EINSTEIN
TELESCOPE

Einstein Telescope, pushing the outer limits of gravitational waves detection

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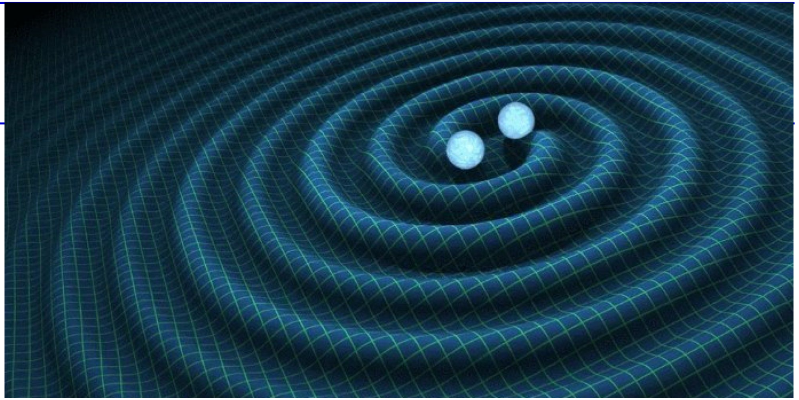
on behalf of the ET collaboration

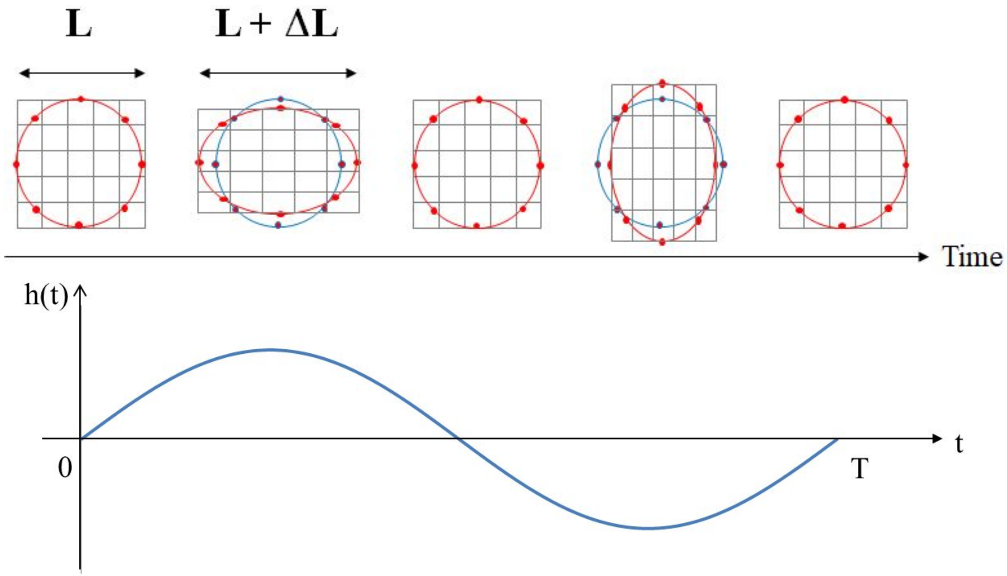
TTC 2026 Meeting - 12 June 2026

Introduction

What are gravitational waves?

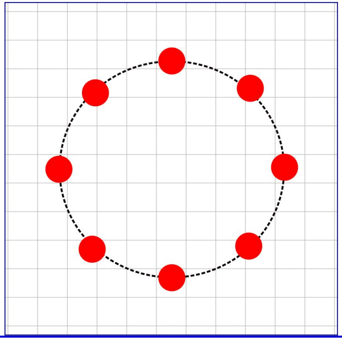
- **Distortion of spacetime**
  - emitted by accelerating masses,
  - travelling at the speed of light





- **Amplitude of the distortion:**

$$h \simeq 2\frac{\Delta L}{L}$$



Can we produce measurable gravitational waves on Earth?

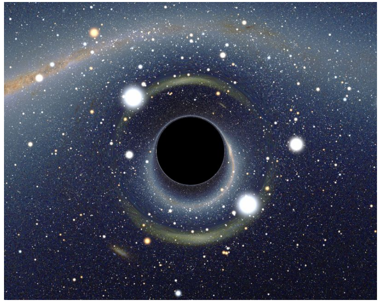
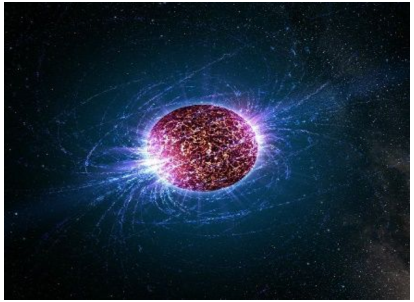
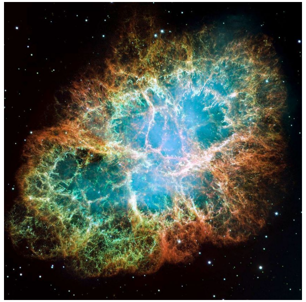
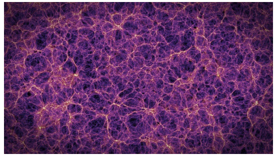
- **Rotating steel bar?**
  - 500 tons, 2m diameter and 20m length
  - Rotating at 5 revolutions per second
  - Gravitational wave amplitude at 1m distance: h ~ 10^{-34}
    => changing the diameter of the Milky Way by 1/100 of atom
    => **not measurable**

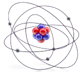
- **H-bomb?**
  - 1 megaton, 10% asymmetry
  - Gravitational wave amplitude at 10km distance: h ~ 10^{-29}
    => changing the distance from Sun to Proxima Centauri by 10 atomic nuclei
    => **not measurable**

What are the observable sources of gravitational waves?

Astronomical sources like compact binary systems (black holes and/or neutron stars), supernovae, etc.

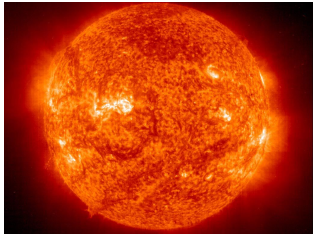
Gravitational wave amplitude decreasing as 1/r but strong amplitude close to the source leads to up to $h \sim 10^{-21}$ on Earth

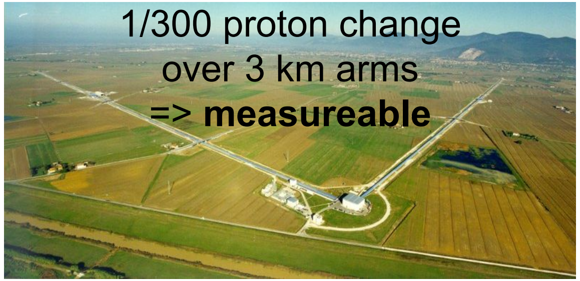






1 atom change (10^{-10}m)

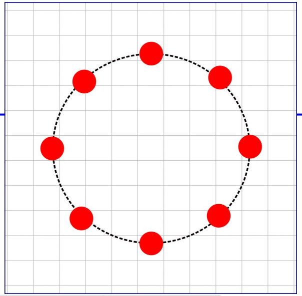
over 150 million kms ($1{,}5.10^{11}$m)



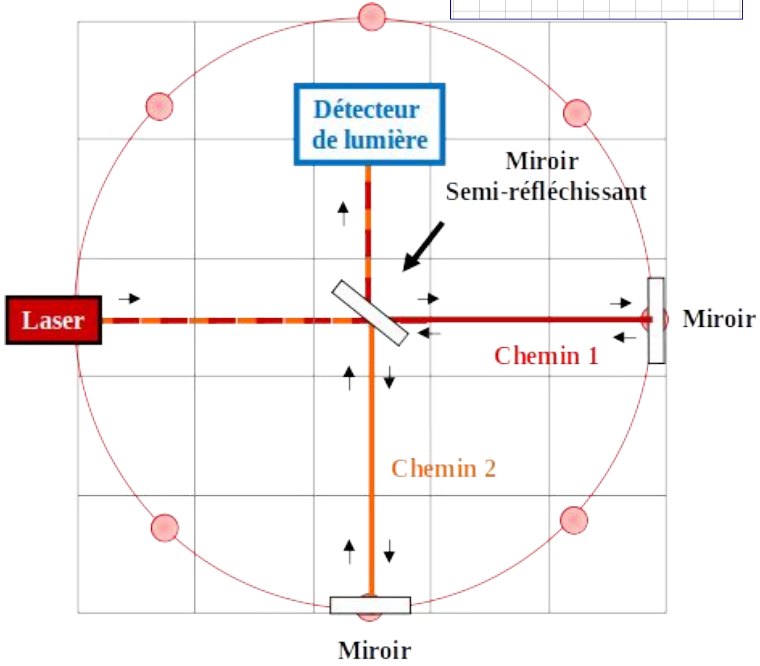


1/300 proton change over 3 km arms
=> **measureable**

How can we detect gravitational waves?



- Gravitational waves cause a distortion of spacetime, involving **contraction and stretching in two orthogonal directions** within the plane perpendicular to the direction of wave propagation
- **Michelson interferometer** is a well adapted instrument to measure tiny orthogonal deformations
- Sensitive to deformation thousands to millions time smaller than a proton



State-of-the-art:
Second Generation of ground based gravitational wave detectors

Advanced Virgo, more than a Michelson interferometer (1/2)

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

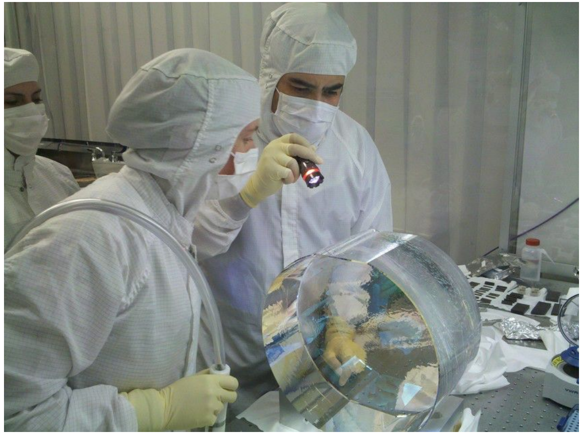
Vacuum

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

Suspensions

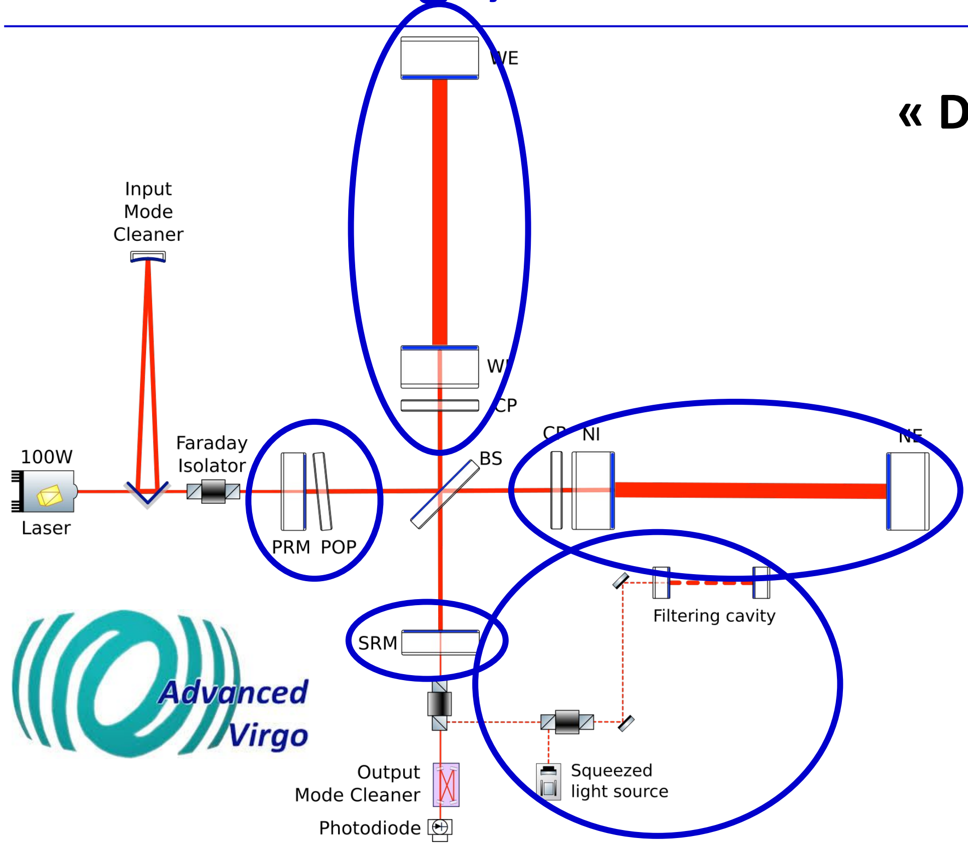
7 pendulum stages to reduce to reduce by a factor 10^{14} the movements from the ground

Mirrors



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

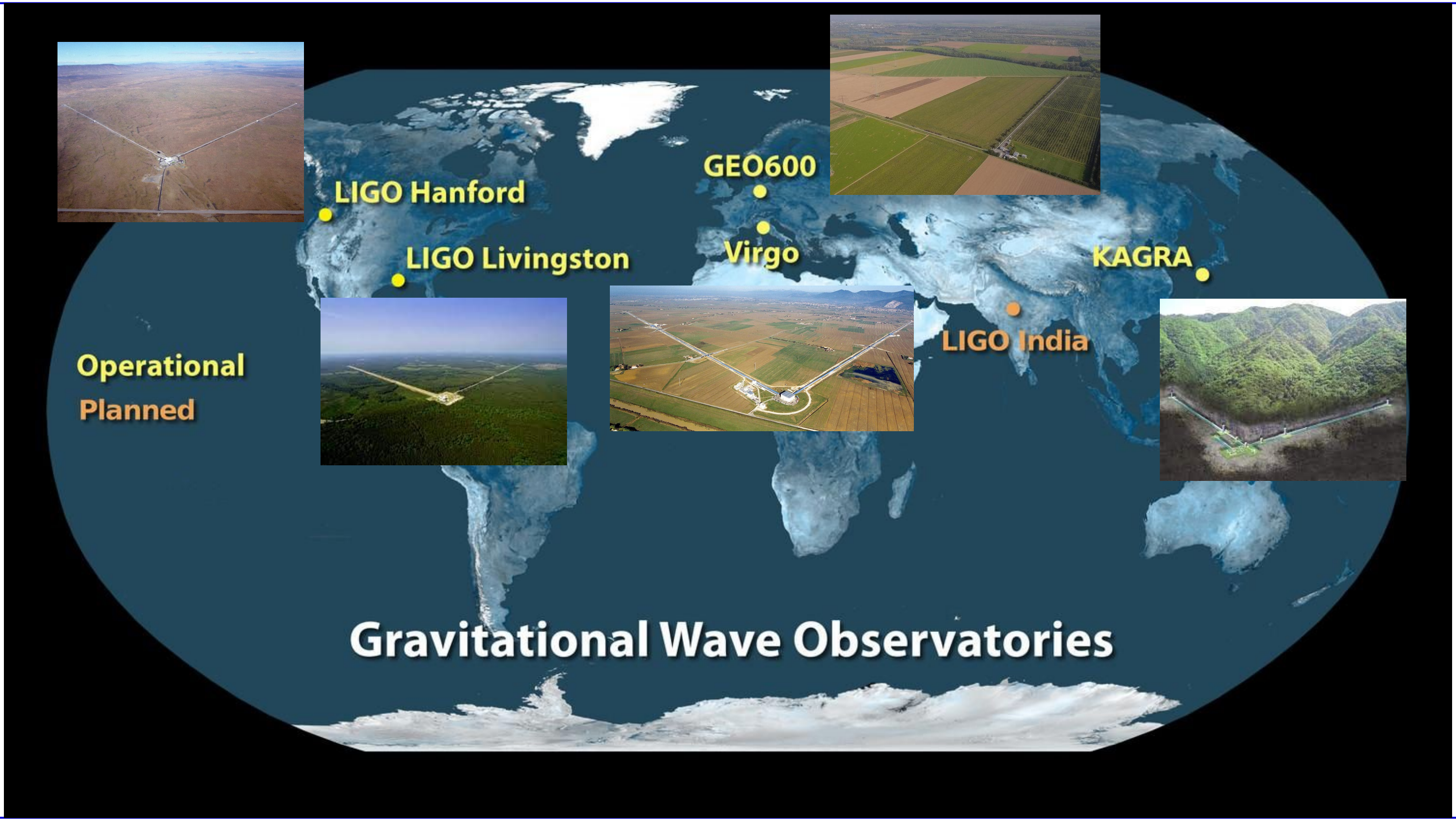
Advanced Virgo, more than a Michelson interferometer (2/2)



« Dual recycled » Michelson interferometer

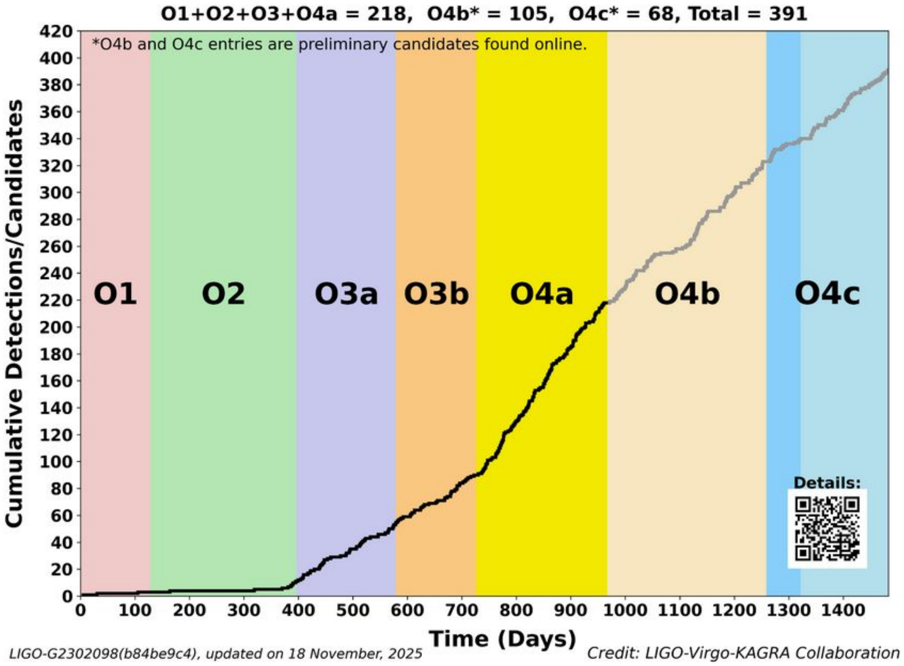
- Fabry-Perot cavities in the arms to increase the optical path length
- Power recycling (operation close to dark fringe)
- Signal recycling to increase signal-to-noise ratio
- Quantum noise reduction

A network of ground-based detectors



Successes of LIGO-Virgo-KAGRA

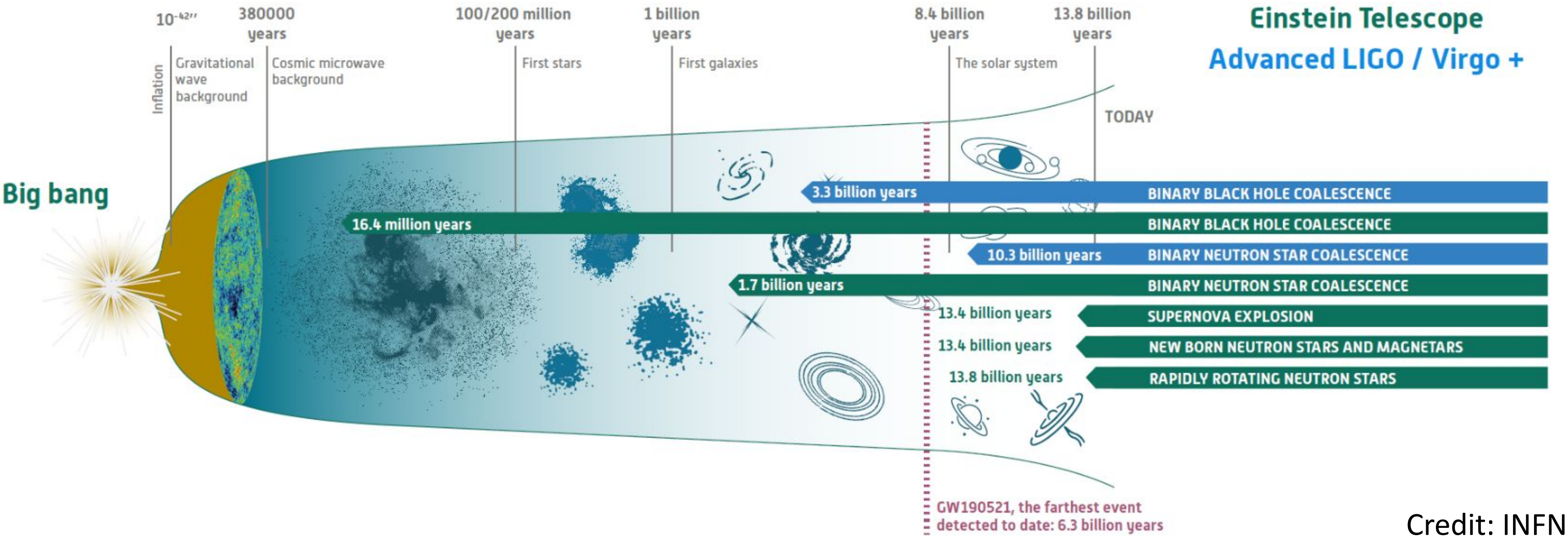
- Highlights from **almost 400 detections in 10 years** :
    - GW150914: first black-hole binary
    - GW170817: first neutron-star binary
    - GW190814: heaviest neutron star or lightest BH to date (~2.6 Msun)
    - GW190521/GW231123: first intermediate mass BHs (>100 Msun), mass gap
    - GW200105/GW200115: first evidence of mixed BH-NS binaries
    - GW250114: loudest event to date, black-hole spectroscopy



Next generation detector: Einstein Telescope

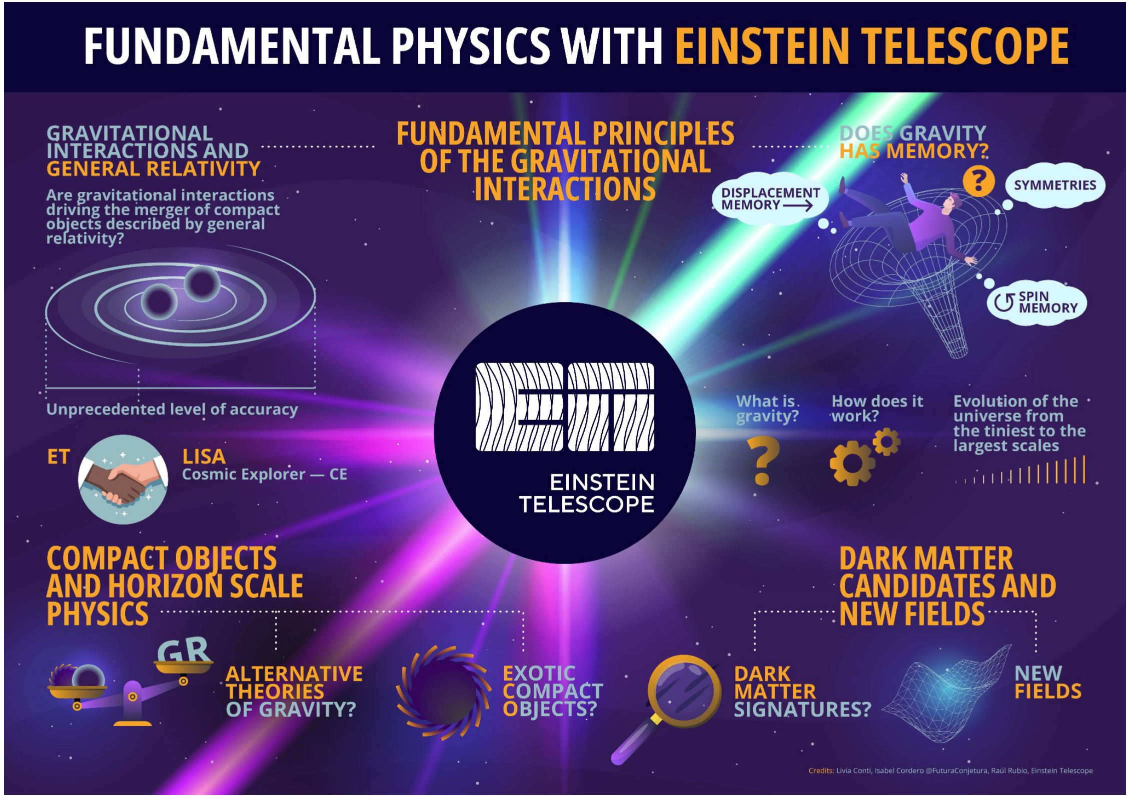
Science targets in a nutshell (1/2)

- 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

Science targets in a nutshell (2/2)



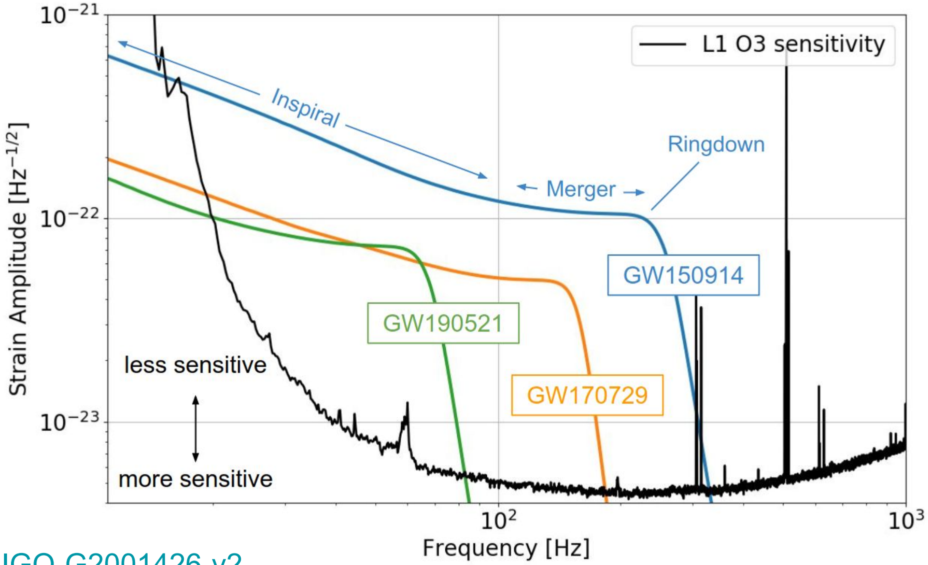
ASTROPHYSICS

- **Black hole properties**
  - origin (stellar vs. primordial)
  - evolution, demography
- **Neutron star properties**
  - interior structure (QCD at ultra-high densities, exotic states of matter)
  - demography
- **Multi-band and -messenger astronomy**
  - joint GW/EM observations (GRB, kilonova,...)
  - multiband GW detection (LISA)
  - neutrinos
- **Detection of new astrophysical sources**
  - core collapse supernovae
  - isolated neutron stars
  - stochastic background of astrophysical origin

Instrumental requirements from science targets (1/3)

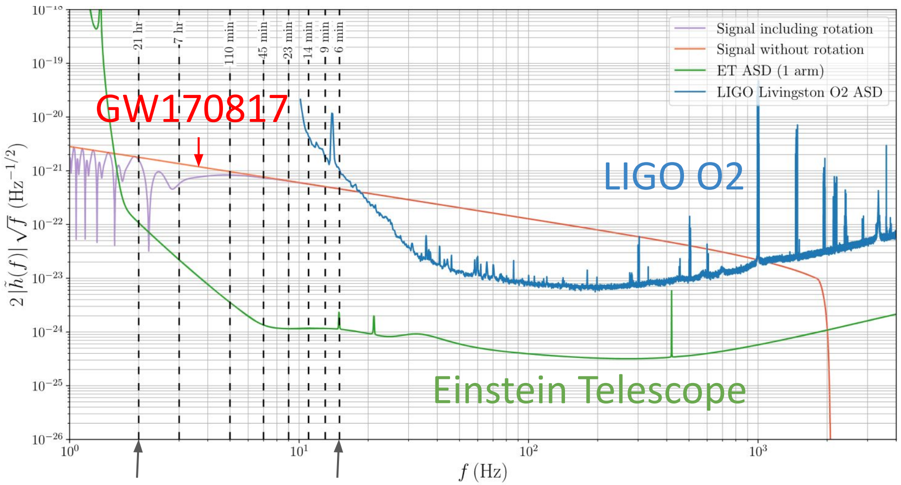
- Increasing the sensitivity to low frequencies…

Higher masses correspond to lower frequency GW emission



LIGO-G2001426-v2

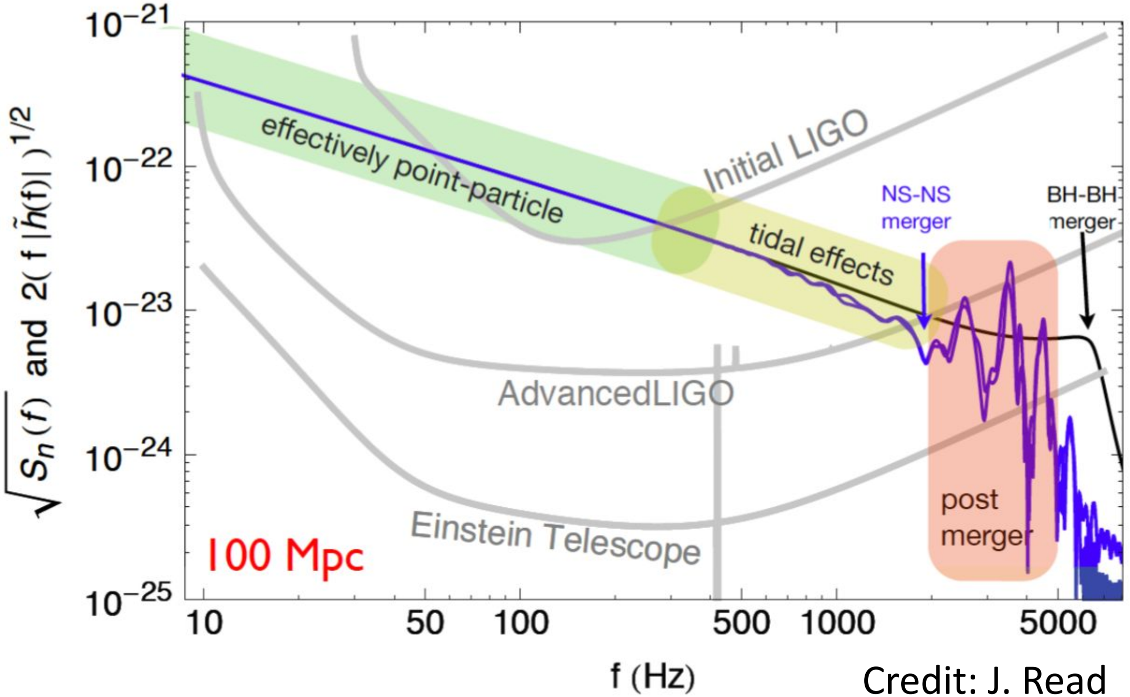
Early warning for Binary Neutron Star mergers to alert the community



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

Instrumental requirements from science targets (2/3)

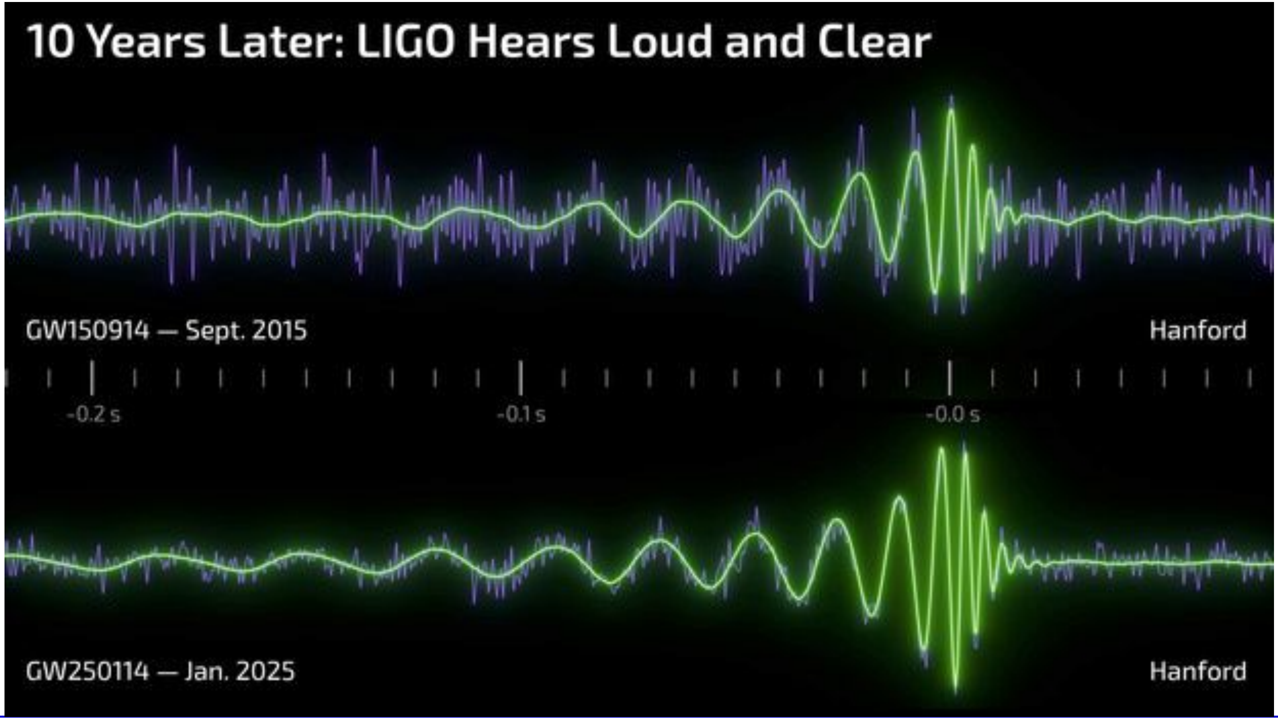
- Increasing the sensitivity to low frequencies… and also to high frequencies



Credit: J. Read

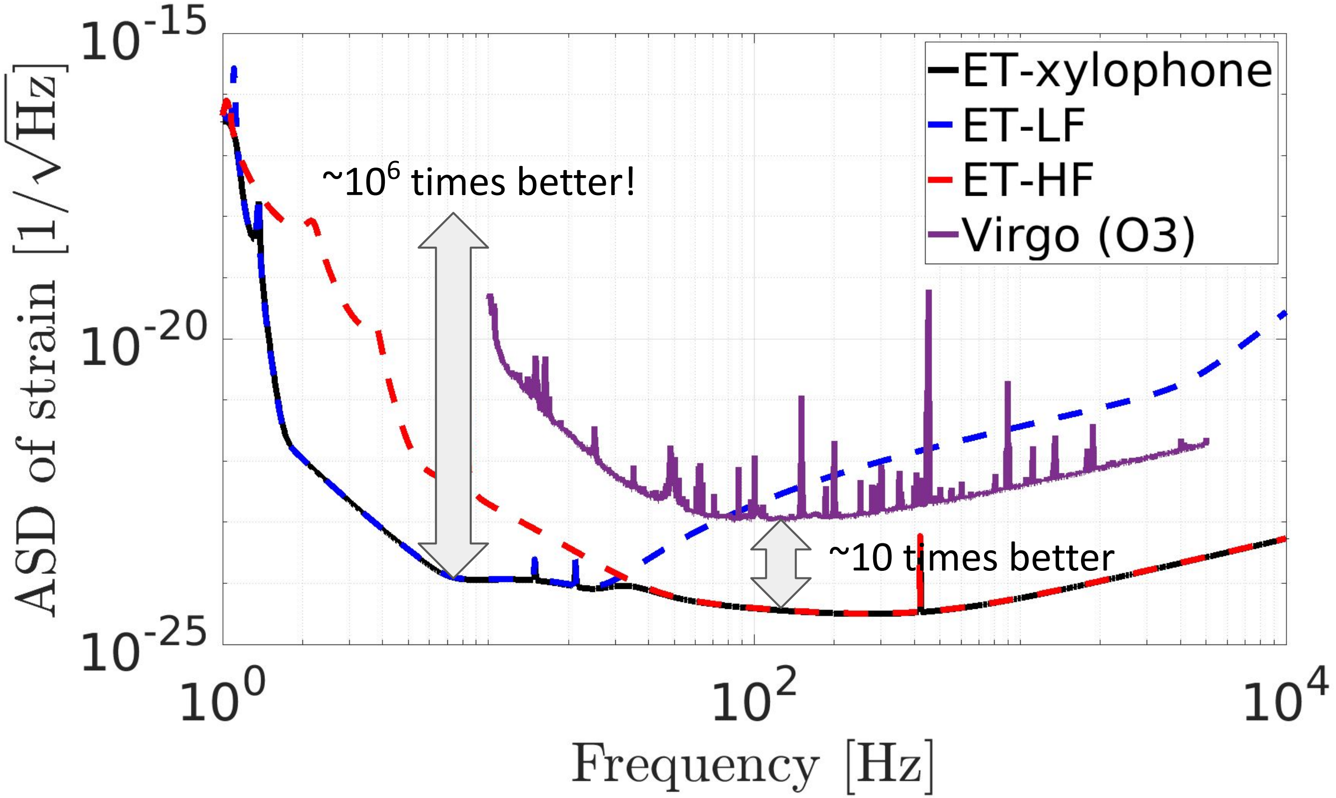
Instrumental requirements from science target (3/3)

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



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

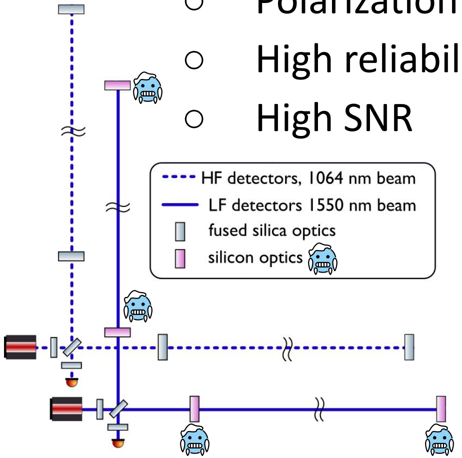
Instrumental challenges - Sensitivity improvement

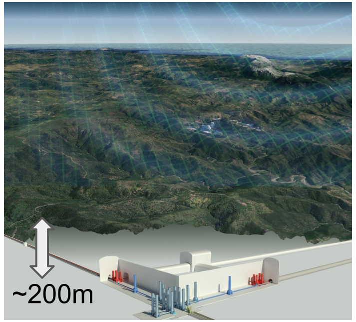


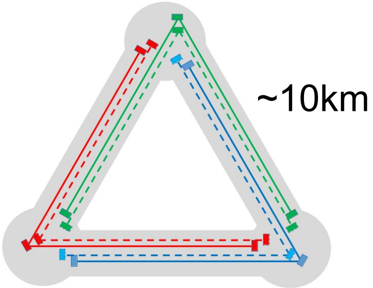
Instrumental requirements - Key elements

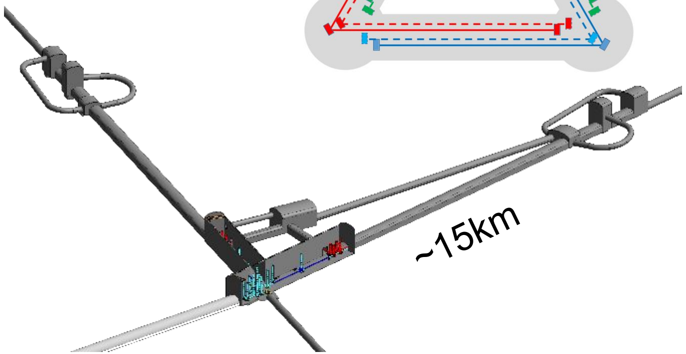
- Requirements
  - **Wide frequency range**
  - **Low-frequency sensitivity**
  - Localization capability
  - More uniform sky coverage
  - Polarization disentanglement
  - High reliability (high duty cycle)
  - High SNR

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





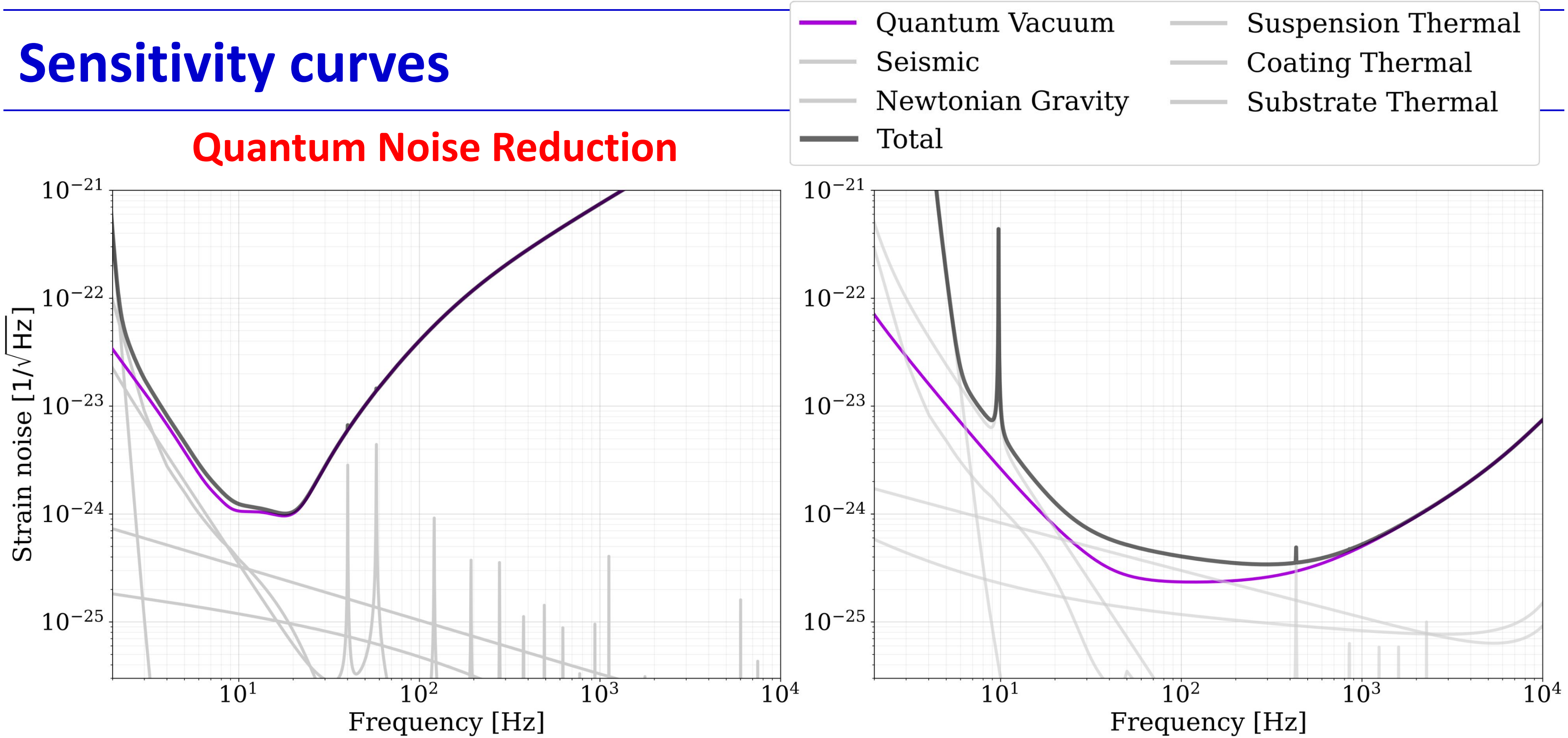




Selected instrumental challenges of Einstein Telescope

Sensitivity curves

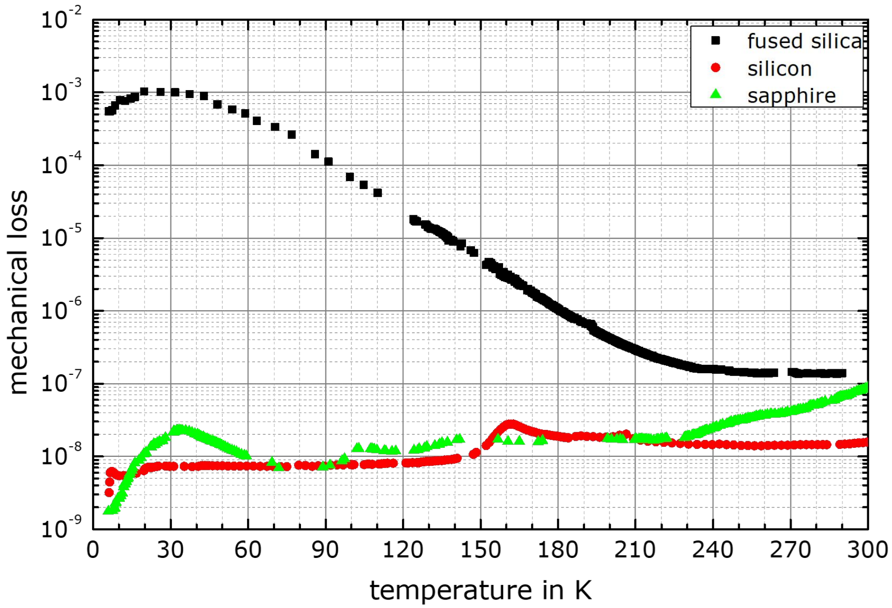
Quantum Noise Reduction



Low-frequency detector

High-frequency detector

Cryogenics challenges - mirror substrate



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

Sapphire

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

Silicon

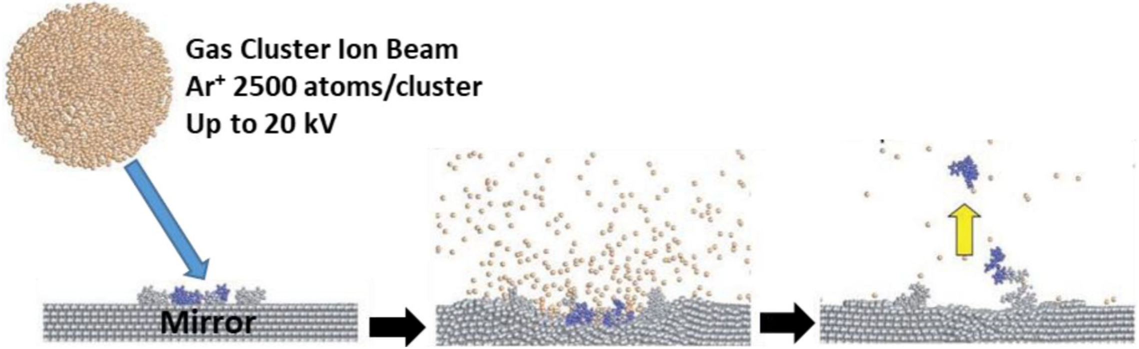
Low optical absorption requires very pure material, i.e. float zone (FZ) silicon or magnetically-stabilized Czochralski silicon.

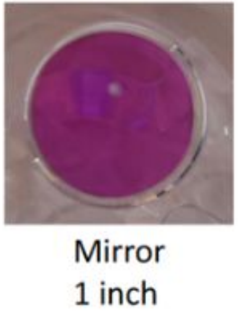
But high-purity material not available in such large size. Challenges:

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

Cryogenics challenges - mirror cleaning

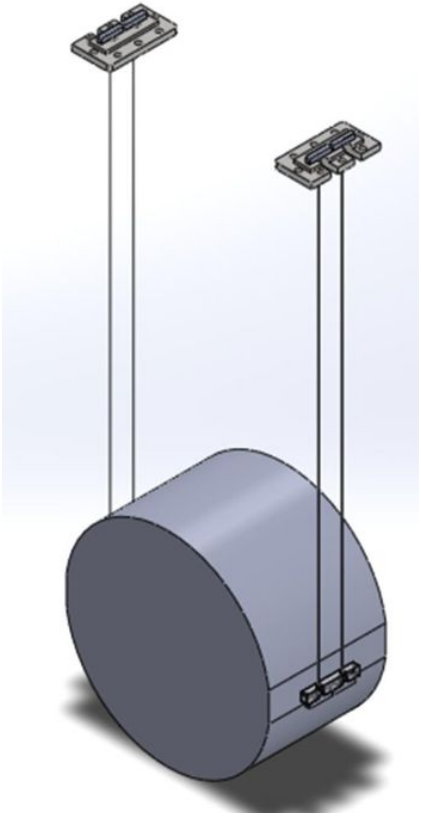
- KAGRA experience: Unstable cooling performance happened resulting in H2O gas release **-> Frosting of mirrors**. Solution: Warm up and re-cooling for 3 months for recovery. (GWADW presentation)
- Proposition at IJCLab to use Cluster Ion Beam for mirror defrosting, cleaning and discharging => first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





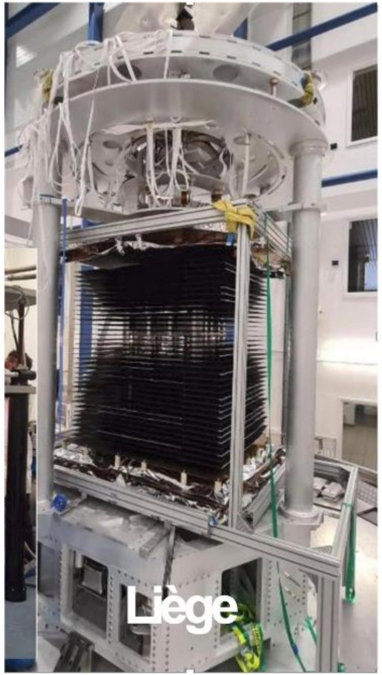
Cryogenics challenges - cooling

- 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



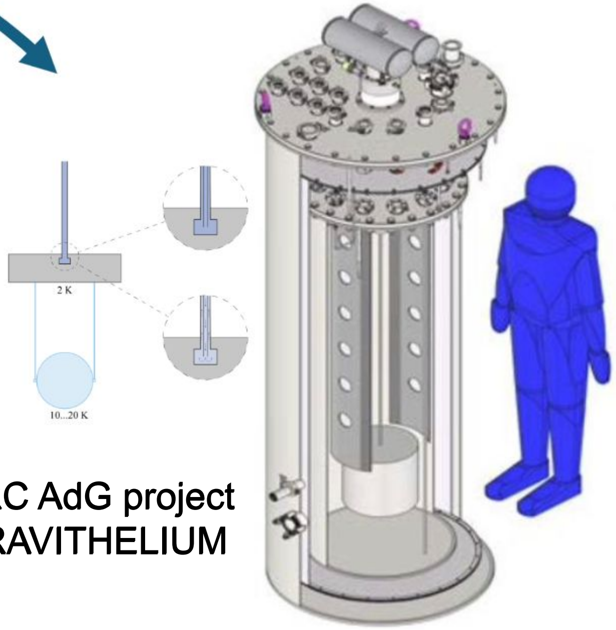
Cryogenics cooling R&D - Large scale prototypes

Ideally radiative non-contact



Intermediate solution?

Ideally conductive contact



ERC AdG project
GRAVITHELIUM

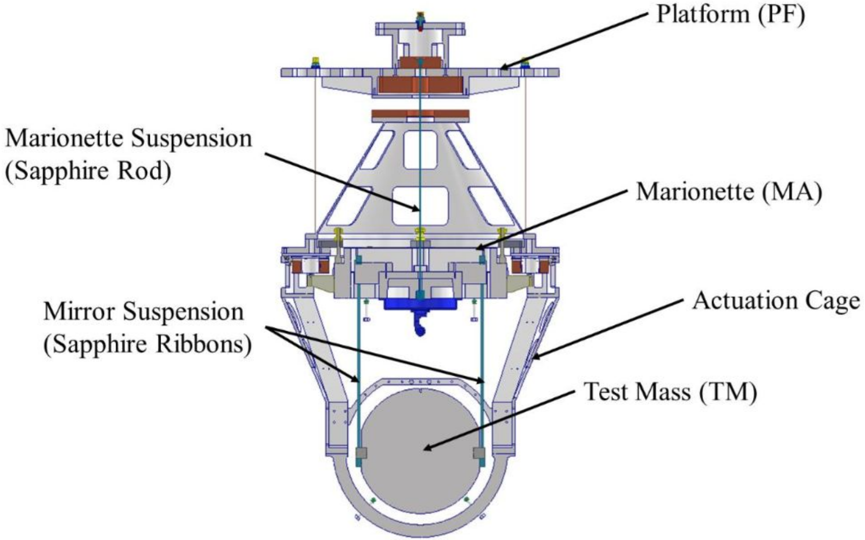
Karlsruhe

Adapted from E. Majorana presentation

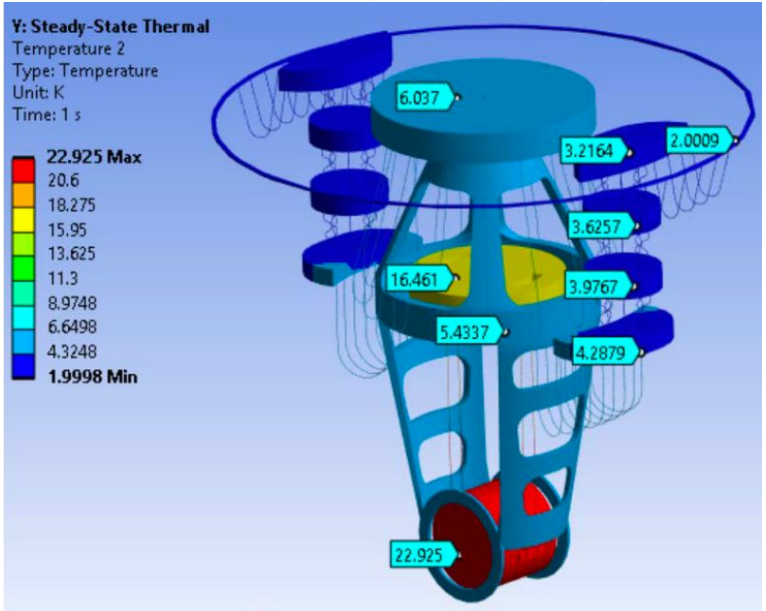
Cryogenics - Baseline payload design

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

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

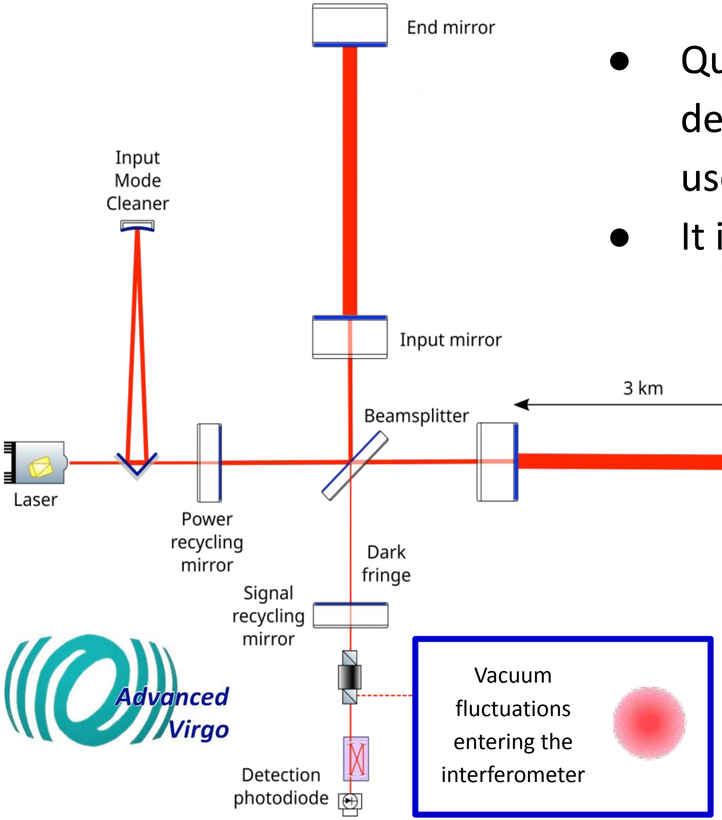


From F. Ricci presentation

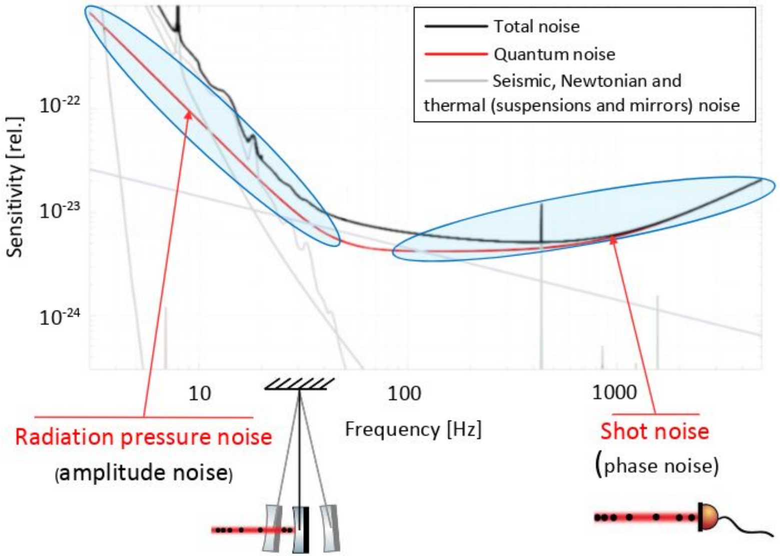


From S. Grohmann presentation

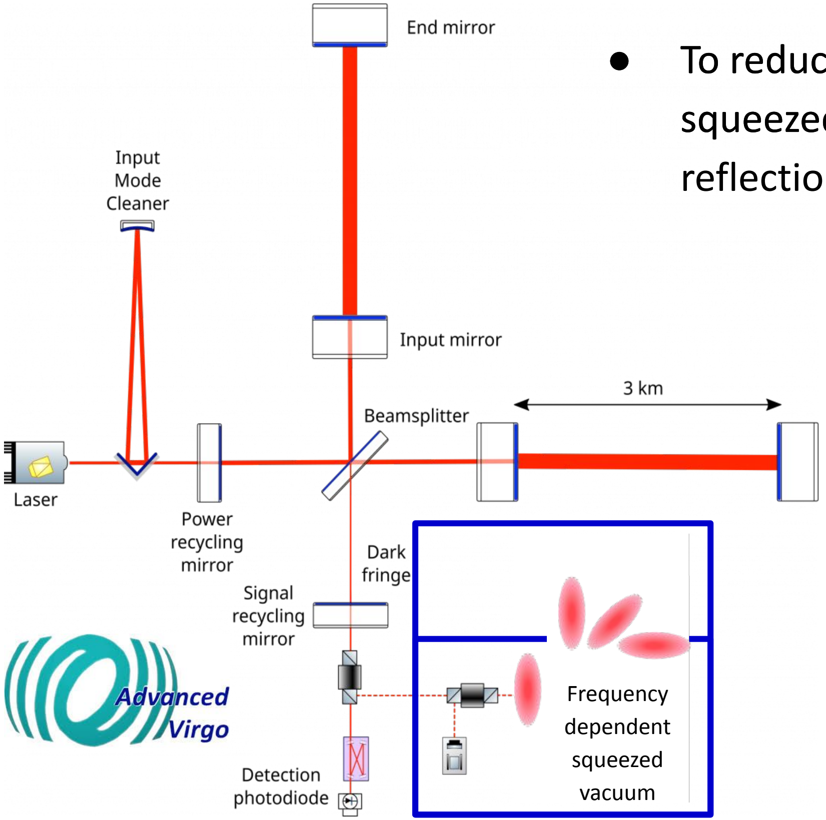
Quantum Noise Reduction - Introduction



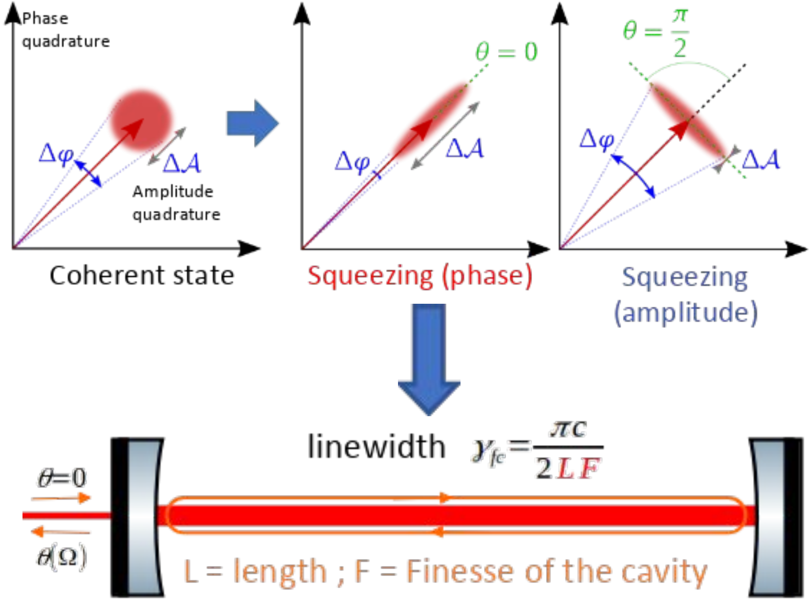
- Quantum noise arises from vacuum fluctuations entering the GW detector through its output port and interfering with the light used for GW detection.
- It impacts the interferometer sensitivity through two ways:



Quantum Noise Reduction - Squeezing

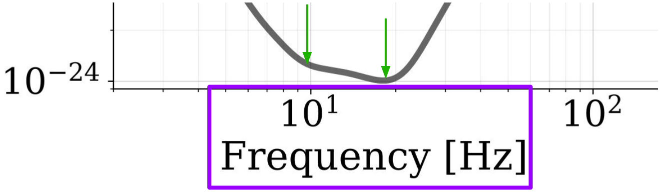


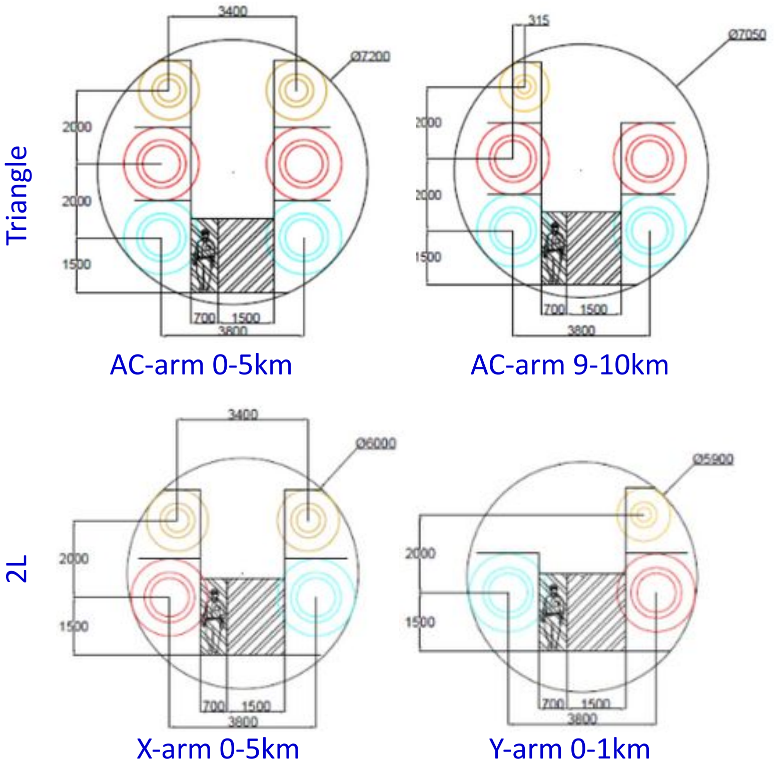
- To reduce quantum noise we replace the coherent vacuum with squeezed vacuum states of light made frequency dependent by reflection on optical resonator(s)



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



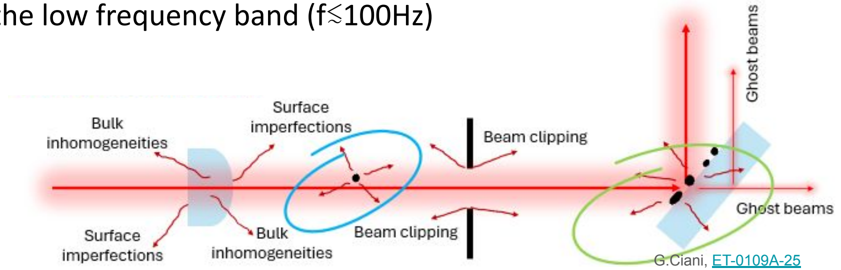


M. Majoor

Scattered and Stray Light

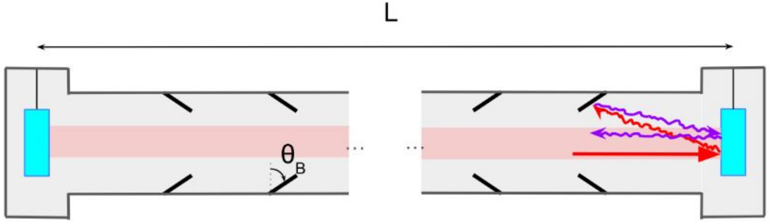
Straylight:

- 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≲100Hz)



G.Ciani, ET-0109A-25

A typical situation in GW interferometers:



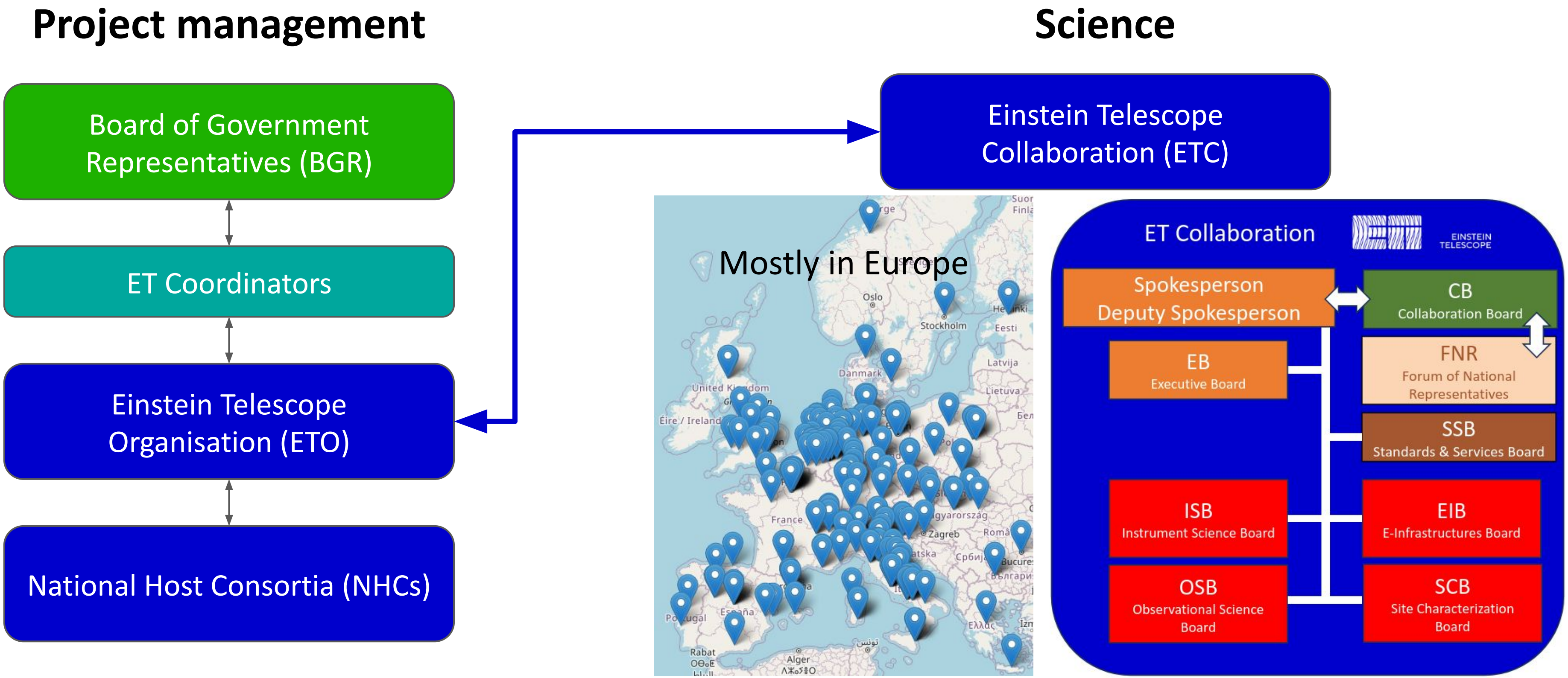
Stray light produced by a Test Mass reaches the pipe tube (or pipe baffle), is scattered back towards the TM and then again re-scattered into the main beam

And many other instrumental challenges

- Suspensions
- Mirror substrate and coating
- High power stable laser
- Vacuum
- Active Noise Mitigation
- Interferometer Sensing and Control
- Environmental monitoring
- …

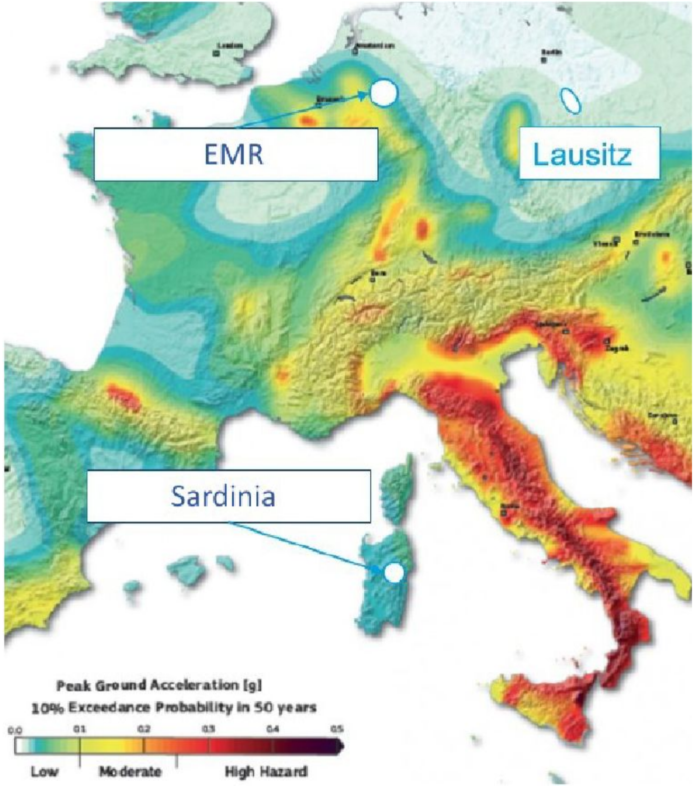
Einstein Telescope landscape

Einstein Telescope Organisation and Collaboration



Site and timeline

- Three sites formally candidates to host ET:
  - EMR Euregio, border region between Netherlands, Belgium and North Westfalia (Germany)
  - Lausitz, Saxony (Germany)
  - Sardinia (Italy)
- ET timeline is under review, 2026-2027 is crucial:
  - Sep-Oct 2026: Geometric comparison report by ET Organization
  - Dec 2026-June 2027: Call for tenders
  - Fall 2027: Site selection decision (after review by international panel)
  - 203X: Opening ET



Conclusion

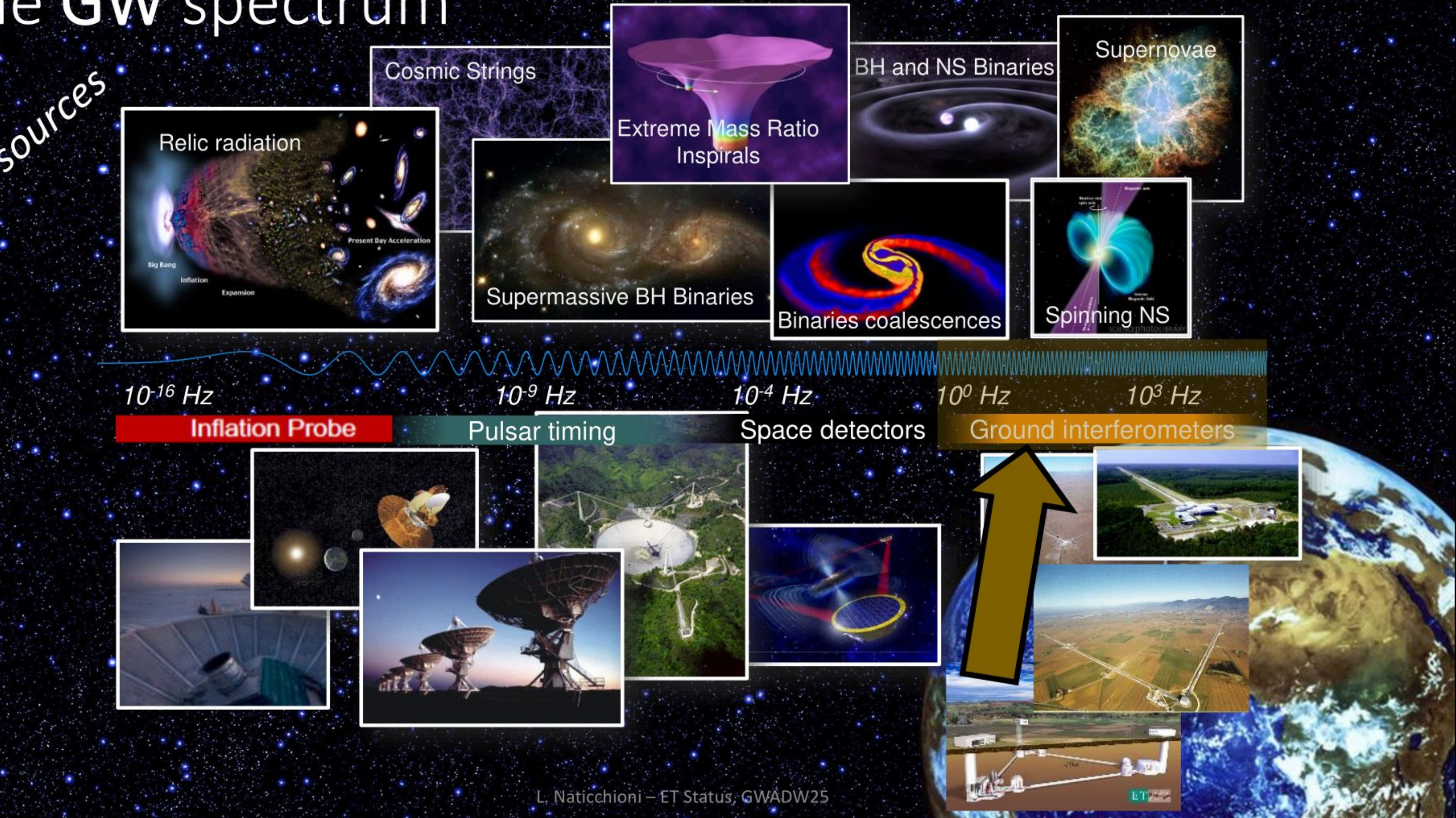
Conclusion

- Einstein Telescope is the next generation of European gravitational wave detector foreseen to operate for half of the century
- The science targets are multifold (see the ~900 pages of the "Blue book" JCAP03(2026)081)
- The gain in sensitivity wrt LIGO-Virgo-KAGRA is tremendous and rely on many complementary technologies: https://www.youtube.com/watch?v=gPZYZDwLYTI
- The Einstein Telescope Collaboration keeps growing!

Thank you!

Back-up material

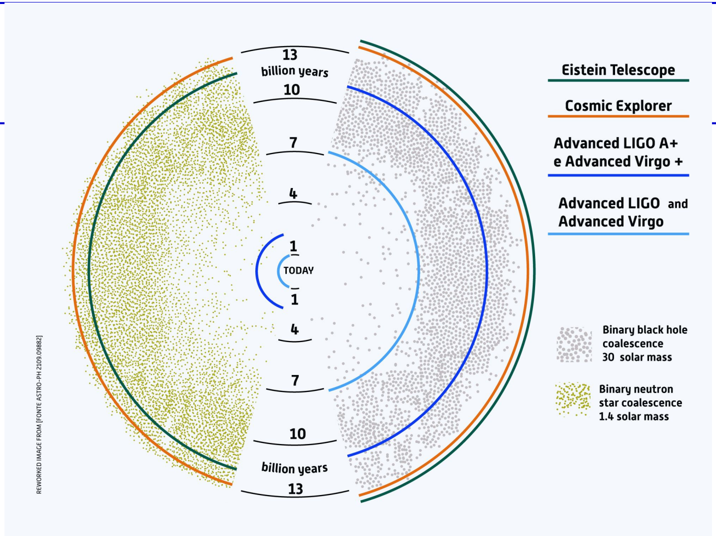
The GW spectrum

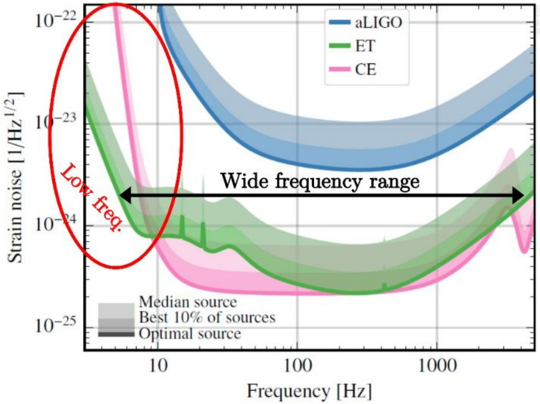


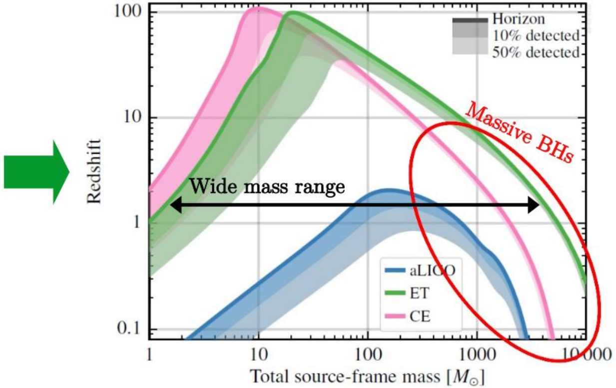
Observation performances

Einstein Telescope and Cosmic Explorer

- BBH up to z~50-100
  - 10^5 BBH/year
  - Masses $M_T \gtrsim 10^3\, M_\odot$
- BNS to z~2
  - 10^5 BNS/year
  - Possibly O(10-100)/year with e.m. counterpart
- High SNR







ET: large scale and complex infrastructure Underground observatory

Pro:

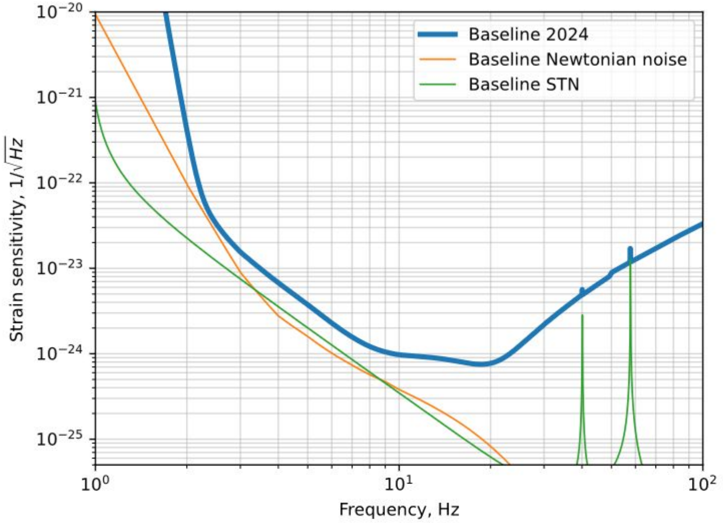
- Access to the low frequency:
  - 2-10Hz for ET
  - Reduction of the seismic and Newtonian Noise
  - Suppression of the atmospheric Newtonian Noise and of the wind impact
  - Reduction of the anthropogenic noise
    - Magnetic
    - Acoustic
    - Vibration
- Easier compatibility with the urbanization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

Cons:

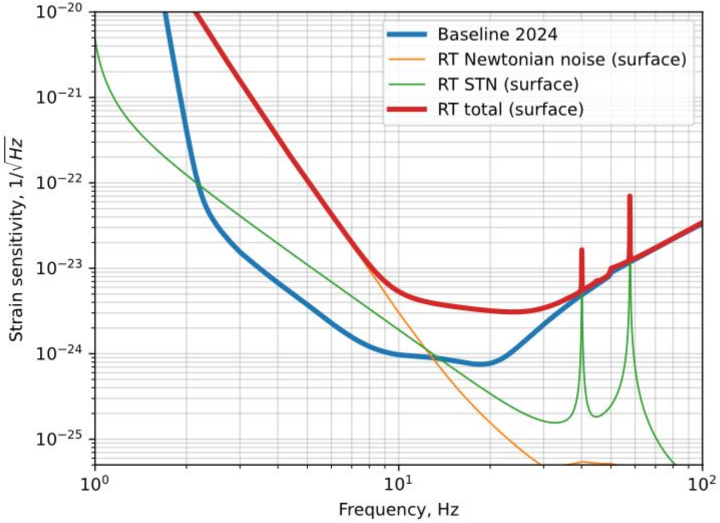
- Costs
- Challenging civil engineering (>30km of tunnels, large caverns…)
- Time needed to build it
- Limited possibility to upgrade the civil infrastructure in a medium-long term timeline
- More difficult operating environment in all the observatory phases (construction, integration, commissioning,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

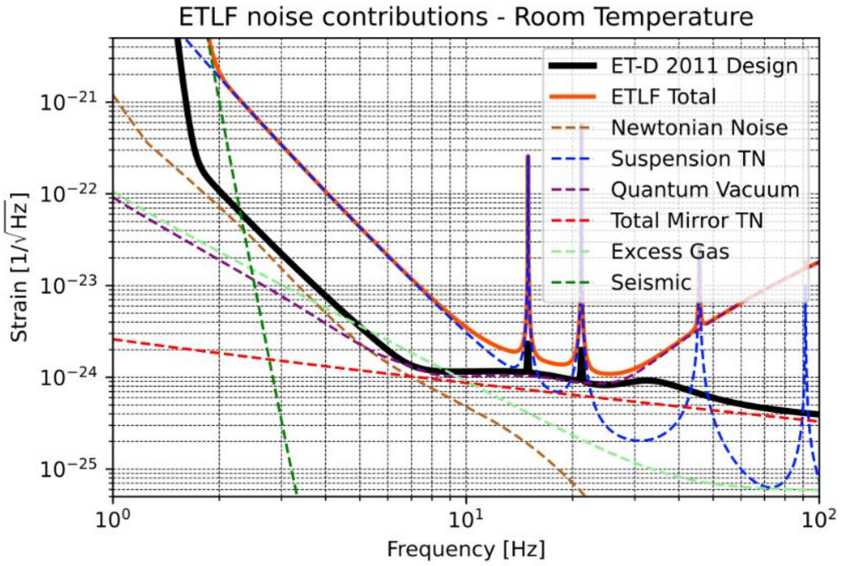
The underground installation and the cryogenic operation are two sides of the same coin

A strong motivation to implement cryogenics in ET

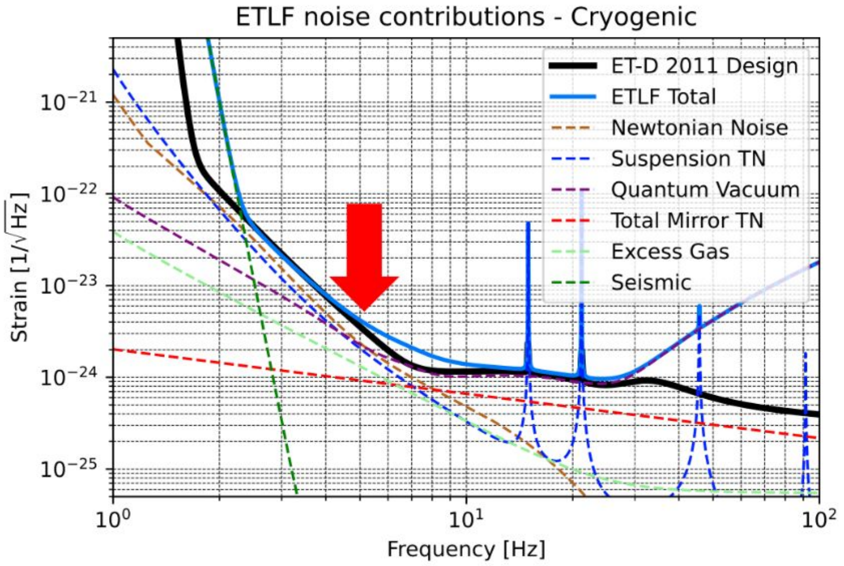
EINSTEIN TELESCOPE

Cryogenics contributes to a significant increase of sensitivity at low frequence

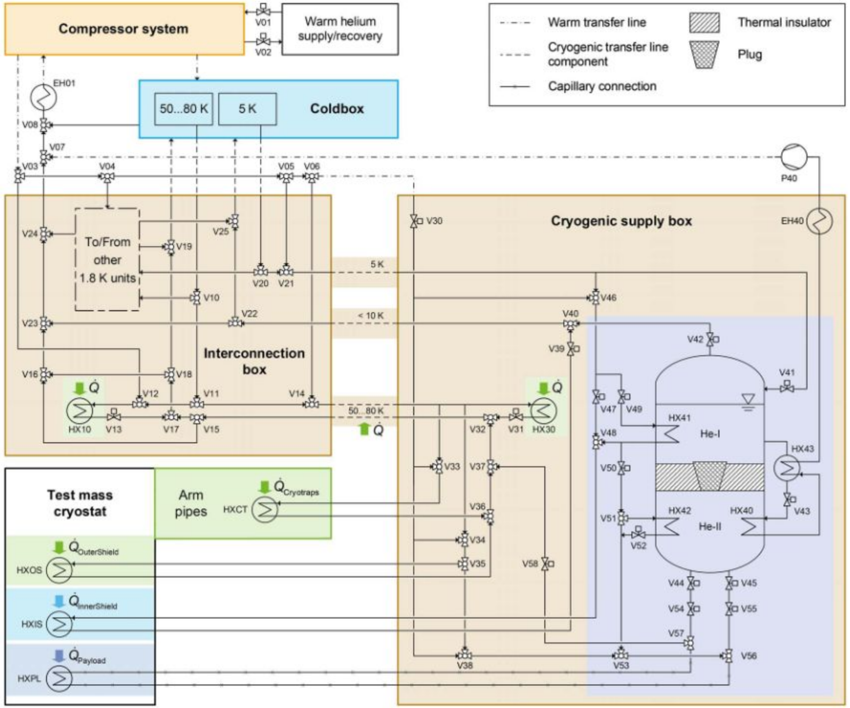
Room-Temperature ET-LF



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

EINSTEIN TELESCOPE

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

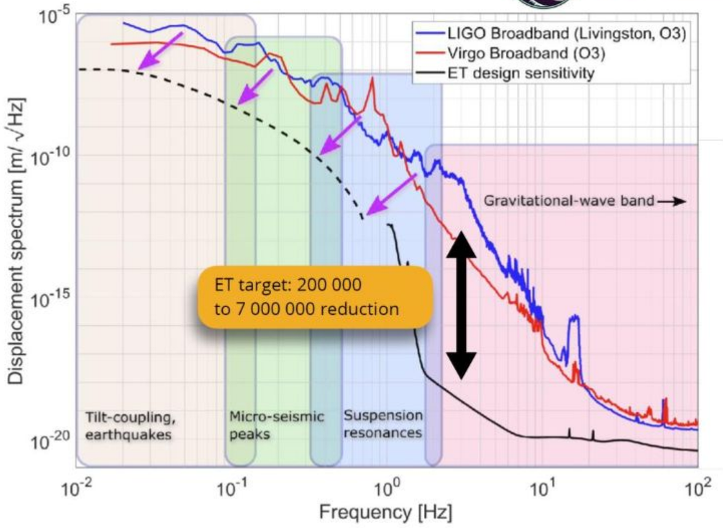
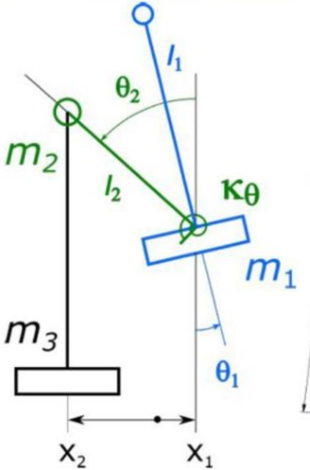
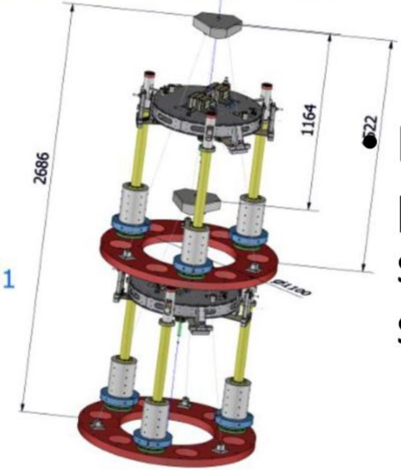


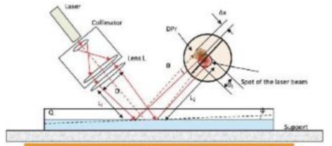
Image: Conor Mow-Lowry



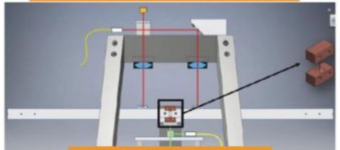


6-D interferometric readout inertial sensor
Credit: Conor Mow-Lowry, VU Amsterdam

Low frequency seismometers
Credit: Christophe Collette, U. Liege



Laser inclinometer, Credit: B. Di Girolamo, CERN



Ultralow frequency tiltmeter
Credit: ARCHIMEDES and VIRGO Coll.

Credits: A.Freise