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Requirements and possible solutions for the Laser Frequency Noise of the Einstein Telescope Interferometers: a review

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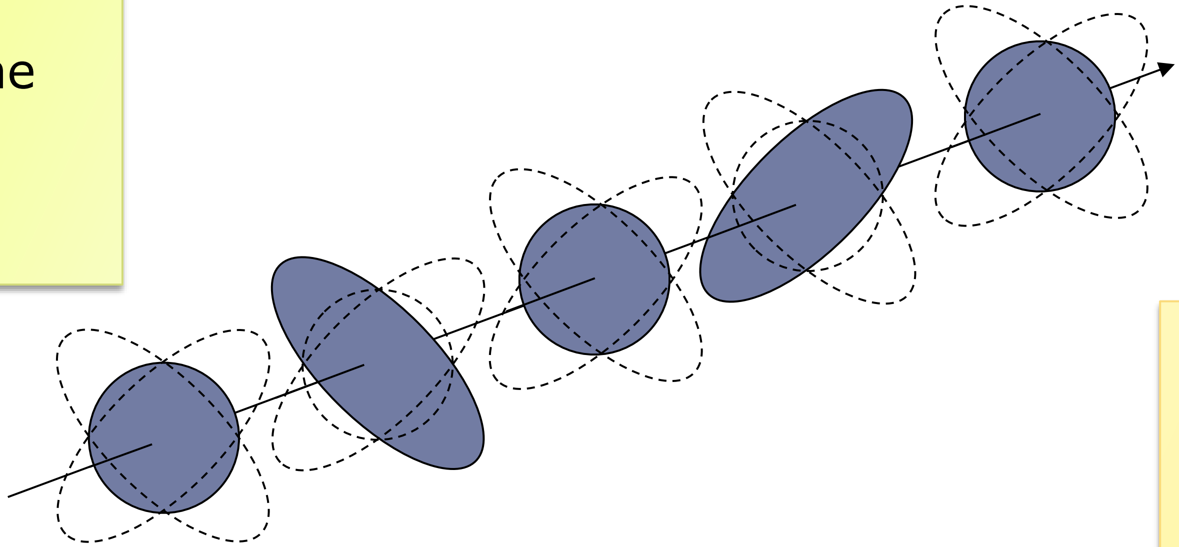
Outline

- Gravitational Waves detectors: a century-old ruler for space-time
- Limiting Noises: Laws of Nature and technical difficulties
- Laser noise: requirements and solutions for 3rd generation GW detectors
- The challenge from 2nd to 3rd generation GW detectors: Einstein Telescope design and technologies
- Conclusions

GW detectors: space-time rulers

❑ Effect of GWs:

Quadrupole radiation, Squeeze and stretch the space in perpendicular directions:
strain ***h* = ΔL/L**

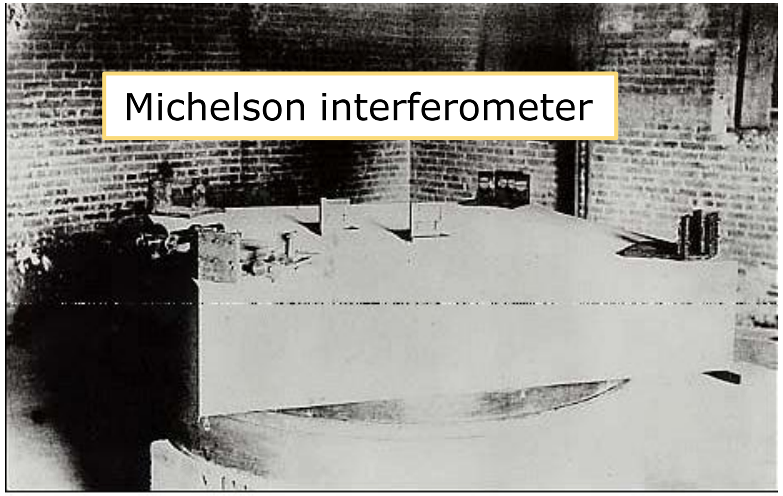


❑ What is the plausible "strain"?

Even for the most tremendous events in Universe, ***h~10^-21***

GW detectors: space-time rulers

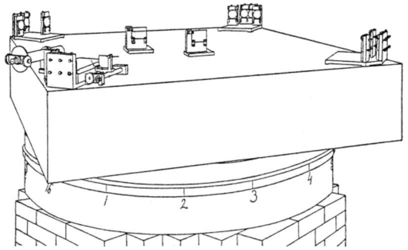
❑ How to detect strain?

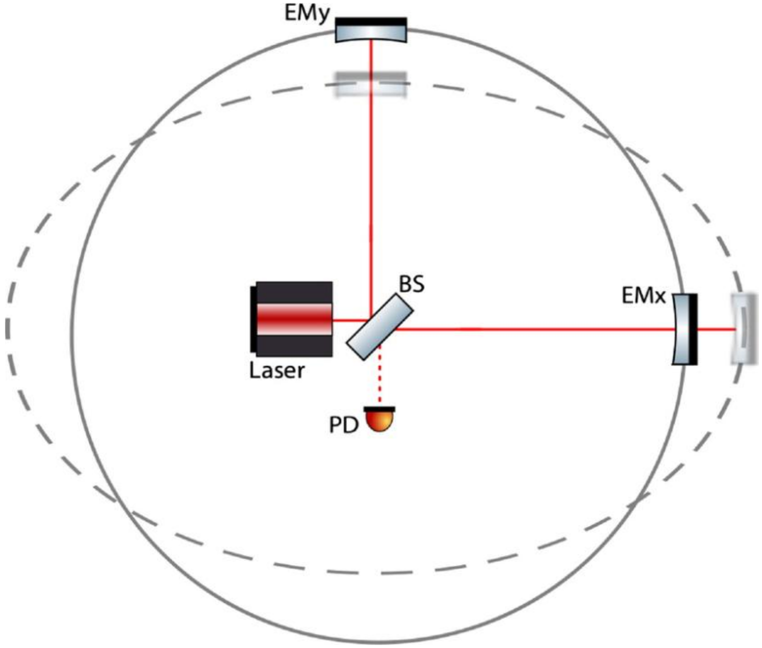


Michelson interferometer

Michelson & Morley's 1887 interferometer
built in the basement of Western Reserve
Photo: Case Western Reserve Archive

ΔL = 0.01 λ ~10^-8m
-> h ~ 10^-8





$$\delta\phi = G\,\delta L$$

- use the interferometer as a transducer:
displacement **ΔL** to Optical signal **Δphi**

-Michelson adjusted so that no light comes out from anti-symmetric port

- GW stretches and squeezes the two arms alternatively

- Wavefront takes longer to go back and forth in one of the arm than in the other

- Interference at anti-symmetric port is no longer completely distructive, and light reachs the photodetector: a signal!

GW detectors: space-time rulers

❑ How to increase strain sensitivity?

-Enhance the signal

-Reduce the noise

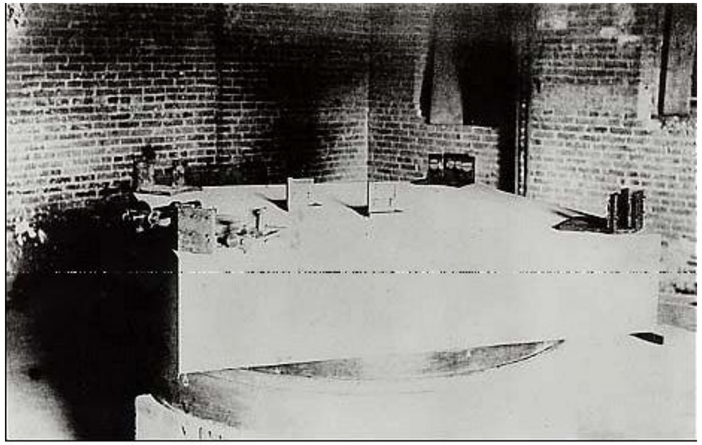
GW detectors: space-time rulers

❑ How to increase strain sensitivity: *enhance the signal*

- Very long arms

To get a larger displacement **ΔL = *h*L**

$$\delta\phi = G\boxed{\delta L}$$



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built in the basement of Western Reserve
Photo: Case Western Reserve Archive

L~1m

Virgo Interferometer, Cascina (Italy)

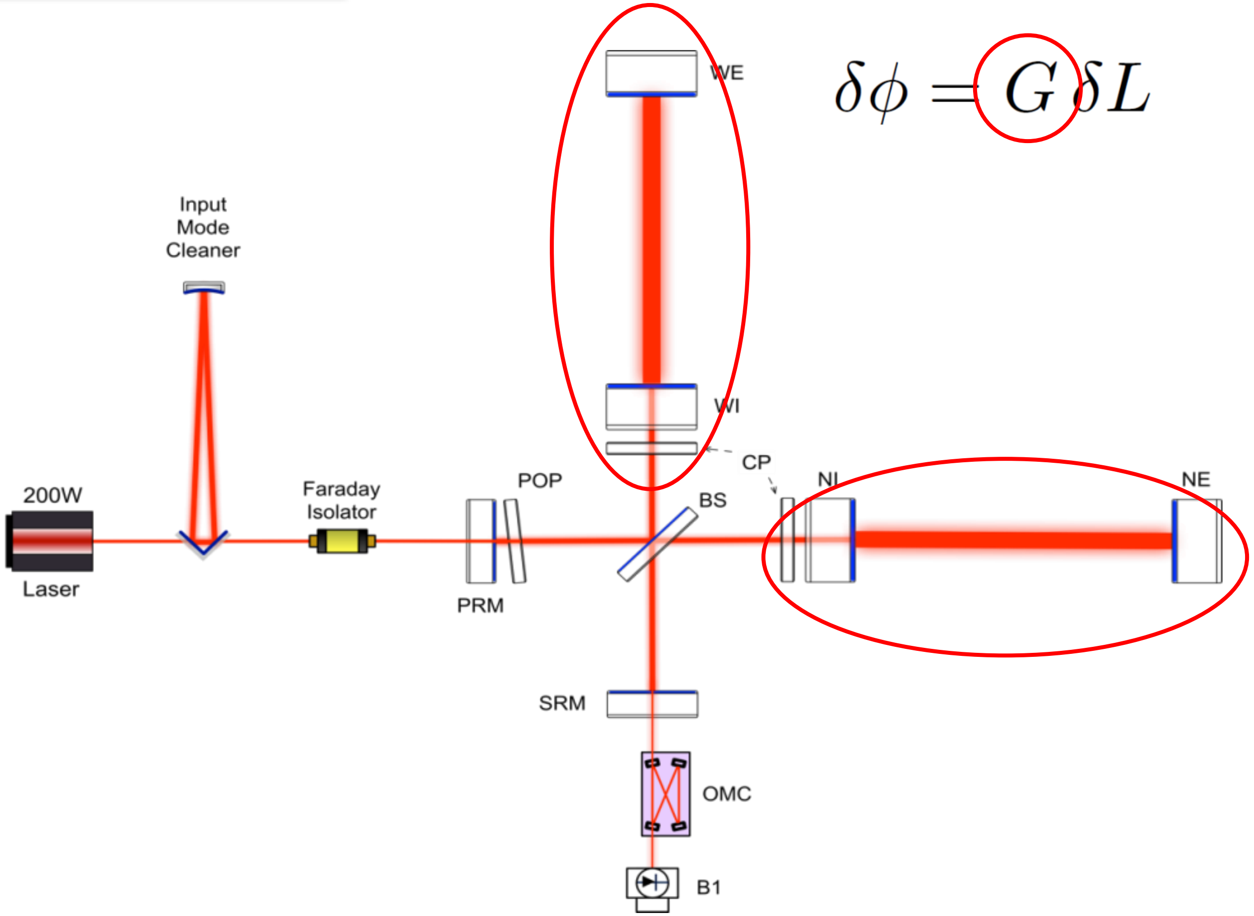
L~3km

GW detectors: space-time rulers

❑ How to increase strain sensitivity: *enhance the signal*

- Fabry-Perot cavity in each arm

To increase phase change



$$\delta\phi = G\,\delta L$$

Phase change enhanced by the finesse of the Fabry-Perot resonators (~400x)

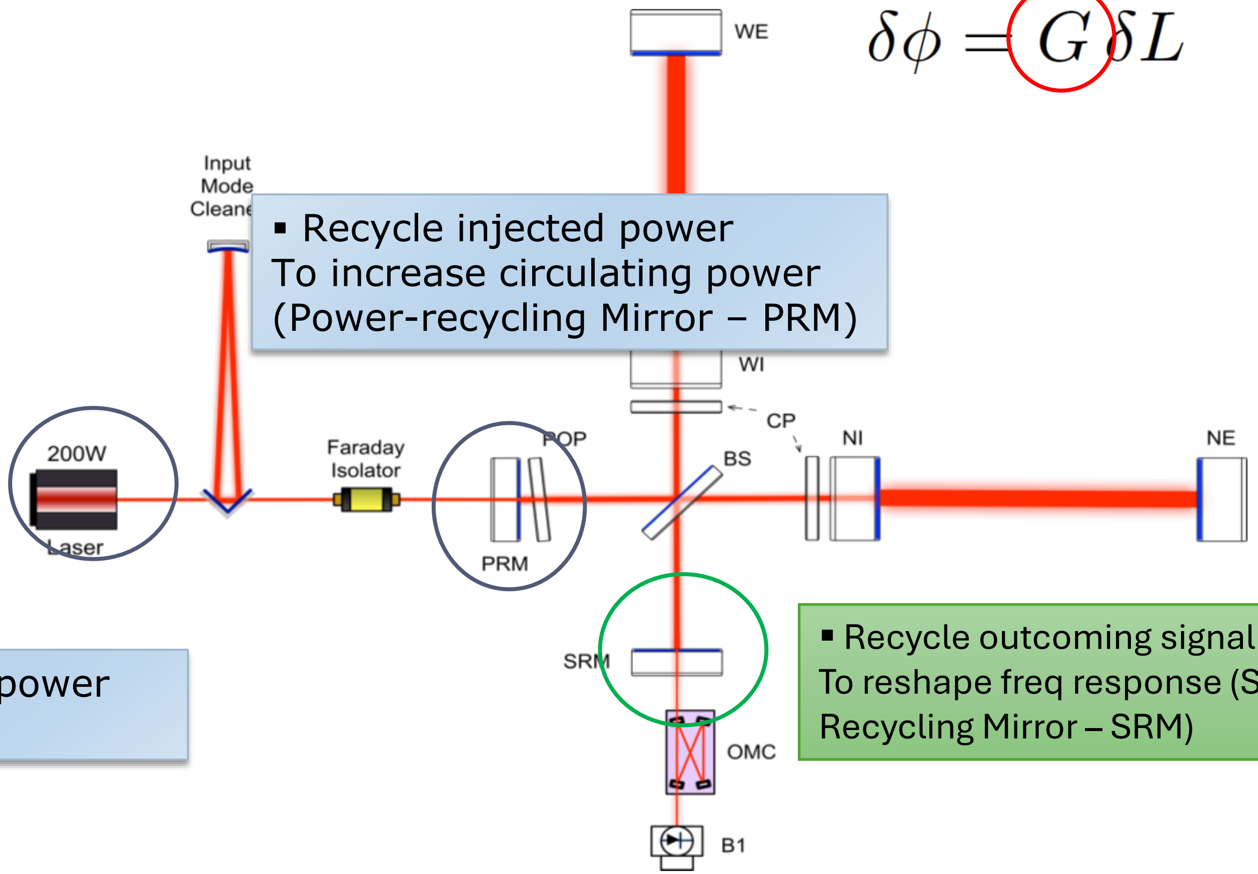
GW detectors: space-time rulers

EINSTEIN TELESCOPE

❑ How to increase strain sensitivity: *enhance the signal*

$$\delta\phi = \boxed{G}\,\delta L$$

2nd Generation Interferometers designed for ~1MW circulating power in the arms



- Recycle injected power
To increase circulating power
(Power-recycling Mirror – PRM)

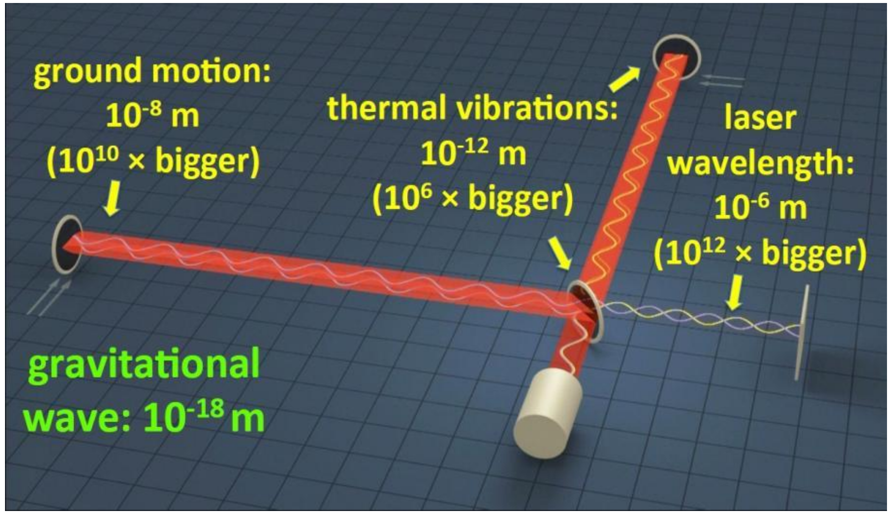
- Increase input power
(~10^2 W Pin)

- Recycle outcoming signal
To reshape freq response (Signal Recycling Mirror – SRM)

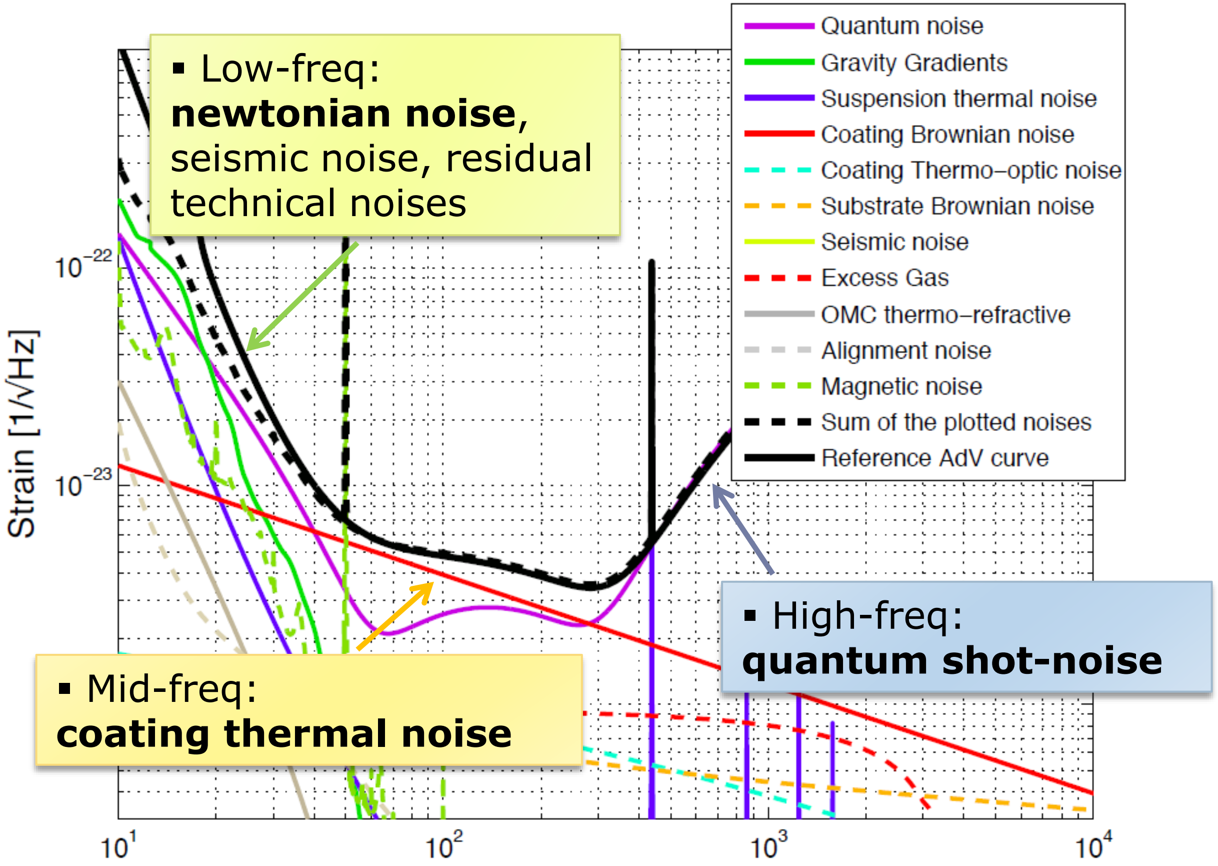
Limiting Noises

❑ How to increase strain sensitivity: *reduce the noise*

Doesn't matter how sensitive you are, if your noise is billions of times larger than your signal



Credits: Stephen Fairhurst



- Low-freq: **newtonian noise**, seismic noise, residual technical noises

- Mid-freq: **coating thermal noise**

- High-freq: **quantum shot-noise**

Focus on one particular source of noise: laser frequency noise

Laser noise

- ❑ Laser frequency noise is the random fluctuations in the frequency of laser light

All lasers exhibit some intrinsic uncertainty in the laser frequency emitted
- Schawlow-Townes limit (spontaneous emission limit) [1]

- ❑ Why do we care about?

The GW signal is in the differential degree of freedom which is in principle perfectly decoupled from the symmetrical degree of freedom

This is only true for perfect interferometer: any amount of asymmetry in the arms reduce the Common mode rejection factor

[1] A. L. Schawlow and C. H. Townes, Infrared and Optical Masers, Physical Review 112, 1940 (1958)

Laser noise

☐ Why do we care about?

1) Unsuppressed frequency noise can mask any GW signals even with very tiny asymmetries in the interferometers (such as intentional length differences for control purposes, residual differences in arm reflectivities, etc.)

2) Also, to bring the interferometer from a random state to its working setpoint and control it, frequency noise has to be greatly reduced

Laser noise

☐ Basics on freq noise suppression (from [2])

To stabilize the laser frequency noise a reference is needed: Optical cavities can be used

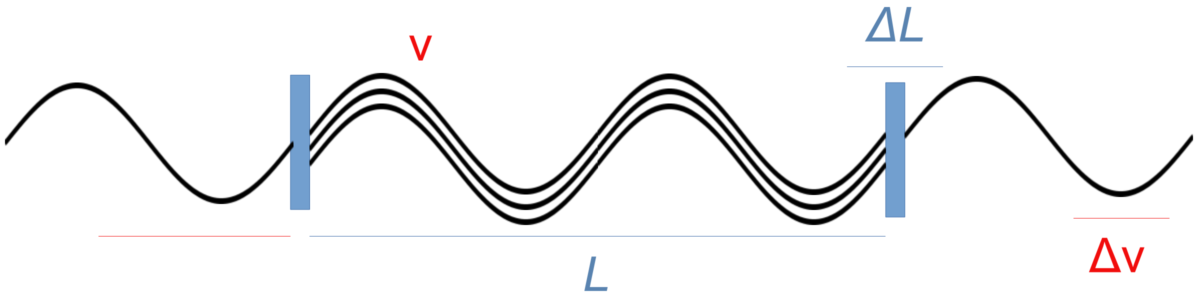
A laser incident on a two mirror Fabry-Perot cavity will resonate (coherently interfere) when the frequency *v*

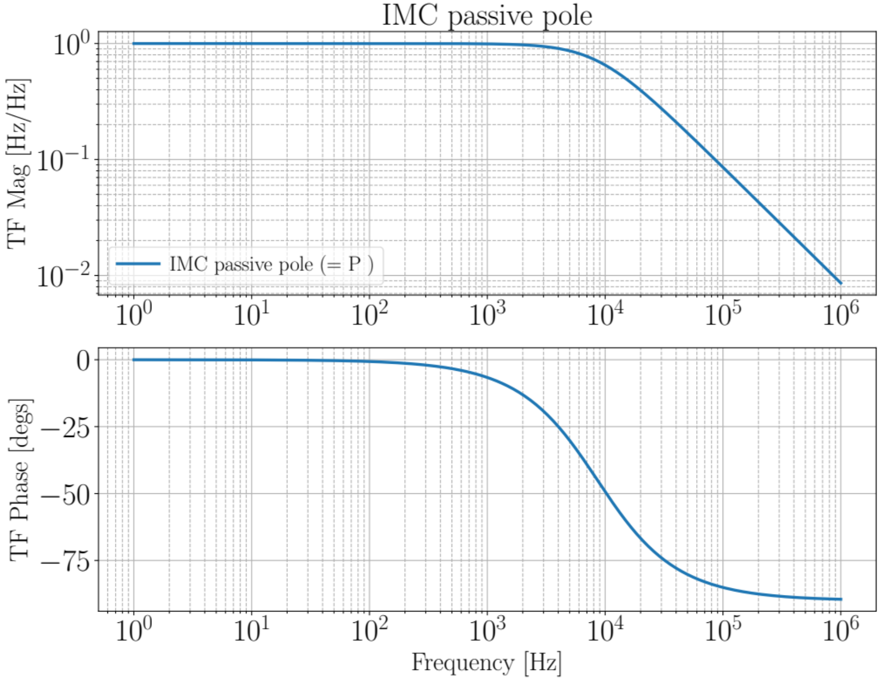
$$\nu = \frac{c}{2L} n$$

Frequencies above the cavity pole (depending on photon life-time in cavity) are attenuated.

Now, the cavity length changes ΔL are related to the frequency changes Δv by

$$\frac{\Delta\nu}{\nu} = \frac{\Delta L}{L}$$





[2] Craig Cahillane, Georgia Mansell, Daniel Sigg, LIGO DCC: G2101271

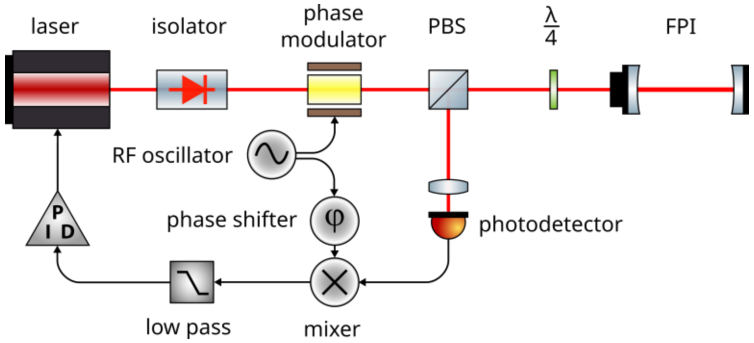
Laser noise

- ❑ Basics on freq noise suppression

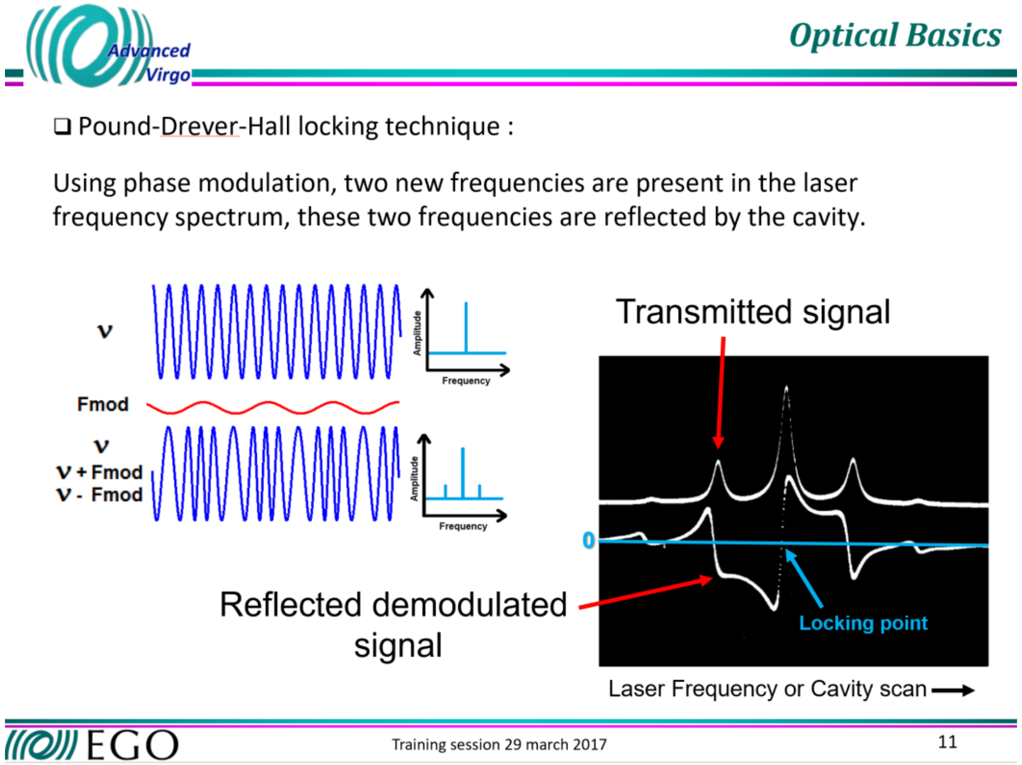
How to “lock” the laser frequency to the cavity length or viceversa?

The Pound-Drever-Hall technique is widely used to derive an error signal for this purpose [3]

The error signal can then be fed:
- Either to actuators on the laser frequency to follow the cavity length as a reference
- Or to cavity length actuators to follow the frequency jitter of the laser source



By Kondephy - Own work, CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=53790278



Optical Basics

❑ Pound-Drever-Hall locking technique :

Using phase modulation, two new frequencies are present in the laser frequency spectrum, these two frequencies are reflected by the cavity.

EGO Training session 29 march 2017 11

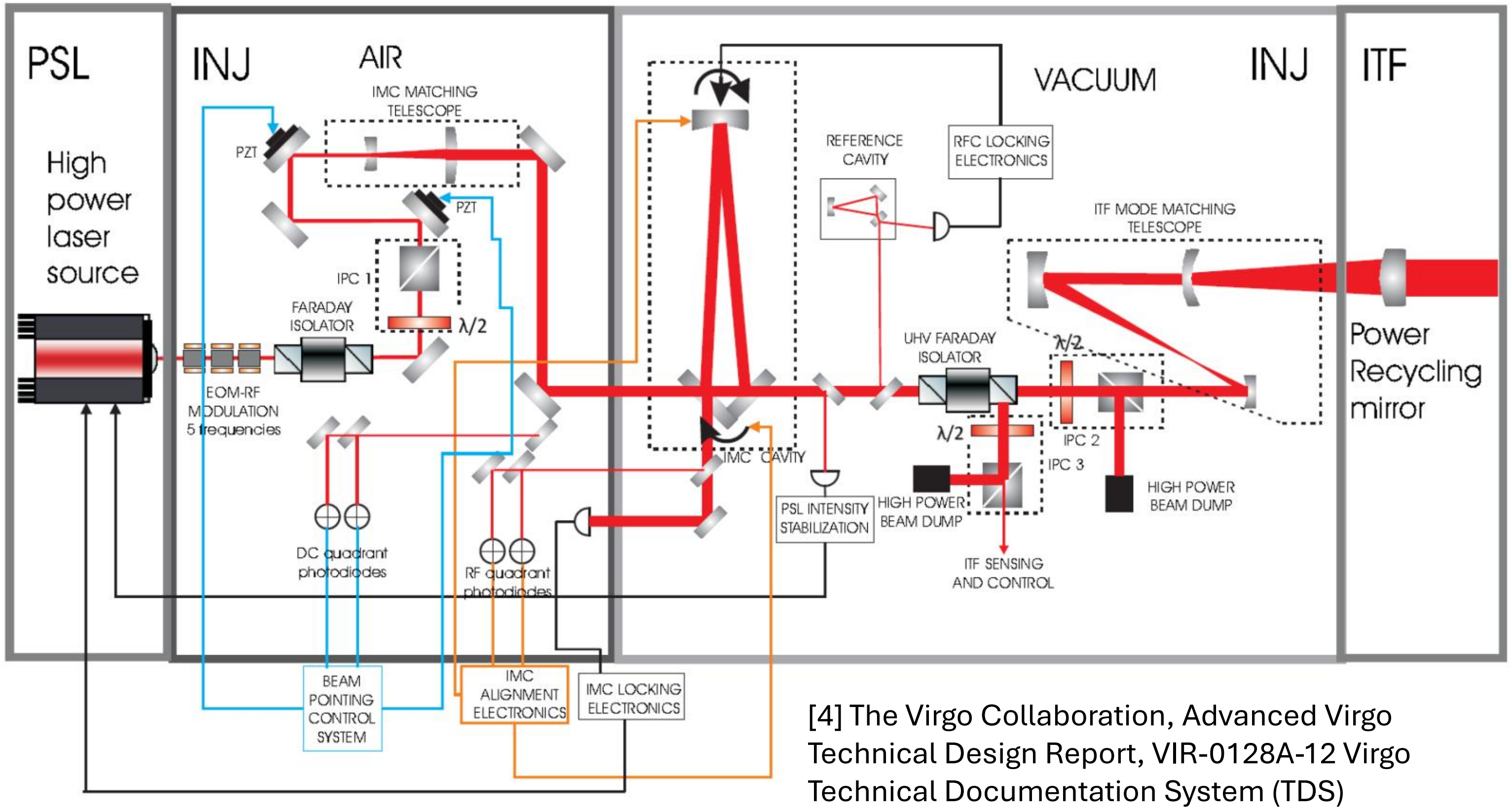
Credits to: Eric Genin, Gabriel Pillant

[3] Drever, R.W.P., Hall, J.L., Kowalski, F.V. *et al.* Laser phase and frequency stabilization using an optical resonator. *Appl. Phys. B* **31**, 97–105 (1983). https://doi.org/10.1007/BF00702605

Laser noise: pre-stabilization

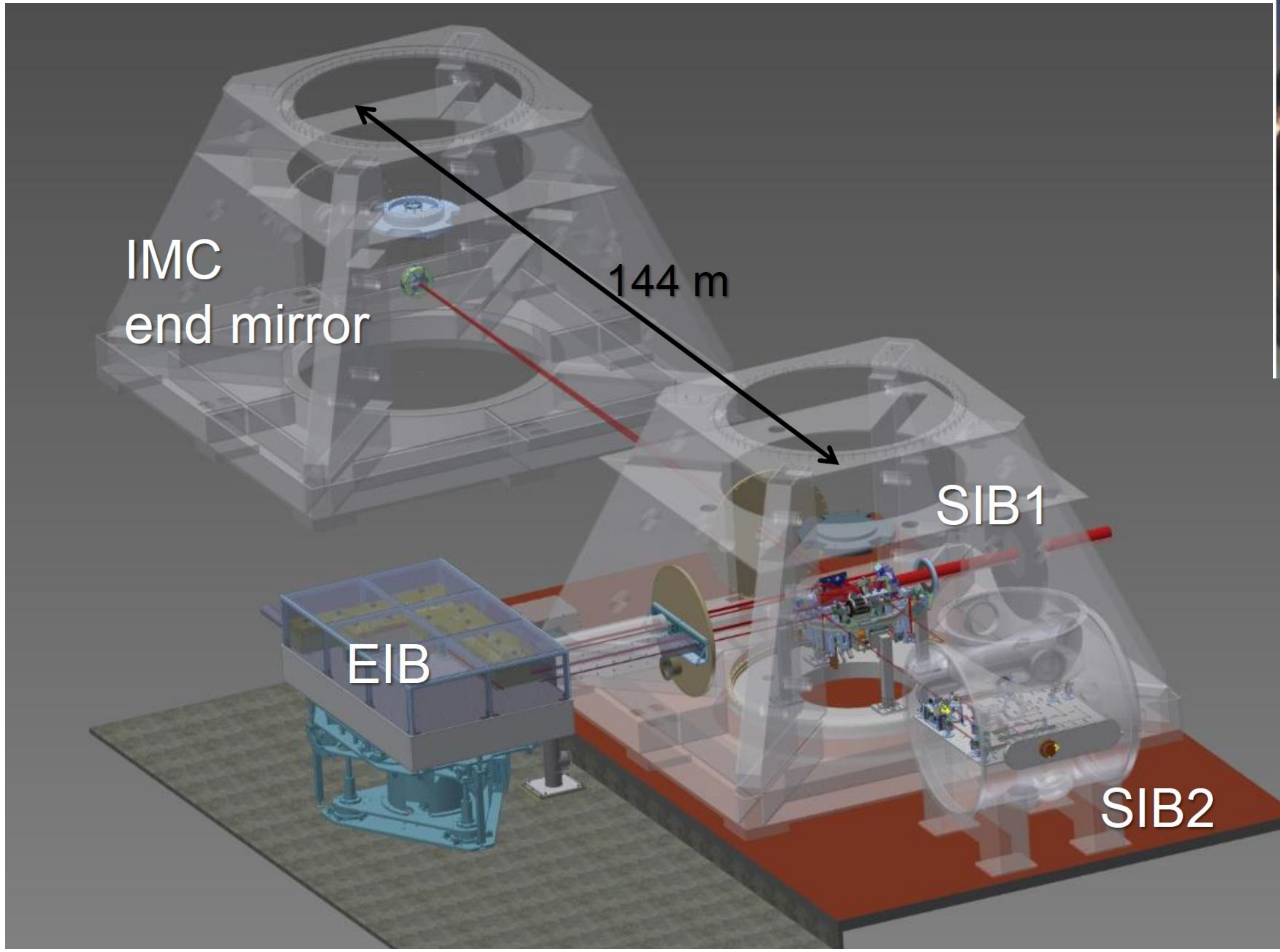
- Control loop for second generation interferometers (Virgo example [4])
  - To lock, the ~km long arm cavities, we have to pre-stabilize the laser frequency
  - A ~100m long triangular cavity - the input mode cleaner (IMC) - and a rigid reference cavity (made of ULE) are used to achieve the required 1 Hz rms.

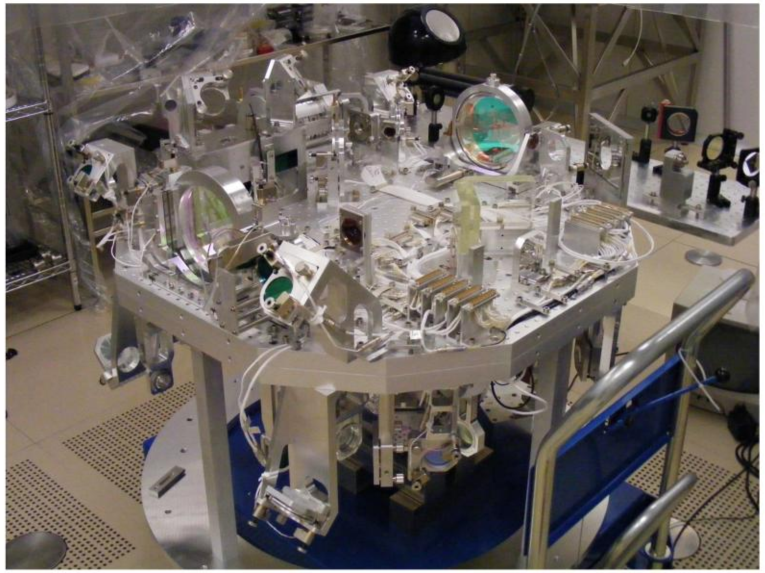
The IMC realized with suspended mirrors is used as reference for the laser frequency above ~150Hz
at lower Fourier-frequencies a rigid Reference Cavity (RFC) is used.
The control scheme acts on the laser frequency to follow the resonance of the IMC, and on the mirror of the IMC to stay locked on the reference cavity.



[4] The Virgo Collaboration, Advanced Virgo Technical Design Report, VIR-0128A-12 Virgo Technical Documentation System (TDS) https://tds.virgo-gw.eu/ql/?c=8940

Input Optics





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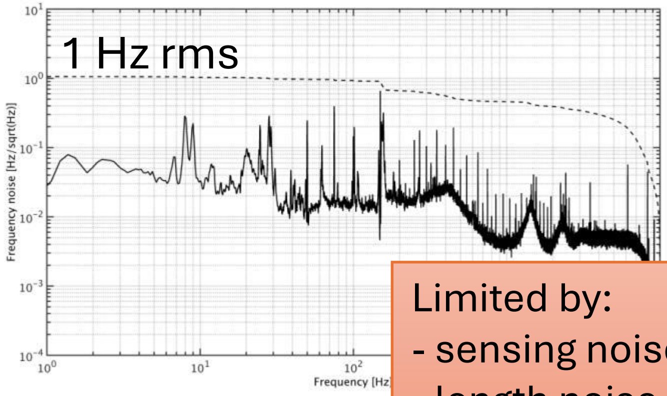
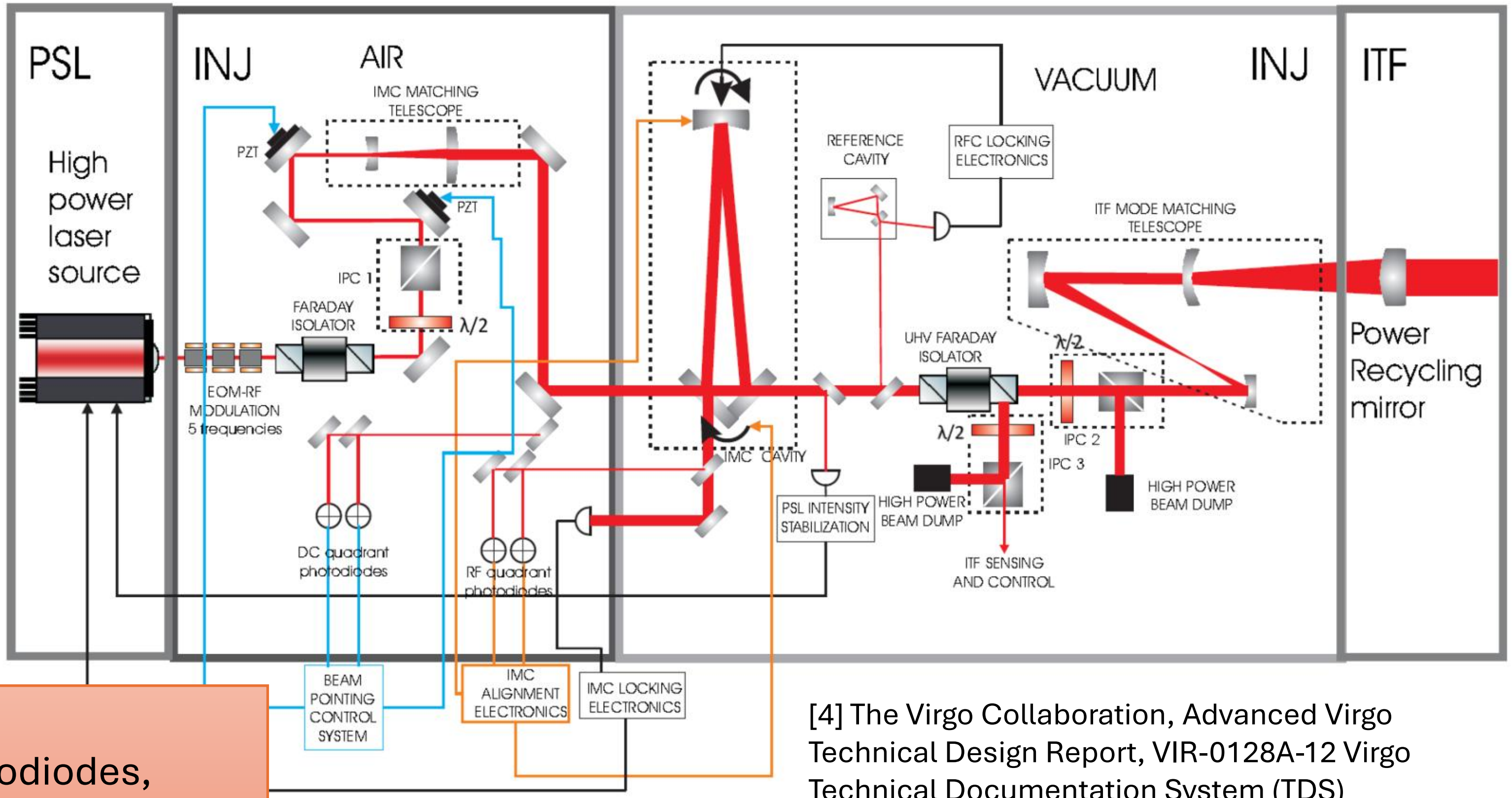


Limited by:
- sensing noise of the photodiodes,
- length noise of the cavities



[4] The Virgo Collaboration, Advanced Virgo Technical Design Report, VIR-0128A-12 Virgo Technical Documentation System (TDS) https://tds.virgo-gw.eu/ql/?c=8940

Laser noise

- ❑ Control loop for second generation interferometers

❑ To achieve the sensitivity required, we should get a relative stability of the laser frequency better δν/ν than 10^{-21} (ν=300 THz) [5]

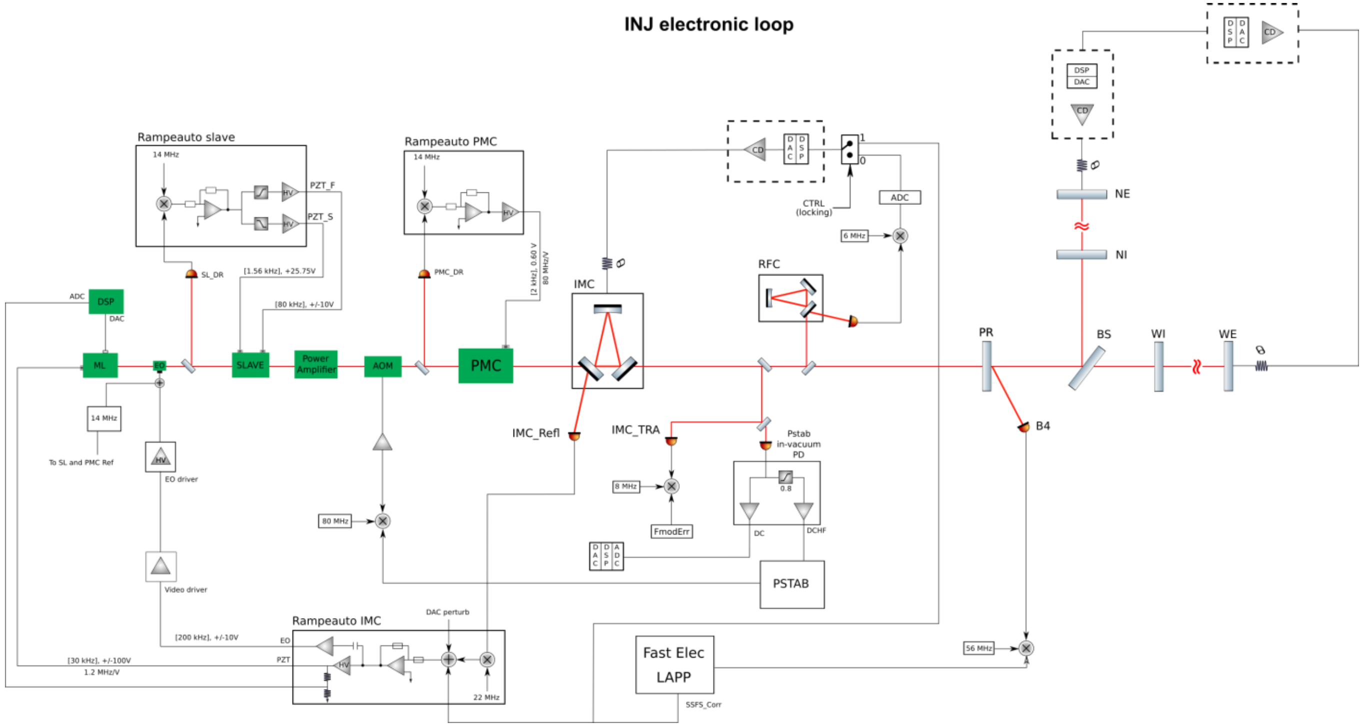
Second stage of frequency stabilization (SSFS):

use the common arm (CARM) degree of freedom as a reference,

the control scheme adds the error signal to the setpoint of the first stage loop.

The bandwidth is limited by the free spectral range (FSR) of the CARM, due to phase change inducing stability problems.

The IMC length noise and sensing noise are suppressed by the gain of the CARM loop when SSFS is engaged with sufficiently high bandwidth.



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[5] The Virgo collaboration, Laser with an in-loop relative frequency stability of 10^{-21} on a 100-ms time scale, PHYSICAL REVIEW A 79, 053824 , 2008.

Laser noise

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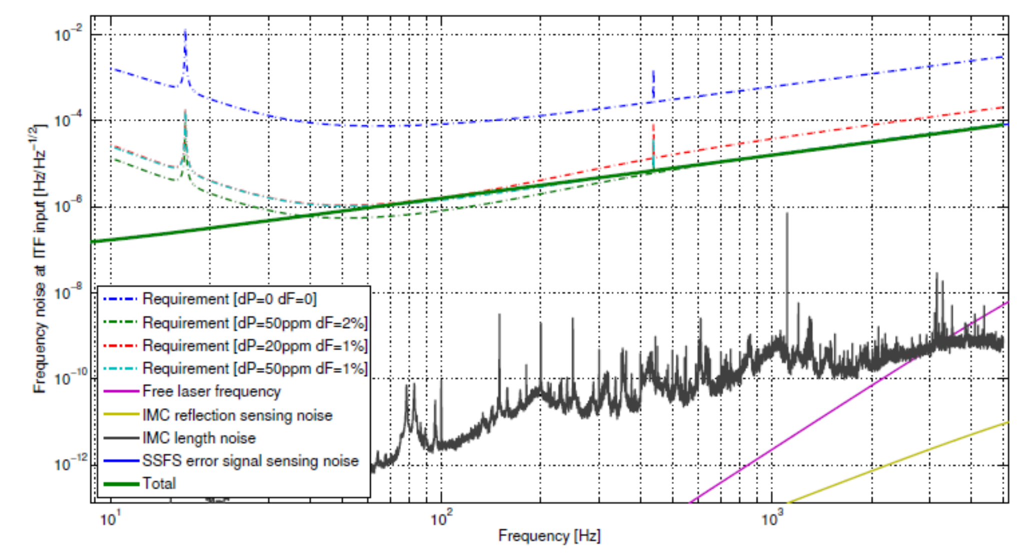

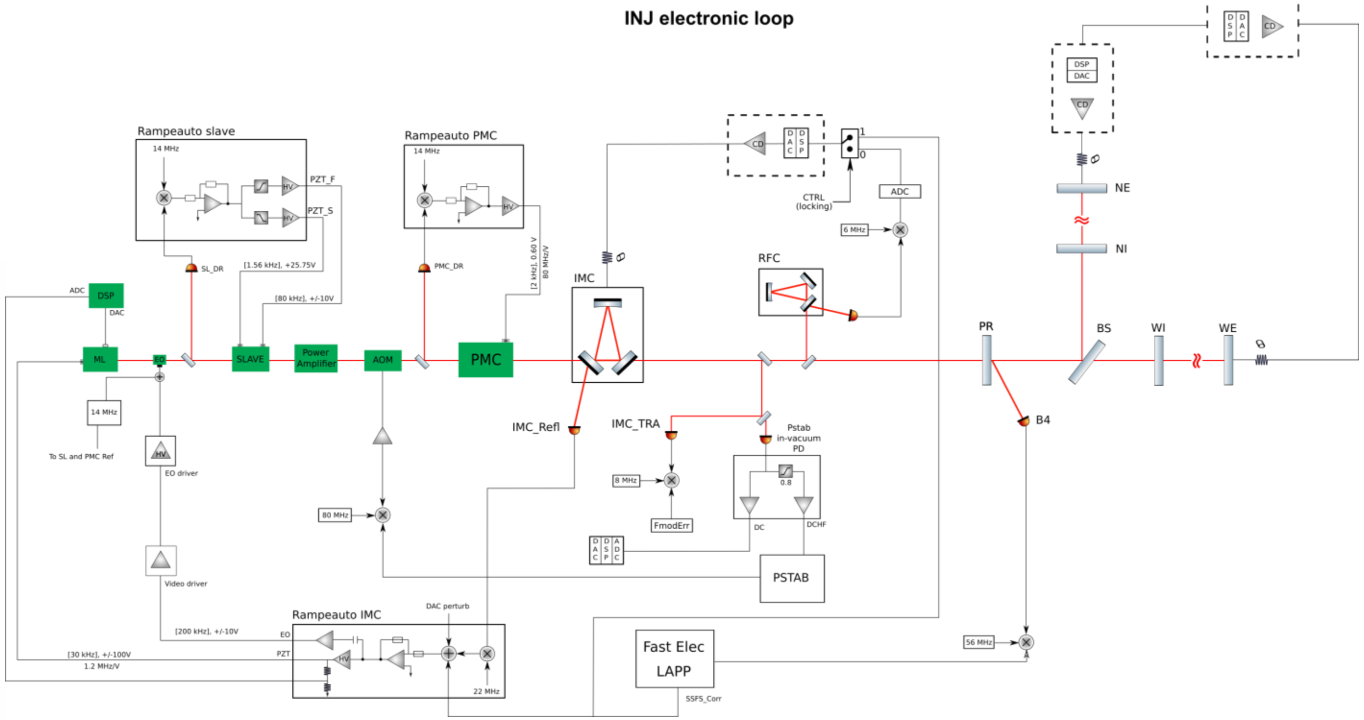

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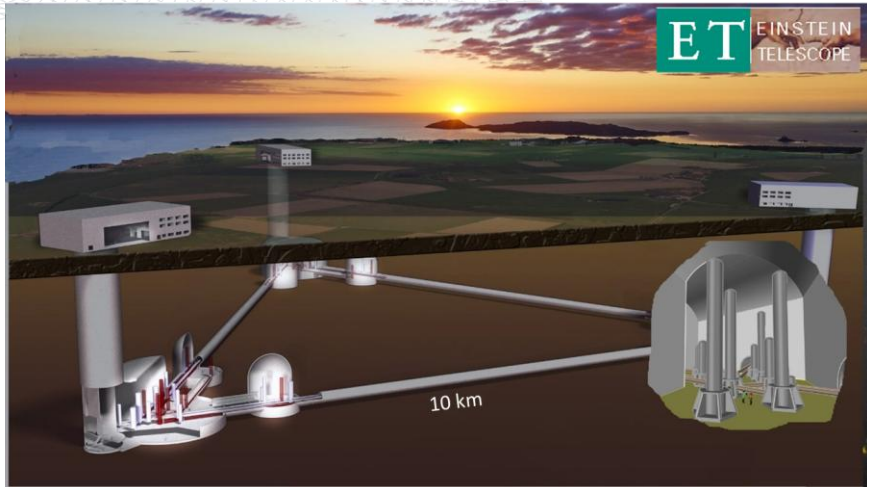
Laser noise: what changes in 3rd generation



Einstein Telescope (EU)

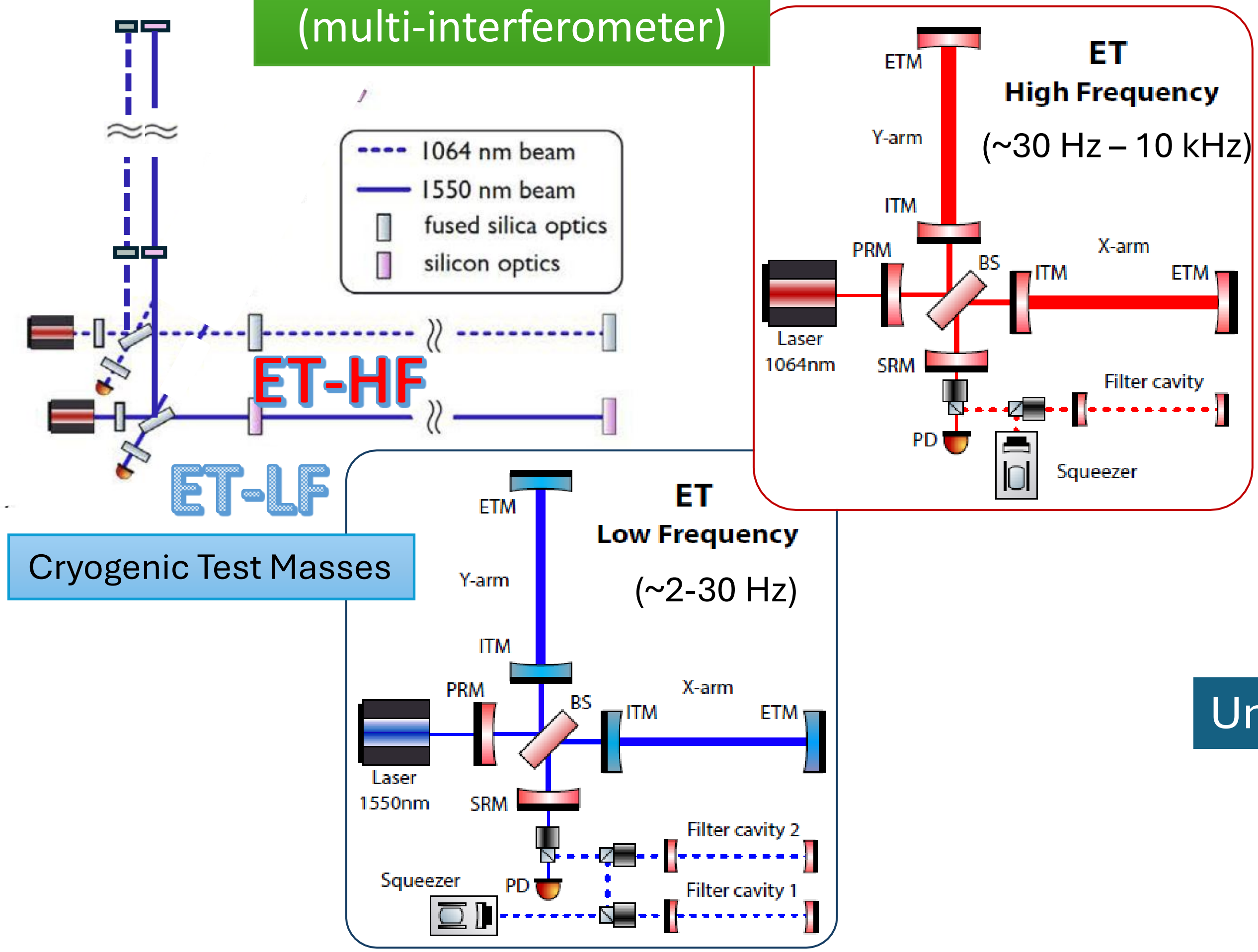
The Einstein Telescope (ET) is a proposed underground infrastructure to host a third-generation, gravitational-wave observatory. It builds on the success of current, second-generation laser-interferometric detectors Advanced Virgo and Advanced LIGO. The Einstein Telescope will achieve a greatly improved sensitivity by increasing the size of the interferometer from the 3km arm length of the Virgo detector to 10km (or 15Km, depending on the final configuration), and by implementing a series of new technologies including a cryogenic system.
https://www.et-gw.eu/
https://apps.et-gw.eu/tds/ql/?c=15418

Cosmic Explorer (US)

The design concept for Cosmic Explorer features two facilities, one 40 km on a side and one 20 km on a side, each housing a single L-shaped detector on surface.

https://dcc.cosmicexplorer.org/public/0163/P2100003/007/ce-horizon-study.pdf

Einstein Telescope key elements

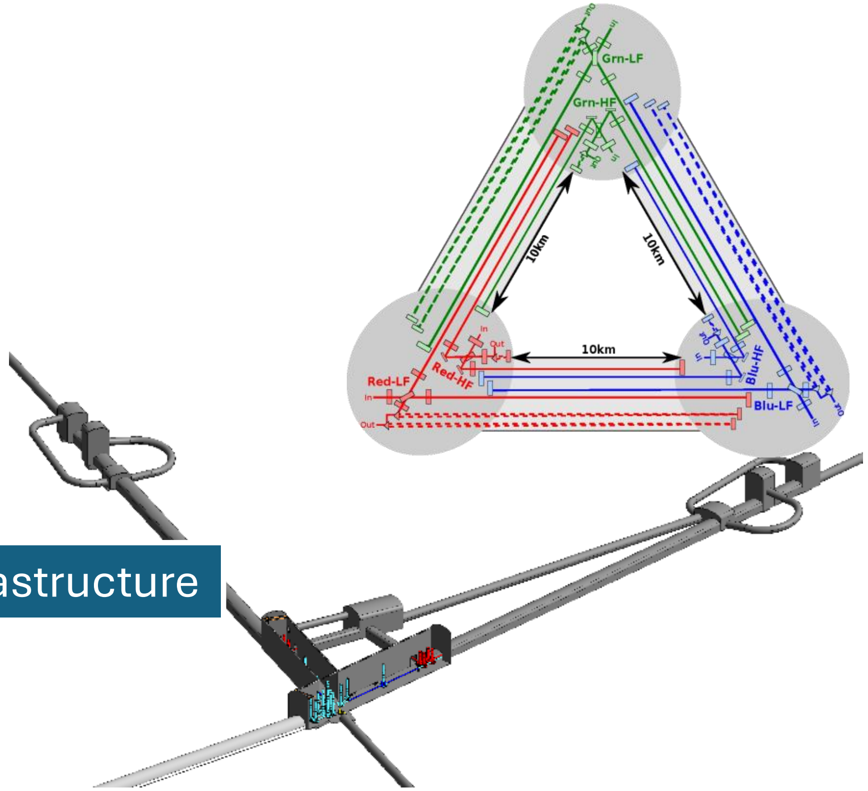


Xylophone configuration (multi-interferometer)

Cryogenic Test Masses

- Either triangular configuration (10Km arms)
- Or 2L (15Km arms) at 45 deg

Covering both + and X polarizations



Underground infrastructure

Laser noise: what changes in 3rd generation

- ❑ Quantitative change: with the goal of a much better sensitivity to GW signals, the frequency noise requirements become more stringent (preliminary results in [6, 7])

[6] Craig Cahillane, Georgia L. Mansell, And Daniel Sigg, Laser Frequency Noise in Next Generation Gravitational-Wave Detectors - arXiv:2107.14349v1 [physics.ins-det] 29 Jul 2021
[7] Teng Zhang, Frequency noise requirement, 3rd Einstein Telescope Annual Meeting ADN conference center, Warsaw https://indico.ego-gw.it/event/764/contributions/7145/

- ❑ Qualitative change: the common arm reference becomes impractical because of longer arms
  - The part of the frequency stabilization loop relying on the CARM needs a huge gain at low frequency, so a very high unity gain frequency (UGF)
  - But the CARM cavity features a 360 deg phase rotation for a f = c/2L (Free Spectral Range, FSR), setting a practical limit to the usable bandwidth

Interferometer	Arm length (Km)	FSR (KHz)	Cavity bandwidth (Hz)
AdVirgo+ (O4)	3	50	110
LIGO (O4)	4	37.5	83
ET-HF (*)	10 / 15	15 / 10	~30 / 20
CE (*)	40	3.75	~5-10

Relevant parameters for selected current and future interferometers.
(*) These are parameters from current designs and not yet consolidated

Laser noise: some proposals

Solution proposed in [2] for CE:

Do not rely on high bandwidth CARM for frequency stabilization.

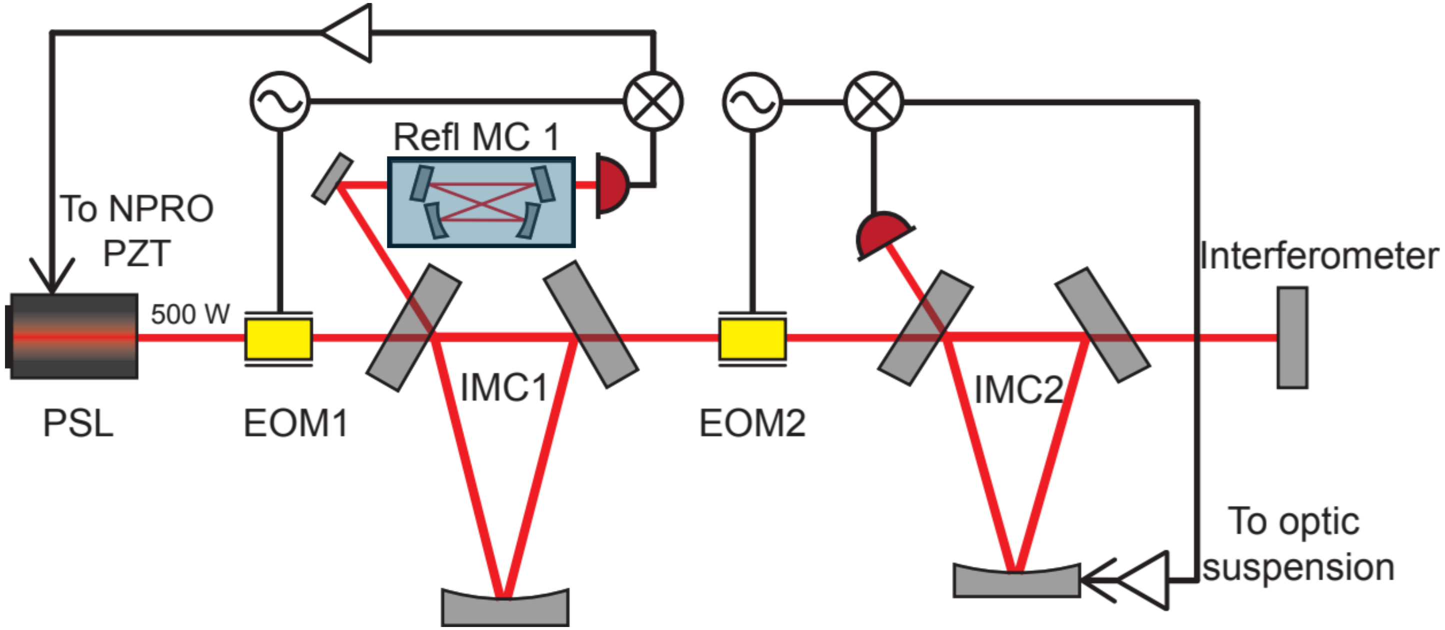
Proposed design for Cosmic Explorer:

- Two long input mode cleaners
- The first (IMC1) with active, high bandwidth feedback to the laser frequency
- The second (IMC2) with passive, low bandwidth feedback to its suspensions

Assuming we tolerate 1% loss:

- Finesse = 700
- IMC1 length = 100 m
- IMC2 length = 330 m
- IMC1 FSR = c/(2L) = 1.5 MHz
- IMC2 FSR = c/(2L) = 450 kHz
- IMC1 pole = 1 kHz
- IMC2 pole = 500 kHz

- A bowtie mode cleaner in reflection of IMC1 (REFL MC1) removes junk light and lowers the shot noise limit.



[2] Craig Cahillane, Georgia Mansell, Daniel Sigg, LIGO DCC: G2101271

Laser noise: some proposals

Analyzing the frequency noise contributions [7]:

❑ Input noise to the Interferometer:

- Free running laser frequency noise

  Suppressed by both RC and IMC gain

- IMC length noise (coating thermal noise, radiation pressure noise, etc.)

  Suppressed by CARM loop gain? If not enough, increase the IMC length

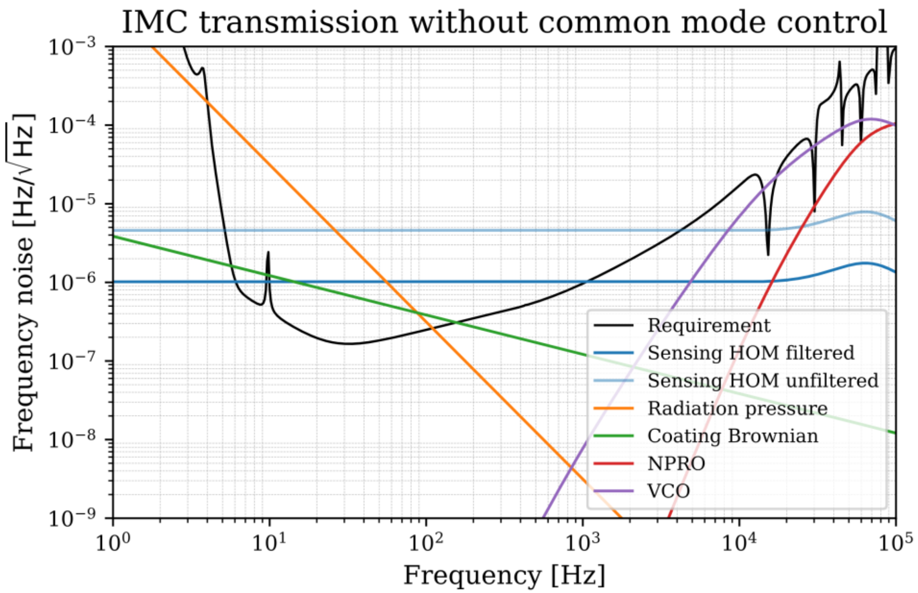
- IMC Sensing noise

  Suppressed by CARM loop gain? If not enough, increase the IMC length/Finesse
  & Increase effective power on sensing PDs

[7] Teng Zhang, Frequency noise requirement, 3rd Einstein Telescope Annual Meeting ADN conference center, Warsaw https://indico.ego-gw.it/event/764/contributions/7145/

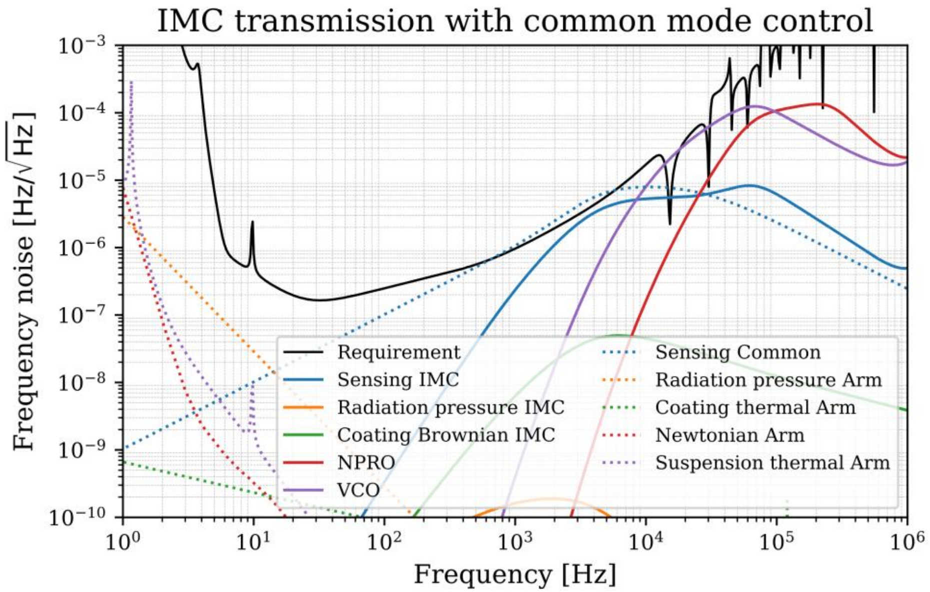
Laser noise: some proposals

Analyzing the frequency noise contributions, ET-HF triangle configuration with perfect compensation of thermal effects in the interferometer [7]:



The frequency noise is computed for 10Km long arms, <u>and a single 100m</u> long IMC to provide frequency reference but with the second stage of stabilization using CARM loop reaching a bandwidth of 14KHz.

The level of the worst offender noise sources is acceptable even without the additional filtering of the light on the IMC-PDH photodiode. Preliminary results TBC [7].



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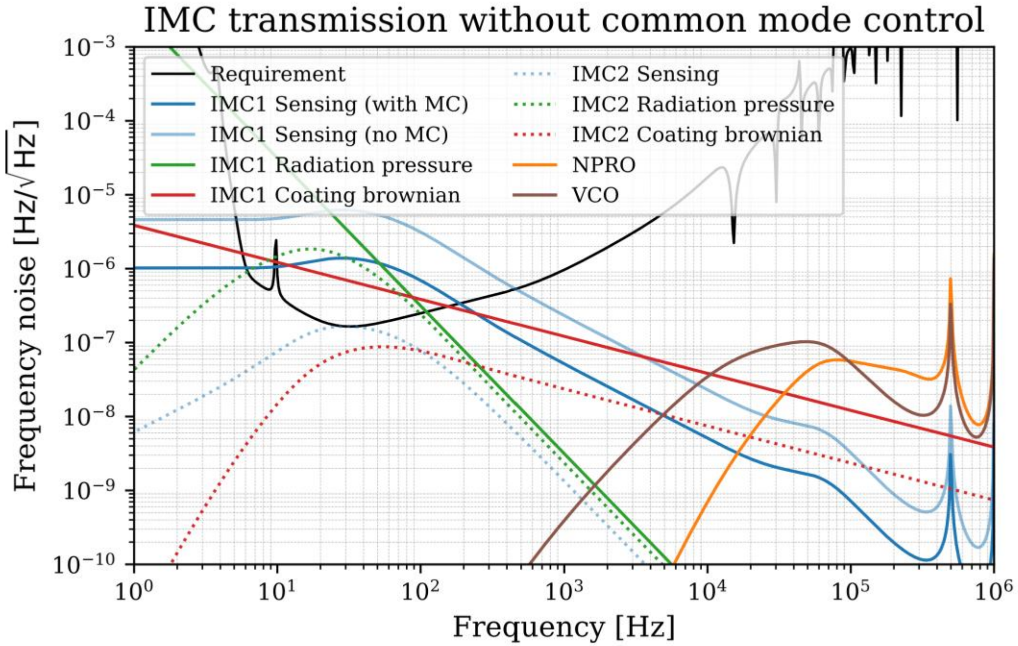


The frequency noise is computed for 10Km long arms, and two (100m and 300m long) IMCs to provide frequency reference and filtering, but without the second stage of stabilization using CARM.

The suppression of the worst offender noise sources is given by the dotted lines. Radiation pressure noise is still above the requirements, while ***sensing noise is acceptable only with the additional filtering of the light on the IMC-PDH photodiode****. Preliminary results TBC [7].*

[7] Teng Zhang, Frequency noise requirement, 3rd Einstein Telescope Annual Meeting ADN conference center, Warsaw https://indico.ego-gw.it/event/764/contributions/7145/

Laser noise: some proposals

Summarizing, the early results obtained in [7] show that ET-HF will likely have strict requirements in terms of frequency noise, and that the architecture to meet the requirements will have an increased complexity.

The baseline configuration at the time being for ET-HF is to employ two IMCs, the second one having a high finesse and 300m long, while for the first IMC an additional filtering (ancillary mode cleaner cavity) for the reflected light is required.

This configuration is promising, but even the optimistic case of having the possibility to use CARM control – requires the capability of handling a very large power and intensity inside a suspended mirror cavity, beyond what has been already achieved with 2nd generation interferometers.

[7] Teng Zhang, Frequency noise requirement, 3rd Einstein Telescope Annual Meeting ADN conference center, Warsaw https://indico.ego-gw.it/event/764/contributions/7145/

Einstein Telescope design and technologies

Challenging engineering

New technology in cryo-cooling

New technology in optics

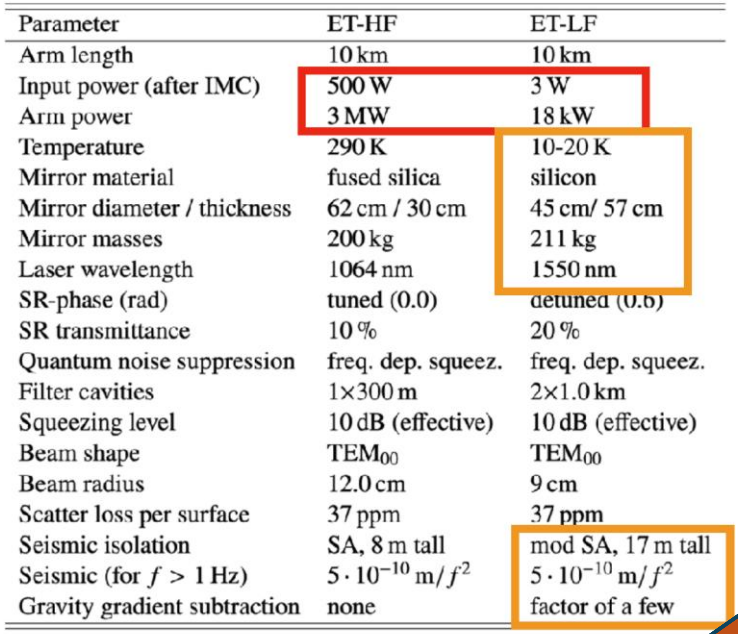
New laser technology

High precision mechanics and low noise controls

High quality opto-electronics and new controls

The multi-interferometer approach asks for two parallel technology developments:

- **ET-LF**:
  - Underground
  - Cryogenics
  - Silicon (Sapphire) test masses
  - Large test masses
  - New coatings
  - New laser wavelength
  - Seismic suspensions
  - Frequency dependent squeezing



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

- **ET-HF**:
  - High power laser
  - Large test masses
  - New coatings
  - Thermal compensation
  - Frequency dependent squeezing

Evolved laser technology

Evolved technology in optics

Highly innovative adaptive optics

High quality opto-electronics and new controls

ET Observational Science in a nutshell

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**
  - multiband GW detection (LISA)
  - joint GW/EM observations (GRB, kilonova,...)
  - 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 accreting on compact objects
- **Dark energy and modifications of gravity on cosmological scales**
  - dark energy equation of state
  - modified GW propagation
- **Stochastic backgrounds of cosmological origin**
  - inflation, phase transitions, cosmic strings

Conclusions

- The discovery of gravitational waves has opened a new window on the universe, launching a new era of astronomy.
- Based on the experience of current detectors, next-generation observatories with higher sensitivity in the same frequency band are being planned: Einstein Telescope (EU) and Cosmic Explorer (US) with similar challenges but some notable differences in key aspects
- Handling the frequency noise for the third generation Interferometers will not be an easy task. The needed architecture will grow in complexity (no CARM, 2 IMCs, 1 PDH-MC) and heavy mirrors with better coating will be required in the IMC cavities.

- However, despite the huge leap required from the Instrument Science development, the scientific return of the 3rd generation is of paramount importance and deserves the effort

Thank you

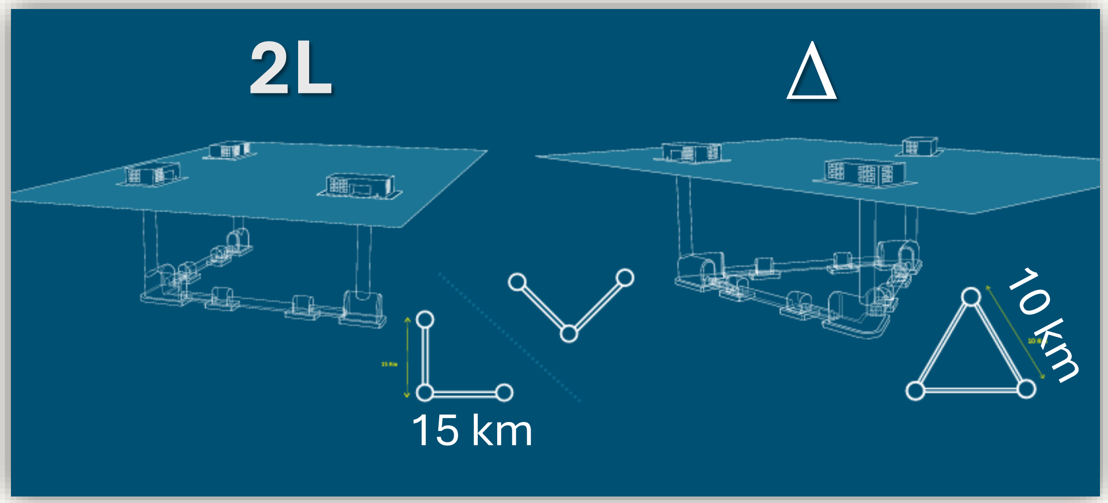
Spare slides

ET science case: Δ or (two) L

- Since 2011 (CDS, triangle configuration) the situation drastically changed:
  - First detections, GTWC-3 catalog ⟶ BH population ⟶ new evolution models;
  - Science case developed;
  - Know-how with advanced (L) detectors;
  - International scenario (+ Cosmic Explorer in US)
- The Collaboration is analyzing both configurations: optimizing science return, differential risk assessment.
  - First results on the science return published in Marica Branchesi et al JCAP07(2023)068: https://doi.org/10.1088/1475-7516/2023/07/068

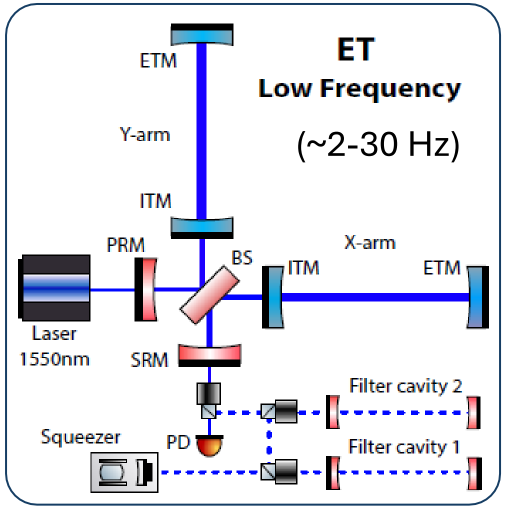
A preliminary differential risk analysis, provided by a specific committee, shown that for integration, commissioning, data taking and upgrade activities, the L geometry has a lower risk level

In the last two of years, the collaboration started the evaluation of the best configuration for ET, considering the alternative of two L configuration (as LIGO, Cosmic Explorer) to maximize the science return and reduce risks.

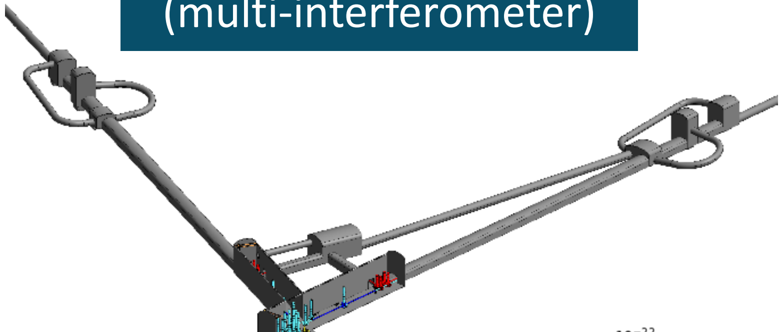


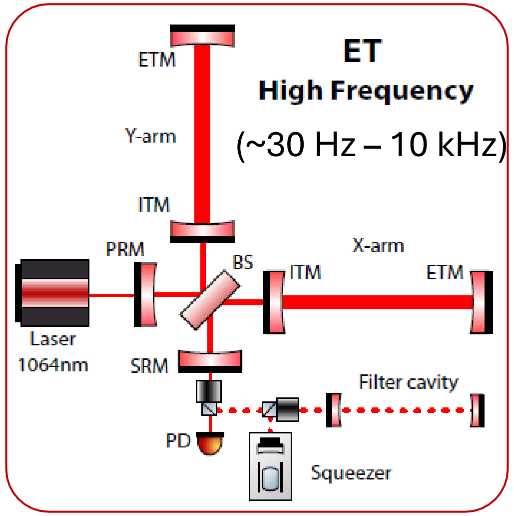
The 2L 15 km geometry shows an improved science return in most of the science targets, improving by factors 2-3 on the errors of relevant parameters

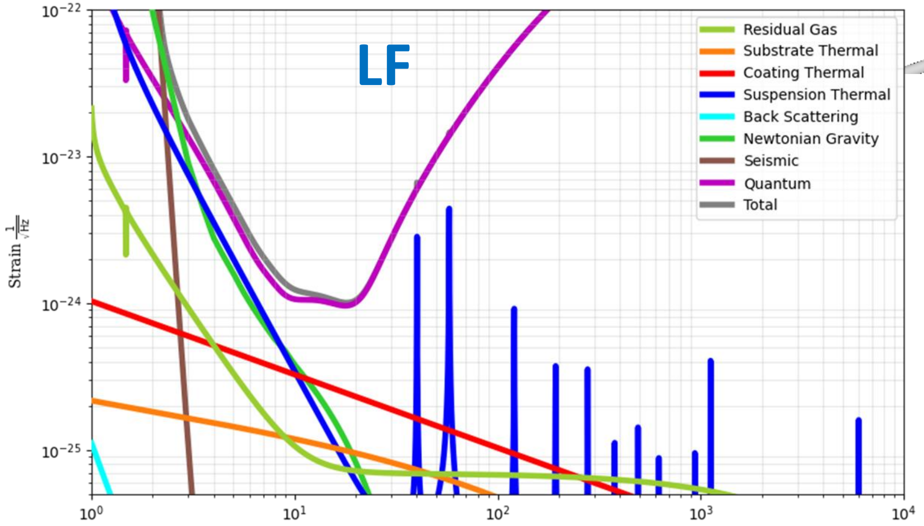
ET design: Xylophone configuration



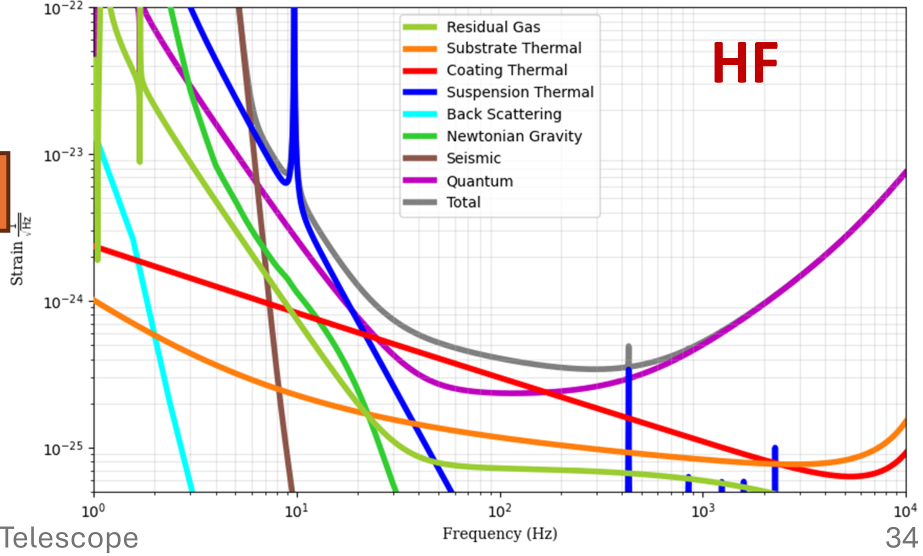
Xylophone configuration (multi-interferometer)



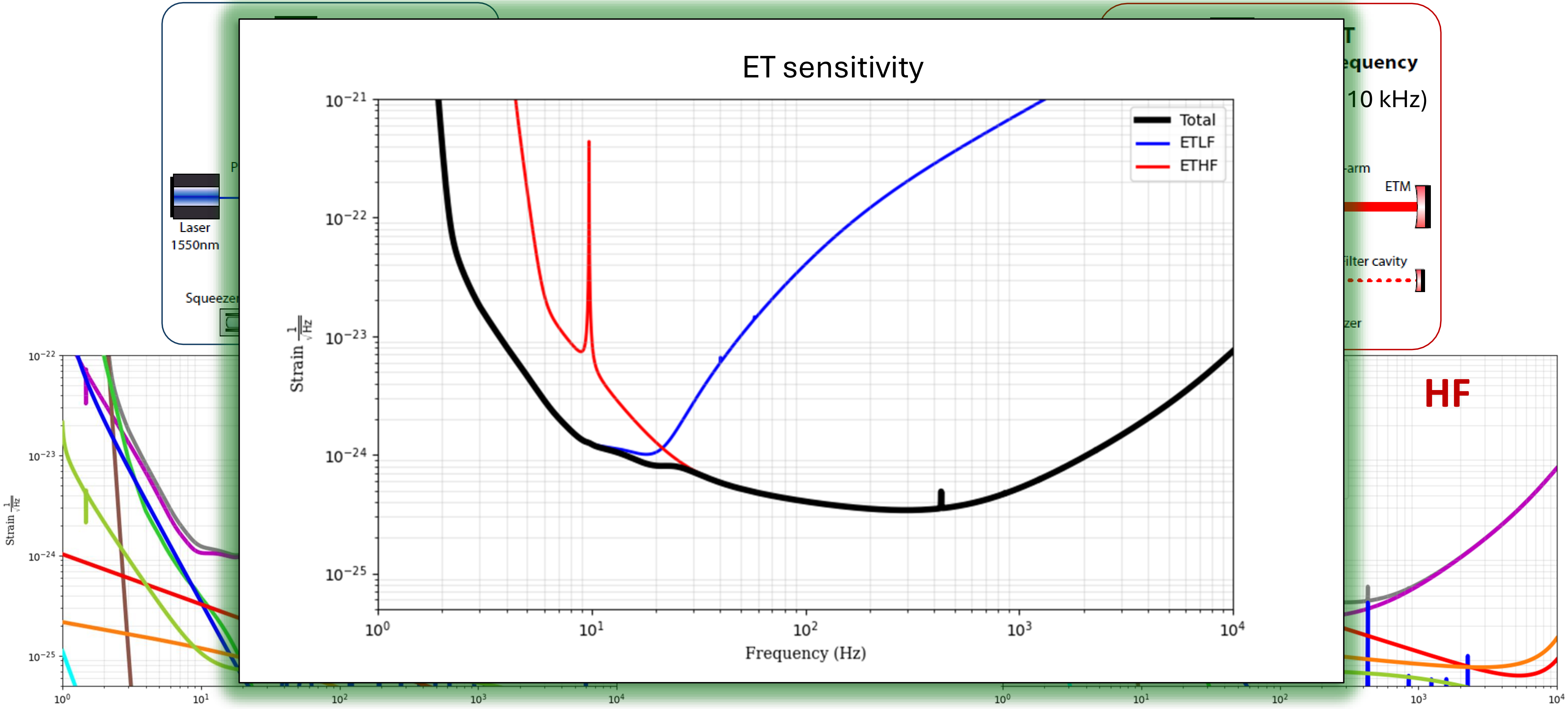




Underground

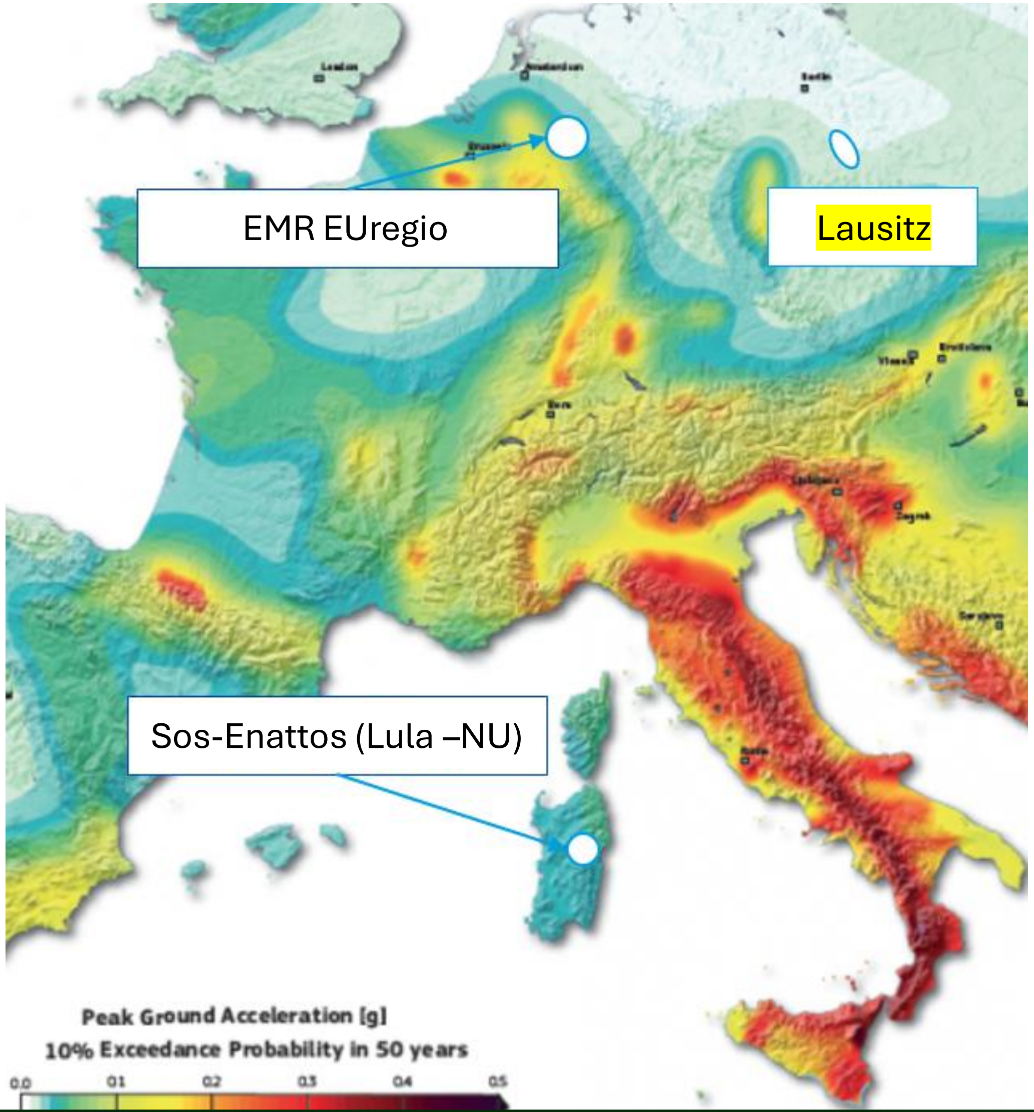


Xilophone configuration



ET candidate sites

- Two sites formally candidate to host ET:
  - EMR EUregio, border region between Nederland, Belgium and Germany
  - Sardinia (Lula area, Barbagia)
- A third potential site, located in Saxony (Lausitz), is now proposed
- Overall site evaluation is a complex task depending on:
  - Detector performance
  - Geophysical and environmental quality
  - Financial and organization aspects
  - Services, infrastructures



Decision about the location expected by 2026