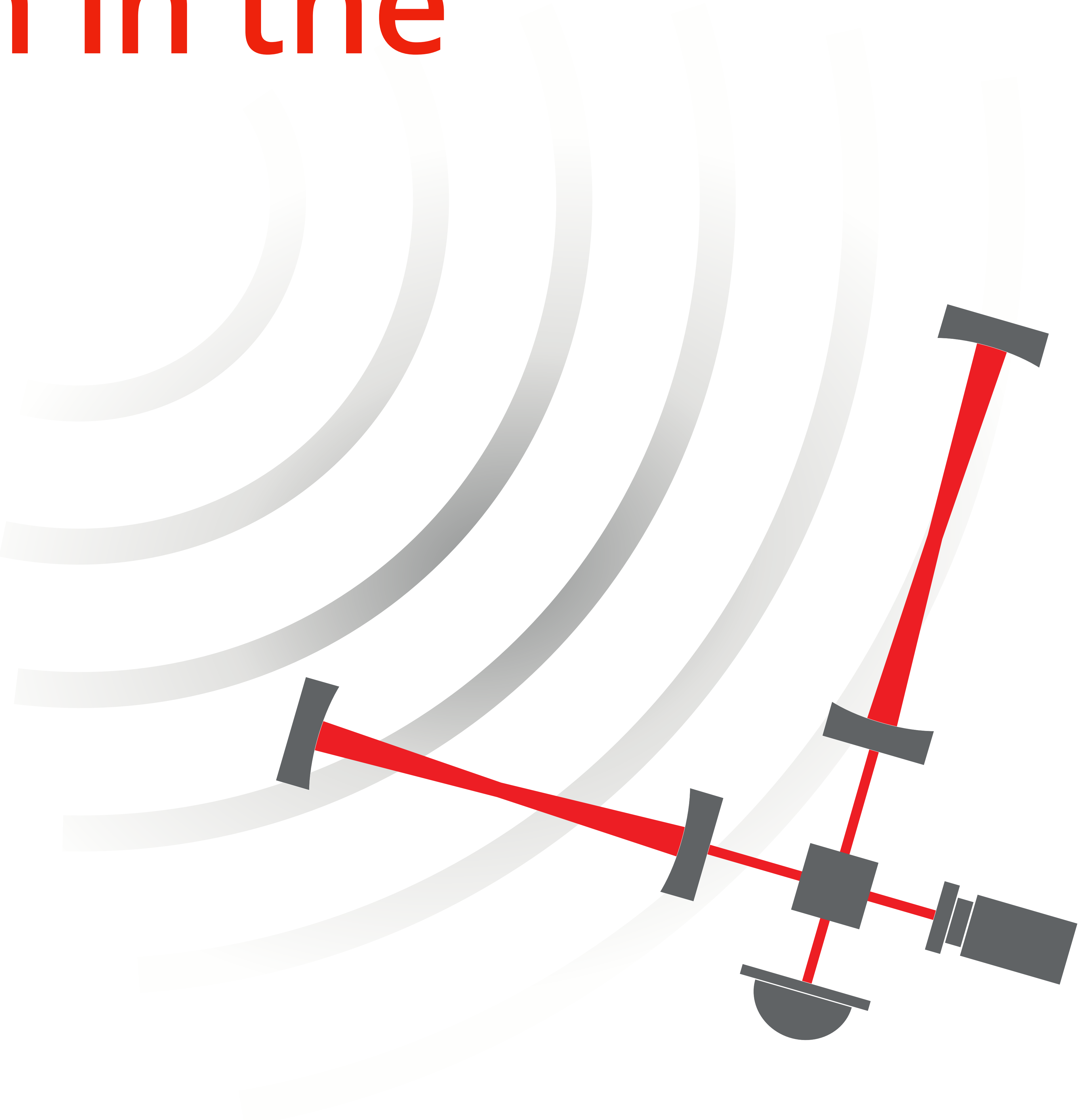
Thermal Deformations, taming the Einstein Telescope

Andreas Freise
NGF R+D, 27.03.2024

Thermal deformation in the Einstein Telescope?

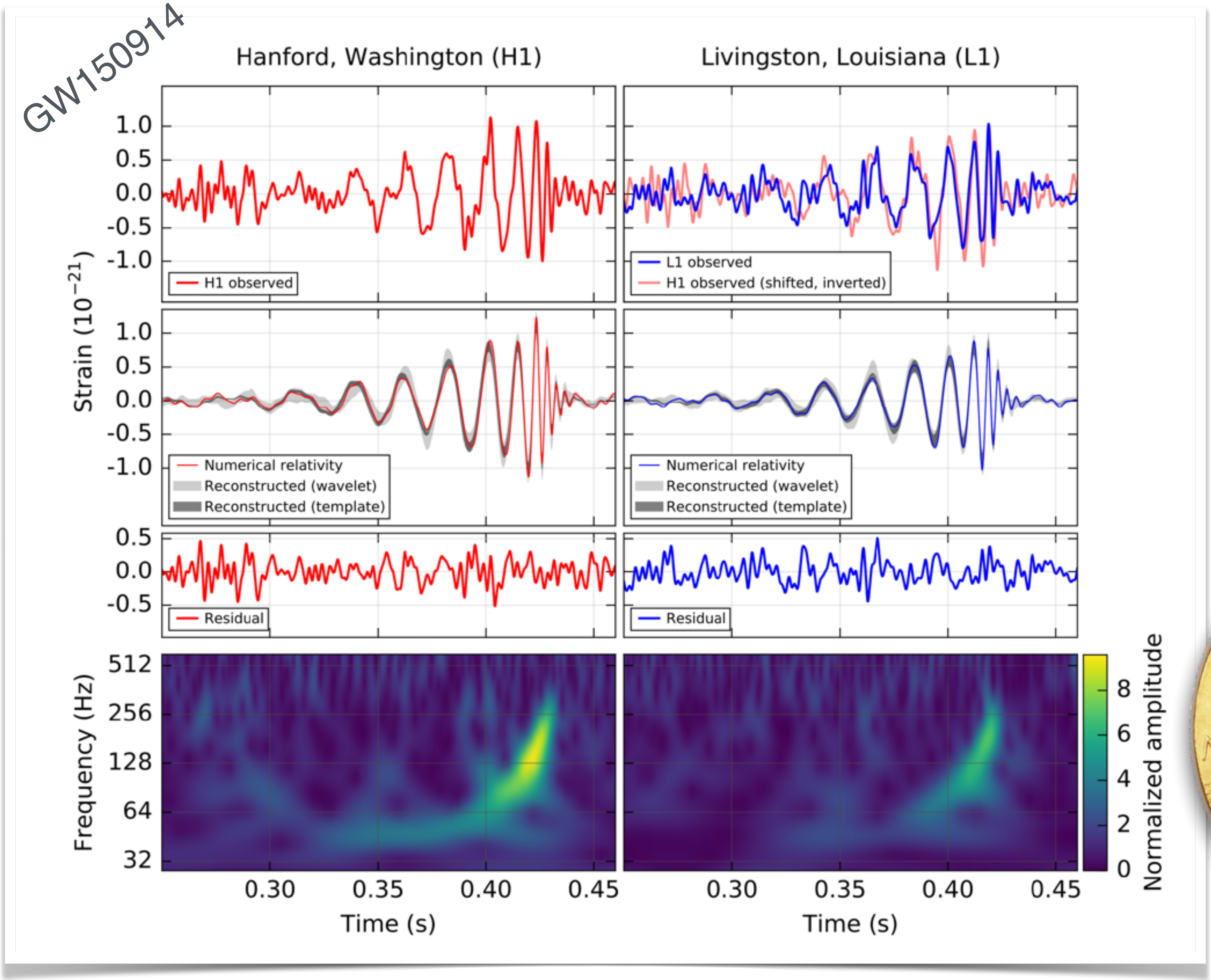


- Introduction
- Gravitational wave detectors
- Thermal deformation
- Challenges

Exploring the dark side of the Universe

- By detecting space-time vibrations on Earth, we can measure dark cosmic objects, such as black holes
- 100 years from prediction to first detection: 2017 Nobel Prize
- New window to the Universe and fundamental physics: discovery space!

LIGO, the first detection, 2015



After several decades of preparation we (LIGO) recorded the first direct detection of a gravitational wave on:
14th of September 2015, at 09:50:45 UTC

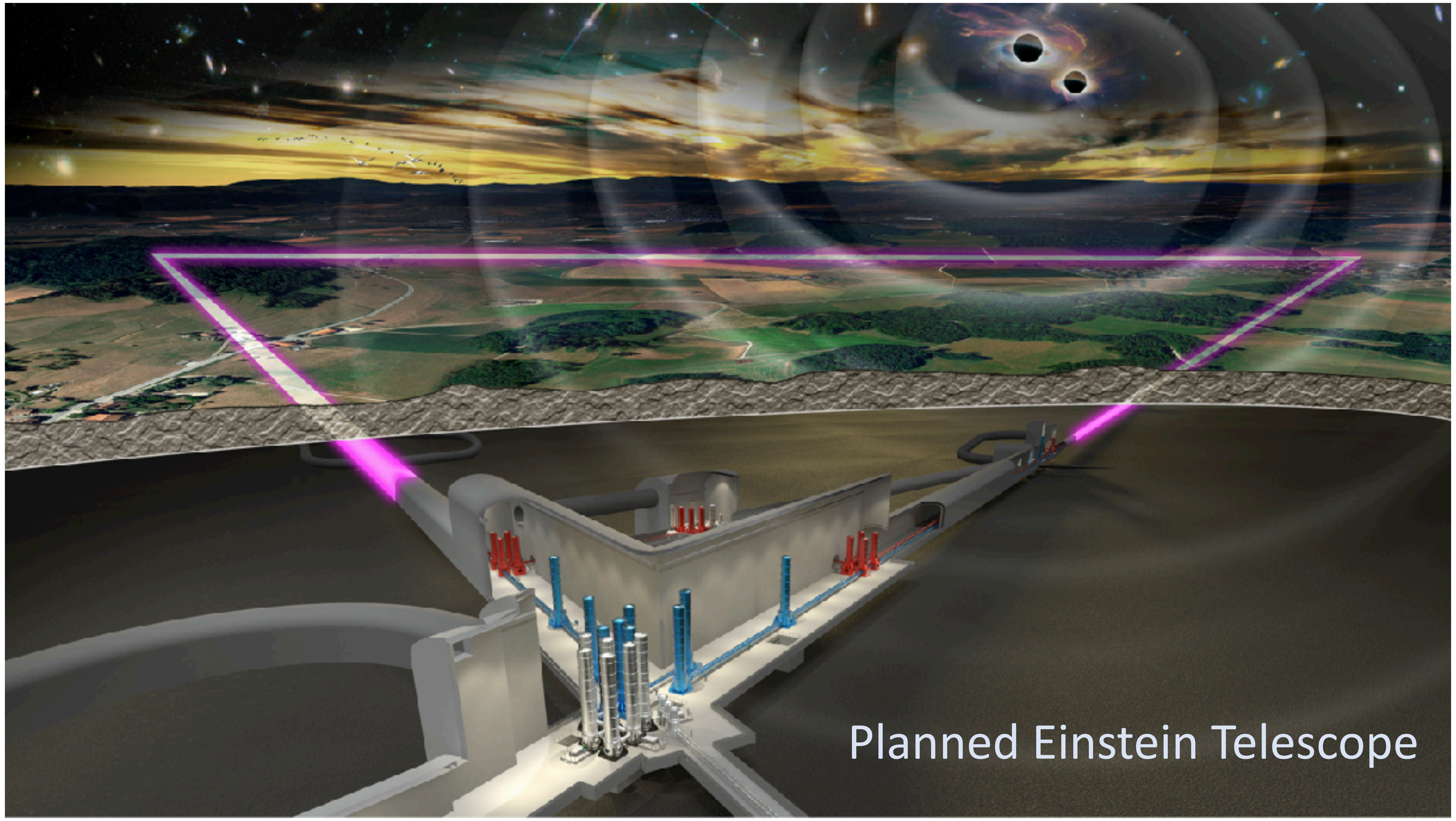
2017 Nobel Prize in Physics

Future: Einstein Telescope


Virgo, Cascina, Italy

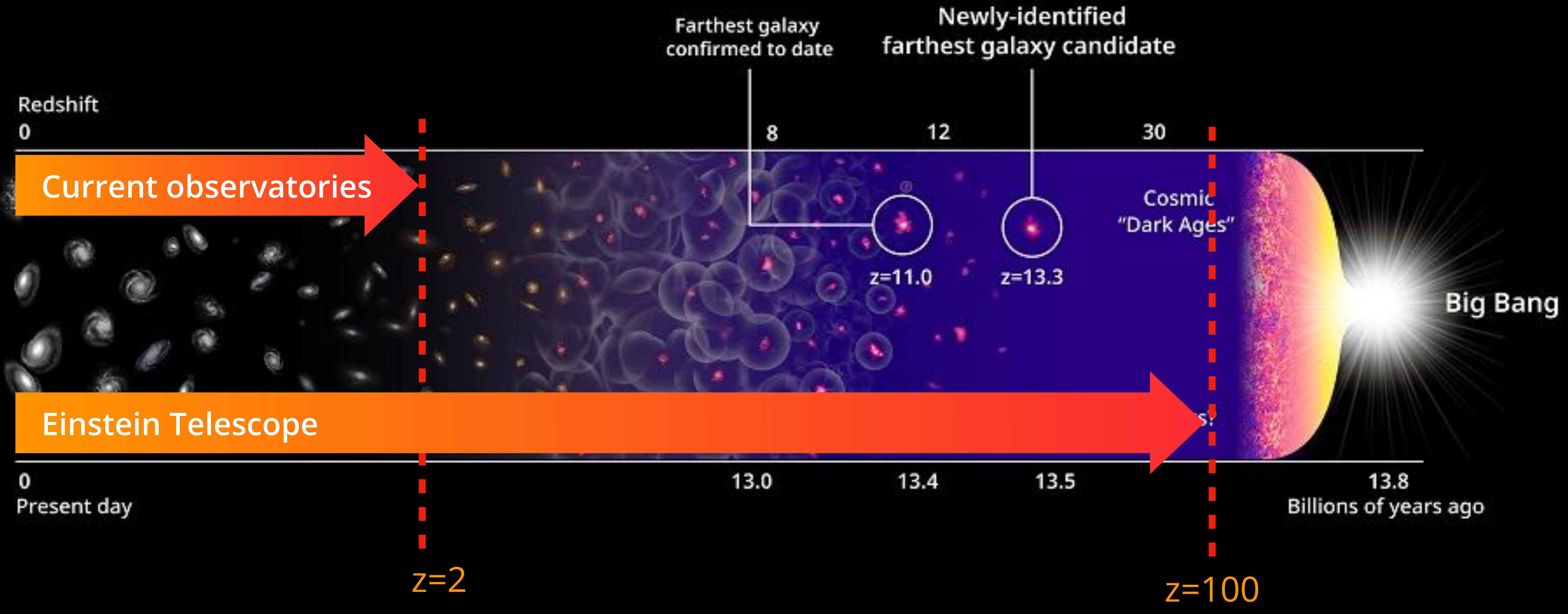

LIGO, Livingston, LA


LIGO, Hanford, WA

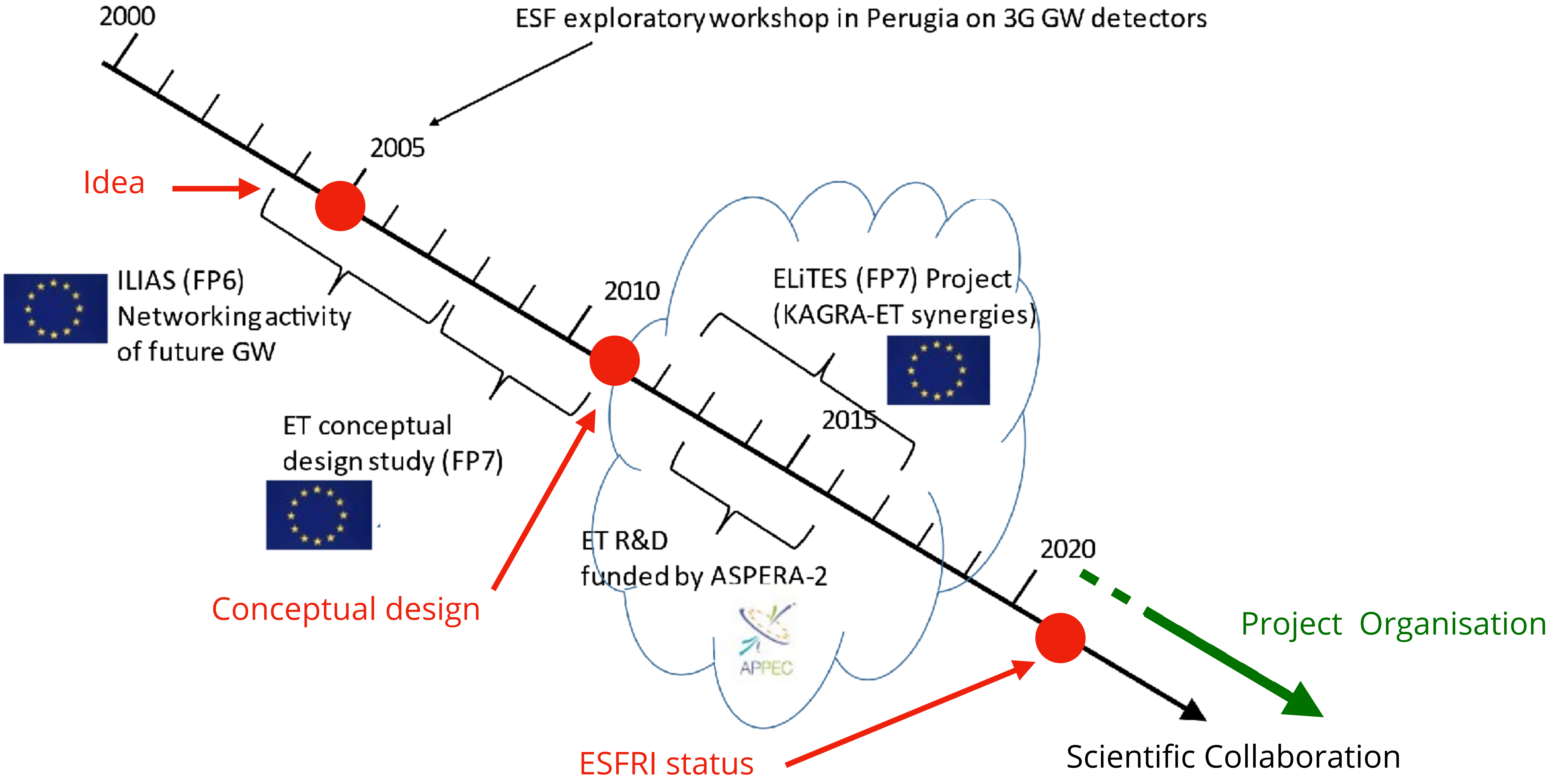

Planned Einstein Telescope

- Large laboratories and three 10 km long tunnels, more than 200m underground.
- 10 times better than design sensitivity of current detectors, providing GW data for astronomy and fundamental physics for at least 50 years.

A leap into the past



Einstein Telescope: from idea to project



2000

2005

2010

2015

2020

ESF exploratory workshop in Perugia on 3G GW detectors

Idea

ILIAS (FP6)
Networking activity
of future GW

ET conceptual
design study (FP7)

Conceptual design

ET R&D
funded by ASPERA-2

APPEC

ELiTES (FP7) Project
(KAGRA-ET synergies)

ESFRI status

Project Organisation

Scientific Collaboration

[Timeline: Michele Punturo]

Success factor, so far

- ET Collaboration:
  - Officially established 09.06.2022
  - **1559 members, 222 institutions, 24 countries and 84 research units**
- Project funding:
  - Large amounts of funding for preparing bids to host ET, for example **50M€** ETIC project (Italy), **42M€** National Growth Fund (Netherlands)
  - EU funded preparation phase project ‘ET-PP’, total value **12M€**
- International coordination:
  - Established the ET Organisation to lead the international partnership
  - **Active international group of ministry delegates meets regularly**

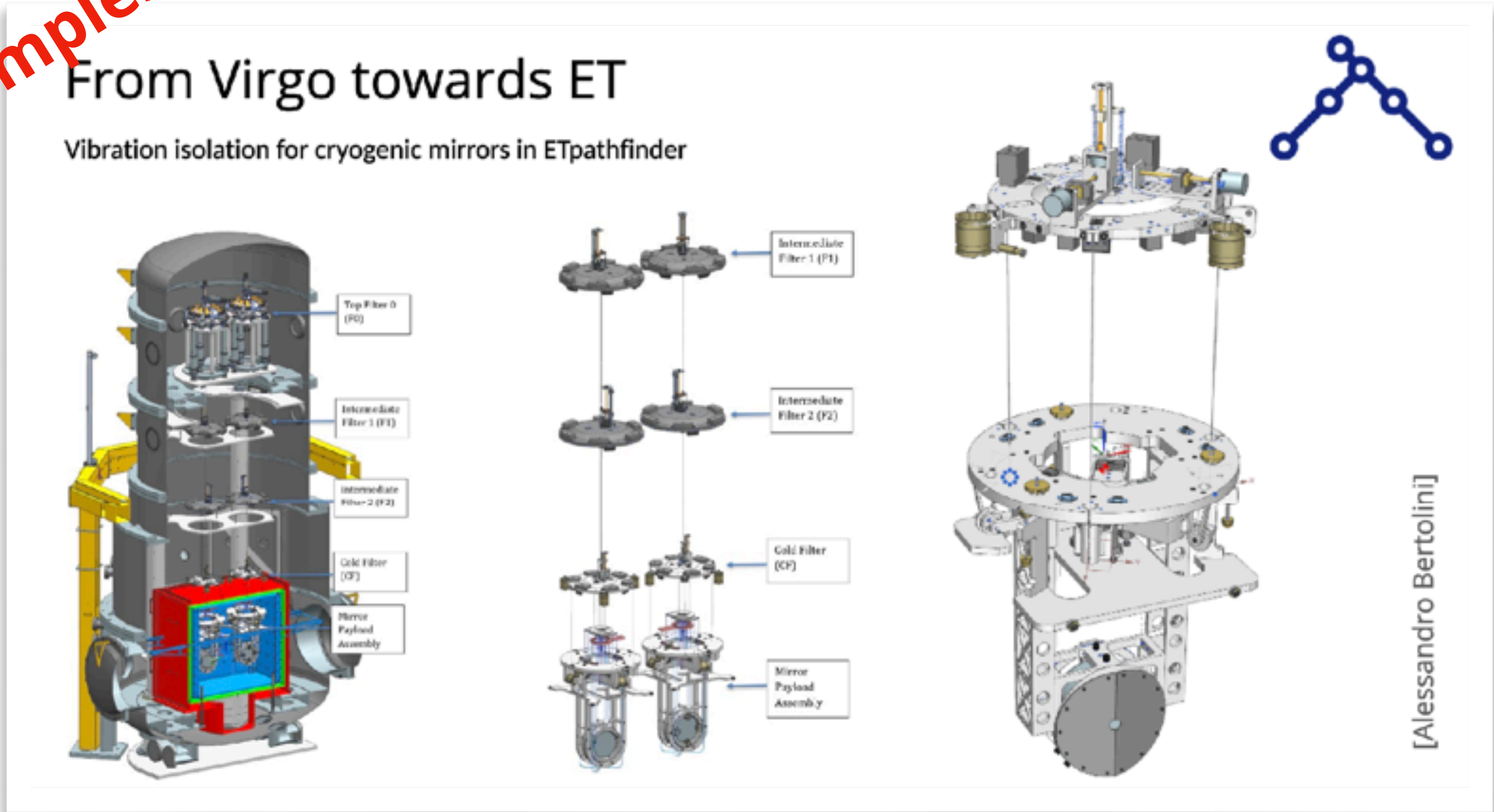
Possible ET sites

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

- 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
- A third option in Saxony (Germany) is under discussion, but not yet a candidate.

Nikhef, broad R+D Programme for essential technologies

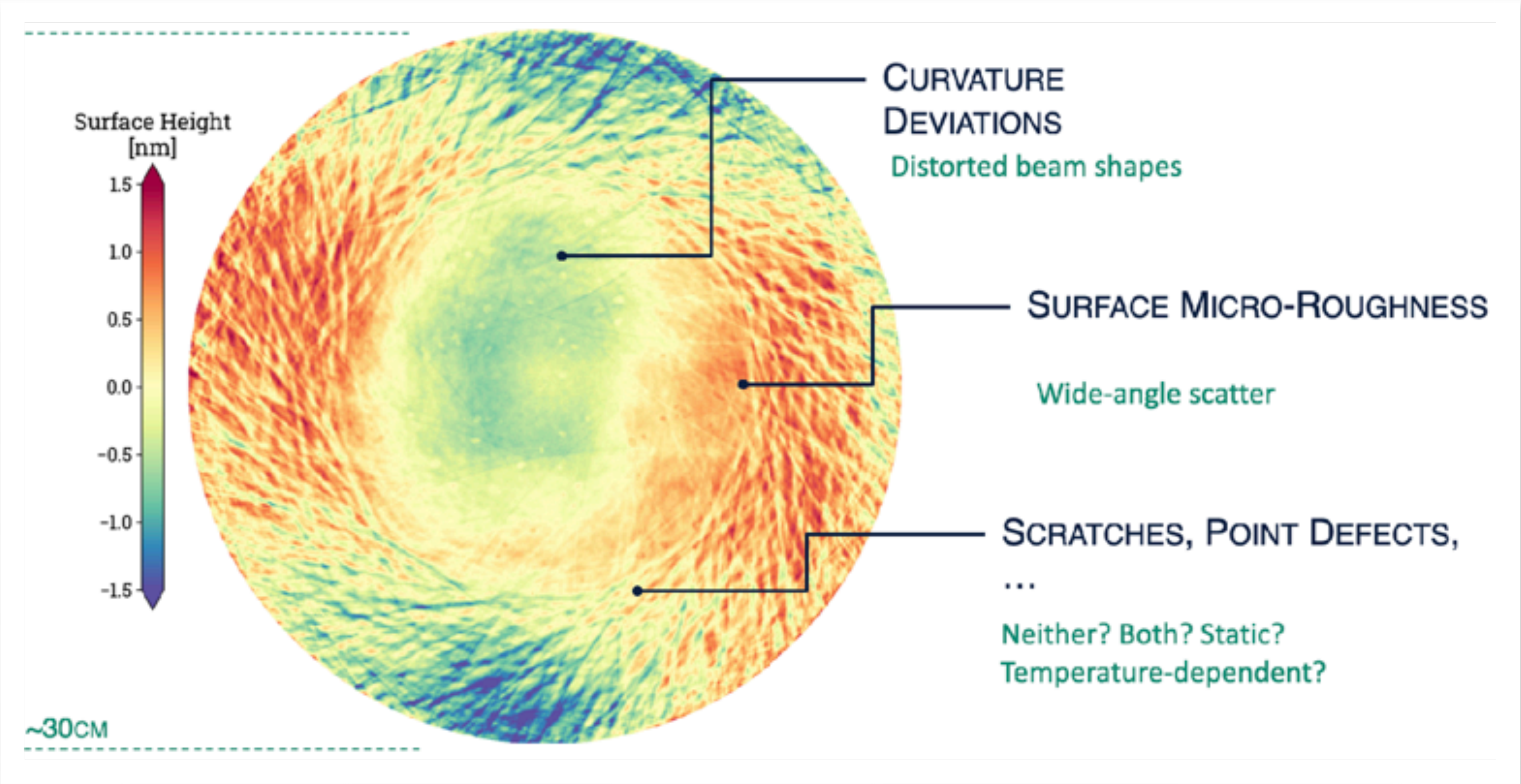
Examples



From Virgo towards ET

Vibration isolation for cryogenic mirrors in ETpathfinder

[Alessandro Bertolini]



CURVATURE DEVIATIONS

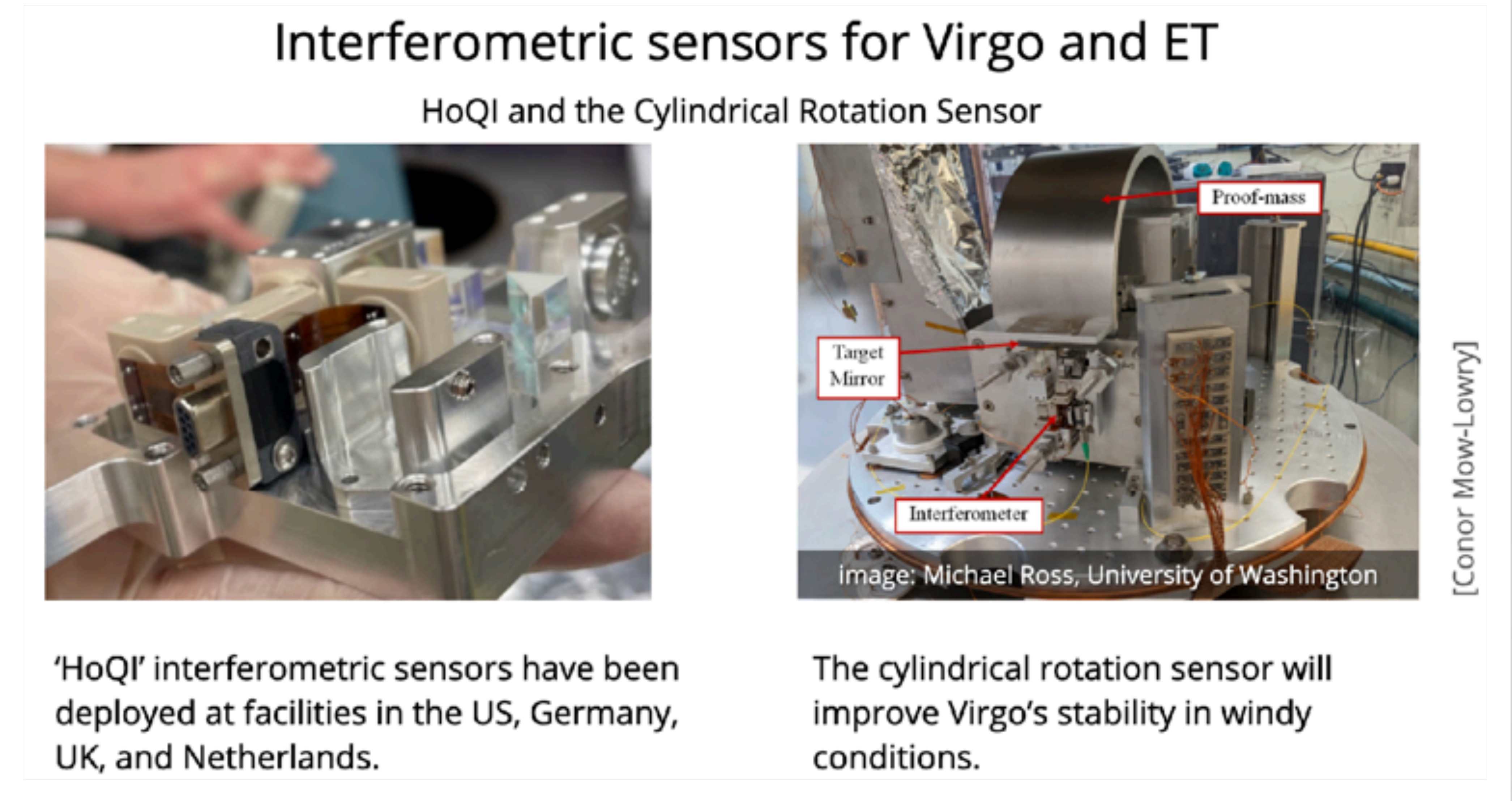
Distorted beam shapes

SURFACE MICRO-ROUGHNESS

Wide-angle scatter

SCRATCHES, POINT DEFECTS, …

Neither? Both? Static? Temperature-dependent?



Interferometric sensors for Virgo and ET

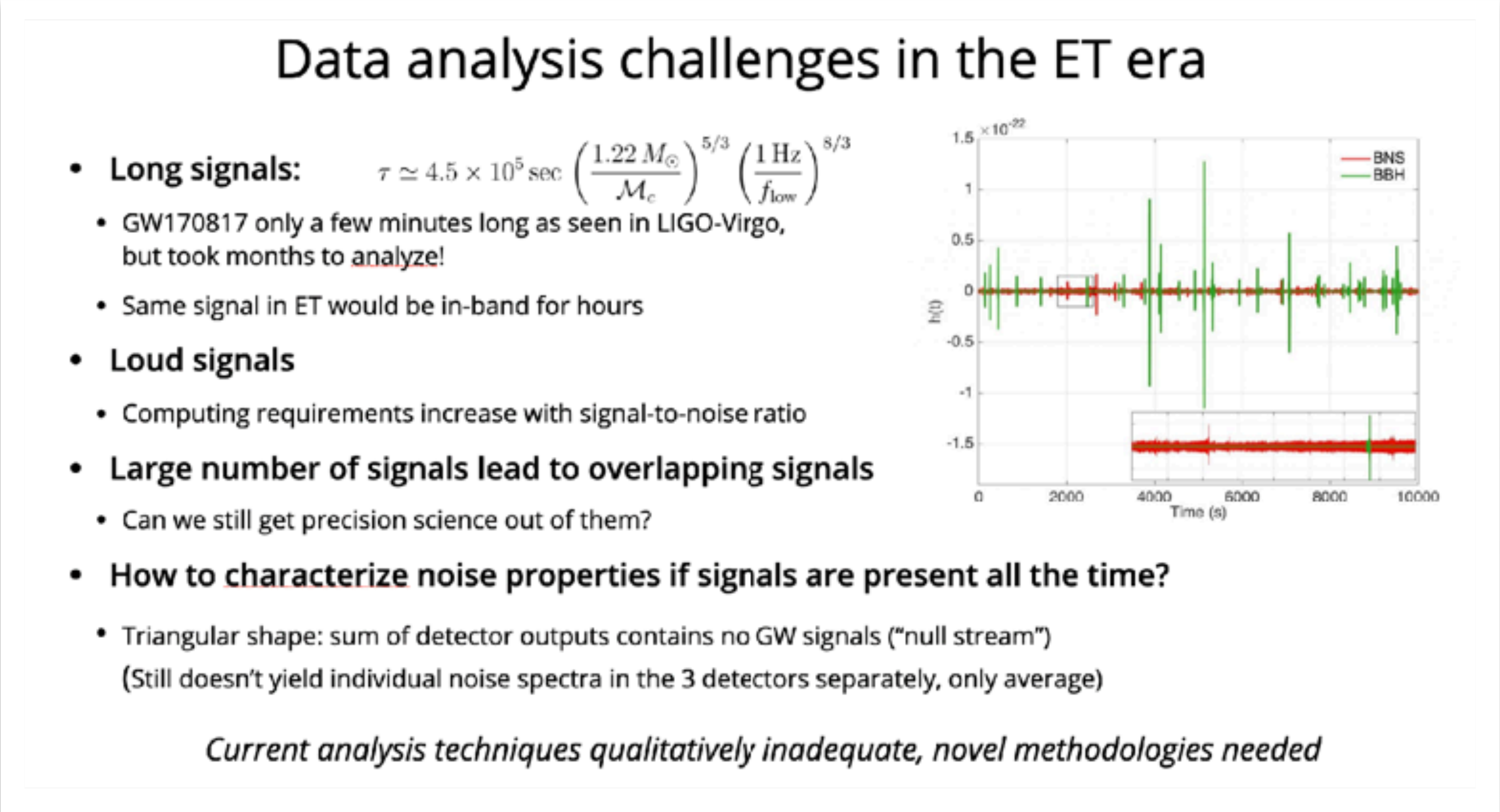
HoQI and the Cylindrical Rotation Sensor

image: Michael Ross, University of Washington

[Conor Mow-Lowry]

'HoQI' interferometric sensors have been deployed at facilities in the US, Germany, UK, and Netherlands.

The cylindrical rotation sensor will improve Virgo's stability in windy conditions.



Data analysis challenges in the ET era

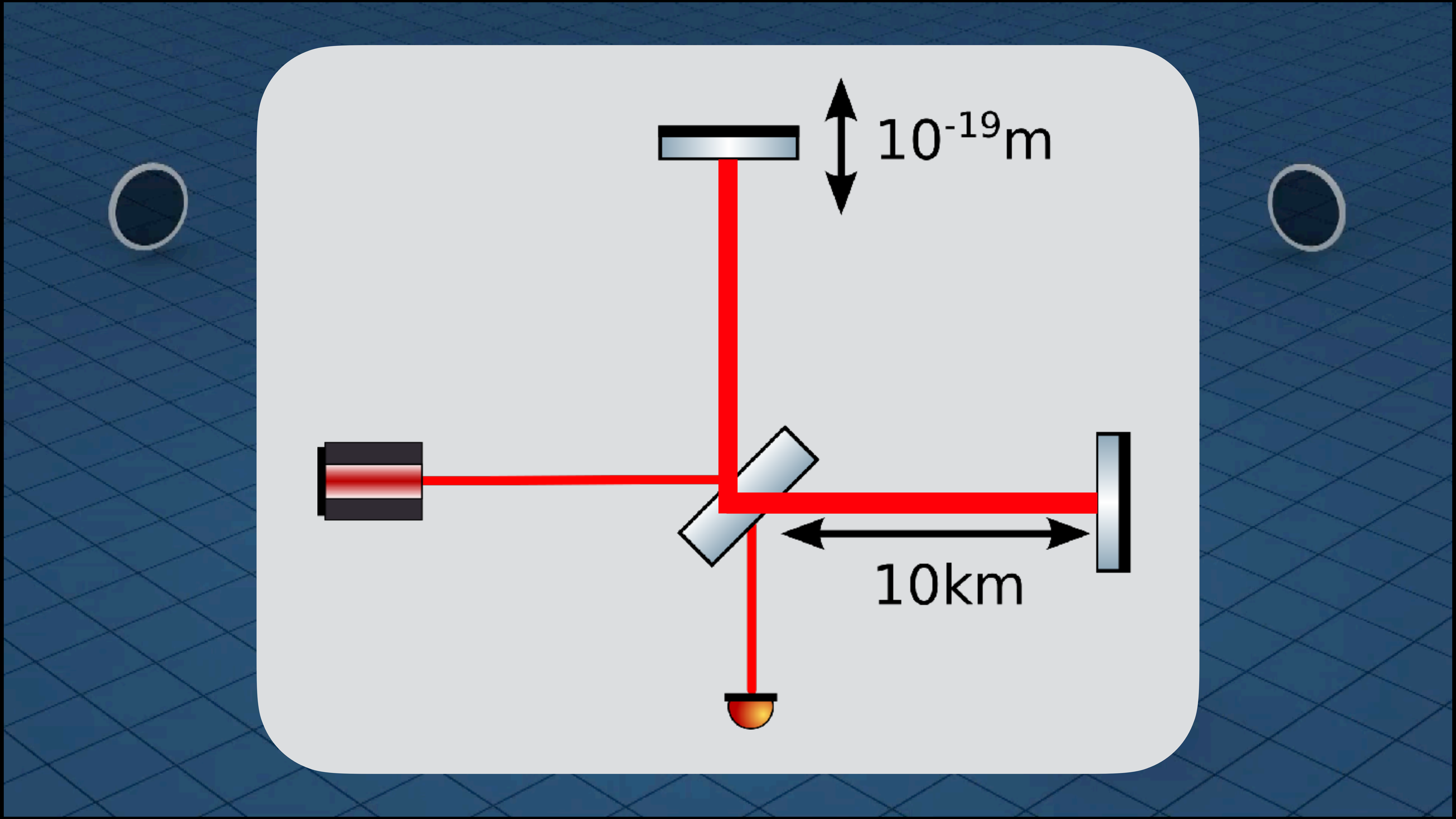
- **Long signals:** $\tau \simeq 4.5 \times 10^5\,\mathrm{sec}\left(\frac{1.22\,M_\odot}{\mathcal{M}_c}\right)^{5/3}\left(\frac{1\,\mathrm{Hz}}{f_{\rm low}}\right)^{8/3}$
  - GW170817 only a few minutes long as seen in LIGO-Virgo, but took months to analyze!
  - Same signal in ET would be in-band for hours
- **Loud signals**
  - Computing requirements increase with signal-to-noise ratio
- **Large number of signals lead to overlapping signals**
  - Can we still get precision science out of them?
- **How to characterize noise properties if signals are present all the time?**
  - Triangular shape: sum of detector outputs contains no GW signals ("null stream")
    (Still doesn't yield individual noise spectra in the 3 detectors separately, only average)

Current analysis techniques qualitatively inadequate, novel methodologies needed

Andreas Freise, 27.03.2024

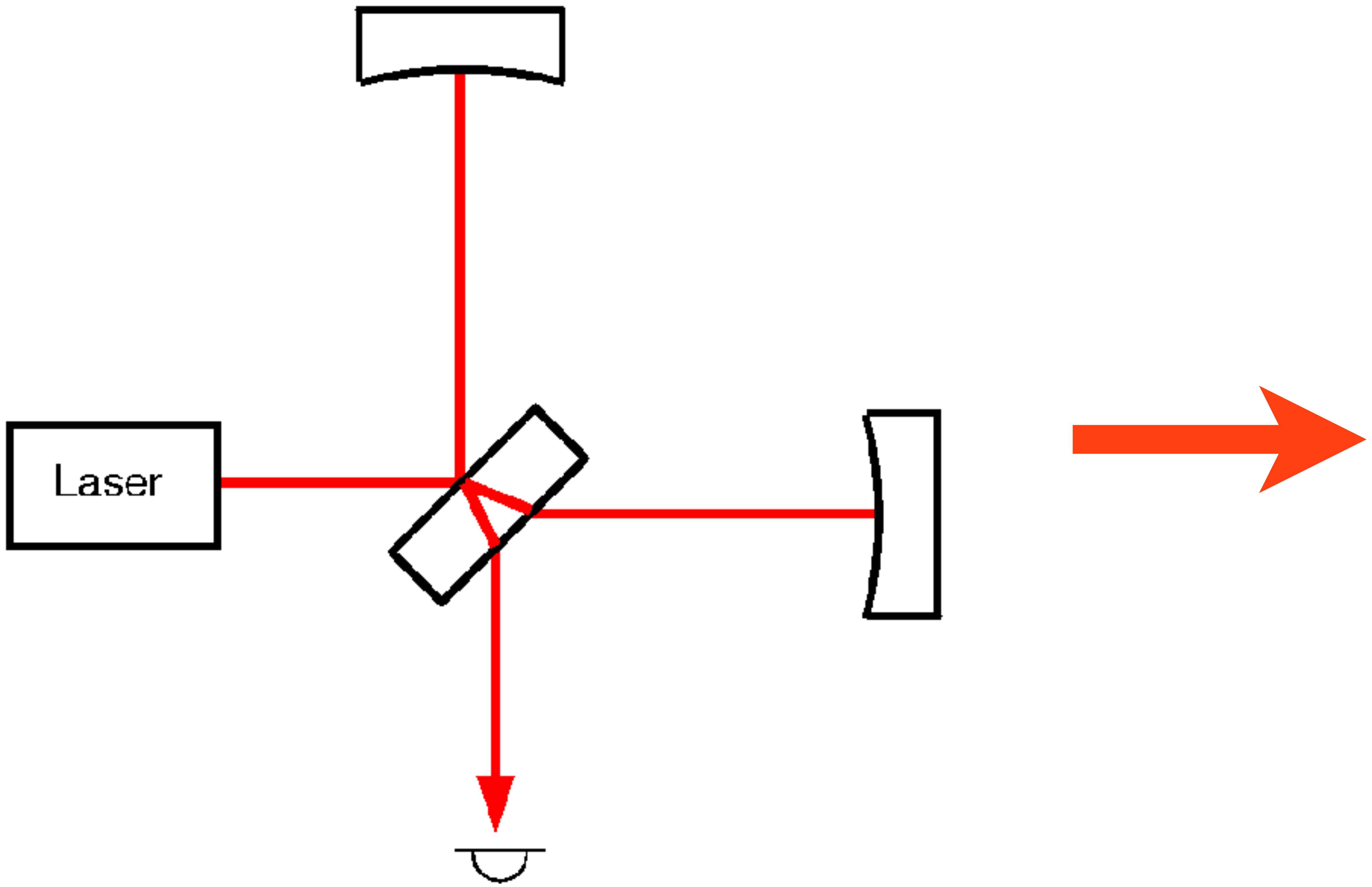
Thermal deformation in the Einstein Telescope?

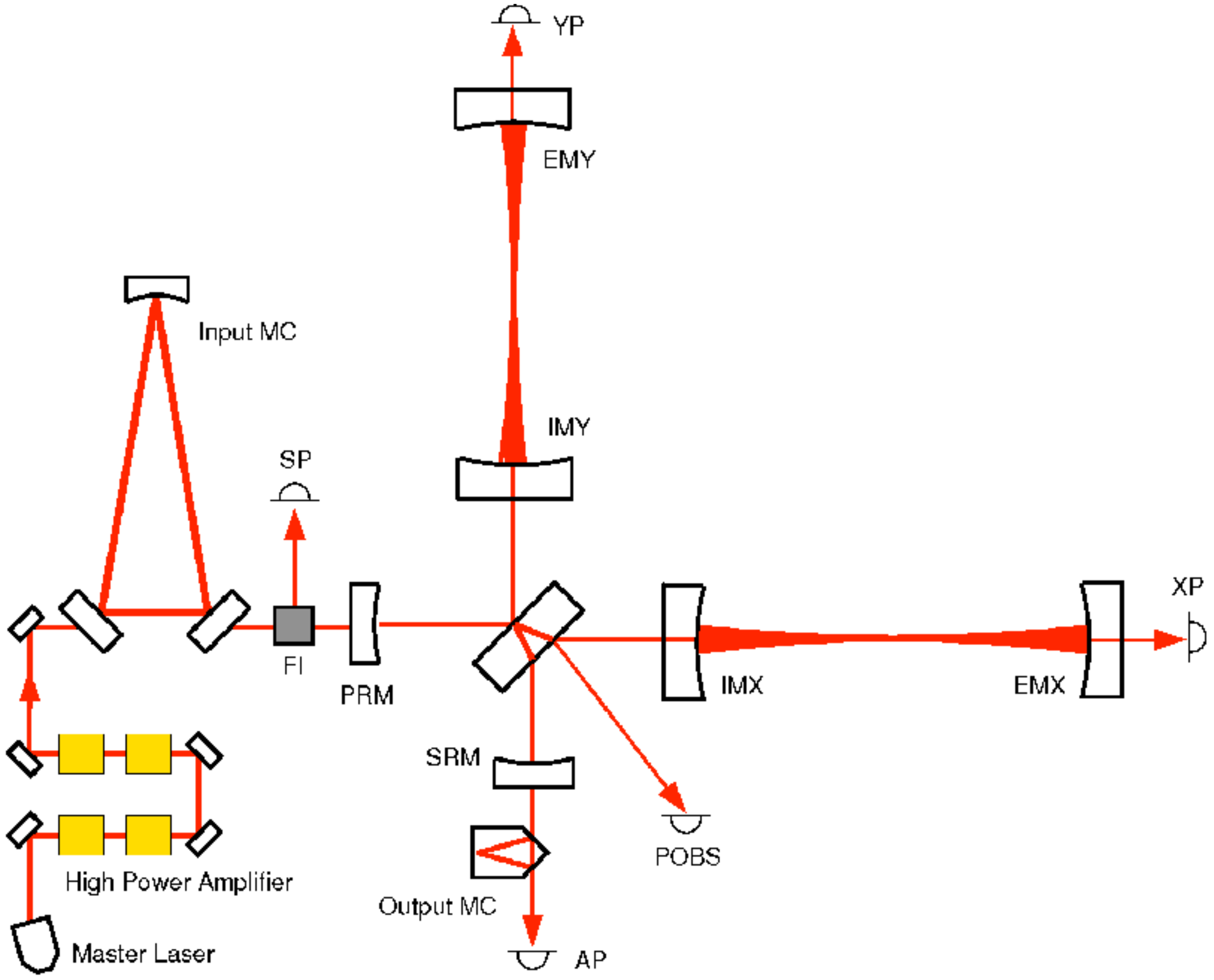
- Introduction
- Gravitational wave detectors
- Thermal deformation
- Challenges



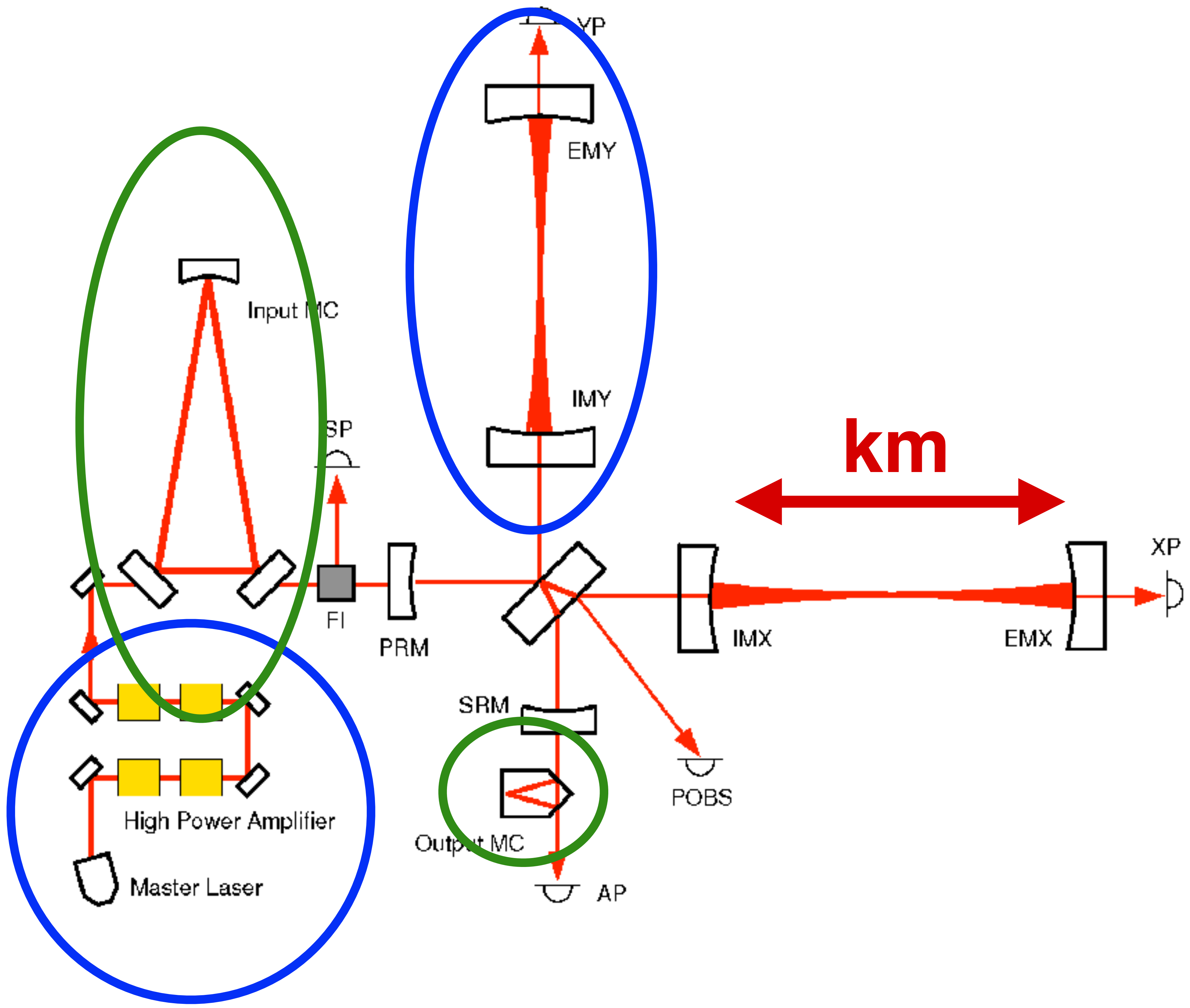
Credit: LIGO/T. Pyle

Advanced interferometry





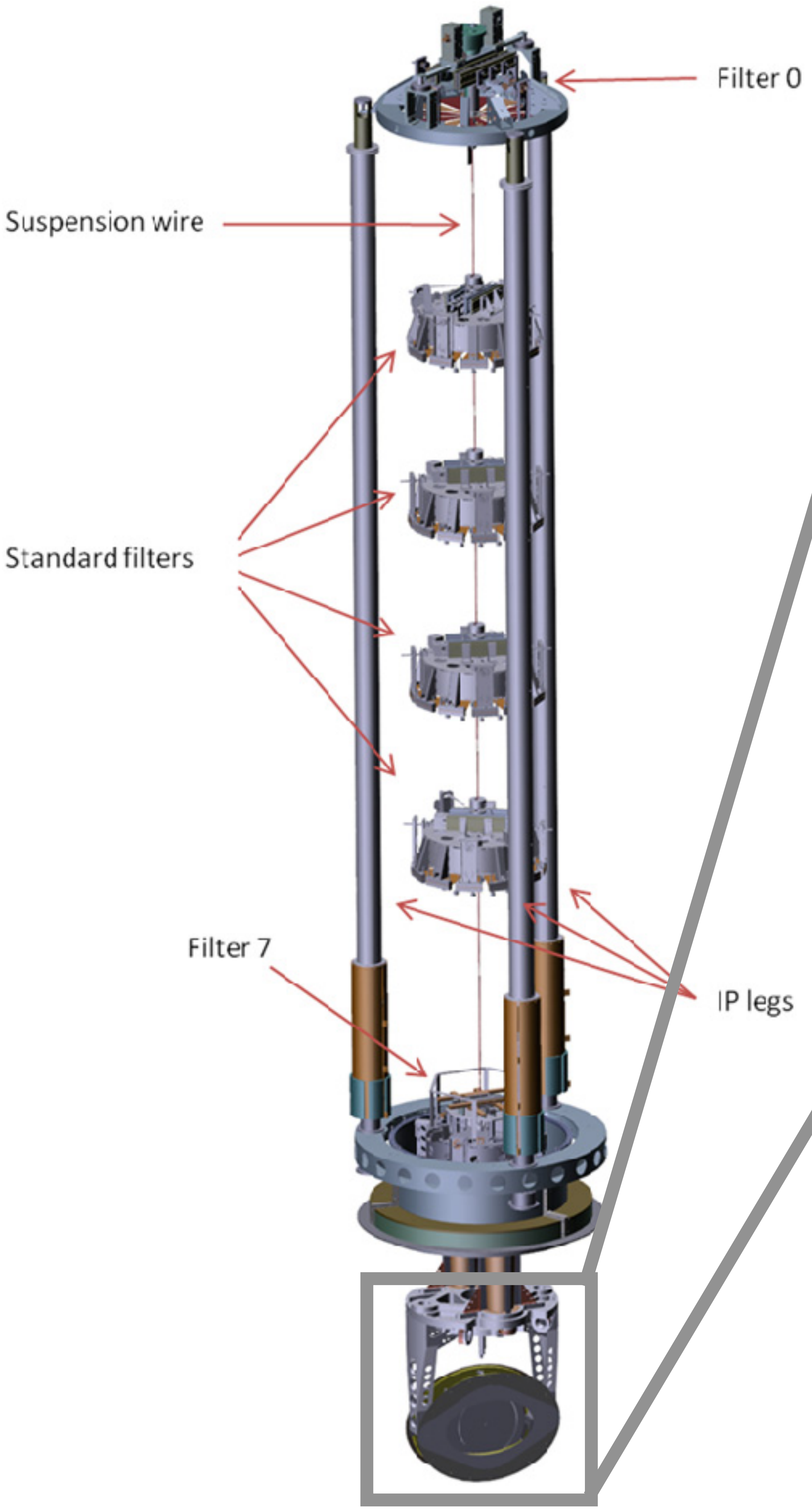
What Makes it Better?

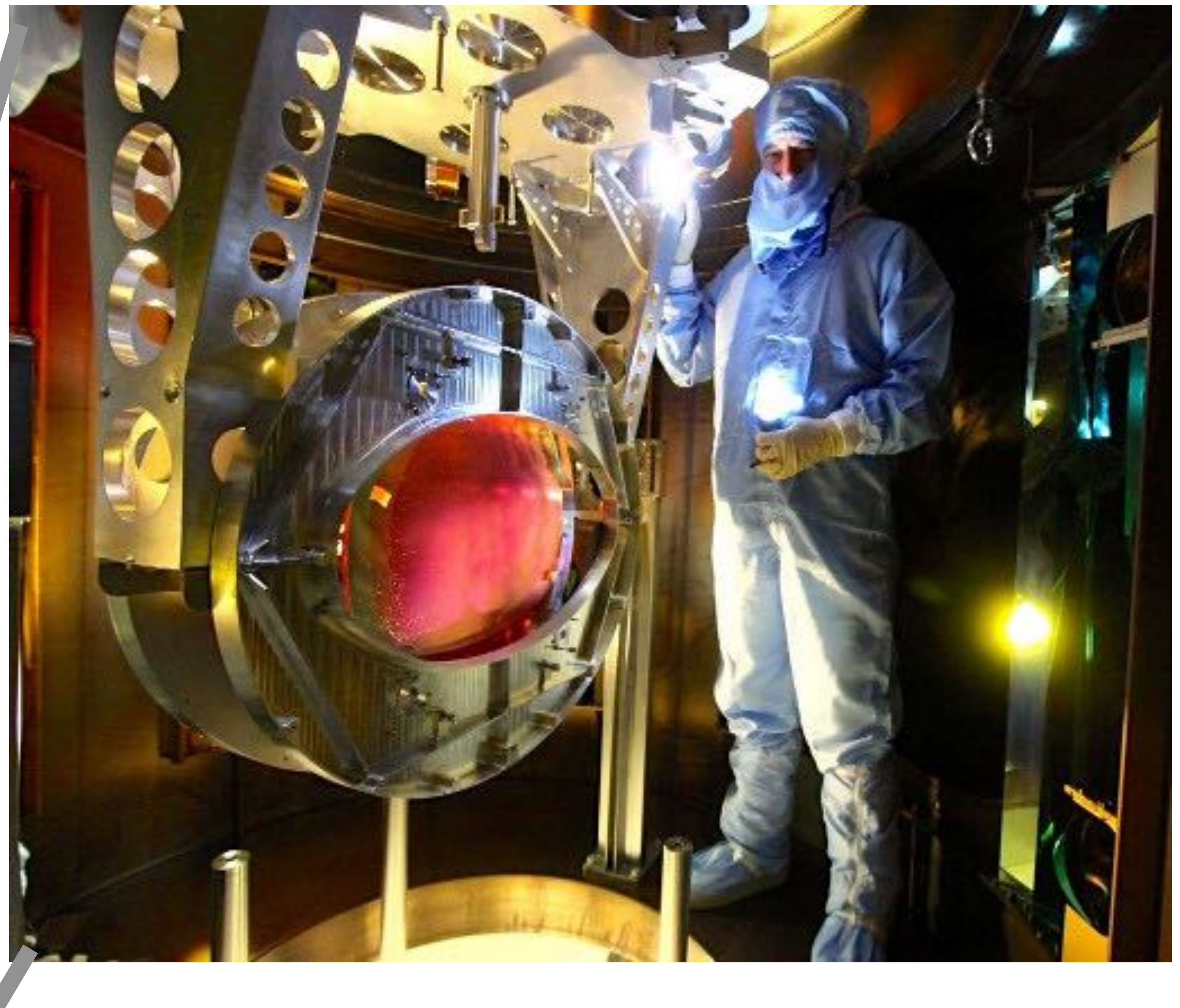


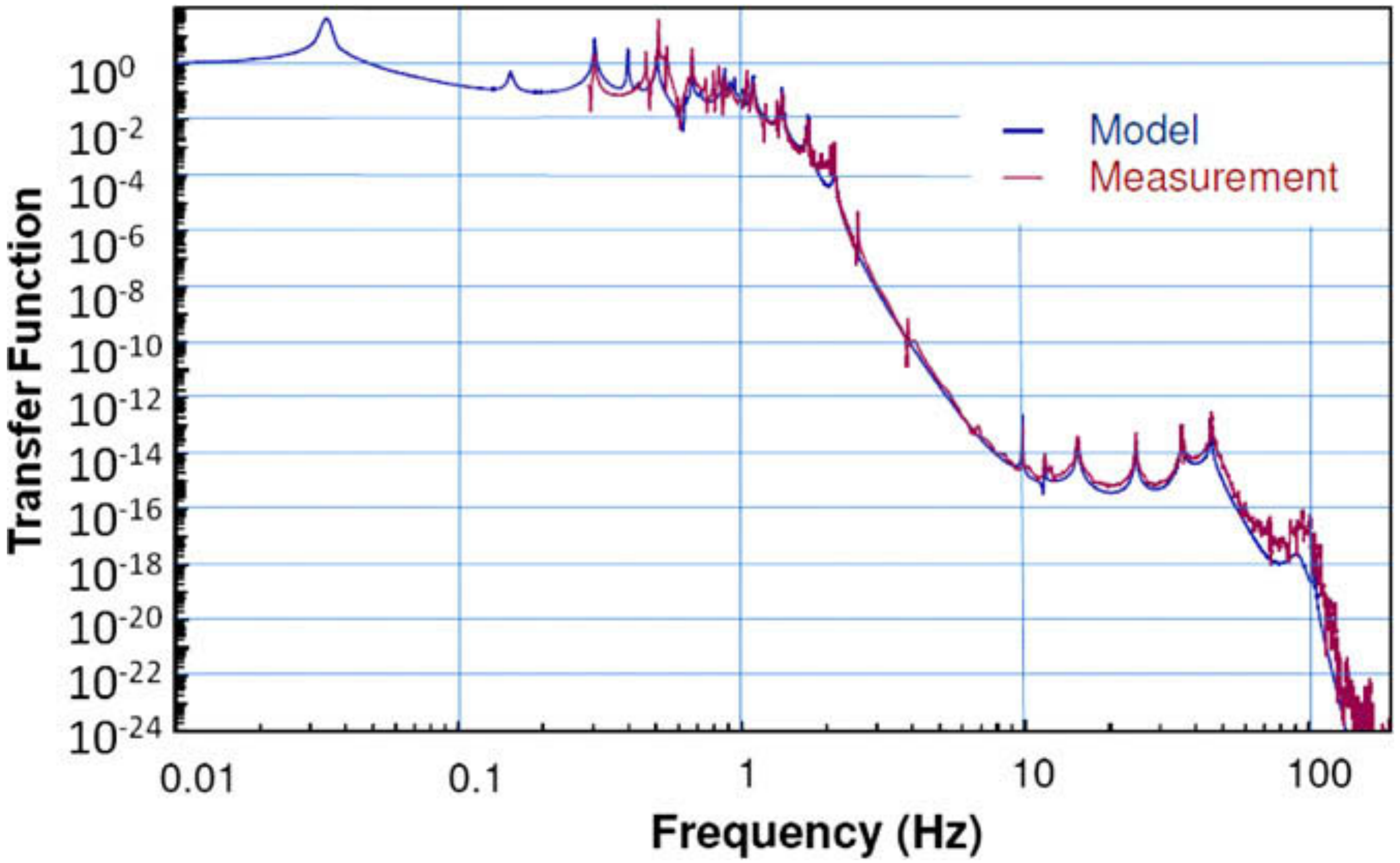
- GW effect scales with arm length: large detectors
- Optical signal scales with light power: high-power laser, optical cavities
- Laser beam fluctuations make noise: filter cavities
- **Stop everything from shaking!**

[M. Perciballi - EGO]

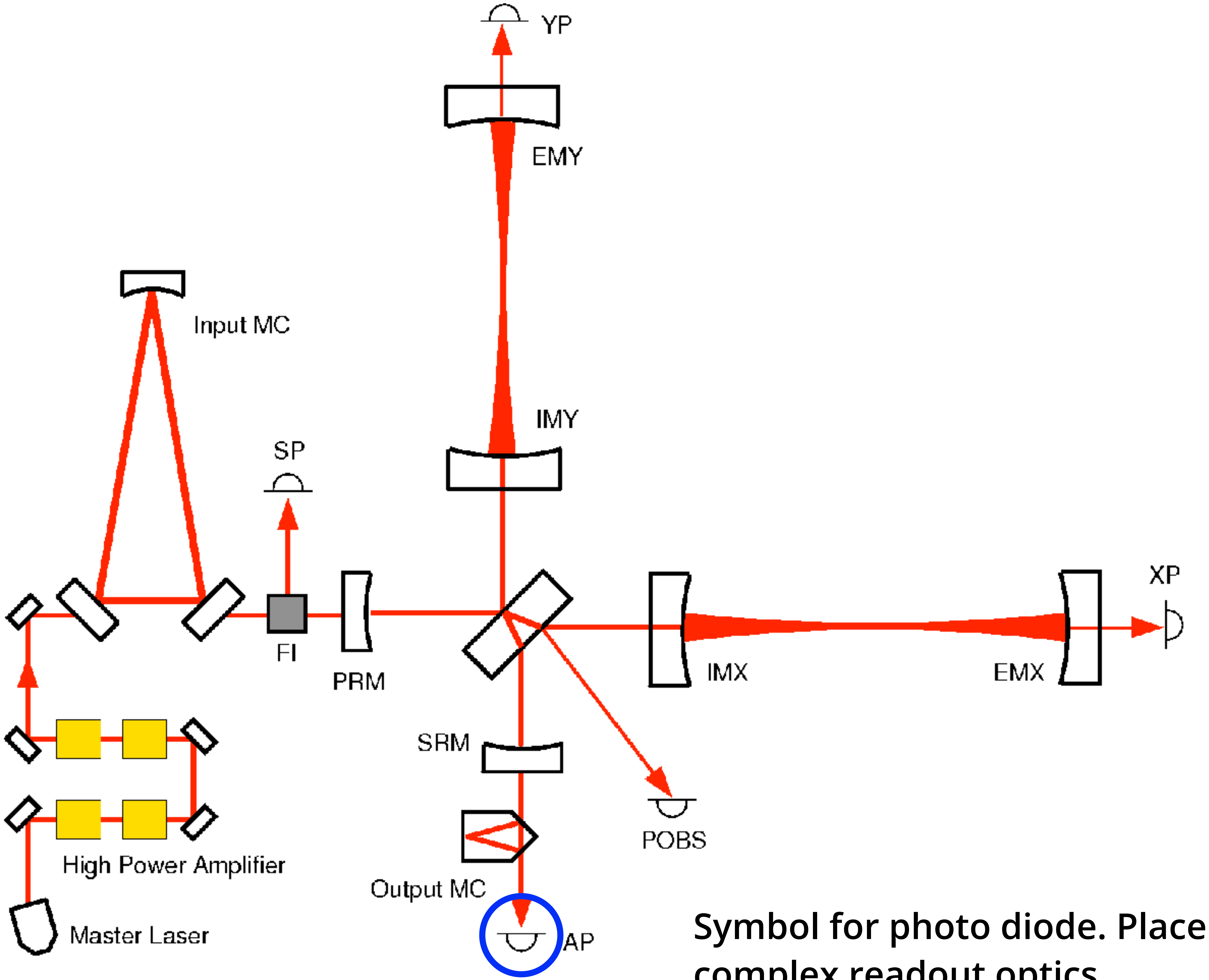
Virgo: seismic isolation



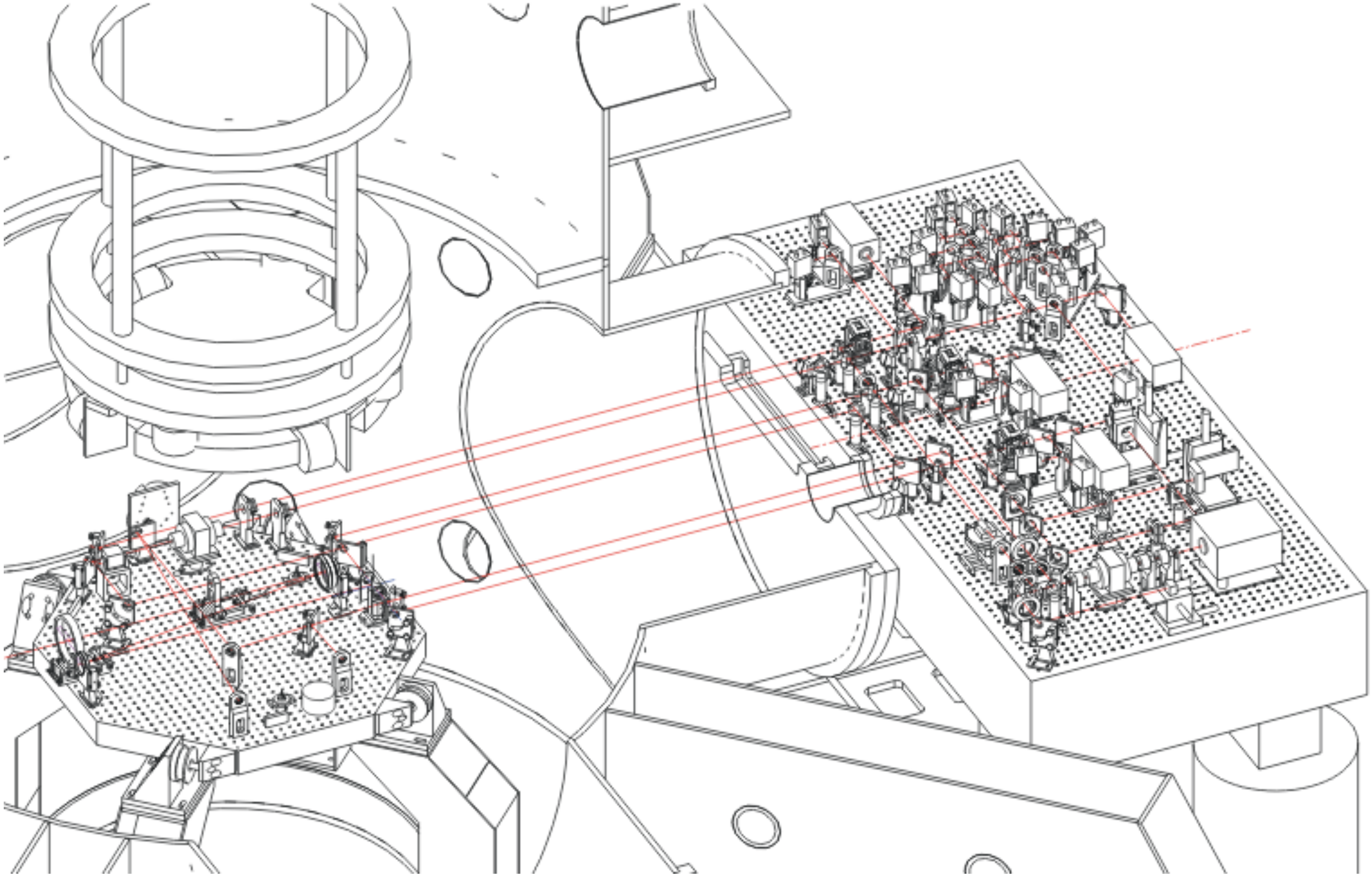




- Need more than a 10 orders of magnitude attenuation above 10 Hz
- Use combination of active pre-isolation stage (inertial free platform balancing on inverted pendulum, using accelerometers and position sensors) and passive multi-stage pendulums and blade springs
- Mirrors are suspended by 4 glass fibers for thermal noise: need materials with low mechanical losses

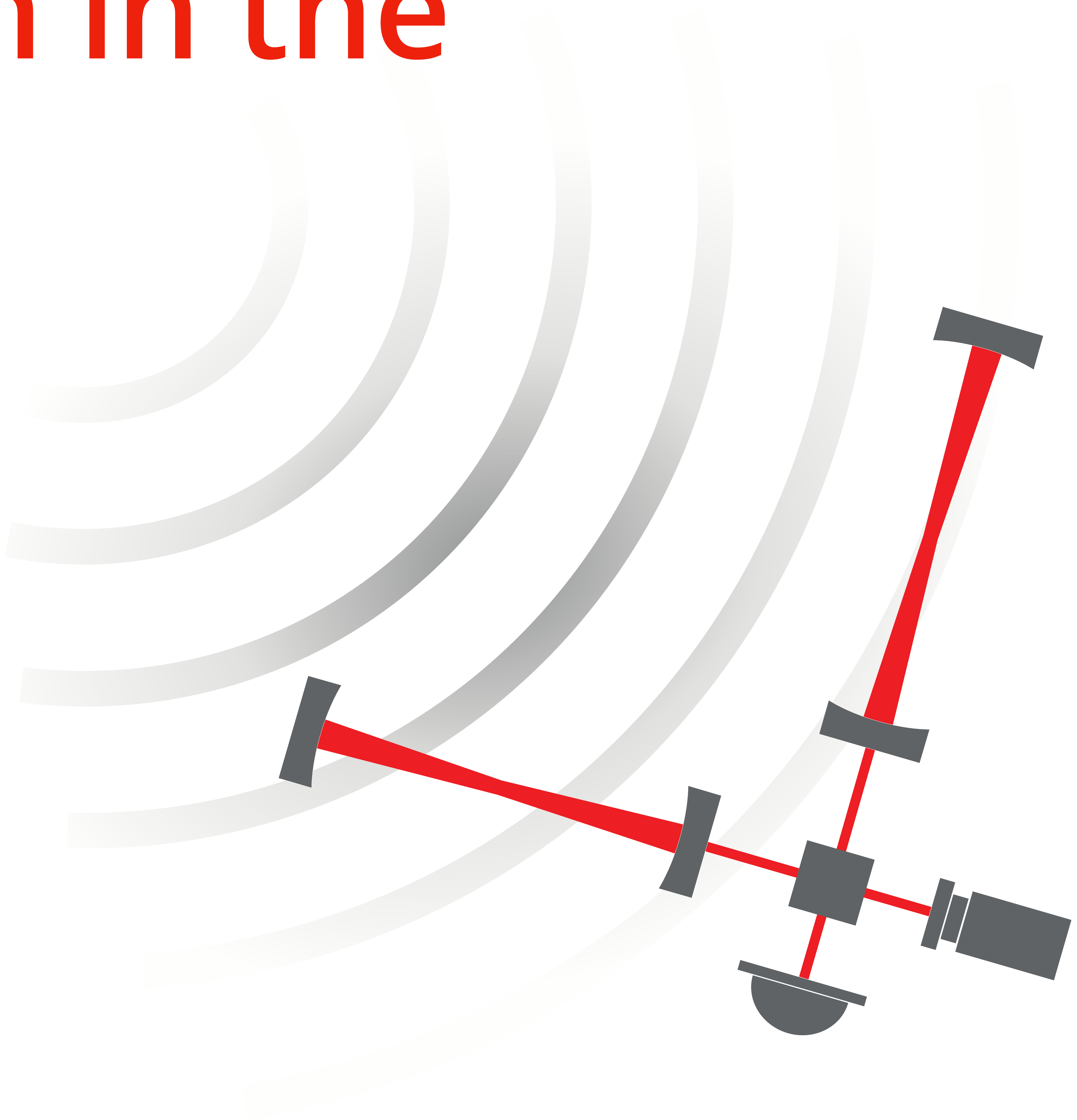


Symbol for photo diode. Placeholder for complex readout optics.



Main Interferometer Beam

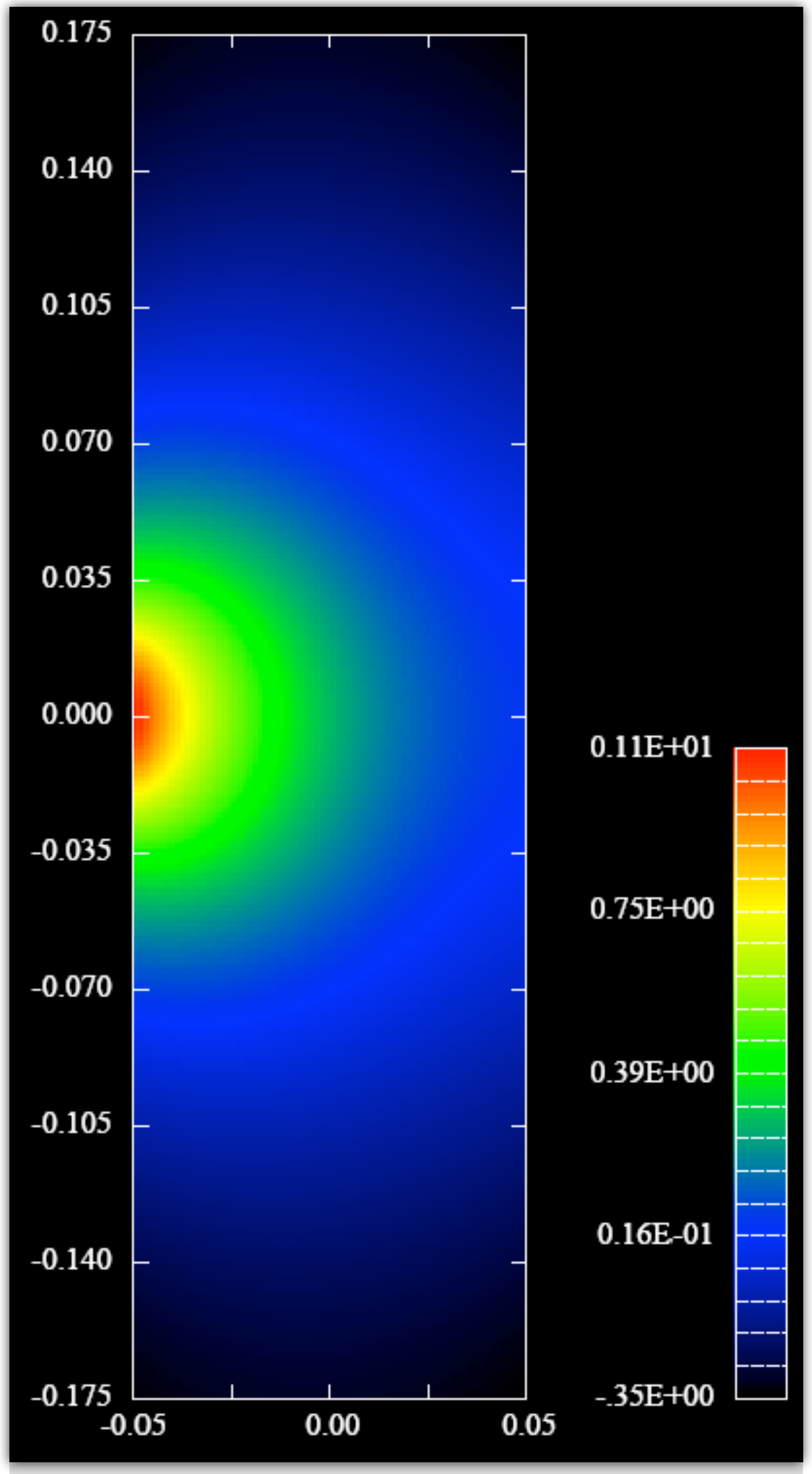
Thermal deformation in the Einstein Telescope?



- Introduction
- Gravitational wave detectors
- Thermal deformation
- Challenges

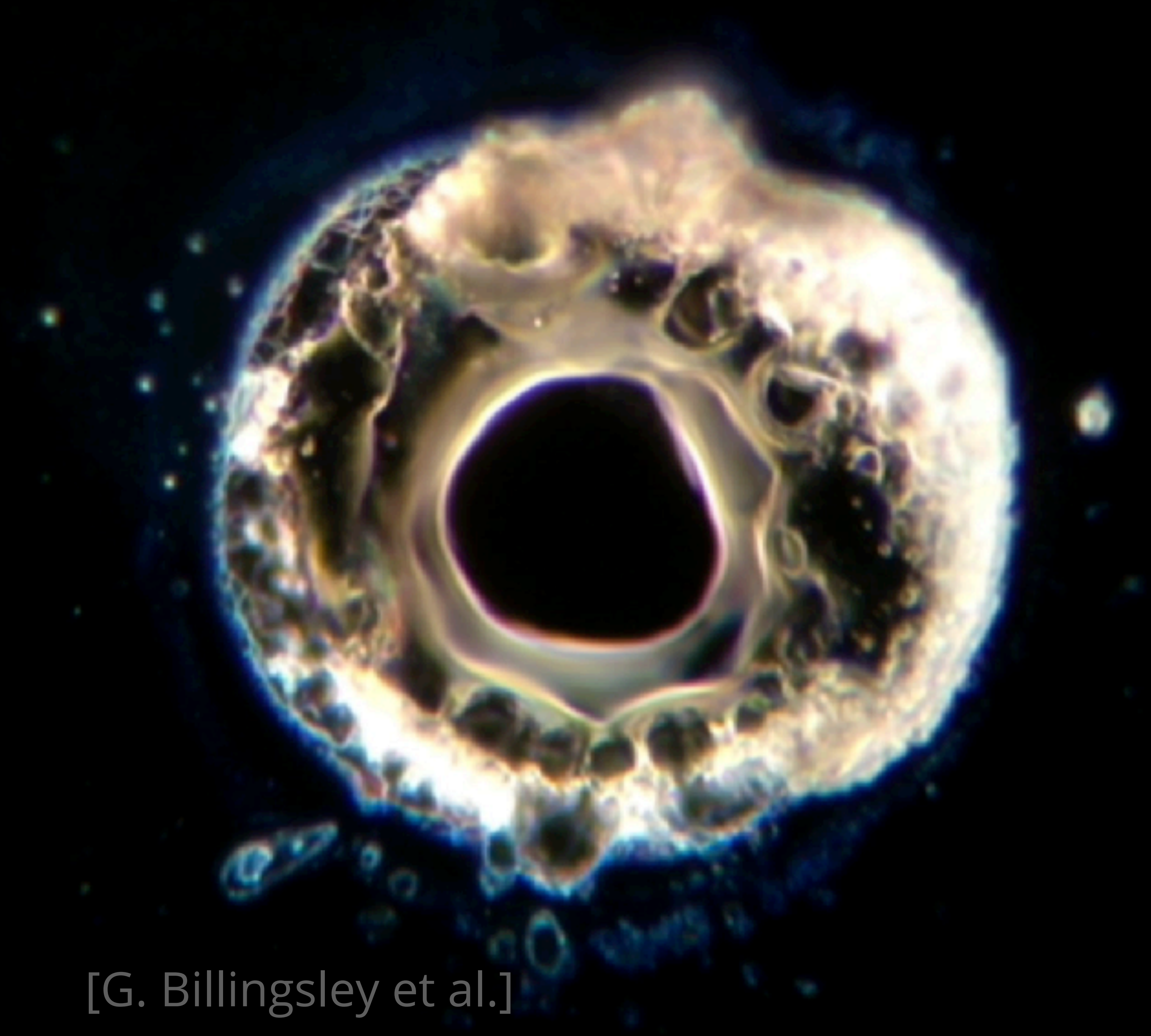
Thermal deformation

- Very high power laser beam hits all the optical elements of the whole interferometer.
- Some watts of power are dissipated and absorbed in the optical elements, resulting in temperature gradients.
- The temperature gradients result in refractive index gradients and geometrical alteration of the elements.
- The optical properties of the elements are affected.
- **A system able to compensate the thermal deformations is needed to guarantee the proper working of the interferometer.**

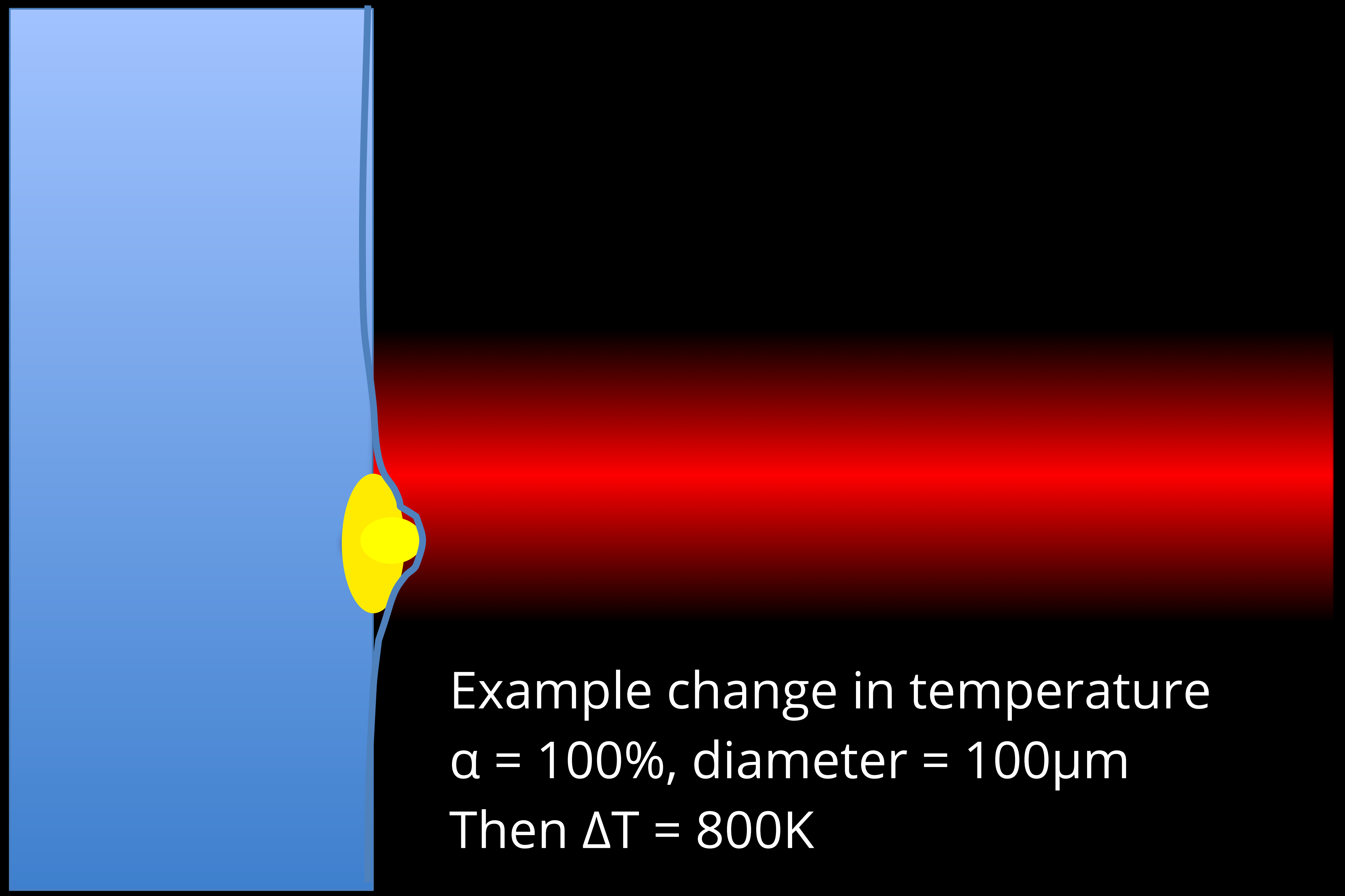


[Image by J.-Y. Vinet]

Mitigating emerging defects



[G. Billingsley et al.]



[Aidan Brooks]

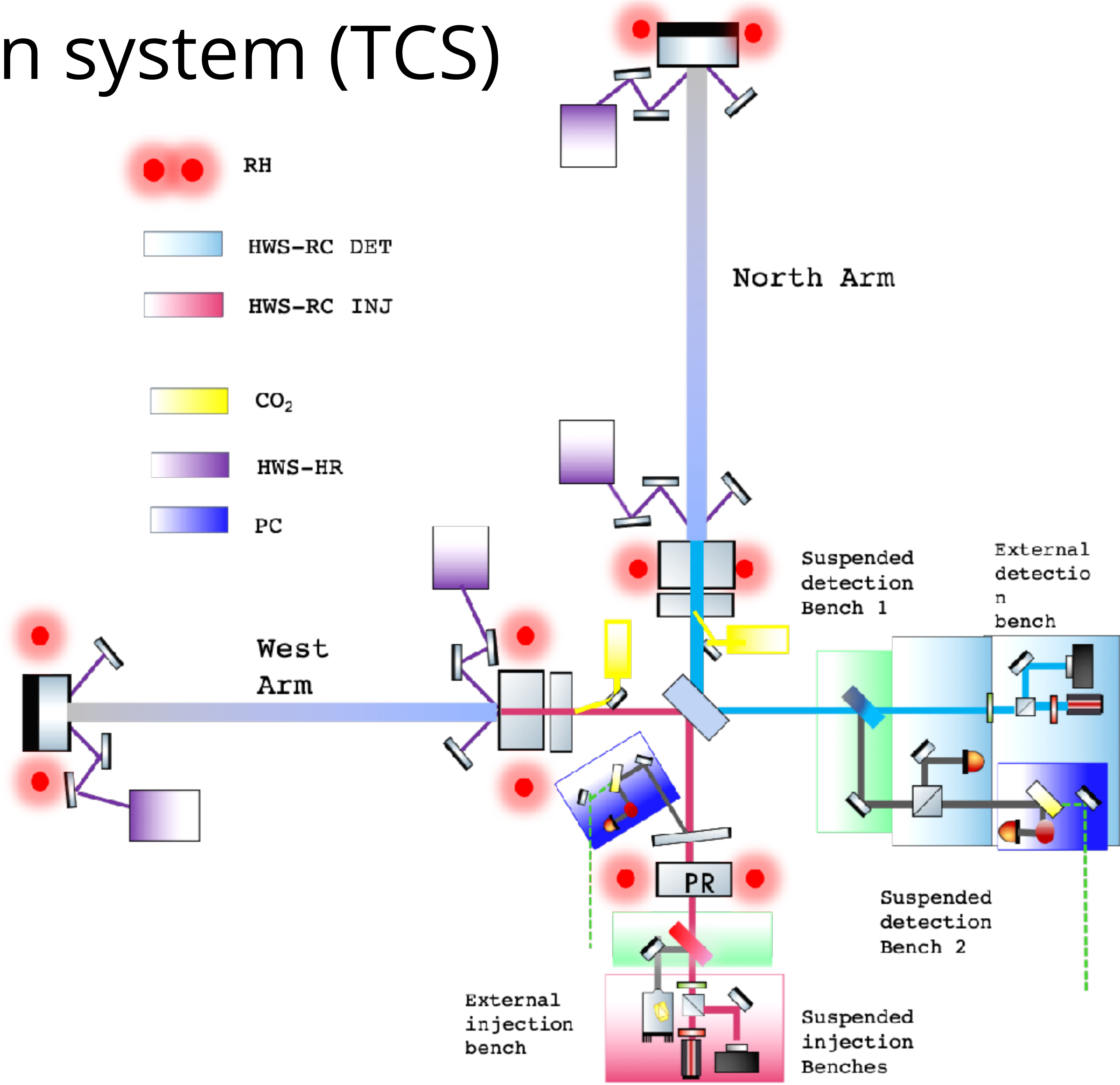
Example change in temperature
α = 100%, diameter = 100μm
Then ΔT = 800K

- Point-like defect (≤ 100μm), highly absorbing (> 1E4 ppm), on test mass HR surface

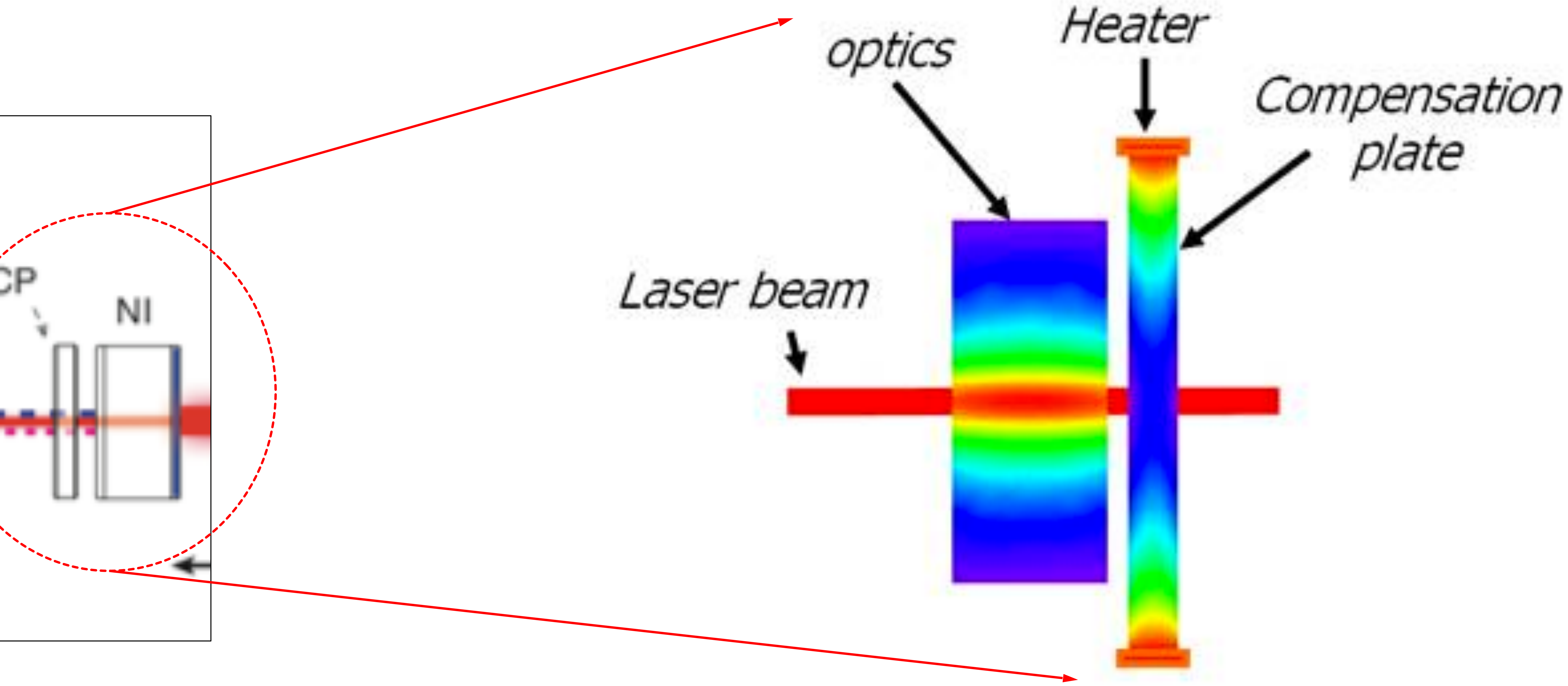
Virgo thermal compensation system (TCS)

TCS actuators:
- CO2 laser projector corrects thermal lensing
- Ring Heater acts on the thermoelastic deformation of the HR surfaces

TCS sensors:
- Hartmann Wavefront Sensors in the recycling cavity to measure thermal lensing
- Hartmann Wavefront Sensors on HR surfaces to measure the thermoelastic deformation of the HR surface
- Phase Cameras to sense independently carrier and sidebands

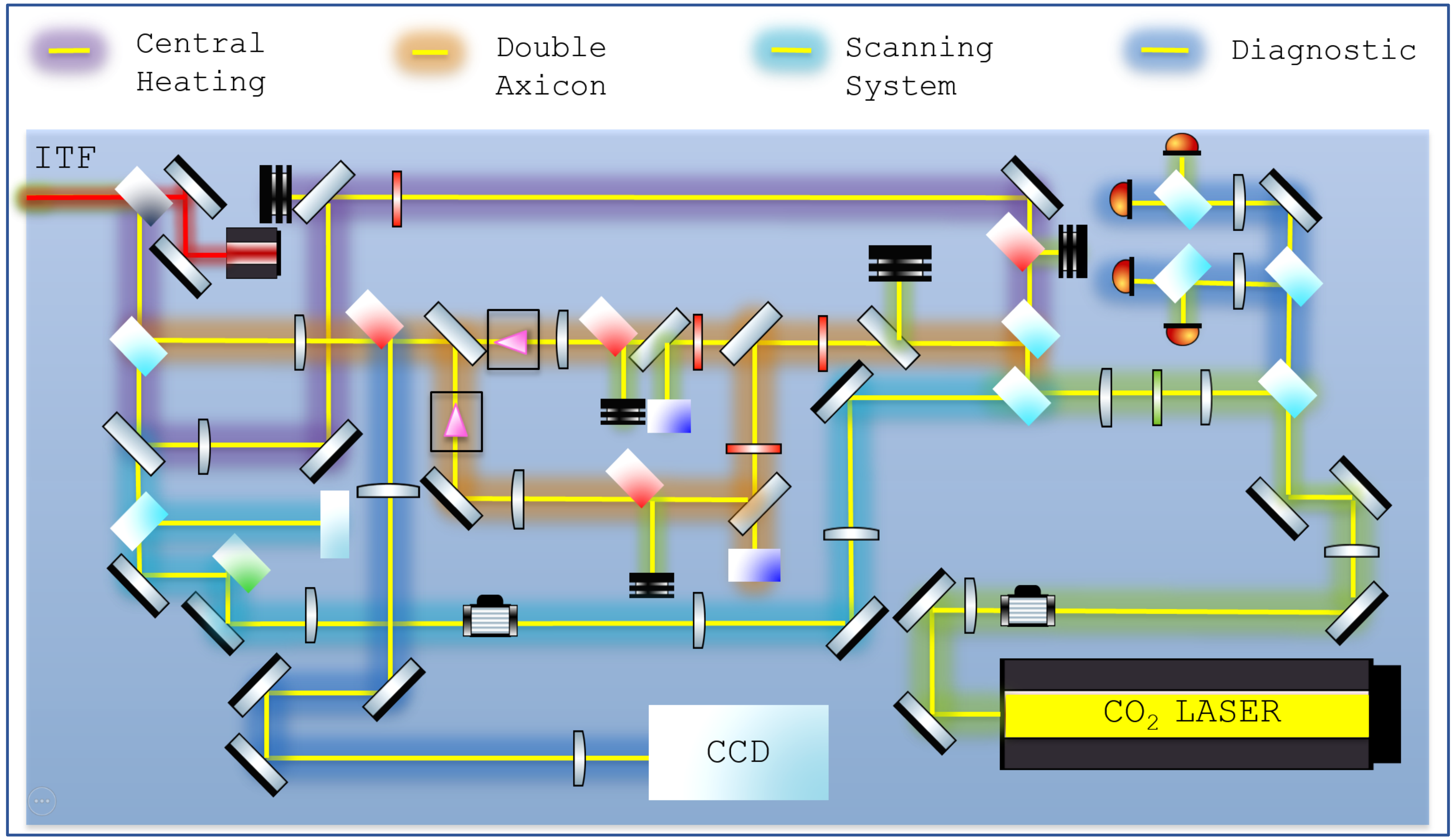


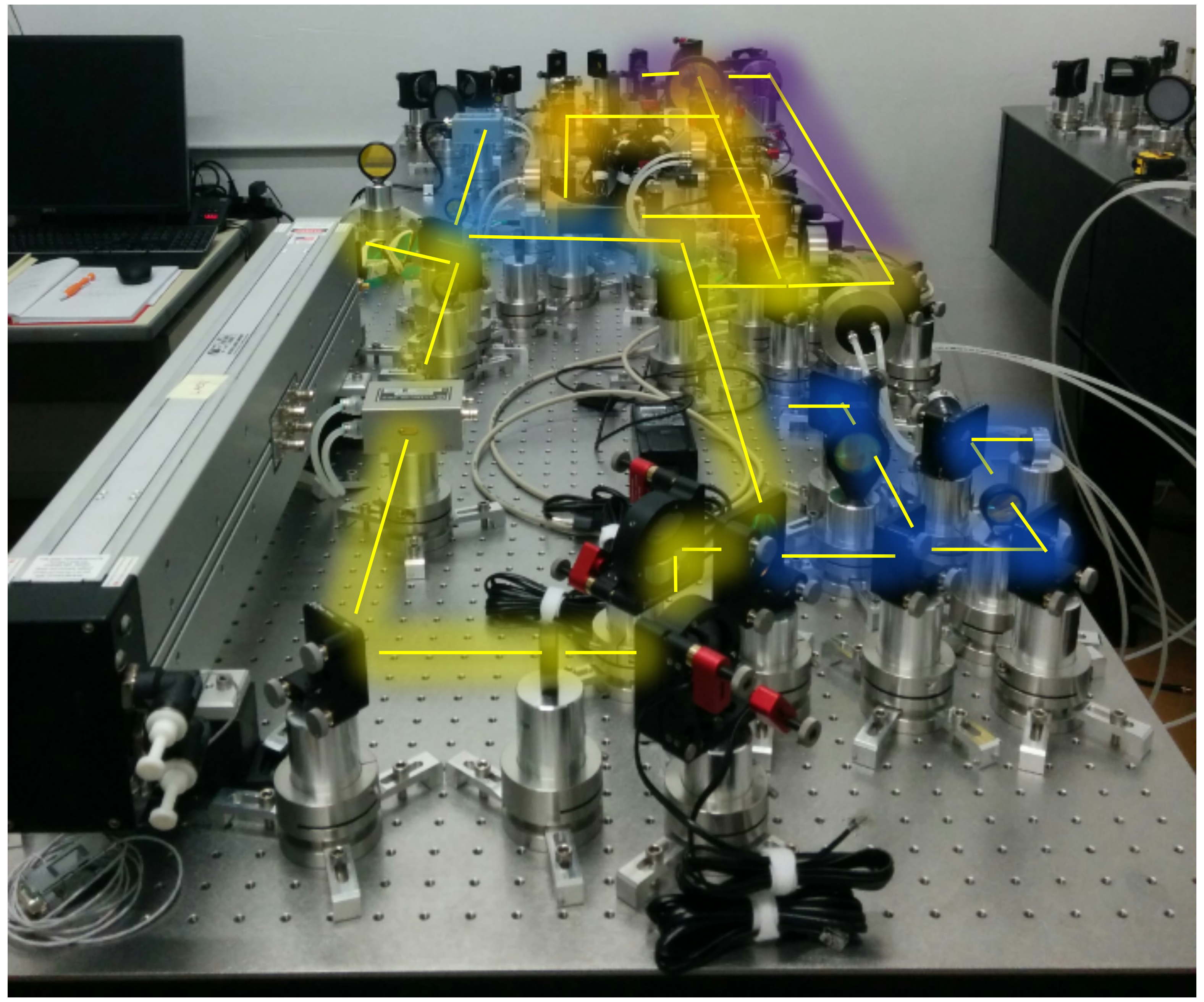
Ring heater actuator



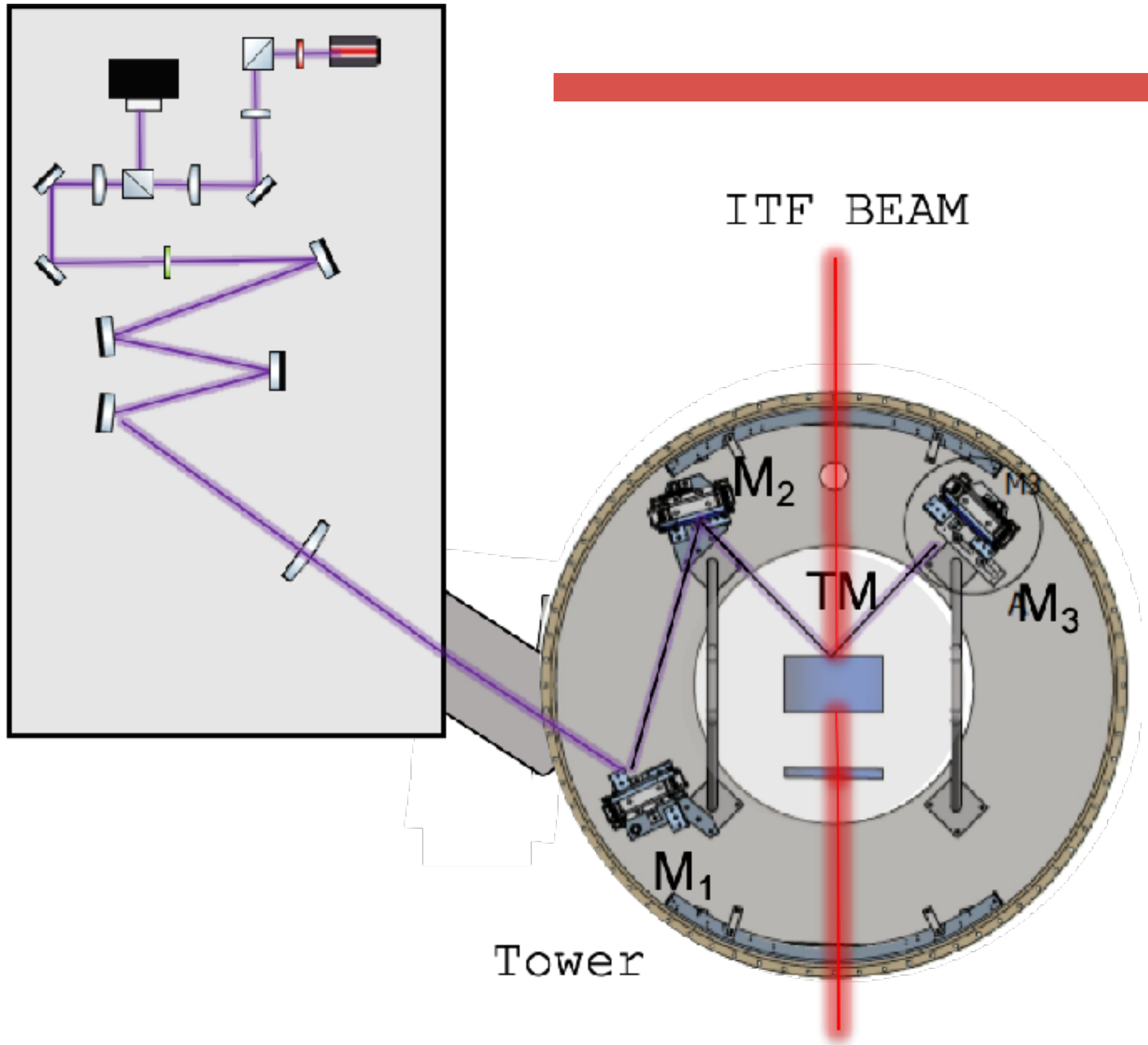
- Absorbed light in input mirror heats mirror and changes RoC
- (Heated) compensation plate necessary to correct for this effect

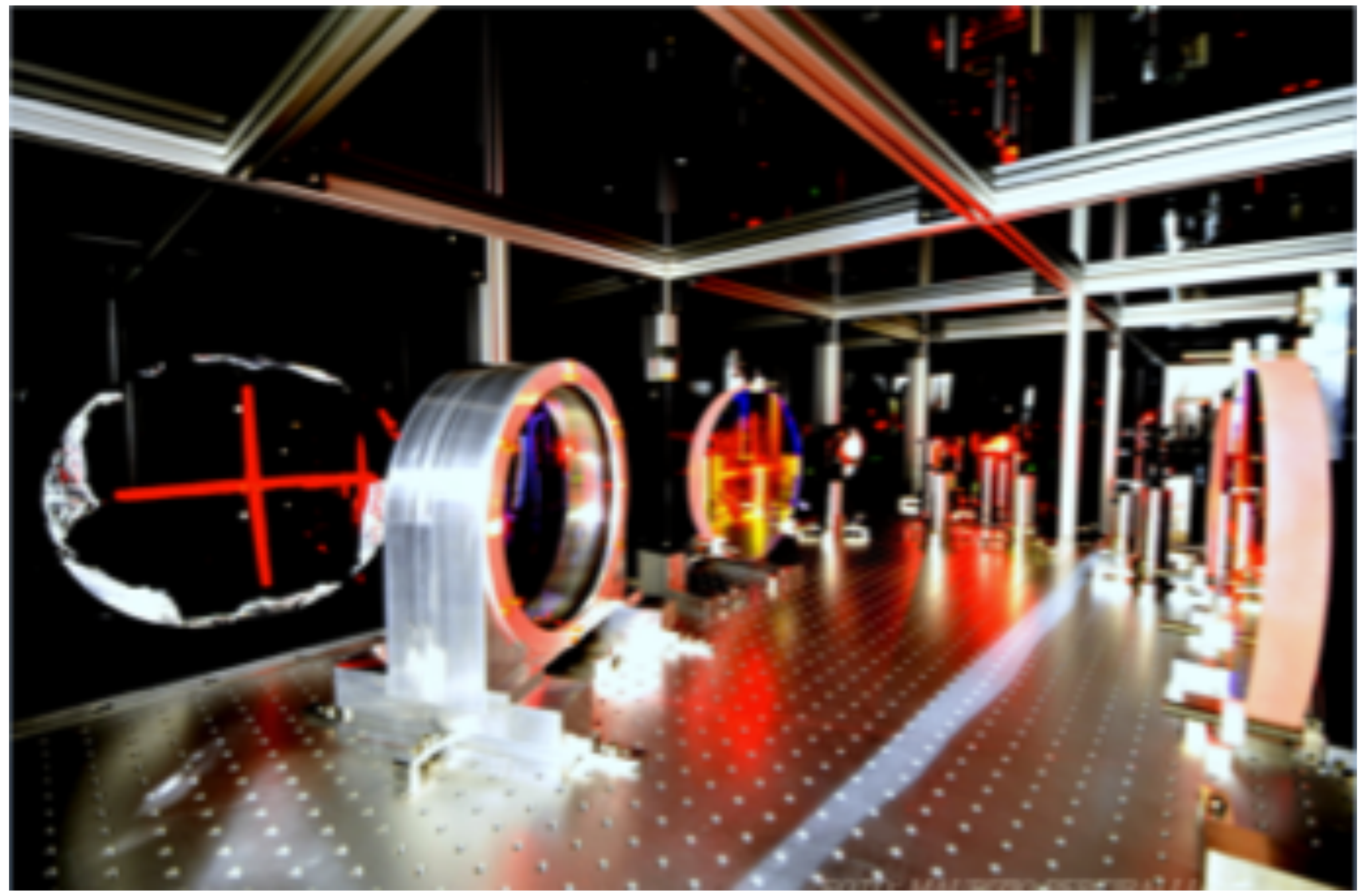
CO2 projector actuator

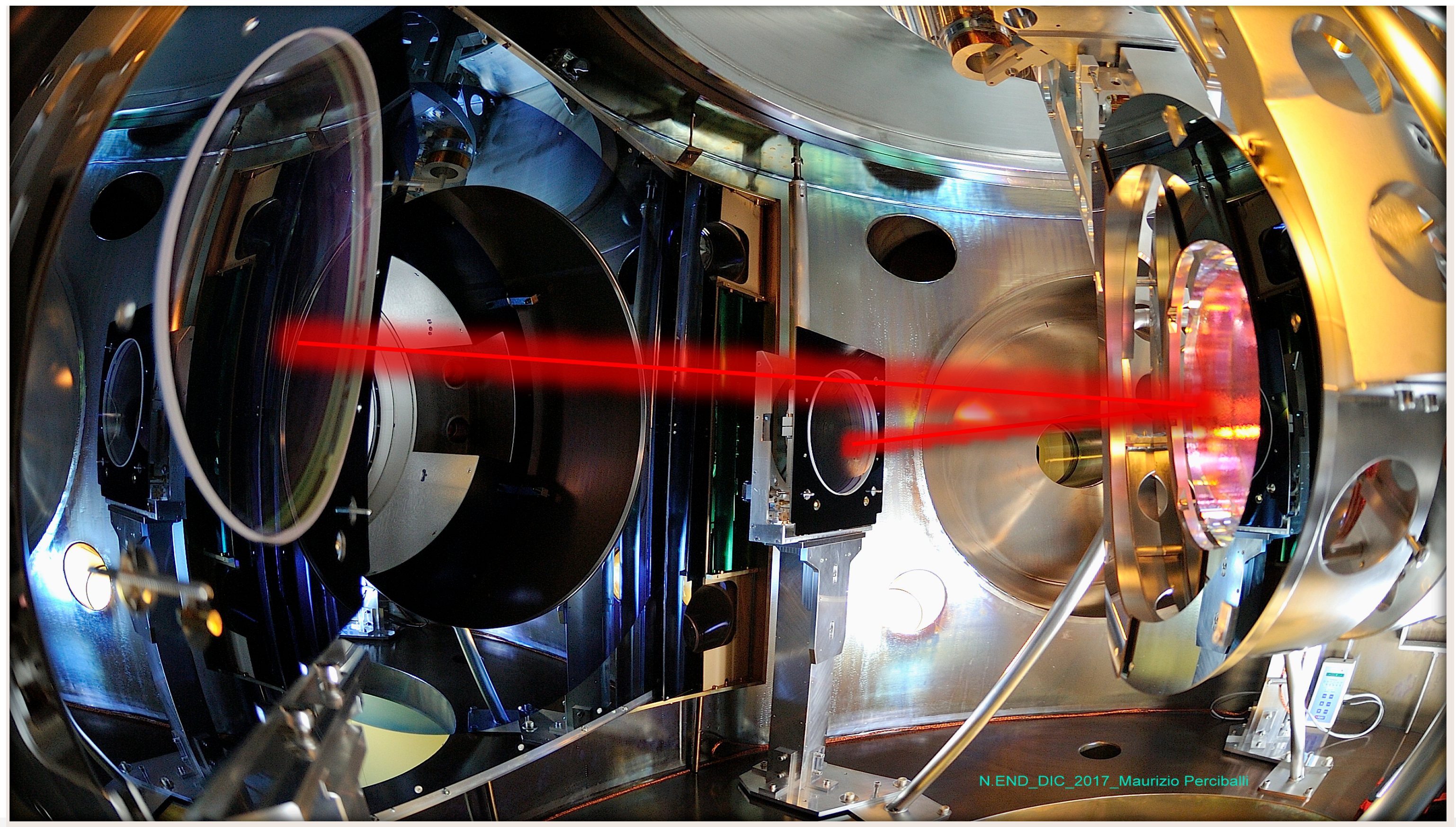




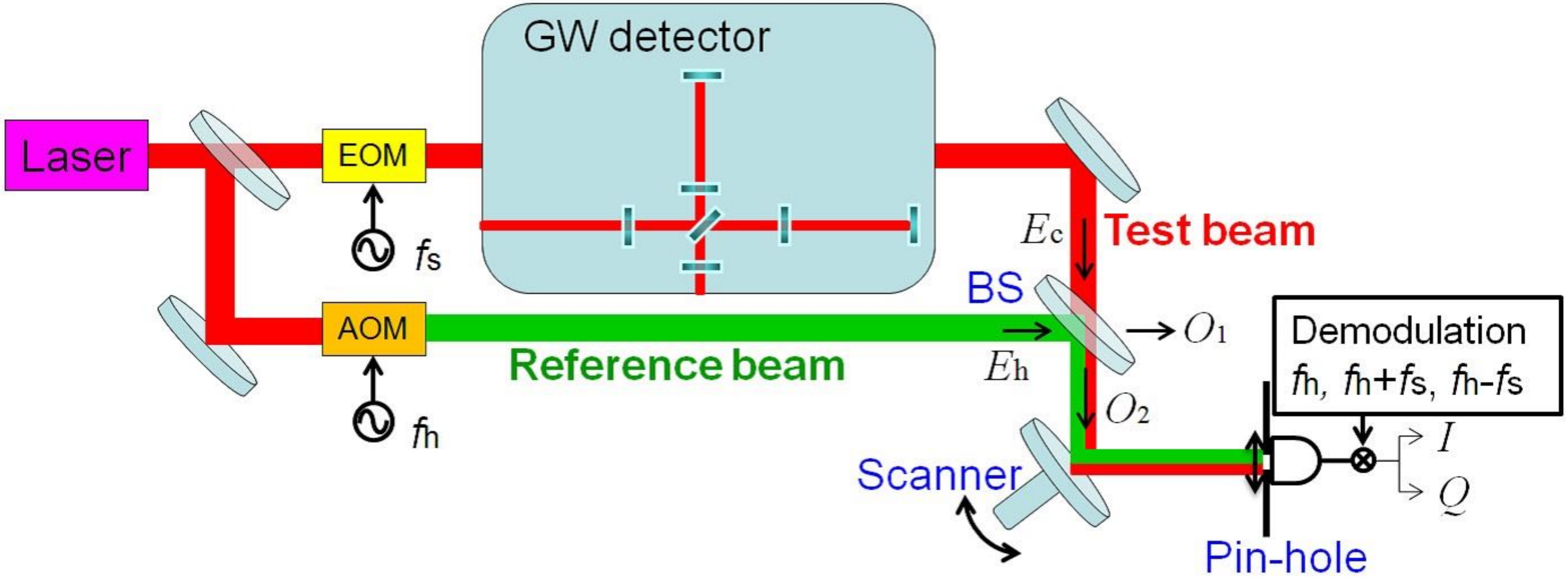
Hartman wavefront sensor

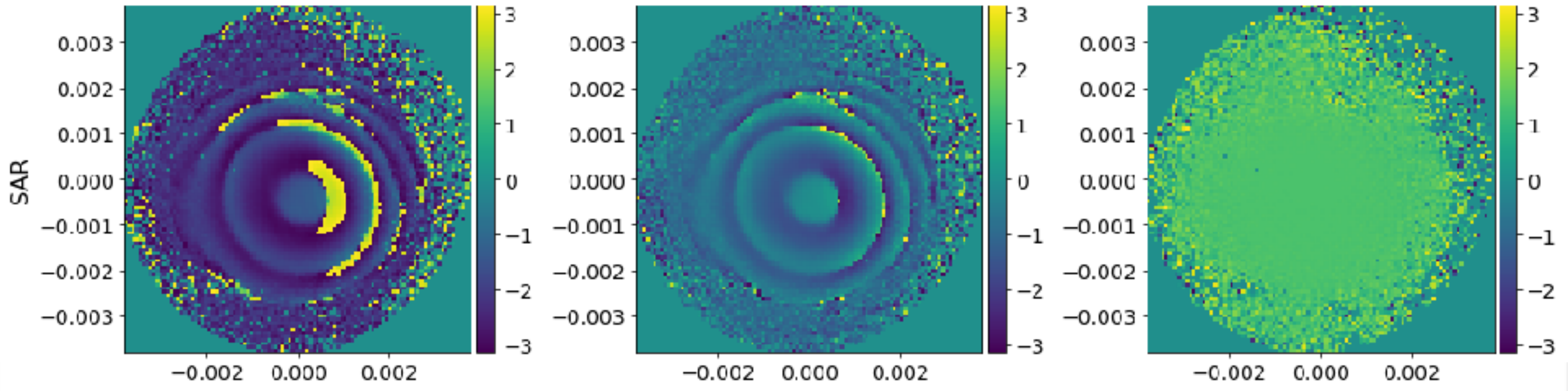




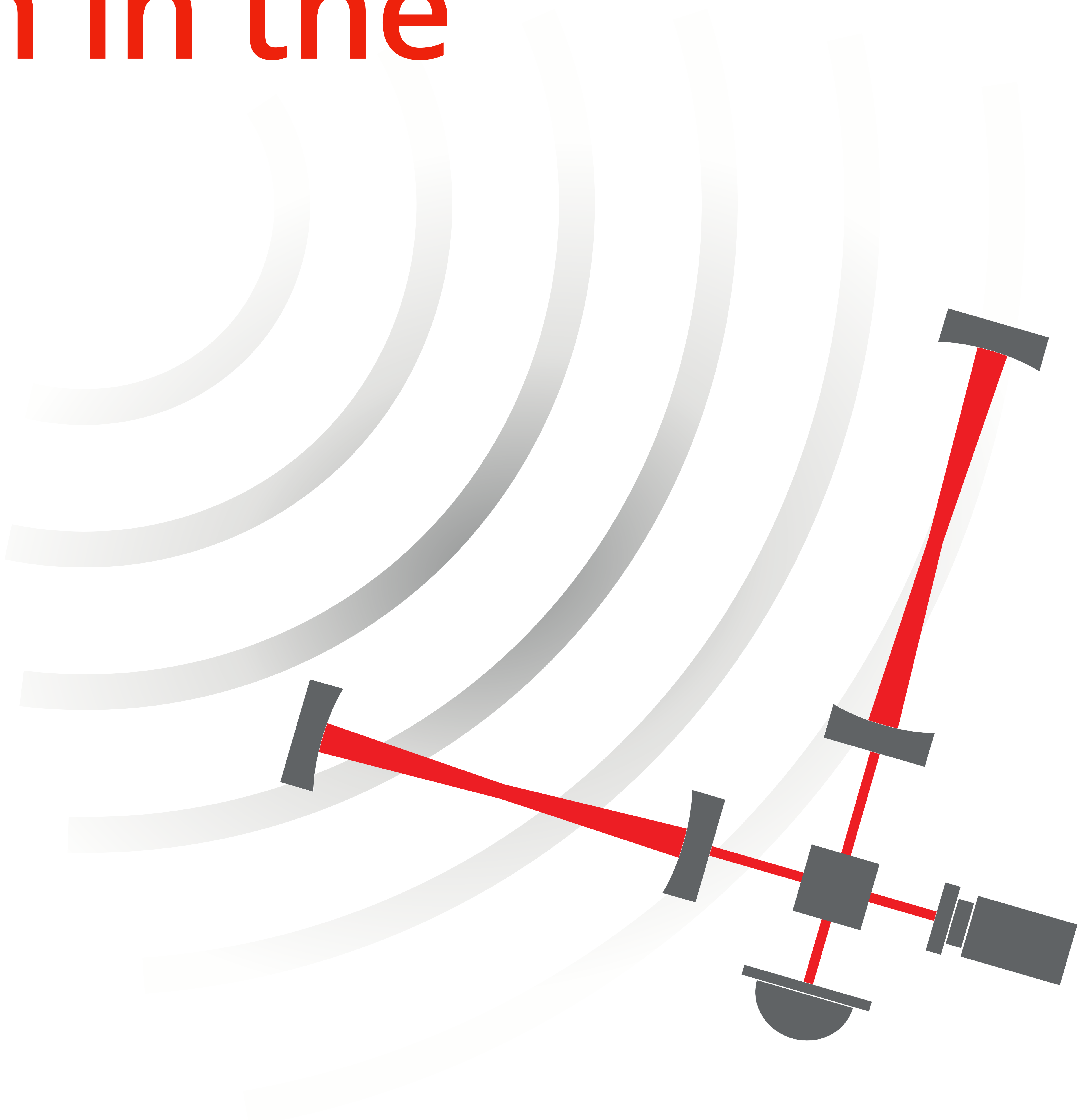


Phase camera sensor





Thermal deformation in the Einstein Telescope?



- Introduction
- Gravitational wave detectors
- Thermal deformation
- Challenges

TCS, the unexpected challenge

- The effect of thermal deformation (together with other optical defects) limit the performance of current detectors Virgo and LIGO. Thermal compensation systems have been added as a work-arounds to the original designs.

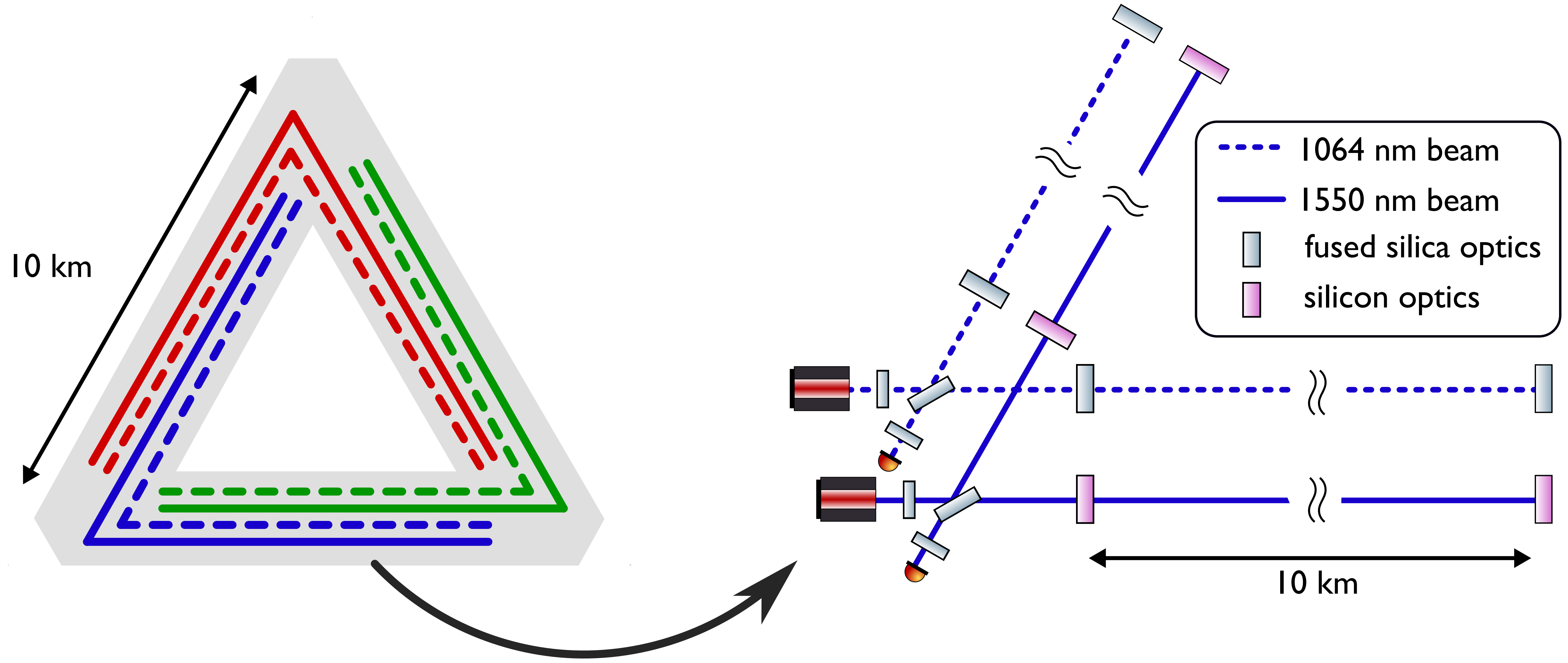
- The coupling from various sensing and control system make **inference of the true interferometer state very challenging**.

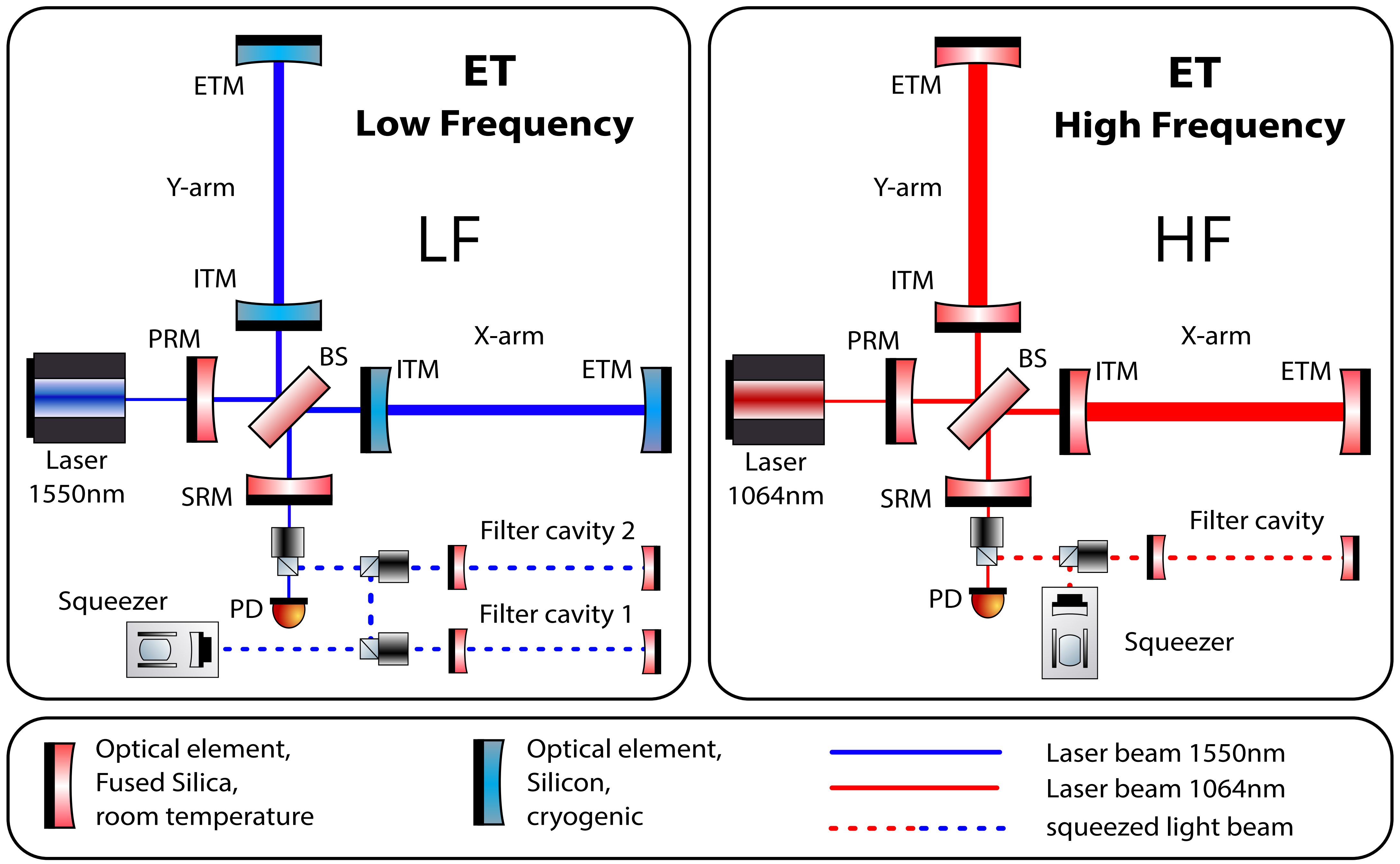
- Existing thermal compensation systems do not allow to increase the power of the main laser any further.

- However, the Einstein Telescope has **much more stringent noise requirements** and needs **more laser power**!

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



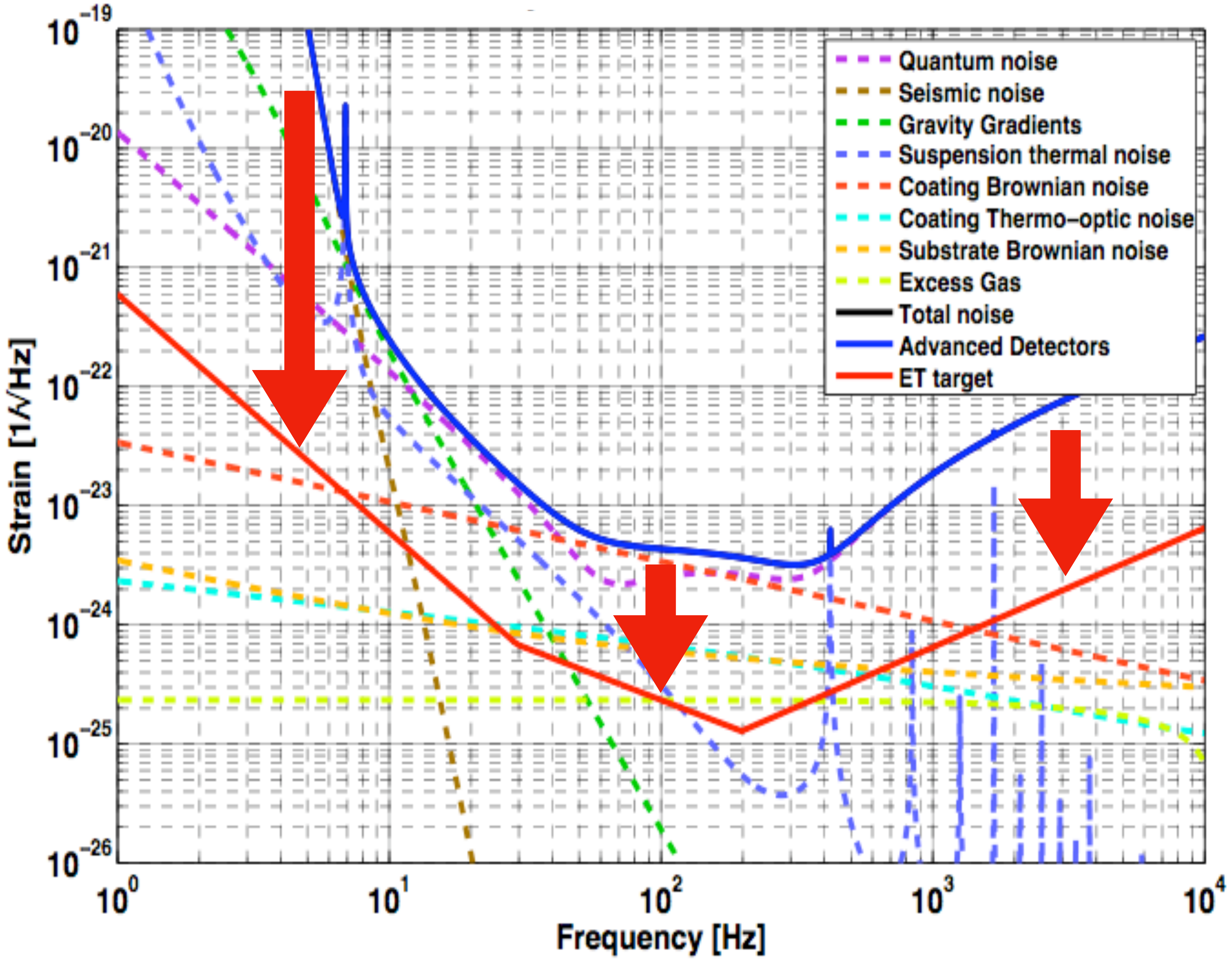


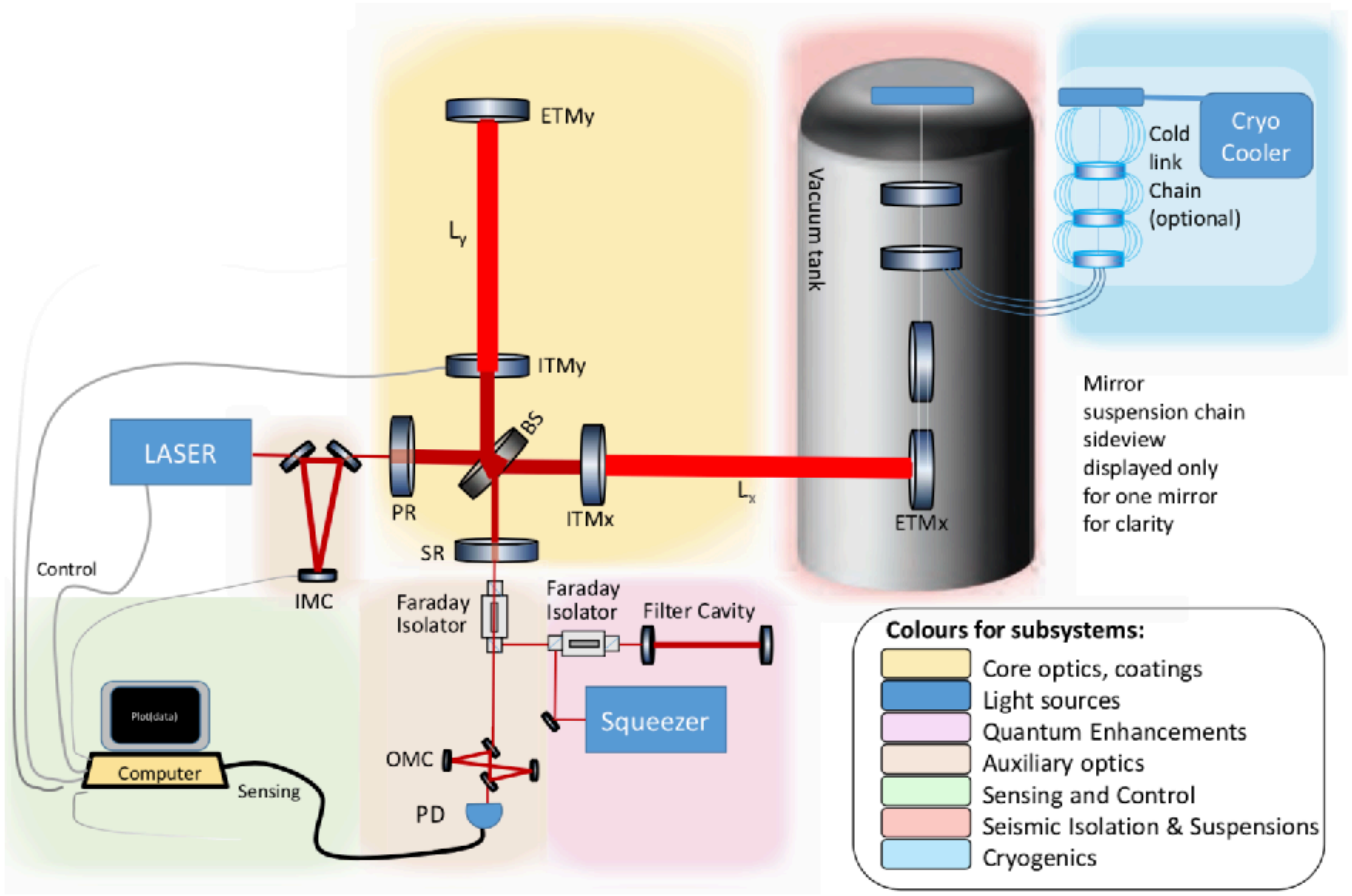
Better sensors, new actuators

- **Better actuators**: The main optics of the ET-LF interferometer are in a cryogenic environment. Existing actuators use heating for compensation. What can we do in ET-LF (without touching any mirror)? ET-HF will have similar optics as Virgo and LIGO but much higher laser power. Better actuators are required to compensate the larger distortions.

- **Better sensors**: ET-LF and ET-HF have at least a factor of 10 stricter noice requirements, so sensor noise of wavefront sensors and other TCS systems must be significantly improved.

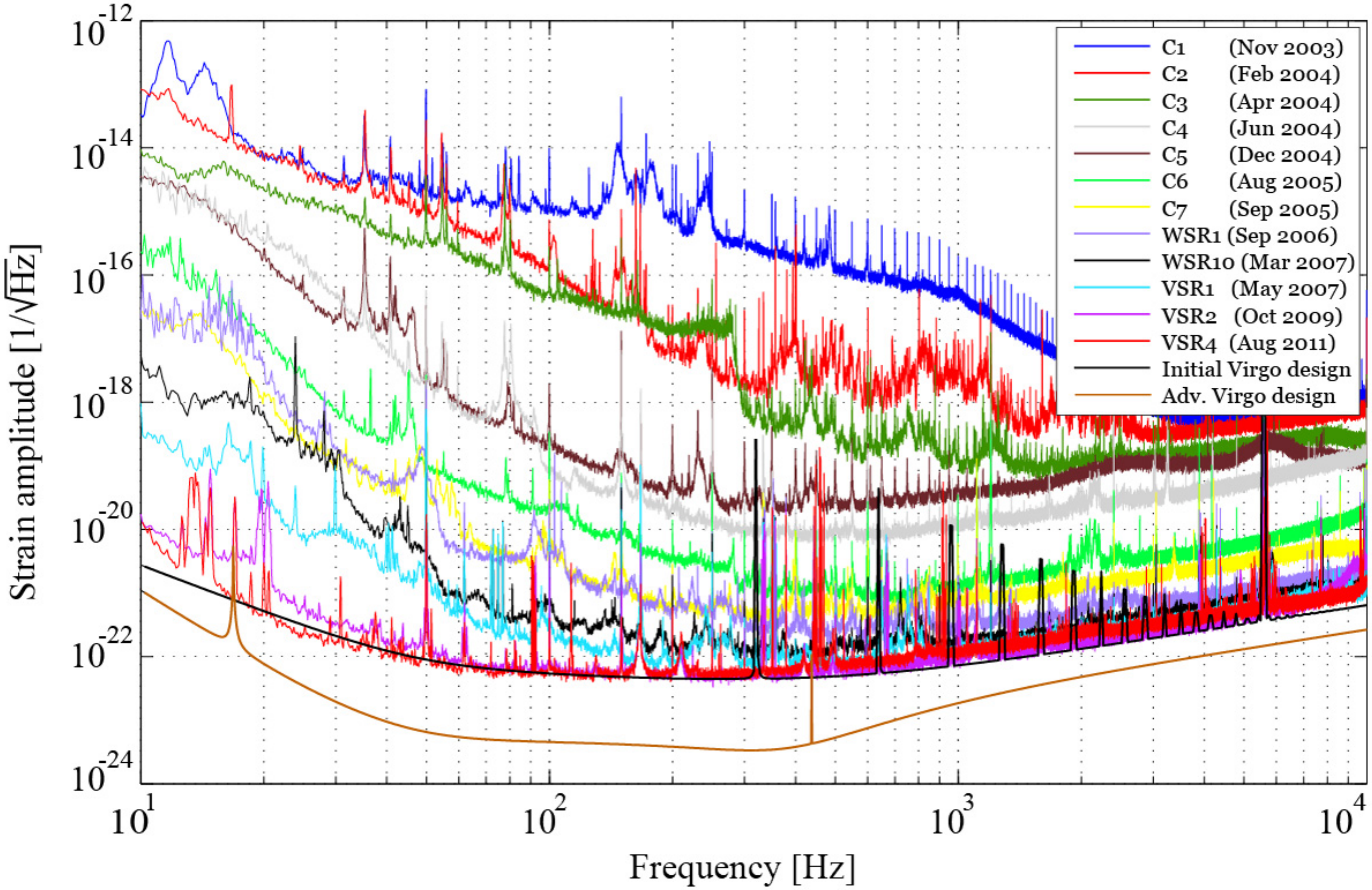
Updating detector technology piece by piece…



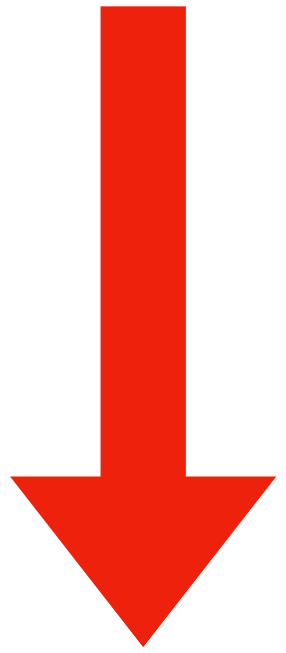


https://gwic.ligo.org/3Gsubcomm/documents/GWIC_3G_R_D_Subcommittee_report_July_2019.pdf

… is not enough. We build a complex machine.



Virgo detector



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

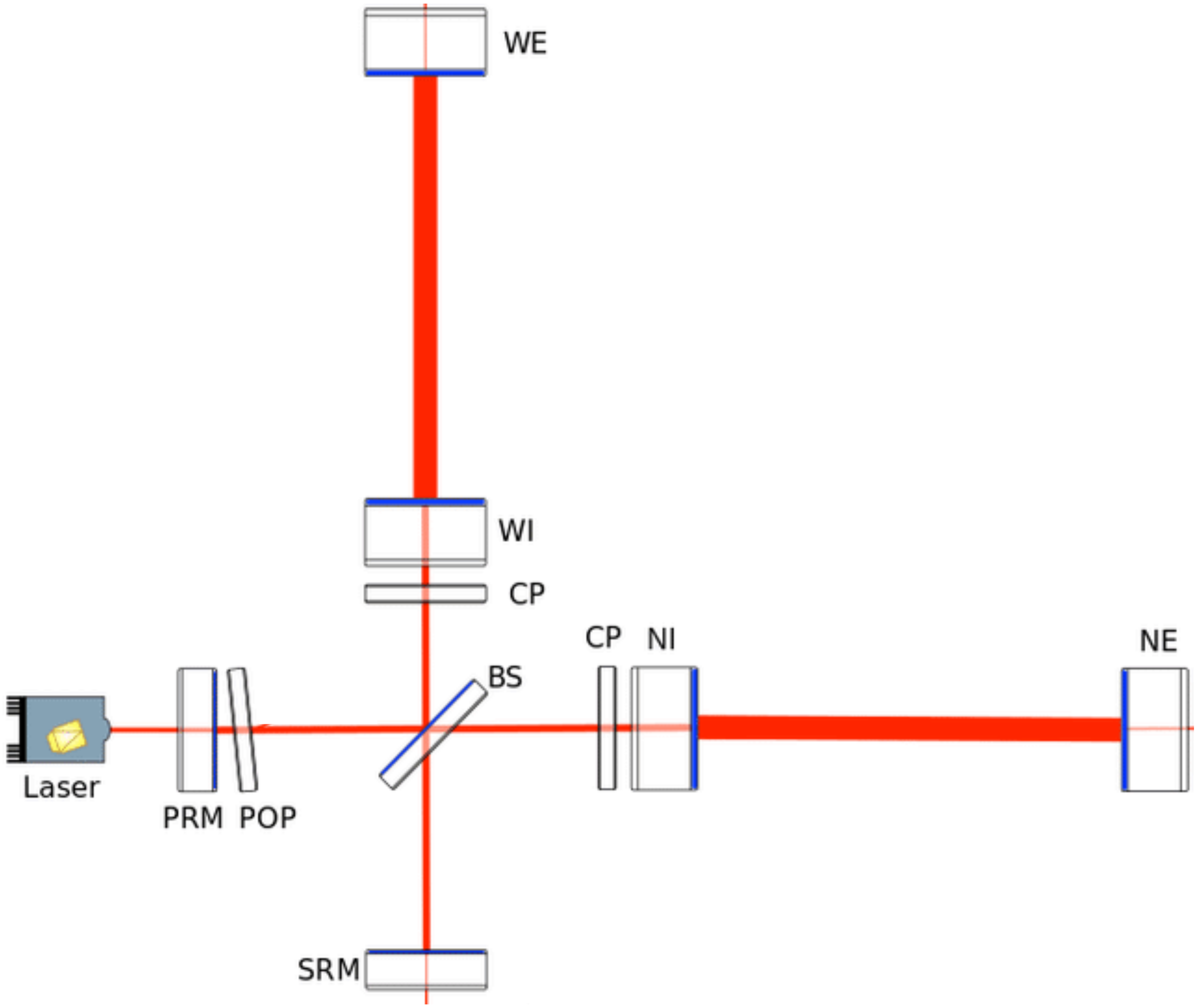
Better inference: key challenge is the operating point

To detect GWs the detector length degrees of freedom must be **locked** at its operating point:

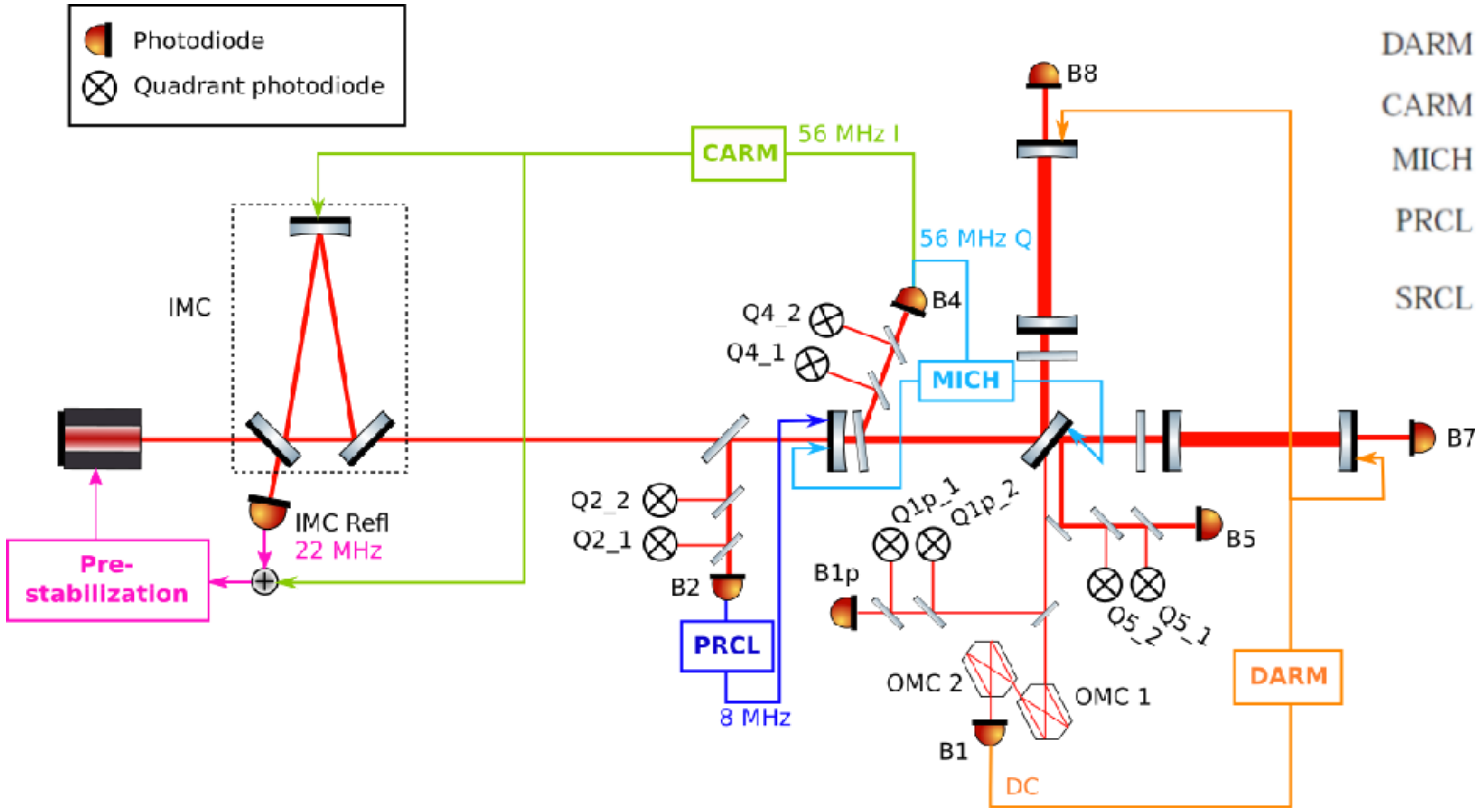
- Resisting environmental effects, maintaining sensitivity
- But also, critically, the operating point depends on the detailed phase relations of higher-order optical modes in the interferometer

All interferometer behaviours change rapidly when **offsets** are introduced

- All optical imperfections affect error signals - so offsets are often produced
- Those offsets also distort the readouts for thermal compensation control



Position sensing and control



$$\mathrm{DARM} = L_N - L_W \text{ (differential arm length)}$$

$$\mathrm{CARM} = \frac{L_N + L_W}{2} \text{ (average arm length)}$$

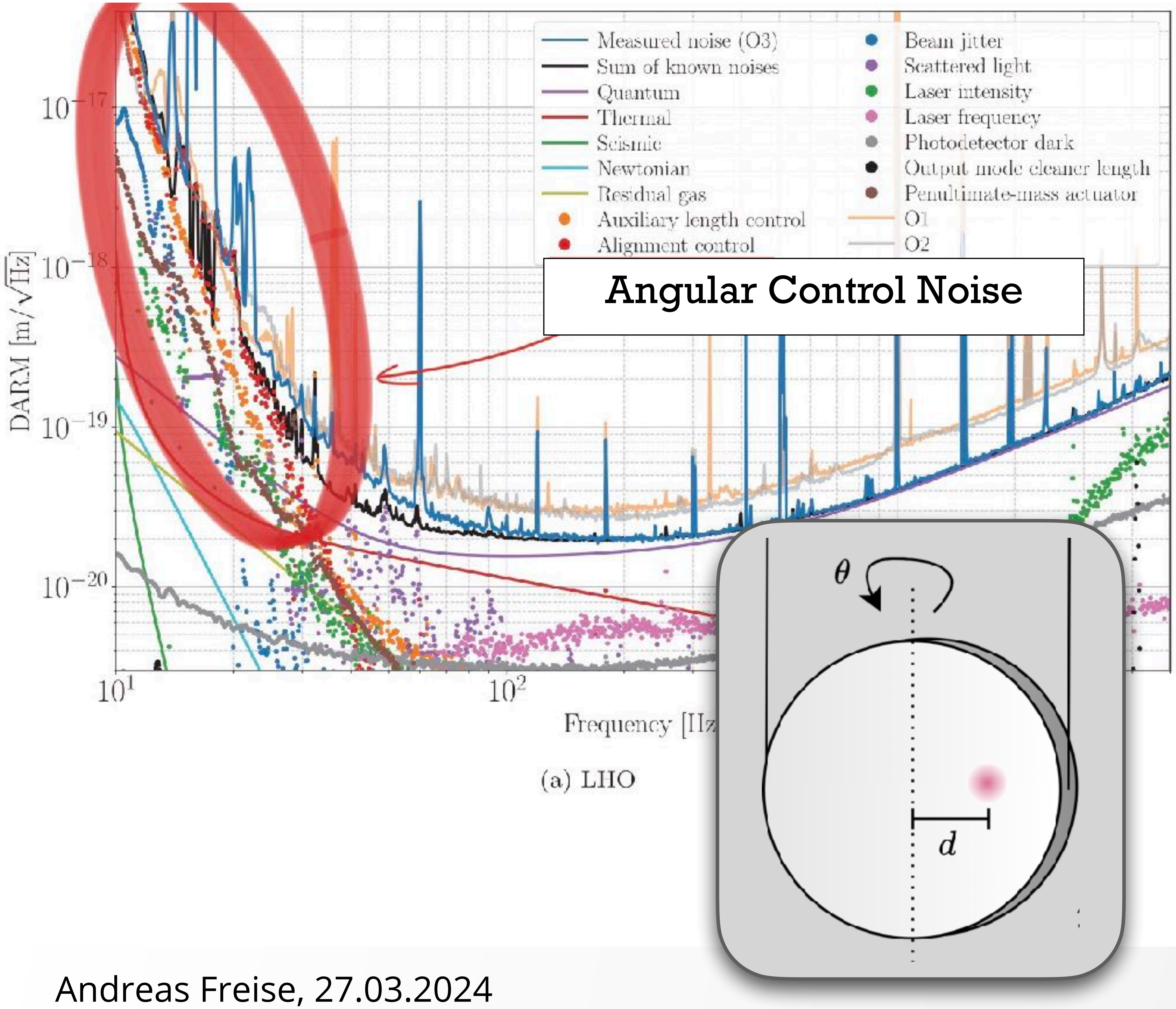
$$\mathrm{MICH} = l_N - l_W \text{ (differential Michelson short arm length)}$$

$$\mathrm{PRCL} = l_P + \frac{l_N + l_W}{2} \text{ (power recycling cavity length)}$$

$$\mathrm{SRCL} = l_S + \frac{l_N + l_W}{2} \text{ (signal recycling cavity length)}$$

- Interferometer is only sensitive when all cavities are on resonance / at dark fringe: use real-time system to control many degrees-of-freedom.
- Error signals obtained mostly using RF-modulation schemes: modulate laser beam with Electro-Optic Modulators, demodulate photodiode/quadrant signals (similar to lock-in amplifiers).
- Actuate on mirrors using voice-coil actuators and electro-static actuation.
- Similar control loops for angular degrees of freedom.

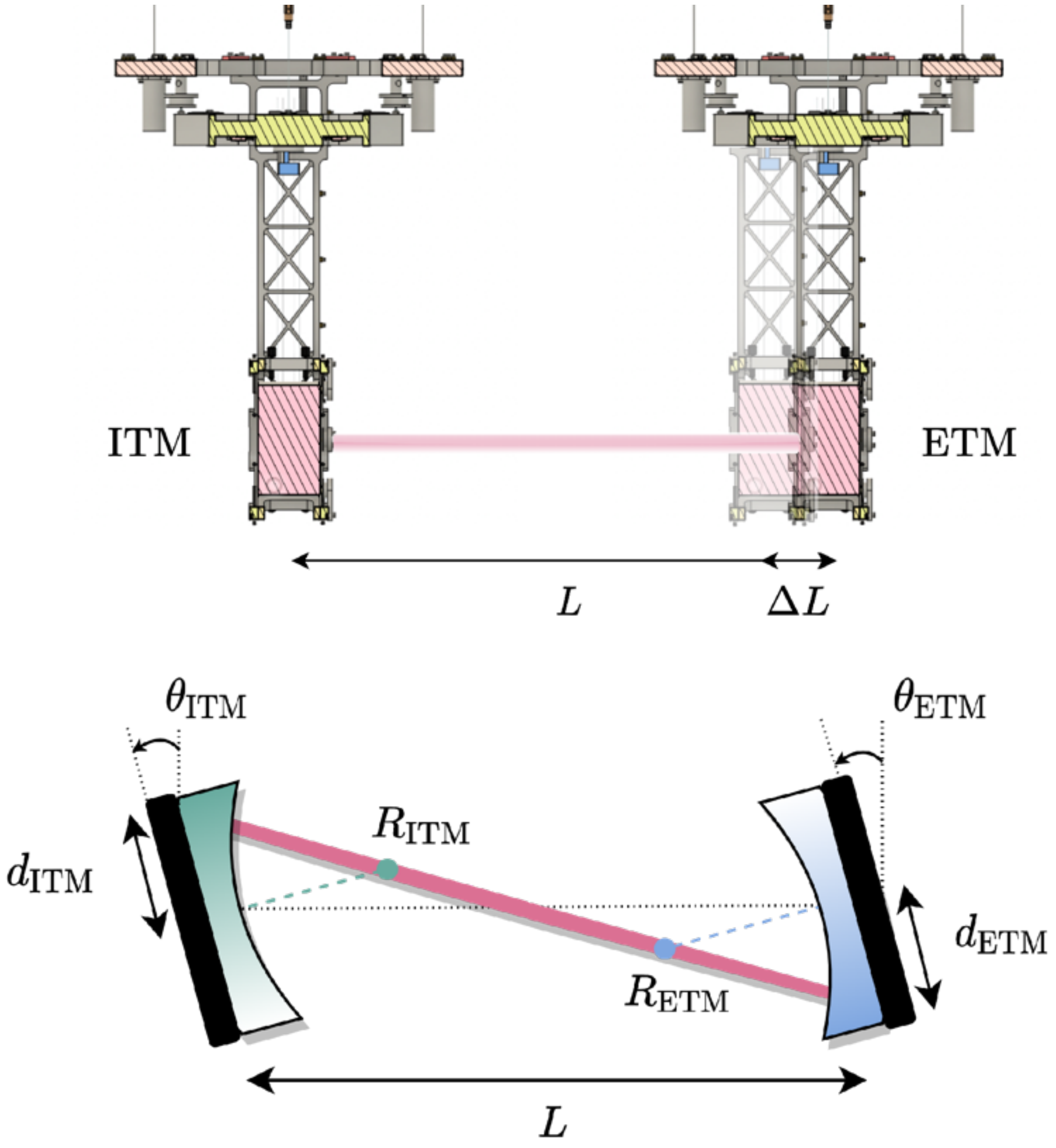
The subtle art of optomechanics



Angular Control Noise

(a) LHO

Phys. Rev. D 102, 062003



[Riccardo Maggiore]

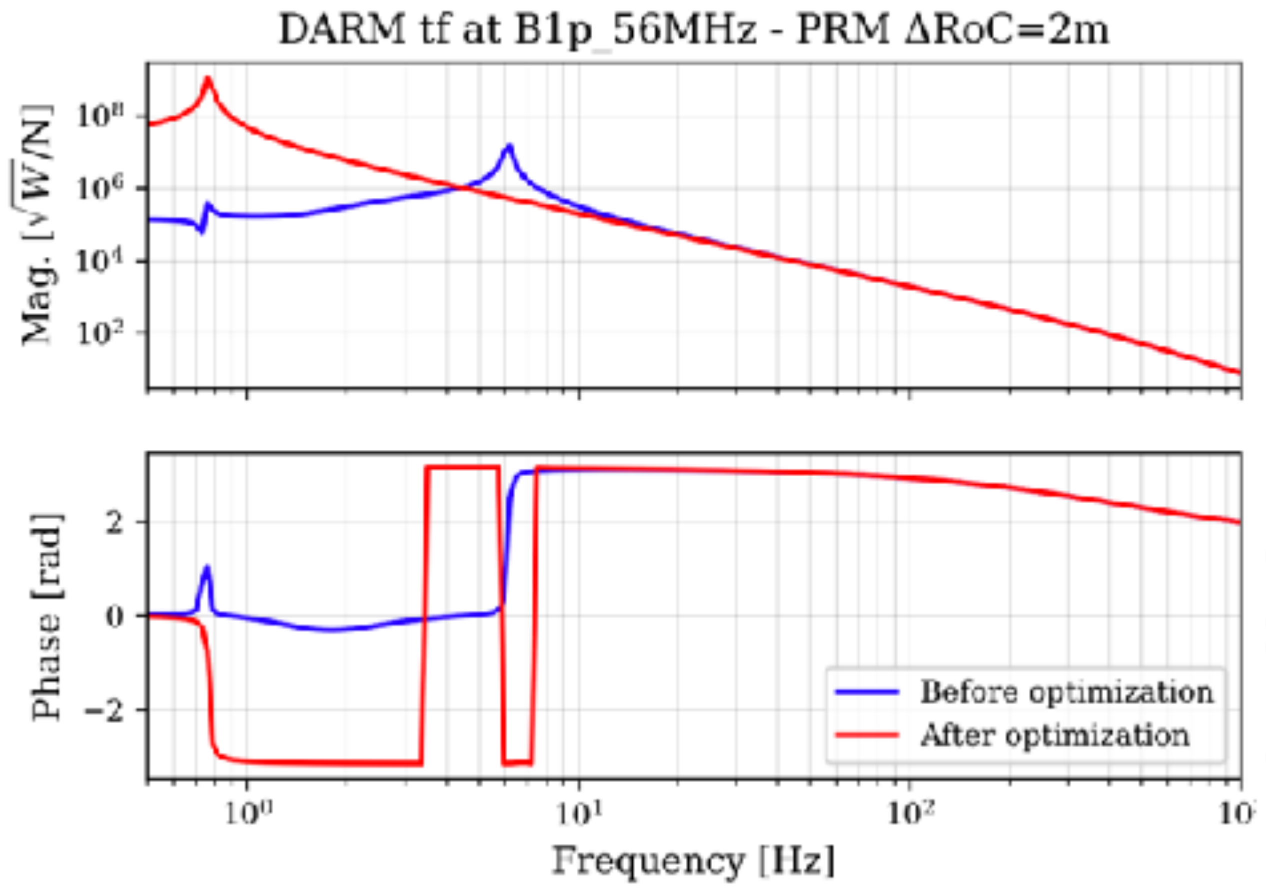
Main interferometers signal as probe

The ‘DARM TF’ is the detector response function, and often our most sensitive probe for detector performance overall.

Common feature: Optical spring in DARM TF is distorted by many defects - in experiment & simulations

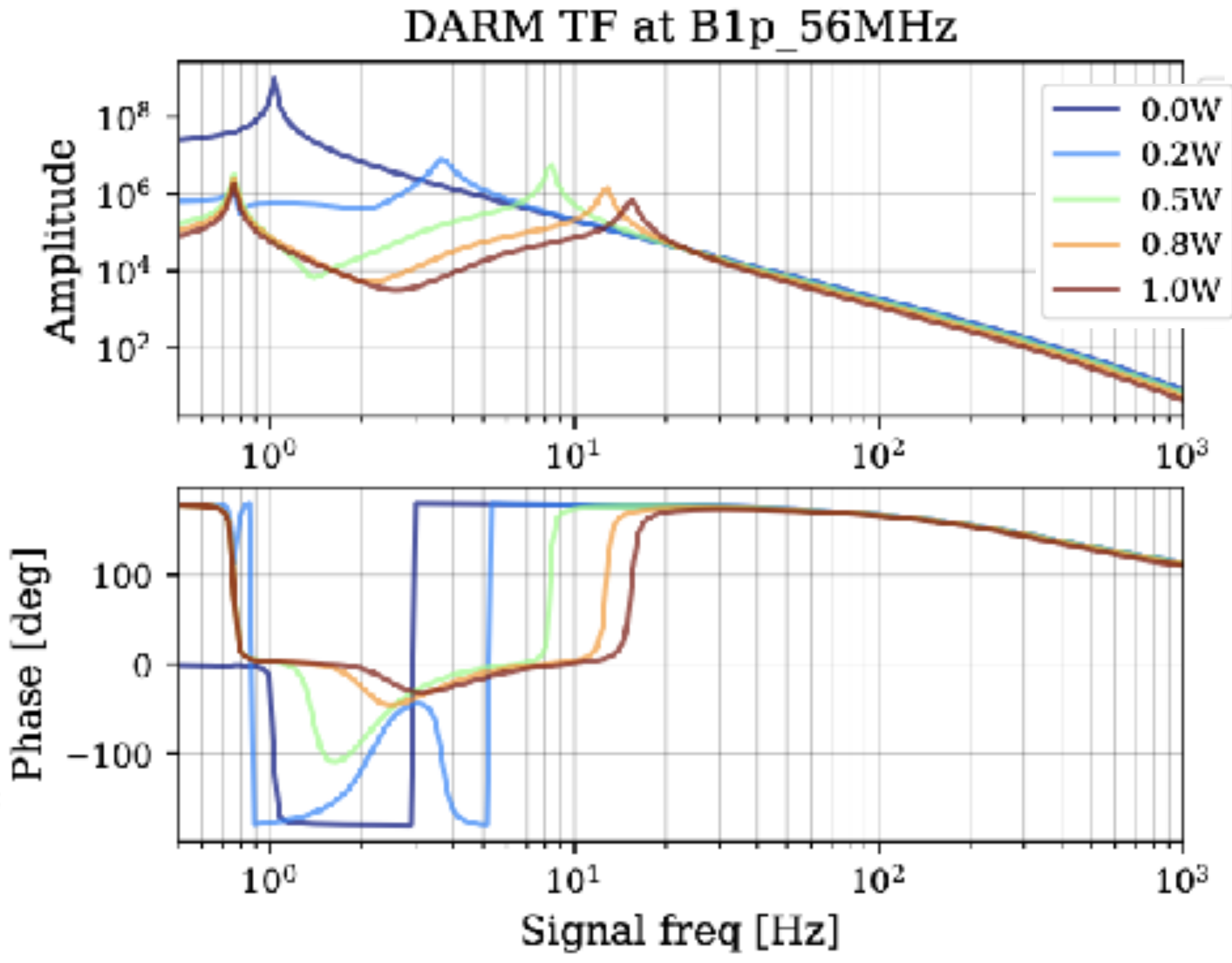
→ we want to understand exactly the dynamic response of a radiation-pressure dominated opto-mechanical object made of 7 complex systems distributed over 10km lengths.

Mode mismatch



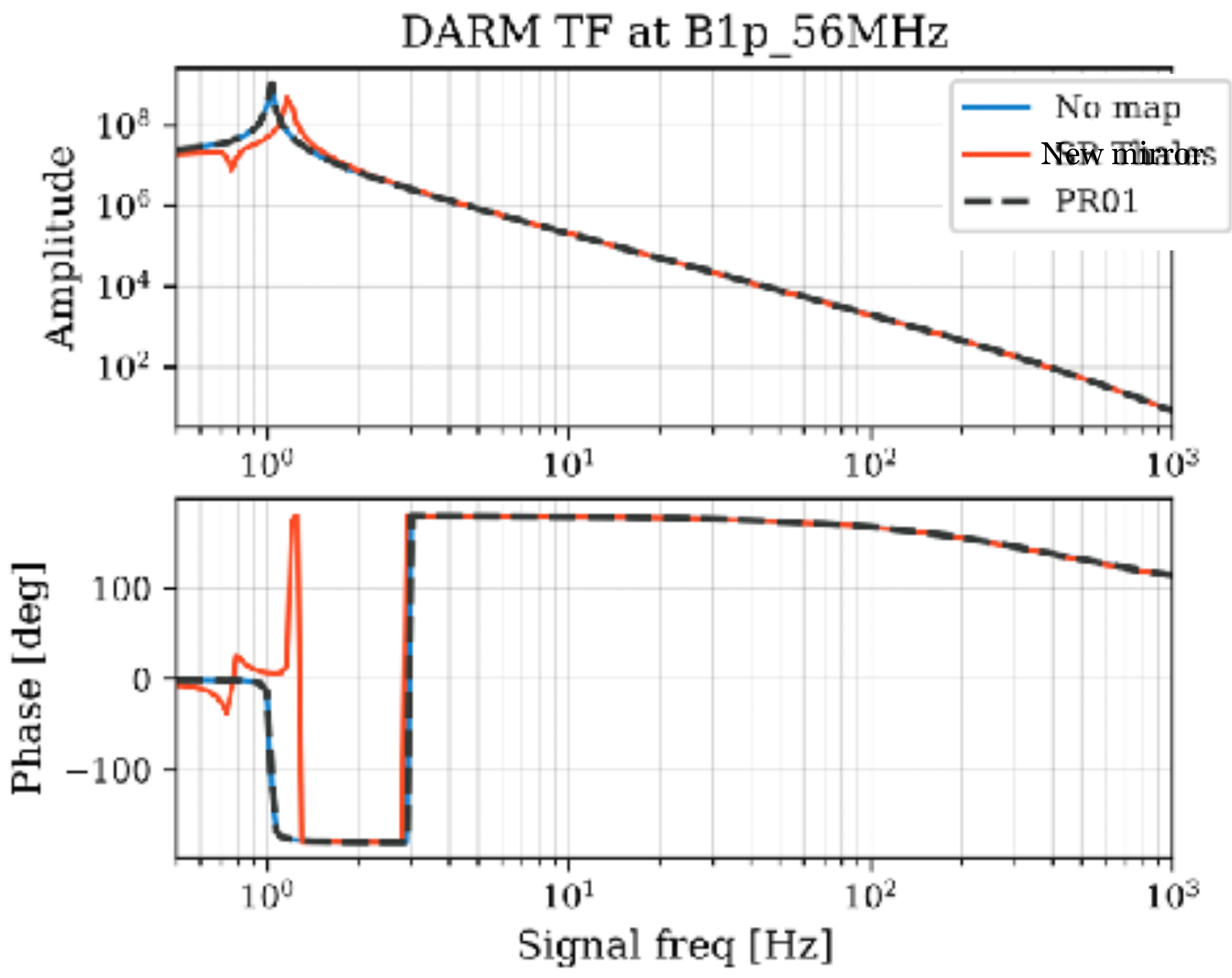
VIR-0801A-22

Thermal effects



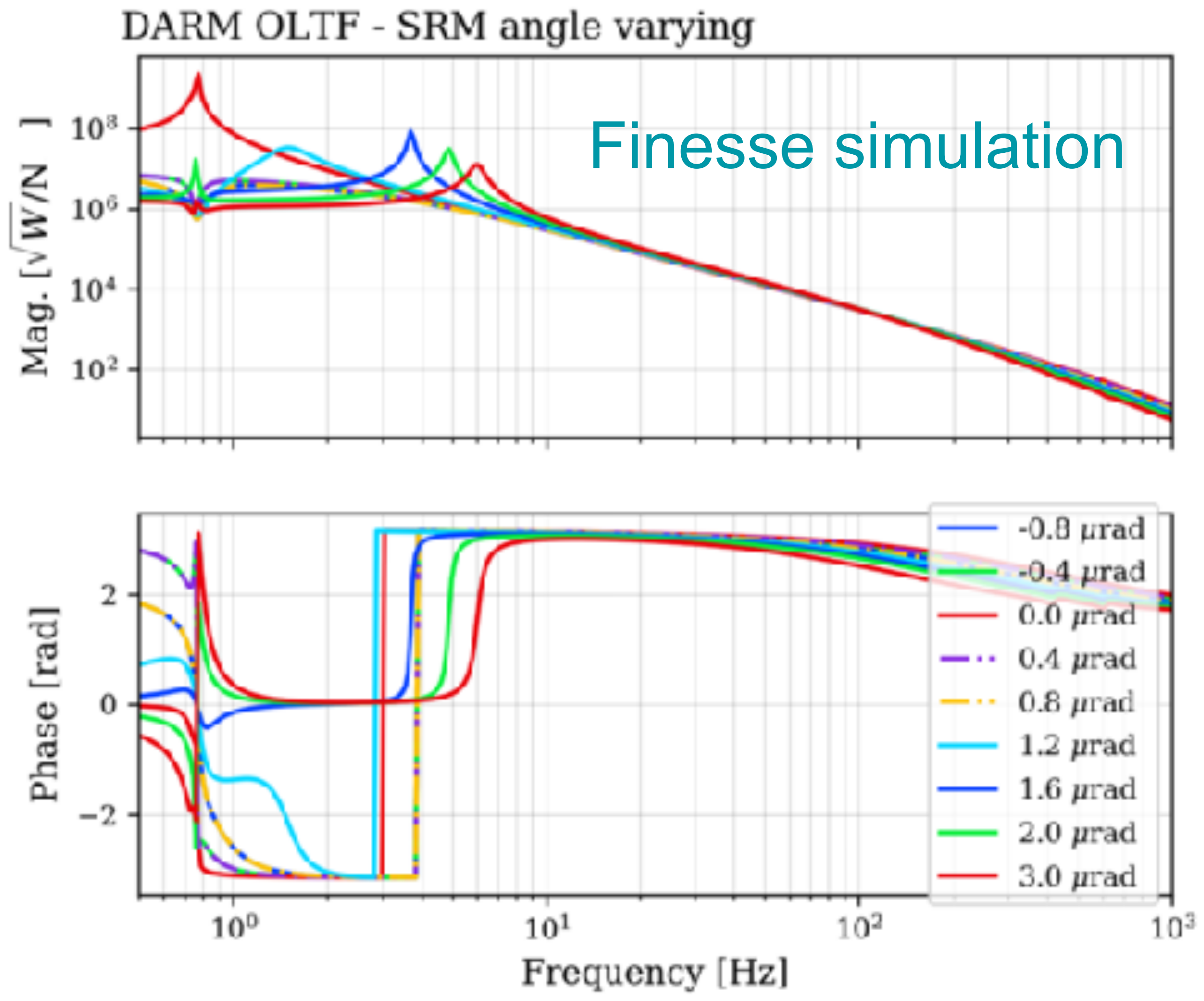
VIR-0738A-22

Surface microroughness



VIR-0909B-22

tilt

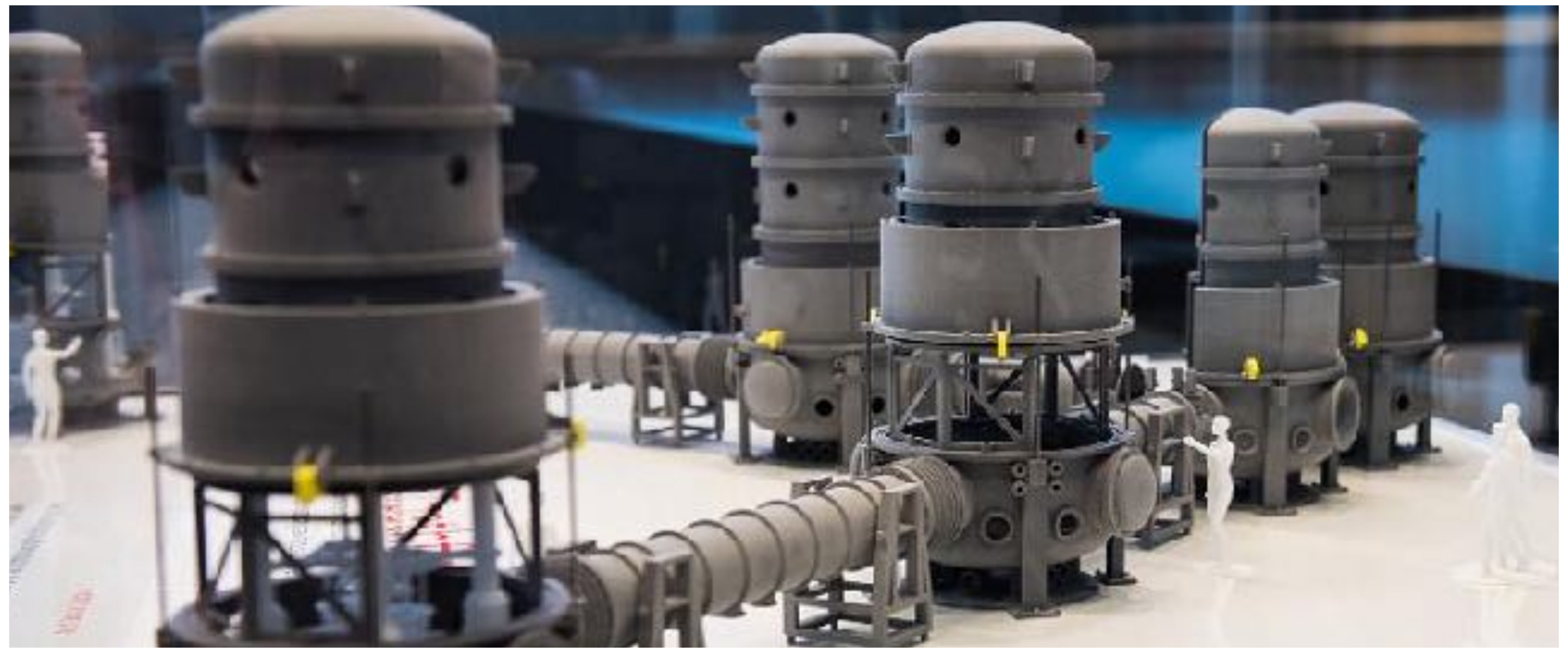


Finesse simulation

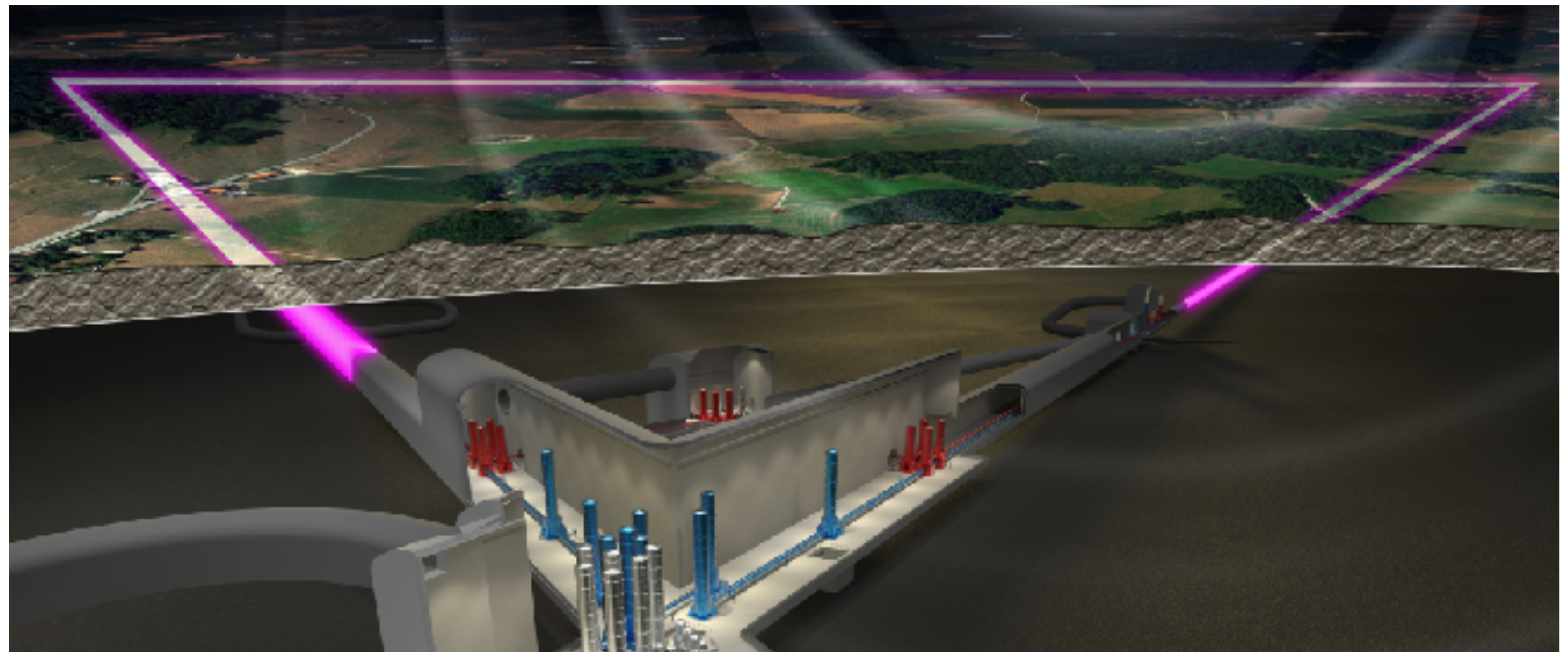
VIR-0282A-22

Nikhef, synergies in instrument development

Virgo: large-scale detector in Italy, able to detect GWs, **currently operating and/or being upgraded.**



ETpathfinder: 10m scale prototype interferometer, a testbed for future GW technologies, **currently under construction.**



Einstein Telescope: plan for future observatory in Europe, currently design, site selection, **research and technology development.**

Summary

- Gravitational wave detectors are currently limited by the effects from thermally deformed optics.
- Key challenges are the actuation for the cryogenic mirrors in ET-LF and for the very high power systems in ET-HF.
- Better wave front sensors are required to meet the more stringent noise requirements of ET (compared to current systems).
- A very good understanding of the strongly coupled detectors as a whole is required for better inference and control strategies.