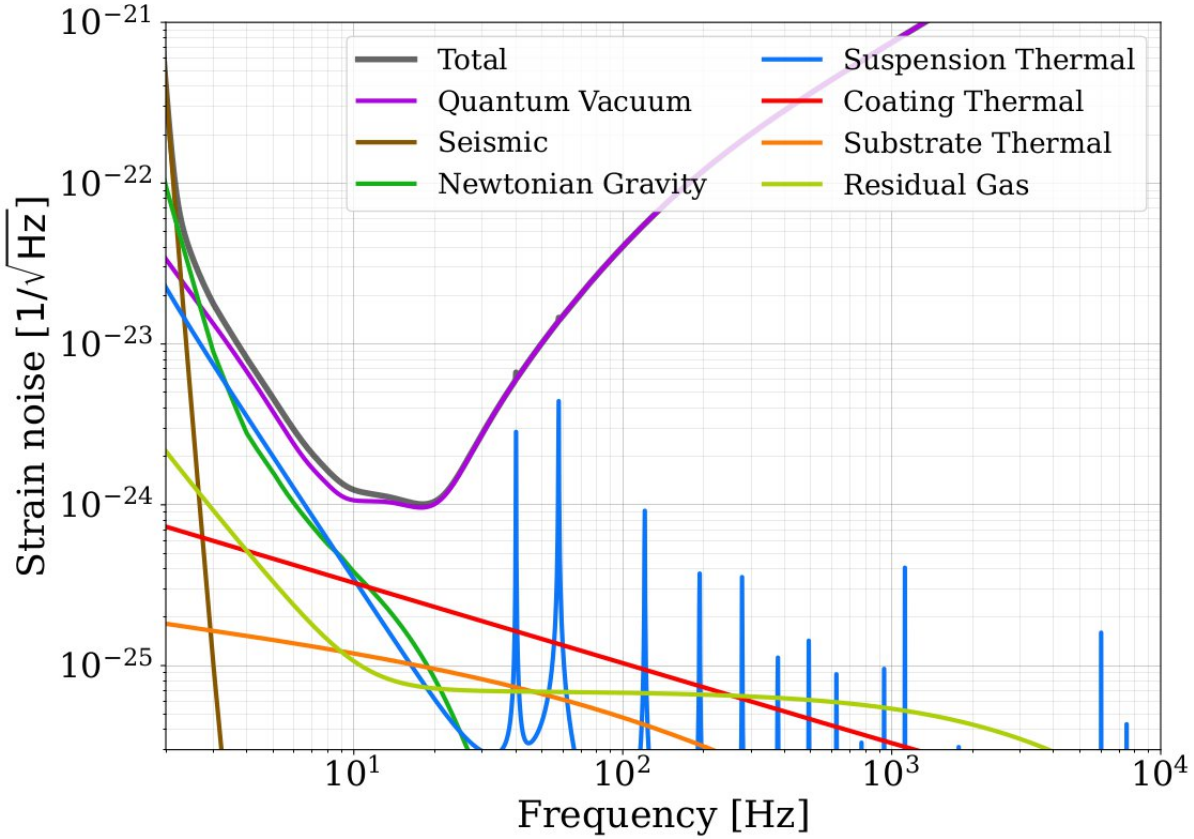
EINSTEIN TELESCOPE

Squeezing activities in France for Einstein Telescope

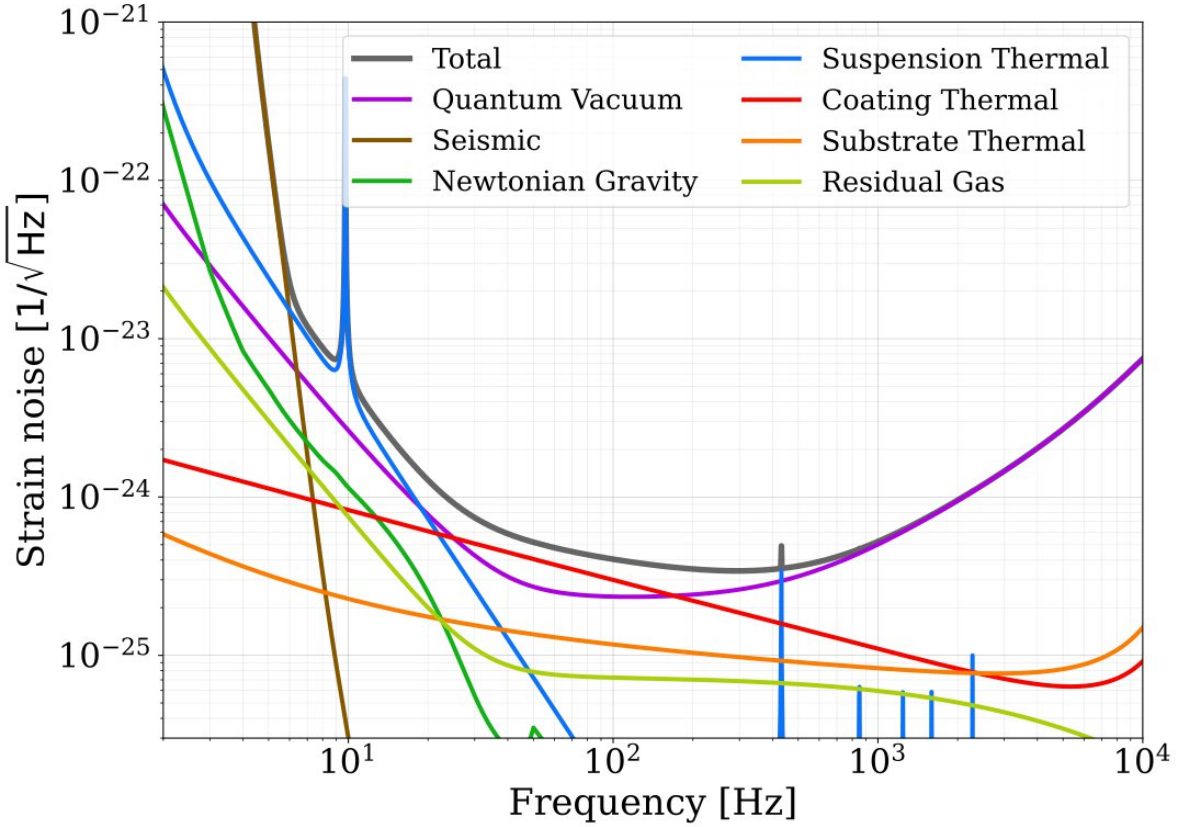
ET France meeting - 08/10/2025

Quantum noise in Einstein Telescope

- Quantum noise is a major limiting noise for both low and high frequency detectors



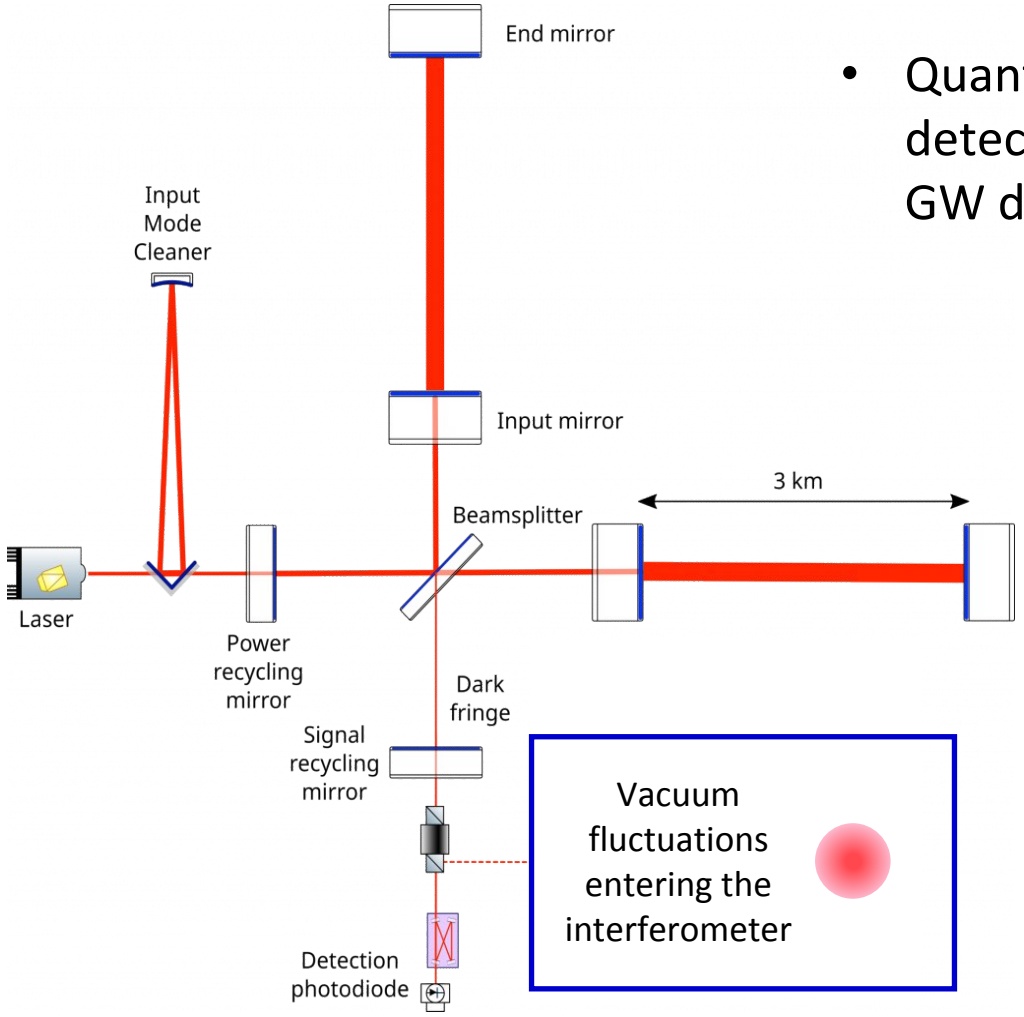
ET-LF sensitivity



ET-HF sensitivity

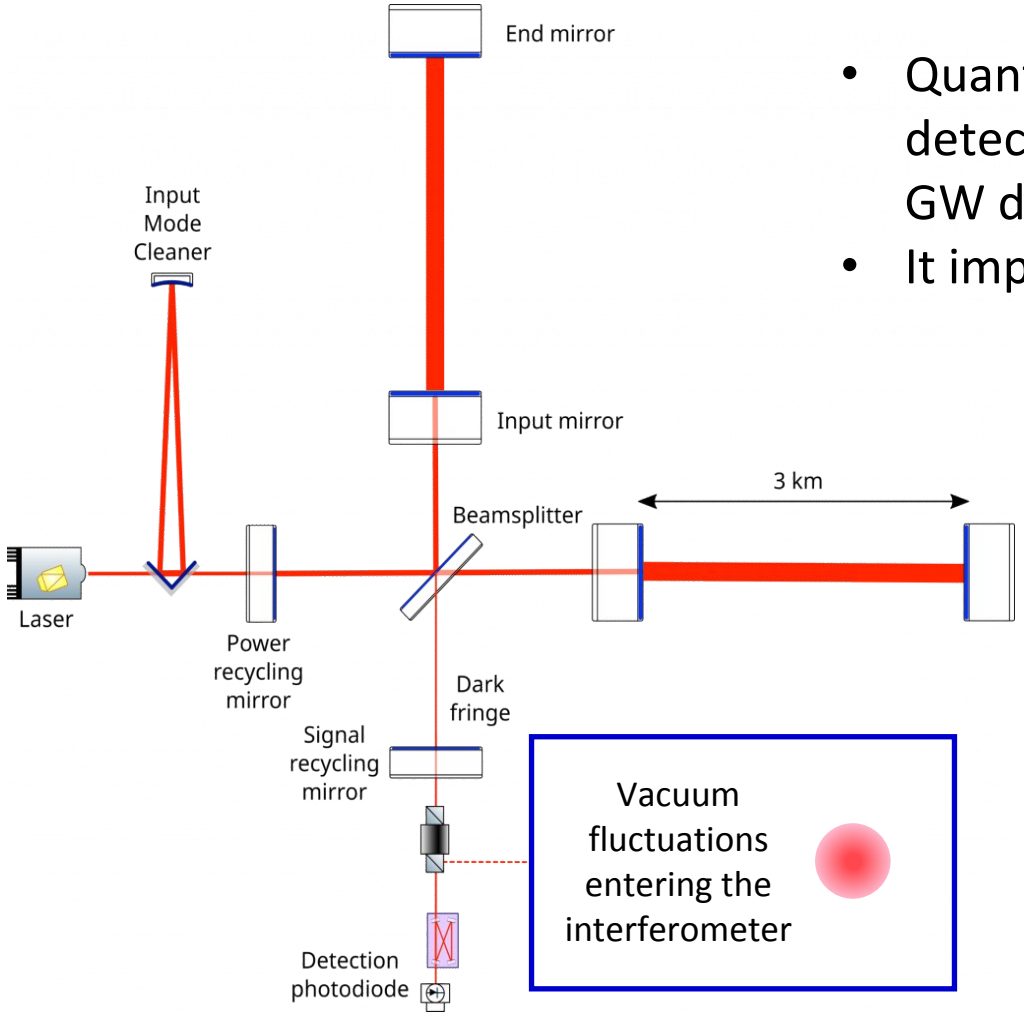
ET-0007B-23

Introduction on quantum noise and squeezing

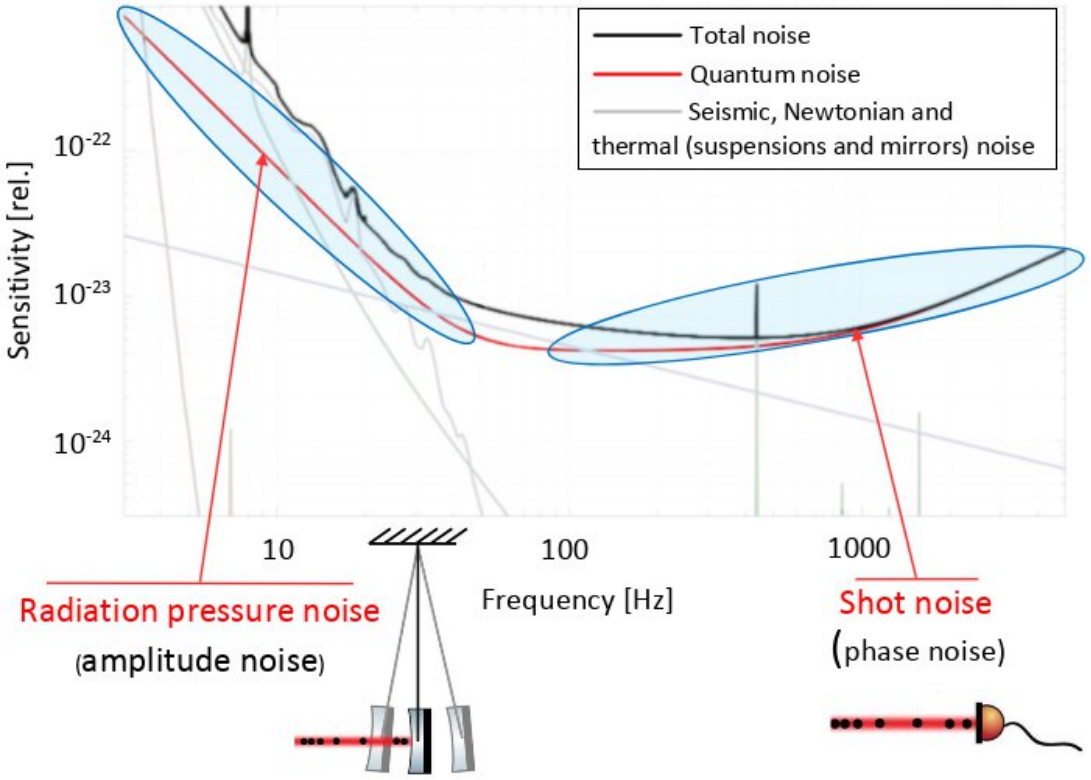


- Quantum noise arises from vacuum fluctuations entering the GW detector through its output port and interfering with the light used for GW detection.

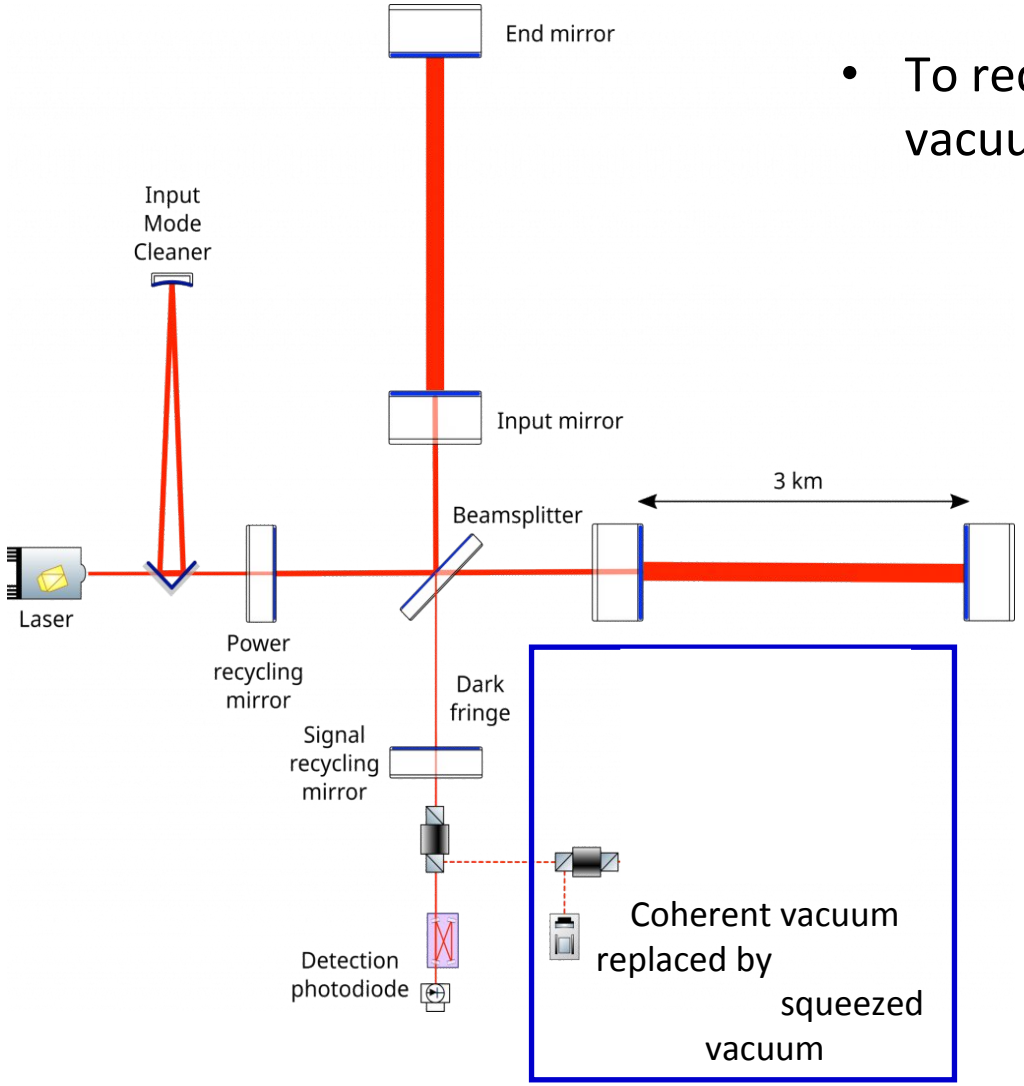
Introduction on quantum noise and squeezing



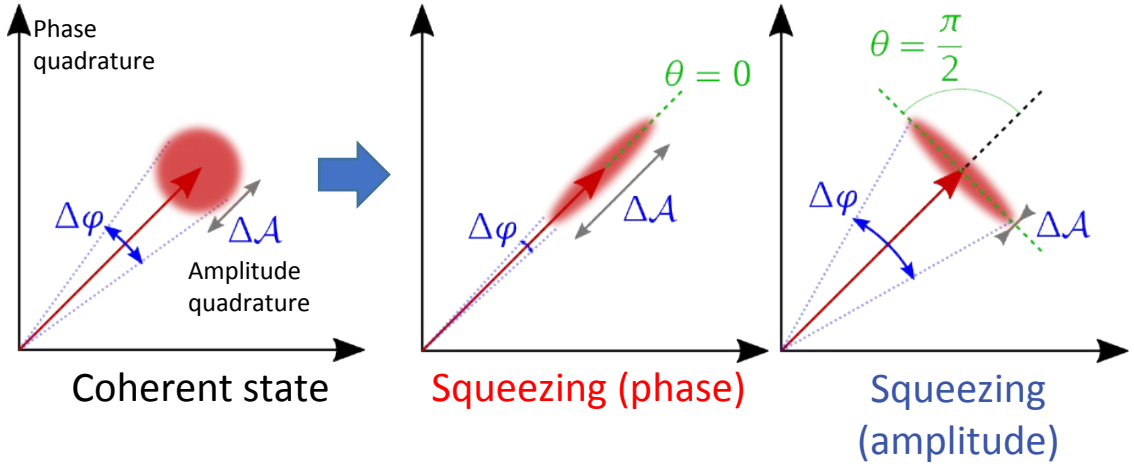
- Quantum noise arises from vacuum fluctuations entering the GW detector through its output port and interfering with the light used for GW detection.
- It impacts the interferometer sensitivity through two ways:



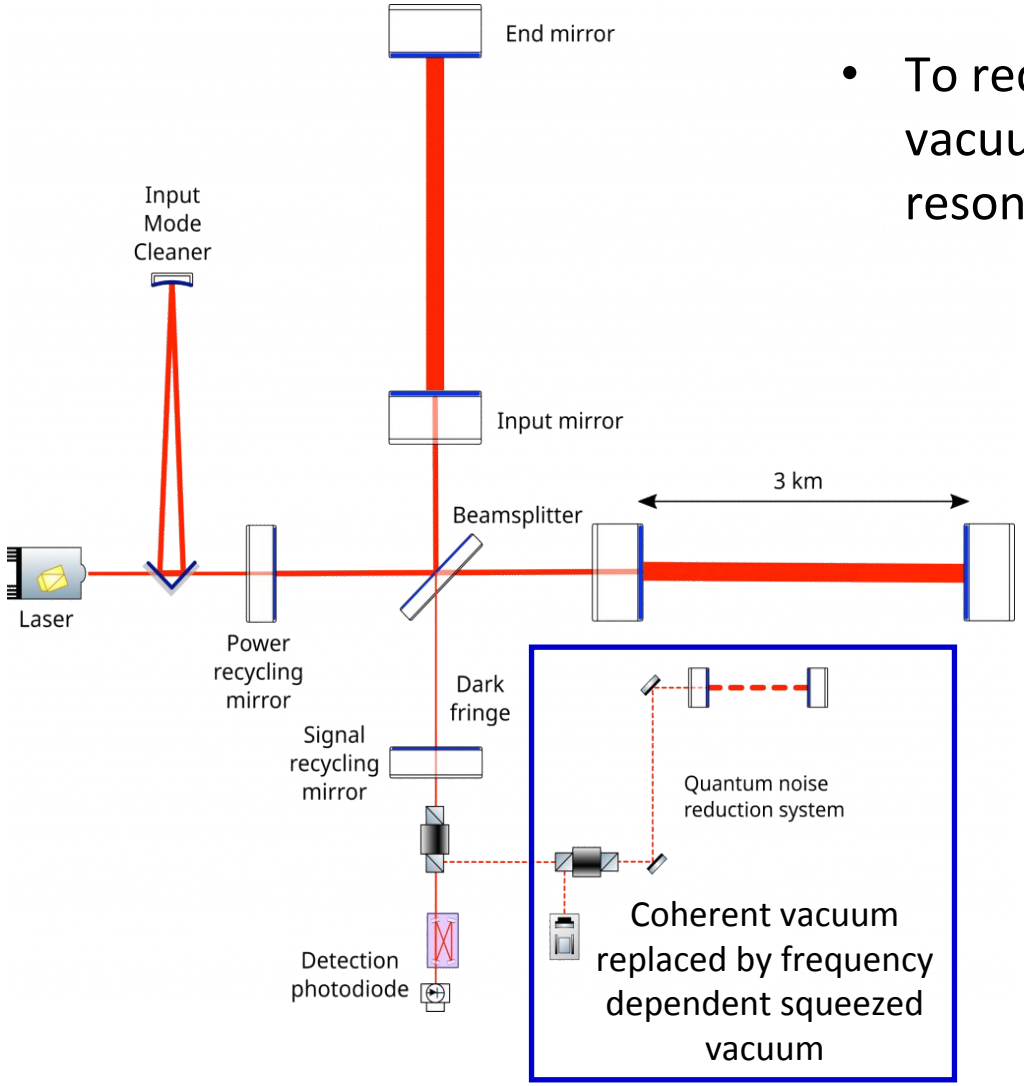
Introduction on quantum noise and squeezing



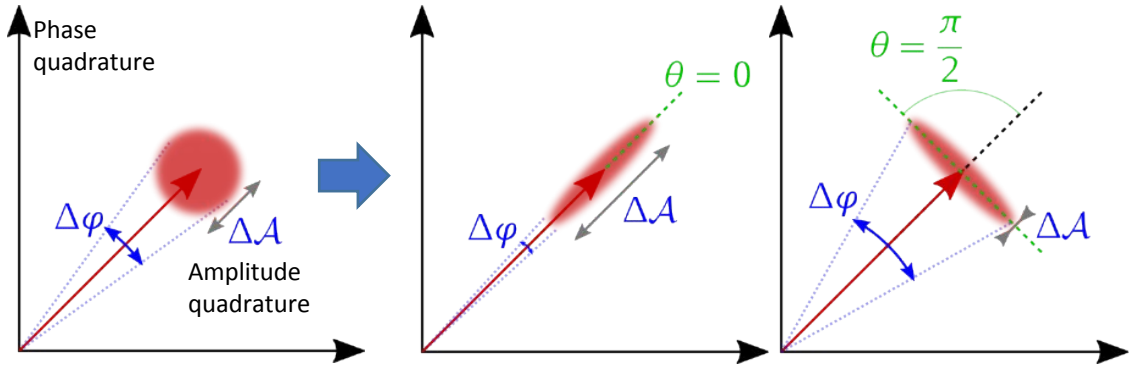
- To reduce quantum noise we replace the coherent vacuum with squeezed vacuum states of light

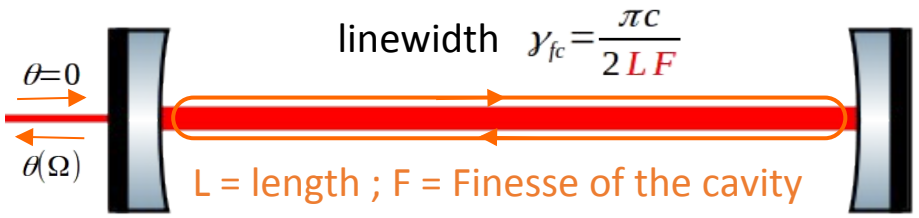


Introduction on quantum noise and squeezing



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

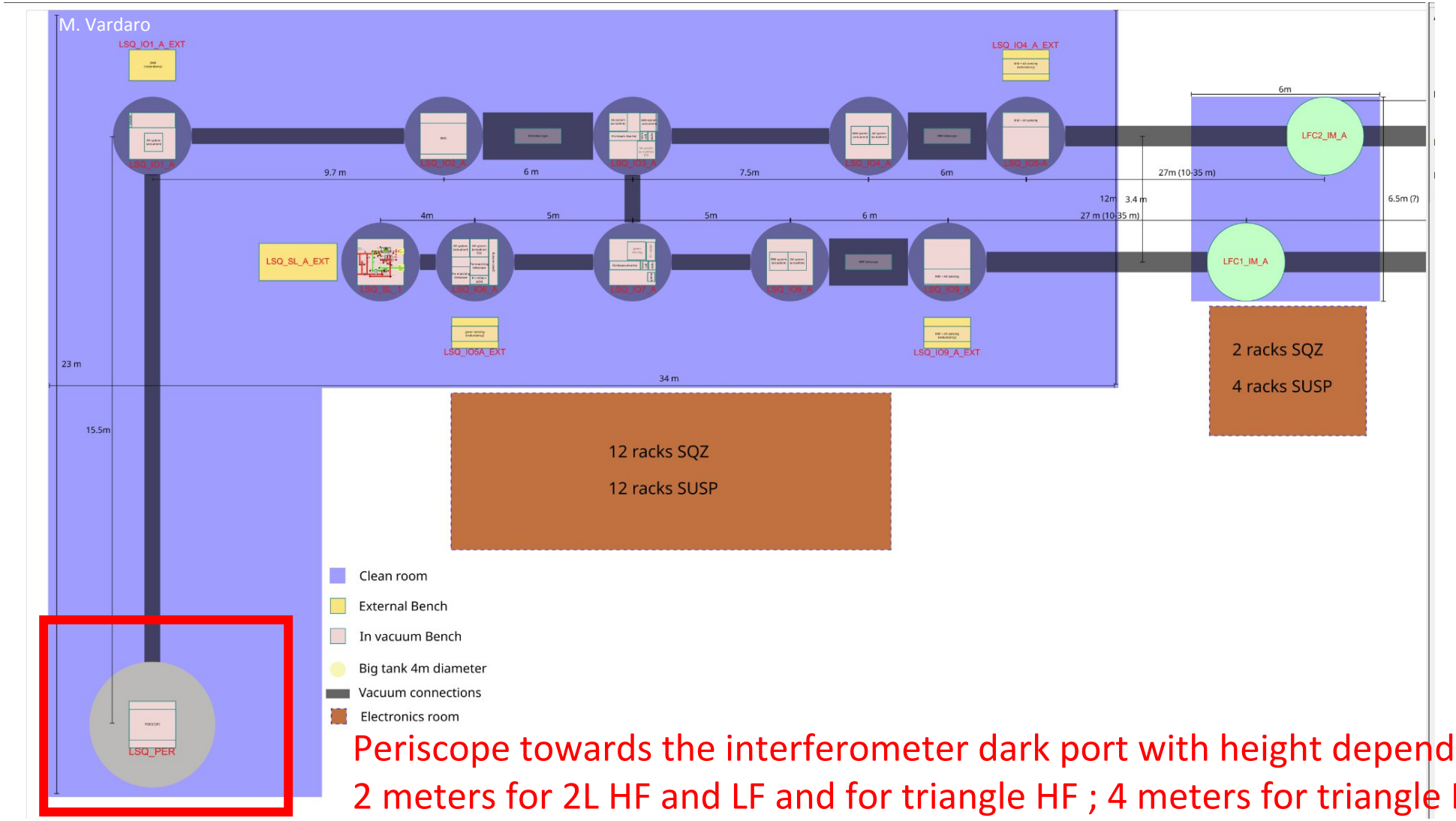




Einstein Telescope Squeezed Light Working Group

- The ET Squeezed Light Working group has a French co-chairing (Eleonora Capocasa and Angélique Lartaux)
- Activities inside the working group are divided into subgroups (French participation in blue from APC, IJCLab and Artemis):
  - Physical subsystems groups:
    - HF Squeezing source at 1064 nm
    - LF Squeezing source at 1550 nm
    - HF Filter cavity (1km) => currently under French responsibility
    - LF Filter cavities (2x5km)
    - Balanced Homodyne Detection
  - Transversal groups:
    - Phase noise
    - Global design => currently under French co-responsibility
    - Pygwinc (link with Interferometer division)
  - Other R&D groups:
    - EPR
    - Squeezing source at 2 µm

Schematic of the Sqeezing Lab (from ET Task force)

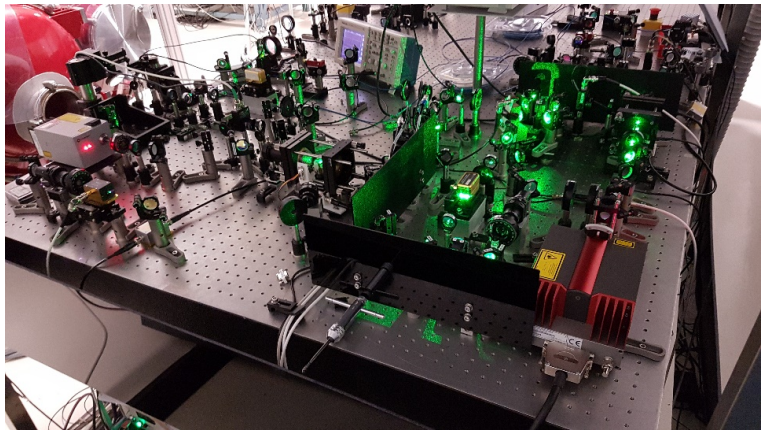


End mirrors
5km away

Periscope towards the interferometer dark port with height depending of the configuration:
2 meters for 2L HF and LF and for triangle HF ; 4 meters for triangle LF

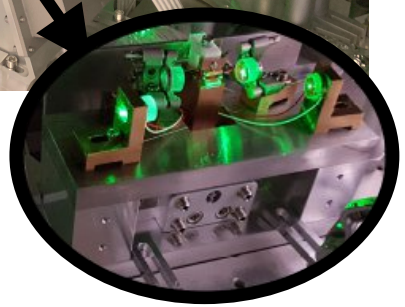
Design of the HF Squeezed Light Source

In-air beams preparation bench



Under vacuum bench

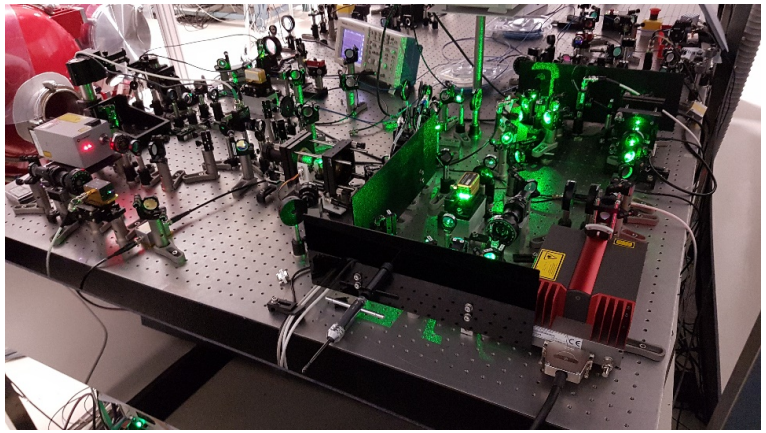
Squeezing source



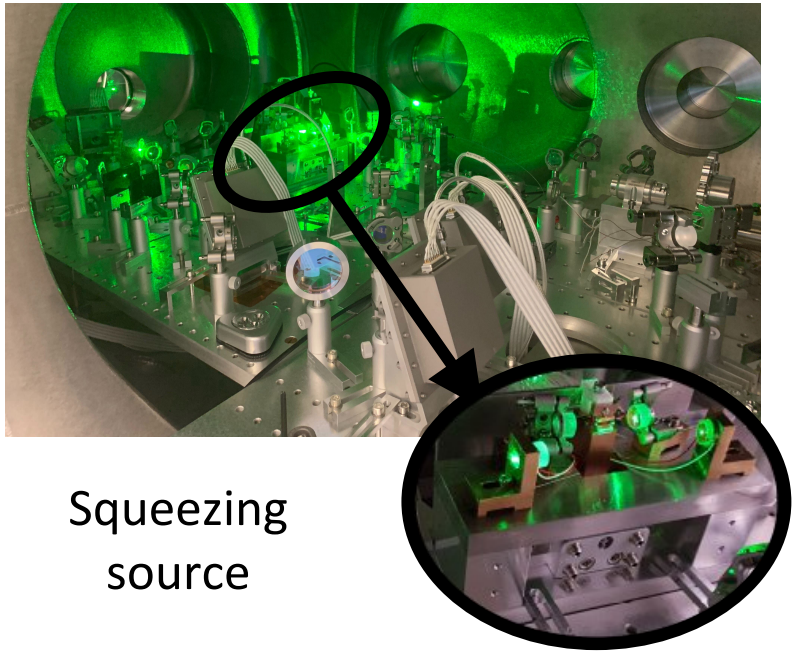
- Main design done independently in Hannover (AEI)
- R&D development of under vacuum Squeezed Light Source at IJCLab on the CALVA facility:

Design of the HF Squeezed Light Source

In-air beams preparation bench

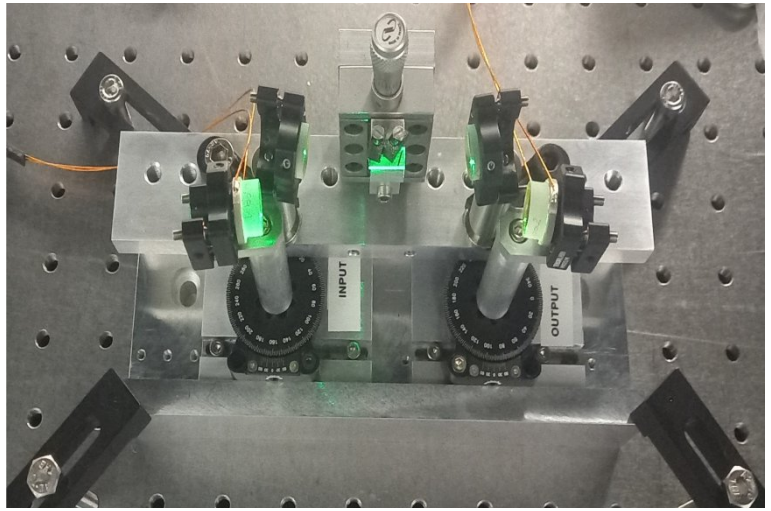


Under vacuum bench



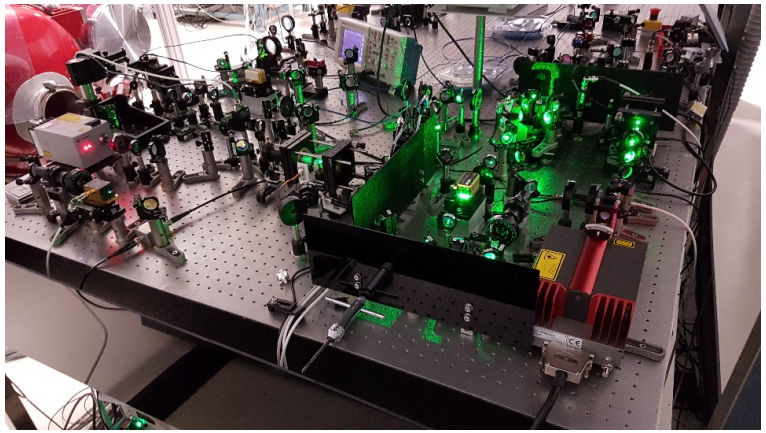
Squeezing source

- 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)



Design of the HF Squeezed Light Source

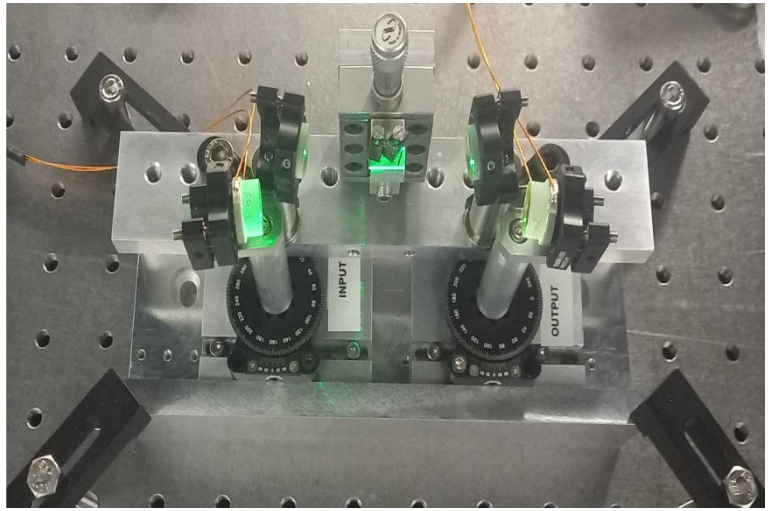
In-air beams preparation bench

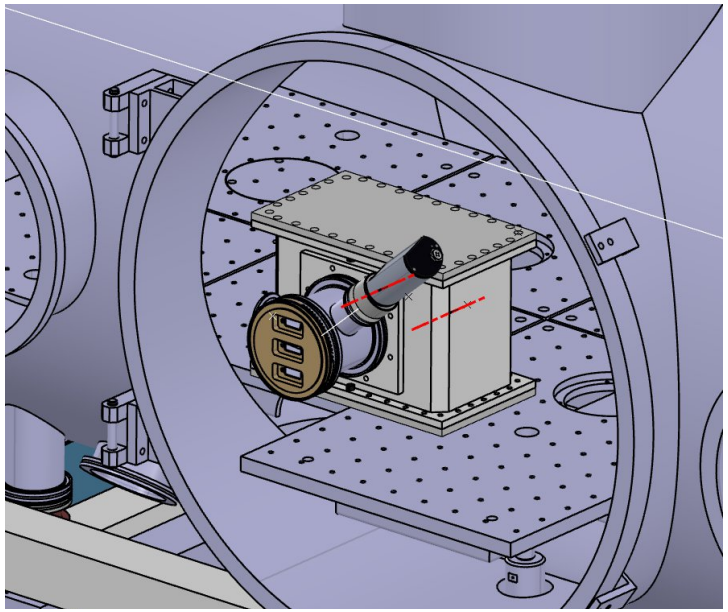


Under vacuum bench

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)



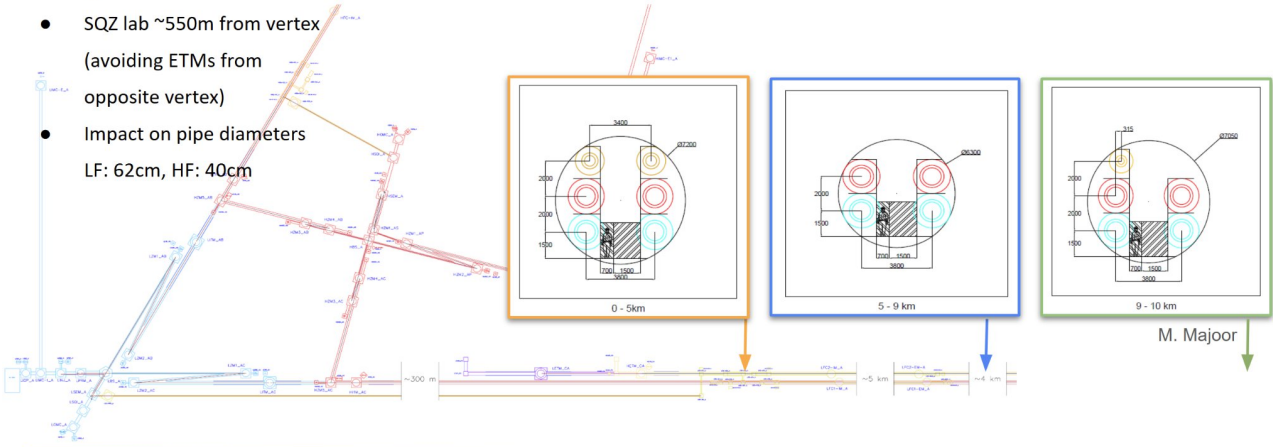


Design of the filter cavities

- Filter cavities will be a important driving cost for Einstein Telescope due to their impact on the infrastructure
- The baseline design consists of 2-mirror cavities in the way done for LIGO and Virgo but requires optimization studies: eg. pipe diameter (taking into account optical losses, scattered light), mode matching, etc.

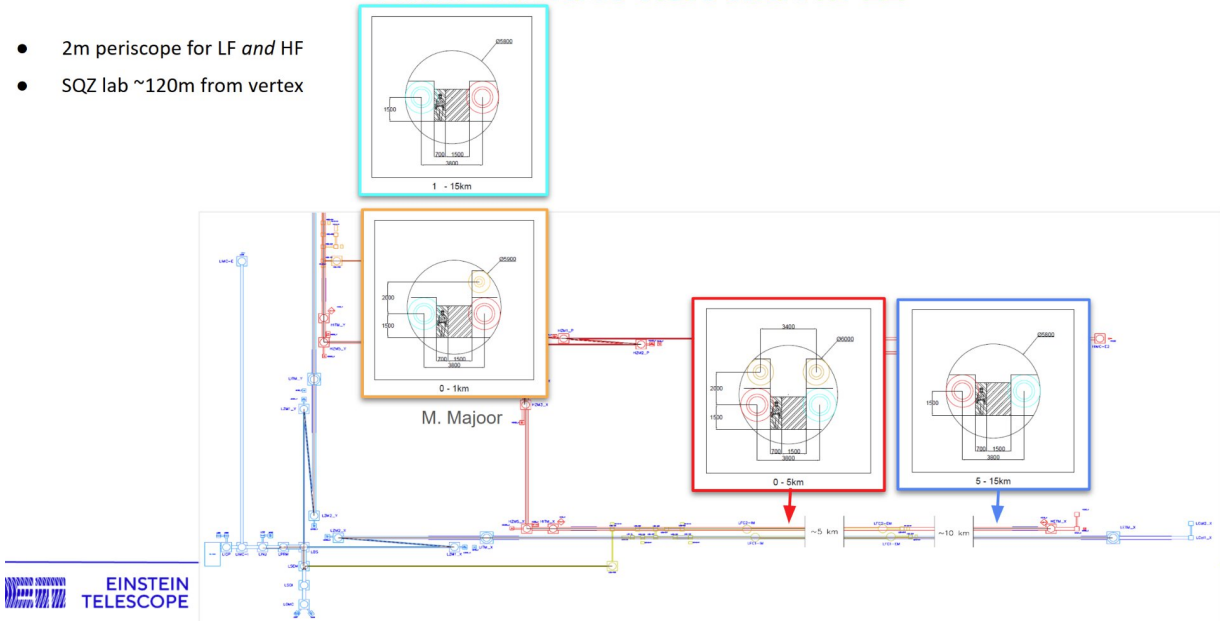
Filter Cavities Relocation: Triangle

- 2m periscope for HF, 4m for LF
- SQZ lab ~550m from vertex (avoiding ETMs from opposite vertex)
- Impact on pipe diameters LF: 62cm, HF: 40cm



Filter Cavities Relocation: 2L

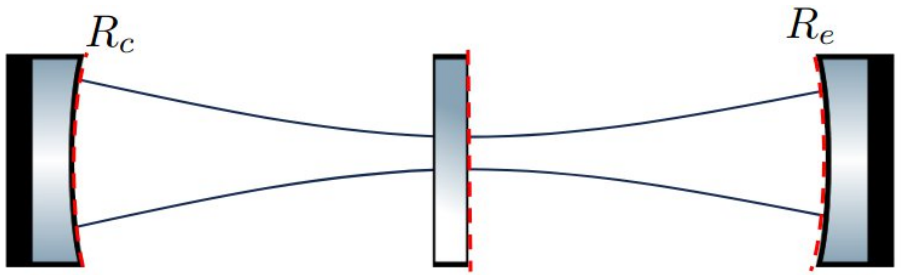
- 2m periscope for LF *and* HF
- SQZ lab ~120m from vertex



ET-0228A-25

Design of the filter cavities

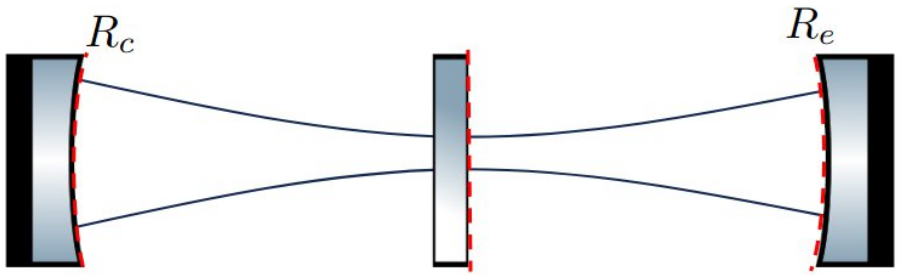
- Alternative design of filter cavities are under study:
  - LF: Replace the two 2-mirror cavities by one 3-mirror cavity (5+5 km) => ANR Quantum-FRESCO (2023-2027) see presentation of J. Ding



arXiv2506.02222

Design of the filter cavities

- Alternative design of filter cavities are under study:
  - LF: Replace the two 2-mirror cavities by one 3-mirror cavity (5+5 km) => ANR Quantum-FRESCO (2023-2027) see presentation of J. Ding

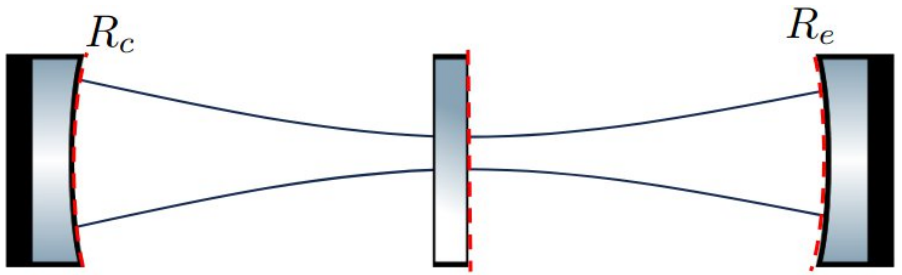


arXiv2506.02222

  - 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

Design of the filter cavities

- Alternative design of filter cavities are under study:
  - LF: Replace the two 2-mirror cavities by one 3-mirror cavity (5+5 km) => ANR Quantum-FRESCO (2023-2027) see presentation of J. Ding

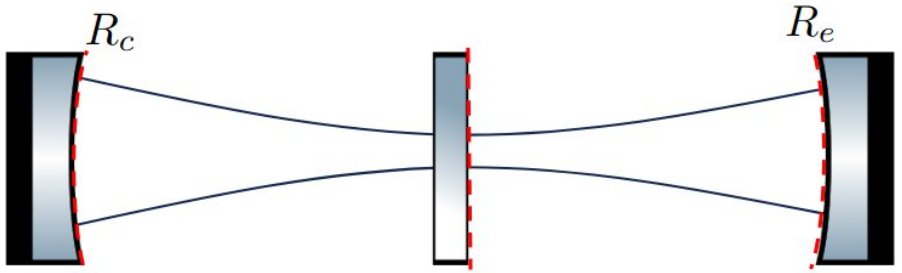


arXiv2506.02222

  - 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 => to be simulated to evaluate the available actuation range

Design of the filter cavities

- Alternative design of filter cavities are under study:
  - LF: Replace the two 2-mirror cavities by one 3-mirror cavity (5+5 km) => ANR Quantum-FRESCO (2023-2027) see presentation of J. Ding



arXiv2506.02222

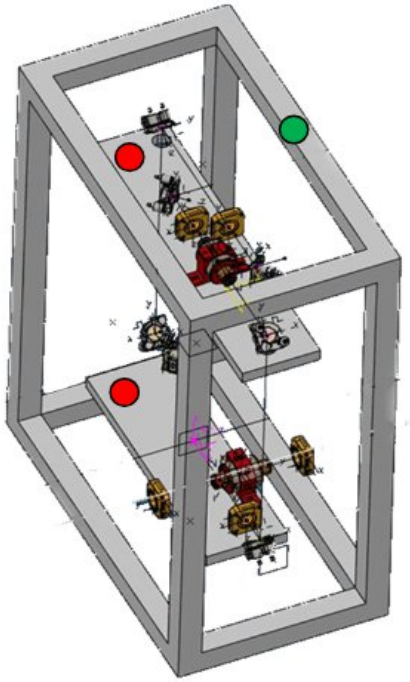
  - HF and LF: variable finesse cavities will be required to allow adaptation of frequency dependent squeezing both to changes in the interferometer during its 50 years lifetime (other solution is to change mirrors with associated risks) and accommodate for loss sources
    - Thermal tuning of the input mirror reflectivity using the etalon effect => 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 + ANR PRC 2026 project)

Design of the control strategy

- It is essential to define the control strategy in order to finalize the full optical scheme
- Several controls are required:
  - Squeezing ellipse angle
  - Filter cavities length
  - Automatic alignment
  - Mode matching

Design of a suspended periscope

- To reduce infrastructure cost, Einstein Telescope will require vertical periscope to bring the squeezed beams from filter cavities level to interferometer level:
  - 2 meters periscope for ET HF (both 2L and triangle configuration) and ET LF in 2L configuration
  - 4 meters periscope for ET LF in triangle configuration
- Periscopes 10 times taller than what has been implemented so far in GW detectors (monolithic periscopes)
- Careful study on suspension stability an controllability but also polarization mixing must be done
- Initial smaller scale simulation test study done at INSA Lyon during a student project
- Collaboration can be done on this project between several French labs each bringing its own expertise (optics, mechanics, suspension)

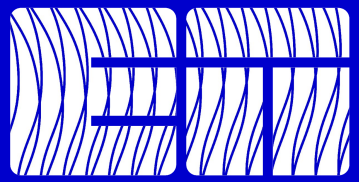


D. Douillet

Conclusions

- The squeezing system could be a strong participation of France to the Einstein Telescope detector
- It can foster collaboration between French labs, both on pure squeezing parts but also cross-disciplinary (mechanics, suspensions, coatings, simulations).
- The current HF baseline is close to existing systems (but with longer cavity) and the current LF baseline only add the change of wavelength and one more filter cavity (again longer).
- **The main unknown of the current baseline are the suspended periscope.**
- Many R&D are done or foreseen in French labs for the squeezing subsystem!

Thank you!



EINSTEIN
TELESCOPE