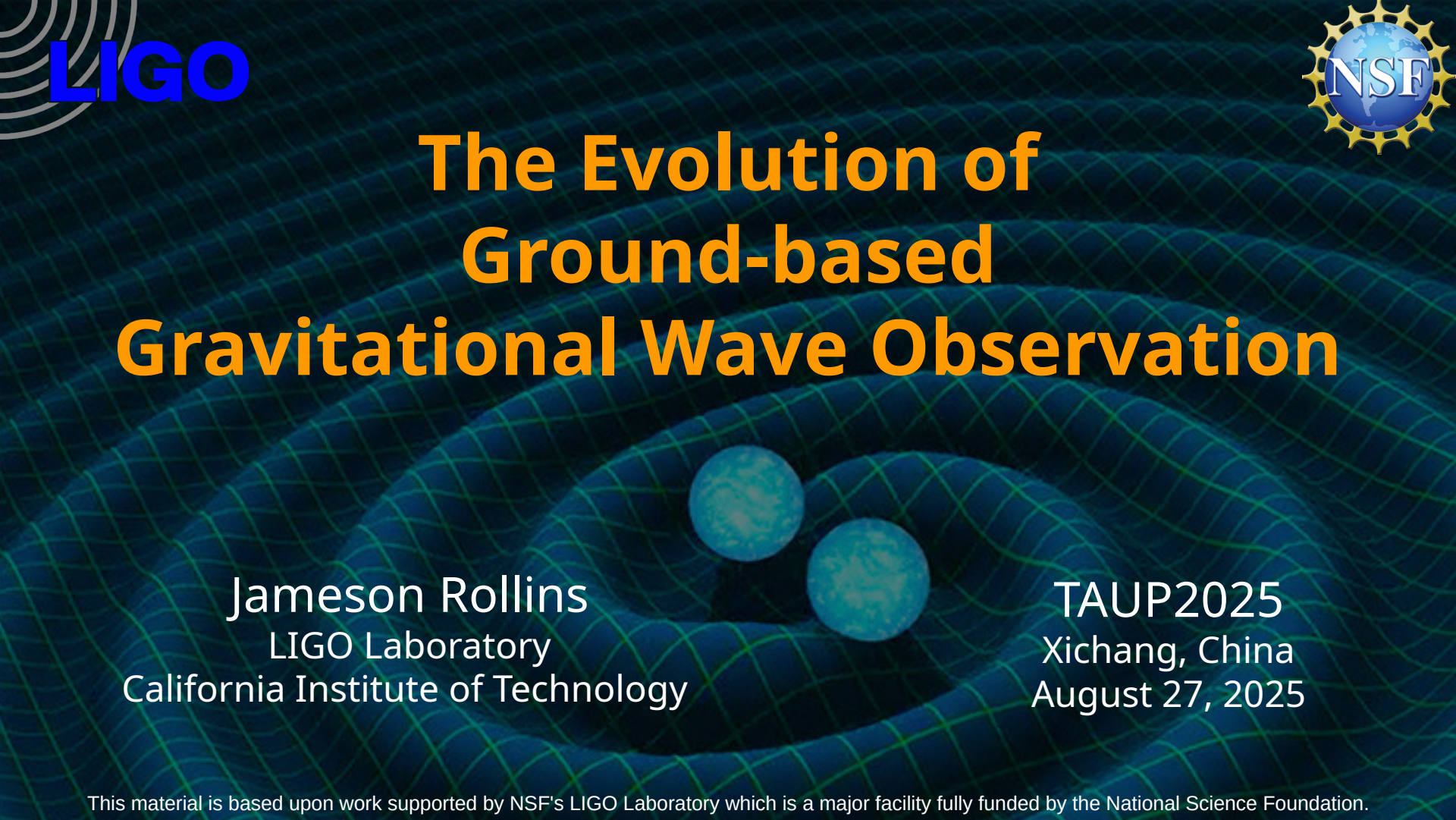
The Evolution of Ground-based Gravitational Wave Observation

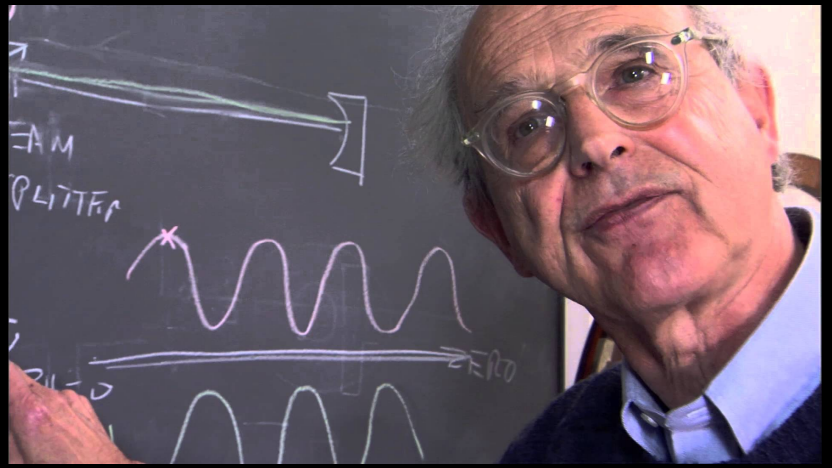


Jameson Rollins
LIGO Laboratory
California Institute of Technology

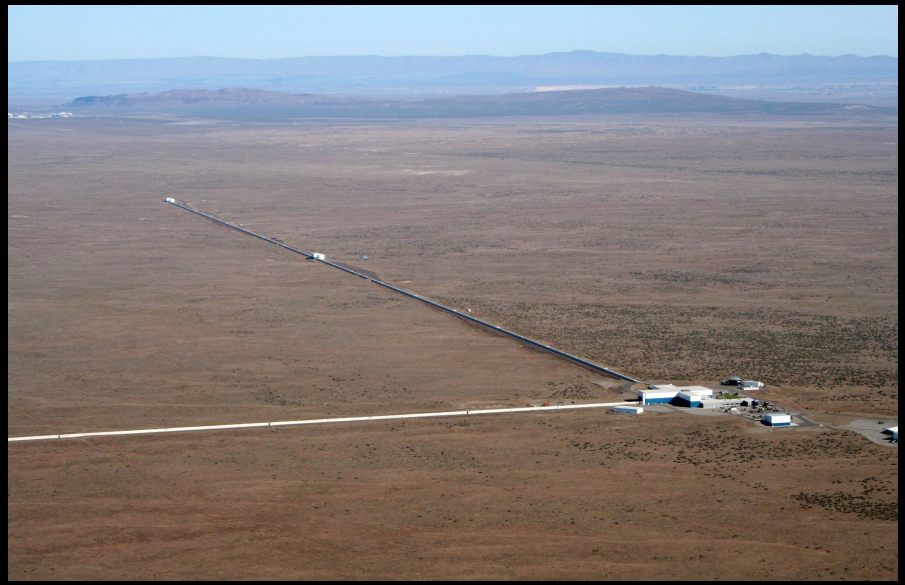
TAUP2025
Xichang, China
August 27, 2025

This material is based upon work supported by NSF's LIGO Laboratory which is a major facility fully funded by the National Science Foundation.

Rainer Weiss
1932-2025



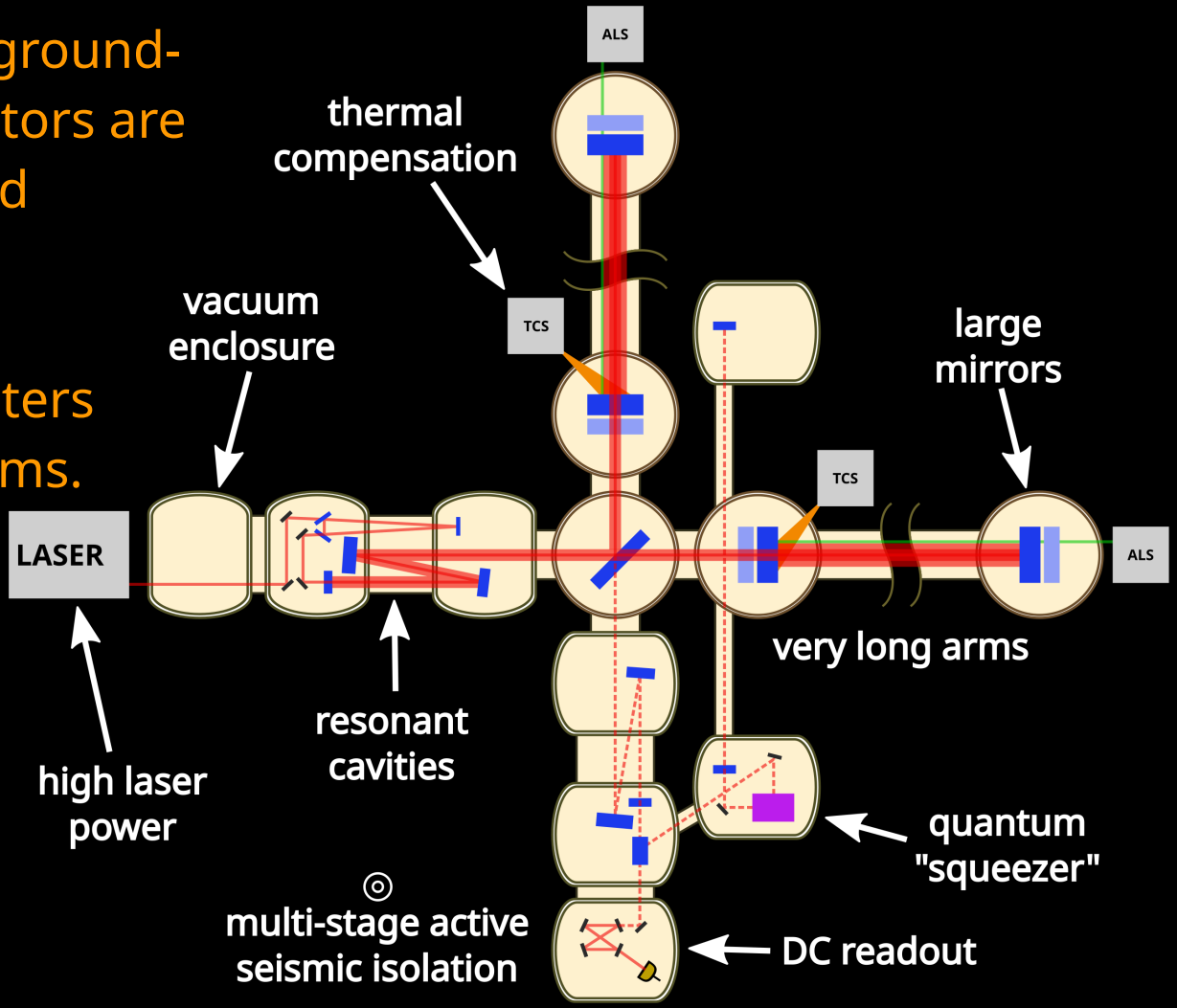
Laser Interferometer Gravitational-wave Observatories

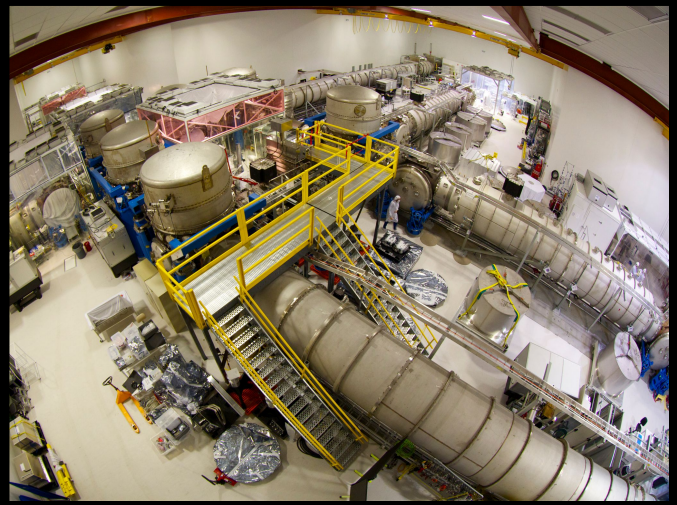


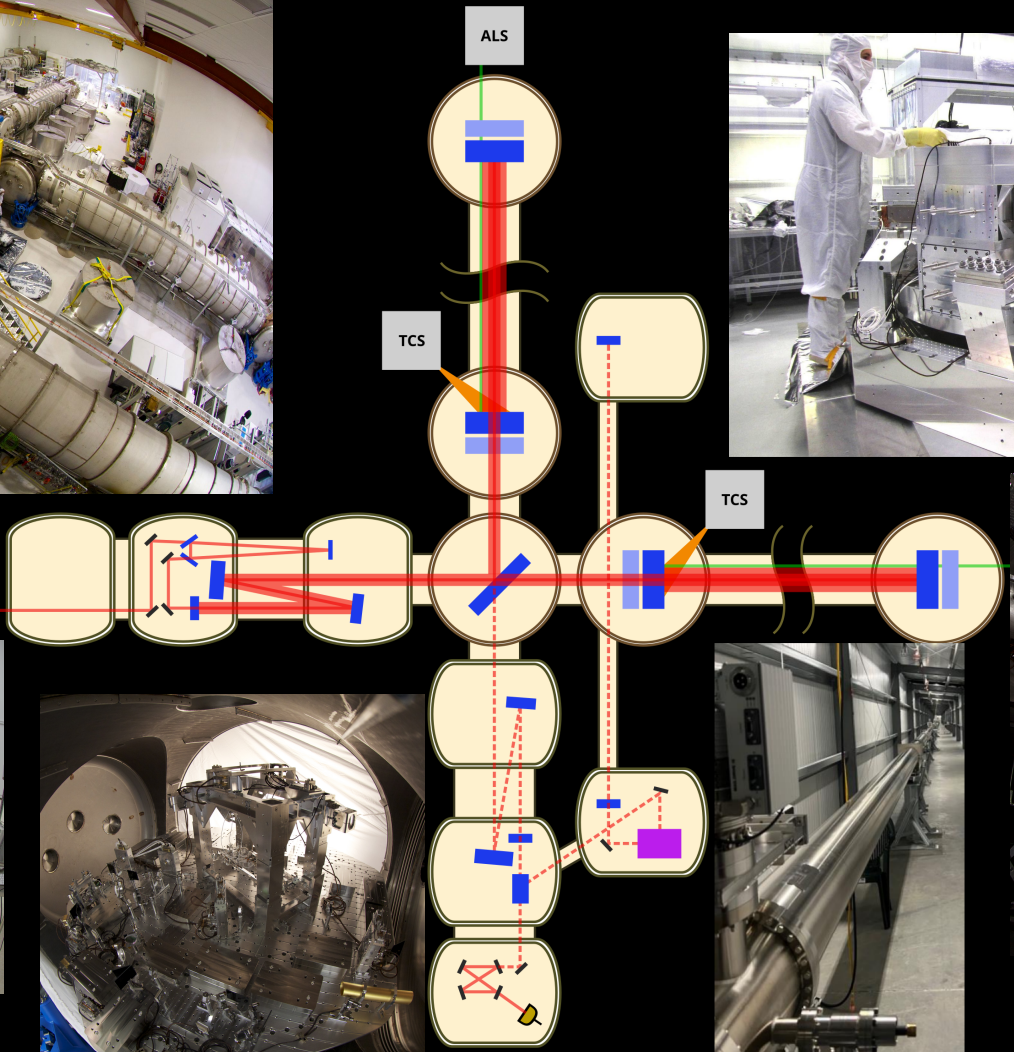
LIGO Hanford Observatory
Washington, USA

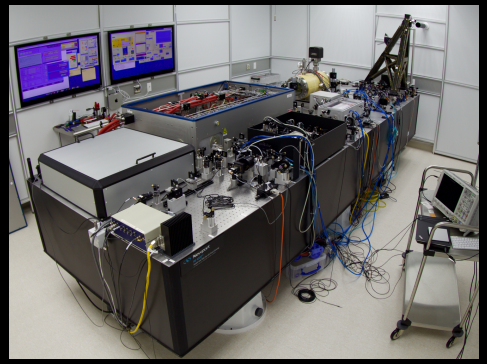
LIGO Livingston Observatory
Louisiana, USA

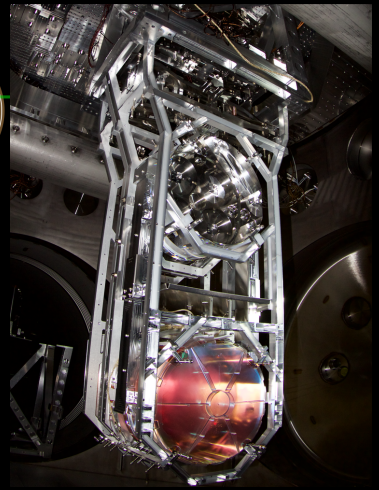
All modern ground-based detectors are dual-recycled Fabry-Perot Michelson Interferometers with long arms.



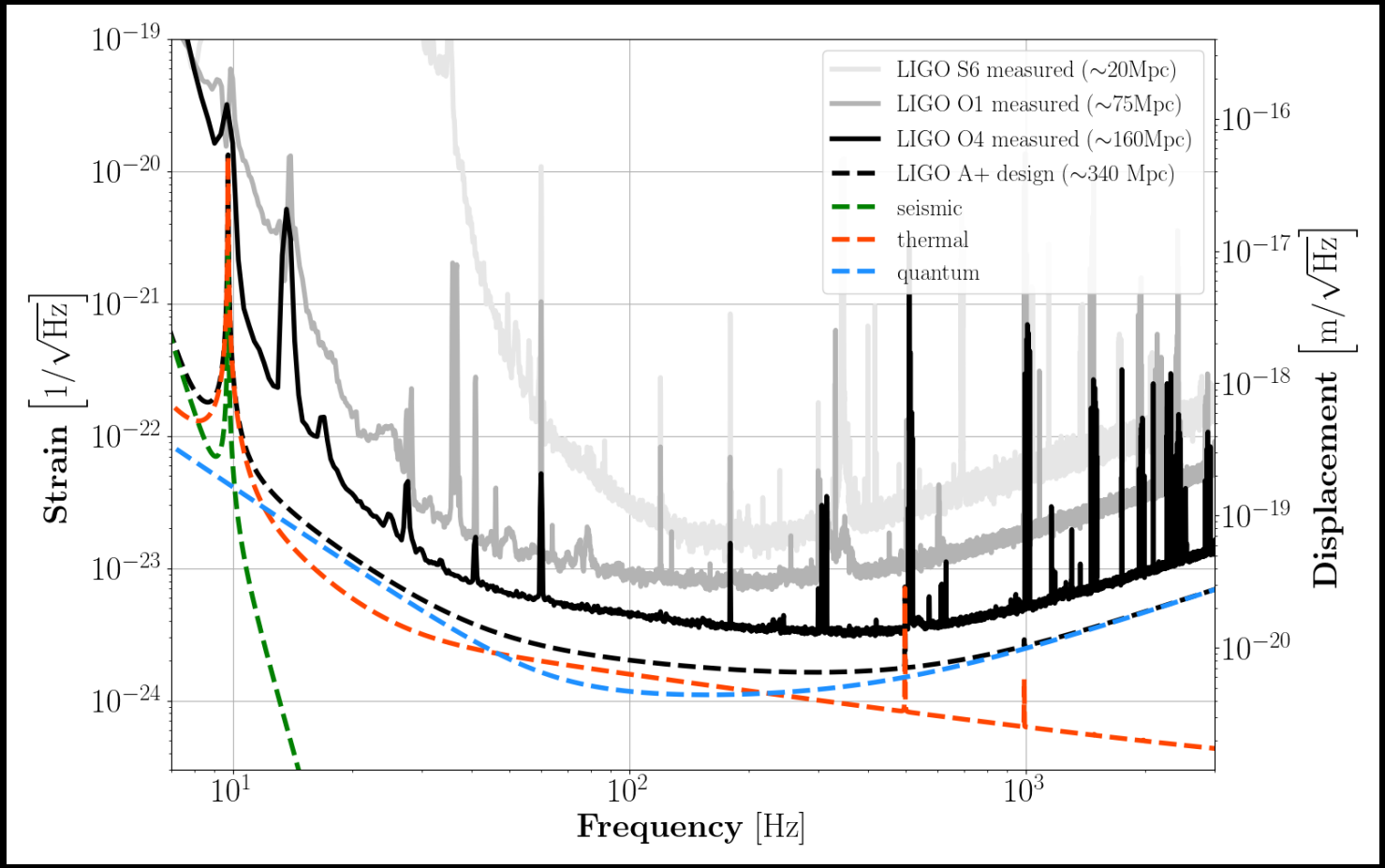



ALS
TCS
TCS
LASER





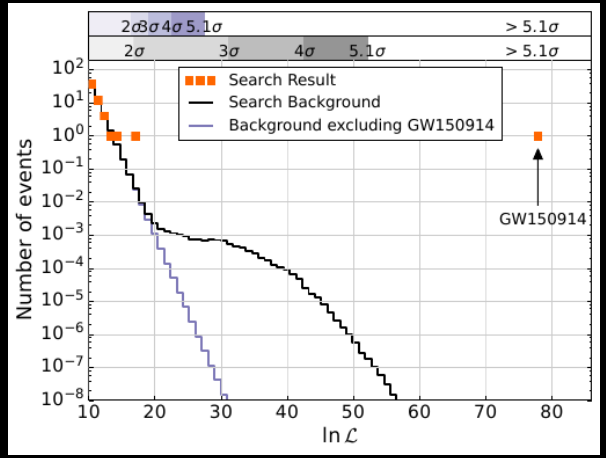
Spacetime microphone: strain sensitivity



Transient searches

Relatively straightforward principle for transient searches:

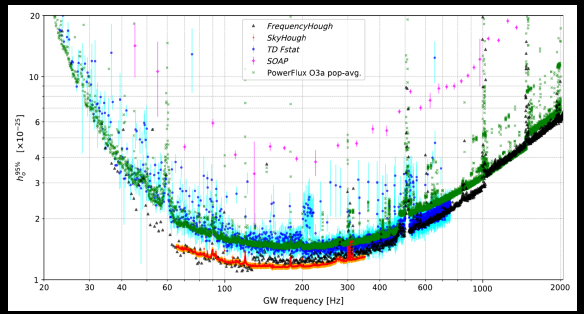
1) Direct broadband measurement of spacetime strain with detector
2) Matched filter search for known waveform morphology
3) Detection statistic weighed against background



Other import science

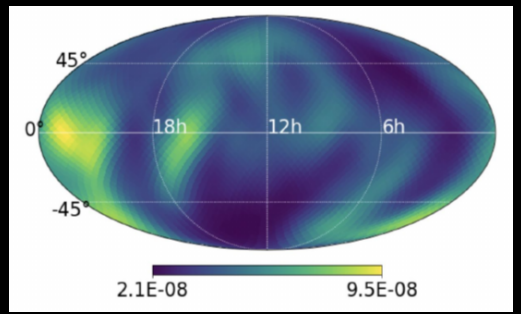
Limits from pulsars

[Phys. Rev. D 106, 102008 (2022)]



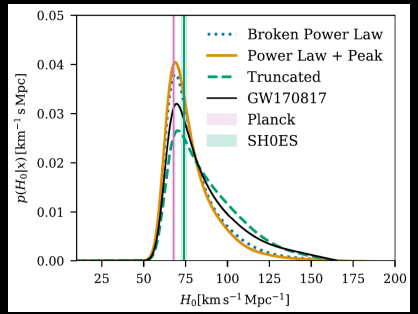
Stochastic background limit

[Phys. Rev. D 104, 022005 (2021)]



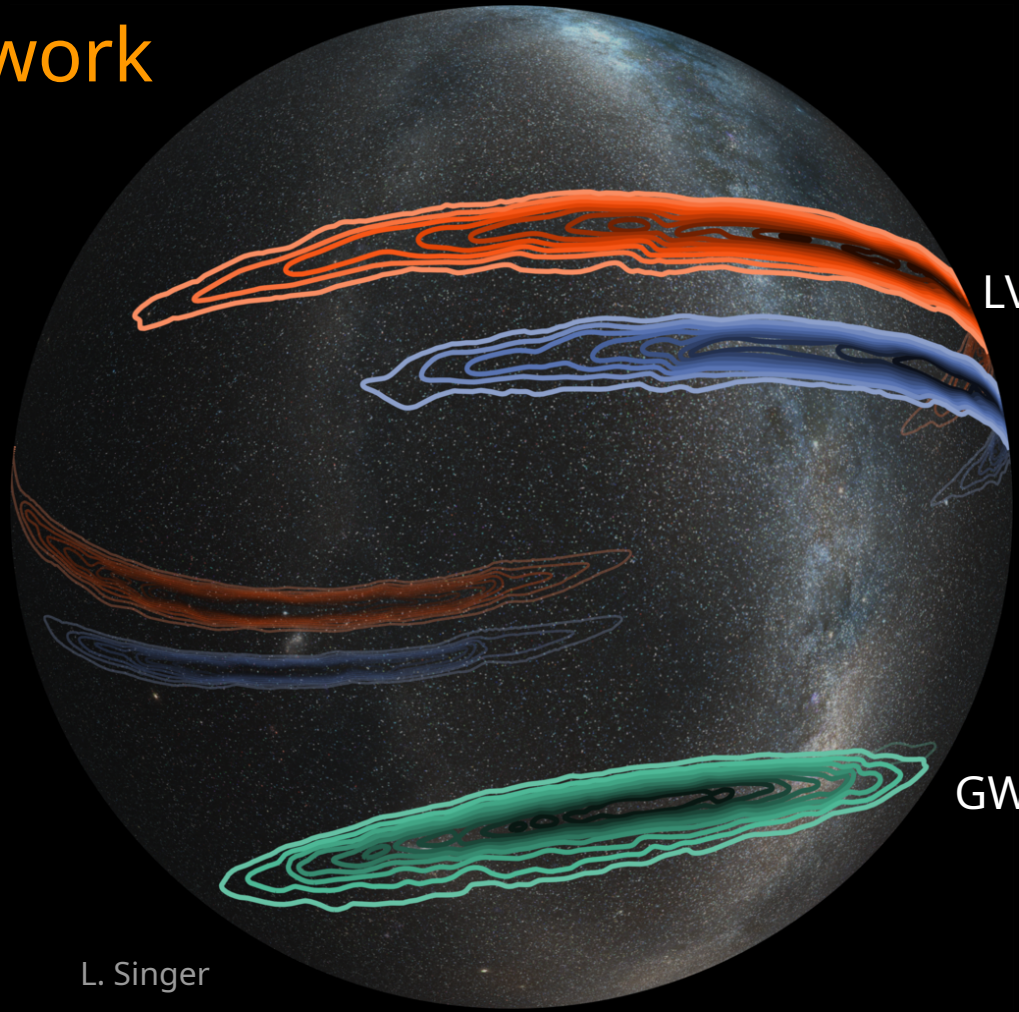
Hubble measurement

[Astrophys. J. 949, 76 (2023)]



Power of the Network

LHO + LLO



L. Singer

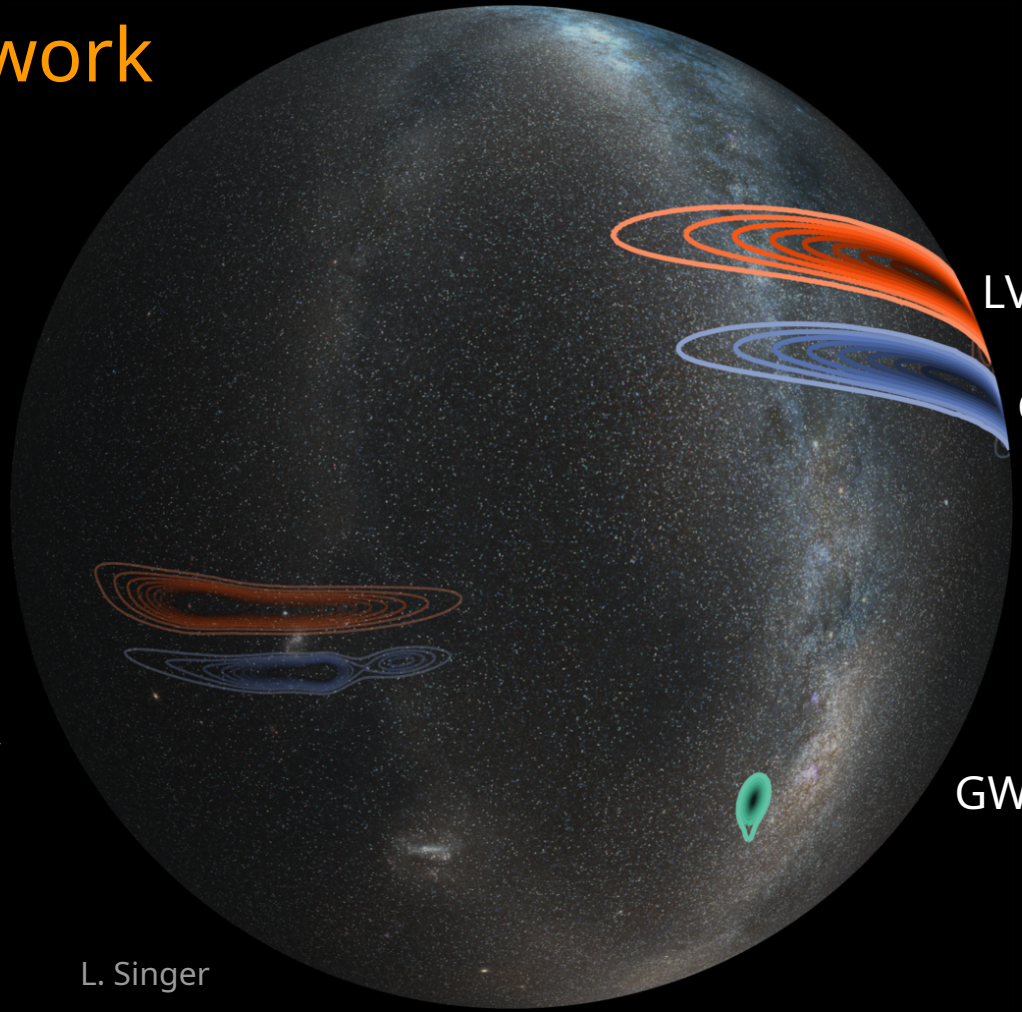
Power of the Network

LHO + LLO
+ Virgo

(simulation)

Localization improves *significantly* as detectors are added to the network.

All observatories must work together to produce the best science.

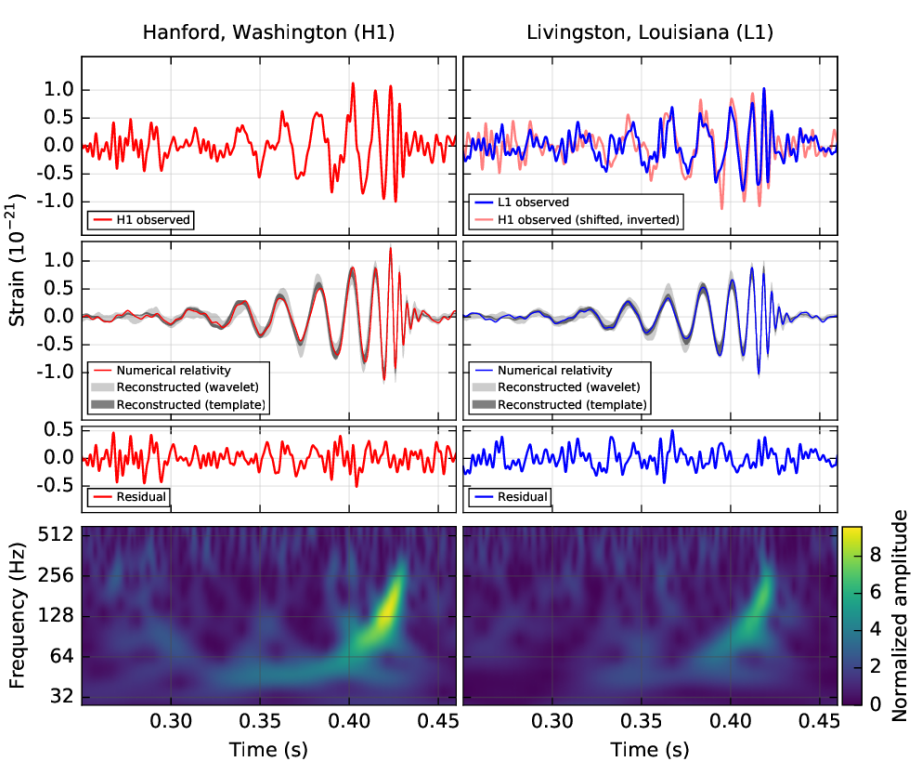


L. Singer

International Network of GW Observatories

The Last Decade of GW Observation

O1: First Detection - GW150914



September 14, 2025, will mark the **10th anniversary** of the first direct observation of gravitational waves during Advanced LIGO's first observing run (O1).

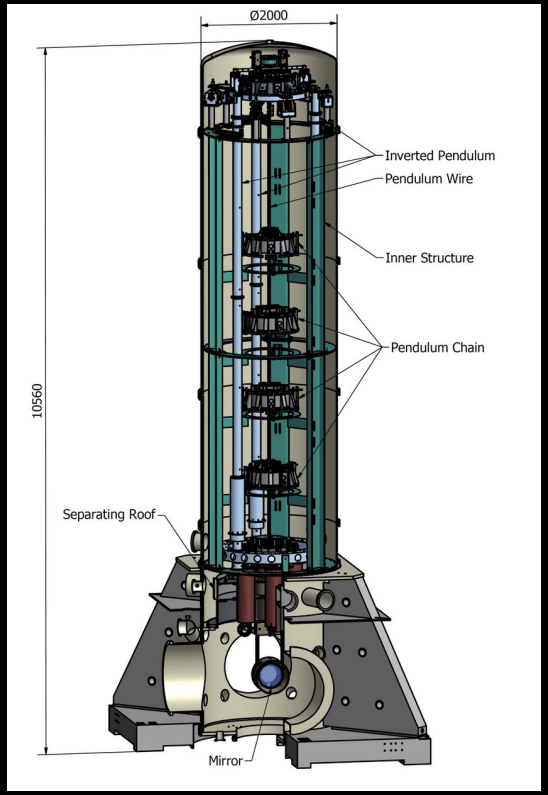
Binary black hole merger:

$$36\ M_\odot + 29\ M_\odot \rightarrow 62\ M_\odot + \mathbf{3\ M_\odot}^{\mathbf{GW}}$$

~400 Mpc away

doi:10.1103/PhysRevLett.116.061102

O2: Virgo joins



Virgo joined the run for the last month, just in time for...

O2: First Multi-messenger Observation - GW170817

Observation of gravitational waves from a **binary neutron star** (~40Mpc):

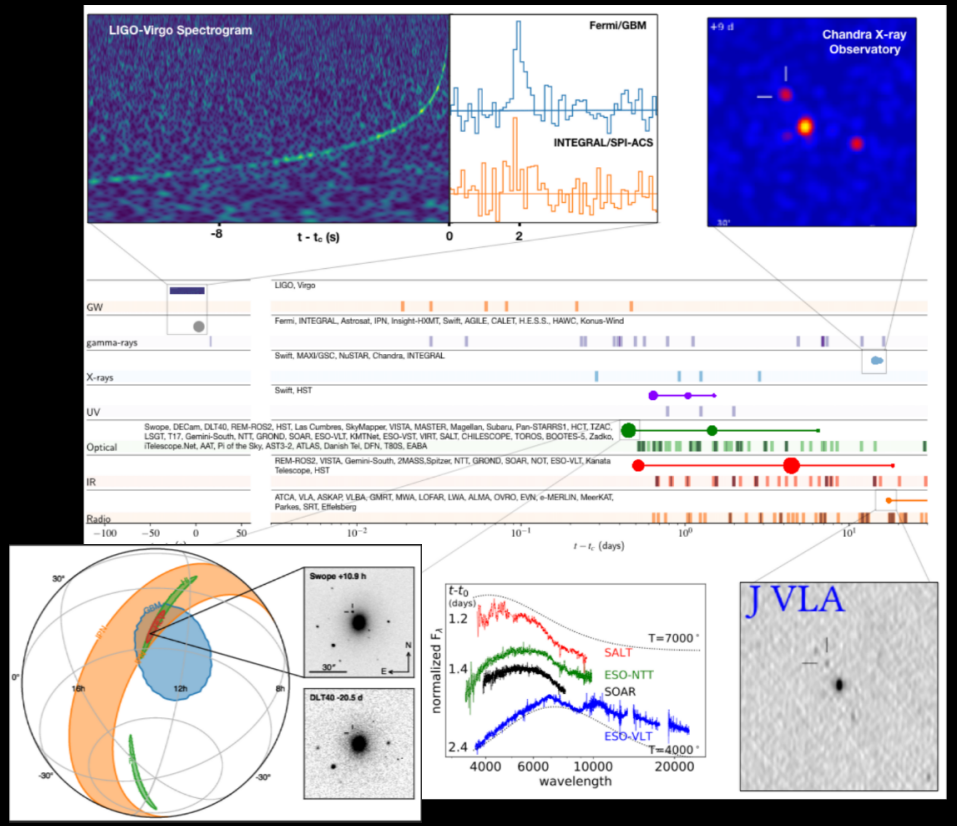
doi:10.1103/PhysRevLett.119.161101

Accompanied by ***many*** electromagnetic observations: the first multi-messenger observation involving gravitational waves.

doi:10.3847/2041-8213/aa91c9

Confirmation of:

- BNS → GRB
- BNS → r-process nucleosynthesis

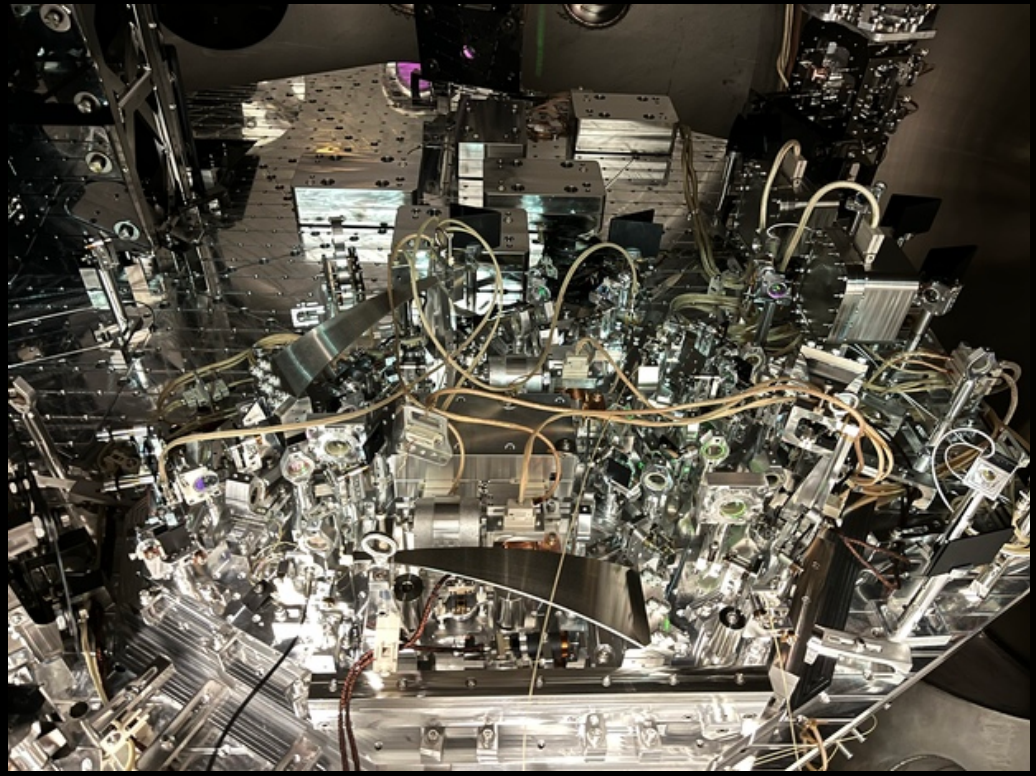


O3: LIGO upgrades and KAGRA joins

Two major upgrades to the LIGO detectors for O3:

- squeezed vacuum →
- 200kW arm power

First run with public alerts of event candidates + localization.



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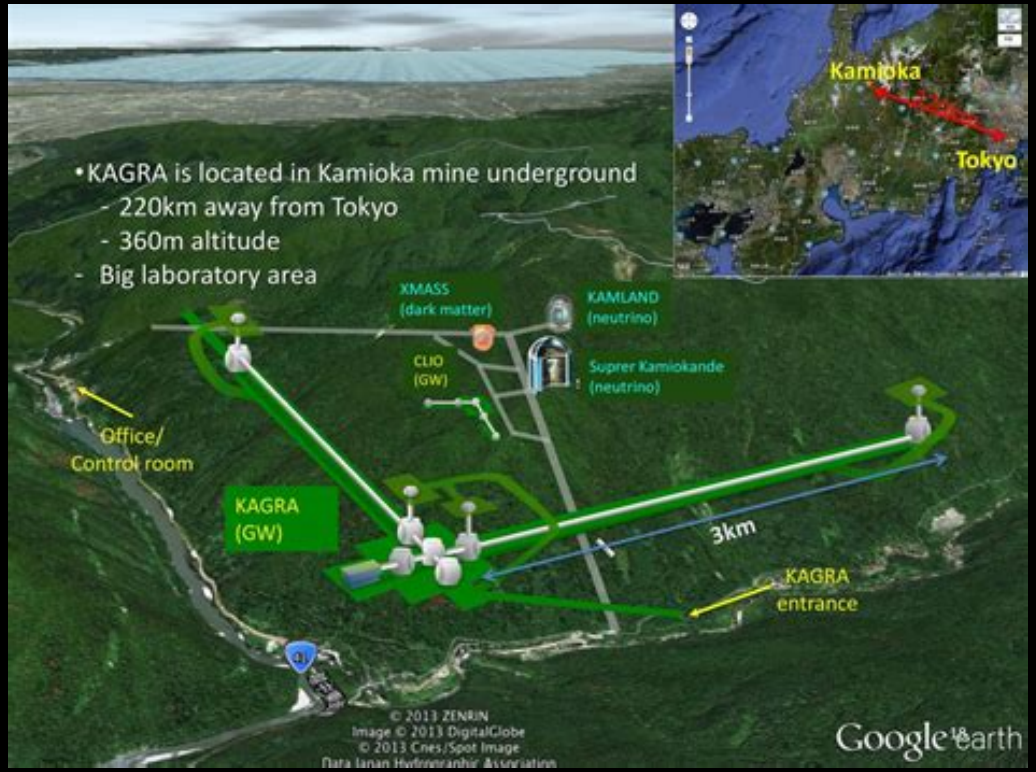
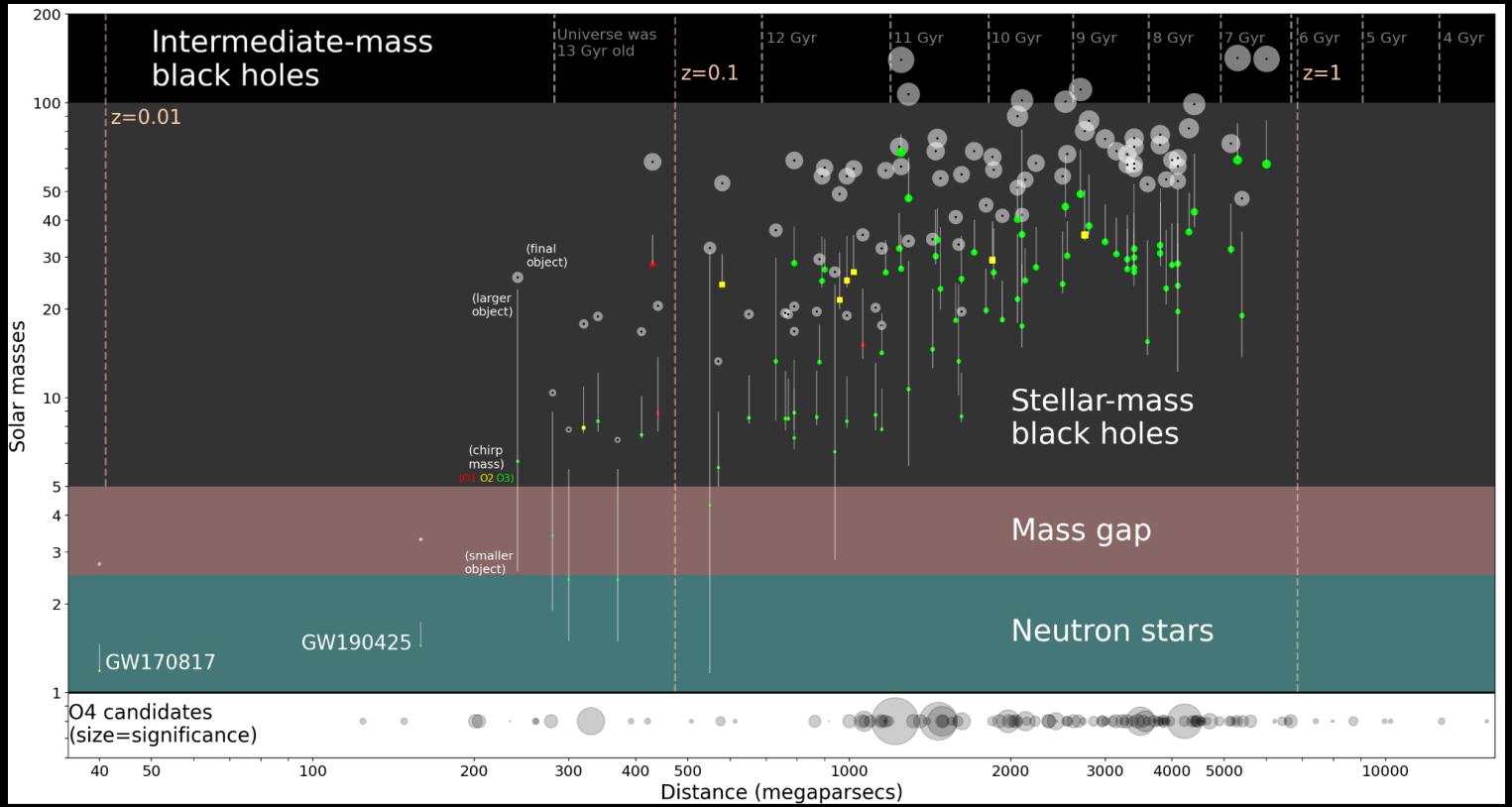
- 200kW arm power

First run with public alerts of event candidates + localization.

KAGRA joins at very end → doi:10.1093/ptep/ptac093



O1-O3 Observations



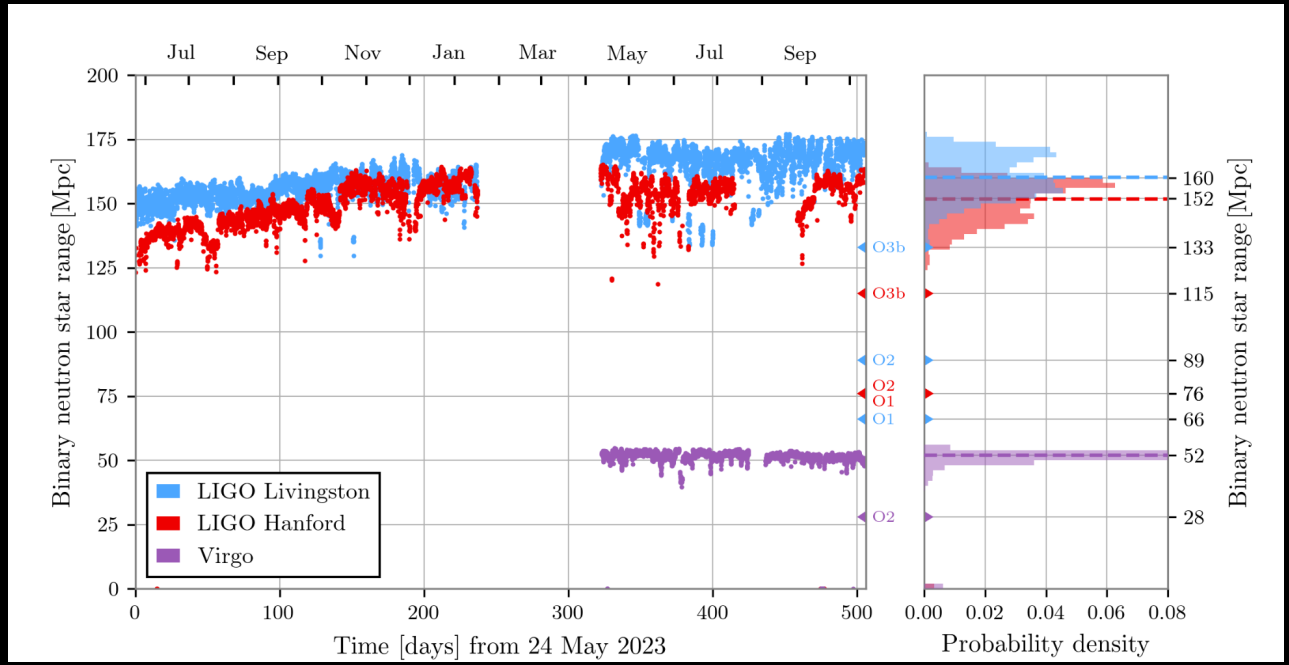
O4

Started in May, 2023.

Virgo joined in early 2024 (O4b).

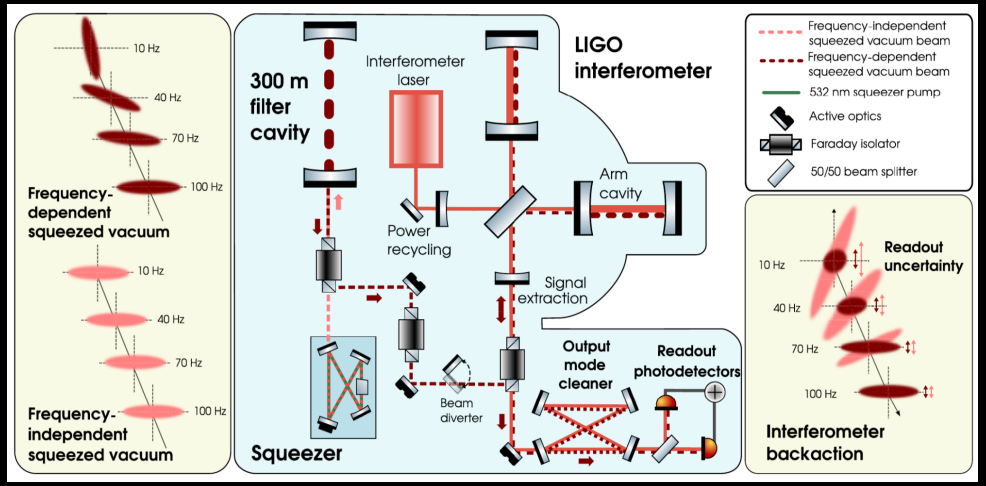
Currently in the middle of O4c.

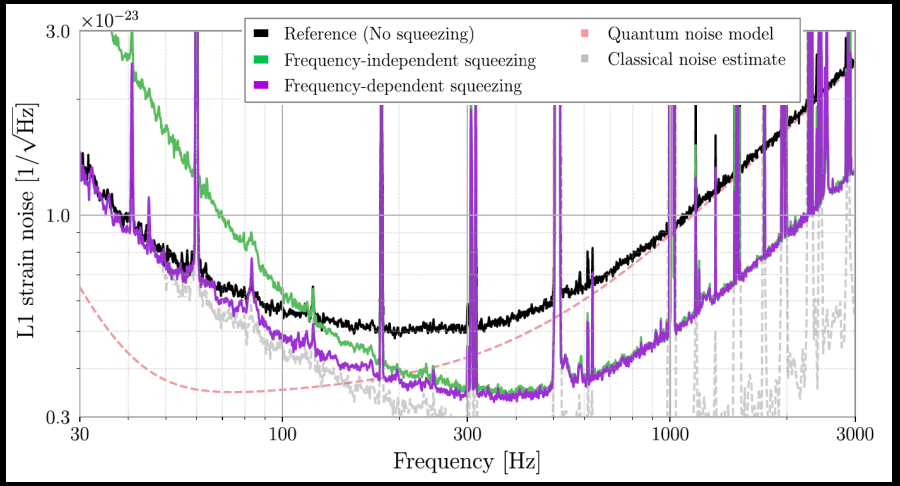
O4 run will continue until Nov. 2025 (three more months).



doi:10.1103/PhysRevD.111.062002

New detector tech: frequency-dependent squeezing





After O3, both LIGO and Virgo added *filter cavities* for their squeezed vacuum fields to allow for rotation of the squeezing ellipse to limit the injection of quantum radiation pressure noise.

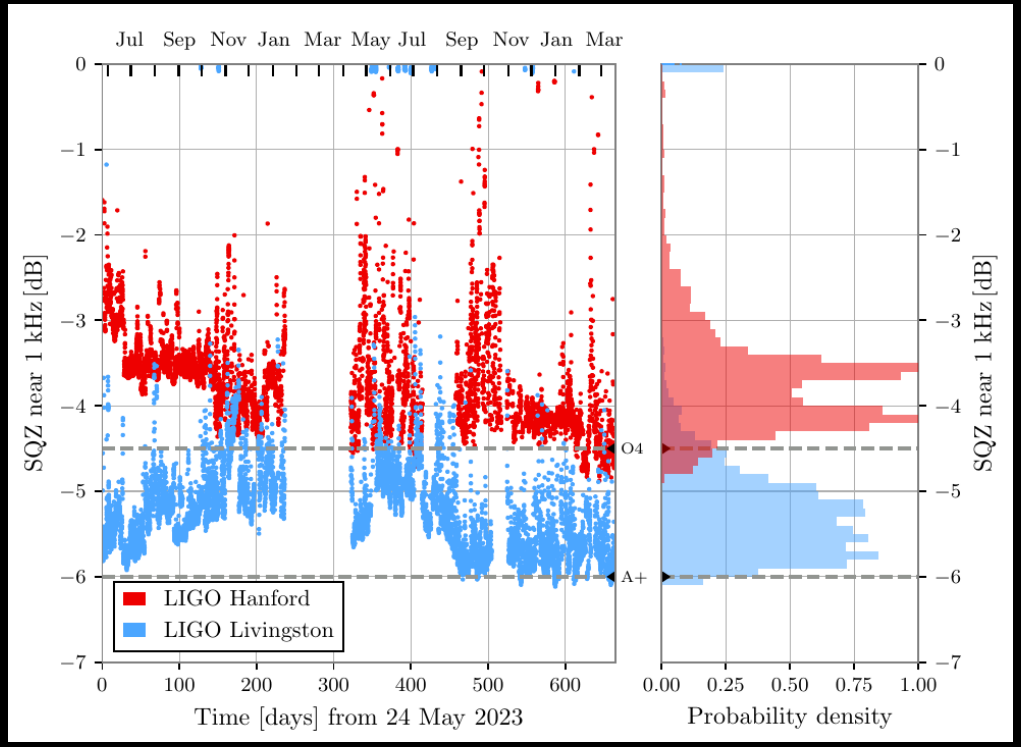
doi:10.1103/PhysRevX.13.041021

O4: LIGO upgrades

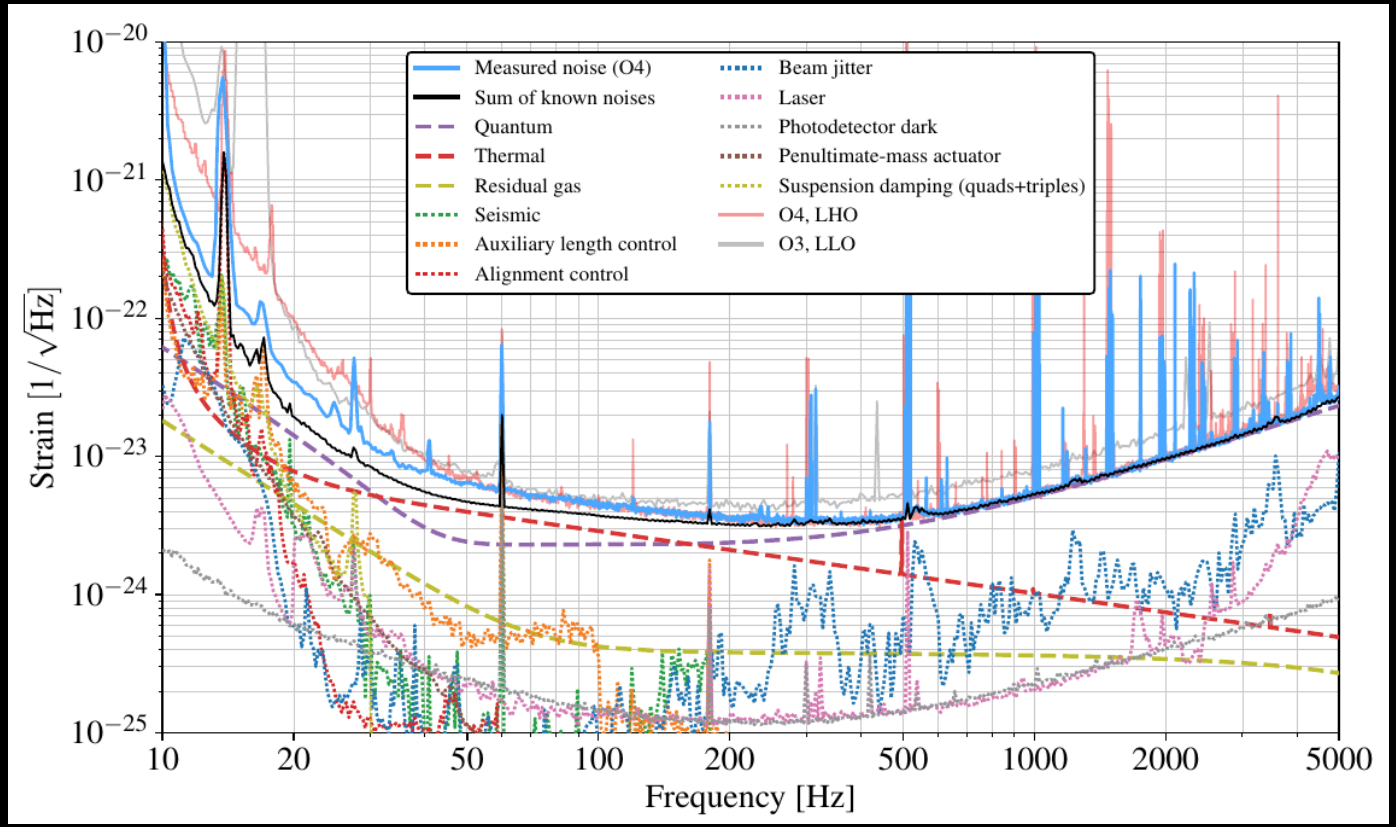
Major changes from O3:

- Frequency-dependent squeezing: **Achieved nearly 6dB @ L1 →**
- More power in the arms:
  - H1: 380 kW
  - L1: 280 kW
- Some light scattering sources and control noises mitigated.

doi:10.1103/PhysRevD.111.062002



O4 LIGO Livingston Noise Budget



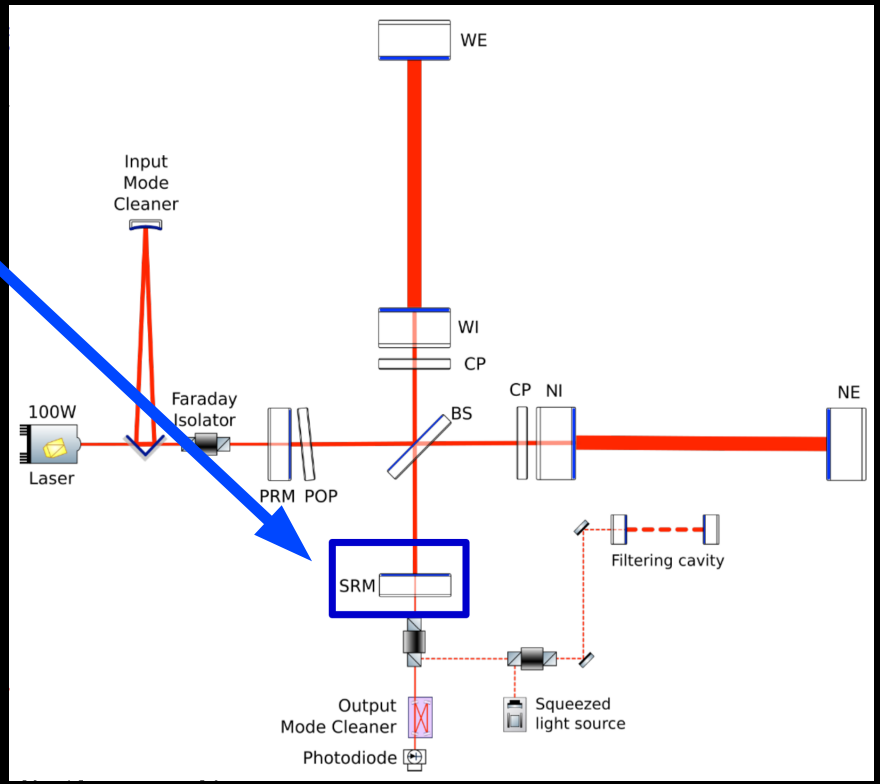
doi:10.1103/PhysRevD.111.062002

O4: Virgo upgrades

Virgo also added a filter cavity, as well as a *signal extraction mirror* to improve detector bandwidth.

The design allowed for degenerate modes in the cavity, which resulted in a range cap of ~50 Mpc.

Virgo now undergoing a complete redesign of vertex, requiring civil engineering work, expected to take multiple years to complete.



O4: KAGRA upgrades

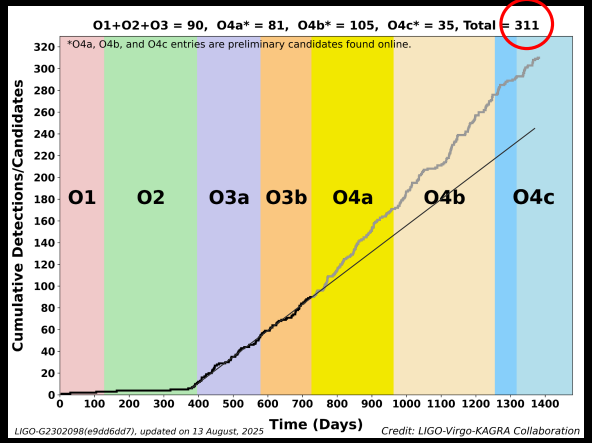
See Prof. Shinji Miyoki (IRCC, U. Tokyo) talk,

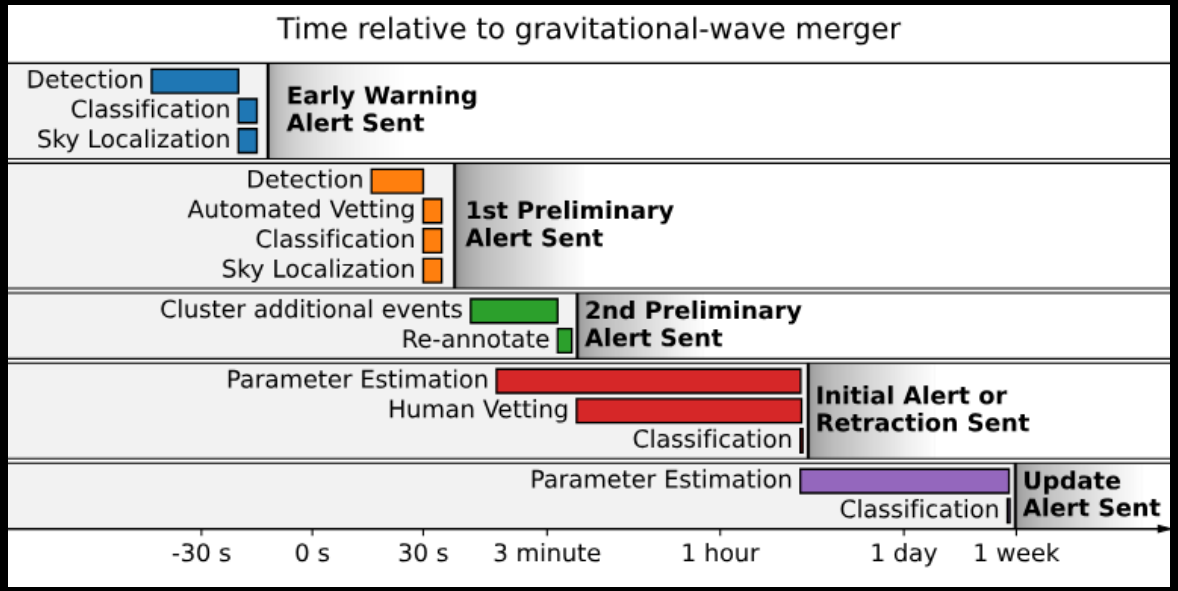
Thursday, 2:00 PM, room F1-R3:

KAGRA gravitational wave telescope in Japan started the 4th international gravitational wave observation(O4) with Advanced-LIGO and Advanced Virgo in May 2023, after repairs, upgrades, and commissioning for 3 years from May 2020. Under the LIGO-Virgo-KAGRA(LVK) O4 scenario, KAGRA restarted its commissioning from July 2023 to upgrade and improve its sensitivity and to rejoin O4 around Spring 2024. However, the magnitude 7.4 Noto Peninsula earthquake severely damaged 10 out of 20 mirror suspension systems, along with other detector components. Recovery efforts began immediately after the earthquake and were completed in July 2024. Thanks to 11 months of dedicated commissioning work, KAGRA achieved a binary neutron star (BNS) range of up to 6.9 Mpc and is officially rejoining O4 in June 2025. In this presentation, we report on the recovery process, upgrades, and commissioning efforts at KAGRA for O4, as well as a portion of the current observational status.

Low Latency Alerts

Because of GW170817, low-latency searches with public alerts of GW candidates have become the most important operational effort in the LVK.

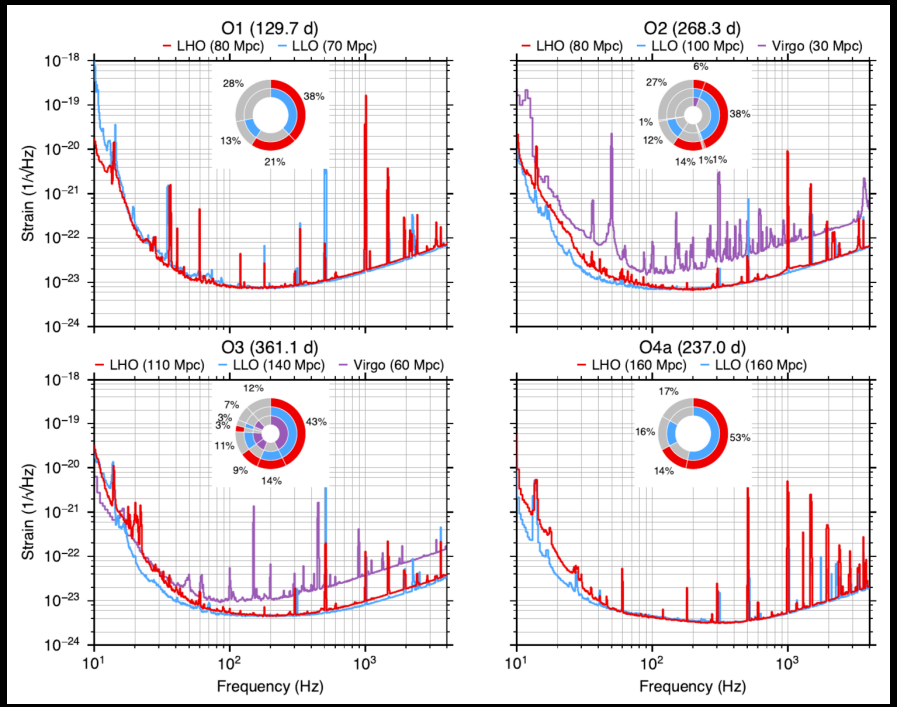


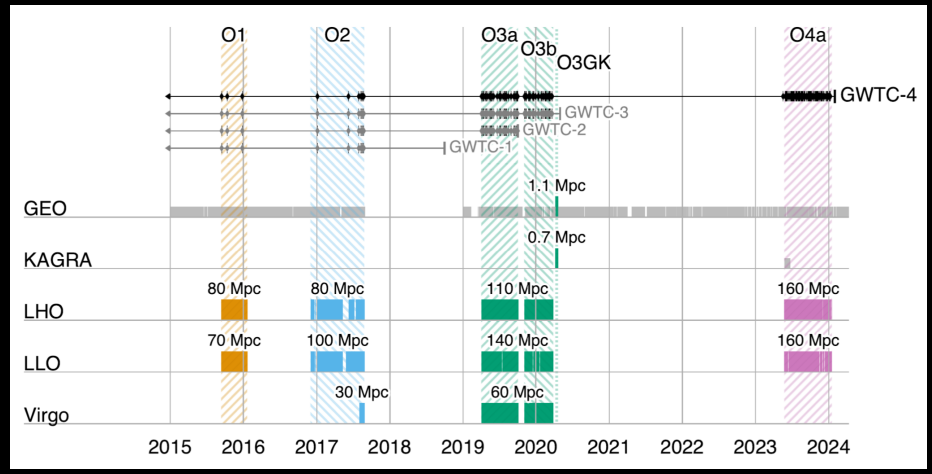


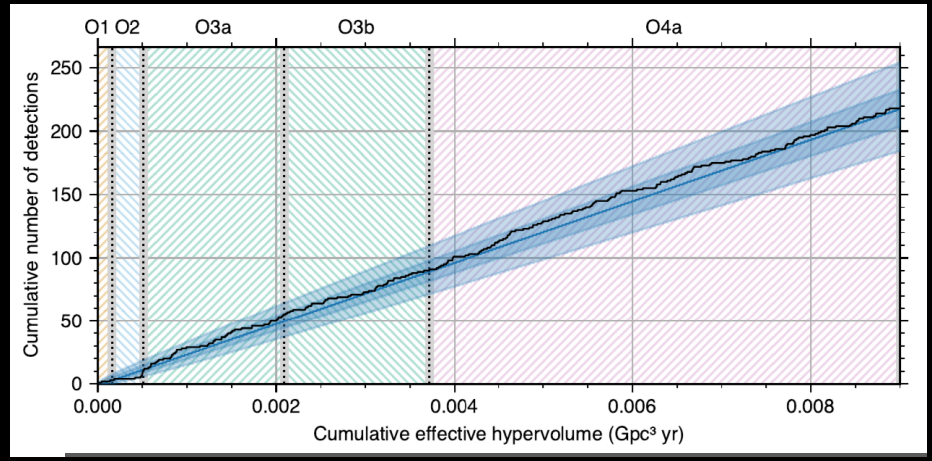
https://emfollow.docs.ligo.org/userguide/

O1-4 summary: GWTC-4.0

arXiv:???







The Next Decade of GW Observation

LIGO funding situation

Operations support for the observatories, as well as detector R&D:

- $50M/yr (2024-2028)

Upgrades separately funded:

- Advanced LIGO: $205M (2008-2015)
- A+: $20M (2018-2025)

Full operations budget confirmed for 2025.

Won't know FY2026 funding until the US Federal budget for 2026 is set.

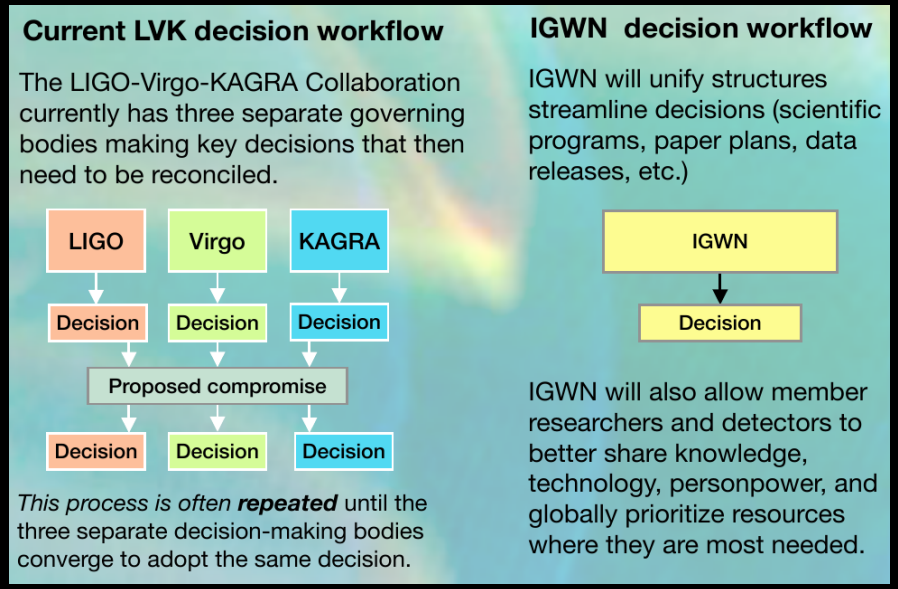
IGWN: International GW Observatory Network

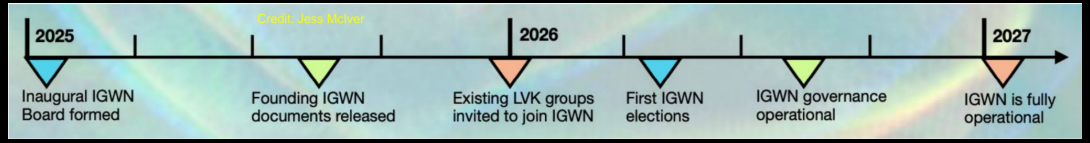
Existing LIGO/Virgo/KAGRA "collaboration of collaborations" is inefficient/lacking.

New unifying collaboration → **IGWN**

Initial formation committees:

- IGWN Design Committee
- IGWN Program Committee
- IGWN Finance Committee

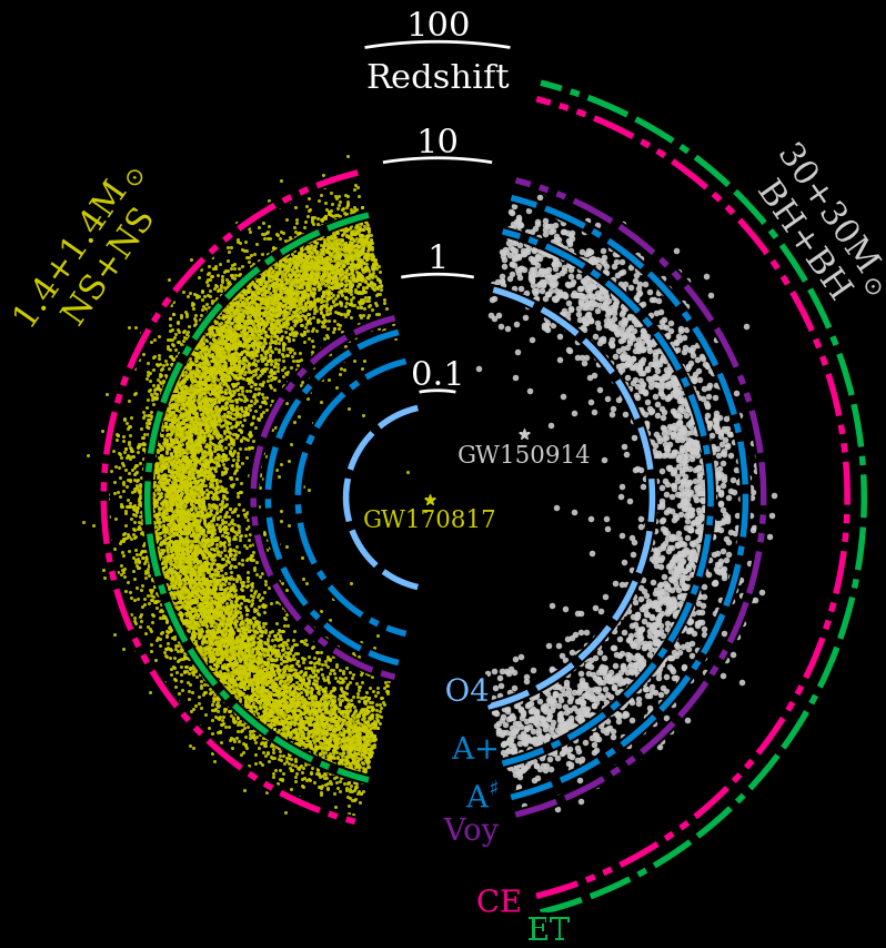




Motivation for continued improvements

Increased sensitivity leads to increased volume observed, leads to more detections, higher precision measurements, better parameter estimation, etc.

[Evan et. al., arXiv:2109.09882 (2001)]

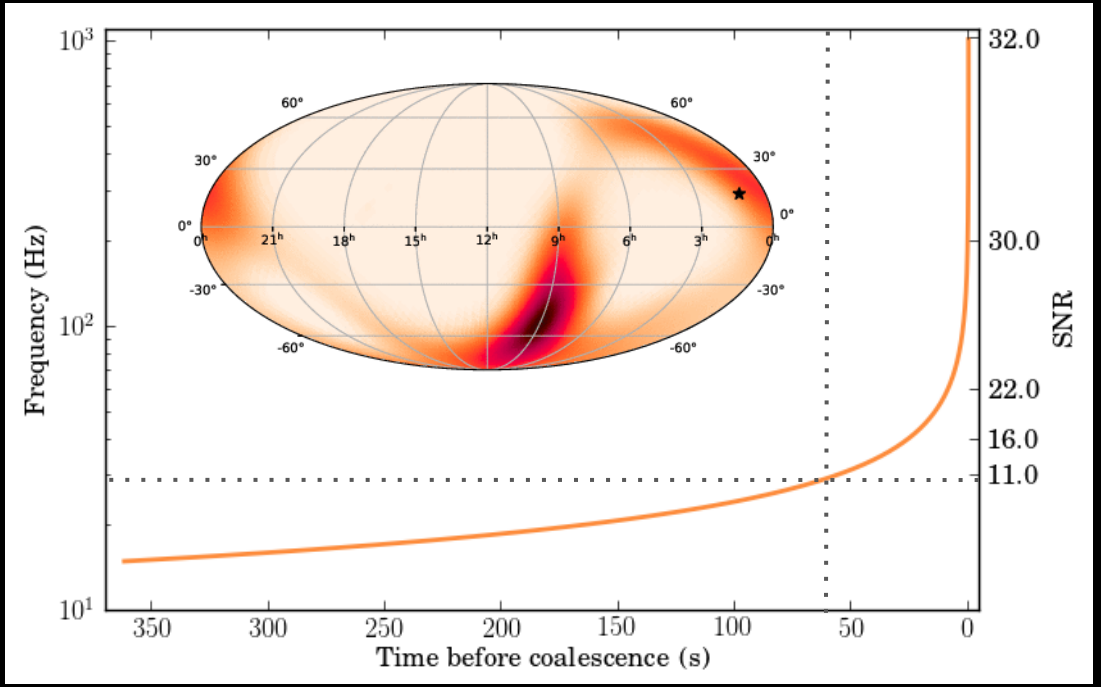


Early warning alerts for potential EM counterparts

BNS signals spend O(minutes) in band. New early warning searches aim to provide alerts *before* merger, with evolving sky maps.

With current sensitivity, BNS spends almost ~minute in band.

Increase time in band with improvements to low-frequency sensitivity.



https://emfollow.docs.ligo.org/userguide/early_warning.html

O5: A+

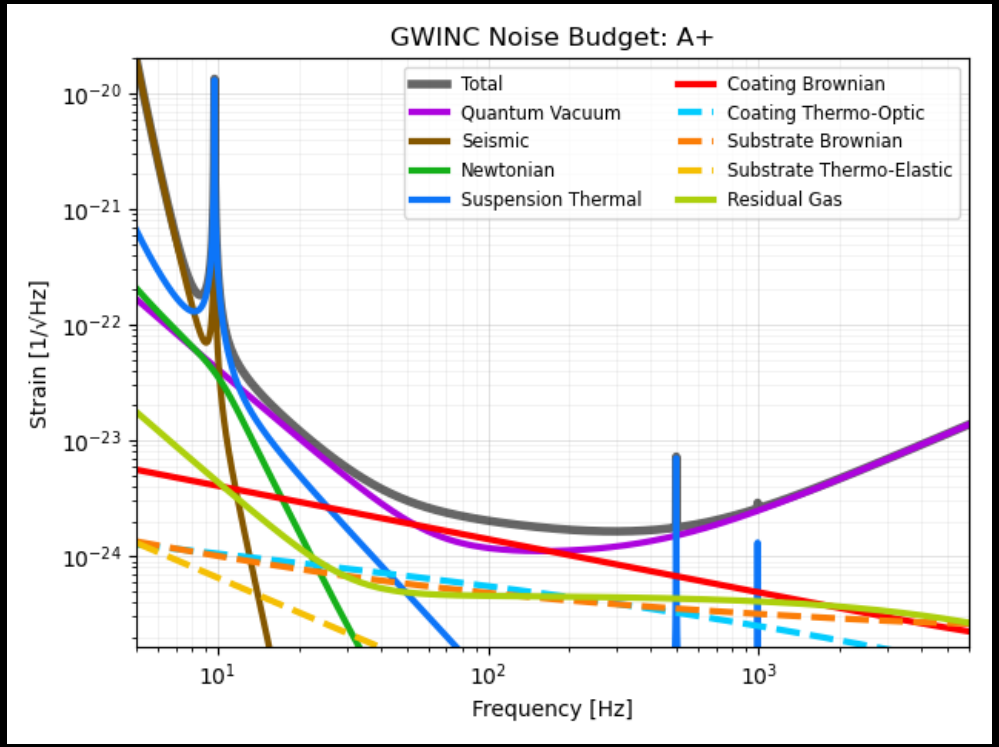
Starting in 2026 after O4 ends, LIGO will complete the “A+” upgrade:

- new test masses with lower loss coatings
- balanced homodyne readout
- 750 kW arm power
- larger beam splitter

Expected range: **340 Mpc** (~3 CBC/day)

Hopefully Virgo will have completed upgrades and recover sensitivity.

O5 schedule: late 2027, for 3+ years.



post O5 study: A#

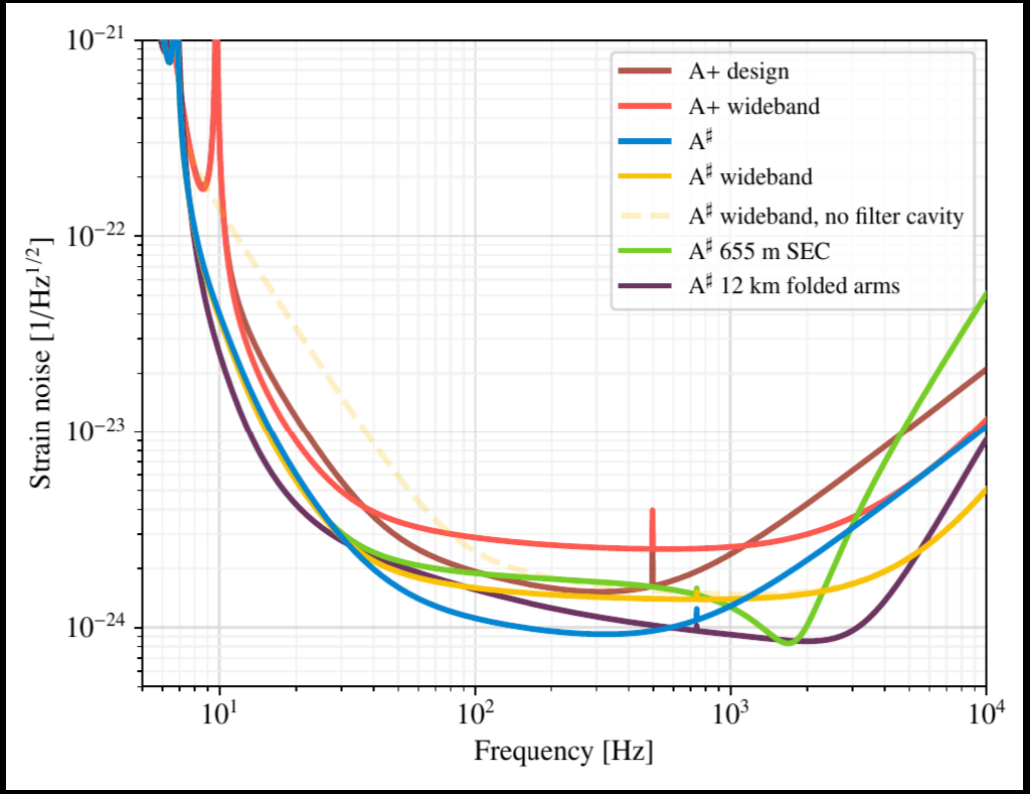
LIGO-T2200287

Evaluate further upgrades in existing LIGO facilities for O6:

- 1.5 MW arm power
- 10db freq.-dep. squeezing
- 100 kg test masses
- Improved suspensions
- improved coatings?

Target sensitivity: **600 Mpc** (~1 CBC/hr)

Increased LF sensitivity, more time in band for BNS.



post O5 study: A#

LIGO-T2200287

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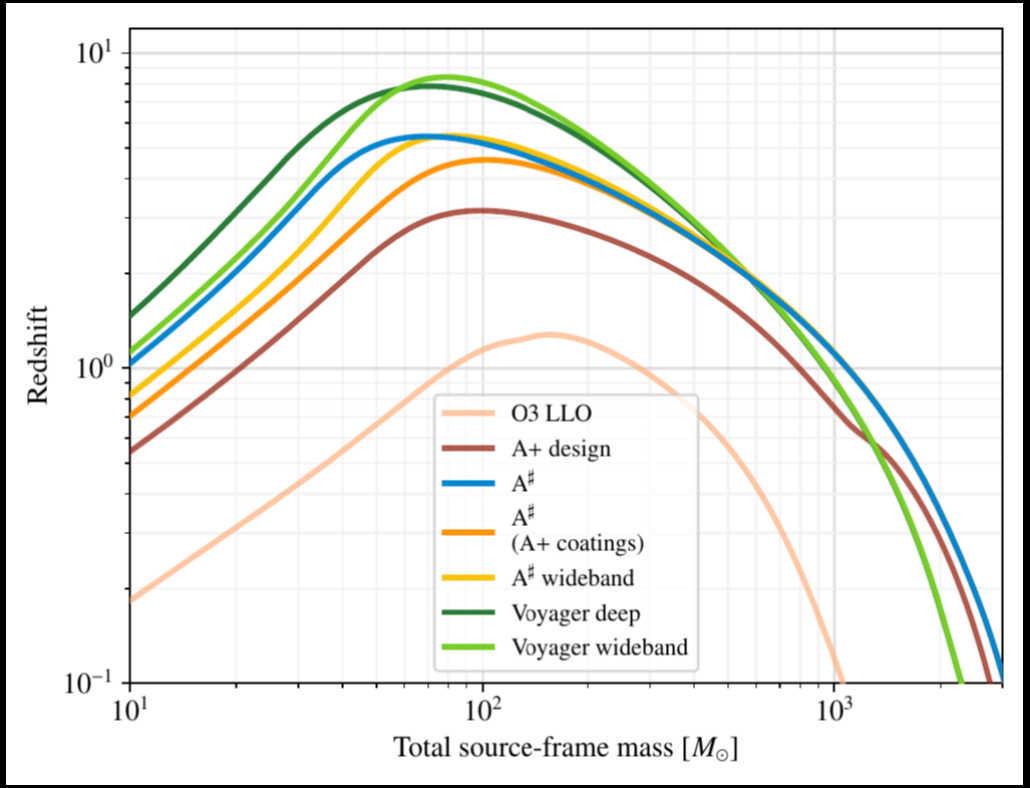


A Third LIGO Observatory in Aundha, India: LIO

NSF+DAE+DST partnership to build third LIGO facility in Aundha, India.

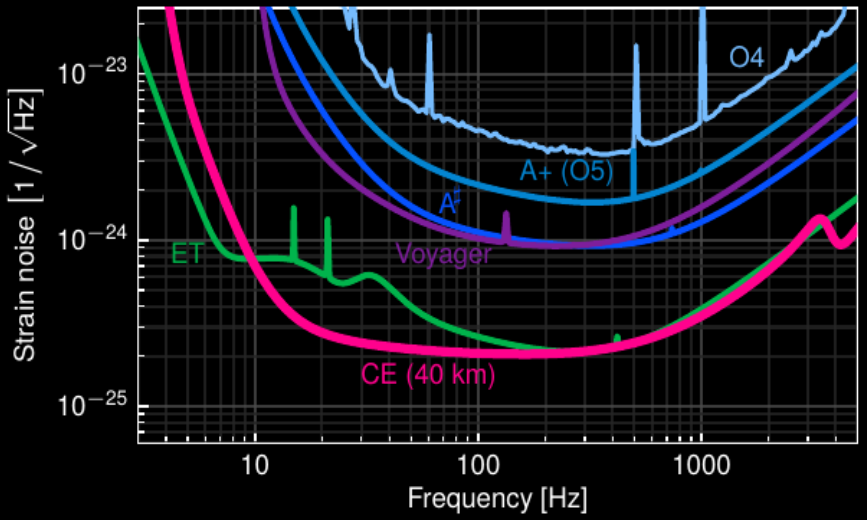
aLIGO base detector in-hand, but targeting A+ technologies (coatings, freq-dept. squeezing)

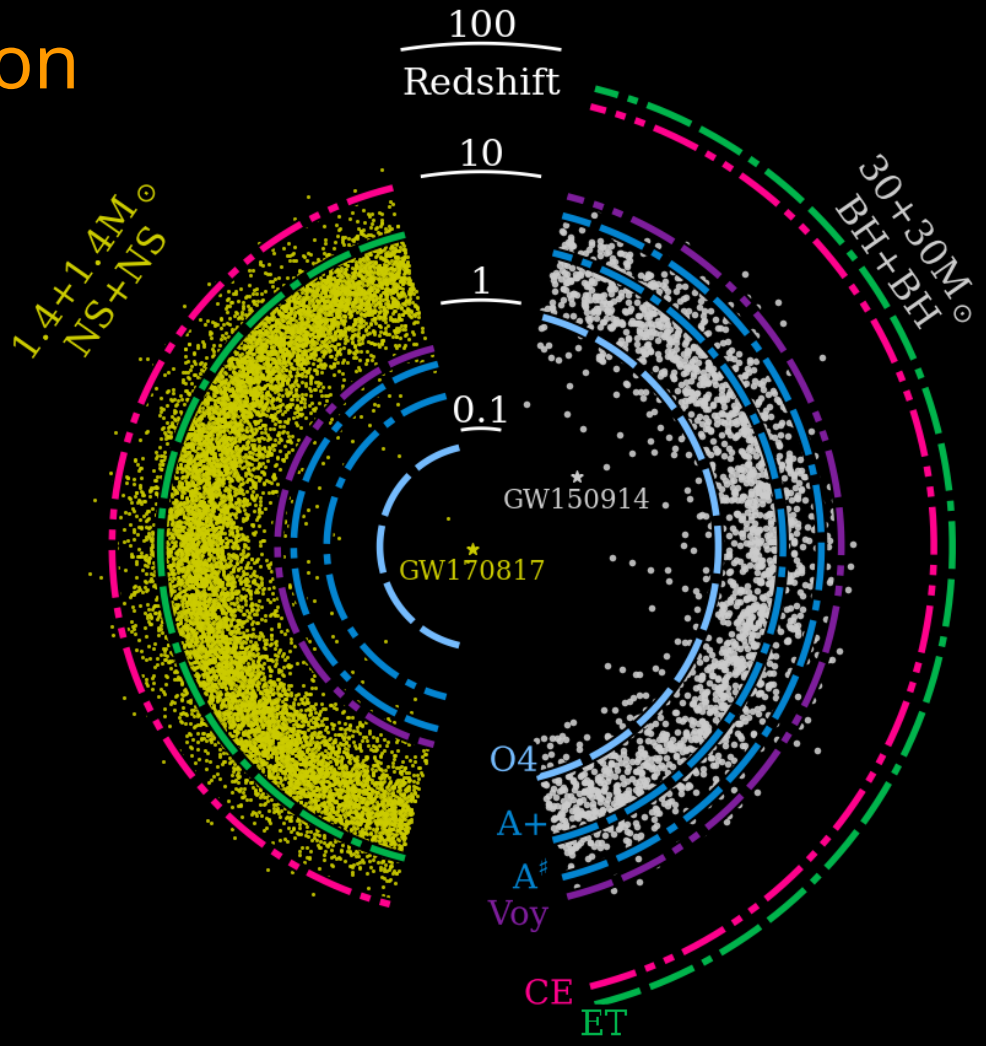
Target sensitivity: **240 Mpc**

- Fully funded.
- Site chosen: Aundha
- Evaluating bids for civil and vacuum infrastructure.

The current “official” schedule → 2030
…but **O6** is a more likely target.

On to the next generation





Next talk: next-generation detector development

Bram Slagmolen

Thank you