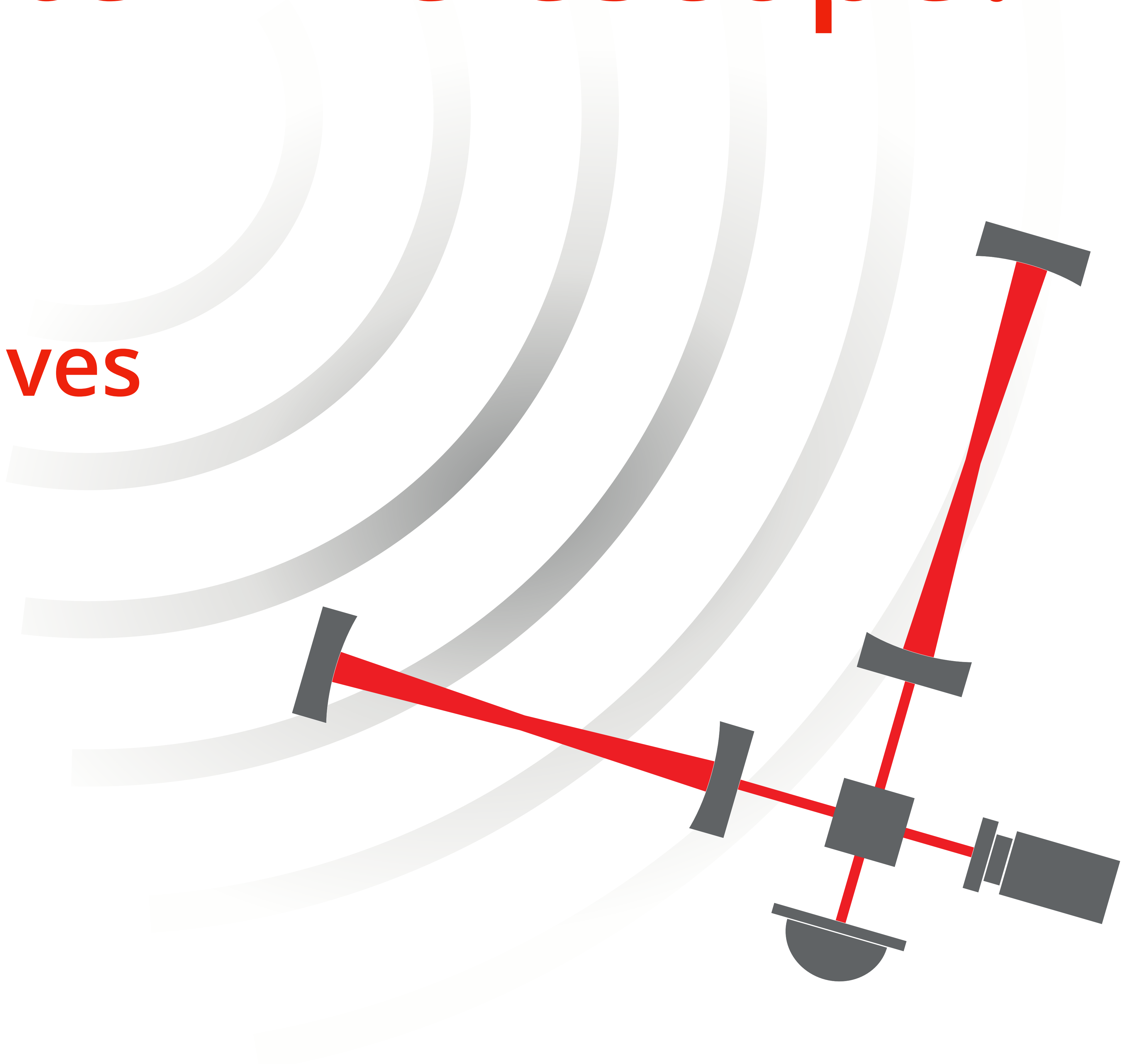
How to build the Einstein Telescope

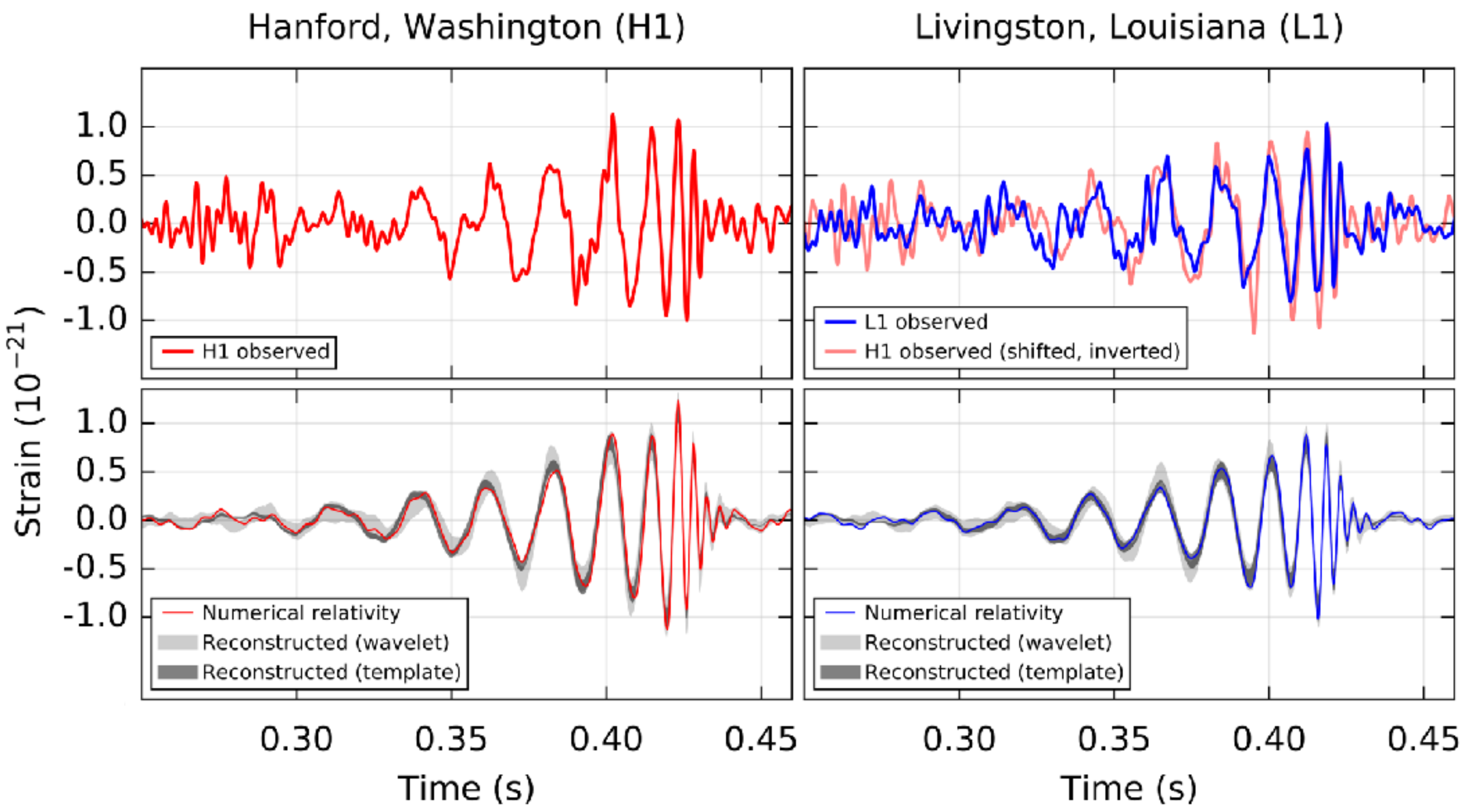
Andreas Freise
NNV, 07.11.2024

How to build the Einstein Telescope?

- Introduction to gravitational waves
- Status of the Einstein Telescope
- Research and development
- Triangle or L shape?

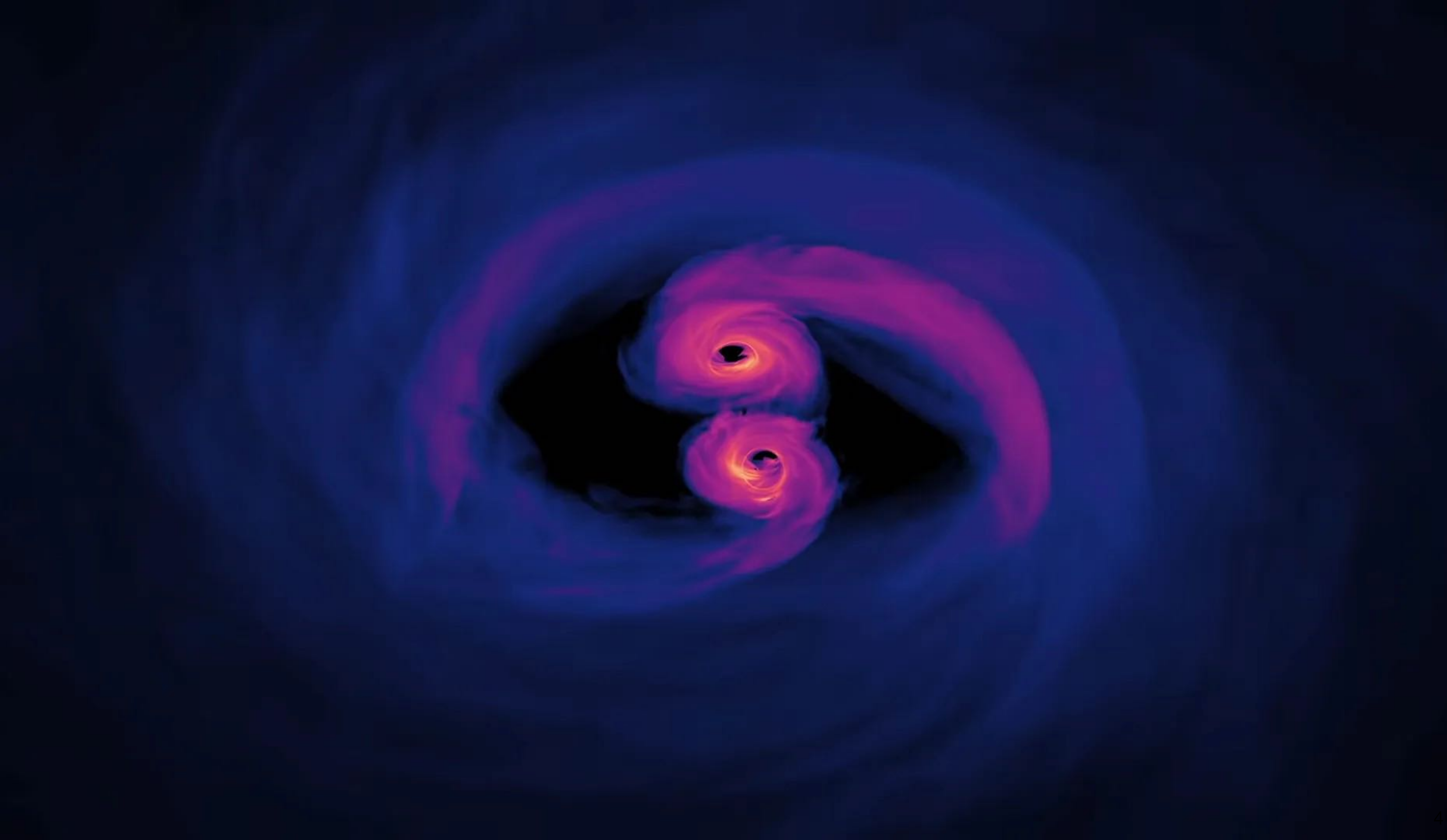


A gravitational wave signal



First detection, in 2015, signal from two black holes colliding.

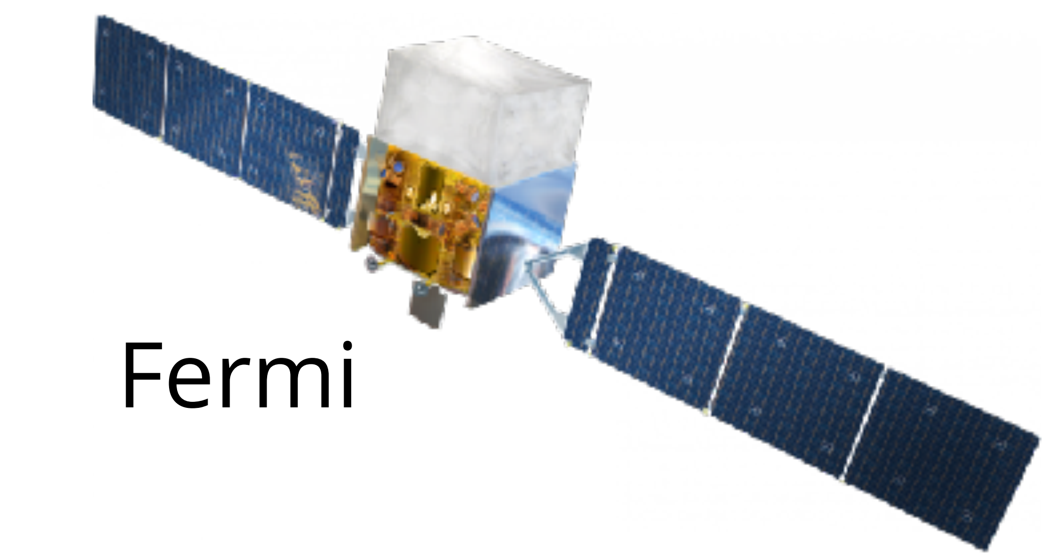
- All our gravitational wave signals come from far away in the universe, an ideal signal is a “wiggle” in **one** output signal per detector
- We extract science by carefully measuring the details of the wiggle and by doing statistics over many such measurements.



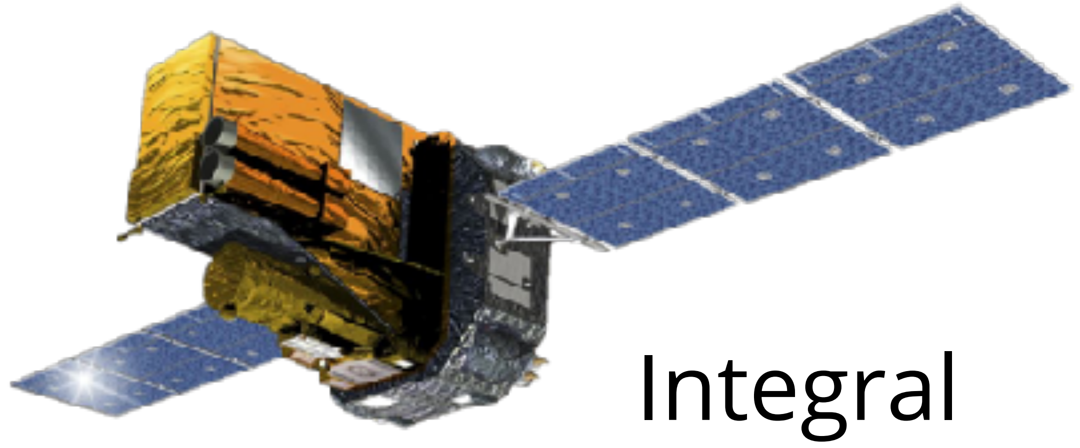
NASA's Goddard Space Flight Center/Scott Noble; simulation data, d'Ascoli et al. 2018

Speed of Gravity

GW170817

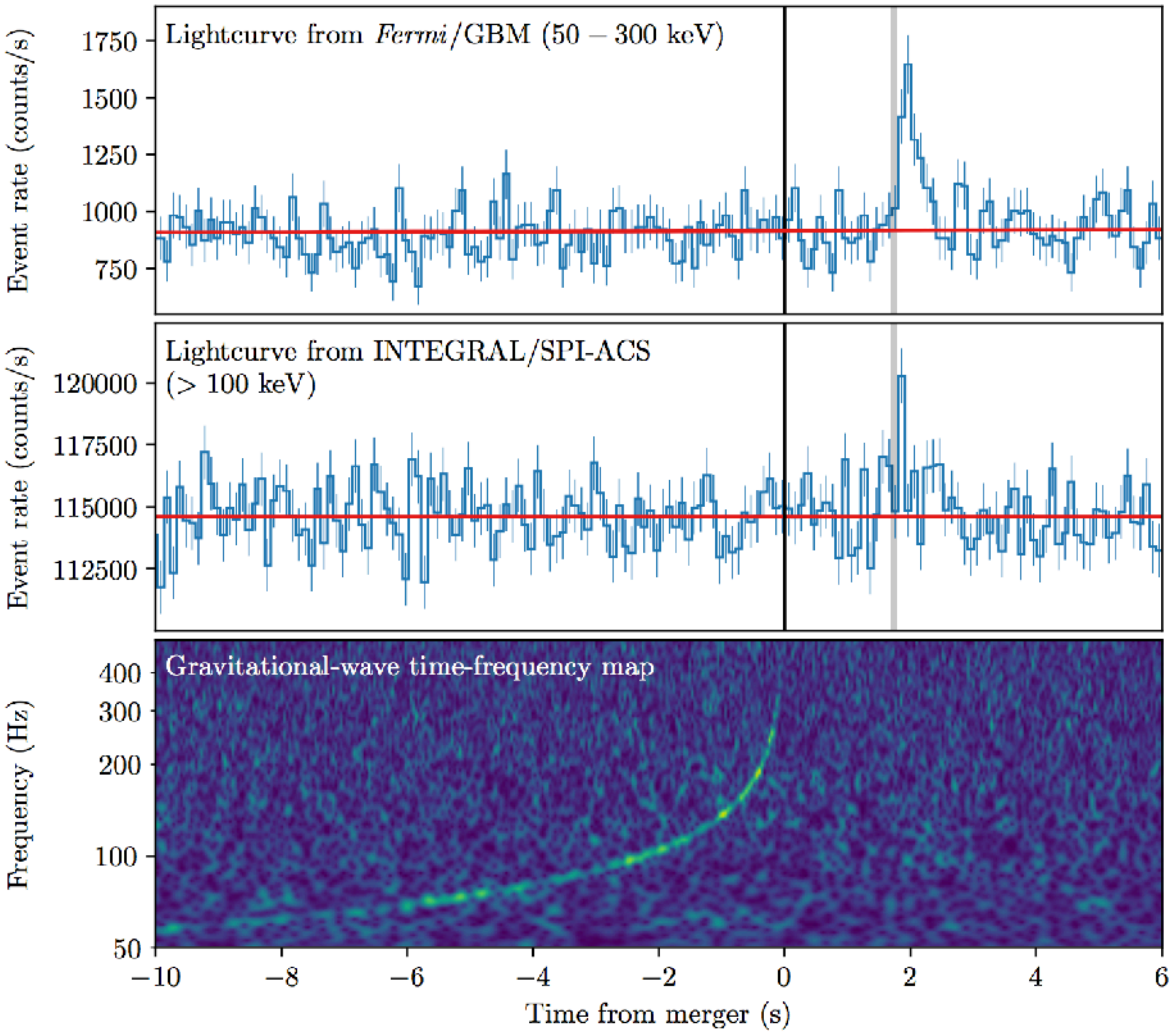


Fermi



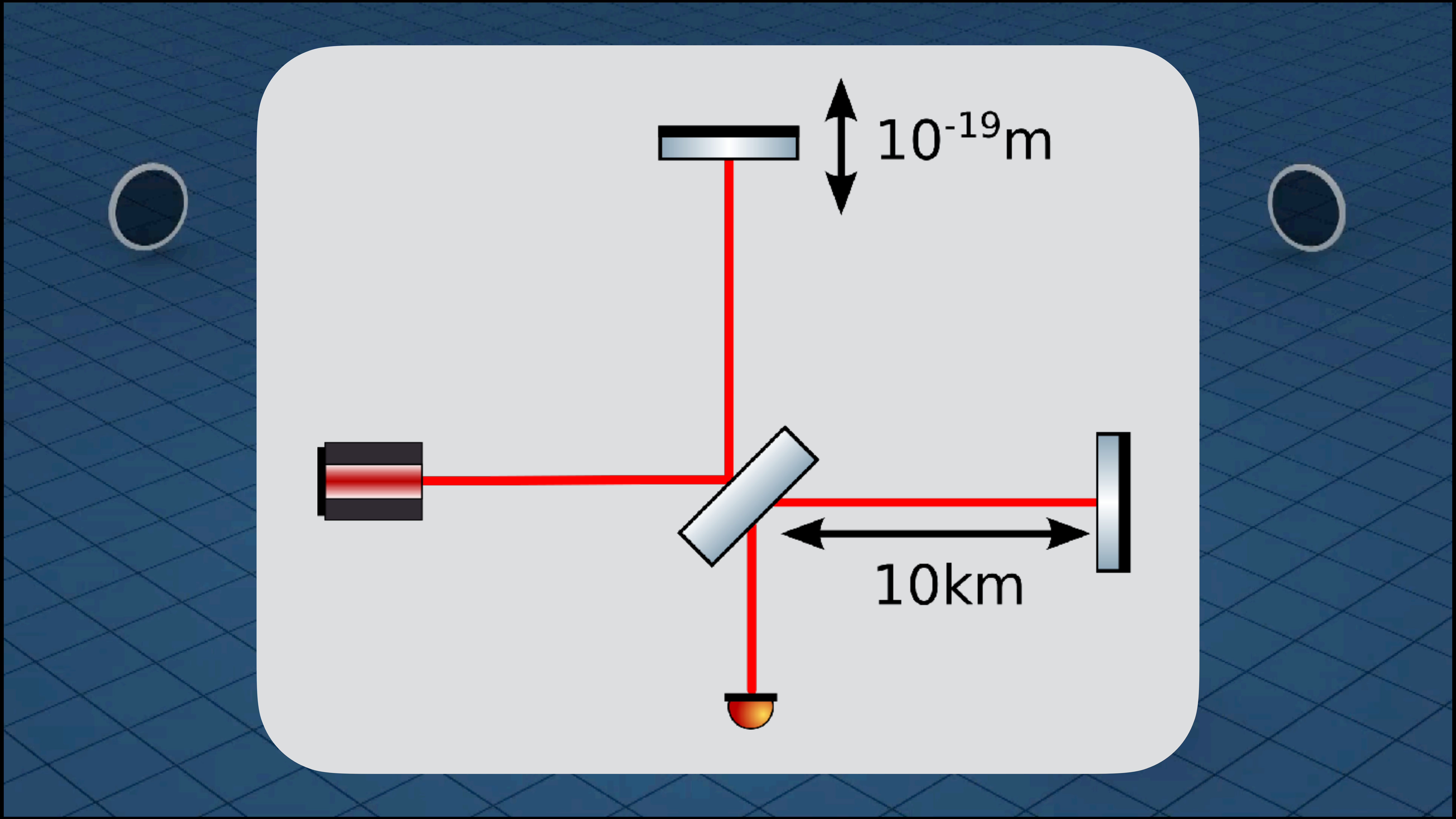
Integral

LIGO-Virgo



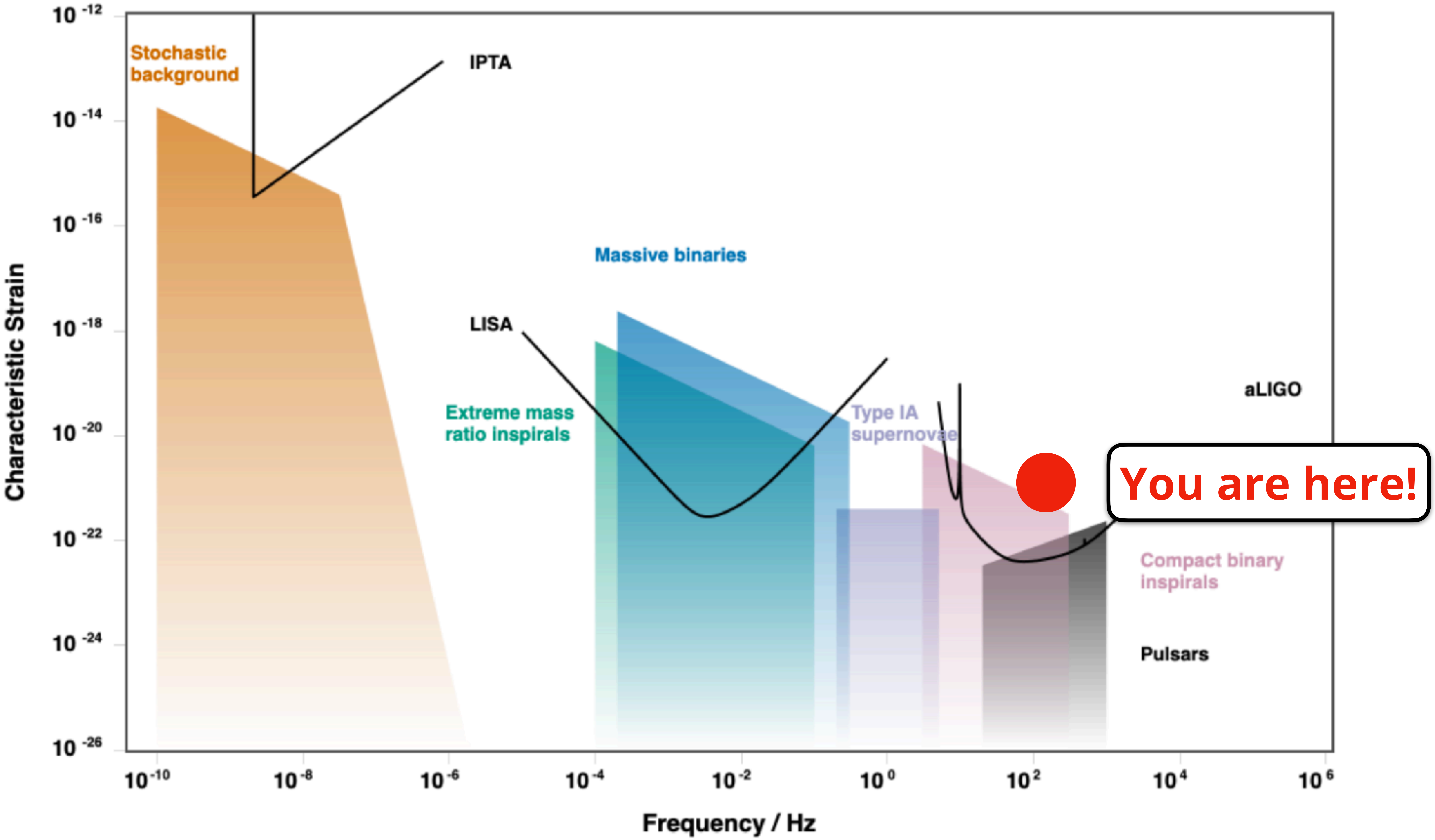
Difference between the speed of gravity and the speed of light: -3×10^{-15} to $+7\times10^{-16}$ times the speed of light!


EGO VIRGO



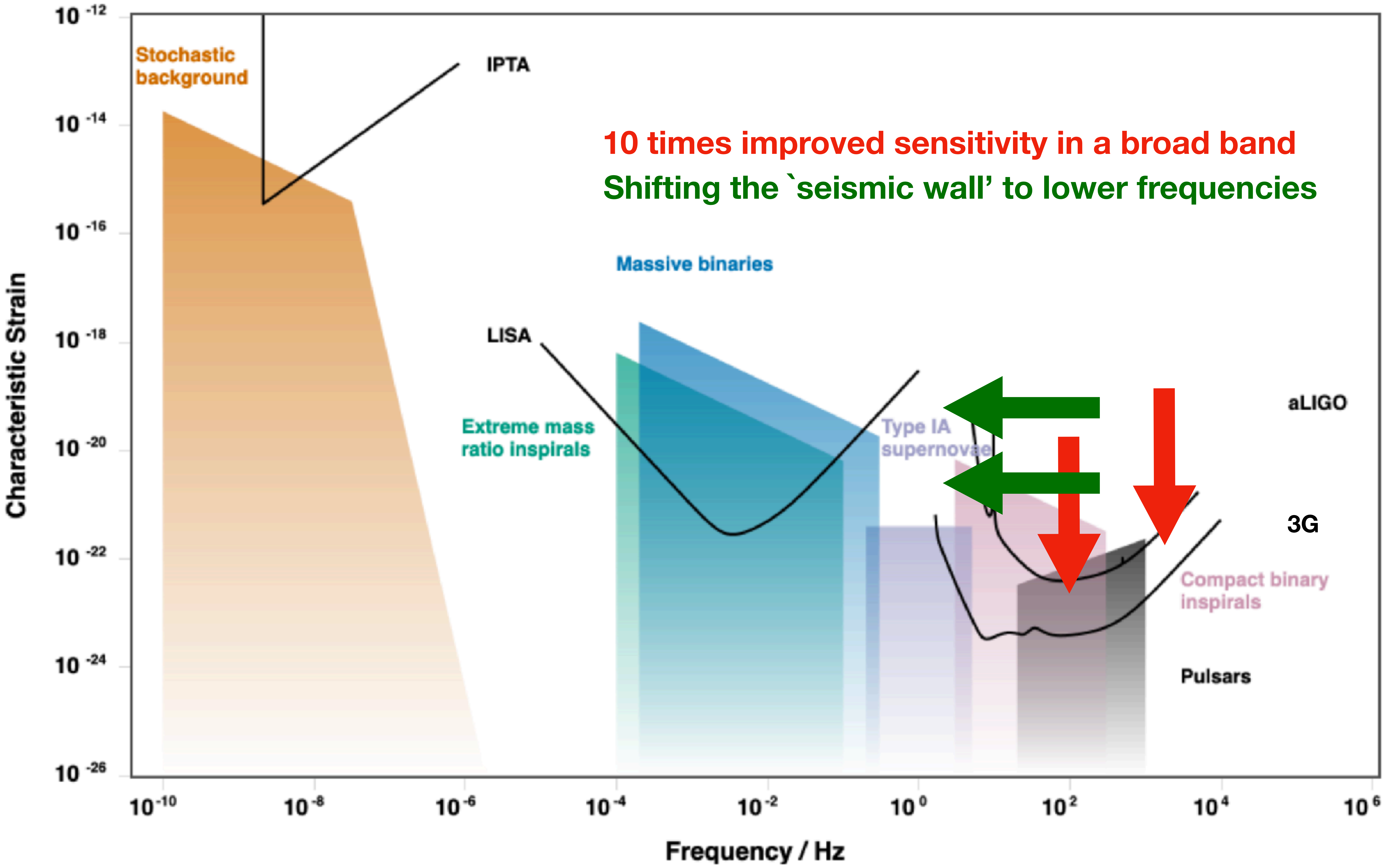
Credit: LIGO/T. Pyle

The GW spectrum



[http://gwplotter.com/]

The GW spectrum



[http://gwplotter.com/]

A leap into the past

The science case for ET

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 (with LISA)
- neutrinos

Detection of new astrophysical sources
- core collapse supernovae
- isolated neutron stars
- stochastic background of astrophysical origin

FUNDAMENTAL PHYSICS AND COSMOLOGY

The nature of compact objects
- near-horizon physics
- tests of no-hair theorem
- exotic compact objects

Tests of General Relativity
- post-Newtonian expansion
- strong field regime

Dark matter
- primordial BHs
- axion clouds, dark matter on compact objects

Dark energy and modifications of gravity
- dark energy equation of state
- modified GW propagation

Stochastic backgrounds of cosmological origin
- inflation, phase transitions, cosmic strings


Einstein Telescope (ET)
A future European gravitational waves observatory
10 km
Large laboratories and three 10 km long tunnels, deep underground
10 times more sensitive over current generation detectors, providing GW data for astronomy and fundamental physics for at least 50 years.

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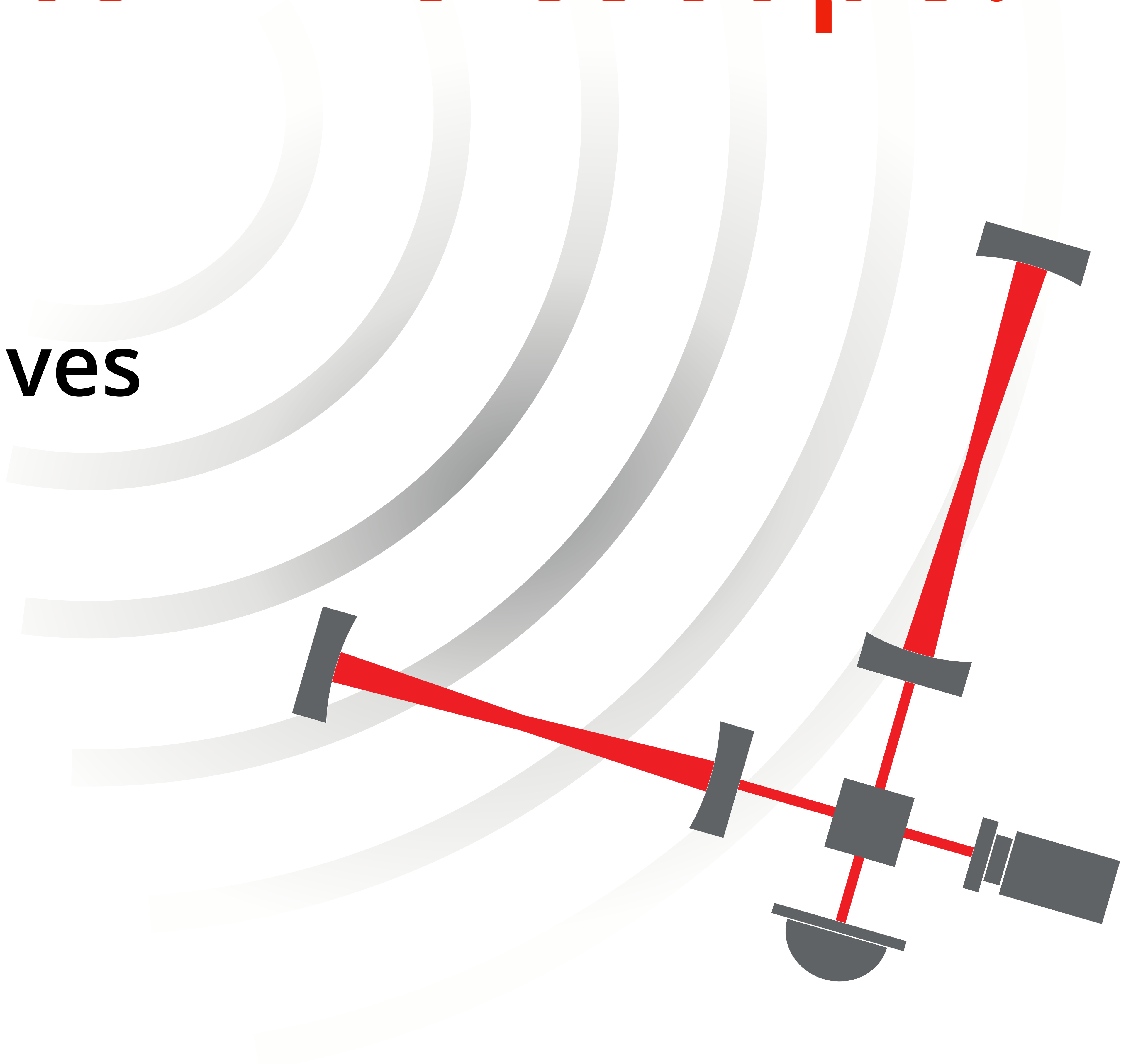
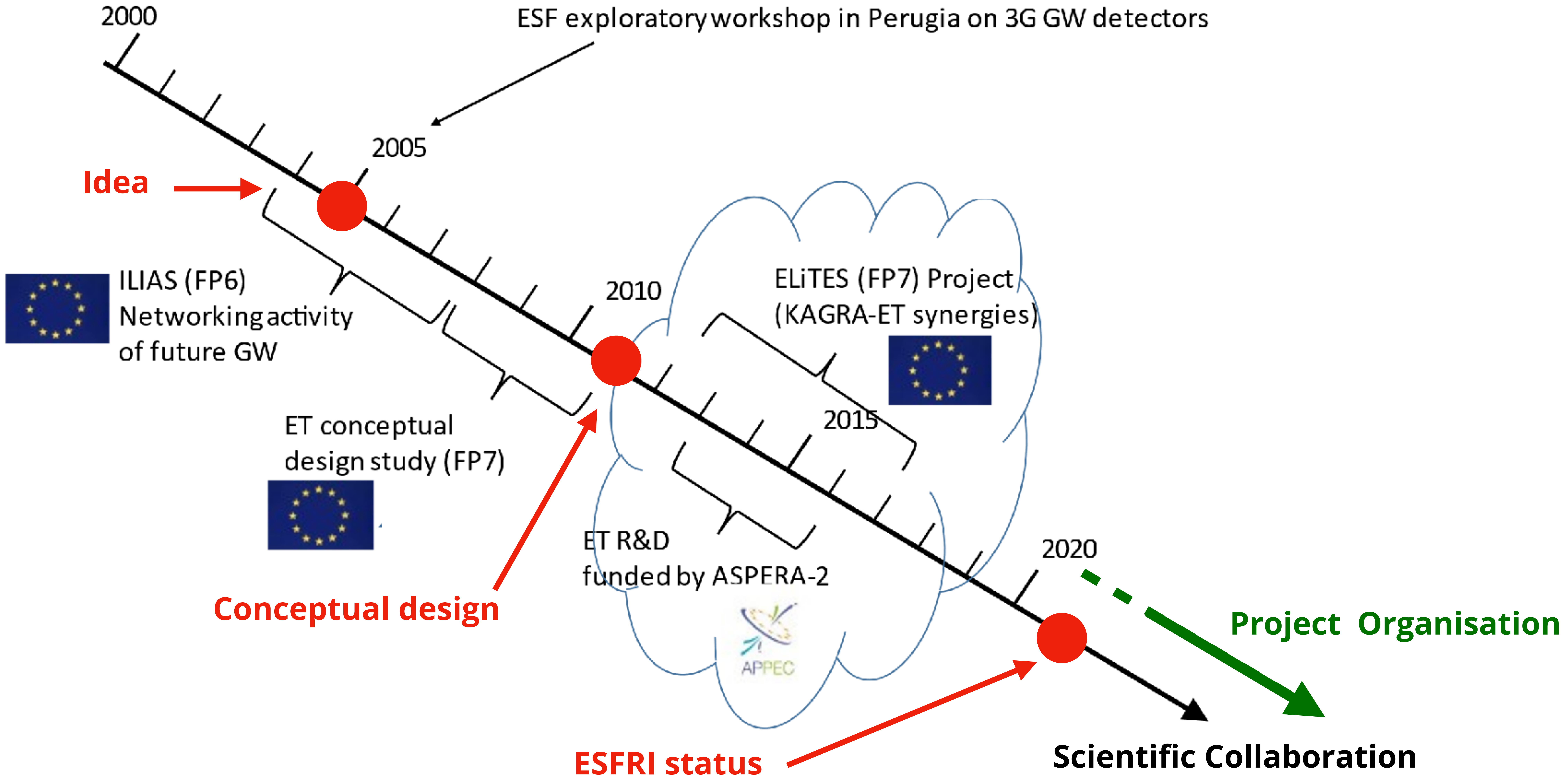


Einstein Telescope: from idea to project



[Timeline: Michele Punturo]

Possible ET sites

- Currently there are two candidate sites in Europe to host ET:
  - The Sardinia site, close to the Sos Enattos mine
  - The Euregio Meuse-Rhine (**EMR**) site, close to the NL-B-D border
- We received a proposal for another option in Saxony (Germany), currently under discussion

[https://www.interregemr.eu/]

ETO = ET Organisation

- More than 100 M€ are already being spend to prepare possible locations.
- More than 2000 M€ are being reserved for construction.
- We need ETO, a **new organisation,** to manage the design and construction of ET.
- A model towards the legal entity that will **manage and operate ET**.
- Think of **CERN or ESA**, but for the Einstein Telescope.
- Current mandate of ETO: deliver all the required **plans and documents** to governments to **approve the construction of ET,** including science case and detector design.
- Our focus is on non-scientific issues such as **project managment, engineering, strategic planning, communication**.
- We are ramping up the team and the work quickly. **We hope to complete our initial mandate by 2027.**

ETO responsibilities and relations

BGR
Site selection;
Legal entity;
Financial framework

Board of Governmental Representatives (BGR)

ET Coordinators

ET coordinators
Coordinate the EU project - ESFRI

ETO Directorate
Strategic coordination and management
- ET Roadmap
- Technical Design Reports
- Site Evaluation Reports
- Technical Plan report
- Organisation report
- Budget report

ETO Directorate and Depts

Host Consortia
- Feasibility studies civil engineering, installations
- Feasibility studies subsurface
- Feasibility studies environment and legal

ET Collaboration
- Scientific vision
- Detector design
- Requirements,
- Common standards

ET Host Consortia (EMR and TETI)

ET Collaboration (ETC)

ETO – structure and capacity

Status on 1 October 2024

ET Directorate
Total FTEs: 4.6
Total staff: 8

ETO Directors:
A. Freise (Nikhef) & F. Ferroni (INFN)

ET-PP
M. Martinez (IFAE)

Project Office
Total FTE: 5.5
Total staff: 16
Head: A. Variola (INFN)

Engineering Department
Total FTE: 7.5
Total staff: 14
Head: P. Werneke (Nikhef)

Communication Department
Total FTE: 0.8
Total staff: 2
Head: M Oudenhoven (Nikhef)

Future Depts:
- **Finance Dept**
- **Human Resources**
- **….**

ETO Team

We work remote, and meet in person typically once a month (e.g. at CERN)
Staff is hired by local institutes and line-managed by ETO directors

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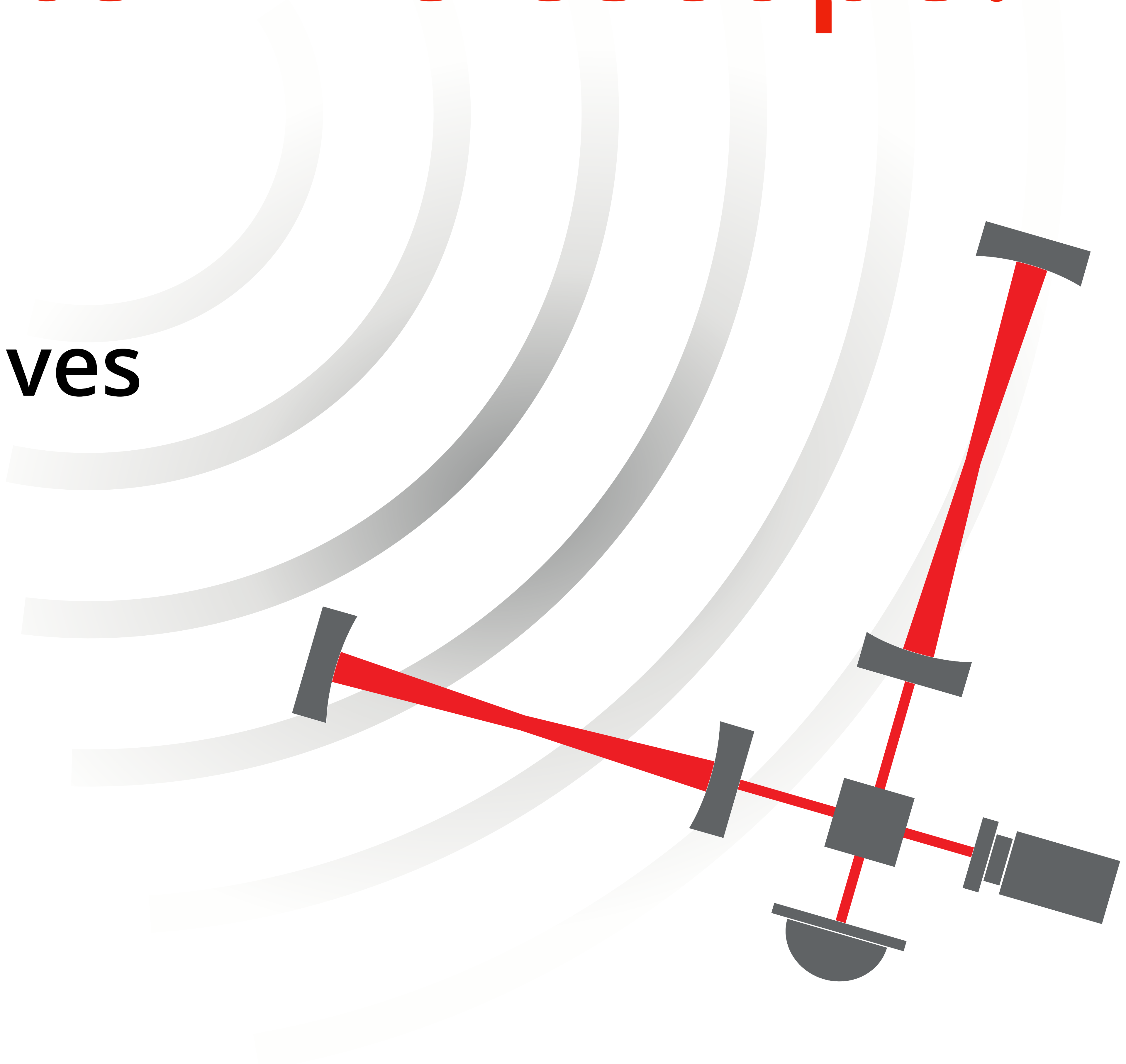
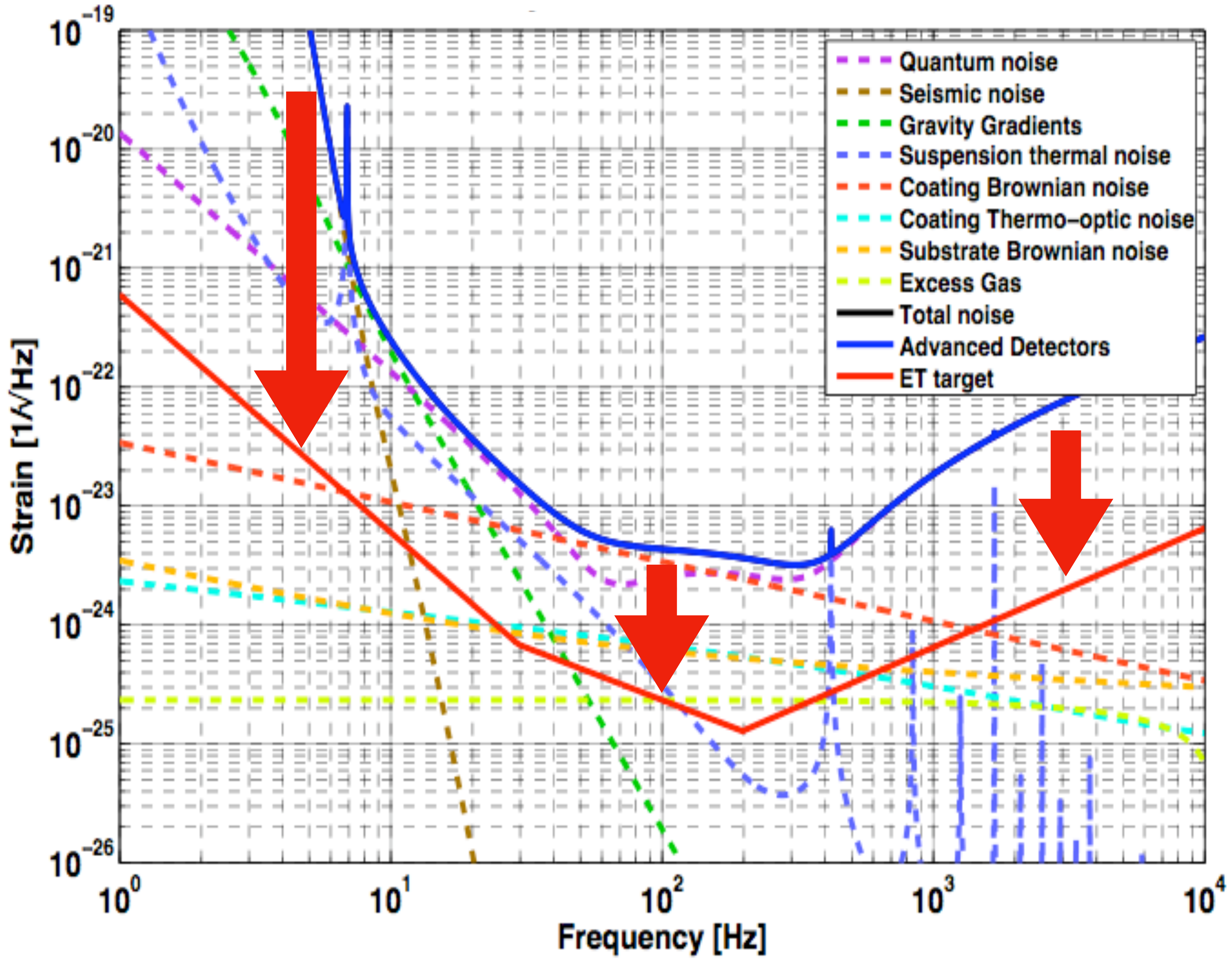
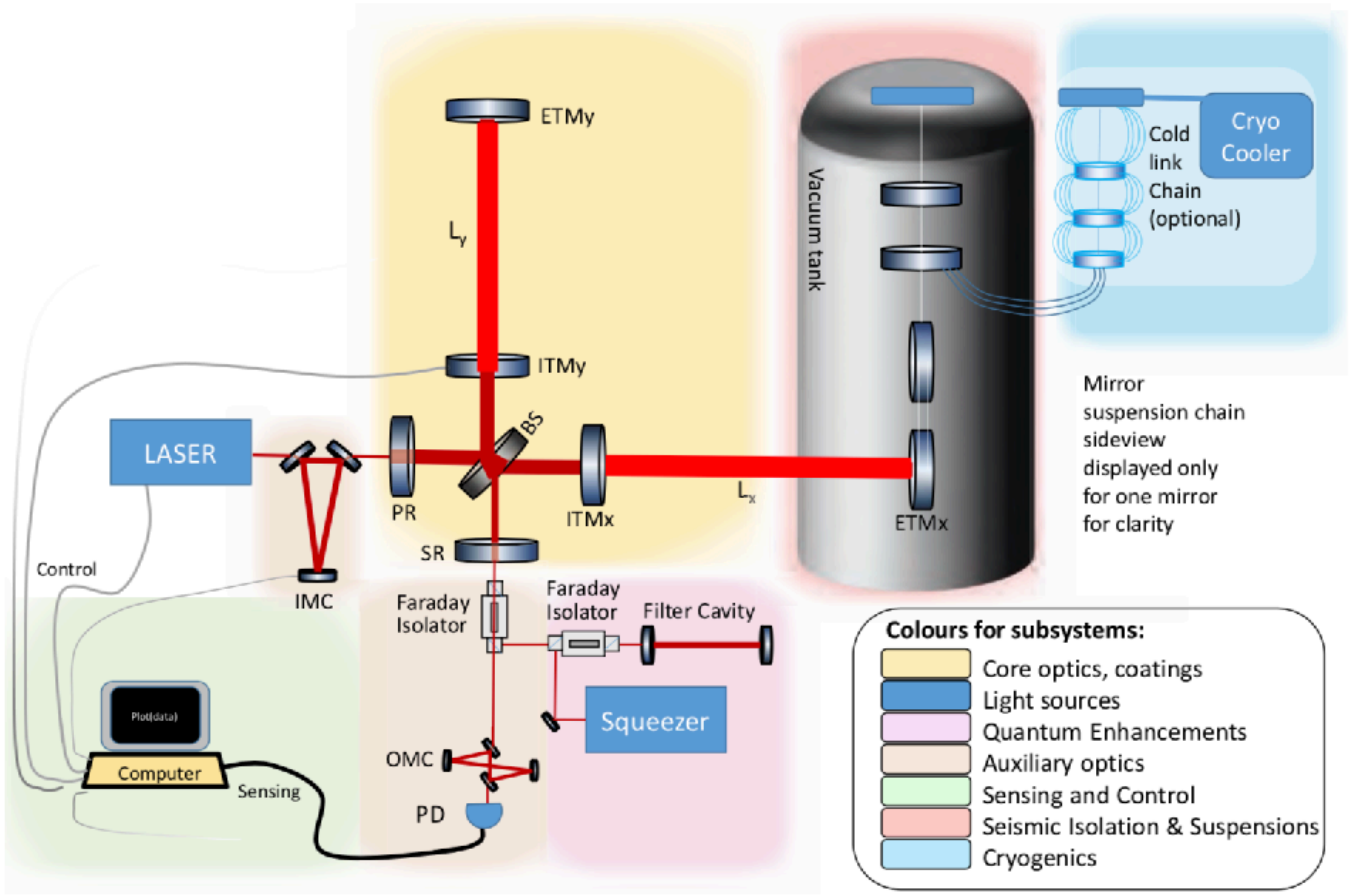


Thanks to the Nikhef ET team

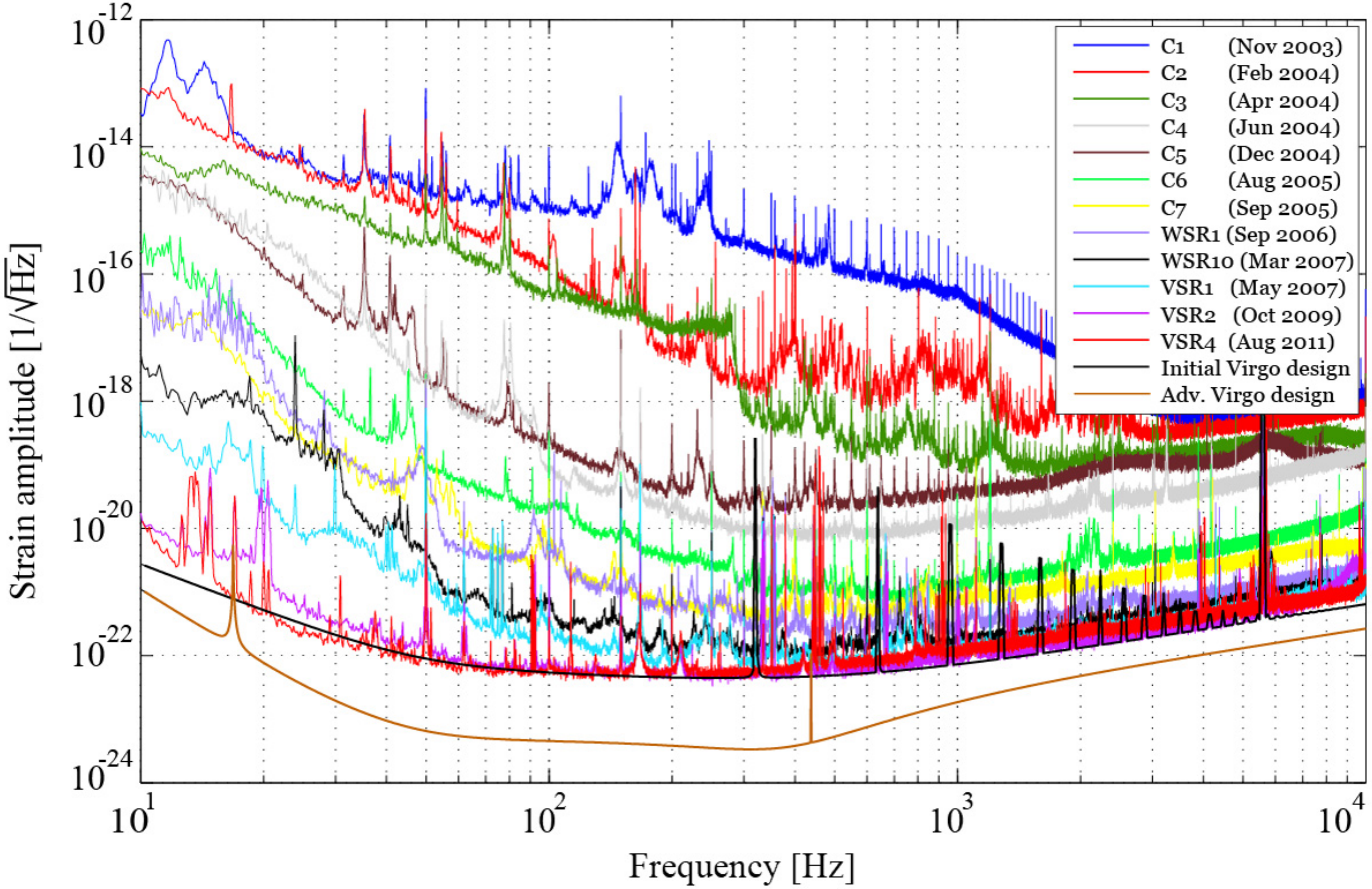
Updating detector technology piece by piece…





https://gwic.ligo.org/3Gsubcomm/documents/GWIC_3G_R_D_Subcommittee_report_July_2019.pdf

… is not enough. We need better designs too!

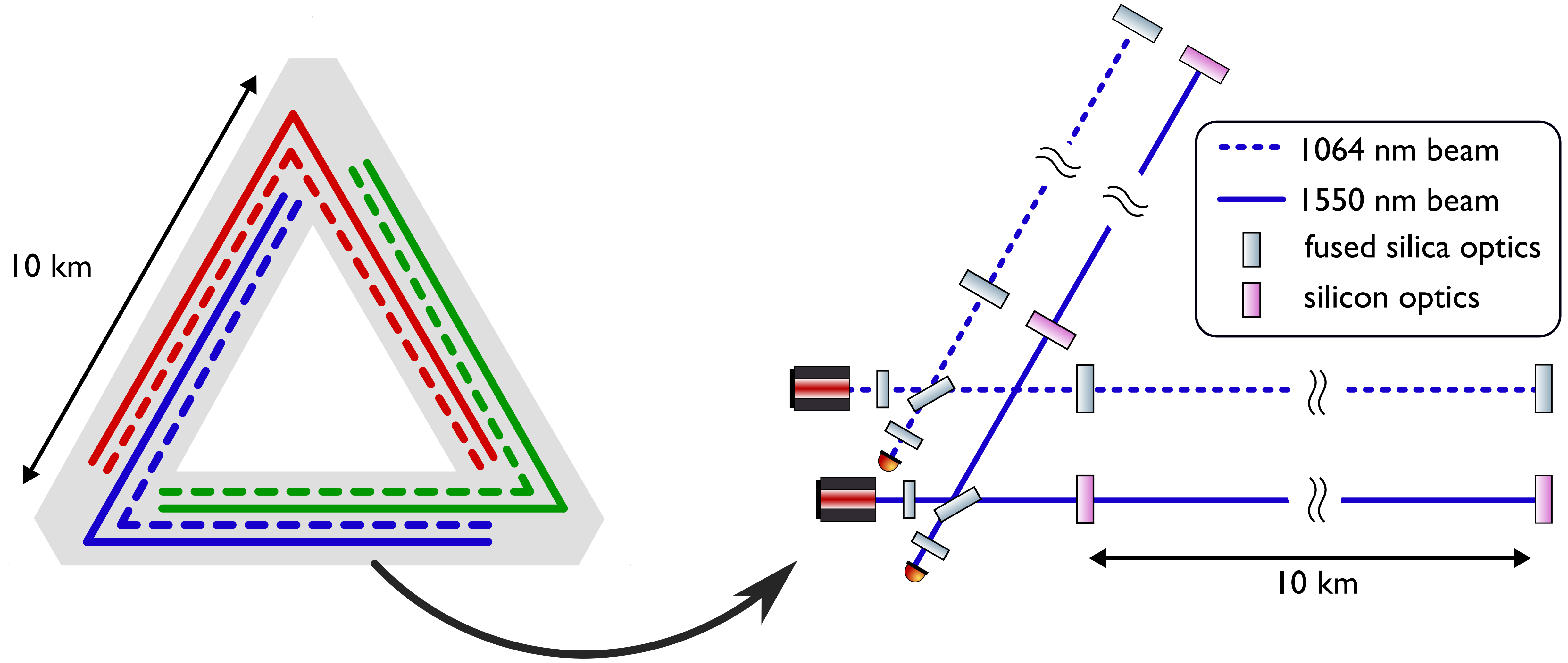


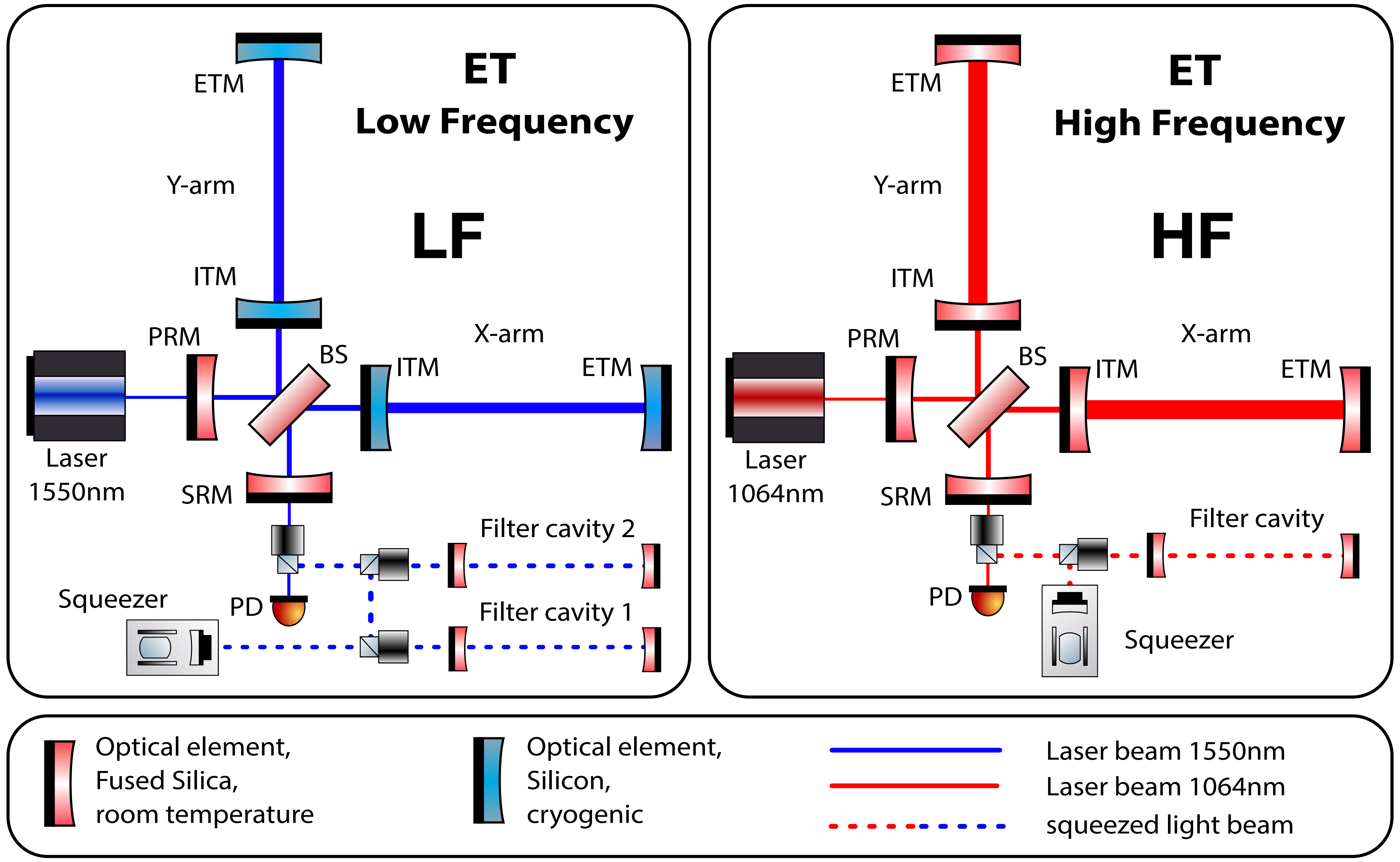
Virgo detector

8 years from first full operation of the detector to (almost) design sensitivity.

Einstein Telescope conceptual design

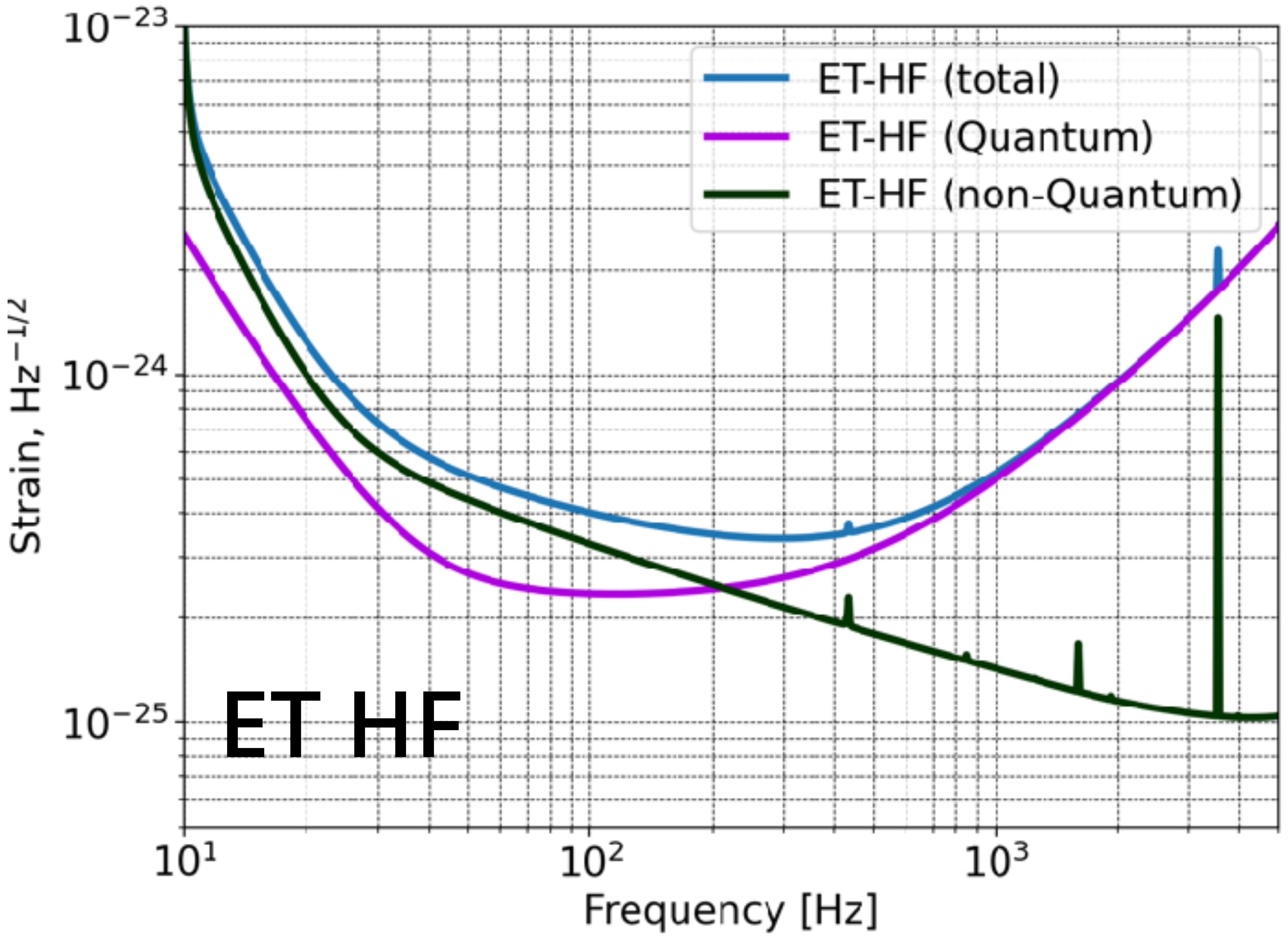
Parameter	ET-HF	ET-LF
Arm length	10 km	10 km
Input power (after IMC)	500 W	3 W
Arm power	3 MW	18 kW
Temperature	290 K	10-20 K
Mirror material	fused silica	silicon
Mirror diameter / thickness	62 cm / 30 cm	45 cm/ 57 cm
Mirror masses	200 kg	211 kg
Laser wavelength	1064 nm	1550 nm
SR-phase (rad)	tuned (0.0)	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)	$5 \cdot 10^{-10}$ m/ f^2	$5 \cdot 10^{-10}$ m/ f^2
Gravity gradient subtraction	none	factor of a few

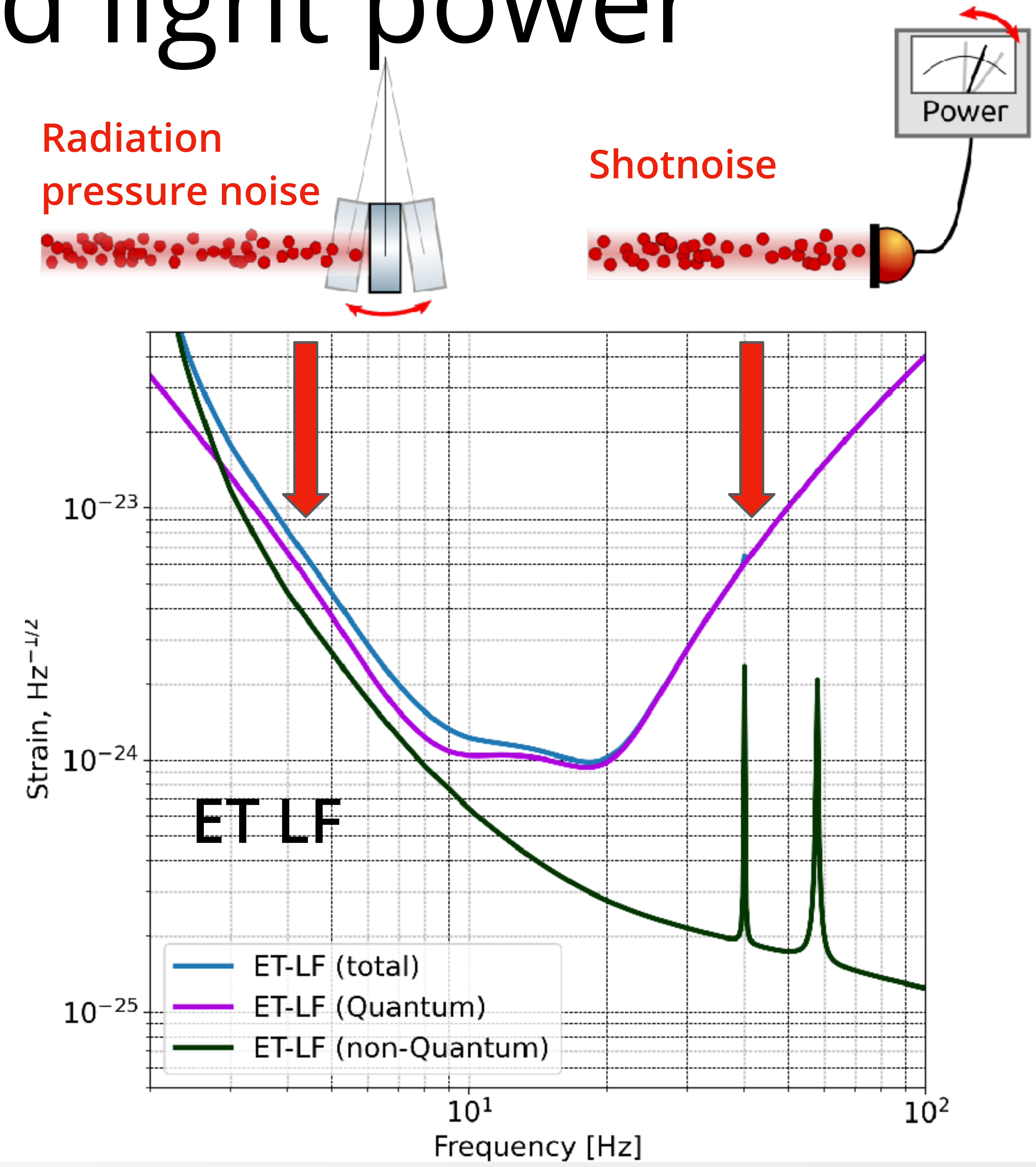




Quantum noise and light power

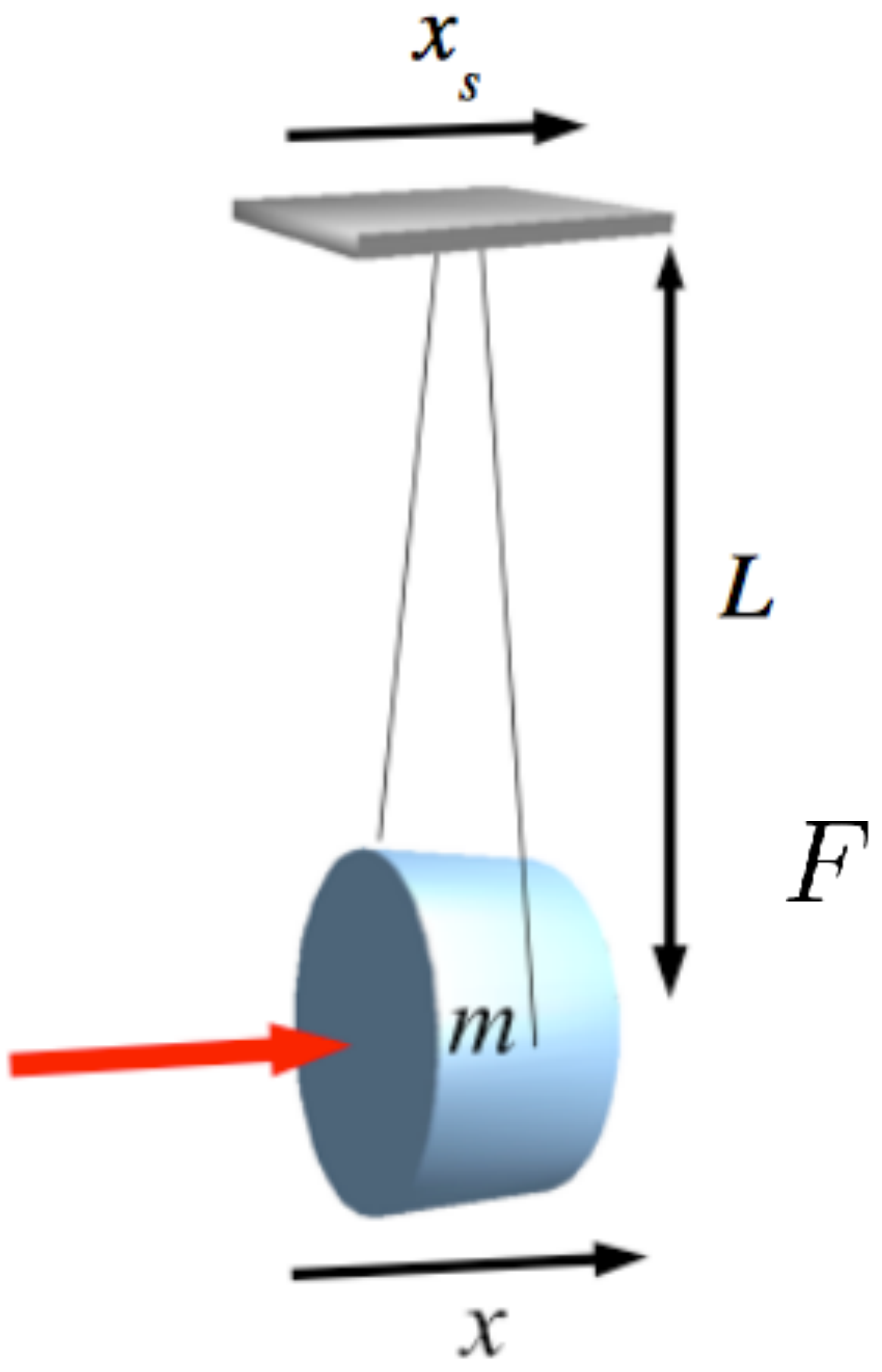
- Quantum fluctuations of light, are one of the main limitations to ET sensitivity
  - In ET-LF, it will limit the sensitivity from 3 Hz onwards;
  - In ET-HF, it will limit from 200 Hz onwards;

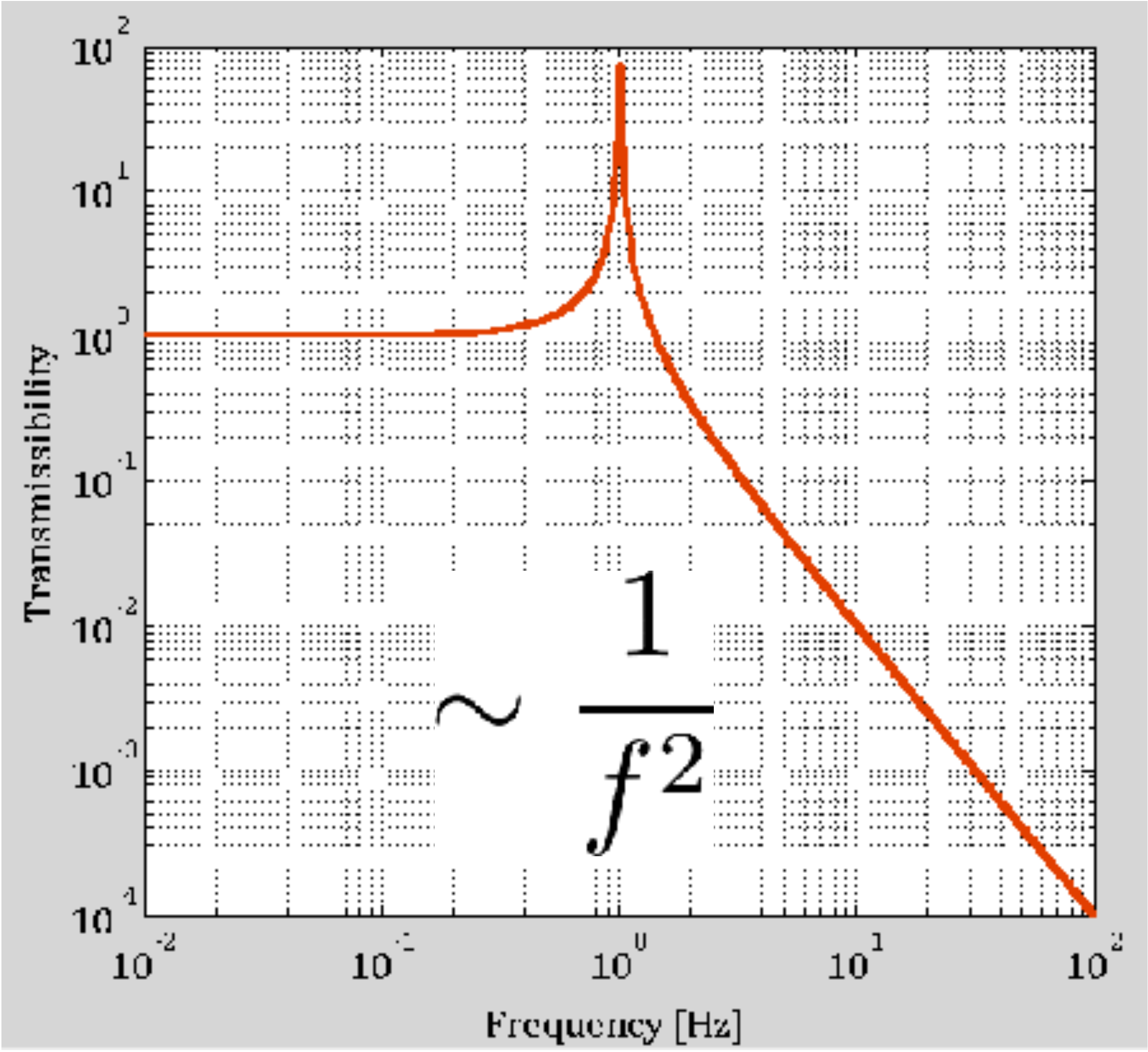


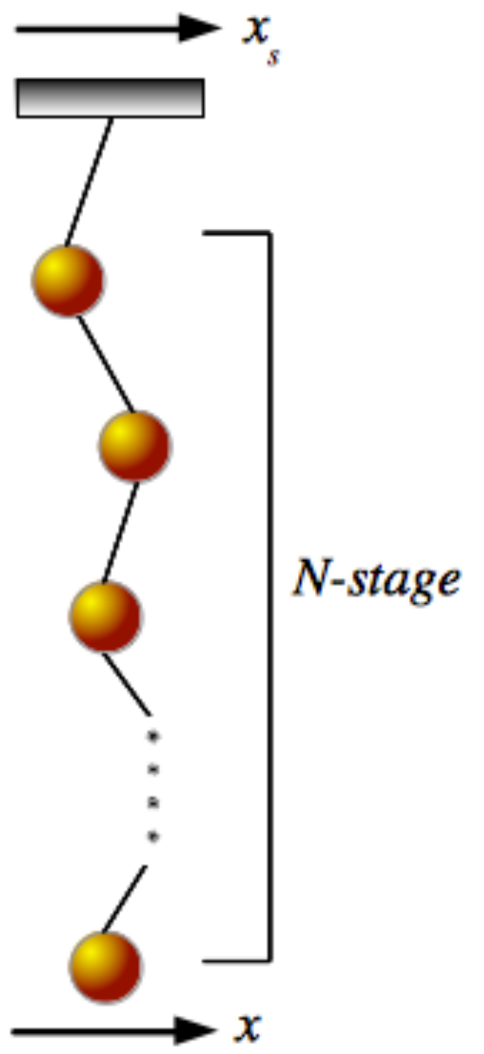


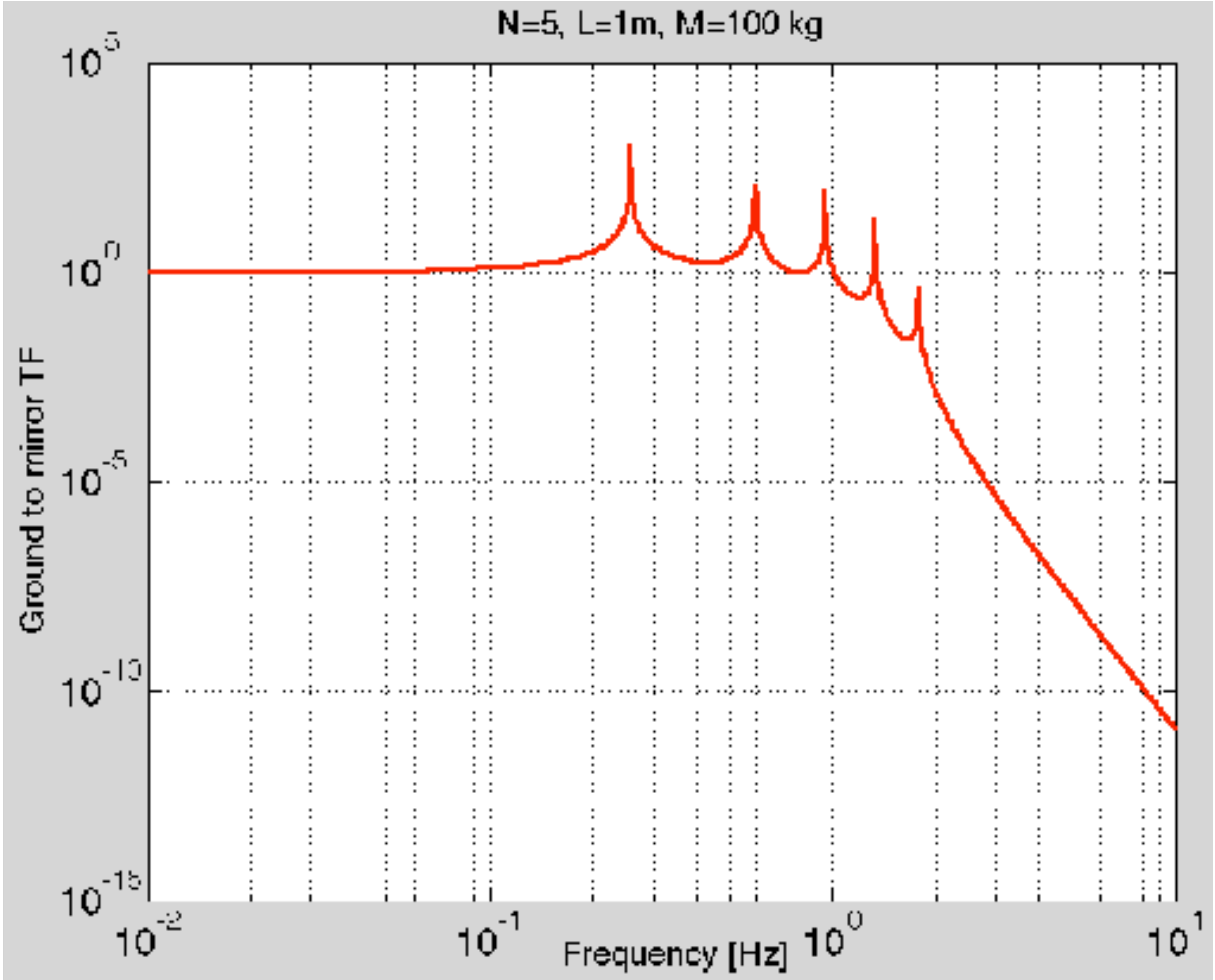
Seismic isolation: the pendulum

- Mirrors on the ground (Earth) would vibrate to much, we need seismic isolation
- Suspension as a pendulum, provides seismic noise attenuation above resonance







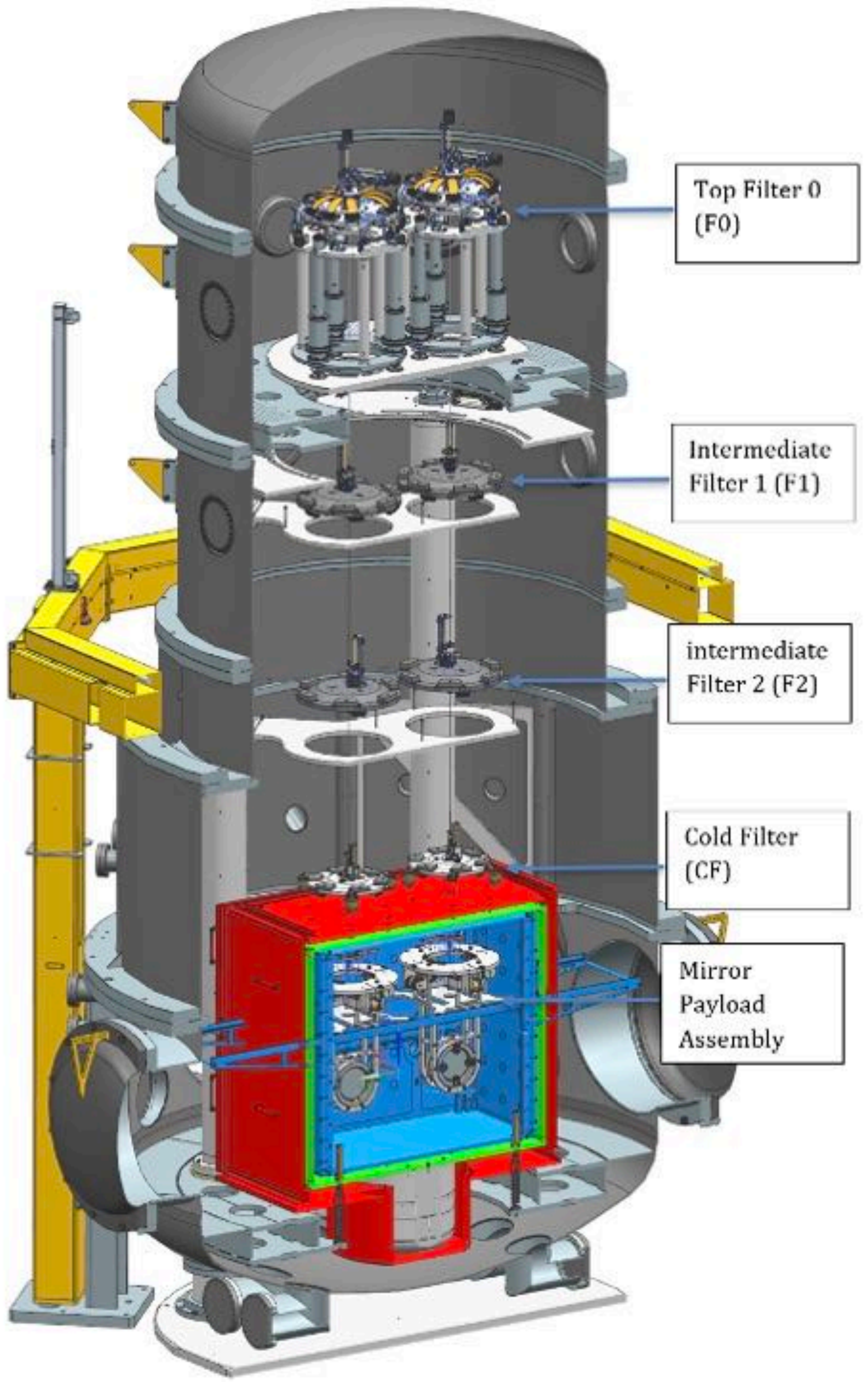


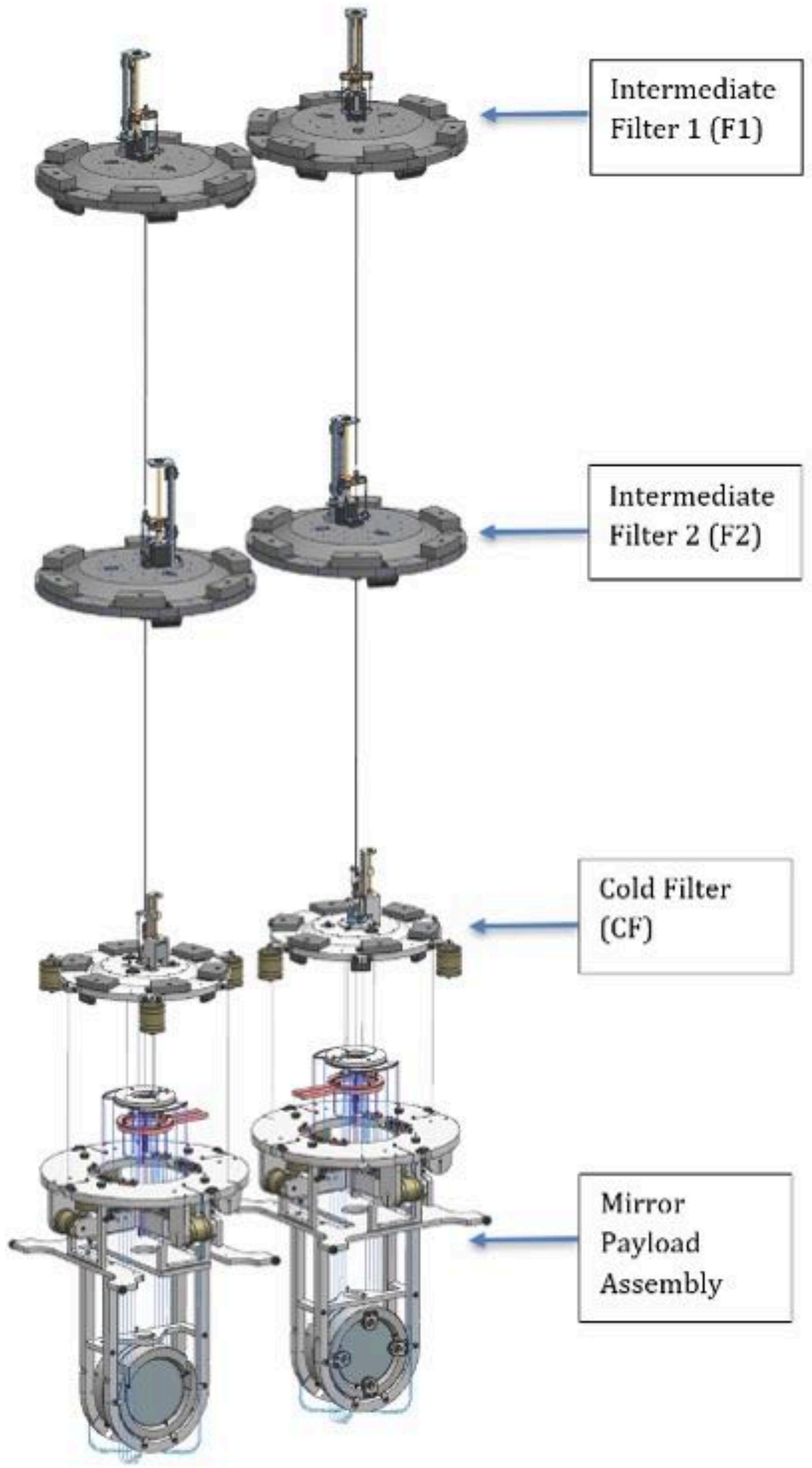
$$f_{\text{res}} = \frac{1}{2\pi}\sqrt{\frac{g}{L}}$$

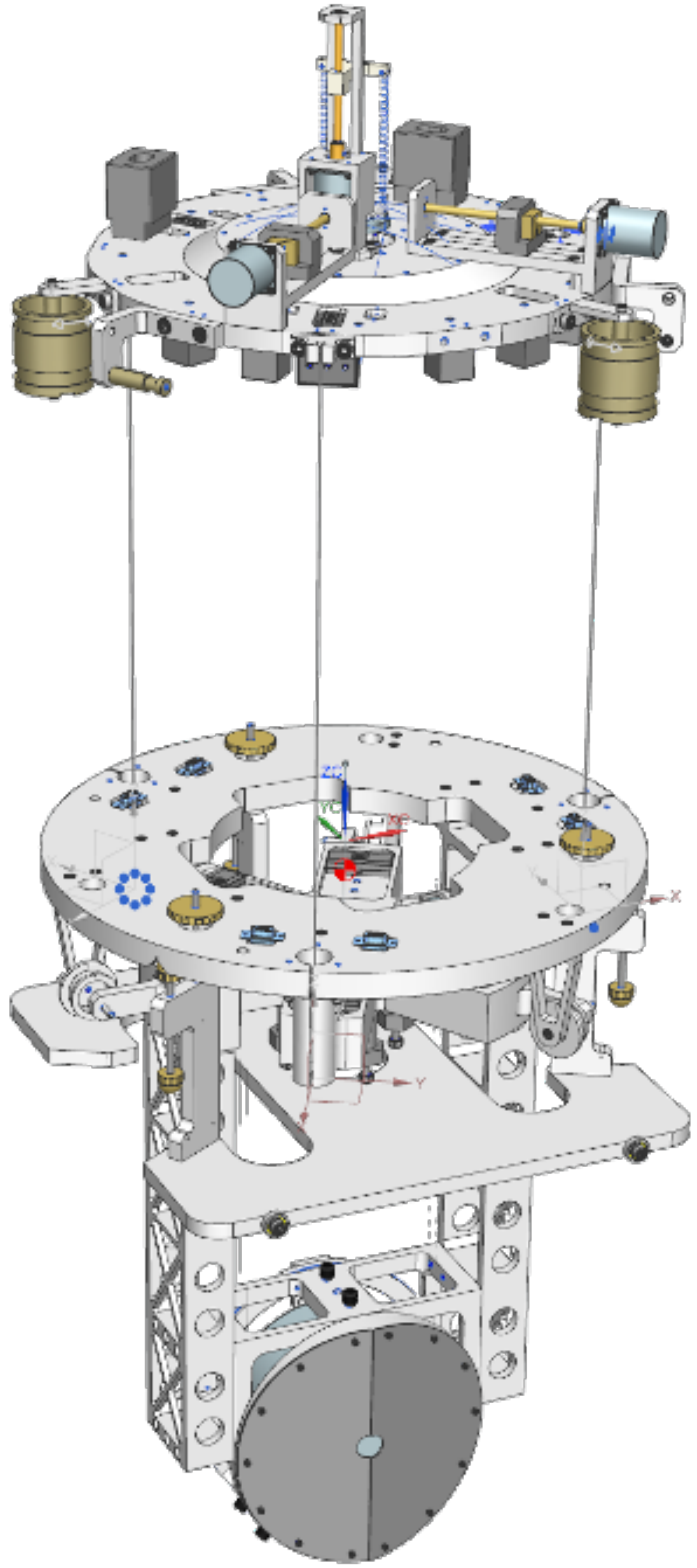
[Alessandro Bertolini]

From Virgo towards ET

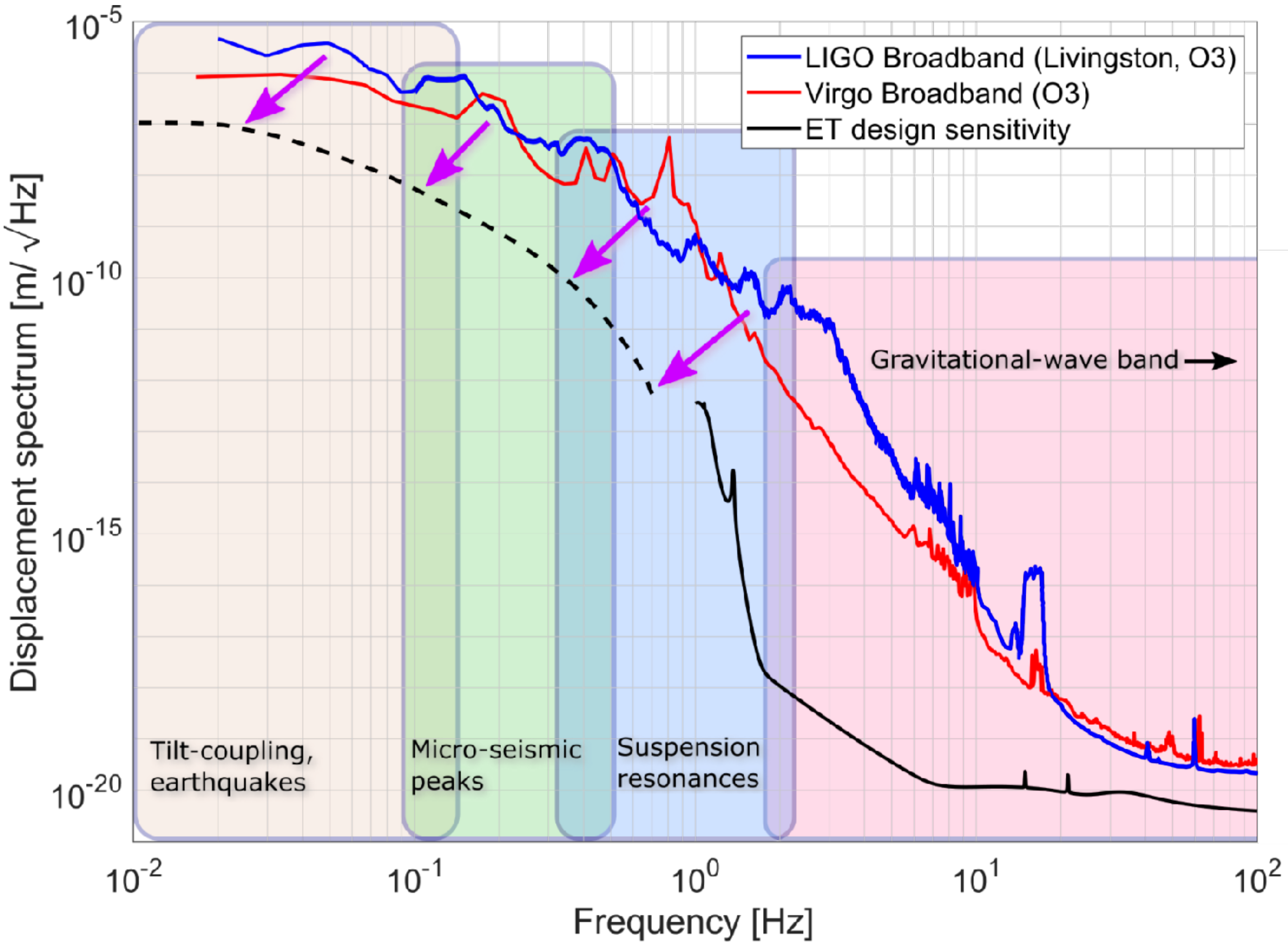
Vibration isolation for cryogenic mirrors in ETpathfinder







[Alessandro Bertolini]



[Conor Mow-Lowry]

ETpathfinder

- The complexity of the future observatory in a 10m scale, providing a long-term focal point for university partners, institutions and industry.

- 14.5 M€ investment, under construction in Maastricht.
- International partners:~ 20 universities and institutes from NL/BE/DE/F.


January 2020

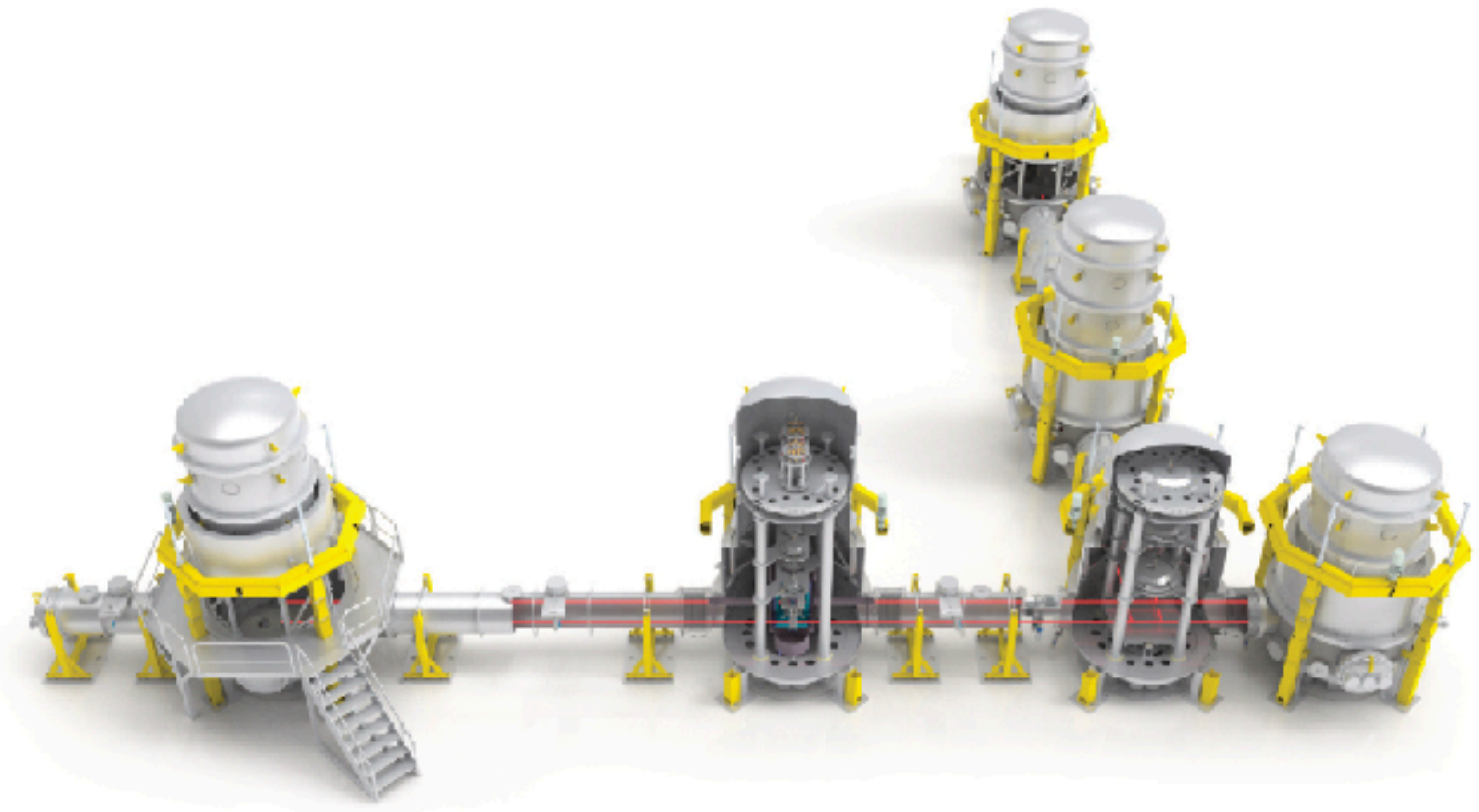
Summer 2021

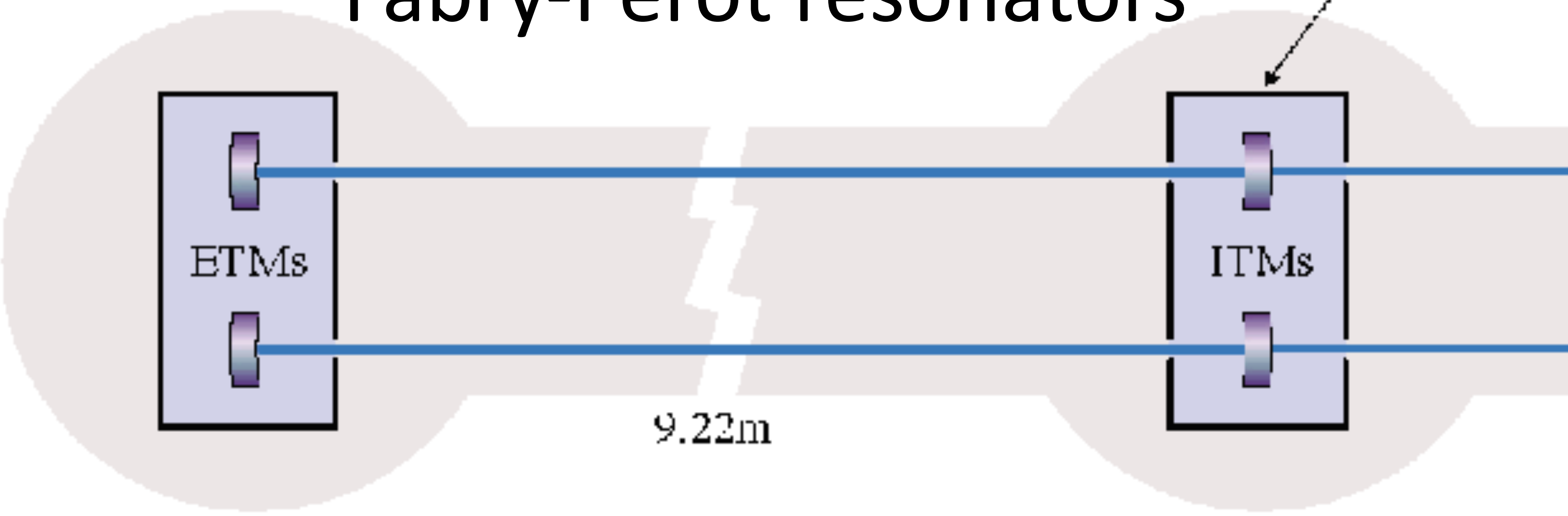
Spring 2023

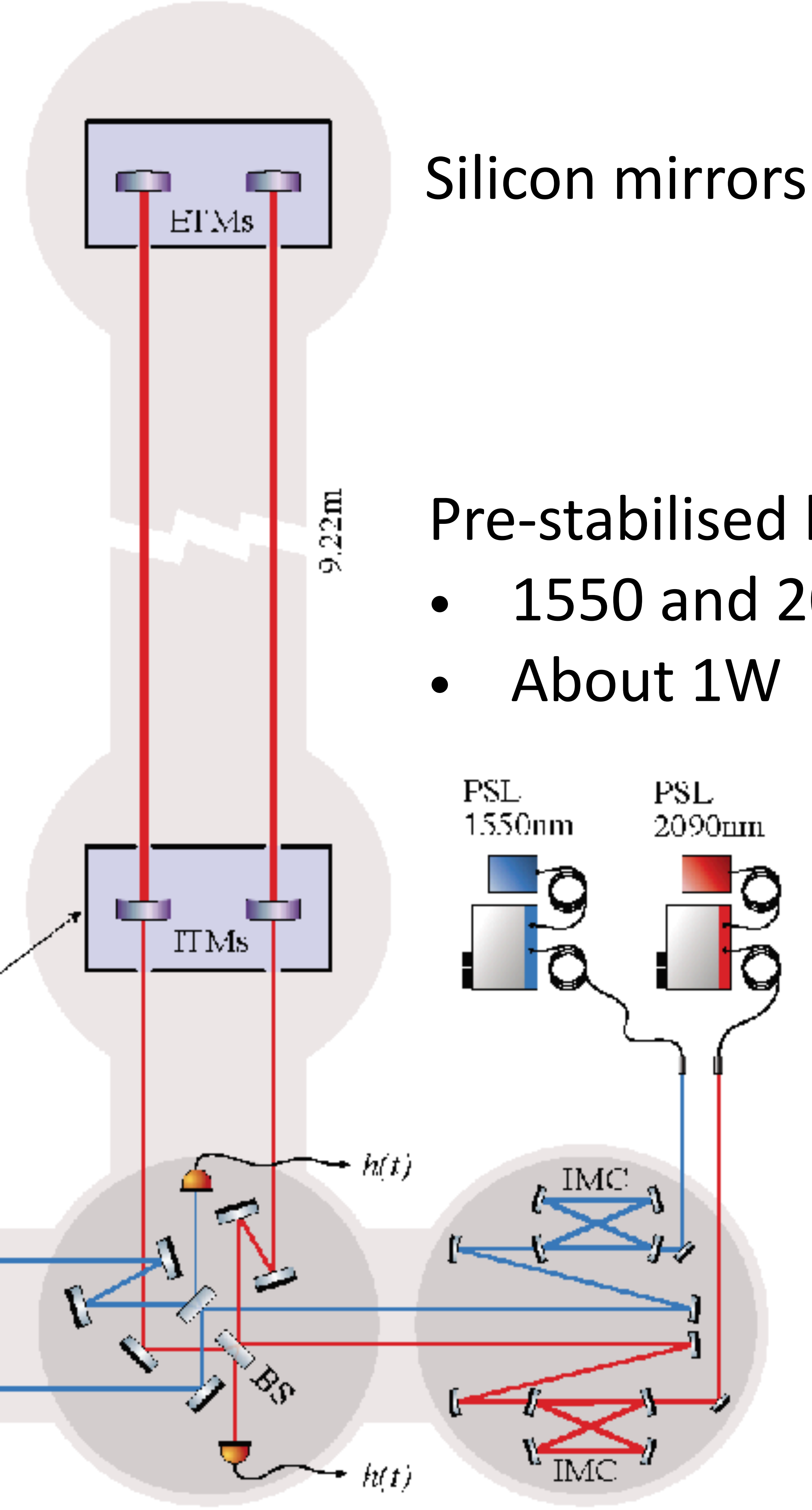
ETpathfinder

Two Michelson interferometers: Each arm allows operating at a different **cryogenic** temperature (123K and 18K).

See also: arXiv: 2206.04905v1 10 June 2022







Silicon mirrors

Pre-stabilised lasers
- 1550 and 2090 nm
- About 1W

Fabry-Perot resonators

Arm length 9.23 m

Input mode cleaners

Robbert Dijkgraaf
@RHDijkgraaf

De #ETpathfinder is een baanbrekende faciliteit met blijvende waarde voor de wetenschap. Ik hoop van harte dat we over een aantal jaar de Einstein Telescoop in Zuid-Limburg kunnen gaan bouwen en het bijzondere werk van de ETPathfinder op nog grotere schaal kunnen voortzetten.

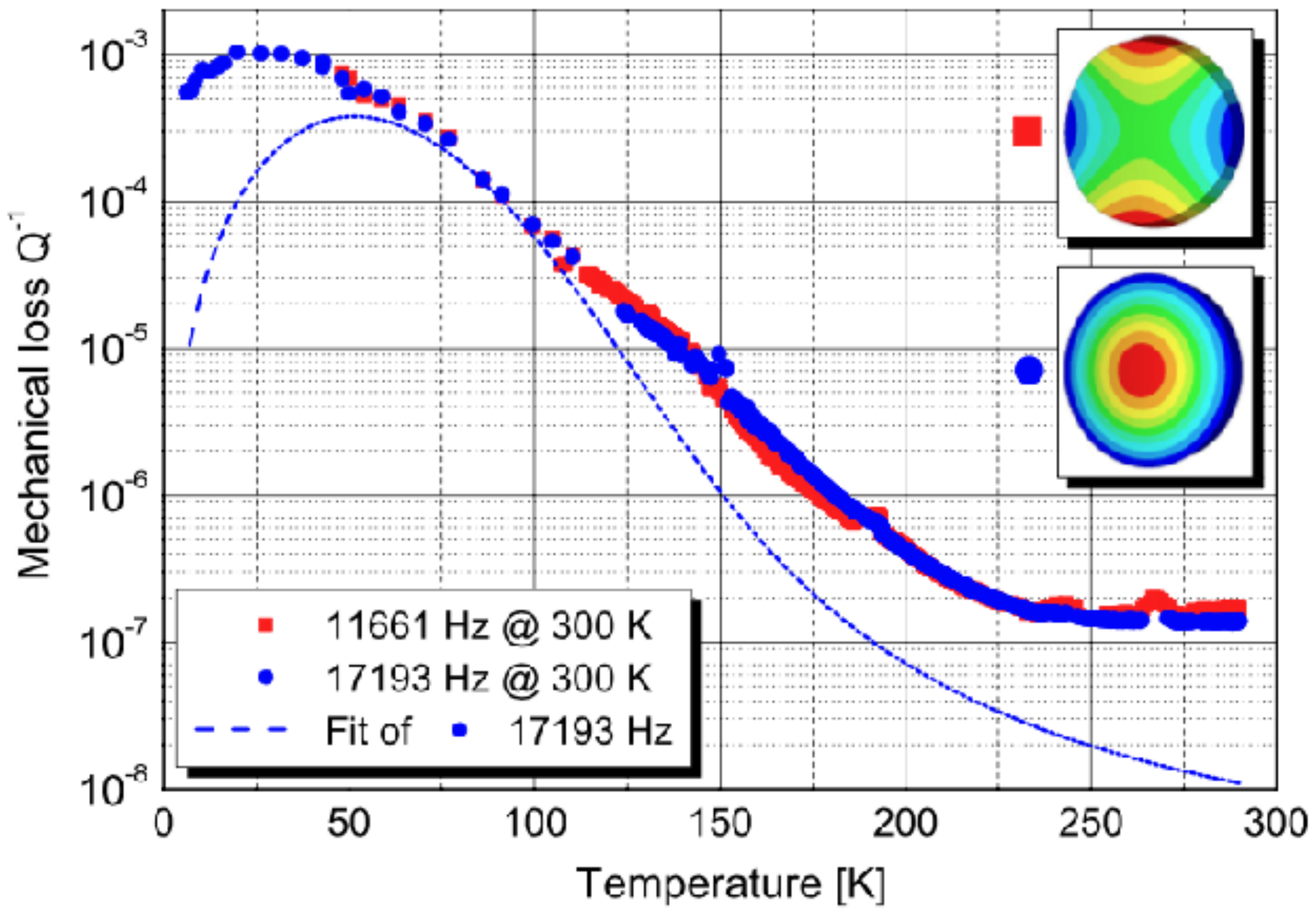
4:08 PM · May 24, 2022 · Twitter Web App

[Paul Kuijer]

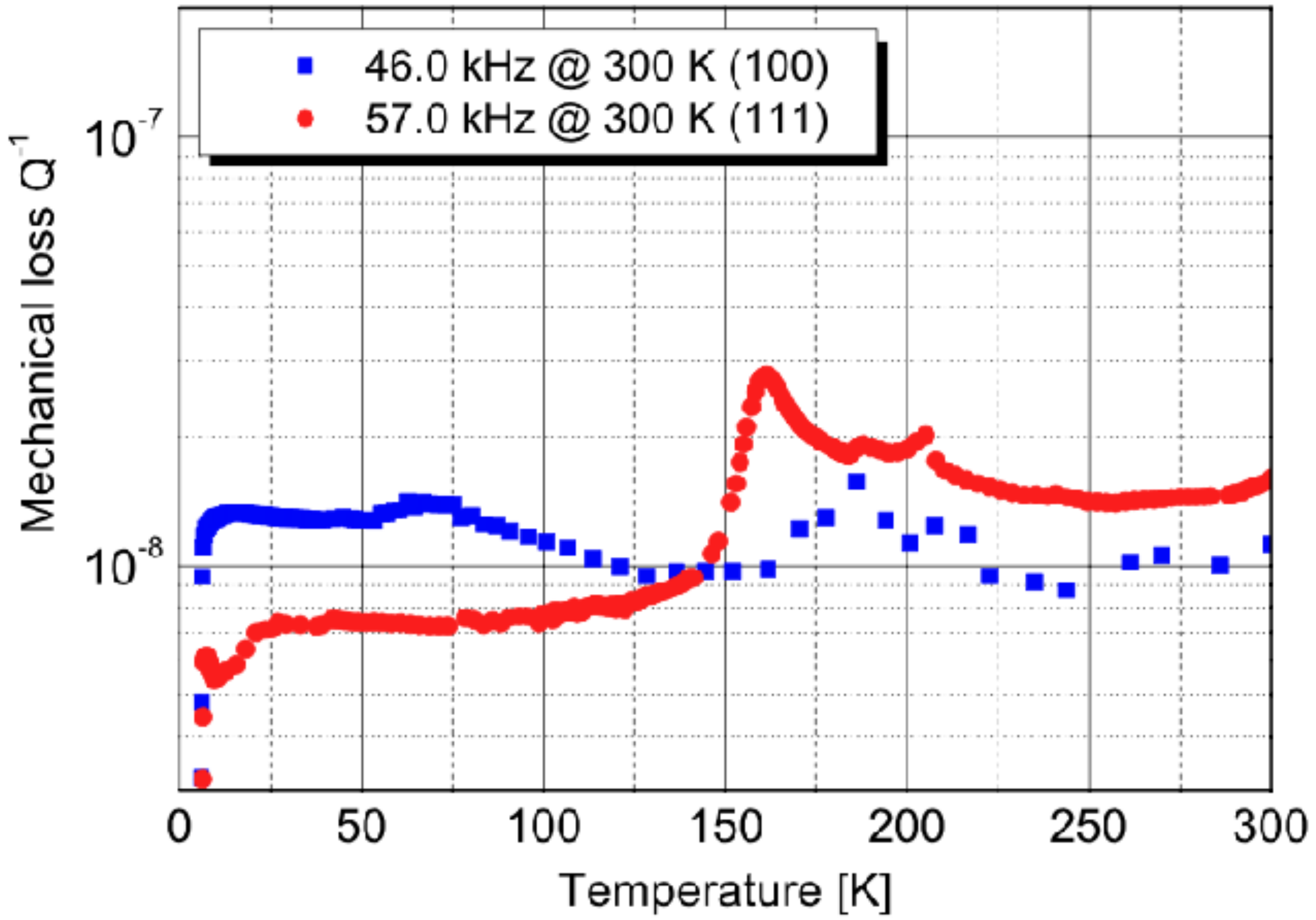
Motivation for long wavelengths

- Thermal noise is a major limiting noise source
- Going cryogenic does not help with current mirror material fused silica: its mechanical loss increases at low temperatures.
- **Silicon would be a solution, but is not transparent at commonly used wavelength 1064nm, requires >1300nm.**
- telecommunication wavelength 1550nm is baseline design, 2000nm also under consideration as it would allow also amorphous silicon as a coating material.

fused silica



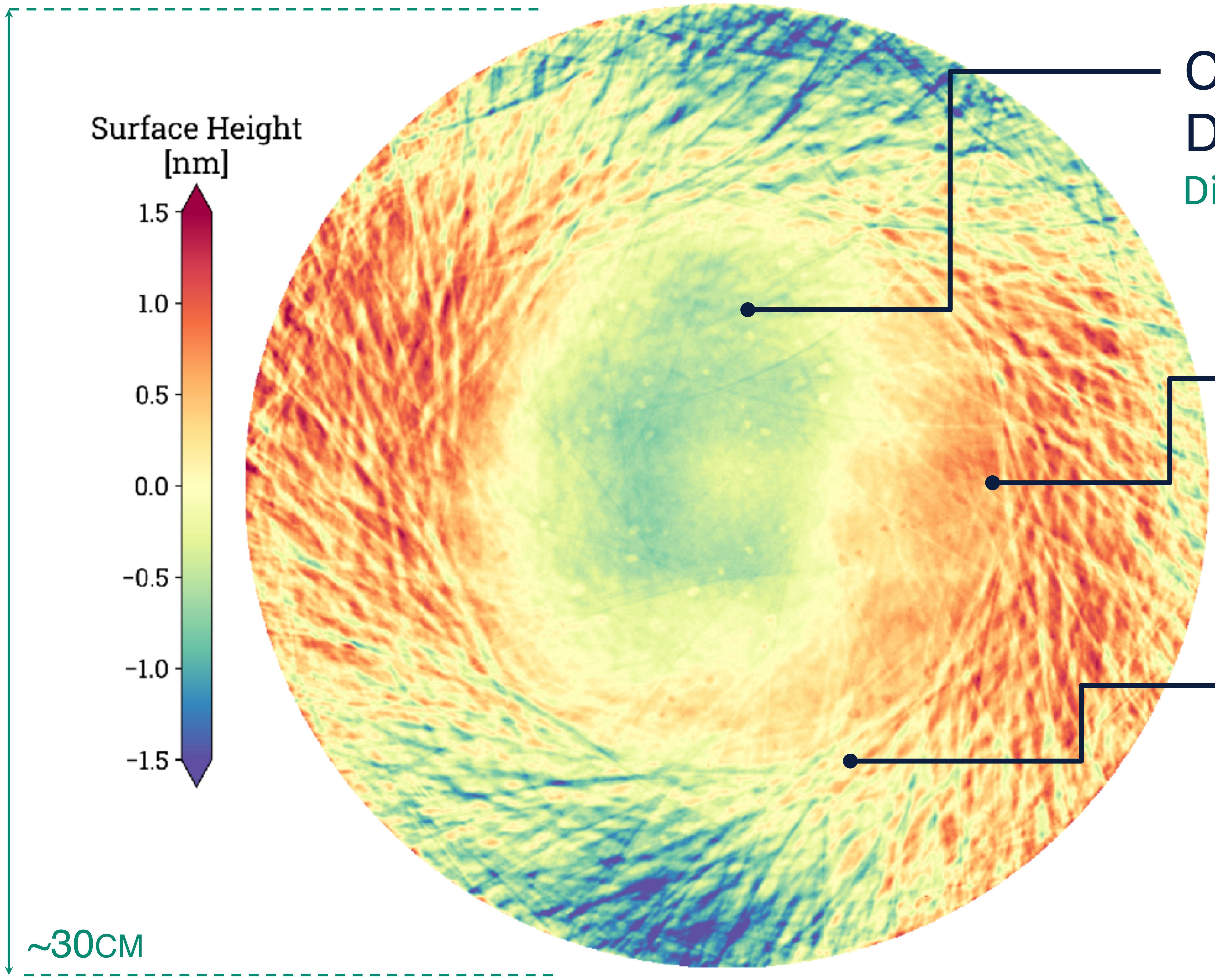
silicon



[Sebastian Steinlechner]

[M. Perciballi - EGO]

Anatomy of a mirror surface



Curvature Deviations
Distorted beam shapes

Surface Micro-Roughness
Wide-angle scatter

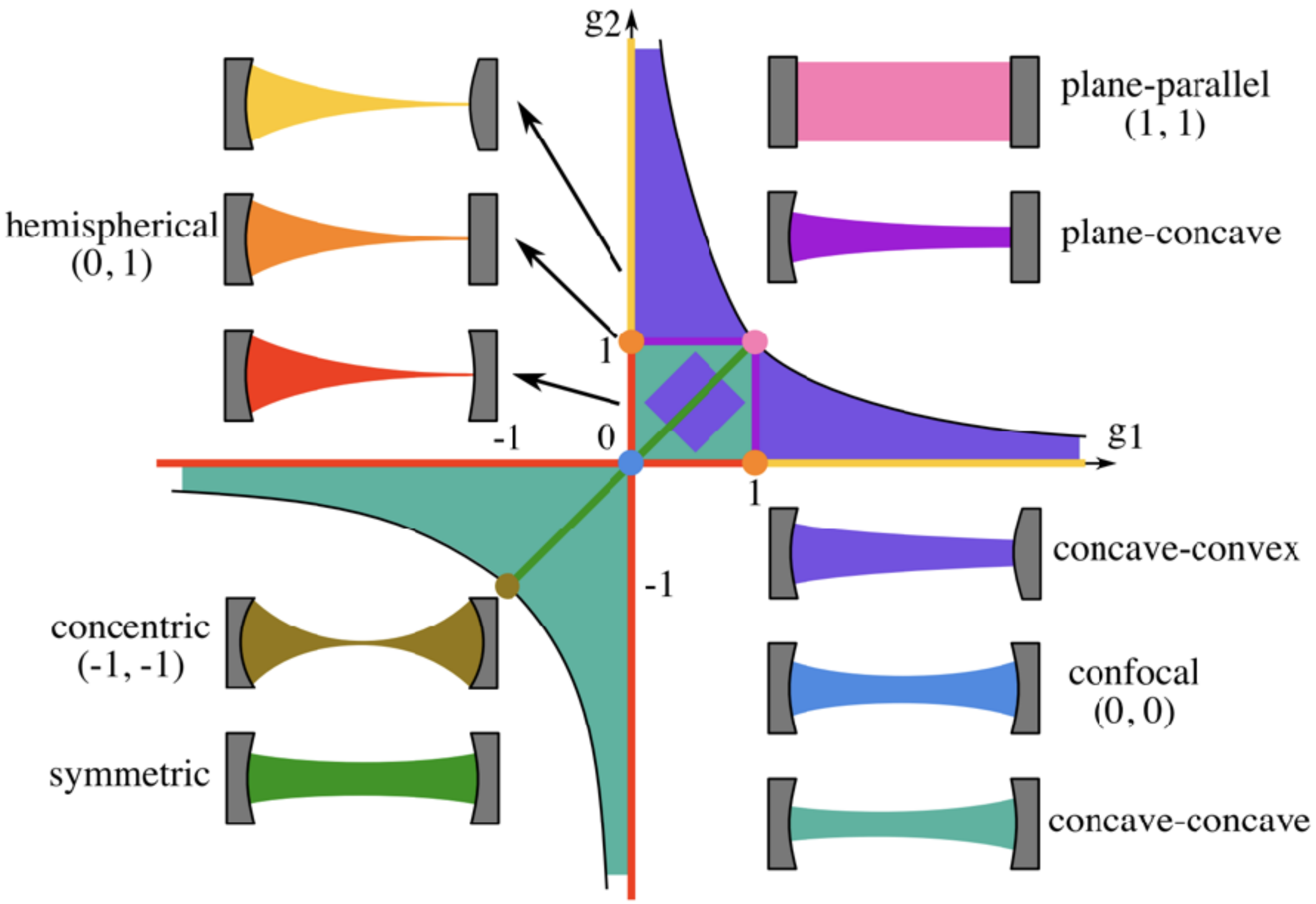
Scratches, Point Defects, …

Neither? Both? Static?
Temperature-dependent?

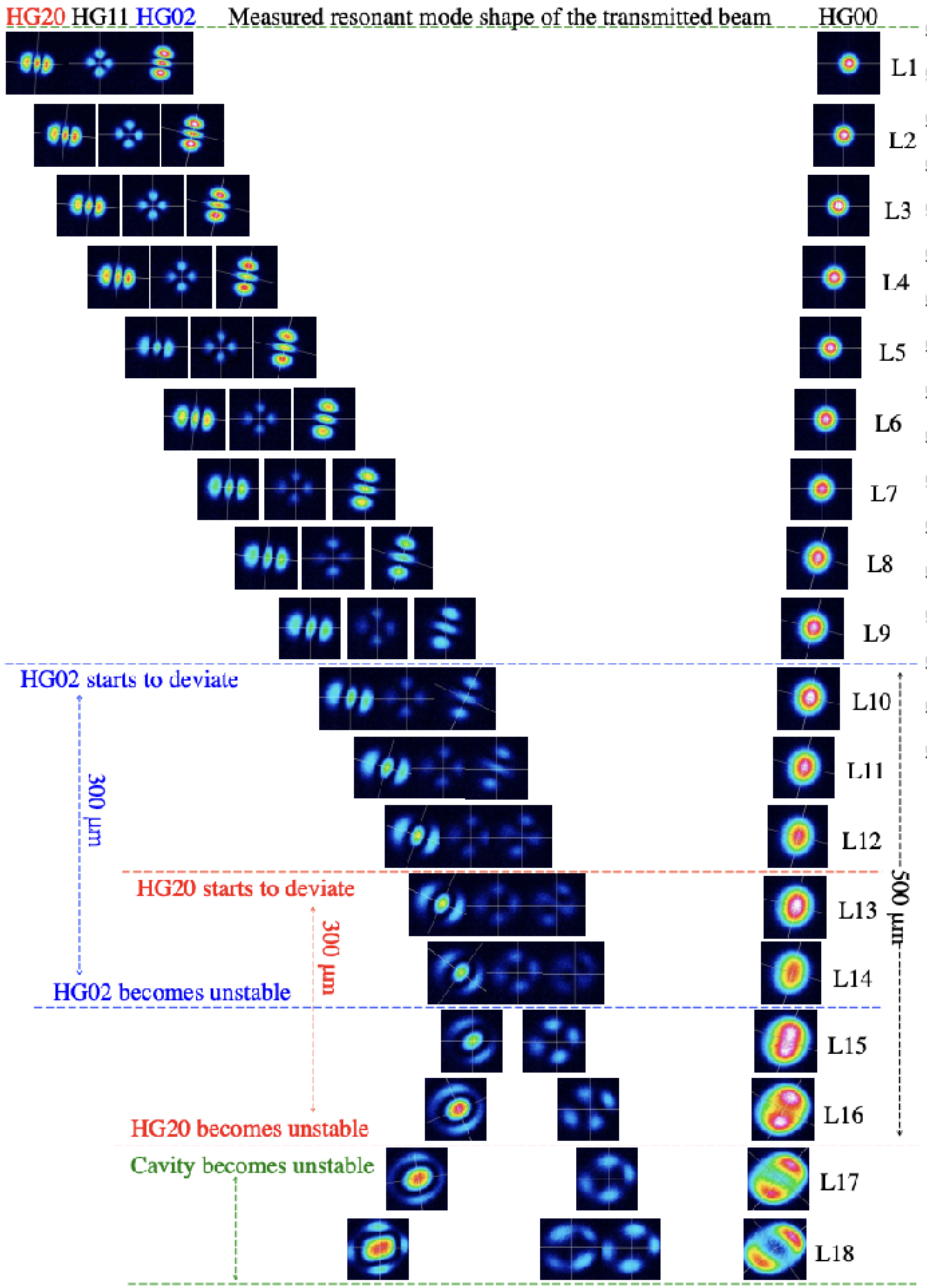
[Anna Green, mirror data: ETM08, LIGO]

Cavity stability

Cavity stability is determined by geometry (lengths & mirror curvatures). Some geometries have advantages (low cost, large beams) **but strongly amplify any mirror-surface defect**.



[https://journals.aps.org/prd/abstract/10.1103/PhysRevD.97.022001]



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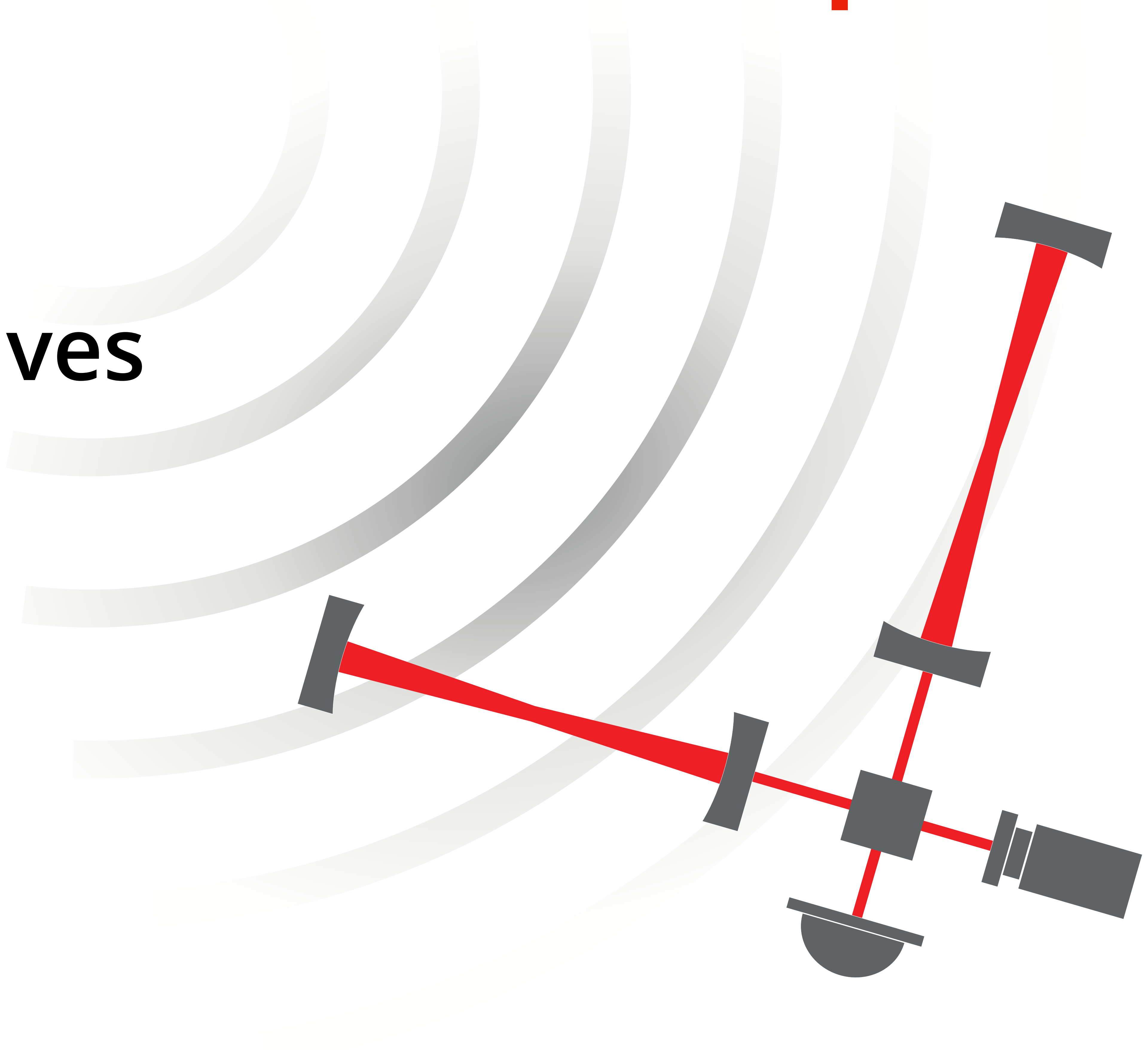
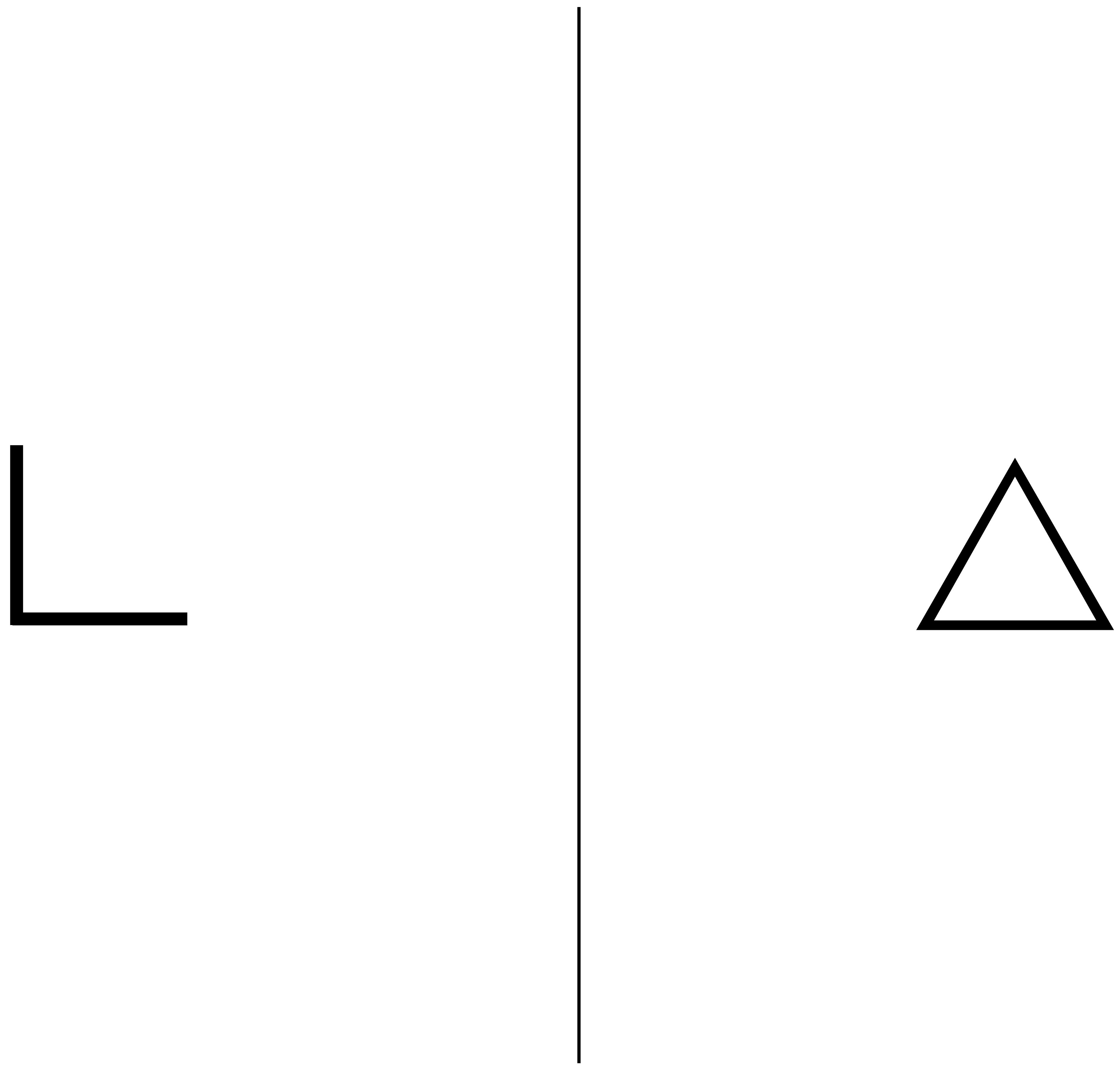
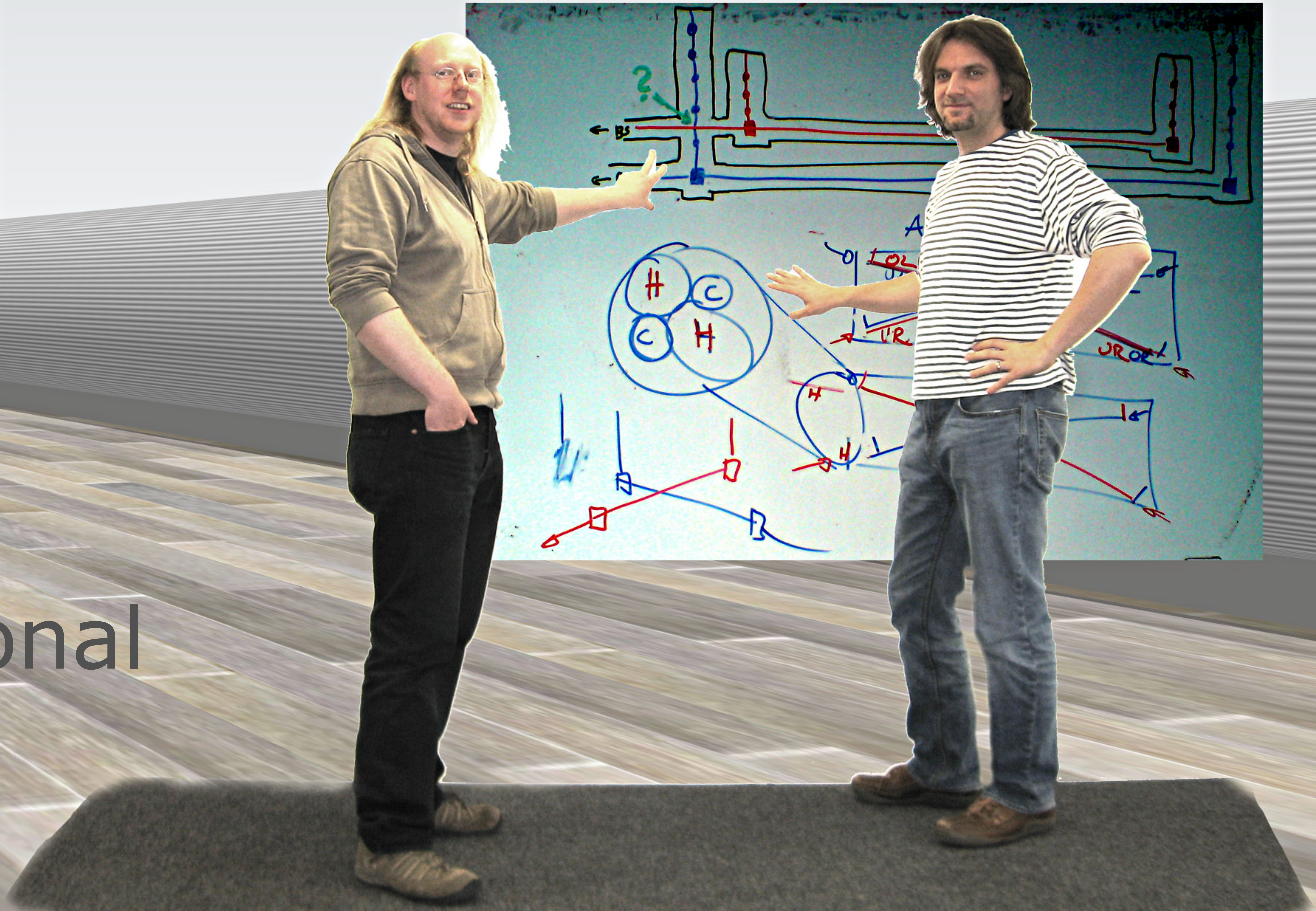


An old classic!



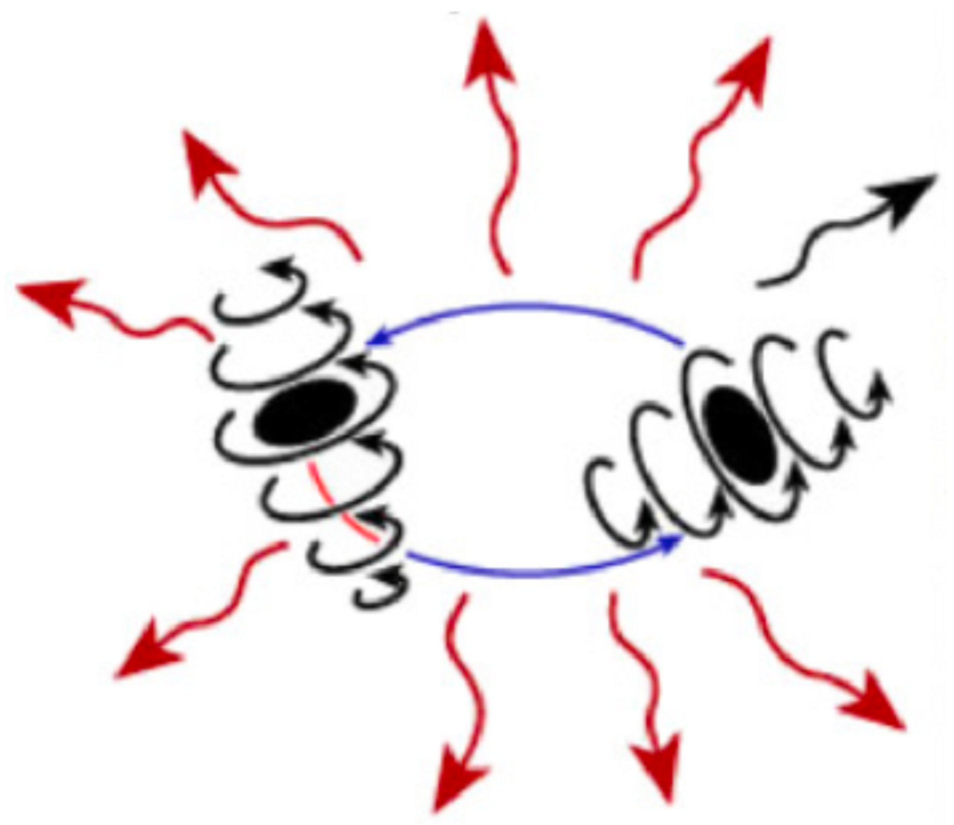
In the following I will explain the basic, original arguments that led to the idea of using the triangle when it was first proposed.

Andreas Freise for the ET WP3 working group
20.05.2010 GWADW, Kyoto



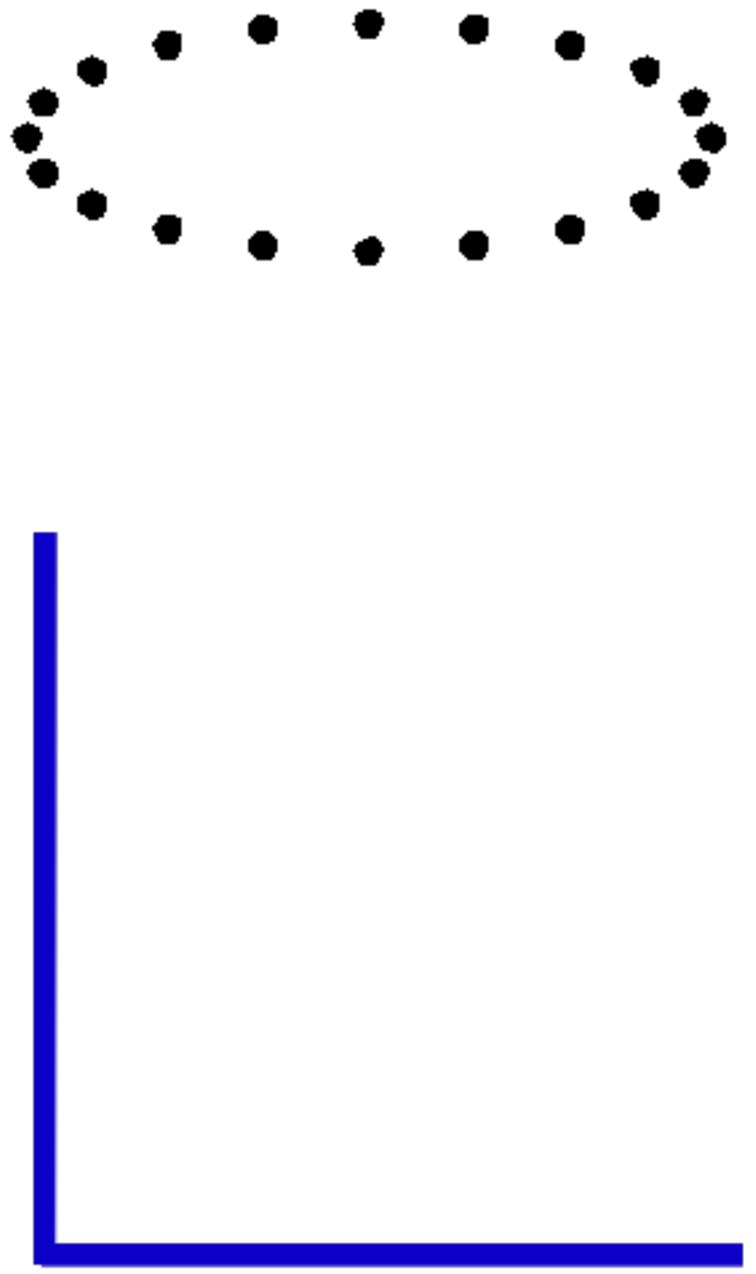
Einstein gravitational wave **T**elescope

A (very!) short lecture on gravitational waves

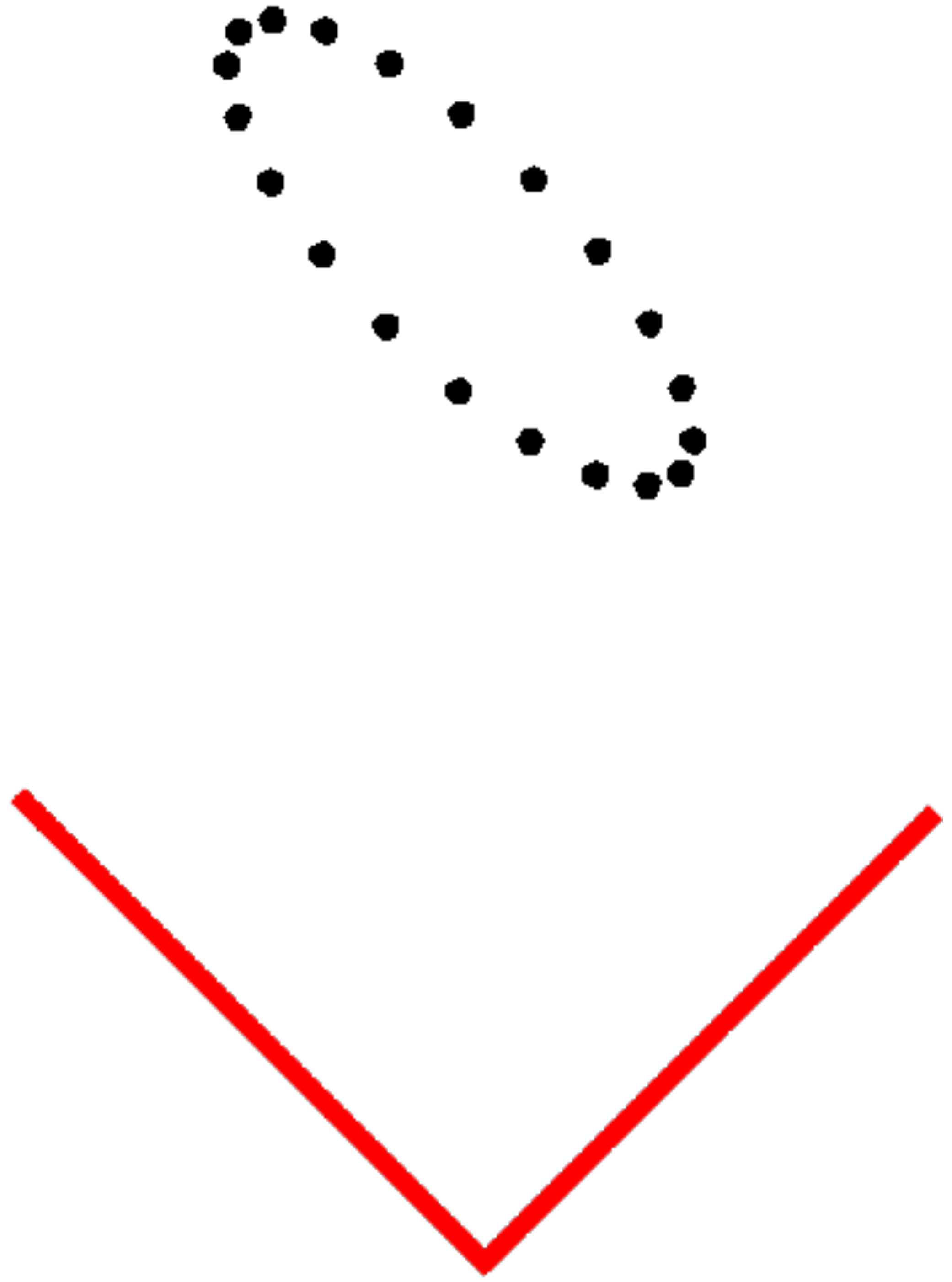


Gravitational wave source

‘plus’ (+) polarisation



‘cross’ (x) polarisation



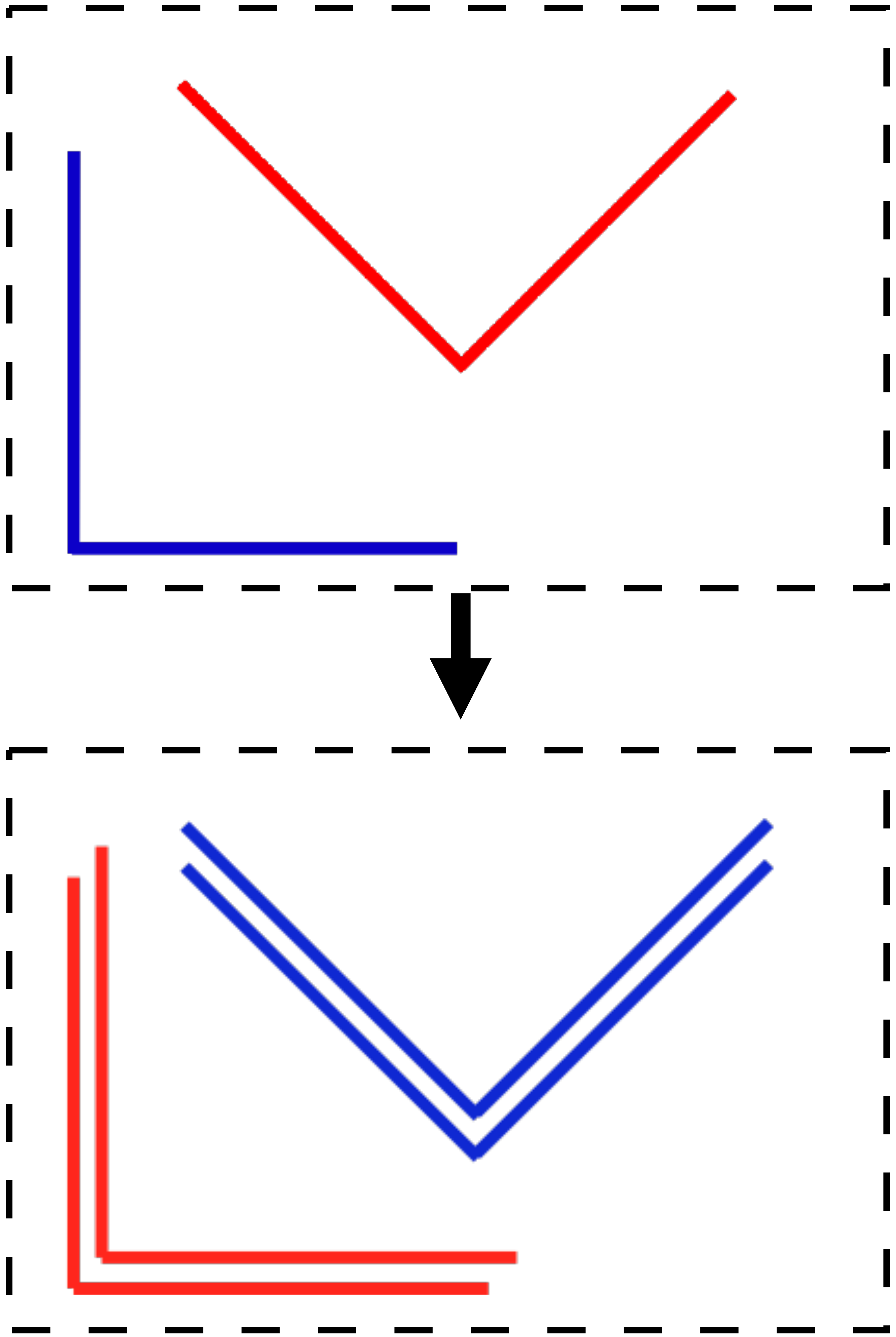
- An L shape is ideal for measuring gravitational waves.
- Gravitational waves signal are spread over two polarisation.

Co-located detectors: redundancy and null stream

- **Co-located:** build two interferometers in one site with the same signal response.

- **Redundancy**: Allows down-time of individual detectors without reducing "on-sky" time of the observatory.

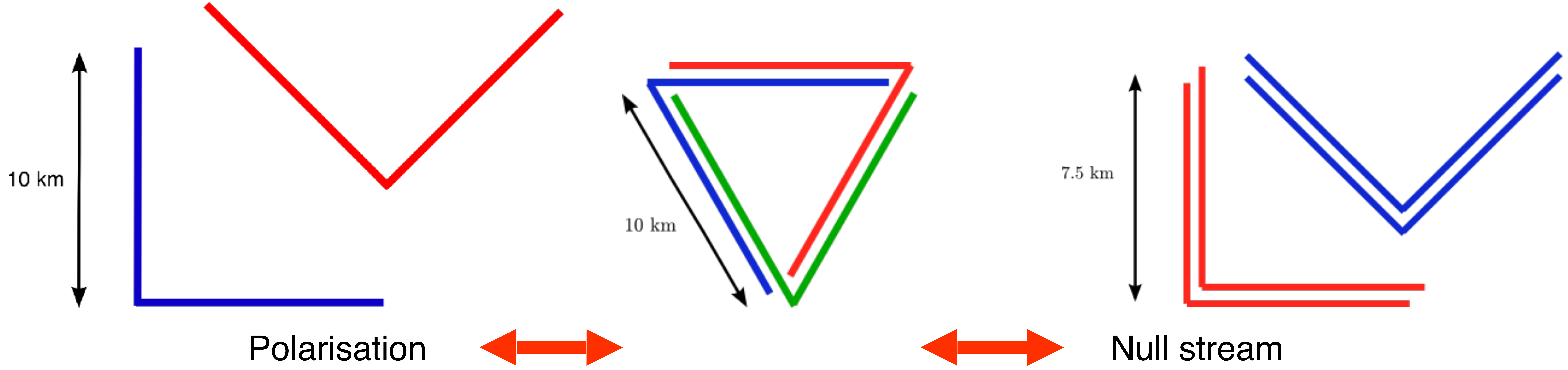
- **Separating noise from signal:** two co-located detectors might be used to generate a data stream *without* signal, which may be utilised for advanced data analysis methods such as better calibration, noise identification.



Optimised single-site: the triangle shape

The triangle hosts three independent detectors in one single location:

- full signal capture in both polarisations
- construction of null-streams
- redundancy for 24/7 operation



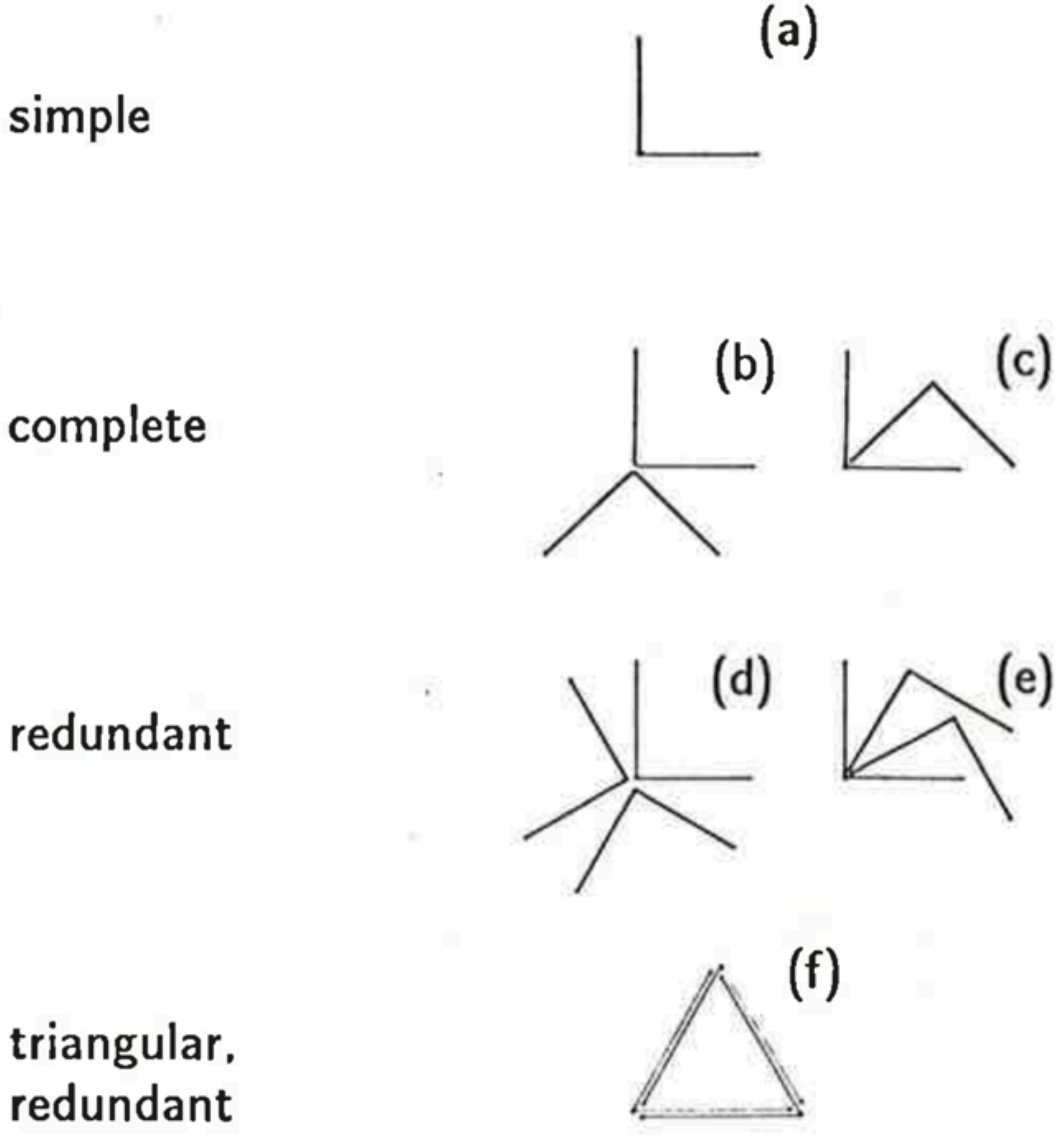
Proposal for GEO, 1985

MAX-PLANCK-INSTITUT FÜR QUANTENOPTIK

Plans for a large gravitational wave antenna in Germany

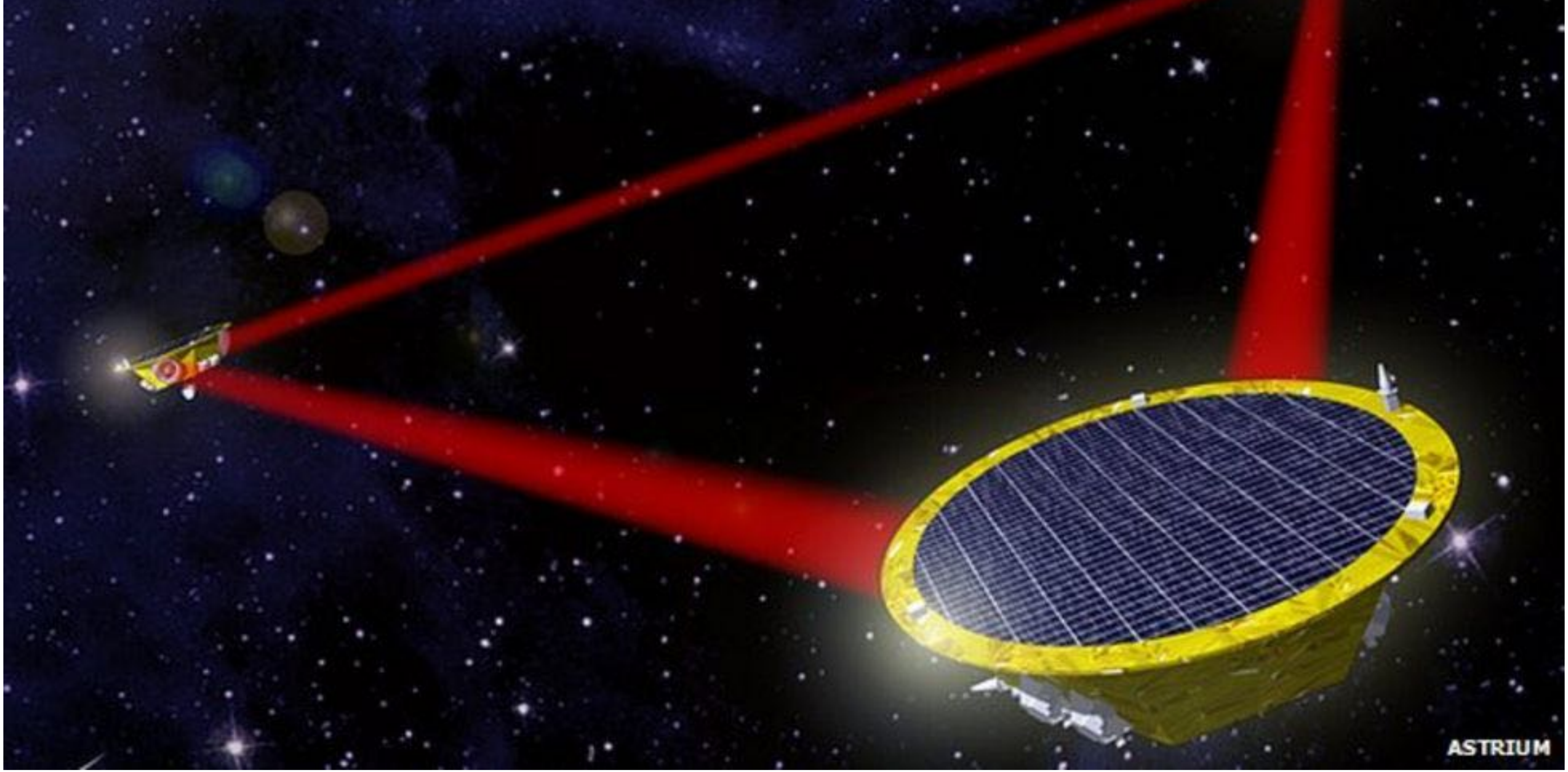
Walter Winkler, Karl Maischberger, Albrecht Rüdiger
Roland Schilling, Lise Schnupp, David Shoemaker

M P Q 101 August 1985



https://www.mpq.mpg.de/5128270/MPQ101.pdf

LISA, a space based gravitational wave detector,
ESA mission, launch planned for 2035.

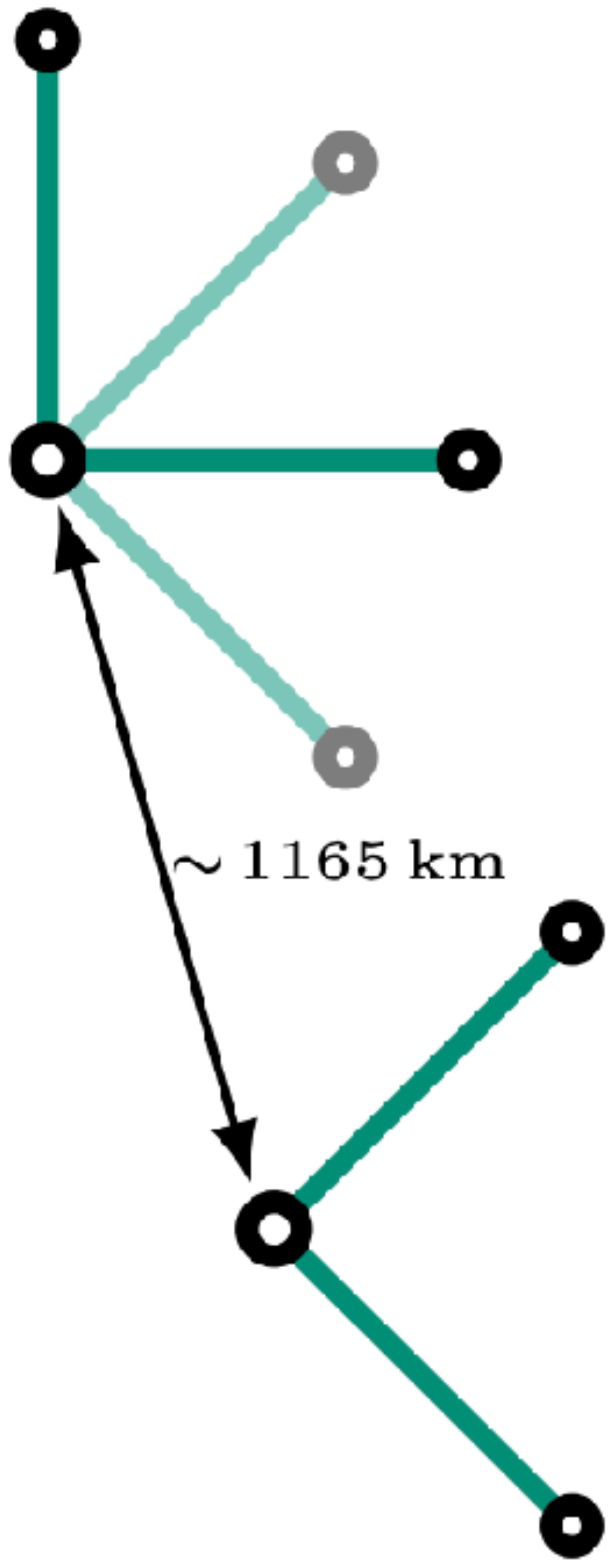


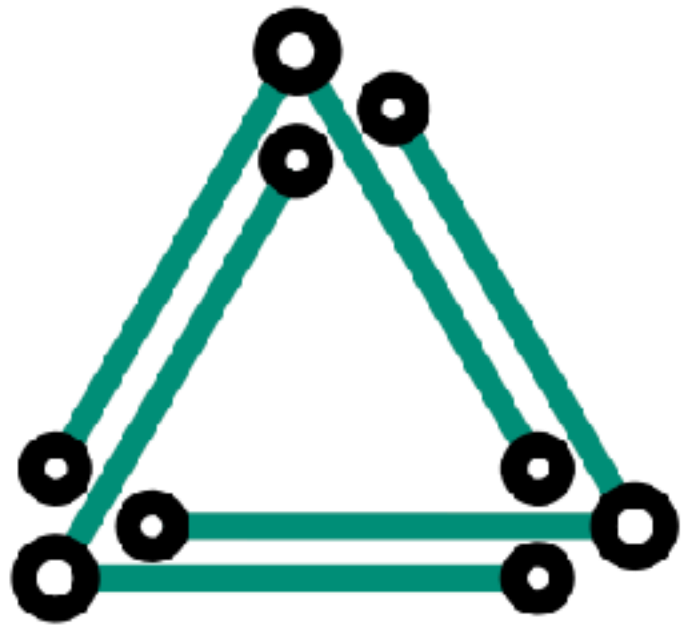
https://www.esa.int/Science_Exploration/Space_Science/LISA_factsheet

Improved analysis for ET in a new scientific study

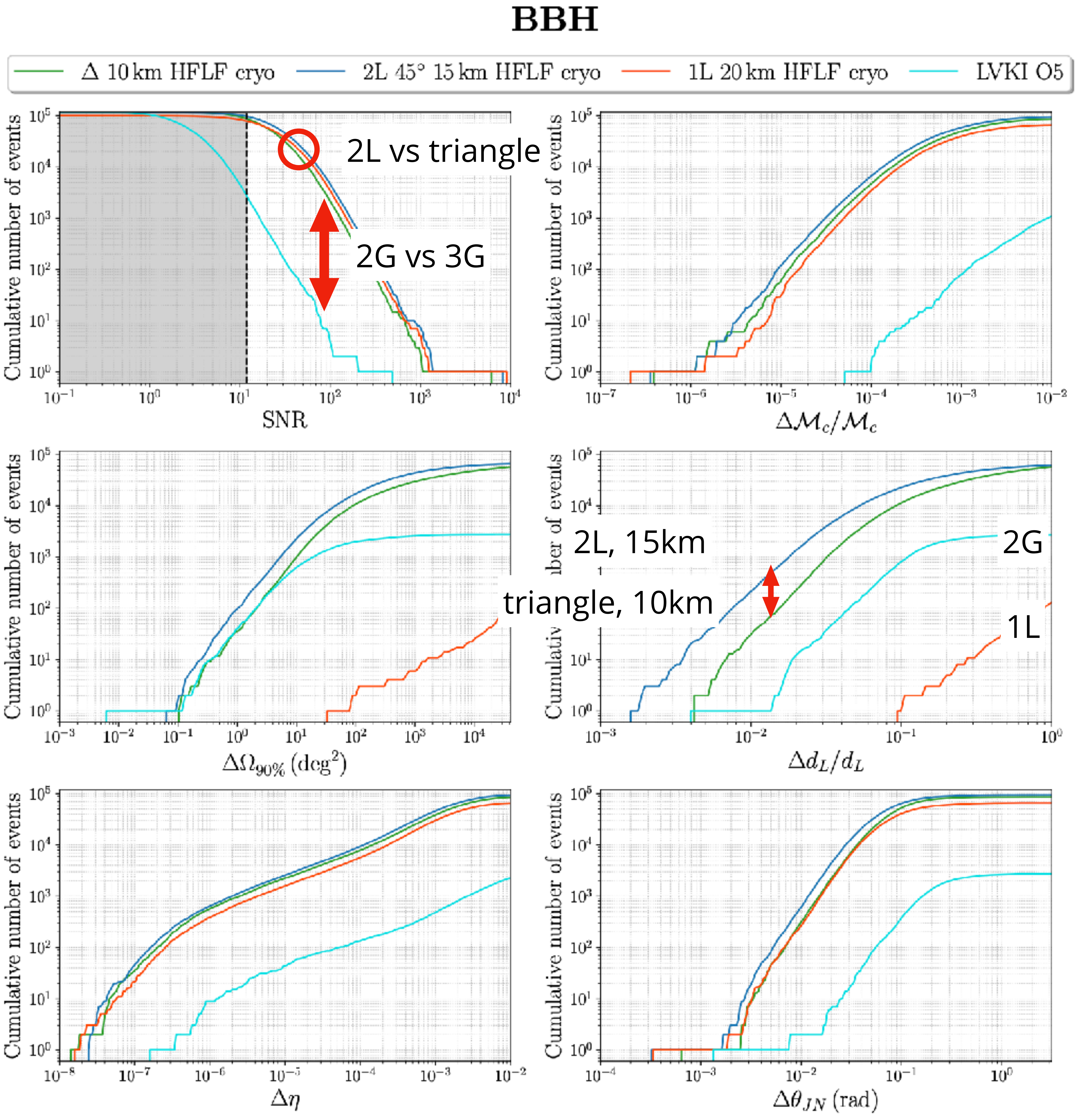
- Instead of simply comparing the detector sensitivity, we ask the question: **"How well can we measure the parameters of a signal?"**.
- The basis of the method is to use simulated signals for a broad range of sources and then perform **parameter estimation** analysis.
- The performance of a geometry can then be quantified by:
  - **how many** of the simulated signals were detected, and
  - **how accurately** was the signal recovered by the detector.

Geometries being studied (in this paper)





- triangle with 10 km arms (the current baseline ET geometry)
- triangle with 15 km arms
- 2L with 15 km arms, with parallel arms
- 2L with 15 km arms, with a relative orientation of 45 deg
- 2L with 20 km arms, with parallel arms
- 2L with 20 km arms, with a relative orientation of 45 deg

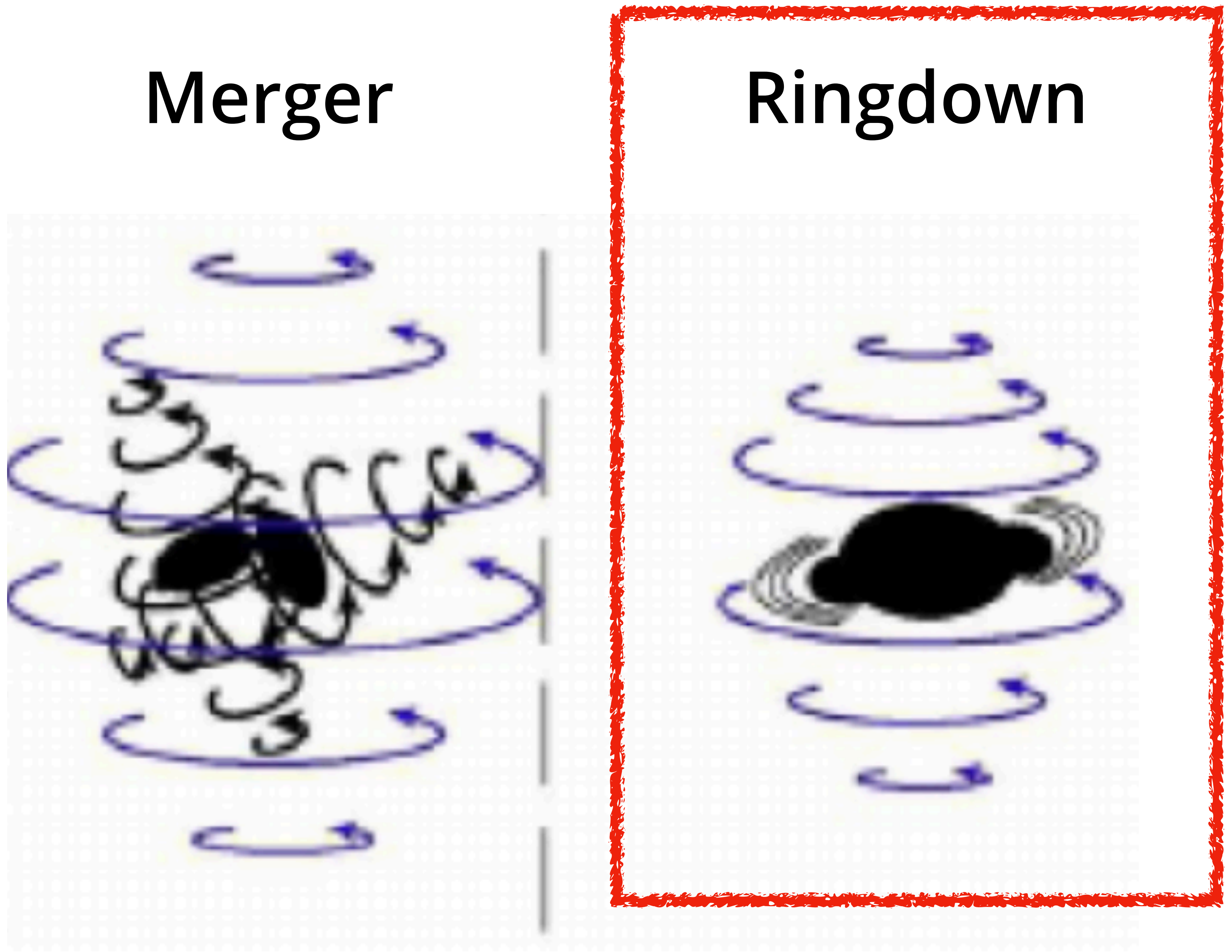


Example graph showing some of many specific results

- 2G = 'second generation', refers to future performance of current detectors (LIGO, Virgo, KAGRA)
- 3G = 'third generation' refers to ET
- y-axis: higher is better, note the logarithmic scale
- x-axes: different parameters of the source signal

The difference can be significant

Two black holes, after a collision:



	N_{det}(SNR $\geq$ 12)	N_{det}(SNR $\geq$ 50)	N_{det}(SNR $\geq$ 100)	max(SNR)
LVKI-O5	15	0	0	38
ET				
Δ-10 km	4665	34	3	262
Δ-15 km	11692	117	13	317
2L-15 km-0°	11627	110	11	281
2L-15 km-45°	10175	97	9	330
2L-20 km-0°	18972	255	21	327
2L-20 km-45°	17185	228	18	384

Table 14. Number of ringdown events per year above the detection threshold (SNR $\geq$ 12), with high signal-to-noise ratio (SNR $\geq$ 50), and golden events (SNR $\geq$ 100) for different proposed detector designs (all taken in the HFLF-cryo configuration) and compared to the most optmistic prospect for LVKI in O5. The last column displays the SNR of the loudest event in the catalogue. Here SNR refers to the ringdown part of the signal only.

- The “small” differences in the logarithmic plot can be significant.
- Longer detectors could make a big difference for some key events.

Selected outcomes of the scientific comparison

- All the triangular and 2L geometries that we have investigated can be the baseline for a superb next-generation detector, that will allow us to improve the number of detections by orders of magnitudes compared to LIGO and Virgo.

- The 2L-15km (45 deg) configuration in general offers better scientific return with respect to the 10 km triangle, improving on most figures of merits and scientific cases, by factors typically of order 2-3 on the errors of the relevant parameters.

- The 2L-15km (45 deg) configuration and the 15 km triangle have very similar performances on all parameters […], except for luminosity distance, where the 2L-15km-45 (deg) configuration is better by a factor ~ 3 in the number events with accurately measured distance.

- The differences between the two geometries become smaller when considered in a network with a US based observatory, Cosmic Explorer.

- A single L-shaped detector is not a viable alternative, regardless of the arm length. If a single-site solution should be preferred for ET, the detector must necessarily have the triangular geometry.

… end