Advanced Virgo Detector

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Outline

- Gravitational Waves and their effect on the matter
- Gravitational Waves detection
- The Virgo detector
- The detector network
- Great discoveries of Advanced GW detectors
- Future perspectives

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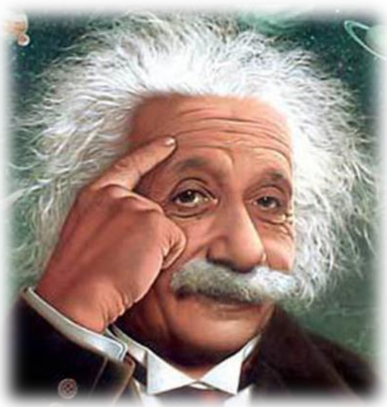
Einstein's Field Equations



$$G_{\mu\nu}(g) = 8\pi T_{\mu\nu}$$

GEOMETRY

MASS-ENERGY DISTRIBUTION

Matter tells the spacetime how to curve, and curved space tells to matter how to move (J. Wheeler)

Non-linear equation, solvable only in case of particular symmetry

The origin of Gravitational Waves

In the *weak field regime* we can linearize:

$$G_{\mu\nu}(g) = 8\pi T_{\mu\nu}$$

$$g_{\mu\nu} \approx \eta_{\mu\nu} + h_{\mu\nu}$$

Flat metric

Small perturbation $h_{\mu\nu} \ll 1$

Notice that GWs travel at the speed of light (so far confirmed by the observations)

$$\left(-\frac{1}{c^2}\frac{\partial^2}{\partial t^2} + \frac{\partial^2}{\partial x_i^2}\right) h_{\mu\nu} = 0$$

$$h_{\mu\nu} = \varepsilon_{\mu\nu} \exp[i(\omega_{GW} t - \mathbf{k} \cdot \mathbf{r})]$$

Gravitational Waves polarization

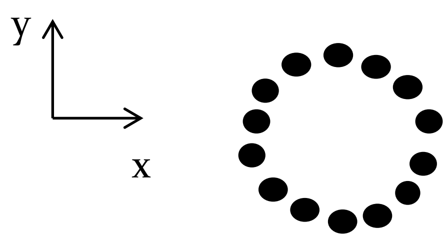
$$h_{\mu\nu} = \varepsilon_{\mu\nu} \exp[i(\omega_{GW} t - \mathbf{k} \cdot \mathbf{r})]$$

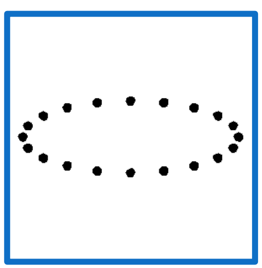
2 degrees of freedom

+ polarization

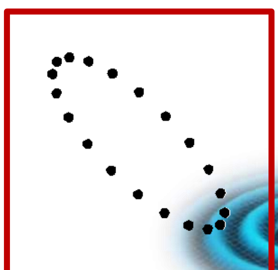
$$\varepsilon_{\mu\nu} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & h^{+} & h^{\times} & 0 \\ 0 & h^{\times} & -h^{+} & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

× polarization





For a wave travelling in the z direction…



GW amplitude and their effect: what we want to measure

The amplitude of gravitational waves is proportional to the quadrupole moment of the source masses through the constant **$G/c^4 \approx 10^{-45}\ N^{-1}$**

$$h_{jk}^{TT} = \frac{2G}{rc^4}\left(\frac{d^2 I_{jk}^{TT}}{dt^2}\right)_{t-r/c}$$

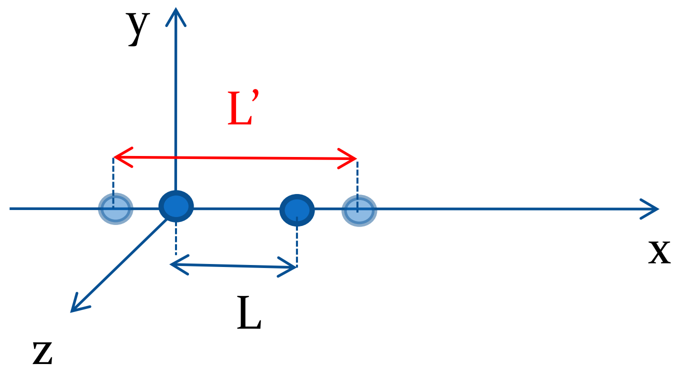
→ Only astrophysical sources can produce detectable effects

Binary compact objects (BBH, BNS, BH-NS), pulsars, bursts, stochastic background

The effect of Gravitational Waves on free falling masses

GW amplitude

$$\delta L \propto h\, L$$



Very weak amplitude: $\boldsymbol{h \approx 10^{-21}}$ for GW produced by huge astrophysical sources

The distance between two free-falling masses separated by ~Km will change by
$\boldsymbol{\delta L \approx 10^{-18}\mathrm{m}}$

"That is comparable to a hair's-width change in the distance from the Sun to Alpha Centauri, its nearest star".

The effect of Gravitational Waves on free falling masses

GW amplitude

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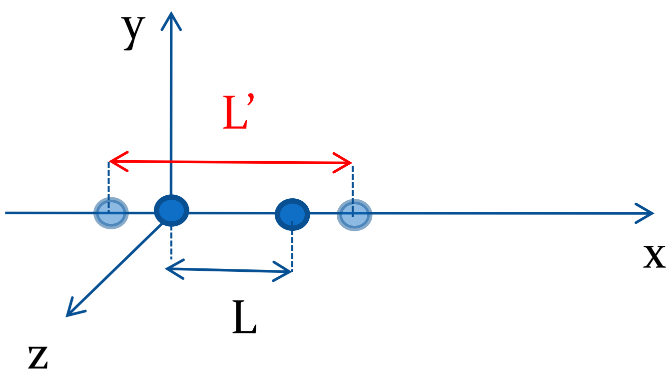

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“That is comparable to a hair’s-width change in the distance from the Sun to Alpha Centauri, its nearest star”.

How small is “small”? Let’s get the feeling…

Let’s suppose you pour a **glass of wine** into the **ocean**.

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

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

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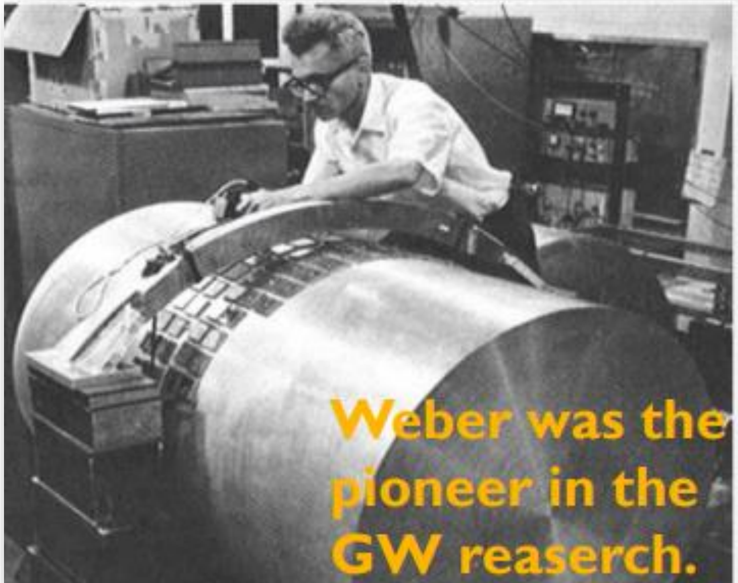
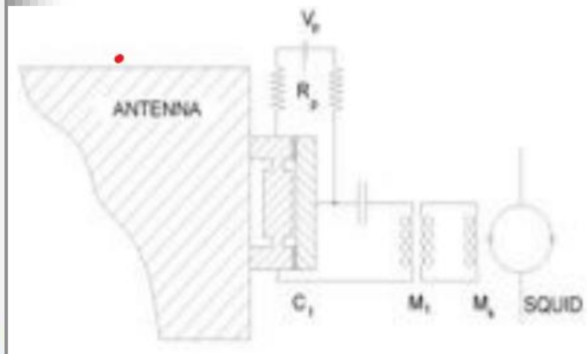
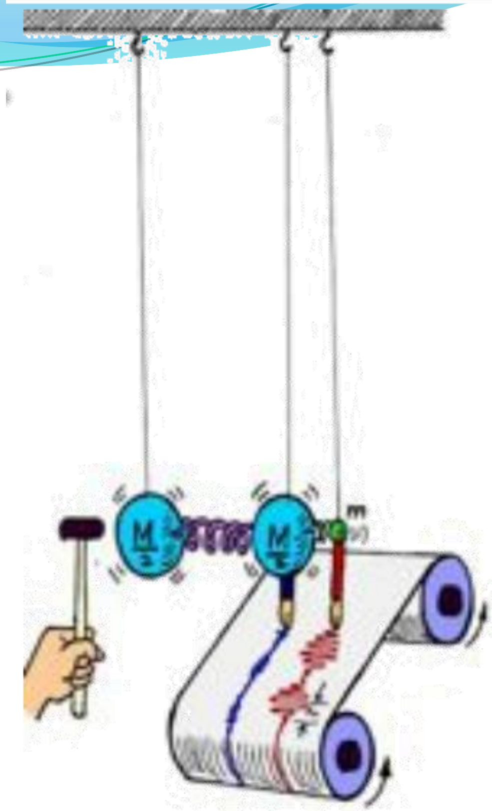
HOW DO WE MEASURE THE EFFECT OF GRAVITATIONAL WAVES?

First attempt: resonant bars







The working principle:

- The gravitational wave induces a vibration in the larger mass
- A coupled smaller mass vibrates with a larger amplitude

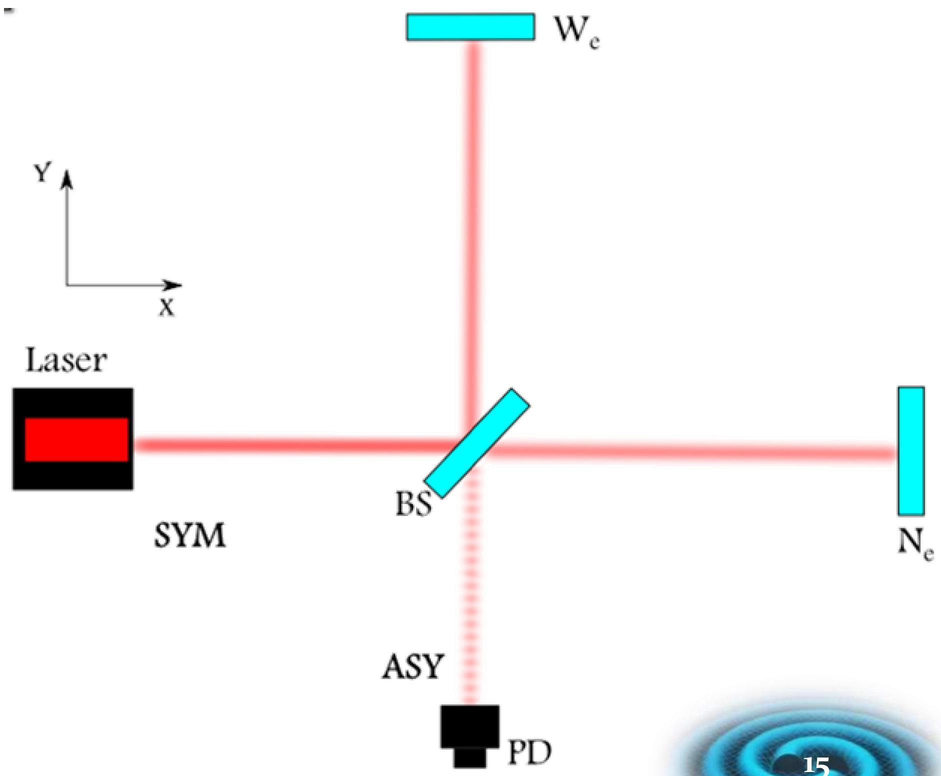
Sensitivity too low. Despite the claims, did not detect any GW

Michelson Interferometry to detect GWs

$$\delta L \propto h\, L$$

Use an interferometer as a transducer: convert **displacements** into **optical signals**

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



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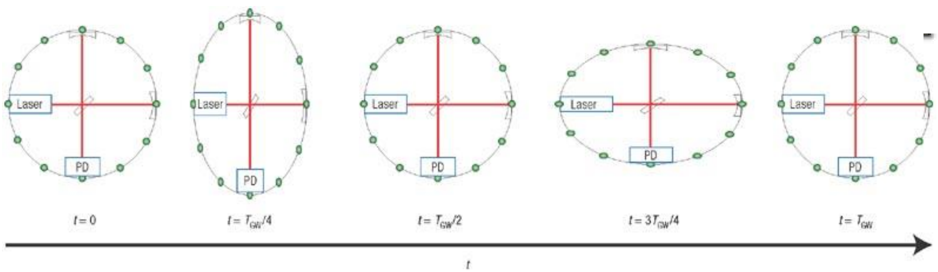
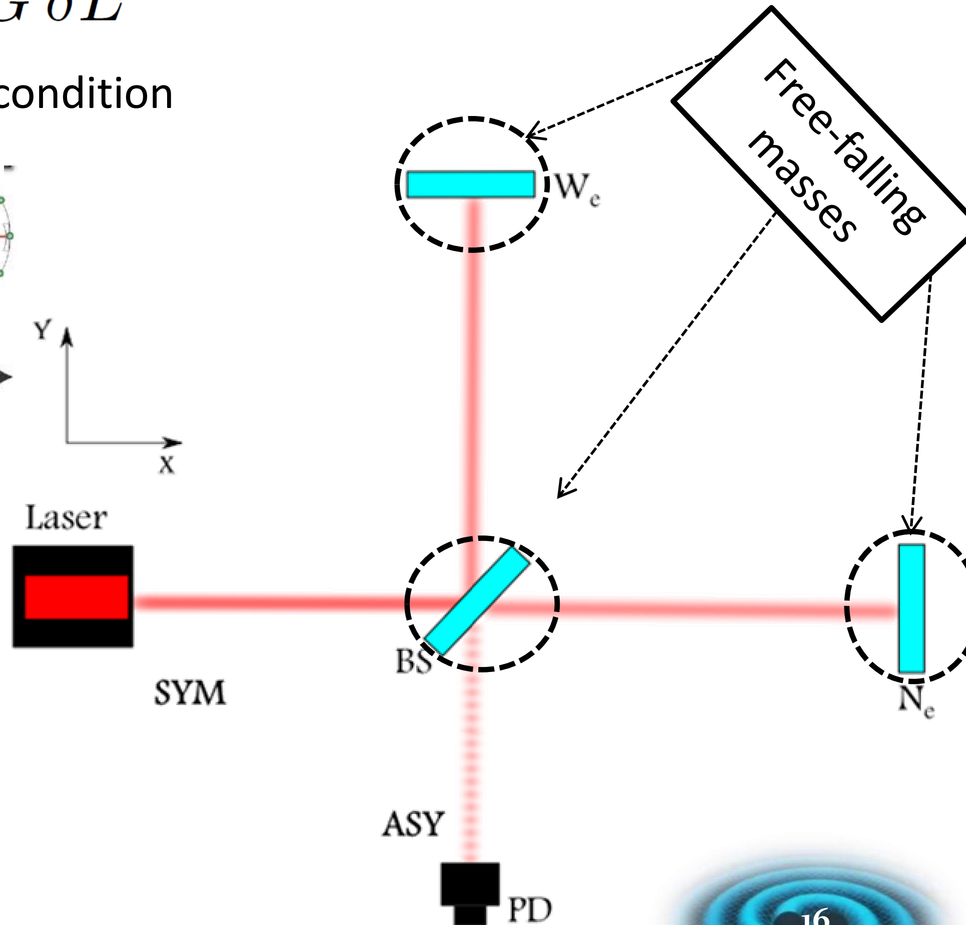
Suspended mirrors to reproduce the free-fall condition





GWs produce a differential variation of the arm lengths which is revealed at the ***antisymmetric port*** (ASY) of the interferometer

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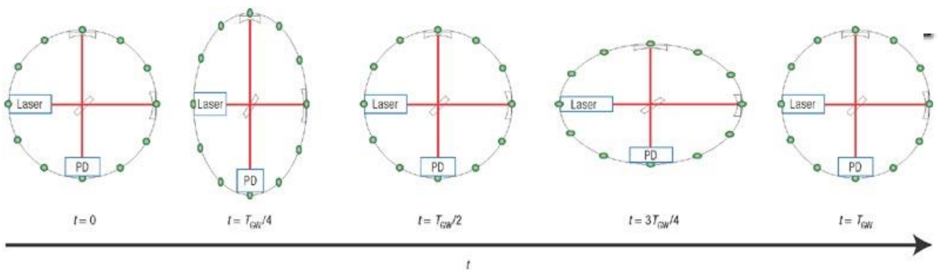
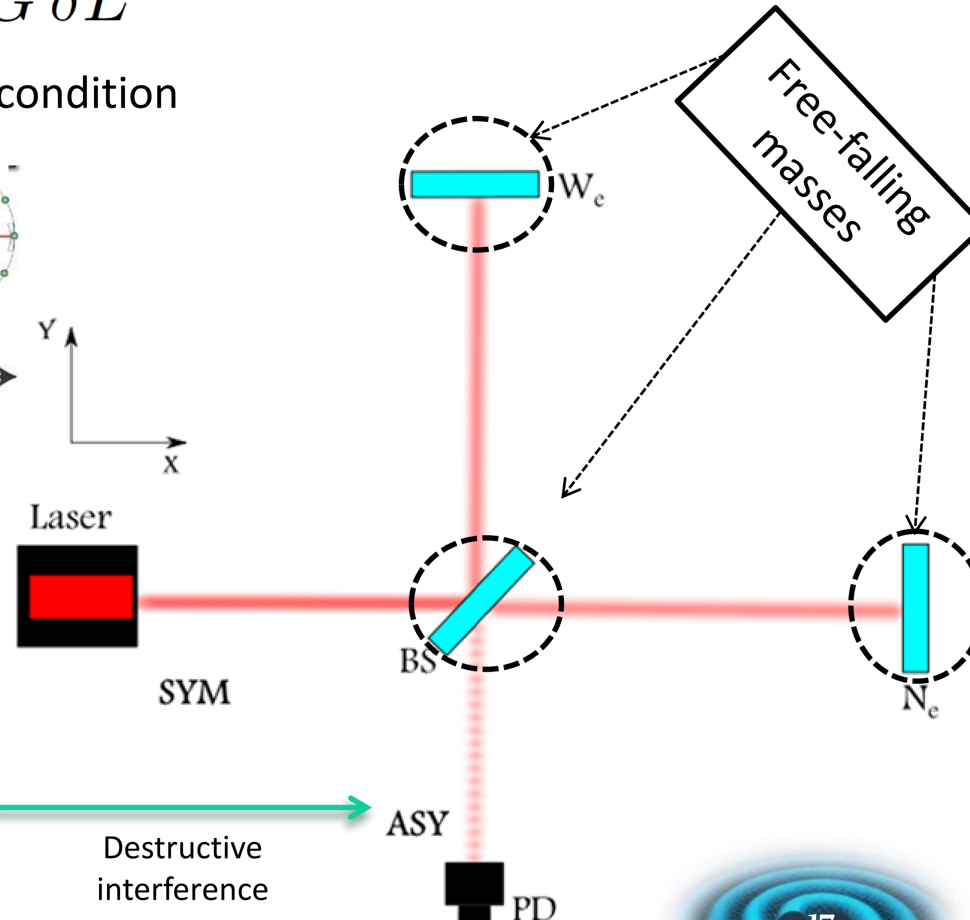
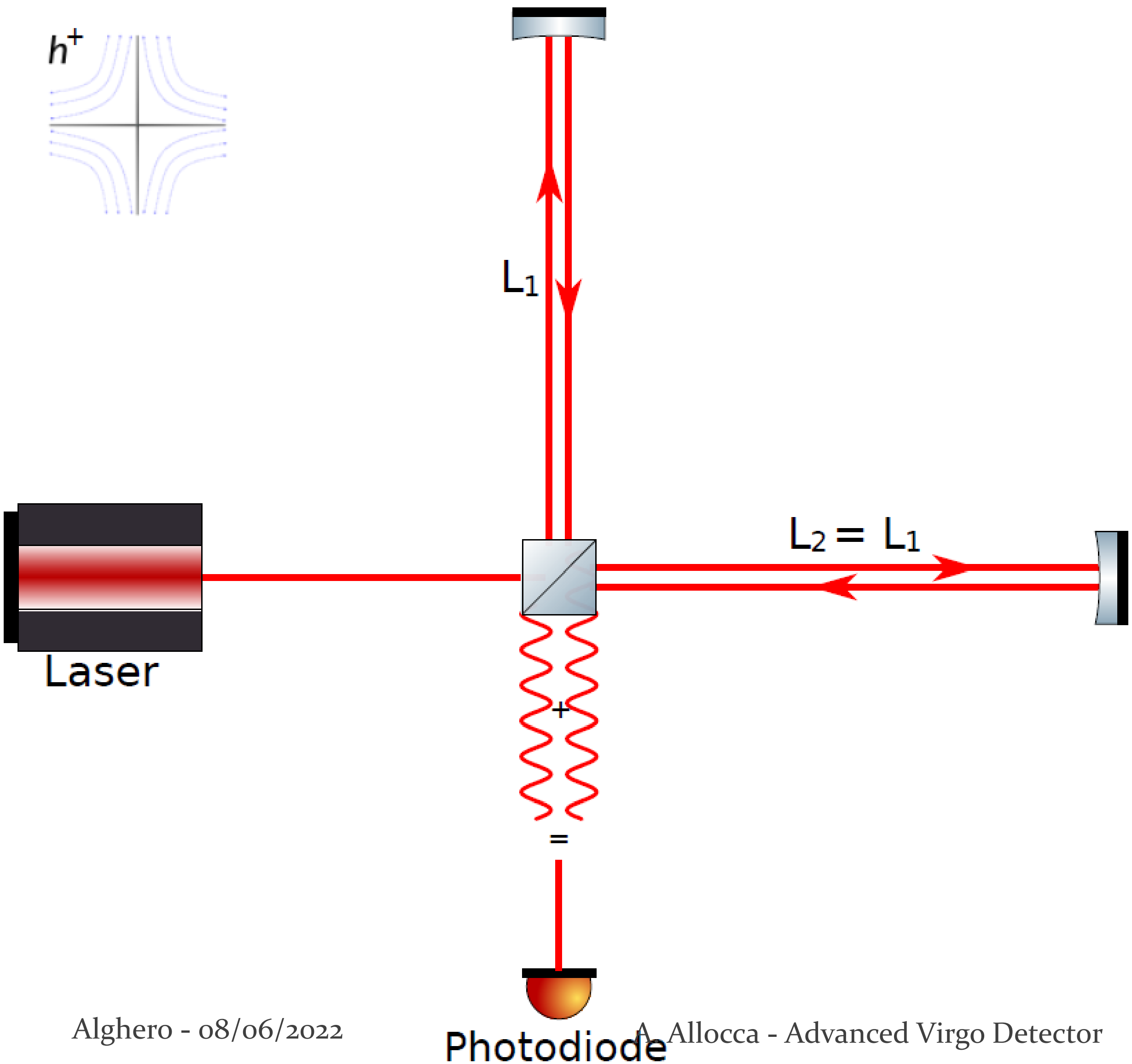


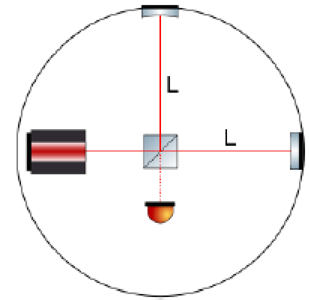
GWs produce a differential variation of the arm lengths which is revealed at the ***antisymmetric port*** (ASY) of the interferometer

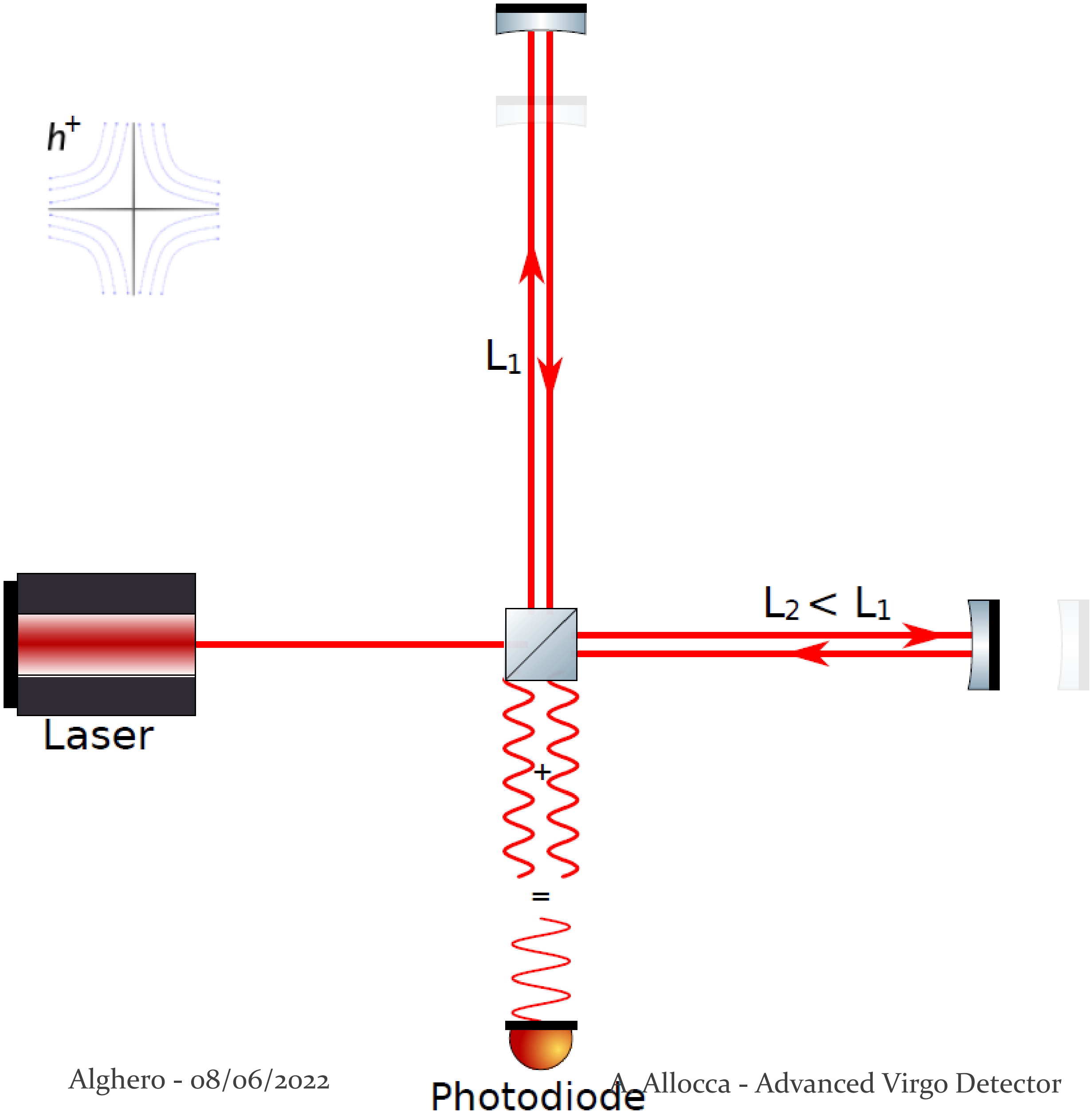
Interferometer working point: **dark fringe** condition (to be more sensitive to power variation due to a Gravitational Wave)



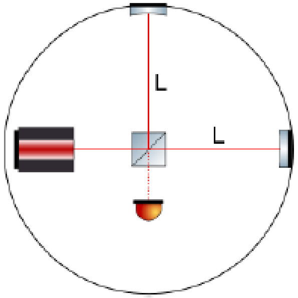
Interferometer response to h^+



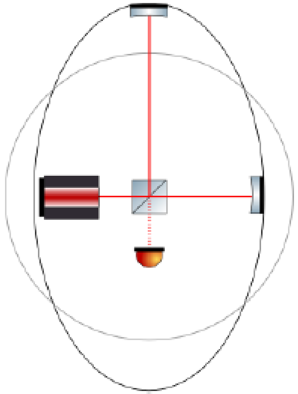




h+
L1
L2 < L1
Laser
+
=
Photodiode



L
L



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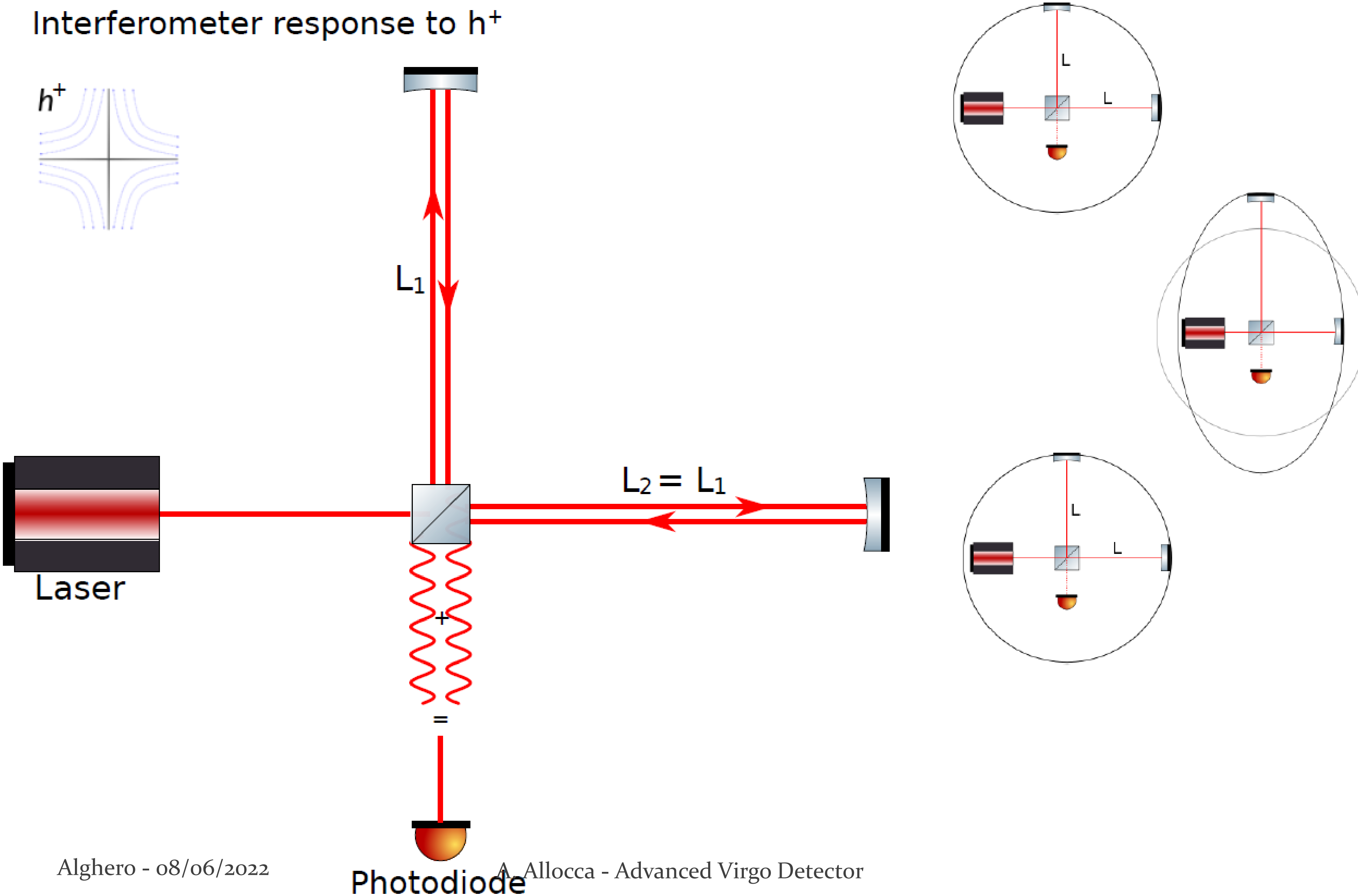

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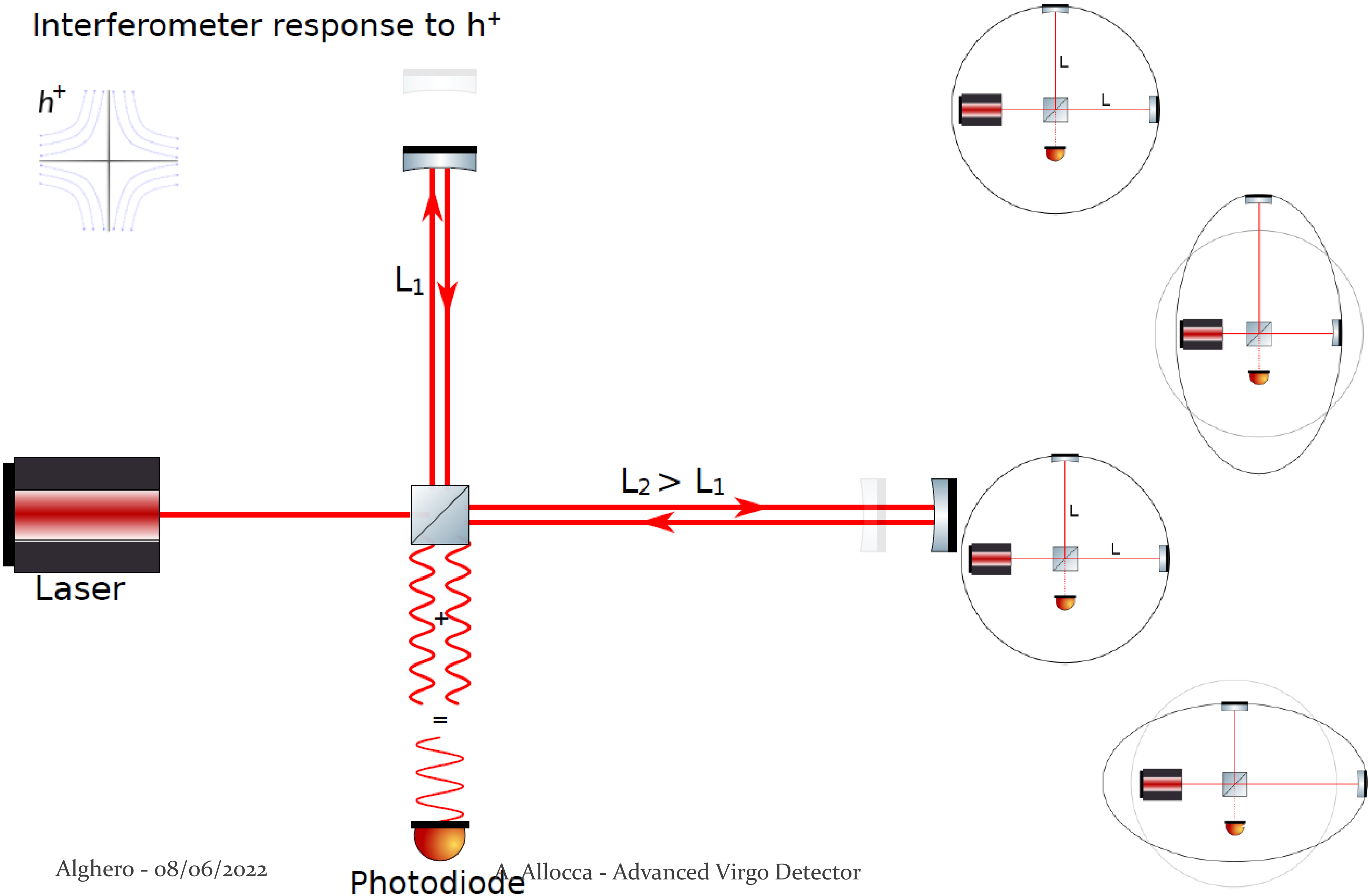

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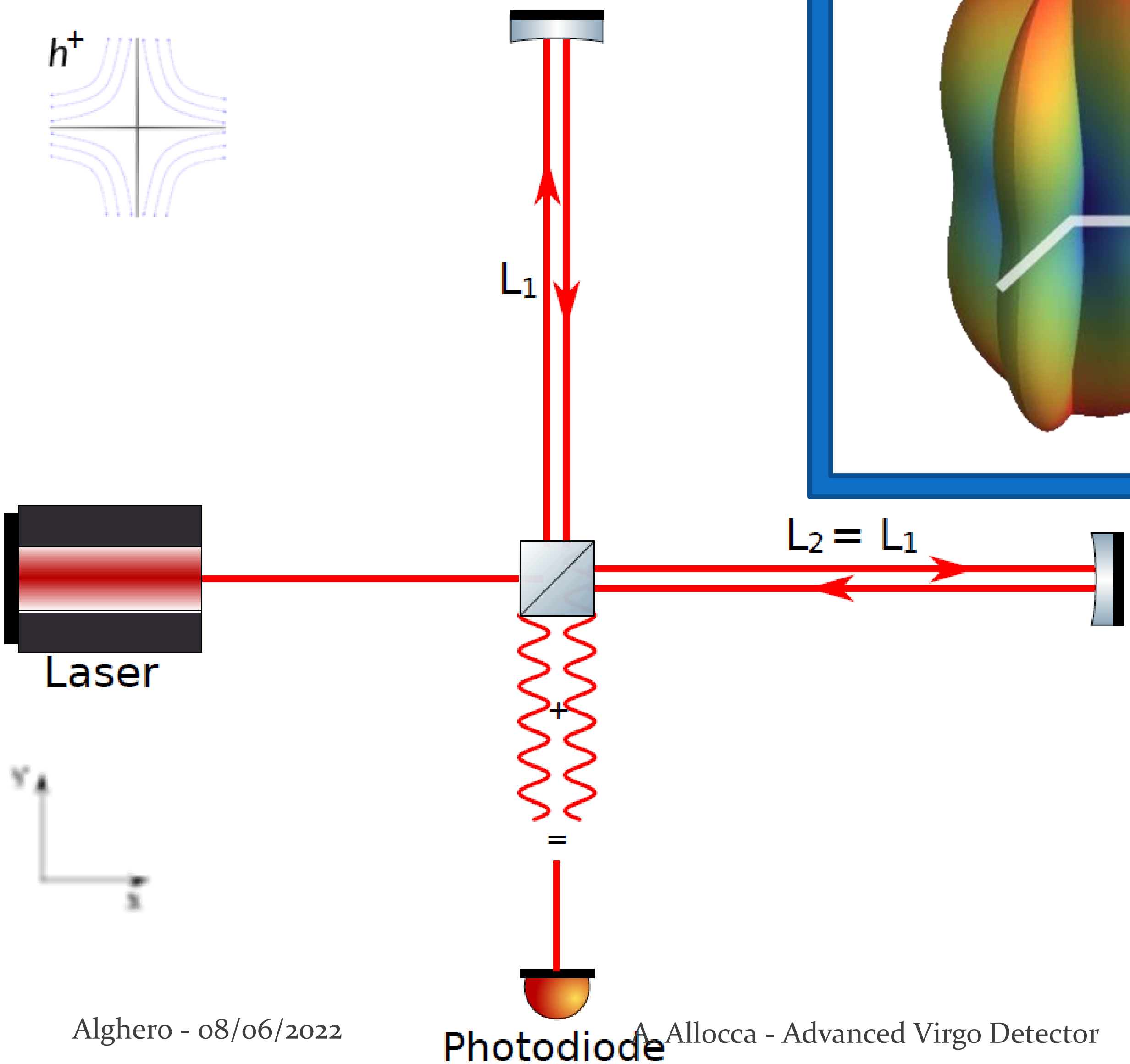
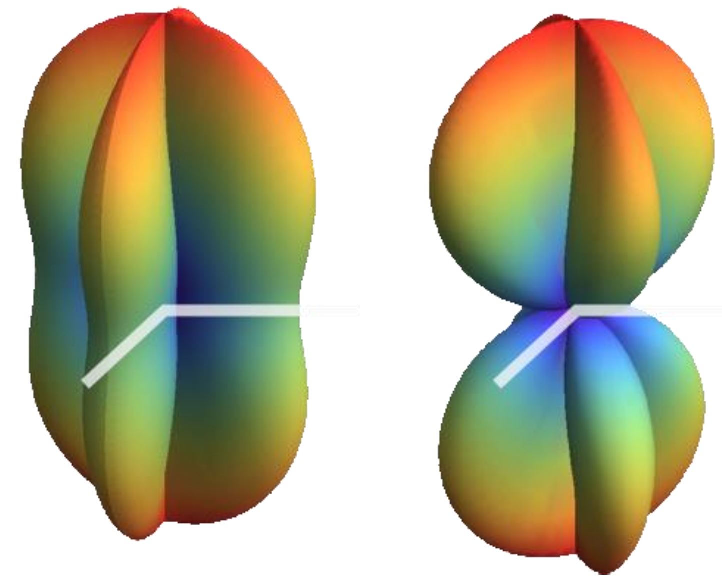


Interferometer response along the xy plan to a «+» polarized and «x» polarized GW



Antenna pattern

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The VIRGO interferometer

The VIRGO interferometer

9 European countries
More than 70 Institutes,
~300 authors

European collaboration

A challenge against noise

Enhance the signal

Reduce the noise

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Enhance the signal

Reduce the noise

Michelson Interferometry to detect GWs

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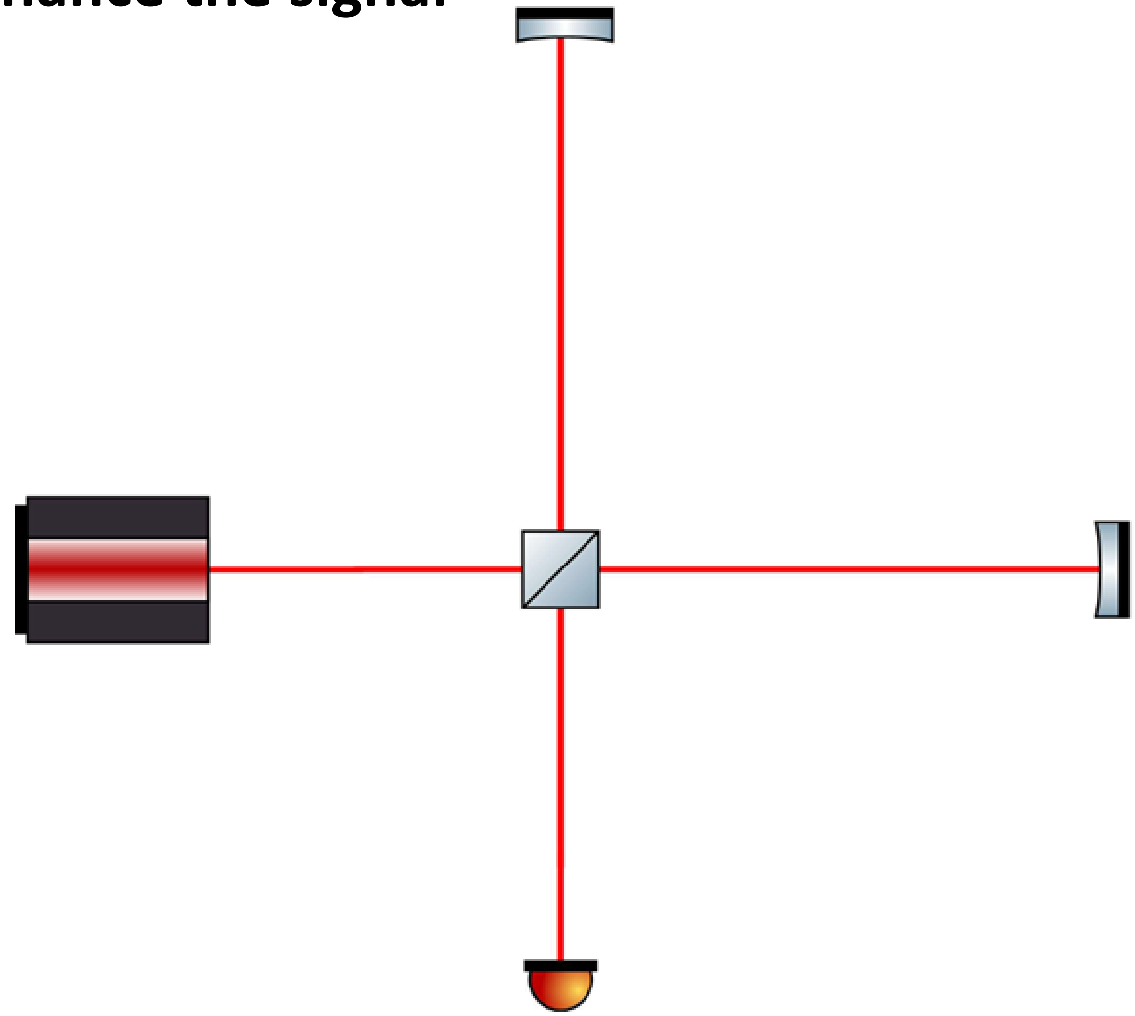
Enhance the signal



Michelson Interferometry to detect GWs

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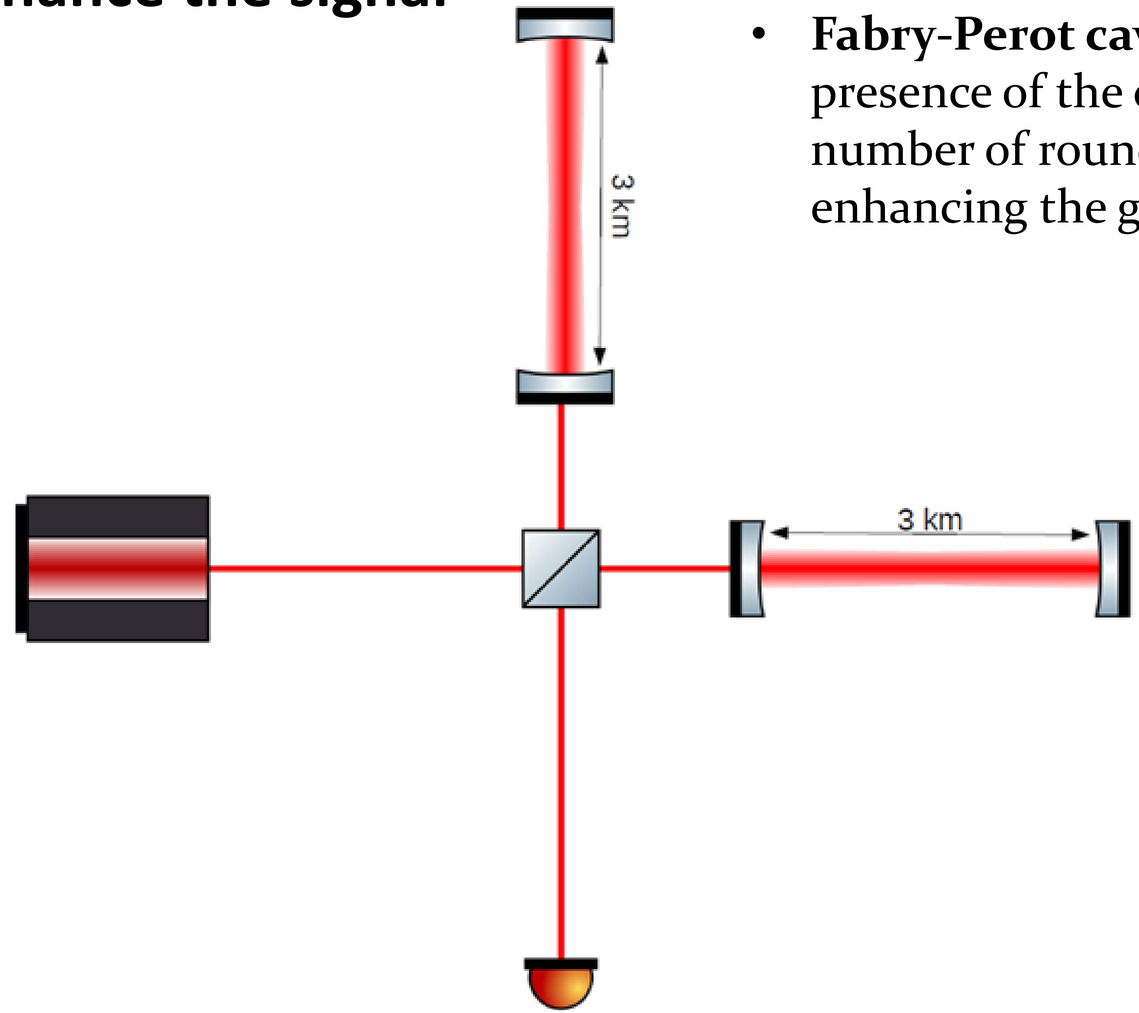
Enhance the signal

- **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



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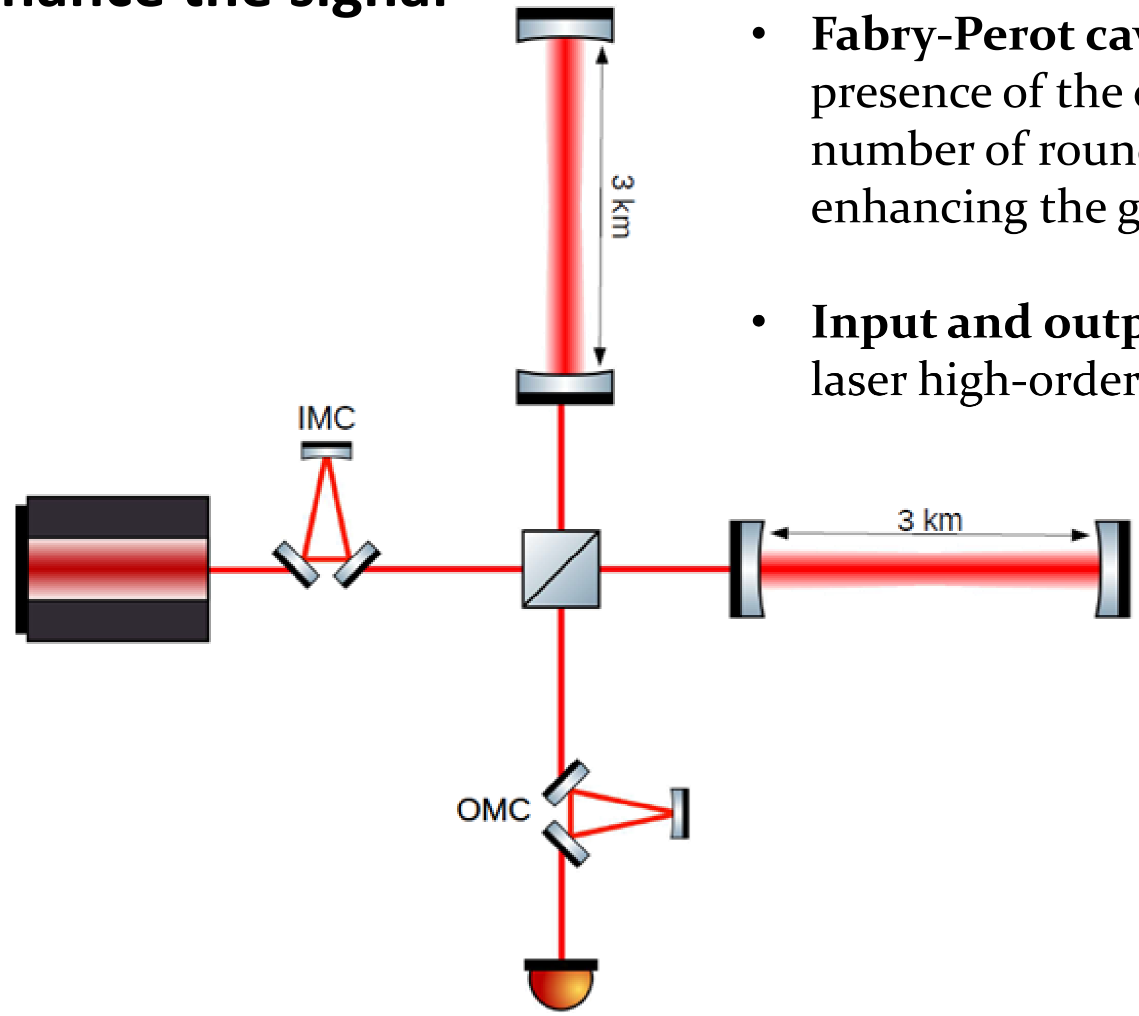

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- **Input and output mode cleaner** to reject the laser high-order modes

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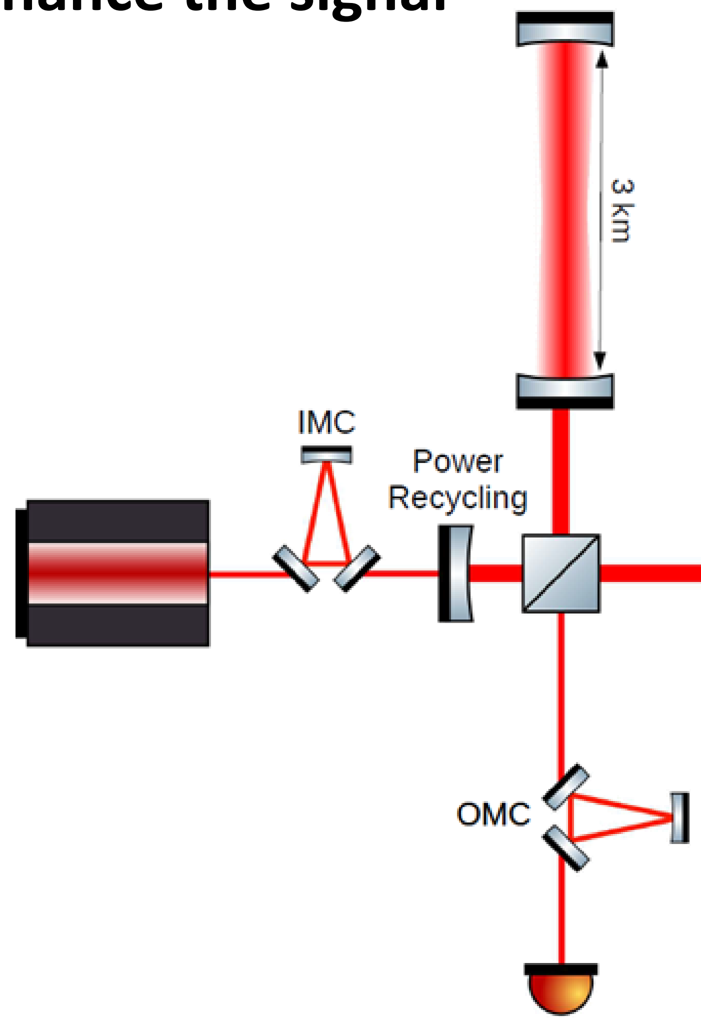

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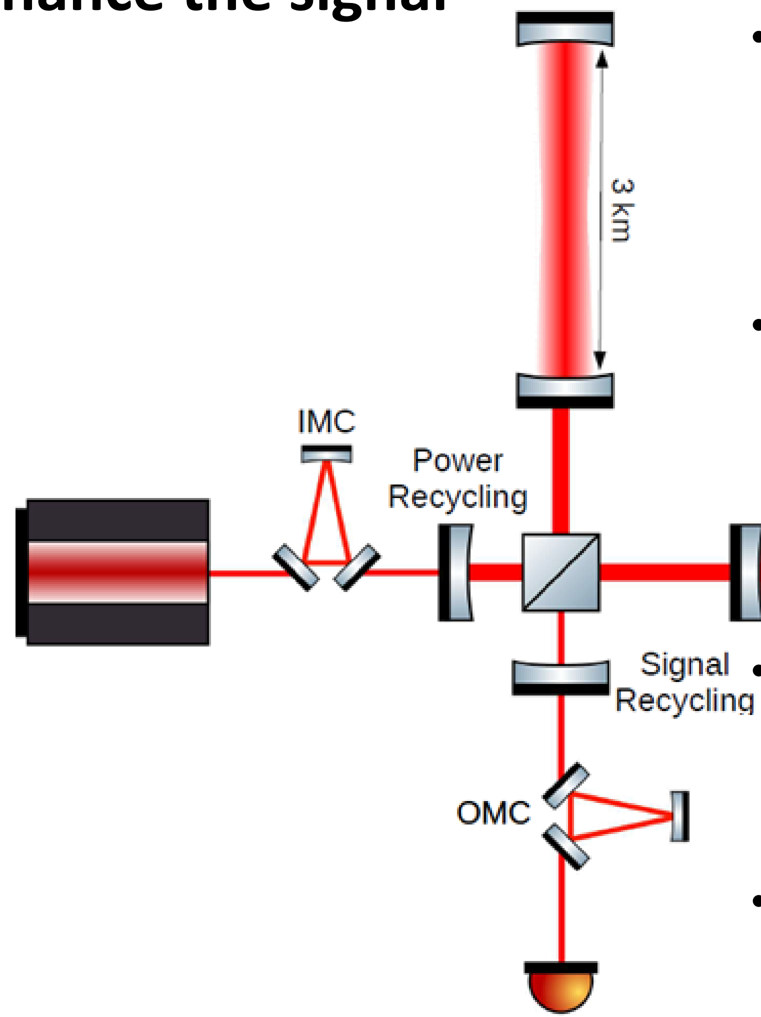
Enhance the signal



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- **Signal Recycling mirror** to reshape the detector frequency response

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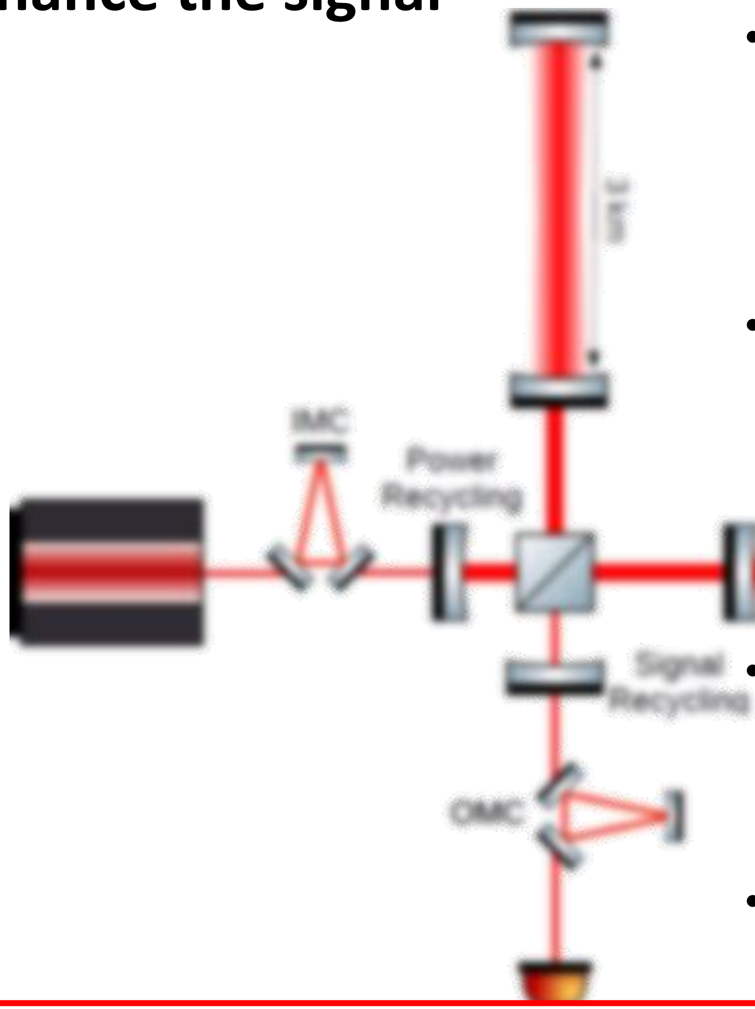

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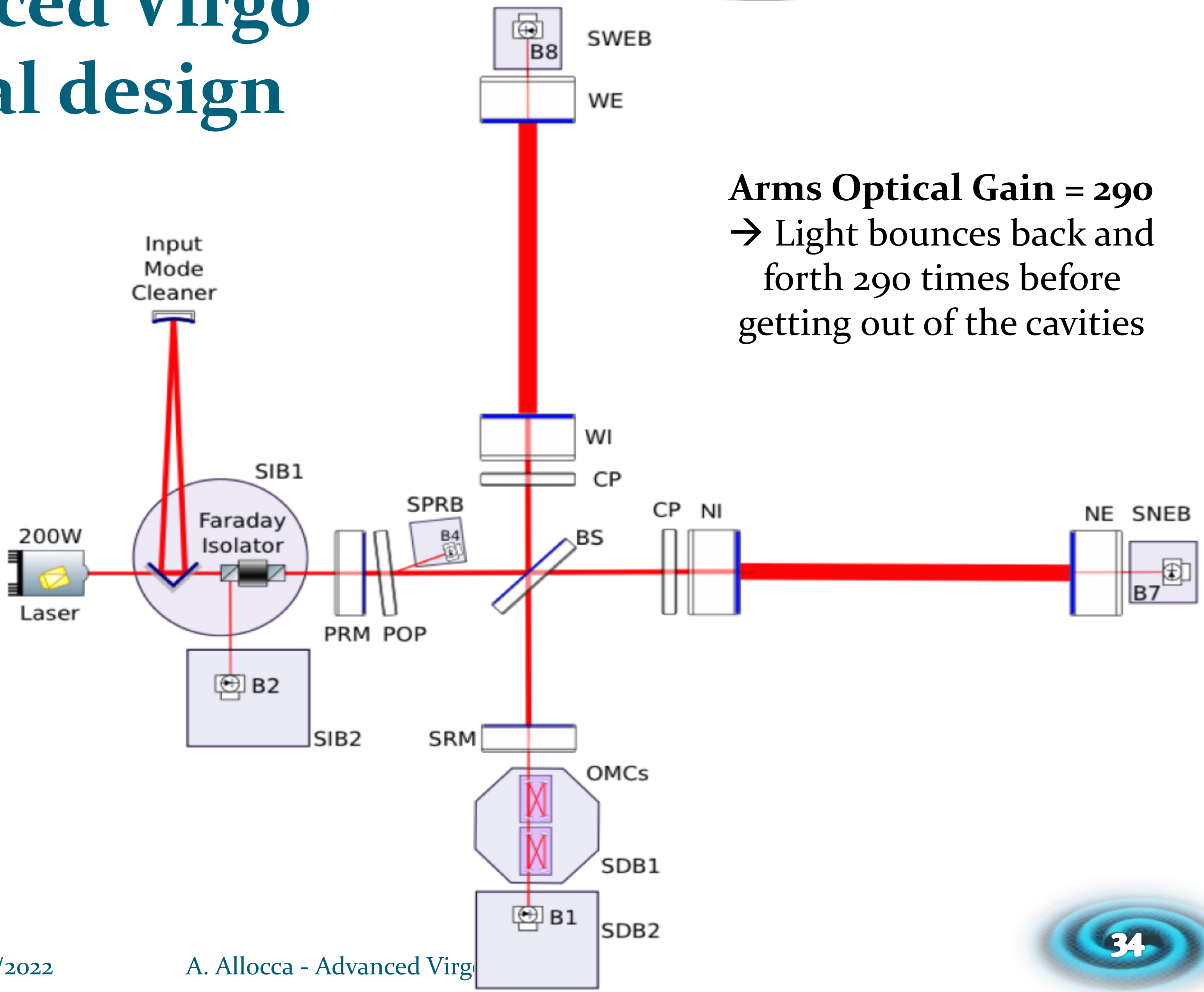
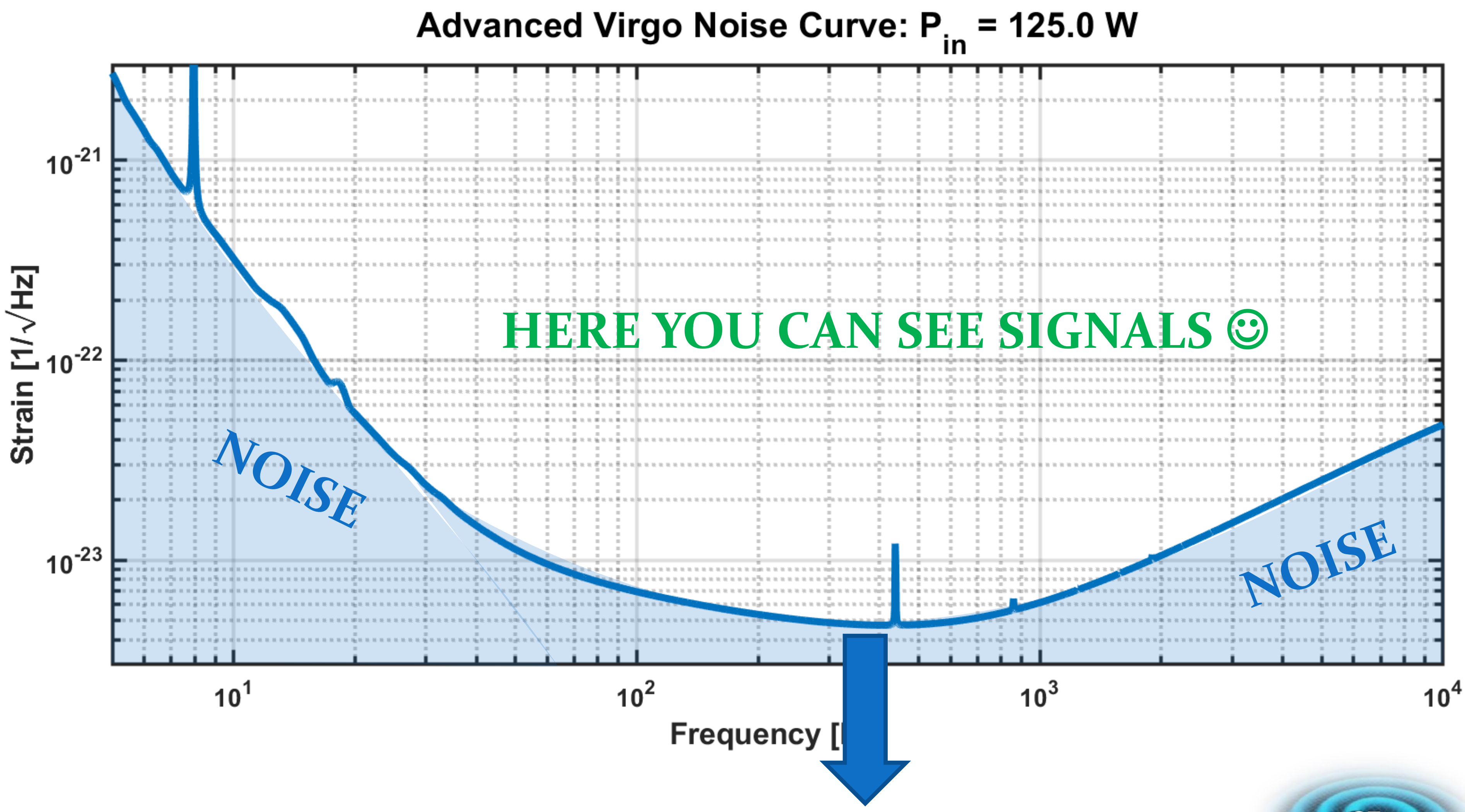
*For a **good sensitivity**: limit effects preventing the perfect destructive interference between recombining beams*

Advanced Virgo optical design



Arms Optical Gain = 290
→ Light bounces back and forth 290 times before getting out of the cavities

Advanced Virgo design sensitivity curve

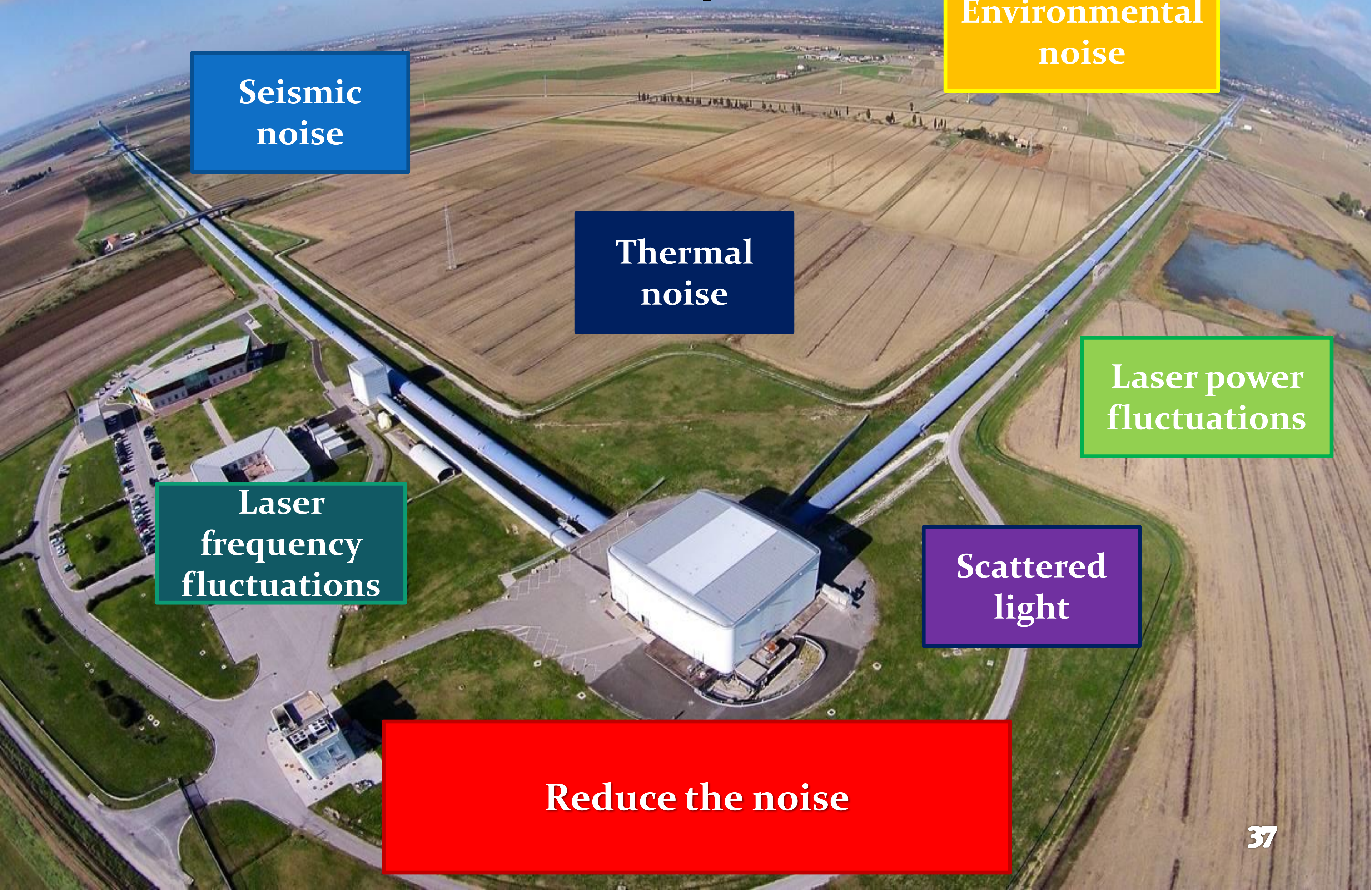


A challenge against noise

Enhance the signal / **Reduce the noise**

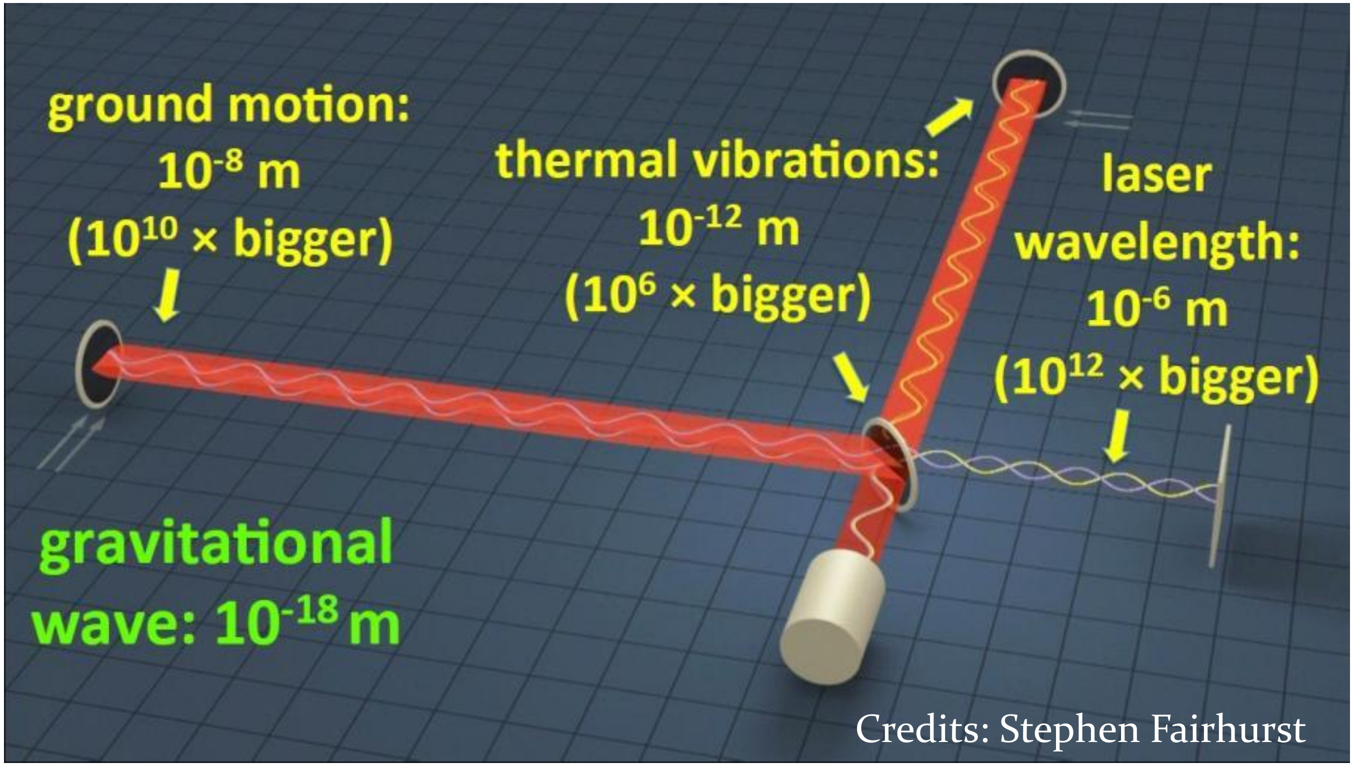
«Displacement» noises

Noises whose effect «mimics» the test mass displacement



Meet the Villain: Noise!

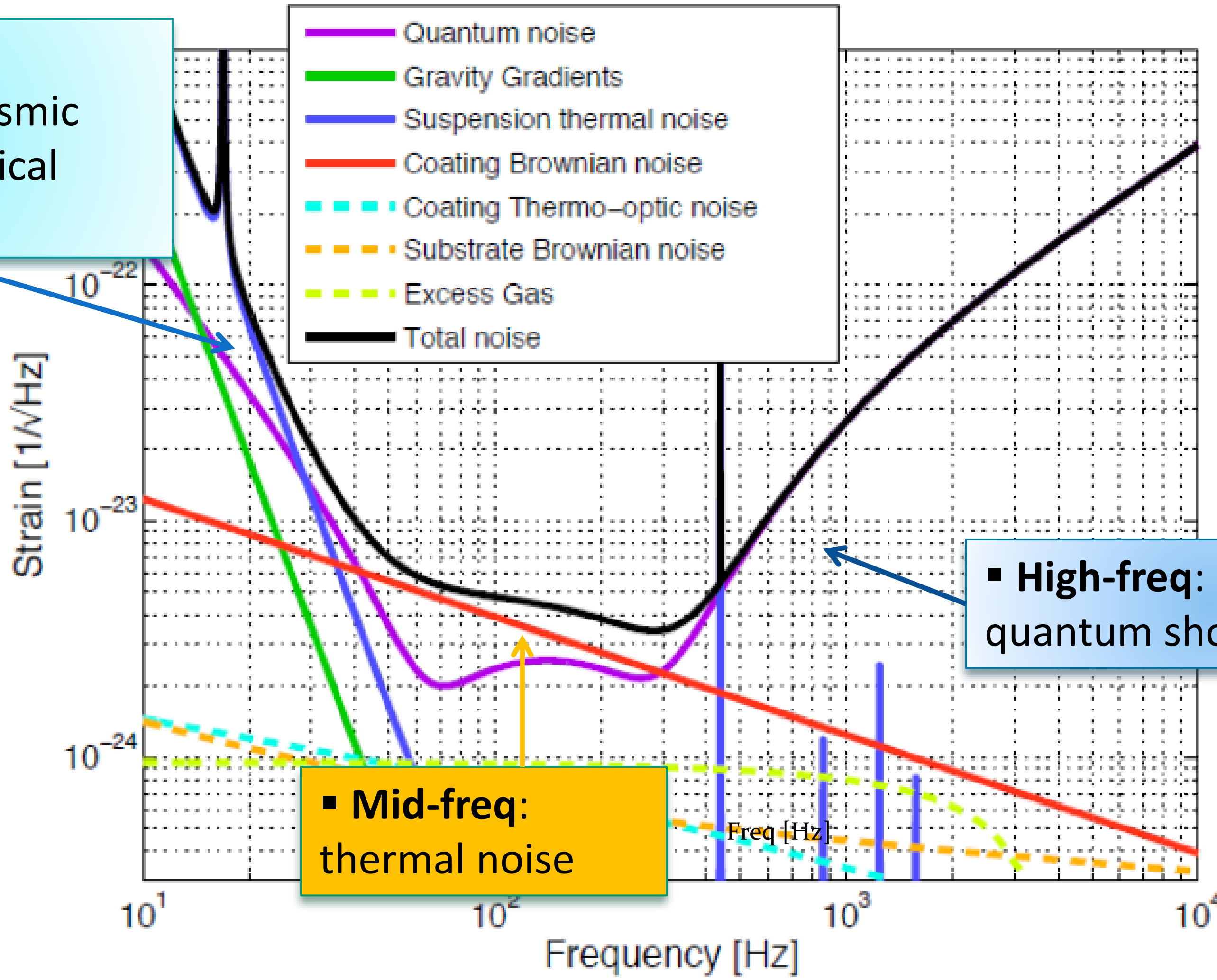
Doesn't matter how sensitive you are,
if your noise is billions of times your signal



Advanced Virgo sensitivity curve

Sum of limiting noises at different frequency ranges:

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



- **Mid-freq**: thermal noise

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

Advanced Virgo sensitivity curve

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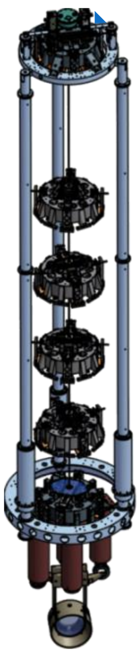
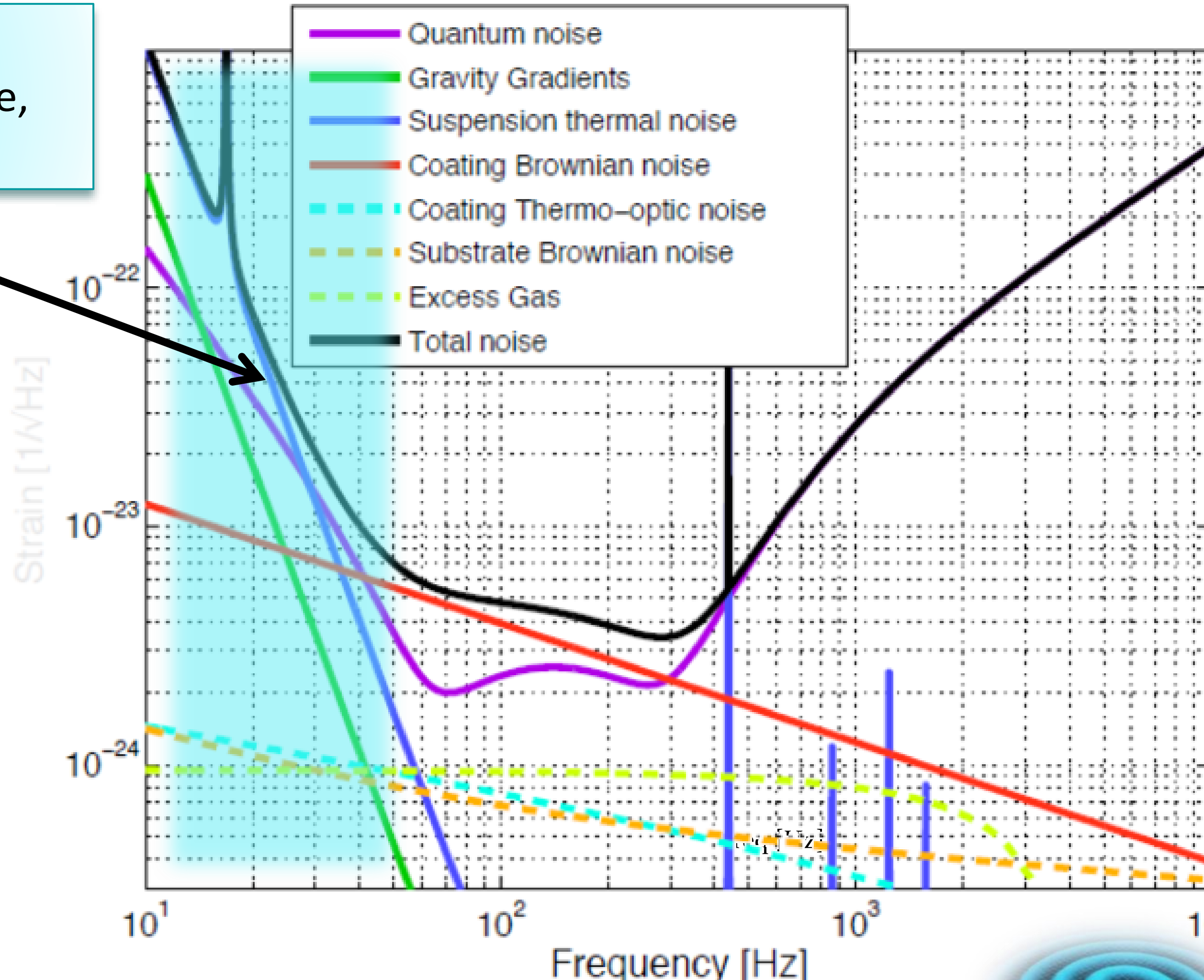


Seismic isolation:

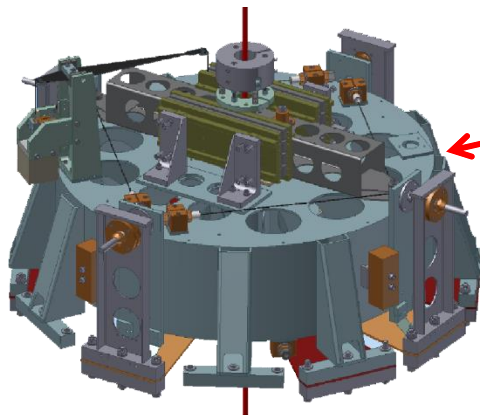
- Superattenuators to reduce seismic vibrations

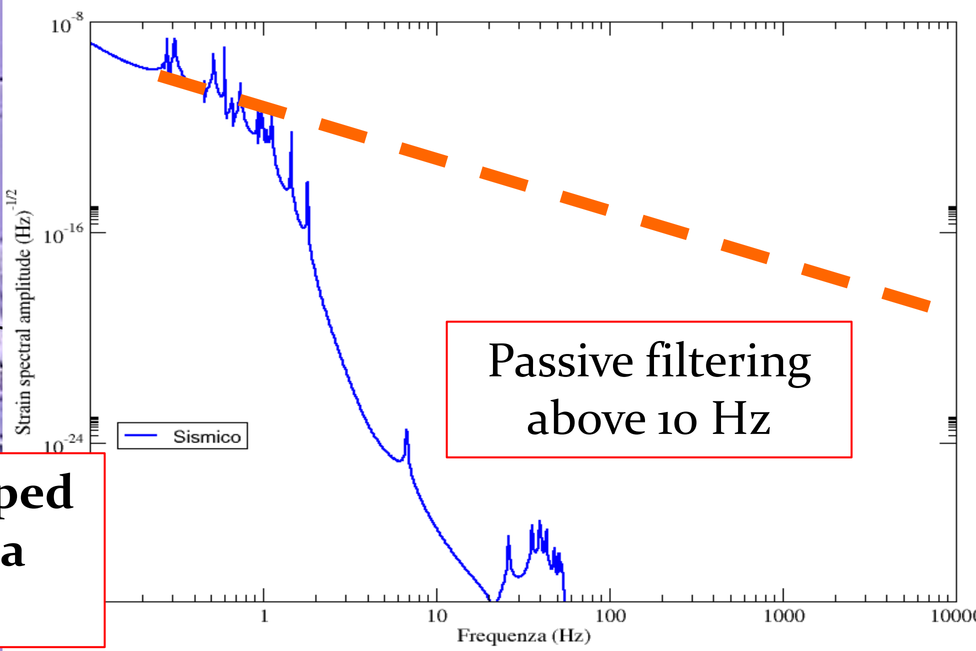


The Superattenuator

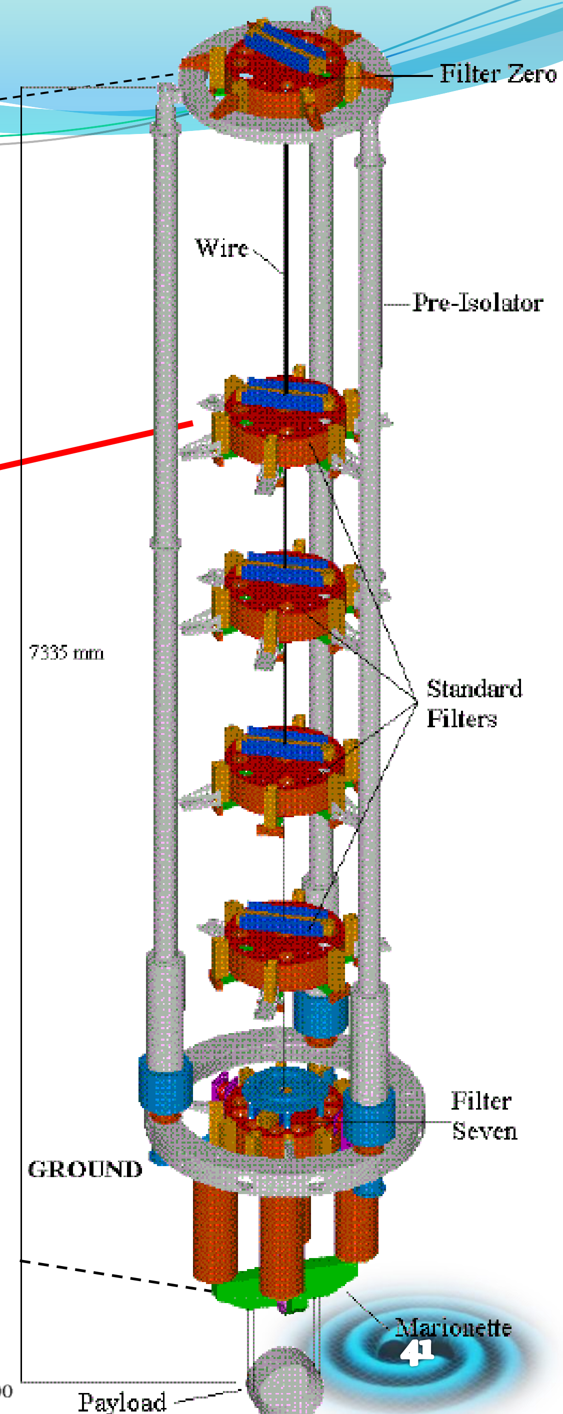
Reduces mirrors seismic vibrations by a factor 10^{12}

Standard Filter

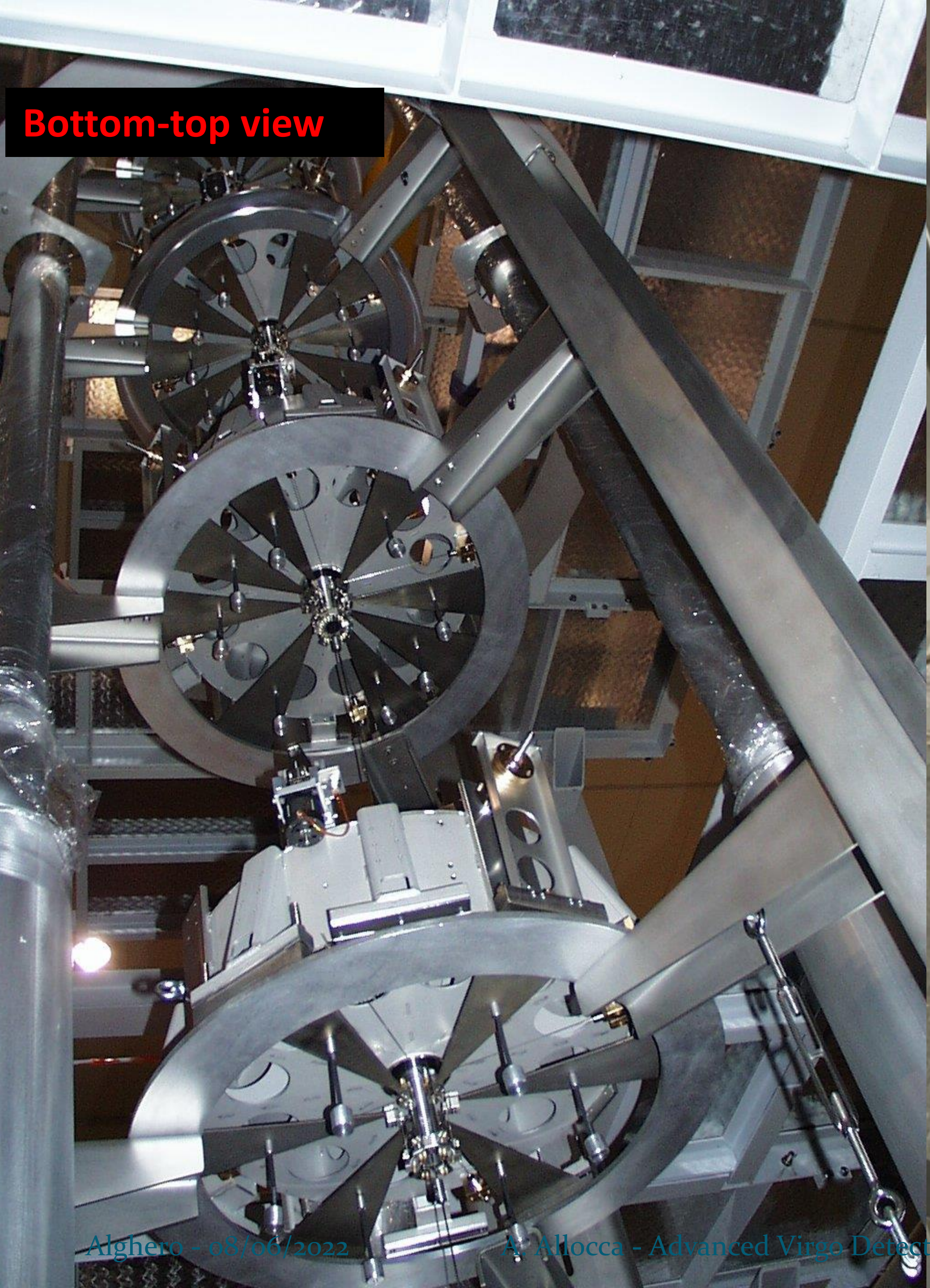
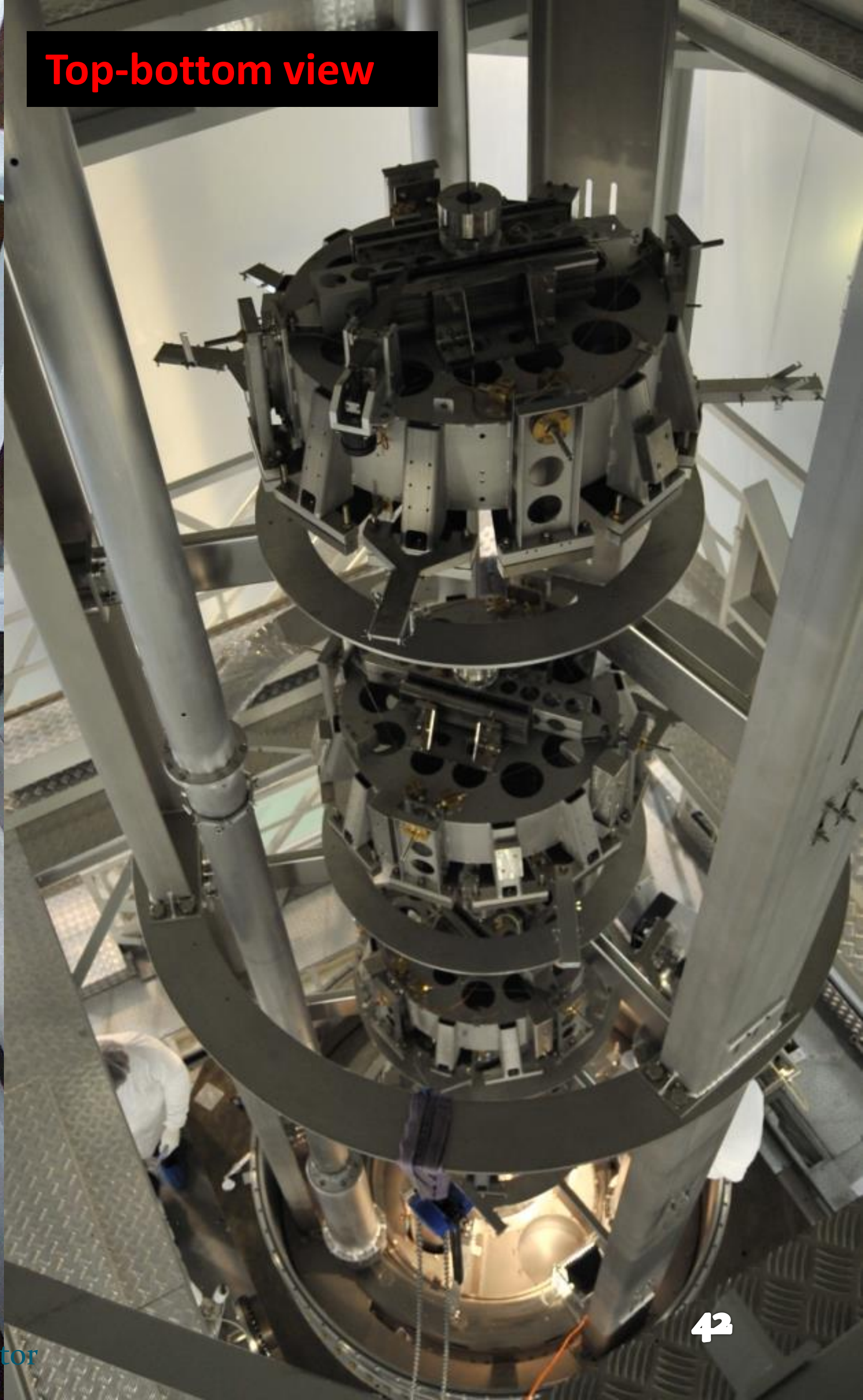




Passive filtering above 10 Hz

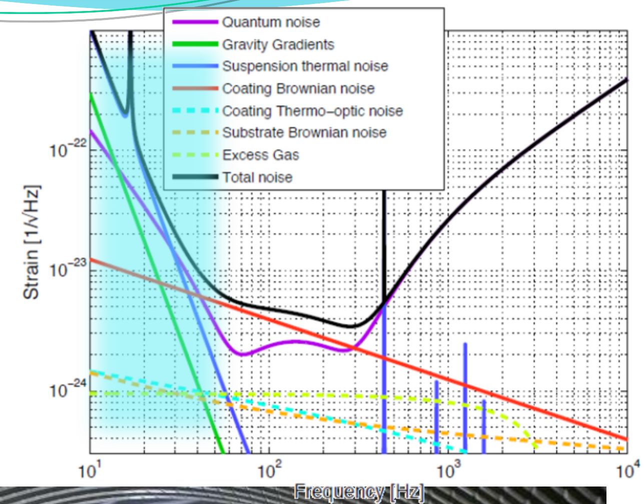


Entirely developed and built by Pisa group


Bottom-top view

Top-bottom view

Coping with Noise

- Low frequency range:
  - gas pressure noise



Ultra High Vacuum

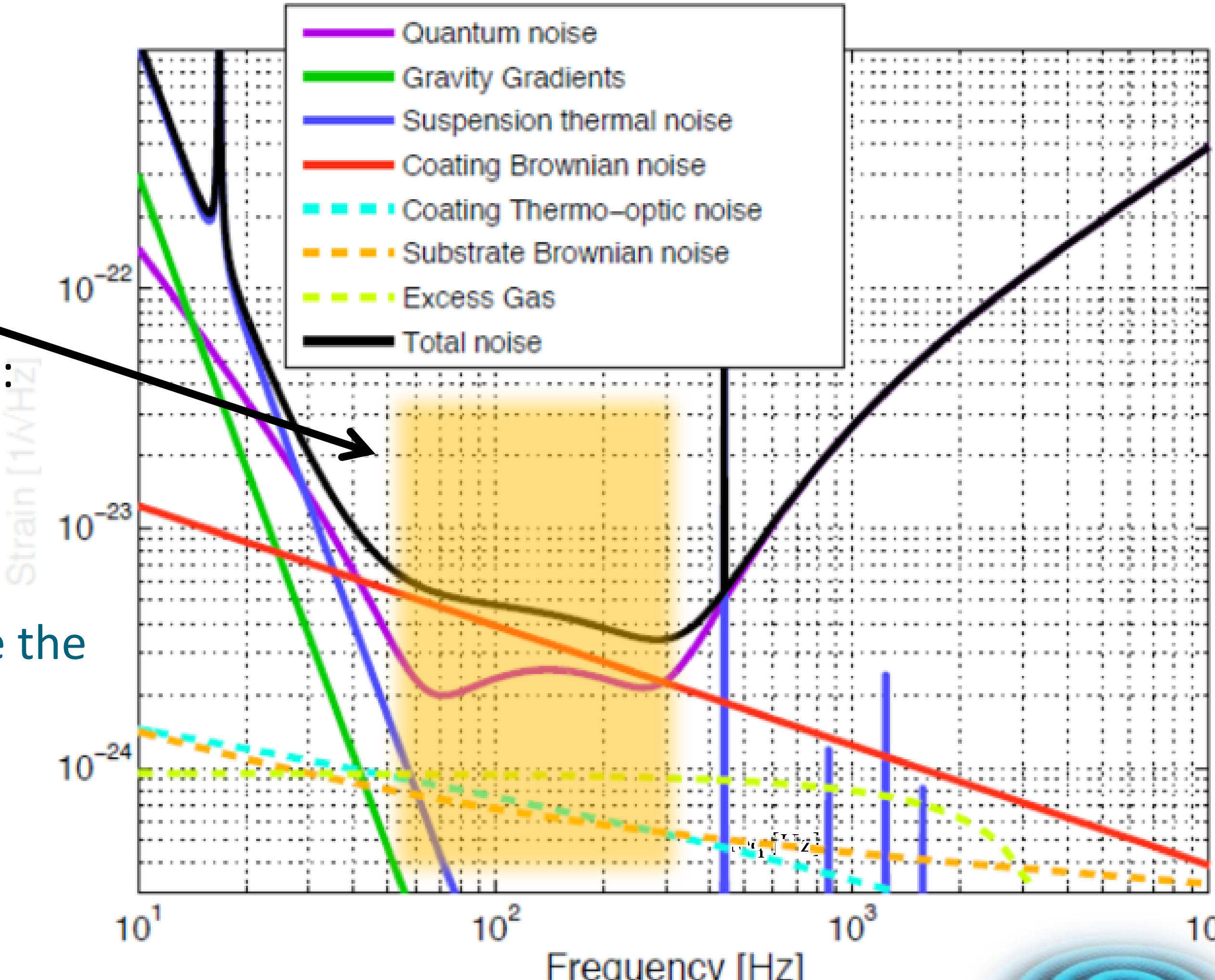
It has a total volume of 7000 m^3 and is kept at a pressure of 10^{-9} mbar : the biggest *ultra-high-vacuum* system in Europe!

AdV design

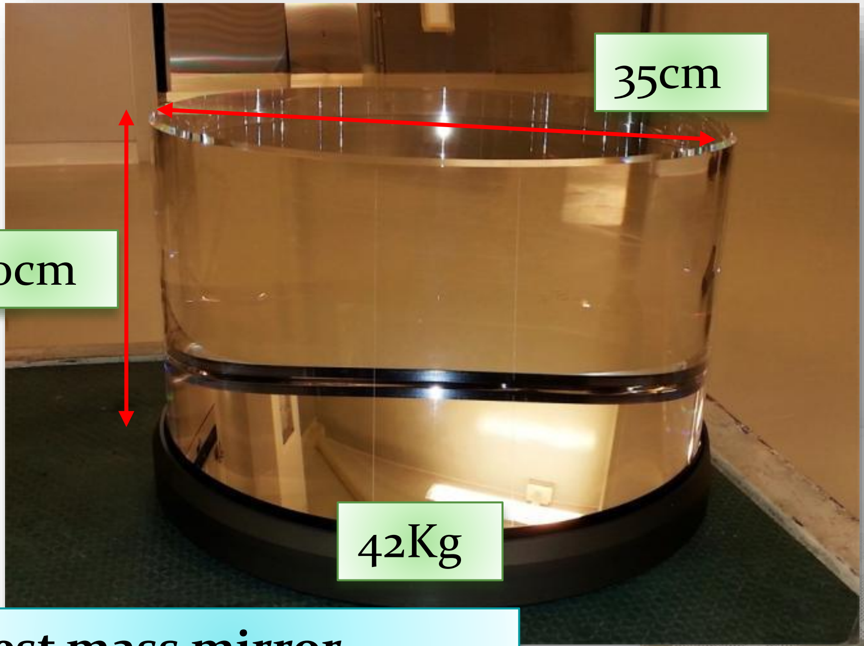
Limiting noises at different frequency ranges:

▪ **Mid-freq**: thermal noise

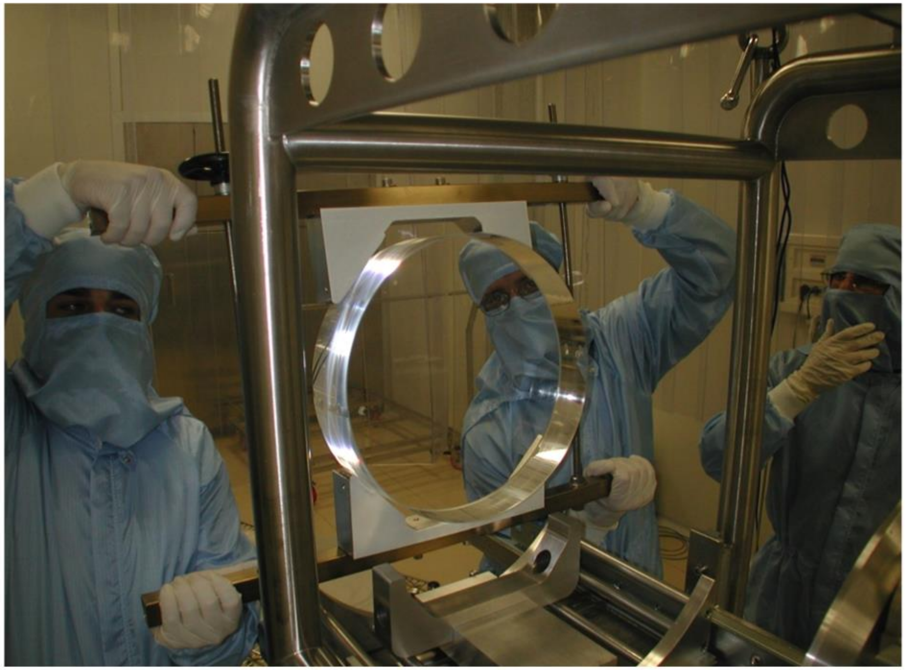
- Reducing thermal noise:
  - beam size as large as possible
  - State-of-art coating techniques to reduce the losses
  - SiO_2 Monolithic suspensions

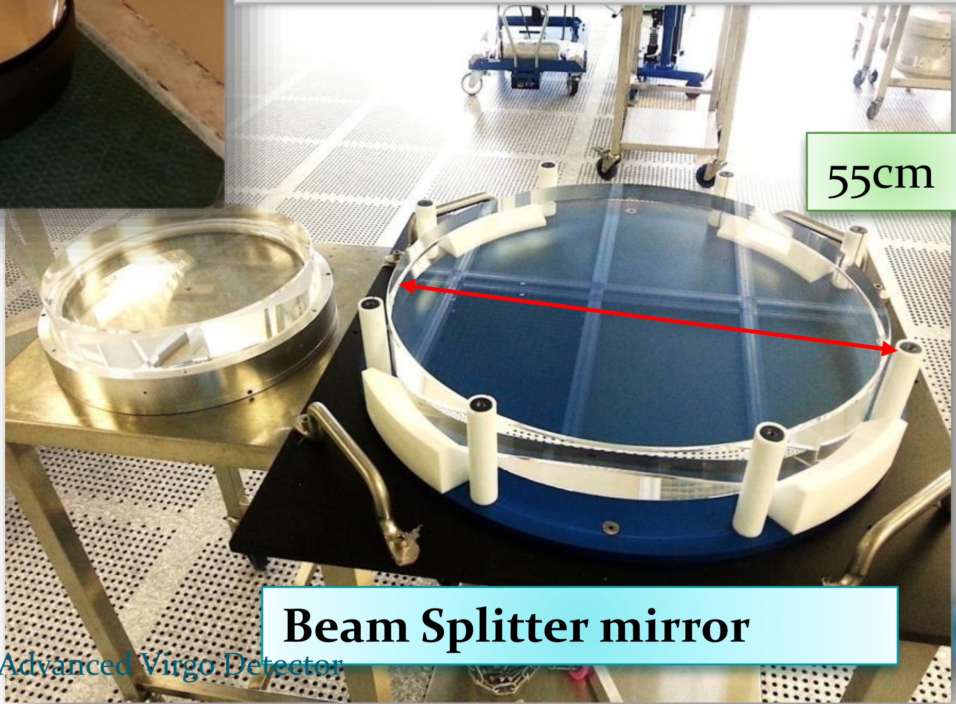


The mirrors



Test mass mirror



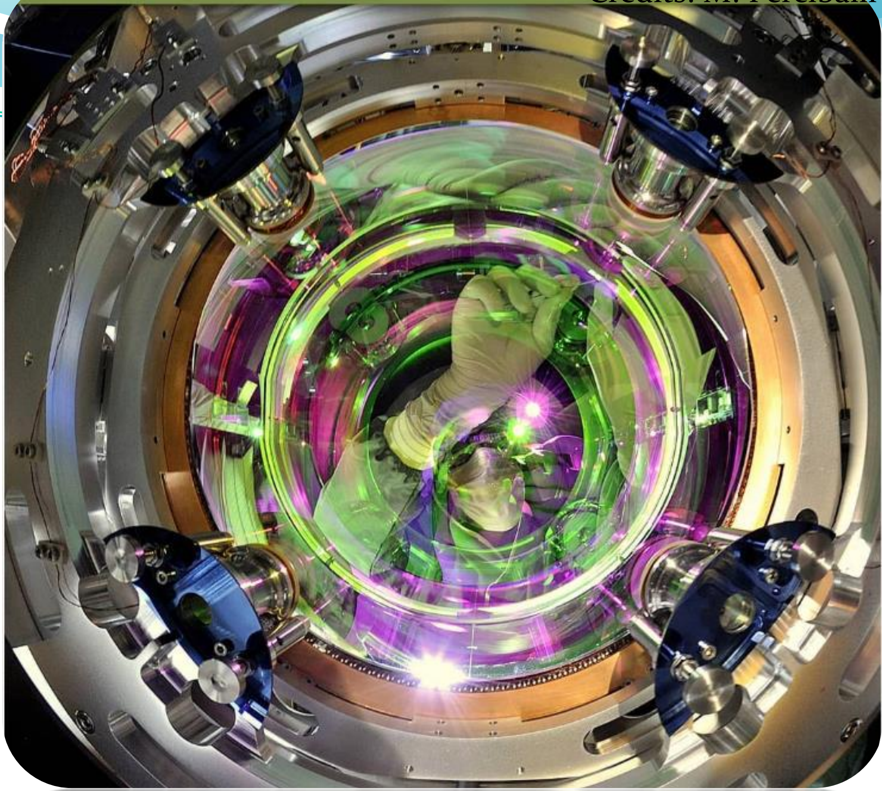


Beam Splitter mirror

The mirrors

- **SiO2 mirrors**, <u>**350 mm**</u> in diameter, <u>**200 mm**</u> thick, with a residual roughness <u>**< 0,5 x 10^{-9} m.**</u>

If the mirror surface was as large as Sardinia, the tallest mountain would be 0.1mm high!!!



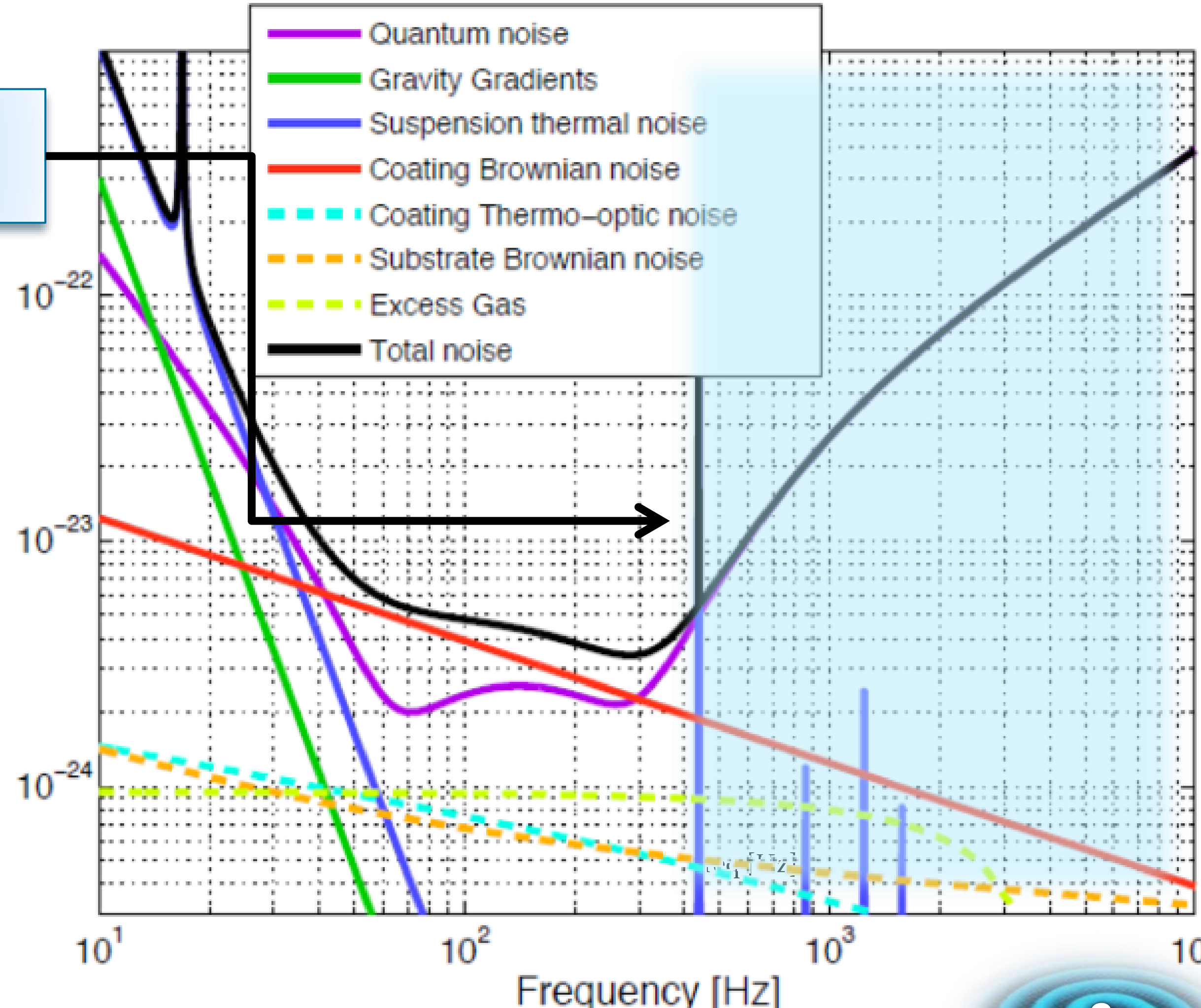
Credits: M. Perciballi

- **Monolithic suspensions:** SiO2 fibers <u>**400 µm**</u> in diameter (thick hair diameter ~ 250 µm) to suspend <u>mirrors **42 kg in weight**</u> (~2x heavier than in Virgo+ to reduce the effect of the radiation pressure).

AdV design

Limiting noises at different frequency ranges:

- High-freq:
quantum shot-noise



- Reducing quantum noise:
  - Increased finesse of arm cavities (9x larger than iVirgo, 3x larger than Virgo+)
  - High power laser
  - Squeezing technique

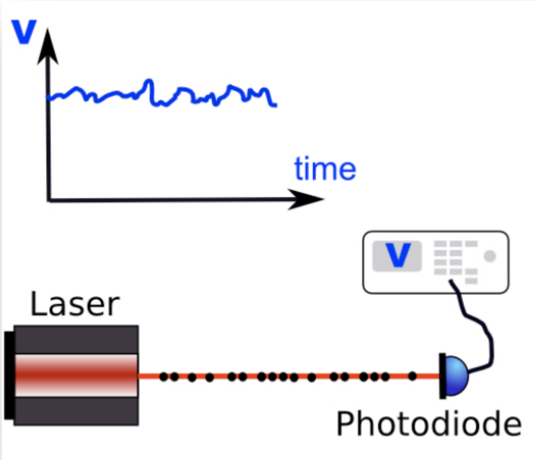
What is quantum noise?

$$h_{quantum} = \sqrt{h_{rad}^{2} + h_{shot}^{2}}$$

The photons in a laser beam are not uniformly distributed, but follow Poissonian statistics

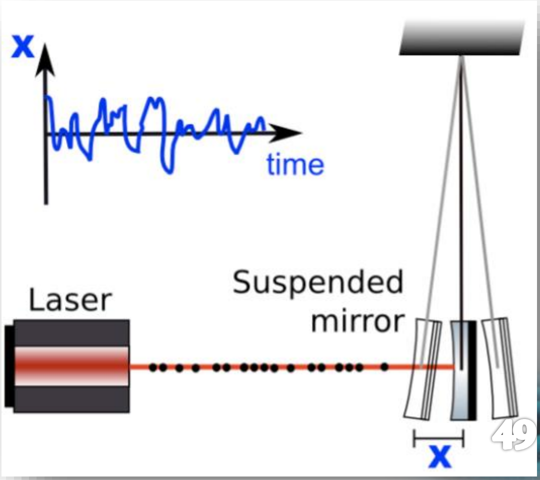
- **Shot noise**
  Photon counting noise

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



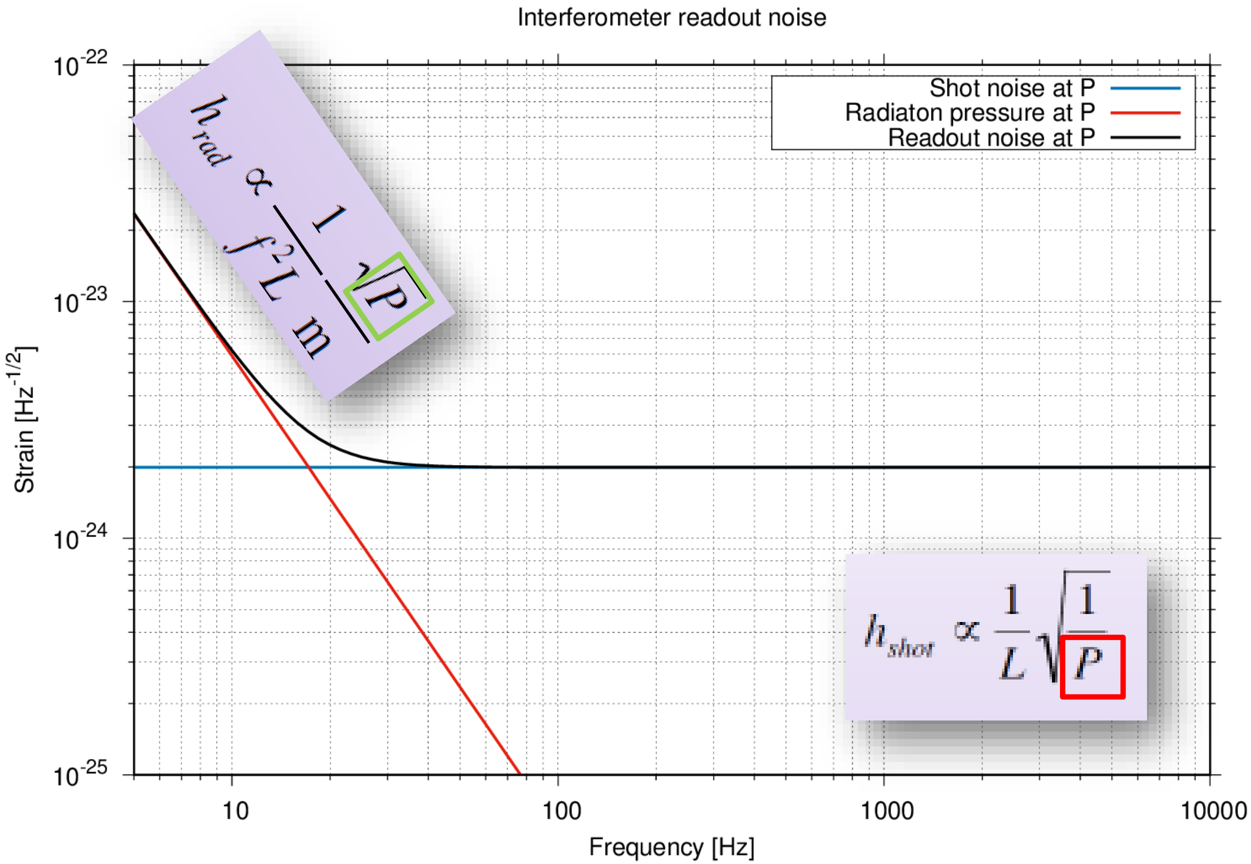
- **Radiation pressure noise**
  Photons fluctuations translate in radiation pressure fluctuations, giving rise to random motion of the mirrors

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

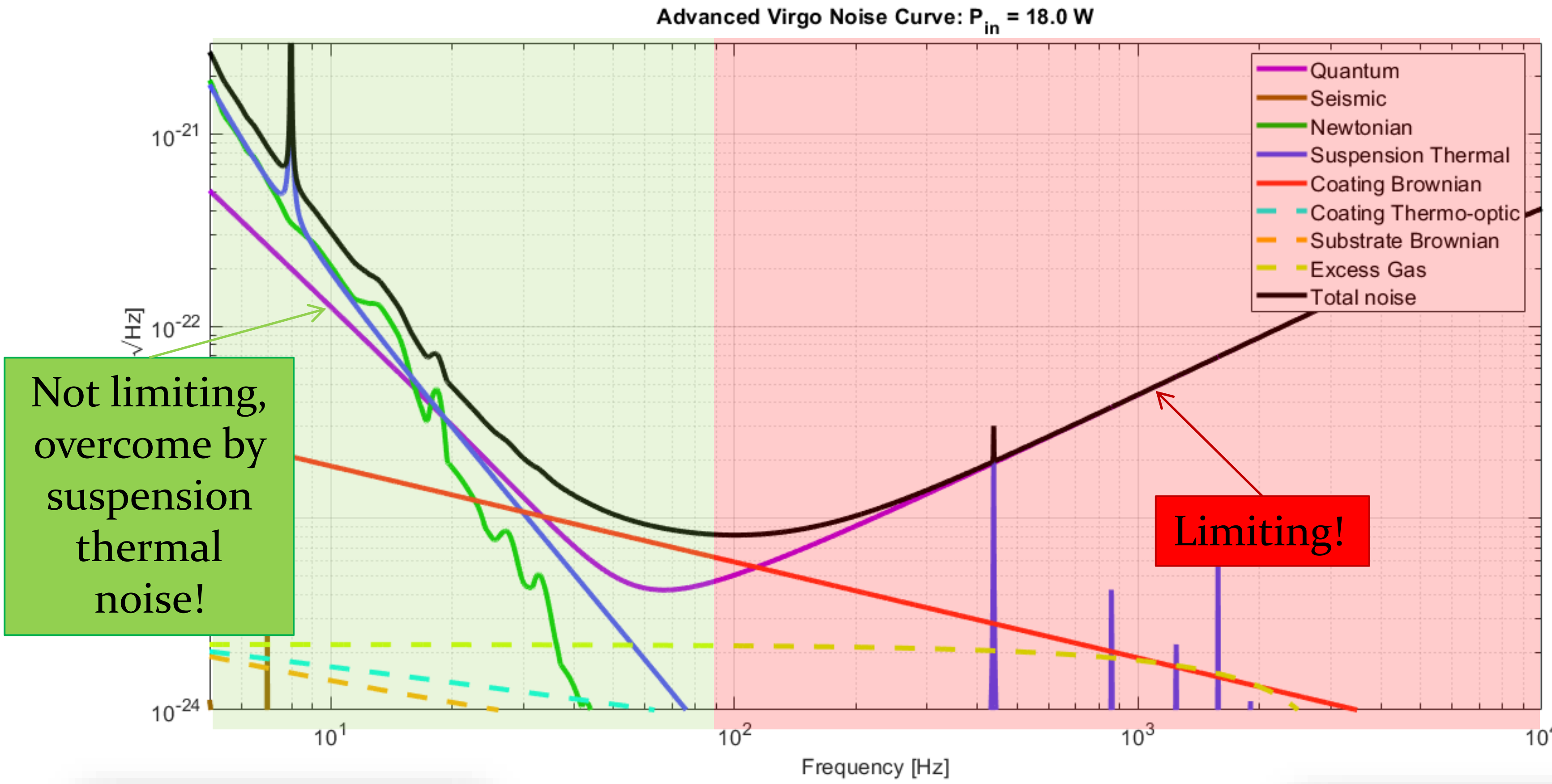


Quantum noise contribution

Power = P



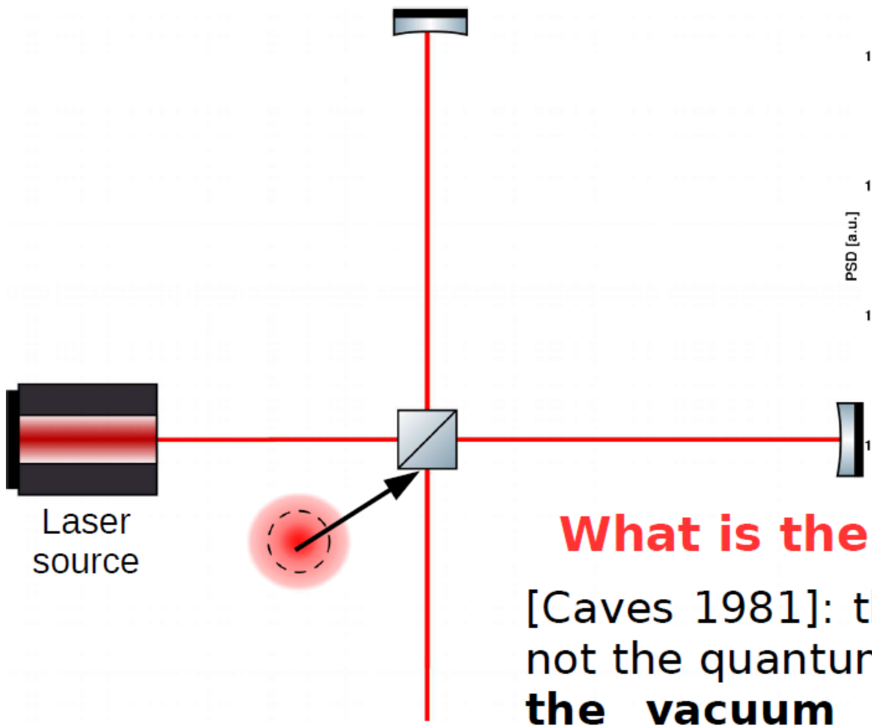
Quantum noise effect on the sensitivity

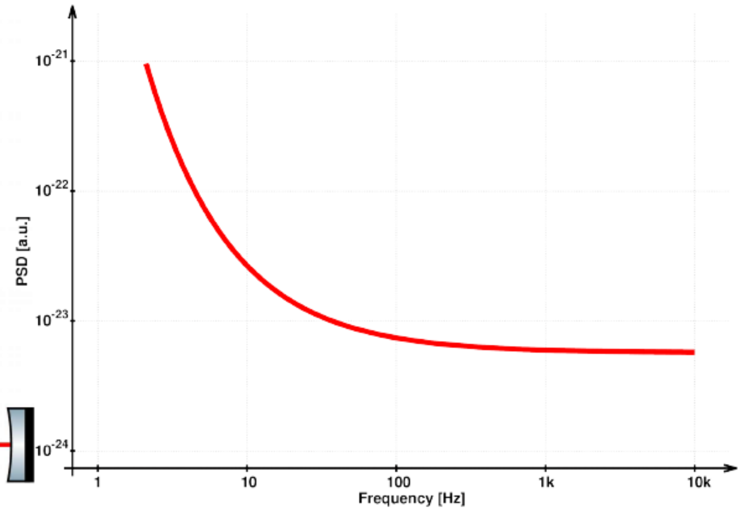


$$h_{rad} \propto \frac{1}{f^2 L} \frac{\sqrt{P}}{m}$$

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

Quantum noise effect on the interferometer





What is the quantum noise origin?

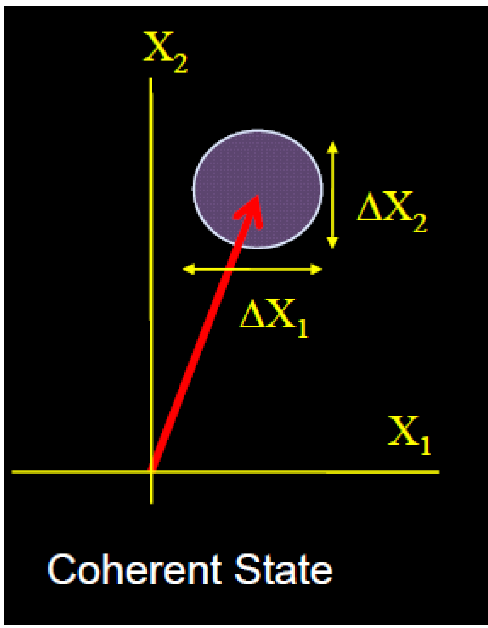
[Caves 1981]: the orgin of quantum noise are not the quantum fluctuations of the laser, **but the vacuum fluctuations which enter from the interferometer dark port**

Quantum noise can be modified *manipulating* the noise at the interferometer dark port → SQUEEZING TECHNIQUE

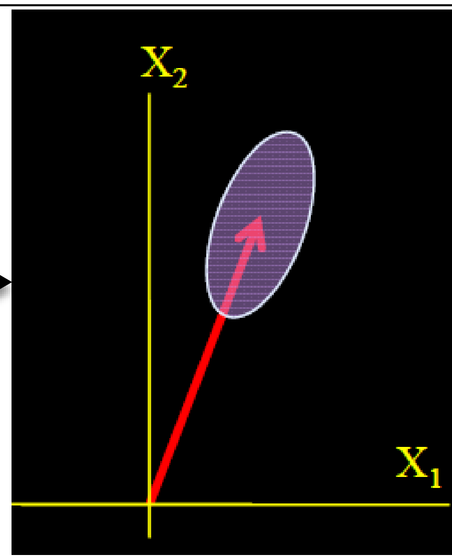
The squeezing principle

Vacuum is a coherent state, for which the uncertainty principle holds

$$\Delta X_1 \, \Delta X_2 \geq 1$$



There is a minimum uncertainty product, but the area can be re-distributed

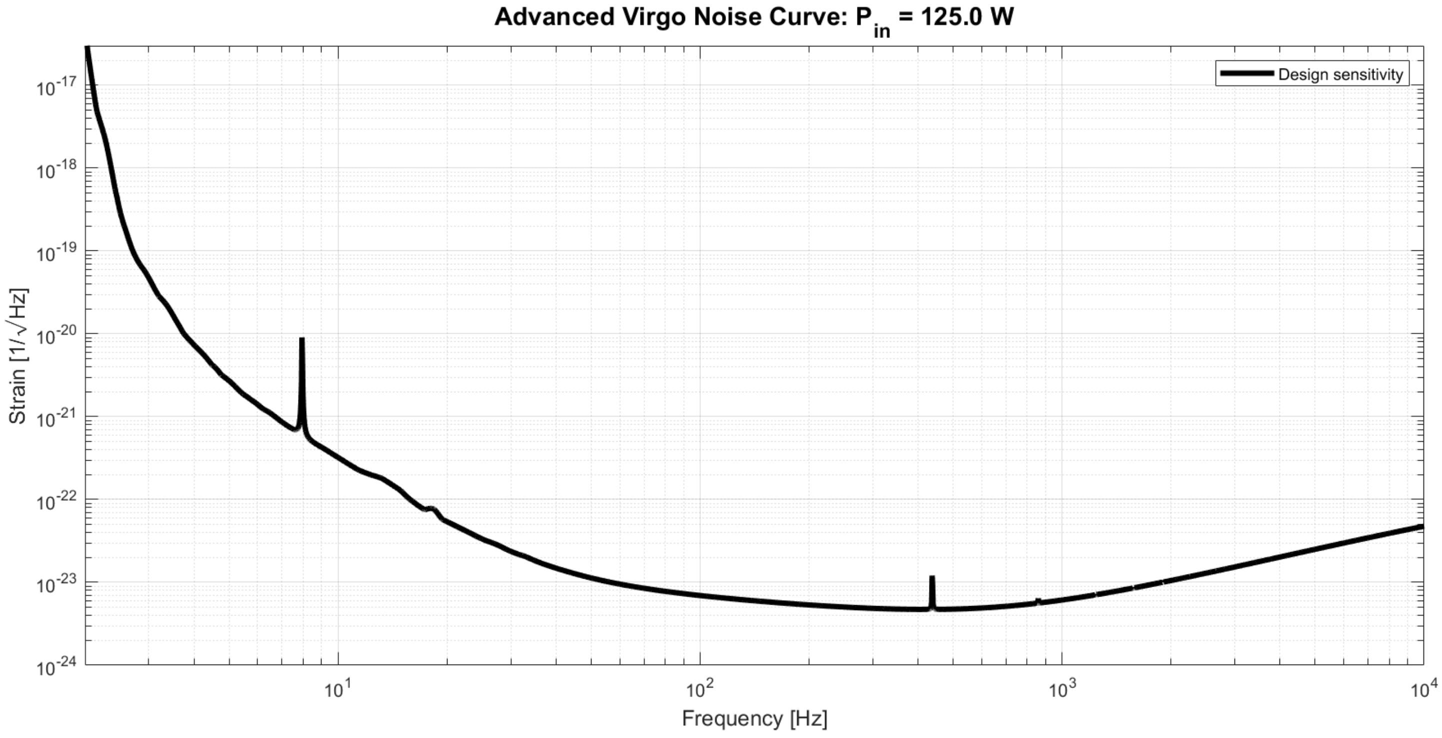


Phase squeezed
Amplitude anti-squeezed

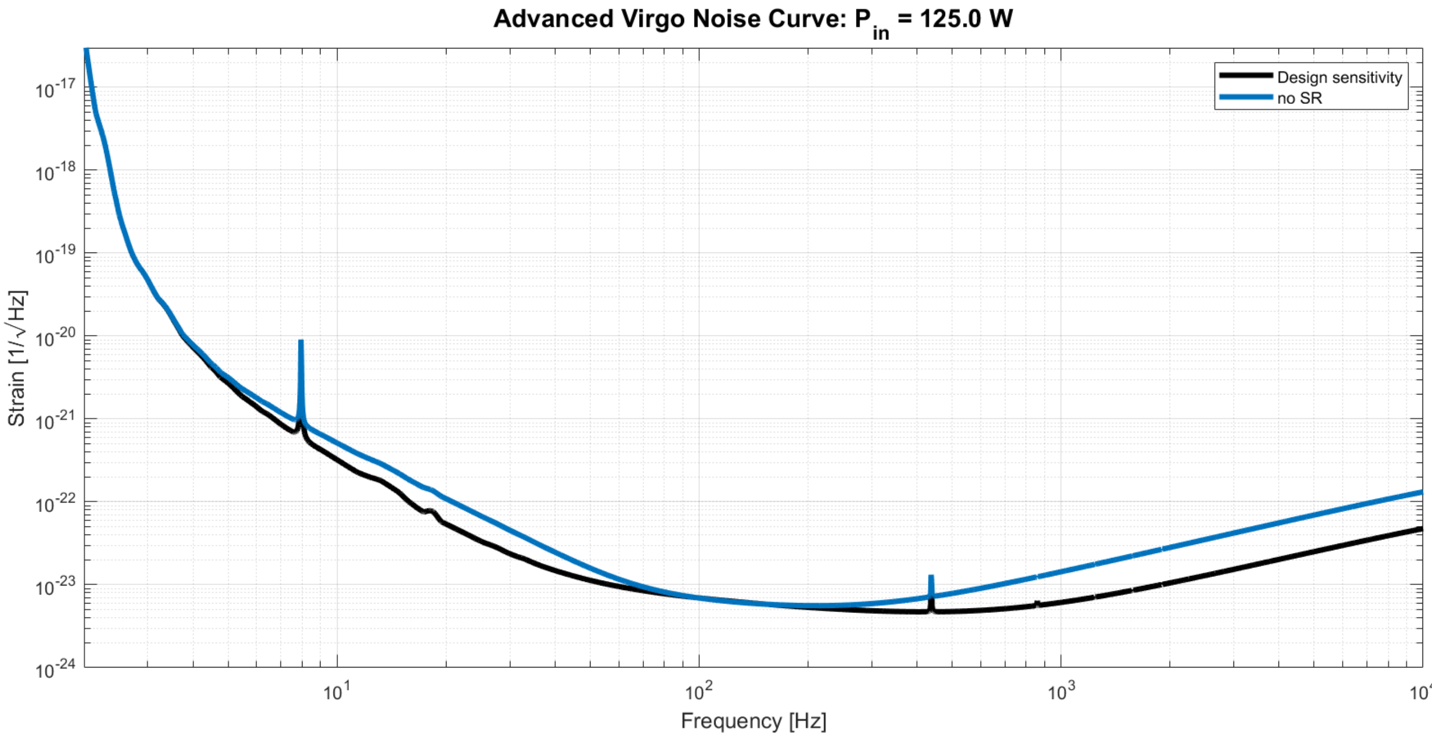
Squeezing the field entering the dark port reduces the noise on the gravitational waves readout

Non-linear optics techniques

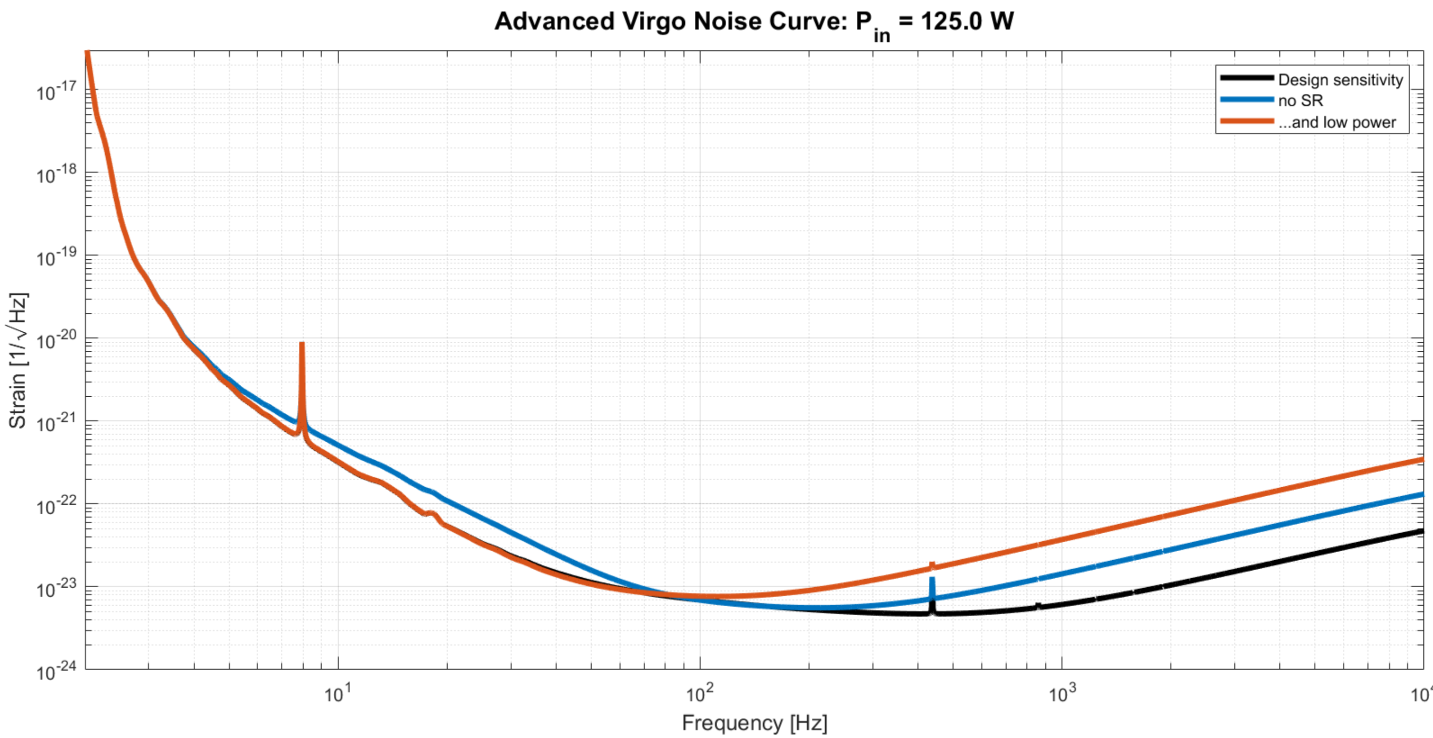
How does the sensitivity change while adding complexity to the interferometer



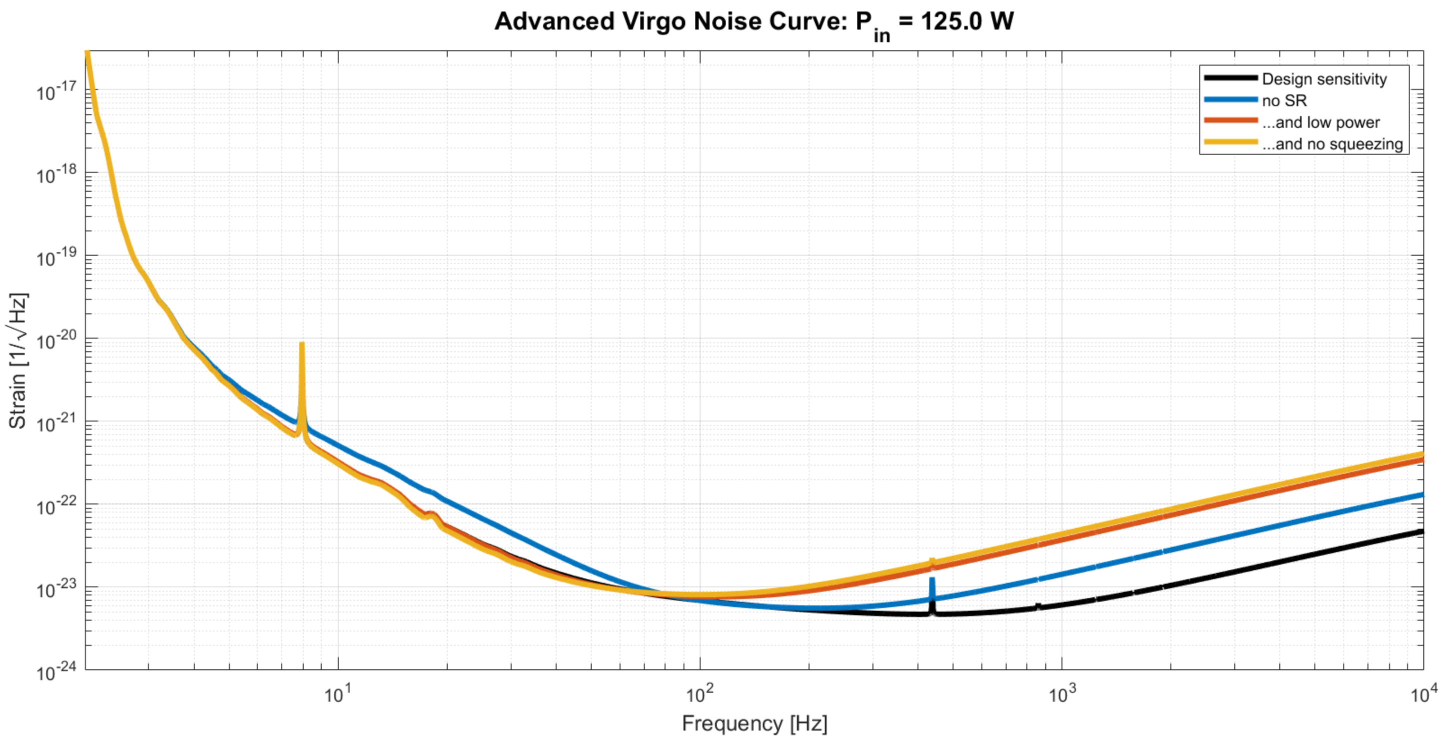
How does the sensitivity change while adding complexity to the interferometer



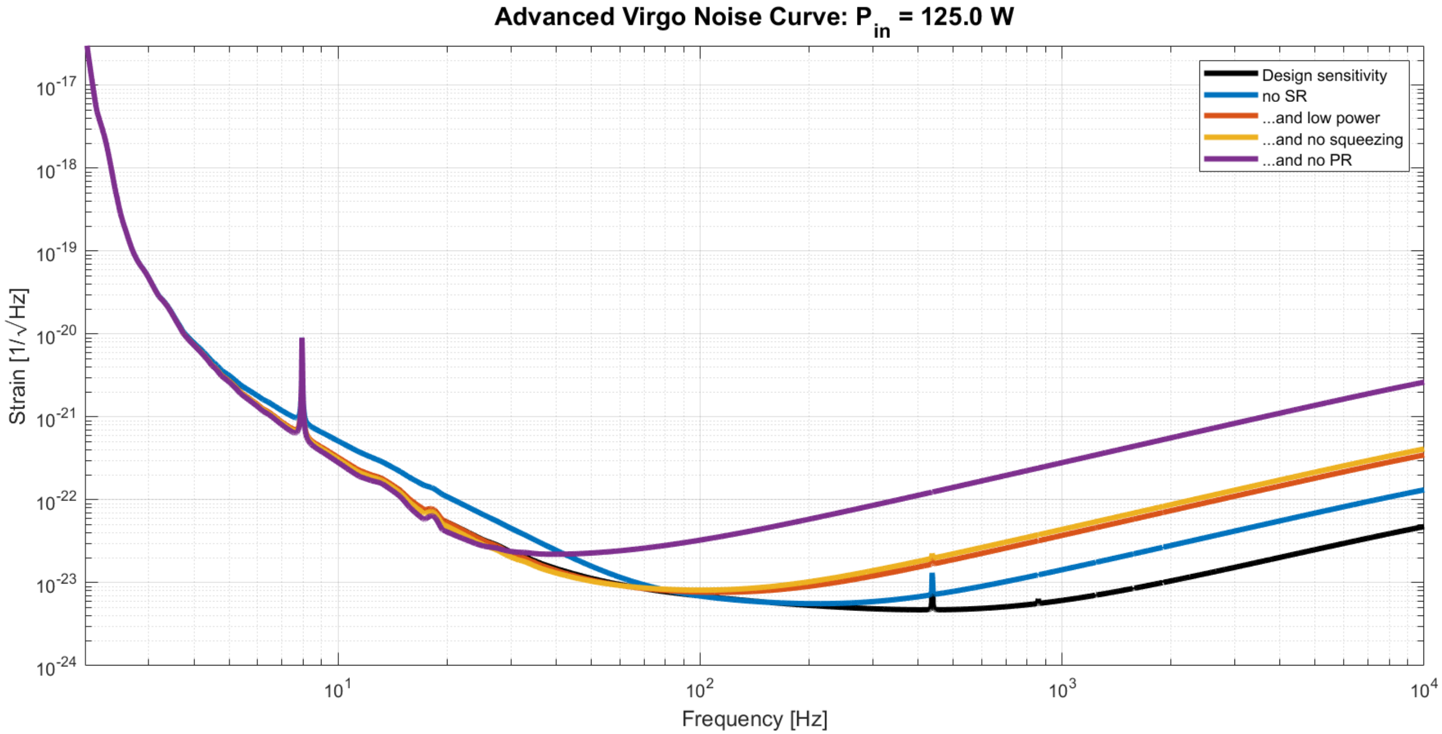
How does the sensitivity change while adding complexity to the interferometer



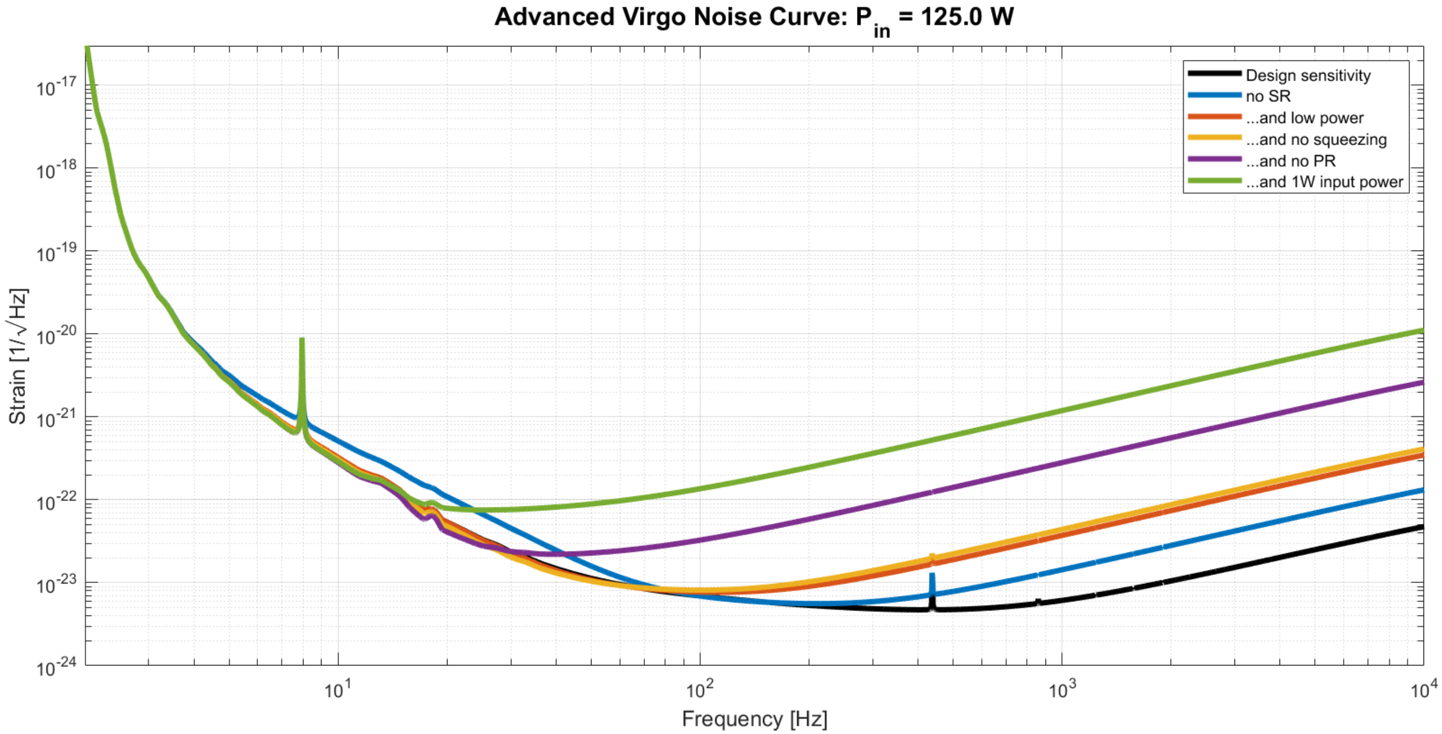
How does the sensitivity change while adding complexity to the interferometer



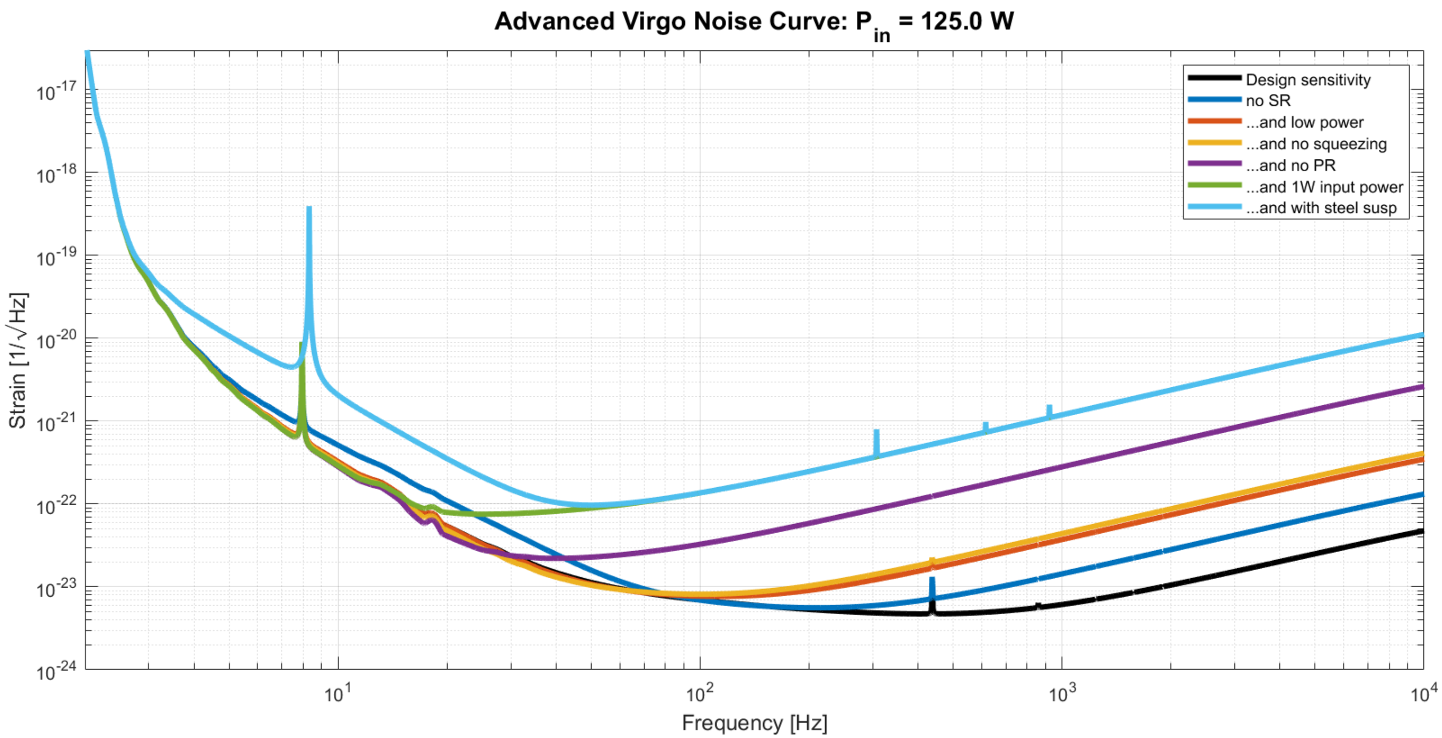
How does the sensitivity change while adding complexity to the interferometer



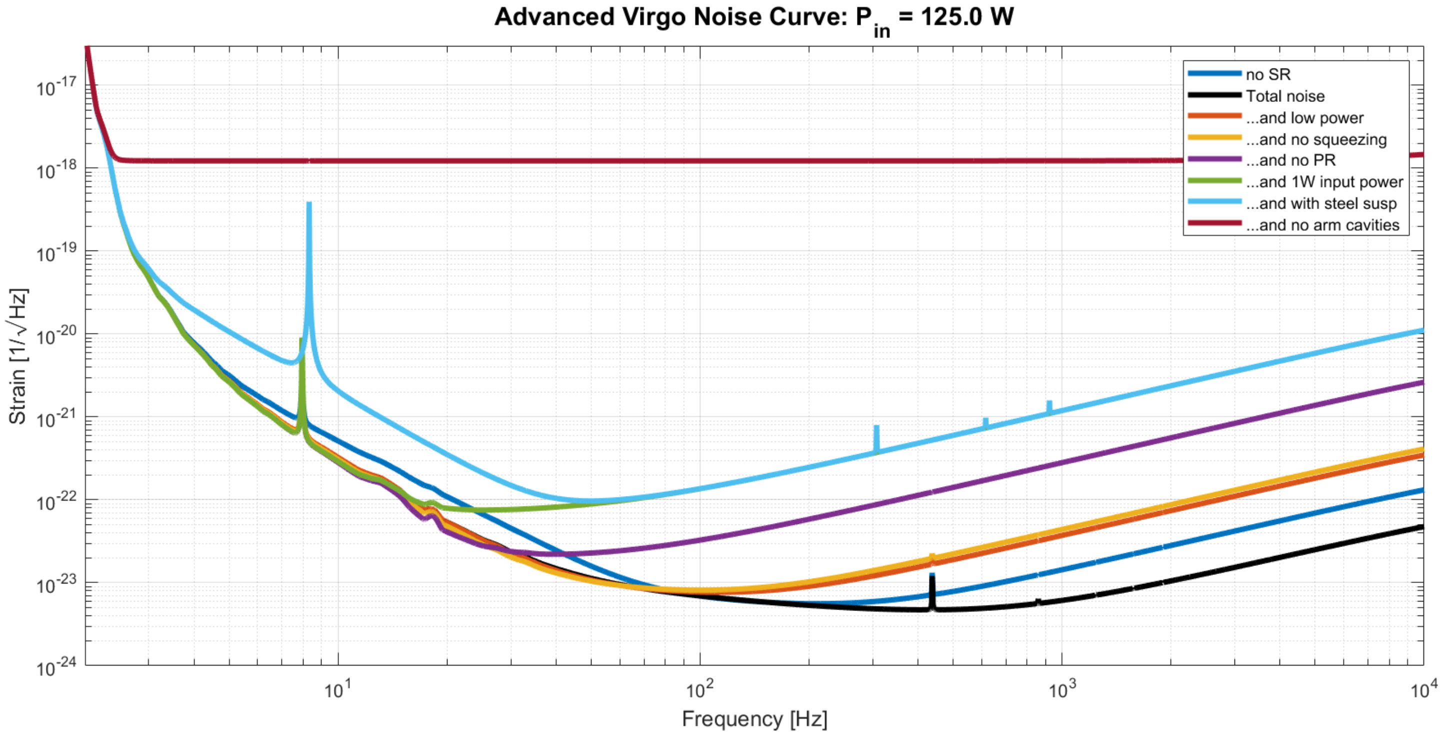
How does the sensitivity change while adding complexity to the interferometer



How does the sensitivity change while adding complexity to the interferometer



How does the sensitivity change while adding complexity to the interferometer



Outline

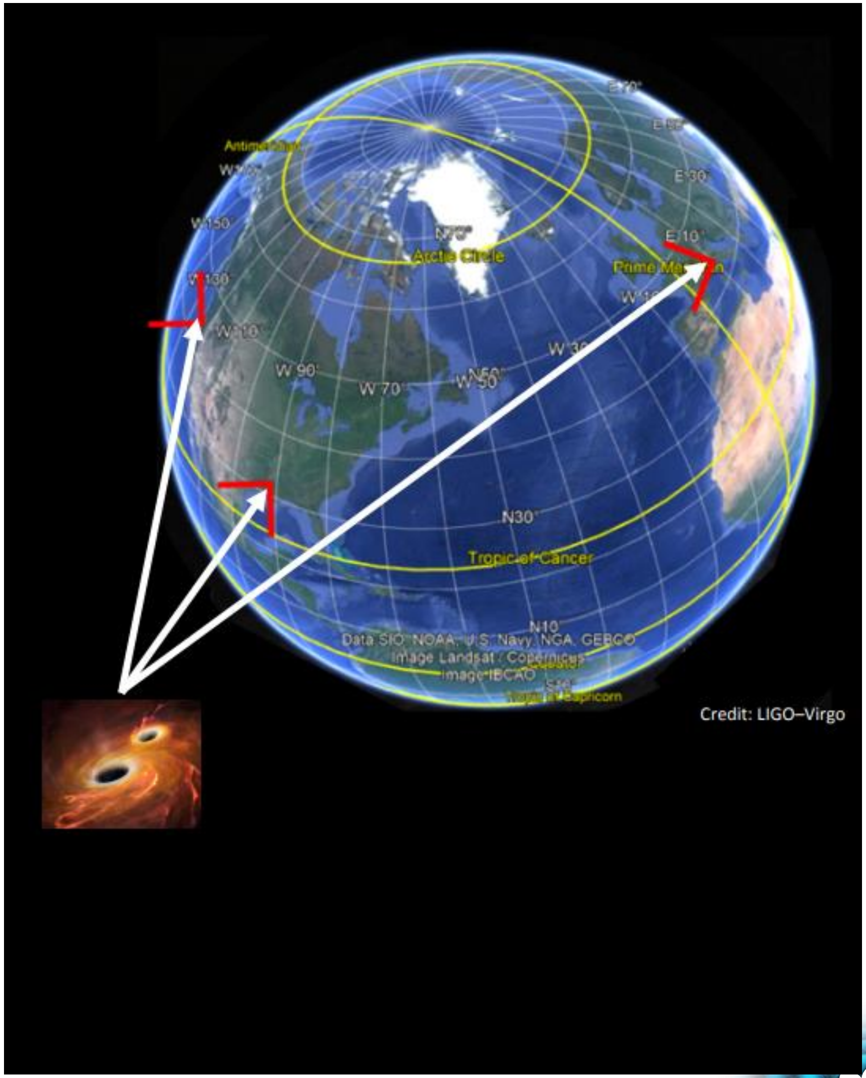
- Gravitational Waves and their effect on the matter
- Gravitational Waves detection
- The Virgo detector
- **The detector network**
- Great discoveries of Advanced GW detectors
- Future perspectives

The detector network

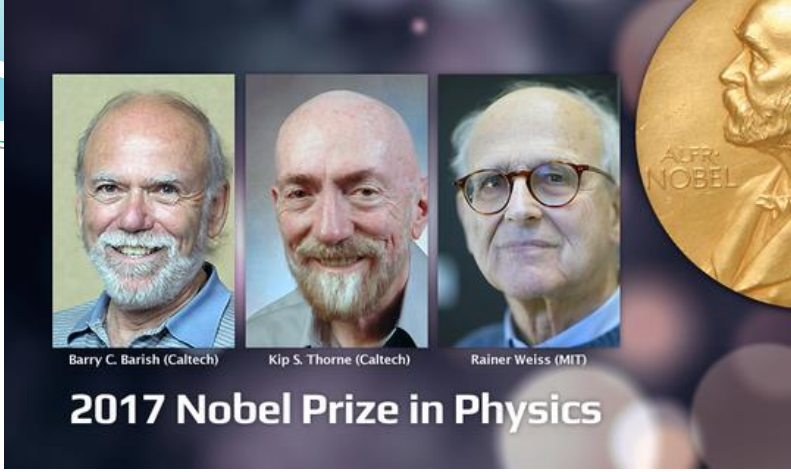
Only one detector can't tell much about from where a gravitational wave has come. Therefore, having more detectors helps in:

- Identifying the direction to the signal
- Rejecting false signals exploiting coincidence

Virgo observed its first BBH coalescence, GW170814



Our partners

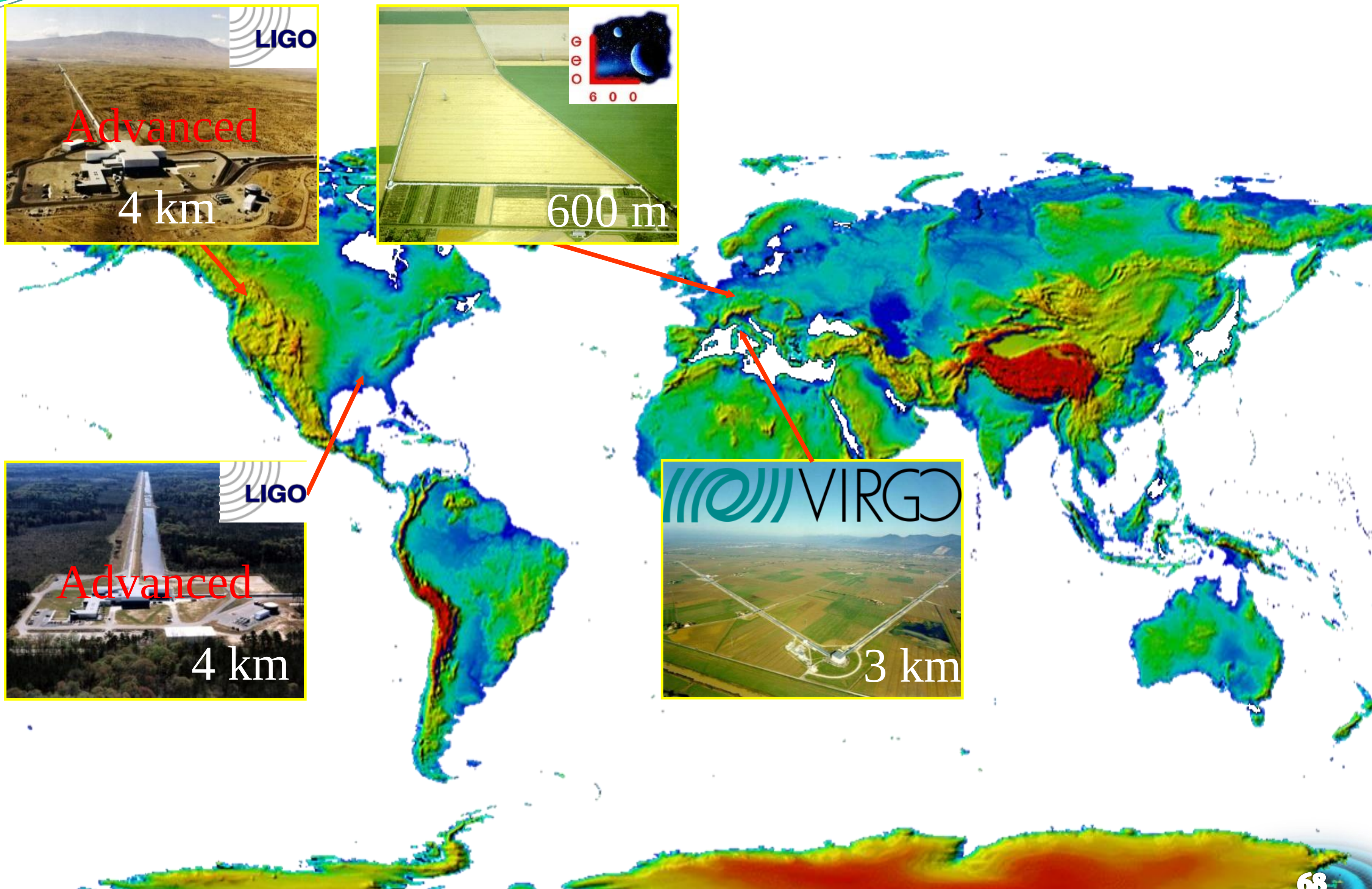


Laser Interferometer

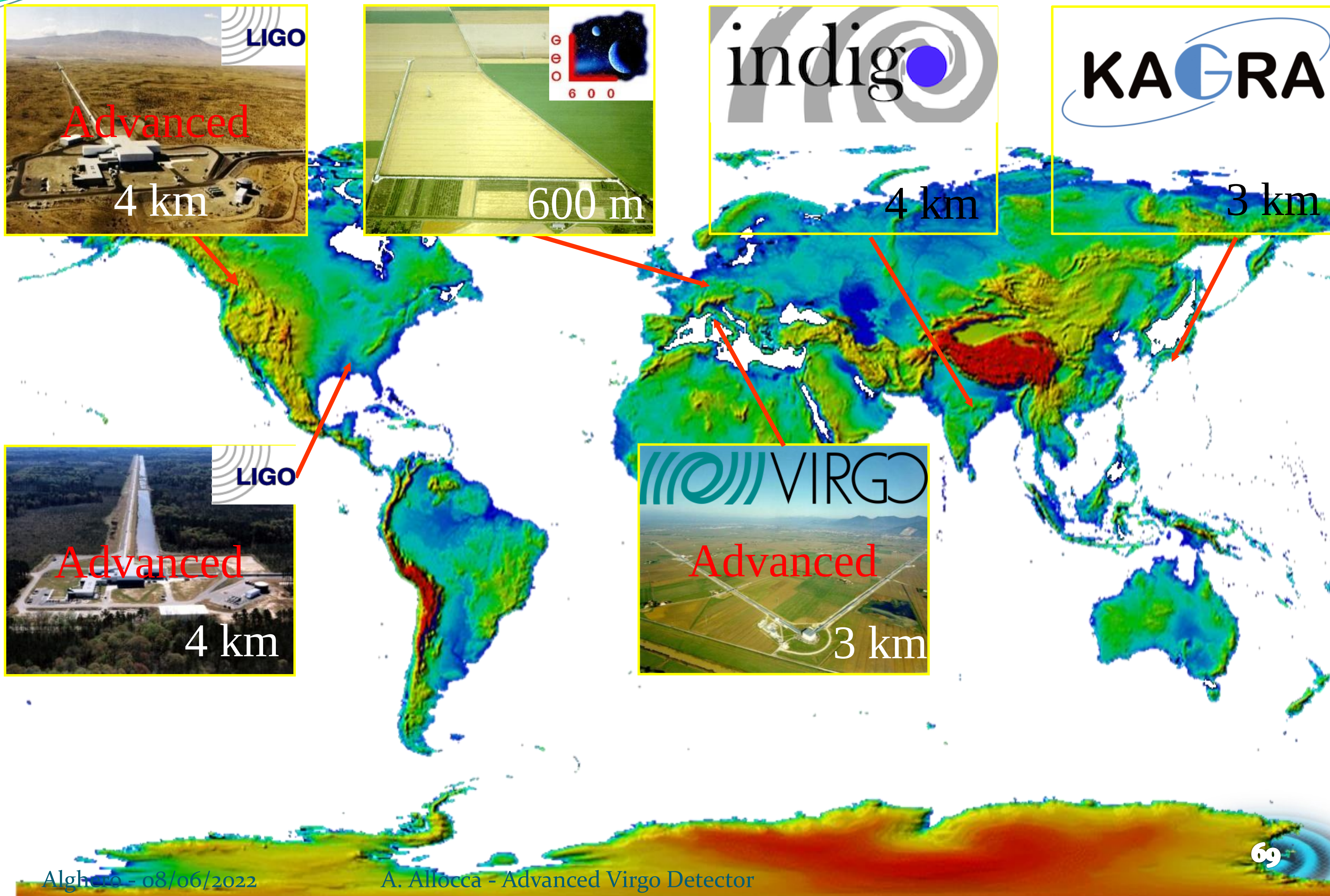
L I G O

Gravitational wave Observatory

The detector network



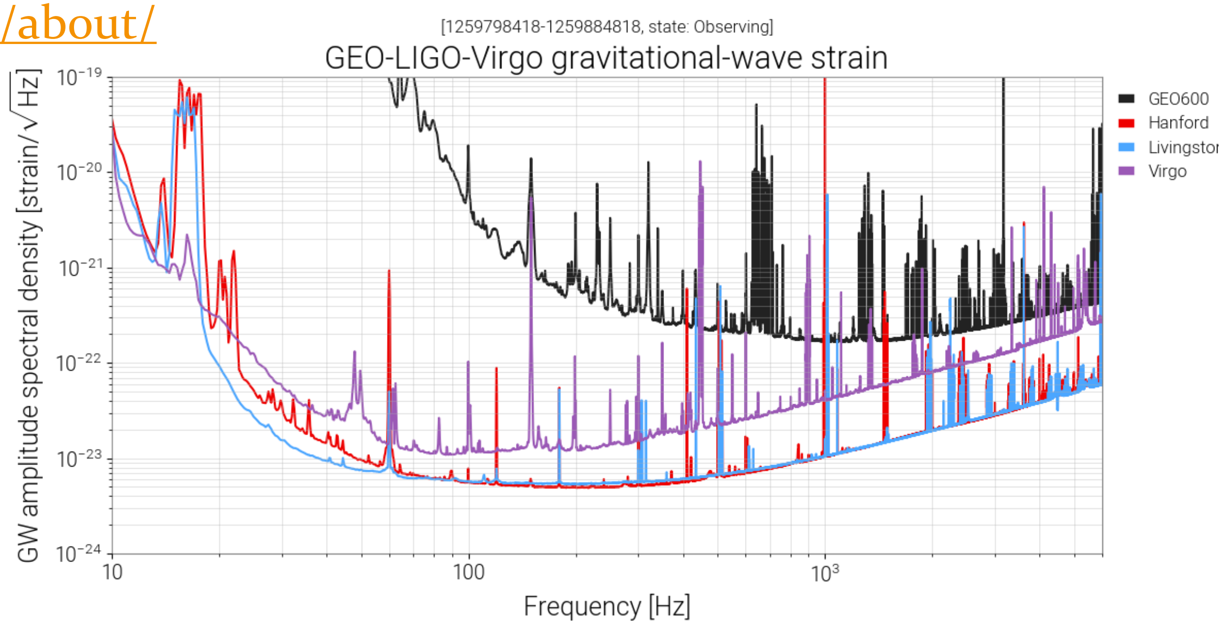
The detector network

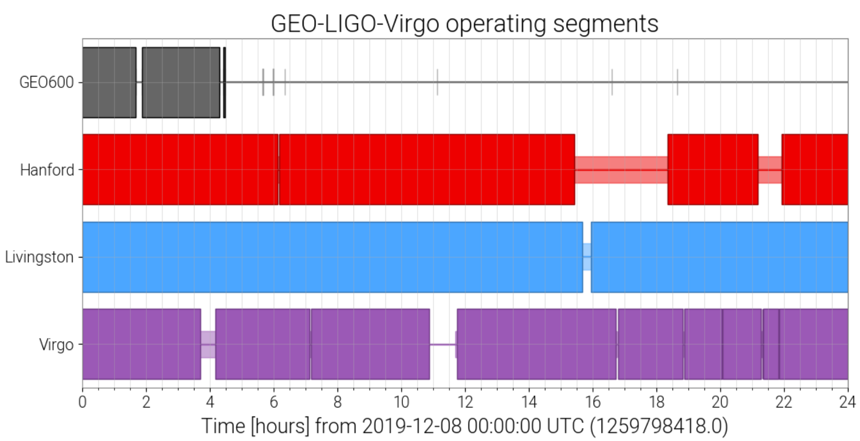


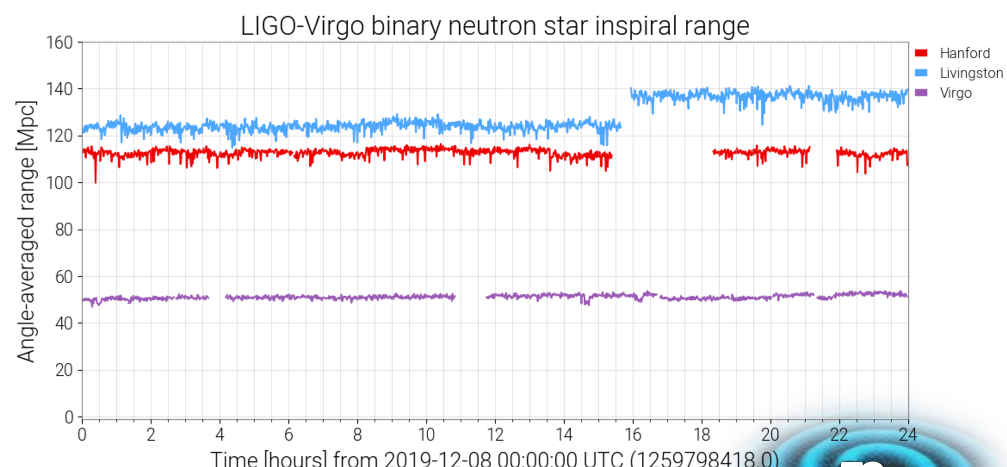
O3 LIGO-Virgo(-GEO600) performance

https://www.gw-openscience.org/about/

BNS range: Standard figure of merit for the sensitivity of the interferometer
Volume- and orientation-averaged distance at which a compact binary coalescence consisting of two 1.4 $M_\odot$ neutron stars gives a matched filter SNR of 8 in a single detector







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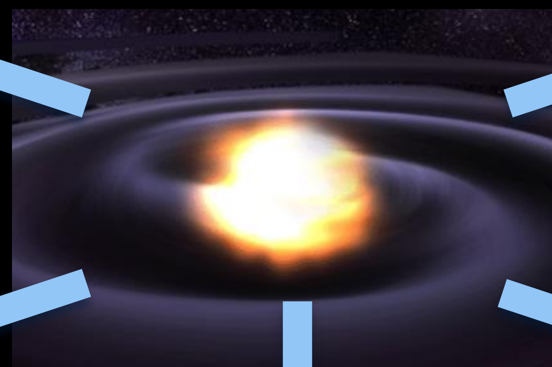
Monumental successes of the Advanced detectors

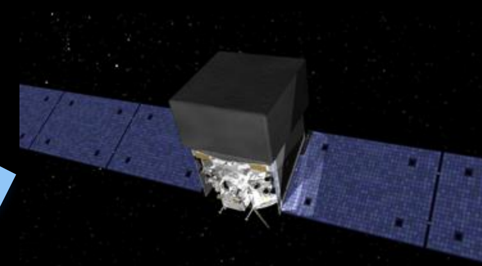
- First detection of GWs from a BBH system (GW150914)
  - Physics of BHs
- First detection of GWs from a BNS system (GW170817)
  - Birth of the multimessenger astronomy with GWs
  - Costraining EOS of NS
- Localisation capabilities of a GW source
- Measurement of the GW propagation speed
- Test of GR
- Alternative measurement of Hubble constant
- GW polarizations
- Intermediate mass black hole (GW190521)

Start of multi-messenger astronomy

Gravitational Waves

Binary Neutron Star Merger

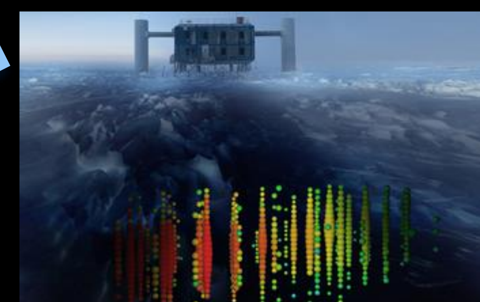




X-rays/Gamma-rays

Visible/Infrared Light

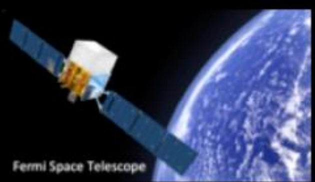
Radio Waves

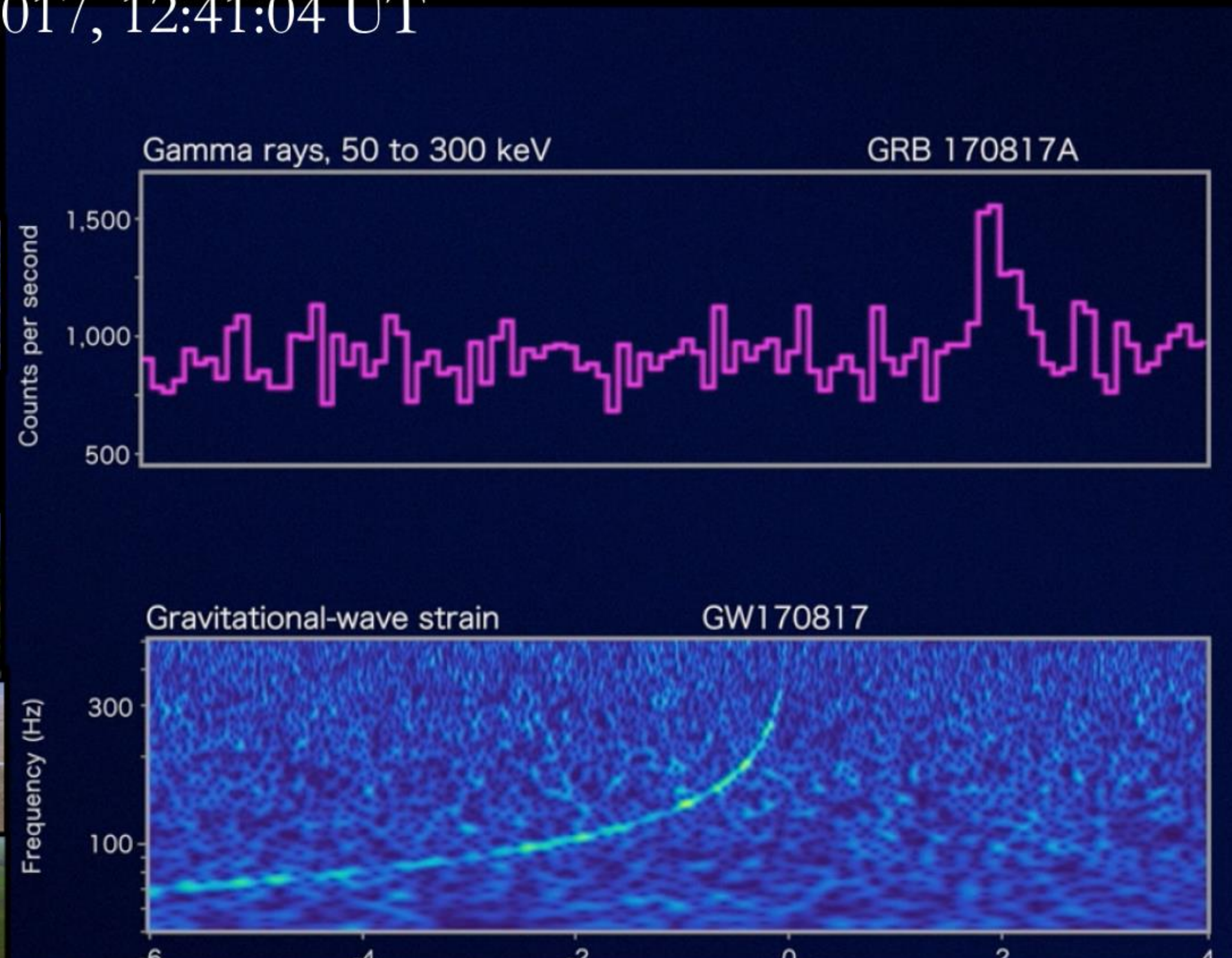


Neutrinos

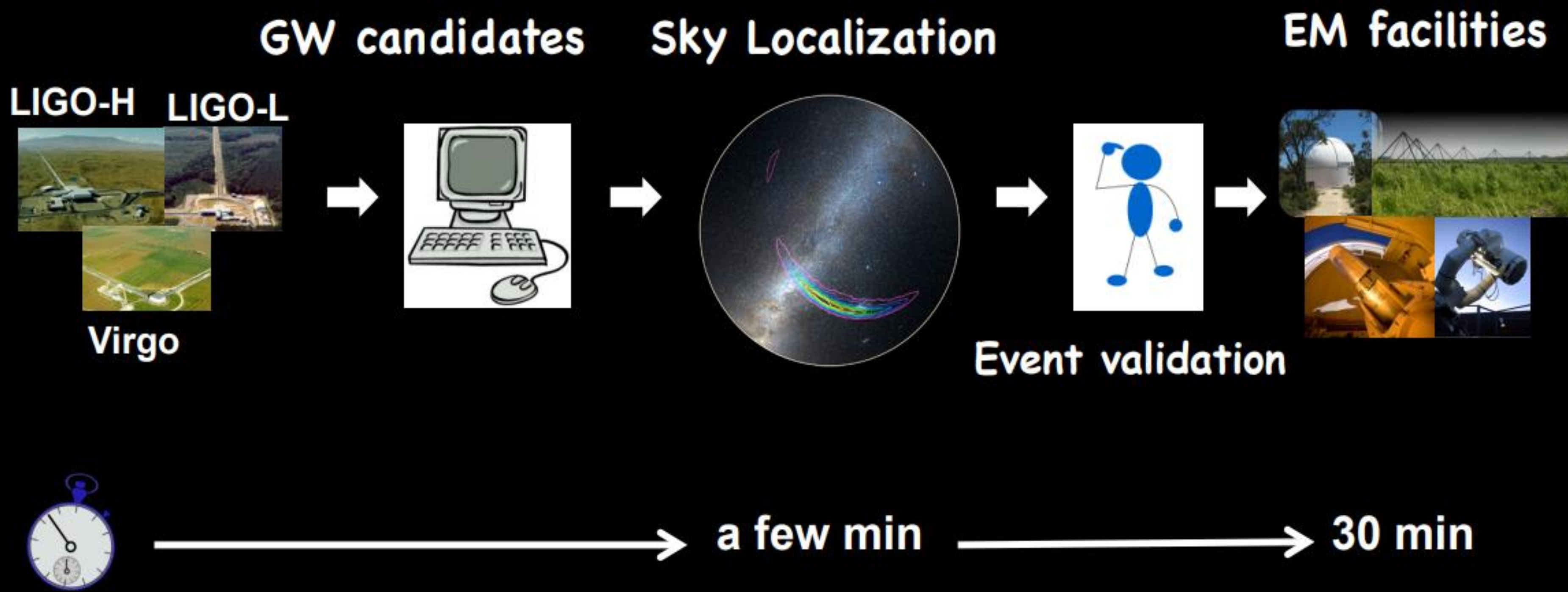
First NS-NS GW triple detection: the beginning of multi-messenger astronomy

17 August 2017, 12:41:04 UT





Low-latency GW data analysis pipelines to promptly identify GW candidates and send GW alerts



GWTC: Gravitational Waves Transient Catalog - 3

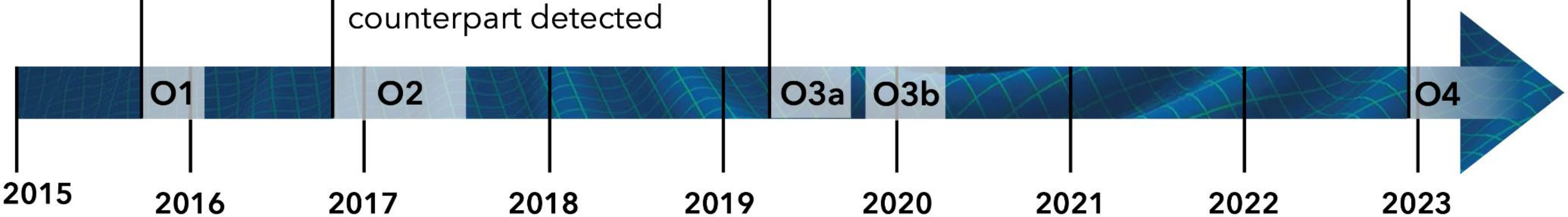
arXiv
1811.12907
2108.01045
2111.03606

3 GW detection during O1
- First direct detection of GW
- From coalescing binary systems of black holes

8 GW detection during O2
- 1 coalescing binary system of neutron stars: electromagnetic counterpart detected

79 GW detection during O3
- 44 during O3a, including 1 confirmed binary system of neutron stars
- 35 during O3b, including 2 confirmed systems of neutron stars - black holes
- No electromagnetic counterpart

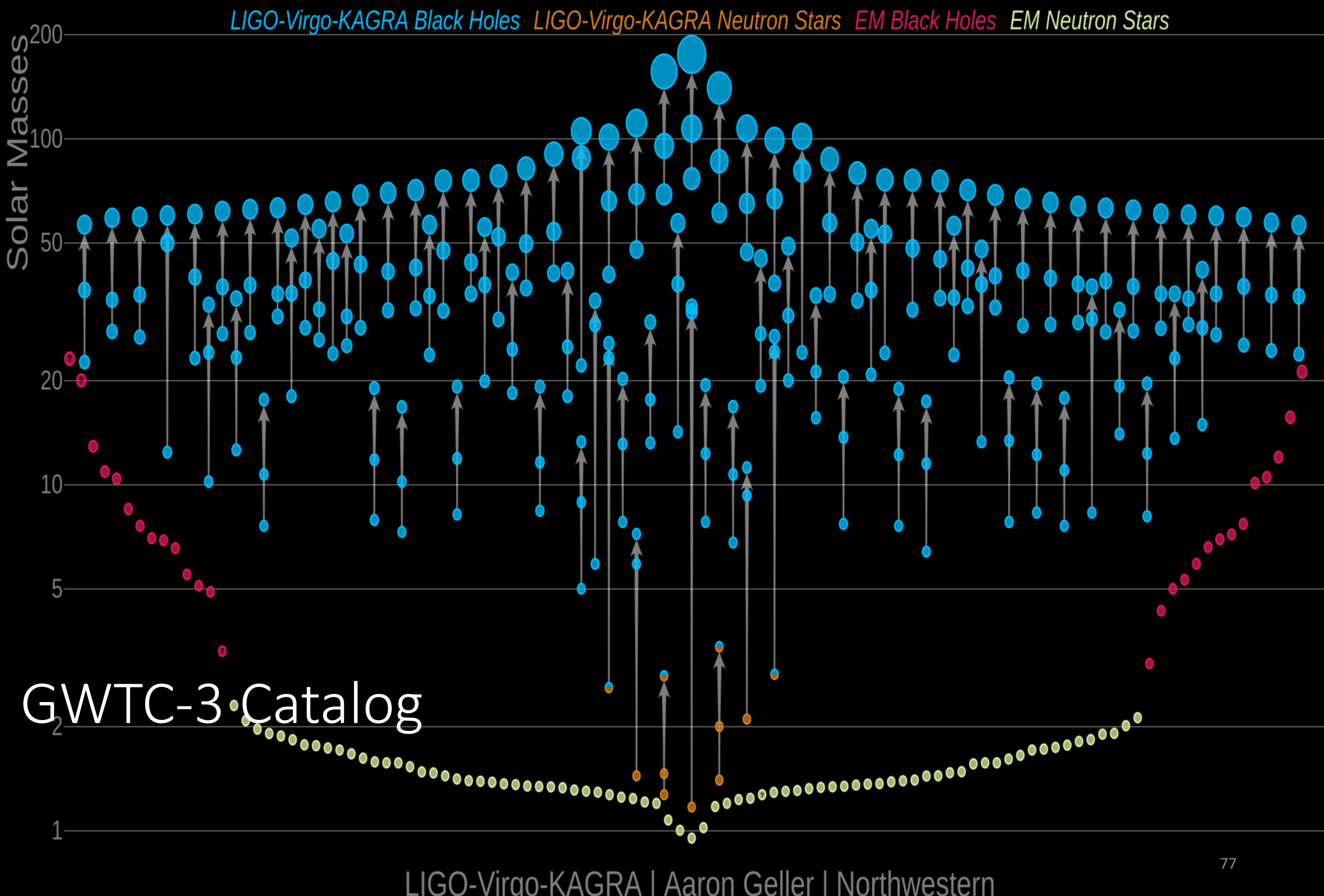
O4 to start end of 2022
- Duration: 1 year



90 GW detections reported	**Coalescence** of black holes and neutron stars	**1 multimessenger** event (GW + EM observation)	**Mass range** 1.2 → 107 $M_\odot$ (stellar)	**Distance range** 40 Mpc → 8 Gpc (z → 1.14)

Leïla Haegel for the LVK collaboration [2022]

Masses in the Stellar Graveyard



GWTC-3 Catalog

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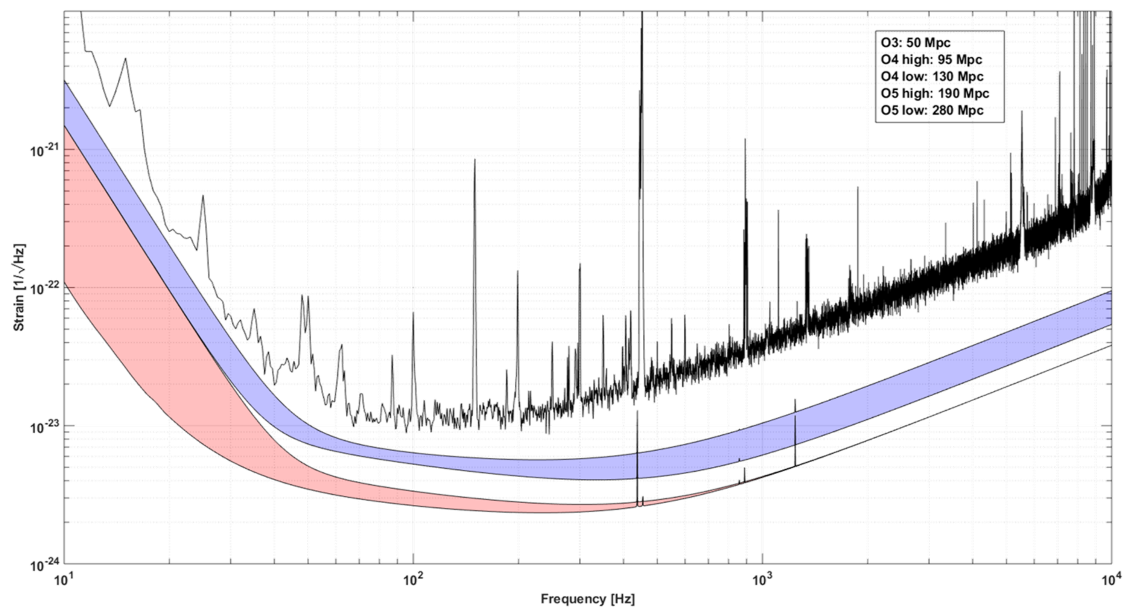
Advanced Virgo +

Upgrade activities with a 2 steps approach:

- Phase 1: reaching the thermal noise wall
  - Higher laser power
  - Tuned signal recycling and HPL
  - Frequency dependent squeezing
  - Newtonian noise cancellation
- Phase 2: pushing the thermal noise wall down
  - Further increase of laser power
  - Larger mirrors (105 kg)
  - Improved coatings



Detection distance of GW Detectors

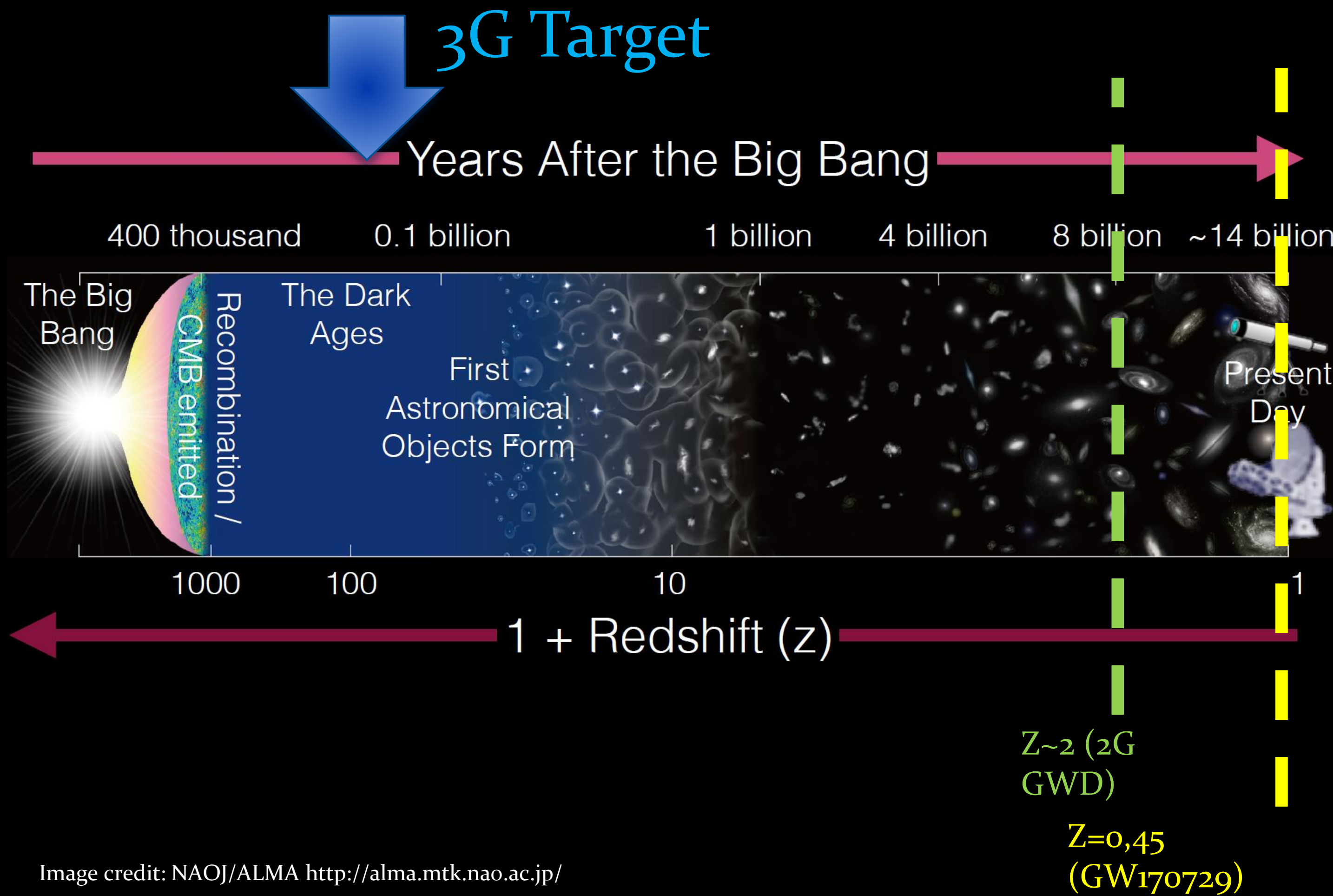
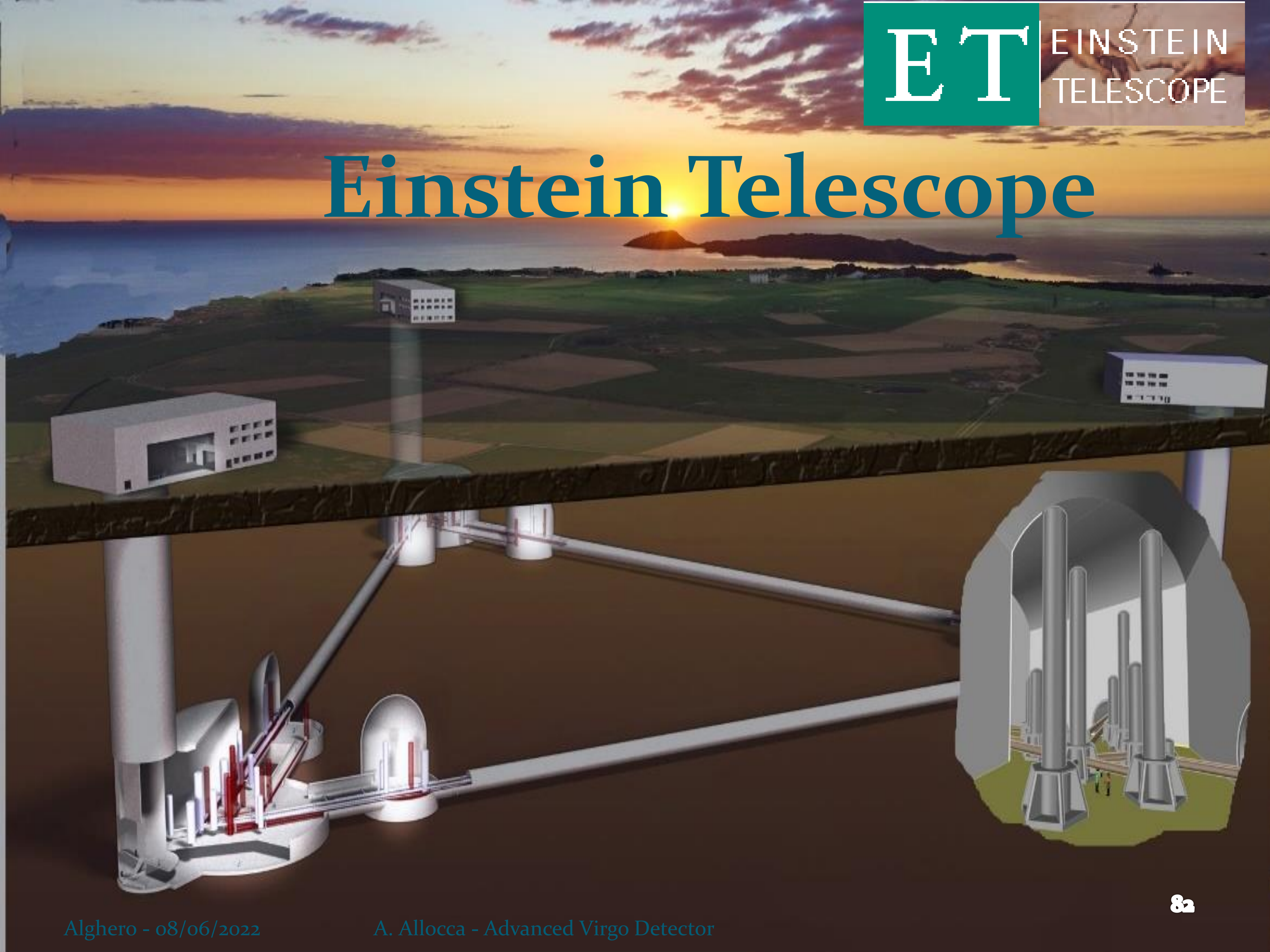


Image credit: NAOJ/ALMA http://alma.mtk.nao.ac.jp/

40 km and 20 km L-shaped surface observatories
10x sensitivity of today's observatories (Advanced LIGO+)
Global network together with Einstein Telescope

Artist: Eddie Anaya (Cal State Fullerton)

Einstein Telescope

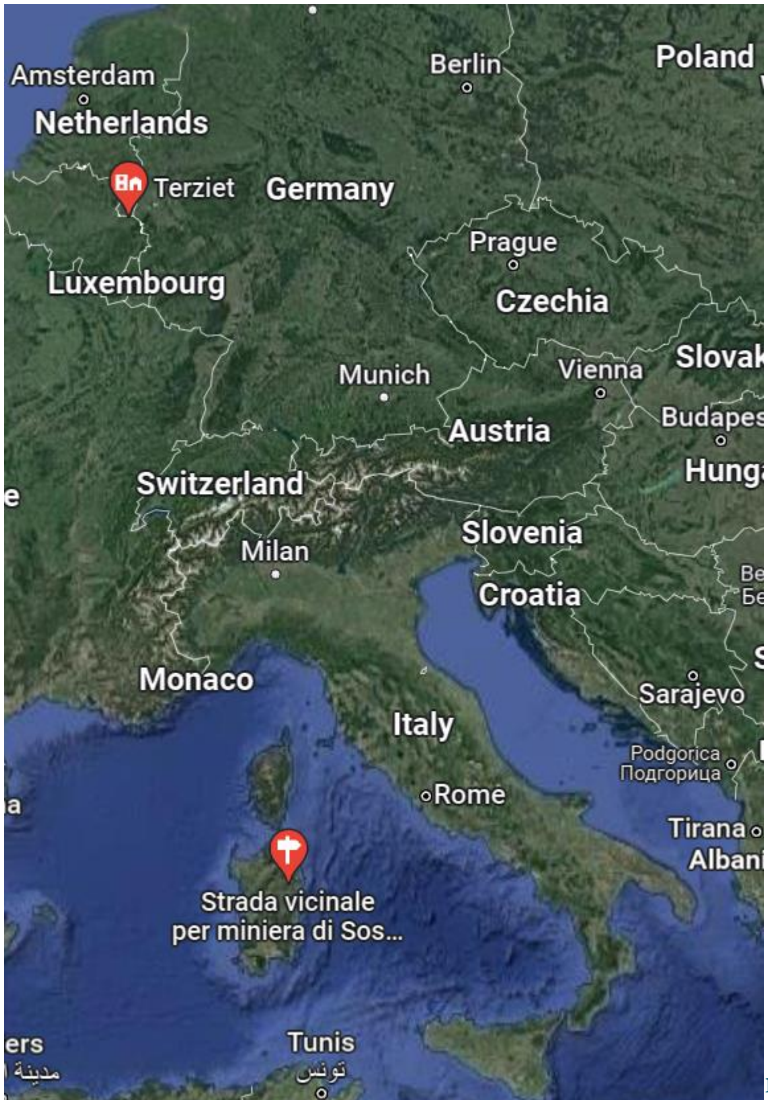


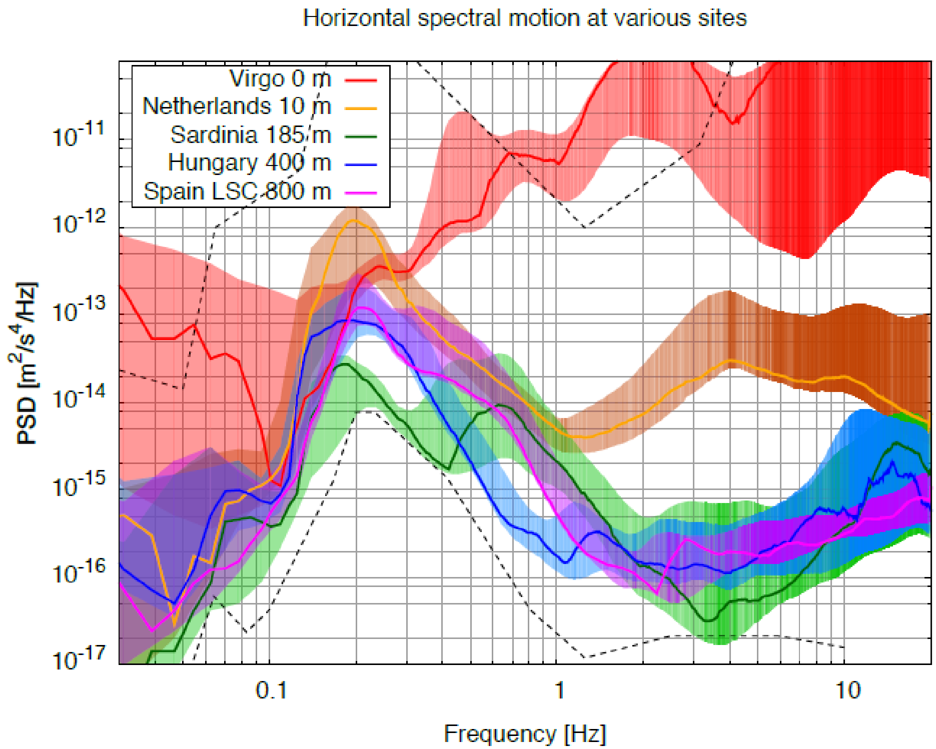
Einstein Telescope

- **Underground**, to reduce the seismic noise contribution
- **Cryogenic**, to reduce the effect of the thermal noise
- **10 Km arm long, 6 interferometers in one**
- **Governance Mondiale together with Cosmic Explorer (USA)**

Two sites candidate for the installation

Requirement: low seismic and antropic noise





- Among Belgium - Germany – Nederland (close to Maastricht)
- Italy (Sardinia - Sos Enattos)

Two sites candidate for the installation

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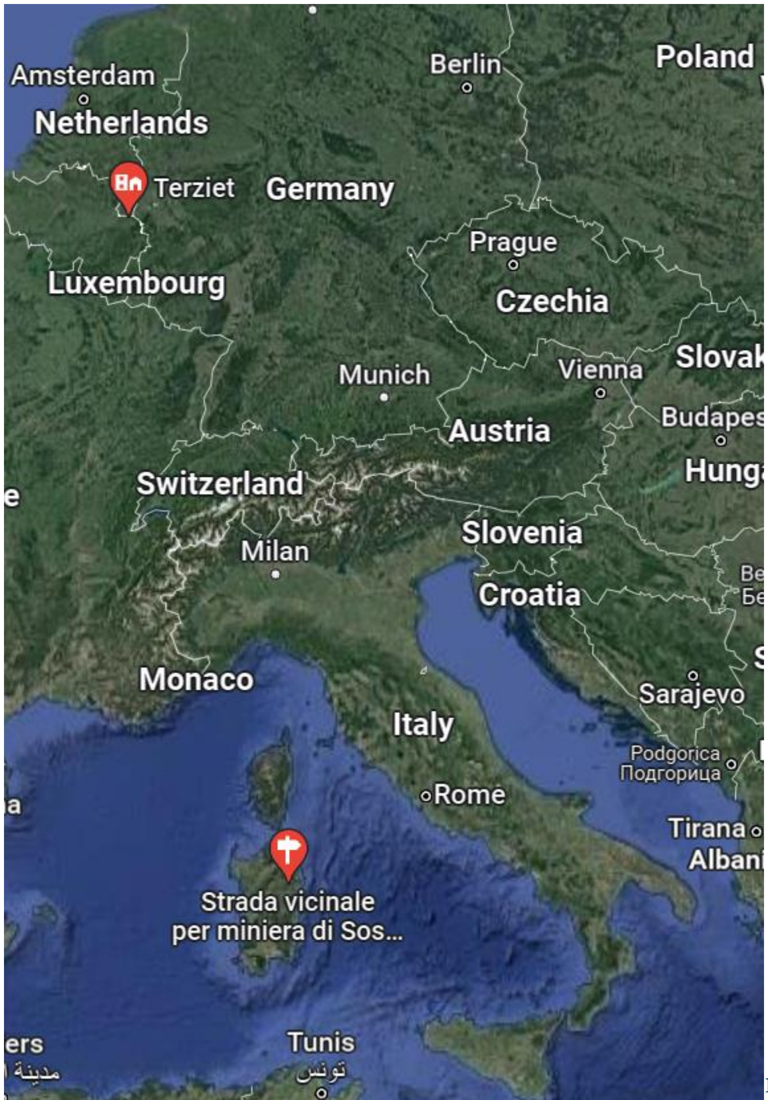

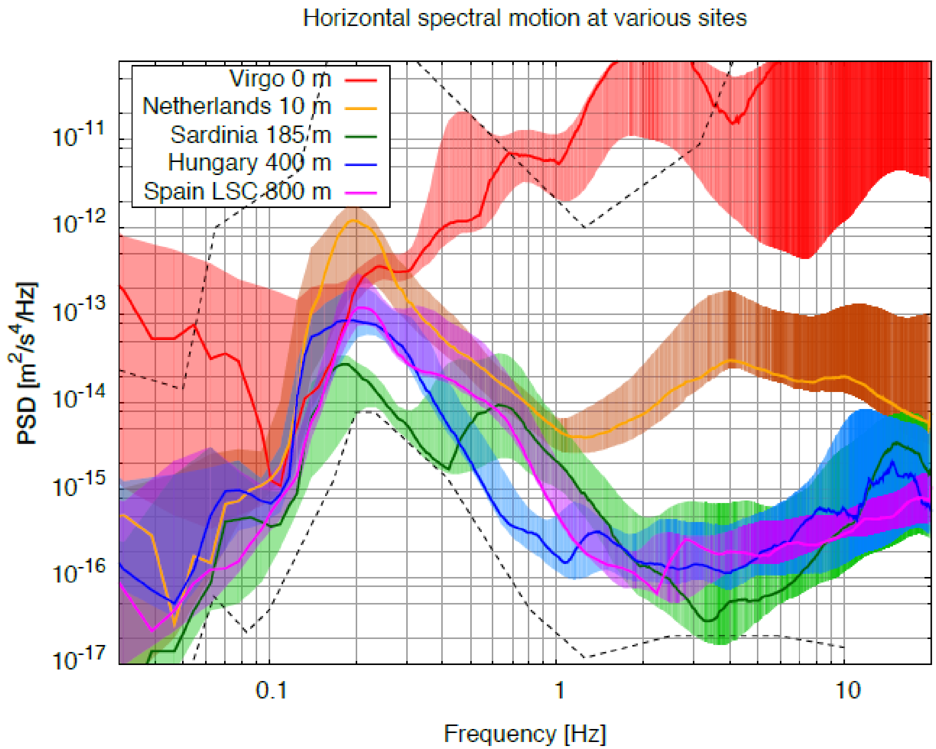

- Among Belgium - Germany – Nederland (close to Maastricht)
- Italy (Sardinia - Sos Enattos)

Further reading

- Paper on the detection: LSC and VIRGO -Observation of Gravitational Waves from a Binary Black Hole Merger Phys. Rev. Lett. 116, 061102 (2016) - http://journals.aps.org/prl/abstract/10.1103/PhysRevLett.116.061102
- Companion papers: https://www.ligo.caltech.edu/page/detection-companion-papers
- Open data: https://losc.ligo.org/events/GW150914/
- On GW detection with interferometer:P. Saulson http://www.slac.stanford.edu/cgi-wrap/getdoc/ssi98-005.pdf
- On Advanced Virgo detector: The VIRGO collaboration - Advanced Virgo: a second-generation interferometric gravitational wave detector http://arxiv.org/pdf/1408.3978.pdf
- On aLIGO detectors: LSC – Advanced LIGO http://iopscience.iop.org/article/10.1088/0264-9381/32/7/074001/meta
- On close-future evolution of GW detectors:VIRGO, LSC - Prospects for Observing and Localizing Gravitational-Wave Transients with Advanced LIGO and Advanced Virgo http://relativity.livingreviews.org/Articles/lrr-2016-1/
- Interferometer 3D response: https://www.nature.com/articles/s41598-020-72850-6

Thank you for your attention