

**EINSTEIN
TELESCOPE**

R&D Roadmap

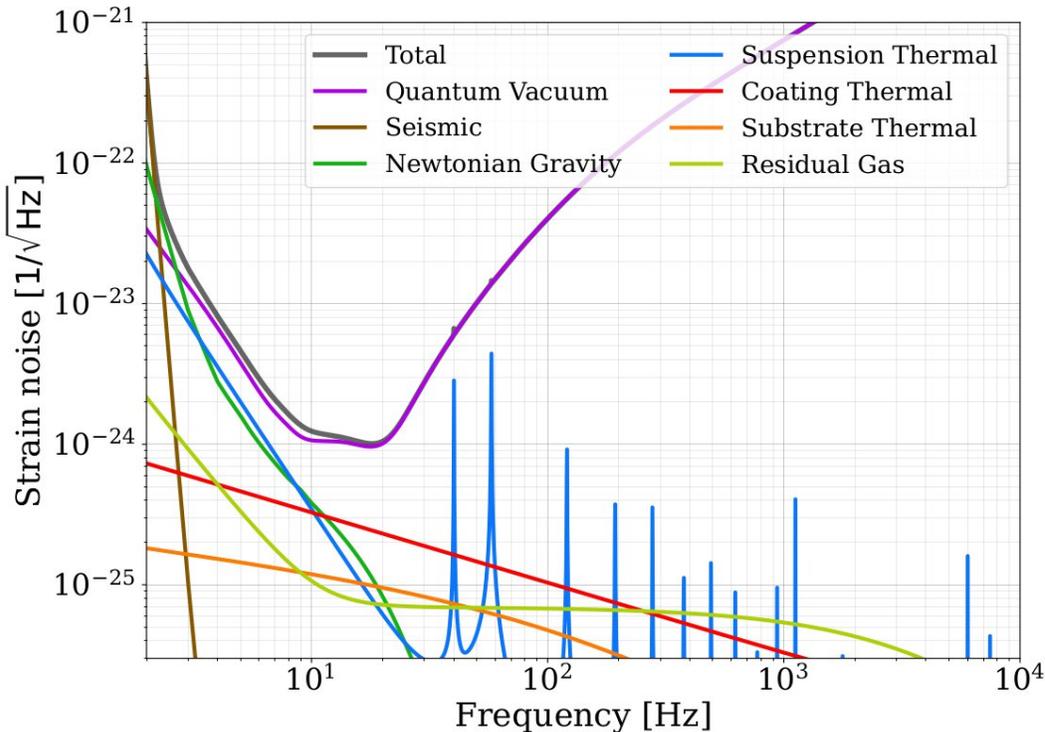
Angélique Lartaux

Einstein Telescope Thematic Day at CEA-Saclay

Introduction

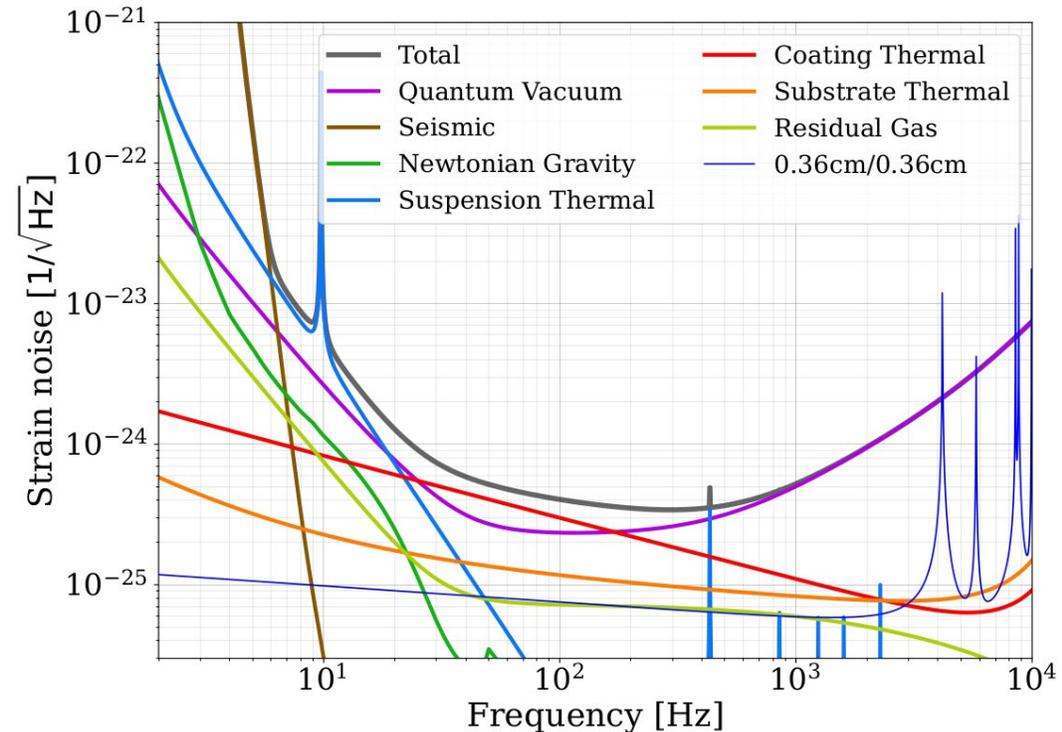
To reach Einstein Telescope sensitivity goal, lots of noise sources must be tackled by R&D developments (here limiting to R&Ds in France)

ET-LF sensitivity



Quantum Noise
=> High Power
=> Squeezing
Coating Thermal
=> New coatings
Substrate Thermal
=> New substrate
Newtonian Noise
=> Acoustic

ET-HF sensitivity



+ Additional R&Ds on stray/scattered light, tower and pipes mechanical design, etc

Discussion on French R&D roadmap

Workshop R&Ds : **2024 March 4 – 6**
at Institut Fresnel

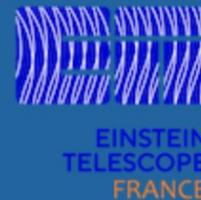
Goal: Writing a French R&D roadmap
<https://indico.in2p3.fr/event/31841/>

ET France workshop : **2026 March 31 – April 2**
at IJCLab

Goal: setting up the organization of ET-France
<https://indico.in2p3.fr/event/37982>

Workshop R&Ds - Développements Instrumentaux / Virgo-ET

4–6 mars 2024
Institut Fresnel - Marseille
Fuseau horaire Europe/Paris



Einstein Telescope France Workshop

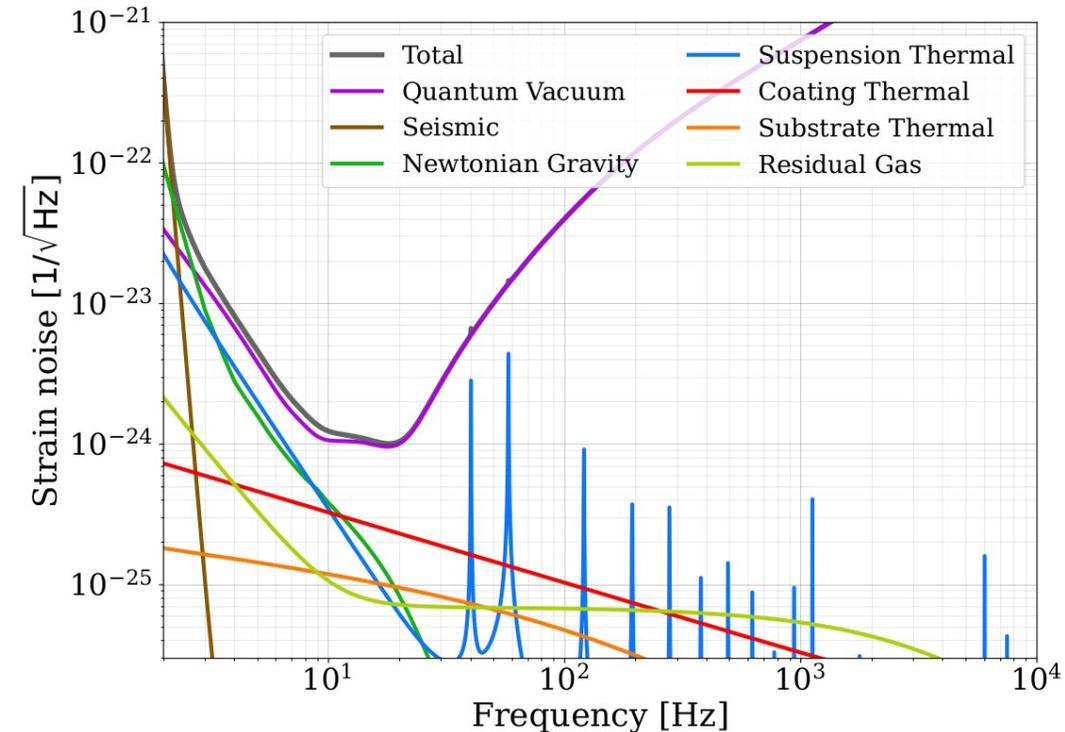
31 mars 2026 à 2 avril 2026
IJCLab
Fuseau horaire Europe/Paris

In the rest of the presentation: highlight of some R&Ds in France (not exhaustive list)

Quantum Noise (QN) – Introduction

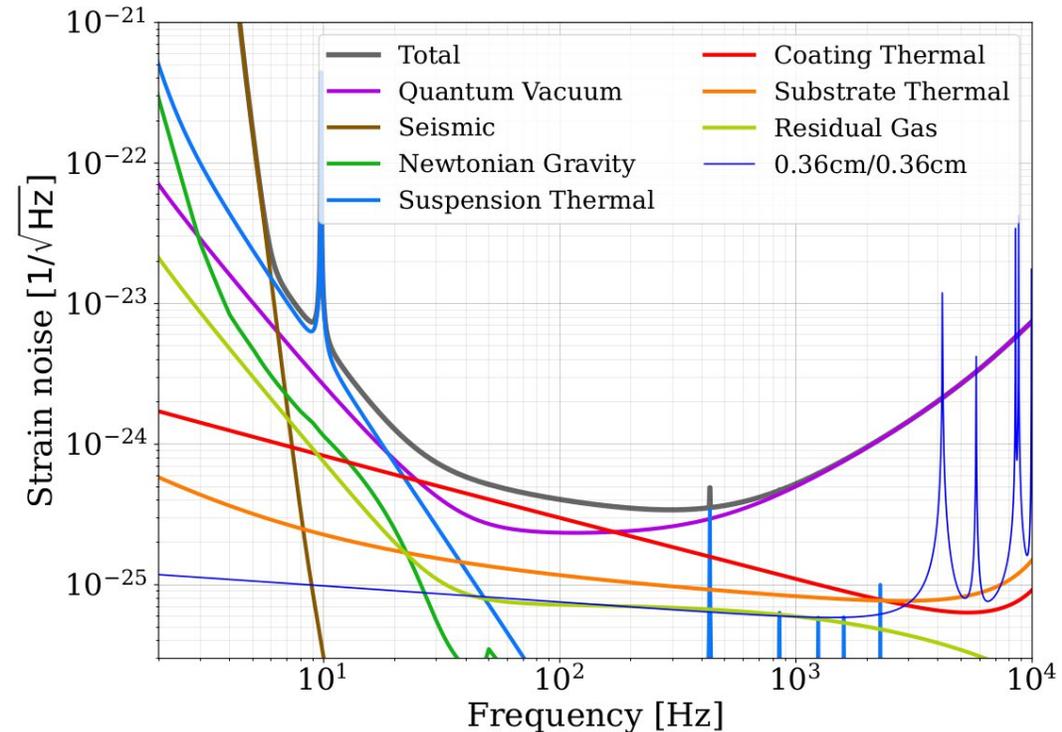
To reach Einstein Telescope sensitivity goal, lots of noise sources must be tackled by R&D developments (here limiting to R&Ds in France)

ET-LF sensitivity



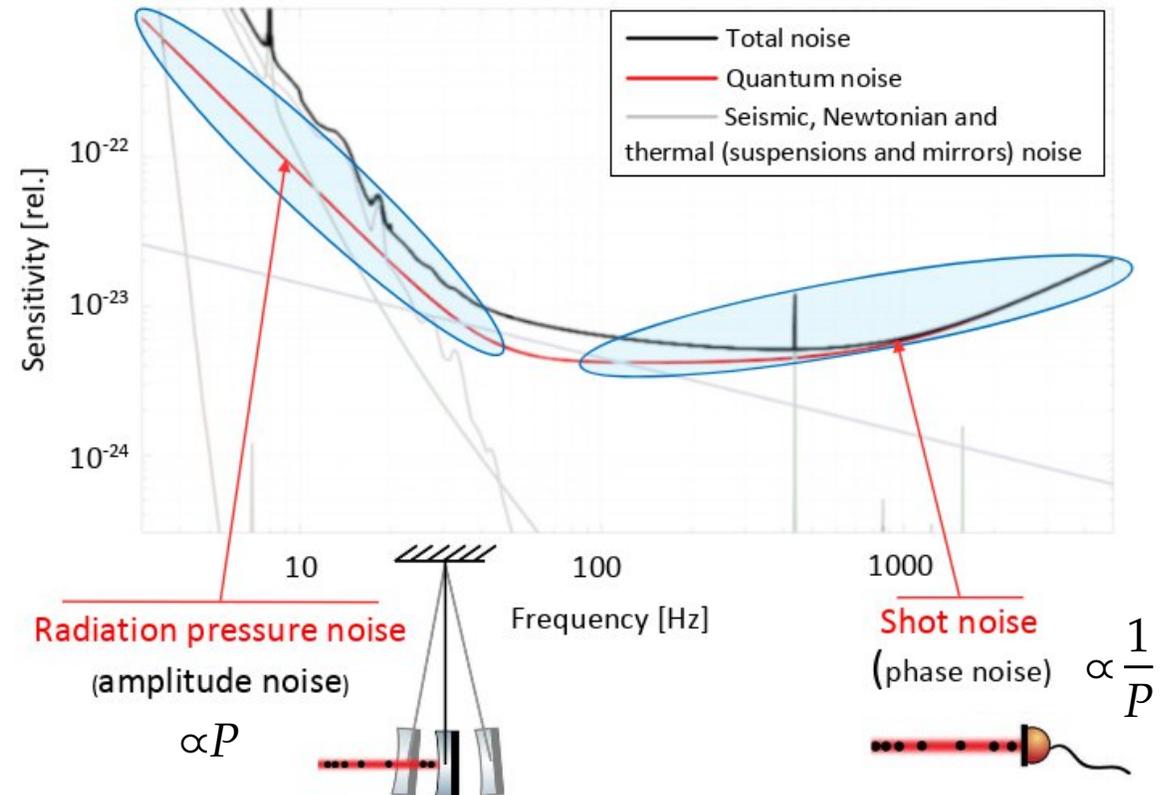
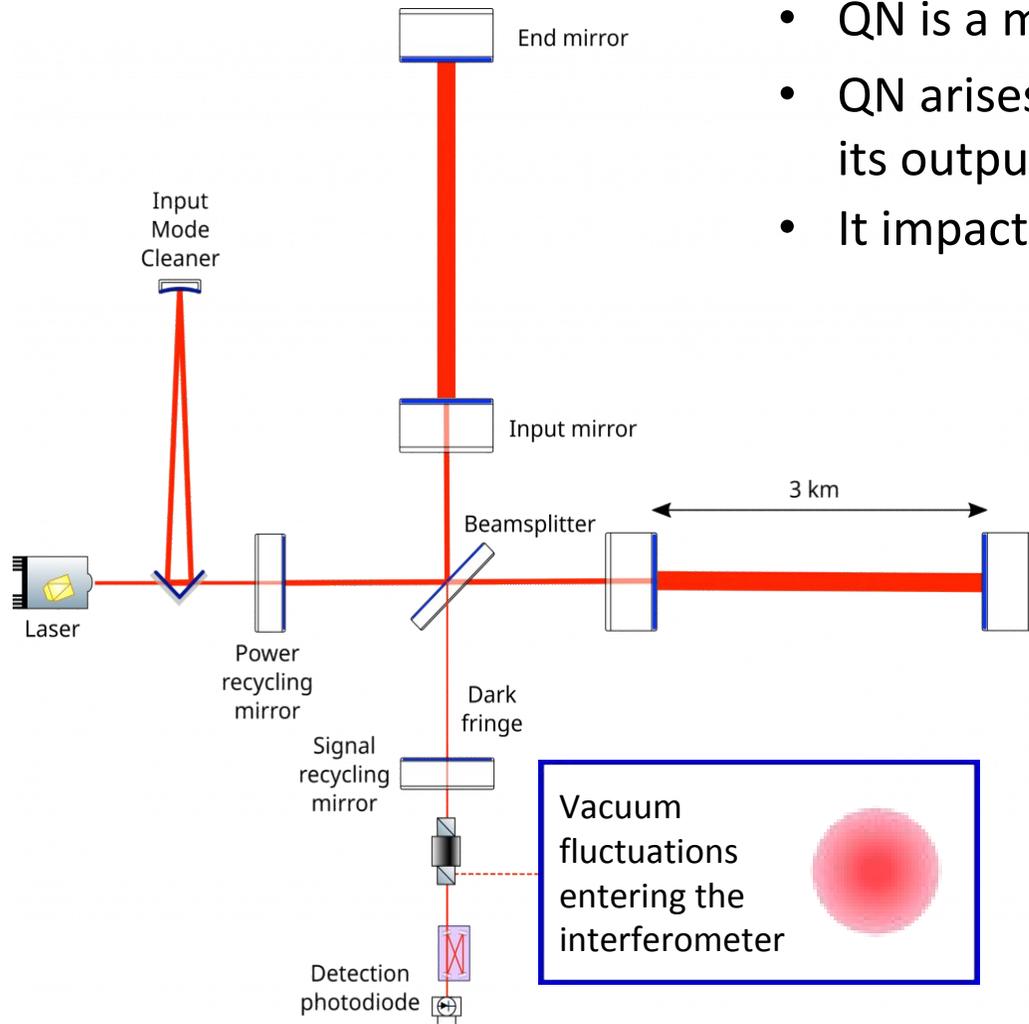
Quantum Noise
=> High Power
=> Squeezing

ET-HF sensitivity



Quantum Noise (QN) – Introduction

- QN is a major limiting noise for both low and high frequency detectors
- QN arises from vacuum fluctuations entering the GW detector through its output port and interfering with the light used for GW detection.
- It impacts the interferometer sensitivity through two ways:



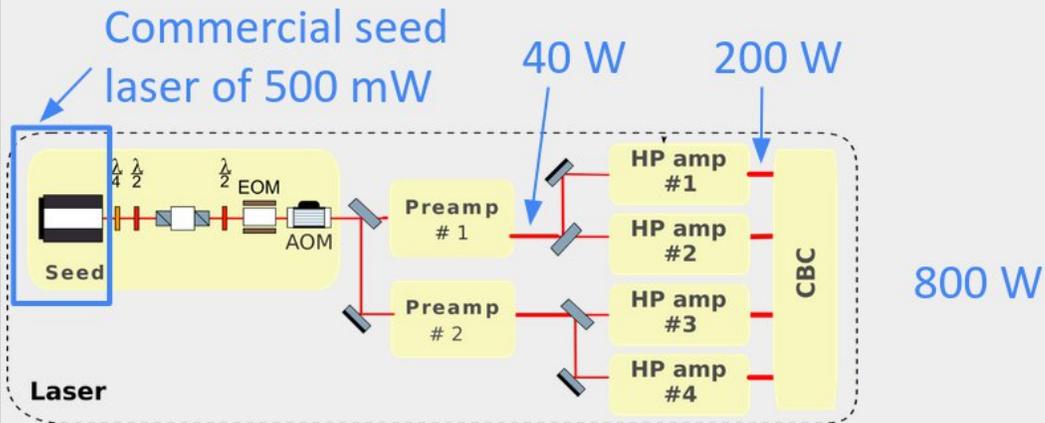
High Power Laser – Introduction

Each interferometer will use a High-Power Laser system with low intrinsic noise as the main light source to **operate non stop 24/7/52**

- What is **high power**? And why?
 - HF \Rightarrow 700 W of continuous laser light at 1064 nm at the output of the system to have 500 W injected in the interferometer required to reduce shot noise at high frequencies
 - LF \Rightarrow 5W of continuous laser light at 1550.12 nm at the output of the system to have 3 W injected in the interferometer as a trade-off between enough power for detection without heating the mirrors
- What is **low intrinsic (power and) frequency noise**? And why?
 - Different requirements depending on the frequency band:
 - Few Hz RMS at the output of the Pre-Stabilized Laser system to be below arm length fluctuations due to seismically driven, locally damped test masses
 - On time scale longer than 100 s, the laser frequency must be stable to within 1 MHz to be below tidal stretching

High Power Laser – Laser power amplification

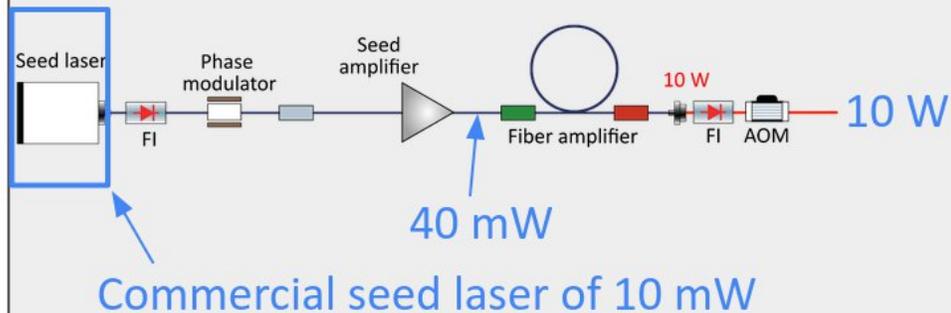
ET-HF Pre-Stablized Laser System



HF (1064 nm): 500 mW → 800 W

- 2 low power amplifiers (Preamp)
- 4 high power amplifiers
- **Coherent Beam Combination (CBC) 2-by-2 three times to reach 800 W**
- State-of-the-art: single High Power stage amplification up to 200 W with stable and reliable operation and 2x200 W combination demonstrated

ET-LF Pre-Stablized Laser System



LF (1550.12 nm): 10 mW → 10 W

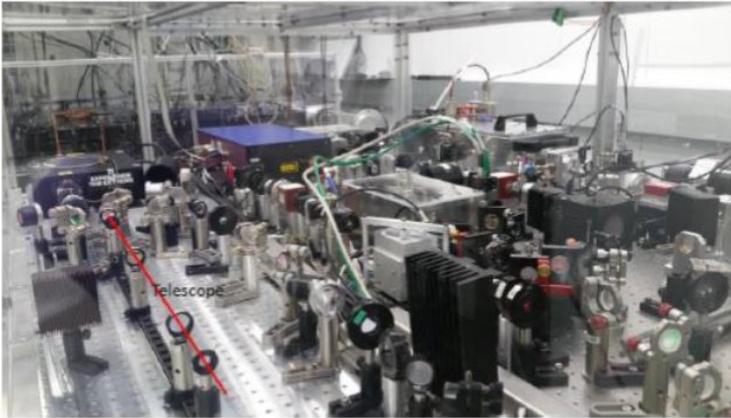
- 1 pre-amplifier
- 1 amplifier to go up to 10 W
- Commercial systems but still on-going R&D for **low frequency specs**

High Power Laser – R&Ds in France

Fiber technology to increase power

ARTEMIS - ALS(Toptica) - ALPHANOV

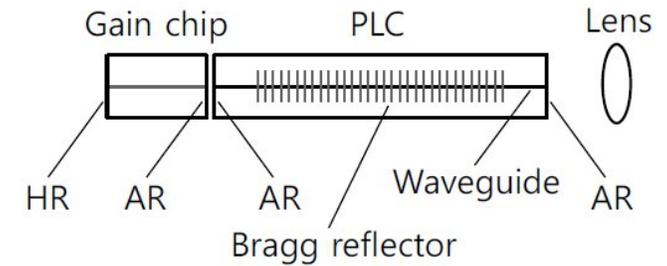
- All fibered system : Mode Field adapter (MFA)
- Phosphosilicate fiber : photodarkening free



Installed and tested on Virgo

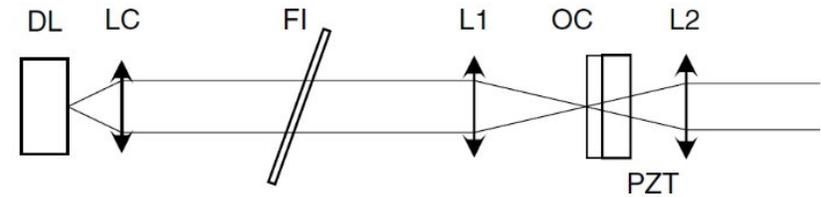
Extended Cavity Diode Laser (ECDL)

RIO system



<https://doi.org/10.1364/OE.18.022781>

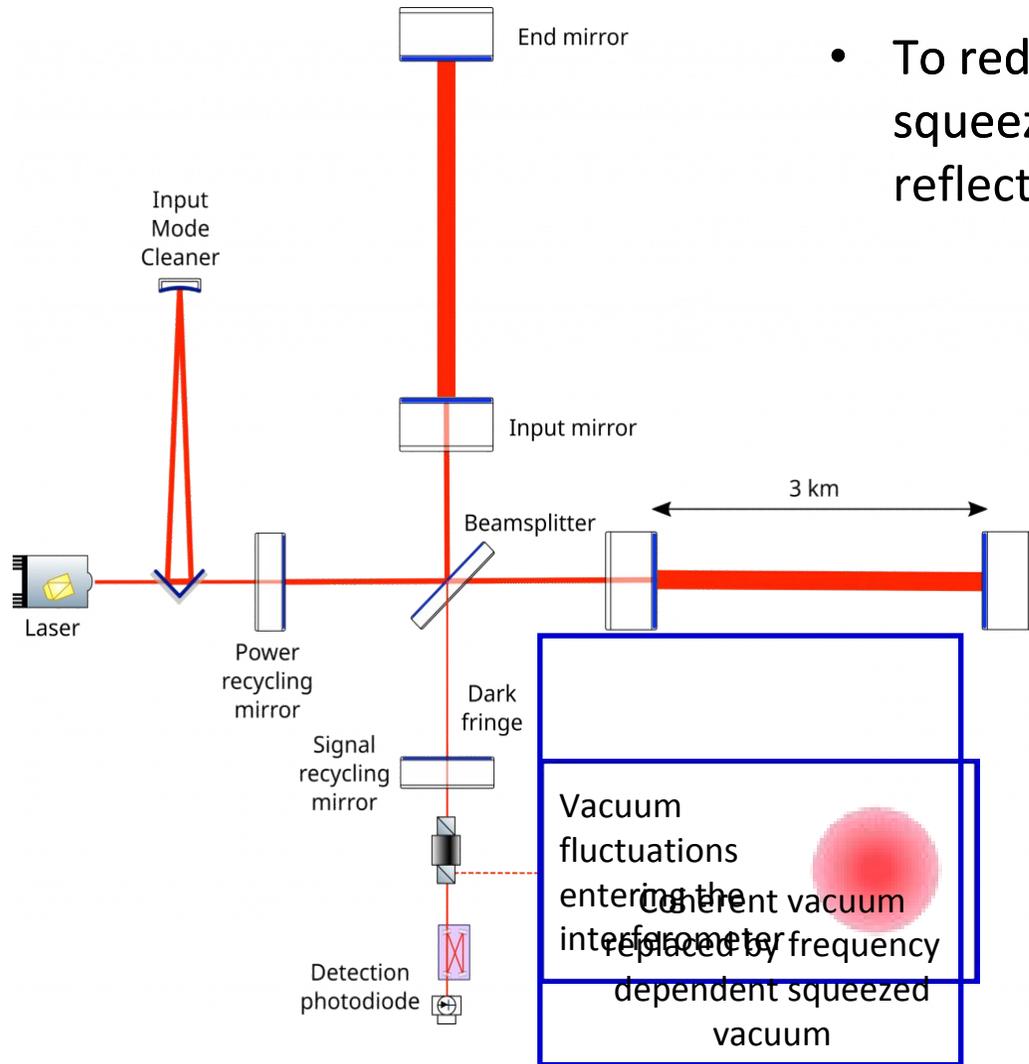
SYRTE



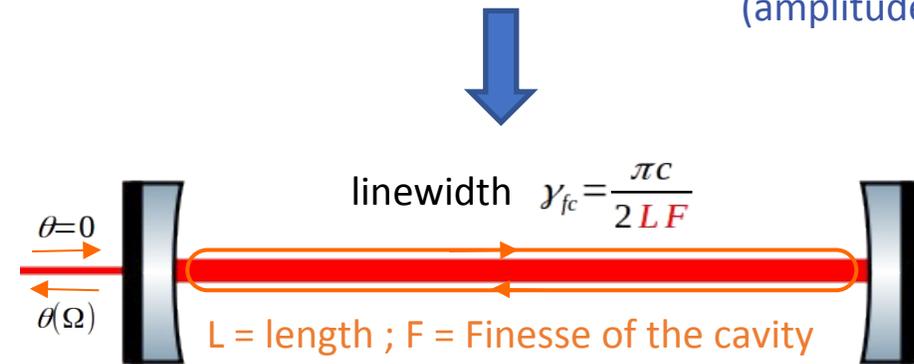
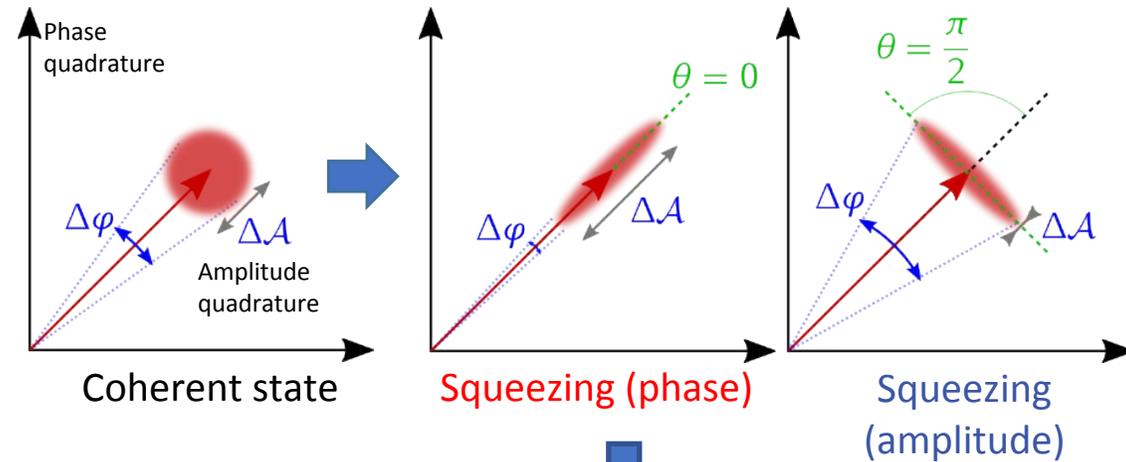
<https://doi.org/10.1016/j.optcom.2006.05.011>

[Presentation at 2024 French R&D workshop](#)

Frequency Dependent Squeezing - Introduction

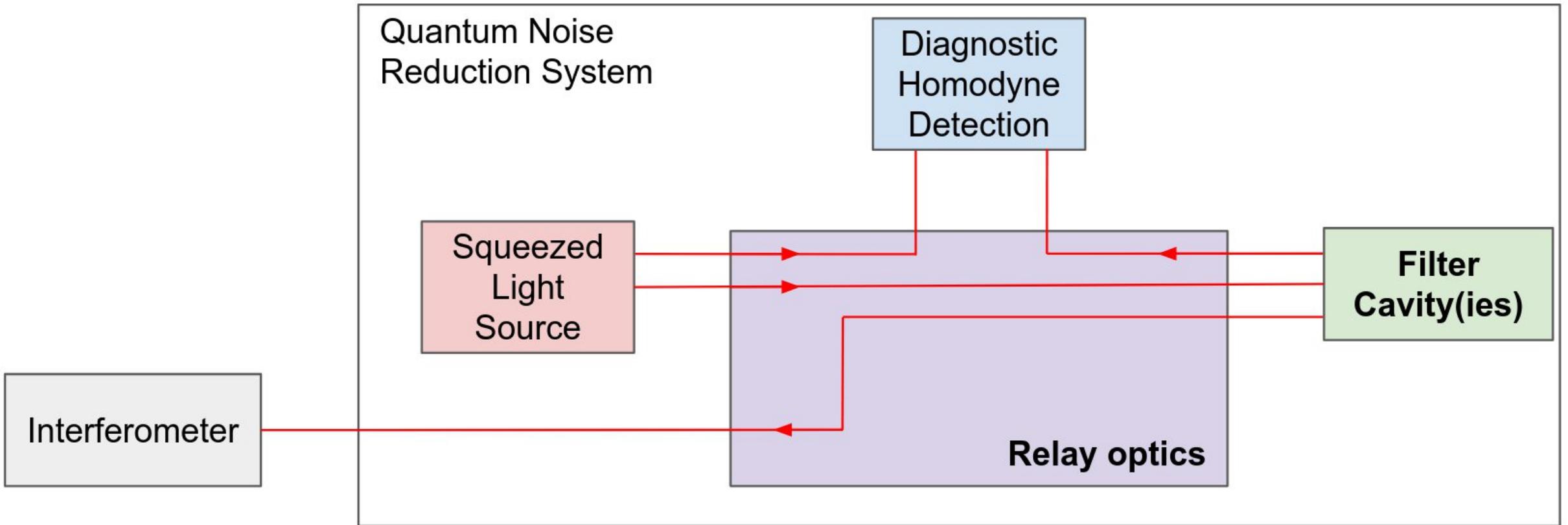


- To reduce quantum noise we replace the coherent vacuum with squeezed vacuum states of light made frequency dependent by reflection on optical resonator(s)

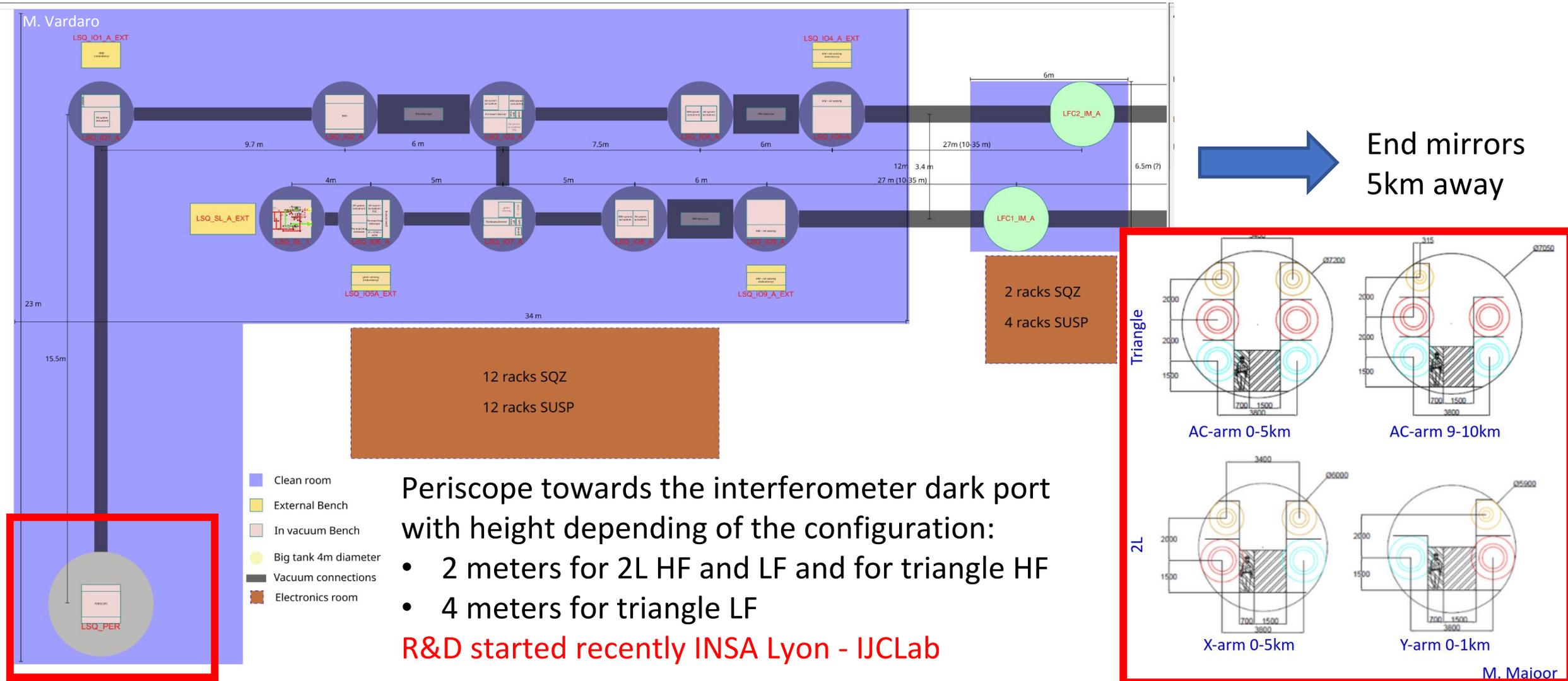


Frequency Dependent Squeezing – Building blocks

- 4 main blocks to produce, characterize and transfer Frequency Dependent Squeezing
- Similar building blocks for HF and LF (except wavelength, number of filter cavities and associated relay optics) and for Triangle and 2L configurations (except relay optics towards ITF)



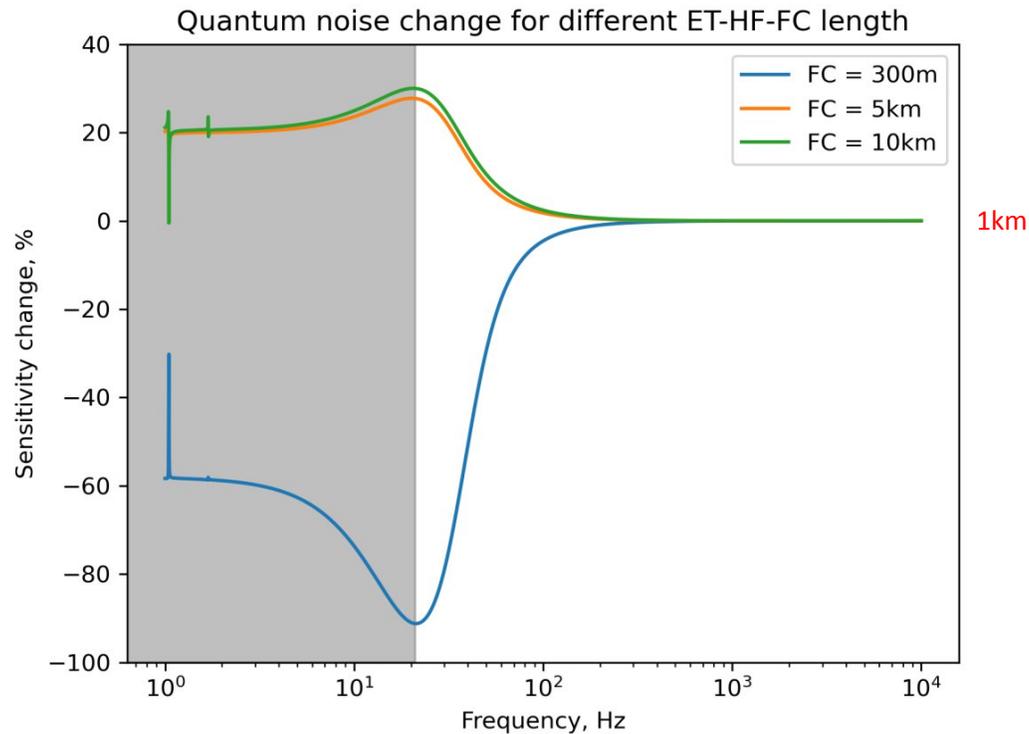
Frequency Dependent Squeezing – Schematic of the (LF) Squeezing Lab



Frequency Dependent Squeezing – Filter Cavities Baseline

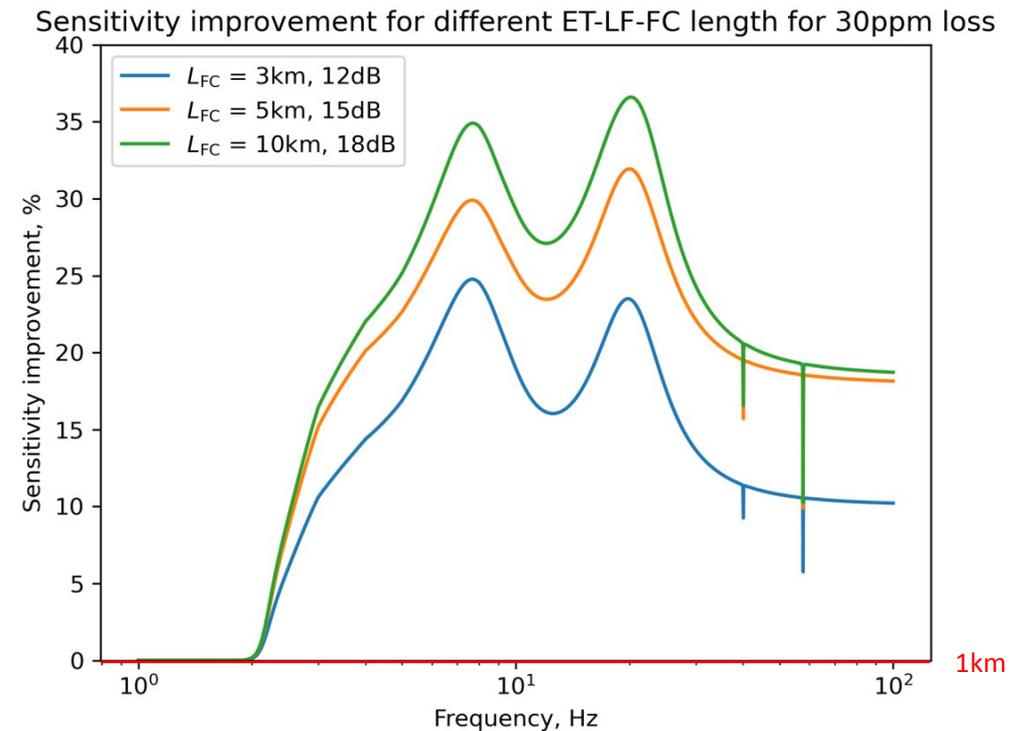
ET-HF:

- Baseline design very similar to LIGO and Virgo filter cavity (2-mirror filter cavity) but longer (1km)



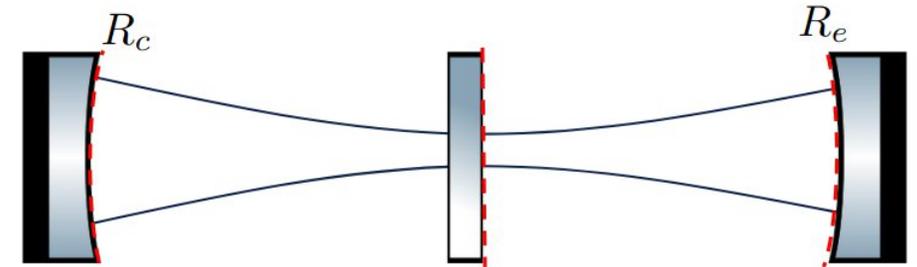
ET-LF:

- The detuned Signal Recycling requires 2 rotations of the squeezing ellipse and thus 2 filter cavities (5km each) in the baseline design



Frequency Dependent Squeezing – Filter Cavities Alternatives

- LF: Replace the two 2-mirror cavities by one 3-mirror cavity (5+5 km) => ANR Quantum-FRESCO (2023-2027)
 - Reduce the number of optics (especially Faraday Isolator)
 - Natural mode matching between both subcavities
 - Can start with 10km 2-mirror cavity and interferometer tuned and then add the central mirror when moving to detuned operation

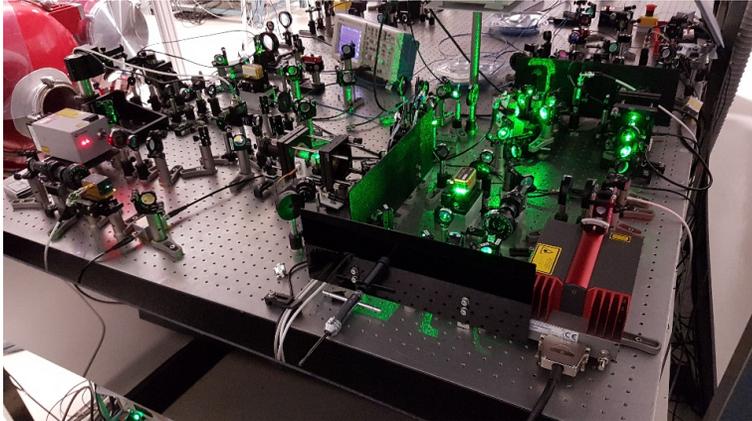


arXiv2506.02222

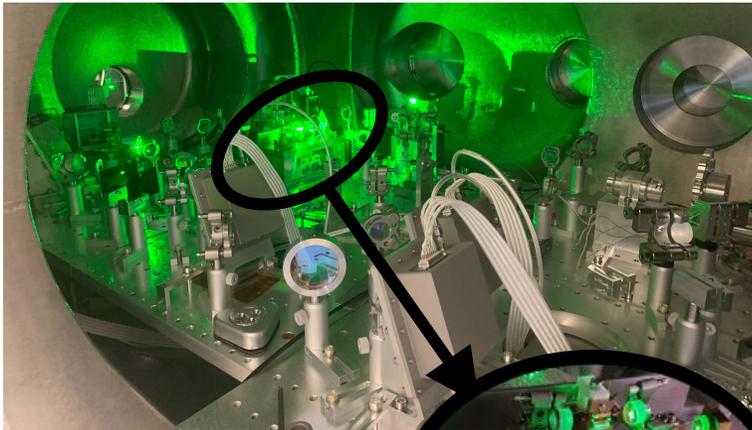
- HF and LF: variable finesse cavities will be required to allow adaptation of frequency dependent squeezing both to changes in the interferometer during its 50 years lifetime (other solution is to change mirrors with associated risks) and accommodate for loss sources
 - Thermal tuning of the input mirror reflectivity using the etalon effect (change of refractive index of the input mirror substrate) => to be simulated to evaluate the available actuation range
 - Replacing each 2-mirror cavity by a 3-mirror cavity, the first sub-cavity acting as an equivalent mirror => to be tested on the CALVA facility (infrastructure change with DIM Origines) => gives access to a larger actuation range

Frequency Dependent Squeezing – R&D on HF Squeezing source

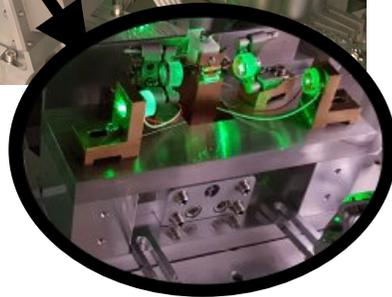
In-air beams
preparation bench



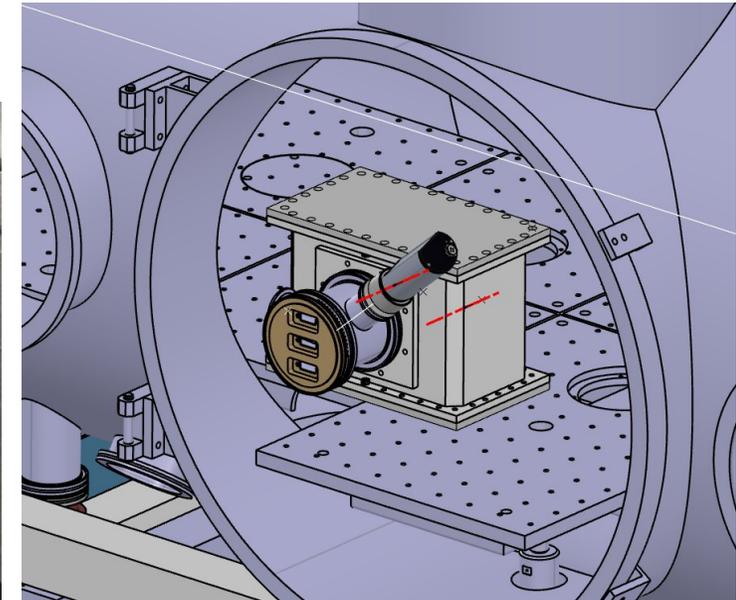
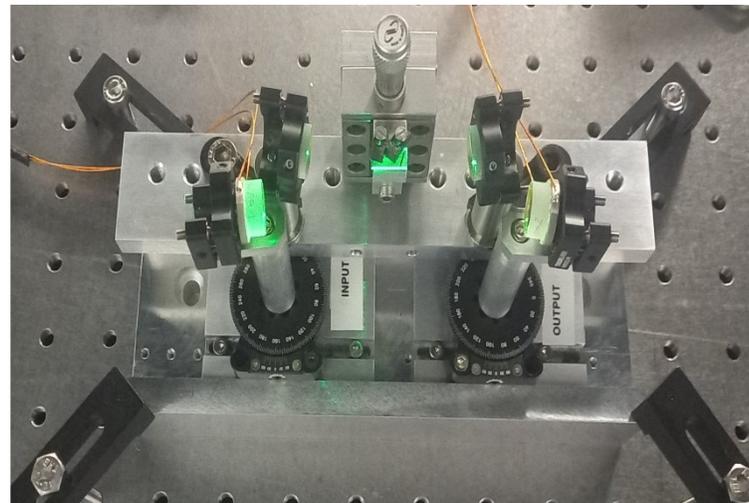
Under vacuum
bench



Squeezing
source



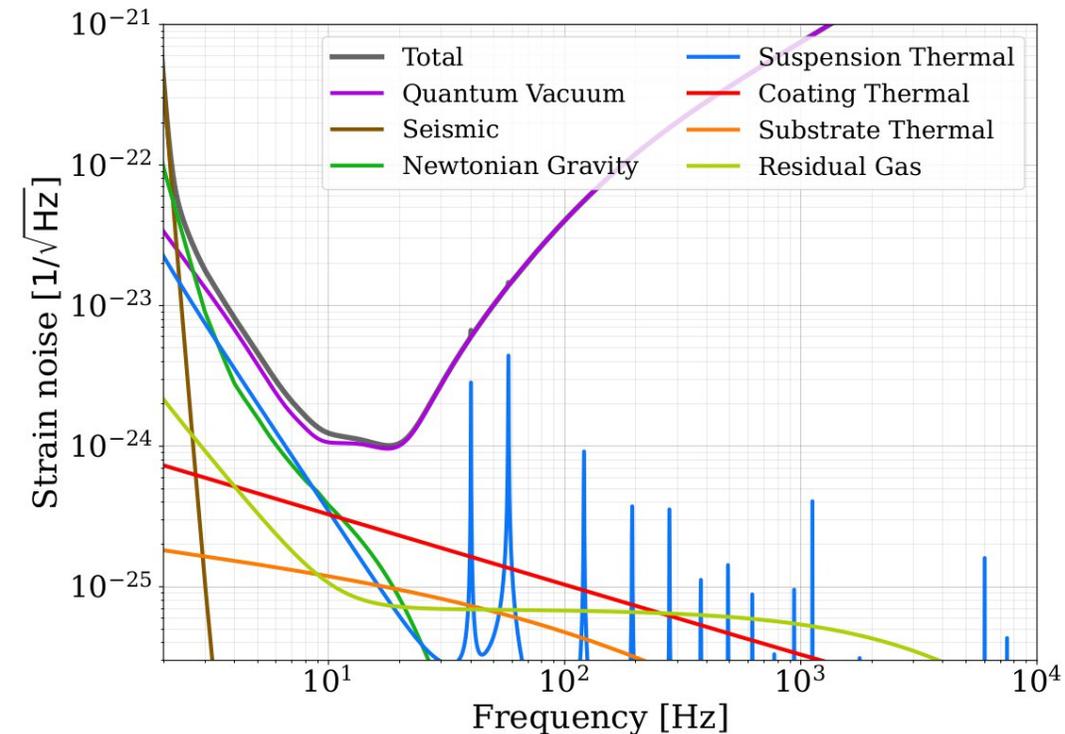
- Main design done independently in Hannover (AEI)
- R&D development of under vacuum Squeezed Light Source at IJCLab on the CALVA facility:
 - Geometry constrains on the design of the bow-tie cavity hosting the squeezing source (non linear crystal)
 - Impact of placing the squeezing source under vacuum (ANR Exsqueez 2015-2019)



Coating and substrate thermal noise - Introduction

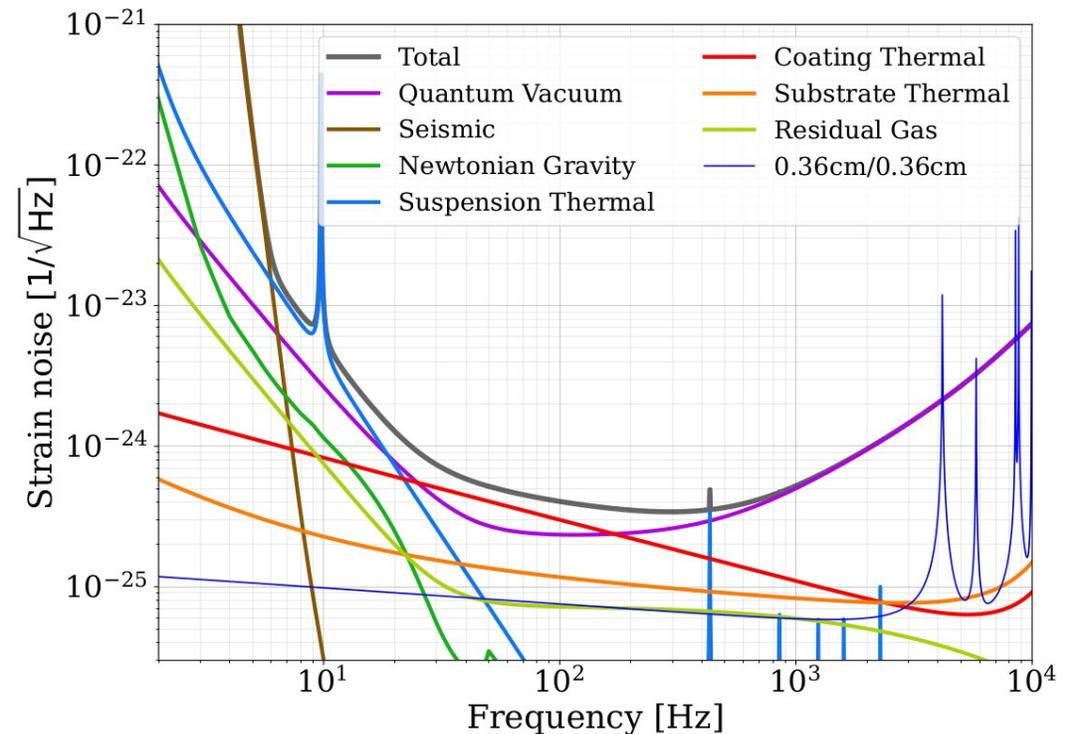
To reach Einstein Telescope sensitivity goal, lots of noise sources must be tackled by R&D developments (here limiting to R&Ds in France)

ET-LF sensitivity

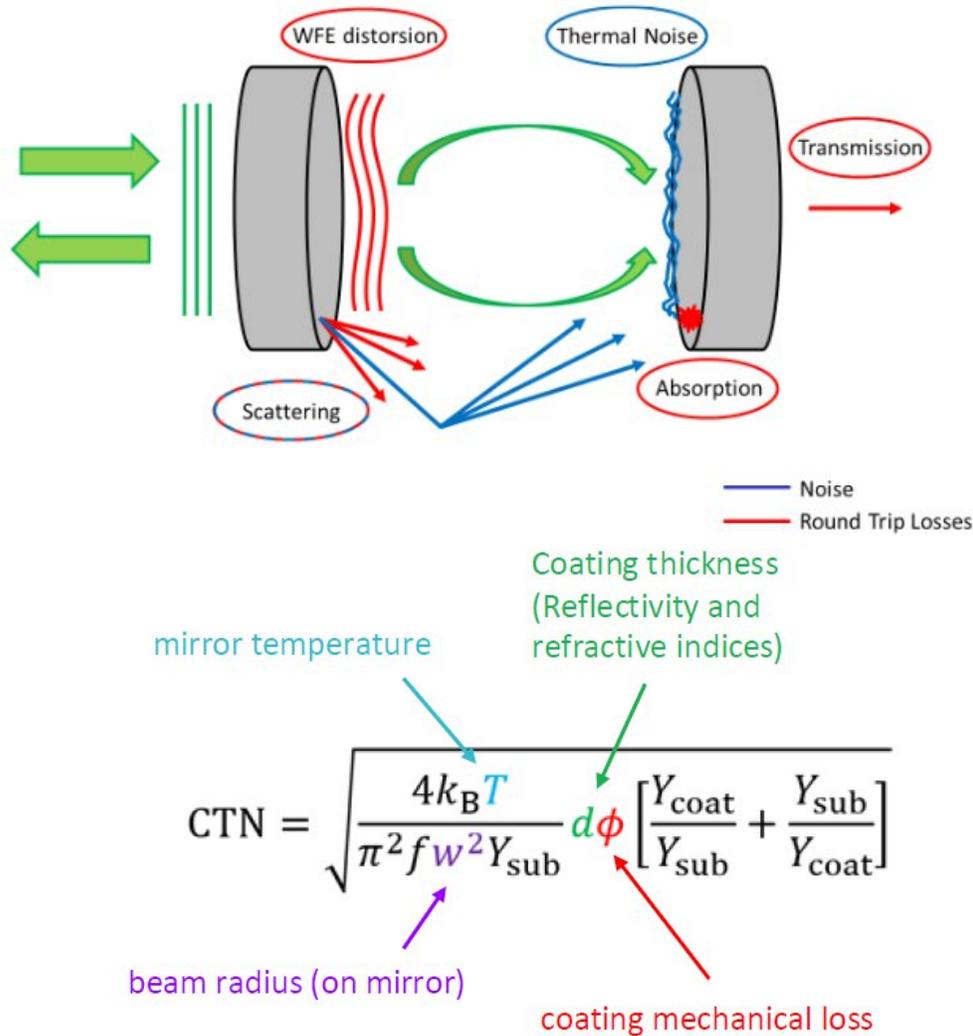


Coating Thermal
=> New coatings
Substrate Thermal
=> New substrate

ET-HF sensitivity



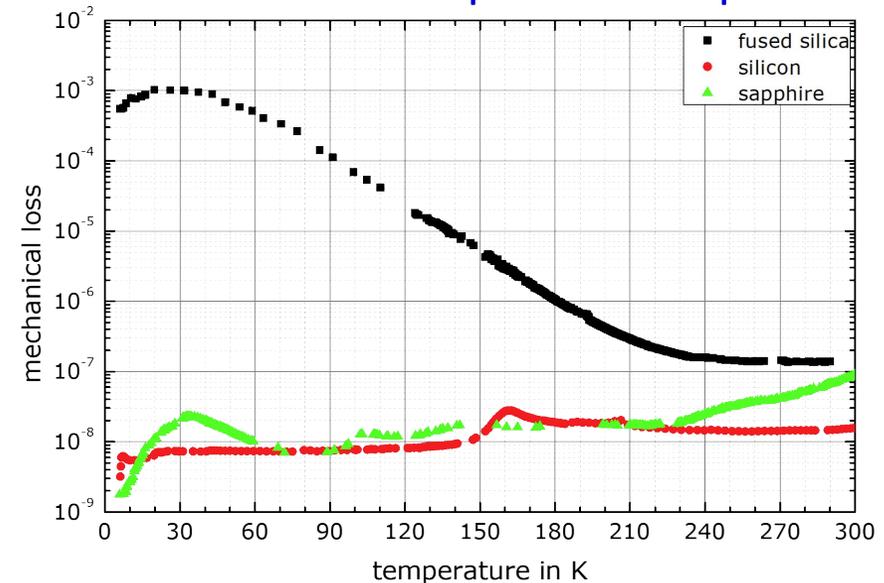
Coating and substrate thermal noise - Introduction



Several approaches to decrease the thermal noise :

- Reducing the temperature (ET-LF) => cryogenic
- Reducing the total thickness => increase the contrast in refractive index
- Increasing the beam diameter => larger mirrors
- Reducing the loss of the coating materials

Substrate loss with respect to temperature



Coating and substrate thermal noise – Comparison to Advanced Virgo

Better for shot noise
 Worse for point absorber
 Worse for thermal lens

Parameters	ET-HF	Adv Virgo	ET-LF
Arm power	3 MW	100-150 kW (O4)	18 kW
Mirror mass	200 kg	42 kg	211 kg
Temperature	290 K	290 K	10-20 K
Laser wavelength	1064 nm	1064 nm	1550 nm
Mirror diameter	62 cm	35 cm	45 cm
Beam radius	12 cm	5-6 cm	9 cm

Better for radiation pressure
 Worse for shot noise

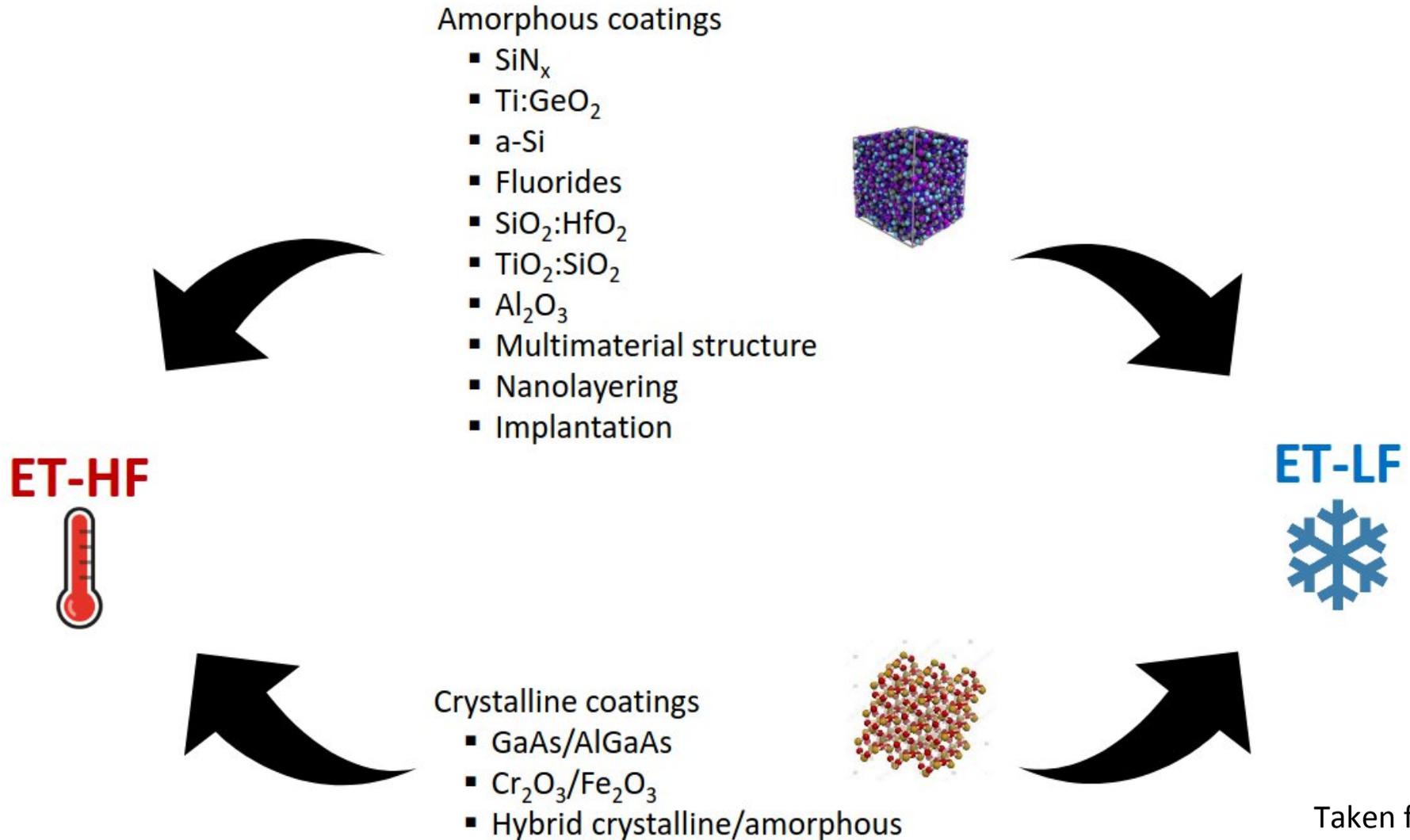
Better for CTN
 Increase complexity of detector (cooling down, ice growth..)

Better for absorption

Better: reduction of a factor 2 of CTN from a 2x larger beam
 Aiming at a 10x reduction @100 Hz (arm length x beam size x better coatings)

Better for radiation pressure
 Better for fiber thermal noise

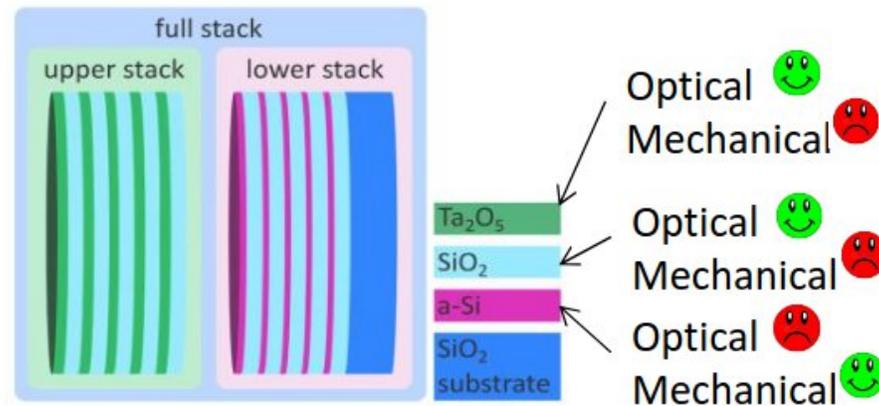
Mirror coating – Strategies



Taken from B. Sassolas

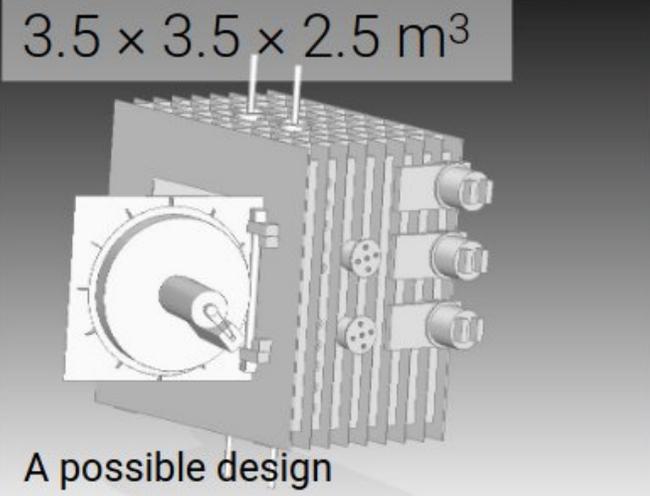
Mirror coating – R&Ds in France on amorphous coatings

Material	CTN (wrt aLIGO)	Absorption (ppm)	Ref.	Comment
$\text{SiO}_2/\text{SiO}_x/\text{Ta}_2\text{O}_5$	0.97	1	Demos et al. Class. Quantum Grav. 42 115012 2025	$T \ll 5\text{ppm}$
$\text{SiO}_2/\text{Ti}:\text{Ta}_2\text{O}_5/\text{SiN}_x$	0.82	1.5	VIR-0888A-25	
$\text{SiO}_2/\text{Ti}:\text{Ta}_2\text{O}_5/\text{TiGeO}_2$	0.81	0.7	VIR-0888A-25	

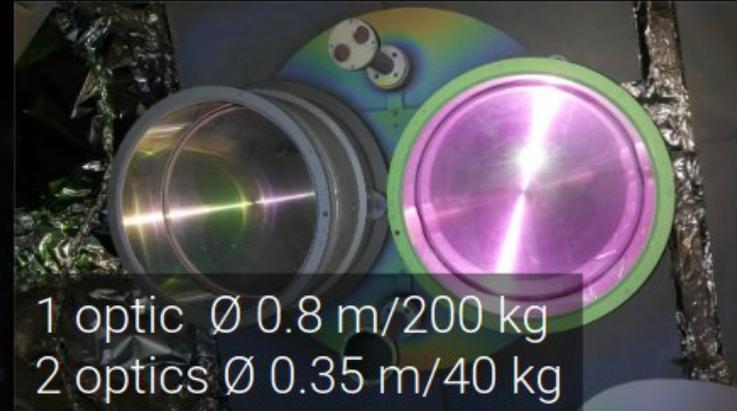


Taken from B. Sassolas

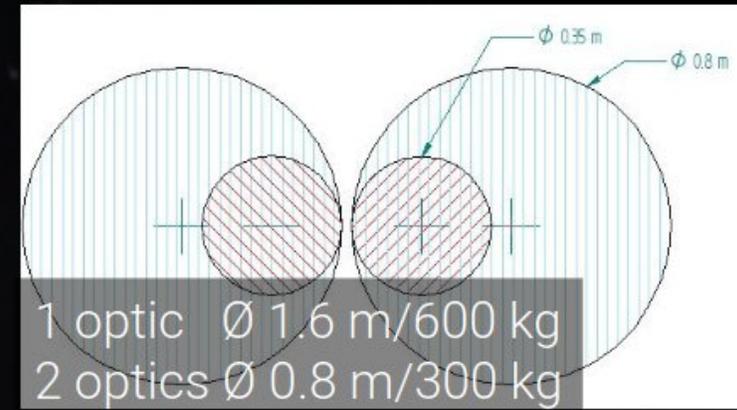
Mirror coating – New large coating machine at LMA



Grand coater current capabilities:



New coater possibilities



Taken from J. Degallaix

Mirror substrate for ET-LF

Goal:

- 45 cm diameter
- 211 kg

Silicon

Low optical absorption requires very pure material, i.e. float zone (FZ) silicon or magnetically-stabilized Czochralski silicon.

But high-purity material not available in such large size.

Challenges:

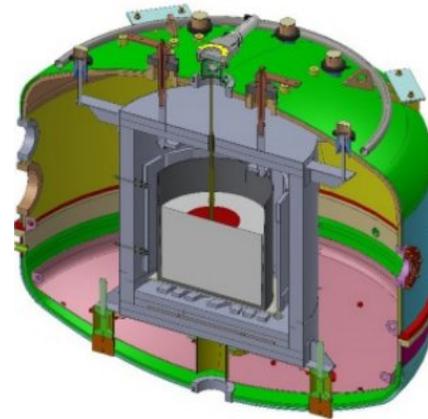
- **make large material purer**, optimizing the fabrication process
- **make pure material larger**, optimizing the process or with composite test masses

=> Composite mirror by melting smaller substrate?

=> Change the design of the arm cavities?

Sapphire

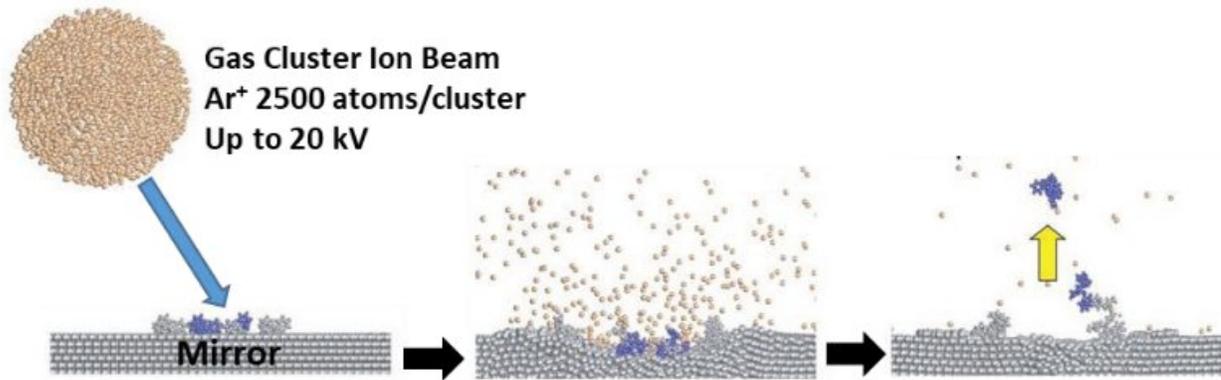
- Already used at 1064 nm in KAGRA, shows challenges in inhomogeneities, birefringence and size availability
- Development in Lyon:
 - Custom made dedicated furnace for 45 cm diameter (30 cm diameter produced)
 - Large optics (not only sapphire) characterization



Mirror cleaning and discharging

In-situ mirror cleaning (R&D at IJCLab)

- Gas Cluster Ion Beams (GCIB) impact a surface with very low energy, down to as little as 1 eV per atom
- At such low energies they sputter material without modifying the surface chemistry, i.e. without breaking bonds
- Cleaning effect without materials damage (unlike single ions)
- First tests done at room temperature on LMA coated substrates

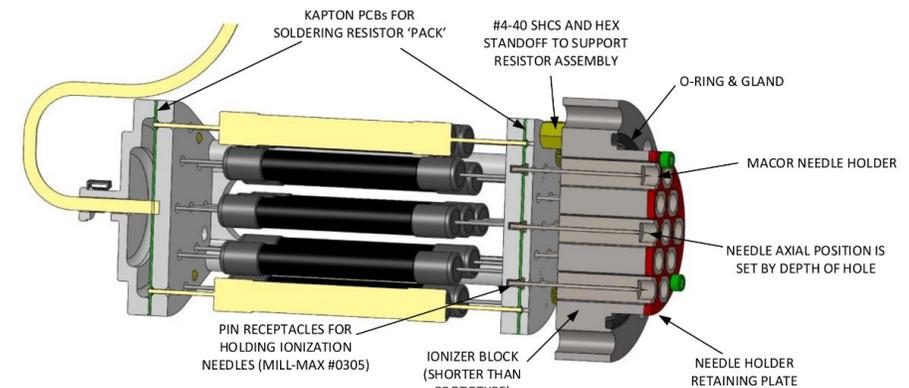


Taken from S. Bilgen

Neutralizing and monitoring the mirrors electrostatic charges (R&D at LPC Caen)

R&D on a pulsed High Voltage system using the Corona effect (streamer):

- Design and production of a prototype
- Plasma is generated by pulsed HV tungsten needles in N₂
- Tests to extract the optimised parameters for the streamer development (pressure, HV, polarity, frequency)

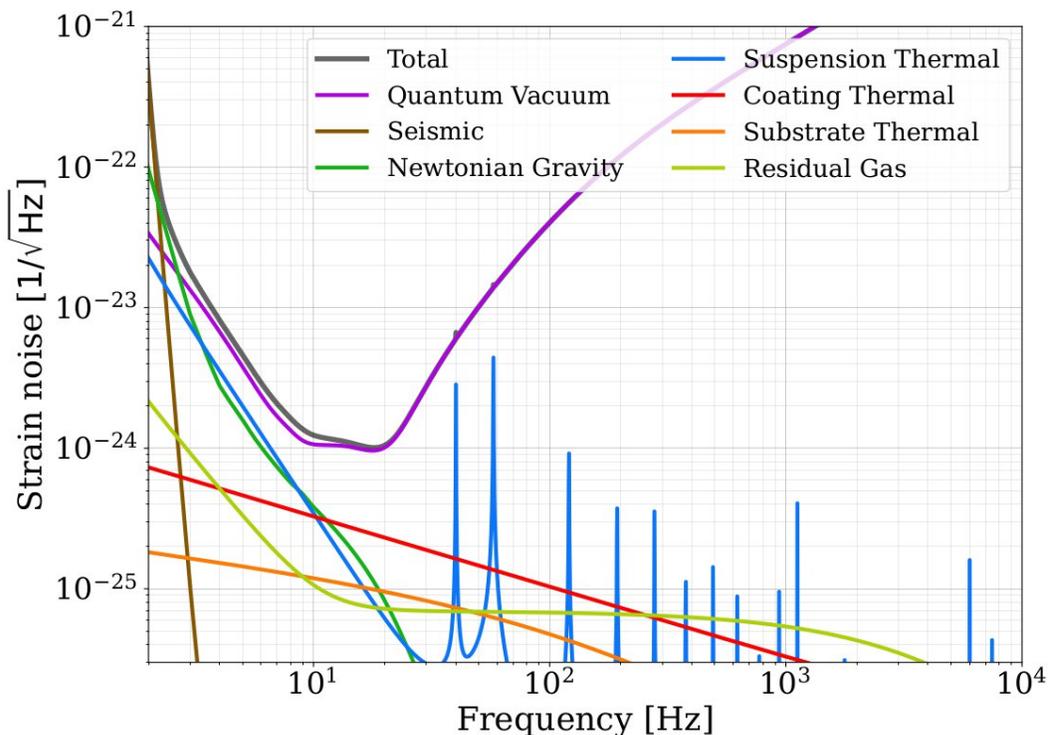


Taken from S. Salvador

Newtonian noise - Introduction

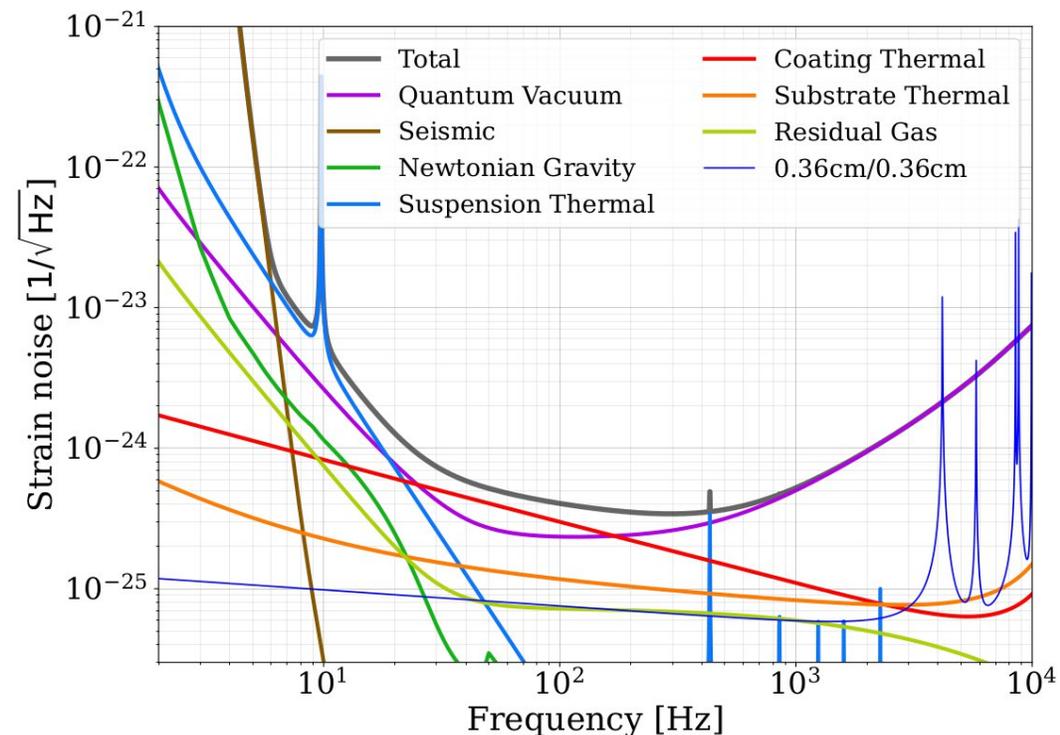
To reach Einstein Telescope sensitivity goal, lots of noise sources must be tackled by R&D developments (here limiting to R&Ds in France)

ET-LF sensitivity



Newtonian Noise
=> Acoustic

ET-HF sensitivity

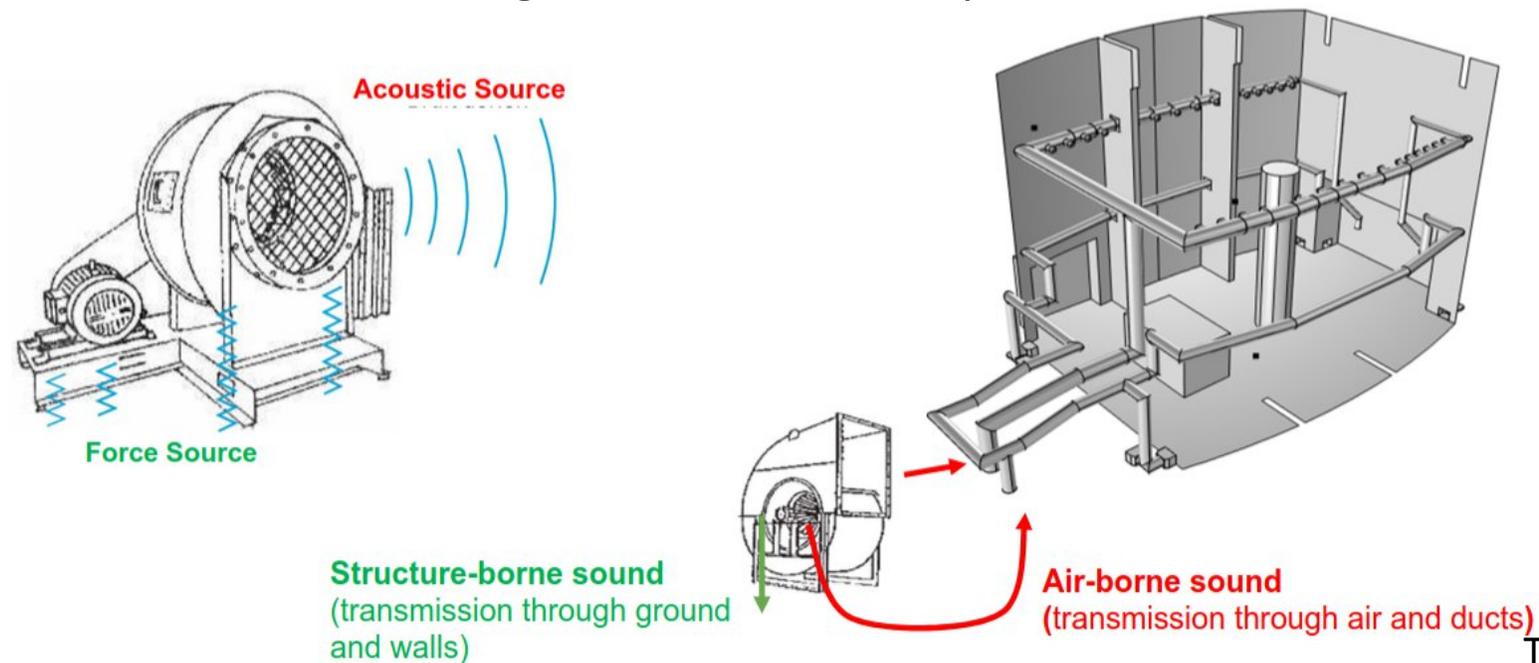


Newtonian noise

Newtonian noise comes from local fluctuation in the gravity field around the mirrors:

- Mass movements in the nearby environment (seismic activity, human activity, ocean waves, wind, etc.)
- Density variations in the atmosphere or the ground (for example, air movements, ground vibrations, or changes in atmospheric pressure) => **acoustic noise**

Modeling of Newtonian noise from acoustic origin at LAUM: HVAC system

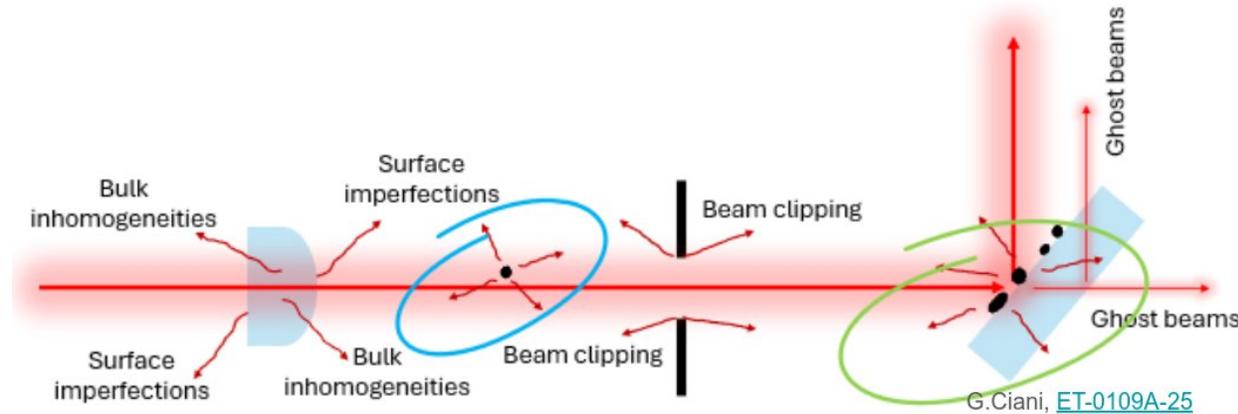


Taken from F. Gautier

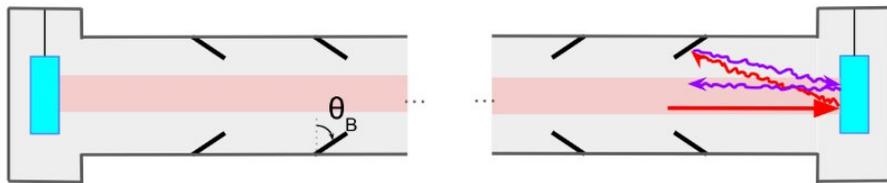
Stray/Scattered Light - Introduction

Straylight:

- any photon that is scattered and do not follow the intended path
- consequences:
 - optical losses
 - photons recouple with random phase: excess noise in the low frequency band ($f \lesssim 100\text{Hz}$)



A typical situation in GW interferometers:



Stray light produced by a Test Mass reaches the pipe tube (or pipe baffle), is scattered back towards the TM and then again re-scattered into the main beam

Stray/Scattered Light – Noise challenges

Strength of mechanical noise changes the coupling of Stray Light (phase) noise depending on amplitude of movement of the scattering surface $x_{bs}(t)$:

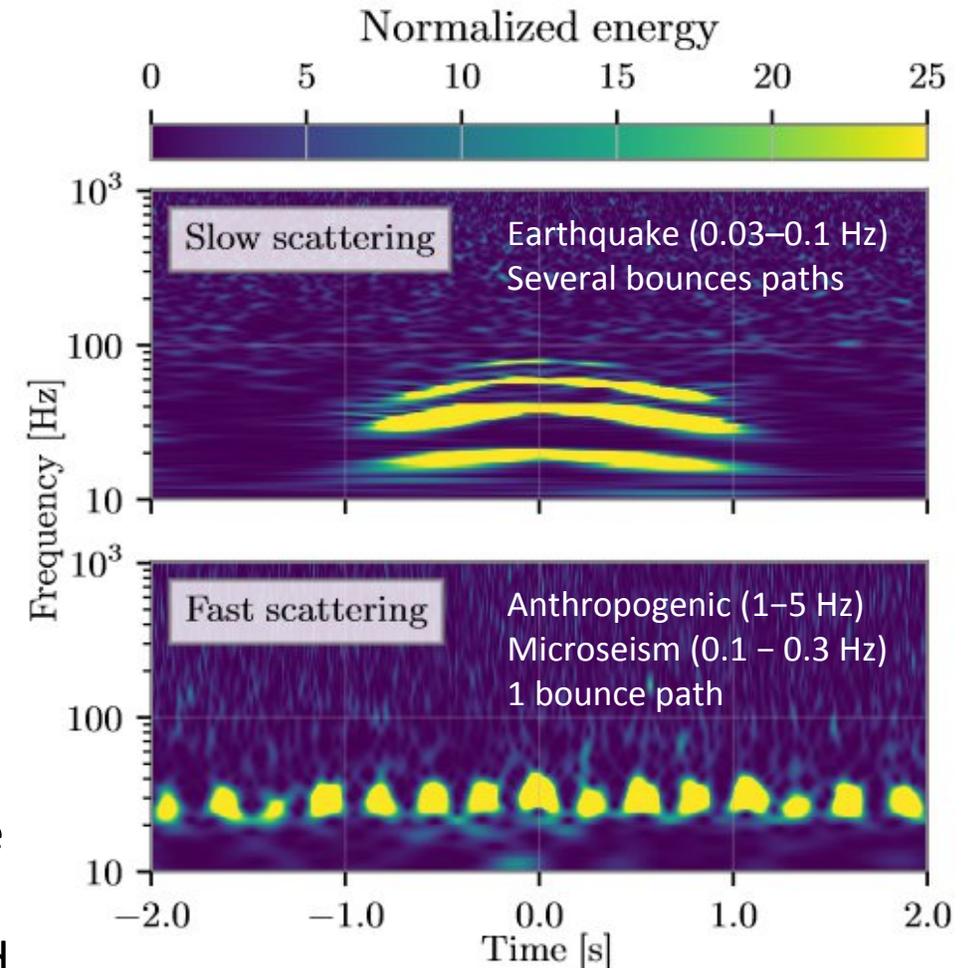
- for $x_{bs}(t) \ll \frac{\lambda}{4\pi} \sim 10^{-7} \text{ m} \rightarrow$ linear effect
- for $x_{bs}(t) \geq \frac{\lambda}{4\pi} \rightarrow$ non linear effect

Stray light is known to cause glitches at a frequency

$$f_{fringe} = \frac{2n}{\lambda} |v_{bs}|$$

Challenges in Reducing Stray Light Noise

1. **Very common**: any optical interface can generate stray light
2. **Hard to trace**: back-reflections may originate far from both the source and the recombination point
3. **Nonlinear effects** complicate identification of critical paths and noise subtraction strategies

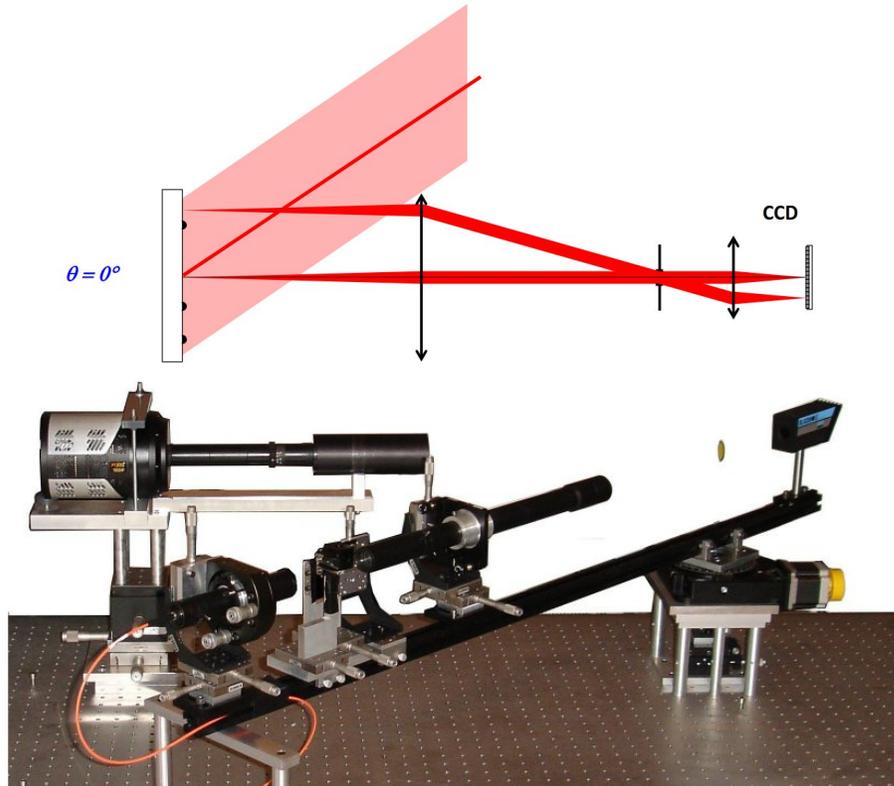


[Phys. Rev. X; 13\(4\):041039; 2023](#)

Stray/Scattered Light – R&Ds on measurement

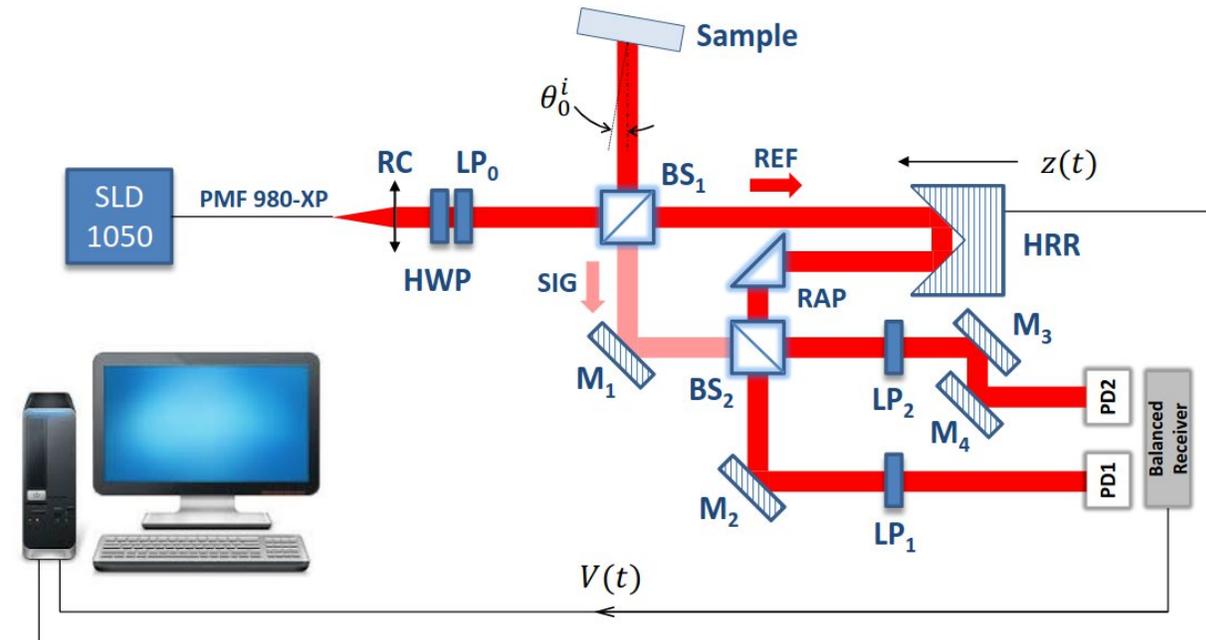
Point defects measurement at Institut Fresnel => SPARSE:

- Detect the presence of point defects on the surface
- Contribution of these defects to scattering loss budget



Retroreflection and Backscattering measurement at Institut Fresnel => BARRITON:

- Detect the axial position and strength of retroreflection and/or backscatter sources along the optical axis of a large instrument.



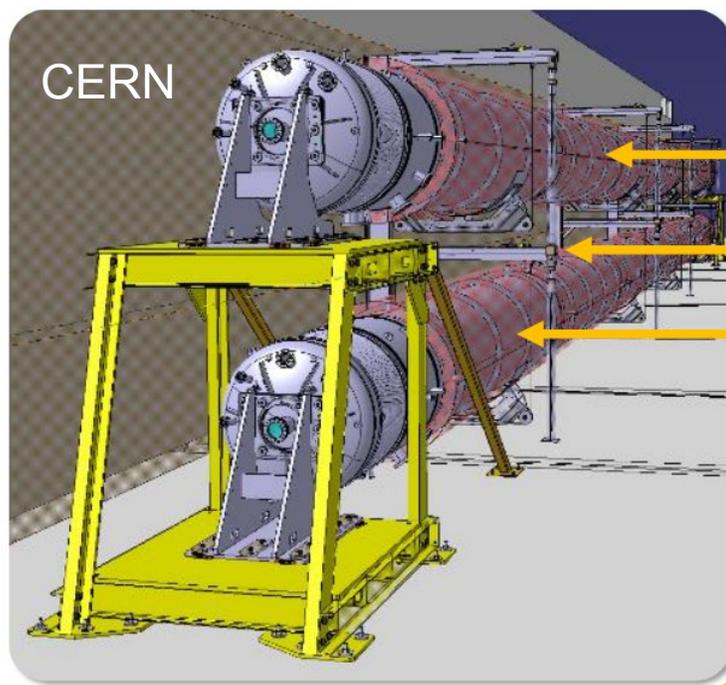
=> Adaptation of SL-OGSE of LISA to Einstein Telescope? (ARTEMIS)

[Presentation at 2024 French R&D workshop](#)

Vacuum envelop design – Vacuum pipes

3 designs under study:

- Smooth with stiffener (Virgo-like) => prototype at CERN
- Corrugated (GEO600-like) => prototype to be done in US (CEBEX)
- Spiral stiffener (R&D at LAPP) => small prototype under fabrication

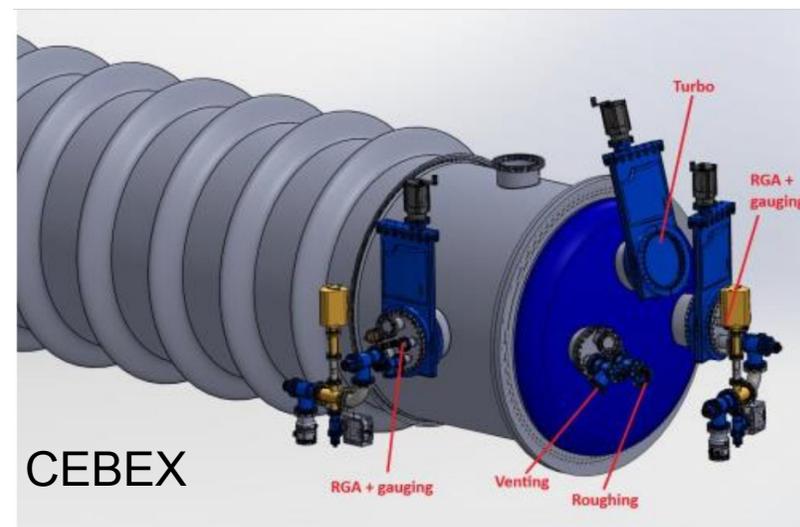


Beam tubes:
Design
Materials
Manufacturing & QA
Installation

Supports

Insulation

**Lessons learned
& Perspectives**



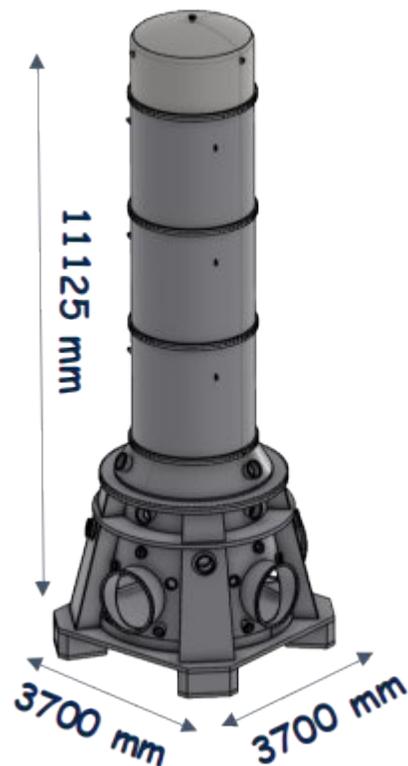
Taken from A. Lacroix

Vacuum envelop design – Towers

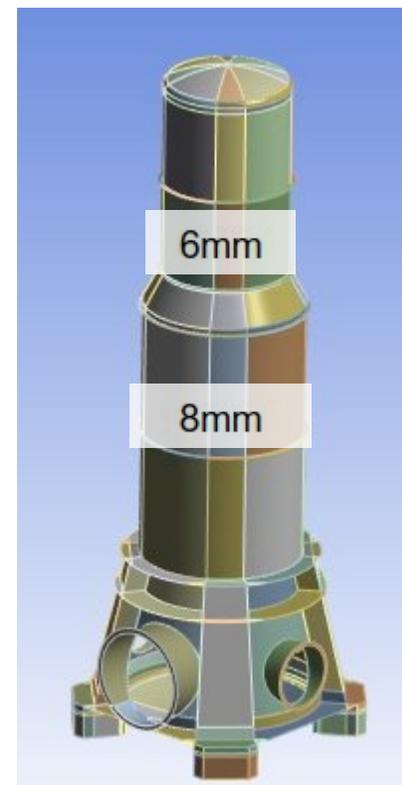
R&D at IJCLab on:

- Mechanical design of the towers
- Mechanical design of cryostat thermal shields supporting structure
- Integration in the overall Einstein Telescope infrastructure

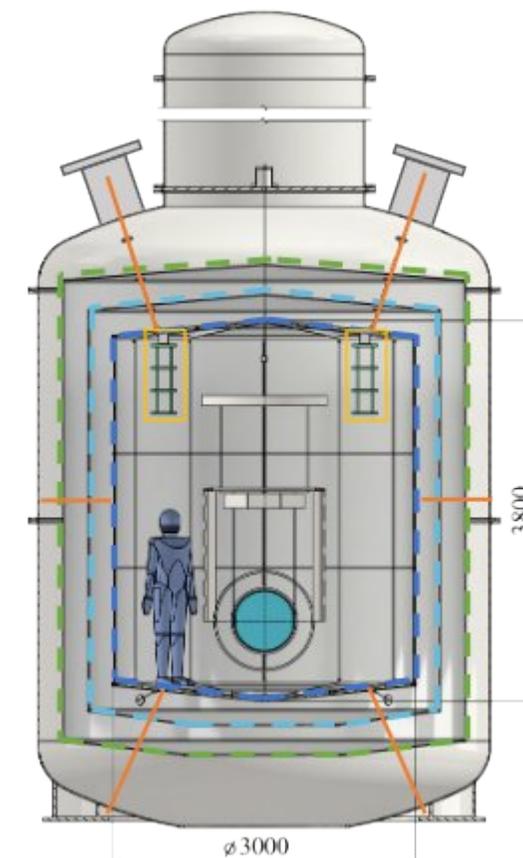
Proposed Einstein Telescope tower (by EGO)



Propositions of optimisation



Cryostat



[Presentation at 2024 French R&D workshop](#)

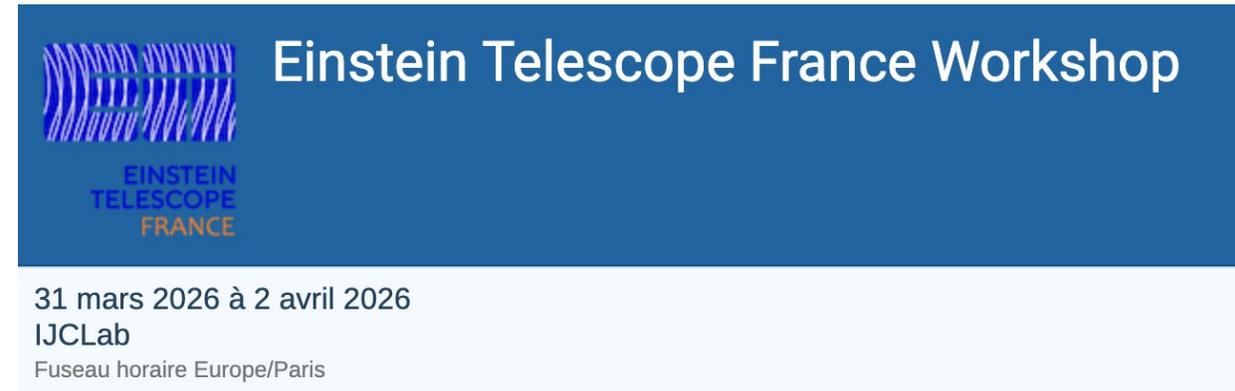
Conclusion

- French R&D roadmap under construction
- Lots of R&Ds activities identified on very different topics:
 - (Quantum) optics
 - Mechanics
 - Acoustic
- But also:
 - Electronics/DAQ
 - Calibration
 - Suspensions
 - Simulations
- Without mentioning other required R&Ds for ET

ET France workshop : **March 31 – April 2 at IJCLab**

Goal: setting up the organization of ET-France

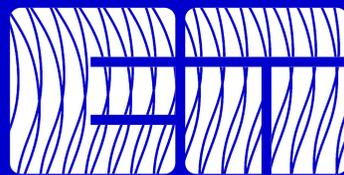
<https://indico.in2p3.fr/event/37982>



The banner features the Einstein Telescope France logo on the left, which consists of a stylized blue and white graphic of a telescope's primary mirror segments above the text 'EINSTEIN TELESCOPE FRANCE'. To the right of the logo, the text 'Einstein Telescope France Workshop' is written in white on a dark blue background. Below this, on a light blue background, the dates '31 mars 2026 à 2 avril 2026', the location 'IJCLab', and the time zone 'Fuseau horaire Europe/Paris' are listed.

=> There's something for everyone!

Thank you!



EINSTEIN
TELESCOPE