Virgo
and
Einstein Telescope
experiments

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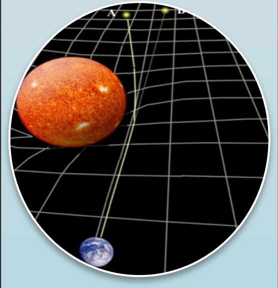
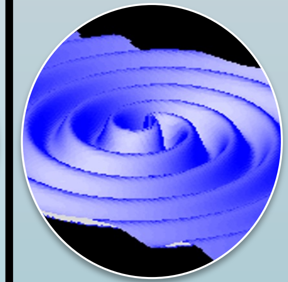
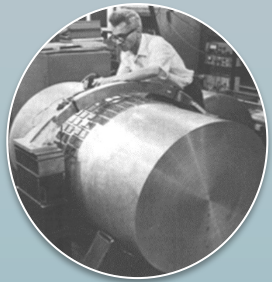
GW: a long history…



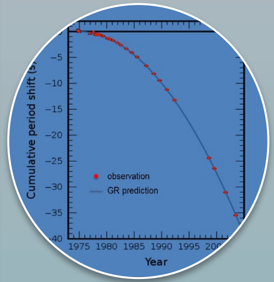
1915
- General Relativity



1916
- Gravitational Waves



1966
- Weber and Resonant Bars

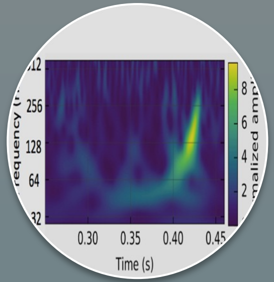


1974
- Hulse-Taylor:Observing the pulsar binary PSR B1913+16

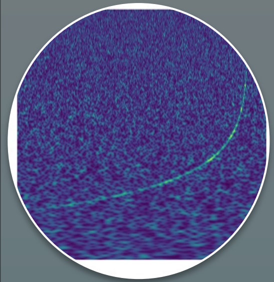
1980-1990
- Cryogenic Resonant Bars

1993
- The approval of Virgo Experiment

1999+
- Data taking from LIGO an Virgo

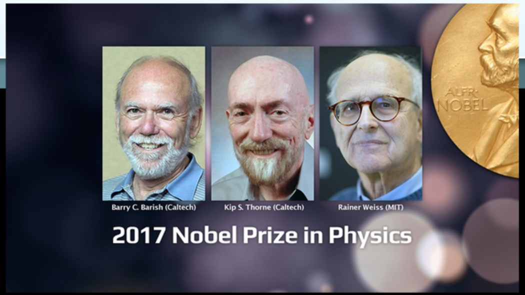


2015
- GW BHBH detection

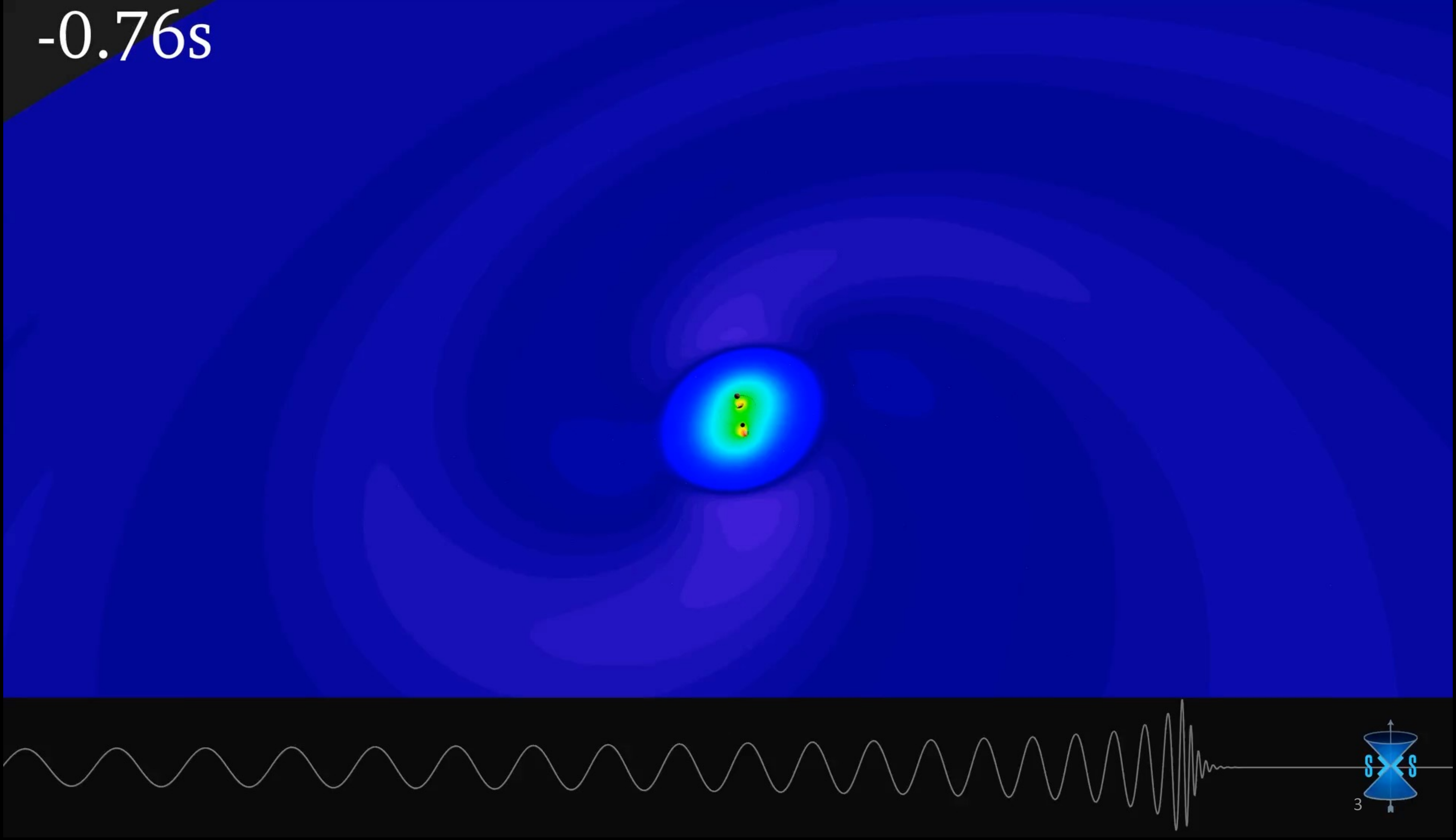


2017
- BNS detection: Multi-messenger Astronomy

~100 years



Credits to E. Cuoco et al.


-0.76s


Scale of Effect Vastly Exaggerated

How small is «small»?

Let’s suppose you pour a glass of beer into the ocean…

What is the rise of the sea-level you get?

That’s the order of magnitude of effect we want to detect!

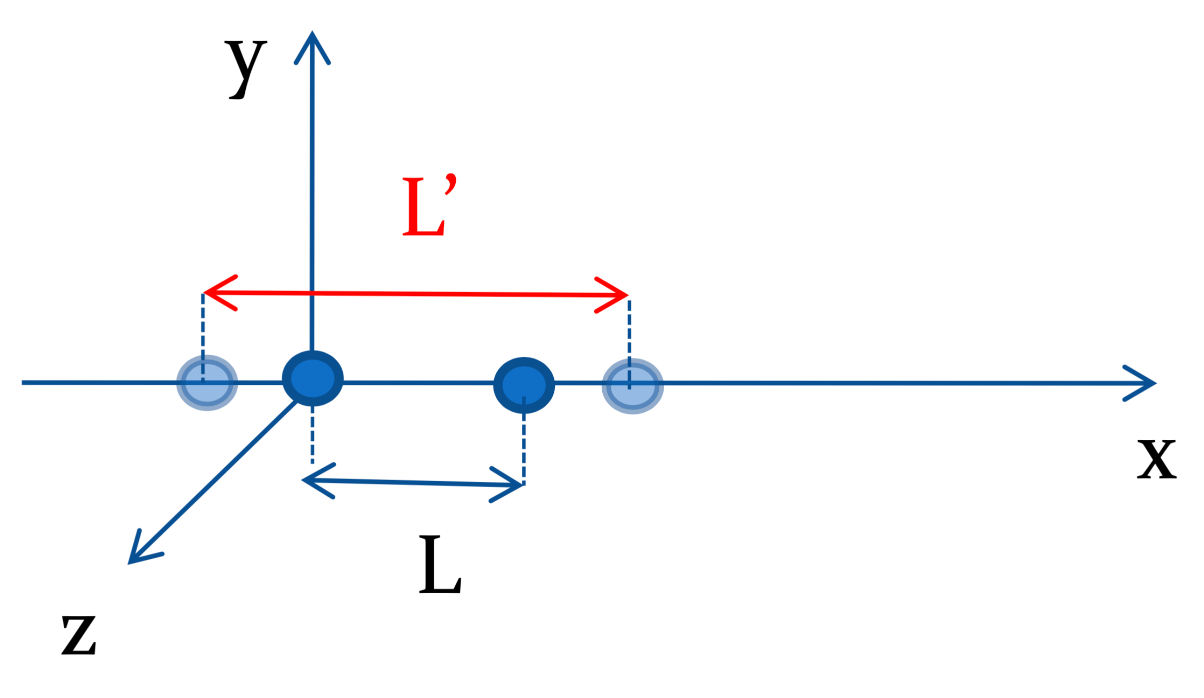
The effect of GW on free-falling masses

$\delta L \propto h \cdot L$

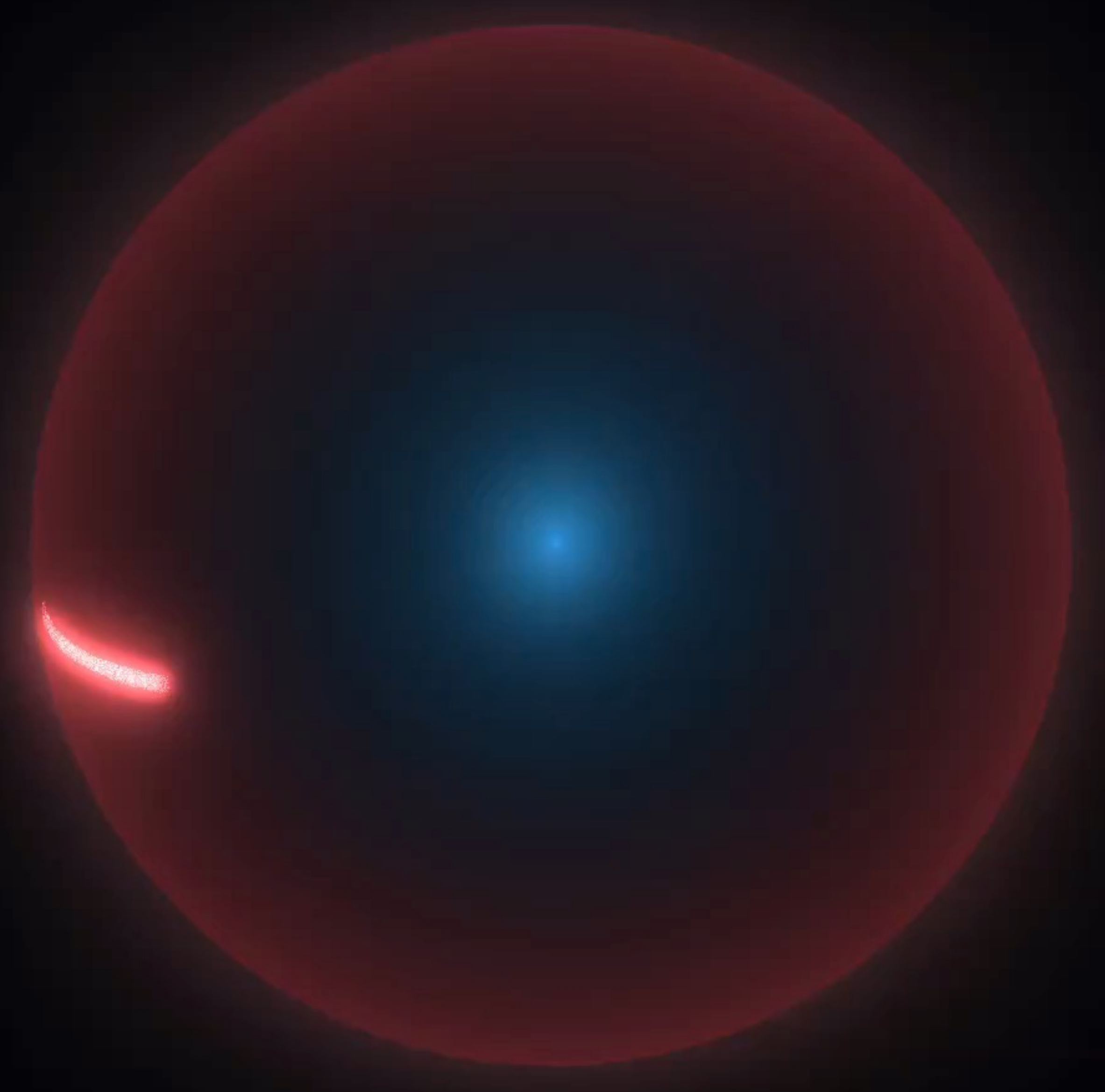
↓

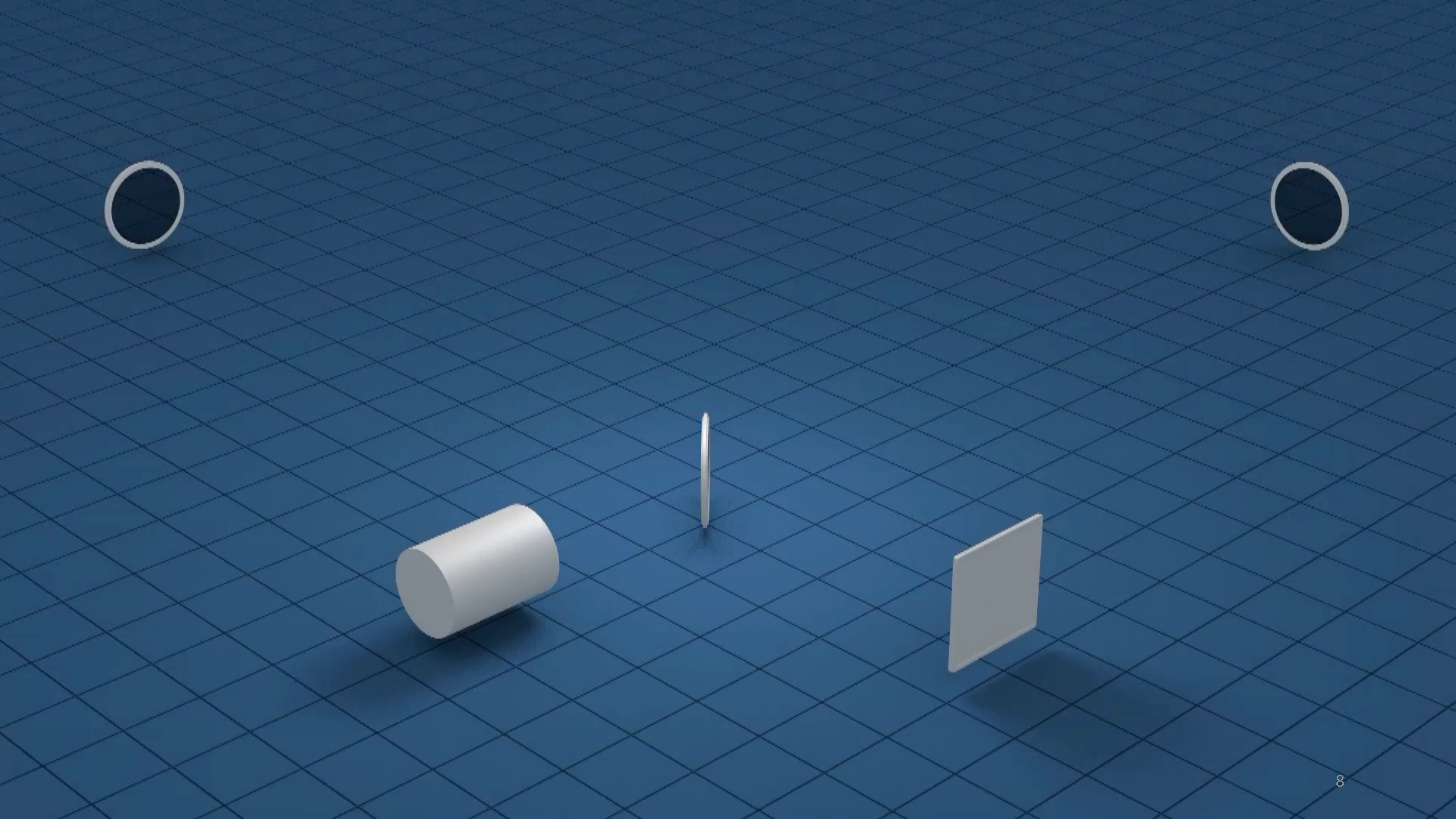
GW amplitude

$h \approx 10^{-21}$



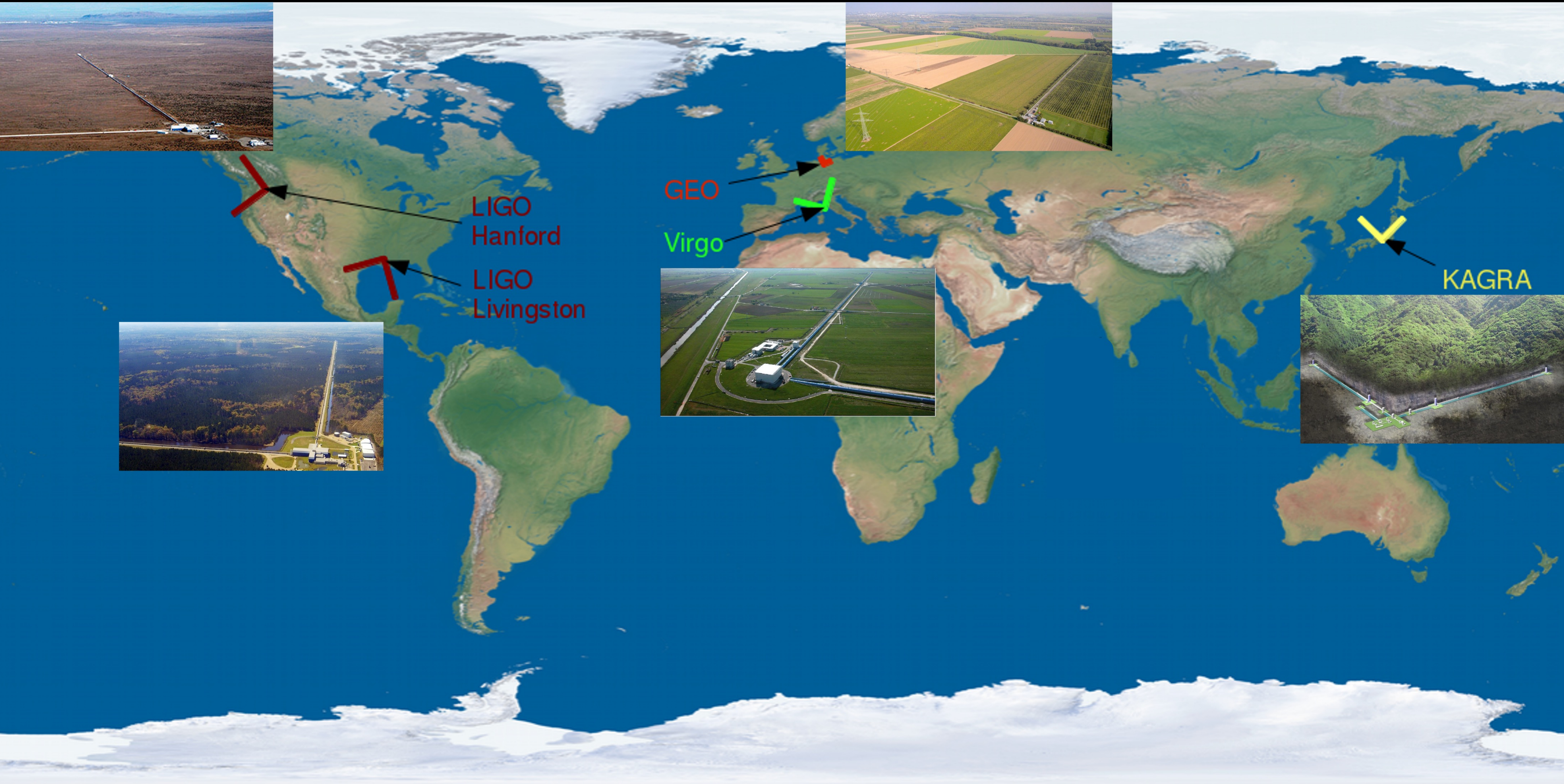
The distance between two free-falling masses separated by a km will change by $\delta L \approx 10^{-18} km$






THORLABS

Gravitational wave interferometers

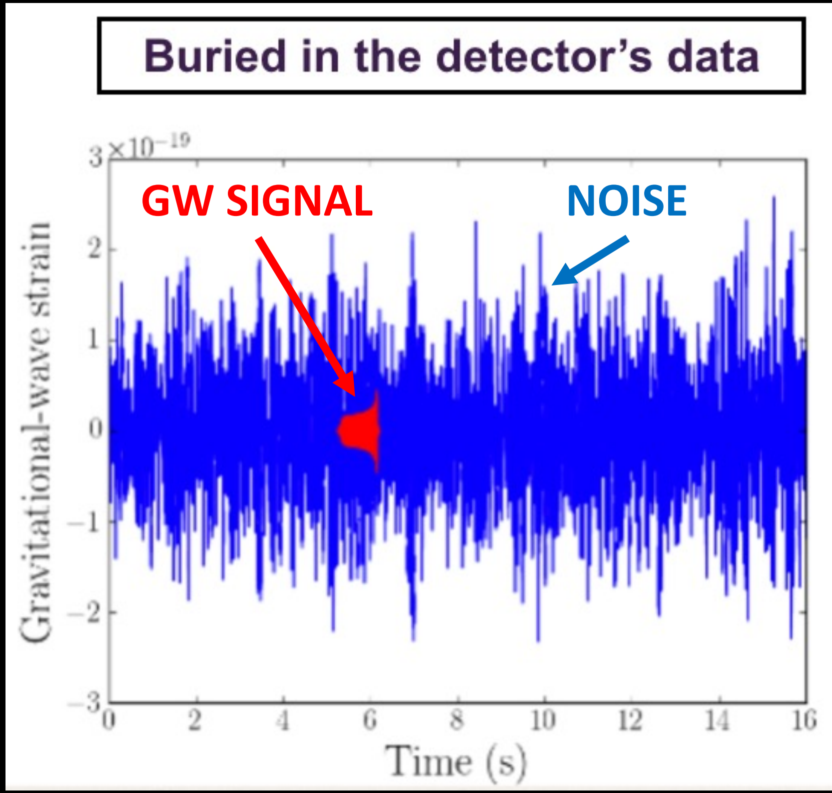


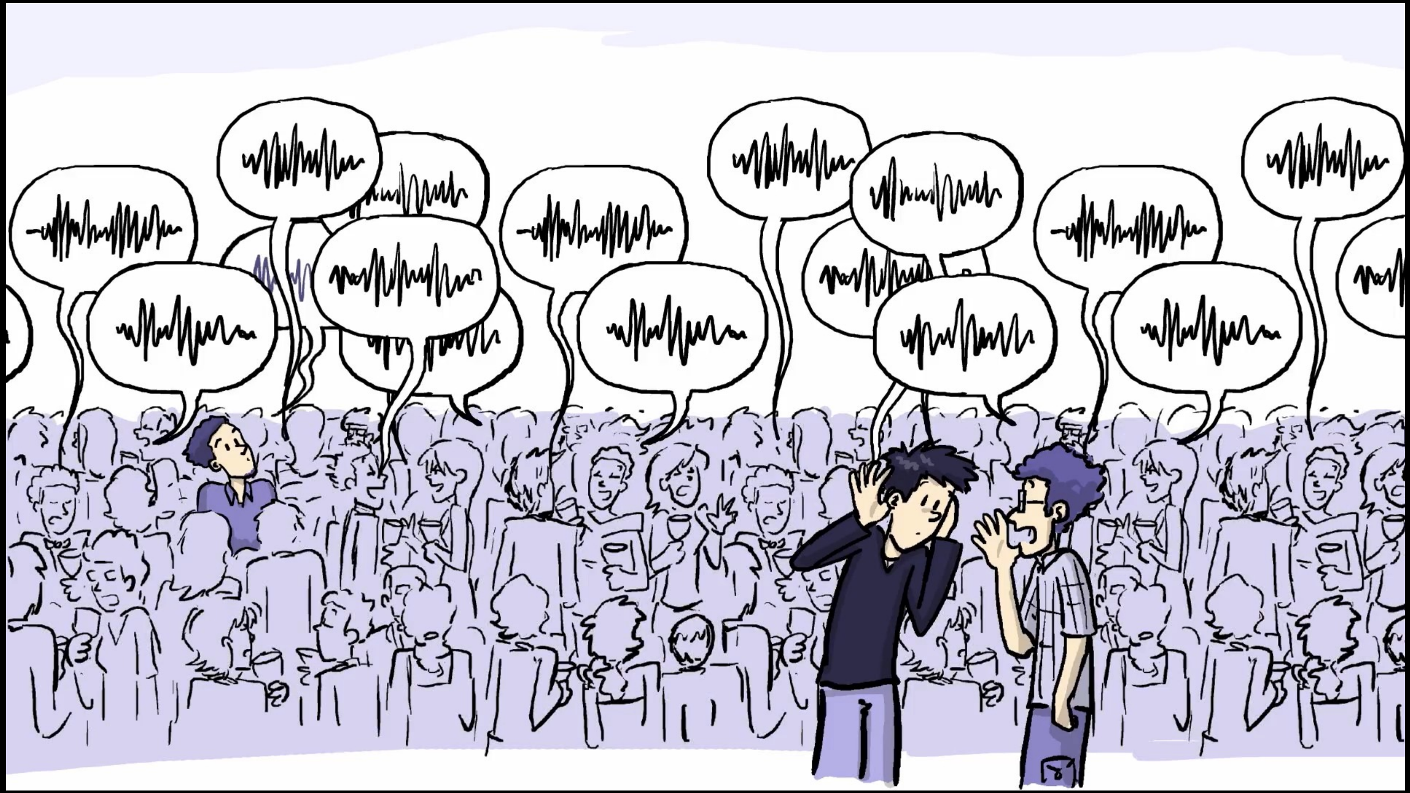
Virgo Collaboration

- ~770 members, ~450 authors, 131 institutions from 15 countries
- 34 Groups:
  - 32 full members
  - 2 in the first year (L2I Toulouse, KU Leuven)
- 9 countries represented in the VSC

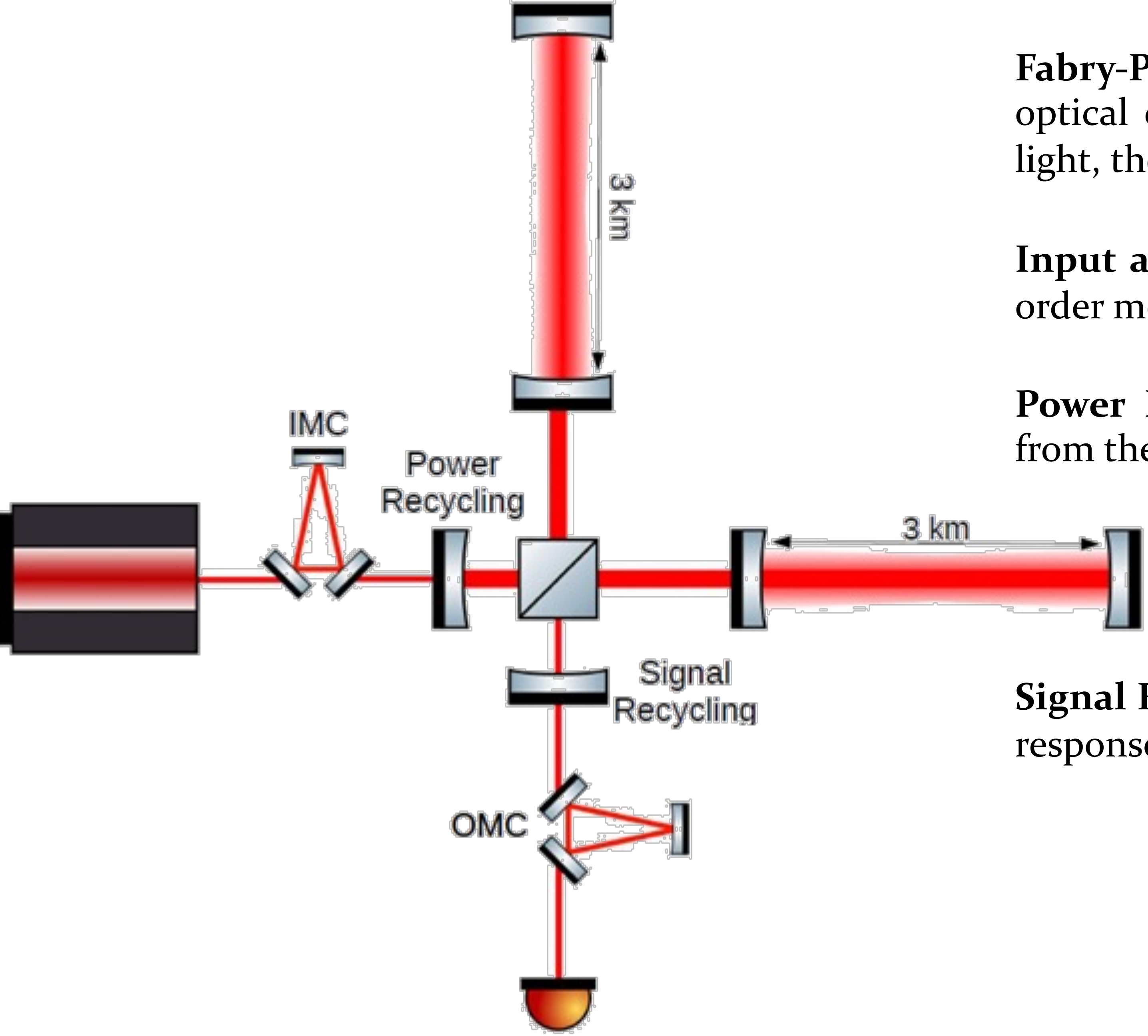
Credits to D. D'Urso et al.

GW DATA ANALYSIS





We need to enhance the signal and reduce the noise



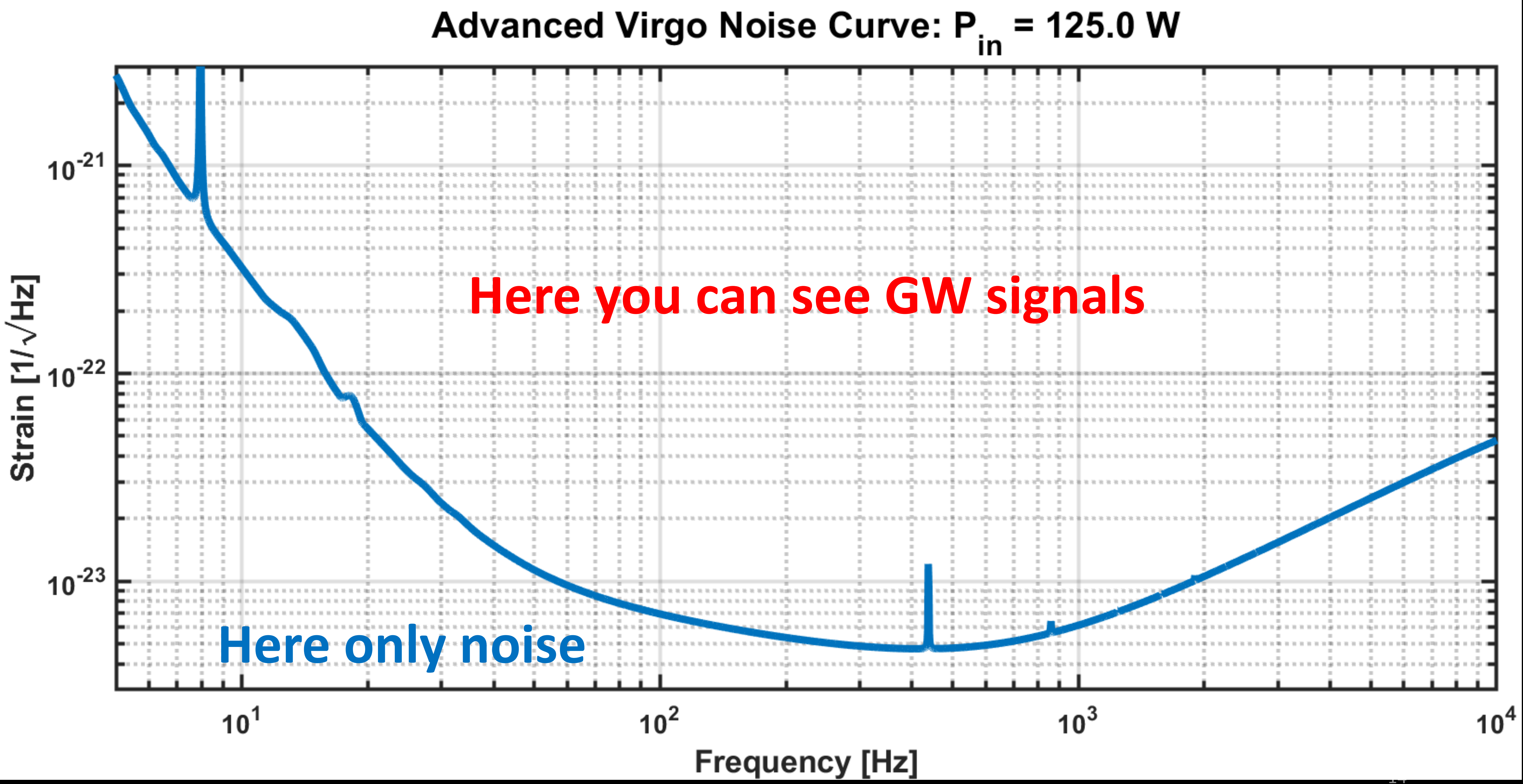
Fabry-Perot cavity for "longer arms": the presence of the optical cavities increases the number of round trip of the light, therefore enhancing the gain of the instrument

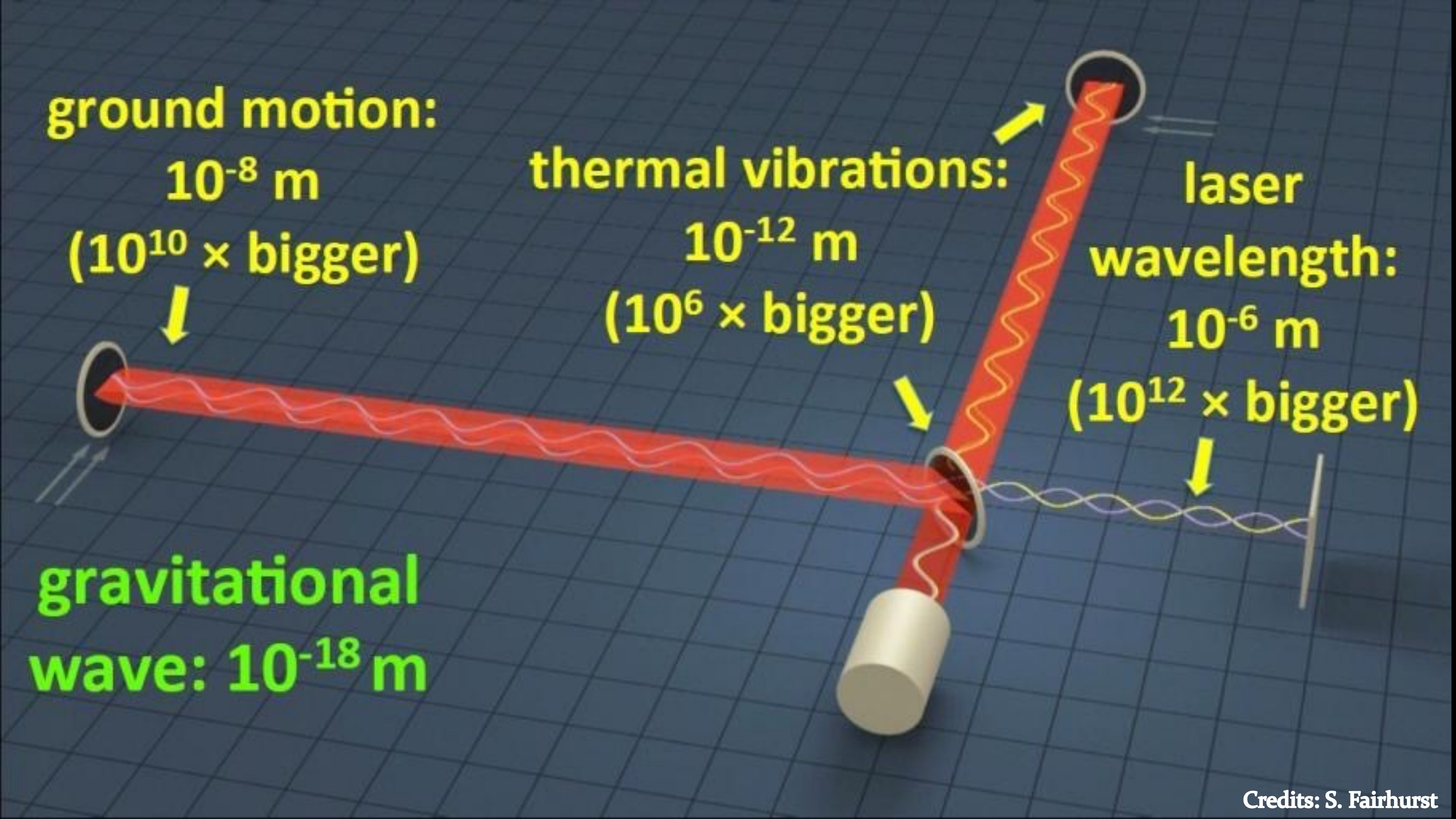
Input and output mode cleaner to reject the laser high-order modes

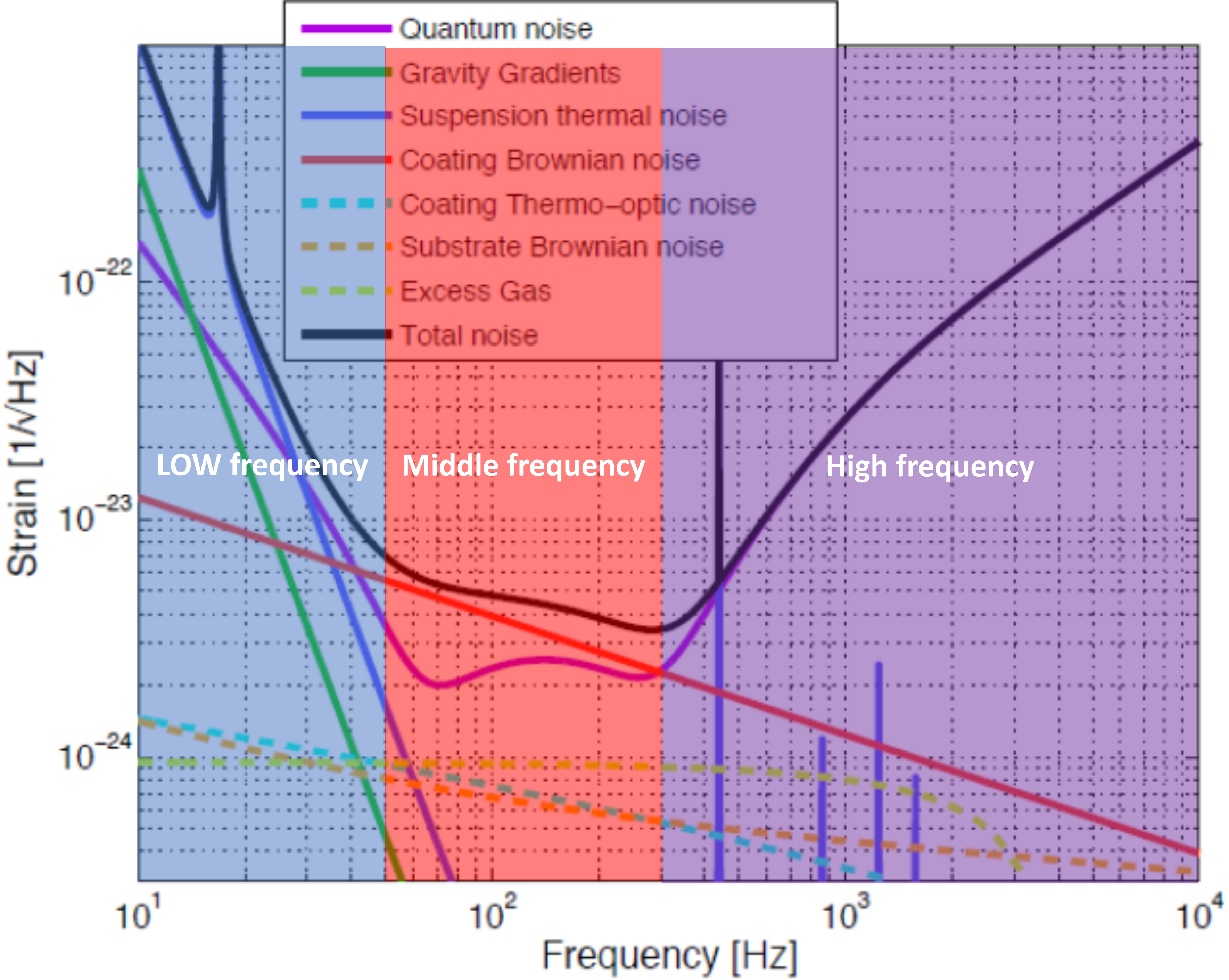
Power Recycling mirror to recover the power reflected from the arms and increase the optical power (***PR***)

Signal Recycling mirror to reshape the detector frequency response

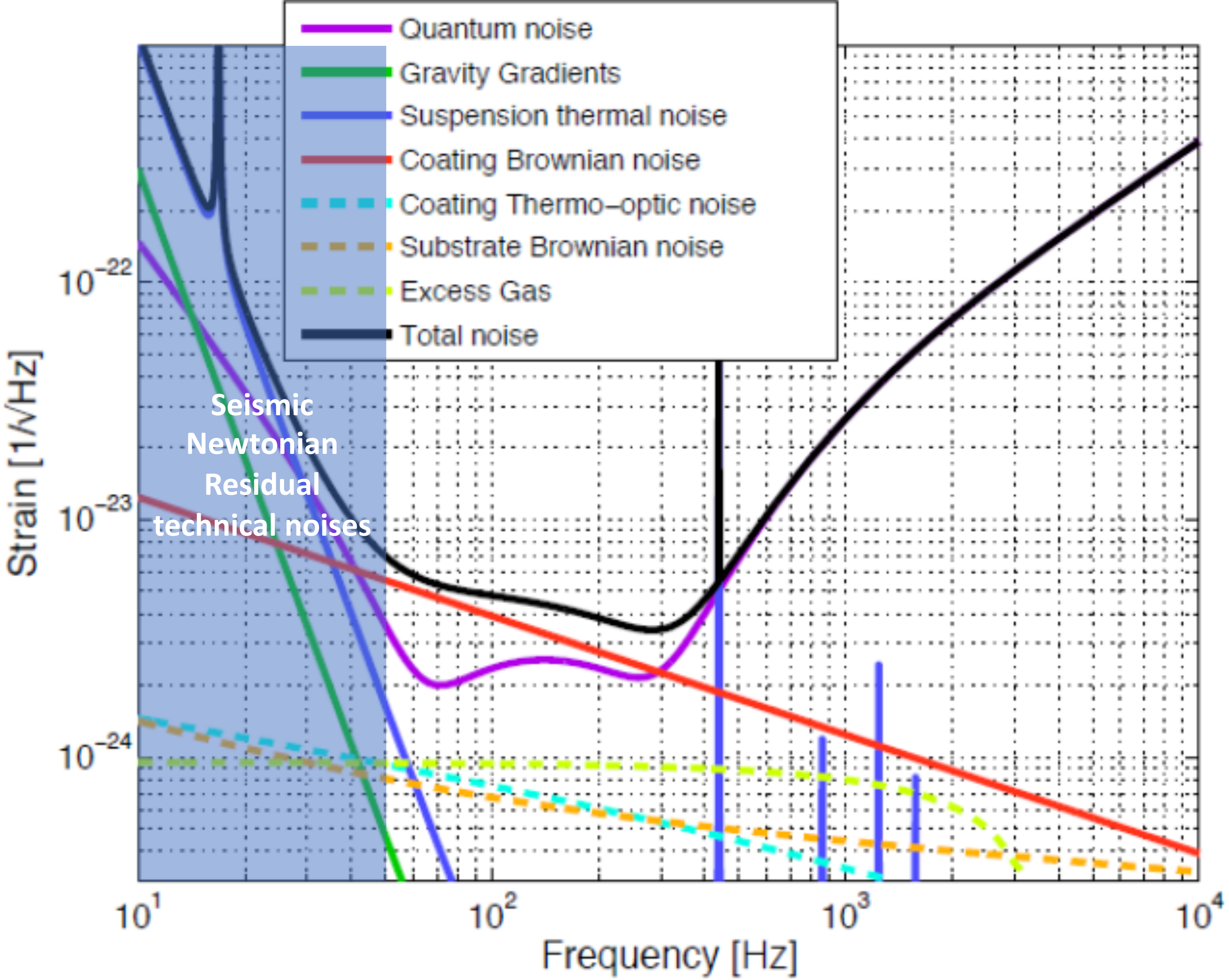
Enhance the signal


Advanced Virgo Noise Curve: P_{in} = 125.0 W
Here you can see GW signals
Here only noise
Strain [1/√Hz]
10^{-21}
10^{-22}
10^{-23}
Frequency [Hz]
10^{1}
10^{2}
10^{3}
10^{4}


ground motion:
10-8 m
(1010 × bigger)
thermal vibrations:
10-12 m
(106 × bigger)
laser
wavelength:
10-6 m
(1012 × bigger)
gravitational
wave: 10-18 m
Credits: S. Fairhurst

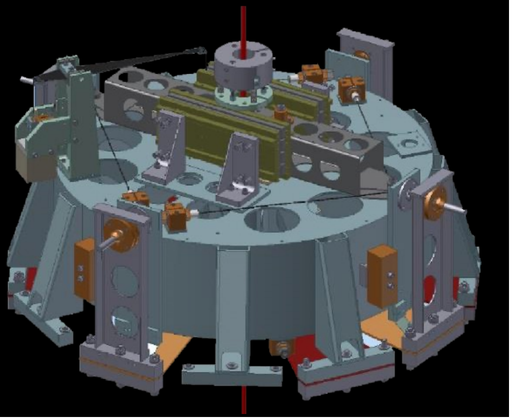


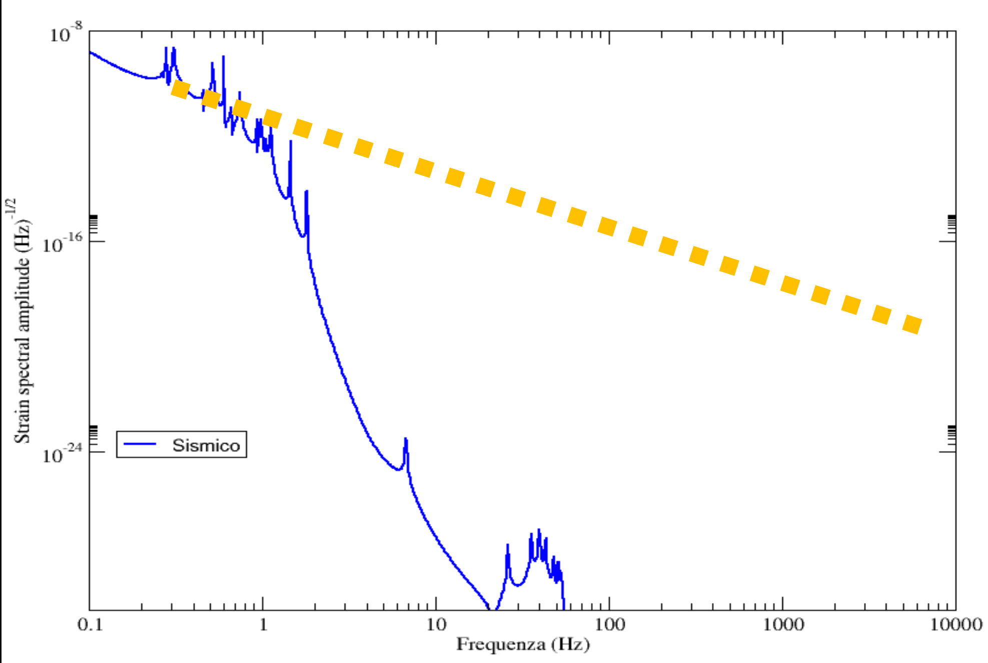
Quantum noise
Gravity Gradients
Suspension thermal noise
Coating Brownian noise
Coating Thermo–optic noise
Substrate Brownian noise
Excess Gas
Total noise
LOW frequency
Middle frequency
High frequency
10^{-22}
10^{-23}
10^{-24}
Strain [1/√Hz]
10^{1}
10^{2}
10^{3}
10^{4}
Frequency [Hz]

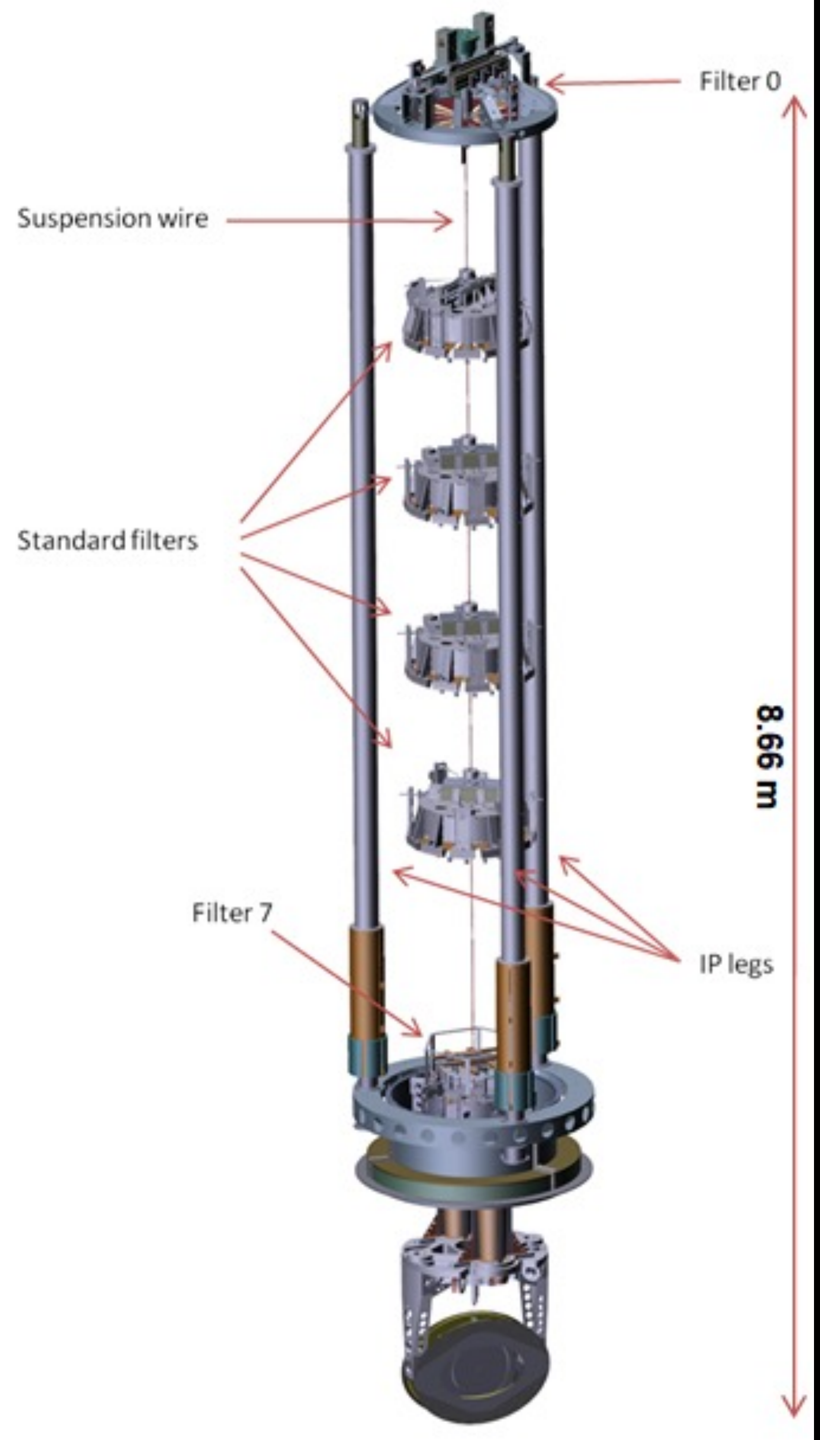

Quantum noise
Gravity Gradients
Suspension thermal noise
Coating Brownian noise
Coating Thermo–optic noise
Substrate Brownian noise
Excess Gas
Total noise
Seismic
Newtonian
Residual
technical noises
Strain [1/√Hz]
10^{-22}
10^{-23}
10^{-24}
10^{1}
10^{2}
10^{3}
10^{4}
Frequency [Hz]

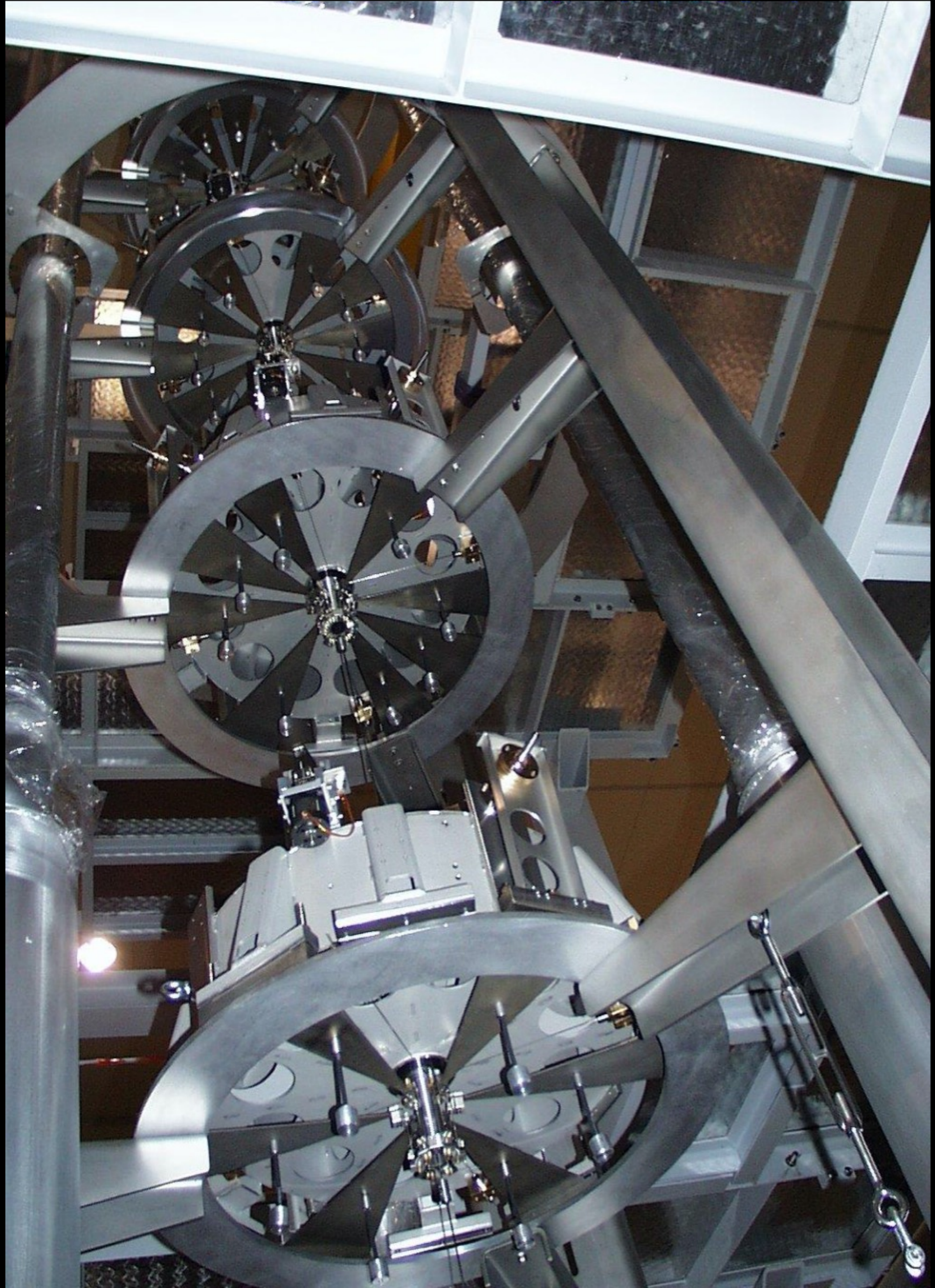
Reducing seismic noise:

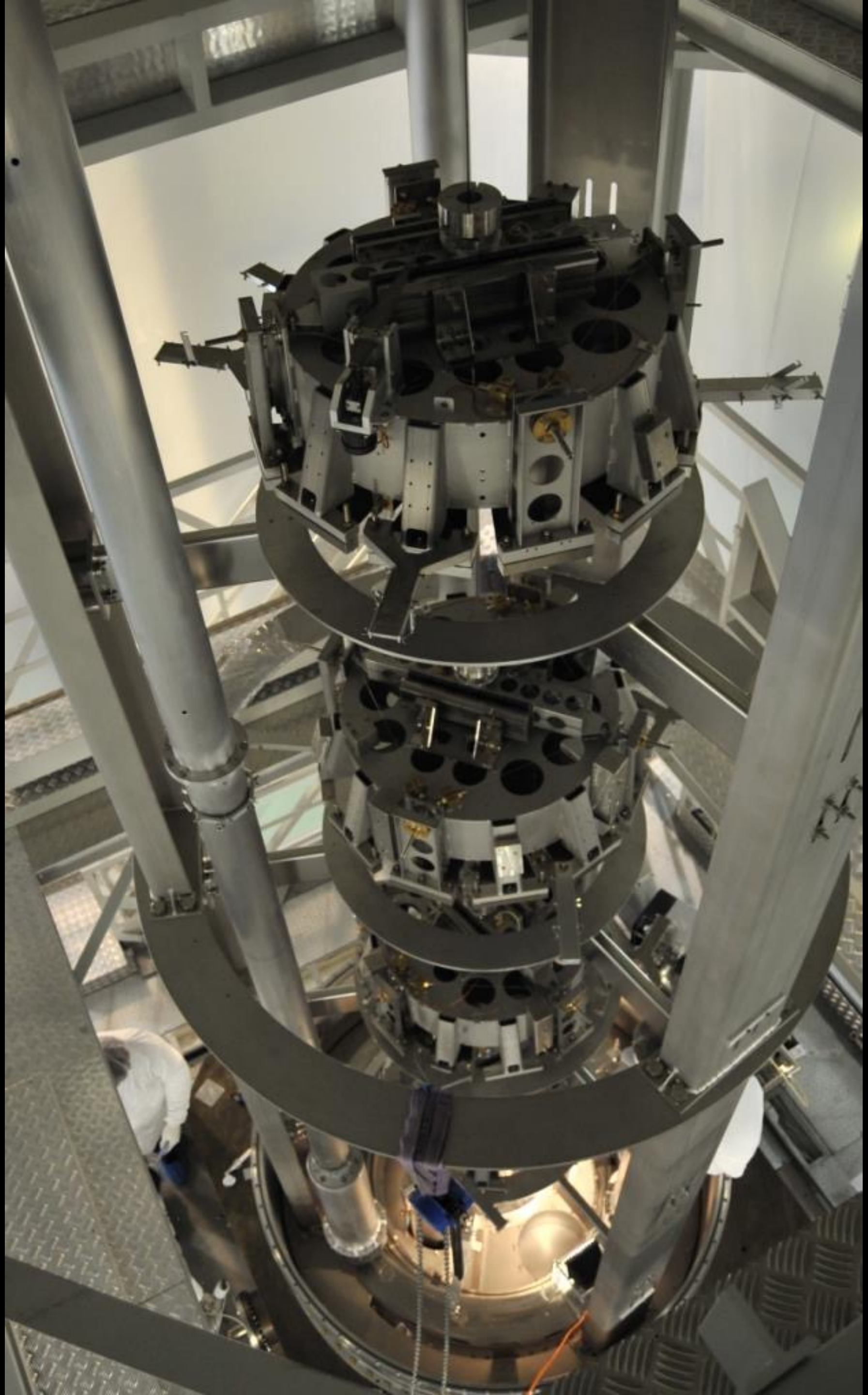
- **Choose a good location**
- **Superattenuator to reduce seismic vibration: reduces mirrors seismic vibration by a factor 10^{12}**





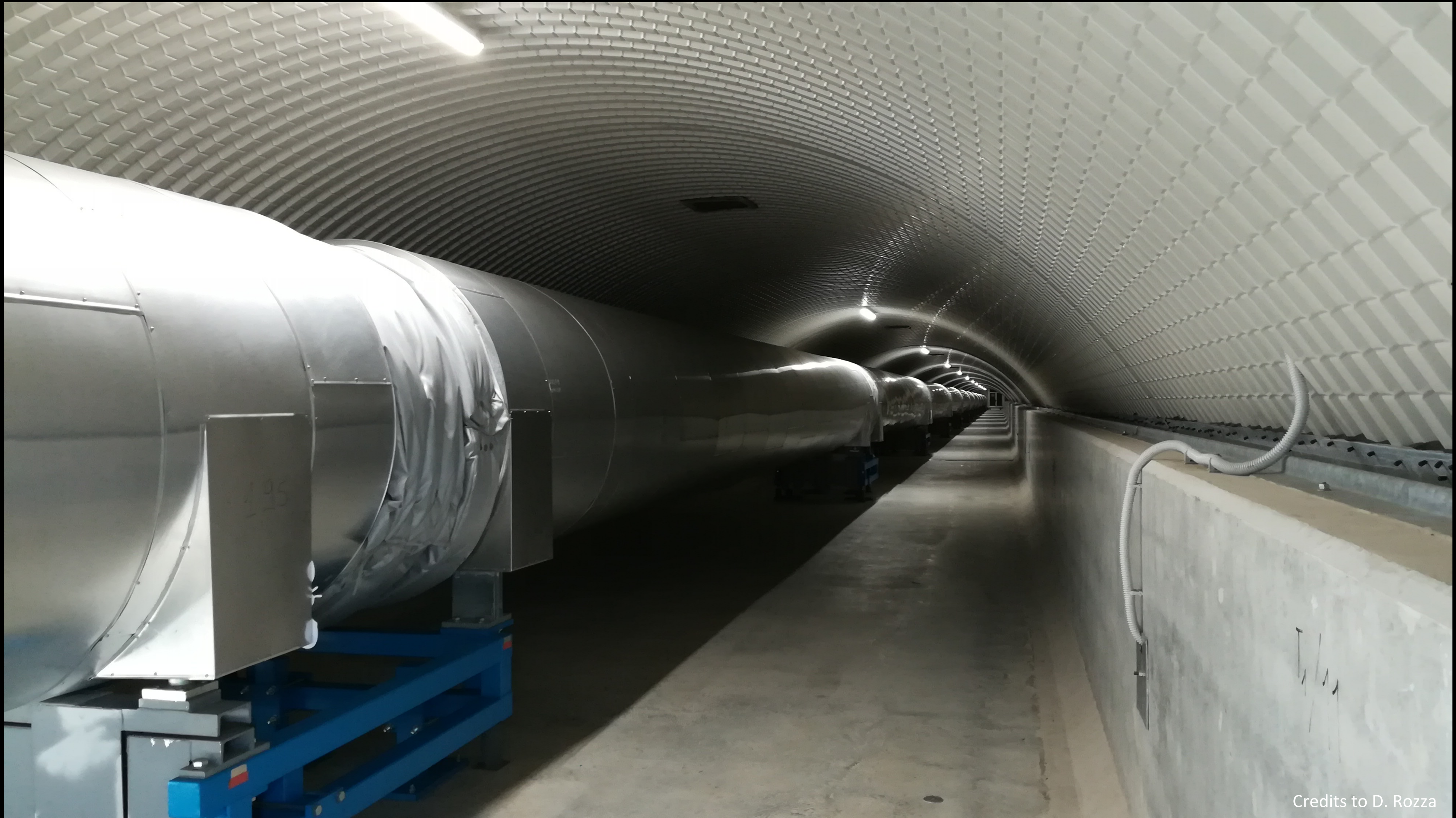






Reducing seismic noise:

- **Ultra high vacuum:**
  7000 m^3 @ pressure of 10^{-9} mbar
  The biggest ultra-high-vacuum system in Europe



Credits to D. Rozza

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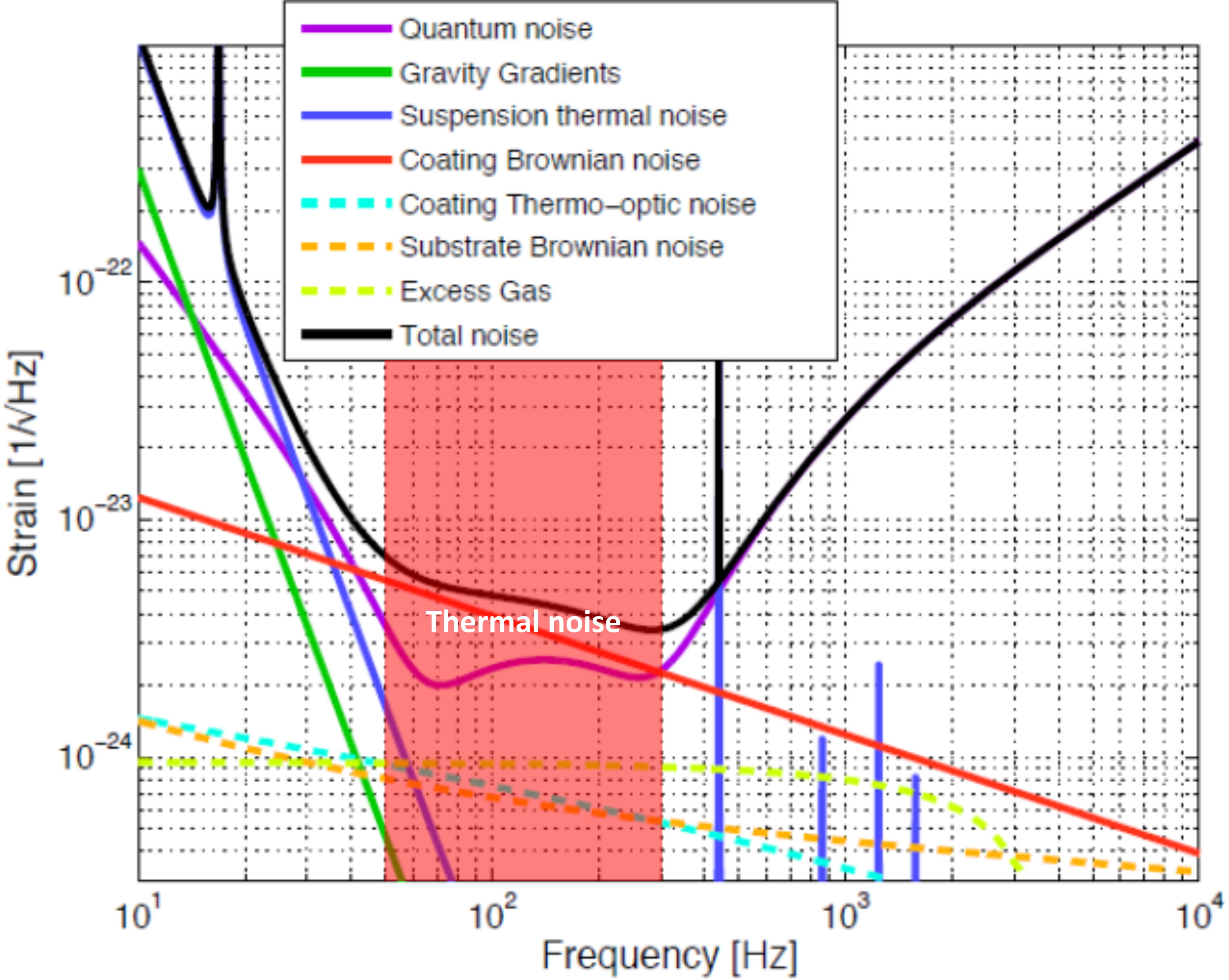
Credits to D. Rozza

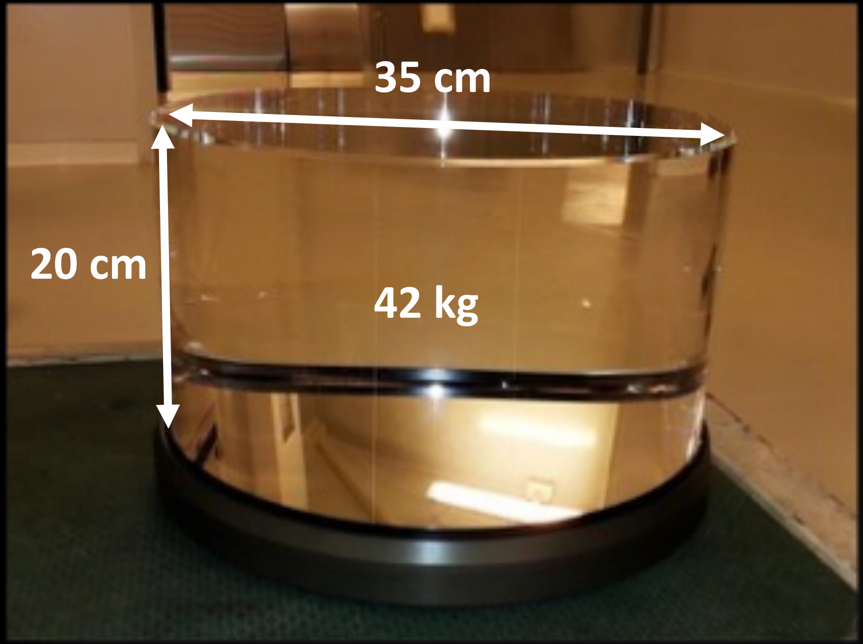


Quantum noise
Gravity Gradients
Suspension thermal noise
Coating Brownian noise
Coating Thermo–optic noise
Substrate Brownian noise
Excess Gas
Total noise
Thermal noise
Strain [1/√Hz]
10^−22
10^−23
10^−24
10^1
10^2
10^3
10^4
Frequency [Hz]

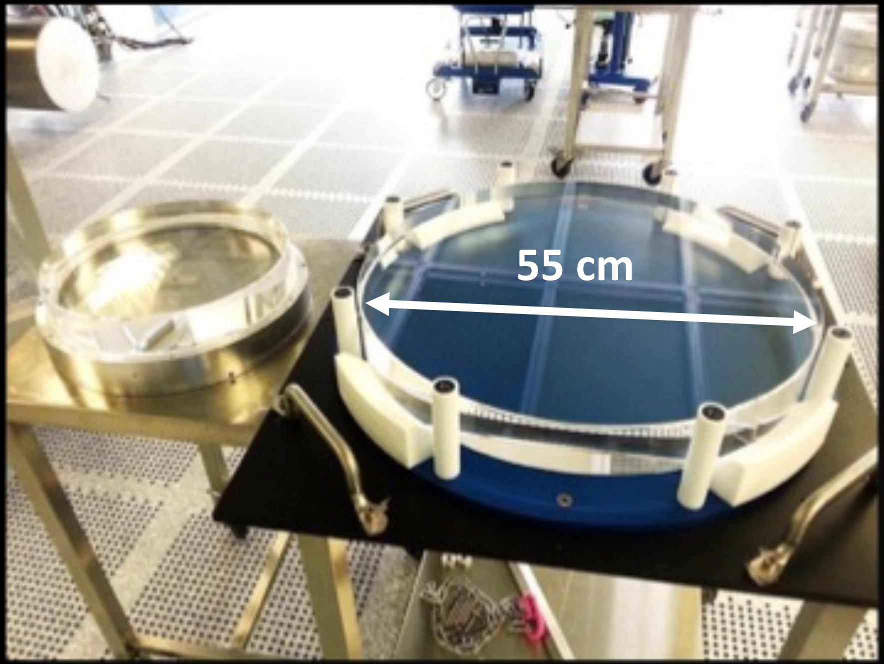
Reducing thermal noise:

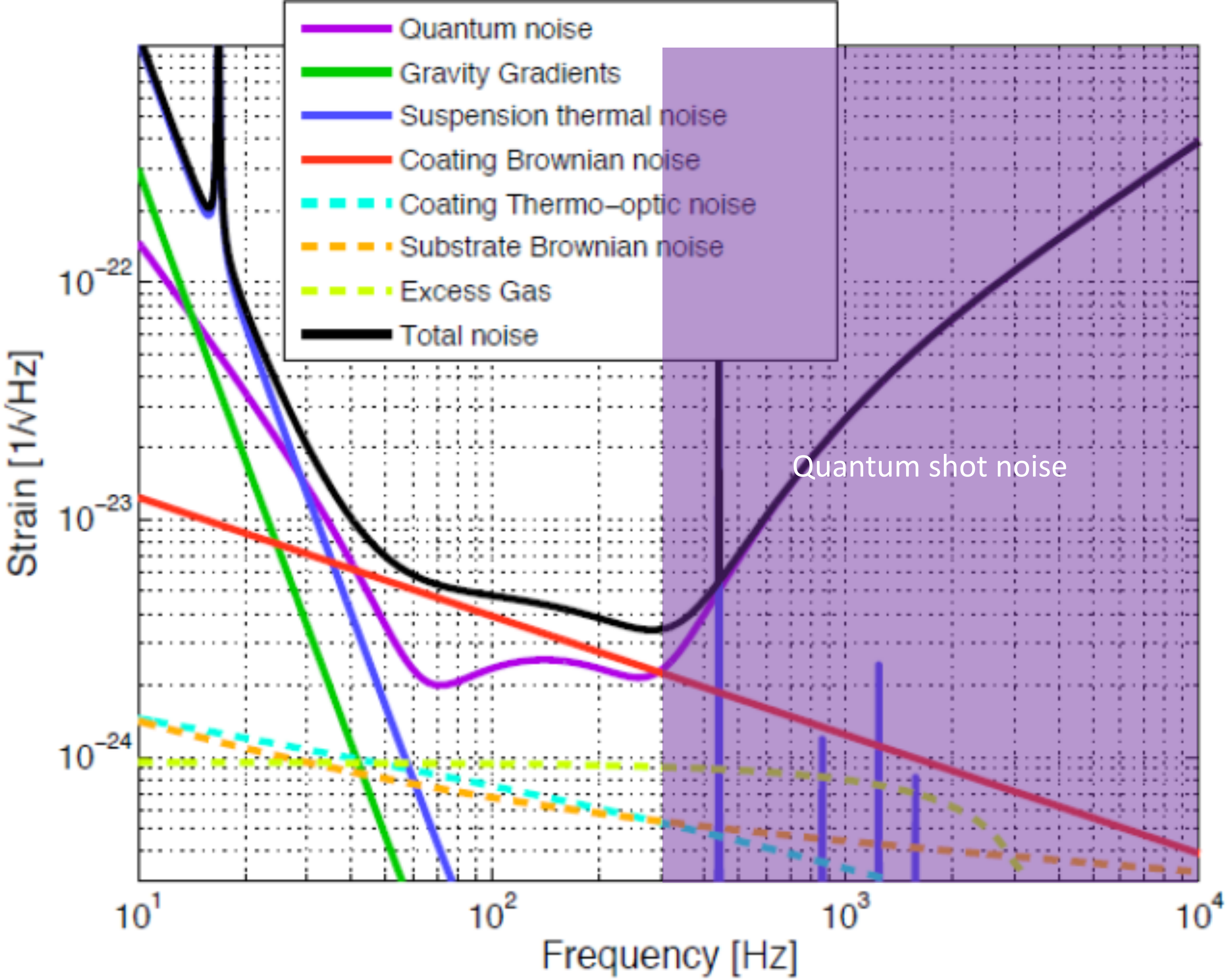
- **Beam size as large as possible**
- **Coating techniques to reduce the losses**
- **SiO_2 monolithic suspensions 400 μm**
- **Mirrors of 42 kg in weight to reduce the effect of the radiation pressure**
- **SiO_2 mirrors with a residual roughness < 0.5 nm**

Test mass mirrors



Beam splitter mirror

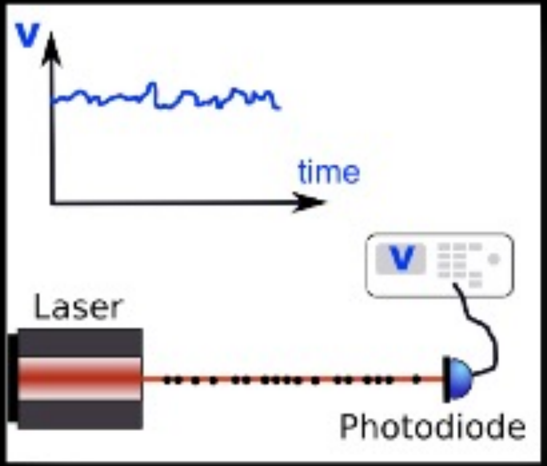



Quantum noise
Gravity Gradients
Suspension thermal noise
Coating Brownian noise
Coating Thermo–optic noise
Substrate Brownian noise
Excess Gas
Total noise
Quantum shot noise
Strain [1/√Hz]
10^{-22}
10^{-23}
10^{-24}
10^{1}
10^{2}
10^{3}
10^{4}
Frequency [Hz]

Reducing quantum noise:

- **Increased finesse of arm cavity**
- **High power laser**
- **Squeezing technique**

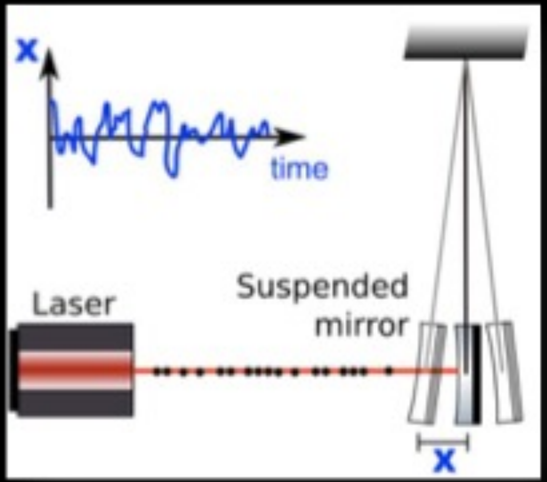
Shot noise: photon counting noise



$$h_{shot} \propto \frac{1}{L}\sqrt{\frac{1}{P}}$$

P = Power

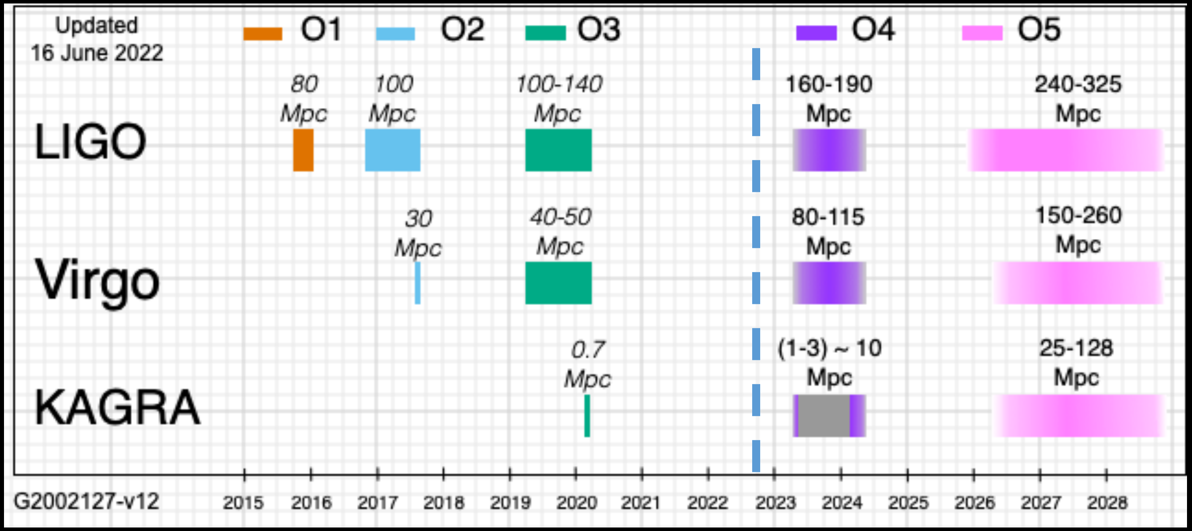
Radiation pressure noise: Photons fluctuations translate in radiation pressure fluctuations, giving rise to random motion of the mirrors



$$h_{rad} \propto \frac{1}{f^2 L}\frac{\sqrt{P}}{m}$$

Credits to D. Rozza

Gravitational wave events

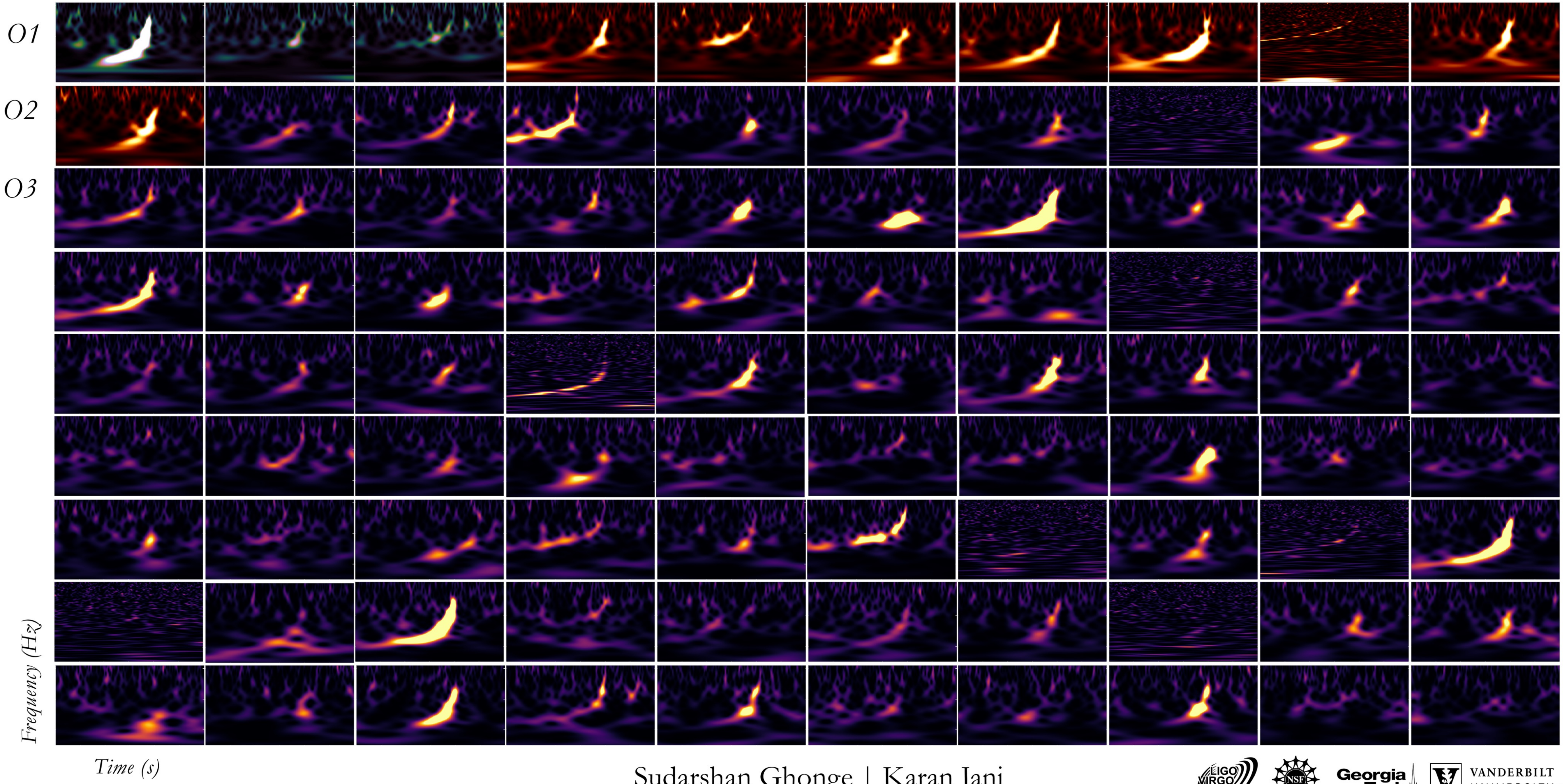


- Advanced LIGO and Advanced Virgo have completed the third observing run and are being upgraded toward LIGO A+ and AdV+ operations (O4: 2023-2024 – O5: 2026-2028)
- Further upgrades are being planned for post-O5

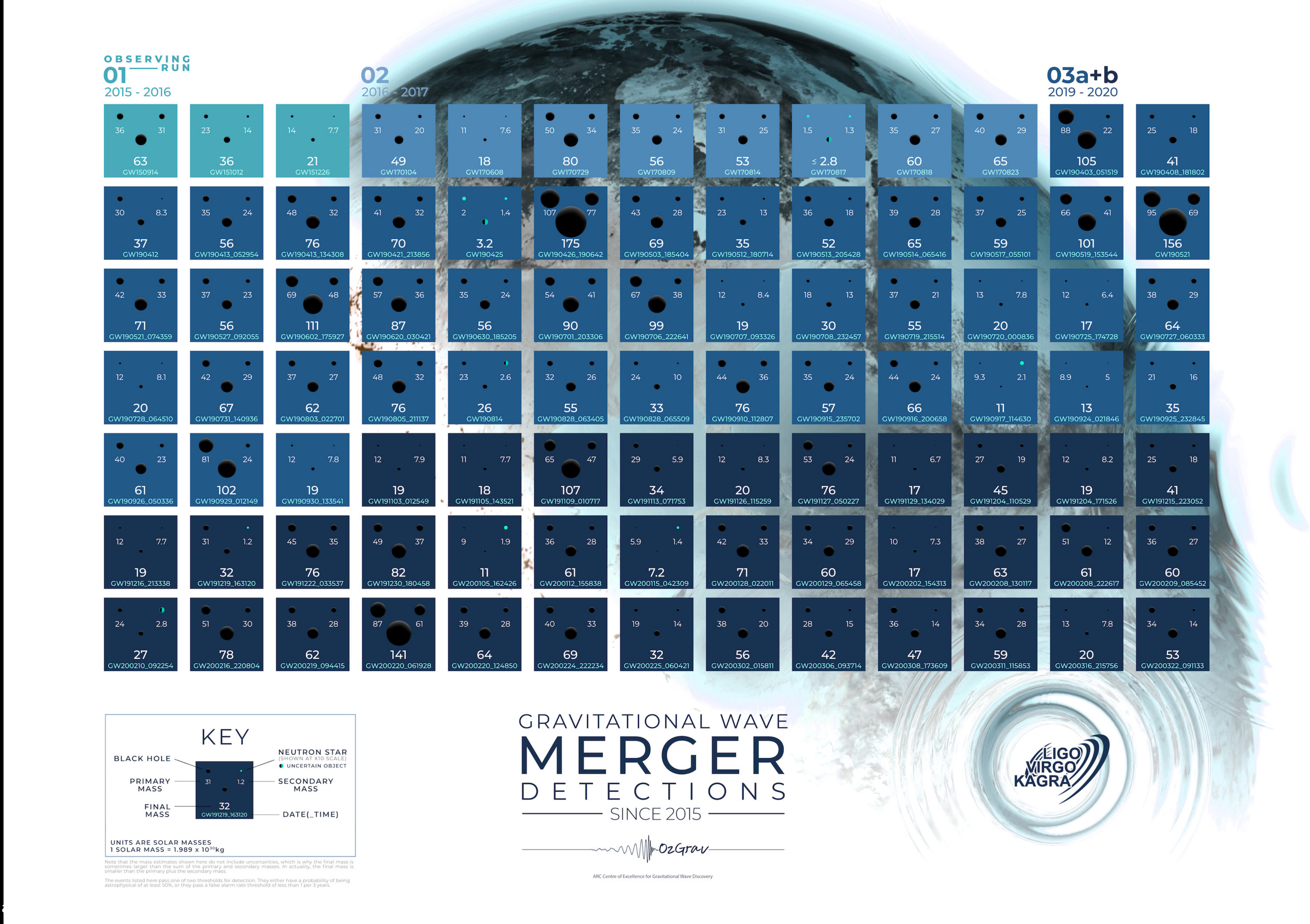
GW150914
GW151012
GW151226
GW170104
GW170608
GW170729
GW170809
GW170814
GW170817
GW170818
GW170823
GW190403_051519
GW190408_181802
GW190412
GW190413_052954
GW190413_134308
GW190421_213856
GW190425
GW190426_190642
GW190503_185404
GW190512_180714
GW190513_205428
GW190514_065416
GW190517_055101
GW190519_153544
GW190521
GW190521_074359
GW190527_092055
GW190602_175927
GW190620_030421
GW190630_185205
GW190701_203306
GW190706_222641
GW190707_093326
GW190719_215514
GW190720_000836
GW190725_174728
GW190727_060333
GW190728_064510
GW190731_140936
GW190803_022701
GW190805_211137
GW190814
GW190828_063405
GW190828_065509
GW190910_112807
GW190915_235702
GW190916_200658
GW190917_114630
GW190924_021846
GW190925_232845
GW190926_050336
GW190929_012149
GW190930_133541
GW191103_012549
GW191105_143521
GW191109_010717
GW191113_071753
GW191126_115259
GW191127_050227
GW191129_134029
GW191204_110529
GW191204_171526
GW191215_223052
GW191216_213338
GW191219_163120
GW191222_033537
GW191230_180458
GW200112_155838
GW200115_042309
GW200128_022011
GW200129_065458
GW200202_154313
GW200208_130117
GW200208_222617
GW200209_085452
GW200210_092254
GW200216_220804
GW200219_094415
GW200220_061928
GW200220_124850
GW200224_222234
GW200225_060421
GW200302_015811
GW200306_093714
GW200311_115853
GW200316_215756
1 s
2 s

Gravitational-Wave Transient Catalog

Detections from 2015-2020 of compact binaries with black holes & neutron stars

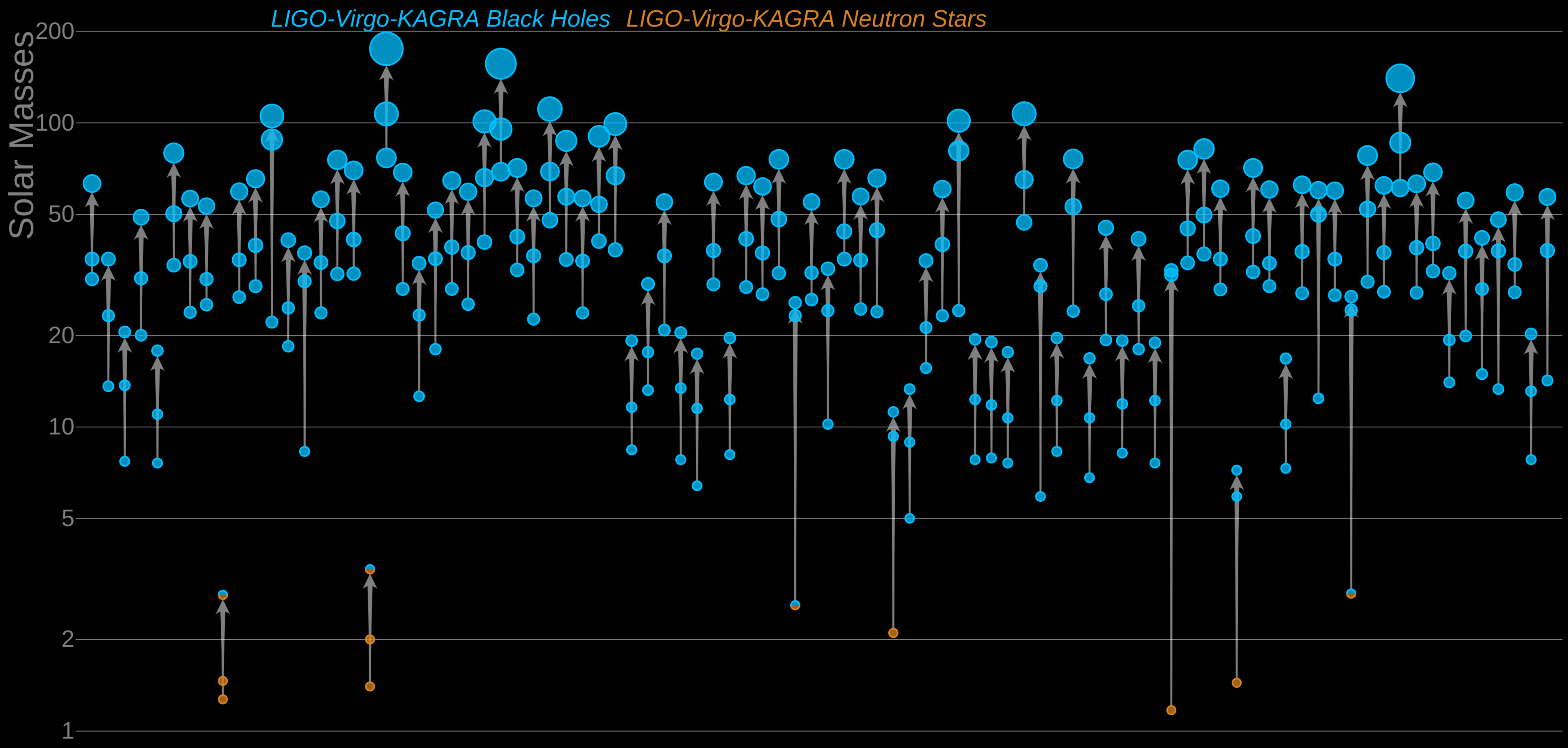


Sudarshan Ghonge | Karan Jani



Credits to E. Cuoco et a

Masses in the Stellar Graveyard

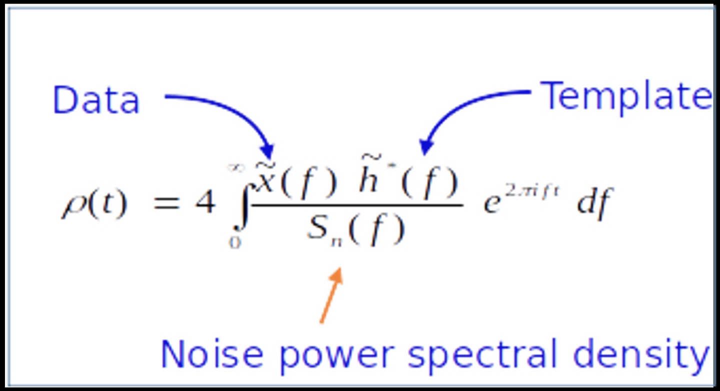


LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

Credits to E. Cuoco et al.

How we detect transient signals: modelled search

Matched-filter



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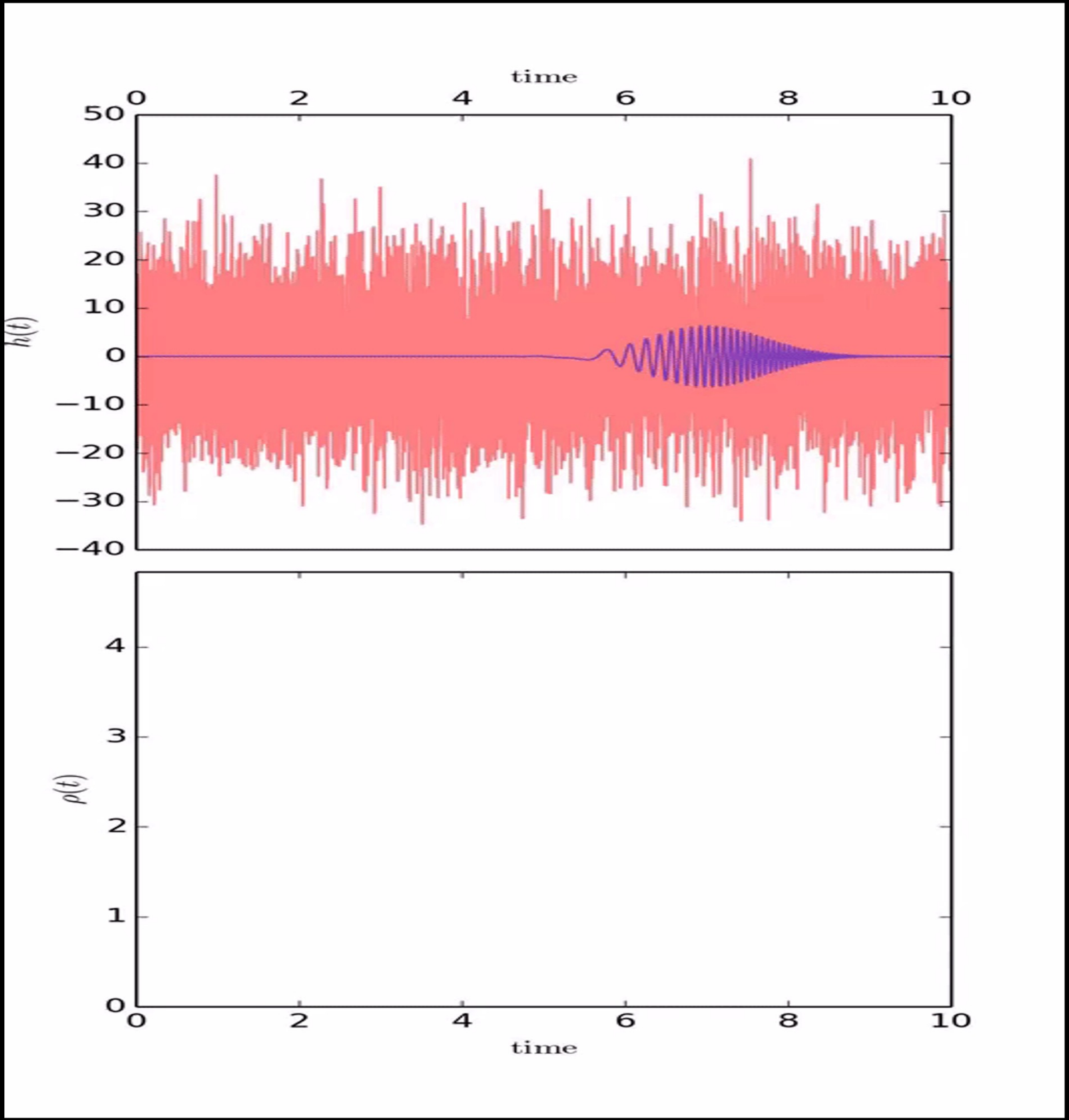
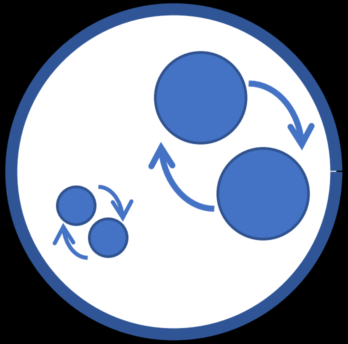


Third generation interferometer requirements

3rd generation GW observatory. Sensitivity aims at least one order of magnitude better with respect to the nominal sensitivity of advanced detectors in all the detection frequency band

Precision measurement and a new discovery project.
A wide frequency band observatory



Special focus on massive (or intermediate mass) black holes. Extraordinary sensitivity at low frequency (few Hz)

High reliability. High observation duty cycle

Lifetime of several decades. Capable to host the evolution of the detectors, without limiting their sensitivity

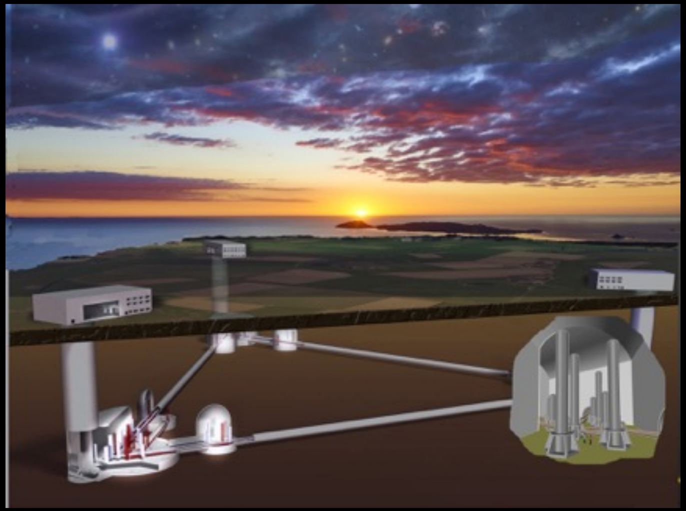
Einstein Telescope detector

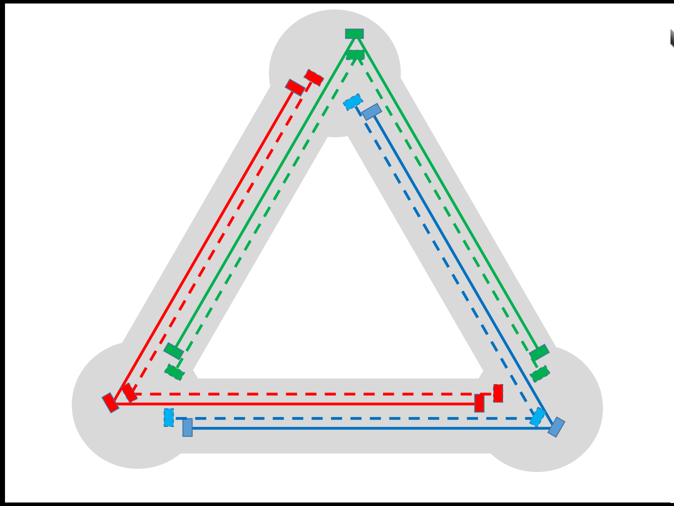
Requirements

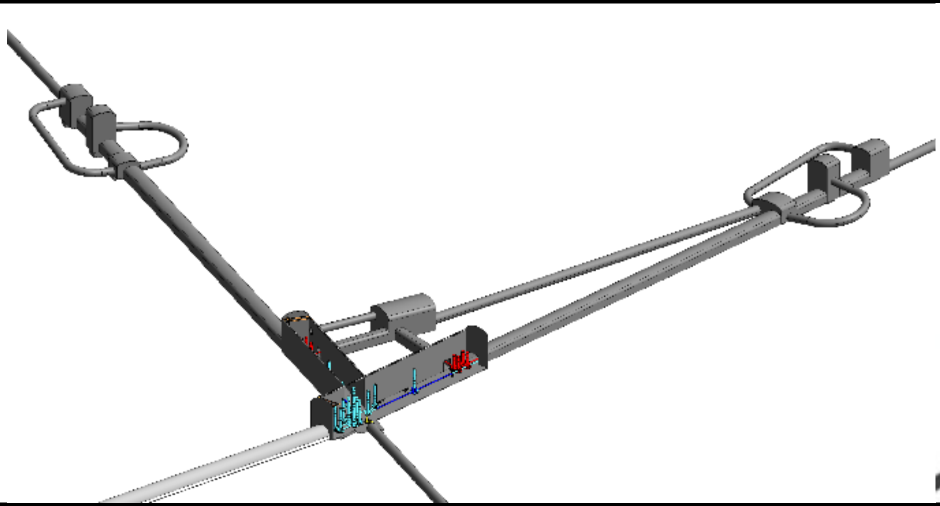
- Wide frequency range
- Massive black holes (LF focus)
- Localisation capability
- (more) Uniform sky coverage
- Polarisation disentanglement
- High Reliability (high duty cycle)
- High SNR

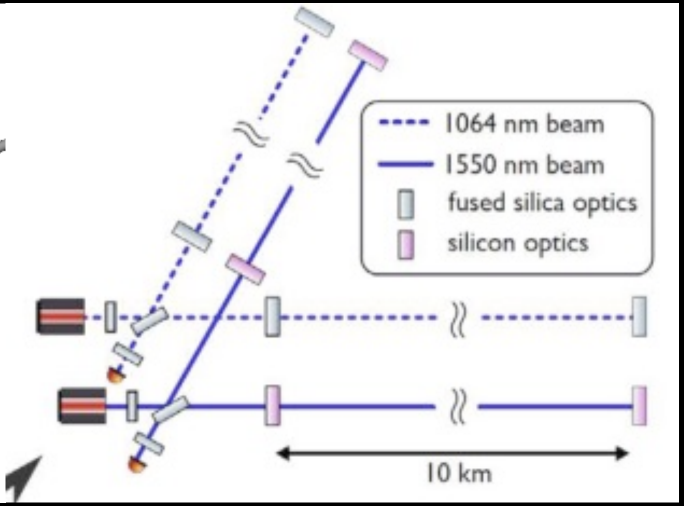
Design Specifications

- Xylophone (multi-interferometer) Design
- Underground
- Cryogenic
- Triangular shape
- Multi-detector design
- Longer arms





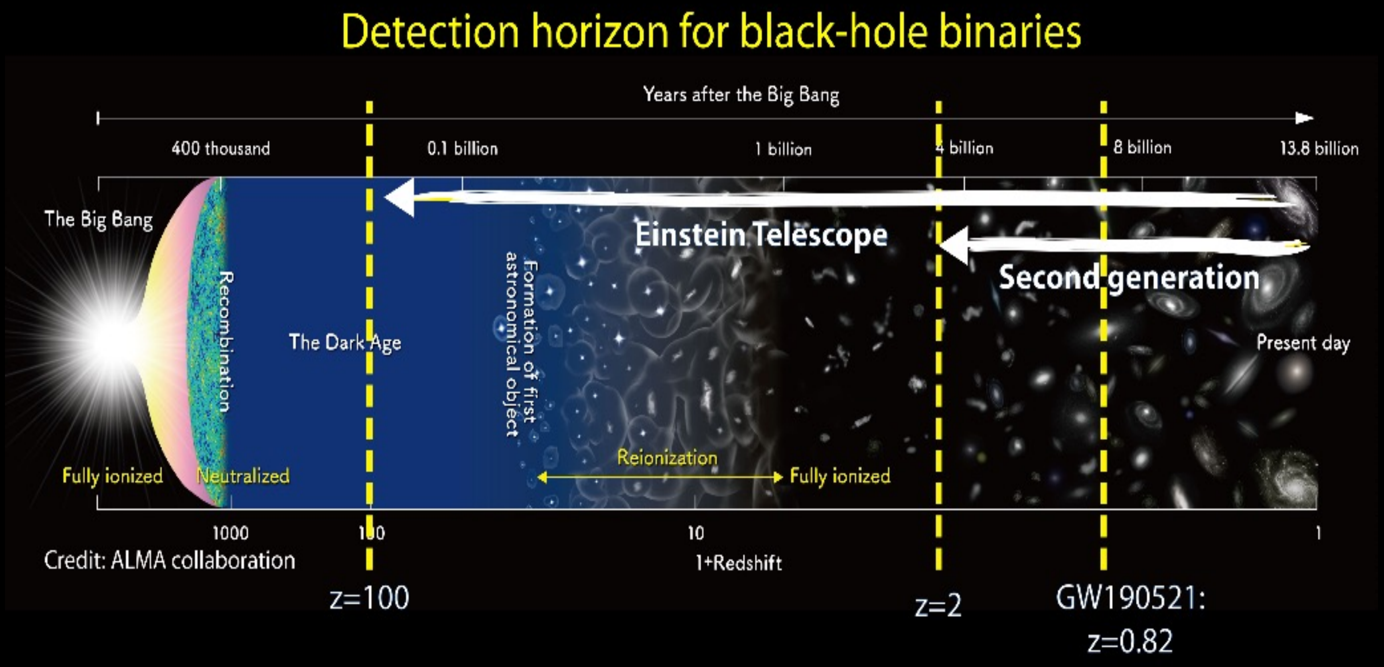


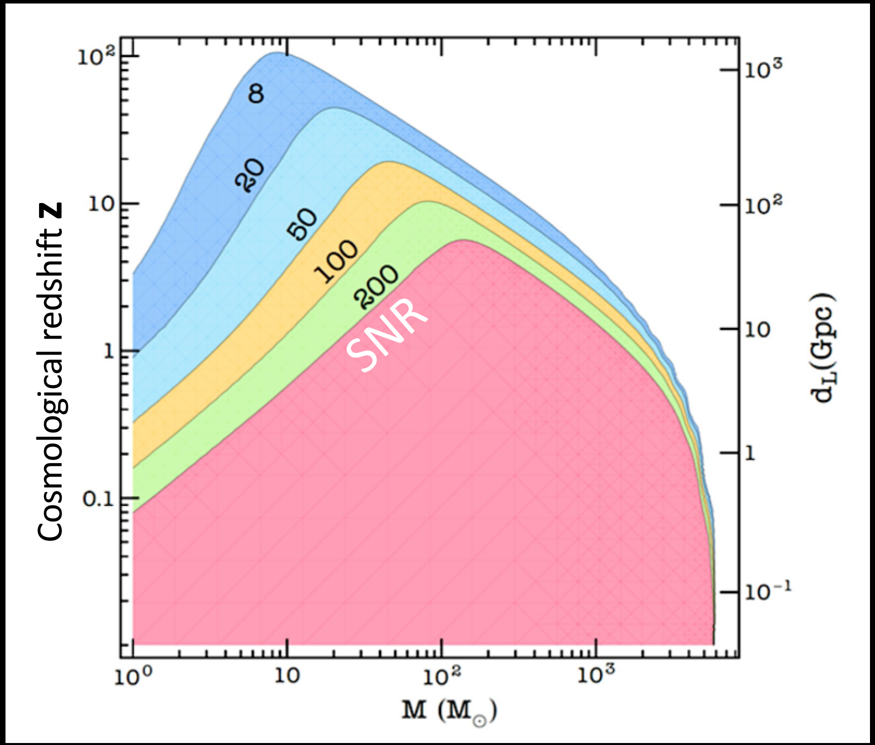


Einstein Telescope science

<u>ET will be a new discovery machine</u>: ET will explore almost the entire Universe listening the gravitational waves emitted by black hole, back to the dark ages after the Big Bang

<u>ET will be a precision measurement observatory</u>: ET will detect, with high SNR, hundreds of thousands coalescences of binary systems of Neutron Stars per year, revealing the most intimate structure of the nuclear matter in their nuclei





Einstein Telescope science

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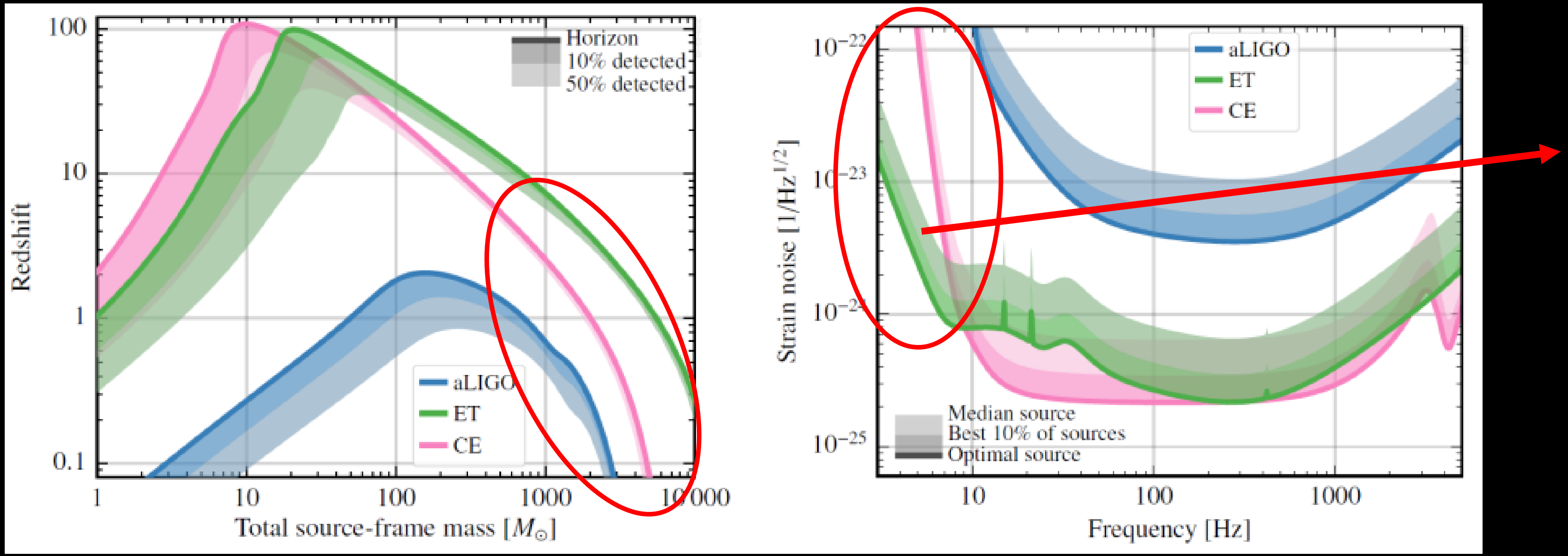
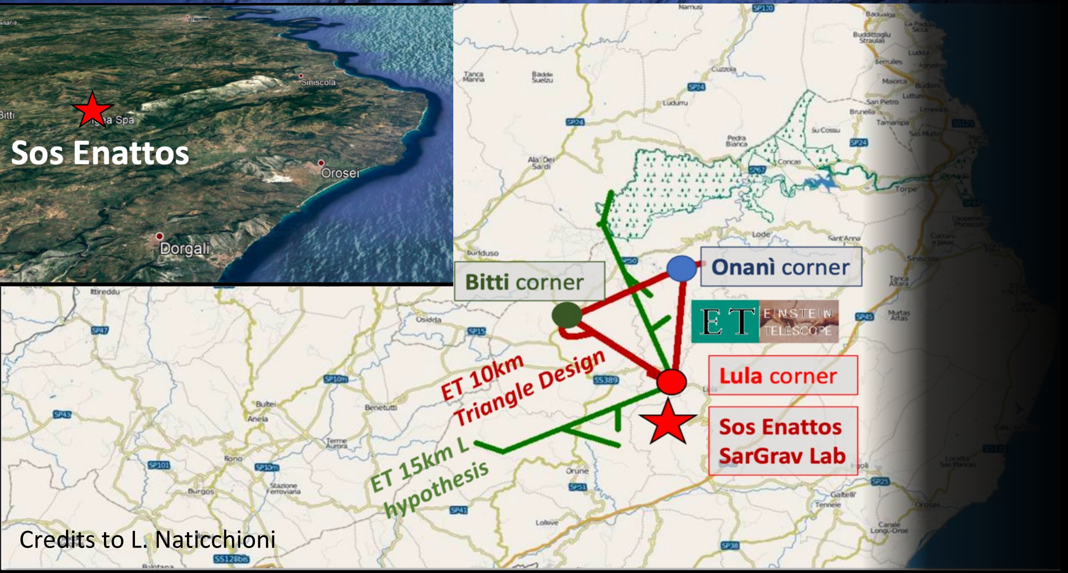


Below 10 Hz the main noise source are due to seismic noise and Newtonian noise

We need to find a place characterized by a low environmental noise

Where we are

The region under analysis is the Sos Enattos former mine, close to the town of Lula (Sardinia, Italy); but the characterization studies regards also other town like Bitti and Onanì.



Credits to L. Naticchioni

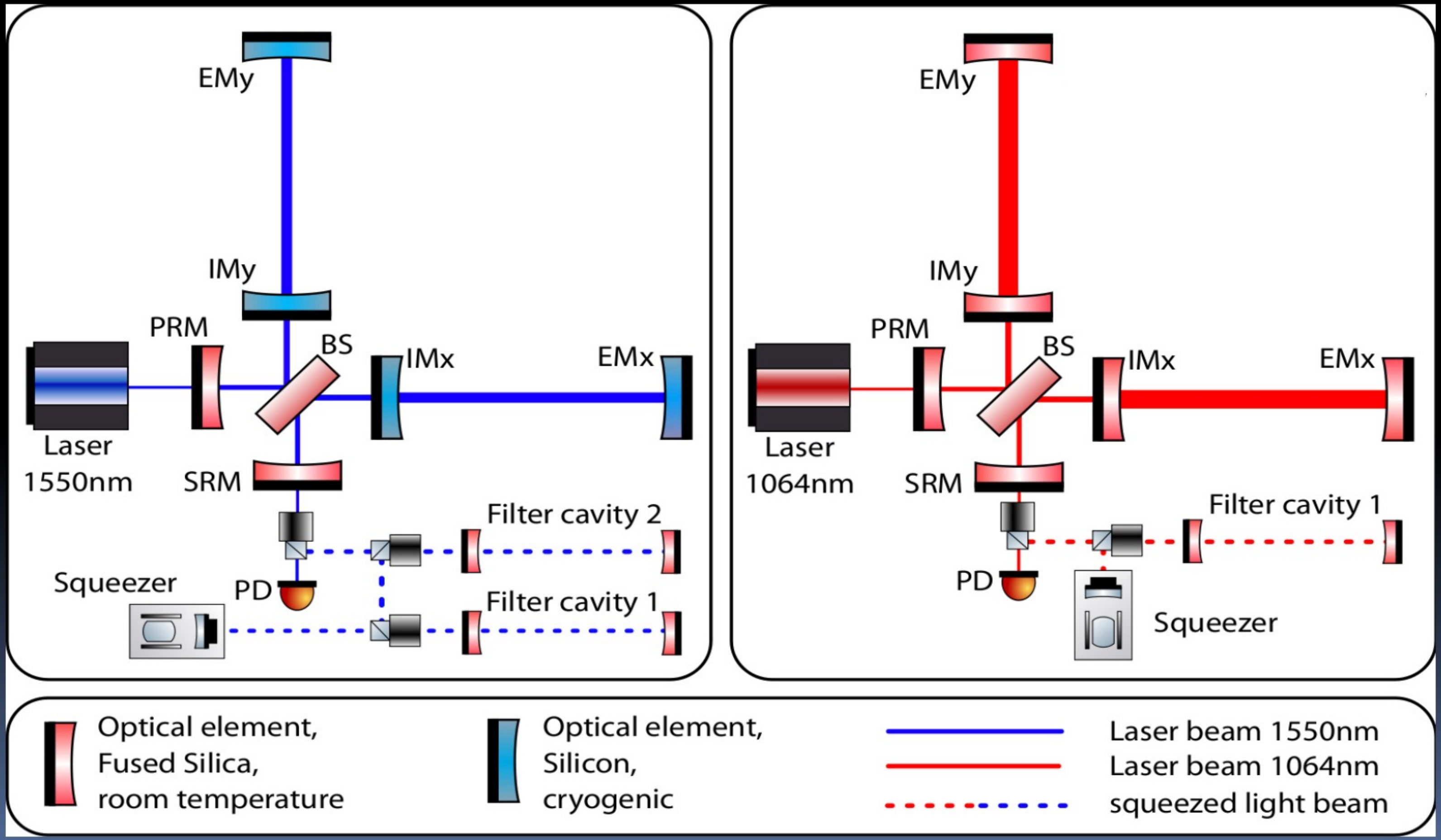
Credits to D. Rozza

- Located in Sardinia (Italy) close to Lula (Nuoro)
- Very low noise infrastructures, designed to host low seismic noise experiments, cryogenic payloads, low frequency and cryogenic sensor development (as confirmed by already published data)
- Large area on surface available for experiments (~900 m^2). Additional facilities will be added in the forthcoming months.
- Several underground stations available for site monitoring. Small underground area available for experiments. Plan to realize a large underground lab (250 m^2), feasibility study completed.

Einstein Telescope

ET - LF
low-power, cryogenic
low-frequency detector

ET – HF
high-power, room-temperature
high-frequency detector



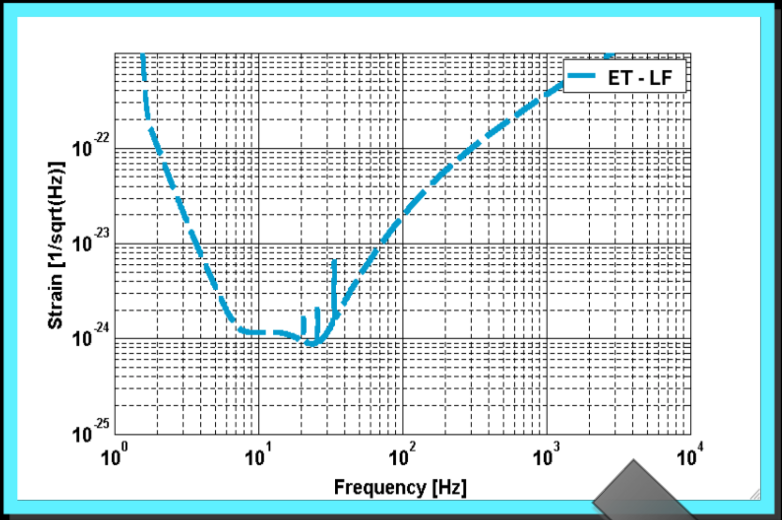
ET-HF: 300 K

- High power laser
- High circulating light power
- Thermal compensation
- Large test masses
- New coatings
- Frequency dependent squeezing

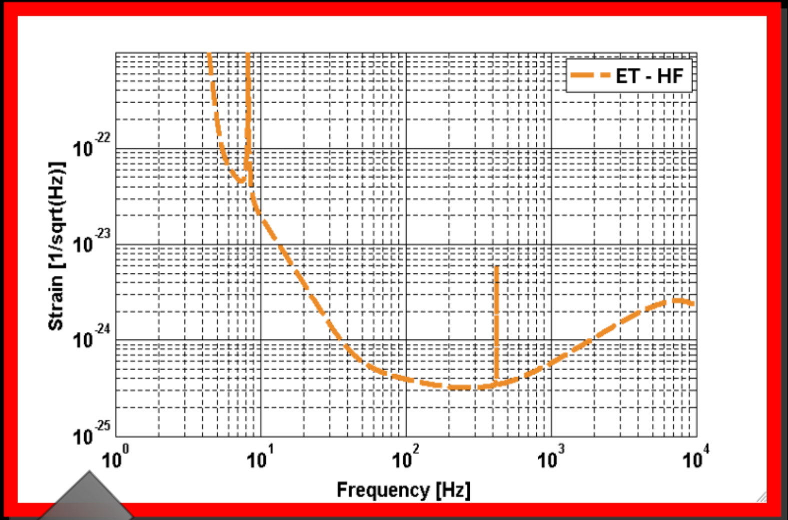
ET-LF: 10 – 20 K

- Cryogenics
- Seismic suspensions
- Silicon (Sapphire) test masses
- Large test masses
- New coatings
- New laser wavelength
- Frequency dependent squeezing, Filter cavities

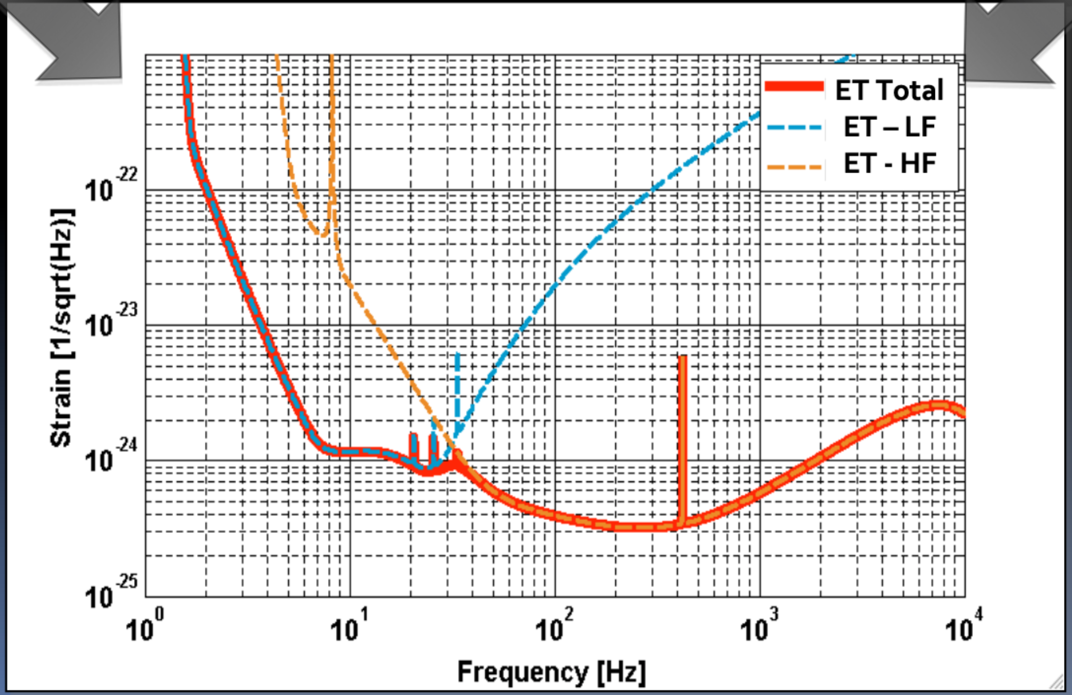
ET noise budget



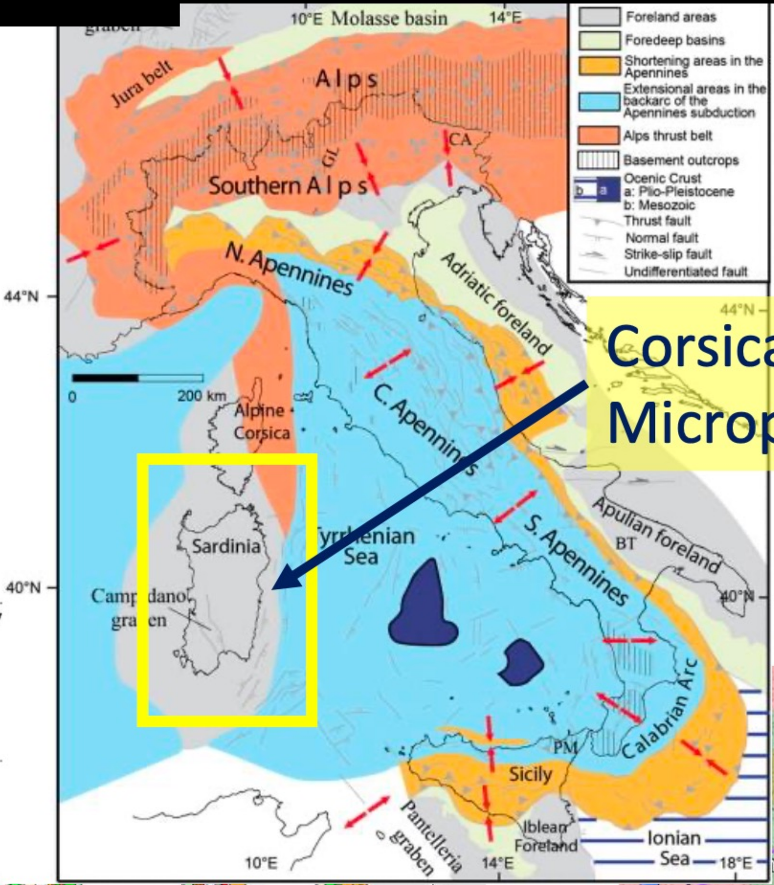
ET-LF



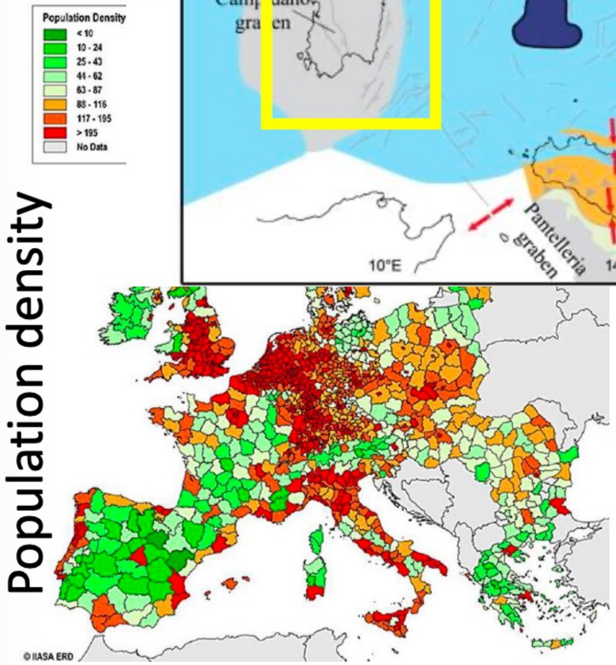
ET-HF



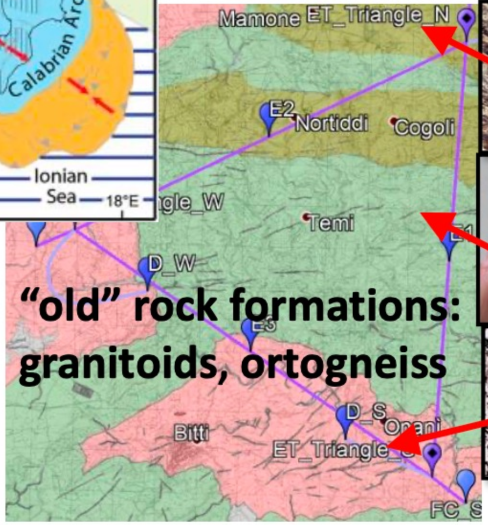
Geophysical frame



Corsica-Sardinia Microplate

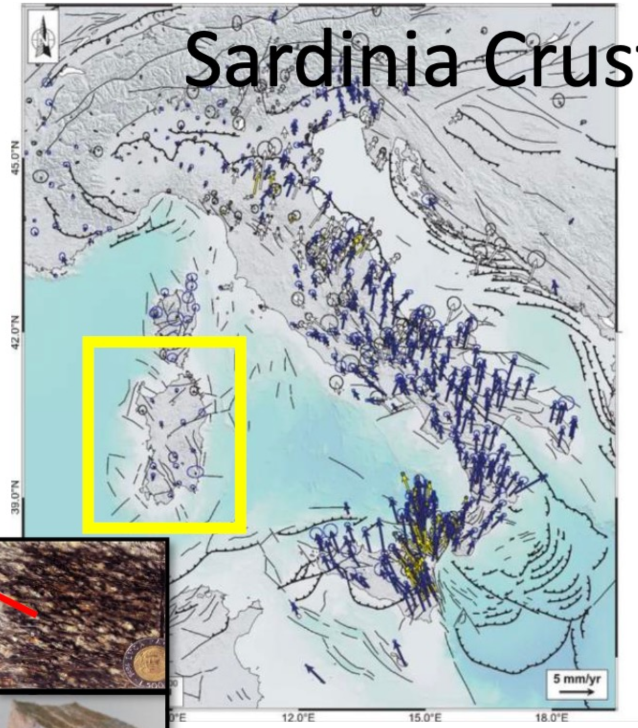


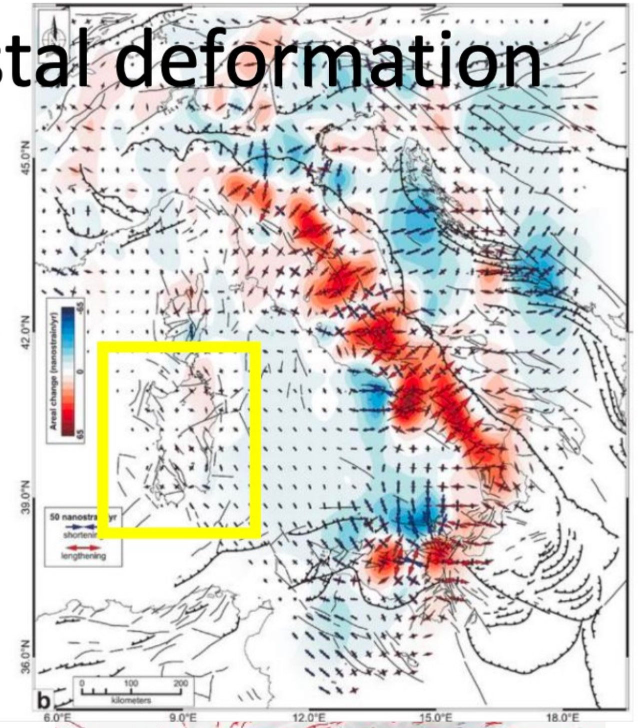
Population density



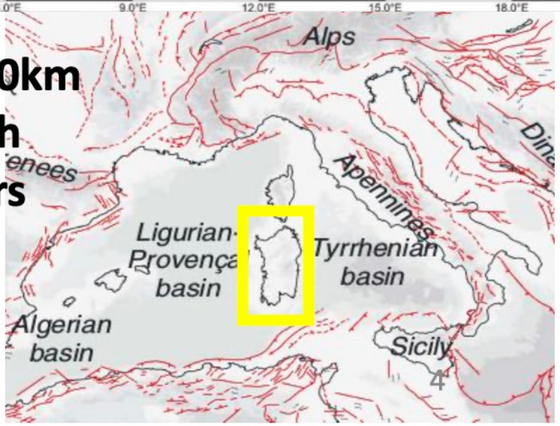
“old” rock formations: granitoids, ortogneiss

Sardinia Crustal deformation

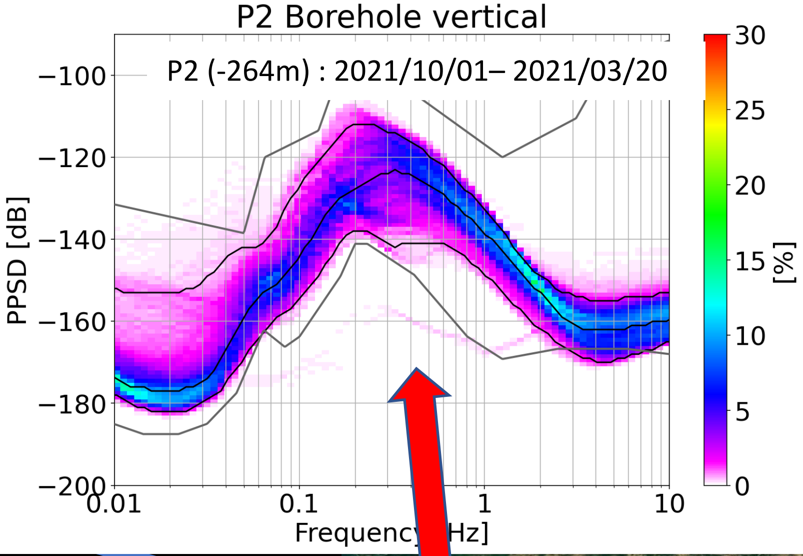




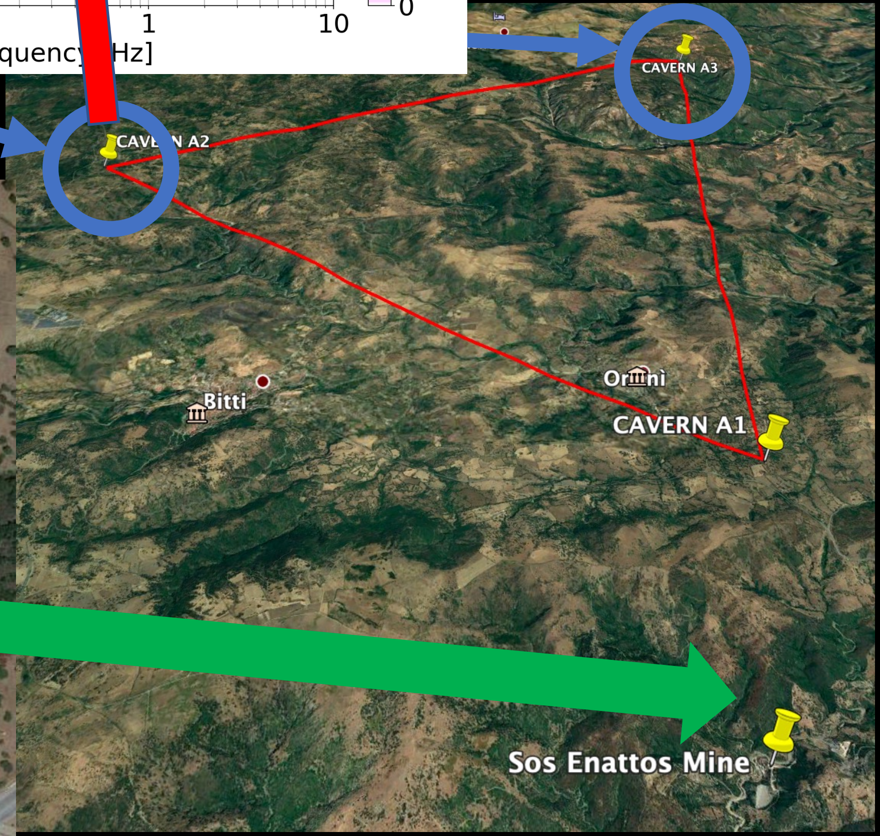
10 earthquakes within 50km from Sos Enattos, all with M<2.5 in the last 40 years

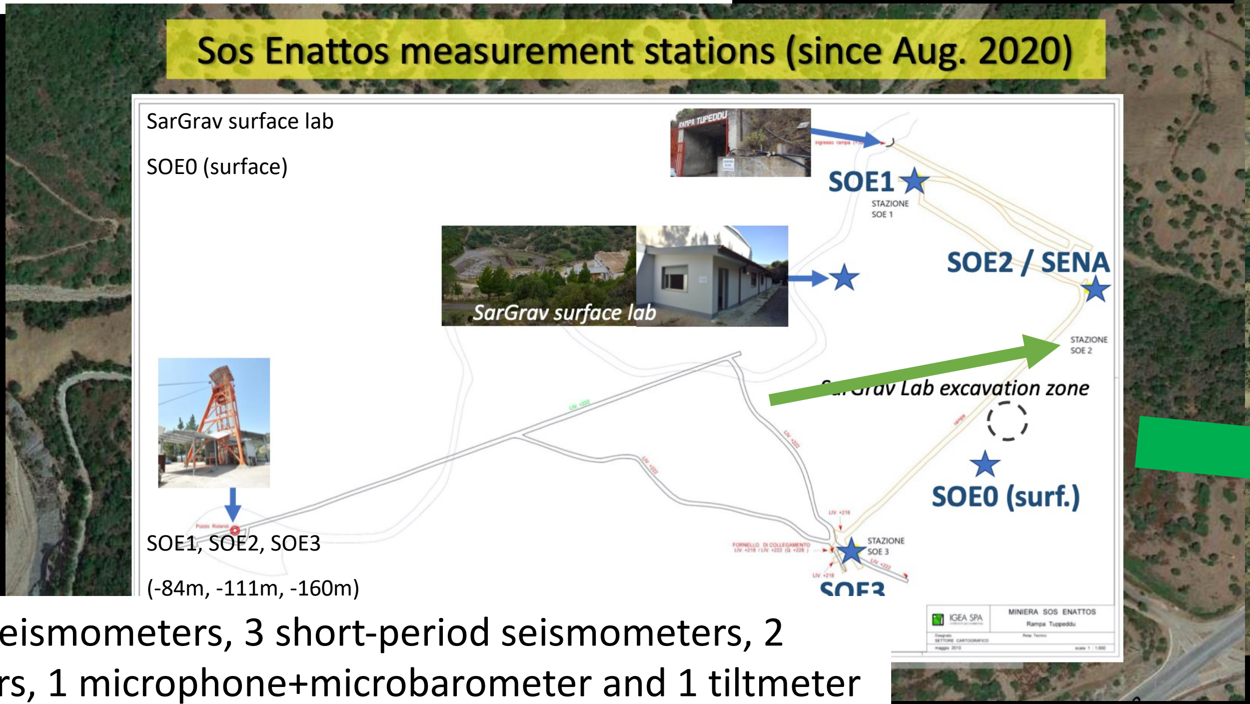


Sardinia Site
Long-term measurements



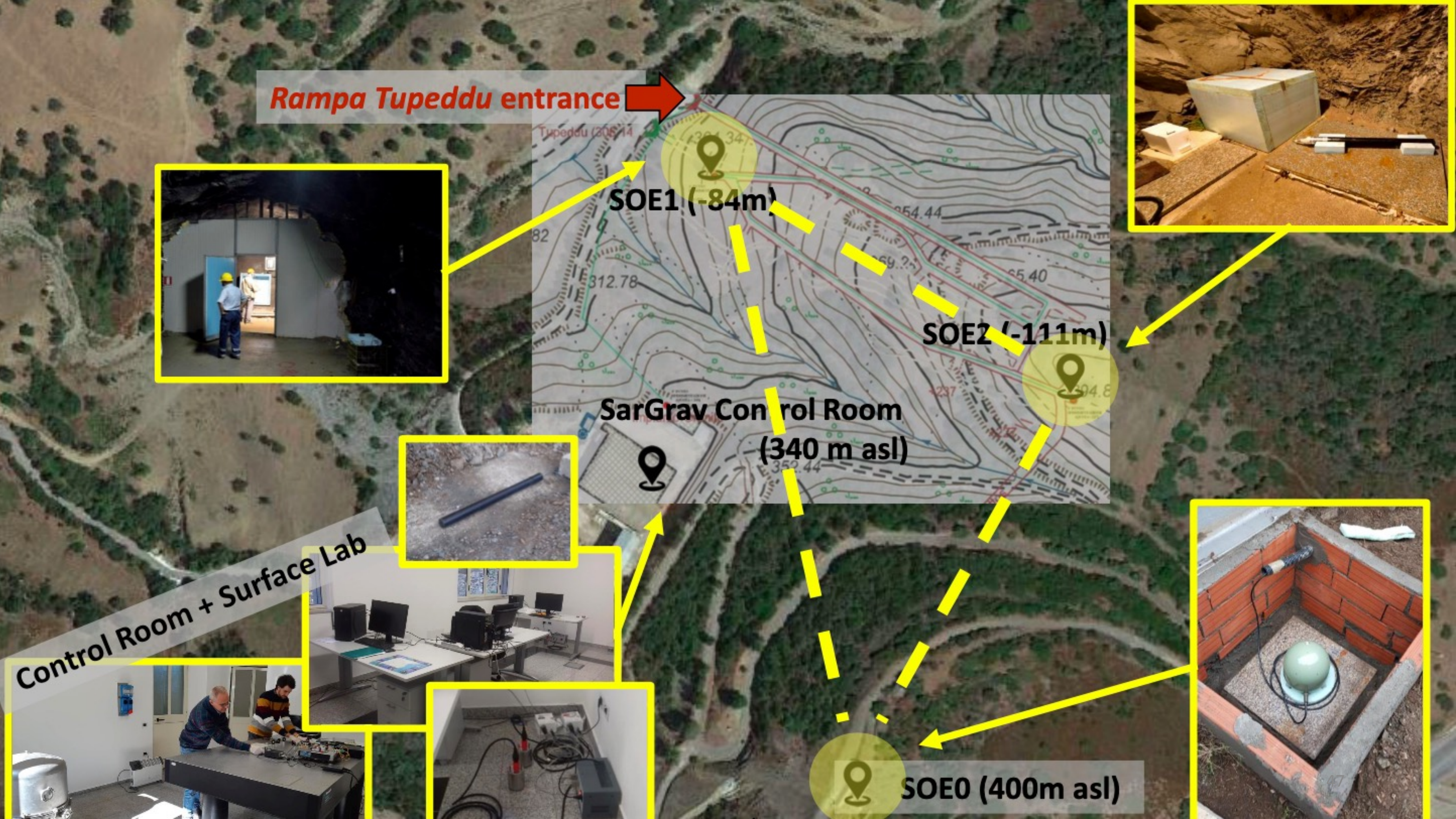
Characterization of the Bitti and Onanì corners:
Surface and underground seismic and environmental measurements





4 broadband seismometers, 3 short-period seismometers, 2 magnetometers, 1 microphone+microbarometer and 1 tiltmeter distributed over underground and surface stations

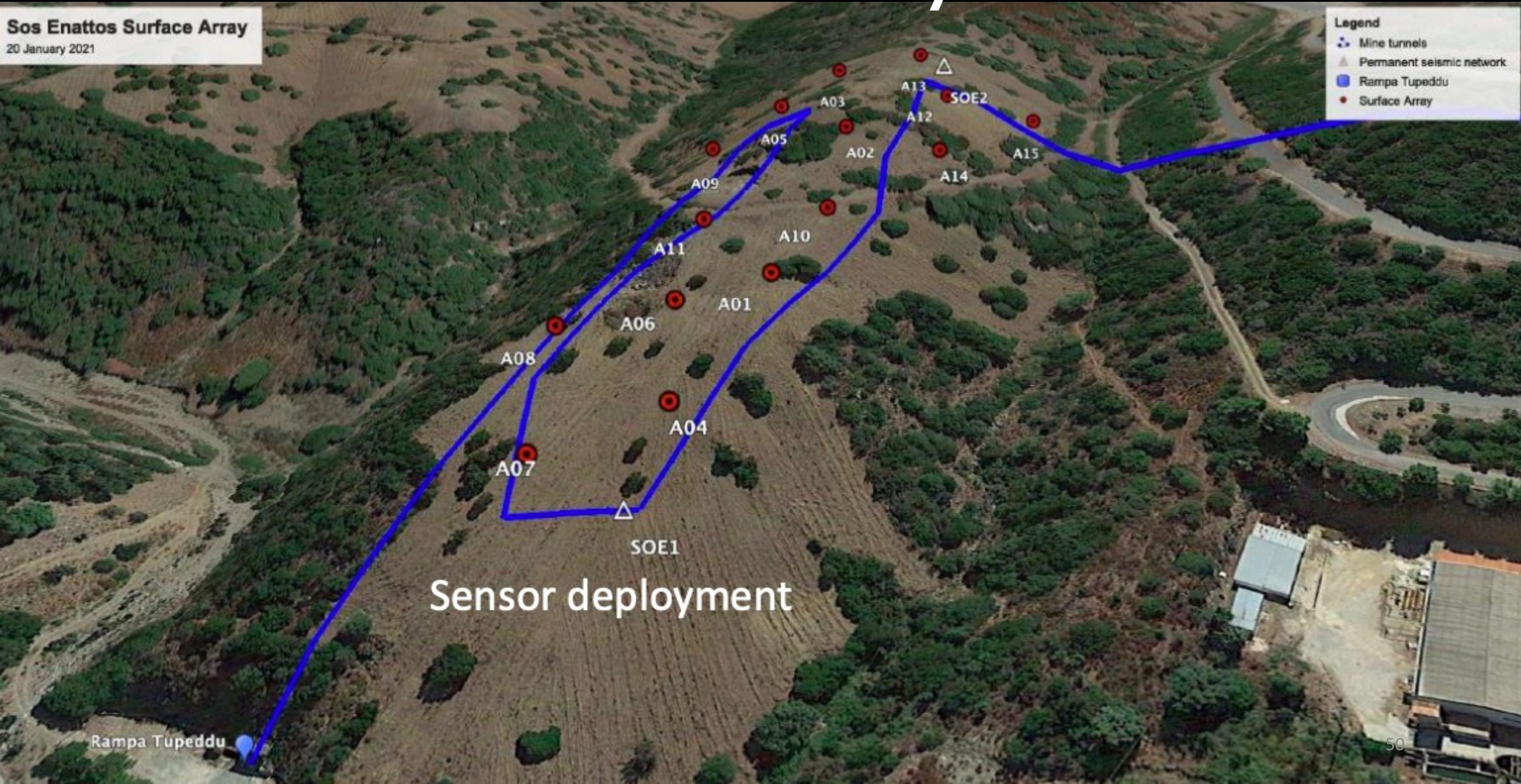
Credits to L. Naticchioni


Rampa Tupeddu entrance
SOE1 (-84m)
SOE2 (-111m)
SarGrav Control Room
(340 m asl)
Control Room + Surface Lab
SOE0 (400m asl)

Credits to L. Naticchioni

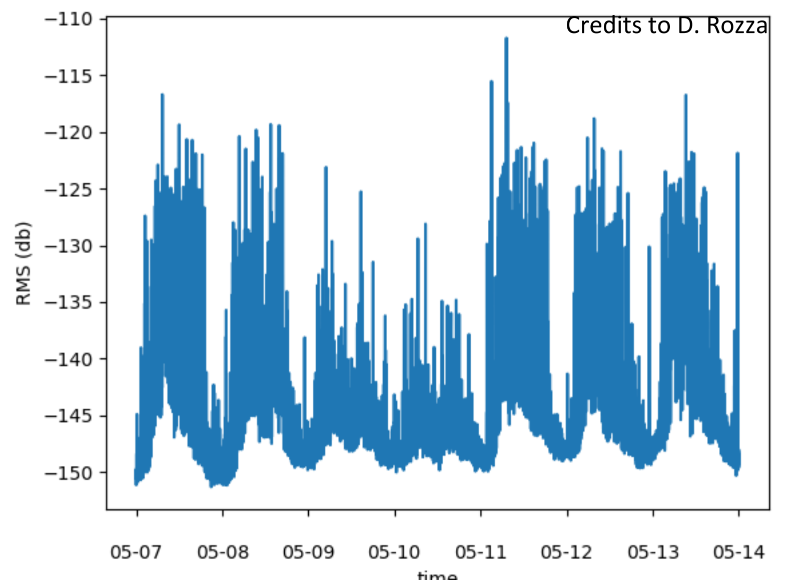

Credits to D. Rozza

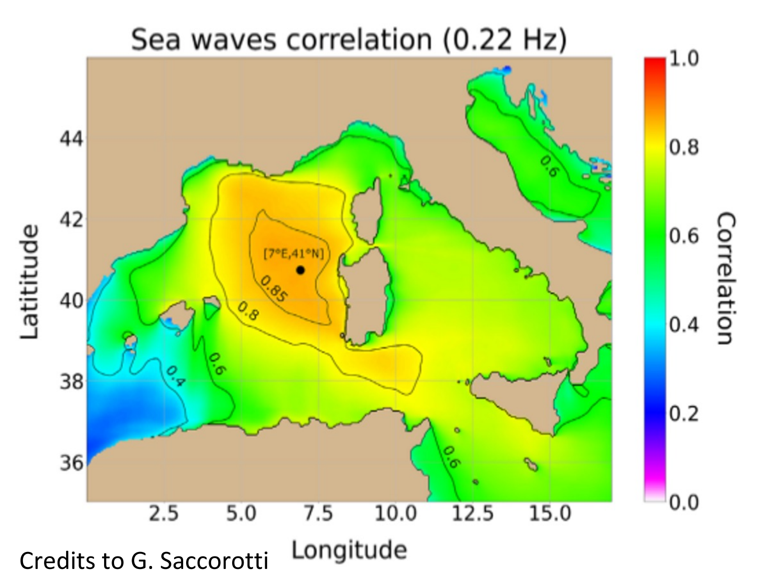
Short term analysis

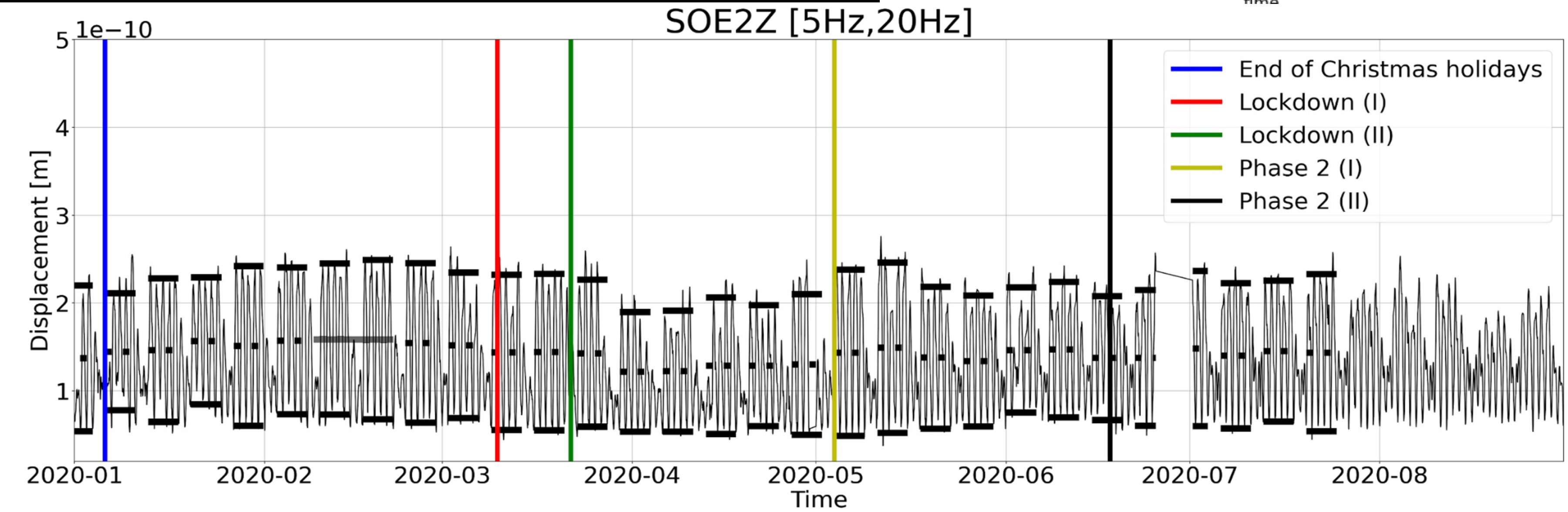


What can we learn?

- Seismic noise analysis due to Ocean and Mediterranean sea
- Local noise sources: weather, rain, wind…
- Anthropic noise

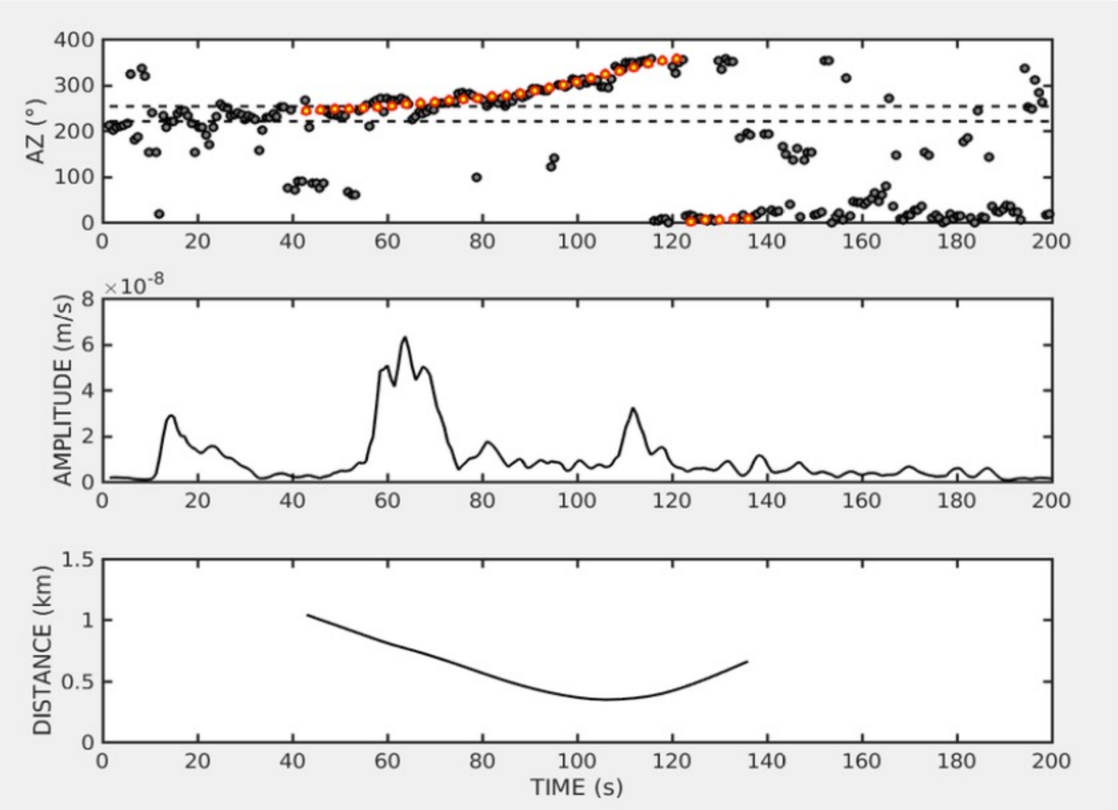


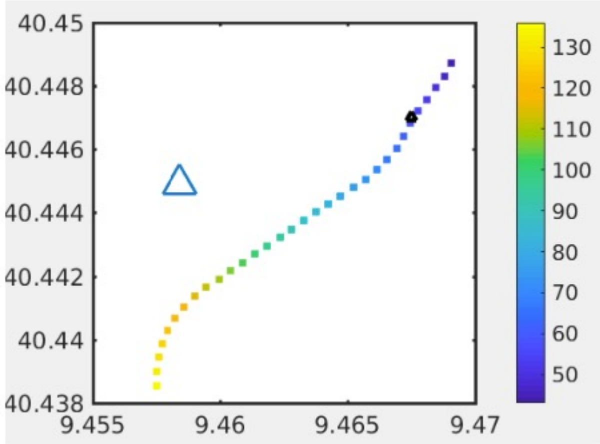


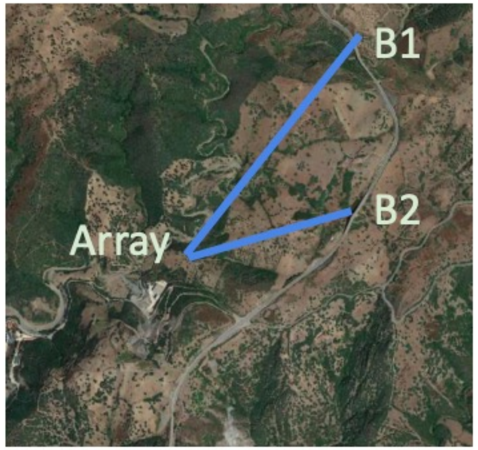


Vehicle speed…

Vehicle Tracking close to the site





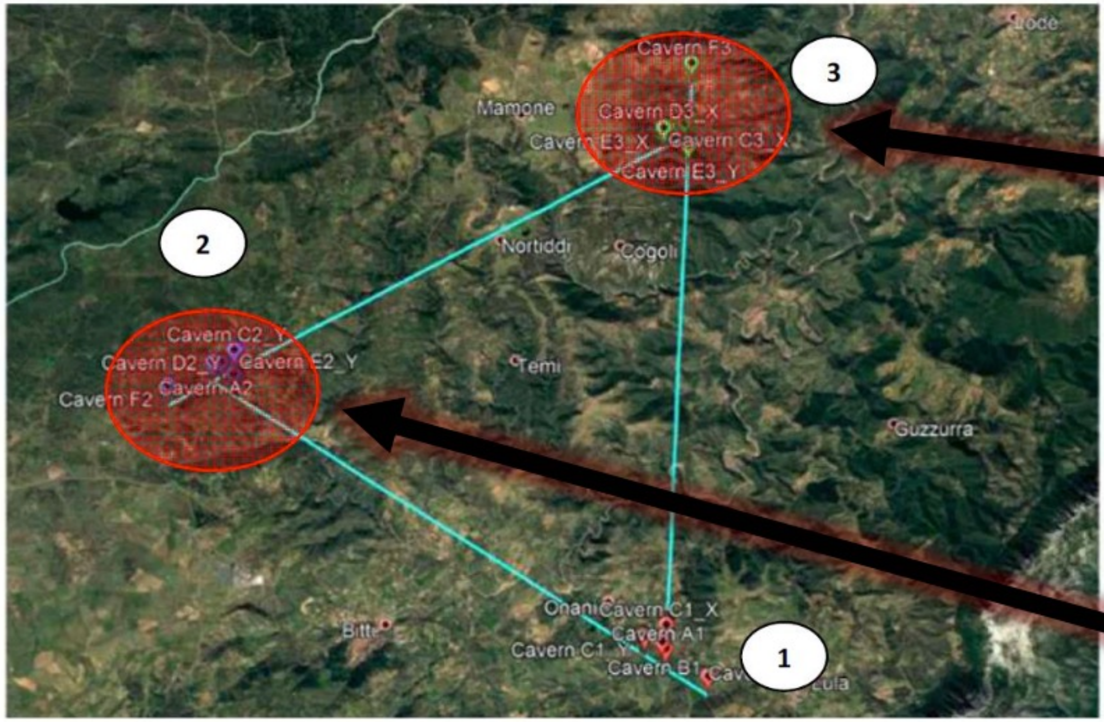


Time evolution of azimuth compatible with a vehicle traveling at 60 km/h southward along road SP73.

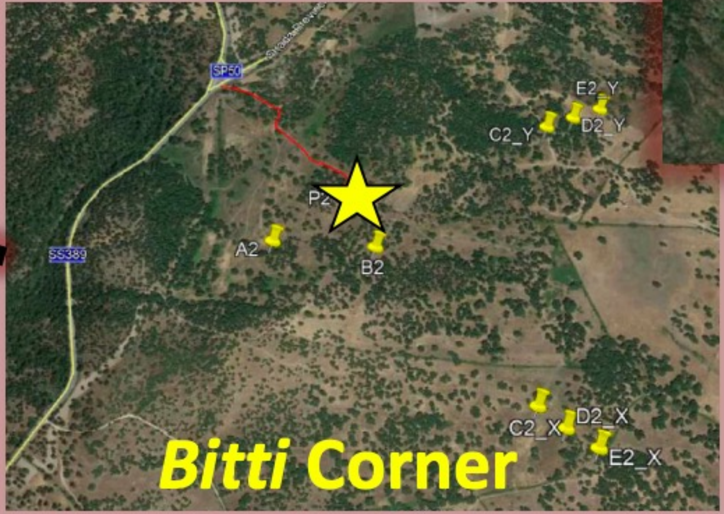
Largest signal amplitude is NOT associated when the vehicle is closest to the array, but when it traverses bridge B2

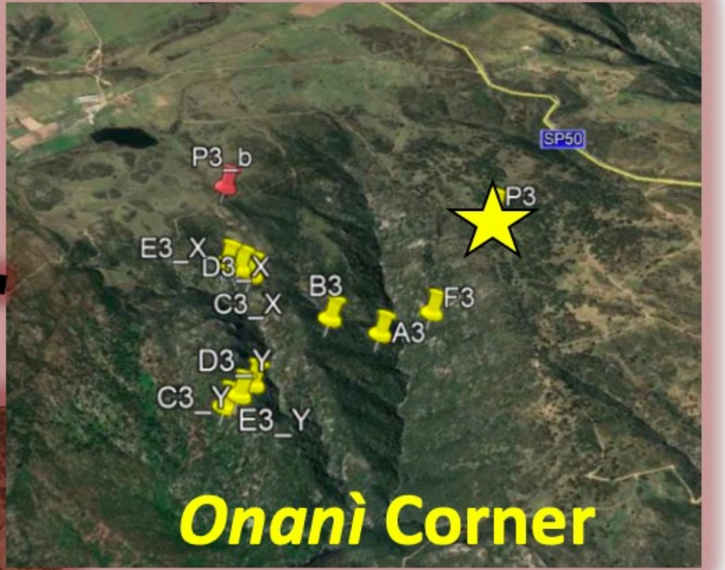
Credits to L. Naticchioni

Bitti and Onanì corners



***Lula* Corner**
Sos Enattos





★ : area for boreholes and surface arrays

📌 : proposed locations for ET main caverns

Bitti and Onanì corners

Bitti corner,
borehole area

Onanì corner,
borehole area


Rent
DA 267YR

SarGrav area

SarGrav control room

The first experiment hosted: ARCHIMEDES

Experimental Goal: measurement of the interaction between vacuum fluctuations with gravity weighting a Casimir multi-cavity while changing the reflectivity of its layers. A change in the reflectivity of its layers corresponds into a variation of the internal vacuum state energy.

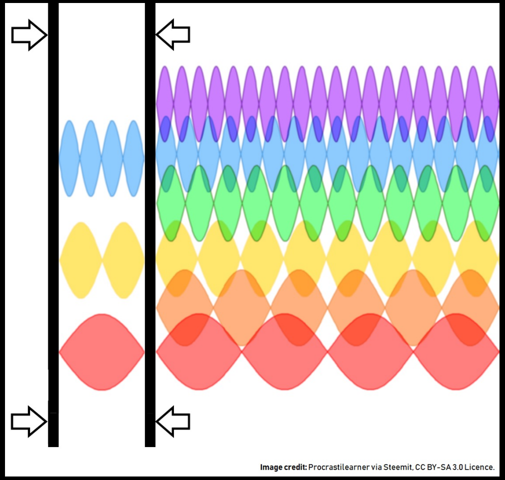
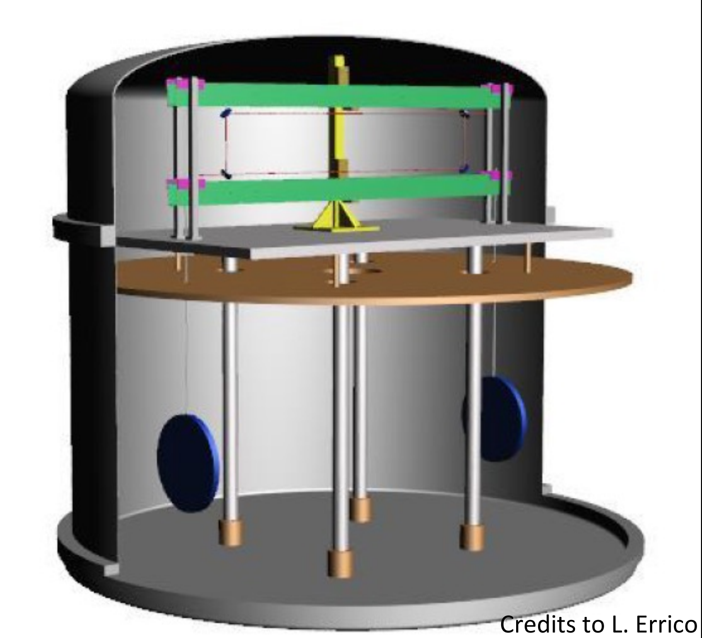


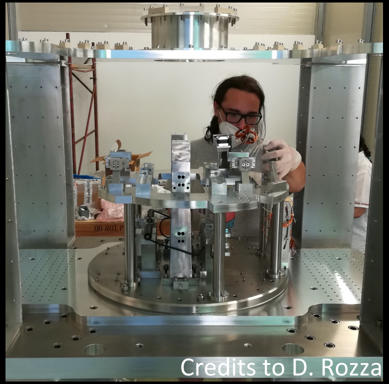
Image credit: Procrastilearner via Steemit, CC BY-SA 3.0 Licence.

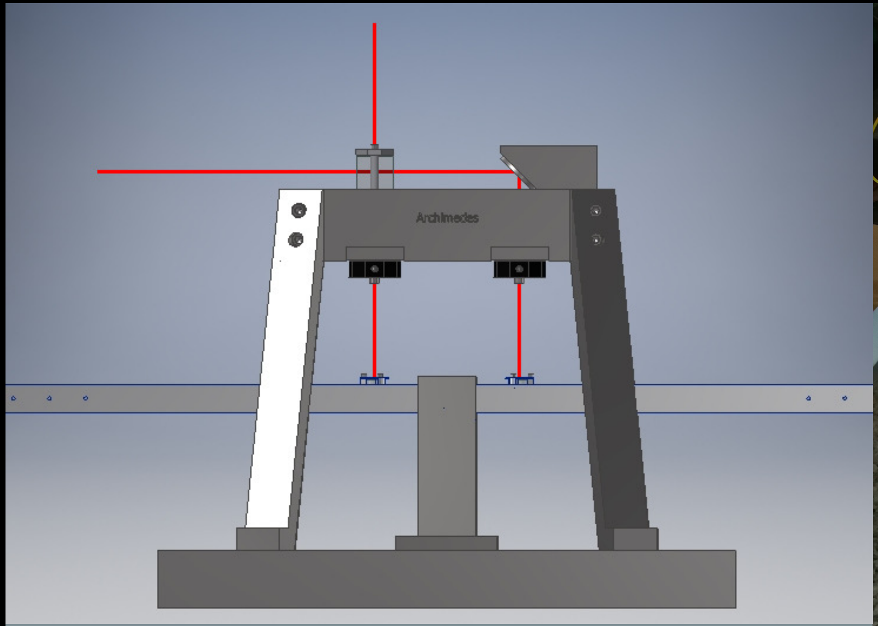

Credits to L. Errico

Apparatus: high sensitivity balance working in cryogenic conditions (~90 °K).

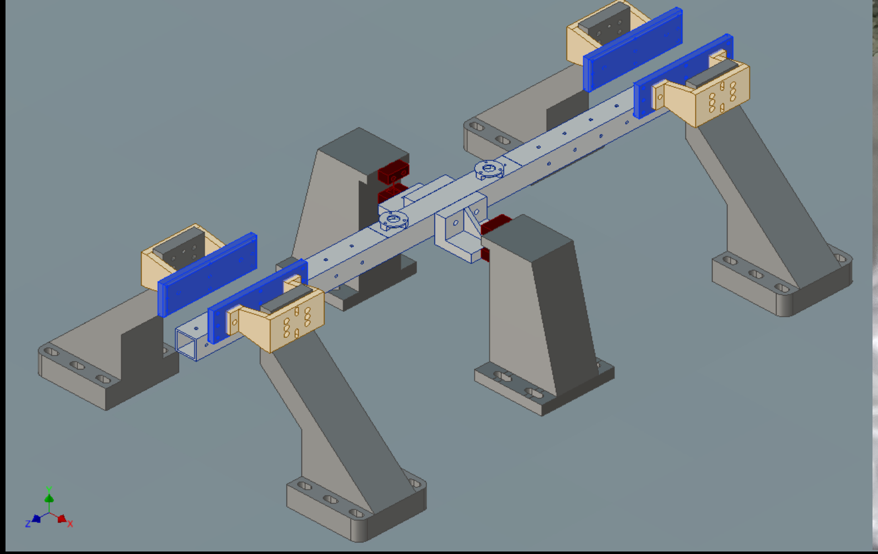

Credits to D. Rozza

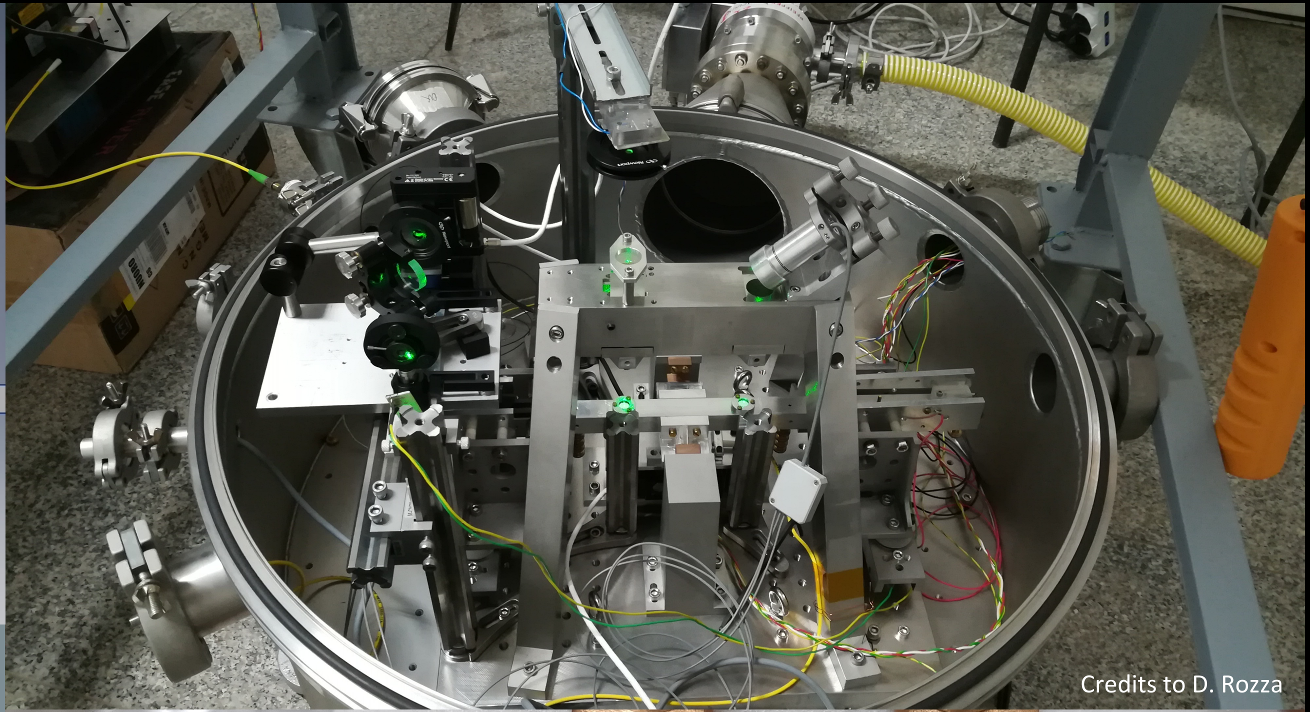
Credits to M. Perciballe


Credits to D. Rozza

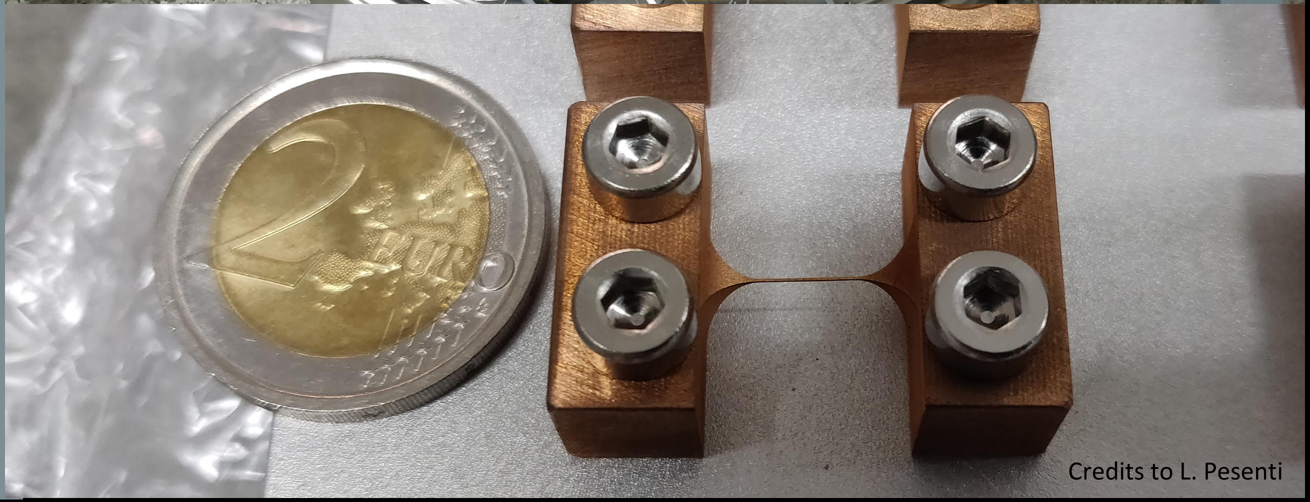


Credits to L. Errico

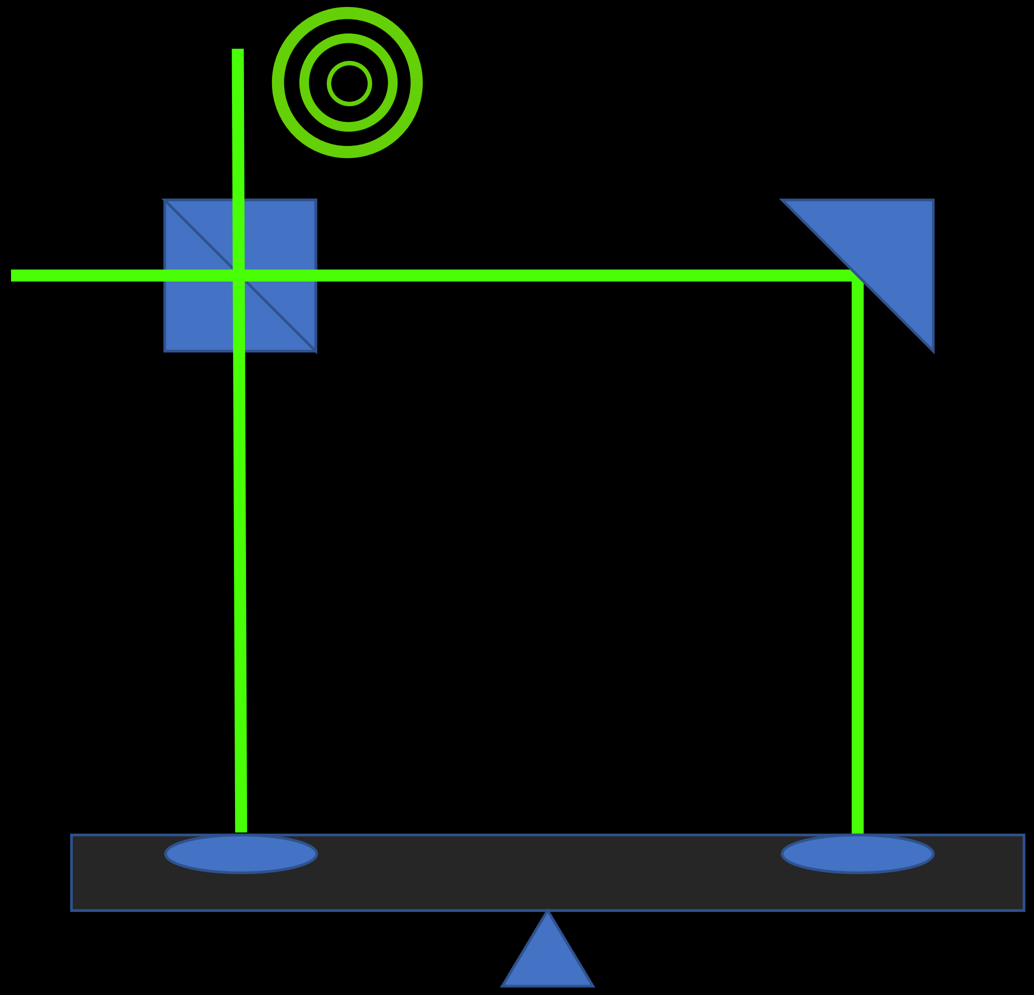


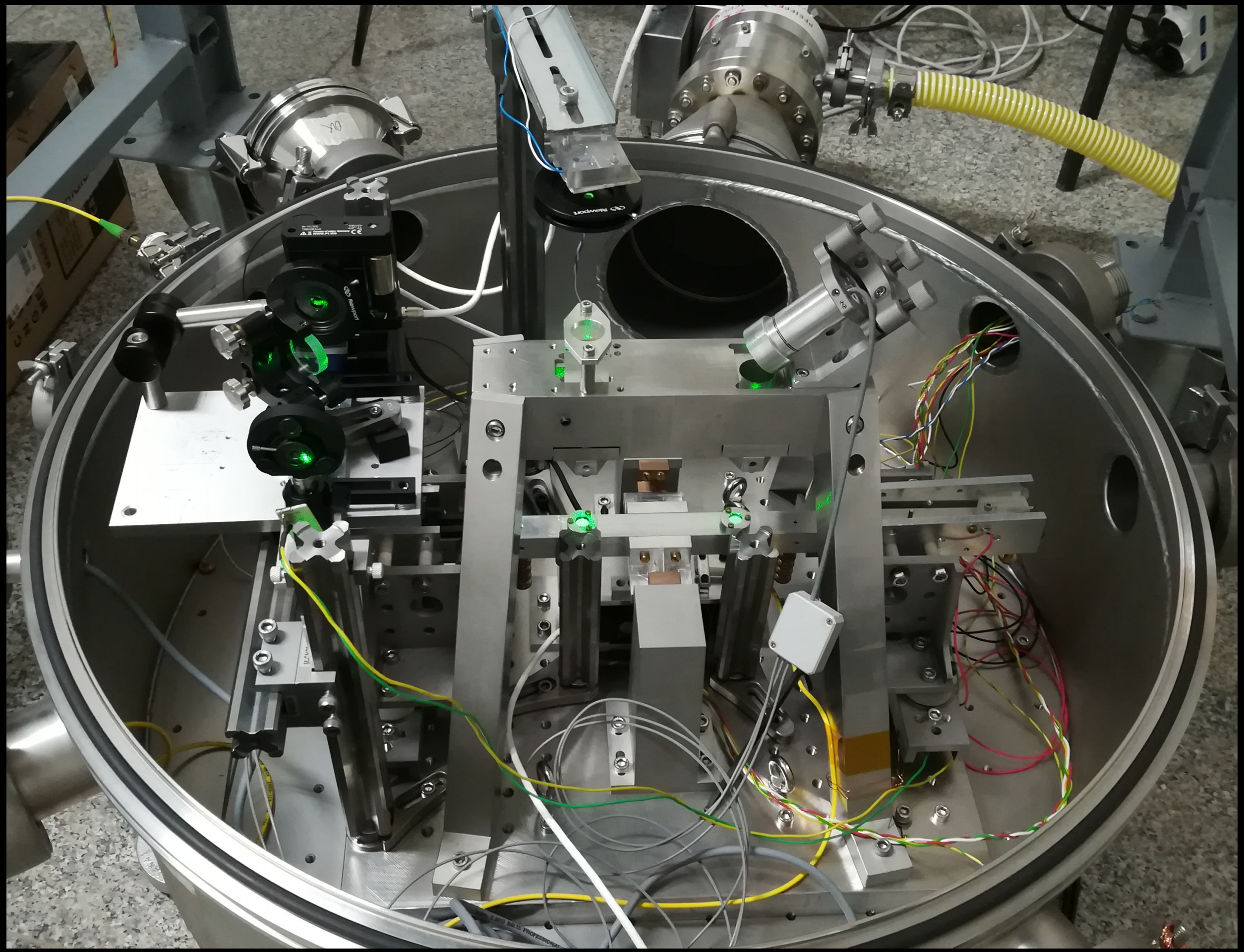


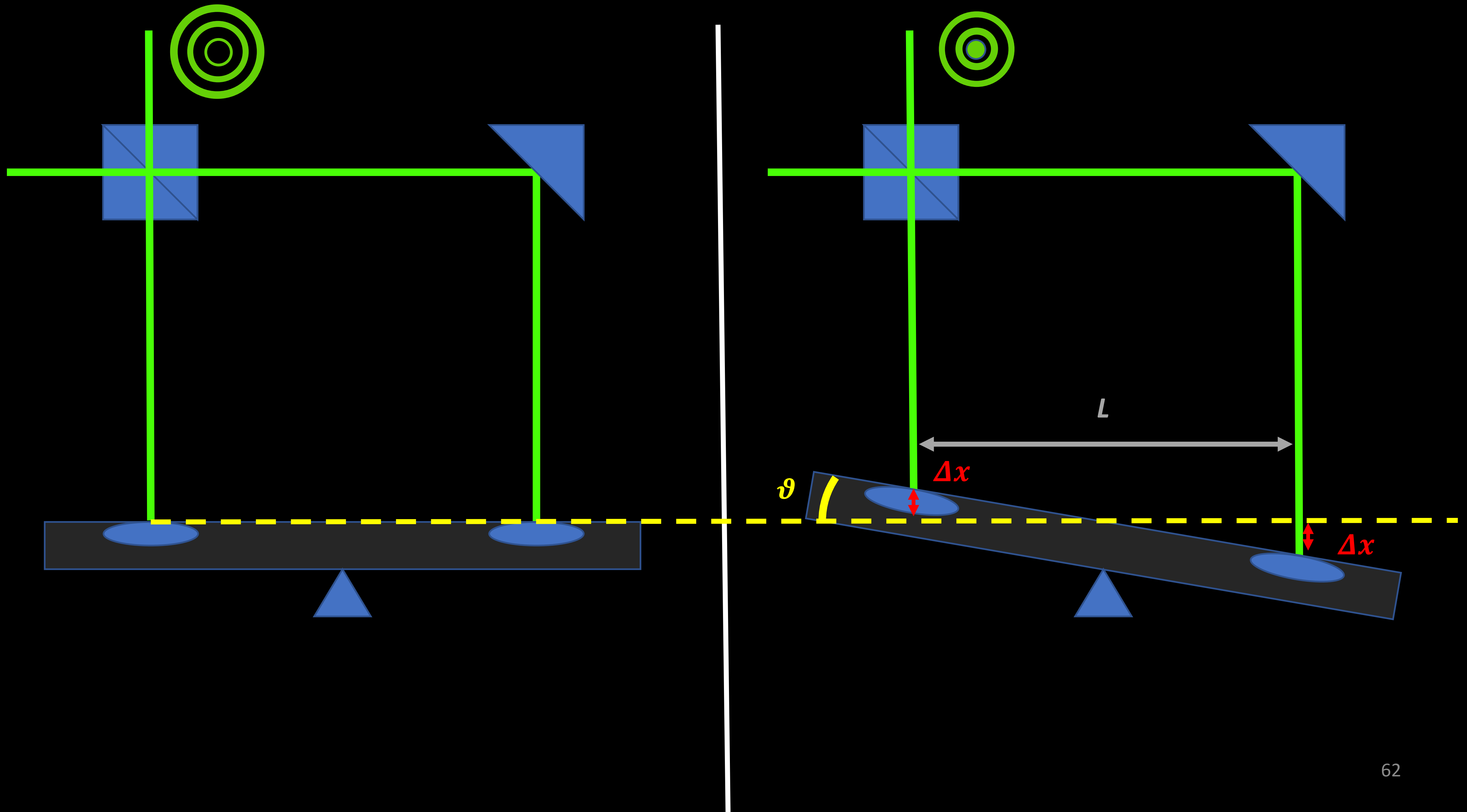
Credits to D. Rozza



Credits to L. Pesenti



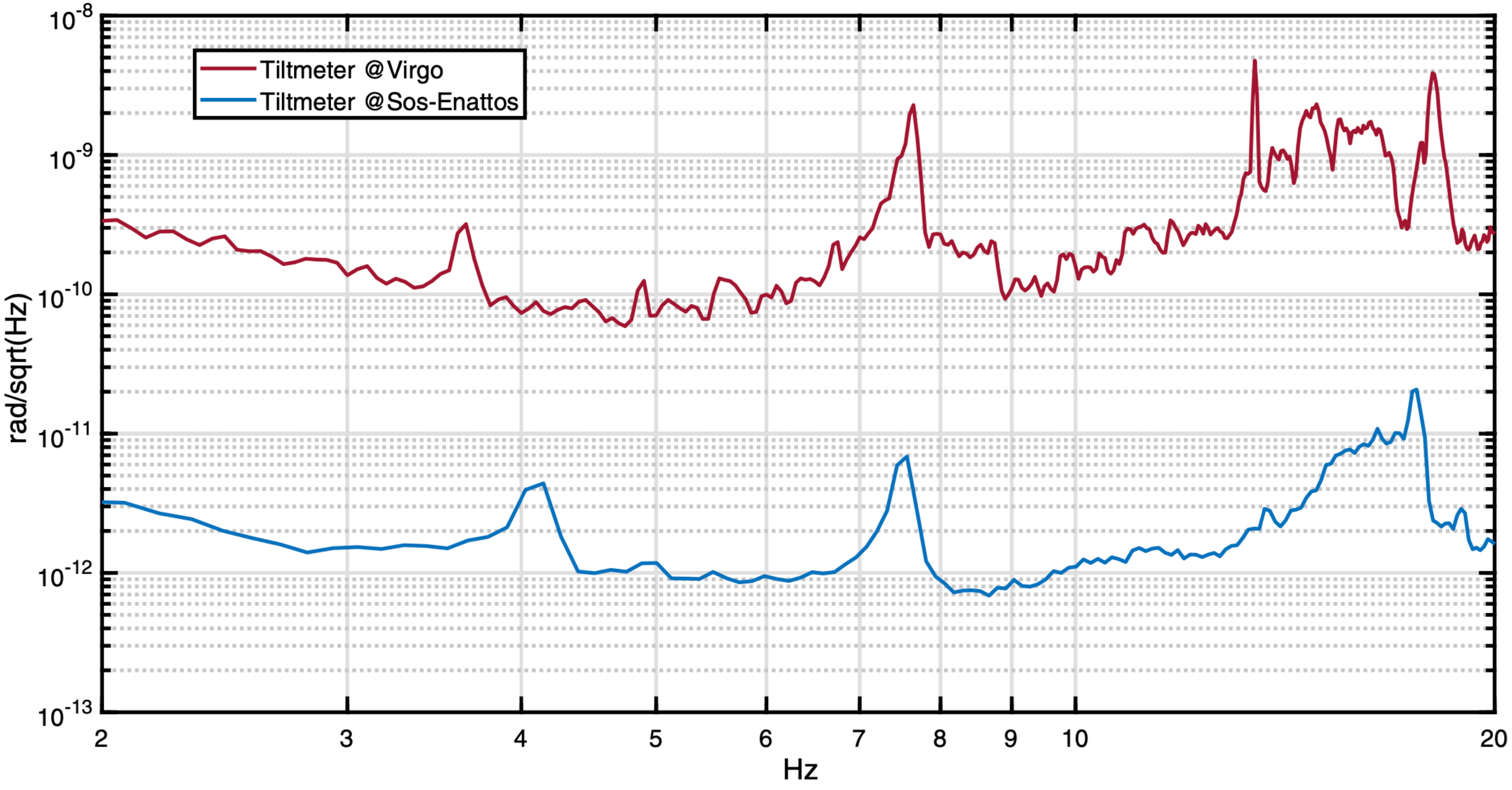



L
Δx
ϑ
Δx

The first experiment hosted: ARCHIMEDES

Eur. Phys. J. Plus (2021) 136:1069
https://doi.org/10.1140/epjp/s13360-021-01993-w

THE EUROPEAN PHYSICAL JOURNAL PLUS

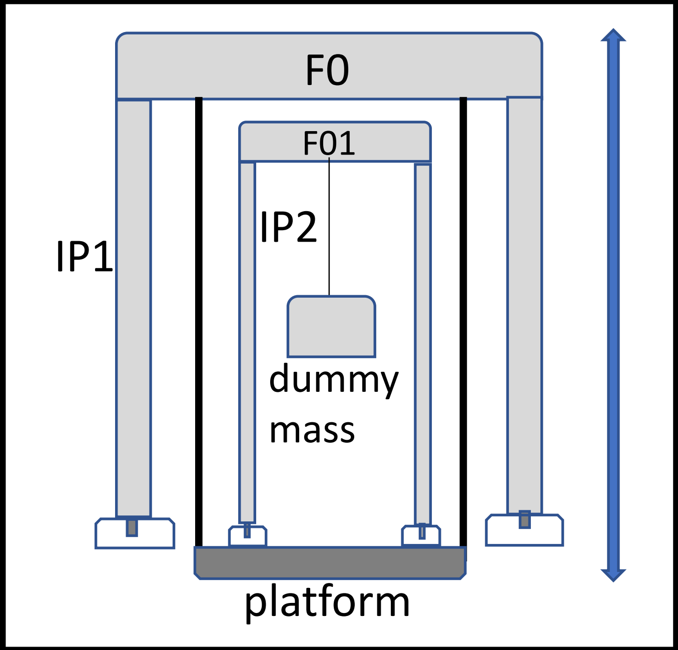



NIEDDU SpA
NIEDDU
NIEDDU


Credits to L. Errico


Credits to L. Pesenti

ET - suspensions



Sar-Grav may host ET technology prototypes to test them in the ET expected noise conditions.

- L. Naticchioni et al., ***Characterization of the Sos Enattos site for the Einstein Telescope***, **JPCS** 1468, 2020, https://doi.org/10.1088/1742-6596/1468/1/012242
- M. Di Giovanni et al., ***A seismological study of the Sos Enattos Area – the Sardinia Candidate Site for the Einstein Telescope***, **SRL**, 2020, https://doi.org/10.1785/0220200186
- A. Allocca et al., ***Seismic glitchness at Sos Enattos site: impact on intermediate black hole binaries detection efficiency***, **EPJP**, 2021, https://doi.org/10.1140/epjp/s13360-021-01450-8
- Others in preparation…

Thanks for the attention!!!

Credits to D. Rozza