on gravitational waves

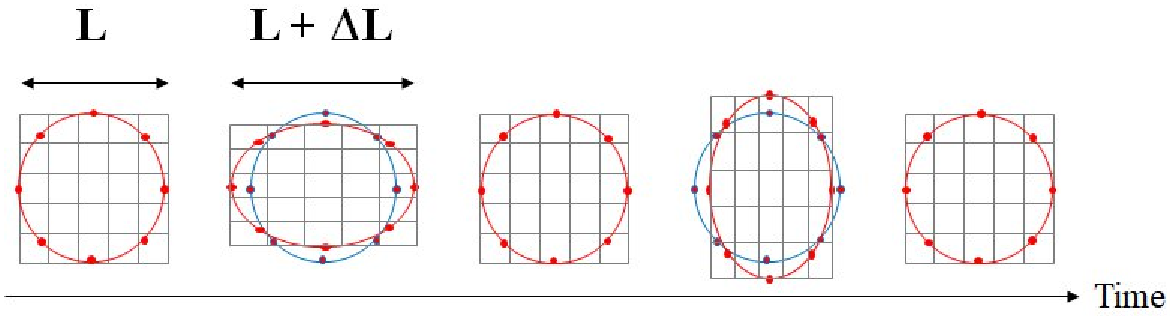
What are gravitational waves?

- ripples in the spacetime curvature predicted by Albert Einstein in 1916
- emitted by accelerating masses: binary compact coalescence, supernovae, etc.
- propagate at the speed of light
- amplitude observable h ~ 10^{-23}-10^{-14} at frequencies f ~ 10^{3} - 10^{-10} Hz



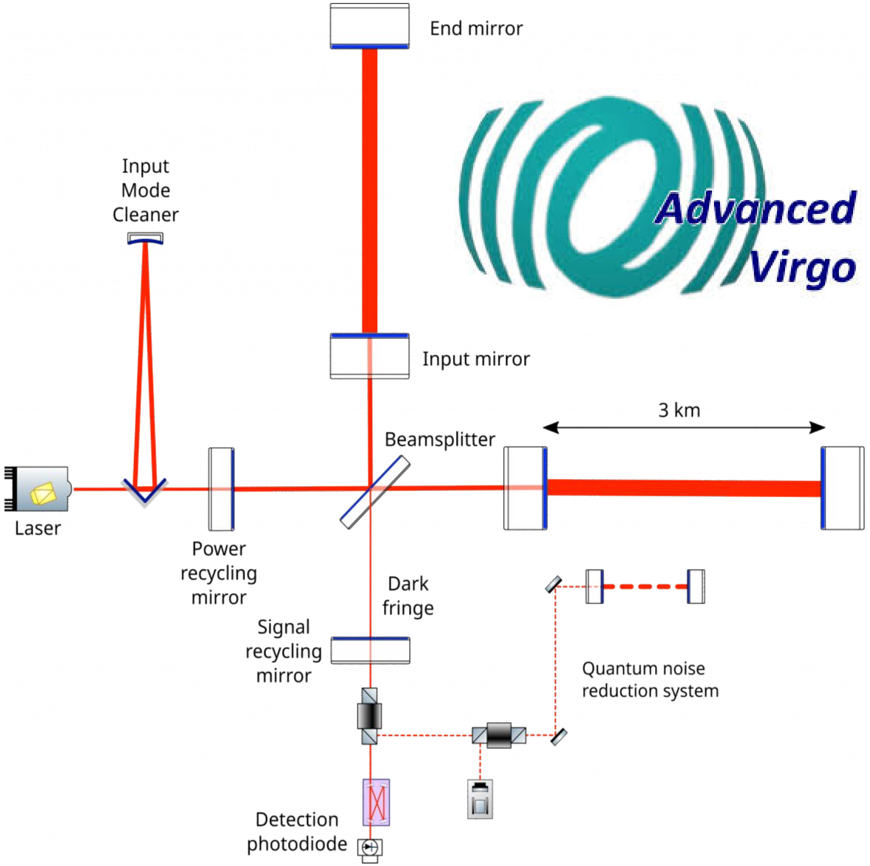
What is the observable?

- differential deformation of spacetime with $\frac{\Delta L}{L} \simeq \frac{h}{2}$

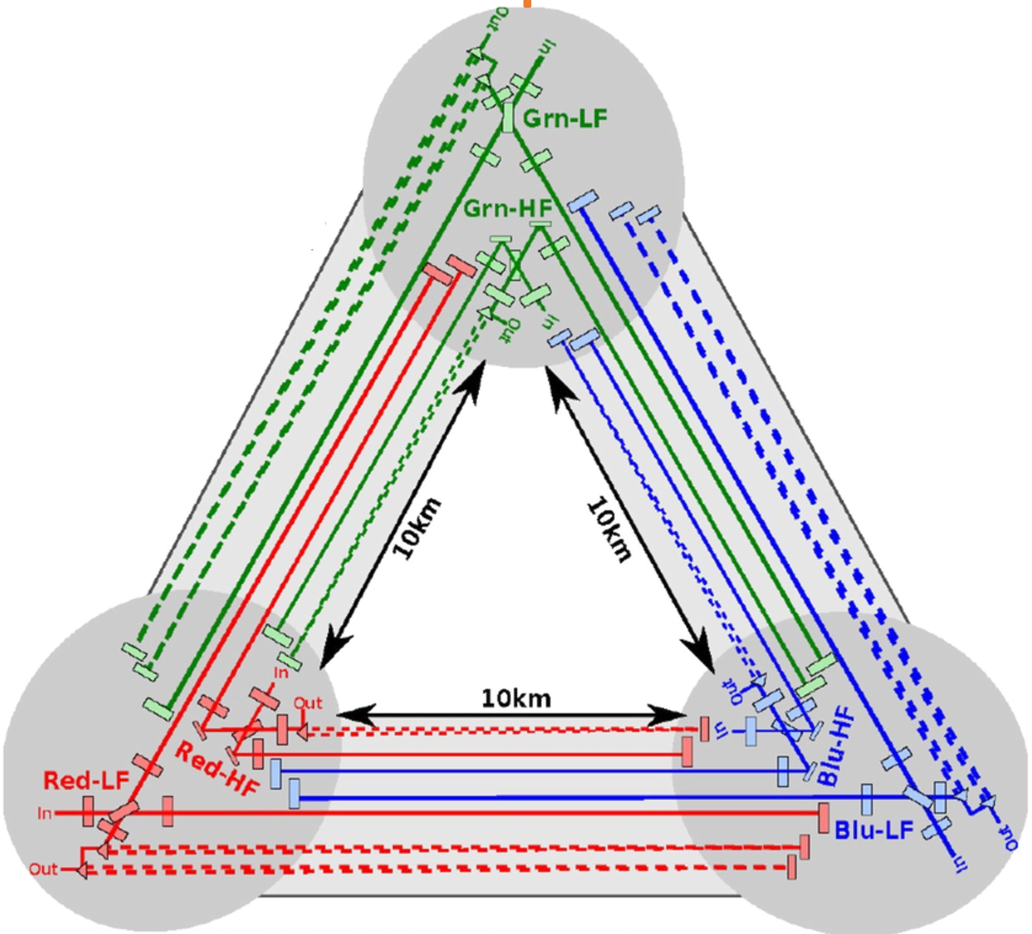


Ground based interferometric gravitational wave detectors

Advanced Virgo

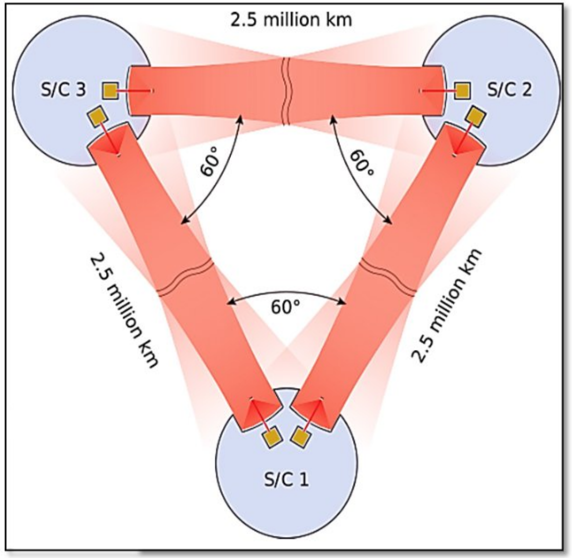


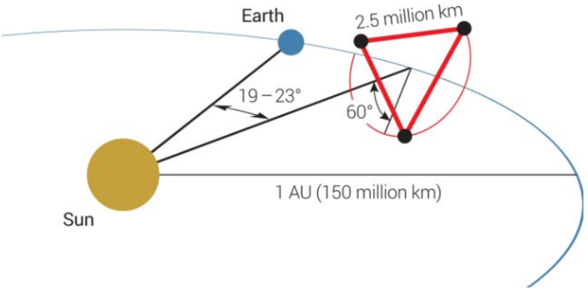
Einstein Telescope



But also other type of detectors on Earth or in space

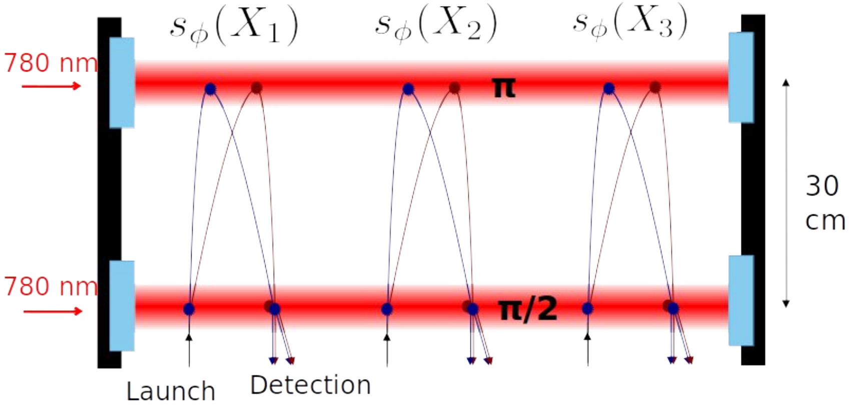
LISA

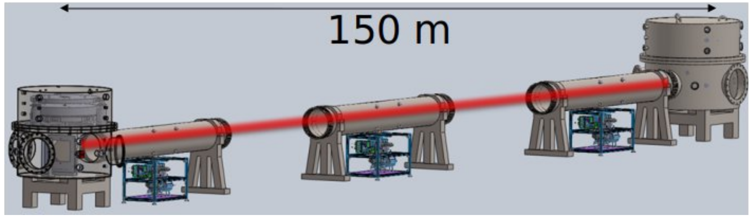




Presentation at GdR Ondes Gravitationnelles

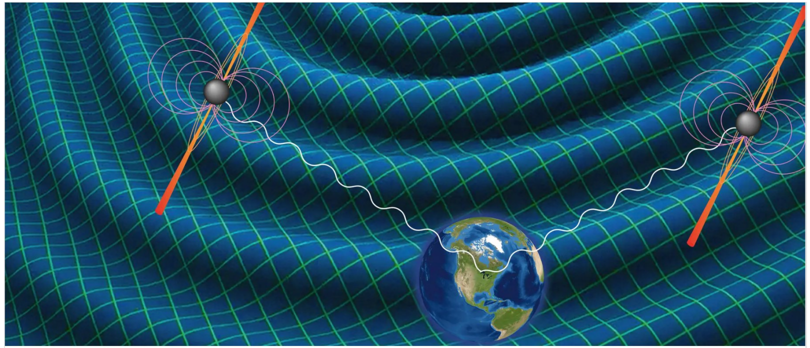
MIGA





Presentation at GdR Ondes Gravitationnelles

EPTA



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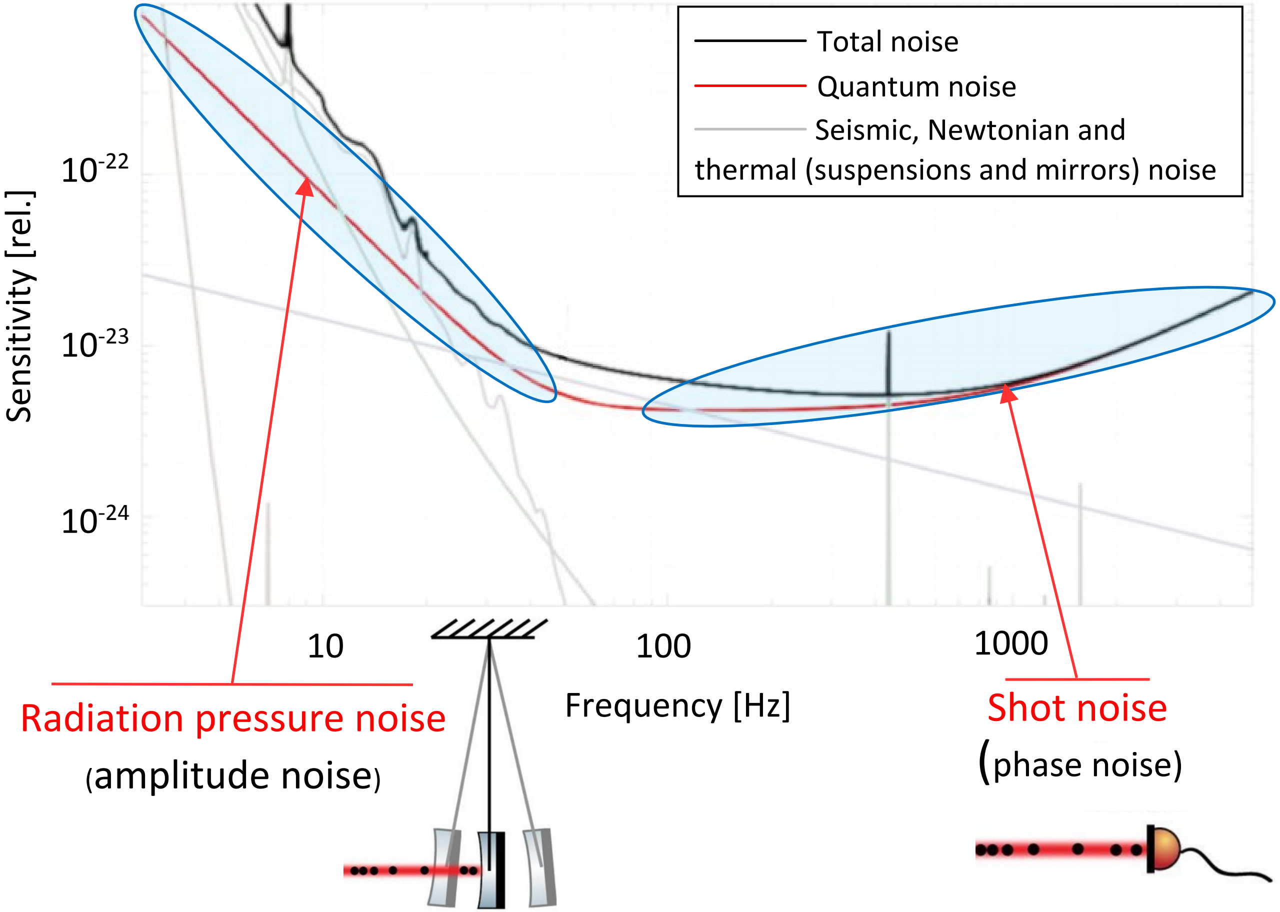
And more in projects

Quantum noise in Advanced Virgo in a nutshell

Sensitivity curve



Radiation pressure noise (amplitude noise)

Shot noise (phase noise)

- Quantum noise is limiting sensitivity at high frequencies
  - shot noise due to laser phase noise
- and close to limiting noises at low frequencies
  - radiation pressure noise due to laser amplitude noise

Squeezed states of light

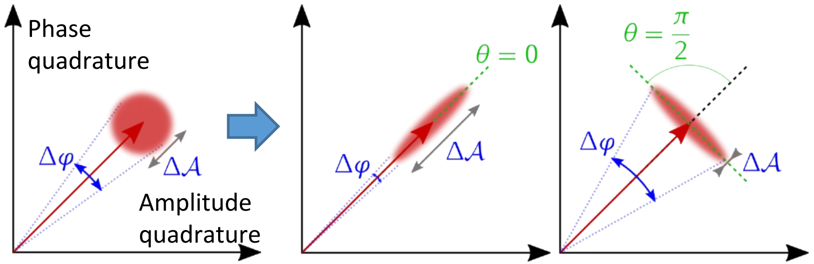
can be used to reduce quantum noise

Take advantage of quantum properties of light

- Heisenberg uncertainty relation:

$$\Delta A \times \Delta\varphi \geq 1$$

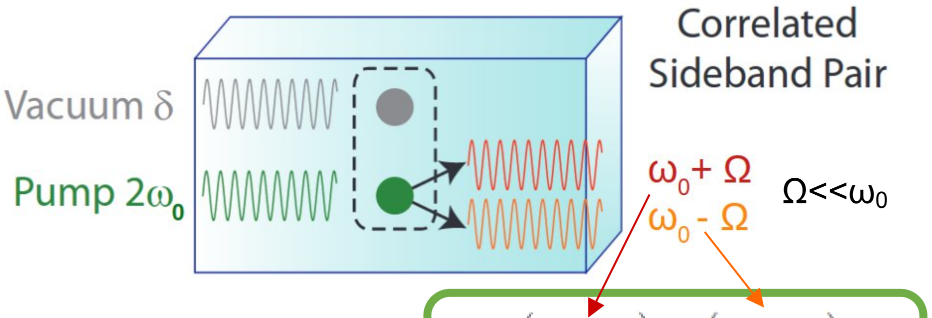
- It is possible to reduce noise in one quadrature (phase or amplitude) at the cost of increasing noise in the other one



Coherent state | Squeezing (phase) | Squeezing (amplitude)

2-photon Frequency Independent Squeezing (FIS) production via nonlinear interaction

- A pair of entangled infrared photons is created from a single green photon



Squeezing ellipse angle: $\boxed{\theta = \frac{\varphi(\omega_0+\Omega)+\varphi(\omega_0-\Omega)}{2}\ [\pi]}$

- A Fabry-Perot cavity is then used to obtain Frequency Dependent Squeezing (FDS)

Developments on Quantum Noise Reduction

State of the art

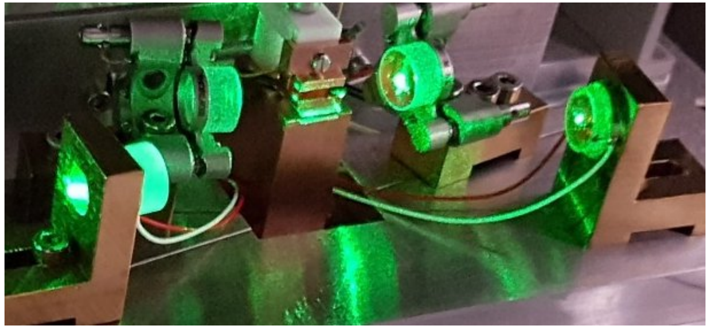
- Up to ~6 dB quantum noise reduction at high frequencies in LIGO using FDS with a 300-m filter cavity and starting from a FIS source of 17 dB
- 3-4 dB quantum noise reduction at high frequencies in Virgo using a FIS source of 8.5 dB
- 285-m filter cavity commissioned in Virgo for FDS

Goals

- 10 dB squeezing in Virgo_nEXT and Einstein Telescope
- Reduce loss sources

On-going R&Ds

- In-vacuum squeezing source @IJCLab



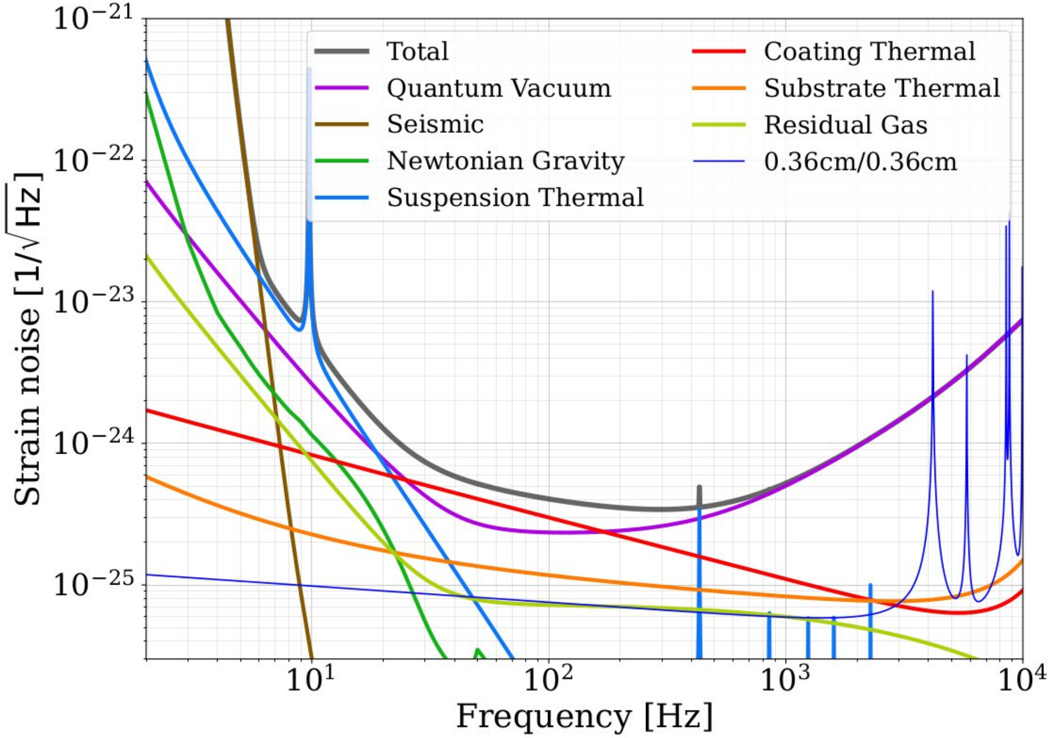
- Reduction of anti-reflective coatings @LMA
- New output mode cleaner @LAPP
- Adaptive matching telescopes @APC
- Filter cavity design:
    - Variable finesse @IJCLab
    - Topology for LF @APC

Presentation at GdR Ondes Gravitationnelles

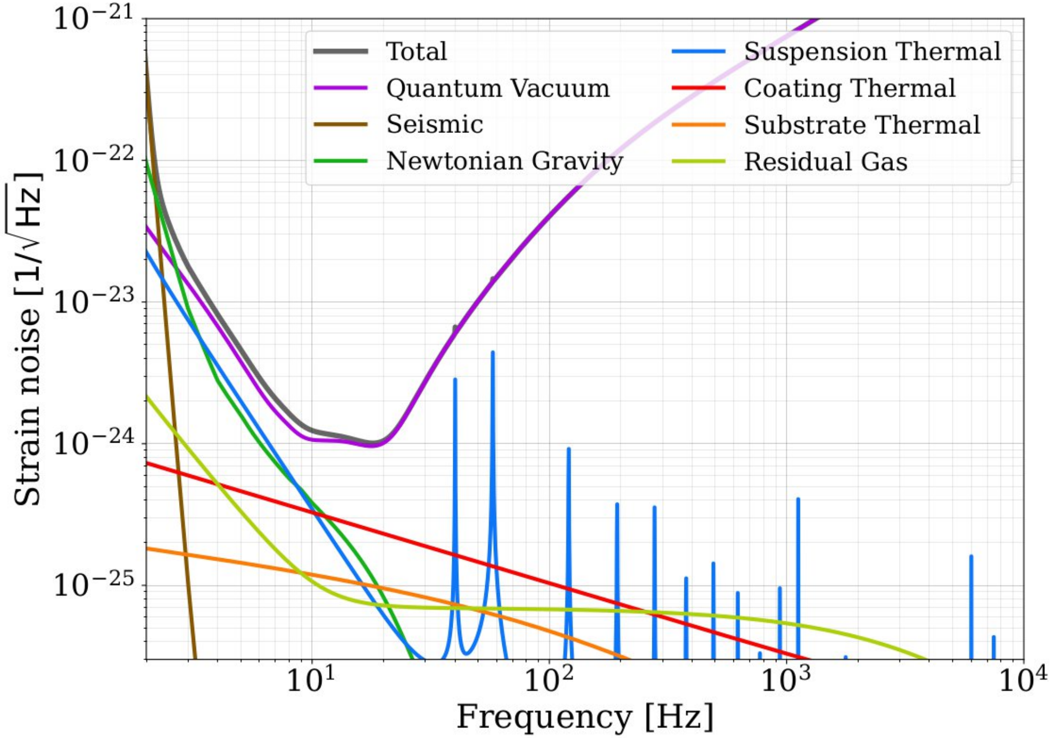
Quantum noise is not the only problem

- The example of Einstein Telescope (but this is also true for Virgo upgrade):

ET-HF sensitivity



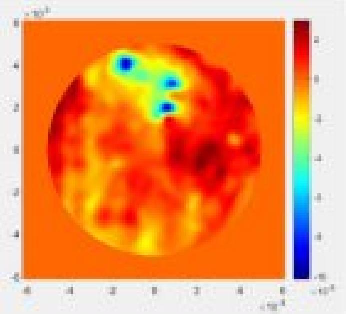
ET-LF sensitivity

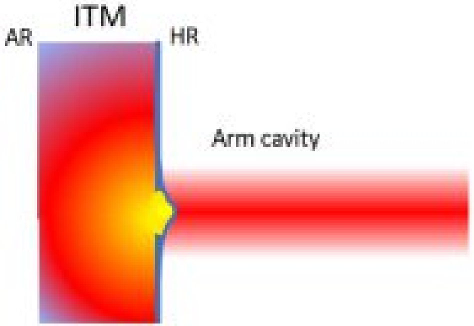


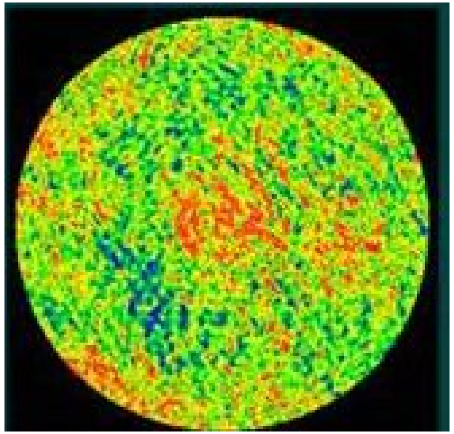
Examples of R&D developments – High quality mirrors

Improvement of optical properties of the mirrors

- Low defects
    - Point absorbers (thermal effects)
    - Point scatterers (optical losses)
- Measurement of the wavefront (reflected and transmitted) during the process
- Metrology / Characterization
- Study of new material: sapphire







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Examples of R&D developments – Coatings

Reduction of thermal noise

- Amorphous coatings
  - LMA is the leading laboratory for amorphous coatings on large optics for GW detectors (Virgo, LIGO)
  - Dedicated chamber for R&D on materials
  - Deposition process on the Grand Coater
  - Improvement of the control of coating layer thickness
- Crystalline coatings
  - Production and characterization of crystalline coatings
  - Demonstration of process on small sample
  - Process to be developped on larger samples:
    Collaboration with industry, Thermal noise measurement

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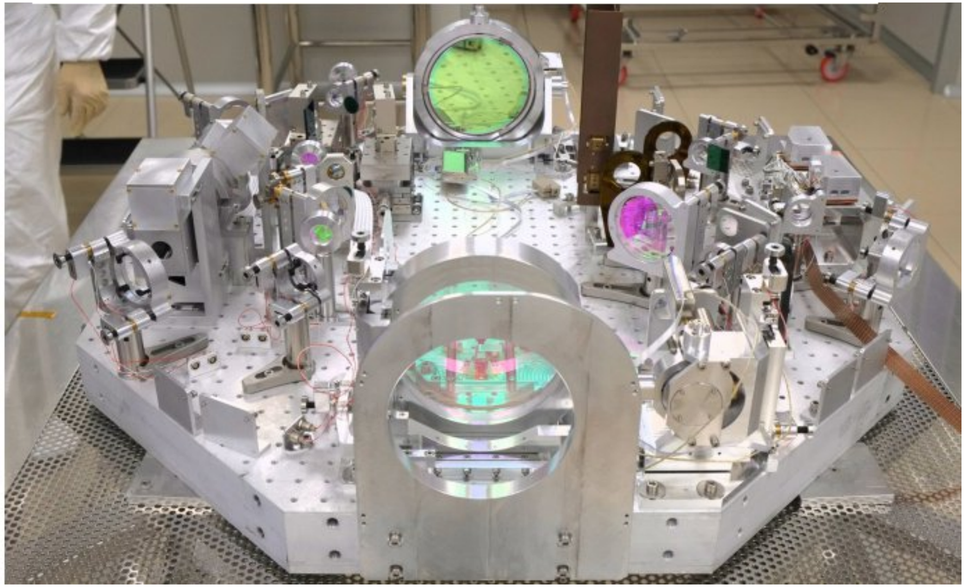
Examples of R&D developments – Suspended benches and auxiliary optics

Reduction of scattered light

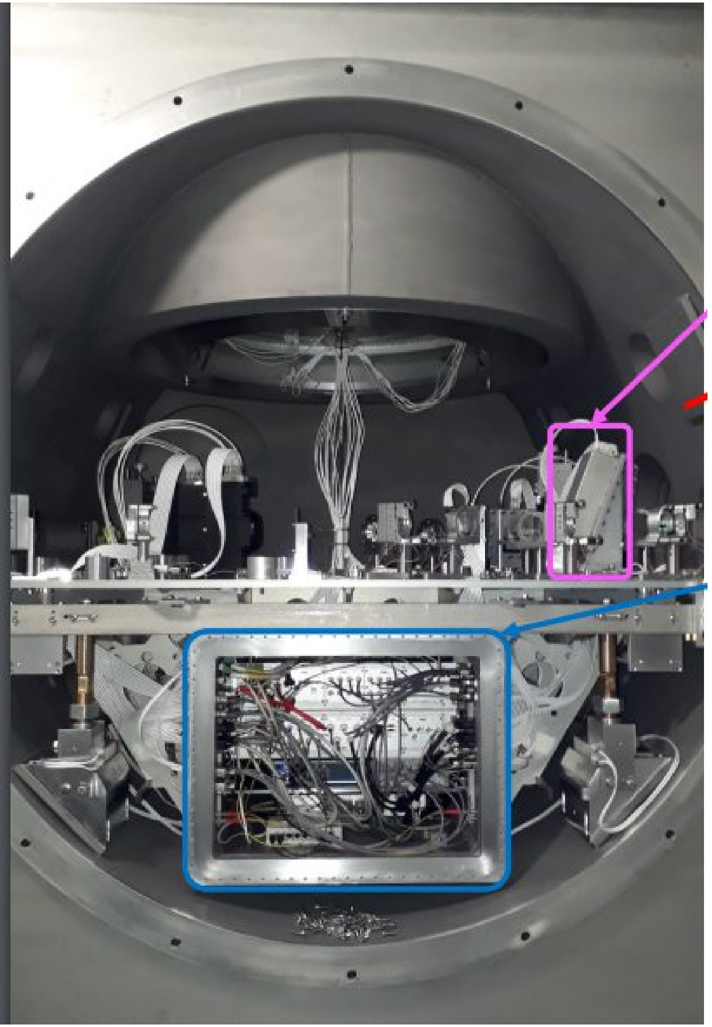
- Characterization of optical elements
- Improved optical elements
- Dedicated bench at Institut Fresnel (presentation at workshop R&D)



Development of suspended benches

- Project to innstall at LAPP an optical bench suspended under vacuum for developments and tests in optics, mechanics and electronics of the next decade (presentation at workshop R&D)
- Develop test benches in laboratories

Examples of R&D developments – Electronic and data acquisition

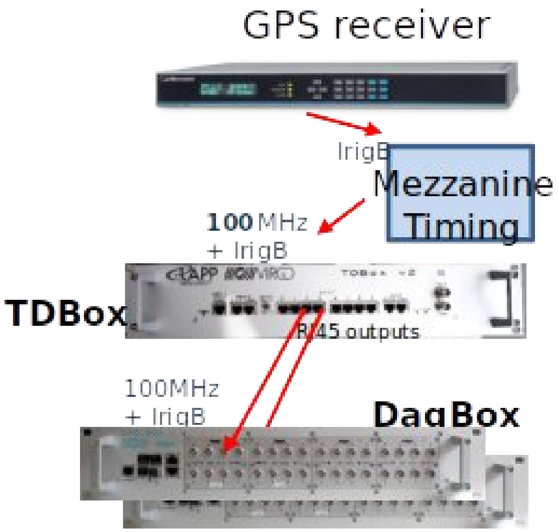


Reduce technical noises

- Analog electronics (photodiodes,...)
- Digital electronics
- Real time data treatment and acquisition
- Slow control

- Reduction of technical noises:
    - Improved photodiode preamplifiers
    - Move digital electronics outside vacuum tank

- White Rabbit timing distribution



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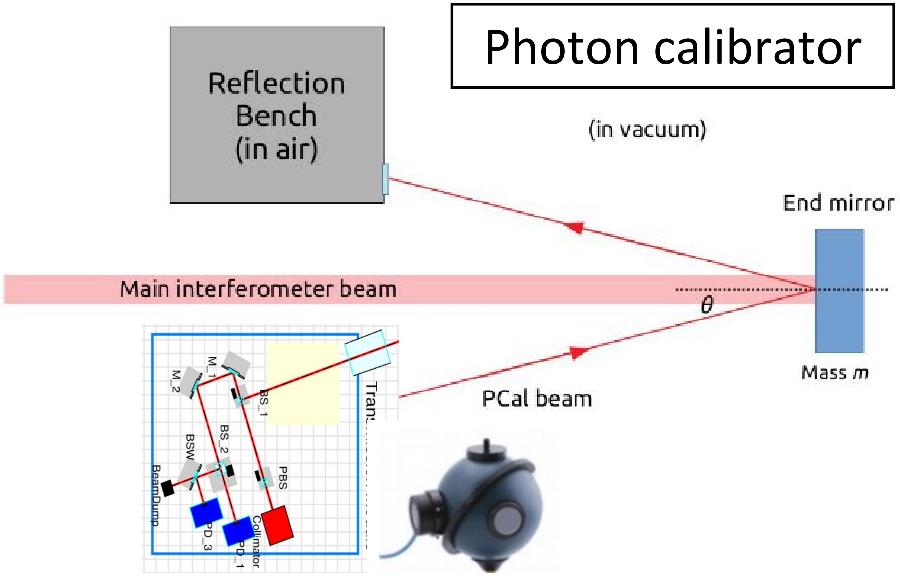
Examples of R&D developments – Calibration and signal reconstruction

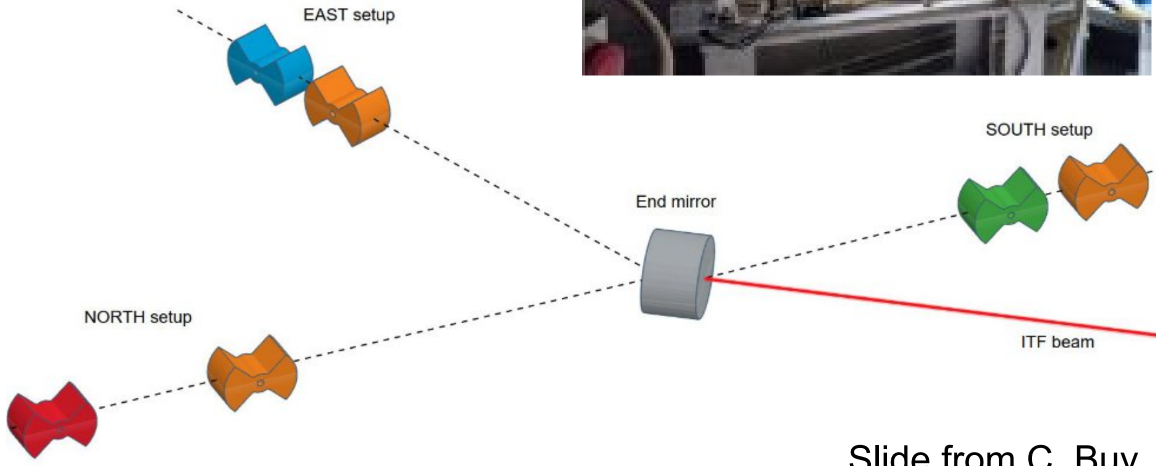
Improve calibration to sub-percent sensitivities

- Photon calibrator: precise powermeters (under vacuum?) , electronics, upgrade of optical benches
- Newtonian calibrator: improved seismic isolation, upgraded rotors
- Signal reconstruction software: reduction of systematic uncertainties

Photon calibrator



Newtonian calibrator



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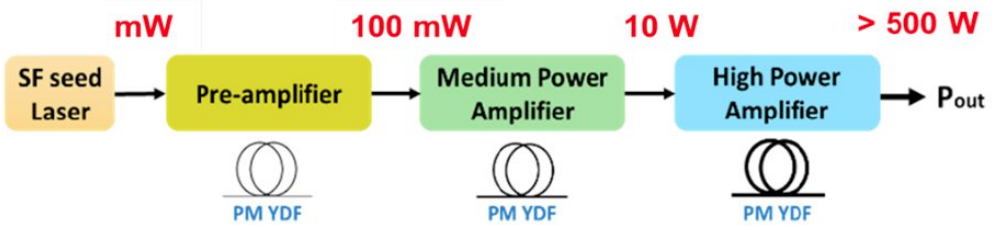
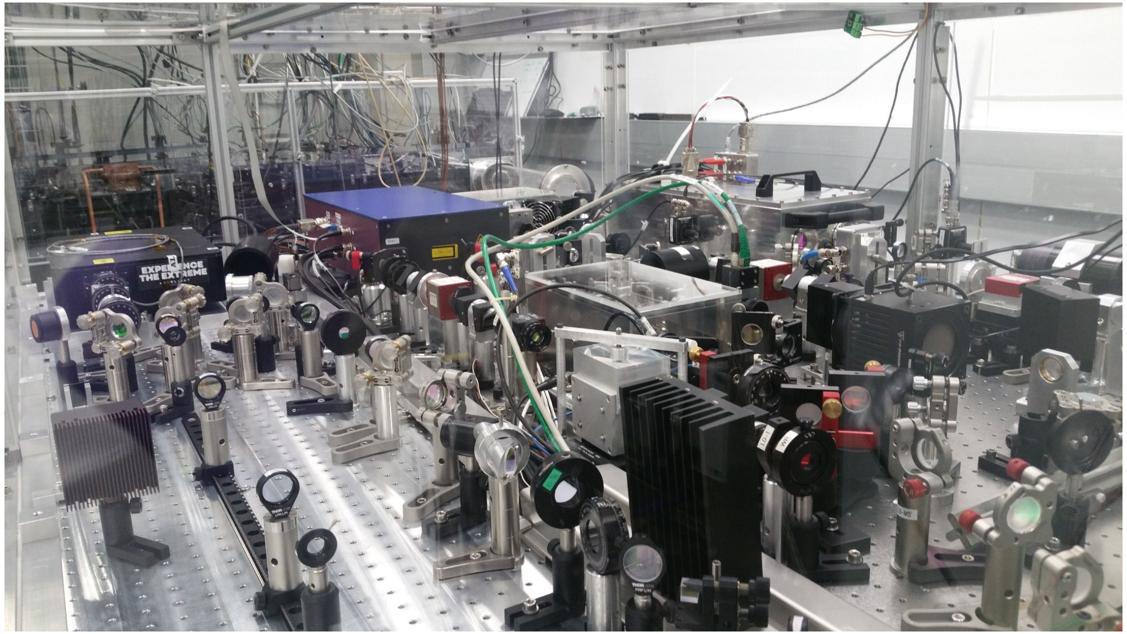
Examples of R&D developments – High power lasers

Have a 300-500W stabilized laser

- Fiber amplifiers technology to reach the goal powers
- Tests this technology with Virgo: improve the noise, the long term stability and use it for O5 (mix fiber amplifier + solid state or home-made fiber amplifier)
- Technology scalable for ET and the only one known to reach 300-500W


mW
100 mW
10 W
> 500 W
SF seed Laser → Pre-amplifier → Medium Power Amplifier → High Power Amplifier → P_{out}
PM YDF
PM YDF
PM YDF



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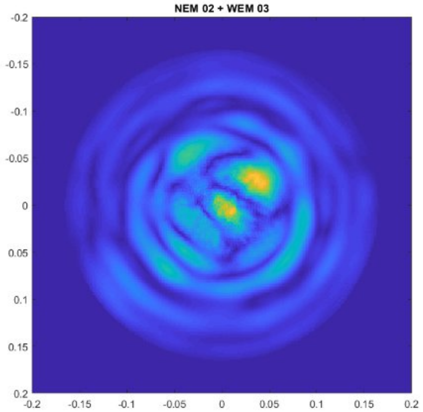
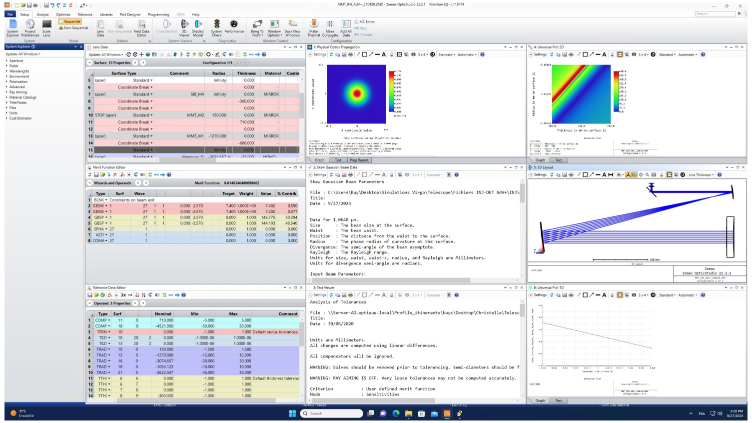
Examples of R&D developments – Optical simulations

Simulation to predict the behavior of complex systems and providing guidance for commissioning



- Development of optical simulation software (OSCAR, DarkF, Finesse...)
- Design studies using optical simulation tools (Zemax, Optocad, OSCAR,...)
- Simulation studies for the understanding/anticipation of the interferometer behaviour:
  - Impact of defects and optical losses
  - Impact of high power
  - Coupling of technical noises
- Simulation studies are (more and more) essential for:
  - the understanding of Advanced Virgo+
  - the design of Virgo_nEXT and ET (guided by AdV+ experience)



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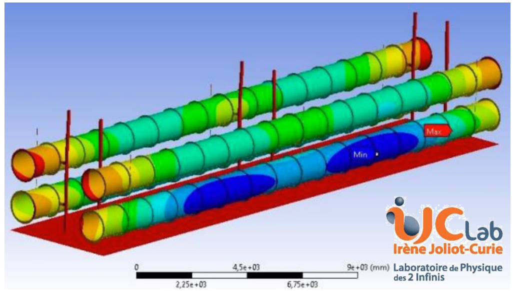
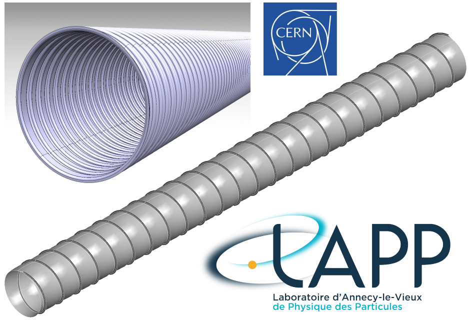
Examples of R&D developments – Vacuum

Beam pipes

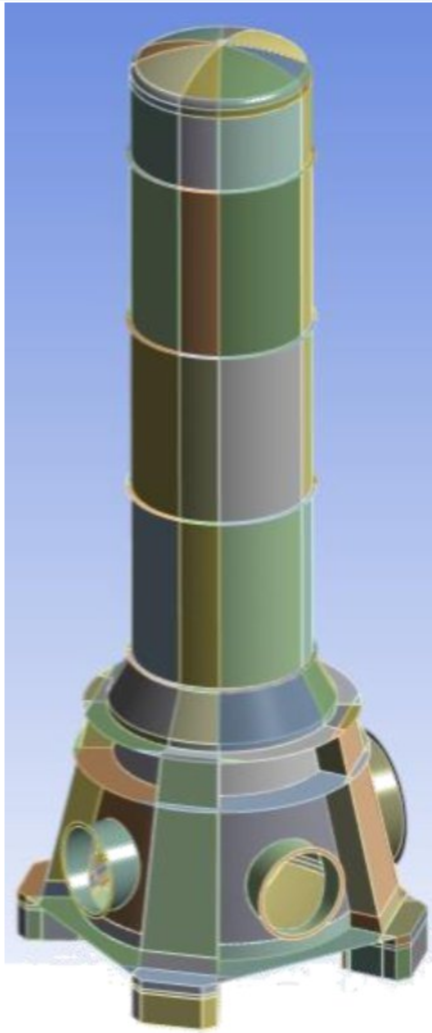
- Agreement with CERN to design the vacuum pipes (TDR + prototype)
- 4 vacuum tubes of 1m diameter per tunnel
- ~50 years lifespan expected
- Virgo as a baseline: 3 designs under consideration
- Undergoing discussions with industry





Towers

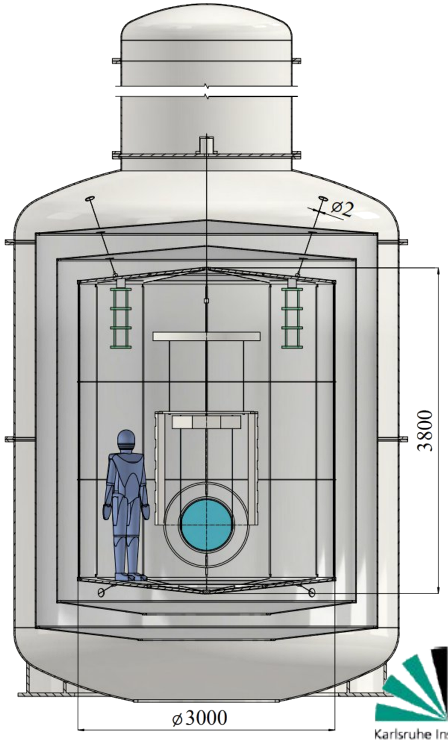
- Design of ET-HF towers adapted from the Virgo towers
- Modal analysis undergoing
- Optimization of the weight and resonance frequency
- Design of ET-LF towers under discussion with several propositions depending on suspension chain and cryostat design
- Clean room infrastructure around the towers



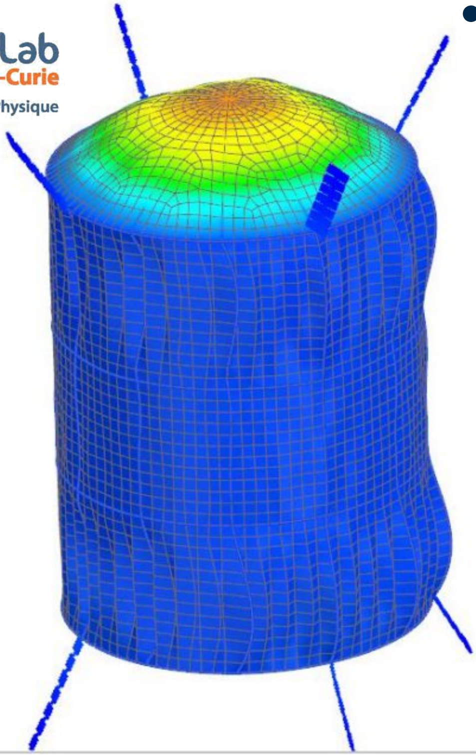
Examples of R&D developments – Cryogenics

Cryostat

- Active cooling of the 2 external thermal shields
- Superfluid Helium-II cooling of inner shield



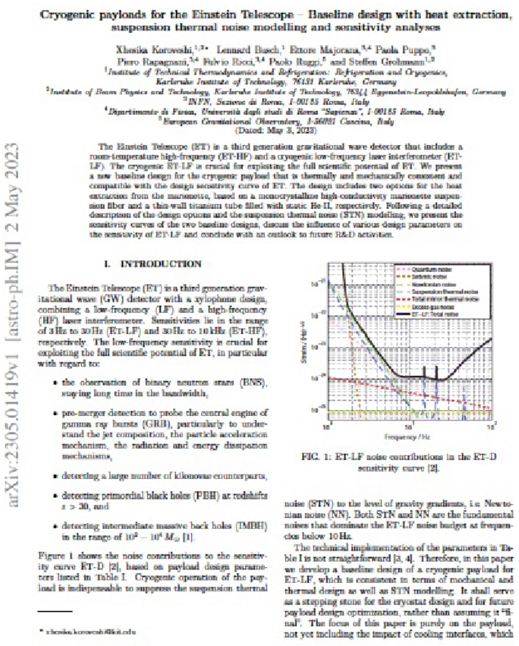
IJCLab
Irène Joliot-Curie
Laboratoire de Physique des 2 Infinis



KIT
Karlsruhe Institute of Technology

ET-LF Payload

- Design for heat extraction with low suspension thermal noise
- Allow for large mirrors



Cryogenic payloads for the Einstein Telescope – Baseline design with heat extraction, suspension thermal noise modelling and sensitivity analyses

Xhesika Koroveshi,[1,2,*] Lennard Busch,[1] Ettore Majorana,[3,4] Paola Puppo,[3]
Piero Rapagnani,[3,4] Fulvio Ricci,[3,4] Paolo Ruggi,[5] and Steffen Grohmann[1,2]
[1]*Institute of Technical Thermodynamics and Refrigeration: Refrigeration and Cryogenics, Karlsruhe Institute of Technology, 76131 Karlsruhe, Germany*
[2]*Institute of Beam Physics and Technology, Karlsruhe Institute of Technology, 76344 Eggenstein-Leopoldshafen, Germany*
[3]*INFN, Sezione di Roma, I-00185 Roma, Italy*
[4]*Dipartimento di Fisica, Università degli studi di Roma "Sapienza", I-00185 Roma, Italy*
[5]*European Gravitational Observatory, I-56021 Cascina, Italy*
(Dated: May 3, 2023)

arXiv:2305.01419v1 [astro-ph.IM] 2 May 2023

The Einstein Telescope (ET) is a third generation gravitational wave detector that includes a room-temperature high-frequency (ET-HF) and a cryogenic low-frequency laser interferometer (ET-LF). The cryogenic ET-LF is crucial for exploiting the full scientific potential of ET. We present a new baseline design for the cryogenic payload that is thermally and mechanically consistent and compatible with the design sensitivity curve of ET. The design includes two options for the heat extraction from the marionette, based on a monocrystalline high-conductivity marionette suspension fiber and a thin-wall titanium tube filled with static He-II, respectively. Following a detailed description of the design options and the suspension thermal noise (STN) modelling, we present the sensitivity curves of the two baseline designs, discuss the influence of various design parameters on the sensitivity of ET-LF and conclude with an outlook to future R&D activities.

I. INTRODUCTION

The Einstein Telescope (ET) is a third generation gravitational wave (GW) detector with a xylophone design, combining a low-frequency (LF) and a high-frequency (HF) laser interferometer. Sensitivities lie in the range of 3 Hz to 30 Hz (ET-LF) and 30 Hz to 10 kHz (ET-HF), respectively. The low-frequency sensitivity is crucial for exploiting the full scientific potential of ET, in particular with regard to:

- the observation of binary neutron stars (BNS), staying long time in the bandwidth,
- pre-merger detection to probe the central engine of gamma ray bursts (GRB), particularly to understand the jet composition, the particle acceleration mechanism, the radiation and energy dissipation mechanisms,
- detecting a large number of kilonovae counterparts,
- detecting primordial black holes (PBH) at redshifts $z > 30$, and
- detecting intermediate massive back holes (IMBH) in the range of $10^2 - 10^4\,M_\odot$ [1].

Figure 1 shows the noise contributions to the sensitivity curve ET-D [2], based on payload design parameters listed in Table I. Cryogenic operation of the payload is indispensable to suppress the suspension thermal noise (STN) to the level of gravity gradients, i.e. Newtonian noise (NN). Both STN and NN are the fundamental noises that dominate the ET-LF noise budget at frequencies below 10 Hz.

FIG. 1: ET-LF noise contributions in the ET-D sensitivity curve [2].

The technical implementation of the parameters in Table I is not straightforward [3, 4]. Therefore, in this paper we develop a baseline design of a cryogenic payload for ET-LF, which is consistent in terms of mechanical and thermal design as well as STN modelling. It shall serve as a stepping stone for the cryostat design and for future payload design optimization, rather than assuming it "final". The focus of this paper is purely on the payload, not yet including the impact of cooling interfaces, which

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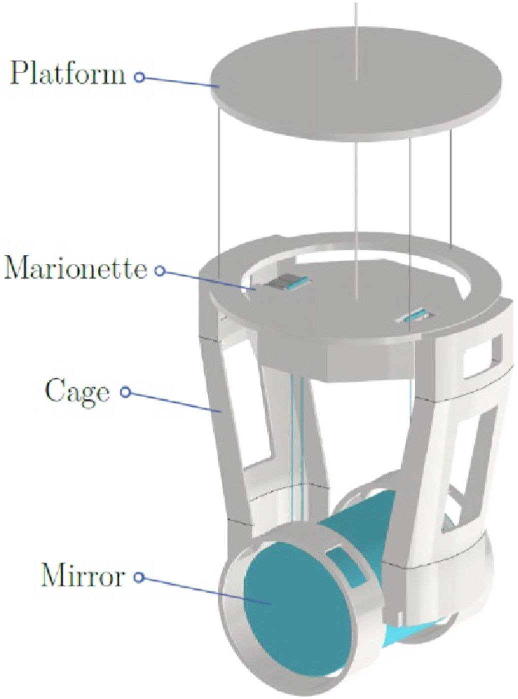
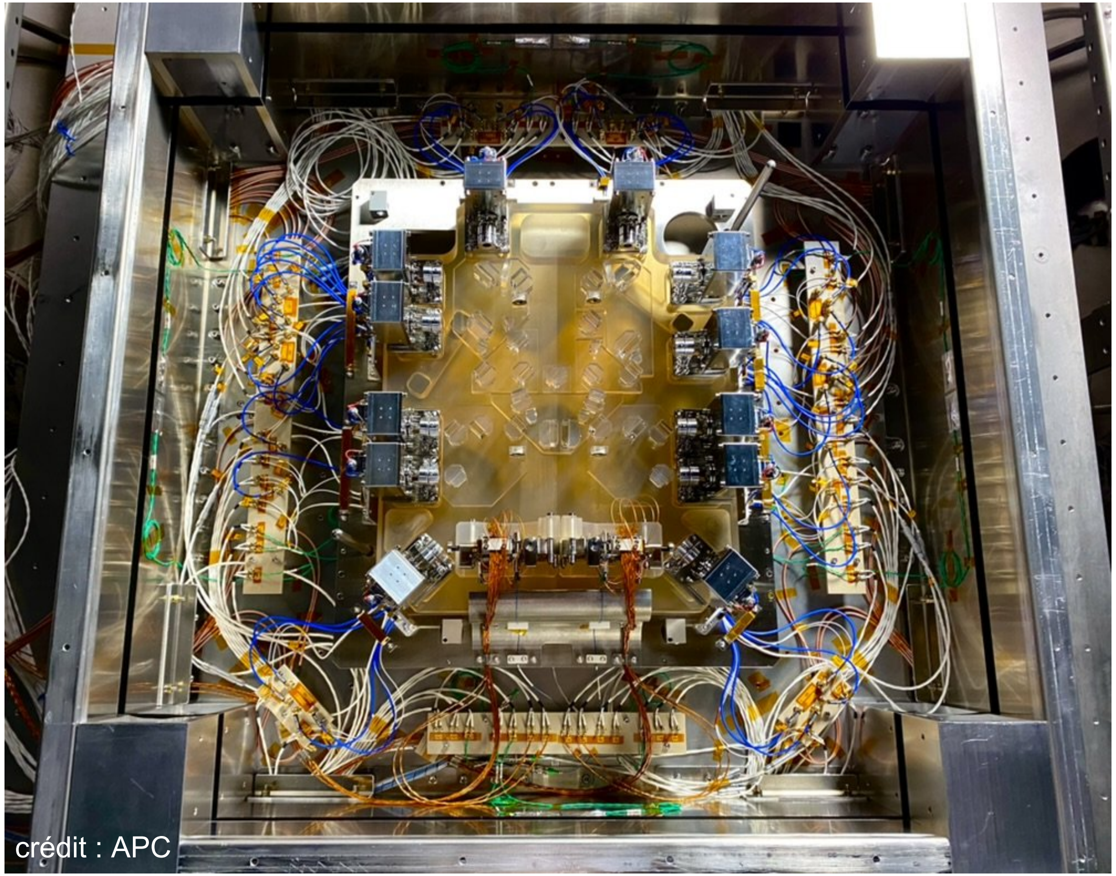
[*] xhesika.koroveshi@kit.edu



Examples of R&D developments – LISA

ZIFO (Zerodur InterFerOmeter)

- Development of an ultra-stable optical bench for demonstrating the on-ground characterization capabilities
- Pathlength stability (few pm/sqrt(Hz))
- Organize the french community towards the MOSA OGSEs developments
- Identify and quantify the main noise sources in a relevant environment
- Evaluate the complexity of MOSA performance tests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Conclusion

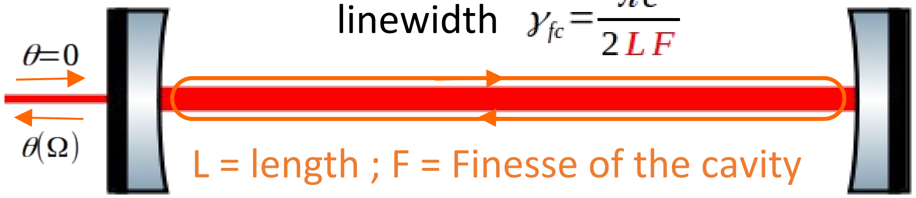
- There are lots of technological developments both for Virgo and LISA now and Einstein Telescope in the future (workshop on Virgo/ET R&D in March 2024)
- Several domains are of interest as quantum technologies, cryogenics, laser (from generation to detection through propagation), electronics, simulation at all levels, etc.
- Other projects of gravitational waves detection based on different principles are under study
- Instrumental development of all gravitational wave detectors are discussed at GdR Ondes Gravitationnnelles

Thank you for your attention

Theory of frequency dependent squeezing

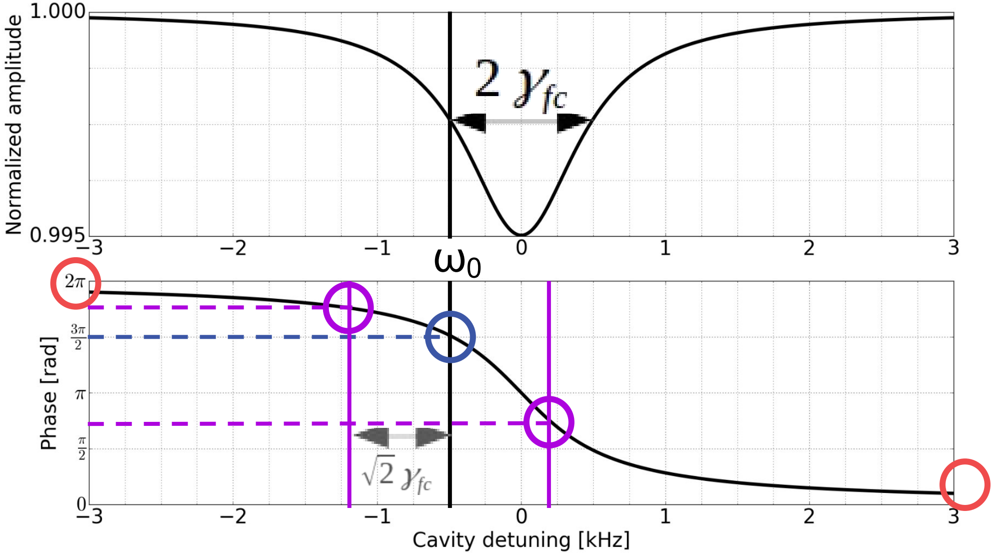
Filter cavity

- FIS in phase enter the cavity => θ = 0

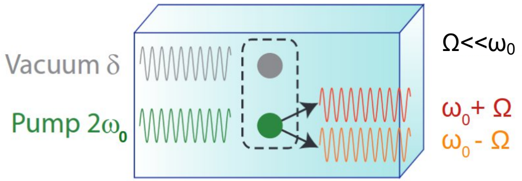


linewidth $\gamma_{fc}=\frac{\pi c}{2LF}$

L = length ; F = Finesse of the cavity



Squeezing angle



$$\boxed{\theta=\frac{\varphi(\omega_0+\Omega)+\varphi(\omega_0-\Omega)}{2}\;[\pi]}$$

- After reflection on the filter cavity :
  - If $\Omega \gg \sqrt{2}\gamma_{fc} \Rightarrow 2\theta = 0 + 2\pi \Rightarrow \theta = \pi = 0\ [\pi]$
  - If $\Omega = \sqrt{2}\gamma_{fc} \Rightarrow 2\theta = 3\pi/4 + 7\pi/4 \Rightarrow \theta = 5\pi/4 = \pi/4\ [\pi]$
  - If $\Omega = 0 \Rightarrow 2\theta = 3\pi/2 + 3\pi/2 \Rightarrow \theta = 3\pi/2 = \pi/2\ [\pi]$

Frequency Dependent Squeezing (FDS) is reflected