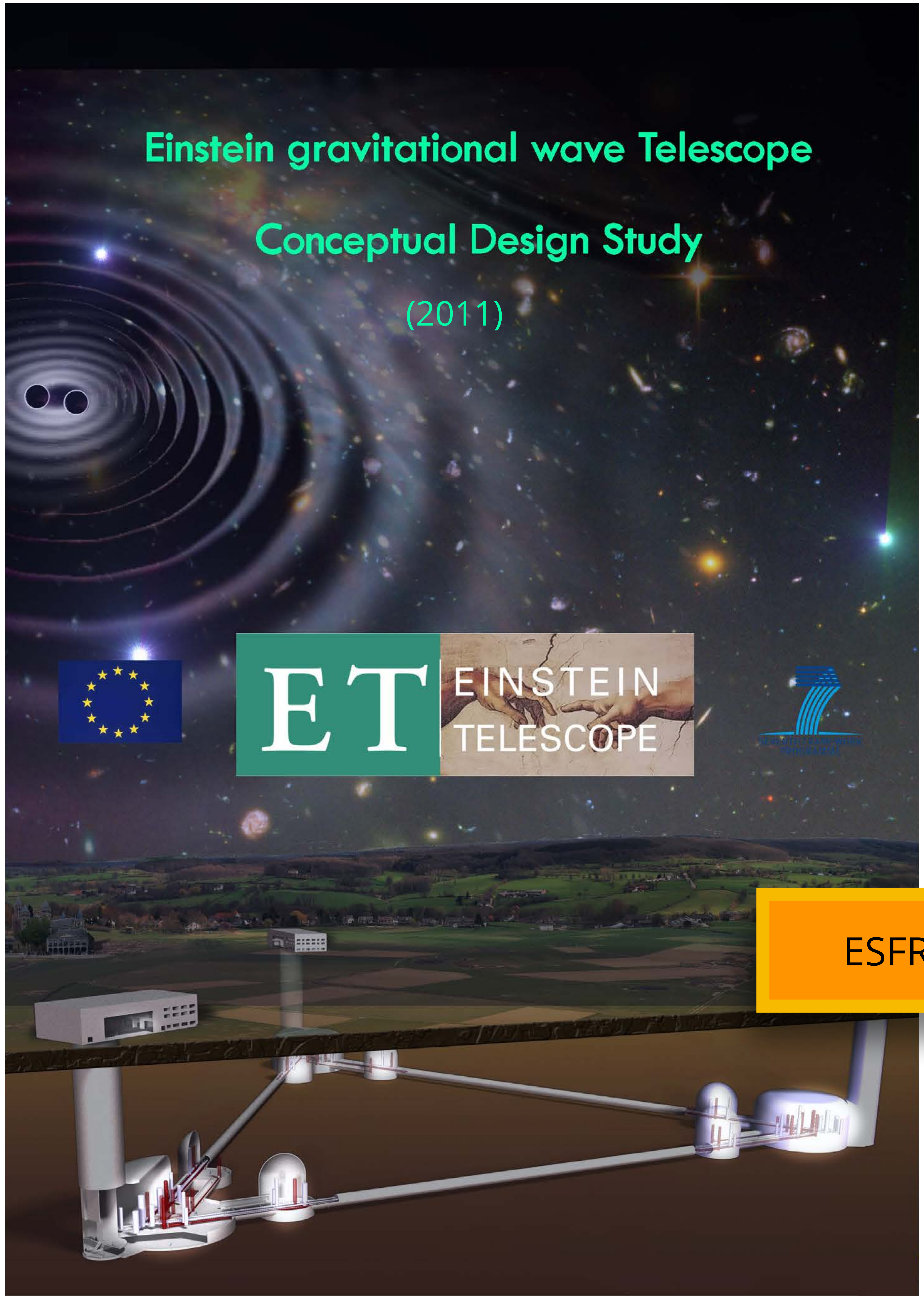
Einstein Telescope Instrument Science

Andreas Freise
for the Instrument Science Board
11th Einstein Telescope Symposium
30.11.2020
ET document number: ET-0073A-20

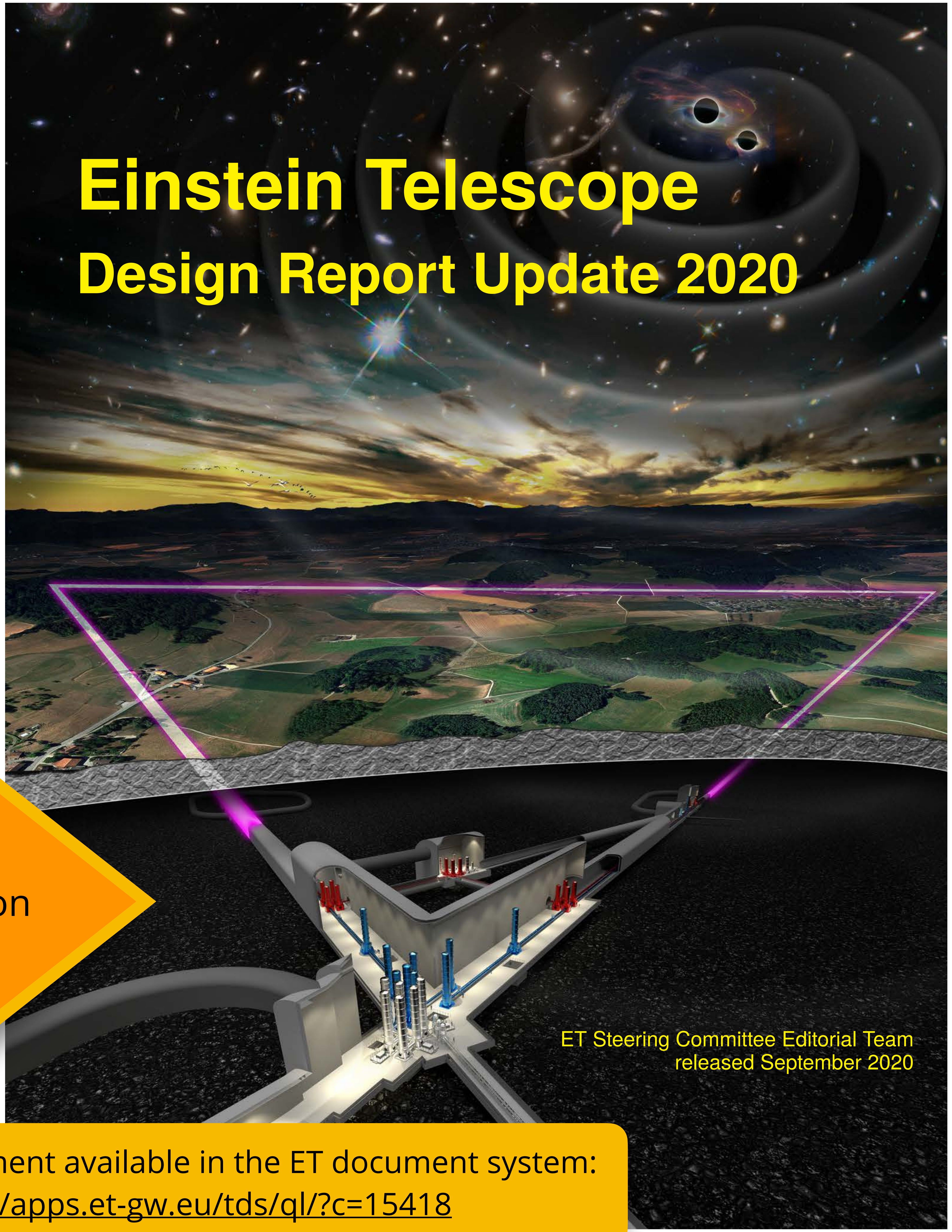
Overview

- **Today**: introduction to the design of the Einstein Telescope
- **Wednesday afternoon session, 14:30 to 18:30**:
  introduction of the Instrument Science Board and its activities
- Also Wednesday:
  presentation of ETpathfinder (17:00) and SarGrav (17:20)
- **Thursday session, 11:15 to 12:35 and 15:00 to 18:00**:
  Research and development in ET instrument science


Einstein Telescope
10 km
• laser interferometers
• super-polished optics
• suspension systems
• ultra-high vacuum
Large laboratories and three
10 km long tunnels, more
than 200m underground



ESFRI Application

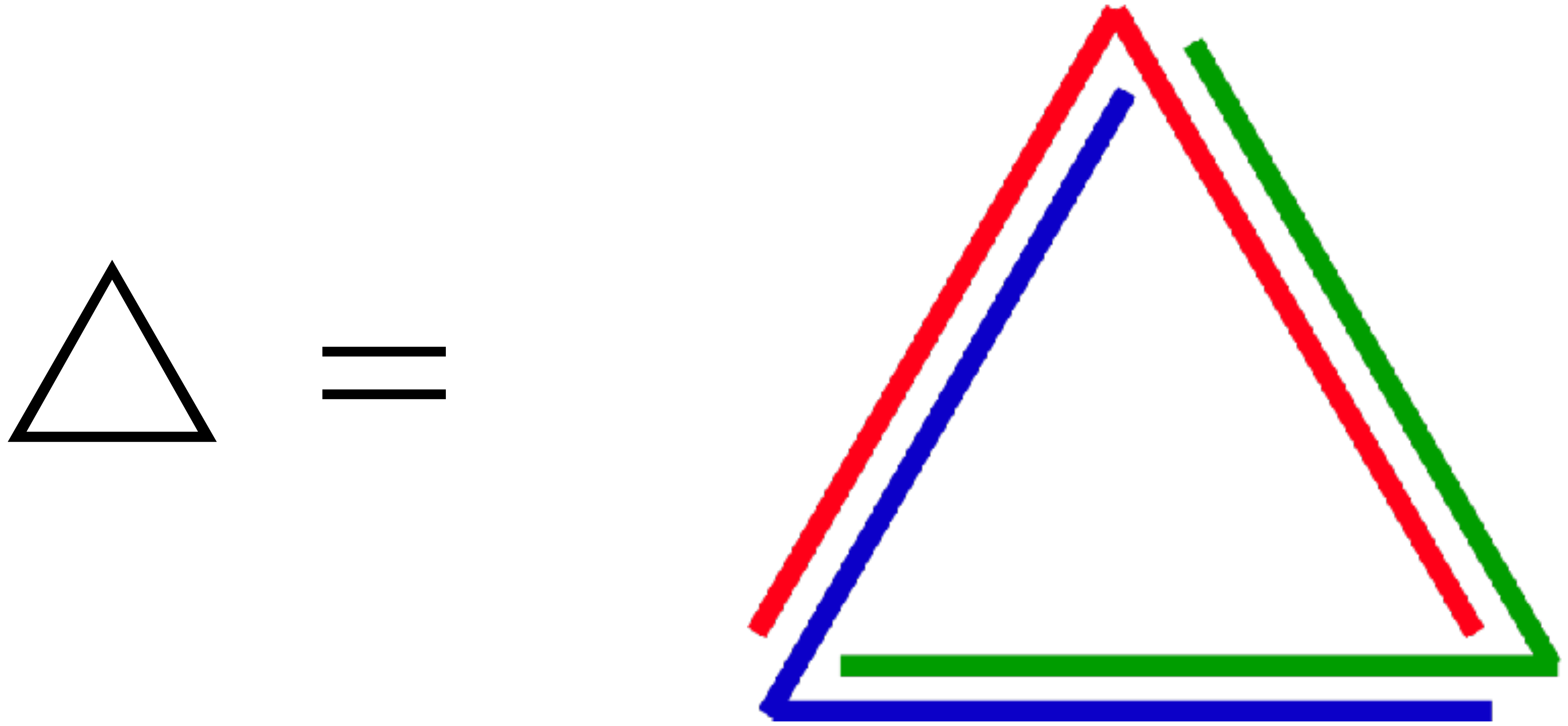


Document available in the ET document system:
https://apps.et-gw.eu/tds/ql/?c=15418

What has changed?

- The design update aims at providing **the same sensitivity curve** with only small design changes that incorporate the state-of-the-art of instrument science in the field.
- The new design document contains **one baseline design**, instead of several alternative design options from the conceptual design.
- Design changes include:
  - Underground infrastructure uses several small caverns instead of single very large caverns at each corner.
  - Filter cavities: removed from main tunnel, located in auxiliary tunnels, cavities are now shorter.
  - Use of beam expander telescopes between beam splitter and input test mass. Noise model now correctly includes finite signal recycling cavity length.
  - ET HF does not use laser beams in a higher-order Gaussian mode, but the fundamental Gaussian mode. The thermal noise target can be achieved with A+ like coatings.

Triangle shape = 3 detectors

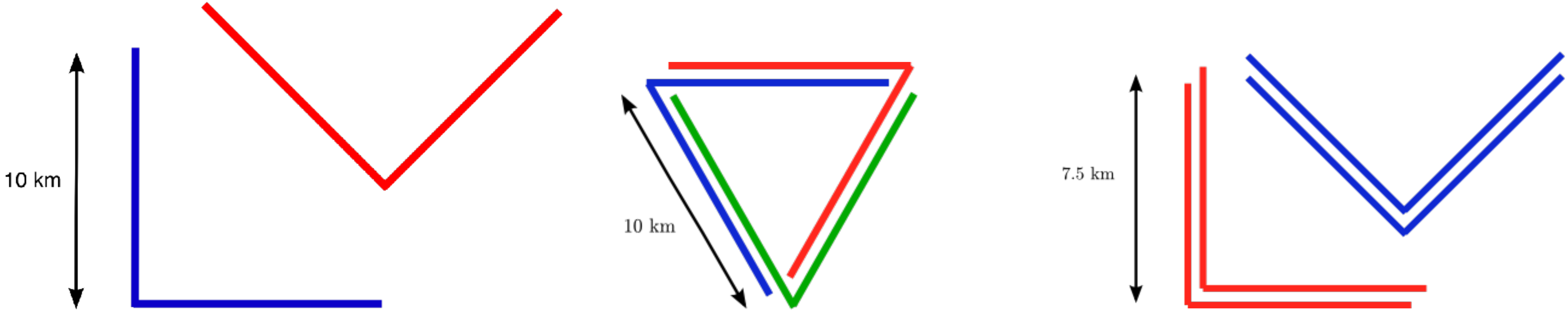


The Einstein Telescope design has **three detectors** hosted in a single triangular site, providing a near-optimal configuration for a single-site observatory in a cost-efficient and prominent infrastructure.

Triangle = multiple functions

A triangle provides (or is equivalent to):

- interferometer orientations for both polarisation
- co-aligned interferometers (null-streams)
- two redundant interferometers (uptime)
- single infrastructure (cost efficient and prominent)



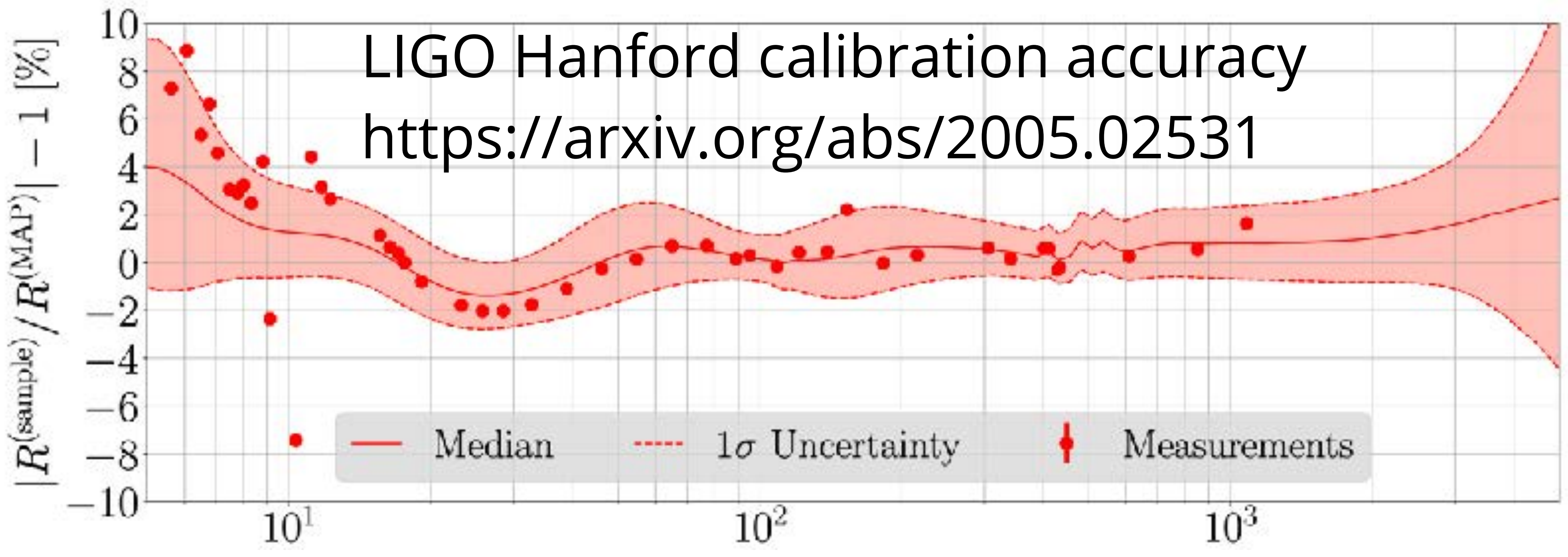
Polarisation ↔ ↔ Null stream

Self-calibration of networks of gravitational wave detectors

- 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

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.

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

Low-frequency performance

- ET should be an observatory with a very **good sensitivity in a wide band**, allowing for surprises!
- In addition we want to **push the low-frequency cut-off to a few Hz.**
- The effect looks small in the sensitivity plot, but it makes a significant difference for accumulating signals, and it requires significant design changes.

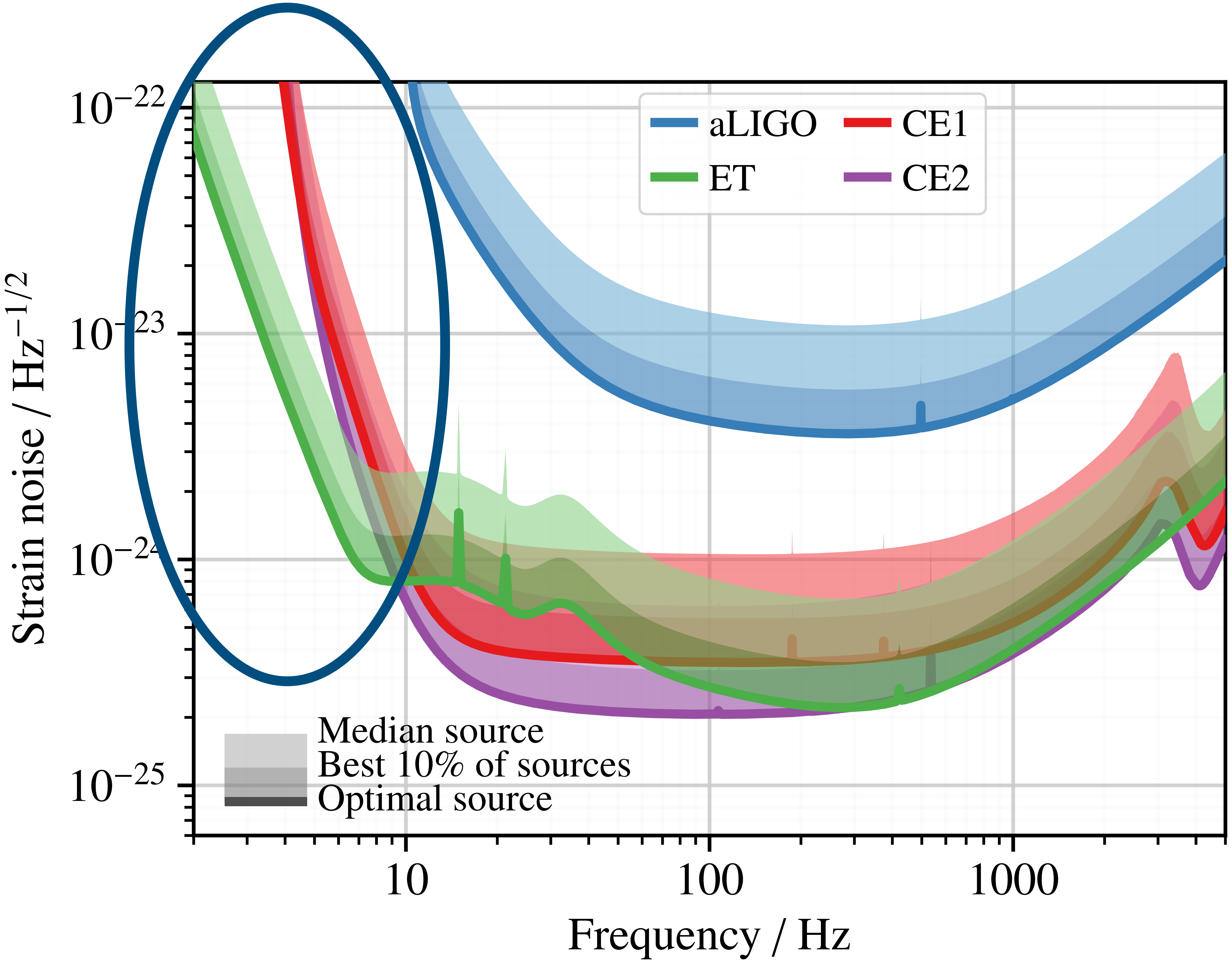
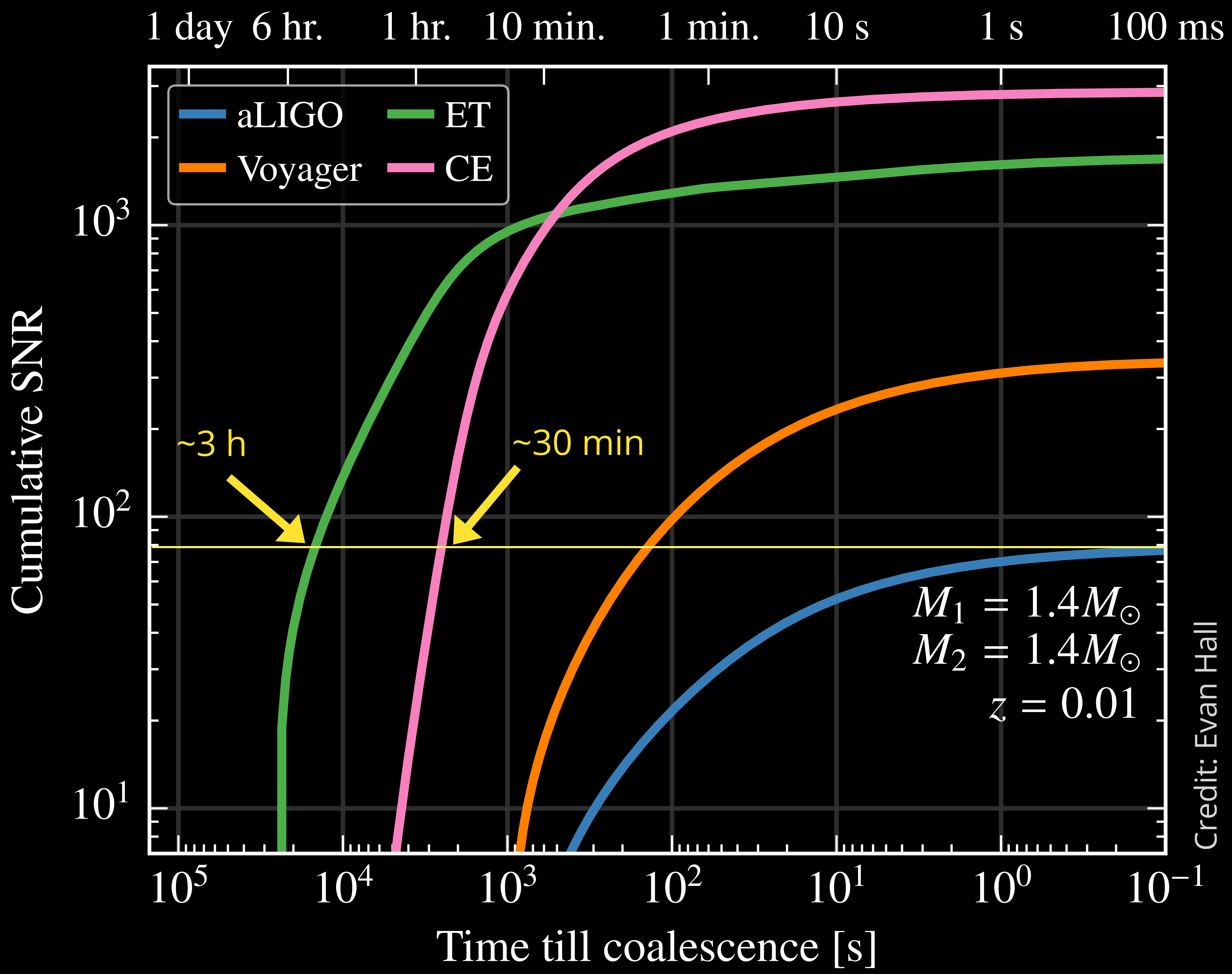
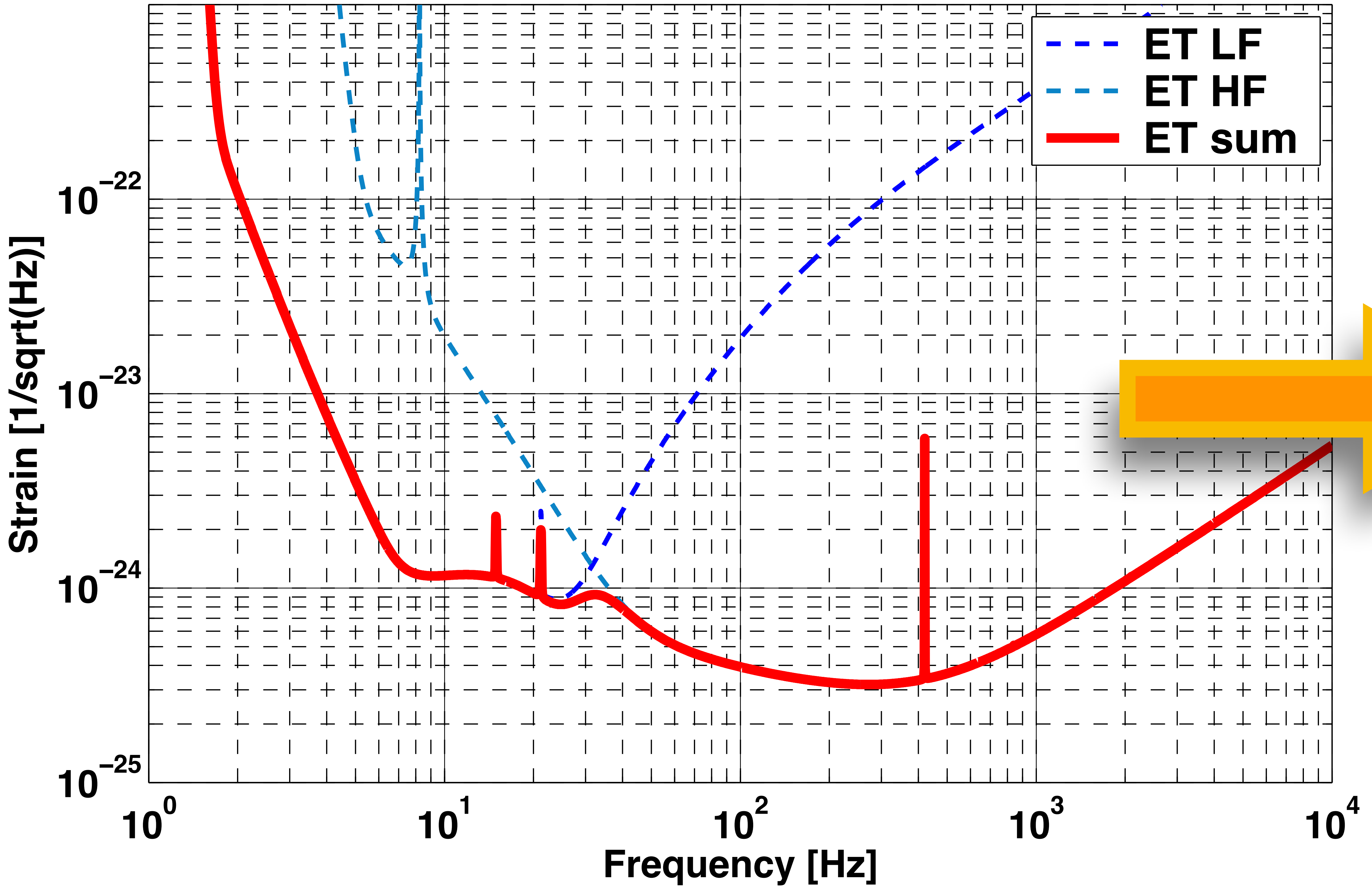
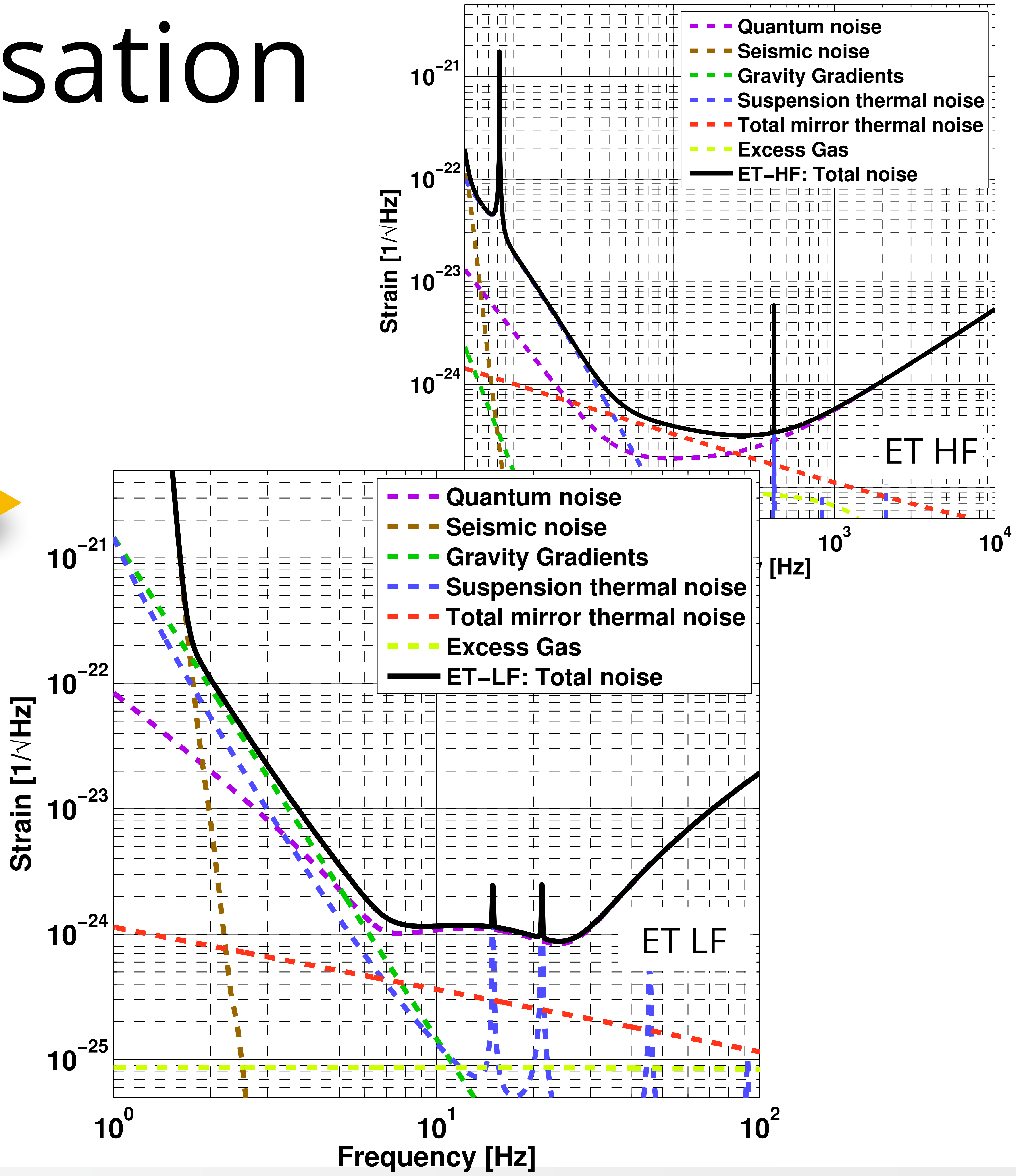


Image: Evan Hall


1 day
6 hr.
1 hr.
10 min.
1 min.
10 s
1 s
100 ms
aLIGO
ET
Voyager
CE
Cumulative SNR
10^3
10^2
10^1
~3 h
~30 min
$M_1 = 1.4 M_\odot$
$M_2 = 1.4 M_\odot$
$z = 0.01$
Credit: Evan Hall
10^5
10^4
10^3
10^2
10^1
10^0
10^{-1}
Time till coalescence [s]

Low-frequency optimisation

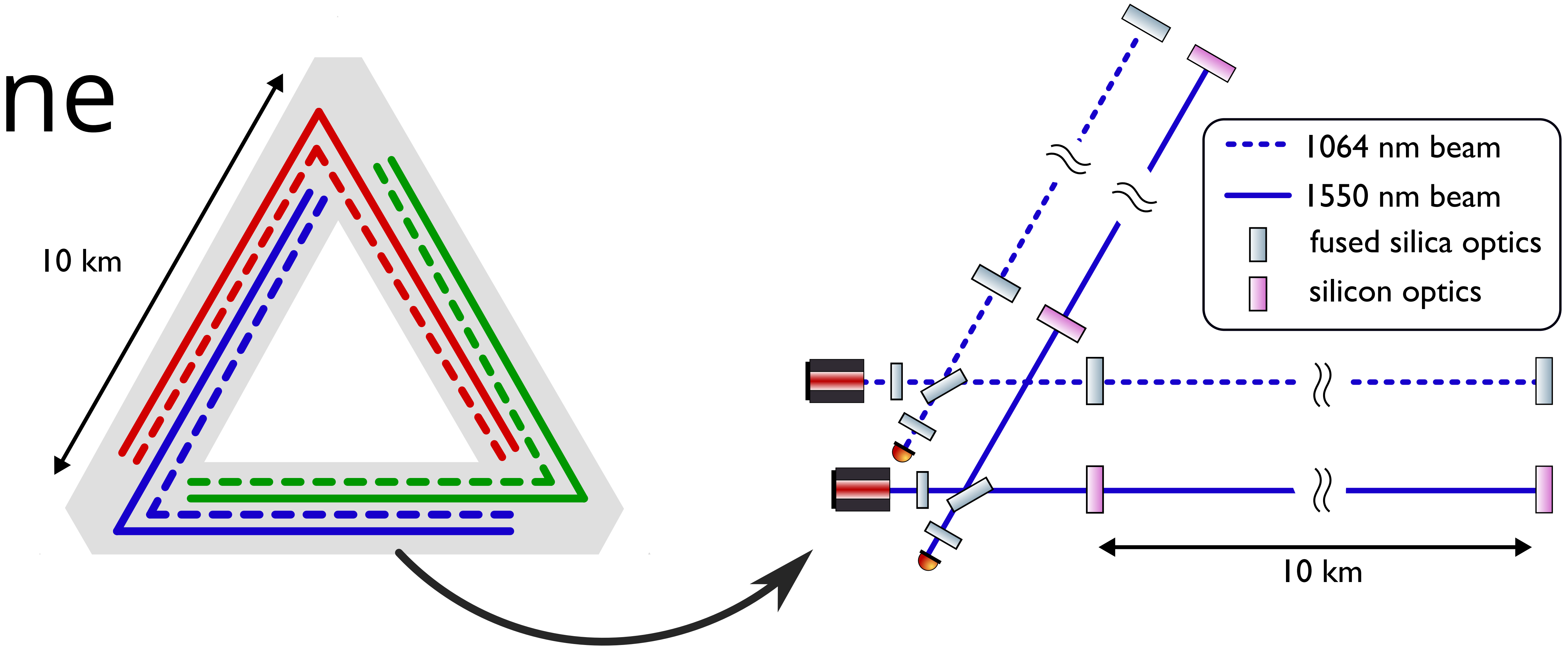


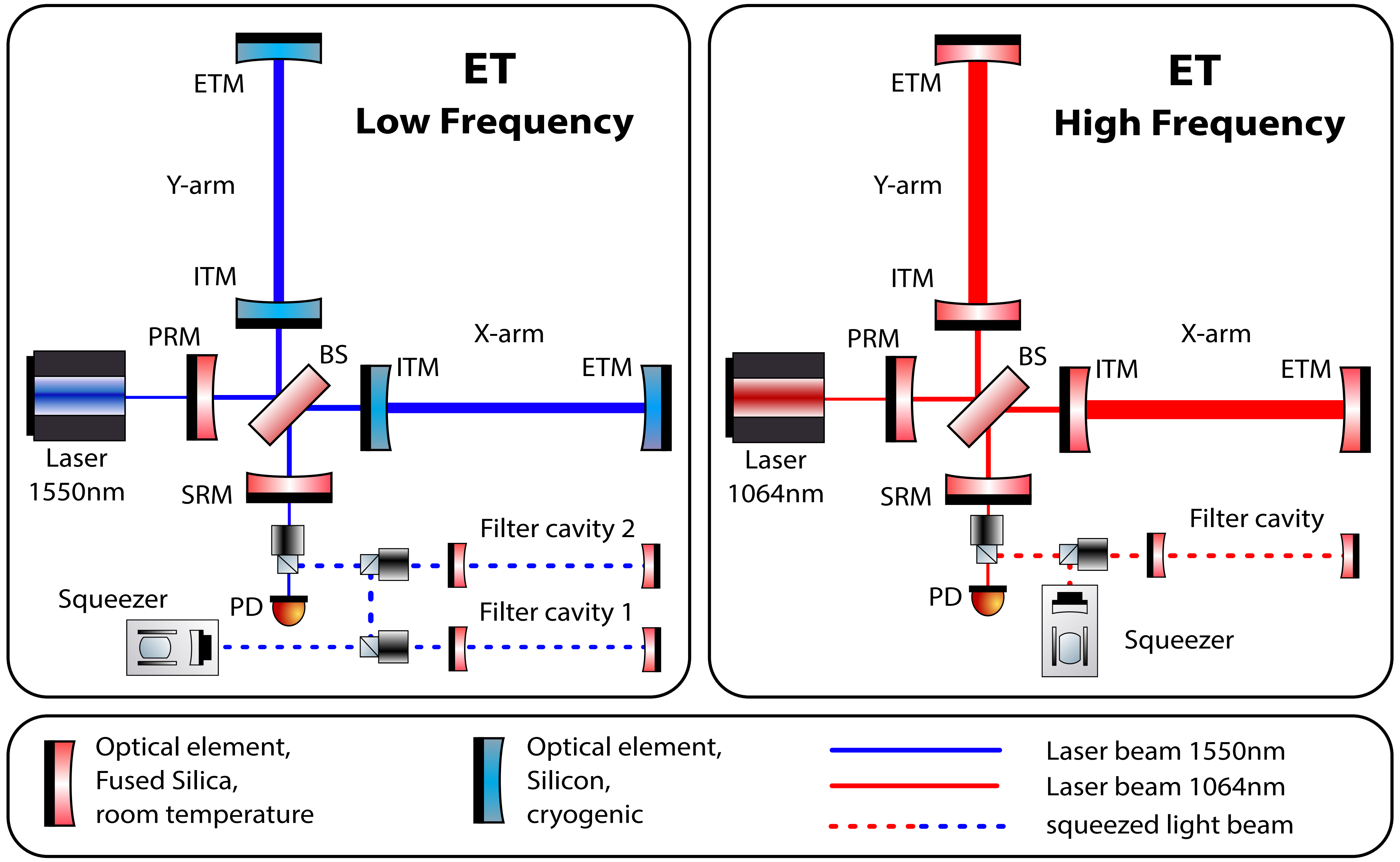


- Split each detector into two interferometers:
- **ET HF:** high power operation, extend current technology
- **ET LF:** optimise for low frequency and **new technology**

ET LF and ET HF, the xylophone

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)	$5 \cdot 10^{-10}\, m/f^2$	$5 \cdot 10^{-10}\, m/f^2$
Gravity gradient subtraction	none	factor of a few



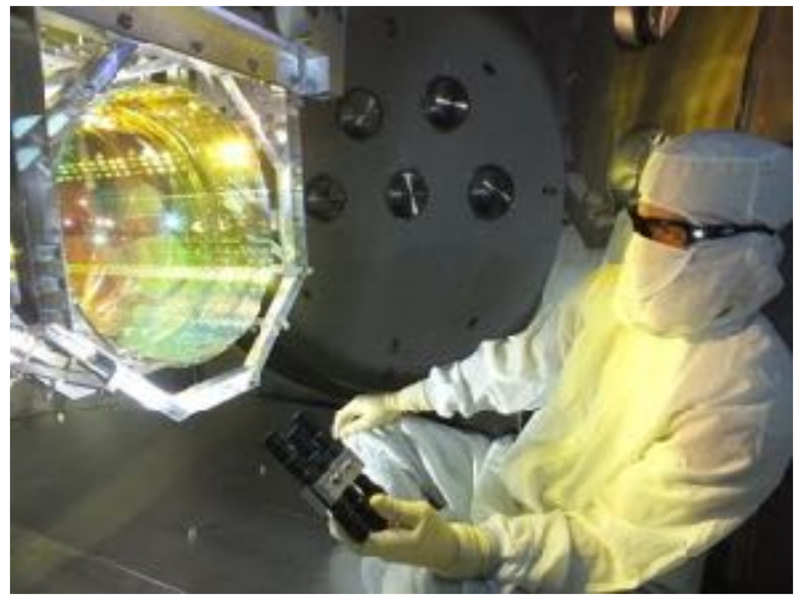
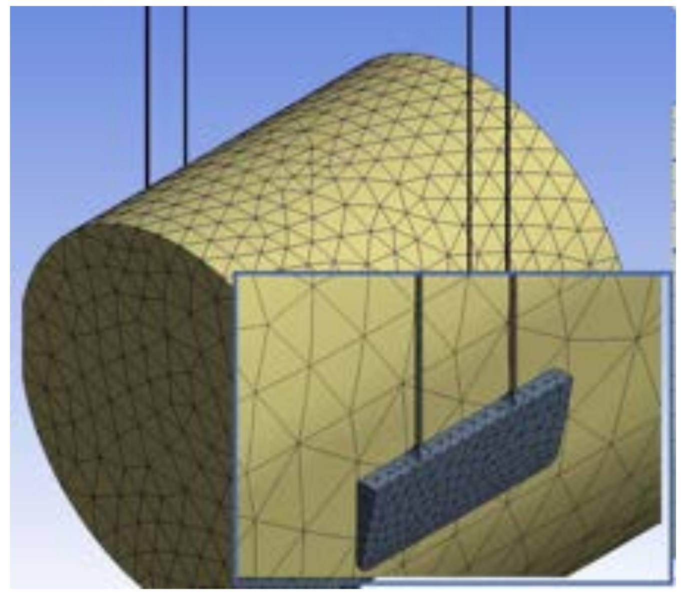


R&D challenge: optics

- 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._

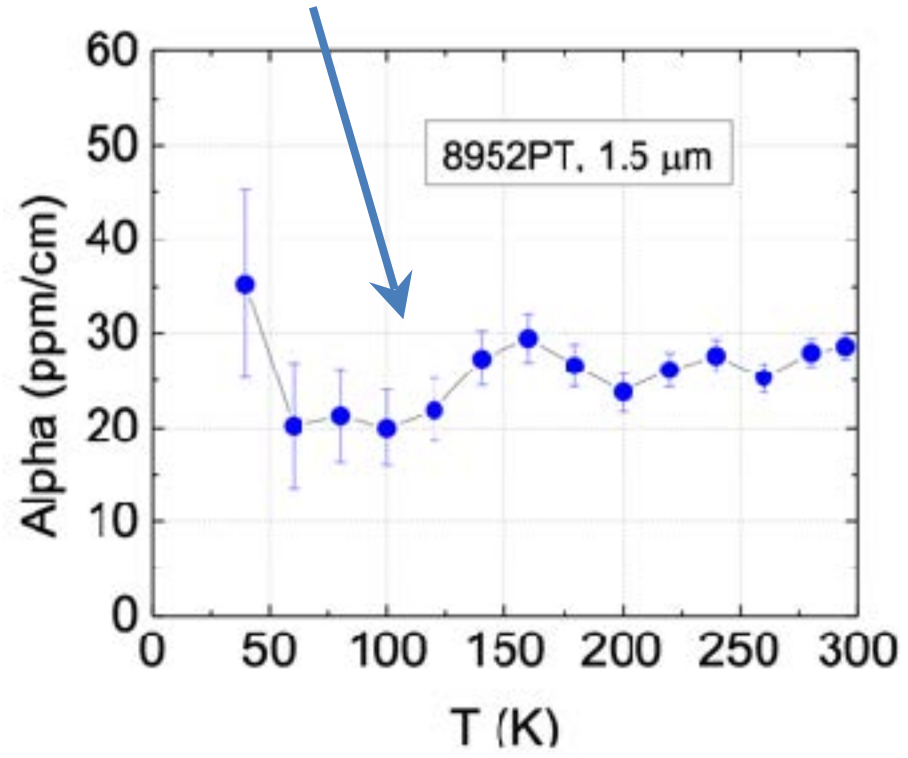
Absorption of “best 45 cm” MCZ Si: 1.5um

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.


PHYSICAL REVIEW LETTERS

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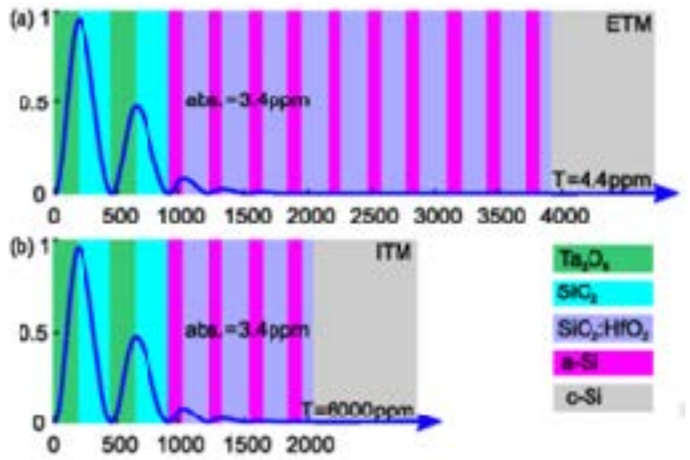
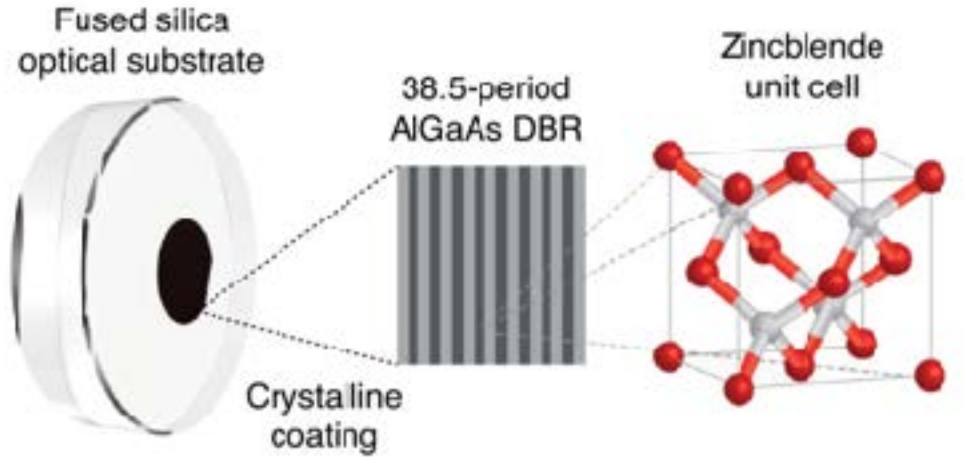
Mirror Coating Solution for the Cryogenic Einstein Telescope

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

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

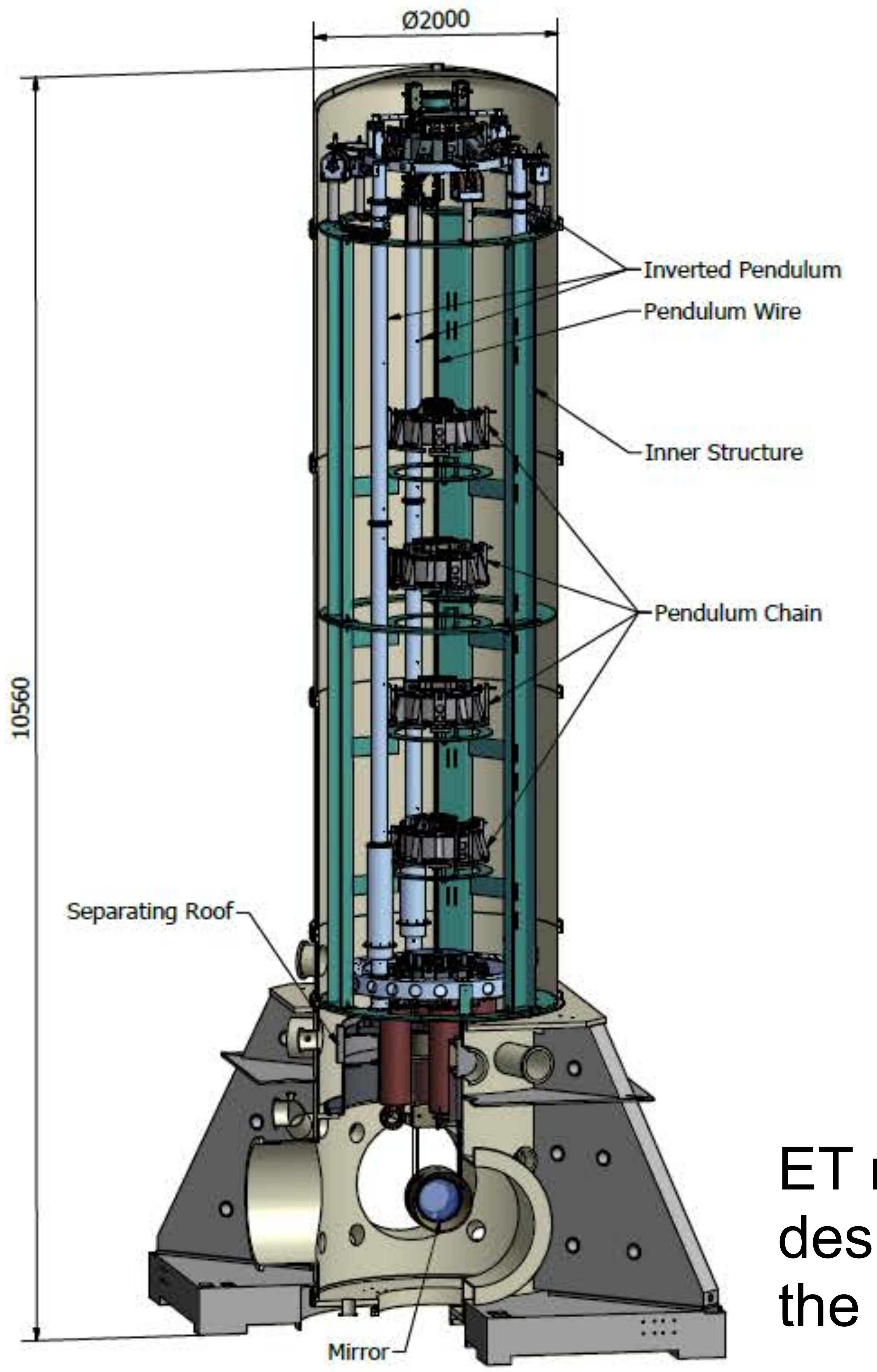


ET-LF coatings: Craig *et al.*, Phys. Rev. Lett. **122**, 231102 (2019)

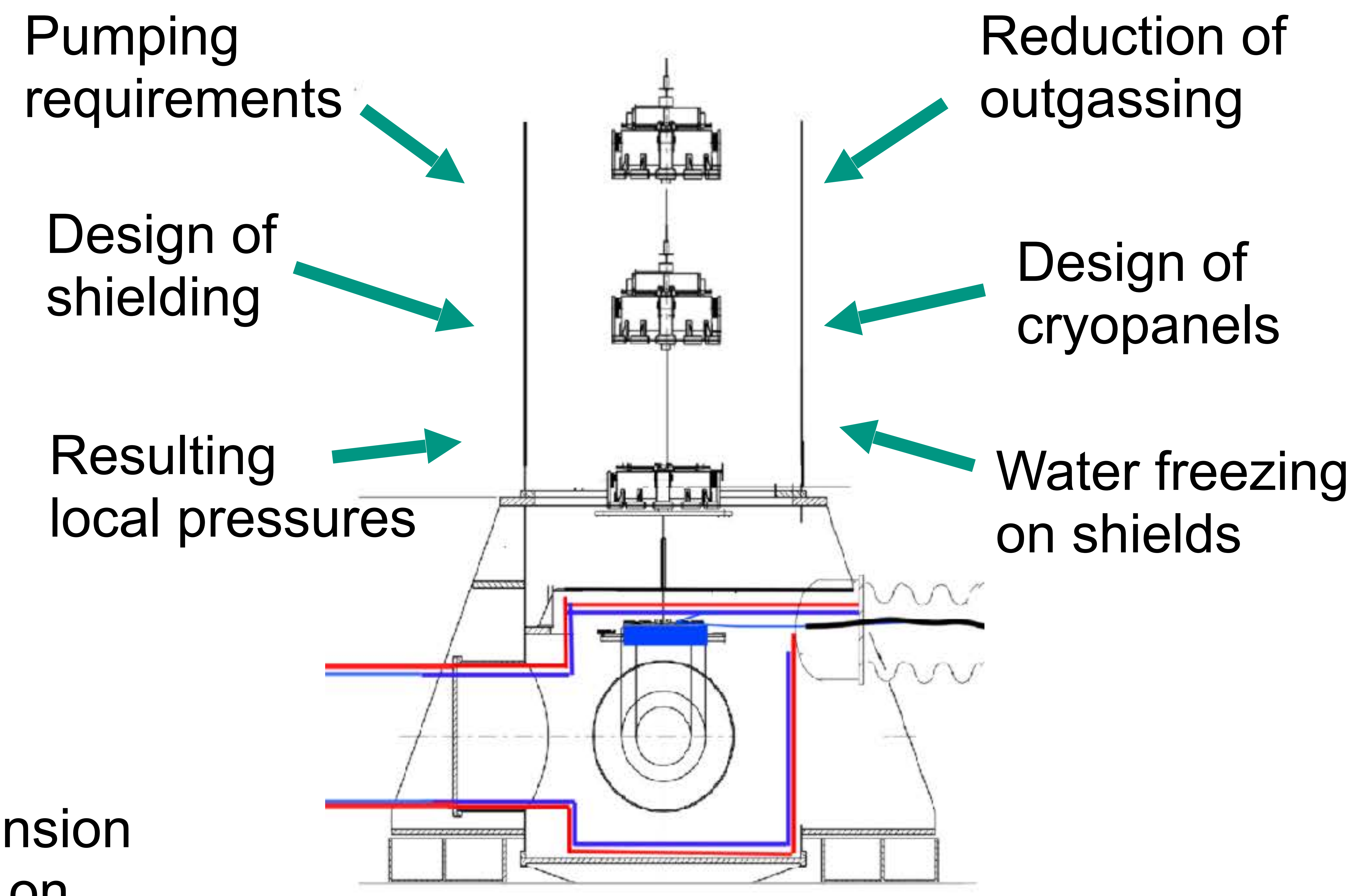


AlGaAs crystalline coatings might satisfy ET-HF but currently limited to ~200mm dia.

Cryogenic suspensions



ET mirror suspension design is based on the Virgo 'towers'



ET cryogenic test mass

New focus: active noise mitigation

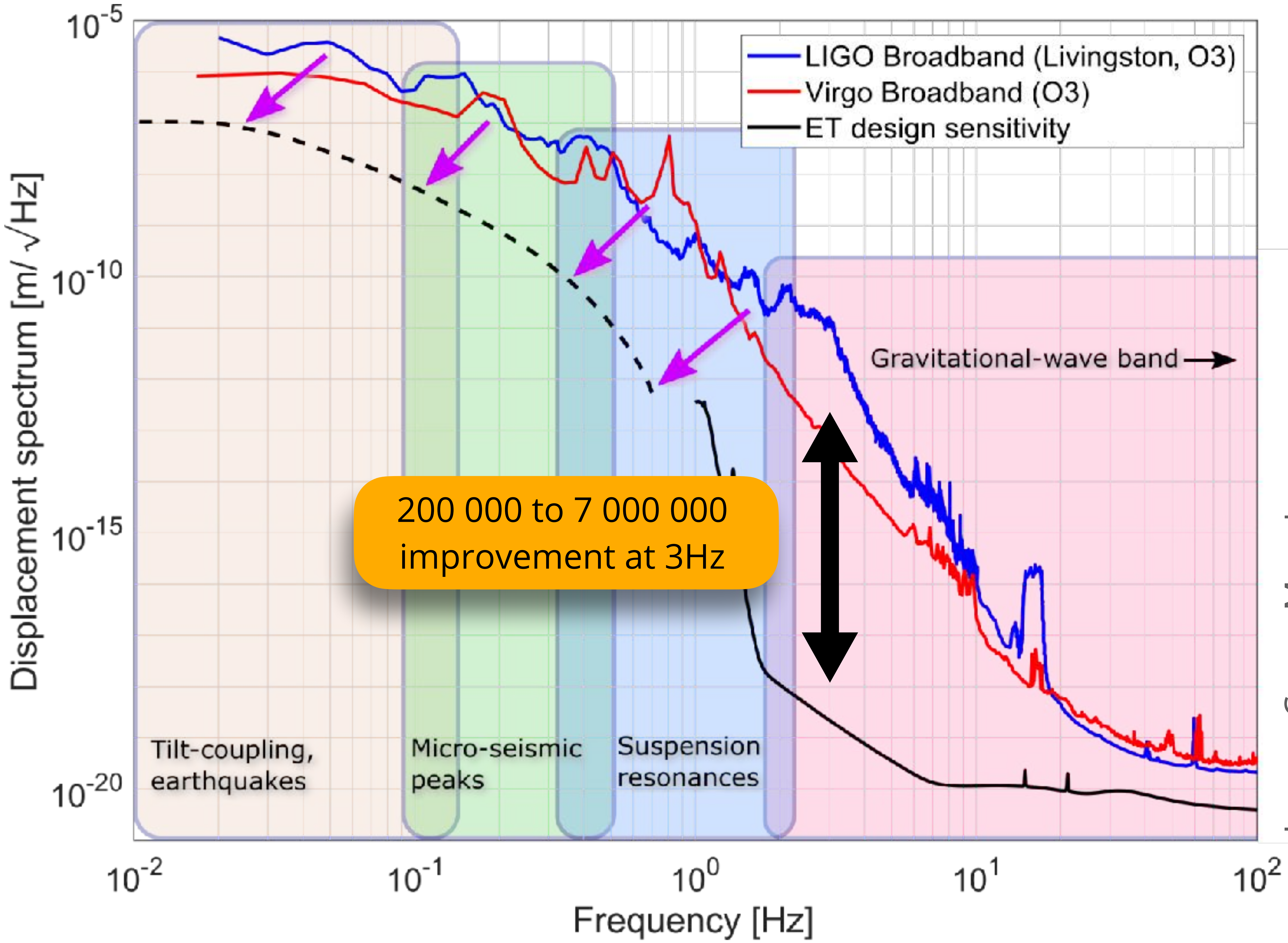
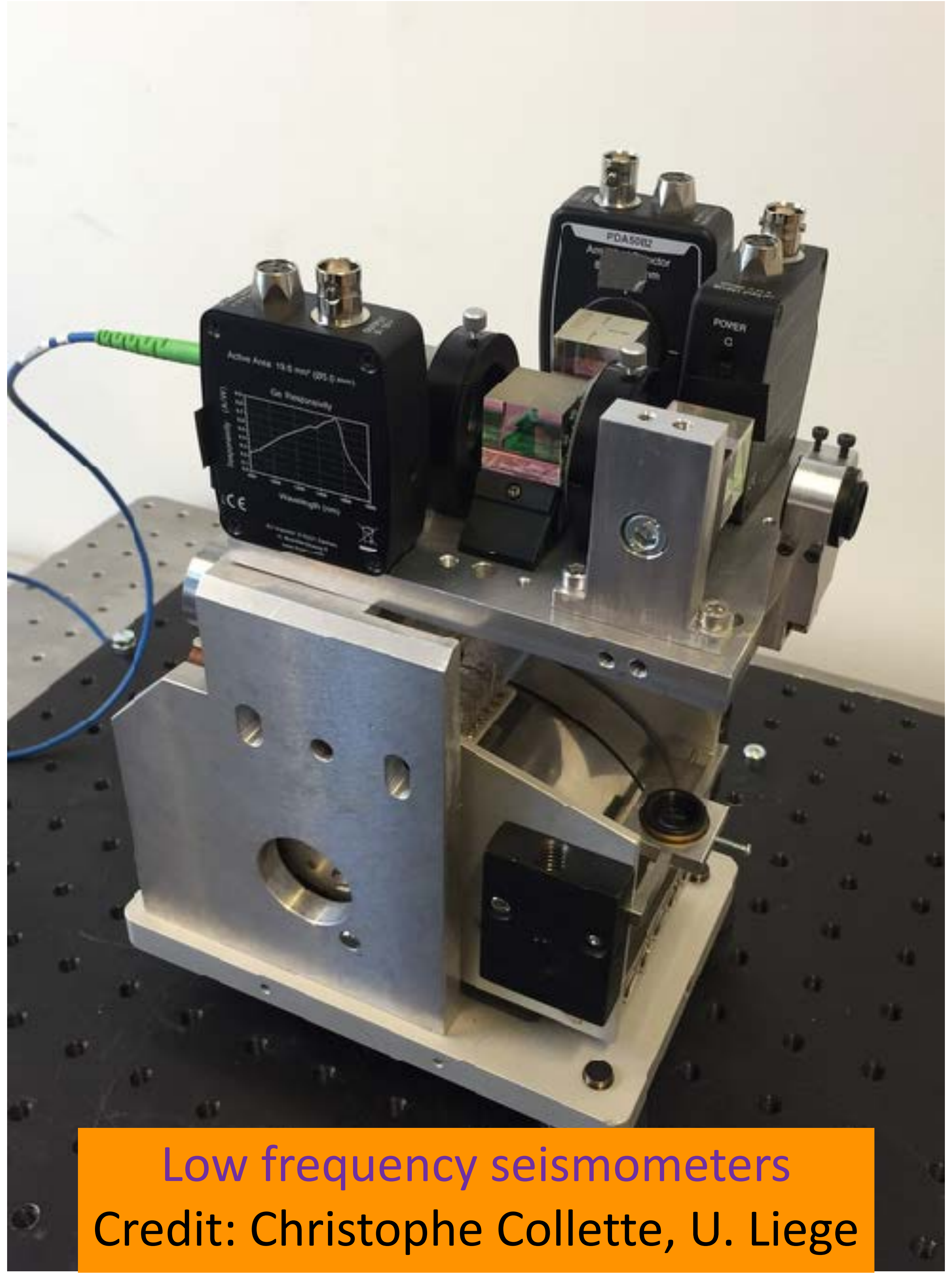


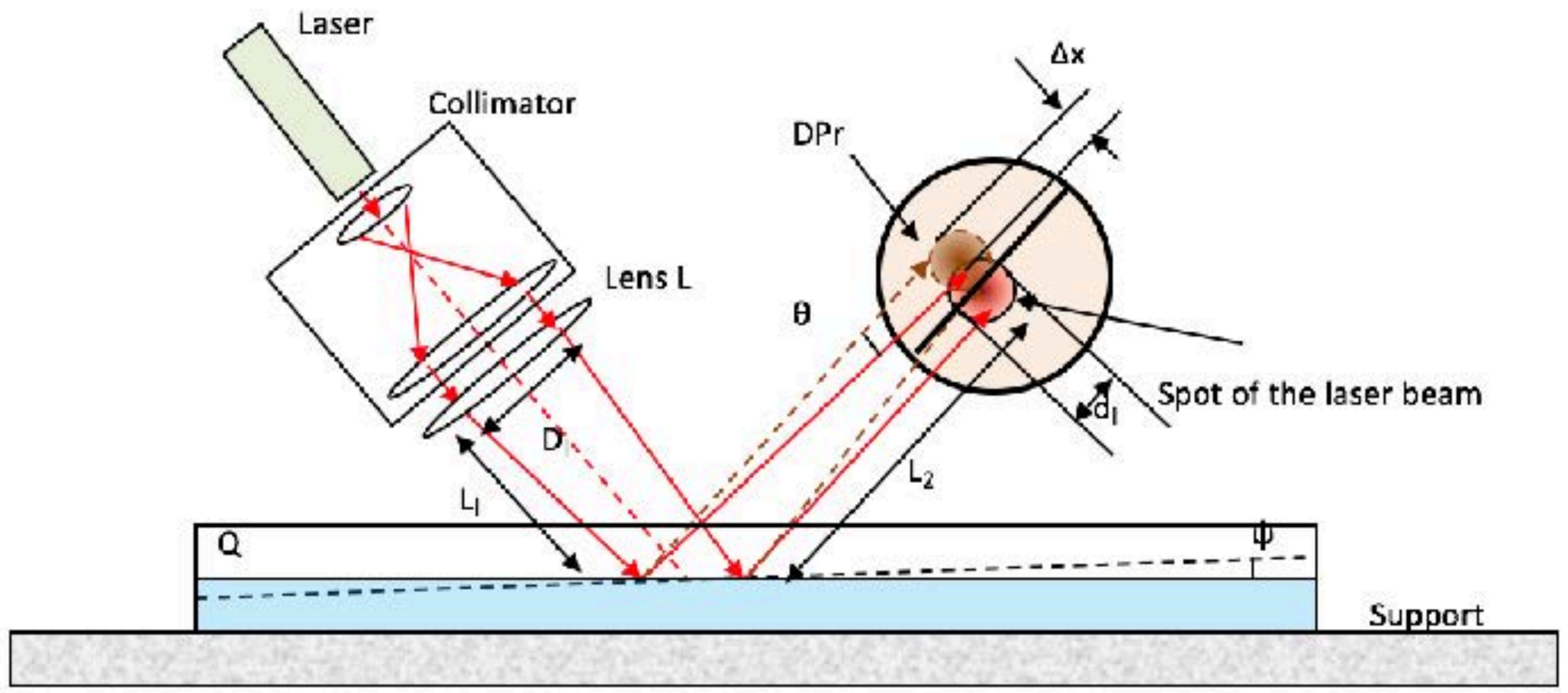
Image: Conor Mow-Lowry

R&D example: advanced seismic sensors

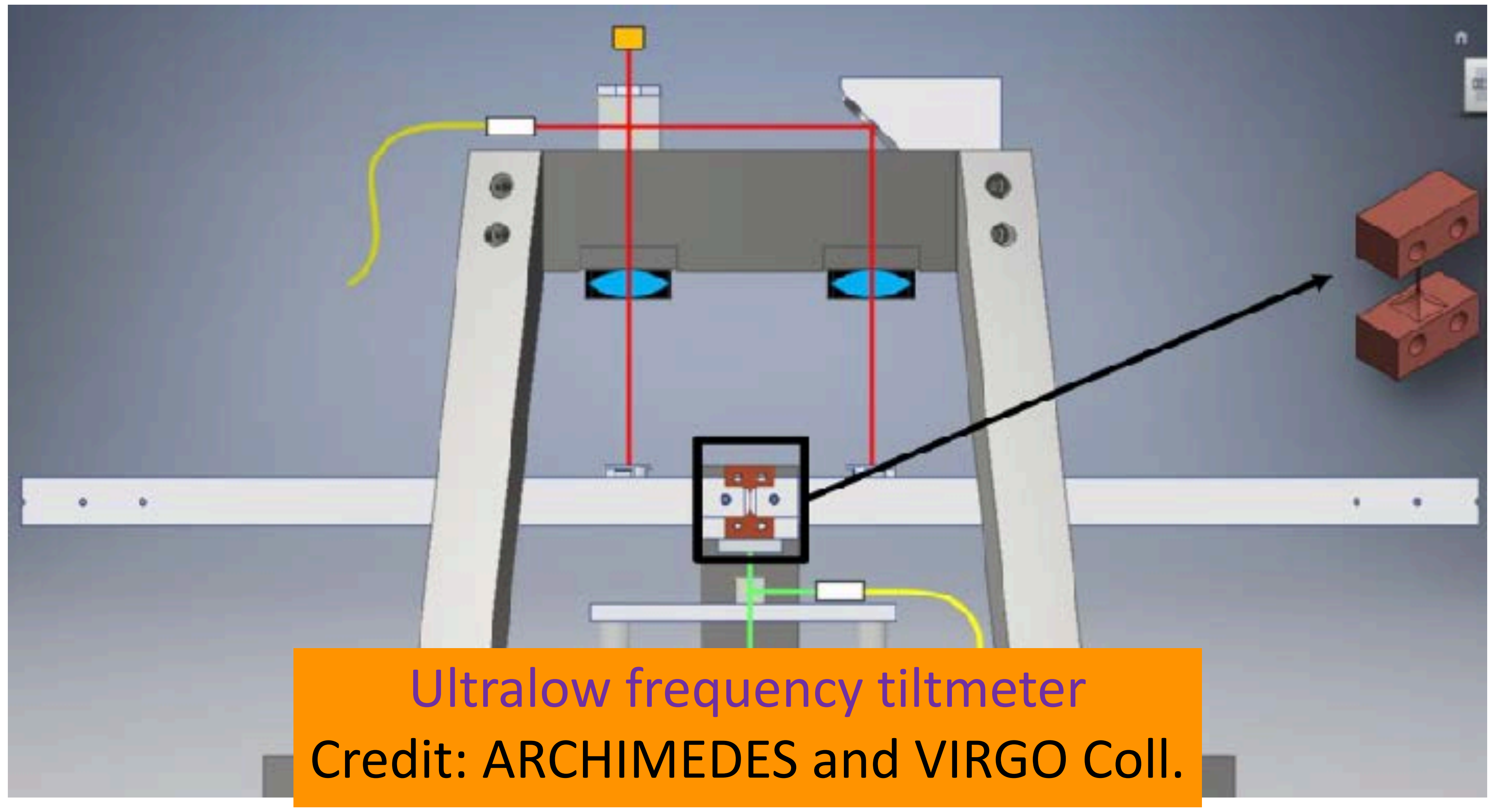
6-D interferometric readout inertial sensor
Credit: Conor Mow-Lowry, VU Amsterdam



Low frequency seismometers
Credit: Christophe Collette, U. Liege



Laser inclinometer, Credit: B. Di Girolamo, CERN

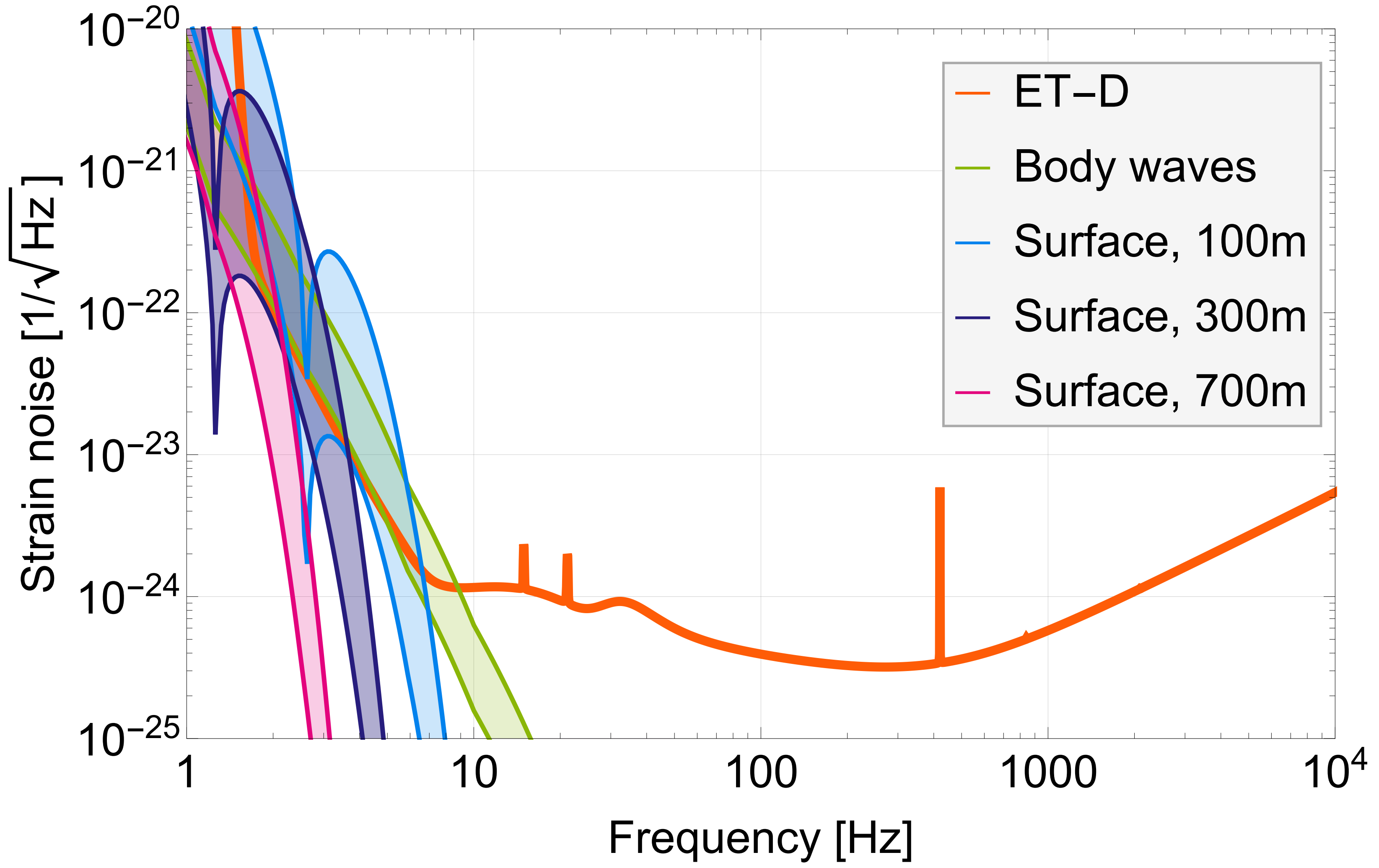


Ultralow frequency tiltmeter
Credit: ARCHIMEDES and VIRGO Coll.

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

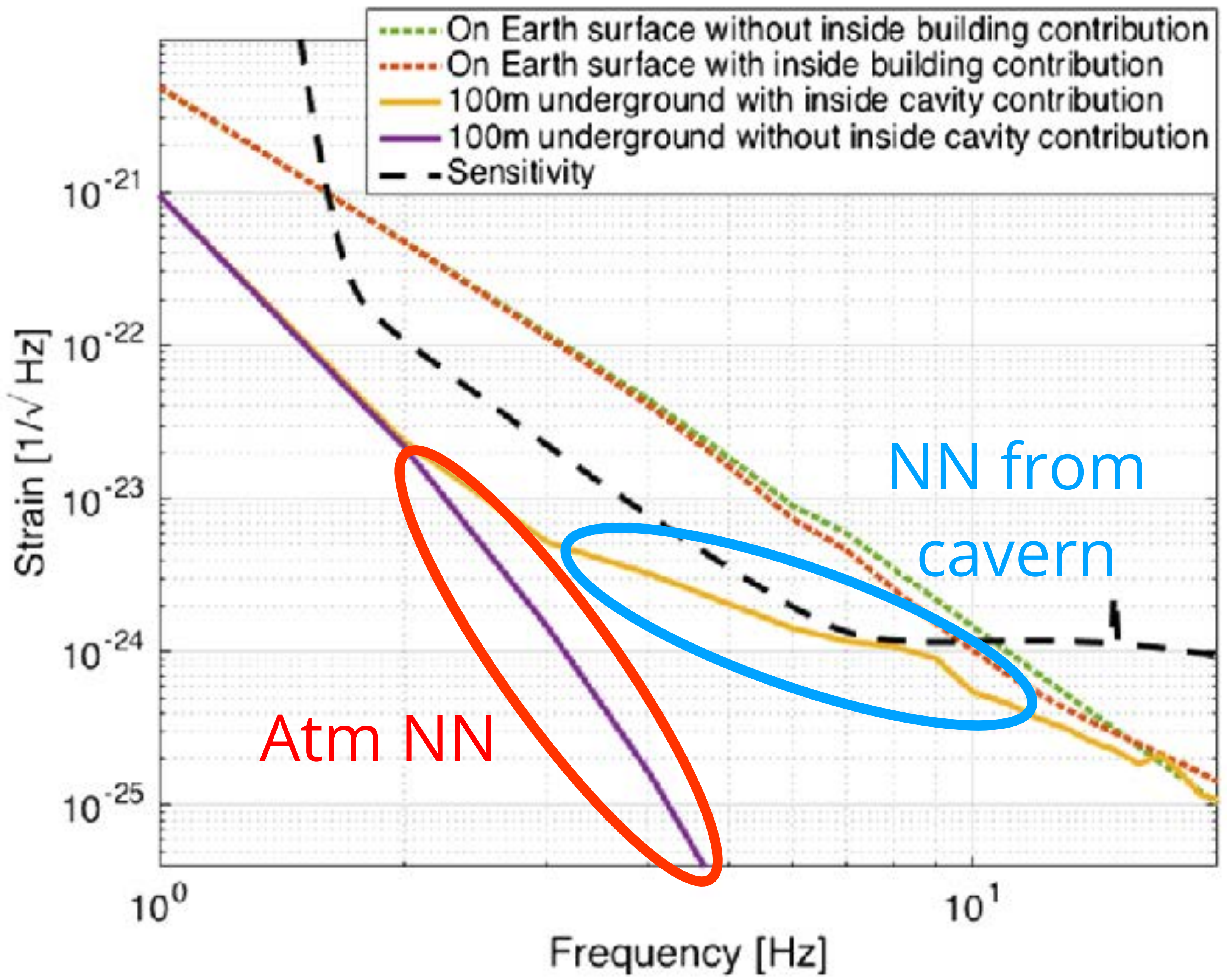
Underground and low noise

Seismic Newtonian noise (NN)



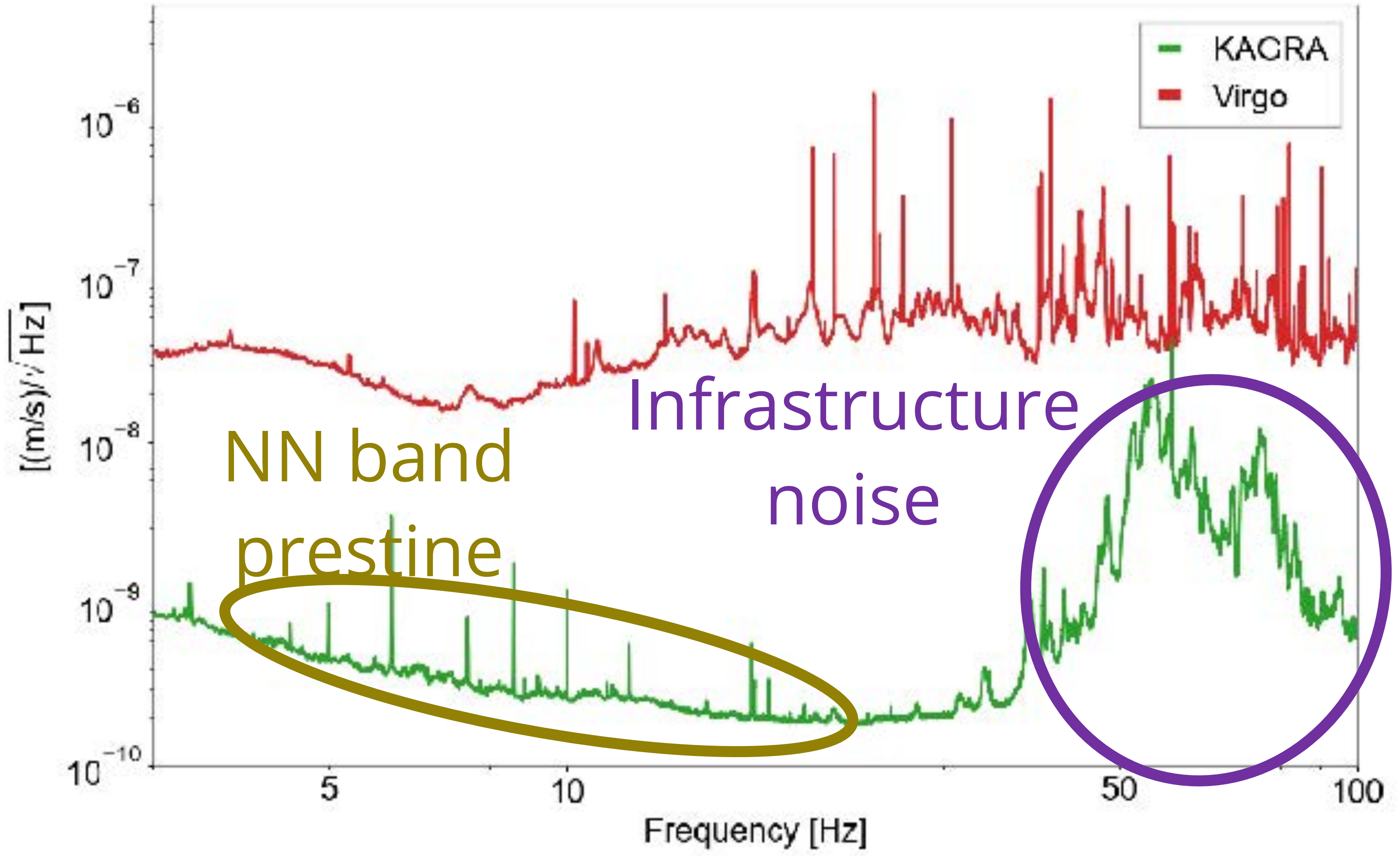
ET is planned >200m underground. Further mitigation of NN from seismic surface and underground fields might be achieved with noise cancellation using arrays of seismometers.

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.

Noise budgets, into the details

- Develop and maintain an up-to-date and openly available fundamental noise model
- Implementation in PyGWINC
- Required for predicting ET target sensitivity (for instance for developing science case or future Mock-Data-Challenges).
- Allows to optimise detector parameters
- Potential future developments: include temperature dependency of parameters, material constants, etc.
- Activity needs input from all divisions and many of the workpackages

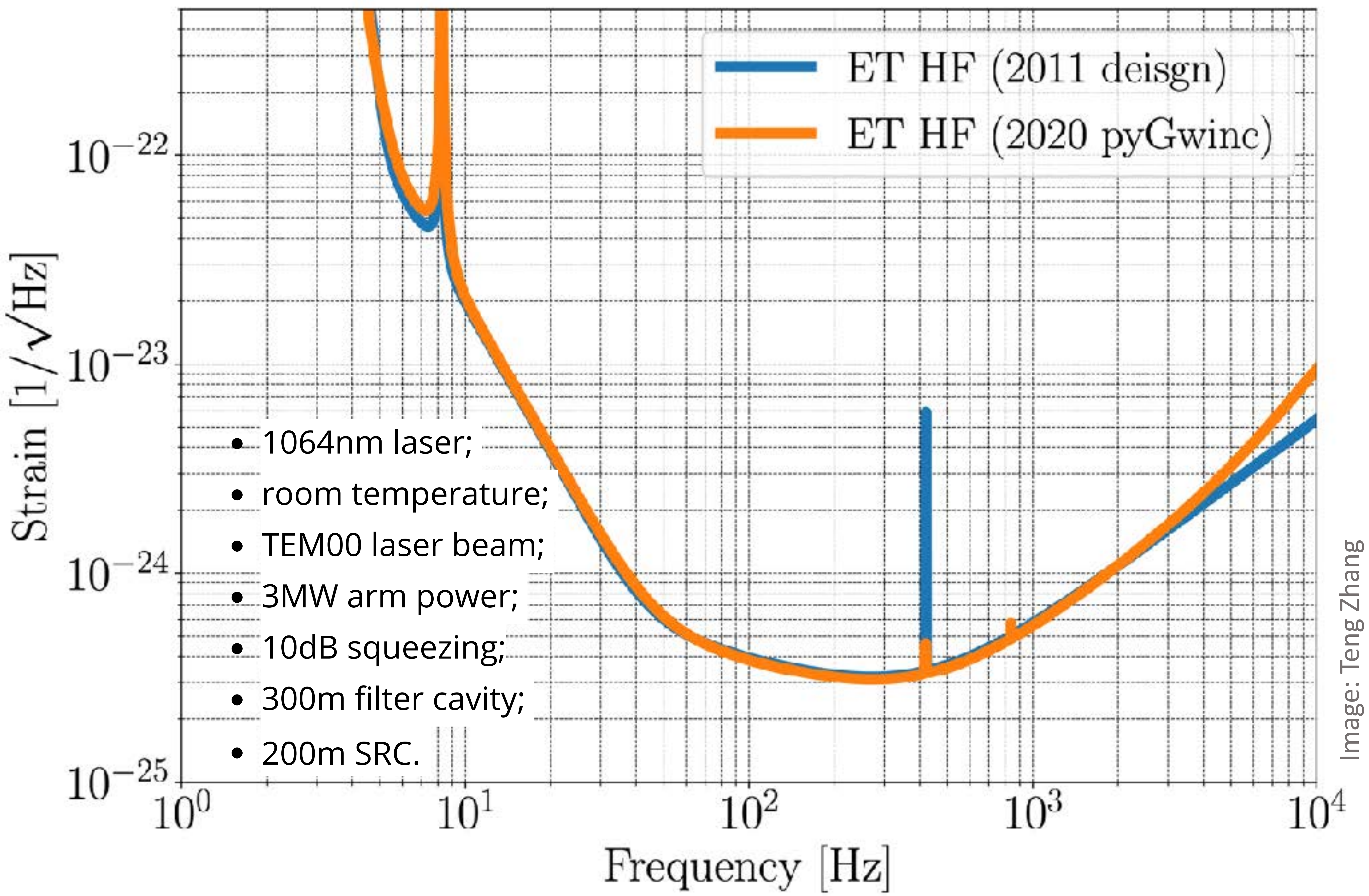


Image: Teng Zhang

https://apps.et-gw.eu/tds/ql/?c=15701
https://arxiv.org/abs/2003.07468

Schematic layout of one corner of the triangle

Feasibility study of beam-expanding telescopes in the interferometer arms for the Einstein Telescope https://arxiv.org/abs/2011.02983

Infrastructure design in 3D

Three identical corner structures

Cavern layout in one corner

ET-HF vacuum for main interferometer optics

ET-LF vacuum for main interferometer optics


ET-LF main
beam splitter
ET-HF beam
expander telescope
ET-LF beam
expander telescope
ET-LF filter cavities


Tunnel to ET-HF
beam splitter
ET-HF beam expander
telescope mirror
ET-HF input test mass
ET-LF beam passing
underneath the ET-HF optics


ET-LF cryoshield
ET-LF input
test mass
Cooling system
not shown!
ET-LF beam expander
telescope mirror

ET LF: central beam splitter and input output optics

Possible access to the optics from clean rooms at lower level

ET HF: central beam splitter and input output optics

Summary

- The Einstein Telescope will be a high-tech laboratory, driving new technologies
- We plan a long-term infrastructure with a prominent and unique design
- The instrument design is based on extending the current state-of-the-art plus a number of specific new technologies
- Many research and development challenges toward realising the detectors
- **More details on Wednesday 14:30 to 18:30 and Thursday 11:15 to 12:35 and 15:00 to 18:00.**

extra slides