Hunting gravitational waves with Virgo

Status, results and future prospects

MATTEO DI GIOVANNI* ON BEHALF OF THE VIRGO COLLABORATION

2ND INTERNATIONAL CONFERENCE OF THE TWO INFINITES - TOKYO NOVEMBER 17-21, 2025

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...obtaining a higher event rate requires the capability of detecting as far as the Virgo cluster...

Giazotto et al. *The Virgo project* (1989)

Spoiler: today we can observe farther than the Virgo cluster

History of GW detection - Einstein's field equations

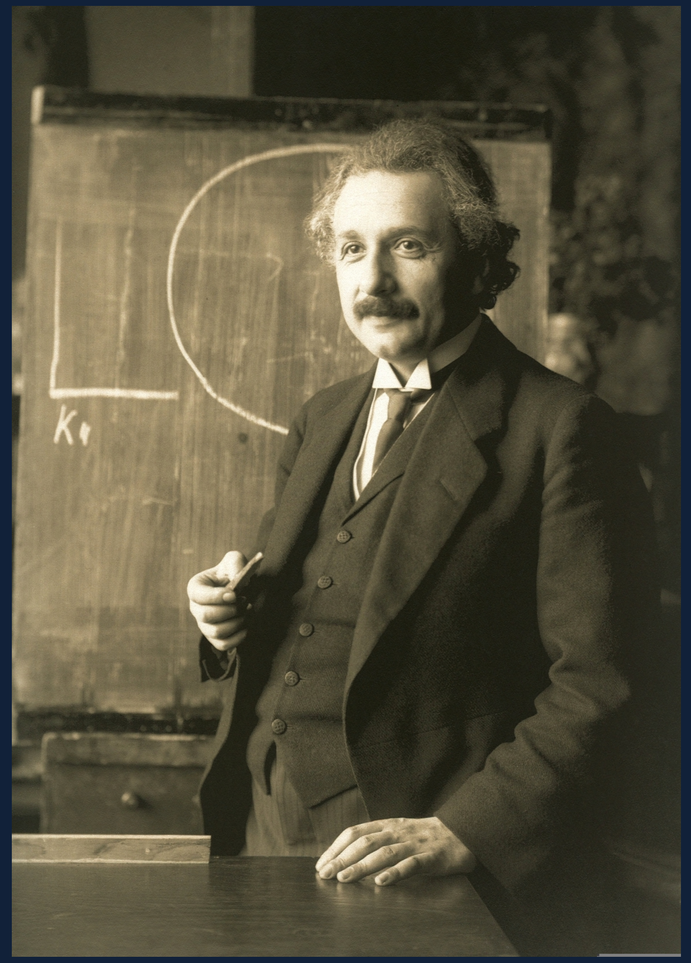
$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Geometrical properties of space-time

Mass-energy distribution

"Space-time **tells matter** how to move; **matter tells space**-time how to **curve"**

J.A. WHEELER



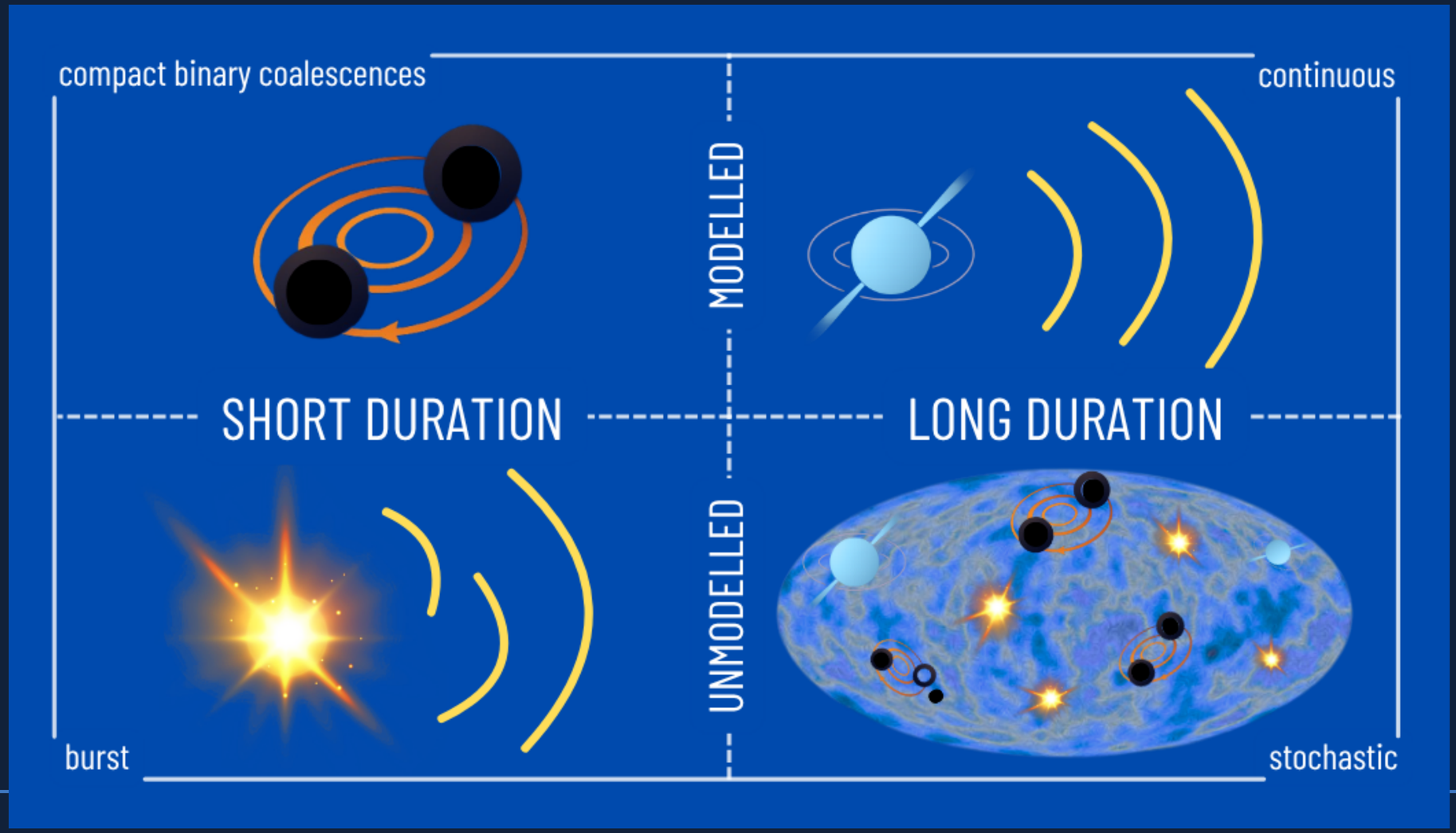
The linear solution of Einstein's field equations is a wave that propagates in vacuum at the speed of light.

This can be seen as the consequence of a mass-energy distribution that changes with time.

$$\begin{cases} \overline{h}^{\mu 0} = 0 \\ \overline{h}^{ik}(t,r) = \frac{2G}{c^4 r} \left[\frac{d}{dt} q^{ik} \left(t - \frac{r}{c} \right) \right]. \end{cases}$$

Deviation from axisymmetry to emit GW!

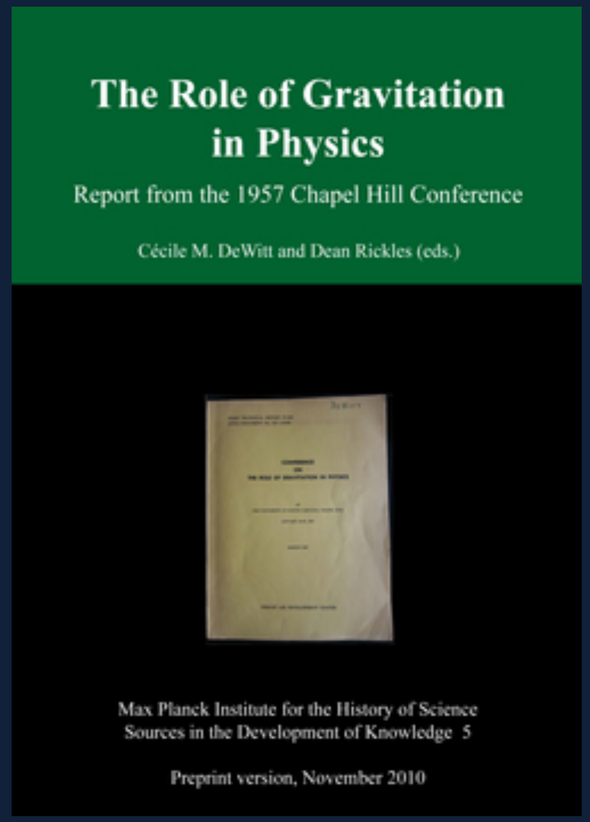
History of GW detection - sources



History of GW detection - Chapel Hill conference

In 1957 Felix Pirani presented a *gedankenexperiment* to observe a gravitational wave, supporting the physical nature of GW.

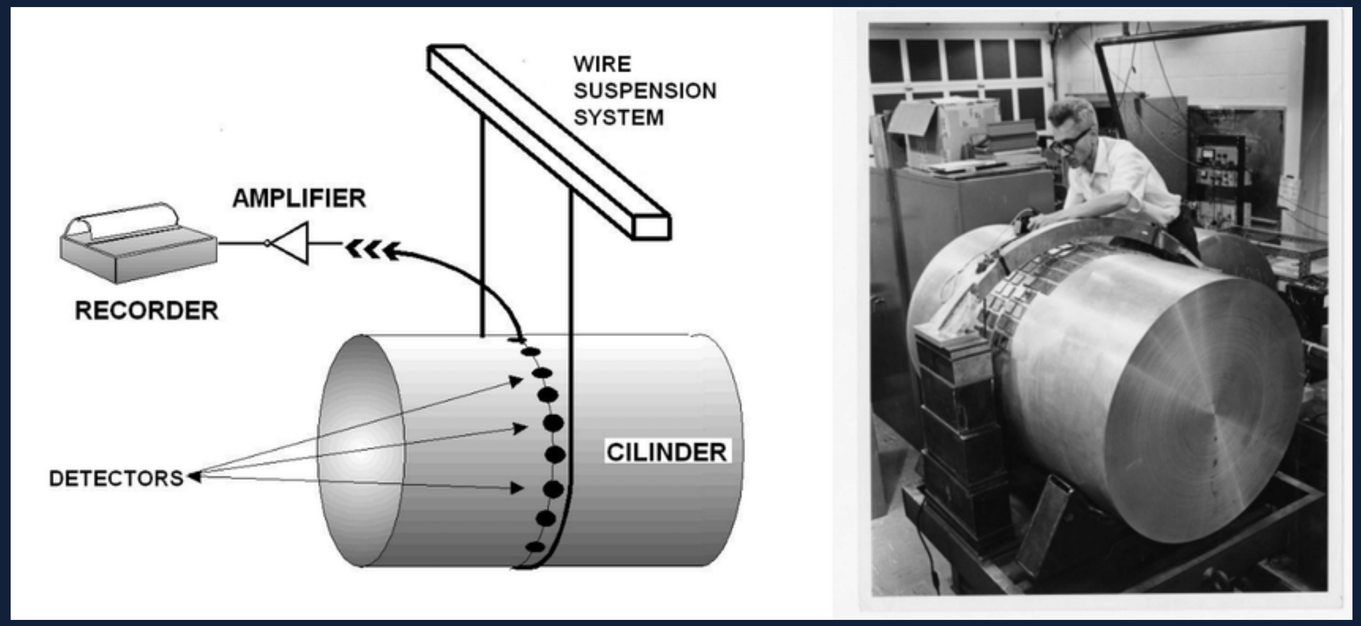
"By measurement of the relative accelerations of several different pairs of [free] particles, one may obtain full details about the Riemann tensor"



Chapter 14
Measurement of Classical Gravitation Fields
Felix Pirani

History of GW detection - Early detectors

1966: prof. J. Weber builds the first prototype of a resonant bar detector



The vibration signal is translated into a measurable electric signal by piezoelectric sensors.

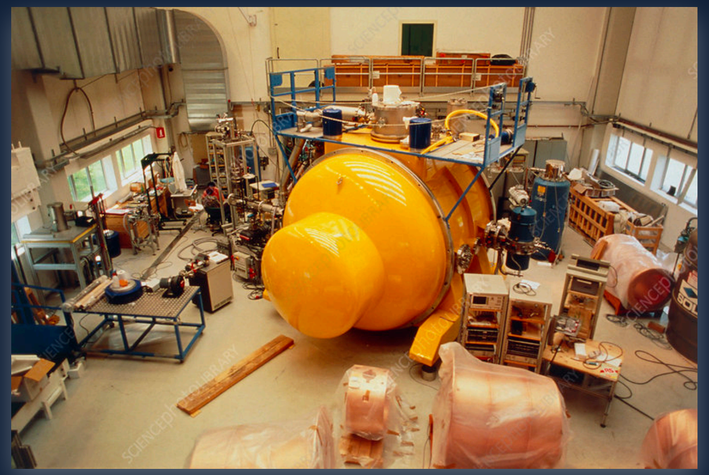
1970: prof. E. Amaldi builds the first resonant bar detector in Italy.

Amaldi and Guido Pizzella become the putative fathers of GW research in Italy.

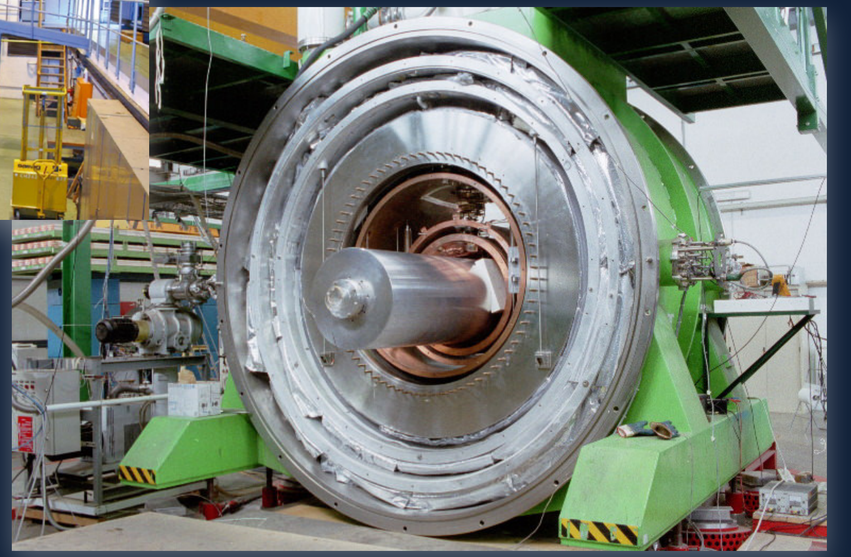
History of GW detection - Early detectors

Resonant bars evolved with time and became the detector of choice until the end of the 1990s

AURIGA



EXPLORER



NAUTILUS

ALLEGRO

Narrow bandwidth and mainly sensitive to nearby supernovae.

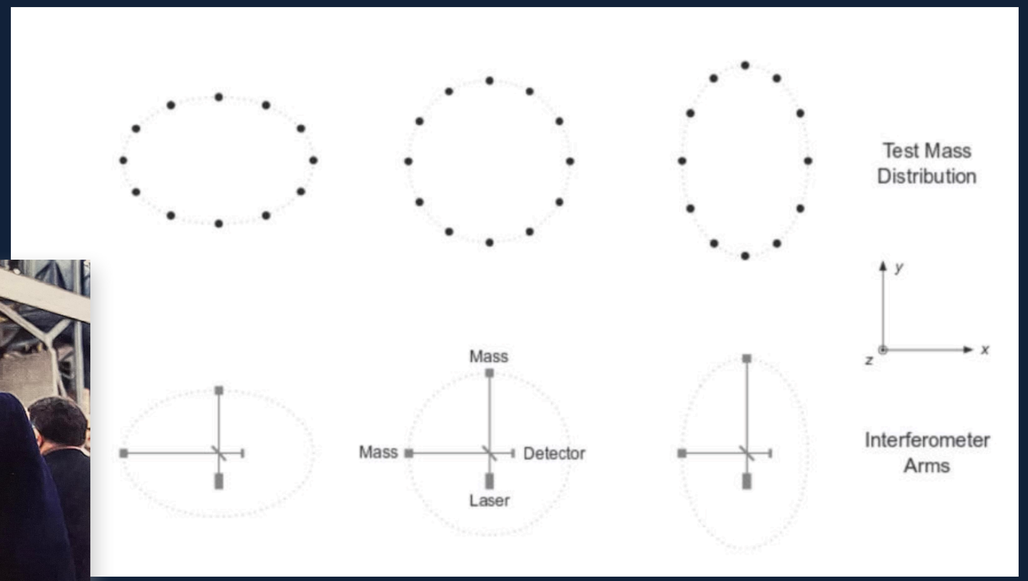
Lab-scale experiments

History of GW detection - Early detectors

1962: Gertsenshtein & Pustovoit introduce the concept a Michelson interferometer for GW detection.

1972: Rainer Weiss carries out the first in depth feasibility study for Michelson interferometers.

1989: the proposals for Virgo and LIGO are submitted for approval.



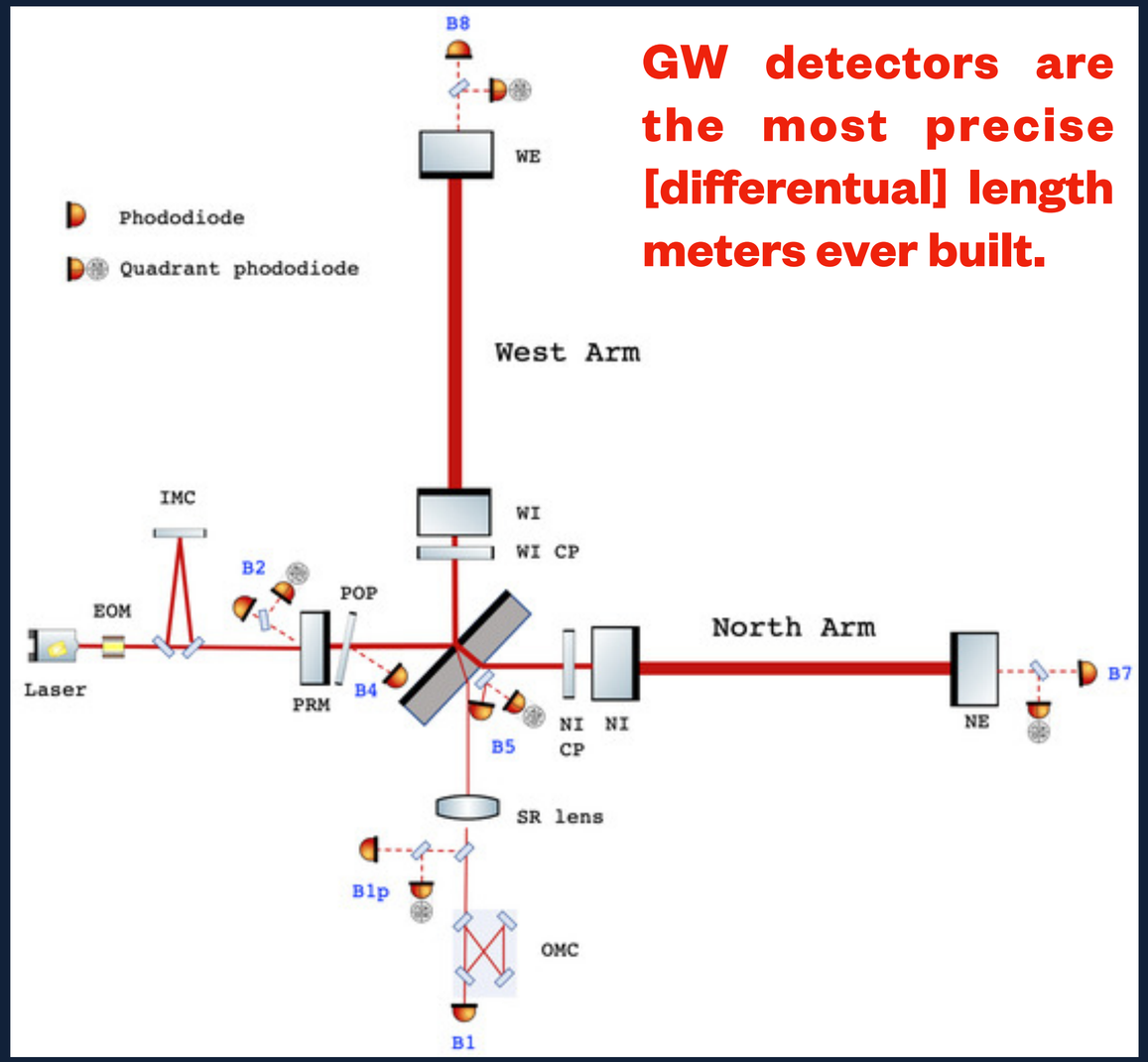
Adalberto Giazotto (INFN) and Alain Brillet (CNRS) lead the Virgo proposal.

More details about ITF detectors in S. Morisaki's talk

Virgo

- Basic layout of a Michelson interferometer;
- Arms 3 km long with Fabry-Perot cavities;
- Effective seismic isolation systems using inverted pendulums (superattenuator);
- measure the phase difference between the laser beams using the output laser power;
- the output is the time series of h(t).

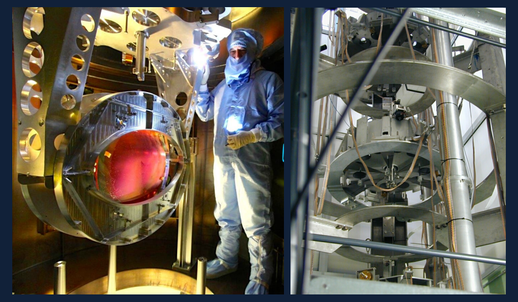
GW interferometers are complex instruments that require large-scale collaborations to be operated effectively



GW detectors are the most precise [differentual] length meters ever built.

Virgo

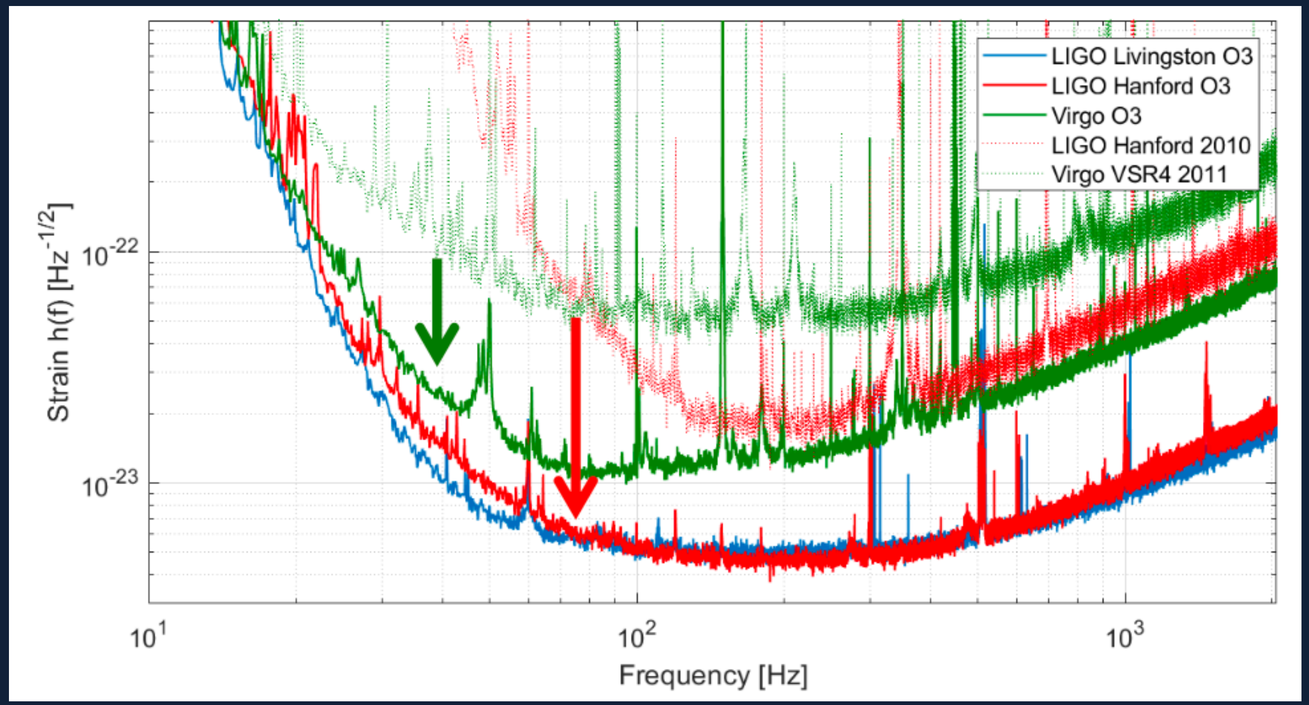
- Virgo is located in the countryside near Pisa (IT).
- 900 collaboration members from 17 European countries and 150+ institutions



Virgo

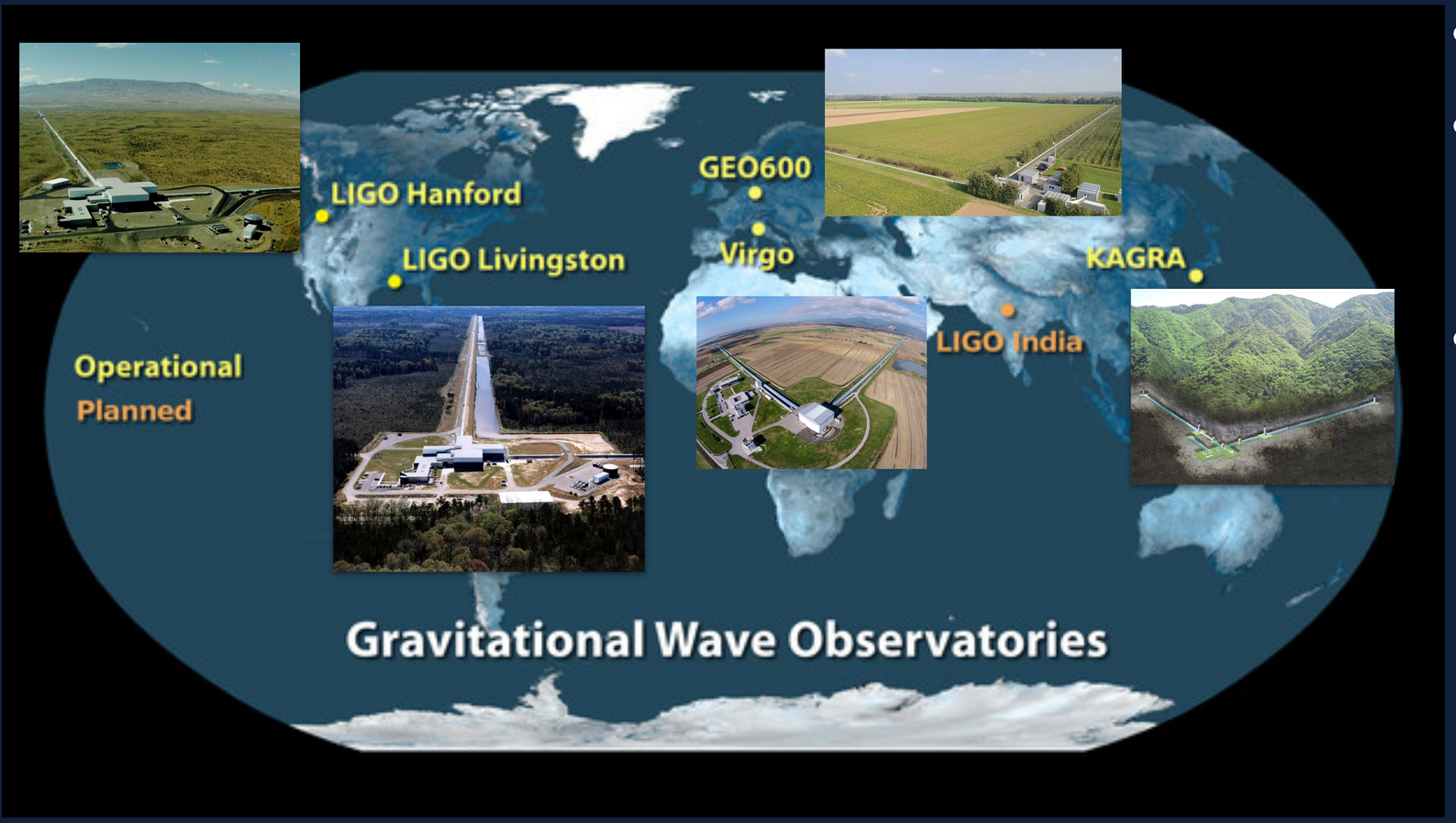
Virgo starts operations in 2003 and up to 2011 in the *initial* configuration.

Upgrades to laser, optical configuration (quantum squeezing and laser power), suspensions and thermal compensations systems

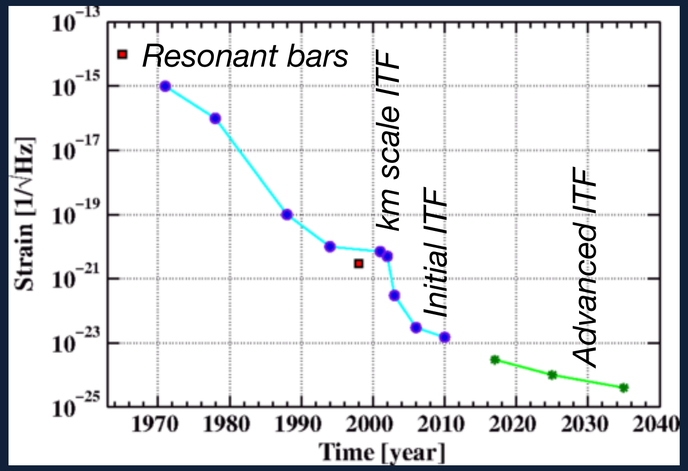


Virgo resumes operations in the summer of 2017 in the *Advanced* configuration

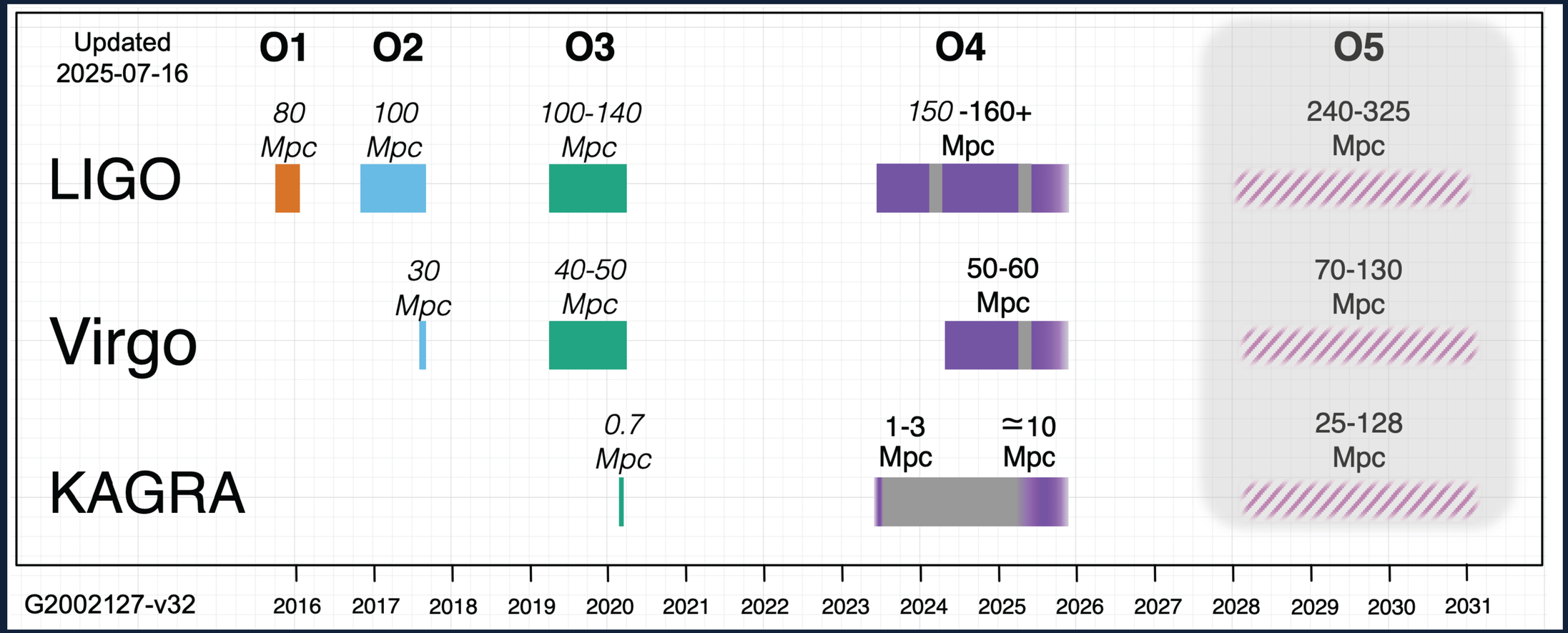
The detector network



- In **2007 LIGO** and **Virgo** signed a **MoU** and joined their efforts for GW detection.
- **KAGRA** joined in **2019**.
- **LIGO-Virgo-KAGRA** is now a large scale international collaboration which makes GW searches more effective.
- The **GEO600** detector is mainly used for **R&D**



The detector network



- The range reported here is the one at which we expect to observe a BNS with a SNR of at least 8;
- The BNS range is usually used to assess the observational capabilities of a GW detector.

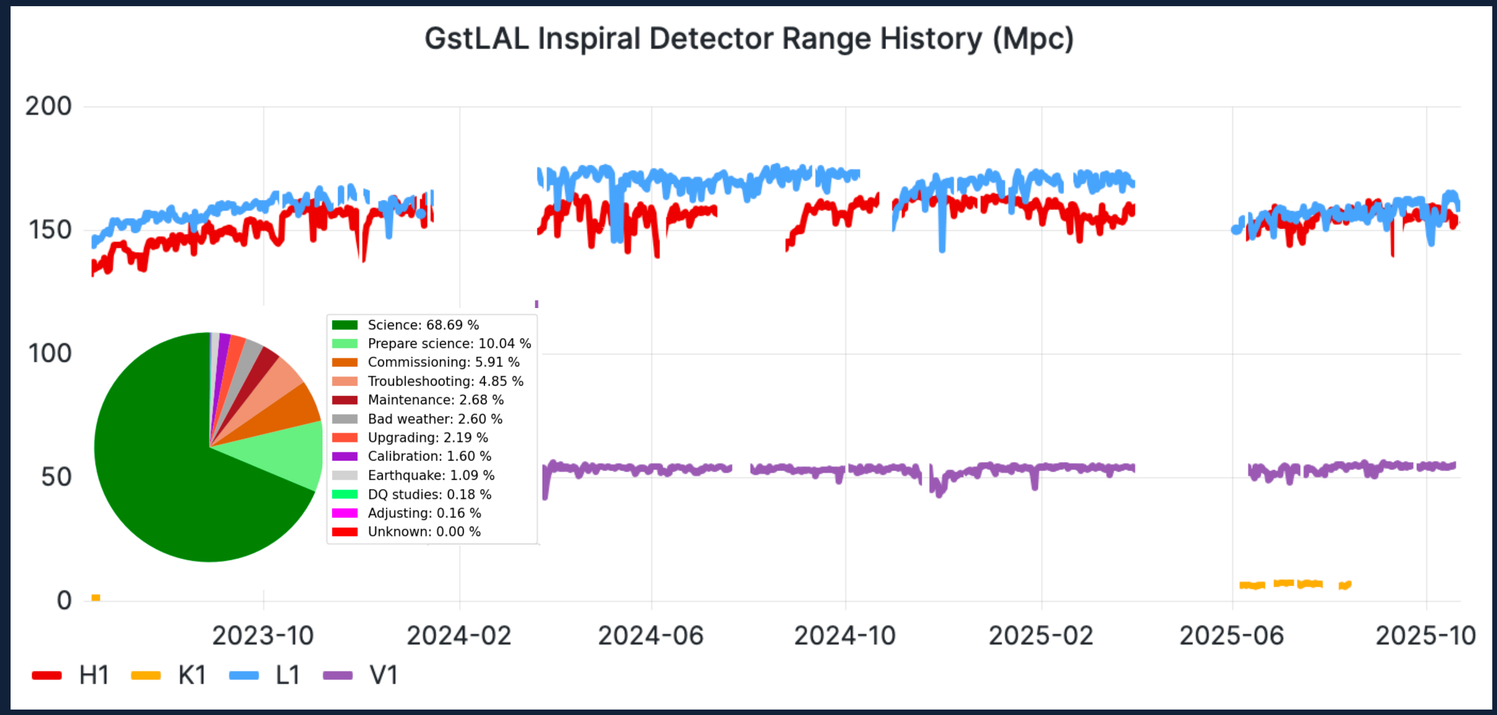
Current status of Virgo

- **O4a**: May 2023 - January 2024
  - Joint observations of LIGO L+H (+ 4 weeks of KAGRA)
- **O4b**: April 2024 - March 2025
  - Joint observations of L+H+V
- **O4c**: June 2025 - November 2025
  - Joint observations of L+H+V(+K)

A commissioning period more troublesome than expected pushed Virgo to skip O4a

O4 summary

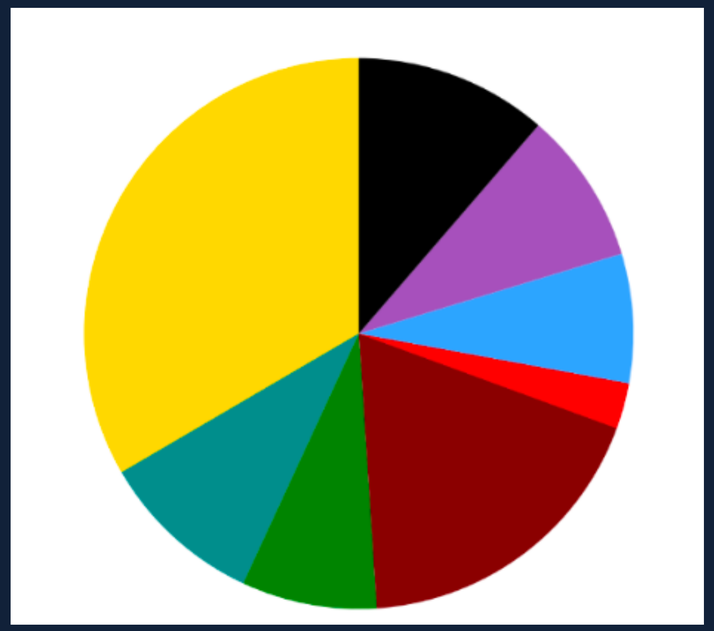
gwistat

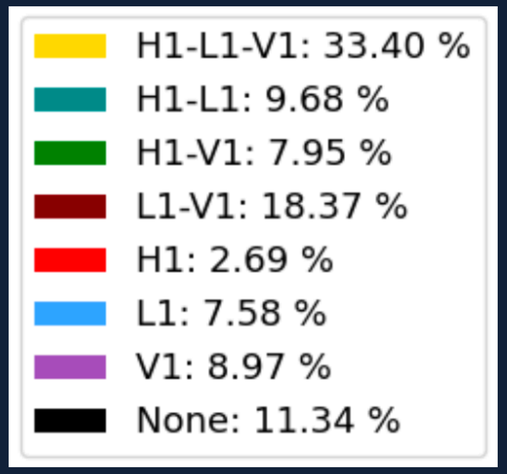


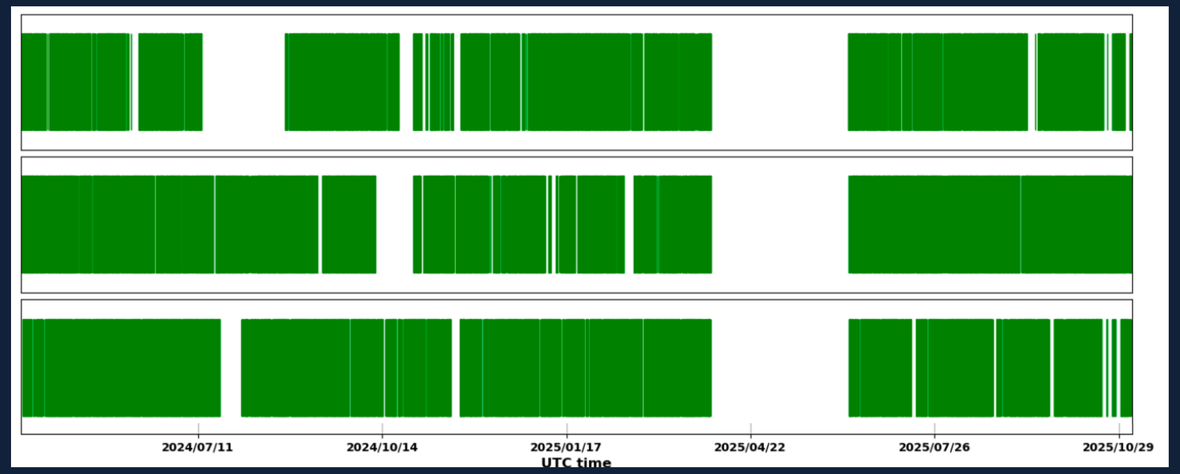
Observing steady at 55 Mpc BNS range (similar to O3) with average duty cycle at 70%

LONGEST DATA TAKING PERIOD EVER!

The detector network status







3 detector network duty cycle inferior to O3 (47%);

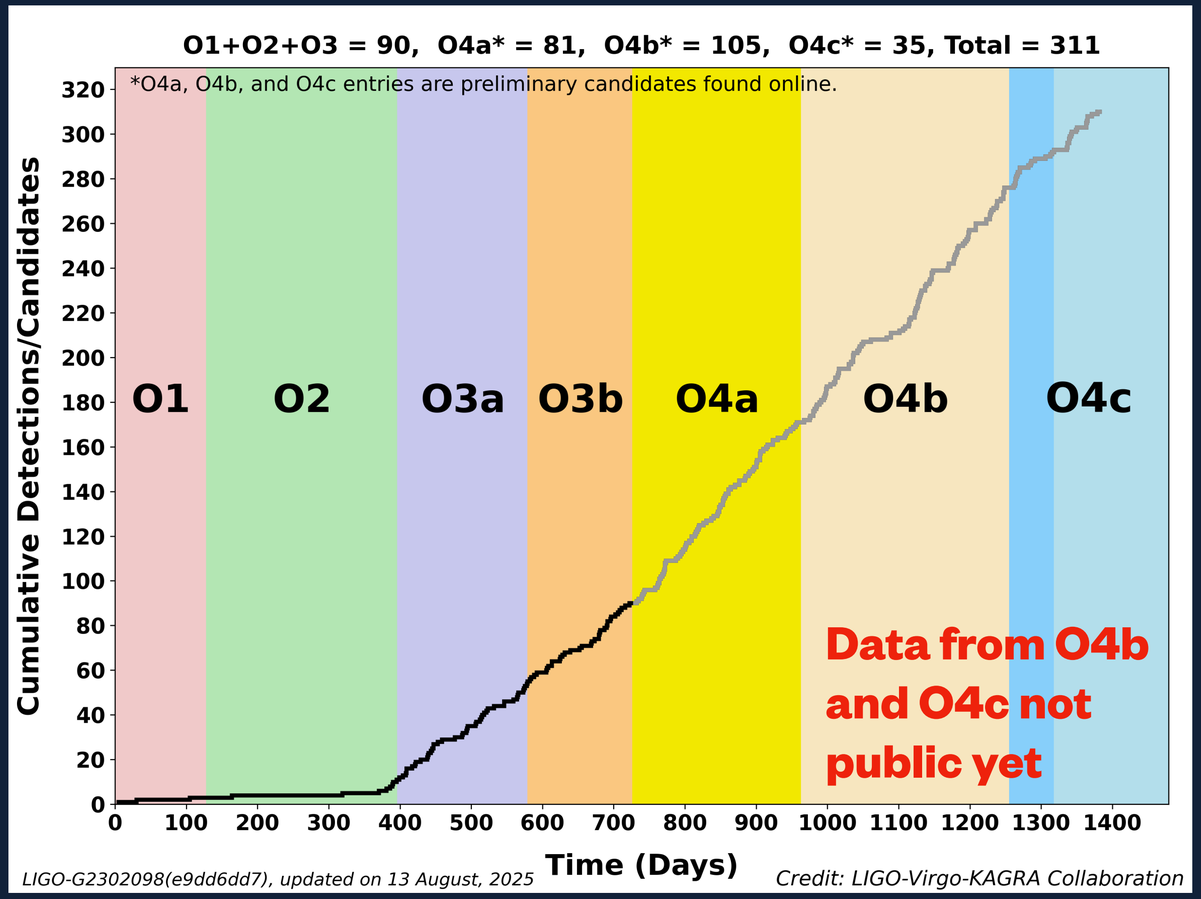
Unexpected maintenance at LIGO Hanford in 2024;

Overall, O4 was much longer and more demanding than O3, pushing both people and machines to their limits.

O4 observations

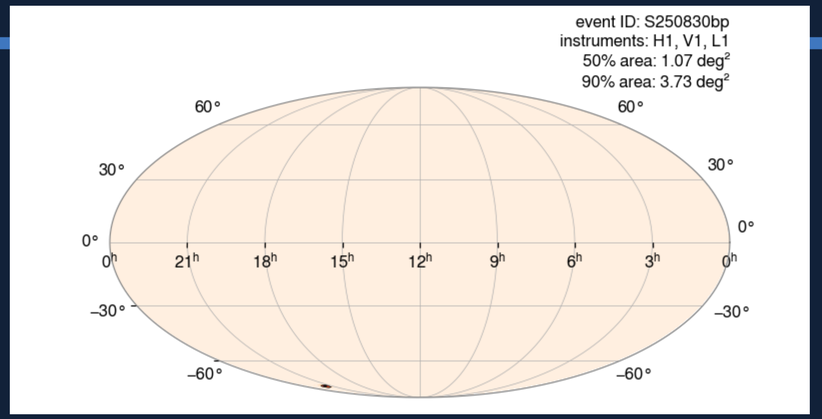
More details in P. Ajith's and A. Ouzriat's talks

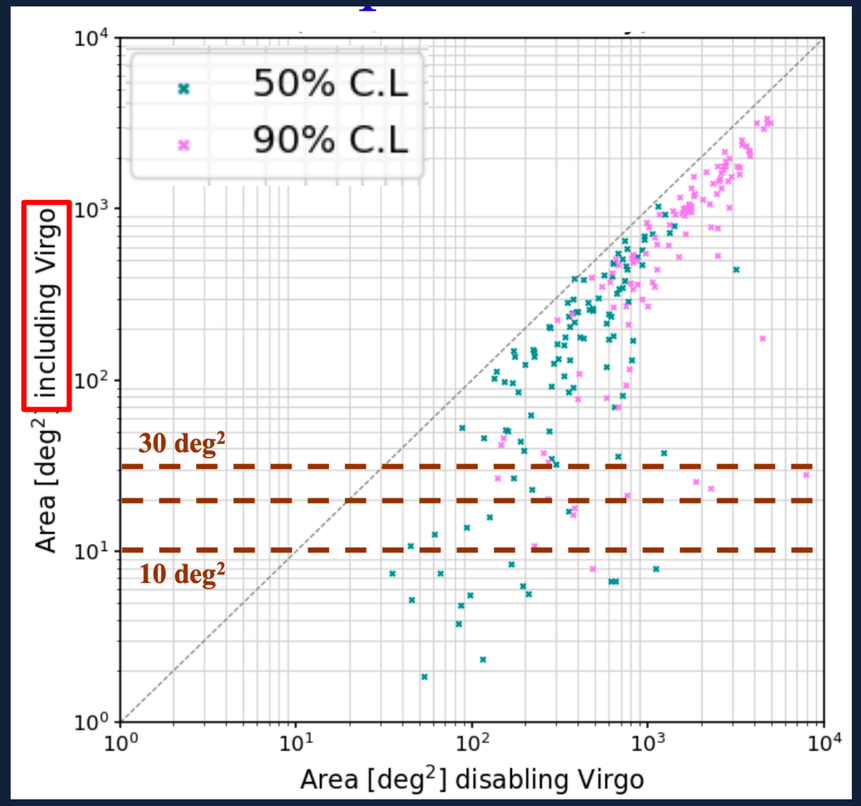
- Detection rate keeps growing;
- Improvements in the detectors' sentivities means that the accessible volume of the Universe scales as r^3;
  - **Accessible volume in O4 is twice as much as in O3**
- GWTC-4 released in August;
  - **218 confirmed detection since O1;**
  - More than 150 significant candidates from O4b+O4c.



O4 observations

- The three detector network is effective;
  - localization of events with great accuracy;
- No BNS detected in O4a, two NSBH events in O4a (GW230529 and GW230518) plus NSBH candidates in O4b+O4c;
  - Revising expectations for BNS mergers;
- Full public alerts list on GraceDB
- Catalogs and open data for O4b+c expected to be released in May 2026 and at the end of 2026, respectively.





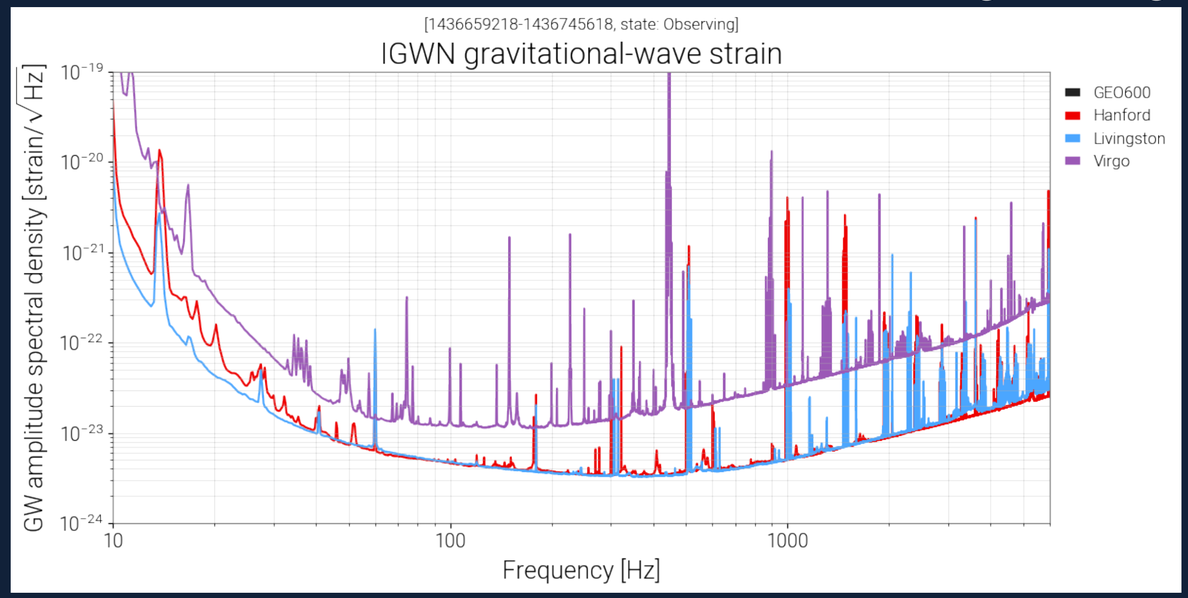
Credits: I. Bentara

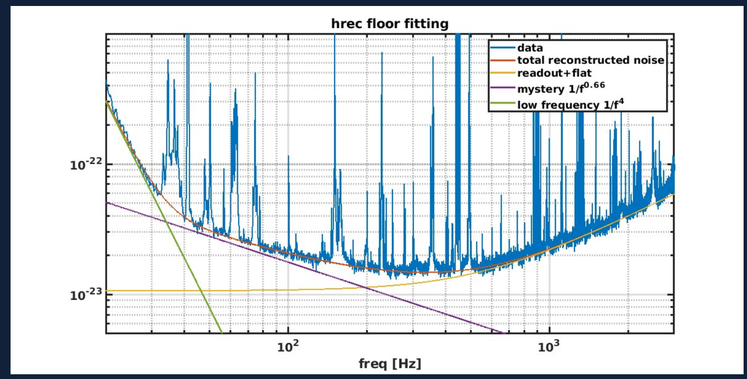
More details in P. Ajith's and A. Ouzriat's talks

Limitations to Virgo sensitivity

gwosc.org

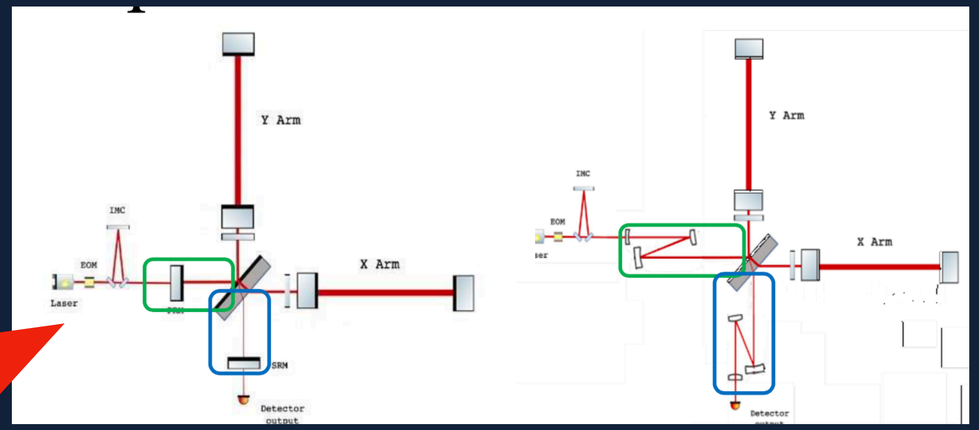
- Virgo is designed with marginally stable signal recycling cavities.
- Sensitive to thermal effects and other imperfections in the optical cavity
  - Cannot be modeled as for stable cavities
  - This makes the interferometer very hard to control, impacting the commissioning schedule
- A 1/f unmodeled noise limits the sensitivity in the bucket (costs about 15Mpc in BNS range);





Plans for the future

- Future timeline is being reassessed;
- Virgo is planning major upgrades
  - The most urgent one is the installation of stable cavities
- Heavier mirrors and higher laser power are in the to-do list as well.



STEP-1 upgrades (2027-2029): 90-100 Mpc

STEP-2 upgrades (2033): 120-160 Mpc

2025 — 2026 — 2027

Commissioning activities for 1/f noise and minor detector upgrades

6 months observing run

Starting upgrades for O5

Virgo_nEXT

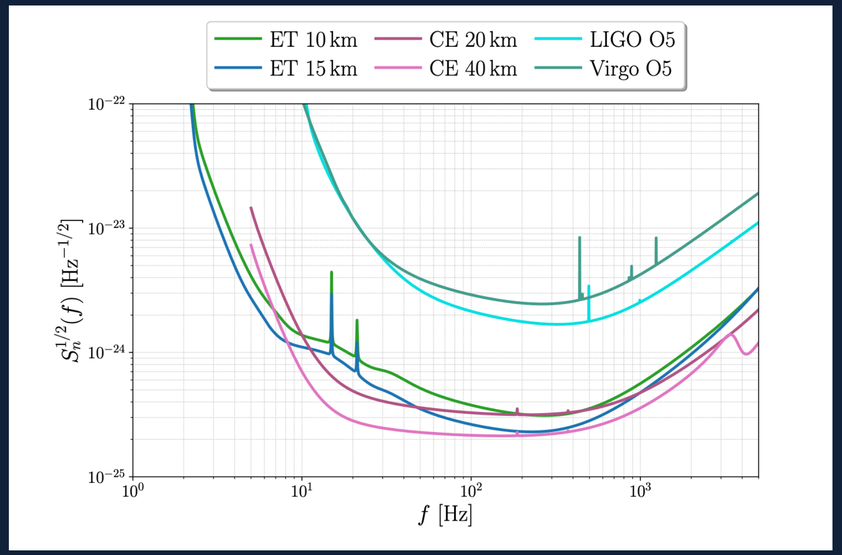
- The goal is to bridge the gap between Adv detectors and XG detectors;
- Concept study released in 2023;
- Baseline report is work in progress
- All the upgrades are compatible with current detector infrastructure

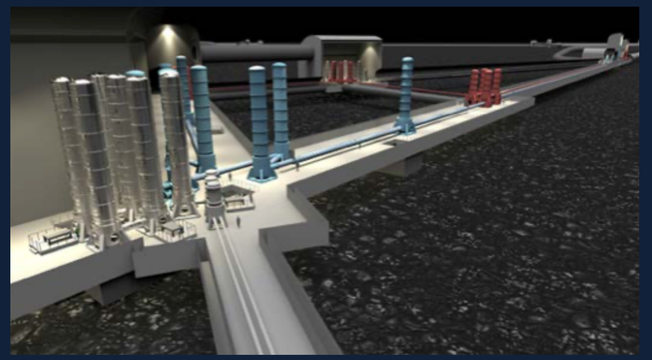
	AdV+	**V_nEXT**
Injected power	125 W	277 W
Arm power	390 kW	1.5 MW
Mirror mass	42 kg	105 kg
Coating losses	5.4e-5	6E-06

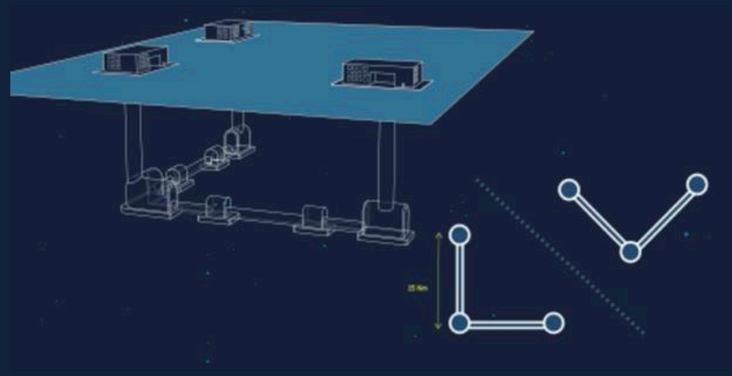
Next Generation

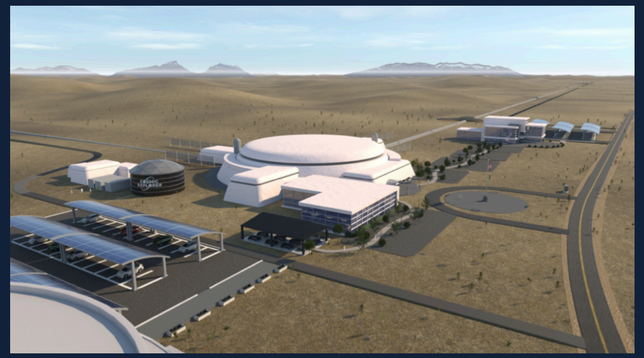
More details in U. Dupletsa talk

- Einstein Telescope and Cosmic Explorer are the future of ground based detectors;
- Up to a factor 8 more sensitive than current detectors;
- Bandwidth extended down to 2 Hz;
- Improved noise mitigation systems;









- Current detectors will be essential in assisting early observations of ET and CE;
- A consistent effort should be undertaken to keep Virgo operative and constantly upgraded until ET and CE will be operative.

Conclusions

- Virgo operated successfully during O4b and O4c with a 80% duty cycle;
- Virgo impacted positively on the sky localization capabilities of the network;
- O4c ended this very week;
- Plans for future observing runs are being reassessed:
  - 2026 might be used for commissioning activities to assess the origin of the 1/f noise and for a short observing run;
- Several upgrades planned for Virgo:
  - installation of folded stable cavities;
  - upgrades to mirrors and laser;
- Virgo_nEXT will bridge the gap with ET and CE.

Aknowledgements

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