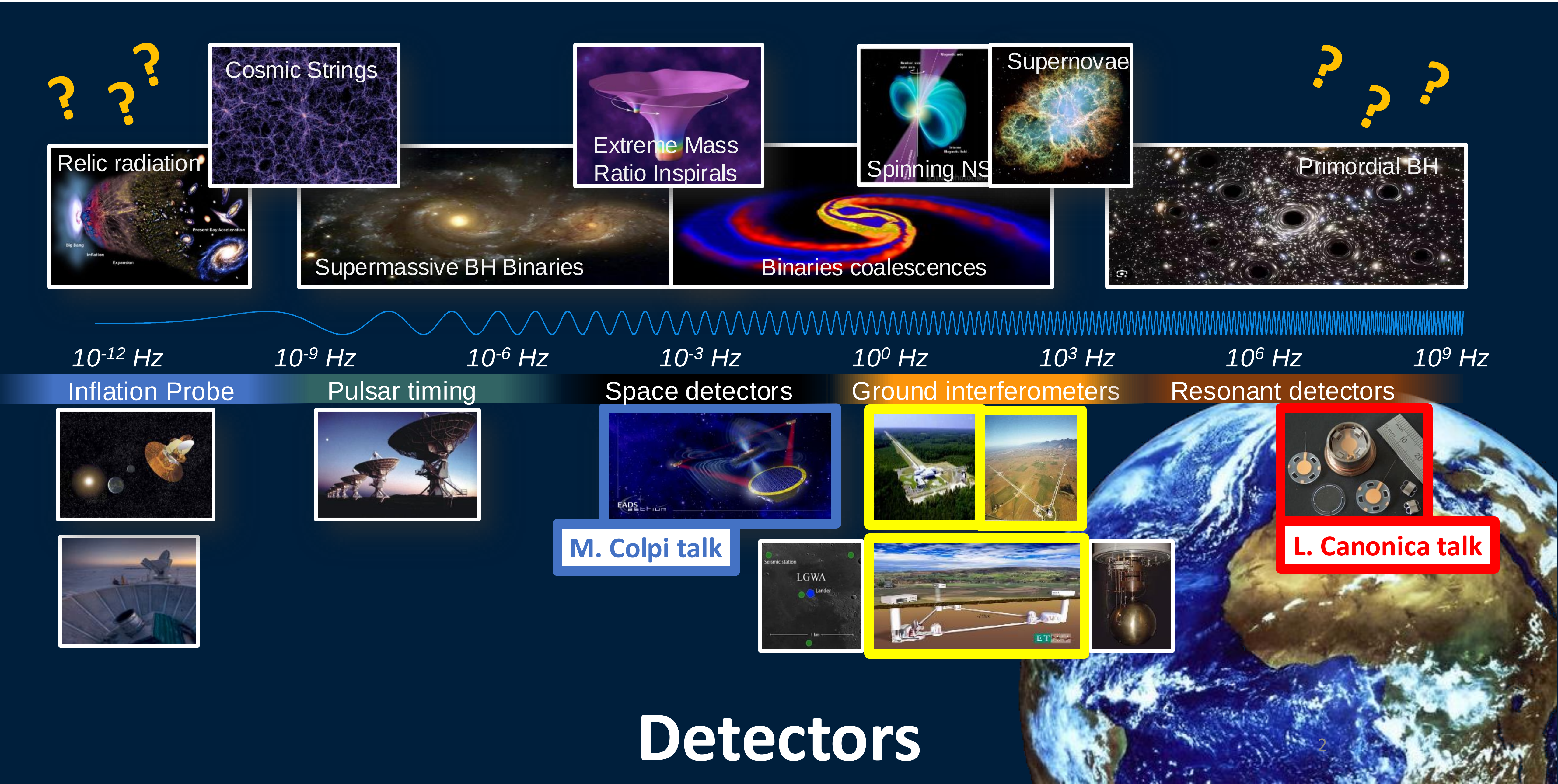
The challenge of interferometry on Earth (Virgo/ET)

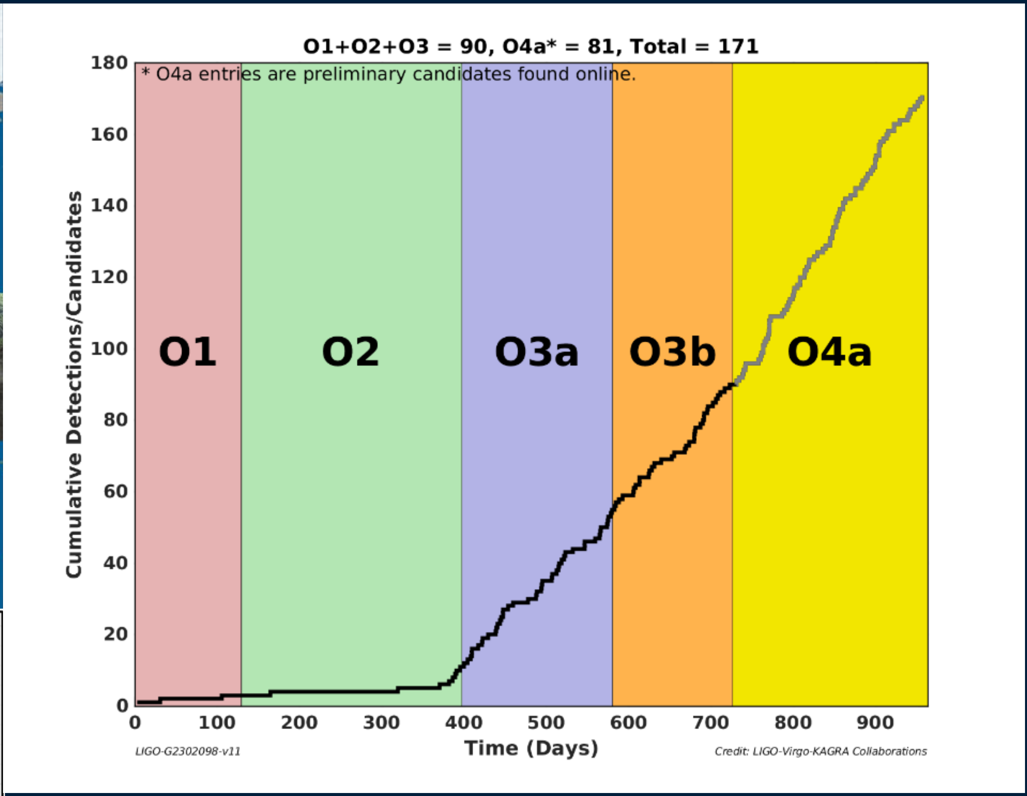
Dott. Davide Rozza

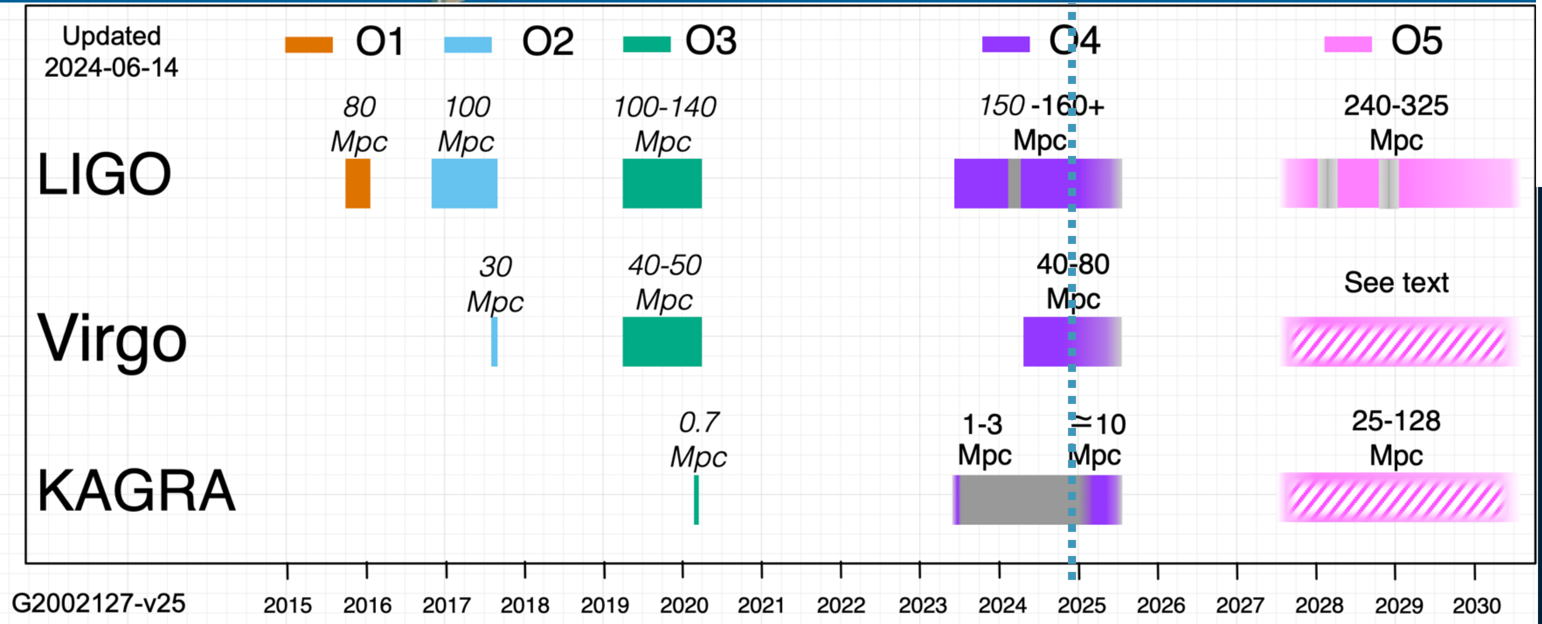
Objective of GRAF: development of new models and analysis techniques for high-precision measurements of gravitational waves

Sources of gravitational waves



Ground interferometers





*O4 entries are preliminary candidates found online

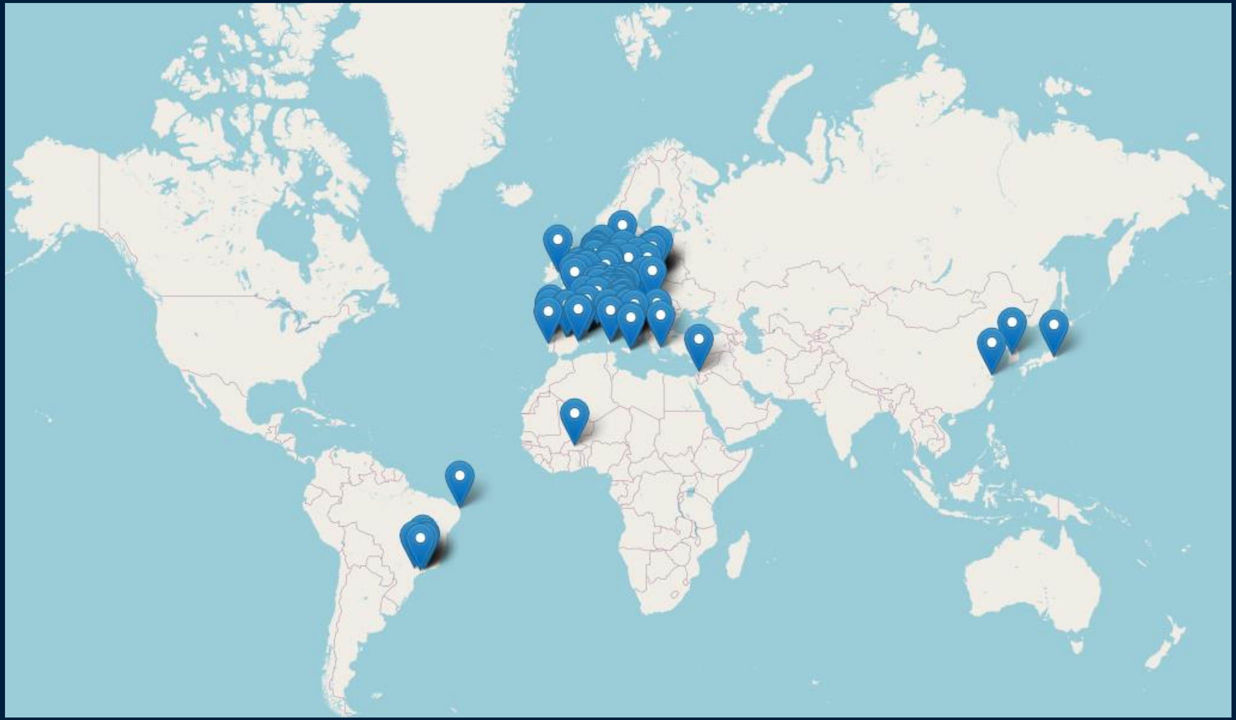
O4a: 2023-05-24 to 2024-01-16
O4b: 2024-04-10 to 2025-01-23
O4c: 2025-01-24 to 2025-06-09

VIRGO

930 members

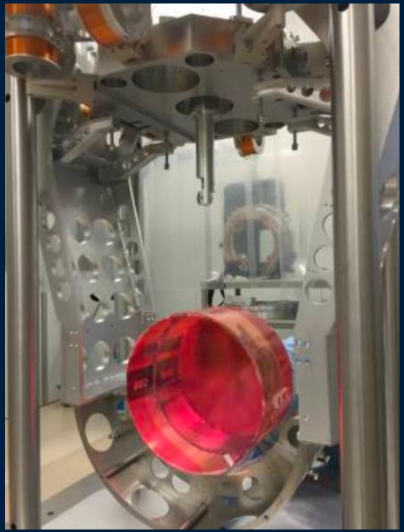
165 institutions

20 Countries



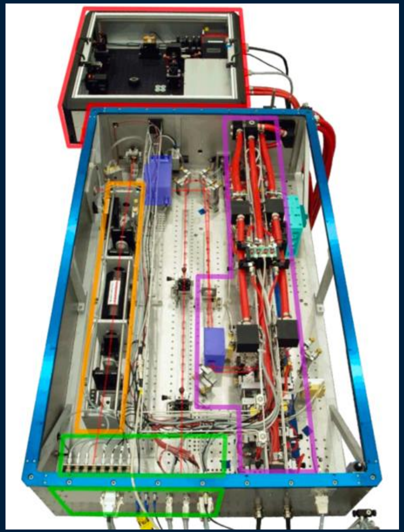
Basic of GW detections

Two test masses

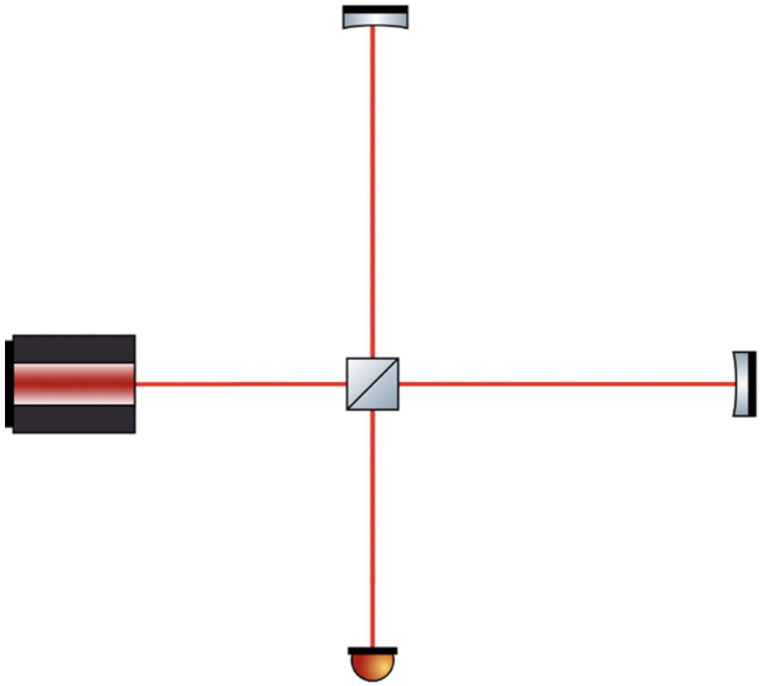


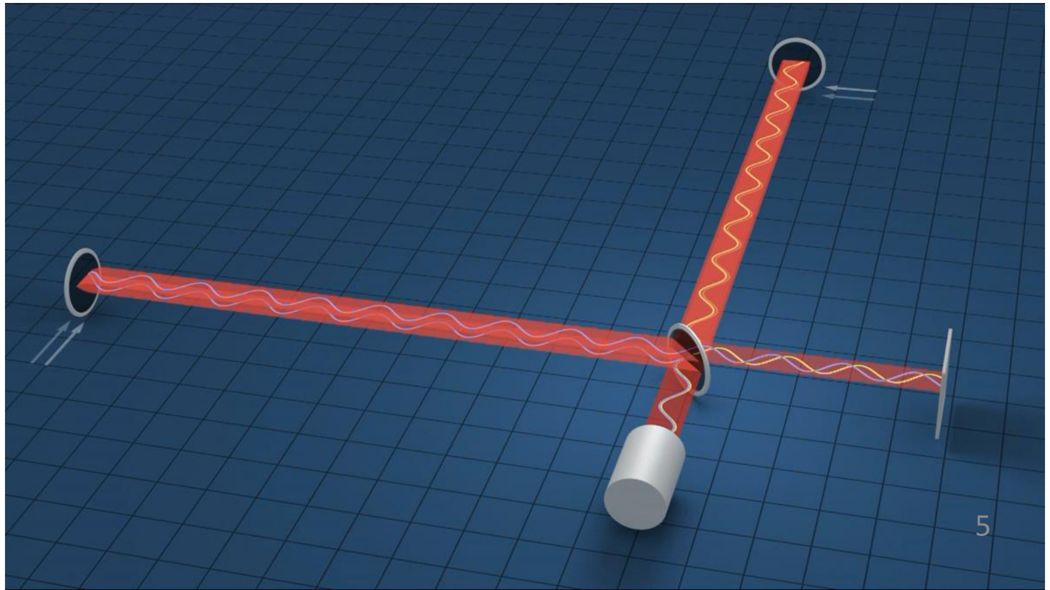
Free falling objects that sense the GW

A ruler

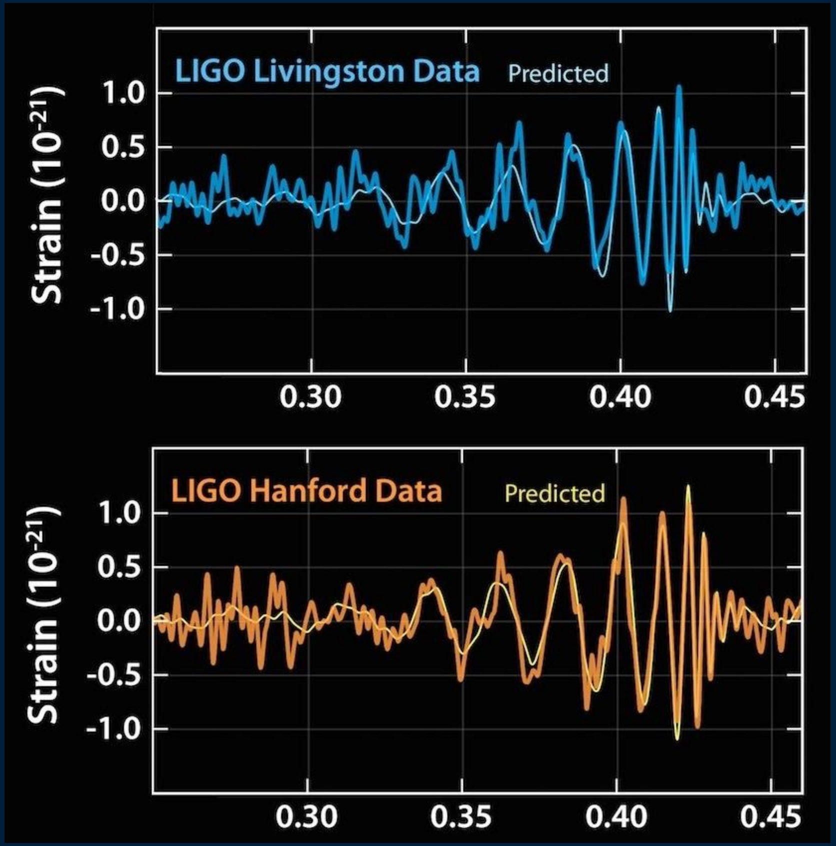


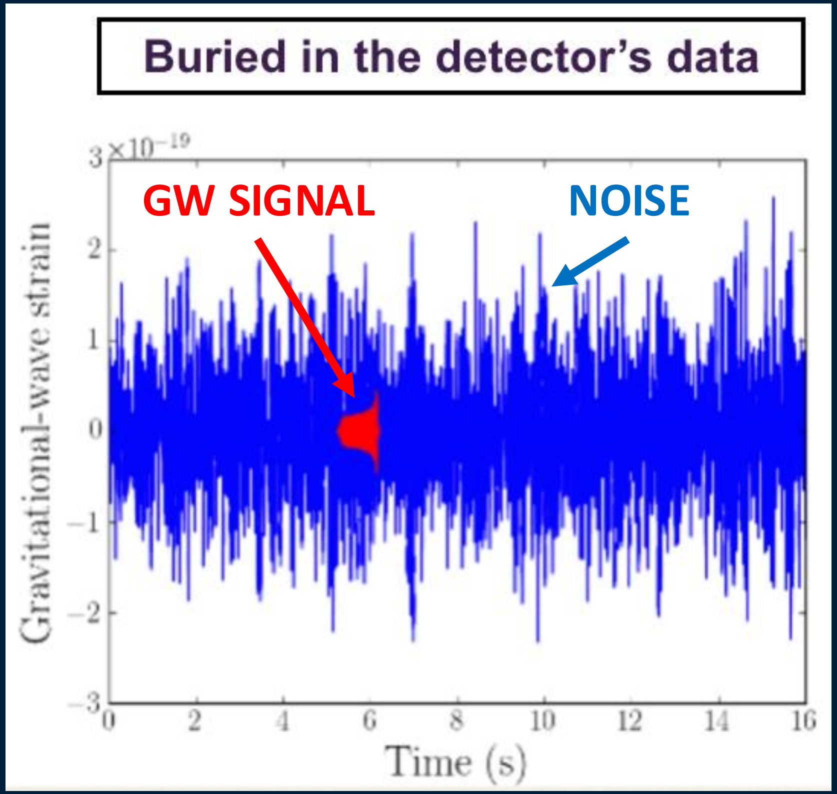
A laser light, λ is the ruler tick mark





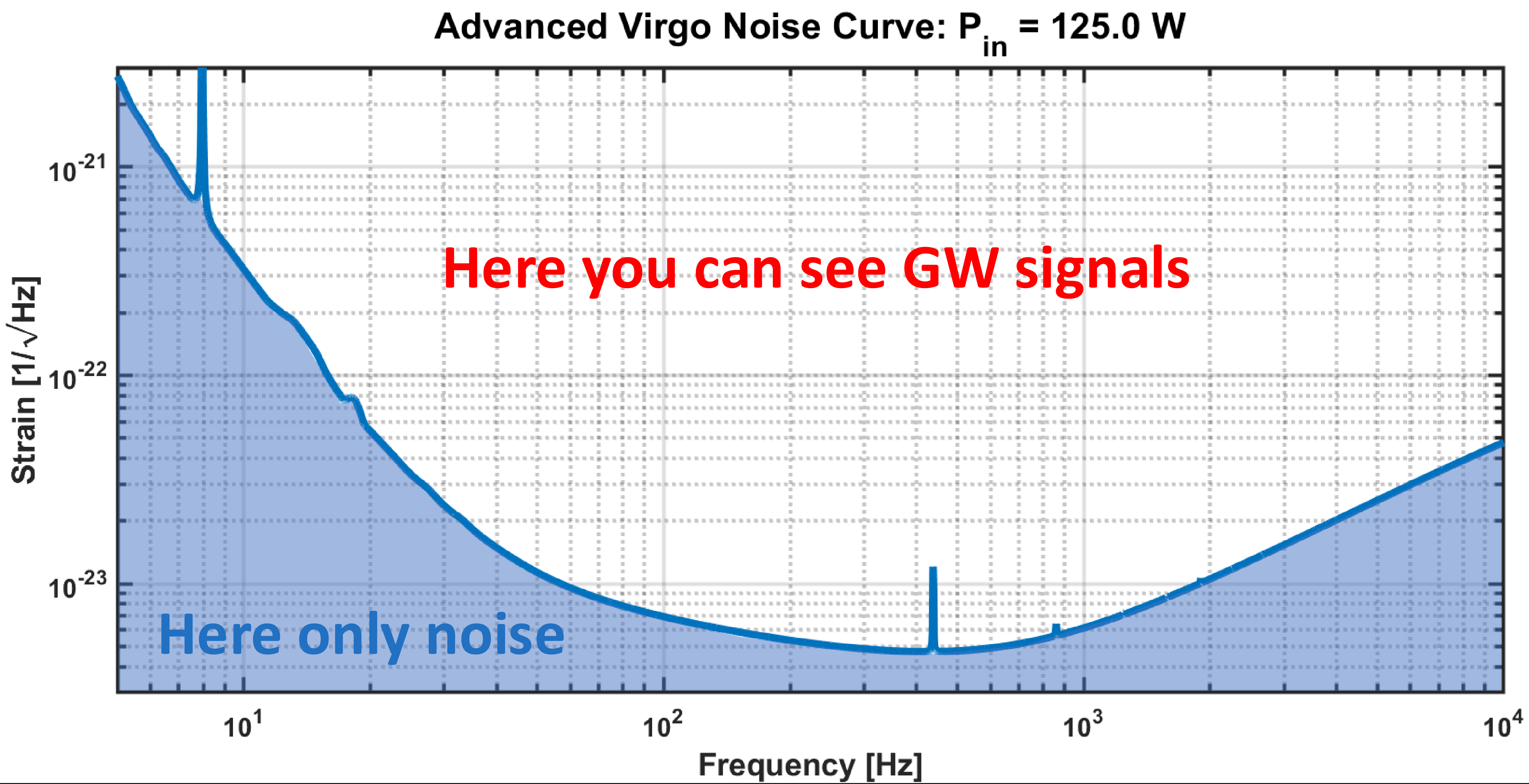
GW signals and… noise



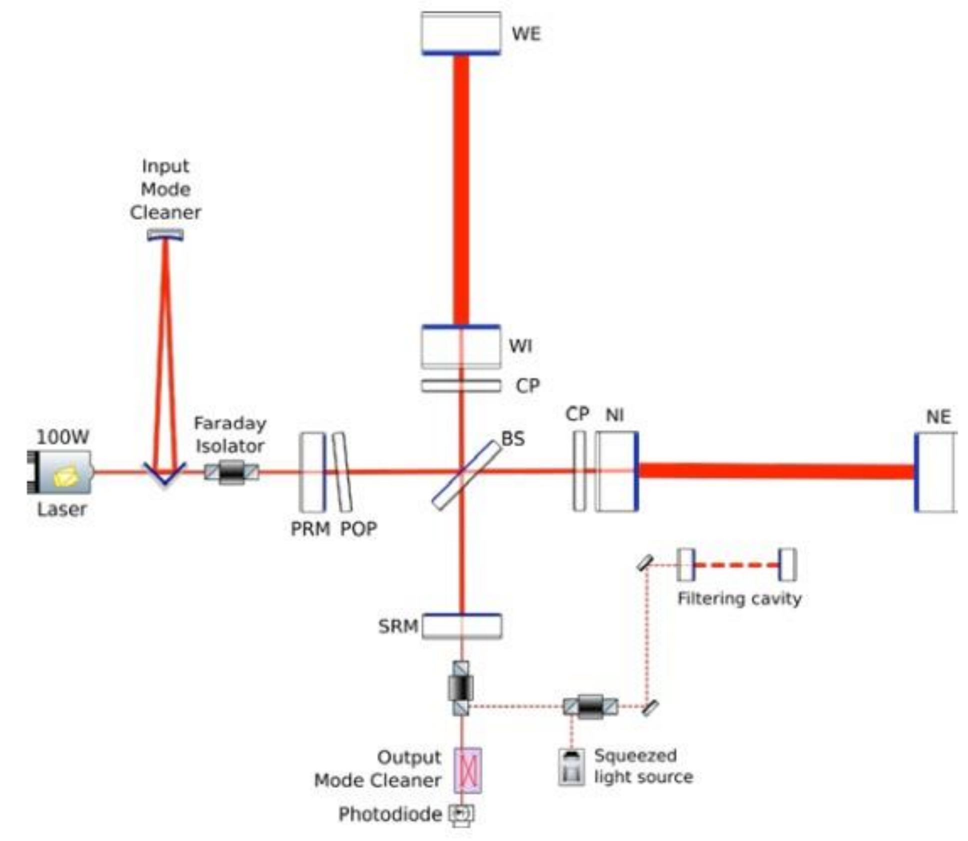


We need to enhance the signal and reduce the noise

Sensitivity curve



Enhance the signal



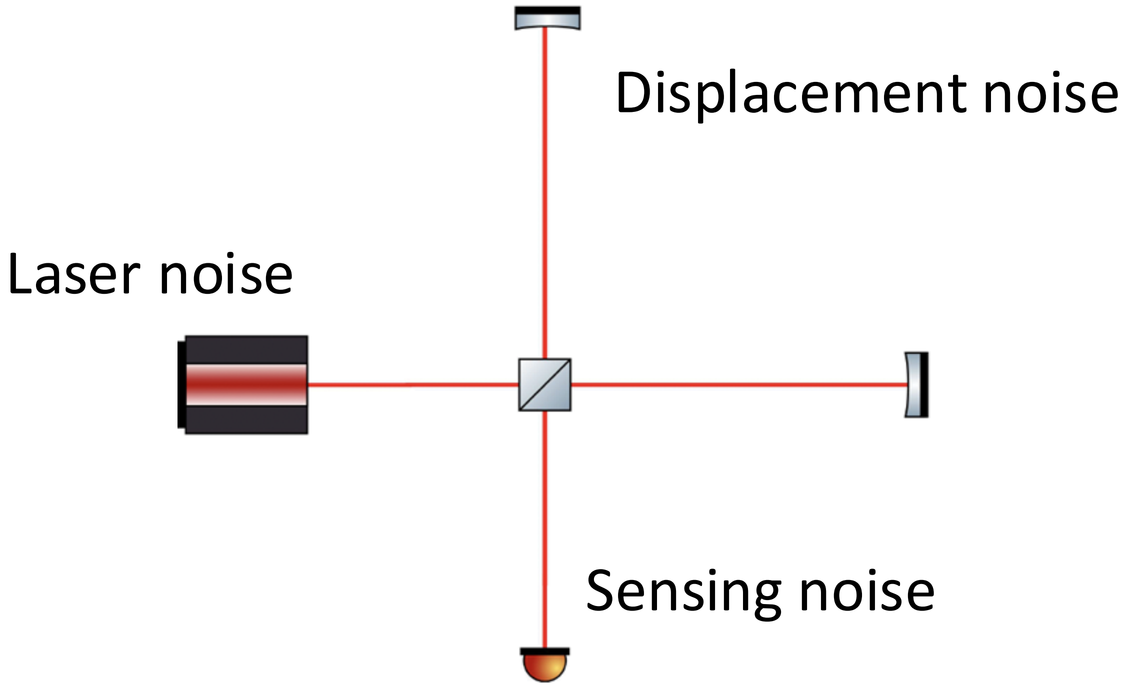
Fabry-Perot cavity for "longer arms": the presence of the optical cavities increases the number of round trip of the light, therefore enhancing the gain of the instrument

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 (***PRM***)

Signal Recycling mirror (SRM) to reshape the detector frequency response

Reduce the noise



Displacement noise

Other forces acting on the mirror moving it

Sensing noise

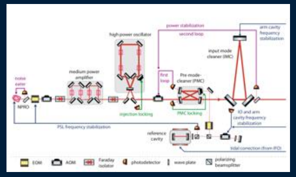
Other signals added to what is read-out from the photodiode

Quantum noise **Electronic noise**

Optical cavities **Scattered light**

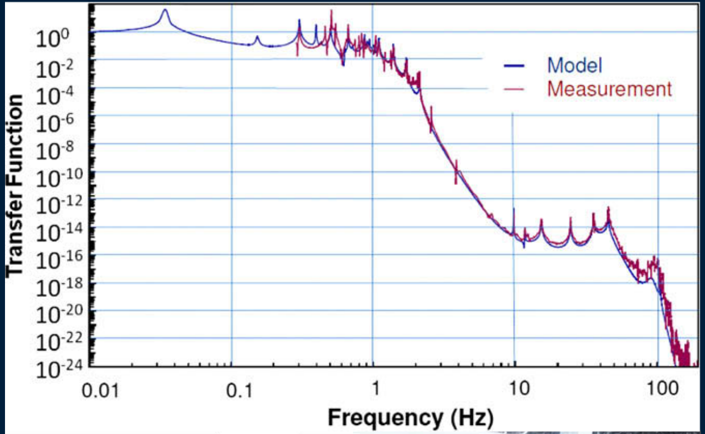
Laser noise

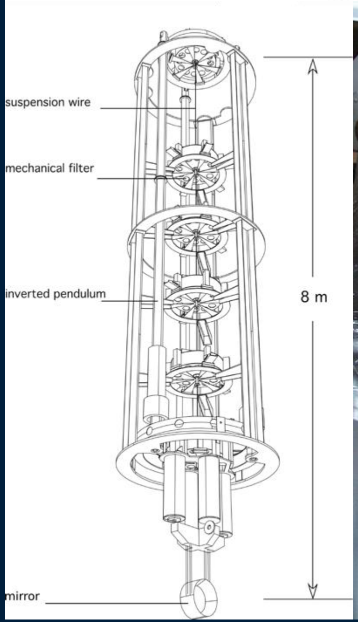
Noise in the light used for the measurement



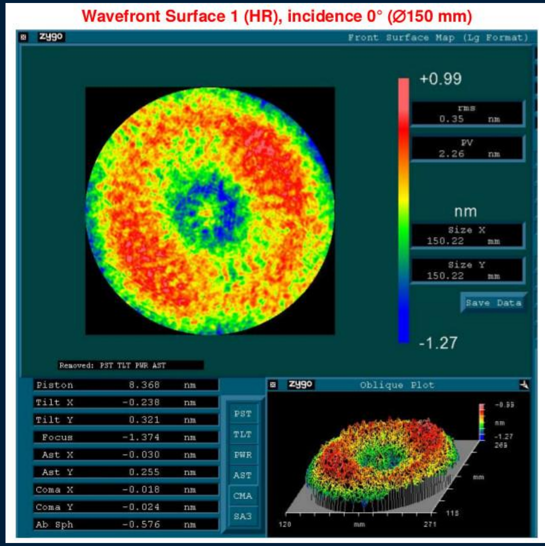
Displacement noise

Superattenuators: reduces mirrors seismic vibration by a factor 10^{15}





Thermal fluctuation of the mirror surface.
40 kg mirrors fused silica



Ultra high vacuum
It has a total volume of 7000 m^3 and is kept at a pressure of 10^{-9} mbar

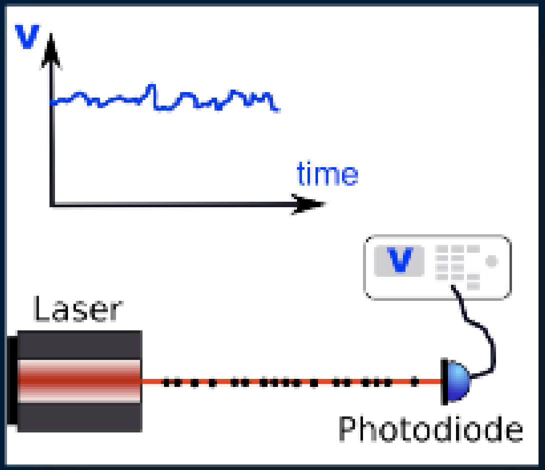
Magnetic noise sources
Magnets are attached to mirrors to allow position control
(electronics at least 10 m from the mirrors, lightning…)

Local gravity (NN)
(ground moves due to seismic earthquakes, sea waves…)

…

Sensing noise

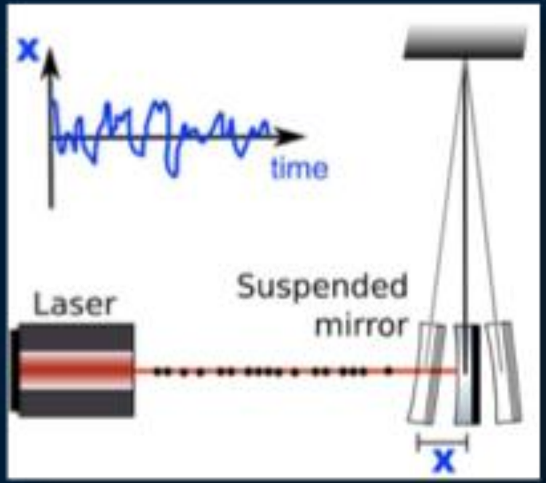
Shot noise: photon counting noise



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

P = Power

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



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

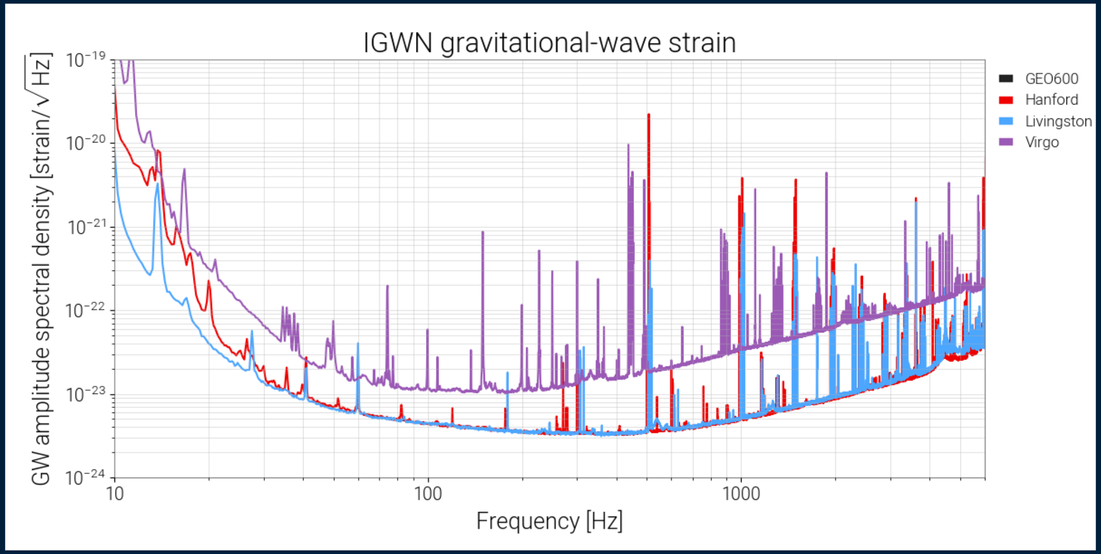
Dark noise

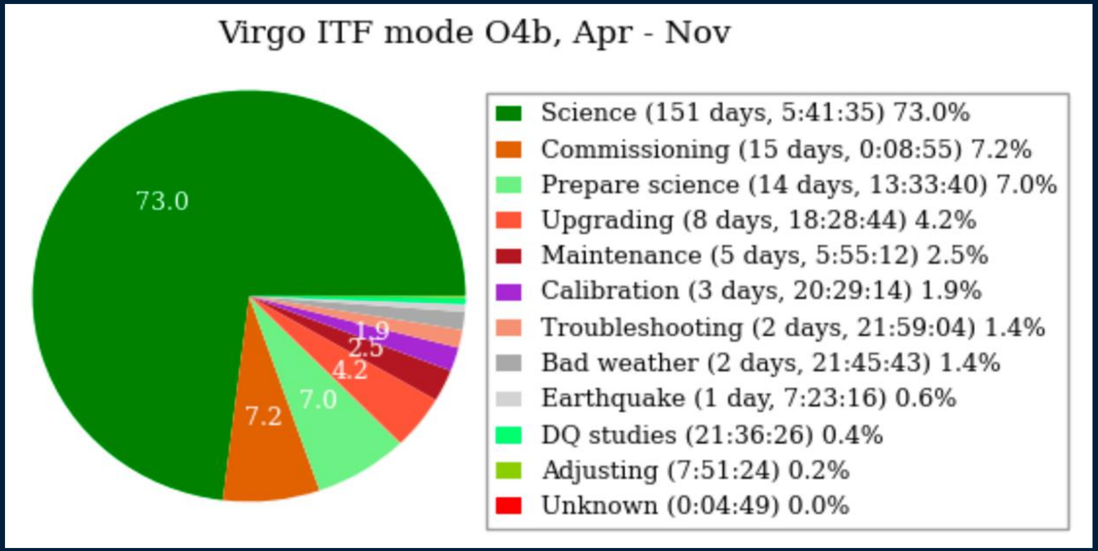
Electronic noise

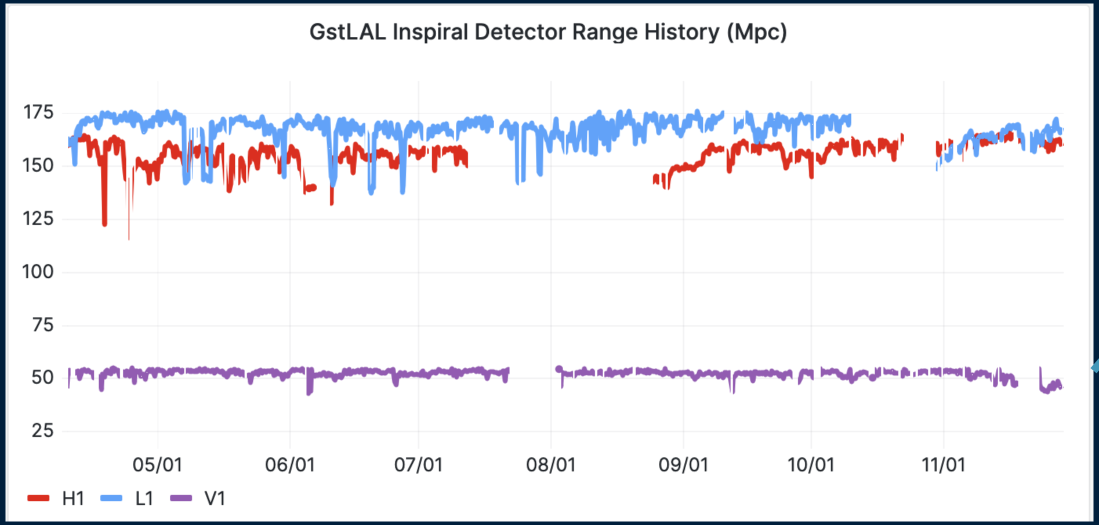
Scattered light
(add absorbing glass everywhere, suspend optical elements, …)

…

VIRGO science







BNS range holes due to:
exceptional intervention, strong wind…
BNS range performance reduction:
bad weather, glitches, issues, photodiode saturation…

VIRGO data used in low latency for sky localization

Still working to identify noise sources and reduce them

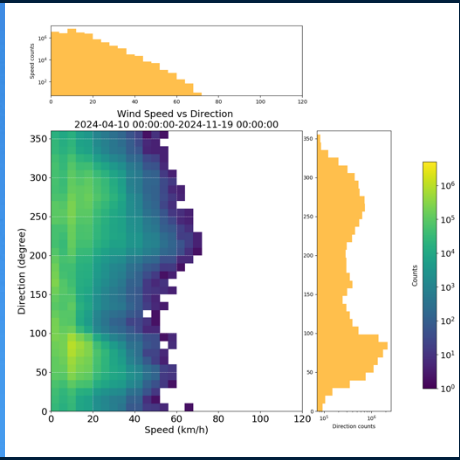
UNIVERSITA' DEGLI STUDI DI MILANO BICOCCA

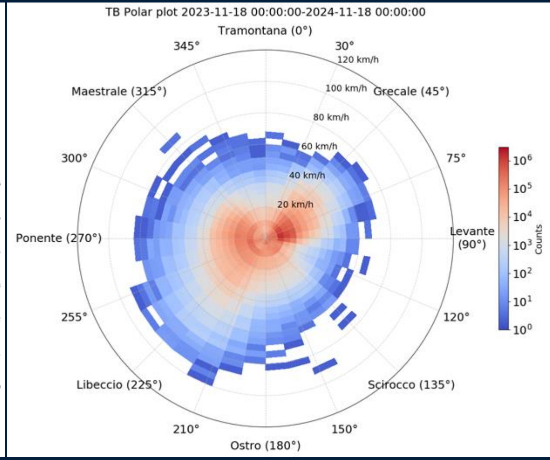
EGO VIRGO

VIRGO @ MIB

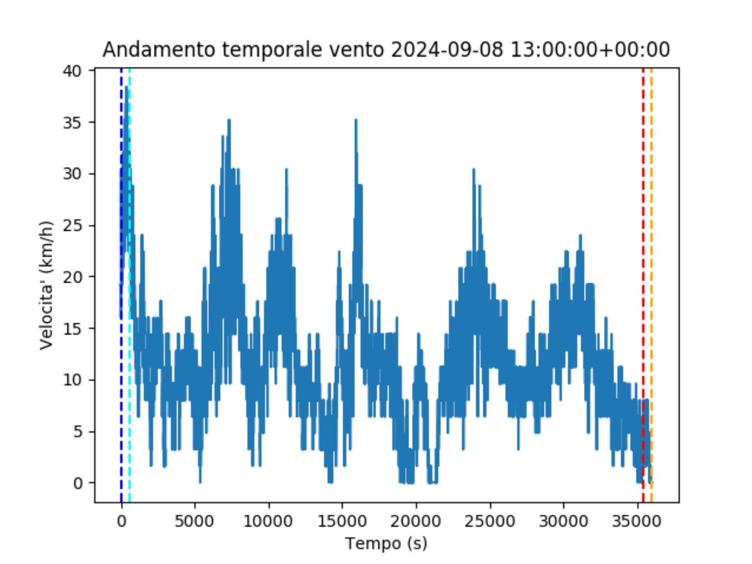
DIPARTIMENTI DI ECCELLENZA 2023 - 2027

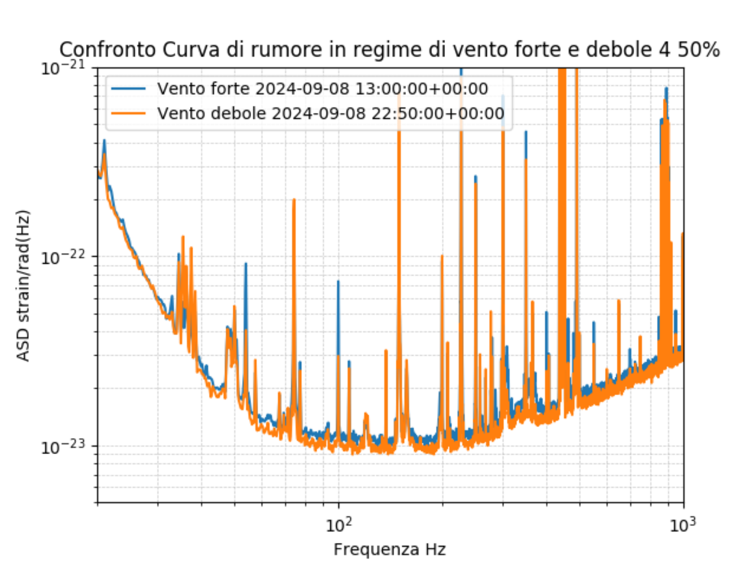
BICoQ

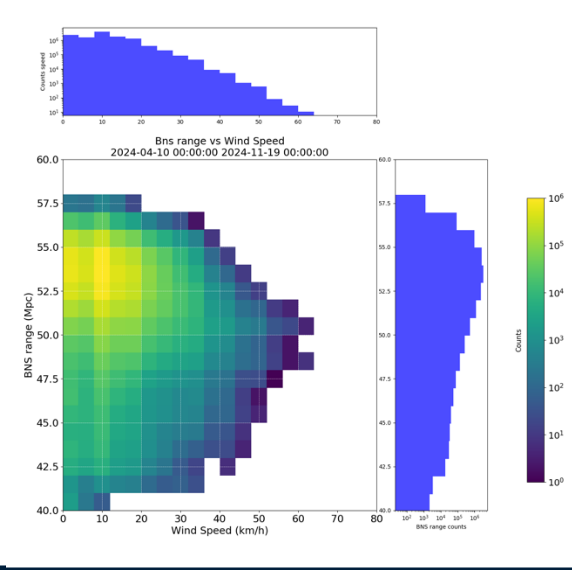




Impact of the wind on the Virgo sensitivity and BNS range



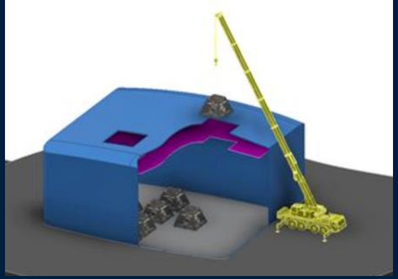




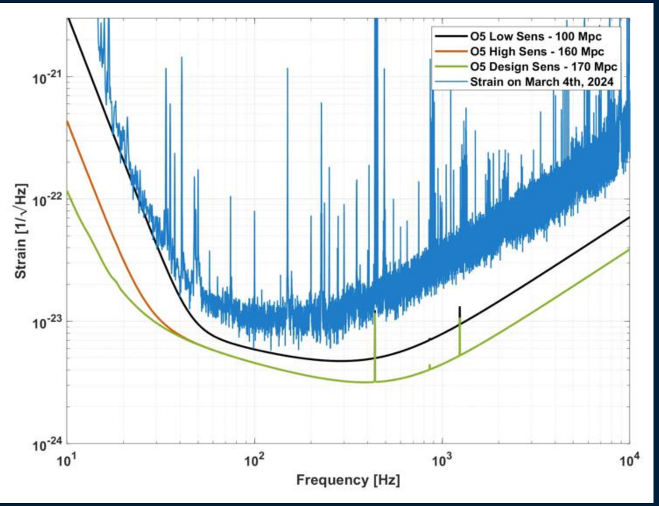
VIRGO post O4

O5 (AdV+)

Improve detector robustness, with the installation of stable recycling cavities
Improve sensitivity, avoiding that gap with LIGO becomes too deep



Current plan: short (internal) stable cavities at the cost of a later start of O5



BNS range = 100 Mpc (Low), 160 Mpc (High)
BBH range = 1 Gpc (Low), 1.42 Gpc (High)

Post O5 (Virgo nEXT)

Same infrastructure
Same laser wavelength
Room temperature mirrors

Upgrades:
O (MW) intracavity power
Larger test masses, better coatings
NN subtraction
Improved LF sensitivity

Virgo_nEXT will be a "pathfinder" for ET(HF)

	AdV+ best	V_next best	ET HF
Power inj.	125 W	277 W	500 W
Arm power	390 kW	1.5 MW	3 MW
FDS detected	6 dB	10 dB	10 dB
Mirror mass	42/105 kg	105 kg	200 kg
beam radius	49/91 mm	91 mm	120 mm

3rd GW detectors

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

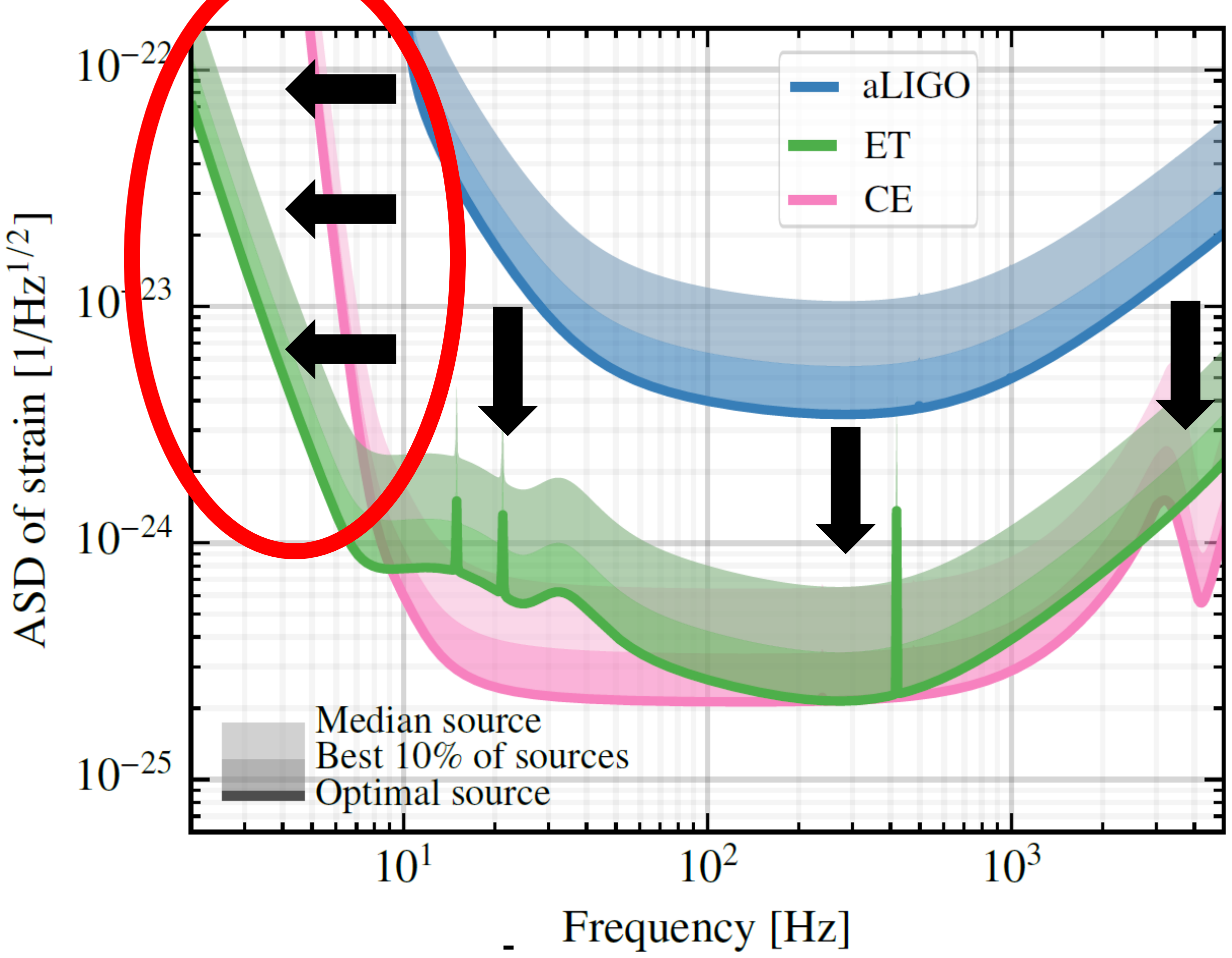
Precision measurement and a new discovery project. A wide frequency band observatory

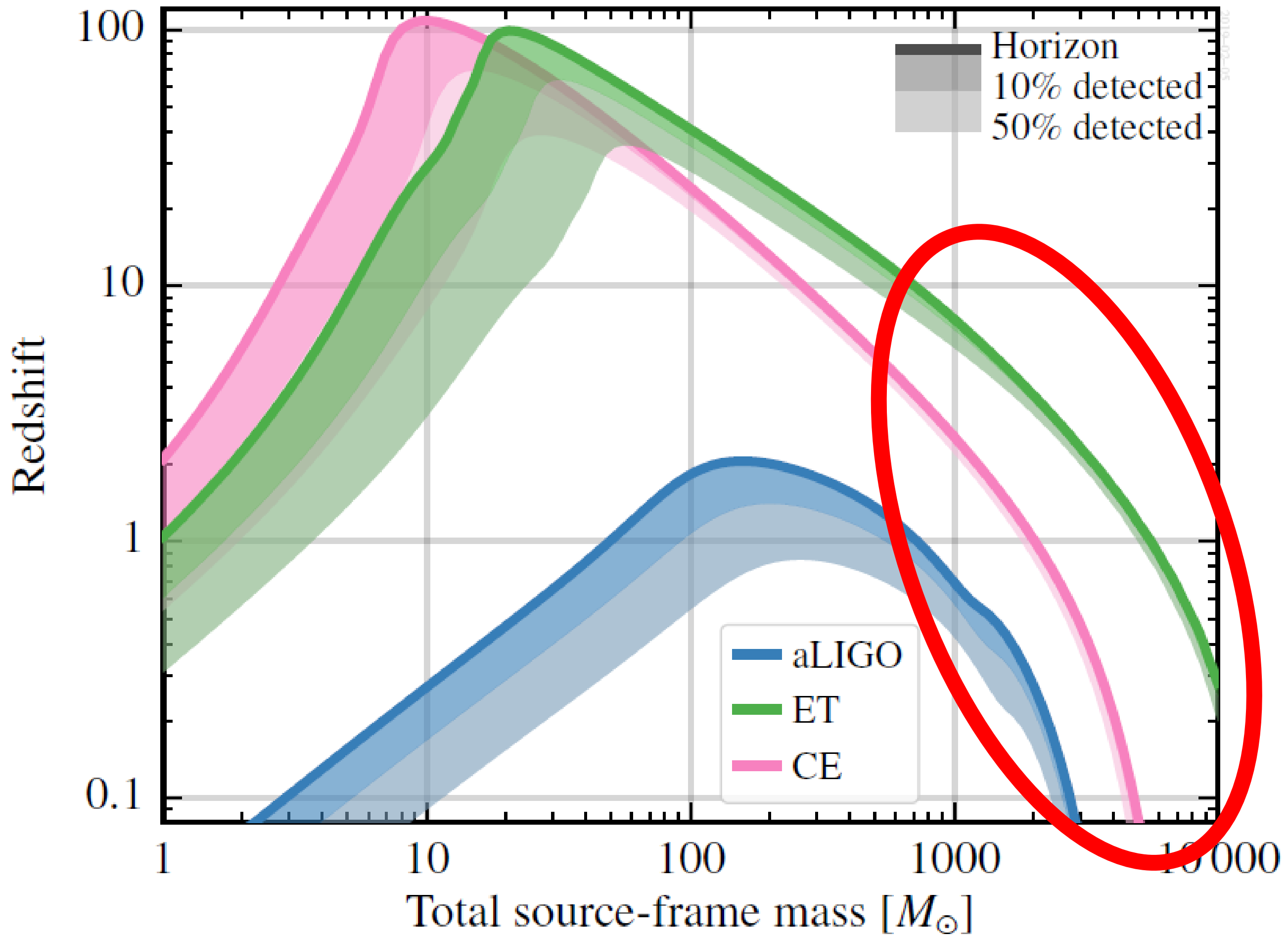
Special focus on massive (or intermediate mass) black holes. Extraordinary sensitivity at low frequency (few Hz)

High reliability. High observation duty cycle

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

Einstein Telescope physics





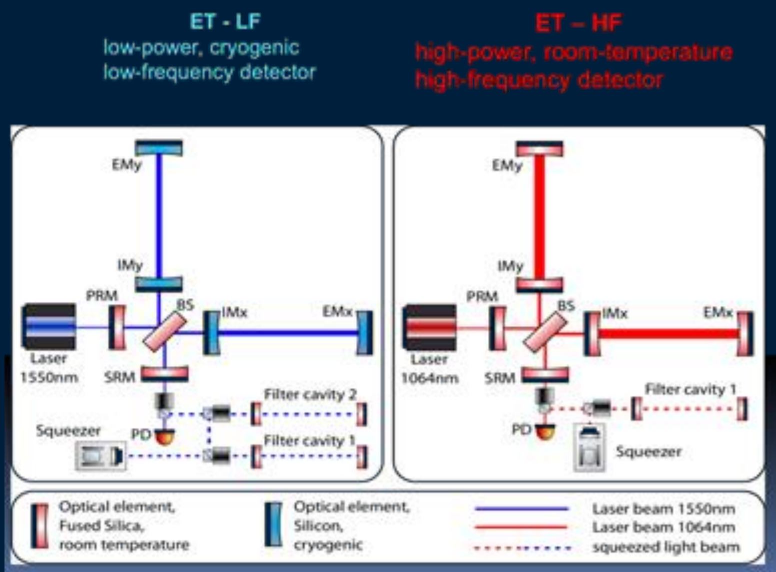
ET challenges

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

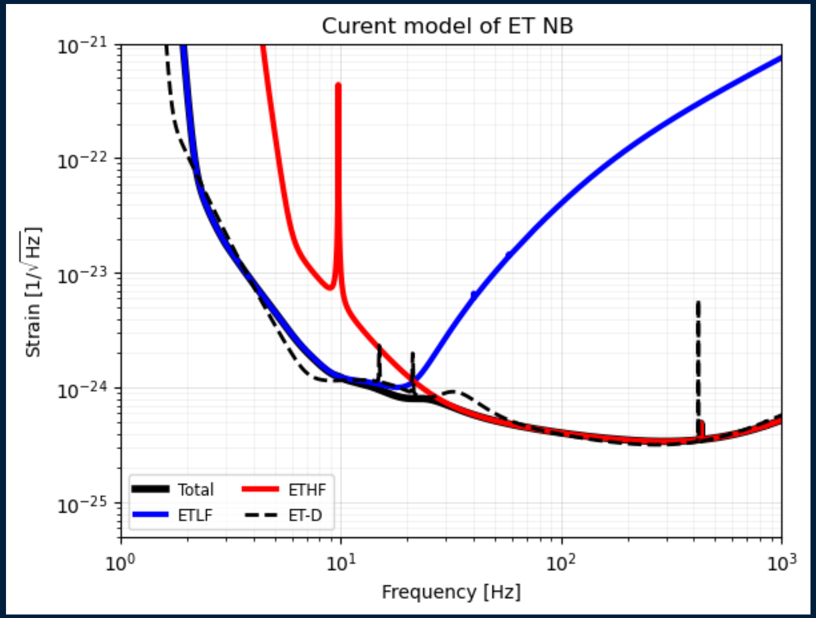


ET-HF: 300 K

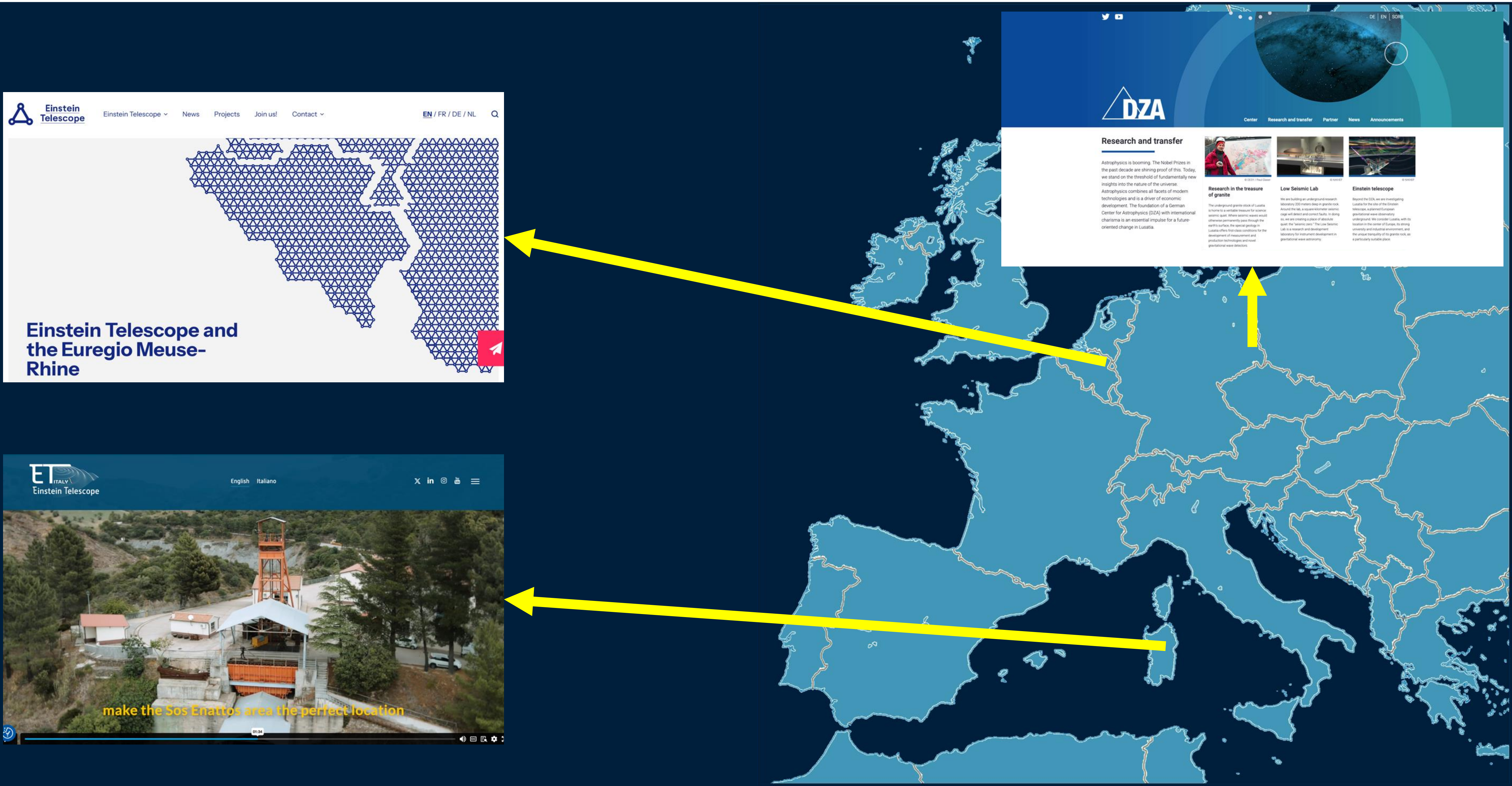
- High power laser
- High circulating light power
- Thermal compensation
- Large test masses
- New coatings
- Frequency dependent squeezing

ET-LF: 10 – 20 K

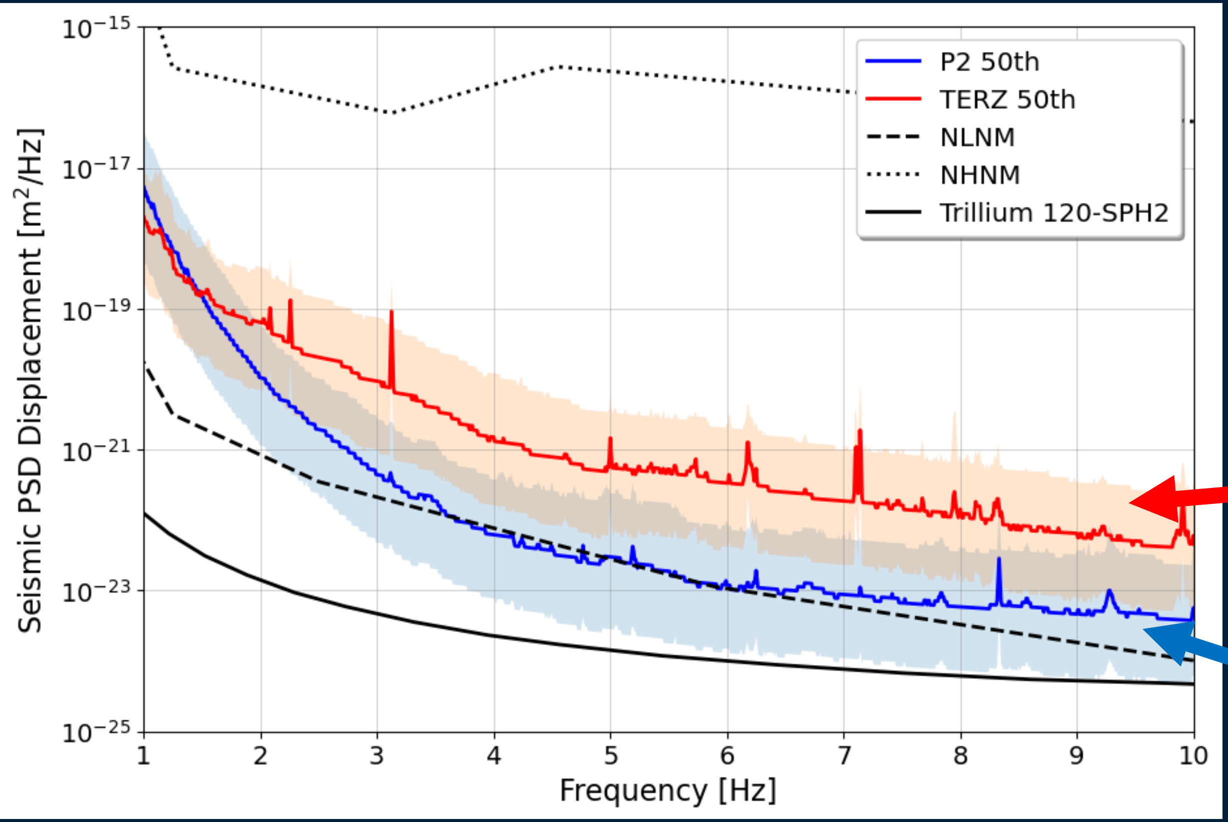
- Cryogenics
- Seismic suspensions
- Silicon (Sapphire) test masses
- Large test masses
- New coatings
- New laser wavelength
- Frequency dependent squeezing, Filter cavities

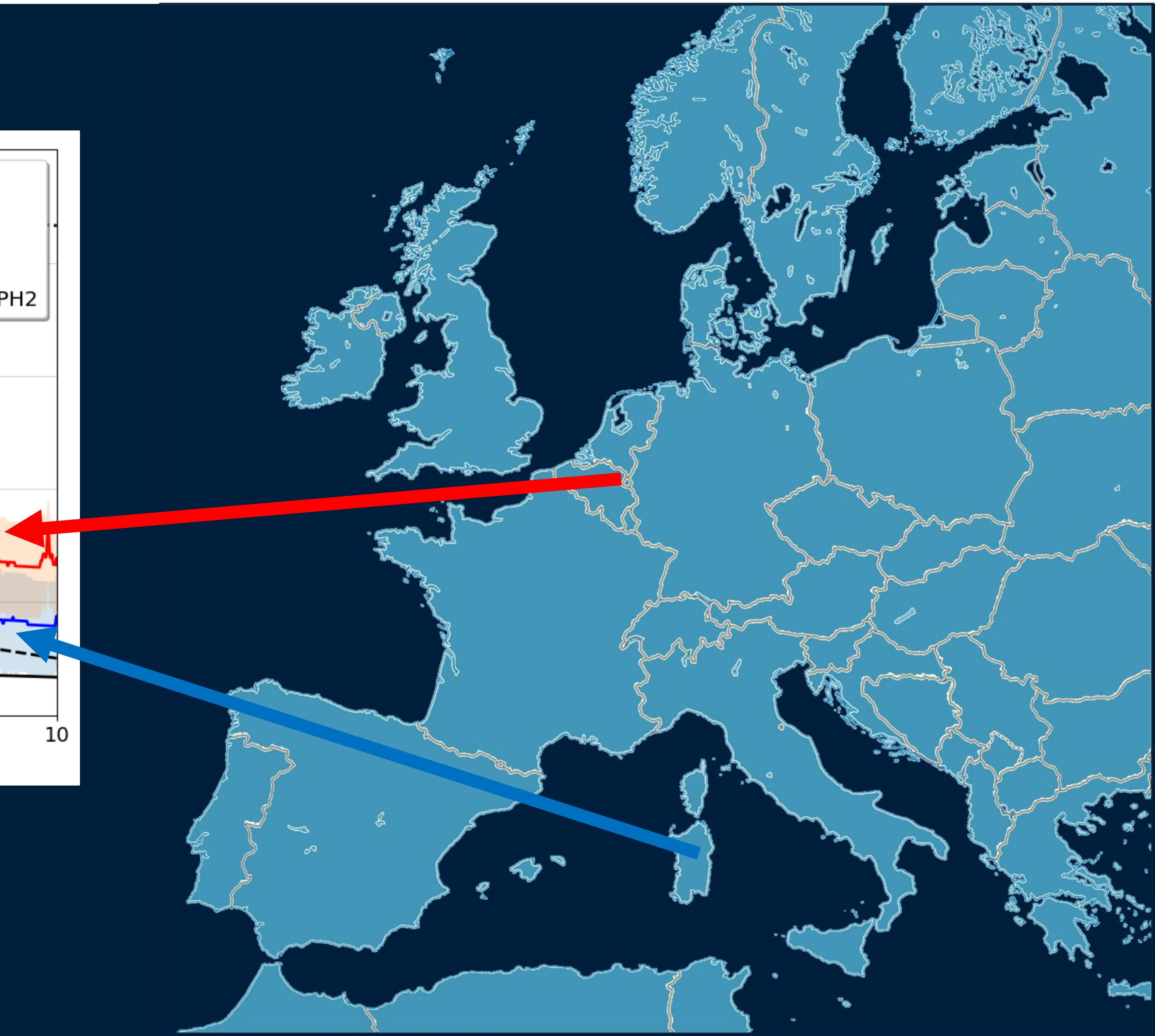


ET candidate sites

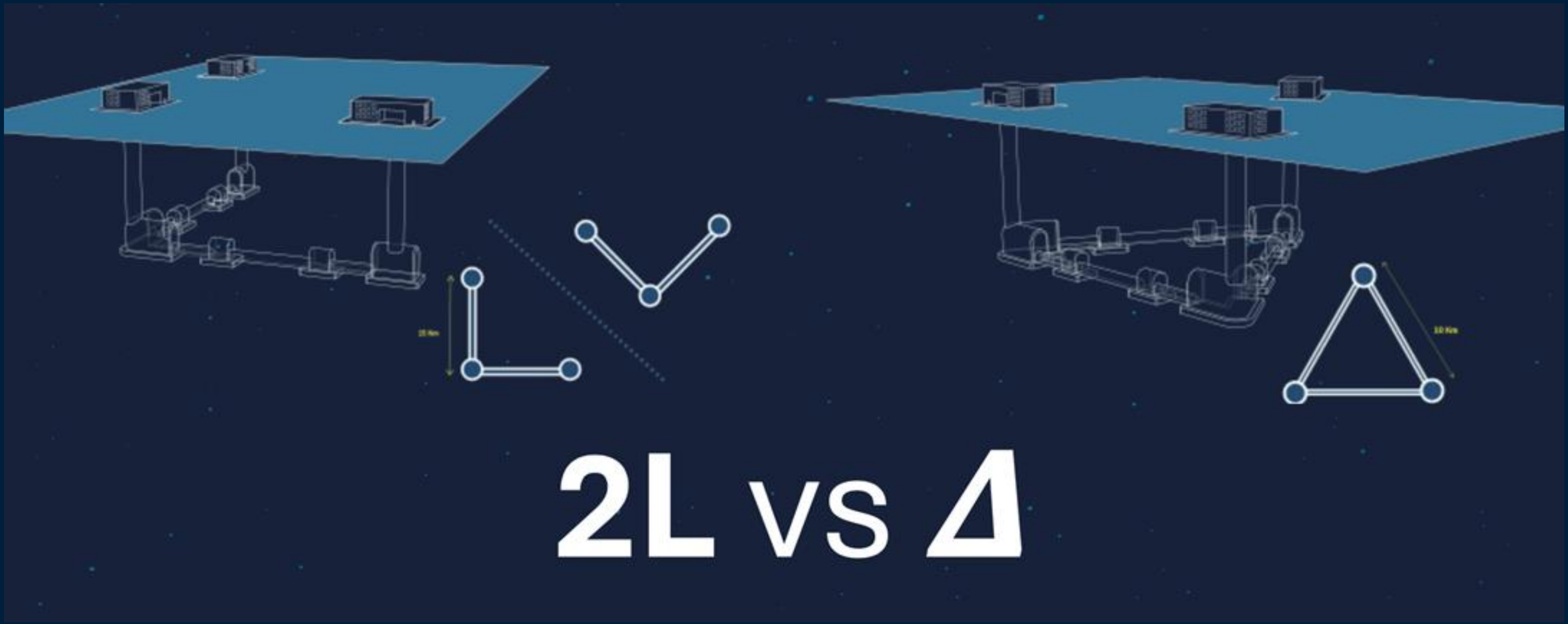


Site characterization



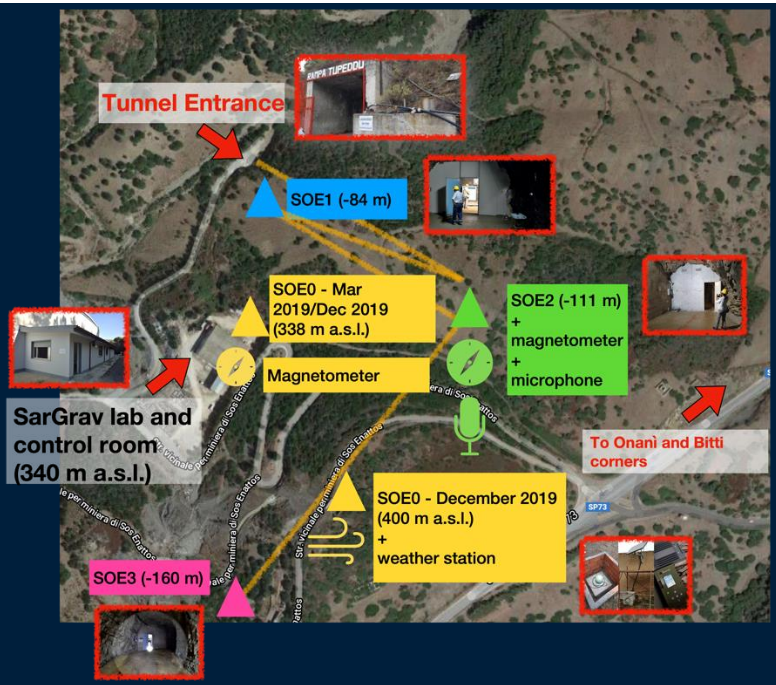


ET layout



Since **COBA** and **ETRAC** analysis are in agreements that 2L are favoured wrt Δ, and thanks to the **geology**, in Sardinia it is possible to host both **Δ and L configurations**

Site characterization



Permanent and temporary ARRAY for **characterization** and **Newtonian noise** purposes

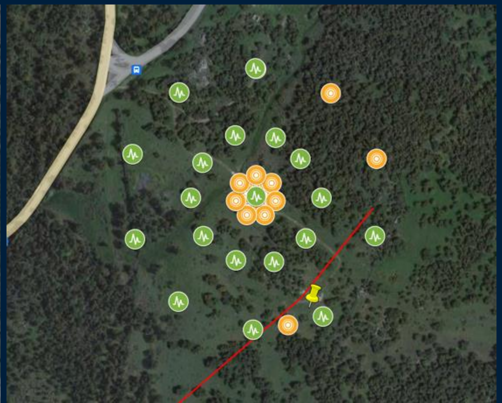
Sos Enattos broadband array (January 2021)

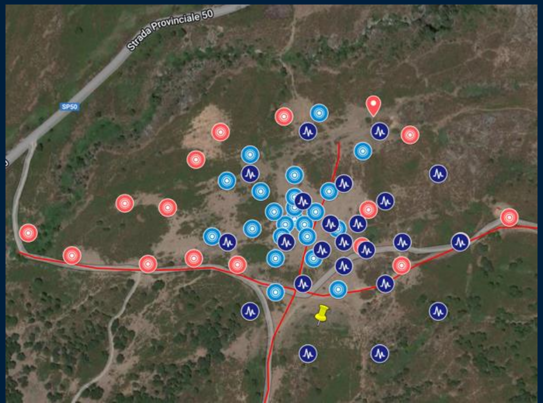
P2 broadband array + geophones (September 2021)

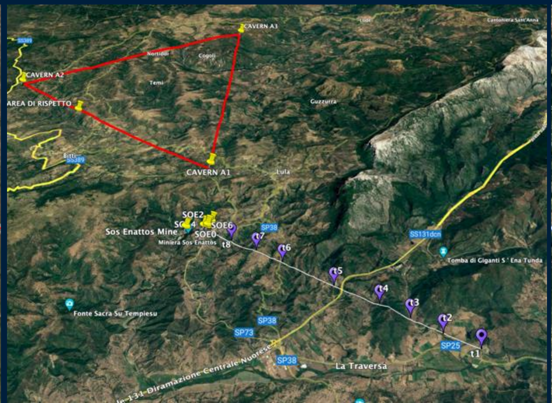
P3 broadband array + geophones (July & Oct 2021)

Explosion broadband array (early 2022)

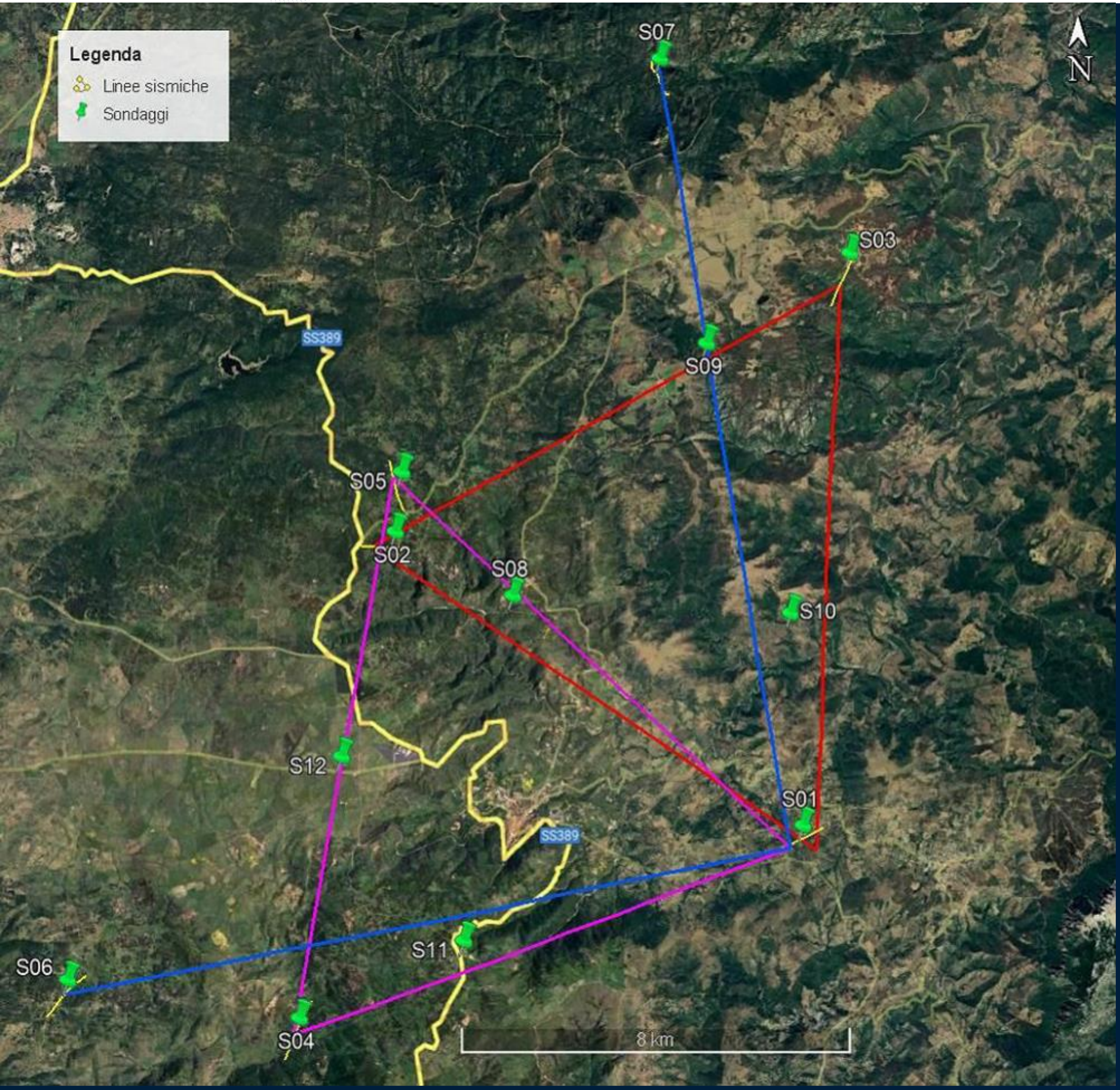
Wind Park broadband array (early 2023)







Site characterization



Sensors installed or to be installed:

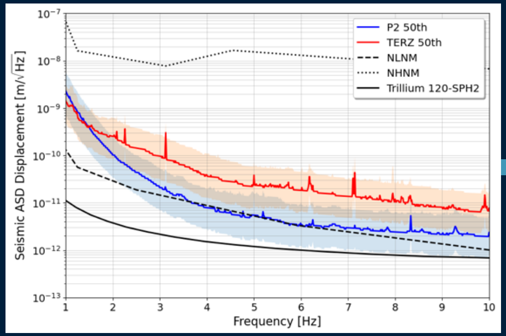
- Seismometers
- Magnetometers
- Micro-barometers
- Acoustic sensors
- Weather stations
- Gravimeters
- …

Drilling campaign

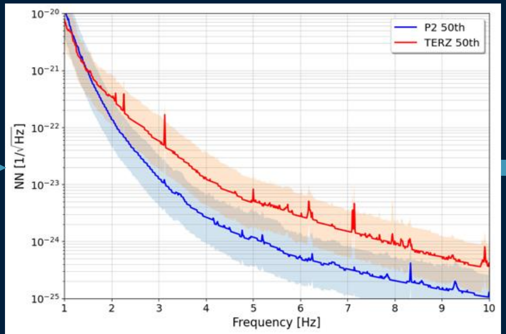
ET @ MIB

Study the impact of site noise on the ET sensitivity curve and its impact on the detectability of the aforementioned GW sources for early warning purposes.

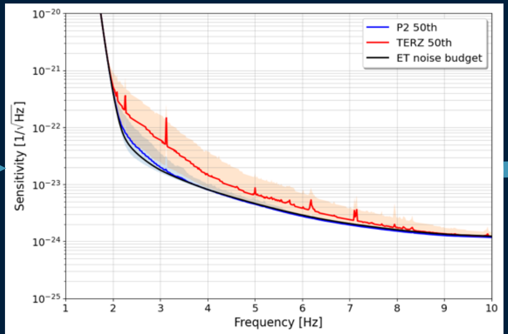
Seismic ASD Displ.



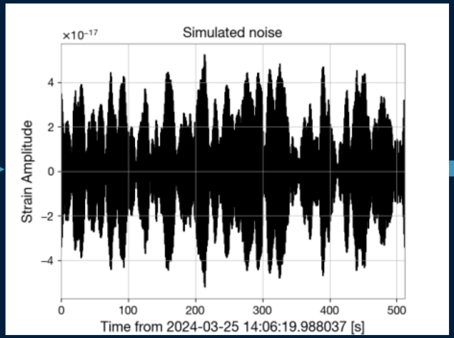
Newtonian Noise ASD



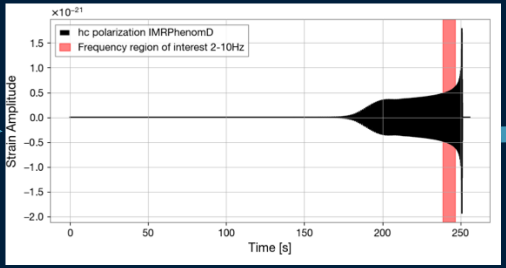
ET sensitivity



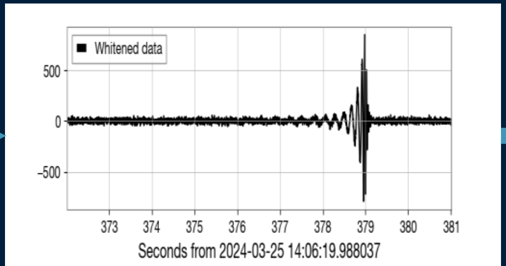
ET noise



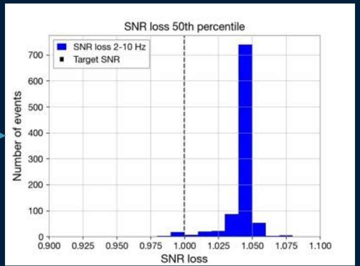
Generate waveforms

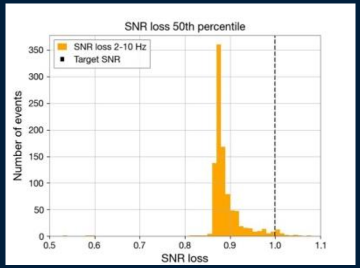


Inject signal into noise



Compare the SNRs with the design case





SNR/SNR_design

GW global network: Kagra

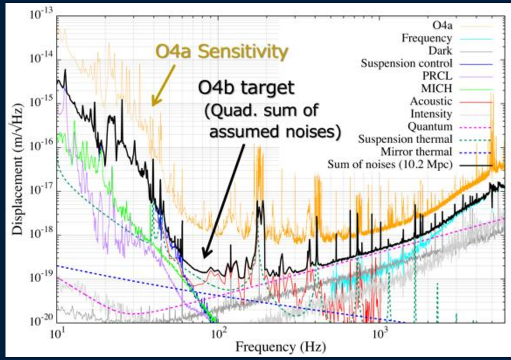
KAGRA (かぐら)
Large-scale Cryogenic Gravitational-wave Telescope
2^{nd} generation GW detector in Japan

Large-scale Detector
- Baseline length: 3km
- High-power Interferometer

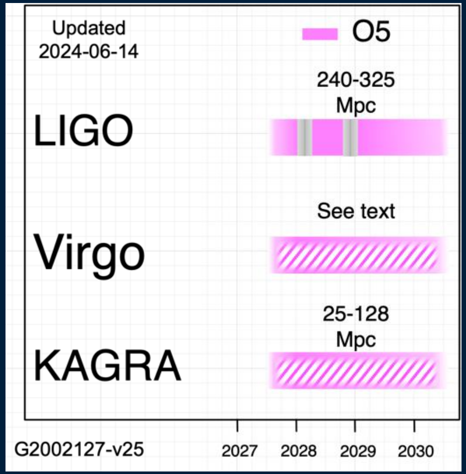
Cryogenic interferometer
- Mirror temperature: 20K

Underground site
- Kamioka site dedicated
- L-shaped tunnel

O4a (may-June) 2023: ~1.3 Mpc
All the noise source are identified
~10 Mpc for the end of O4b



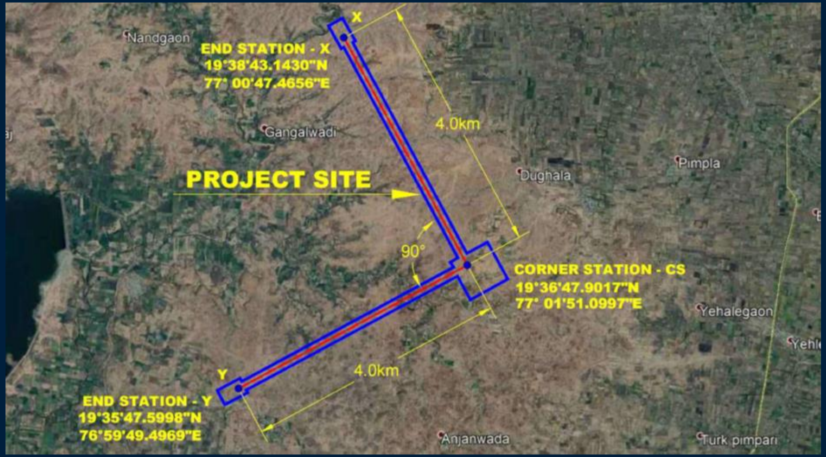
Kagra will join O5 with > 25 Mpc



- New ITMs for O5 (better symmetry and birefringence)
- Mirror/Suspension Q-factor improvement
- New SRM/ITM
- High Power Laser
- Squeezer
- Possibly a Filter Cavity
-
- O5 is expected to run for 3 years from 2027 (TBC)
- Make a detailed plan for post-O5 upgrade in 2025
- Start the preparation for the post-O5 upgrade from 2026

- O6 plan is too ambiguous at this moment ?

GW global network: LIGO-India



Planned for 2030

GW global network: LIGO→CE

LIGO Hanford, Washington

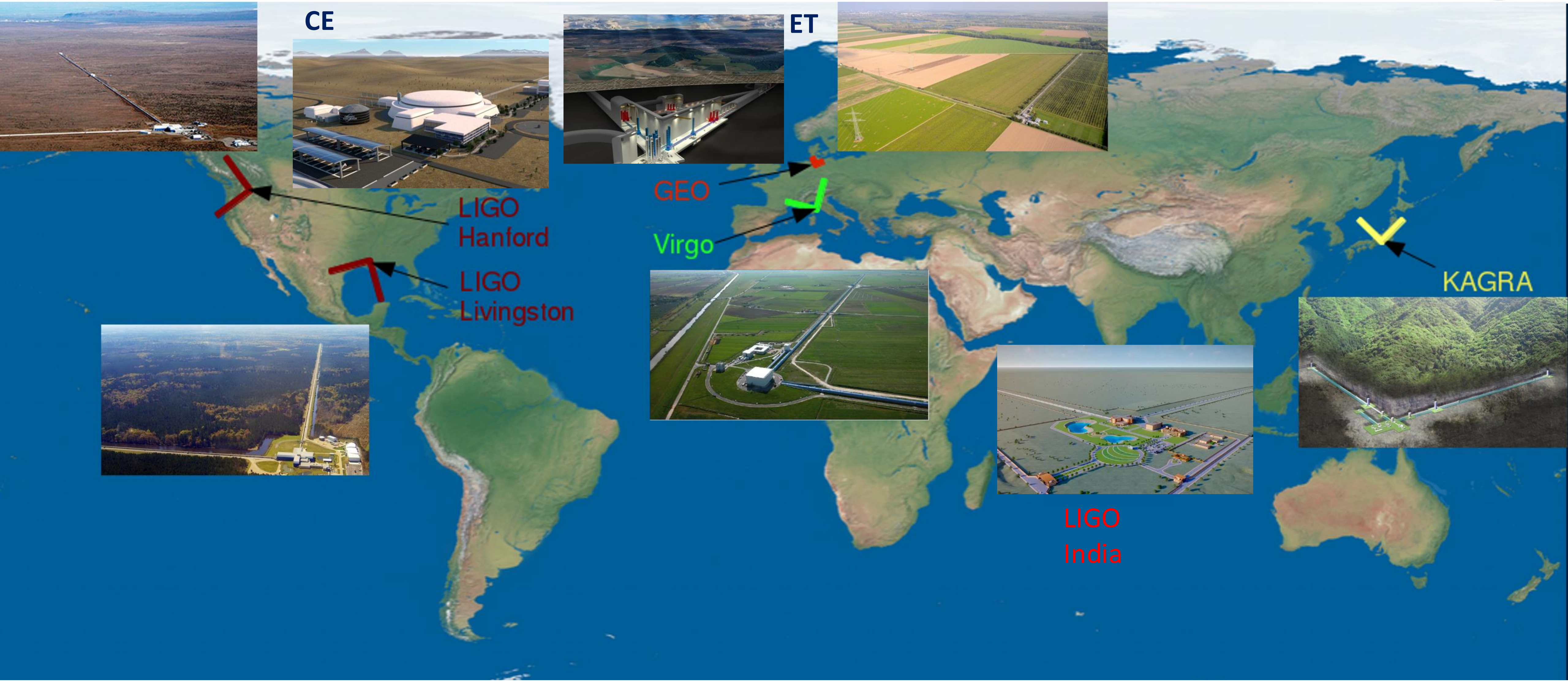
LIGO Livingston, Louisiana

Quantity	A+ (O5)	$A^{\#}$ (O6)	CE
Arm length (km)	4	4	40
Wavelength (nm)	1064	1064	1064
Mirror mass (kg)	40	100	320
Mirror diameter (cm)	34	46	70
Arm power (MW)	0.8	1.5	1.5
Squeezing (dB)	6	10	10

Credit: Angela Nguyen, Virginia Kitchen, Eddie Anaya, California State University Fullerton

Cosmic Explorer

Future GW global network



To obtain meaningful astronomical results, we need a network of gravitational wave detectors.