Gravitational Waves, Experiment
Lecture 3

Andreas Freise

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Schedule

Lecture 1:

- Introduction to GWs
- History of ground-based GW detection
- Basics of interferometric GW detection

Lecture 2:

- Calculating optical signals in basic interferometers
- Properties of optical cavities

Lecture 3:

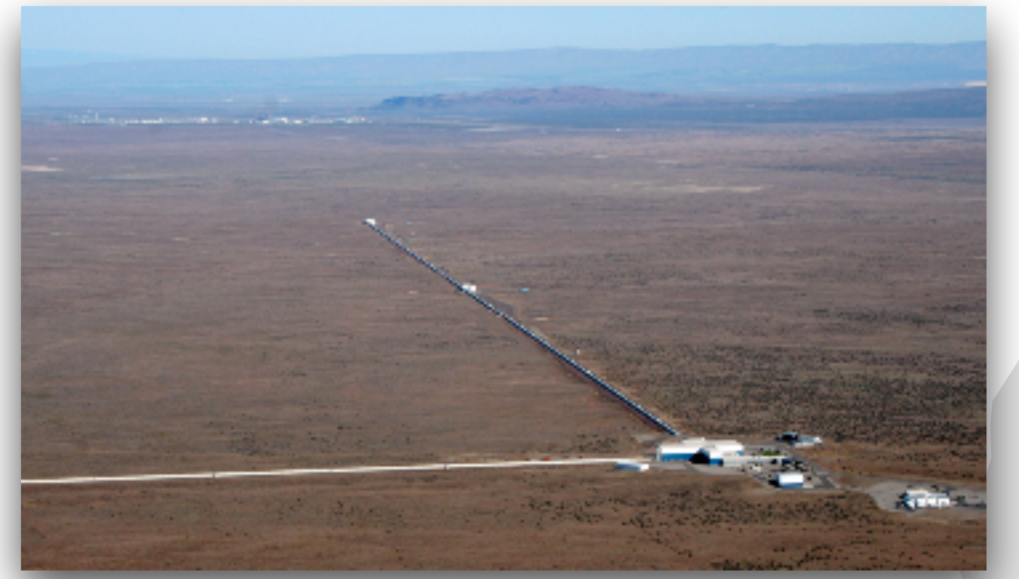
- Modern interferometric detectors
- Plans for future detectors
- Einstein Telescope

Hands-on:

- Using the interferometer simulation Finesse
- Properties of optical cavities

Modern interferometric detectors

Two LIGO Instruments

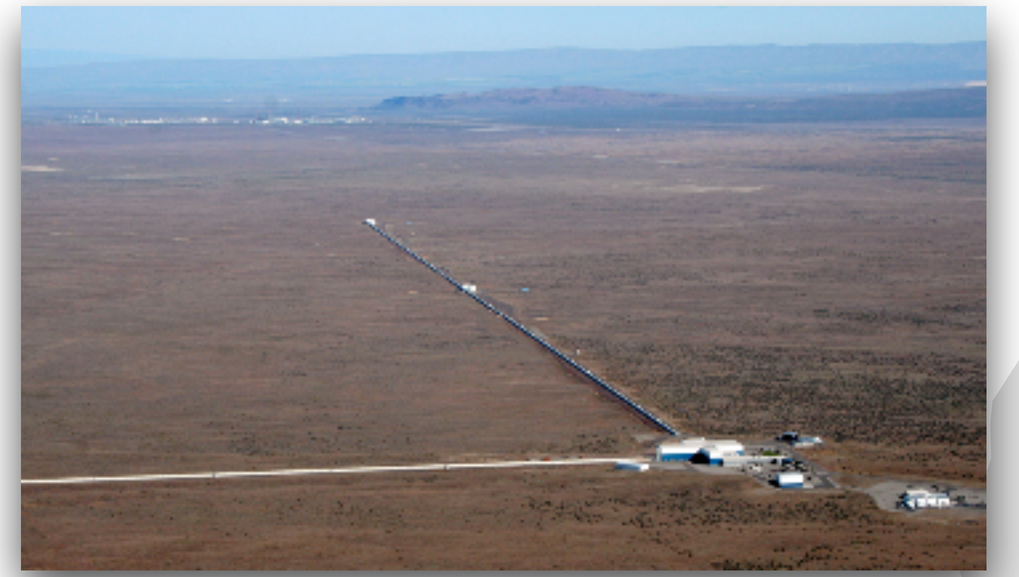


Sensitivity:
0.000 000 000 000 01 of a fringe
or 10^{-20} m

Question:

Why build two large detectors? One even larger would be better value for money?

Two LIGO Instruments



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[Images: Google Earth and LIGO]


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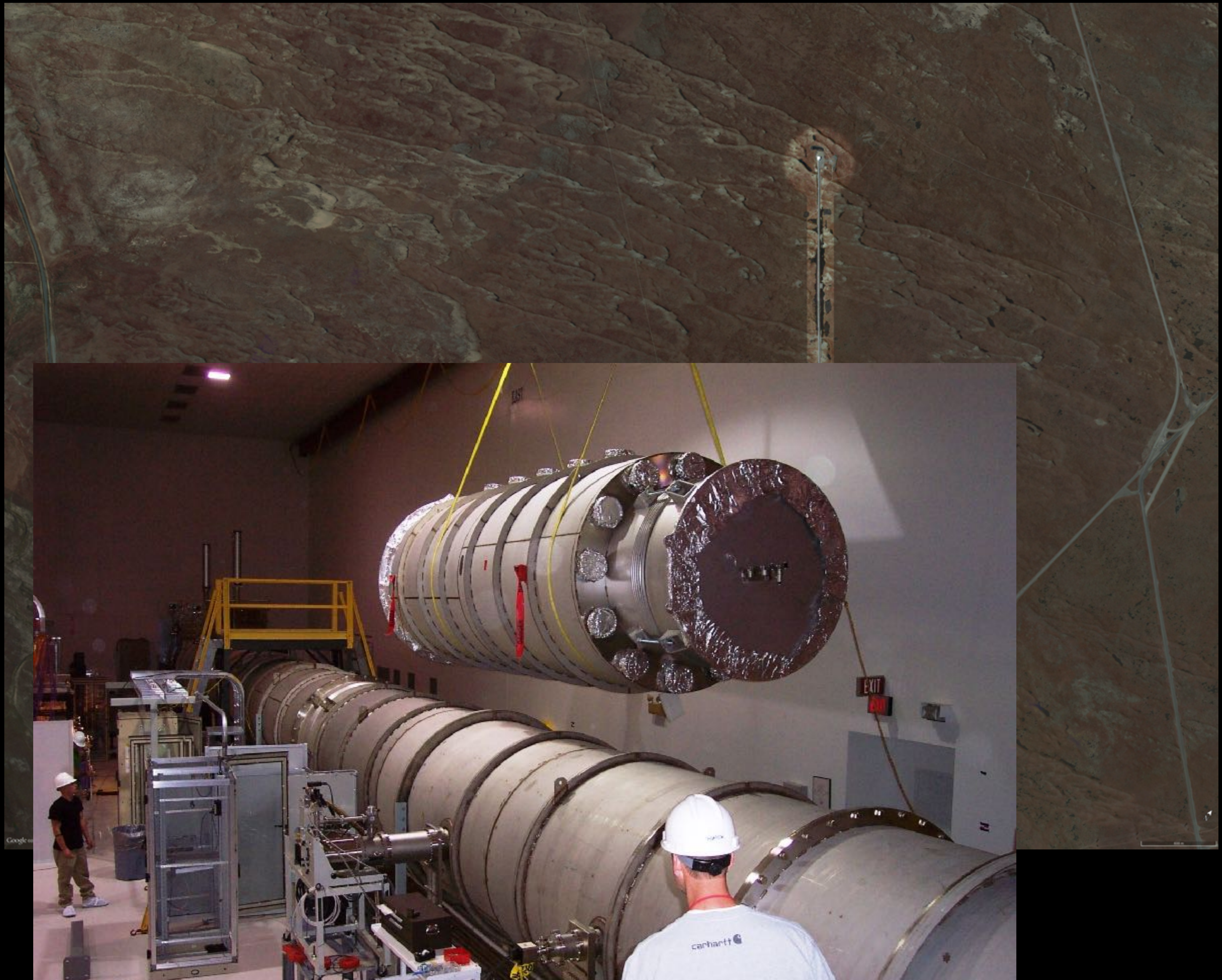
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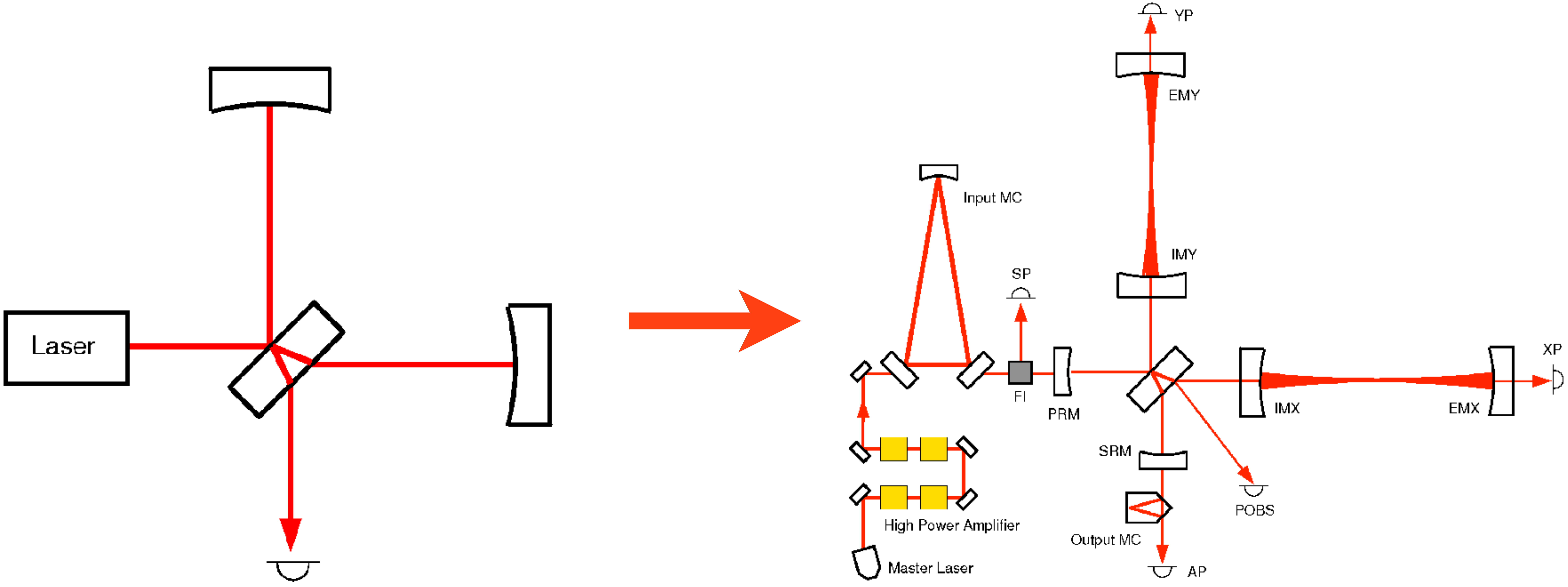
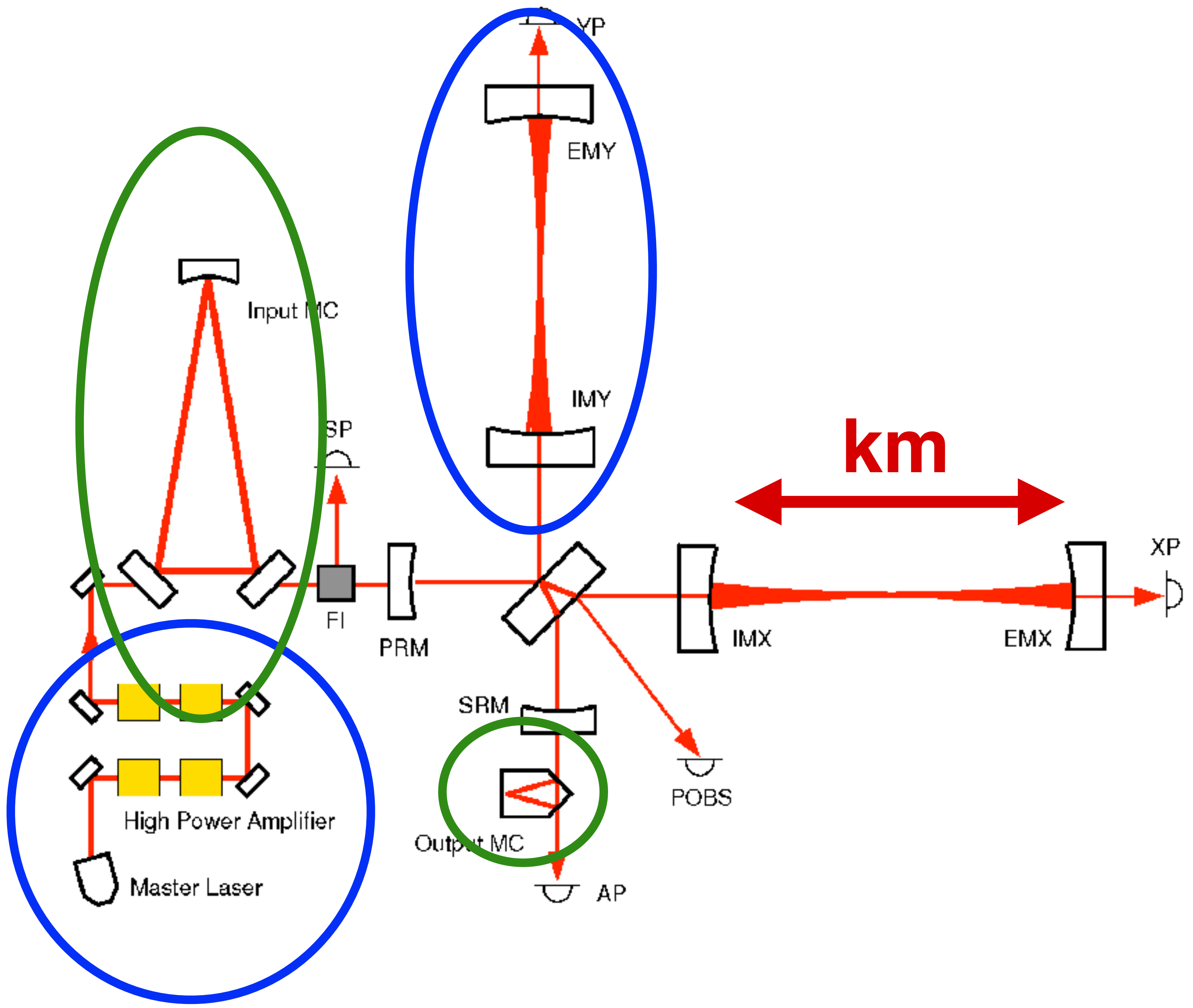
carhartt

Advanced interferometry

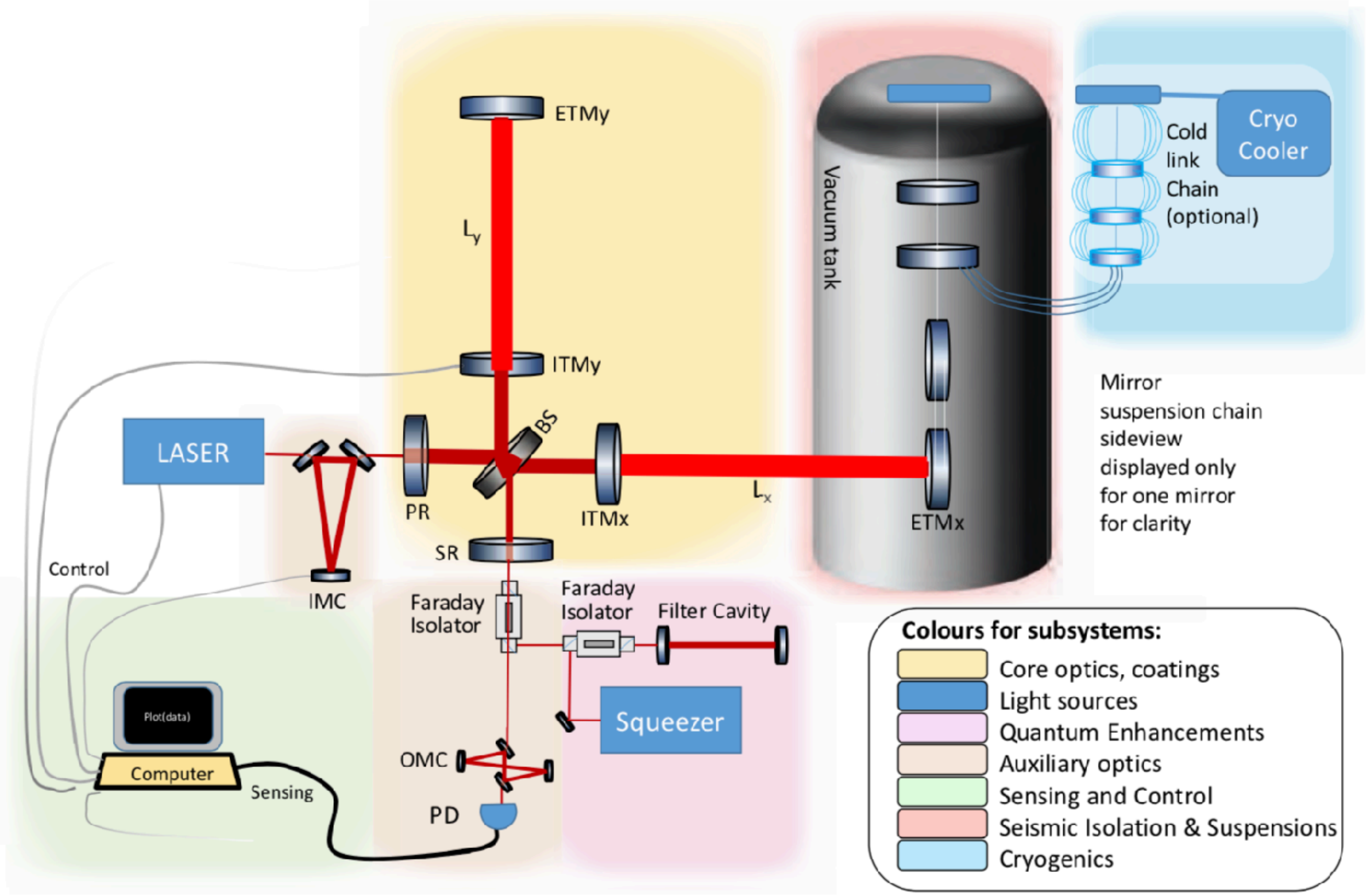


What makes it better?



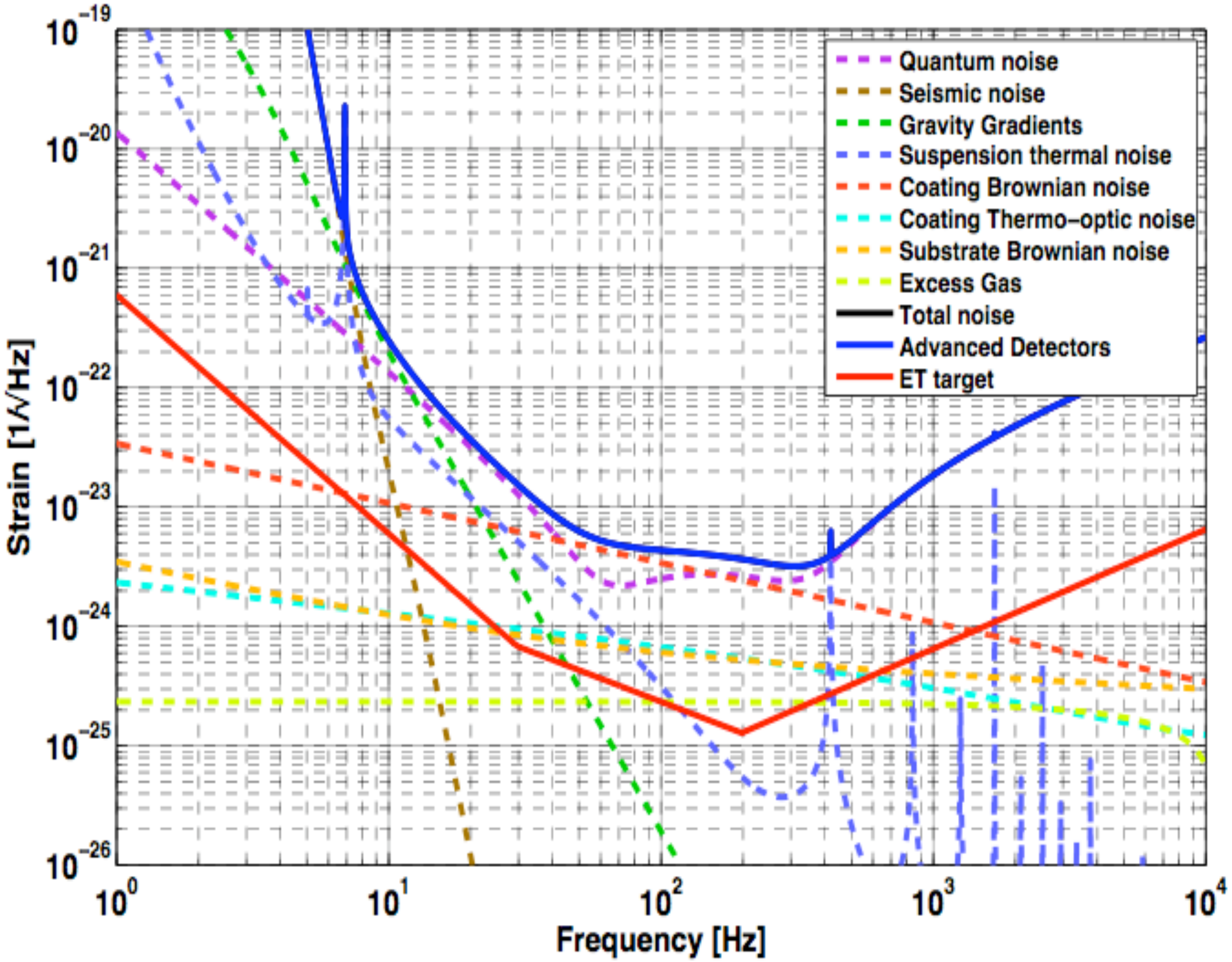
- GW effect scales with arm length: large detectors
- Optical signal scales with light power: high-power laser, optical cavities
- Laser beam fluctuations make noise: filter cavities

- **Stop everything from shaking!**



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

What is limiting the detector? Self-noise!



- Each trace is a detector noise projected into the signal channel, i.e. these are noise/signal curves).
- The noises are plotted as **amplitude spectral densities**
- The sum of the the noises is called the detector sensitivity.
- Terrestrial noises provide the so-called **seismic wall**, limiting sensitivity at low frequencies

Quantum uncertainty

LIGO displacement sensitivity:

$$\Delta x \sim \sqrt{S_h(f) L \Delta f}|_{100\mathrm{Hz}} \sim 10^{-19}\,\mathrm{m}$$

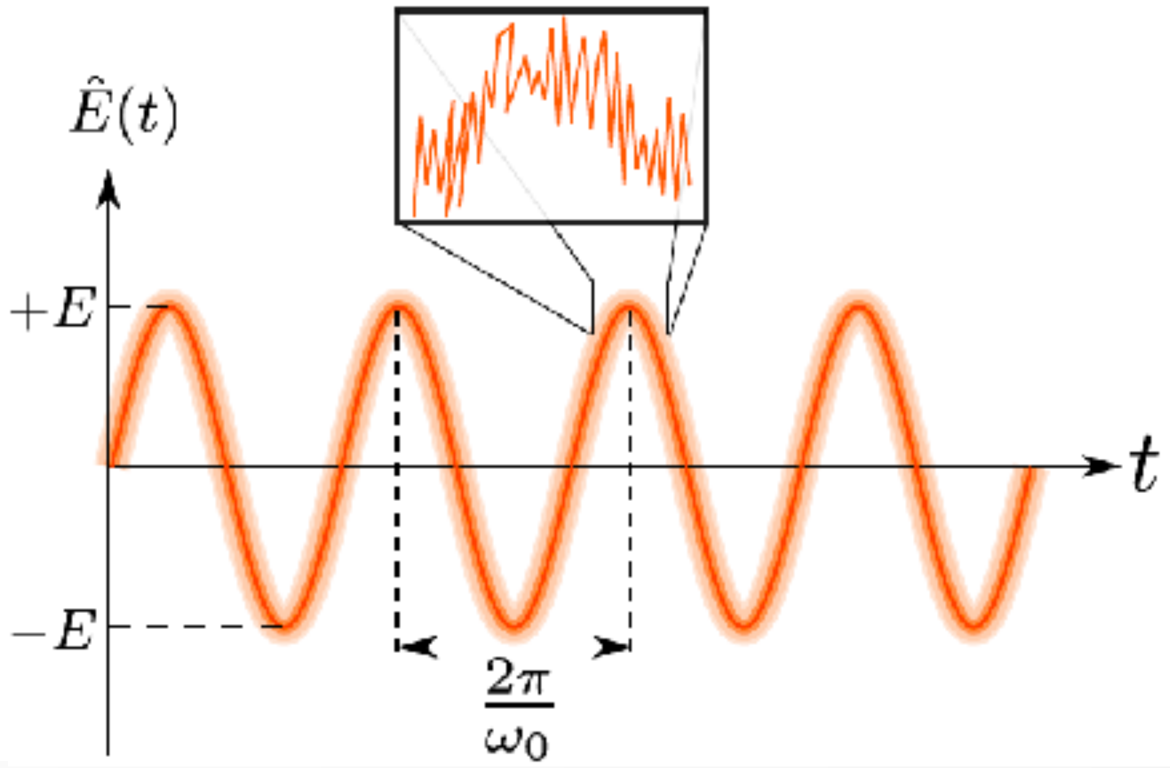
de Broglie wavelength of 40kg test mass:

$$\lambda_\mathrm{d} \sim \sqrt{\hbar/(2\pi\, m\, f)}|_{100\mathrm{Hz}} \sim 10^{-19}\,\mathrm{m}$$

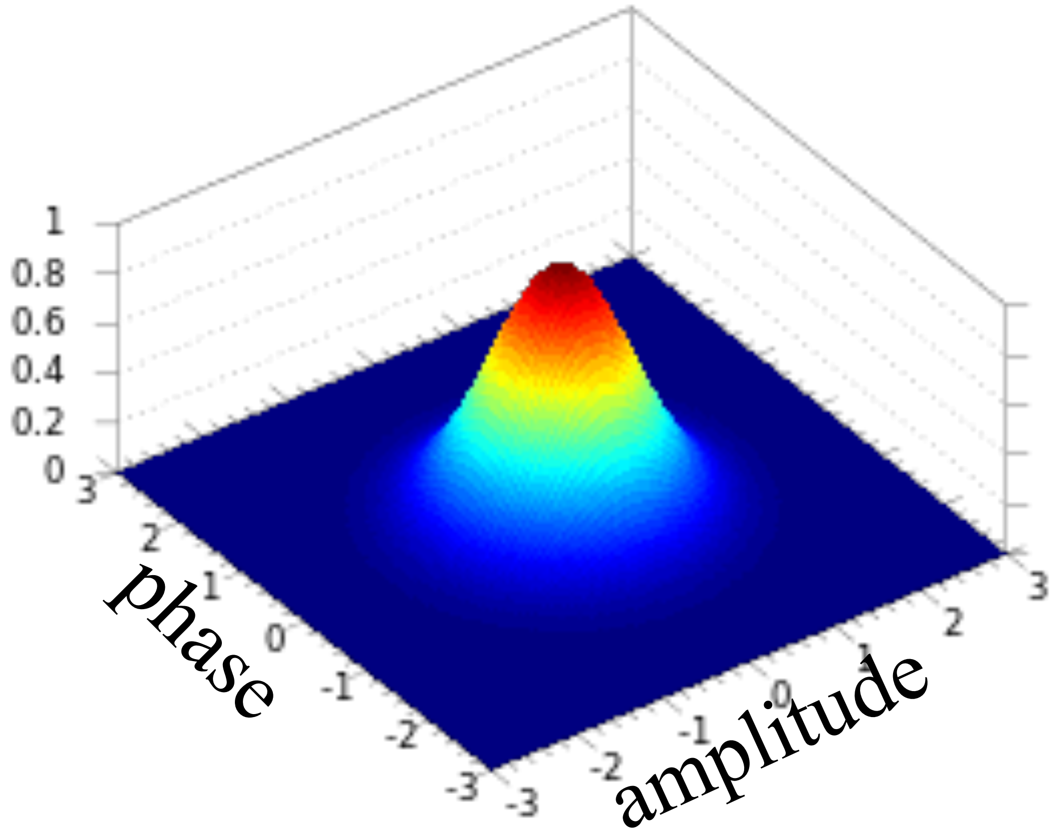
Quantisation of optical field:

Field "position": Phase quadrature

Field "momentum": Amplitude quadrature

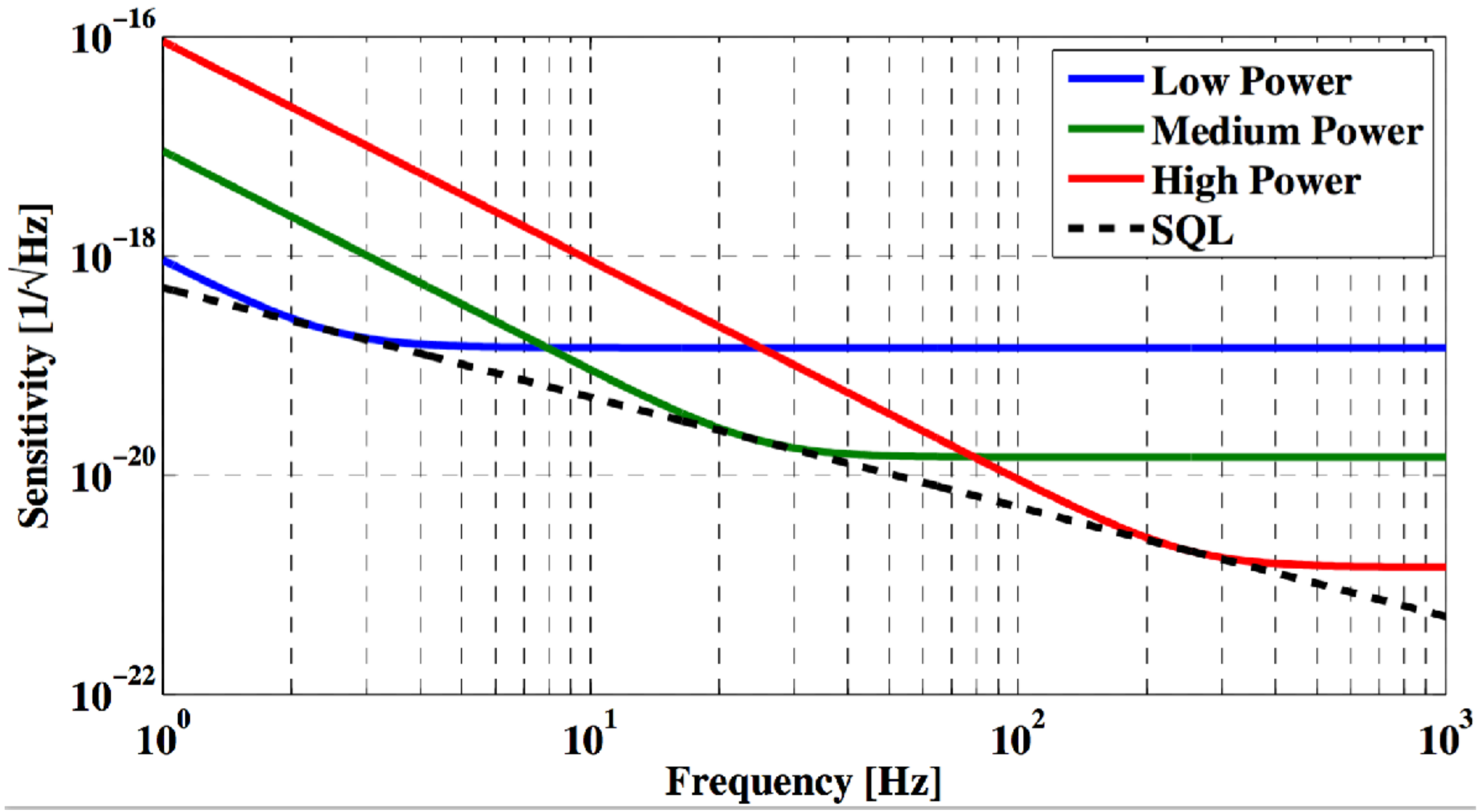


Satisfying
Heisenberg Uncertainty



Ramp up the power

Quantum-noise limit of a Michelson interferometer



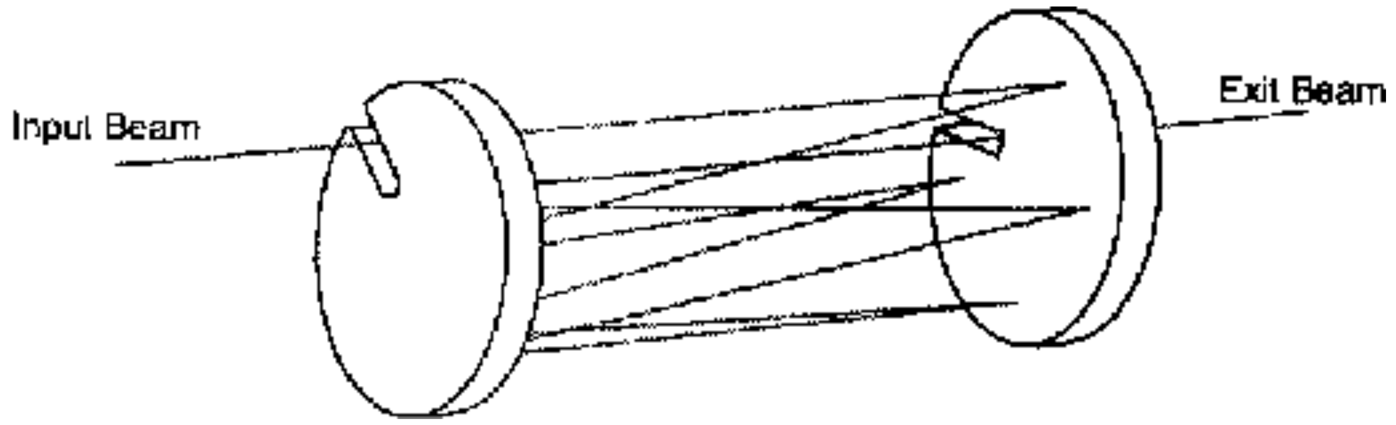
(SQL = Standard Quantum Limit)

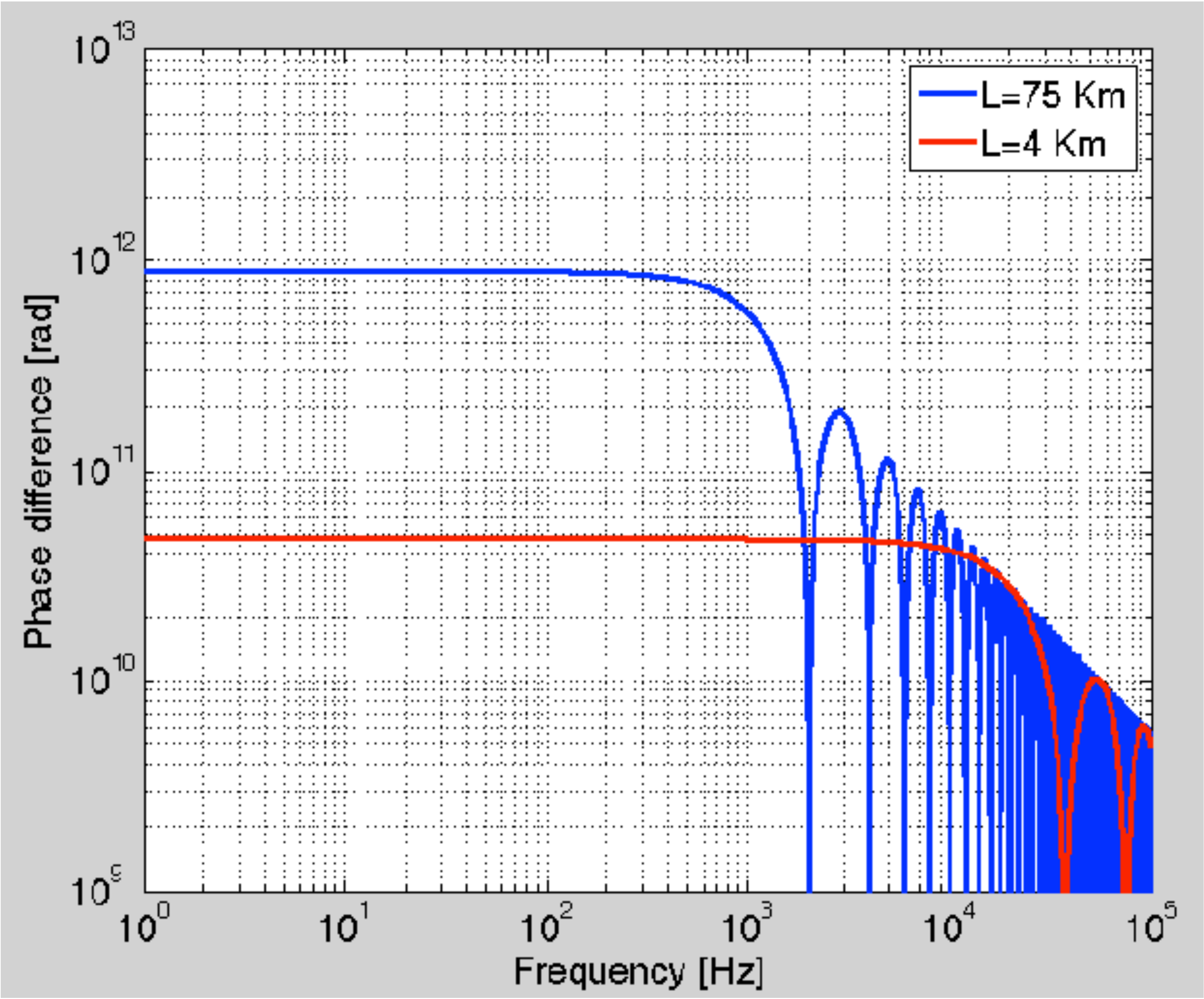
Increasing the arm length

$$\phi(t) = 2kL\frac{1}{\tau}\int_{t-\tau}^{t} h(t')dt'$$

$$\phi = 2kLh$$

Herriott delay line



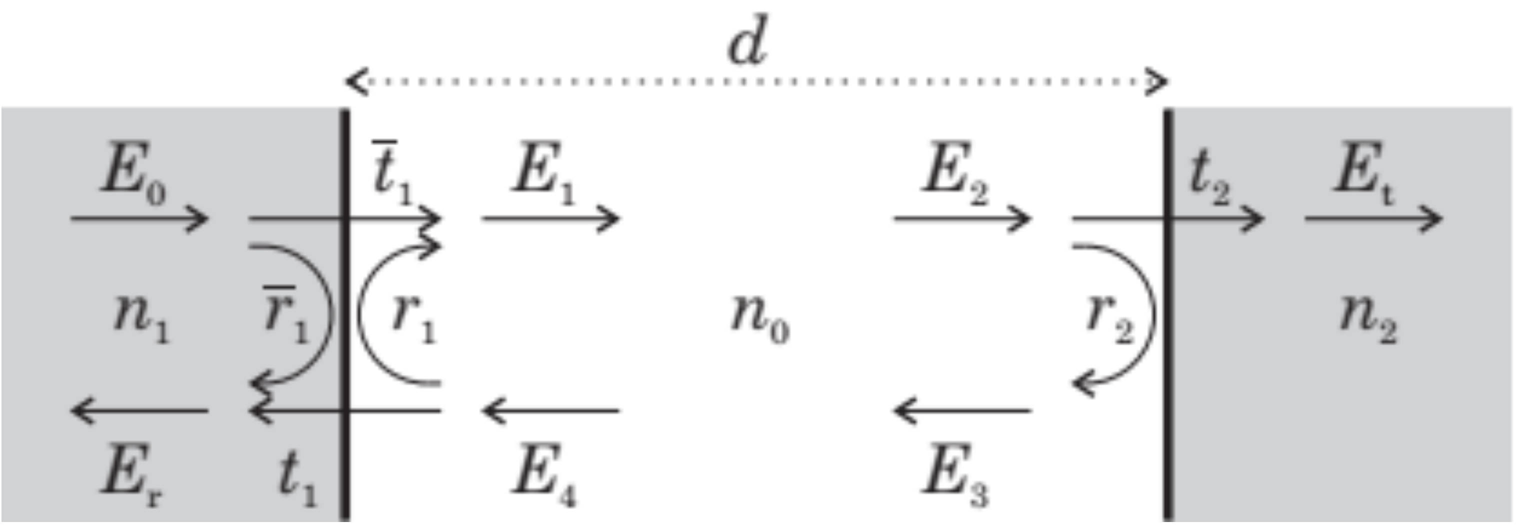


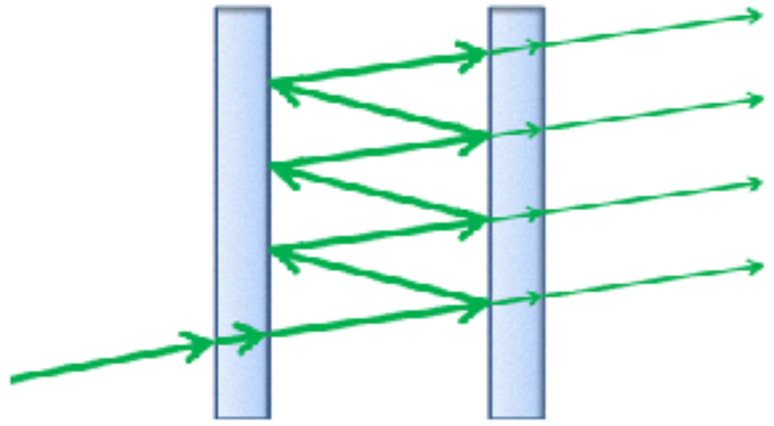
- Sensitivity of Michelson interferometer can be increased by making the arms longer (signal propositional to L)
- Note that longer interferometers have a smaller bandwidth, since GW signal gets 'averaged' over the round-trip time. The response function is a Sinc-function in the frequency domain, with zeros.
- Ideally few 100 km long (for certain interesting astrophysical sources), but money/terrain limits this to few km.
- Could use a delay line (Herriott cell), but this has practical issues.

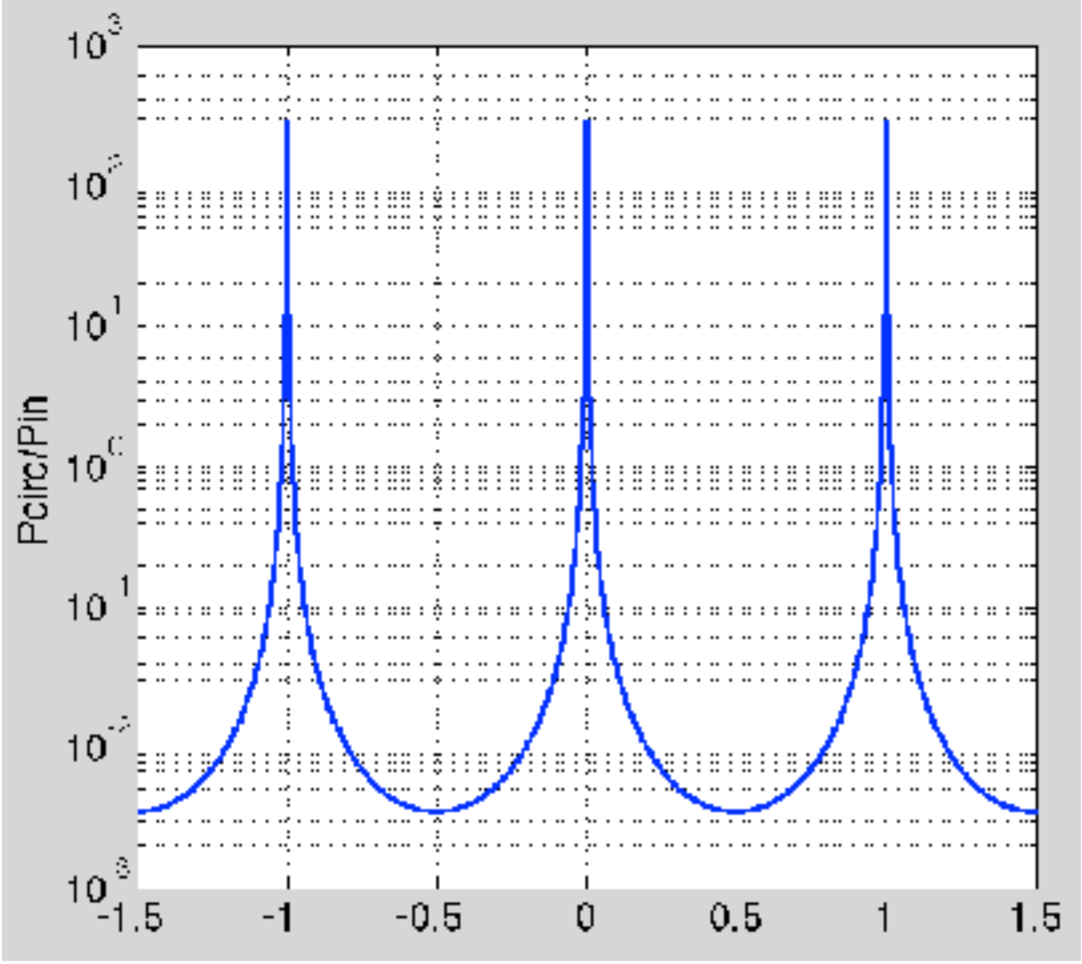
Question:

The space detector LISA has millions of km long arms?
What about those dips (zeros)?

Optical cavity (Fabry-Perot)

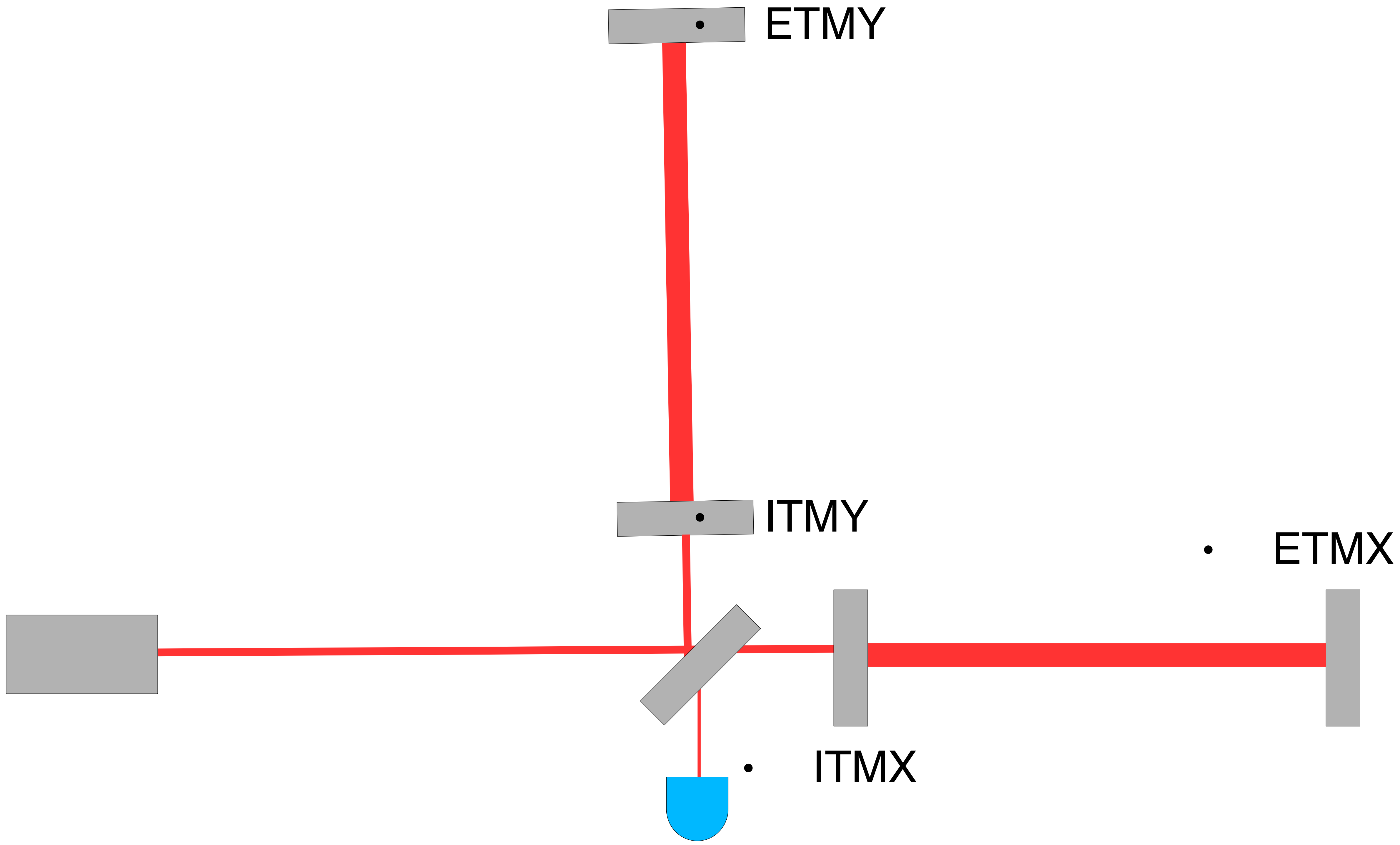






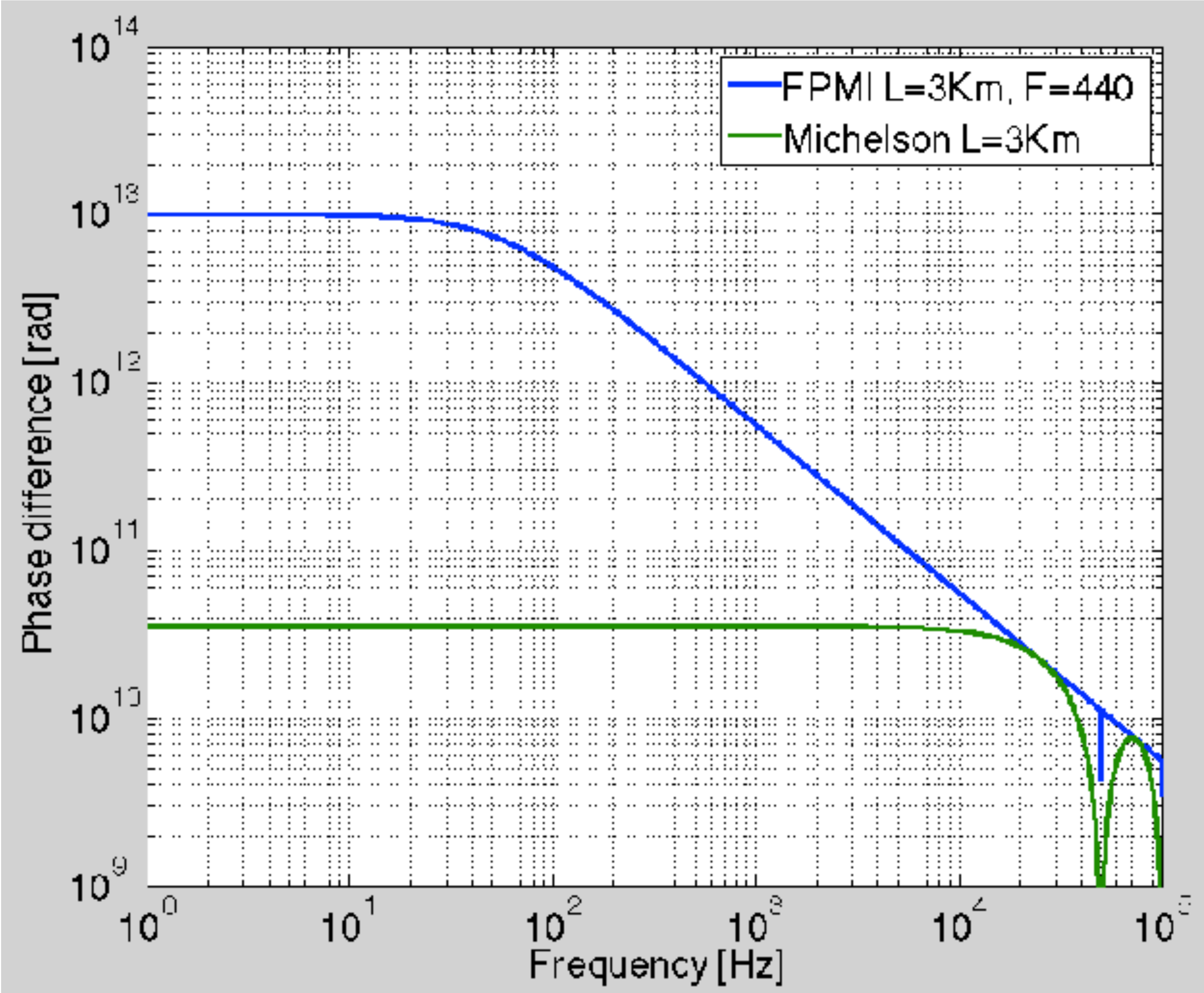
- Resonant optical cavity formed by two highly reflecting mirrors
- Reflection: $$\frac{E_r}{E_0} = -r_1 + \frac{t_1^2 r_2 e^{i\phi}}{1 - r_1 r_2 e^{i\phi}} \qquad \phi = 2kL$$
- Resonances spaced by Free-Spectral Range: $$\delta L_{\mathrm{FSR}} = \frac{\lambda}{2} \qquad \delta\nu_{\mathrm{FSR}} = \frac{c}{2L}$$
- Finesse: $$\mathcal{F} = \frac{\delta L_{\mathrm{FWHM}}}{\delta L_{\mathrm{FSR}}} = \frac{\delta\nu_{\mathrm{FWHM}}}{\delta\nu_{\mathrm{FSR}}} = \frac{\pi\sqrt{r_1 r_2}}{1 - r_1 r_2}$$
- Effective number of round-trips: $$N_{\mathrm{eff}} = \frac{2}{\pi}\mathcal{F}$$

Fabry-Perot Michelson



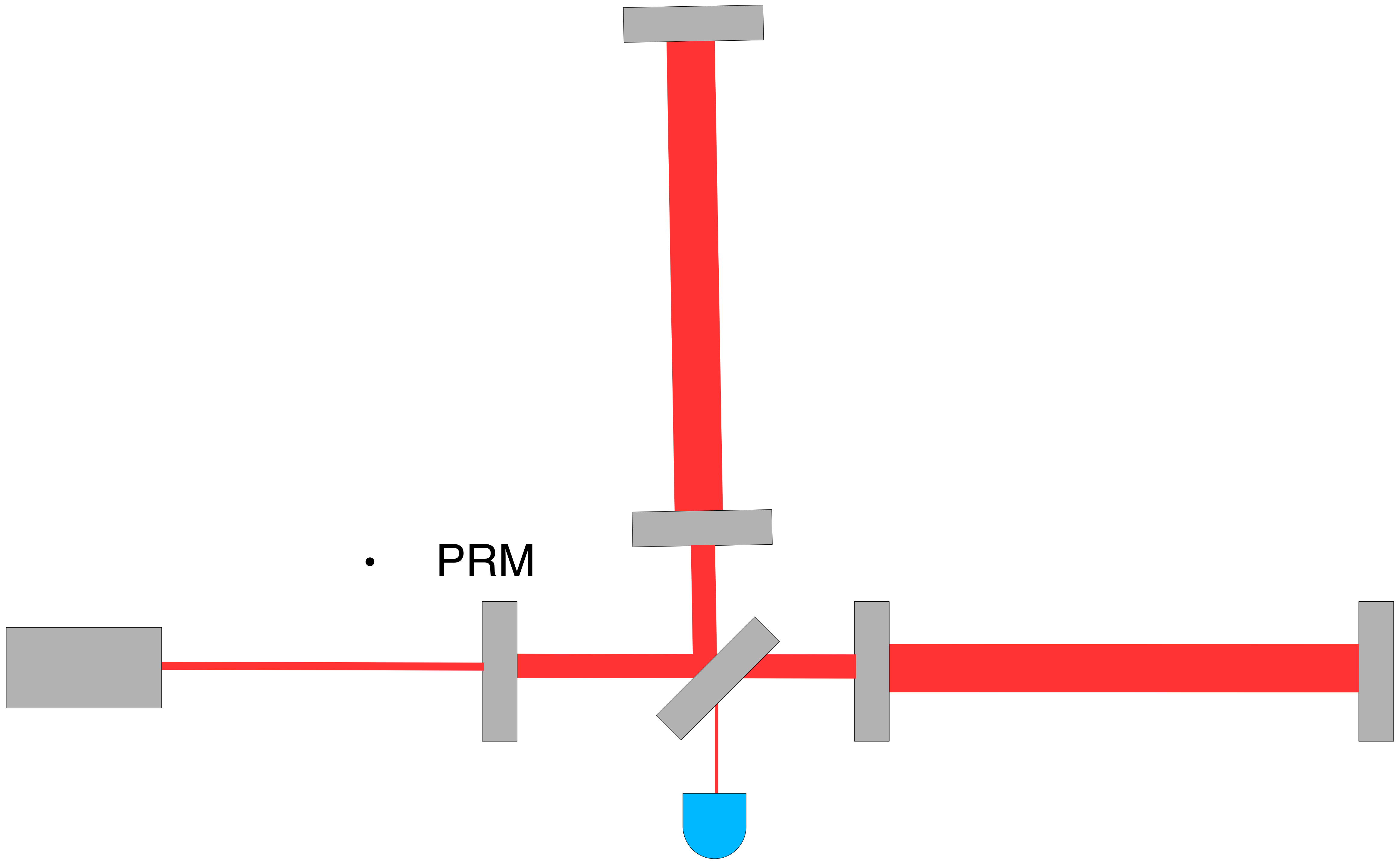
- Add partially reflecting 'Input Test Masses' at the beginning of the long arms, so that light will 'bounce many times' up and down arm cavities.
- For Virgo: F = 440, L = 3 km, L_{eff} = 840 km!
- Only works when cavity lengths are actively kept on resonance, so comes at cost of complexity

Fabry-Perot Michelson



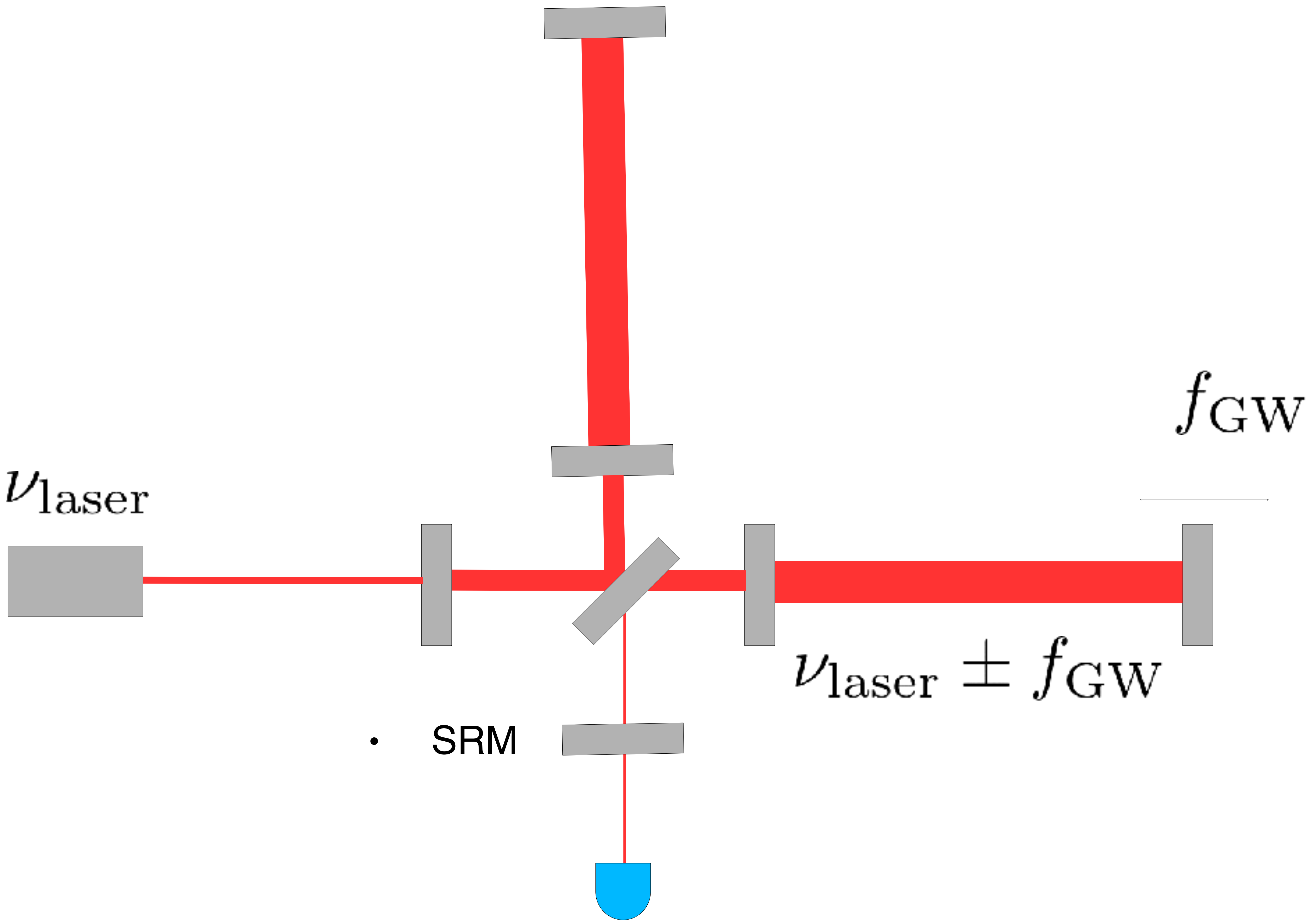
- Effect on sensitivity of adding a FP to the arms is similar to increasing the arm lengths by a factor N_{eff} , but without the extra zeros in frequency domain
- Cavity behaves like a low-pass filter with $f_{\mathrm{cut-off}} = \delta L_{\mathrm{FWHM}}/2$
- For Advanced Virgo: $f_{\mathrm{cut\text{-}off}}$ = 57 Hz

Power recycling



- Michelson is tuned to dark-fringe, light is reflected back to the laser
- Add a 'Power Recycling Mirror', to form another resonant cavity, effectively increasing the laser power in the arms by a factor ~37
- Laser power ~25 W, power in central cavities ~500 W, power in long arm cavities ~100 kW!

Signal recycling

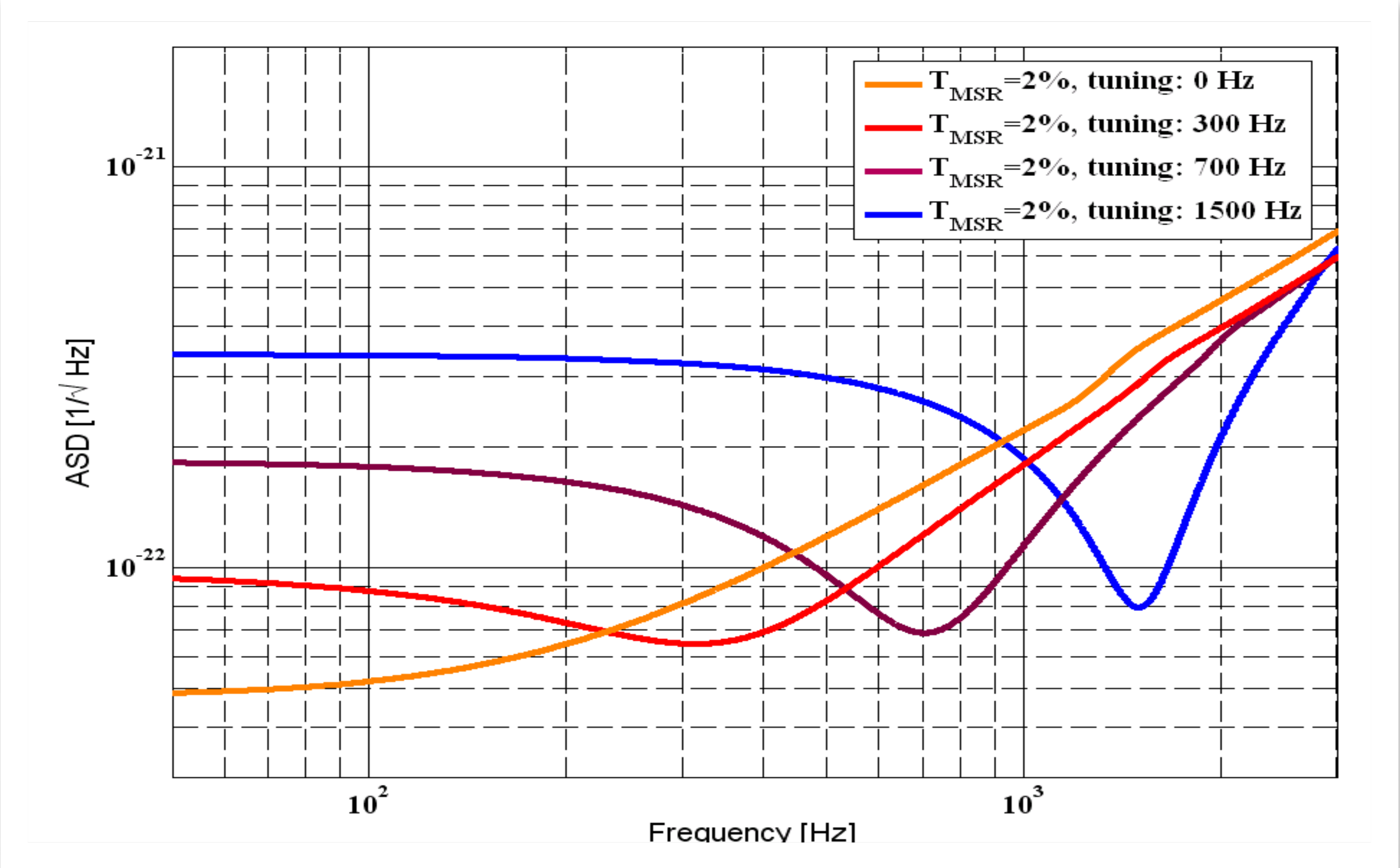


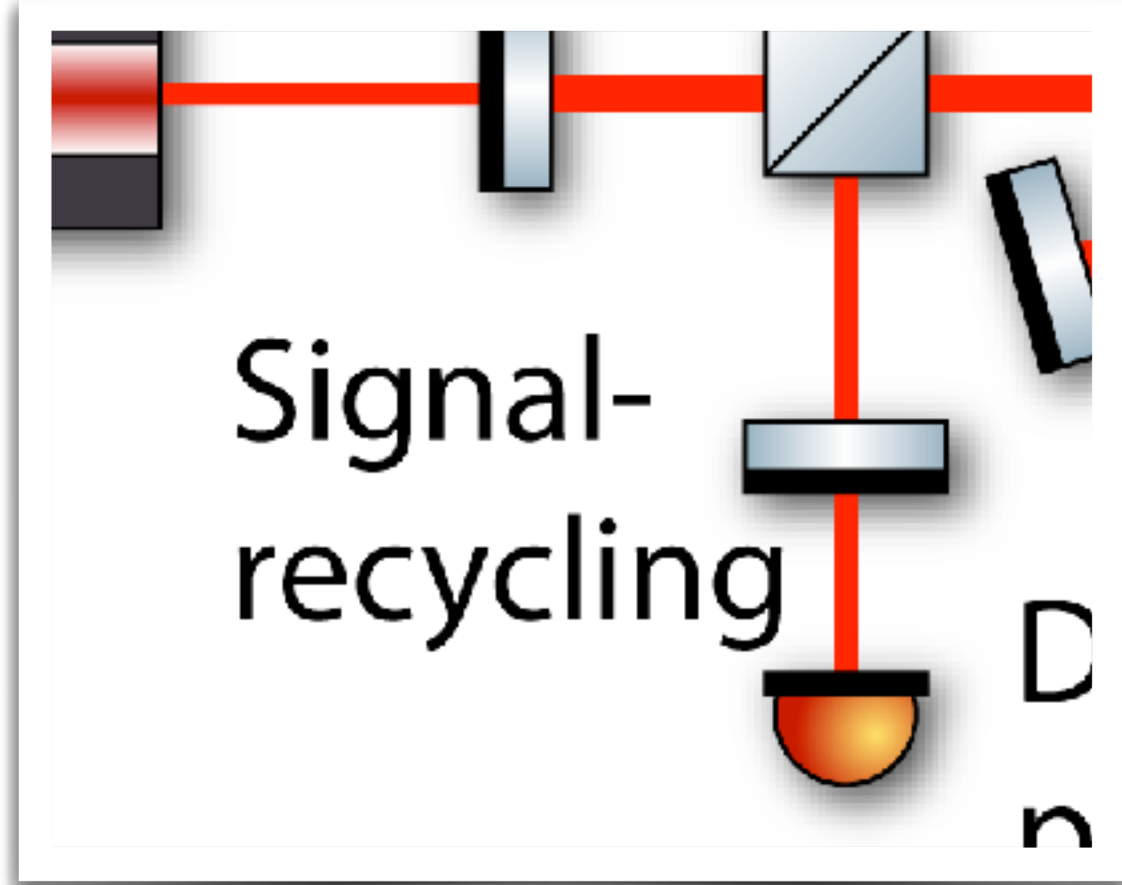
- Passing GW causes 'audio sidebands' around laser frequency. By adding an extra Signal Recycling Mirror, these signal sidebands can be sent back into the interferometer to gain more phase
- Technique already used at LIGO since O1 science run, new for Virgo in O4 run

Signal recycling

Placing a highly-reflective mirror in front of the photo detector makes detector resonant to signal at specific frequency, allows shaping of the quantum-noise limited sensitivity.

Quantum-noise limit

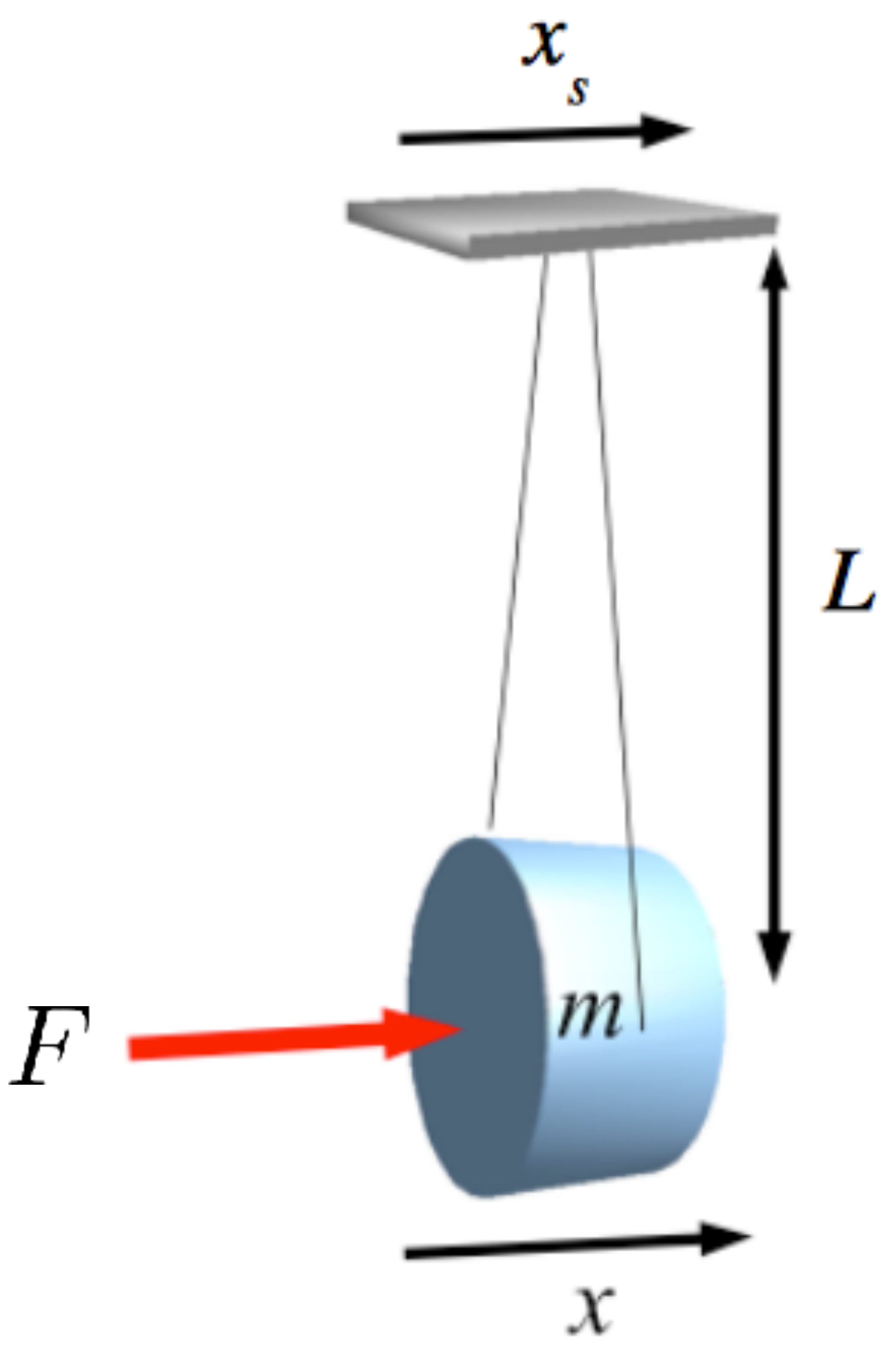




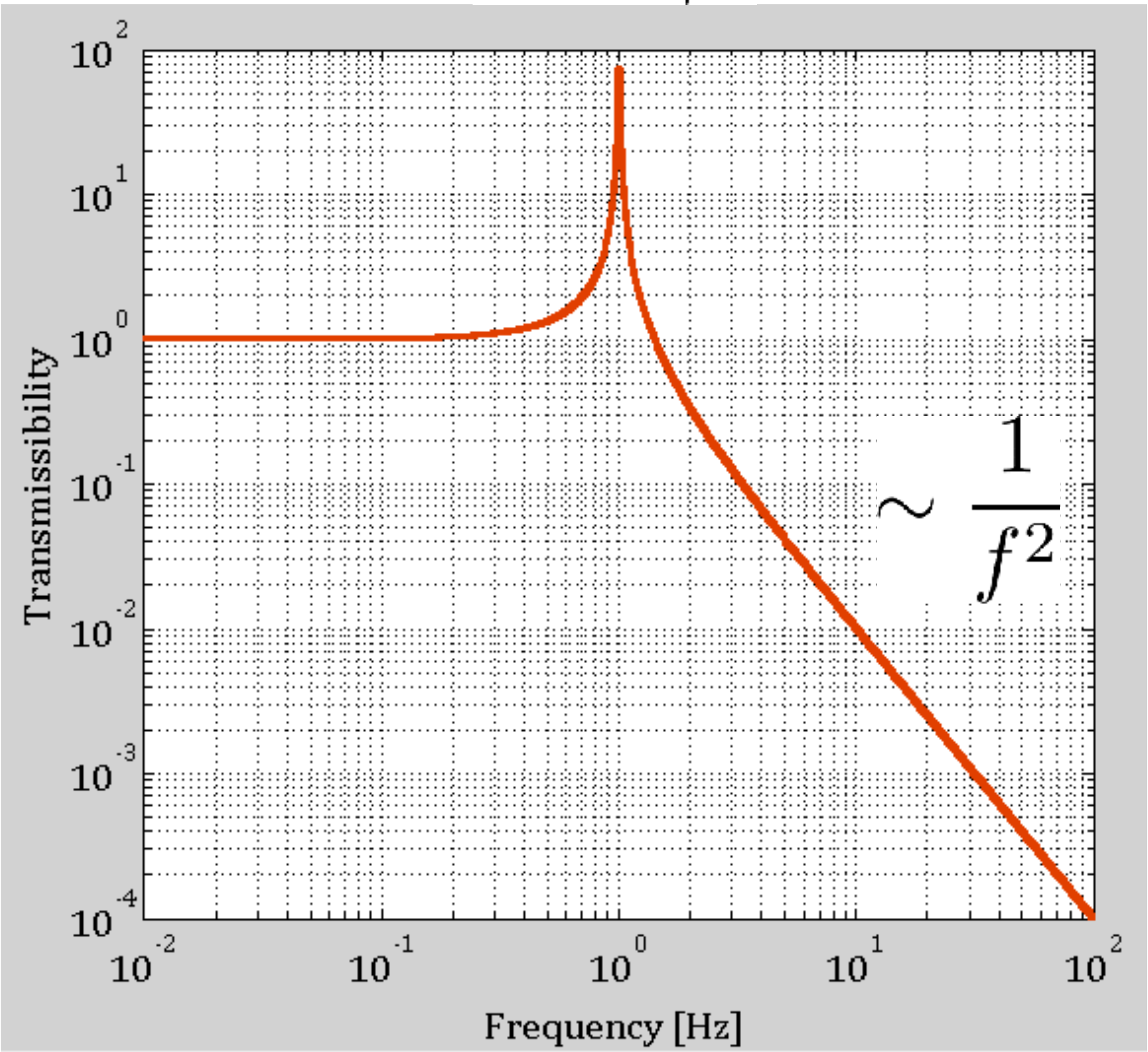
Question:

Interferometer is on the 'dark fringe'. How can a mirror in the 'dark' port make the signal stronger?

Seismic isolation: the pendulum

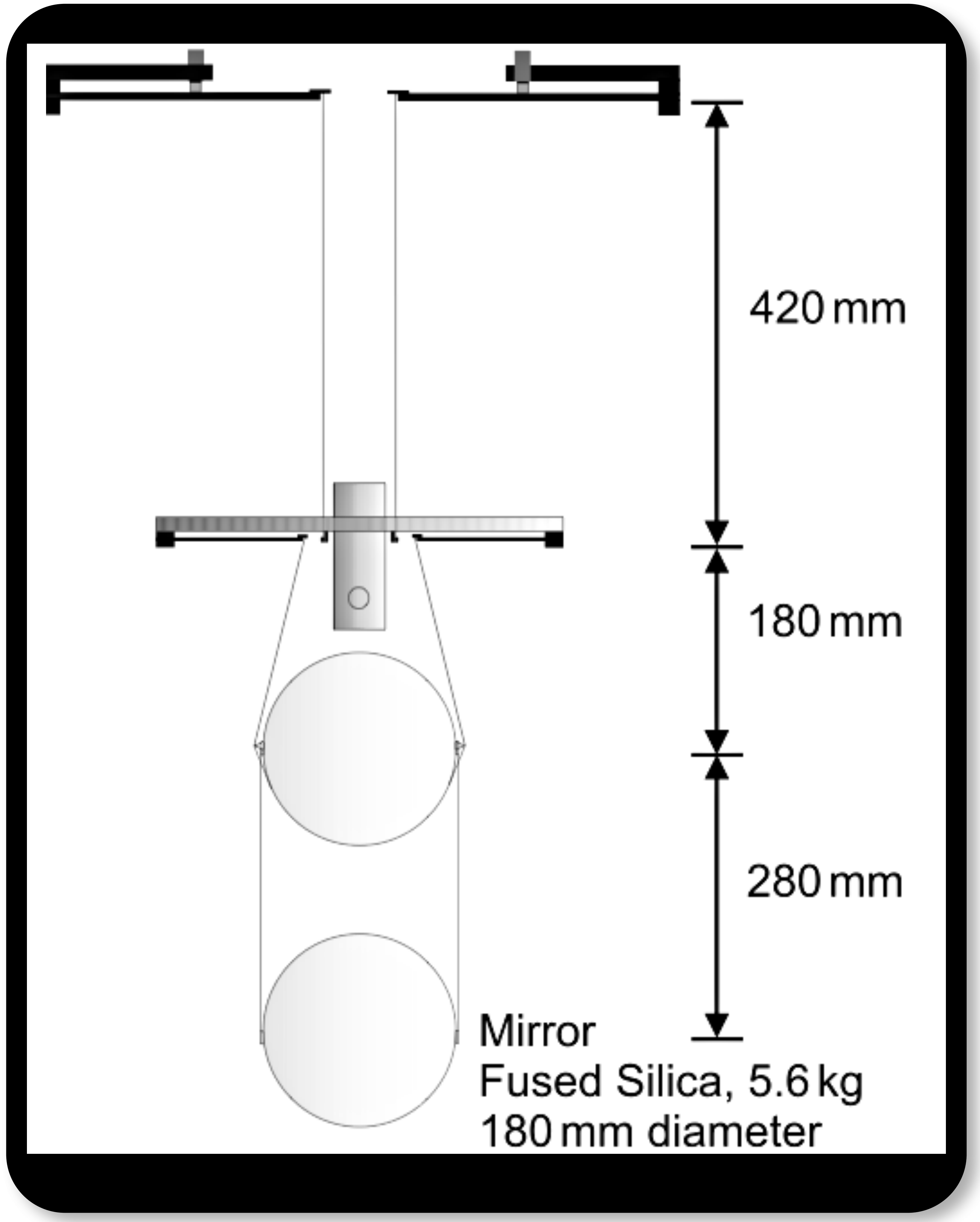


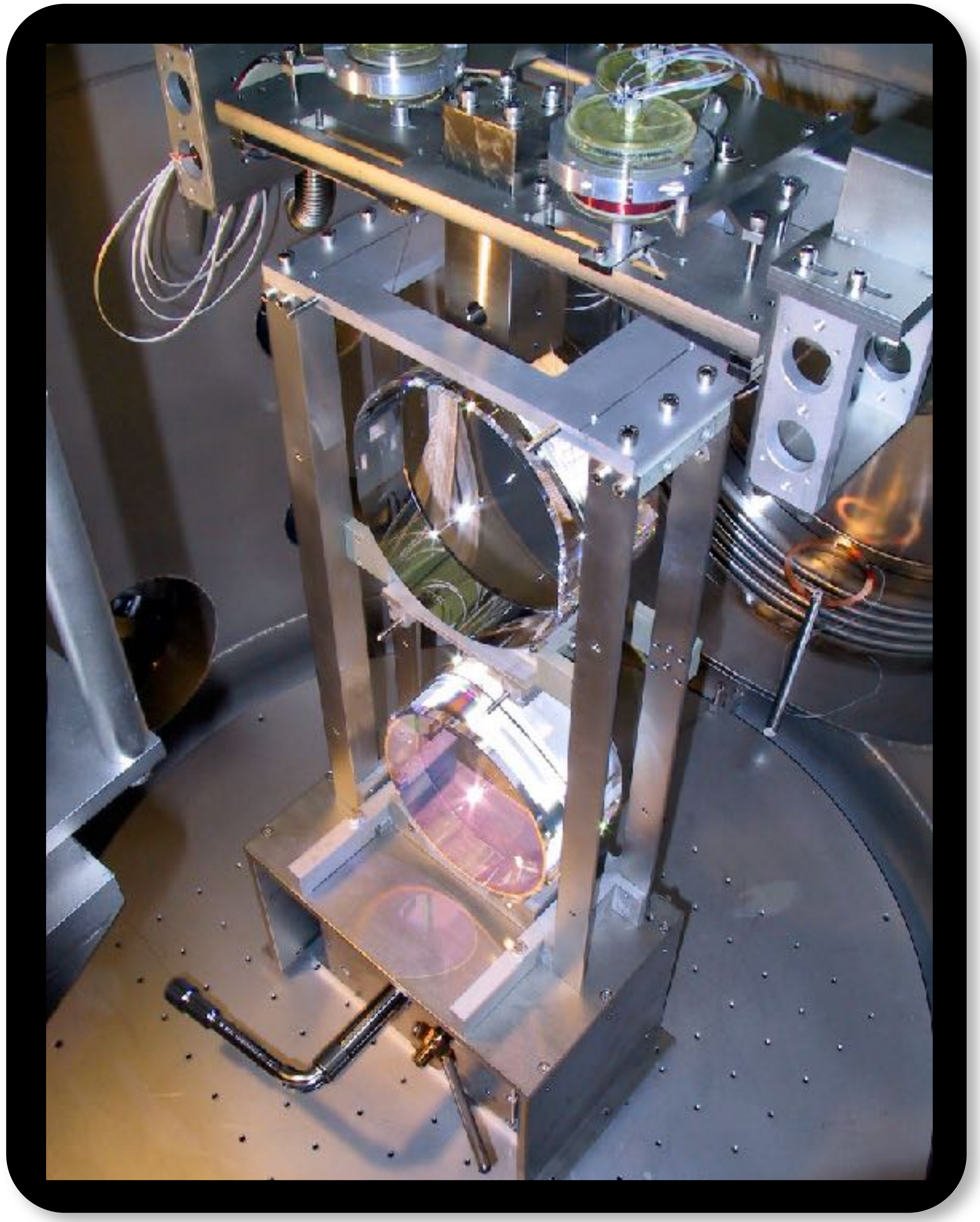
$$f_{\text{res}} = \frac{1}{2\pi}\sqrt{\frac{g}{L}}$$



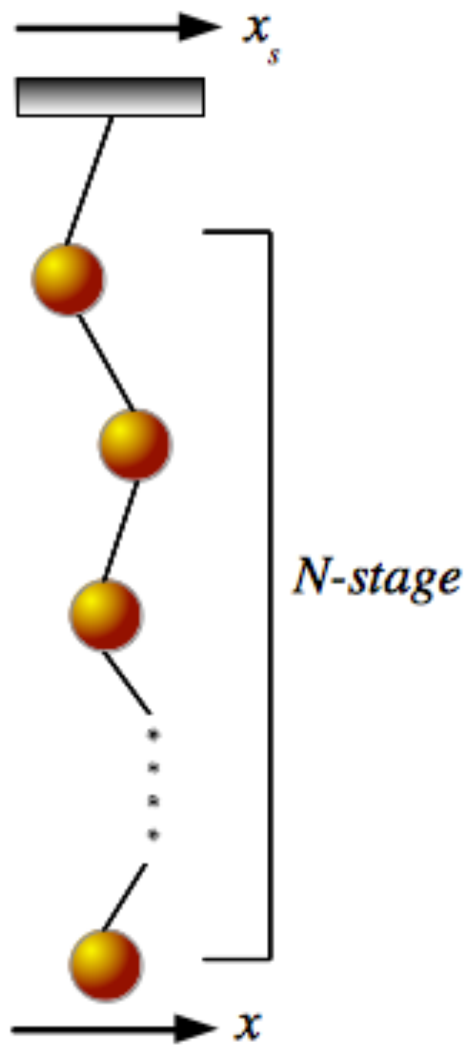
- Mirrors on Earth would vibrate to much, needs seismic isolation
- Suspend them by wires to form a pendulum, you attenuate seismic noise above resonance

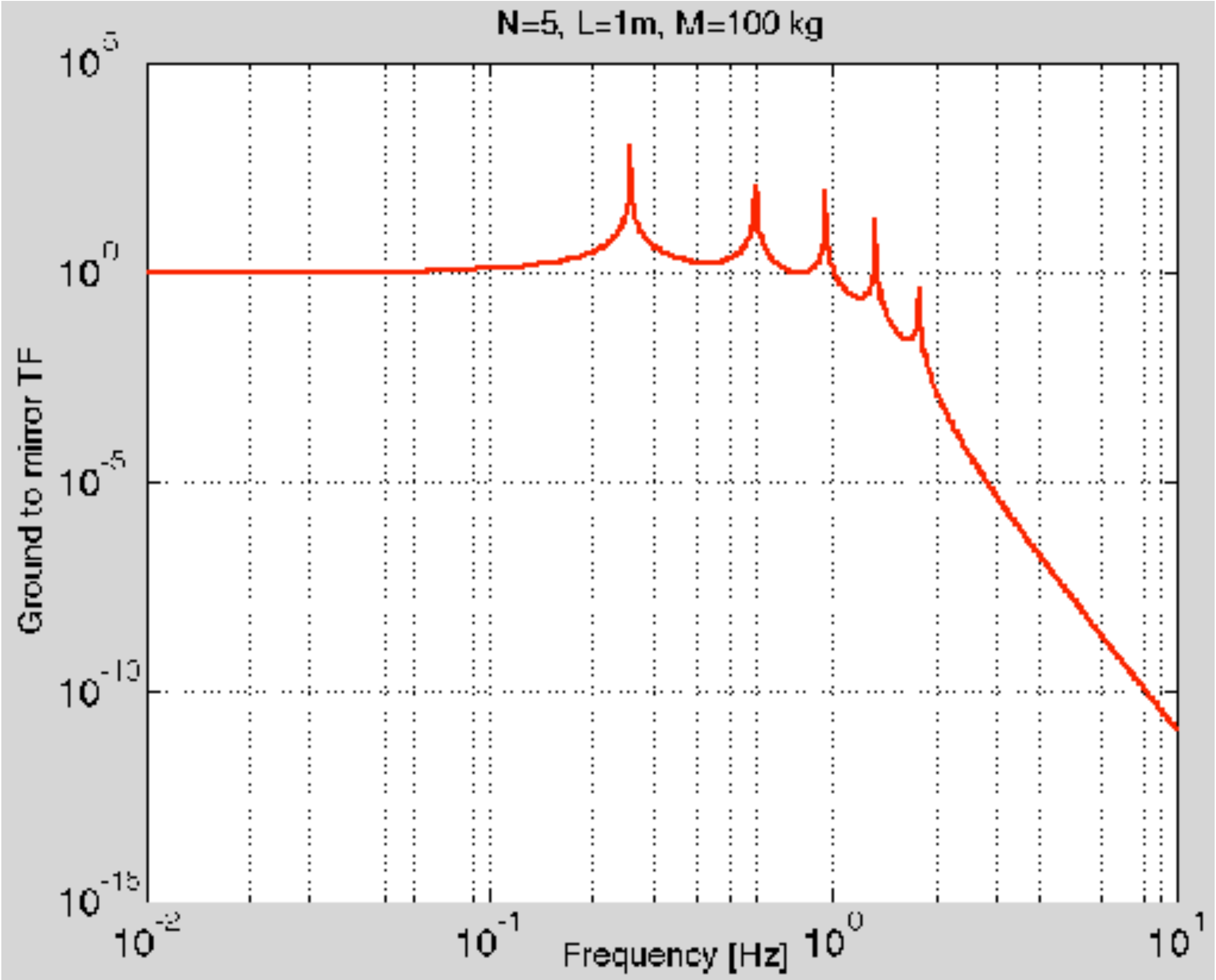
A GEO600 Mirror Suspension



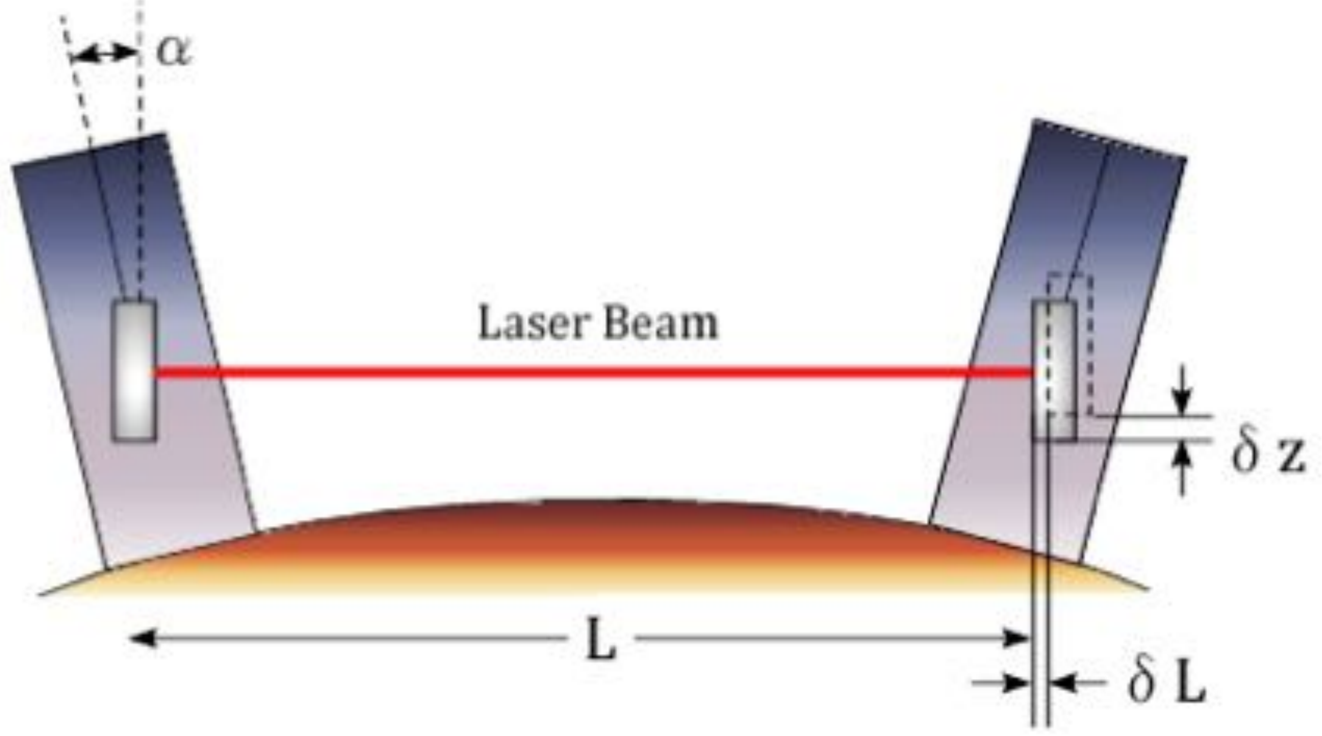


Multi-stage pendulum for more isolation



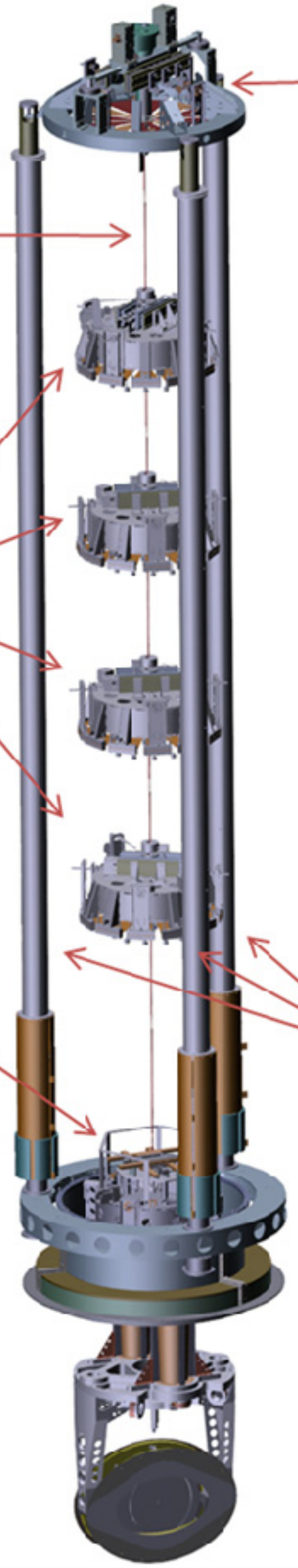


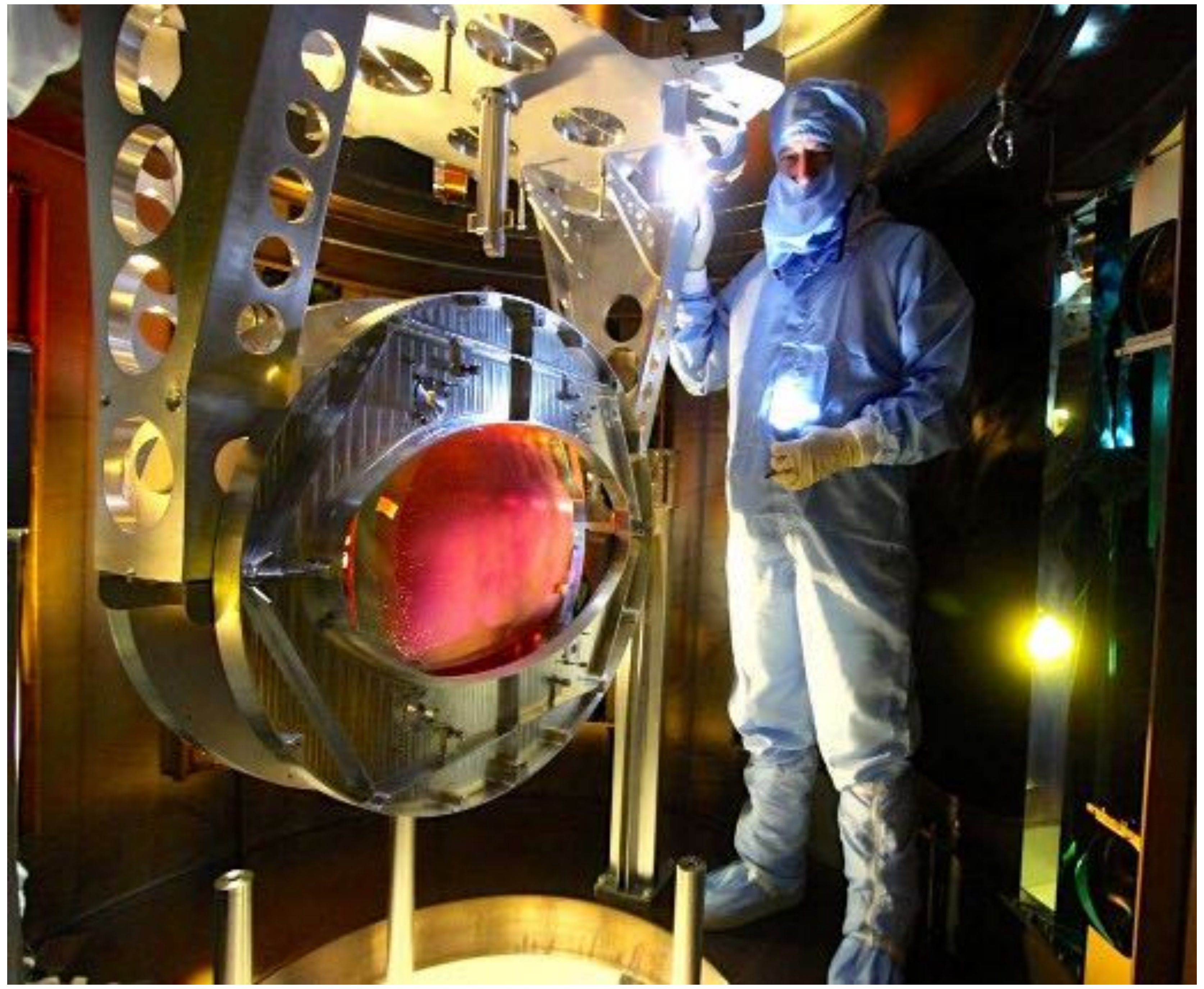
$$\sim \frac{1}{f^{2N}}$$

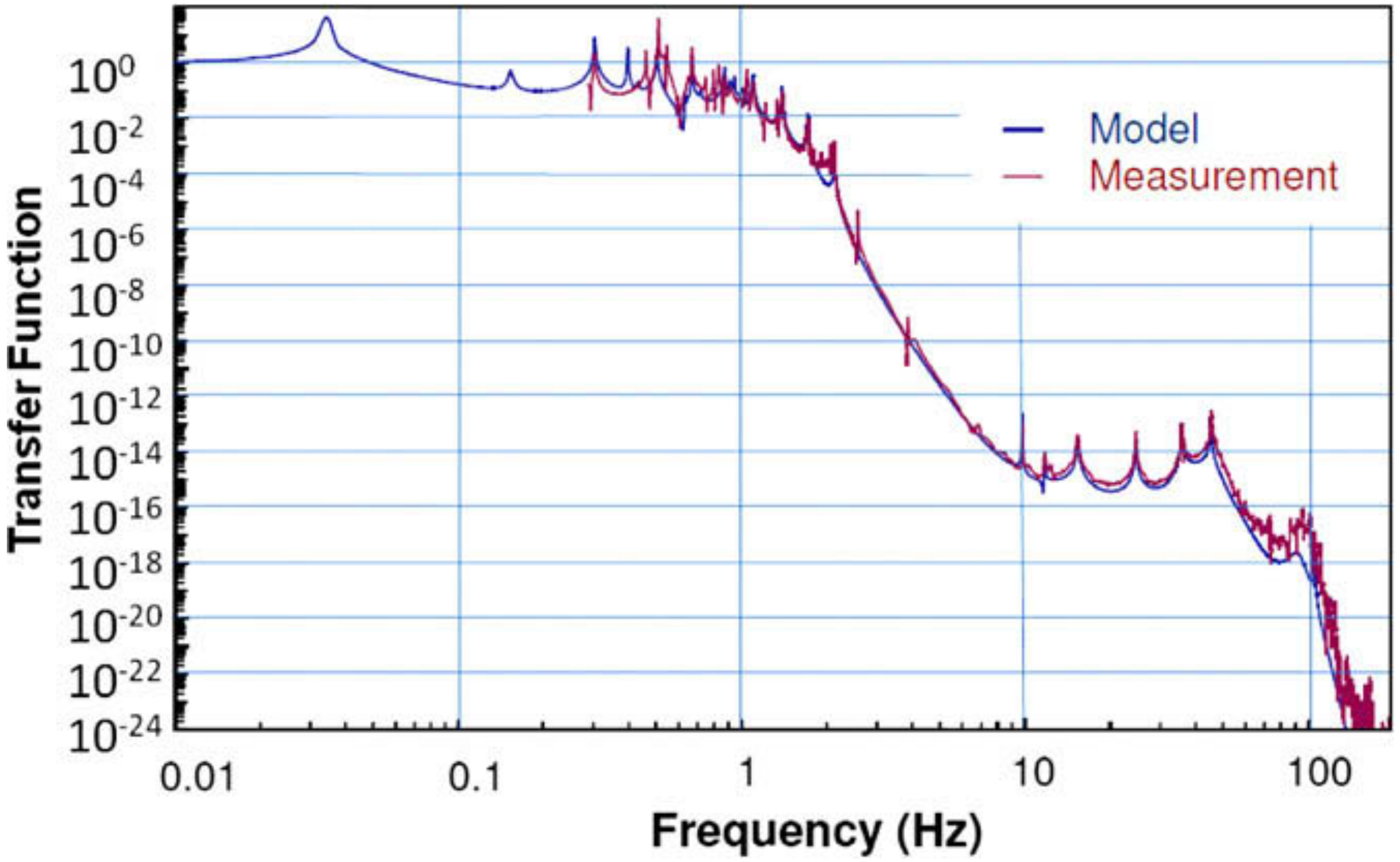


- In reality, a single pendulum is not enough: use multiple stages
- Also need to isolate vertically due to curvature of the earth, vertical to horizontal coupling ~ 1/10000

Virgo: super-attenuator





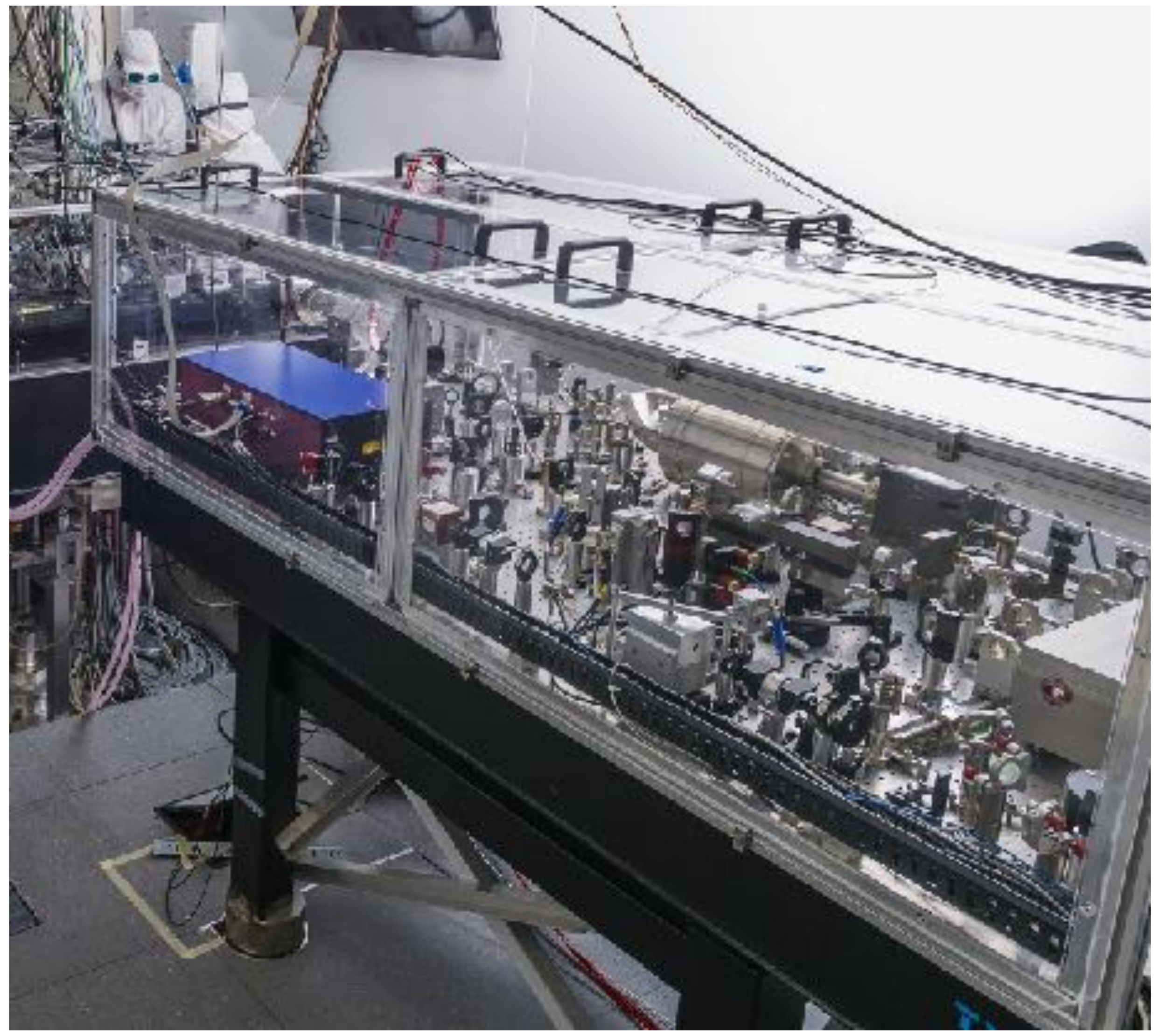
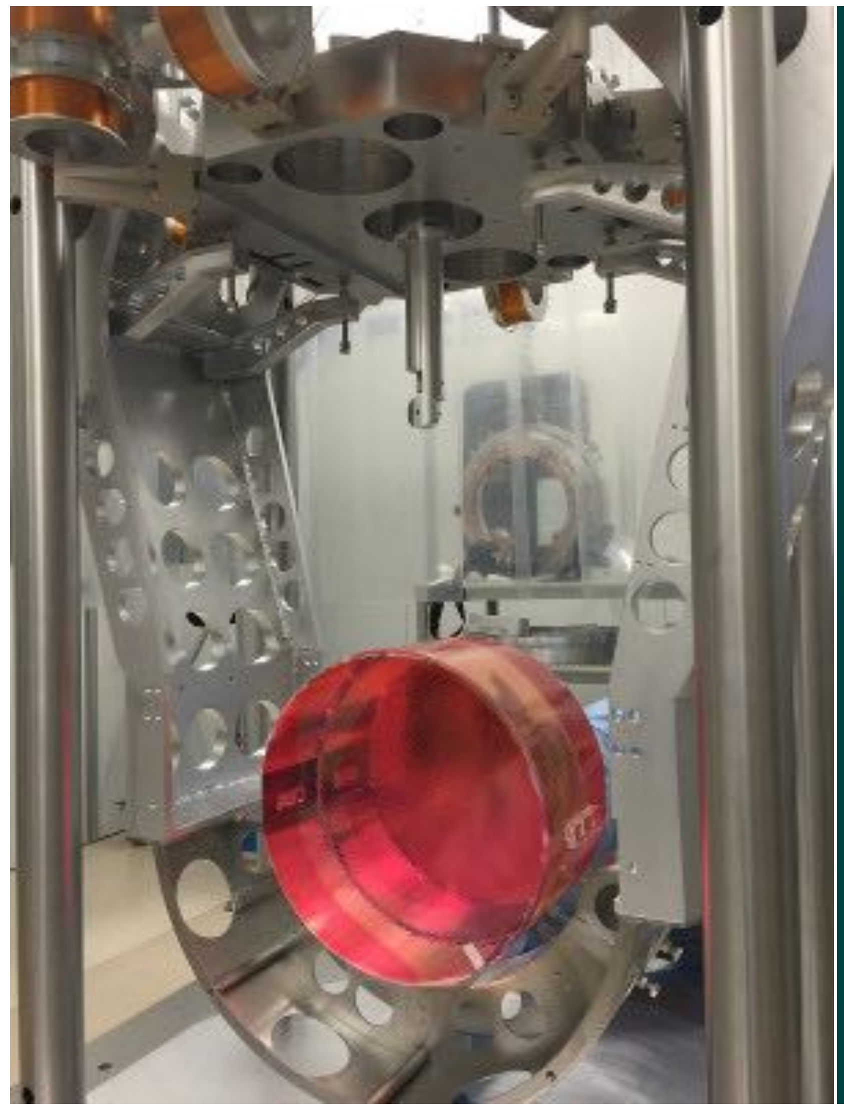
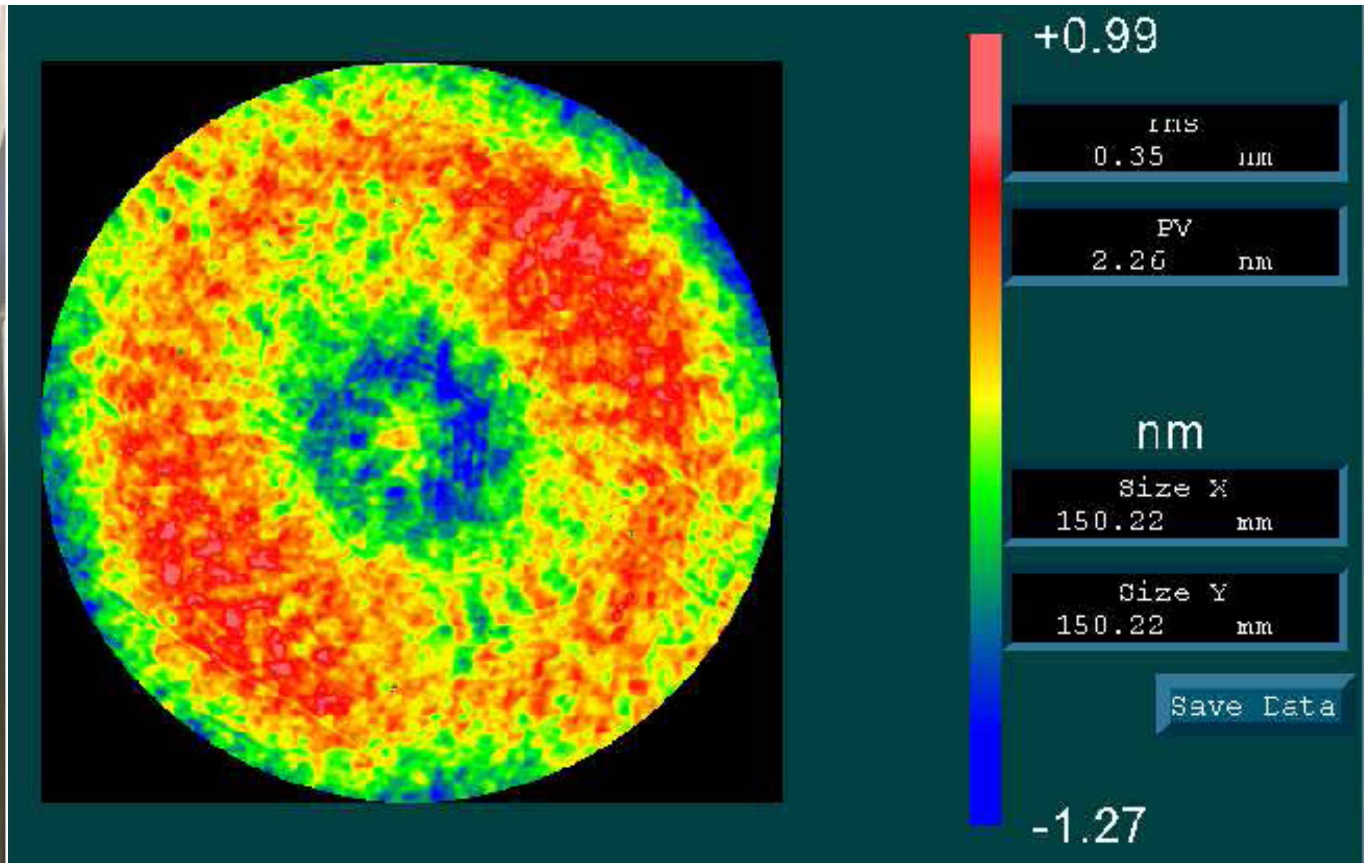


- Need more than a 10 orders of magnitude attenuation above 10 Hz
- Use combination of active pre-isolation stage (inertial free platform balancing on inverted pendulum, using accelerometers and position sensors) and passive multi-stage pendulums and blade springs
- Mirrors are suspended by 4 glass fibers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

Vacuum envelope

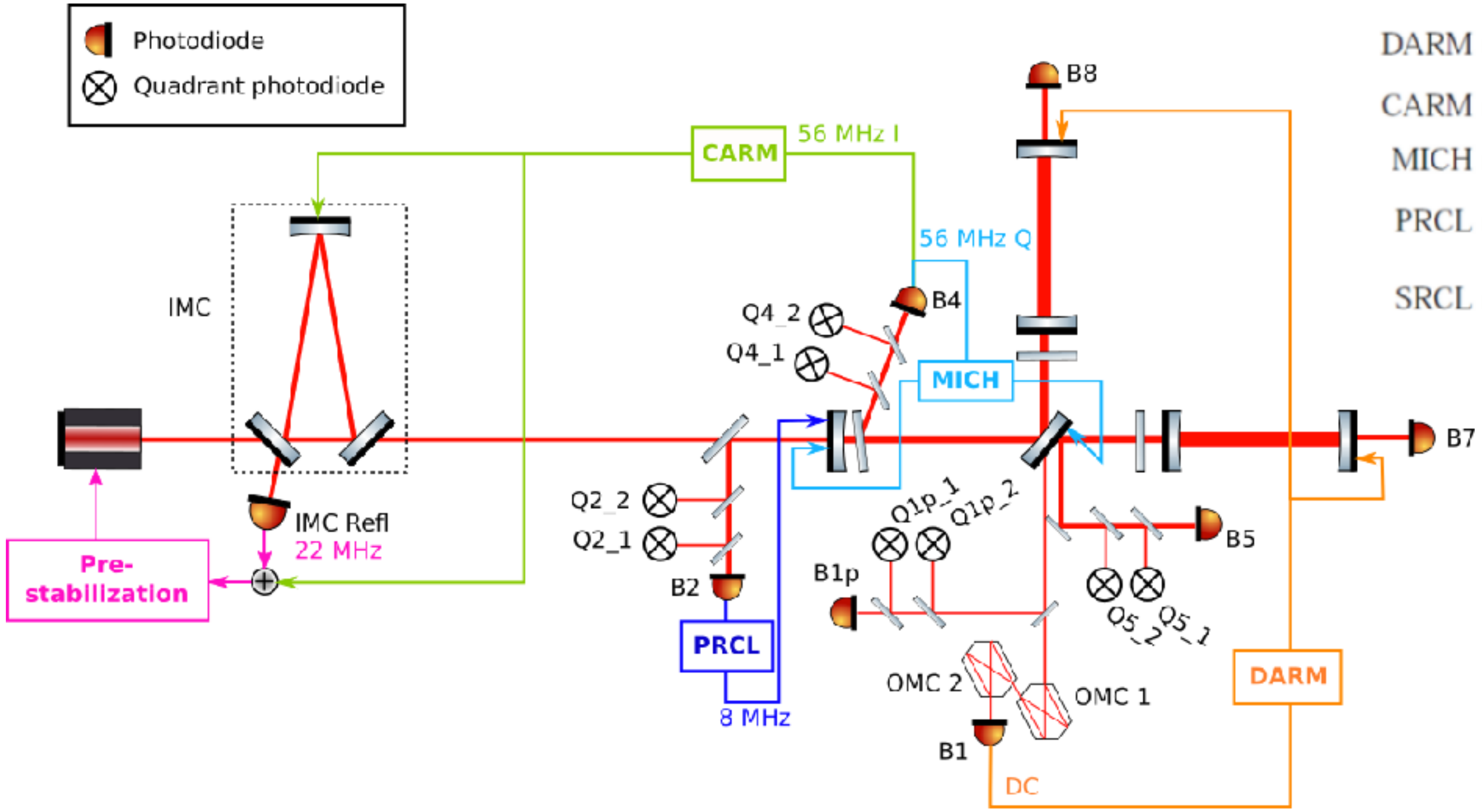
- Fluctuations of air-pressure changes optical path length, so GW interferometers are located inside large vacuum tubes
- Virgo interferometer: 7000 m^3 vacuum, long tubes have pressure ~10^{-9} mBar
- Biggest UHV system in Europe, only LIGO is bigger

Optics

- Main laser: 1064 nm Nd:YAG NPRO, amplified in 2 stages to ~60 Watt
- Main mirrors: 41 kg low absorbing fused silica, polished with RMS < 0.1 nm
- Low loss multi-layer coatings (both optical and mechanical), reflectivity up to 99.996 %
- Beam shape: Gaussian with radius of a few cm, input/output telescopes for matching to laser and photodiodes

Position sensing and control



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

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

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

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

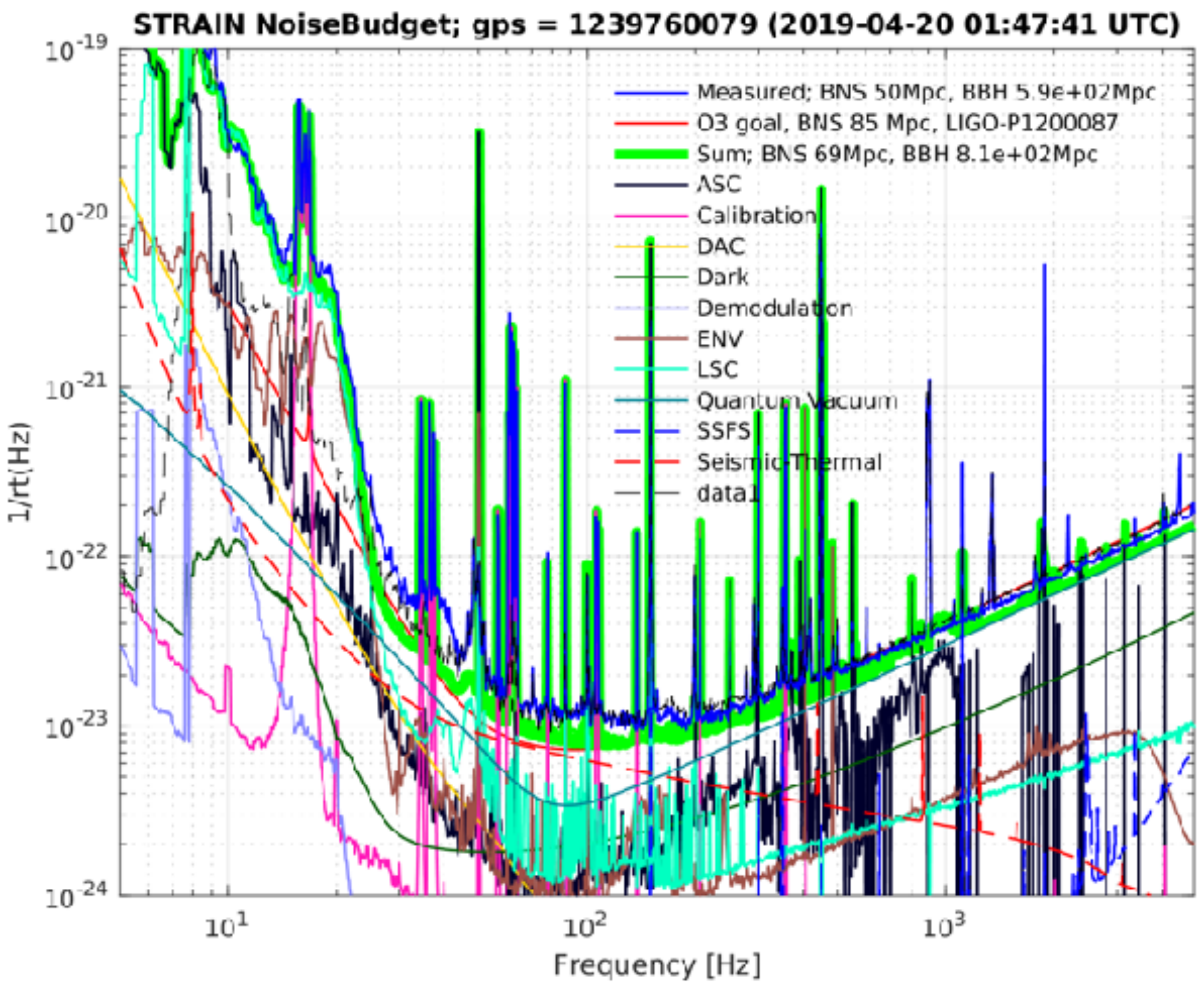
$$\mathrm{SRCL} = l_S + \frac{l_N + l_W}{2} \text{ (signal recycling cavity length)}$$

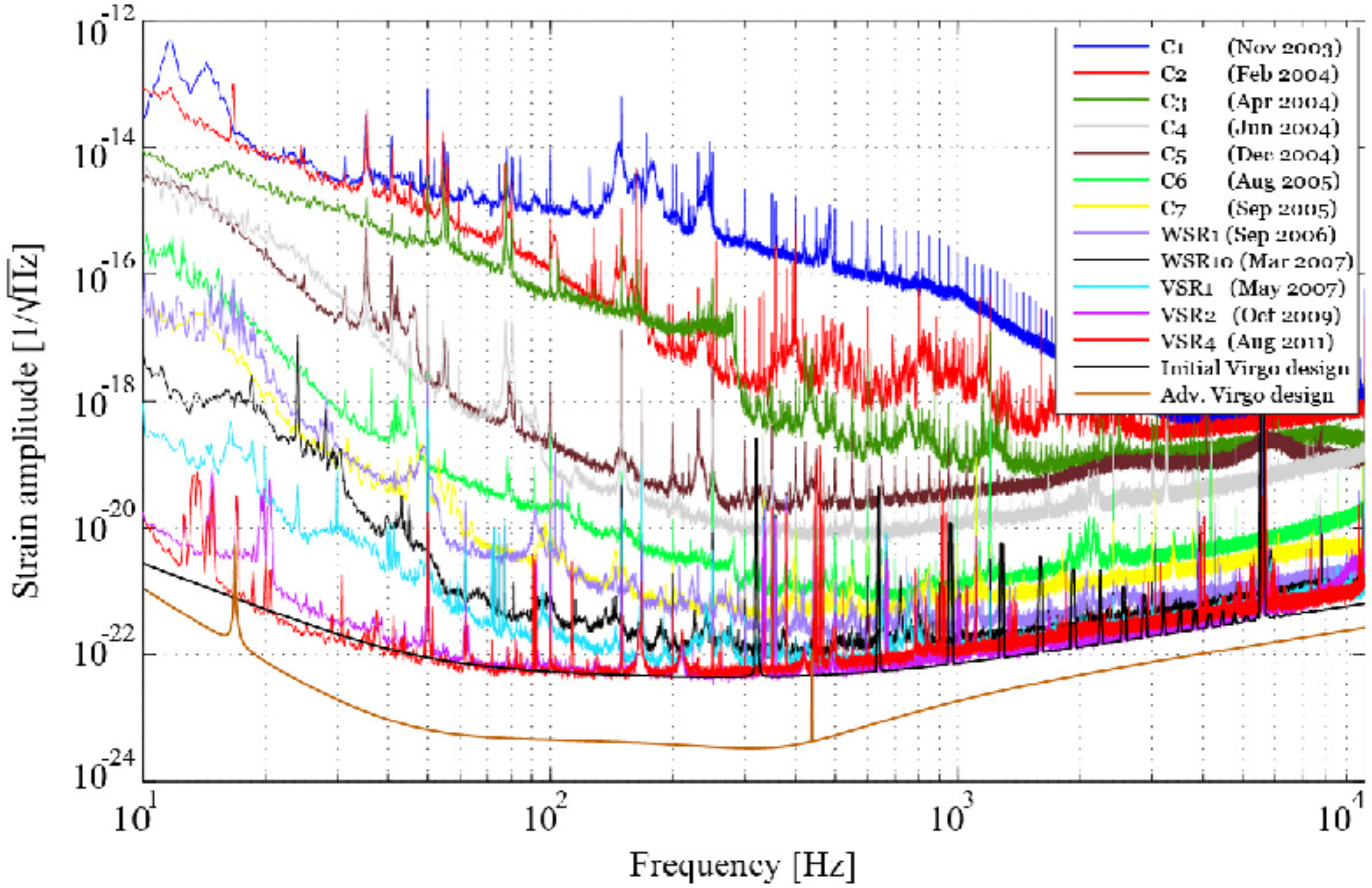
- Interferometer is only sensitive when all cavities are on resonance / at dark fringe: use real-time system to control many degrees-of-freedom
- Error signals obtained mostly using RF-modulaiton schemes: modulate laser beam with Electro-Optic Modulater, demodulate photodiode/ quadrant signals (similar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

Question:

GWs mimic the motion of the end mirrors. Position-sensing and control should correct for that and remove the GW signal, no?

Technical detector noise

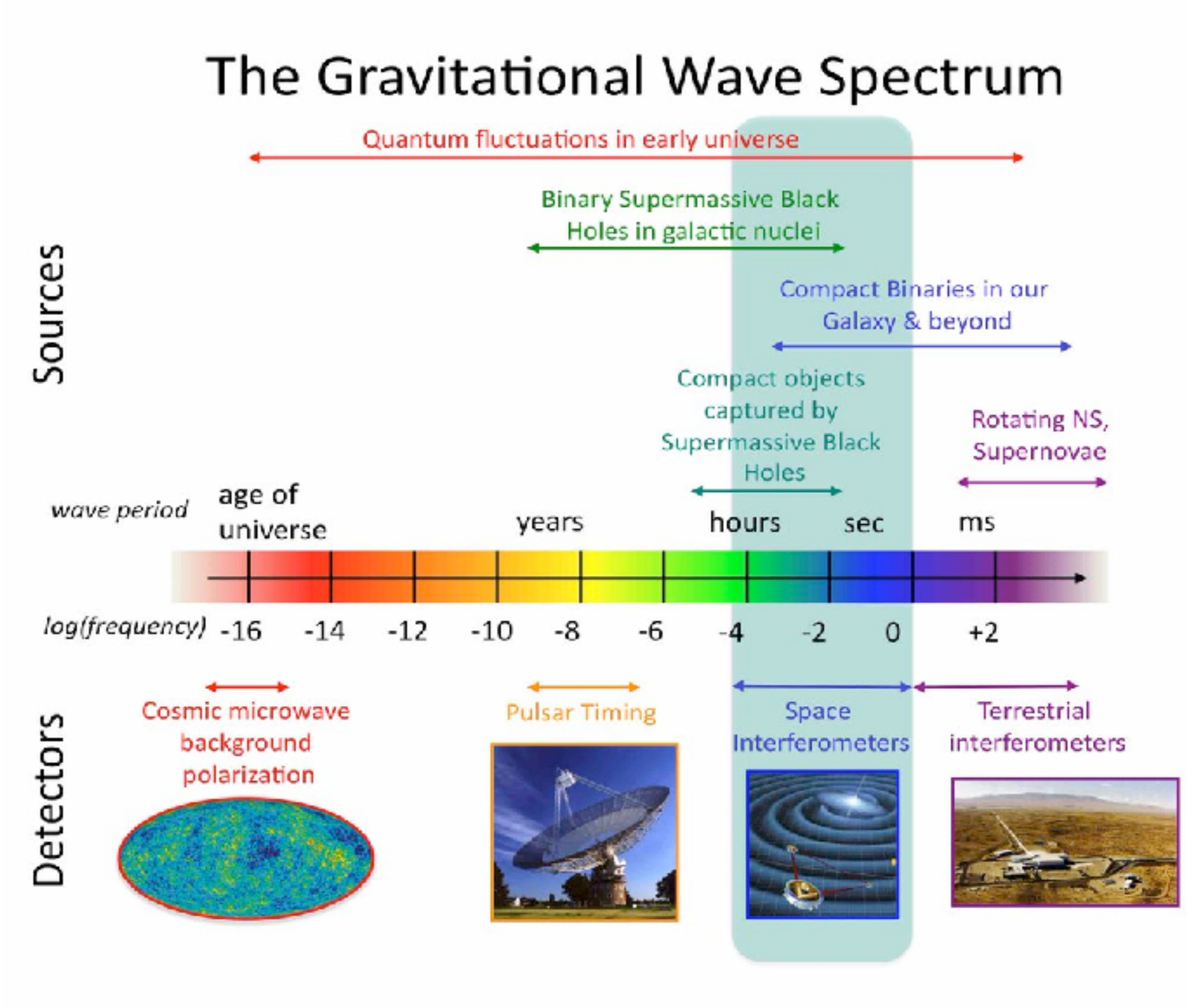


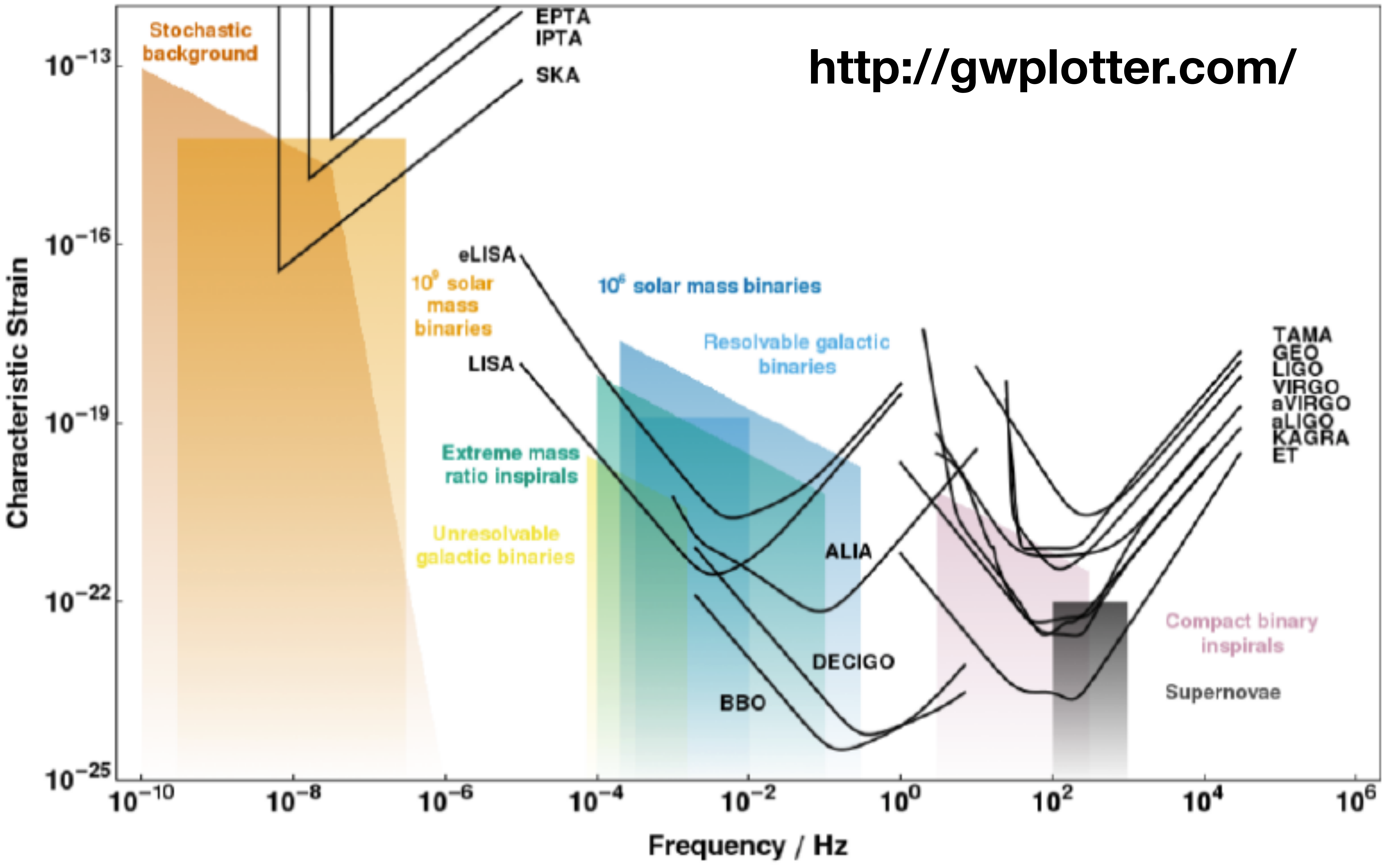


- In practice, the sensitivity is also spoiled by various 'technical noises':
  - coupling to environmental noise: magnetic, acoustic, seismic
  - scattered light: non-linear process!
  - ADC/DAC/electronics noise, ...
- Takes many years of commissioning and ‘noise hunting’ to mitigate all of these

Scattered light

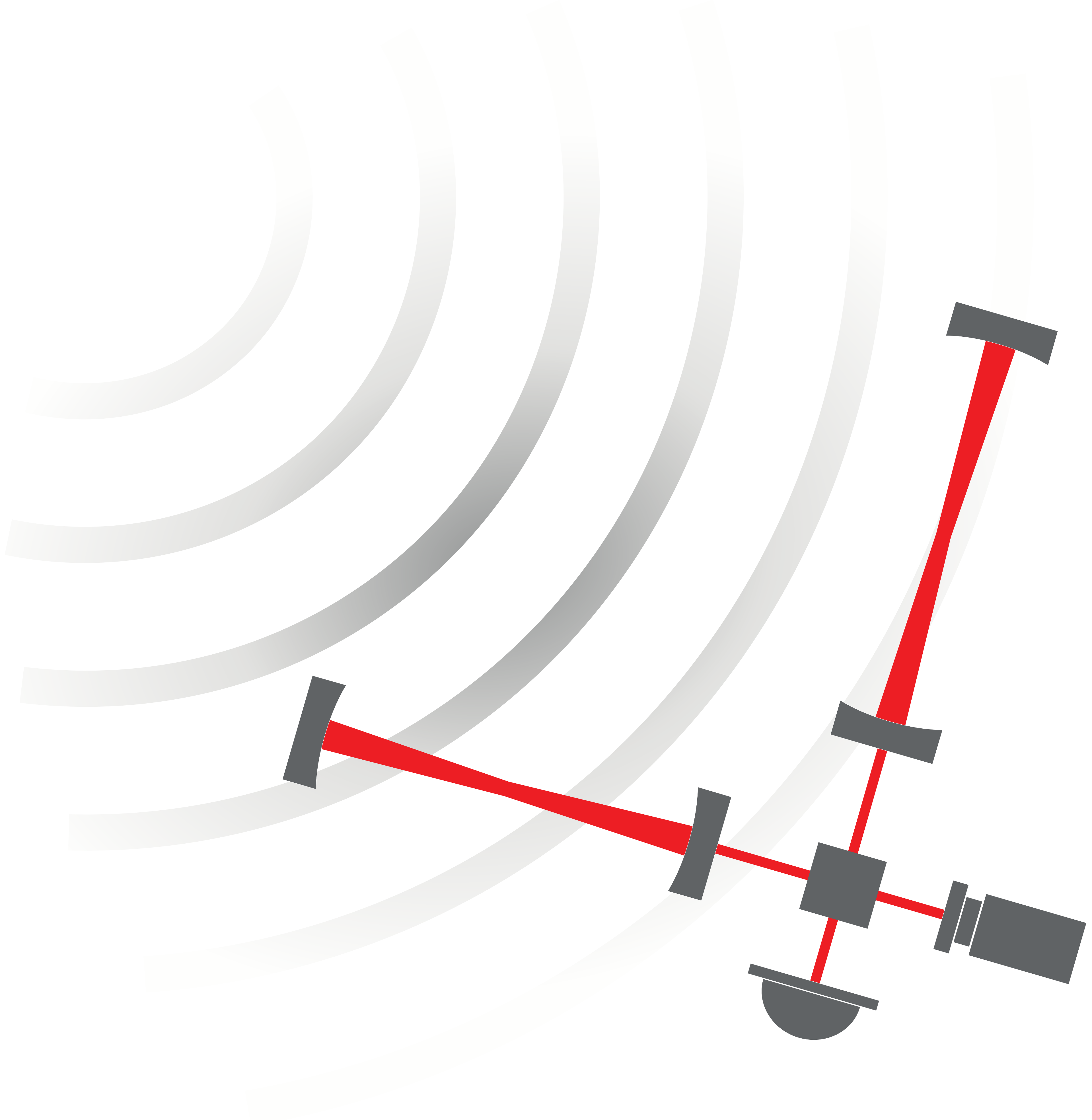
The GW spectrum





- Interesting science over a huge frequency range
- Science of PTA/space/ground is complementary, similar to IR/VIS/UV astronomy
- In 20 years, we might see sources scanning through LISA band into ET band!

The Einstein Telescope

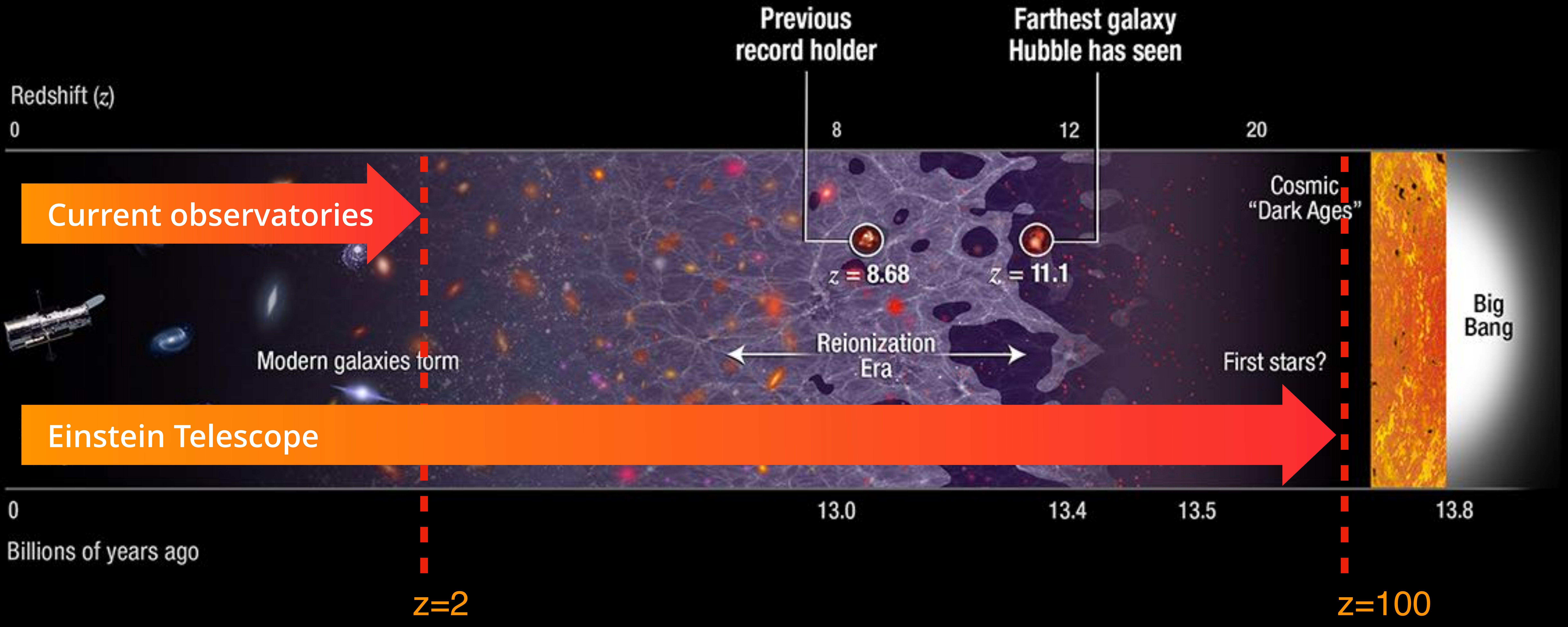



Einstein Telescope
10 km
Laser beams and super-polished optics in ultra-high vacuum systems
Large laboratories and three 10 km long tunnels, more than 200m underground

Question:

OK, now it's a triangle? Why not two L-shaped detectors?

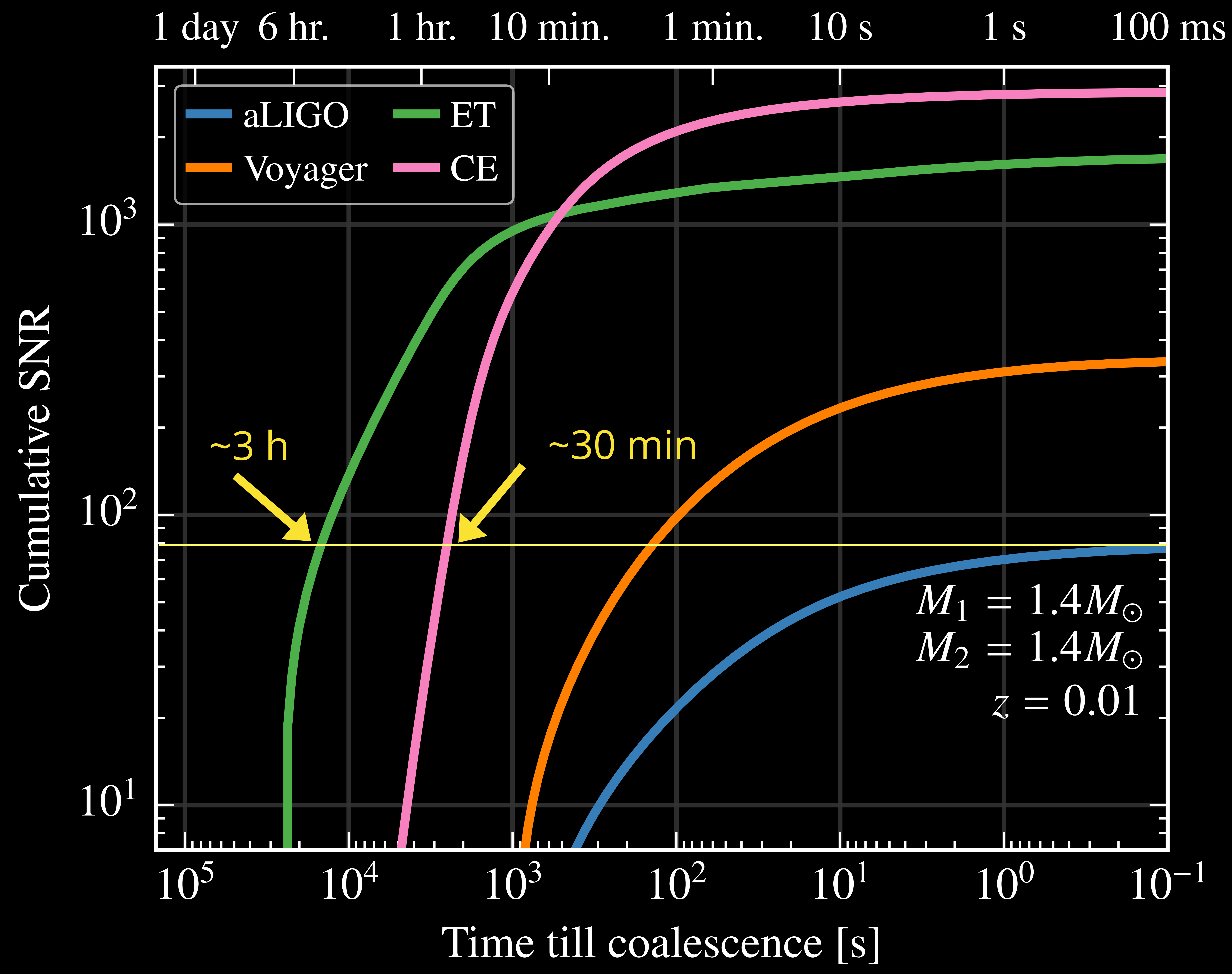
The case for future GW observatories



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

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

Set the alarms for astronomers



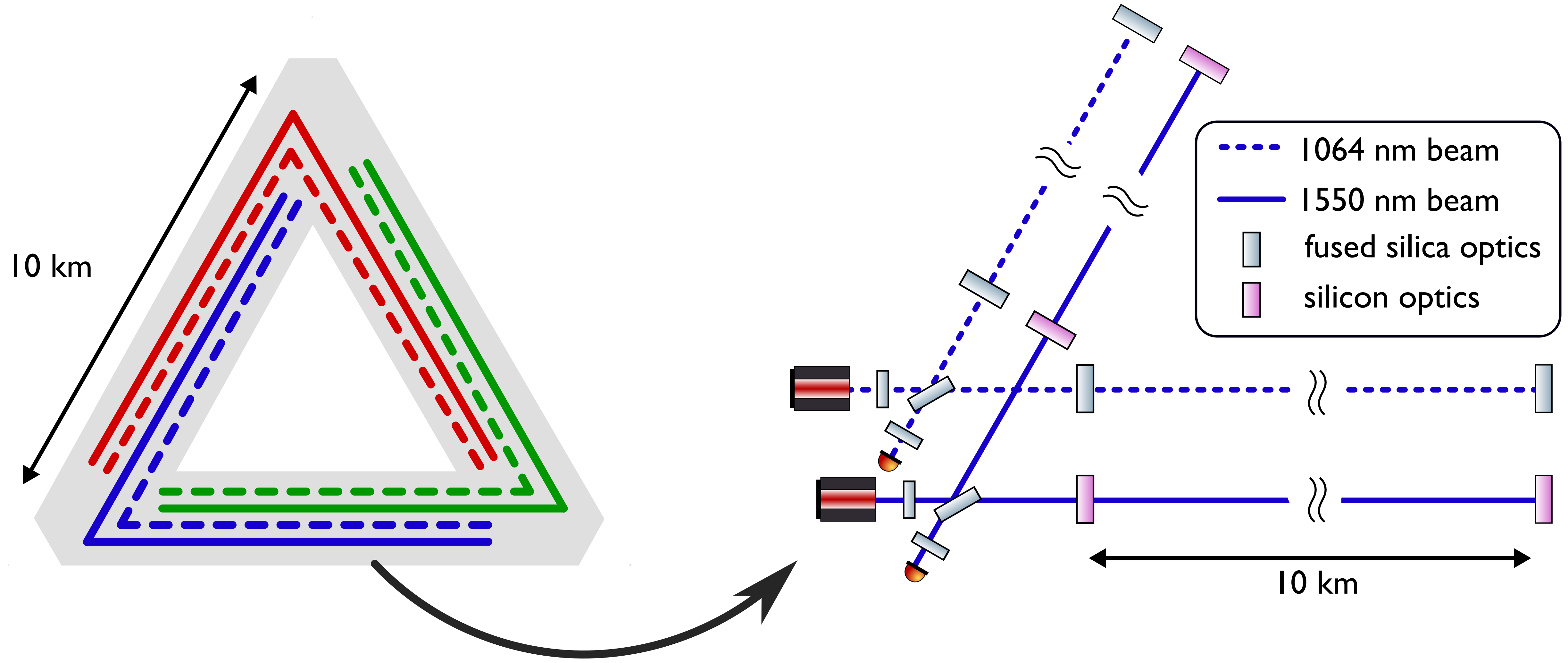
Credit: Evan Hall

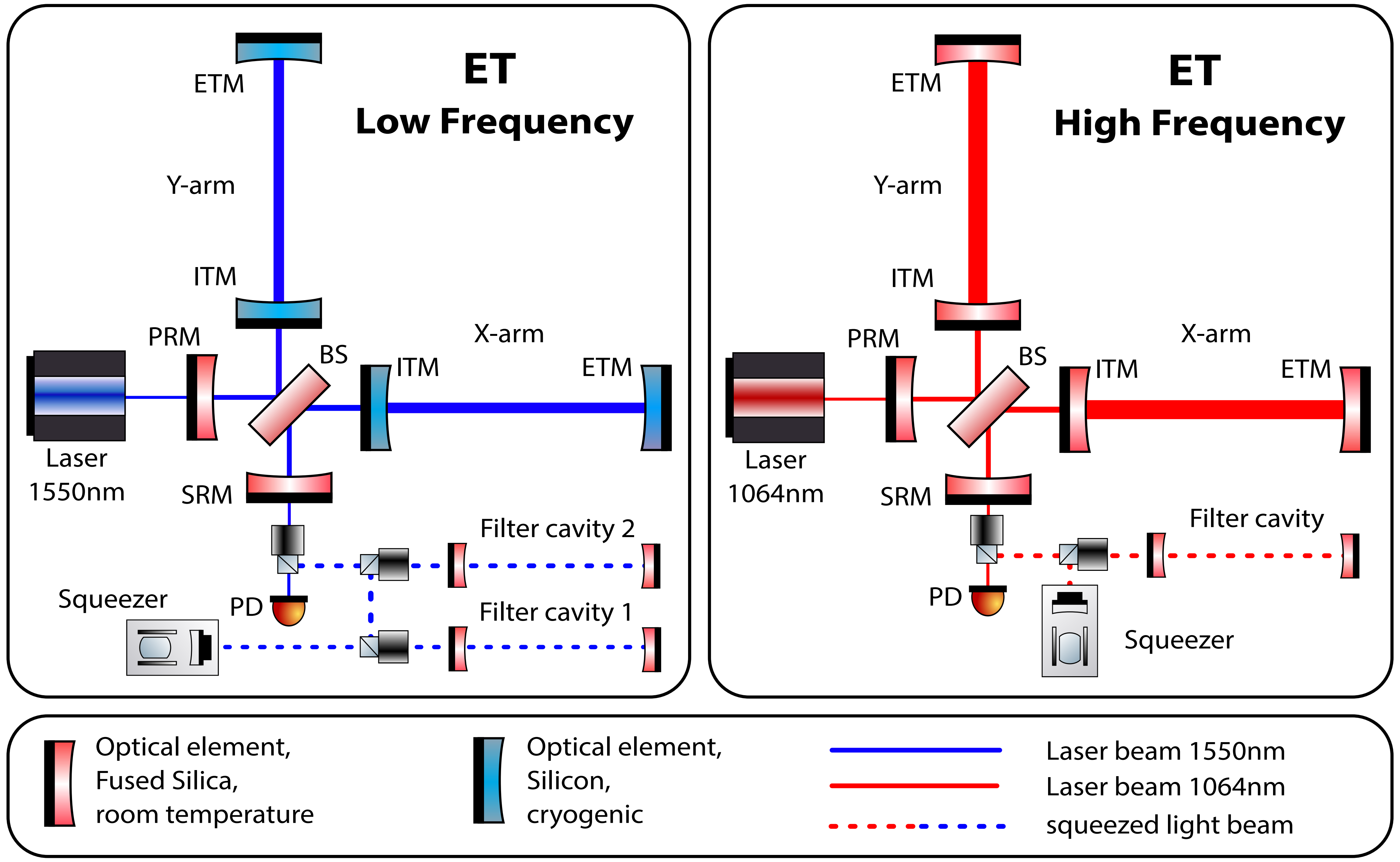
Possible ET site(s)

- There are now **three 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
  - Saxony (Germany) near the Polish border

Einstein Telescope design

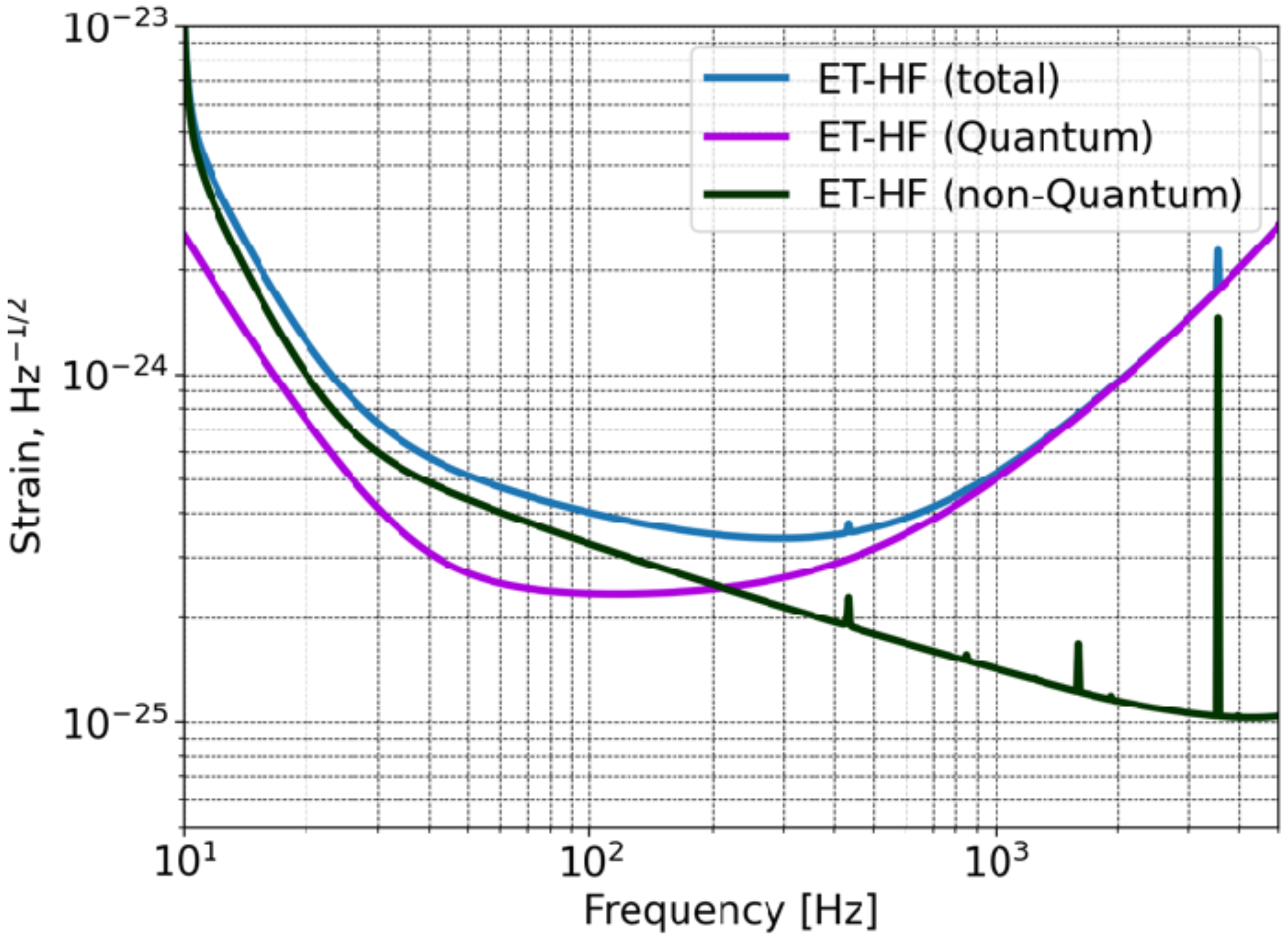
Parameter	ET-HF	ET-LF
Arm length	10 km	10 km
Input power (after IMC)	500 W	3 W
Arm power	3 MW	18 kW
Temperature	290 K	10-20 K
Mirror material	fused silica	silicon
Mirror diameter / thickness	62 cm / 30 cm	45 cm/ 57 cm
Mirror masses	200 kg	211 kg
Laser wavelength	1064 nm	1550 nm
SR-phase (rad)	tuned (0.0)	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

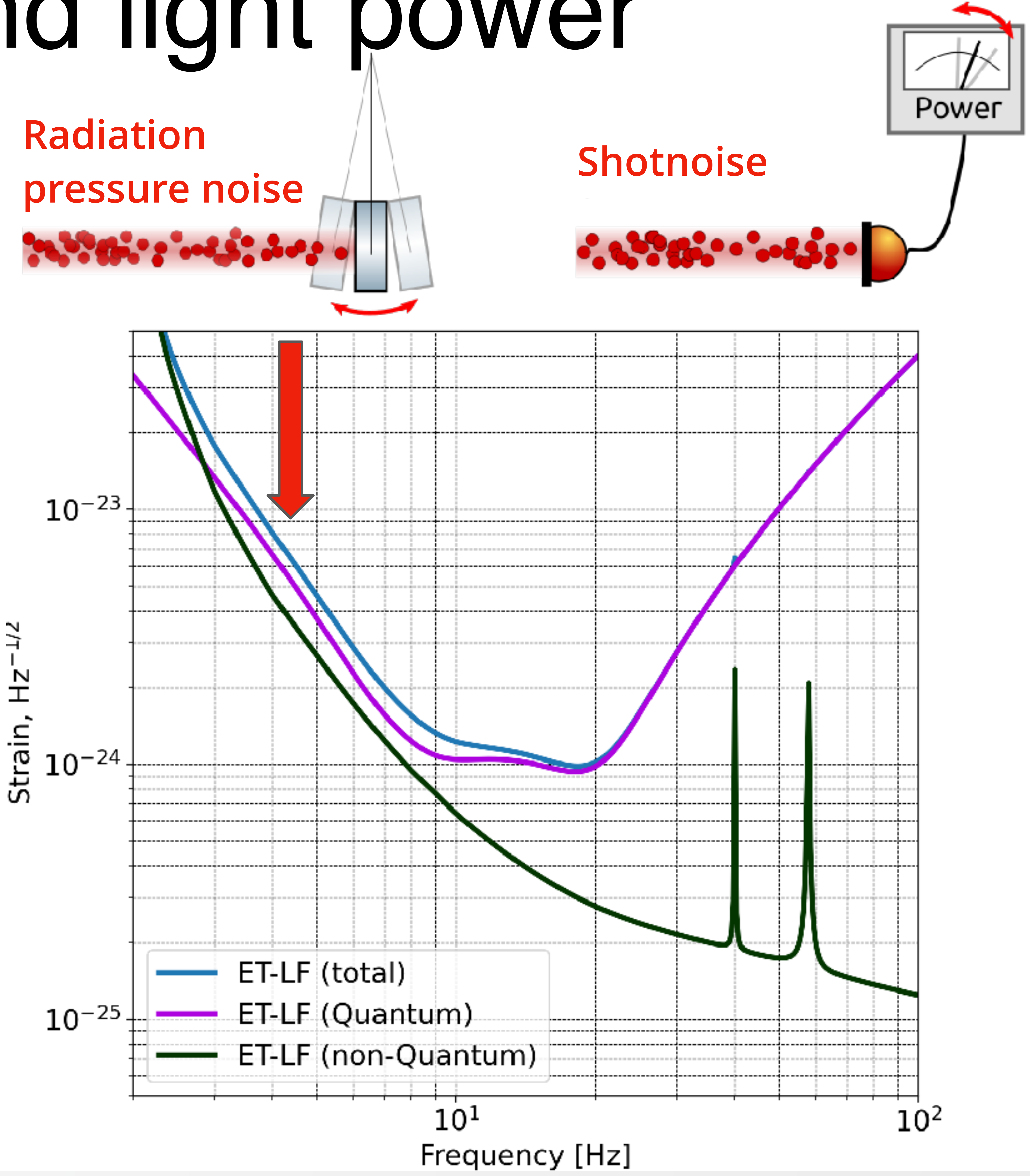




Quantum noise and light power

- 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;





New special focus: noise at low frequencies

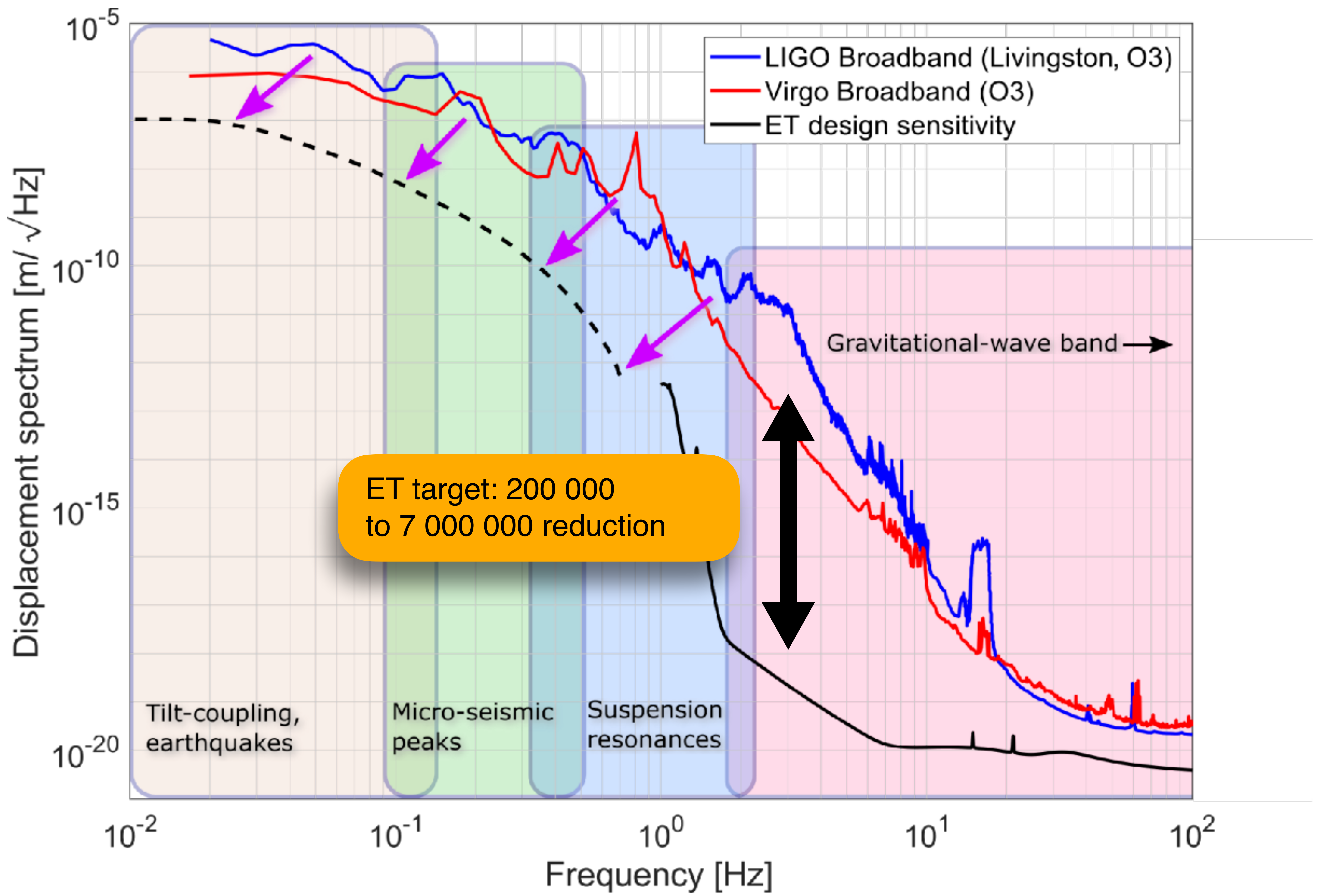
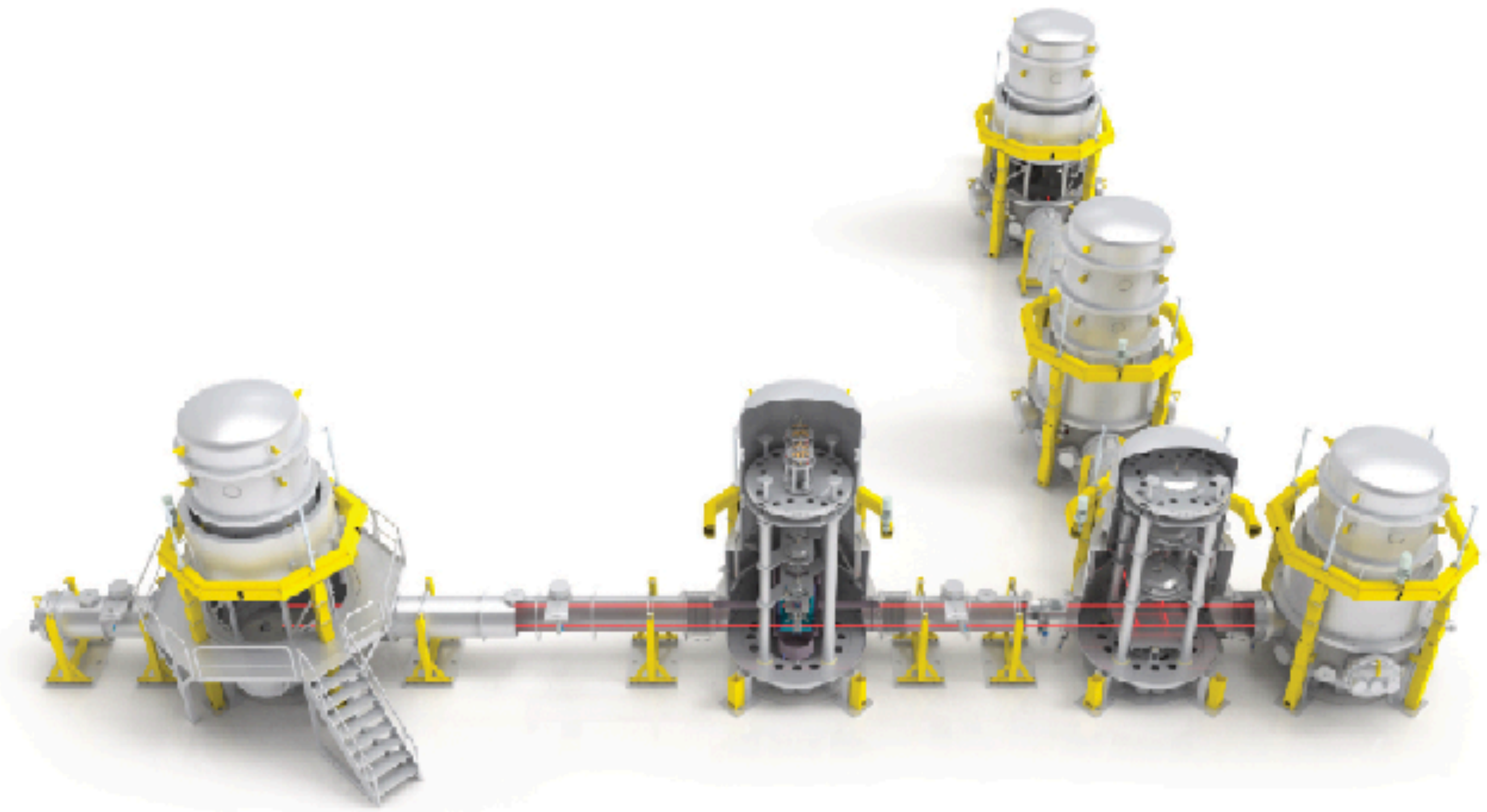


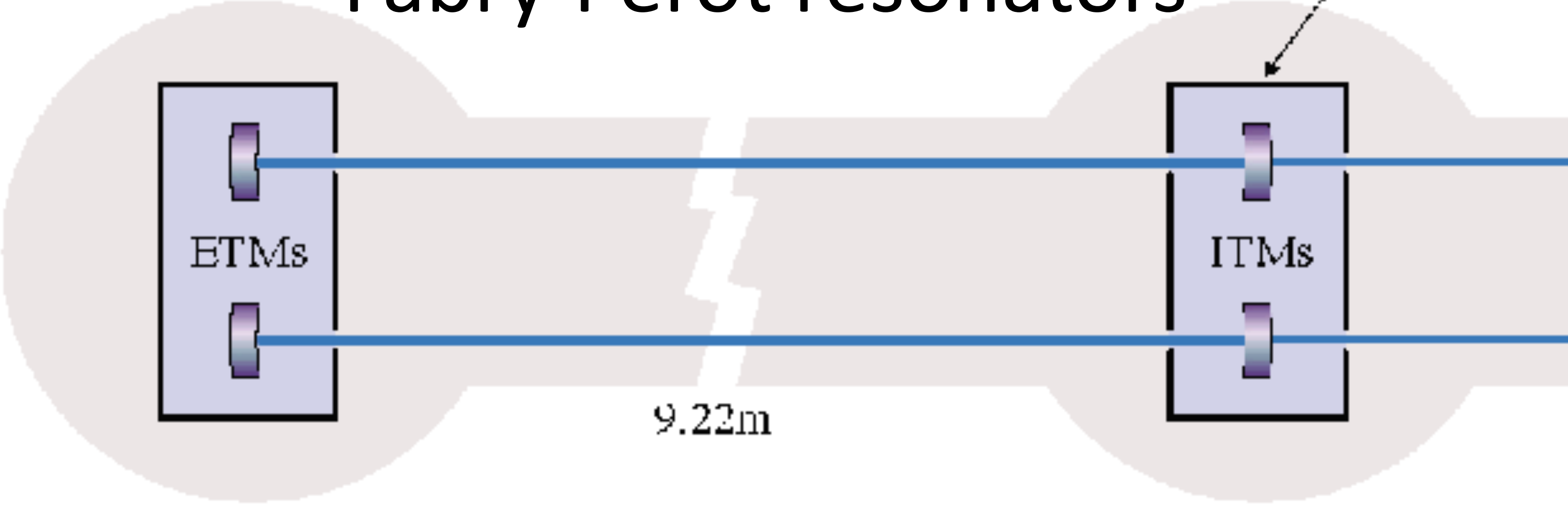
Image: Conor Mow-Lowry

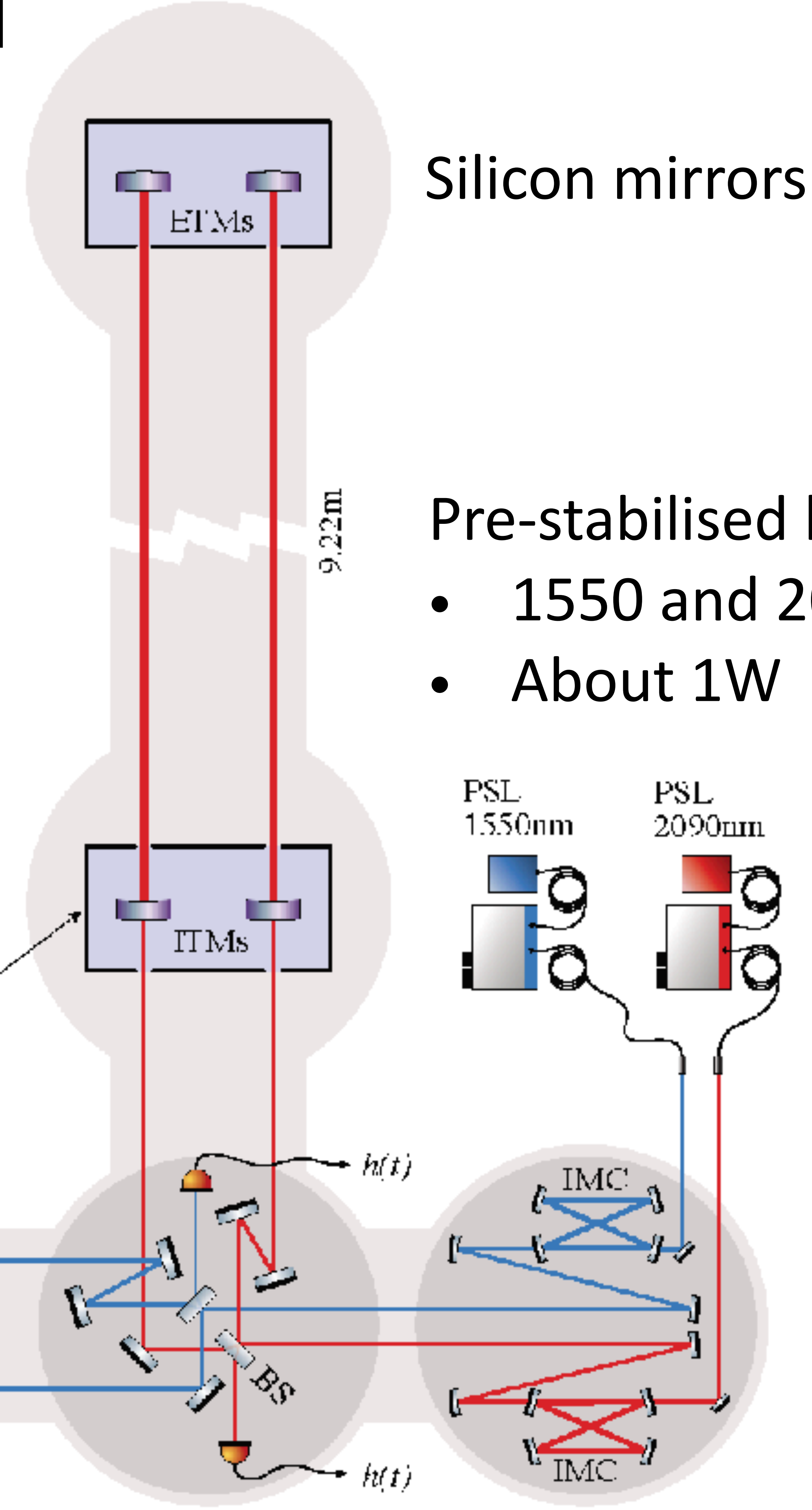
ETpathfinder

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

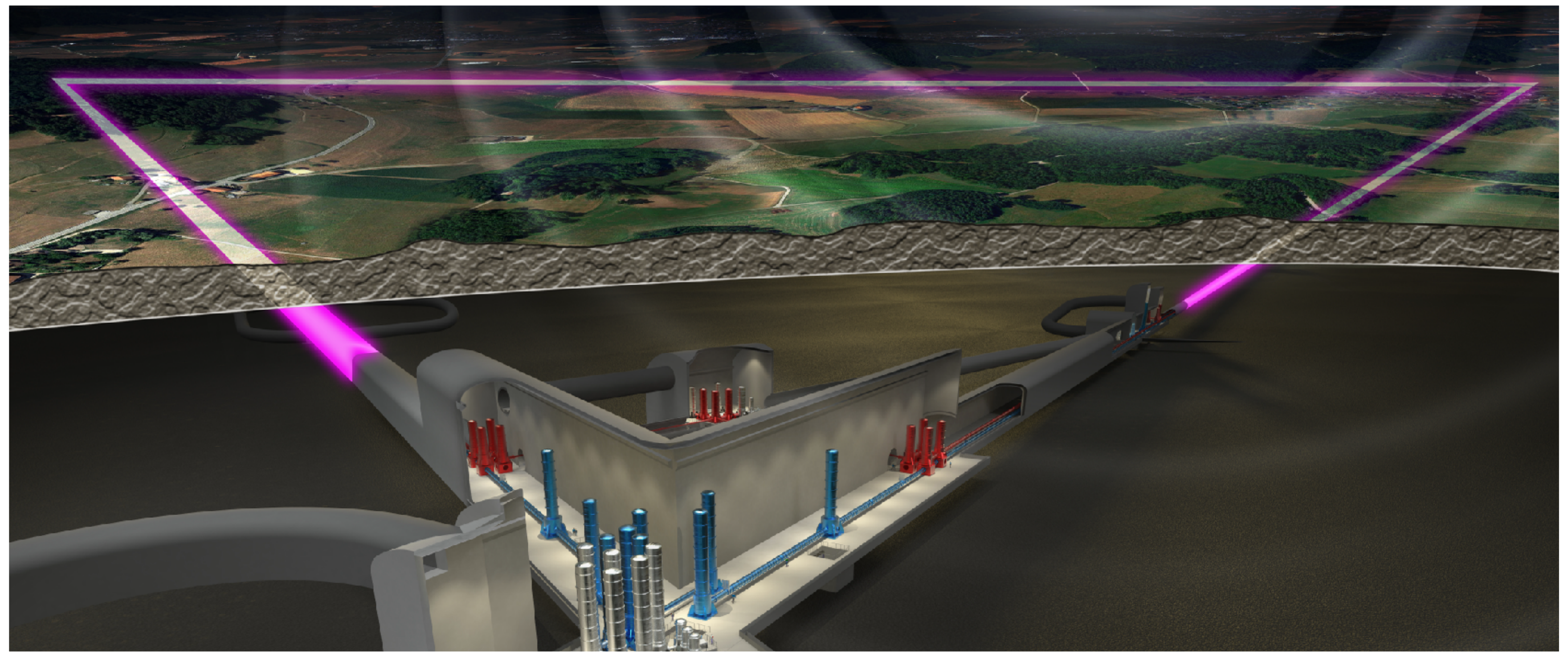
De #ETpathfinder is een baanbrekende faciliteit met blijvende waarde voor de wetenschap. Ik hoop van harte dat we over een aantal jaar de Einstein Telescoop in Zuid-Limburg kunnen gaan bouwen en het bijzondere werk van de ETPathfinder op nog grotere schaal kunnen voortzetten.

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

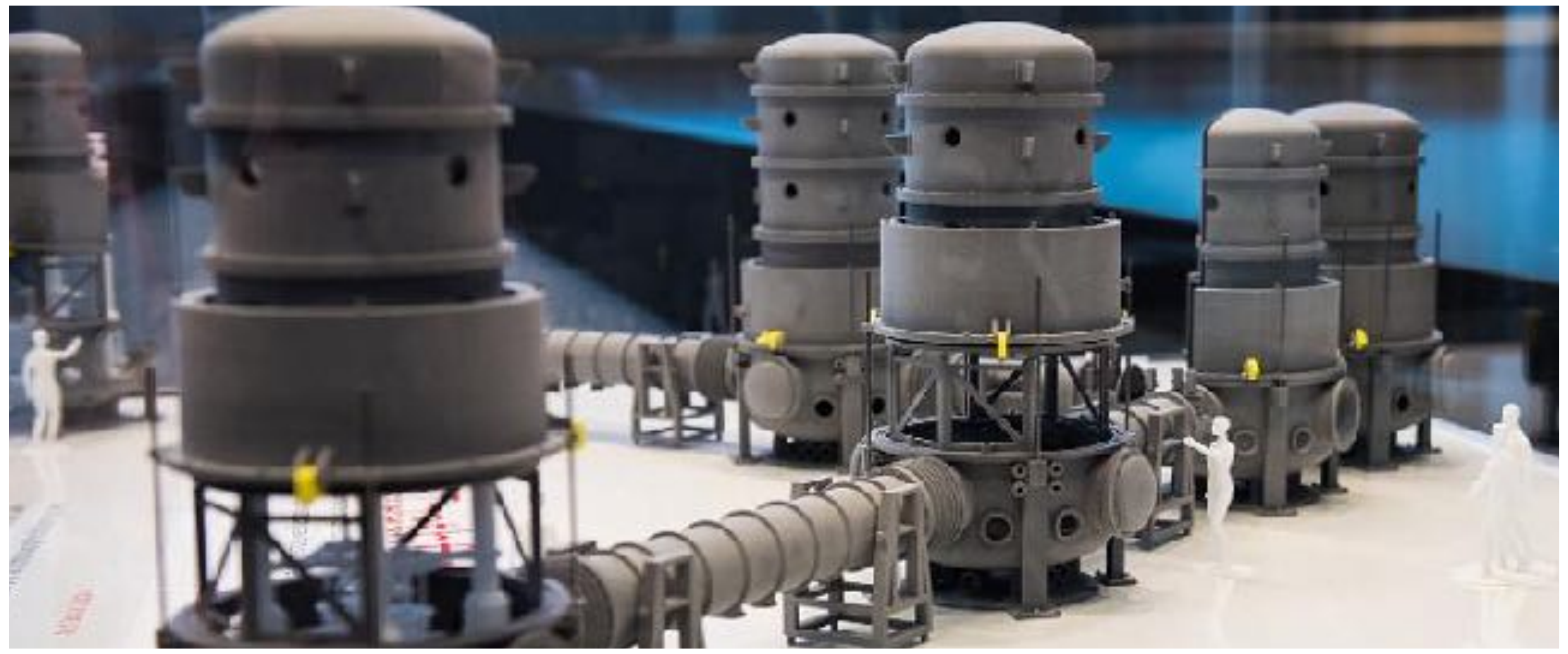
[Paul Kuijer]

Dutch involvement in ground-based GW instrument science

Virgo: large-scale detector in Italy, able to detect GWs, **currently taking scientific data, hardware upgrades are being prepared.**



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



Einstein Telescope: plan for future observatory in Europe, **research and technology development, preparation for new large infrastructure.**

Summary

- Moder interferometric detectors are still based on the Michelson interferometer.
- The sensitivity is increased by better design and by better technology, reducing limiting self-noise of the detectors.
- We are just a few years after the first breakthrough detection. The next decades will bring beautiful science and exciting technical projects.
- The Netherlands has a leading role in the Einstein Telescope, a unique opportunity for defining the future of an entire scientific field.