Instrument science challenges of the Einstein Telescope

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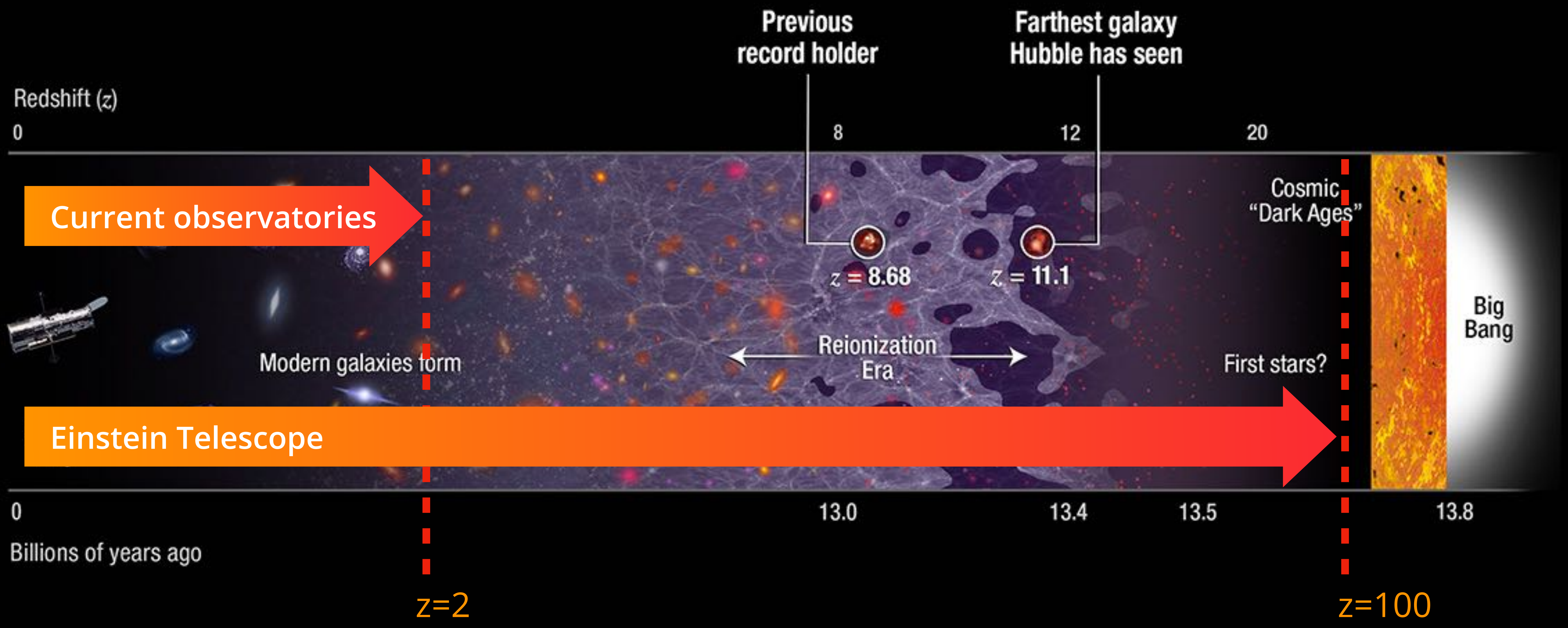
for the ET Instrument Science Board
EPS-HEP2021, 26.07.2021


LIGO Hanford 4km
GEO600 600m
Virgo 3km
LIGO India
(approved)
KAGRA 3km
LIGO Livingston 4km
Cosmic Explorer
(planned)
EINSTEIN TELESCOPE
Einstein Telescope
(planned)

New observatories or upgrading existing facilities?

- Ground-based GW observatories are currently being upgraded. Project pans exist up to the O5 observing run, planned for **2025-2027**.
- Discussions have started to plan further upgrades of existing detectors in the **post-O5 period**.
- However, eventually the benefits of such upgrades will be **limited by the facilities** (length of the arms, space in the building, environmental noise of the site, paging material)
- New observatories hope to use much **greater arm lengths**, which is not possible in the current locations.
- New locations allow potentially joint observation by a network of 3G and 2G detectors.

The case for future GW observatories



Early star formation, primordial black holes, seeds of supermassive black holes, standard-sirens to measure Hubble constant to much earlier ages ...

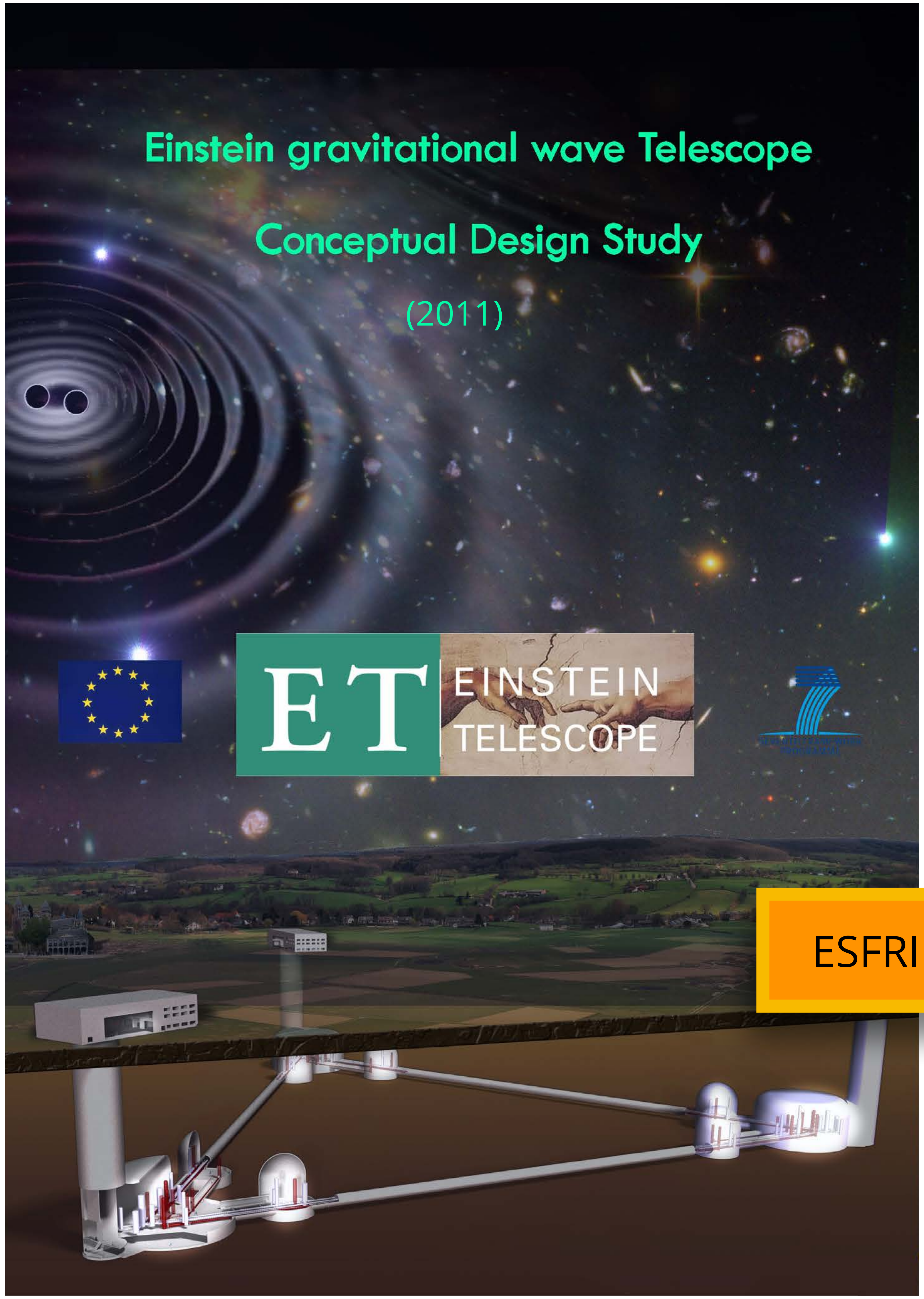
[Credits: NASA, ESA, P. Oesch and B. Robertson (University of California, Santa Cruz), and A. Feild (STScI)]


Einstein Telescope
10 km
Large laboratories and
three 10 km long tunnels,
more than 200m underground
A future European
gravitational waves
observatory

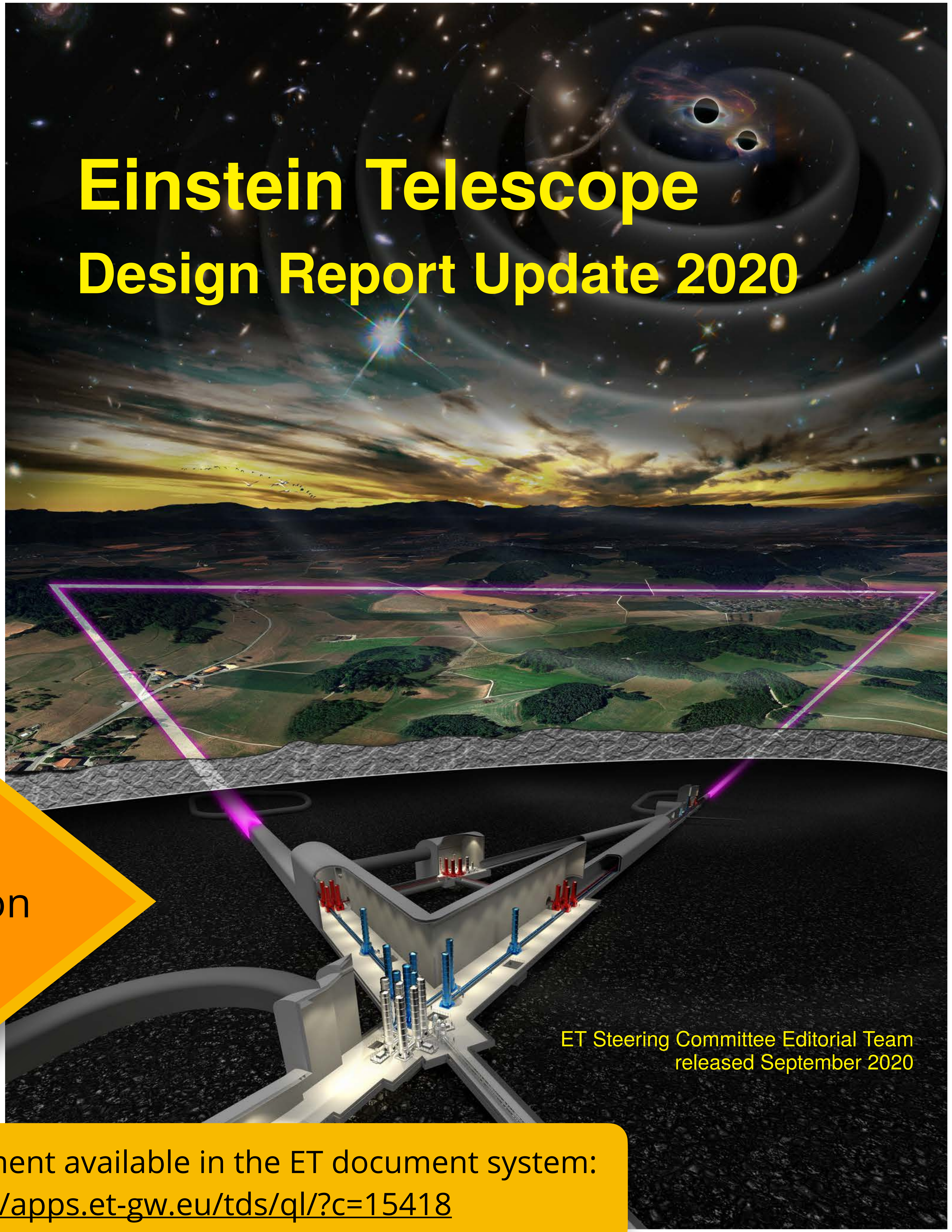
Einstein Telescope timeline

The Einstein Telescope is planned as a large underground facility with a **50+ years lifespan.**

- 2010 ET conceptual design completed
- **2020/2021 Design update, forming the ET collaboration, ESFRI approval**
- 2021- 2025 stagewise technical design updates
- 2021-2024 detailed site characterisation, refine cost evaluation
- **2024/2025 Site selection**
- 2026 Full technical design
- 2027 Infrastructure realisation start (excavation, ...)
- 2032+ installation / commissioning / operation



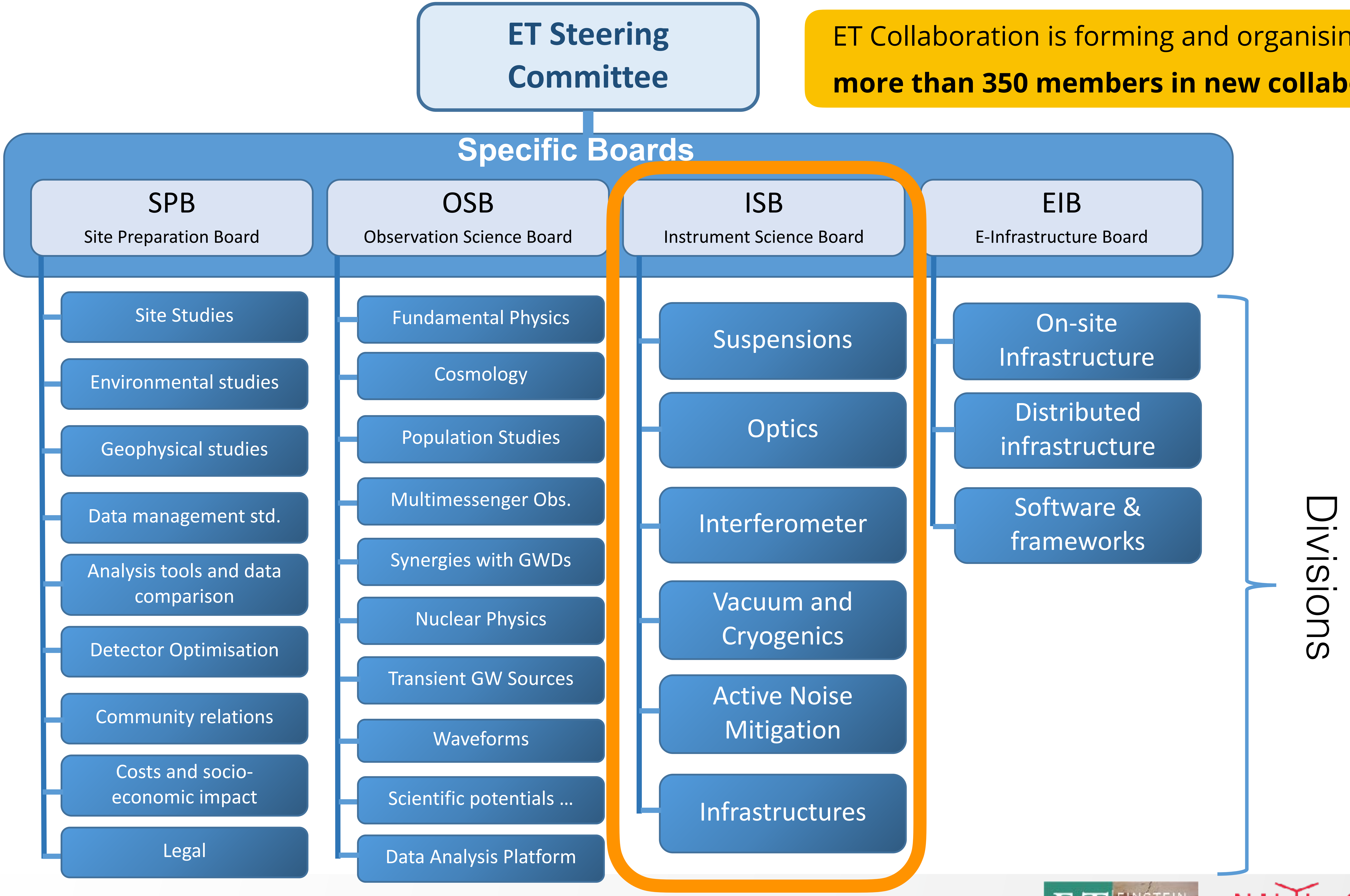
ESFRI Application



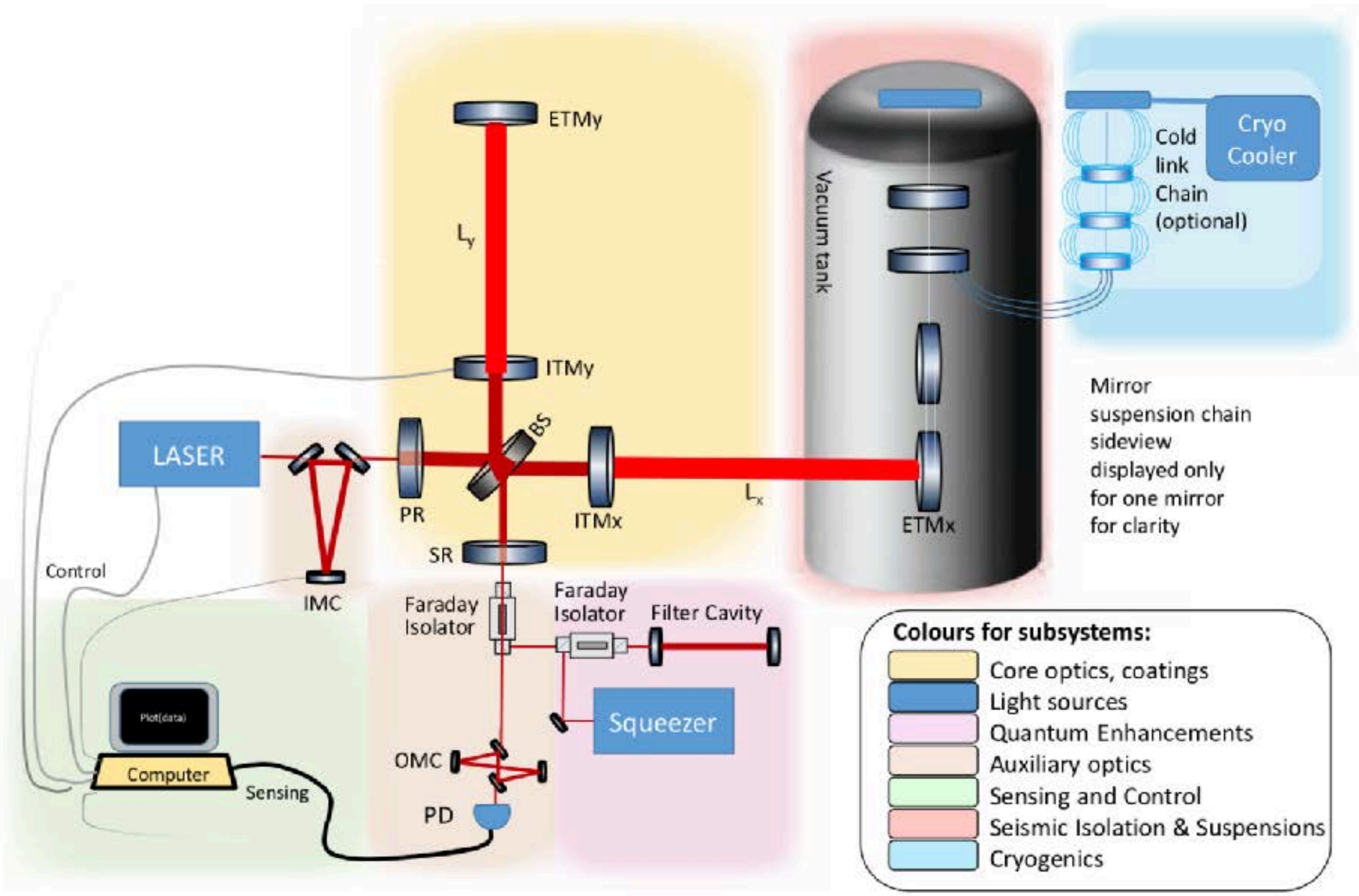
Document available in the ET document system:
https://apps.et-gw.eu/tds/ql/?c=15418

ET Collaboration is forming and organising

more than 350 members in new collaboration database



Improving technology



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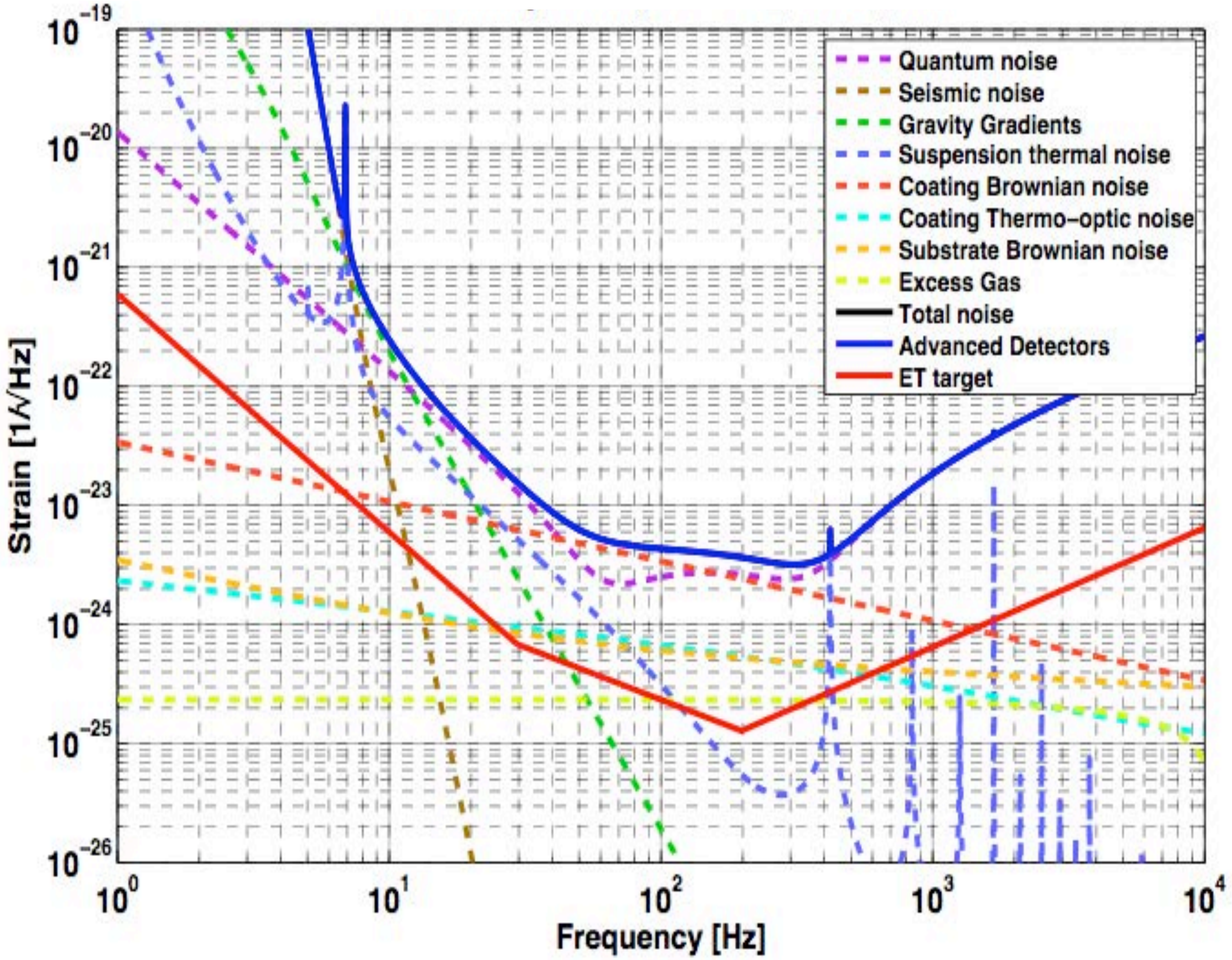
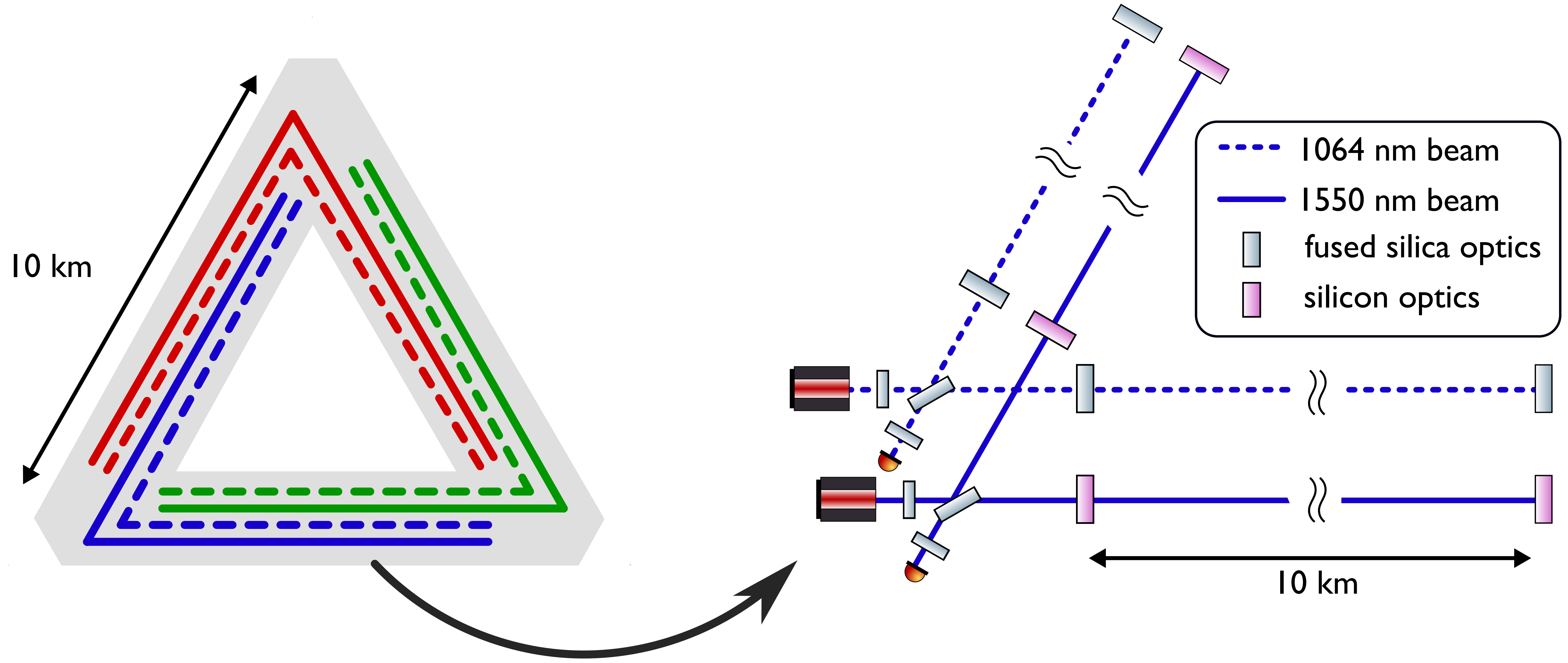
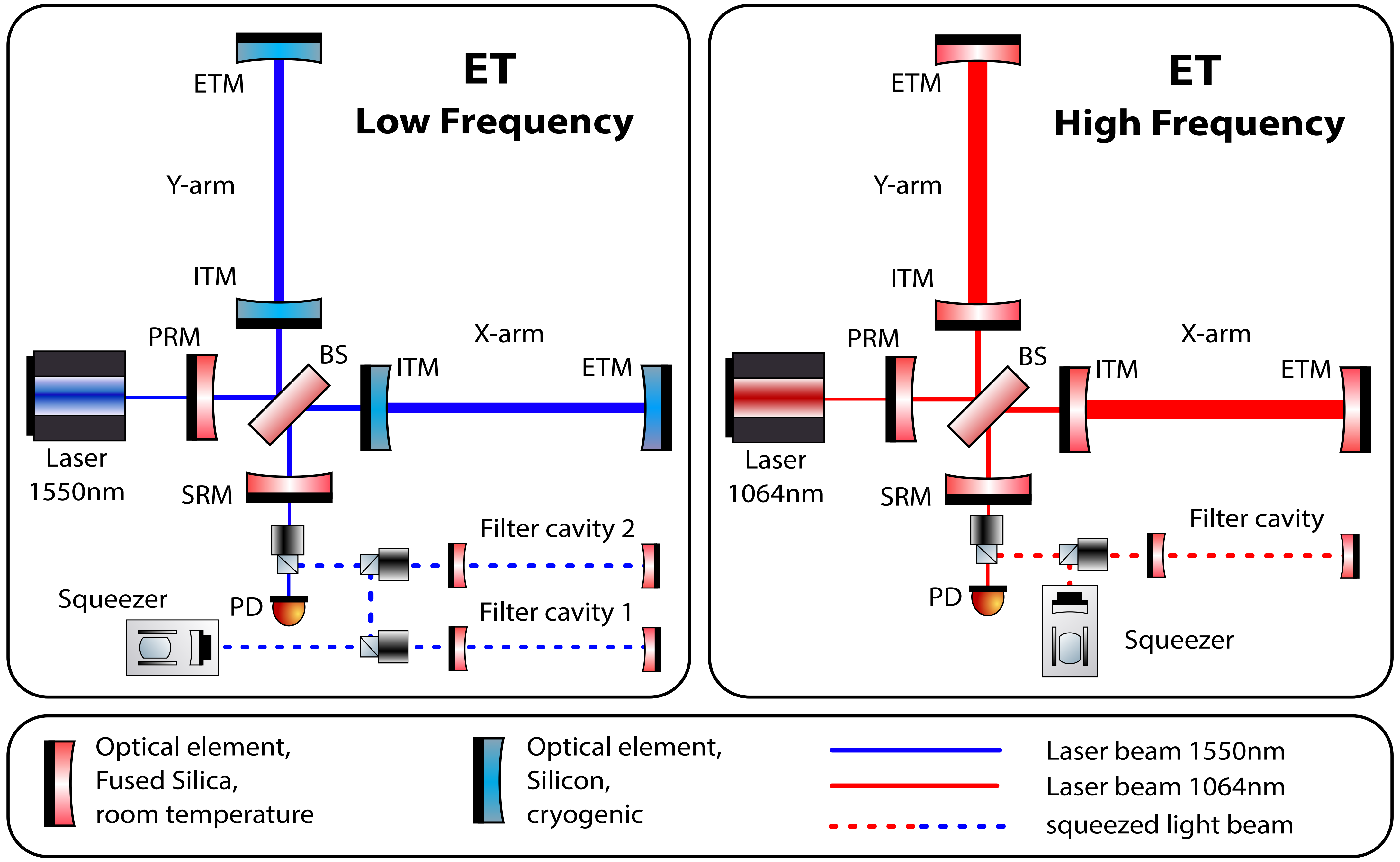


Einstein Telescope design

Parameter	ET-HF	ET-LF
Arm length	10 km	10 km
Input power (after IMC)	500 W	3 W
Arm power	3 MW	18 kW
Temperature	290 K	10-20 K
Mirror material	fused silica	silicon
Mirror diameter / thickness	62 cm / 30 cm	45 cm/ 57 cm
Mirror masses	200 kg	211 kg
Laser wavelength	1064 nm	1550 nm
SR-phase (rad)	tuned (0.0)	detuned (0.6)
SR transmittance	10 %	20 %
Quantum noise suppression	freq. dep. squeez.	freq. dep. squeez.
Filter cavities	1×300 m	2×1.0 km
Squeezing level	10 dB (effective)	10 dB (effective)
Beam shape	TEM_{00}	TEM_{00}
Beam radius	12.0 cm	9 cm
Scatter loss per surface	37 ppm	37 ppm
Seismic isolation	SA, 8 m tall	mod SA, 17 m tall
Seismic (for $f > 1$ Hz)	$5 \cdot 10^{-10}\,\mathrm{m}/f^2$	$5 \cdot 10^{-10}\,\mathrm{m}/f^2$
Gravity gradient subtraction	none	factor of a few





New special focus: noise at low freqencies

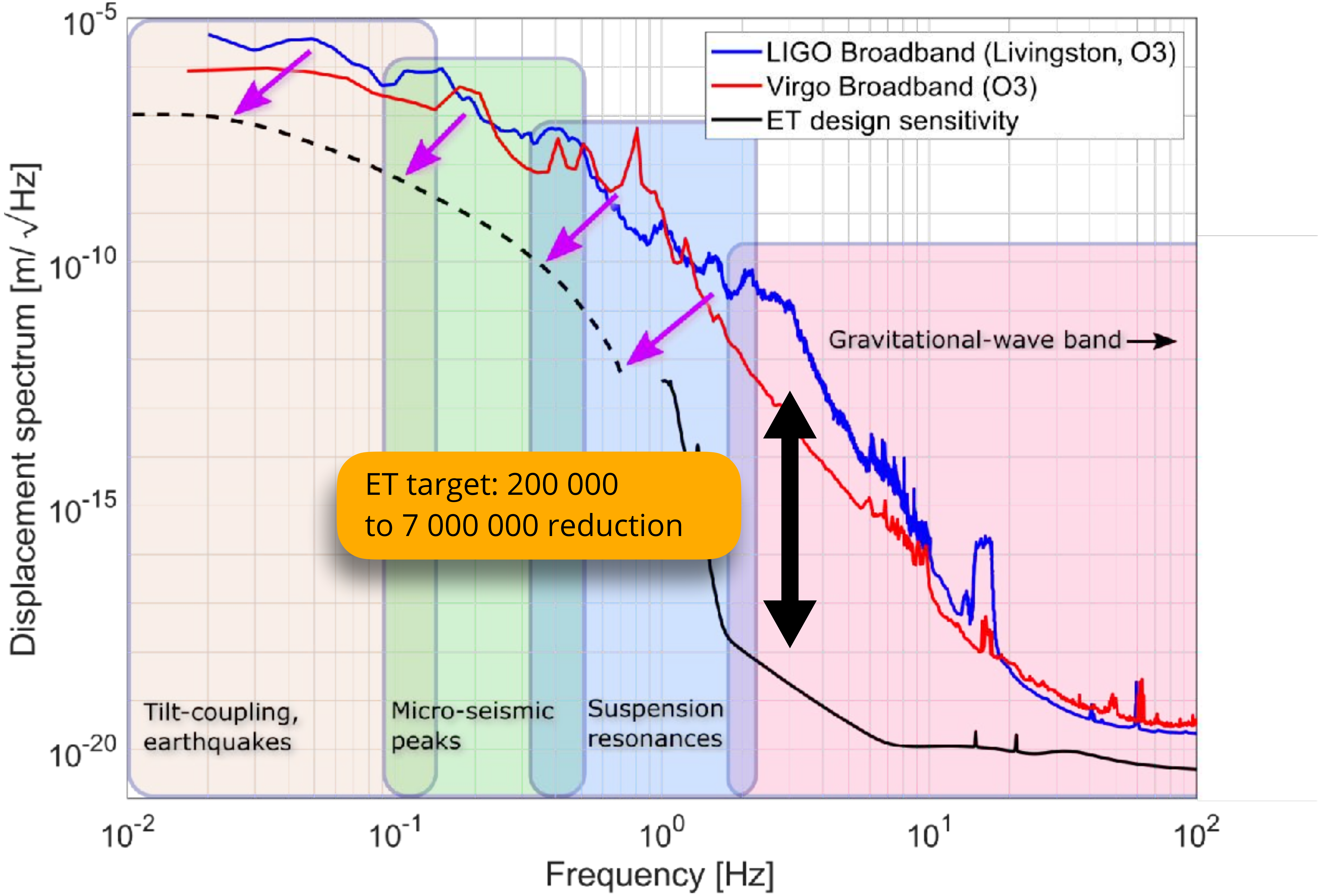
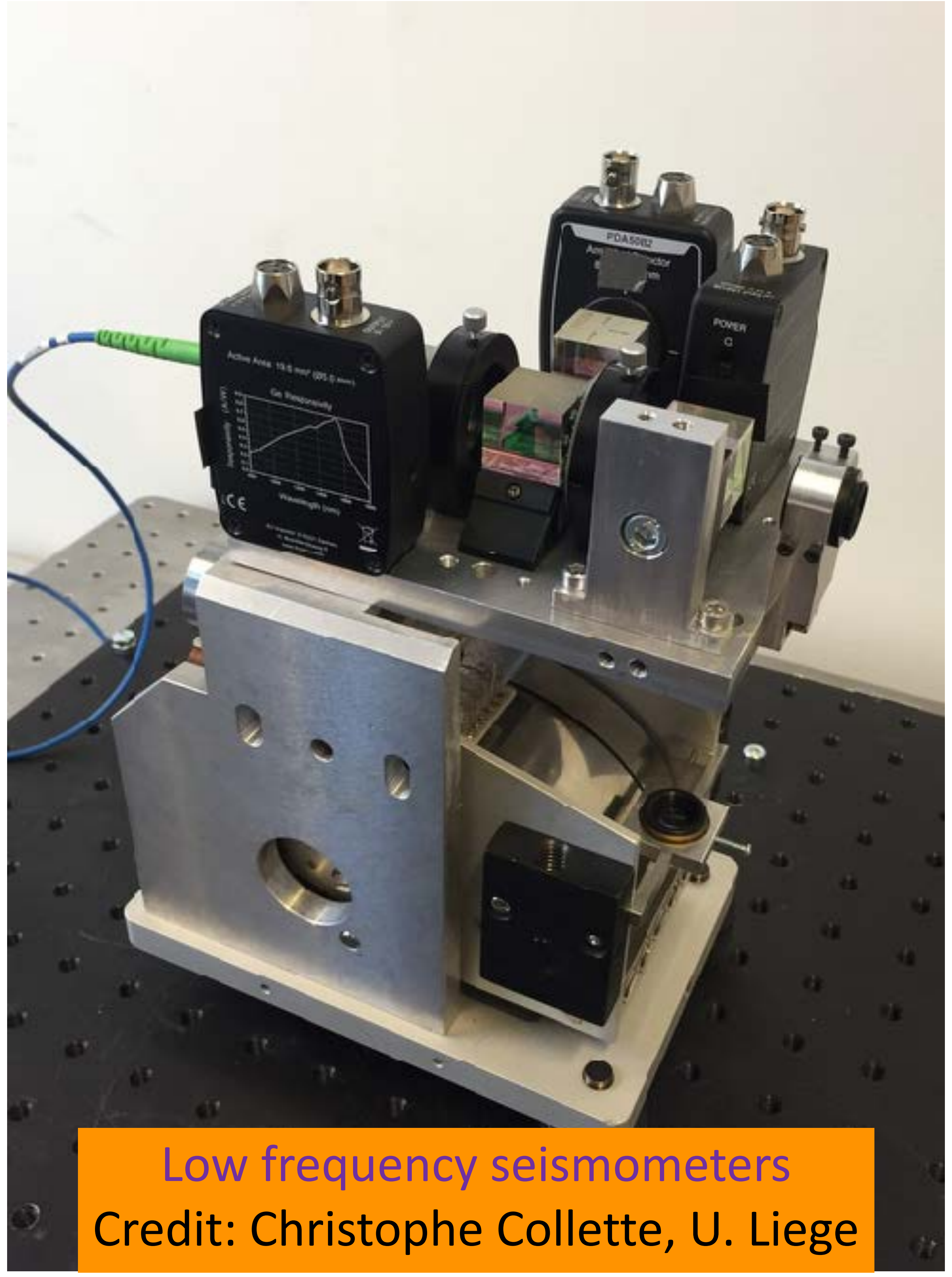
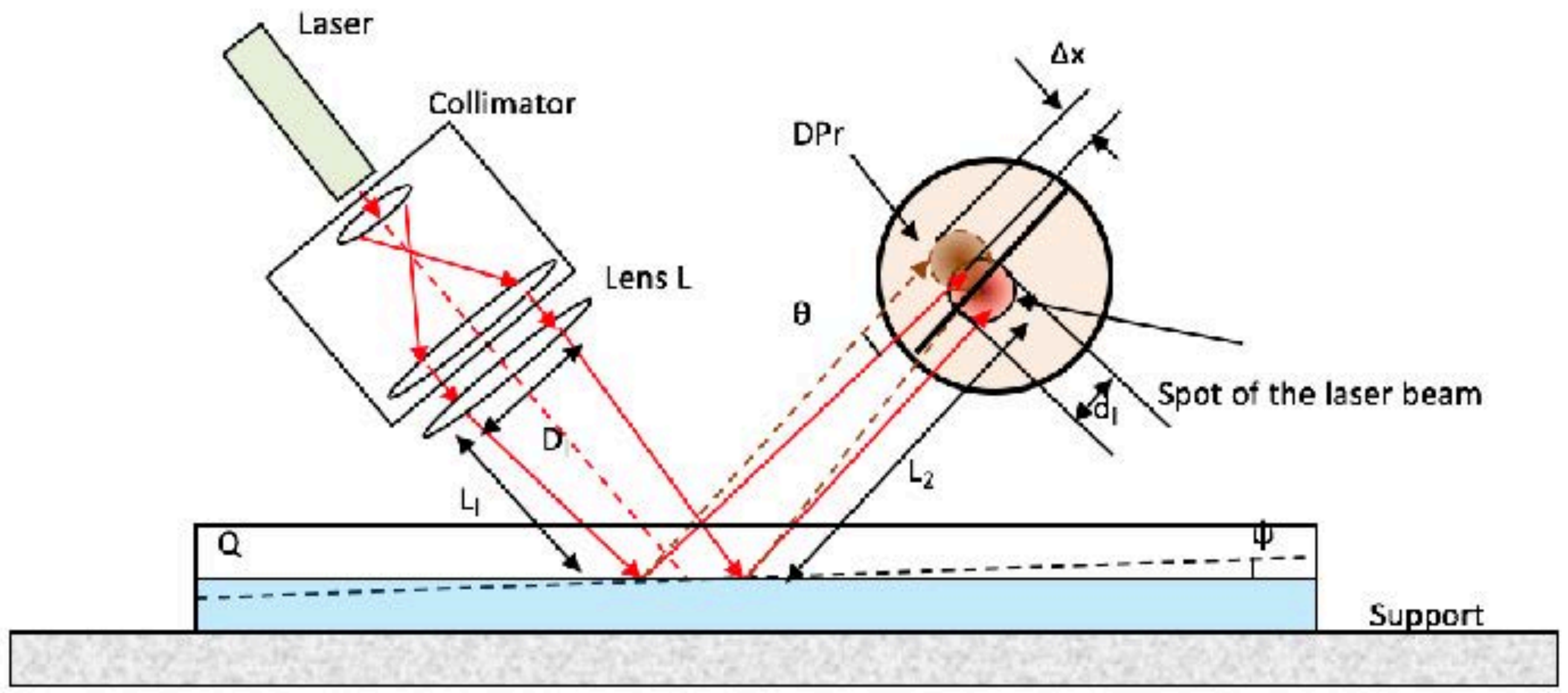


Image: Conor Mow-Lowry

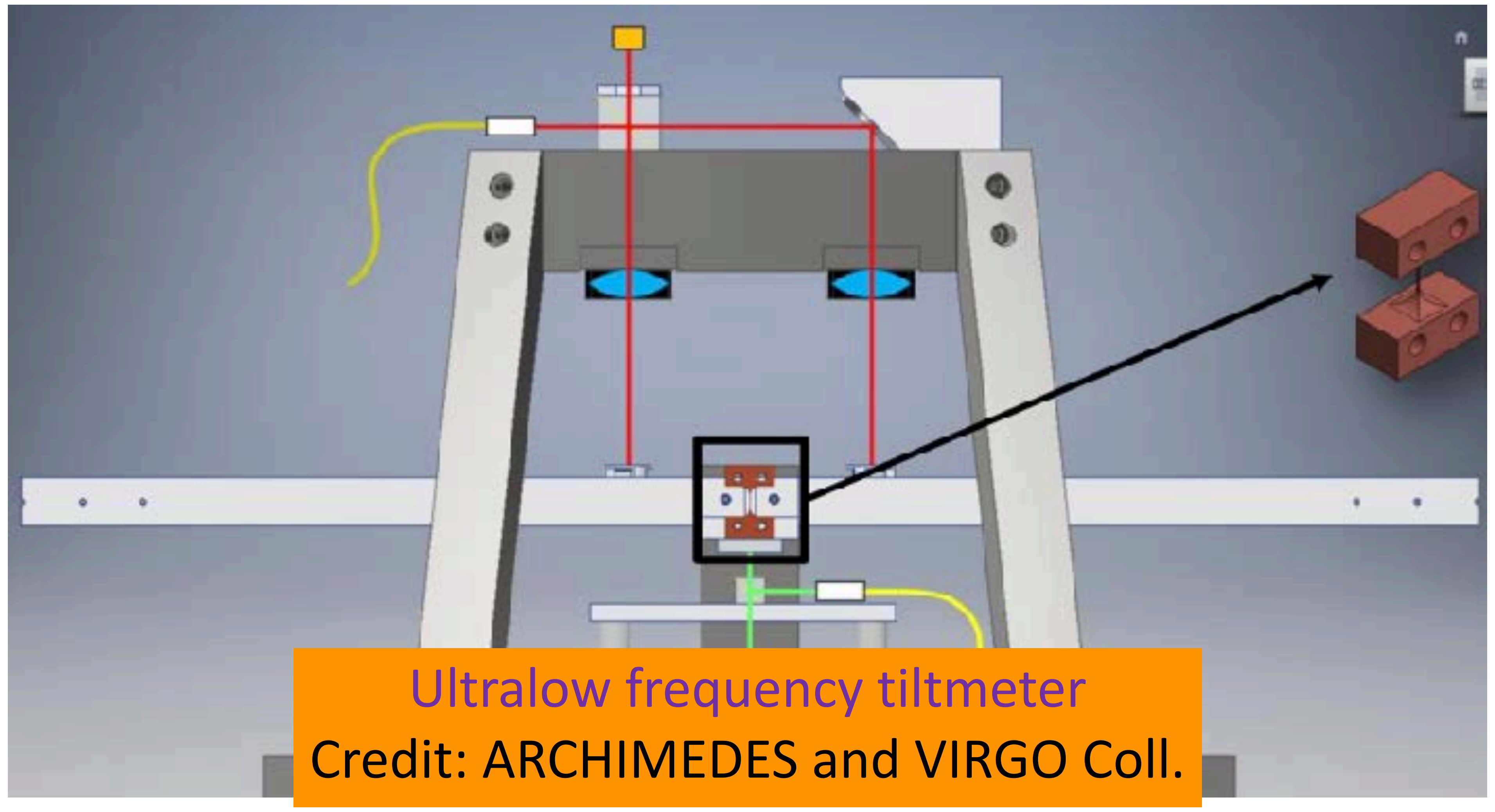
R&D example: advanced seismic sensors


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


Low frequency seismometers
Credit: Christophe Collette, U. Liege



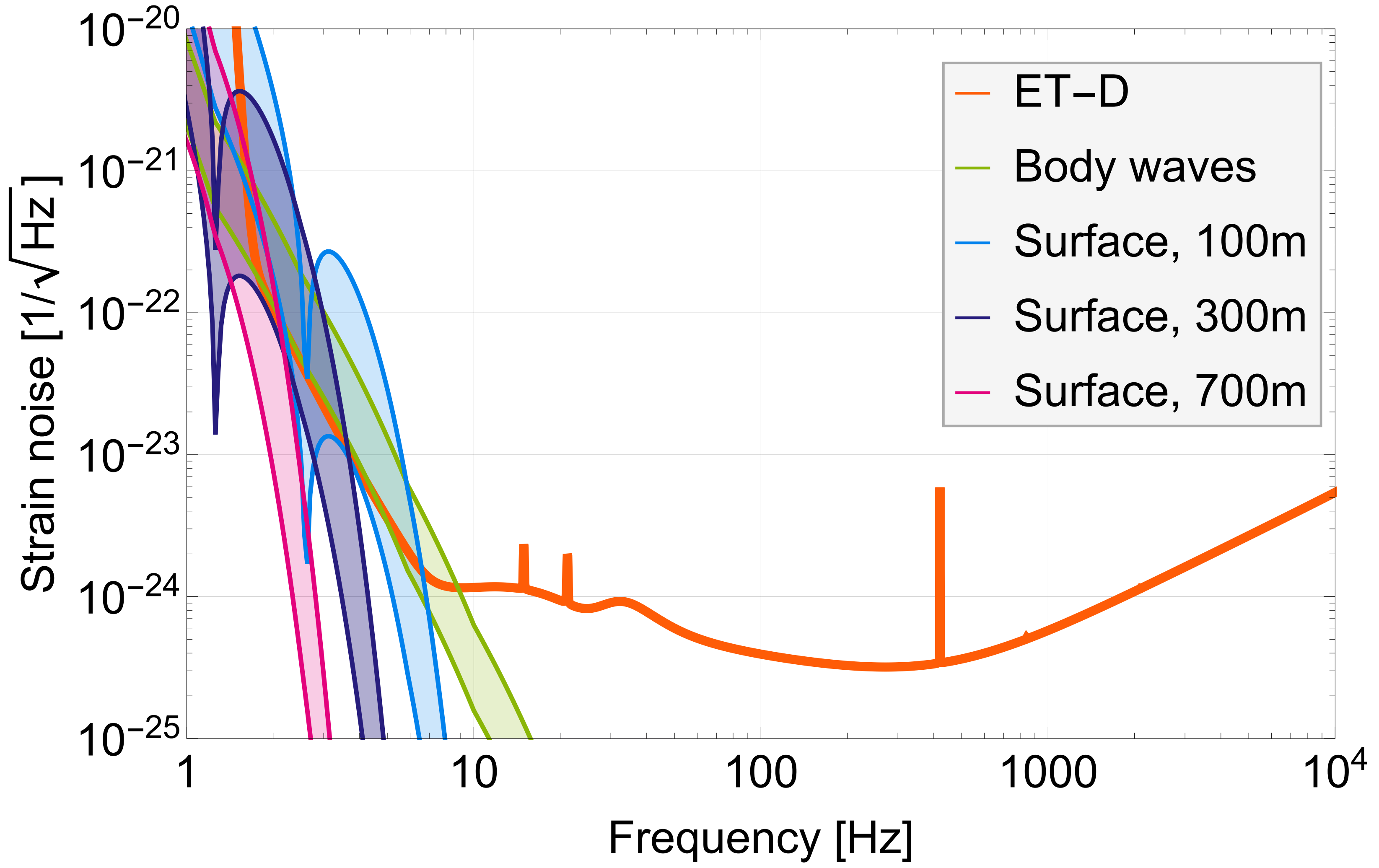
Laser inclinometer, Credit: B. Di Girolamo, CERN


Ultralow frequency tiltmeter
Credit: ARCHIMEDES and VIRGO Coll.

Goal: inertial control at low frequencies for suspension shortening and RMS motion suppression

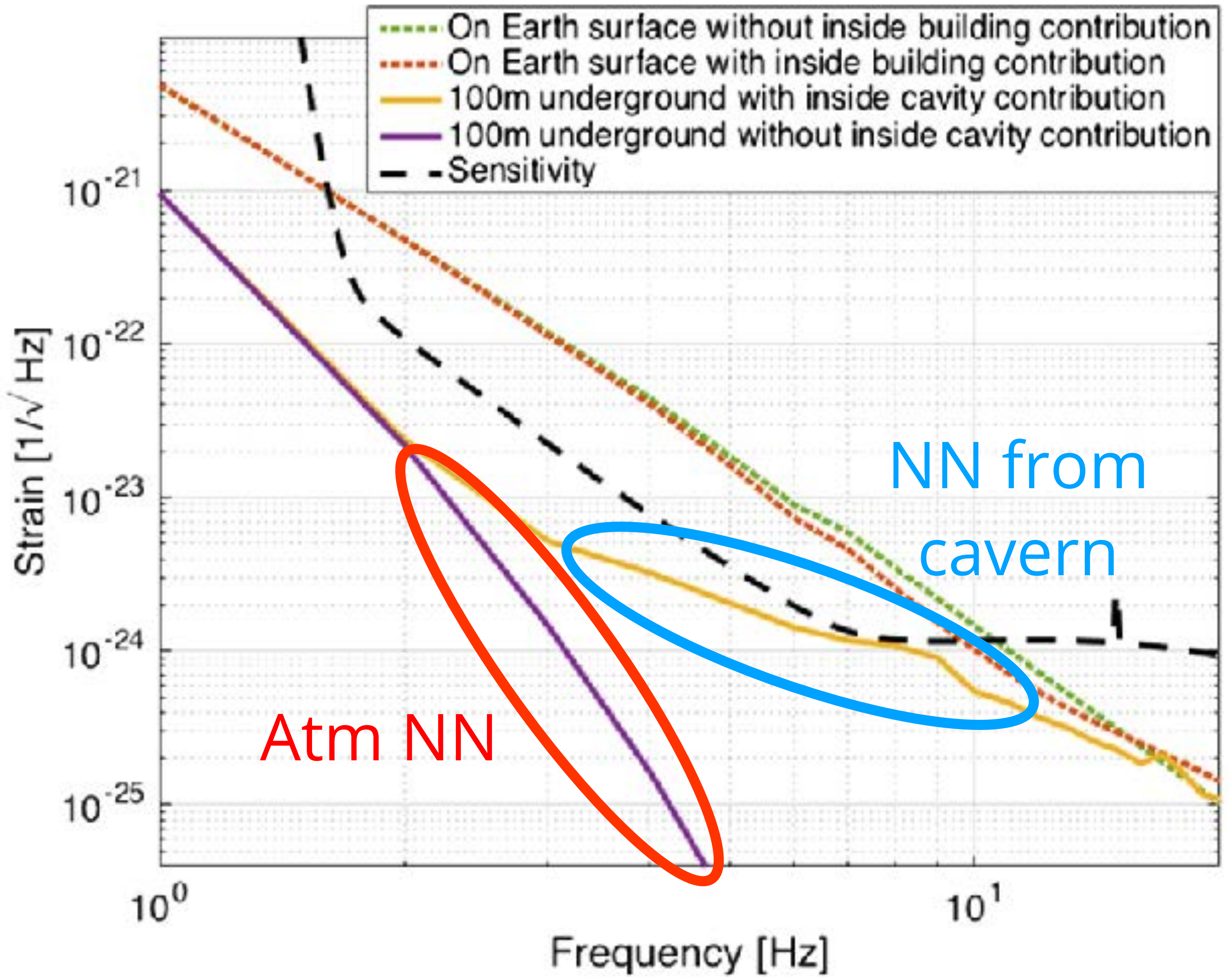
Underground and low noise

Seismic Newtonian noise (NN)



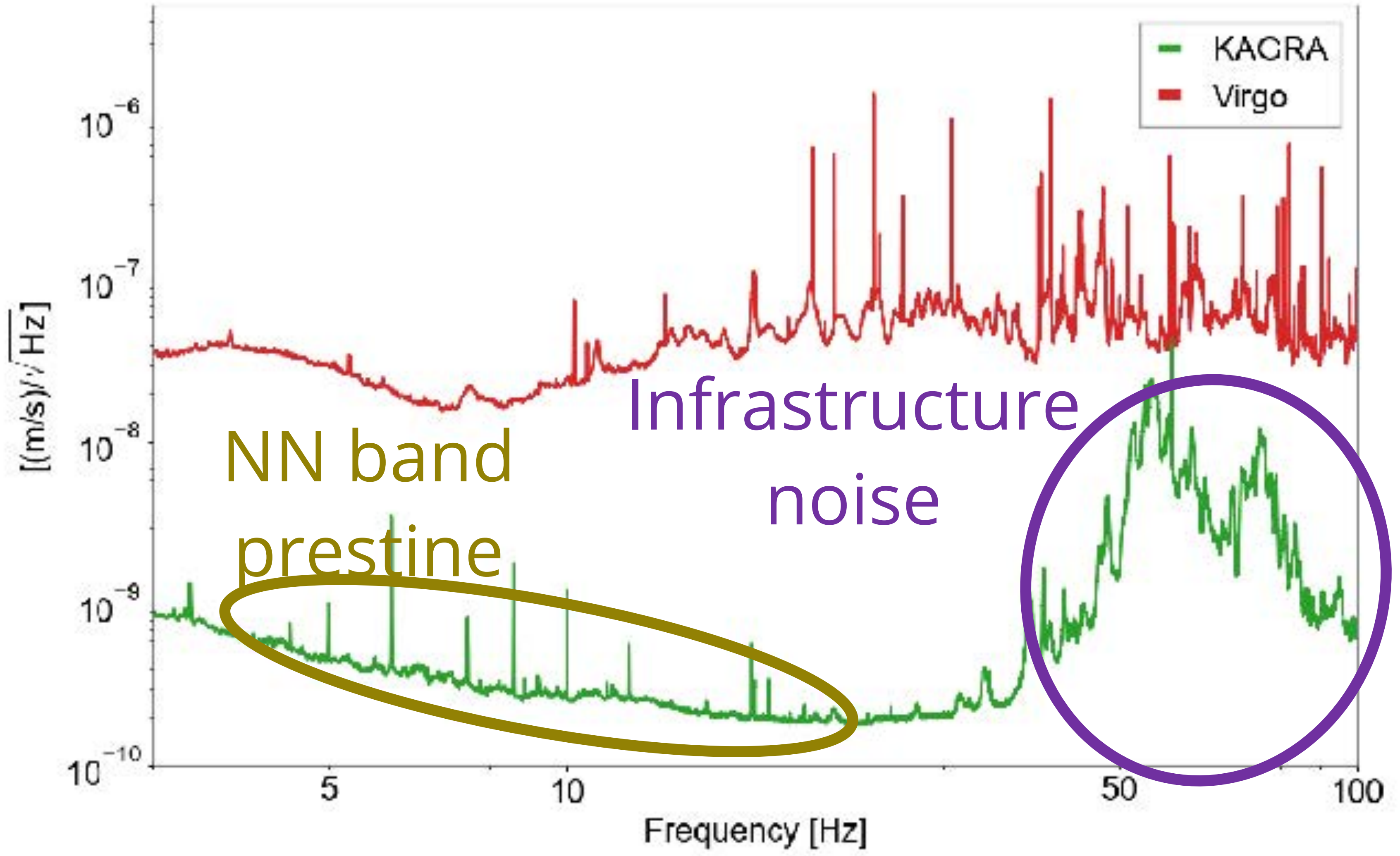
ET is planned >200m underground. Further mitigation of NN from seismic surface and underground fields might be achieved with noise cancellation using arrays of seismometers.

Acoustic NN



Atmospheric NN cancellation would be extremely challenging due to lack of a good monitoring system. ET can avoid it by going underground!

Low-noise environment



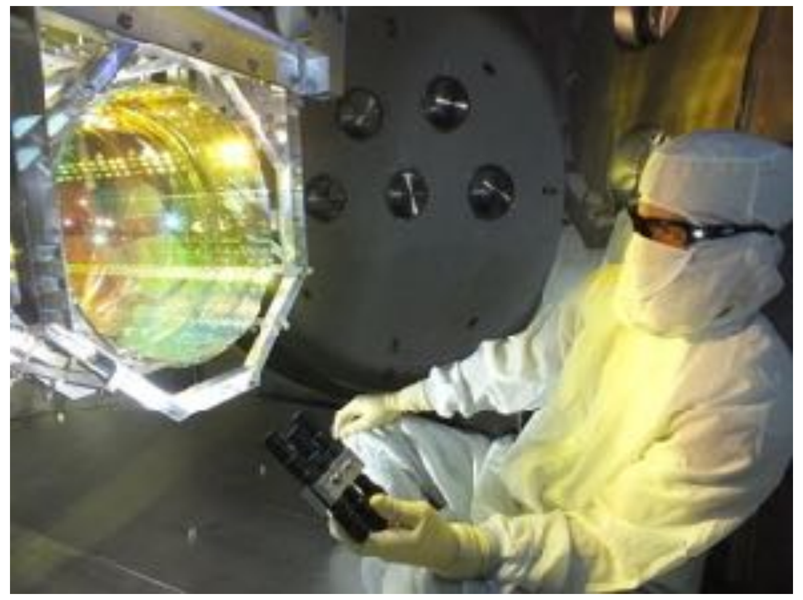
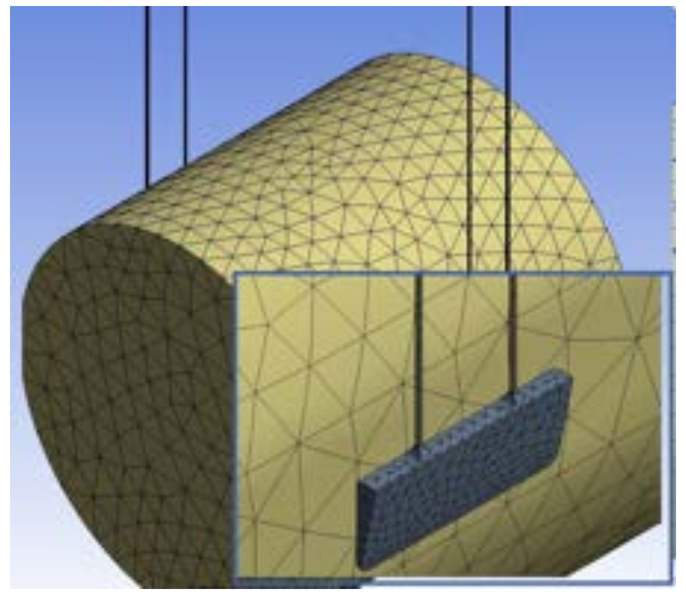
We must create a low-noise infrastructure. If KAGRA can do it (not creating excess noise in the NN band), so can the Einstein Telescope.

R&D challenge example: Optics

- Scaling challenge: *substrate* (ET-HF silica / ET-LF silicon) of 200 kg-scale with required purity and optical homogeneity/abs. is a challenge, and *coating challenge.*

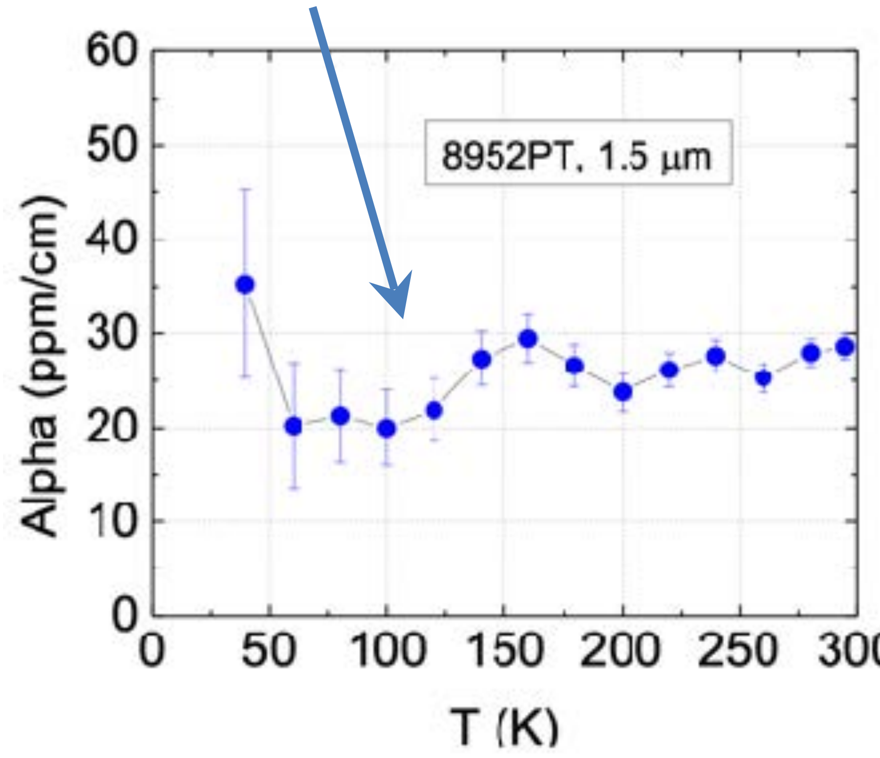
Absorption of “best 45 cm” MCZ Si: 1.5um

Stanford/Glasgow/Berkeley/Caltech 2019

Advanced LIGO – 40 kg / ET 200 kg

Nikon SiO_2



- Coatings: major challenge over recent years: coating solutions often either satisfy thermal noise requirement *or* optical performance requirement – not both.
- Progress towards first scalable design for ET-LF, however ET-HF target not met.

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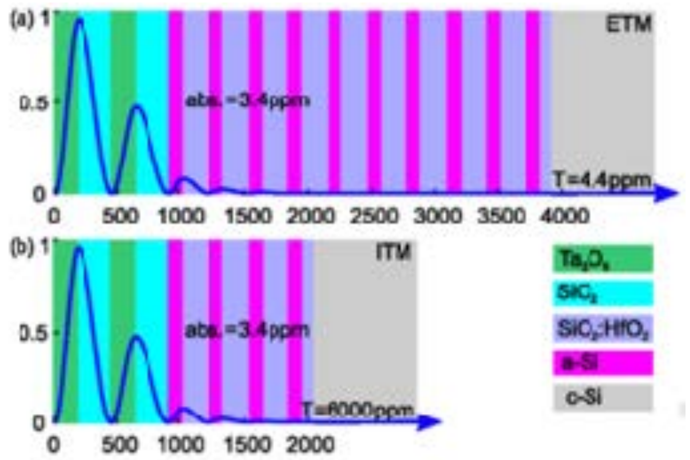
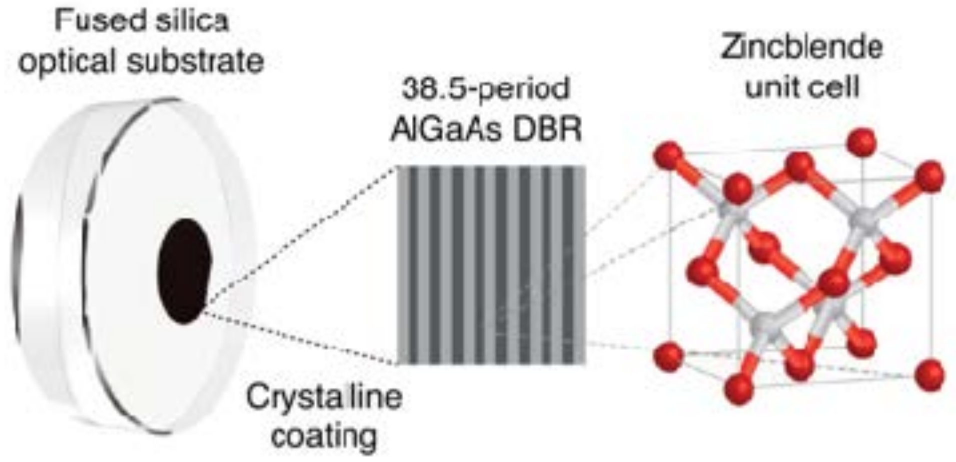
Mirror Coating Solution for the Cryogenic Einstein Telescope

Kieran Craig, Jessica Steinlechner, Peter G. Murray, Angus S. Bell, Ross Birney, Karen Haughian, Jim Hough, Ian MacLaren, Steve Penn, Stuart Reid, Raymond Robie, Sheila Rowan, and Iain W. Martin

Phys. Rev. Lett. 122, 231102 – Published 13 June 2019



ET-LF coatings: Craig *et al.*, Phys. Rev. Lett. **122**, 231102 (2019)



AlGaAs crystalline coatings might satisfy ET-HF but currently limited to ~200mm dia.

Cryogenics and laser wavelength

- Cryogenic mirrors and mirror suspensions can significantly reduce the thermal noise
- This requires change of material as fused silica does not show this effect. Alternatives crystalline materials such as silicon and sapphire
- Silicon cannot be operated at 1u, different wavelength is requires
- Wavelength change impacts many aspects of the interferometer and depends on many technology developments

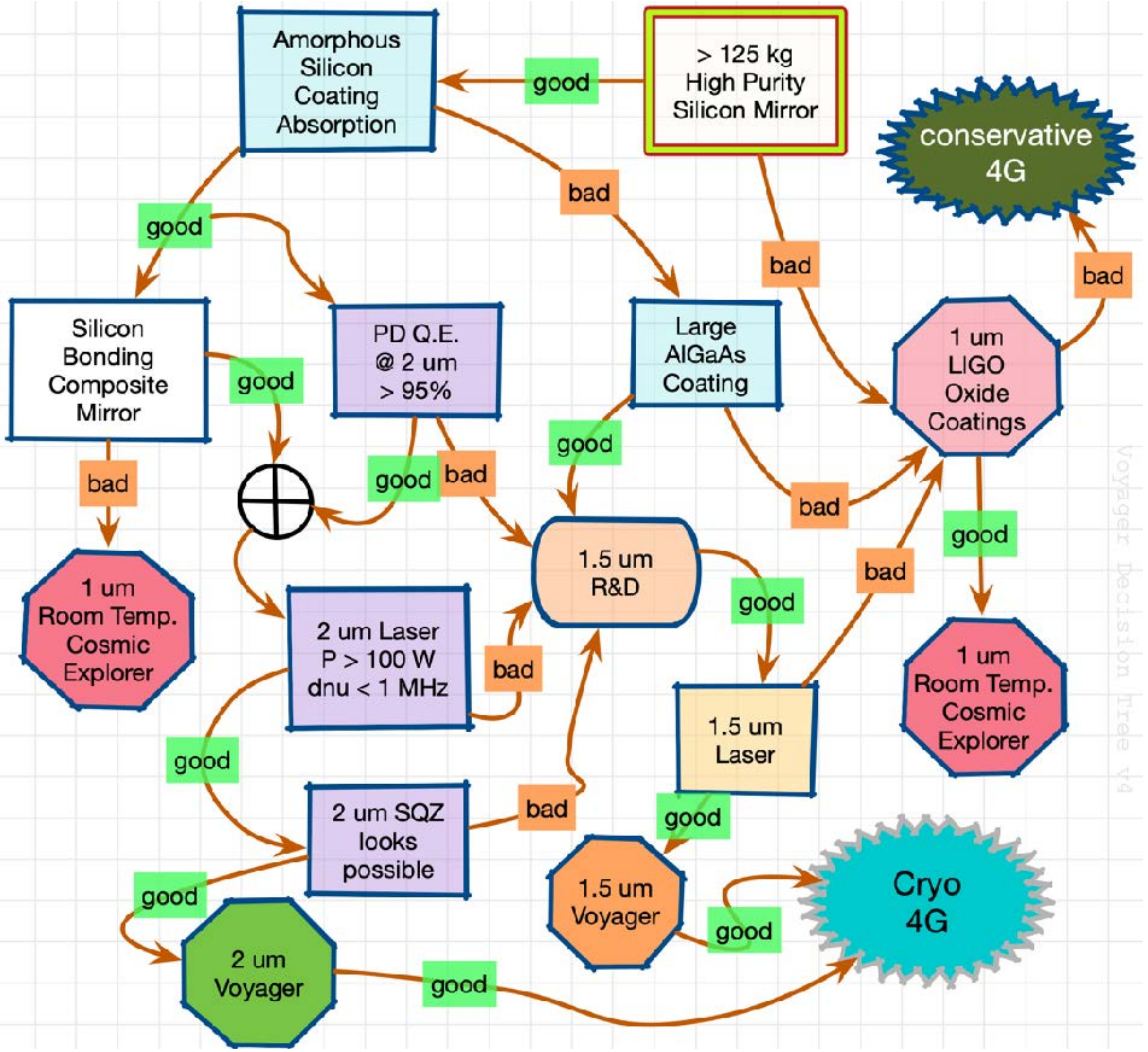
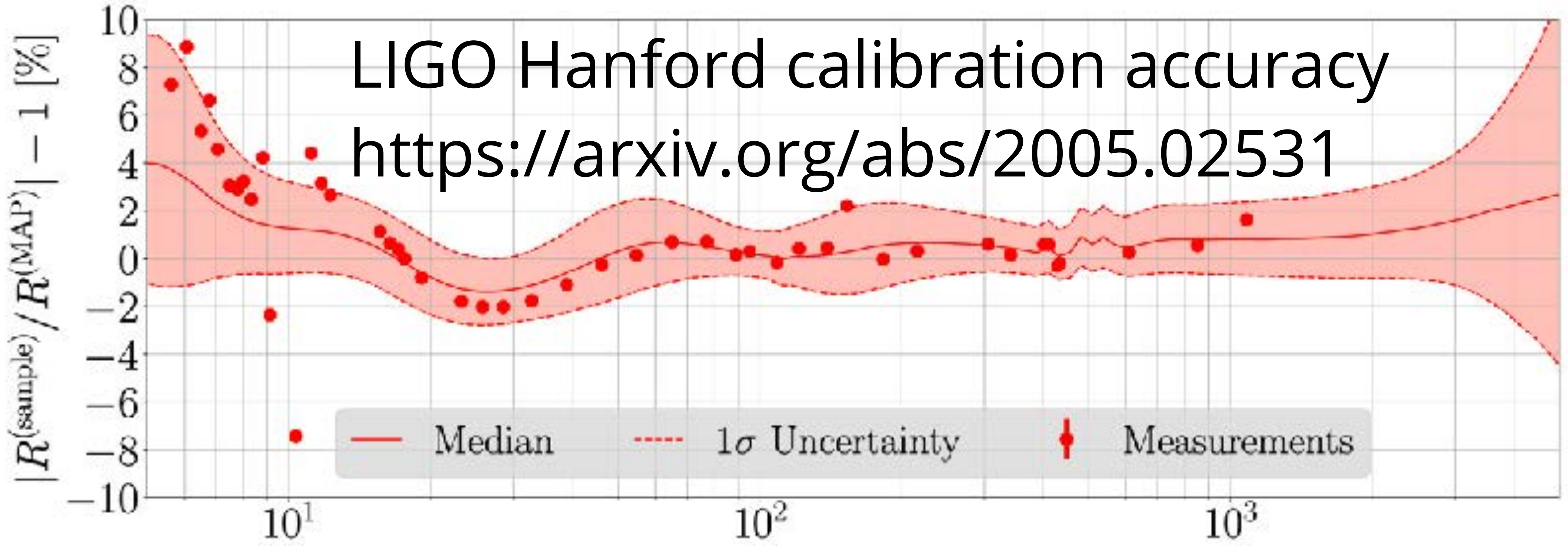


Image: Rana Adhikari GWADW 2018

Calibration must improve as much as SNR

- 3G detectors such as ET will require sub-one-percent calibration accuracy in order to fully benefit from their increased sensitivity
- Self-calibration, i.e. calibrating the detector using the detected signal and null-streams can help to achieve that.
- ET provides such a null-stream stand-alone, which is sky-position and polarisation independent (this is not the case for a distributed network).



LIGO Hanford calibration accuracy
https://arxiv.org/abs/2005.02531

Self-calibration of Networks of Gravitational Wave Detectors

Bernard F. Schutz
School of Physics and Astronomy, Cardiff University, Cardiff, UK, CF24 3AA and
*Max Planck Institute for Gravitational Physics (Albert Einstein Institute), 14476 Potsdam/Golm, Germany**

B. S. Sathyaprakash

September 2020, https://arxiv.org/abs/2009.10212

B. Sky-independent null stream

The design of the proposed 3G detector ET envisages three V-shaped interferometers, one each at the three vertices of an equilateral triangle. The sum of the responses of the three interferometers, as we shall see below, is a null stream no matter where the source is in the sky. In fact, this is true more generally for any configuration that has a closed topology. Consequently, self-calibration with ET is significantly simpler.

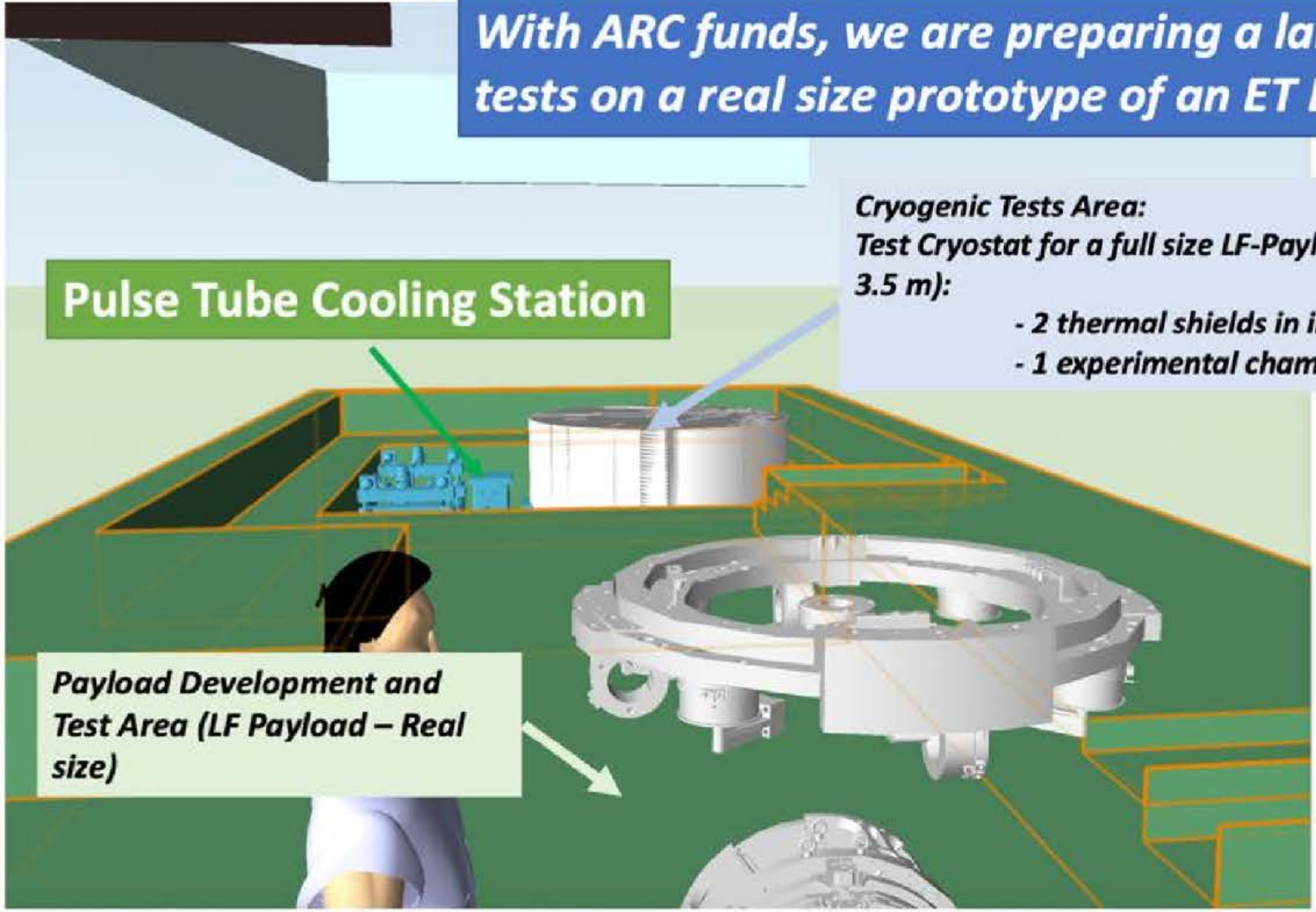
ETpathfinder

- 10m prototype facility, currently under construction in Maastricht
- 14.5M€ investment
- ~20 universities and research institutes from NL/BE/DE/F contribute

[Slide: Jan-Simon Henning]

3G Gravitational-Wave Lab

With ARC funds, we are preparing a lab for low temperature tests on a real size prototype of an ET LF-Payload



Cryogenic Tests Area:
Test Cryostat for a full size LF-Payload, cooled by two PT (~Ø 3 m x 3.5 m):
- ***2 thermal shields in insulation vacuum***
- ***1 experimental chamber with separated vacuum***

The Rome1 ET Group:

From Virgo:

Sibilla	Di Pace	(Post Doc Researcher)
Ettore	Majorana	(Full Professor)
Valentina	Mangano	(Post Doc Researcher)
Luca	Naticchioni	(INFN Researcher)
Maurizio	Perciballi	(INFN Technician)
Paola	Puppo	(INFN Researcher)
Piero	Rapagnani	(Associate Professor)
Fulvio	Ricci	(Full Professor)

From CUORE:

Angelo	Cruciani	(INFN Researcher)
Antonio	D'Addabbo	(Post Doc Researcher LNGS)
Stefano	Pirro	(INFN Researcher)

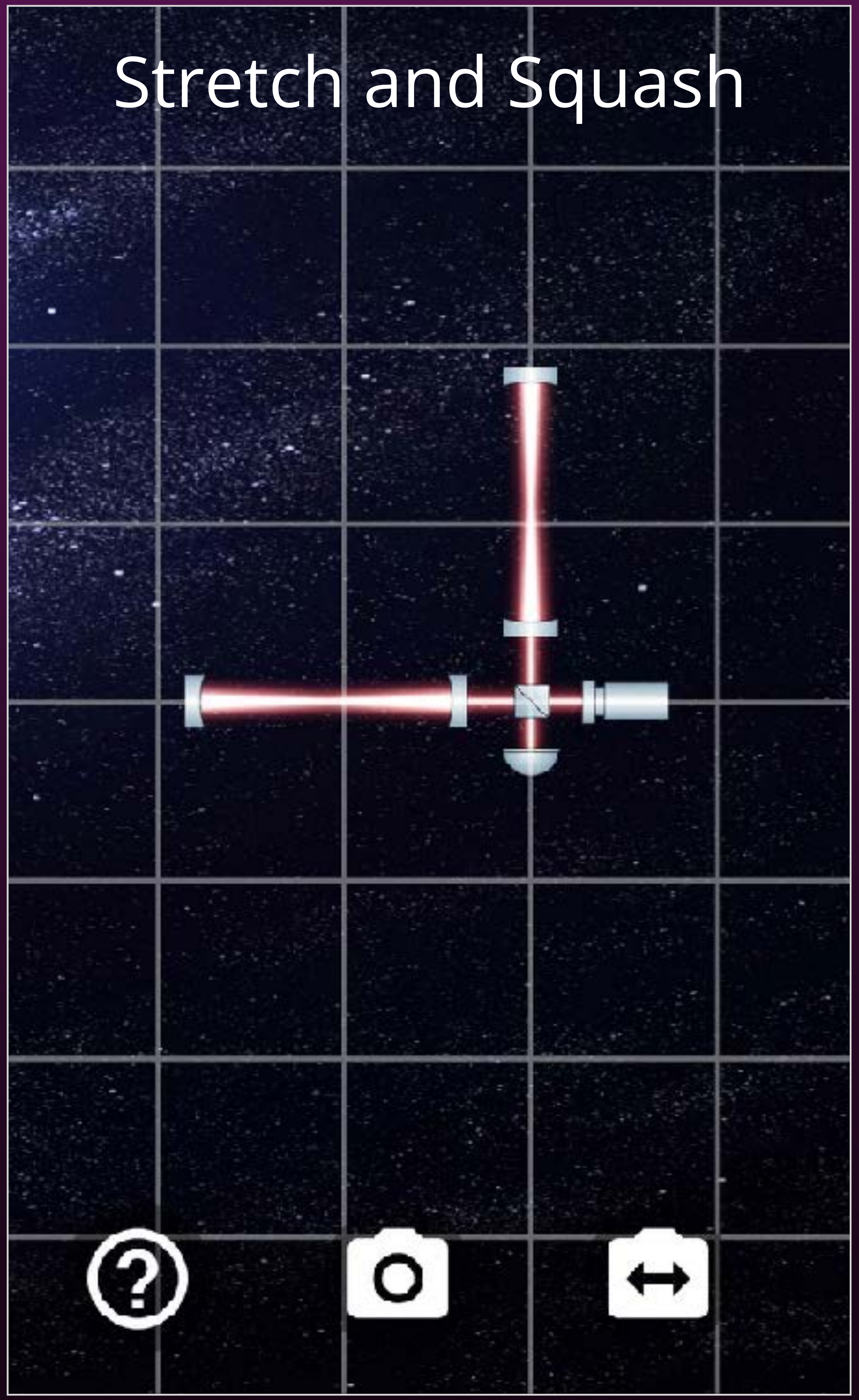
From EGO:

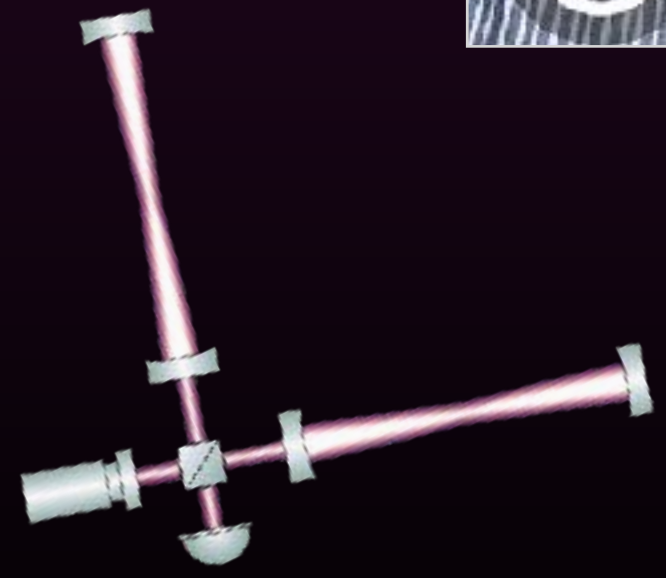
Paolo Ruggi (EGO Researcher)

Examples for 3G challenges

- the identification of a facility site with low seismic and acoustic noise, and other suitable environmental properties
- development of mitigation techniques for Newtonian noise
- development of low-noise, efficient cryogenic mirror suspension
- the production of large, high-quality test mass substrates, both silica and silicon or sapphire
- the polishing and coating of large test mass substrates to very low spatial roughness at larger spatial scales
- the development of suitable mirror coatings
- the development of multi-stage suspensions supporting test masses of several 100 kg
- the development lower cost vacuum technology for ultra-high vacuum in vacuum chambers and the beam tubes
- …

[adapted excerpts from ET and CE design studies]





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