

EINSTEIN
TELESCOPE

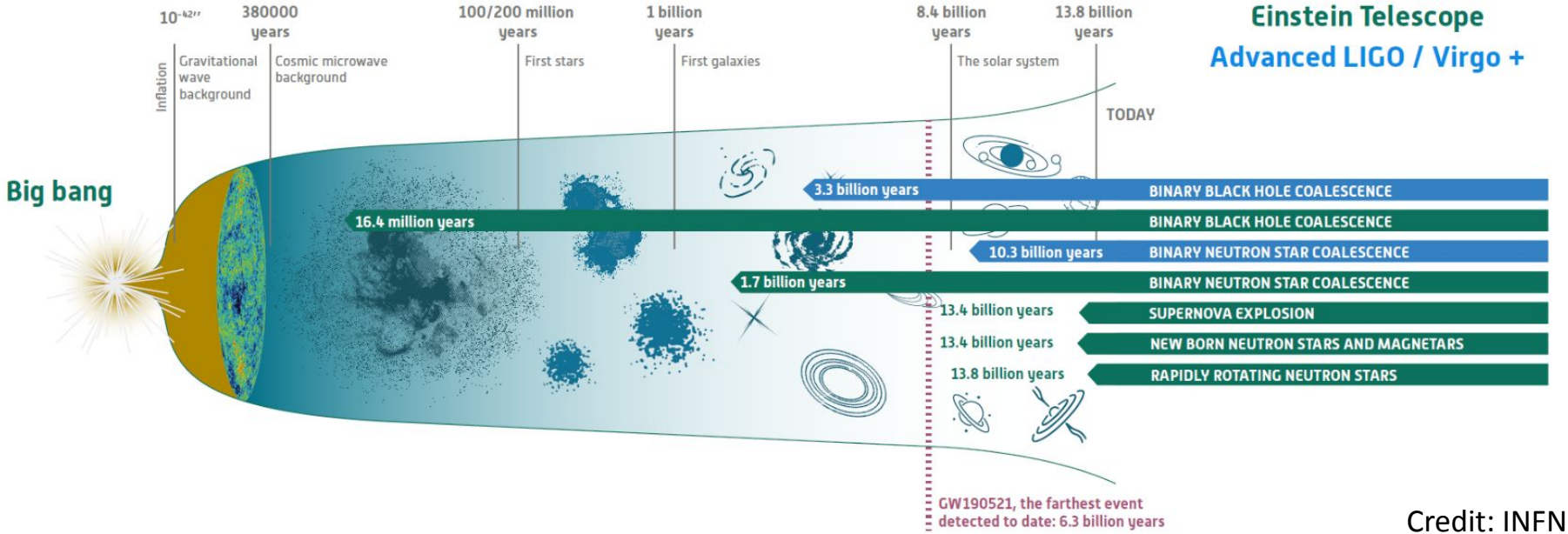
# Einstein Telescope detector technologies

Angélique Lartaux
on behalf of the ET collaboration

ET-Spain - 4 November 2026

# Introduction to Einstein Telescope

- A precision instrument for gravitational wave sources in the nearby Universe
- A discovery machine investigating back to the dark ages of the Universe

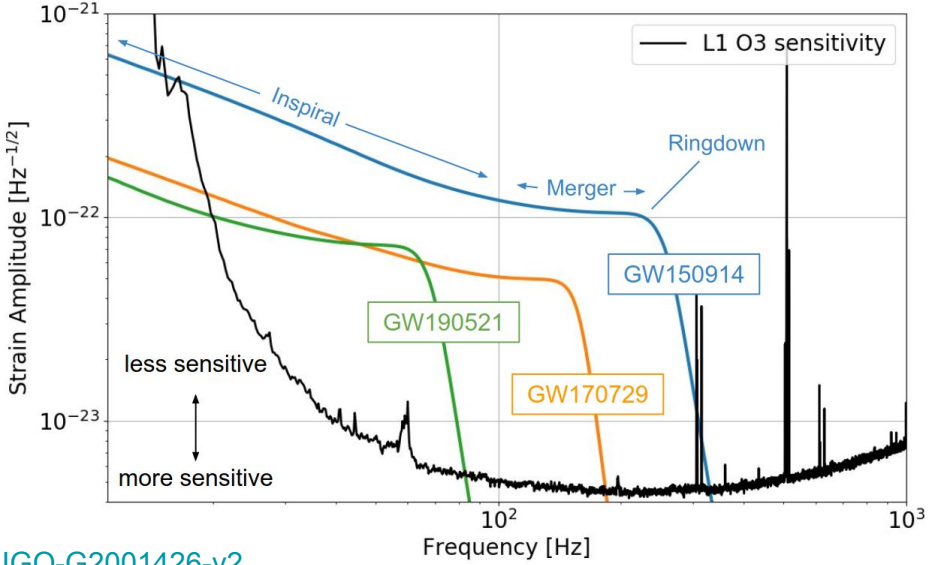



Credit: INFN

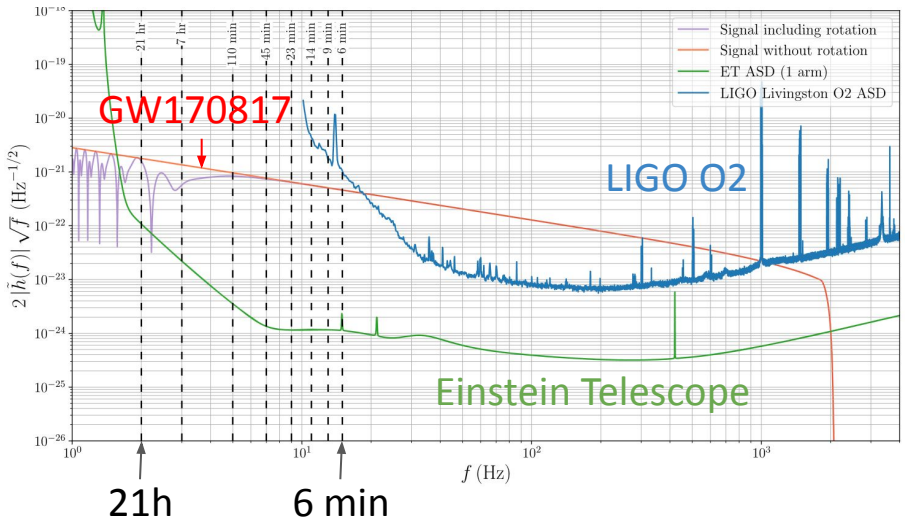
# Instrumental requirements from science targets (1/3)

- Increasing the sensitivity to low frequencies…

**Higher masses correspond to lower frequency GW emission**




**Early warning for Binary Neutron Star mergers to alert the community**

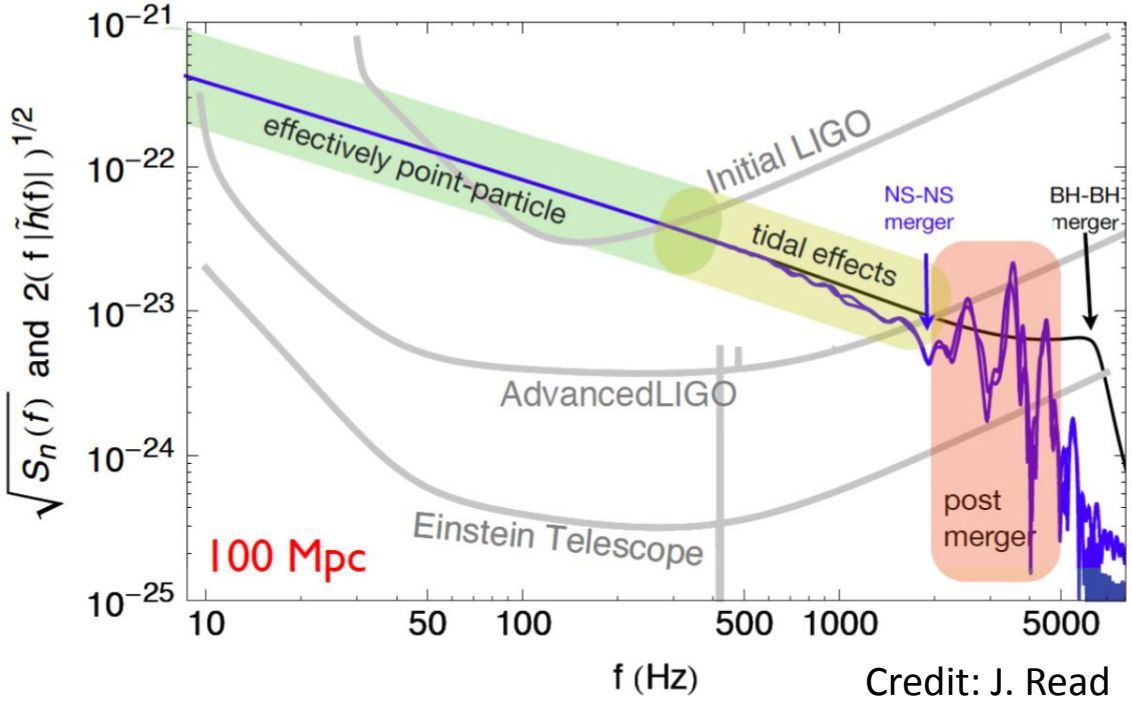



LIGO-G2001426-v2

Francesco Iacovelli *et al* 2022 *ApJ* **941** 208

# Instrumental requirements from science targets (2/3)

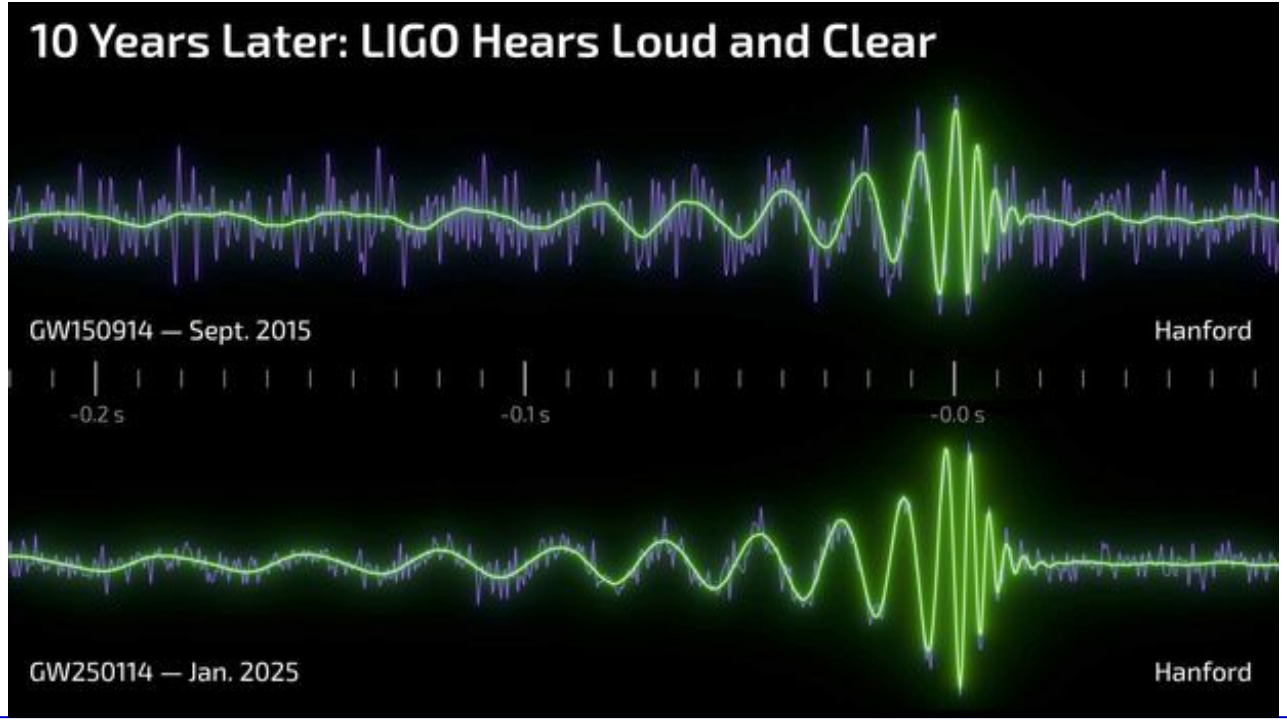
- Increasing the sensitivity to low frequencies… and also to high frequencies




Credit: J. Read

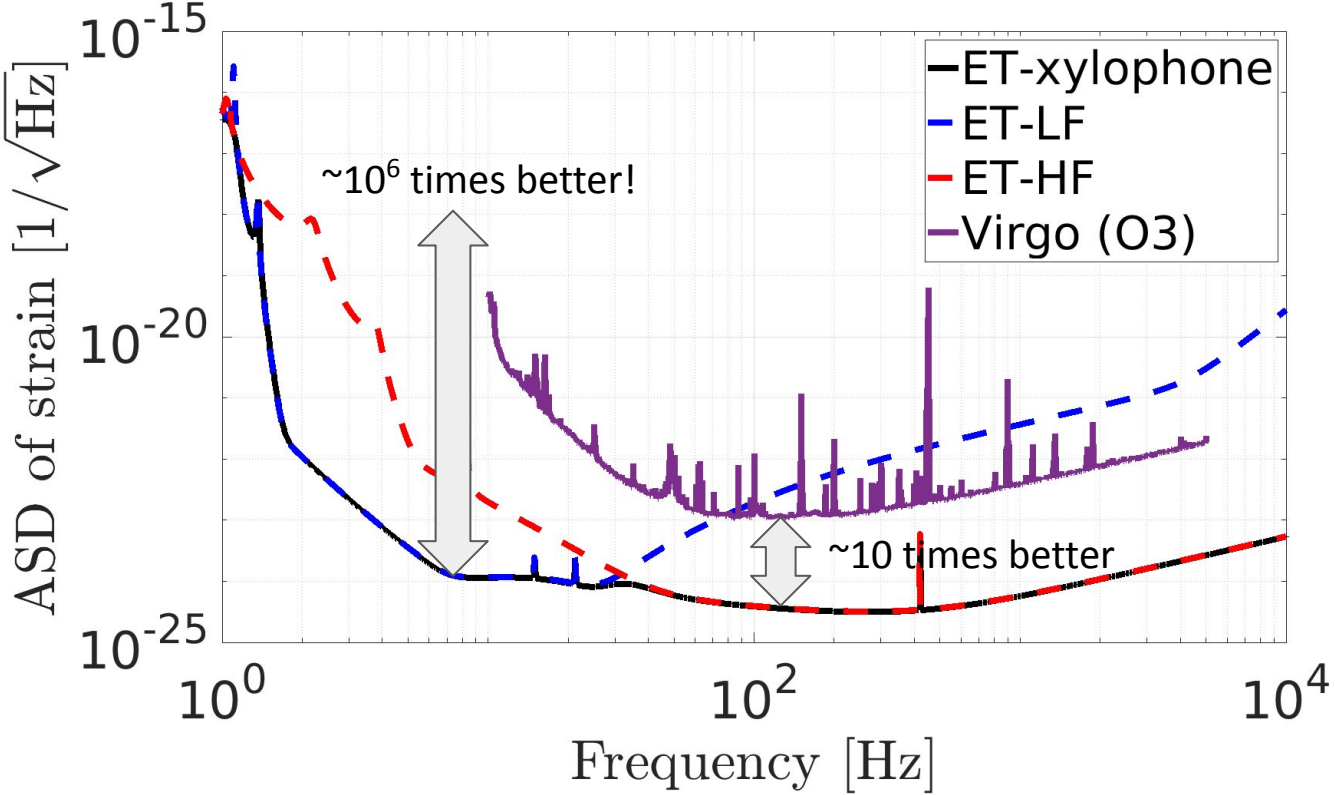
# Instrumental requirements from science targets (3/3)

- Having better signal-to-noise ratio for tests of General Relativity



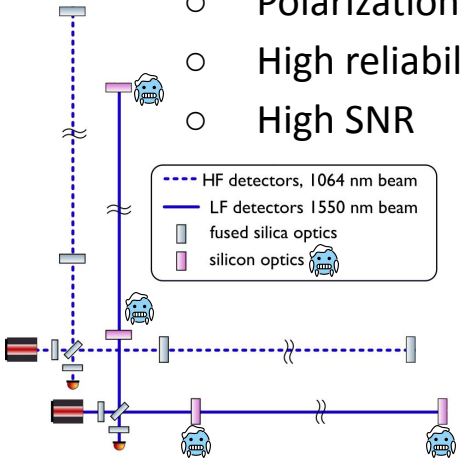

Credit: LIGO / J. Tissino (GSSI) / R. Hurt (Caltech-IPAC)

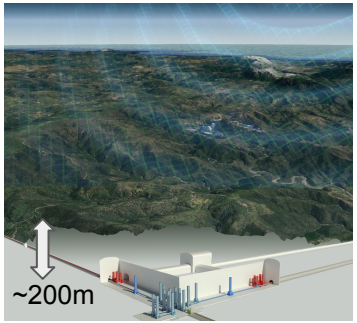
# Instrumental challenges - Sensitivity improvement



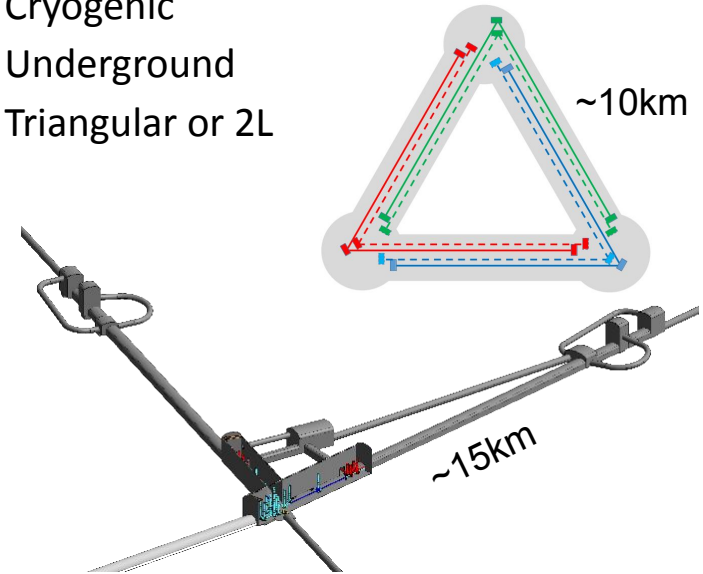
# Instrumental requirements - Key elements

- Requirements
  - Wide frequency range
  - Low-frequency sensitivity
  - Localization capability
  - More uniform sky coverage
  - Polarization disentanglement
  - High reliability (high duty cycle)
  - High SNR



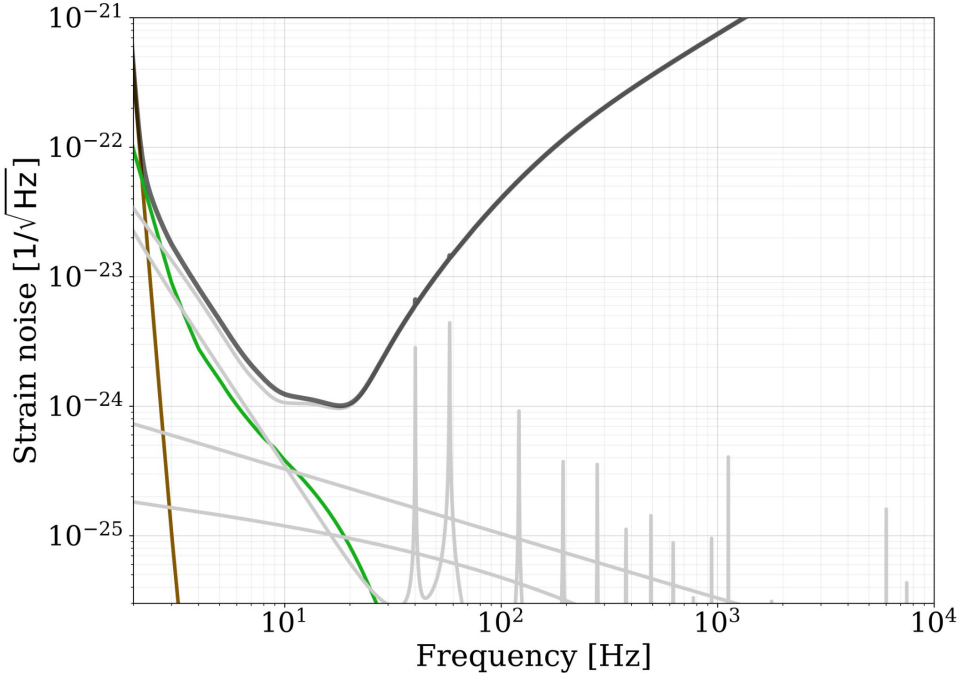




- Design specifications
  - Longer arms (10-15km)
  - Xylophone (multi-interferometer) design
  - Cryogenic
  - Underground
  - Triangular or 2L

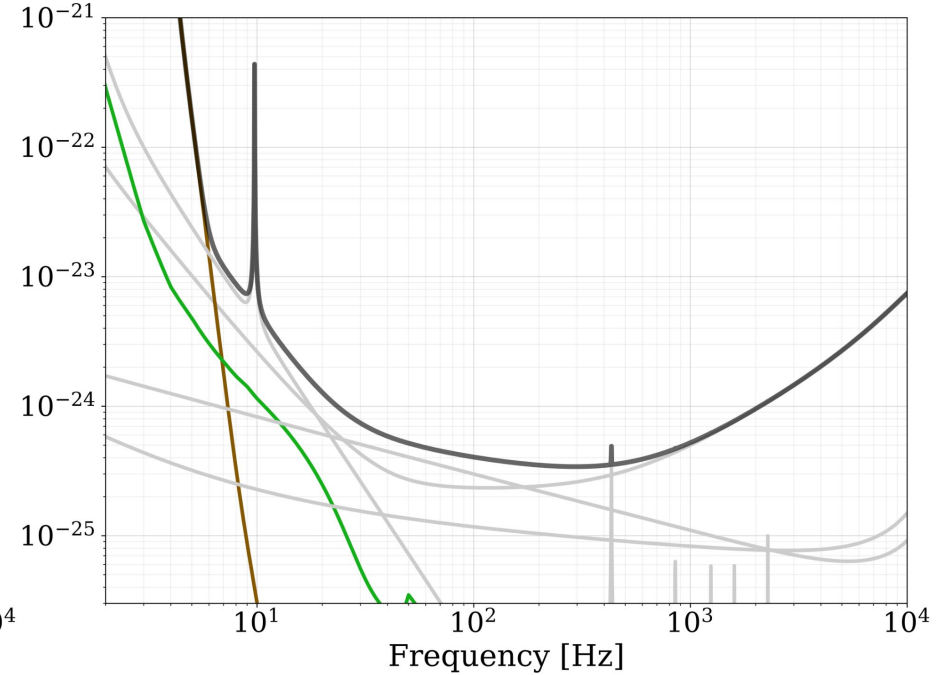


# Sensitivity curves

## Underground operation



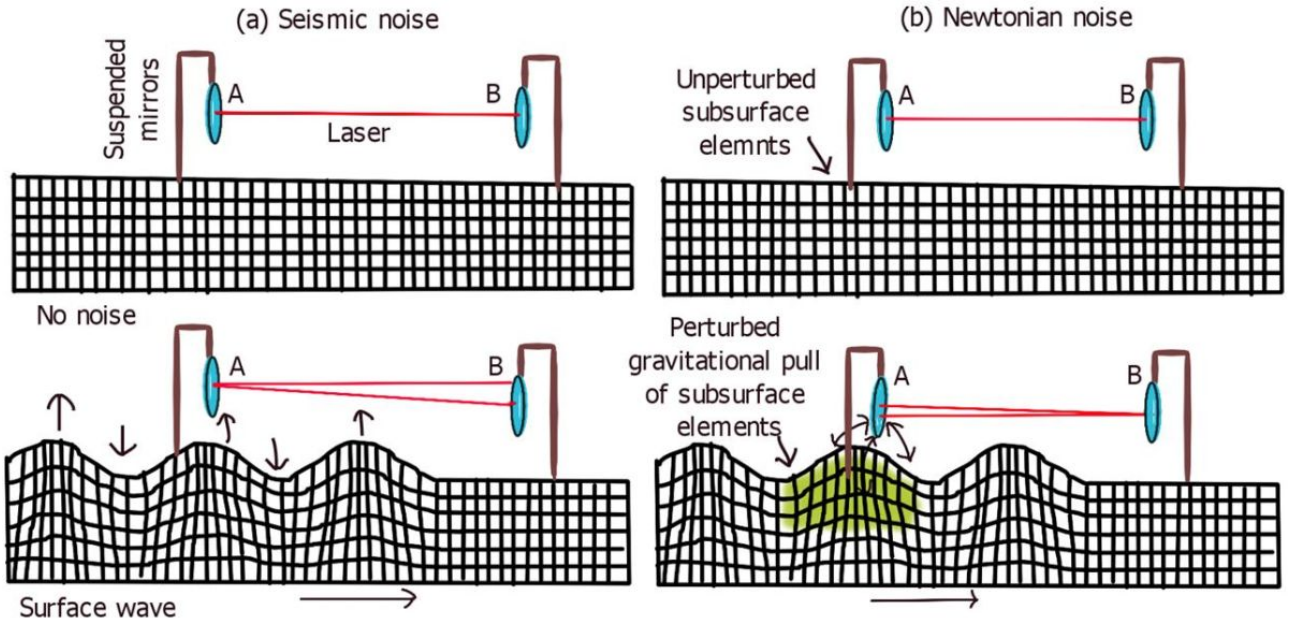

## Low-frequency detector




## High-frequency detector

# Newtonian noise

- It was shown that a seismic tiltmeter has the maximal coherence of all types of seismic sensors with NN produced by a field of Rayleigh waves
- A single tiltmeter would allow us to fully cancel NN from Rayleigh waves

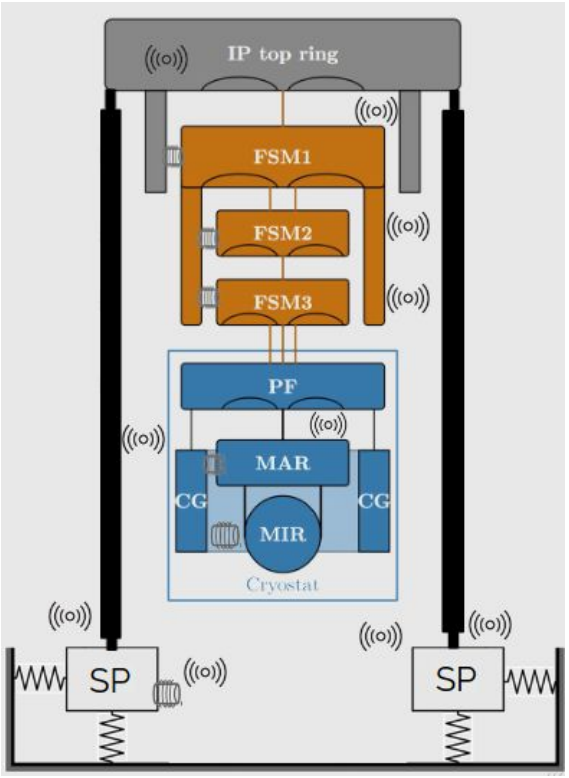



From L. Errico presentation

# Suspension system

- Active and Passive pre-attenuation stage
- Mechanical Filter Chain
- Payload
- Sensors, Actuators and their driving electronics boards

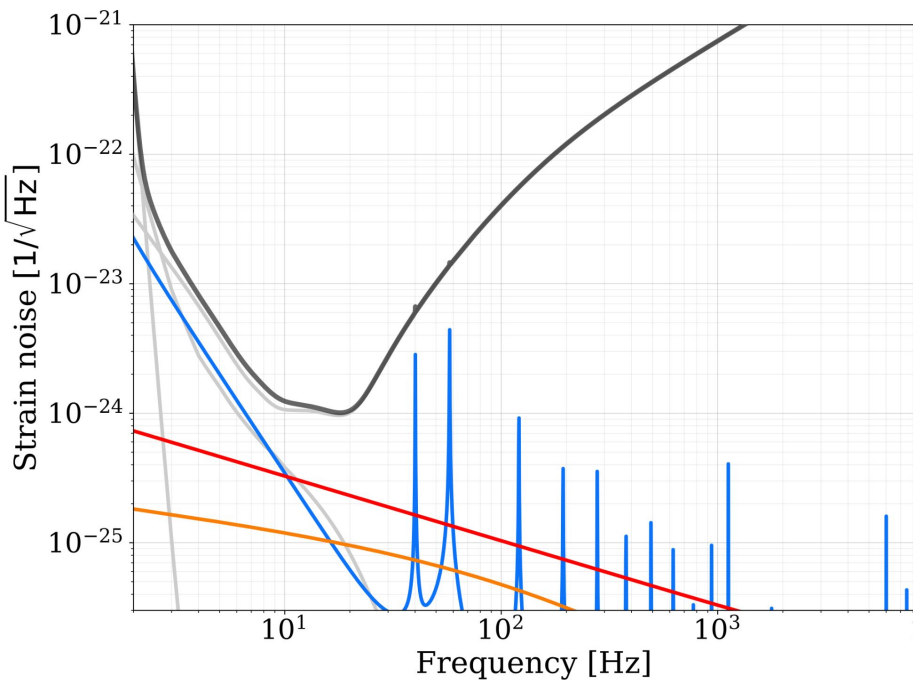




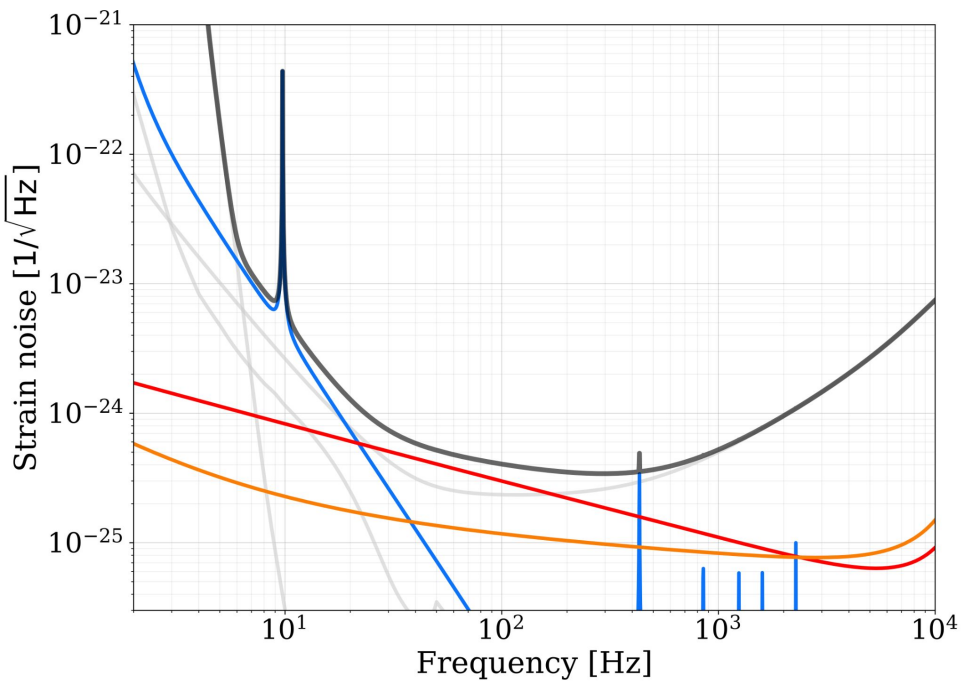

From R. Cornelissen and J. Docherty presentation

# Sensitivity curves

Cryogenics operation

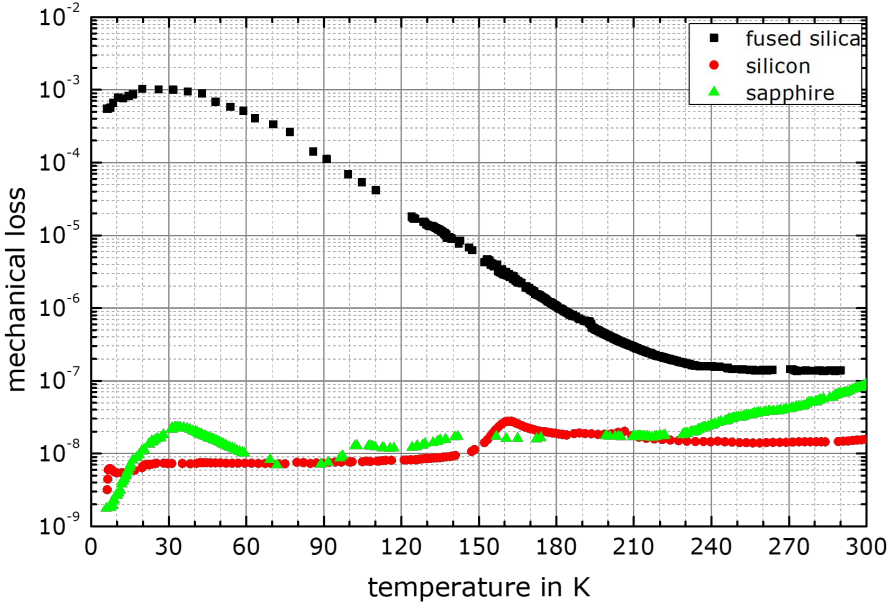



Low-frequency detector




High-frequency detector

# Cryogenics challenges - mirror substrate




R. Nawrodt et al. 2009, Proceedings of ICEC22-ICMC2008

From L. Silenzi presentation

## Sapphire

Already used at 1064 nm in KAGRA, shows challenges in inhomogeneities, birefringence and size availability

## Silicon

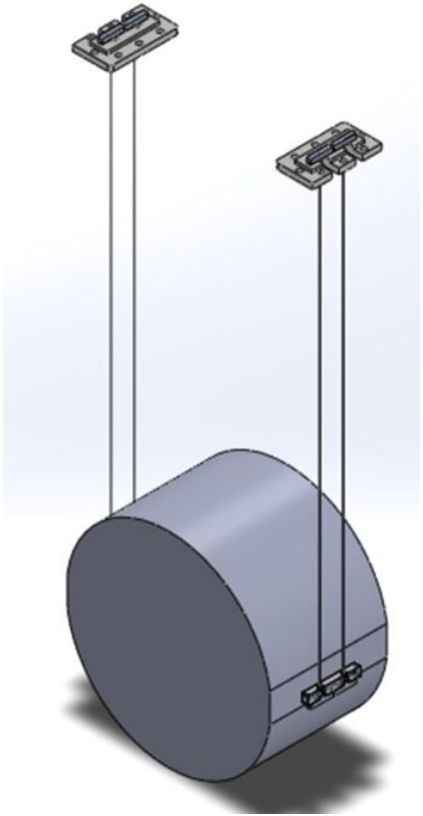
Low optical absorption requires very pure material, i.e. float zone (FZ) silicon or magnetically-stabilized Czochralski silicon.

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

# Cryogenics challenges - cooling

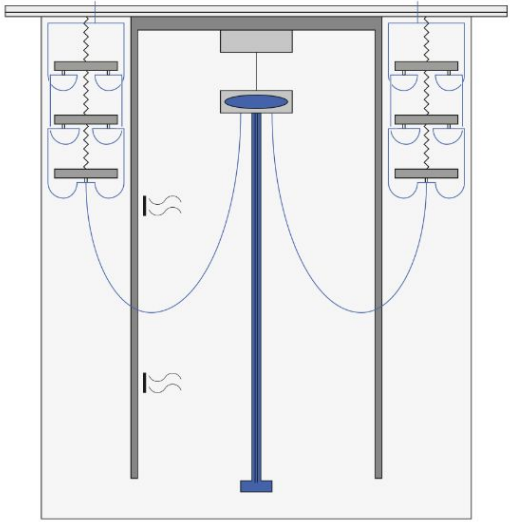
- Thermal noise from suspensions, mirror substrate and coating impact the position of the mirror seen by the laser
- The cooling of a 200 kg test-mass hosted by an 800 kg articulated structure at few K IS NOT a technological challenge
- Cooling-down with mechanical constraints impacting on the structural dynamics of the payload and then on the control noise reflected on its position is a BIG CHALLENGE
- Cooling-down a test-mass that is indeed a mirror that is a core optical element of an interferometer is a BIG CHALLENGE



Adapted from E. Majorana presentation

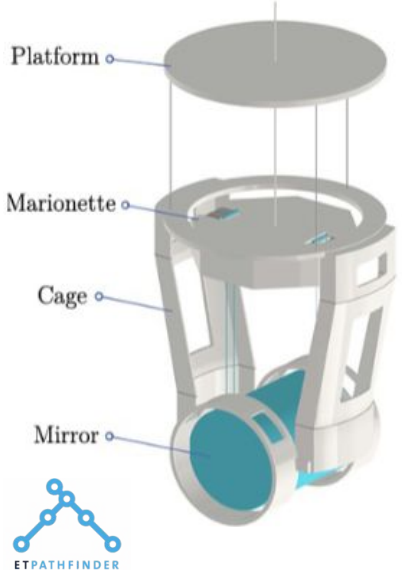
# Cryogenics - Baseline payload design

- 4 concepts presented to ETO during a dedicated workshop

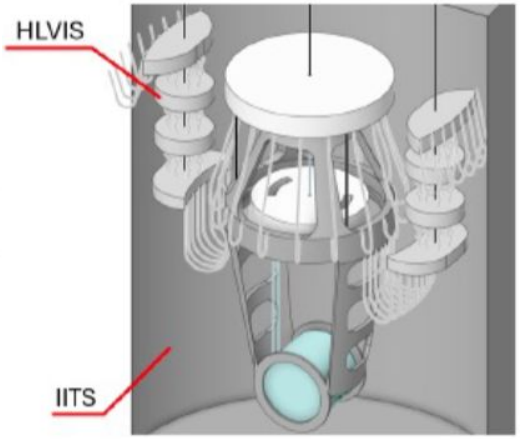


KIT Karlsruhe Institute of Technology

Steady-state: Static He-II
Cool-down: He-I counter-flow




Cooling via sub-cooled LN2 and sorption compressors (He, H, Ne) – laminar flow




ARC-ETCRYO

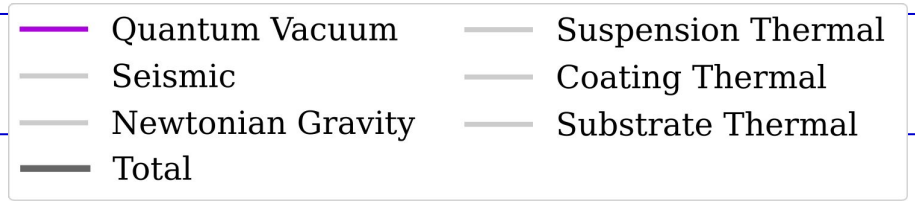
Cooling down with Pulse Tube cryocoolers (KAGRA)



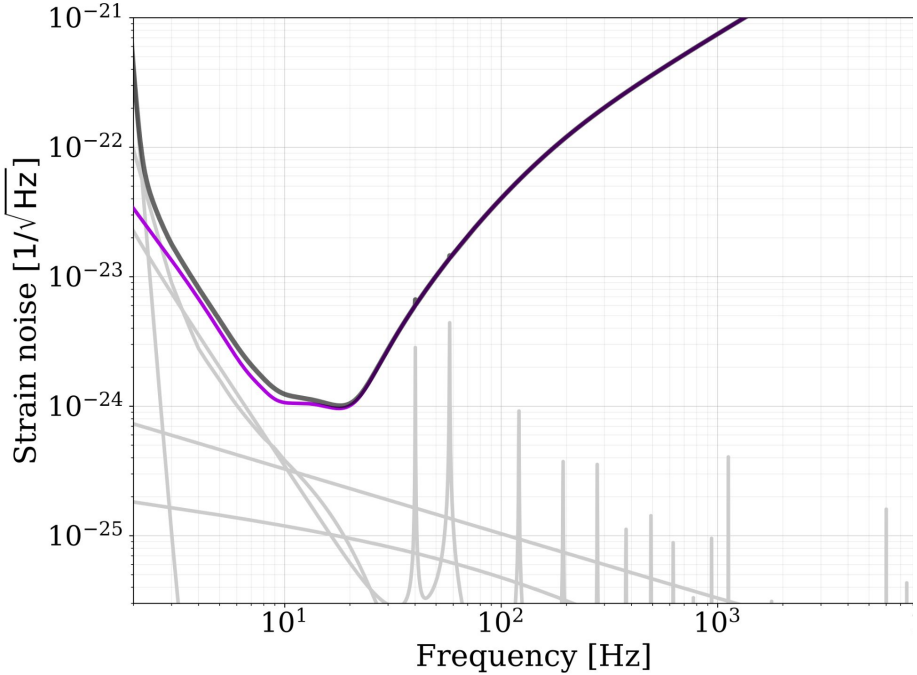
E-TEST

Cryogenic radiative heat exchange

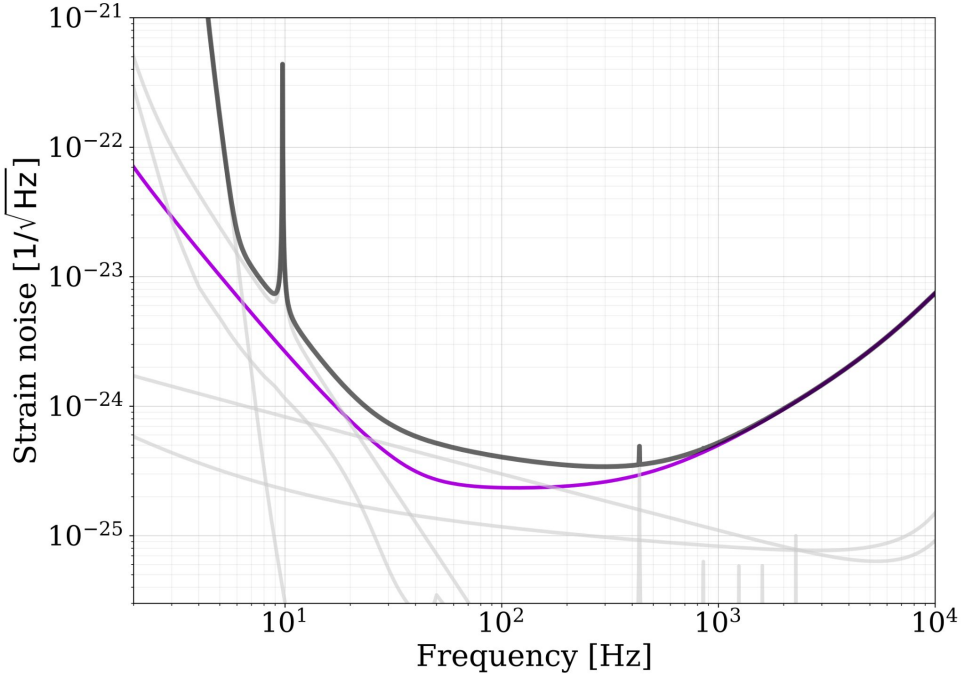
# Sensitivity curves




**Quantum Noise Reduction**

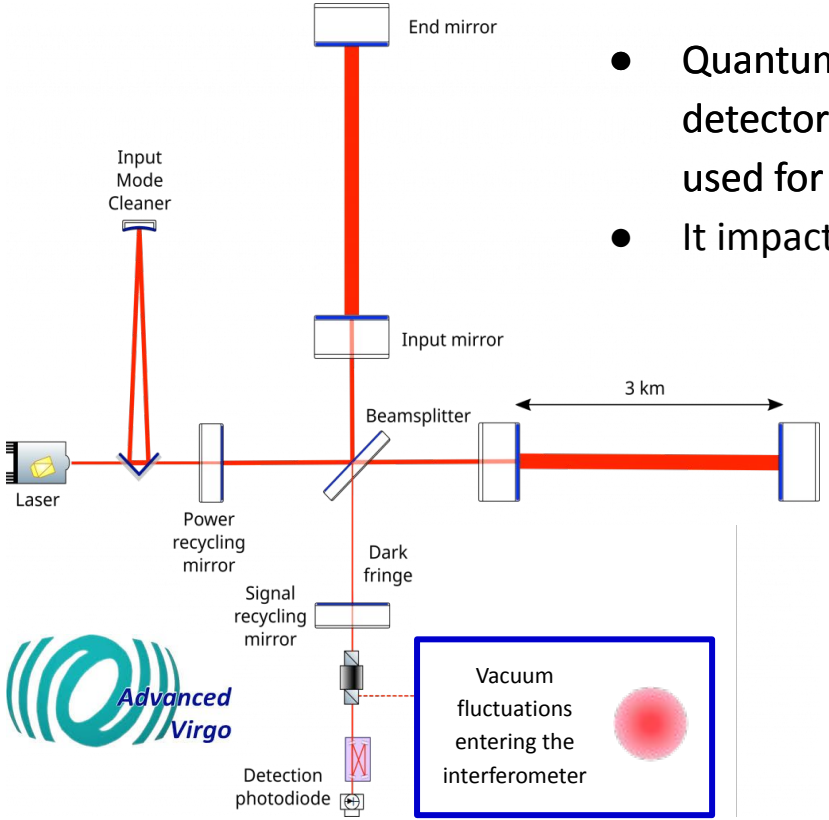



**Low-frequency detector**

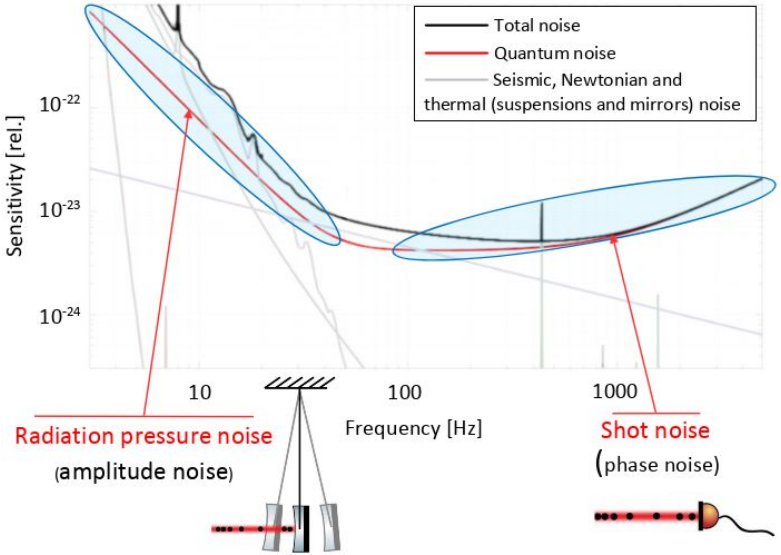



**High-frequency detector**

# Quantum Noise Reduction - Introduction

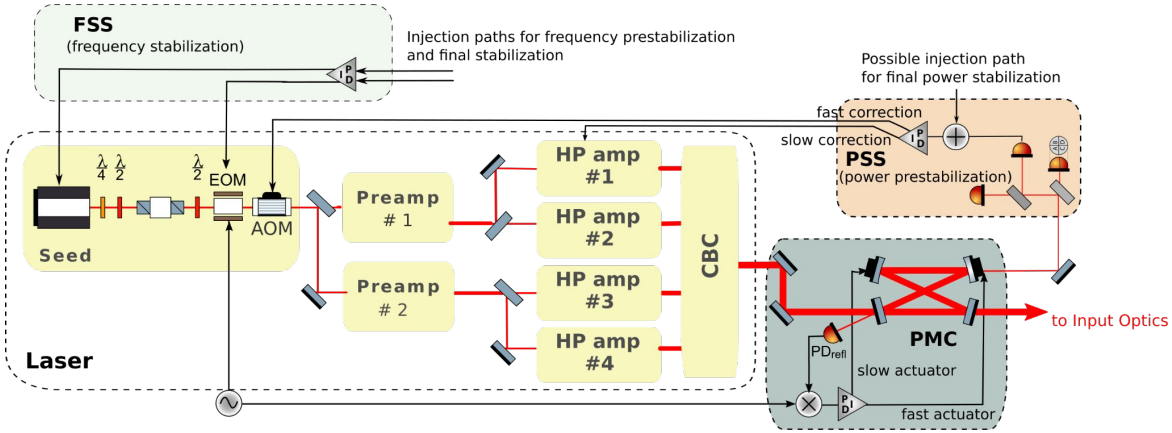



- Quantum noise arises from vacuum fluctuations entering the GW detector through its output port and interfering with the light used for GW detection.
- It impacts the interferometer sensitivity through two ways:

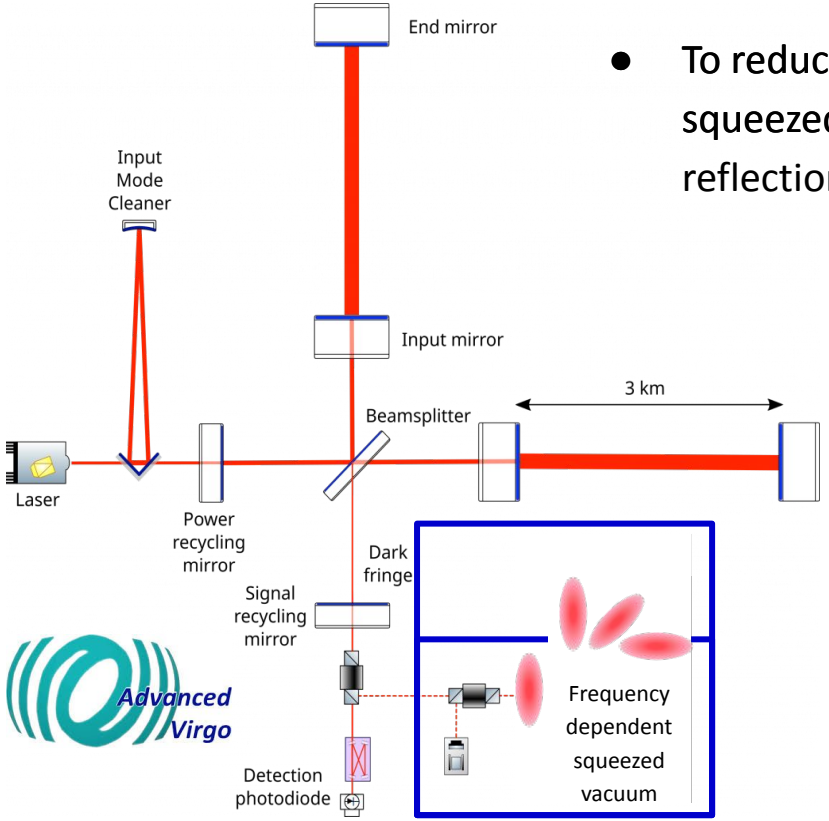


# Quantum Noise Reduction - High laser power (ET-HF)

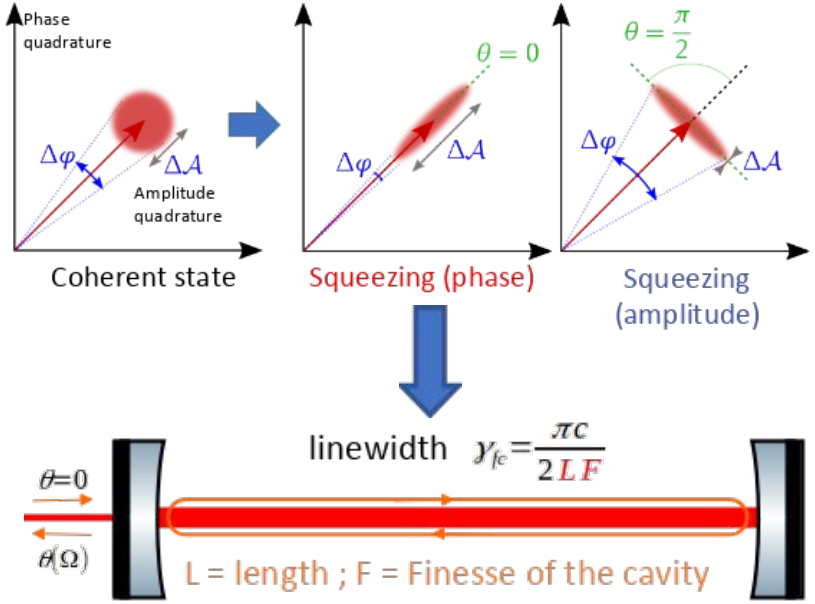
- HF ITF shot noise reduce by high laser power (500 W injected)
- High power obtained coherent beam combination of amplified laser seed
- Beam content cleaned using a Mode Cleaner cavity
- Stabilisation is required both for power (using Mode Cleaner) and frequency (using nested feedback loops)
- Challenges of High Laser circulating in the arms:
  - Parametric instabilities
  - Wavefront distortion
  - Coatings



# Quantum Noise Reduction - Squeezing

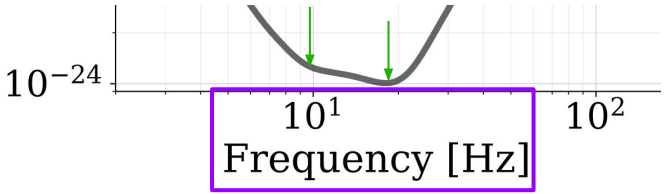


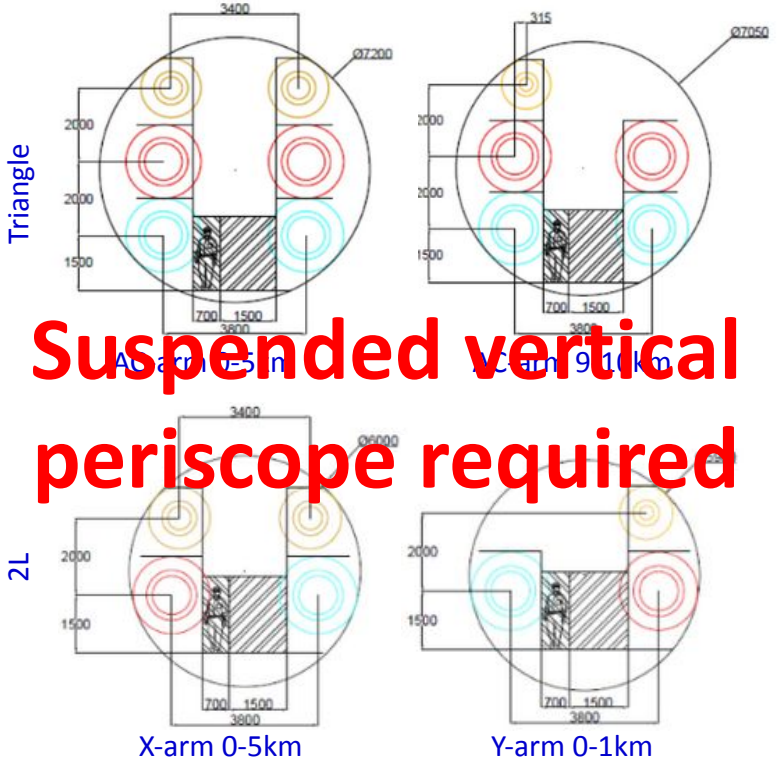

- To reduce quantum noise we replace the coherent vacuum with squeezed vacuum states of light made frequency dependent by reflection on optical resonator(s)



# Quantum Noise Reduction - Squeezing for Einstein Telescope

- High-Frequency detector:
  - Squeezing similar to LIGO-Virgo
  - Wavelength = 1064nm
  - 1 filter cavity of 1km
- Low-Frequency detector:
  - Wavelength = 1550 nm (due to cryogenics operation)
  - 2 filters cavities of 5 km each
  - 2 dips at low frequencies on LF sensitivity curve



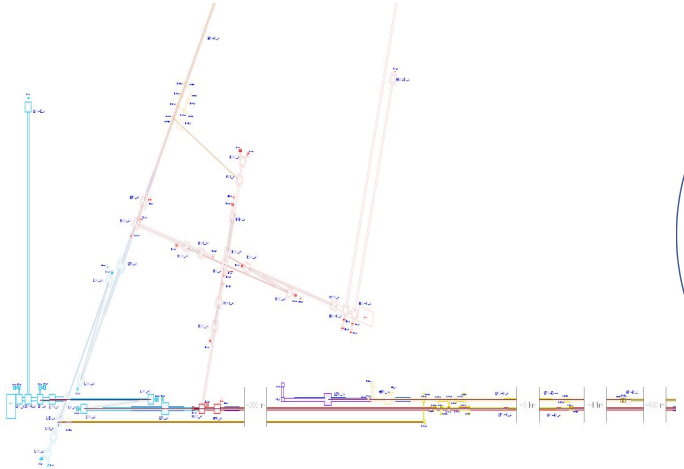



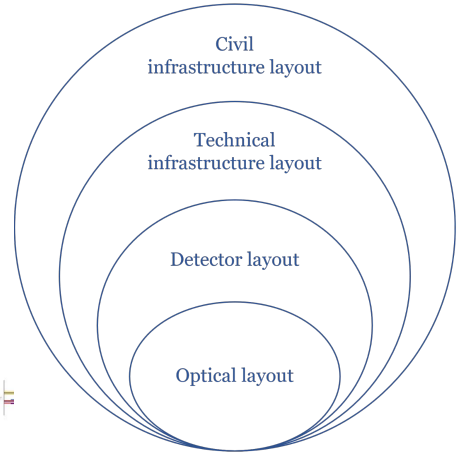

**Suspended vertical periscope required**

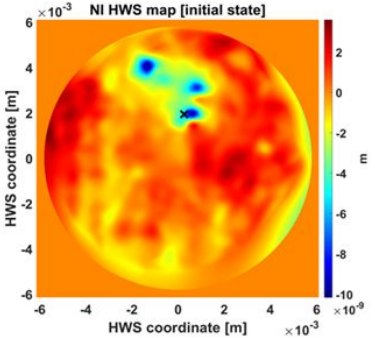
M. Majoor

# General challenges - Optical design

- Optical design link to infrastructure: **LF and HF are not independent designs**
- Need to define:
  - Cavity stability (arms, recycling, MC)
  - Wavefront sensing and control
  - Interferometer Sensing and Control scheme (including locking strategy, auxiliary laser system)
  - Noise budget





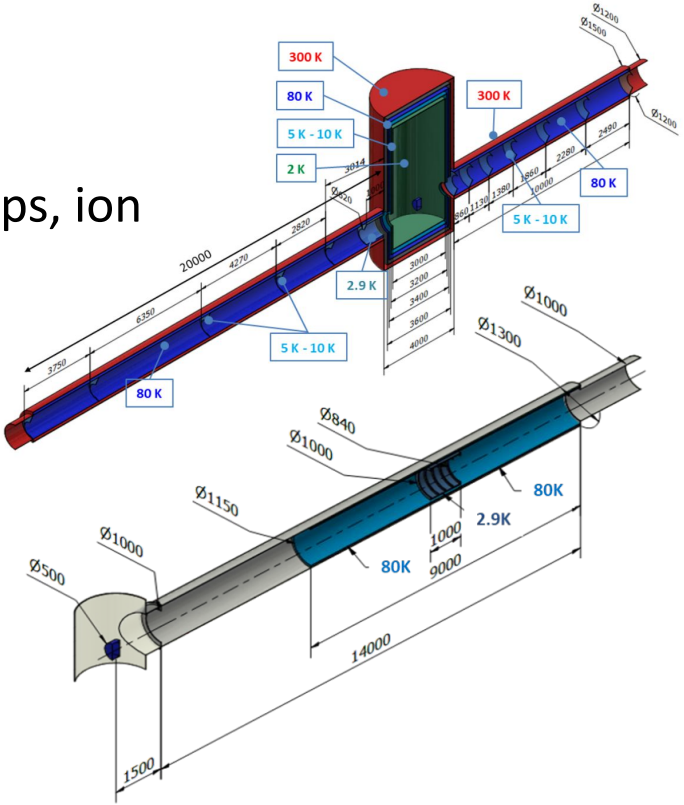



# General challenges - Vacuum

- Beam pipes => MoA with CERN
- Vacuum vessel => adapted from Virgo
- Pumping system => valves, Turbo-molecular pumps, ion pumps, cryogenic and NEG pumping stages



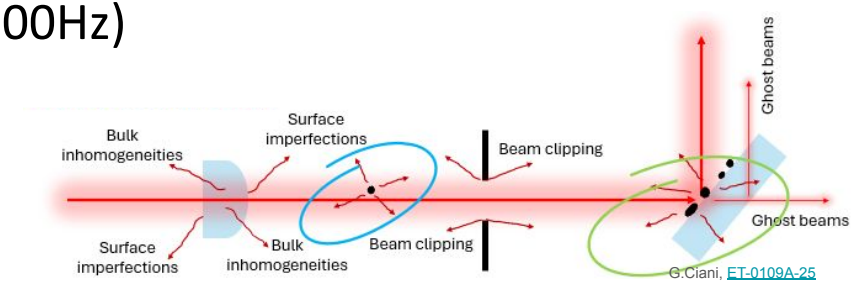




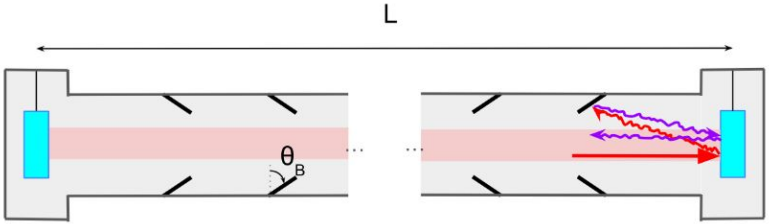
# General challenges - Stray/Scattered light

- any photon that is scattered and do not follow the intended path (both on optical benches and in the arms)
- consequences: optical losses, photons recouple with random phase: excess noise in the low frequency band (f≲100Hz)



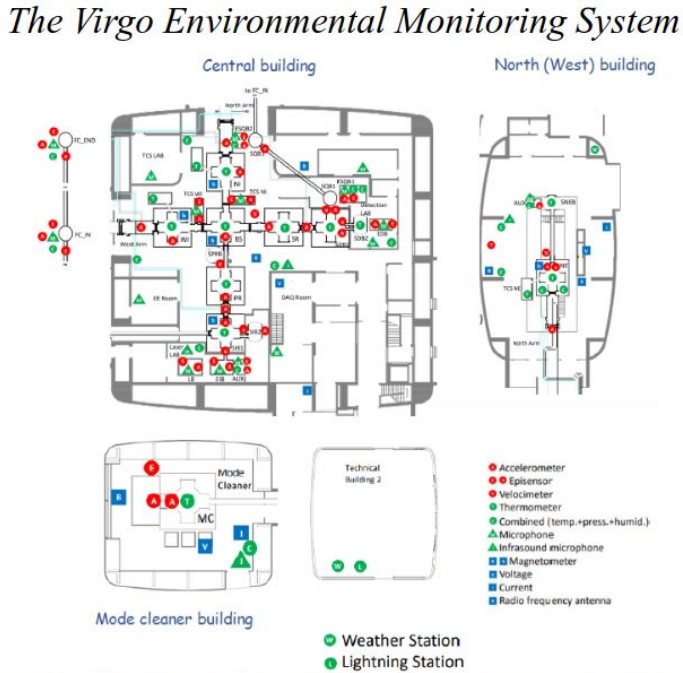




A typical situation in GW interferometers:



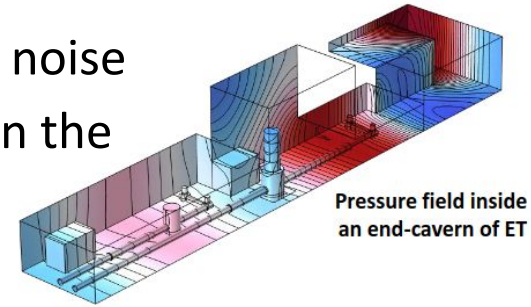

Stray light produced by a Test Mass reaches the pipe tube (or pipe baffle), is scattered back towards the TM and then again re-scattered into the main beam

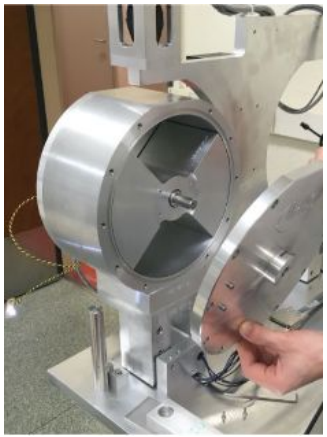
# General challenges - Control

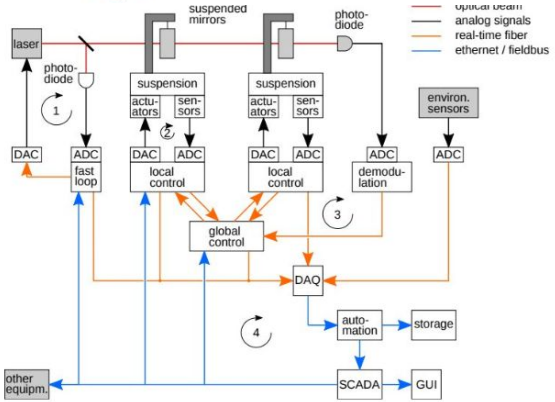



*Galaxies***2020**, *8*(4), 82;https://doi.org/10.3390/galaxies8040082

- Taking into account noise from environment in the early design phase






- Calibration and DAQ must be adapted

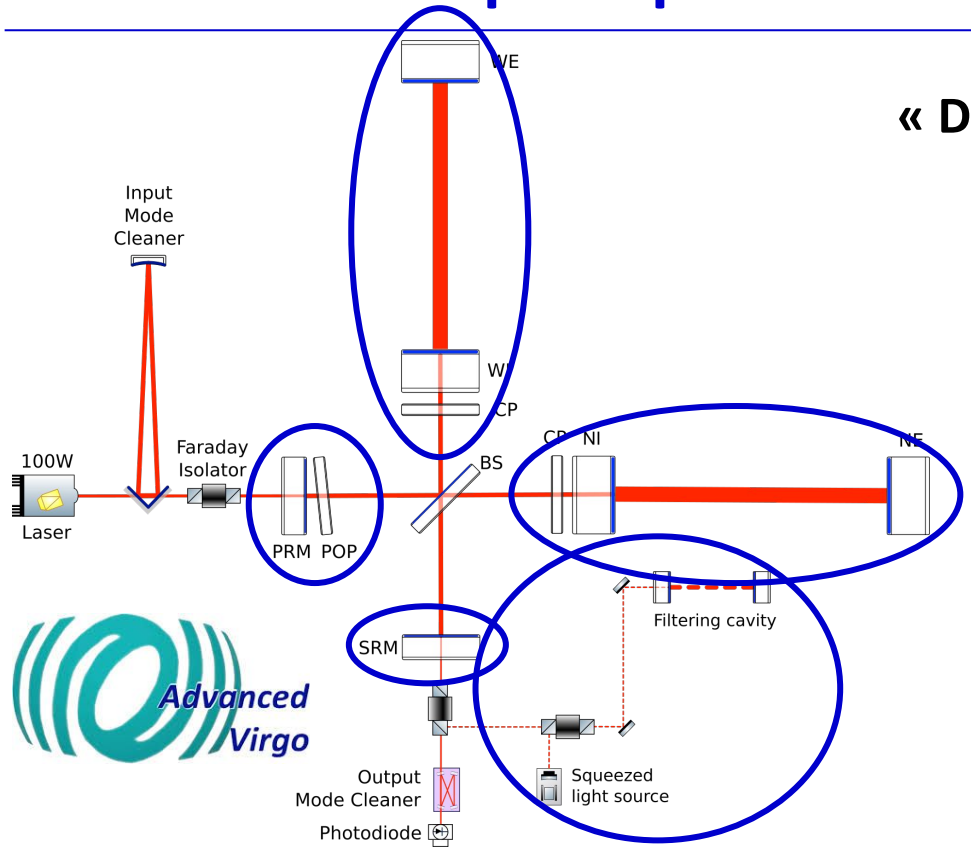
# Conclusion

- Several technologies are required for ET to meet its scientific targets.
- Some of them are common development with 2G detectors (high power laser, suspension, squeezing, etc.), other are more specific to ET (cryogenics, even if links exist with KAGRA).
- A new figure of R&D coordinator (Giovanni Losurdo) has been tasked by the collaboration to list (enabling) technologies and existing associated R&D activities along with coordinating with other stakeholders (2G detectors, Cosmic Explorer, national funding agencies)

# Thank you!

# Back-up material

# Interferometer principle




## « Dual recycled » Michelson interferometer

- Fabry-Perot cavities in the arms to increase the optical path length
- Power recycling (operation close to dark fringe)
- Signal recycling to increase signal-to-noise ratio
- Quantum noise reduction

# Common challenges

- To reach the required sensitivity, ground based gravitational wave detectors must be isolated from their environment, with state-of-the-art optics

## Vacuum



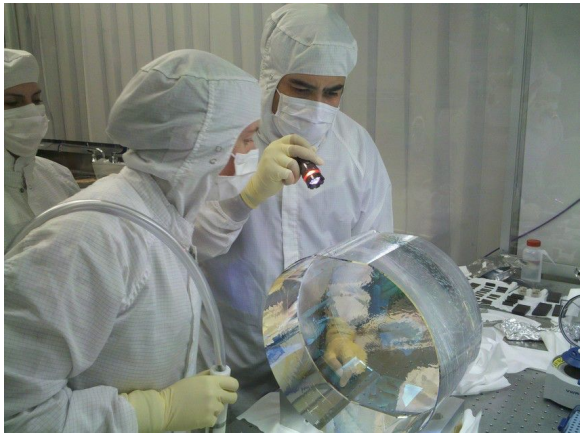
~ 10 000 $m^3$ of vacuum at $10^{-9}$ mbar

## Suspensions



7 pendulum stages to reduce to reduce by a factor $10^{14}$ the movements from the ground

## Mirrors



Surface area accurate to within 5 atoms, less than 10 ppm not reflected

# ET: large scale and complex infrastructure
# Underground observatory

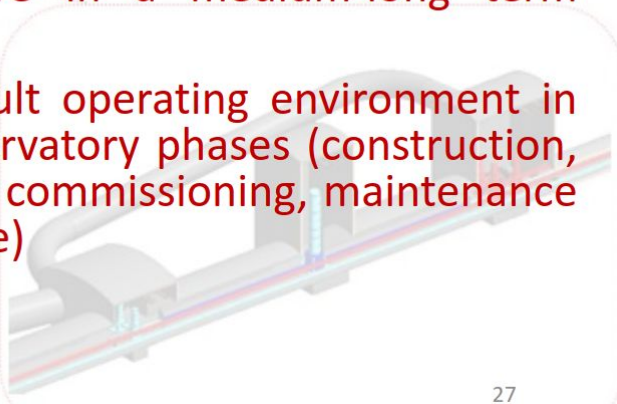
## Pro:

- Access to the low frequency:
  - 2-10Hz for ET
  - Reduction of the seismic and Newtonian Noise
  - Suppression of the atmospheric Newtonian Noise and of the wind impact
  - Reduction of the anthropogenic noise
    - Magnetic
    - Acoustic
    - Vibration
- Easier compatibility with the urbanization of the hosting region
  - Europe is generally a strongly urbanized continent
- Landscape impact

## Cons:

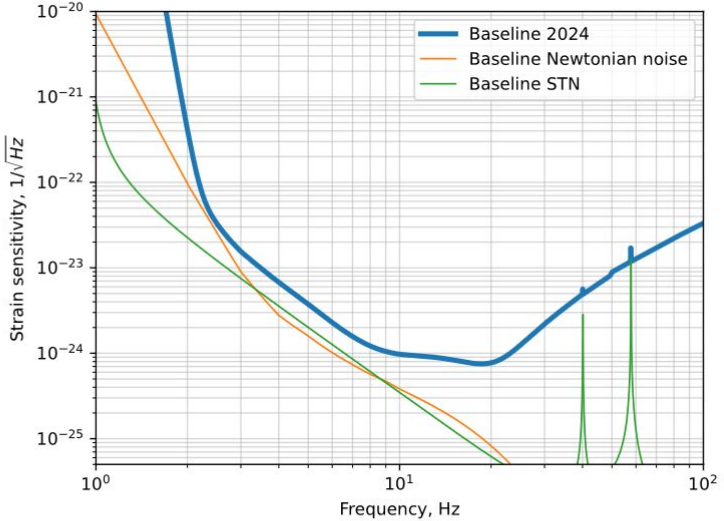
- Costs
- Challenging civil engineering (>30km of tunnels, large caverns…)
- Time needed to build it
- Limited possibility to upgrade the civil infrastructure in a medium-long term timeline
- More difficult operating environment in all the observatory phases (construction, integration, commissioning, maintenance and upgrade)



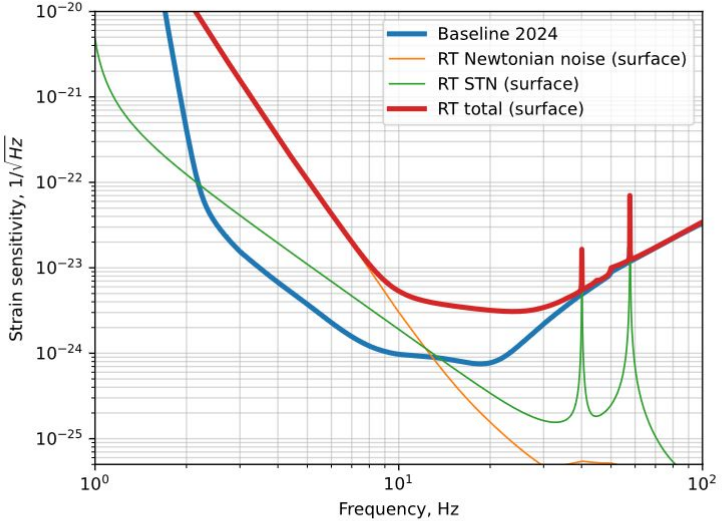


# Limiting noise contributions to ET-LF sensitivity

- Baseline cryogenic LF




- Comparison (RT, surface)



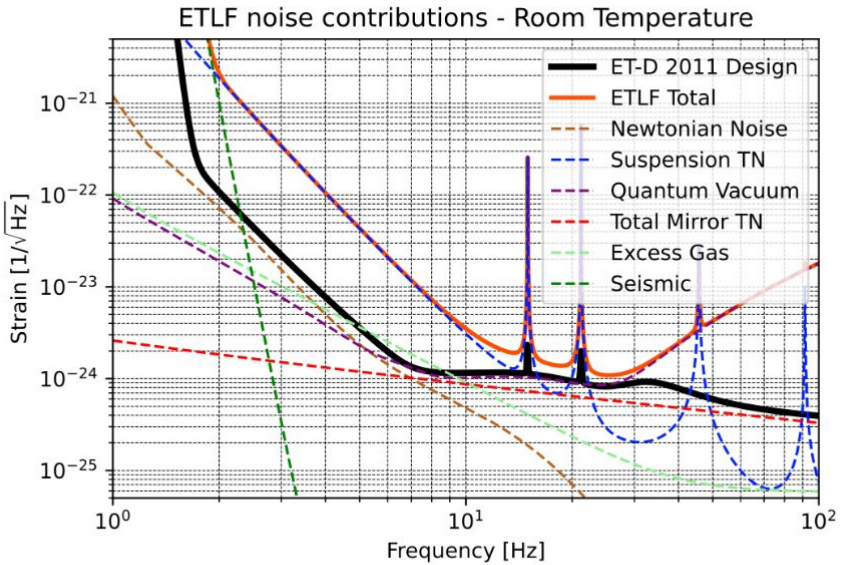

Figures based on ET-Noise Budget Gitlab - PyGwinc Code (29.05.2025) - https://gitlab.et-gw.eu/et/isb/interferometer/ET-NoiseBudget

The underground installation and the cryogenic operation are two sides of the same coin

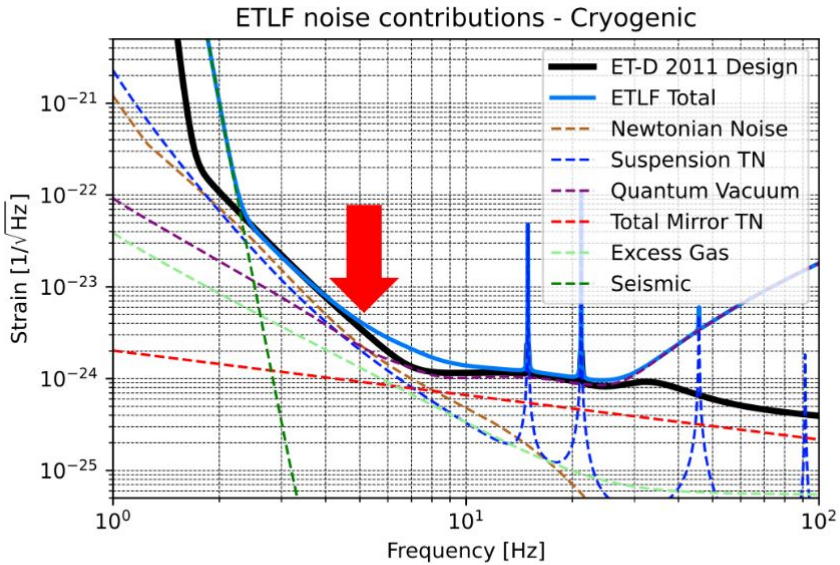
# A strong motivation to implement cryogenics in ET

**Cryogenics contributes to a significant increase of sensitivity at low frequence**

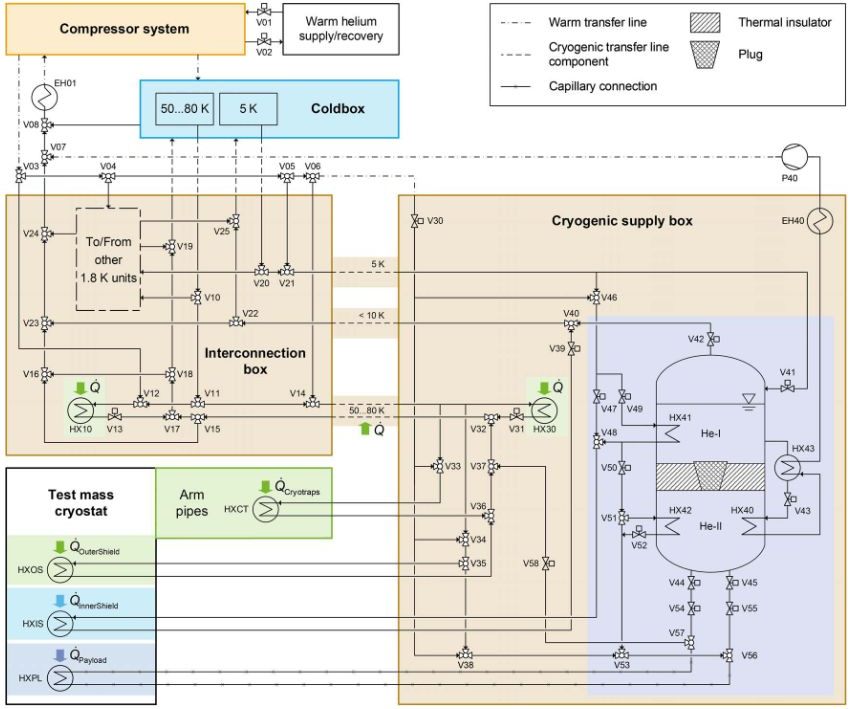
## Room-Temperature ET-LF




## Cryogenic ET-LF



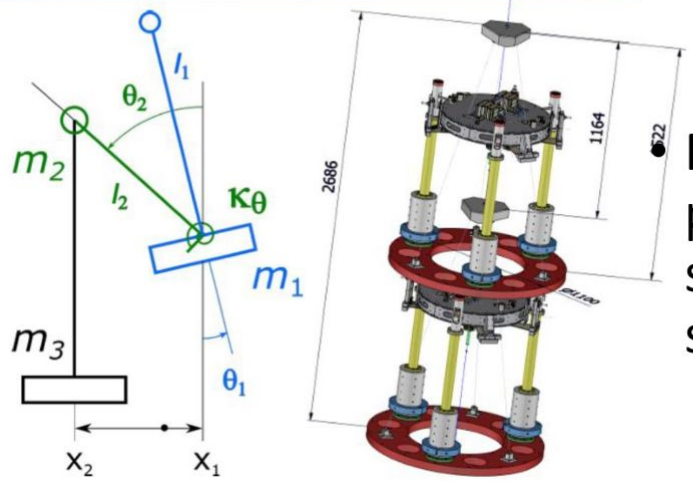
# Cryogenic infrastructure concept [*]




- No underground $LN_2$ (safety)
- One He refrigerator at each vertex
  - (Remote) surface compressors
  - Underground coldbox
  - Interconnection box to several cryogenic supply boxes (1 for each tower/cryostat)
    - Up to c. 500 m long transfer lines
  - 1-phase cooling for 80 K cryopumps/ outer shields
  - 1-phase cooling for 10 K baffles, 5 K inner shields and 3.7 K cryopumps
  - He-II payload cooling/inner shield

# Low Frequency special focus

- Low noise site
- Underground infrastructure
- 17m tall seismic filtering suspensions
  - Large impact on cavern engineering and costs
- R&D in active-passive filtering systems and seismic sensors



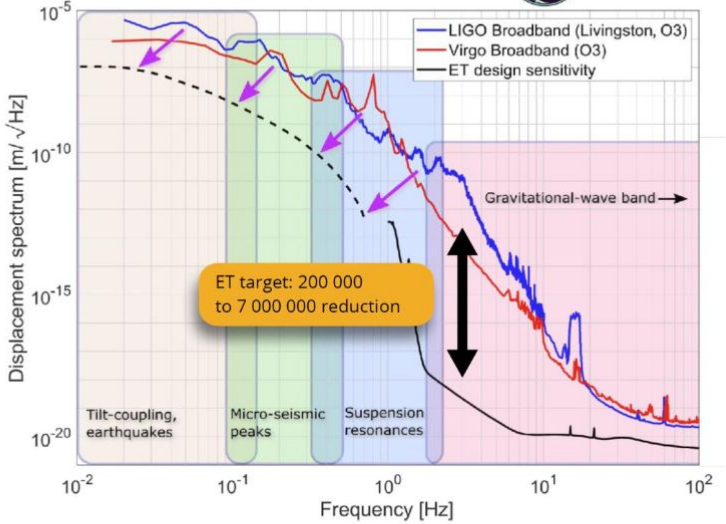
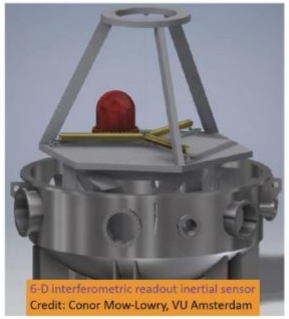
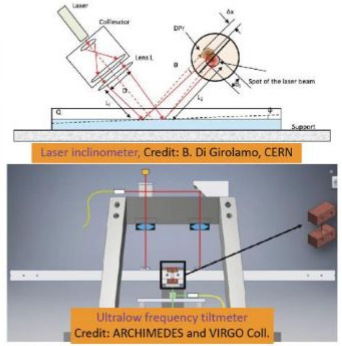




Image: Conor Mow-Lowry





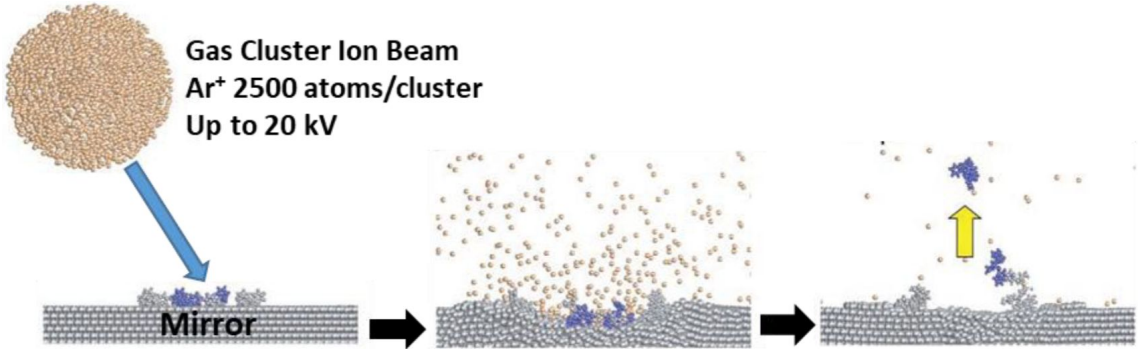


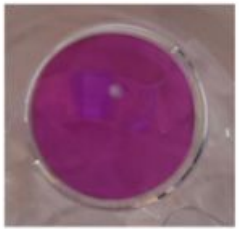



Credits: A.Freise

# Cryogenics challenges - mirror cleaning

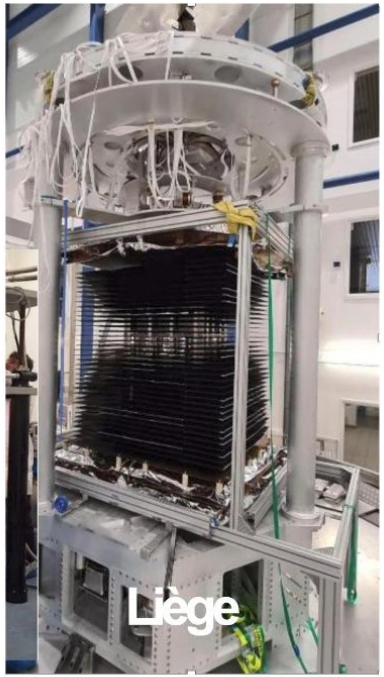
- KAGRA experience: Unstable cooling performance happened resulting in H2O gas release **-> Frosting of mirrors**. Solution: Warm up and re-cooling for 3 months for recovery. (GWADW presentation)
- Proposition at IJCLab to use Cluster Ion Beam for mirror defrosting, cleaning and discharging => first tests at room temperature on high quality coating substrates





Mirror
1 inch

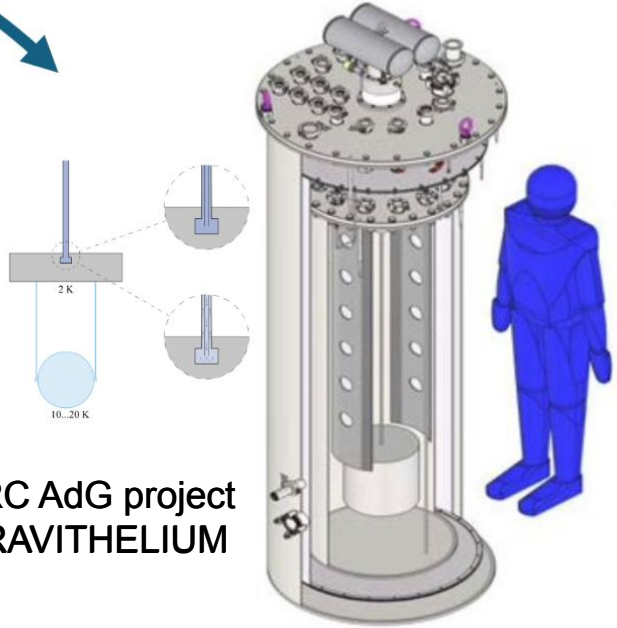
# Cryogenics cooling R&D - Large scale prototypes

Ideally radiative non-contact




Intermediate solution?

Ideally conductive contact



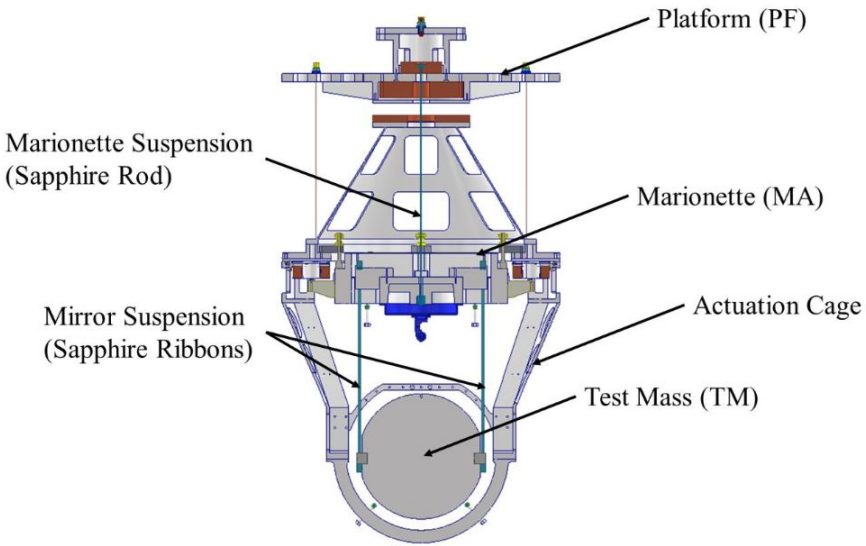

ERC AdG project
GRAVITHELIUM

Karlsruhe

Adapted from E. Majorana presentation

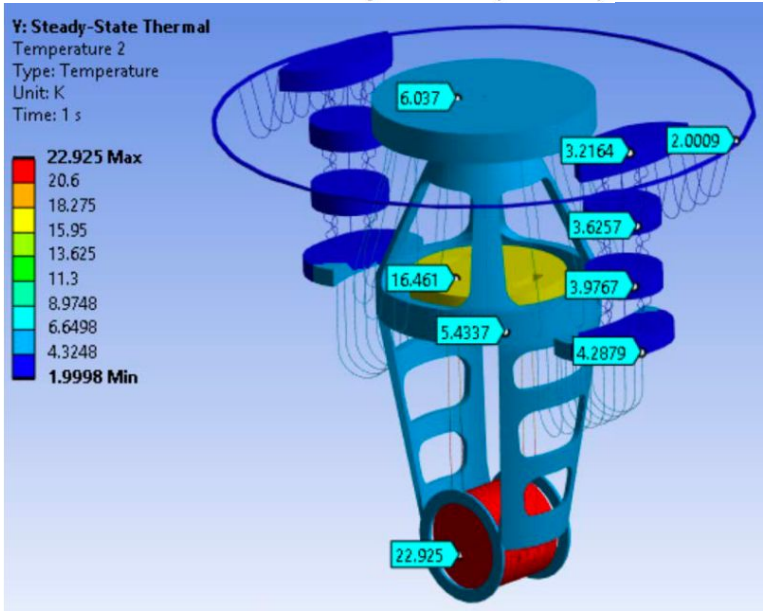
# Cryogenics - Baseline payload design

Heat extracted via the 4 wire suspensions:
*Cristals* made of Silicon or Sapphire




From F. Ricci presentation

- Application of 2 K heat sink
- Payload connection via heat link vibration isolation systems (HLVIS)




From S. Grohmann presentation