

The **LIGO-Virgo-KAGRA** Observing Run 4 **O4**: May 2023 → November 2025

Nicolas Arnaud (nicolas.arnaud@ijclab.in2p3.fr)
Institut de Physique des 2 Infinis de Lyon
(Université Claude Bernard Lyon 1 & CNRS/IN2P3)

On behalf of the **Virgo Collaboration**,
the **LIGO Scientific Collaboration** and
the **KAGRA Collaboration**

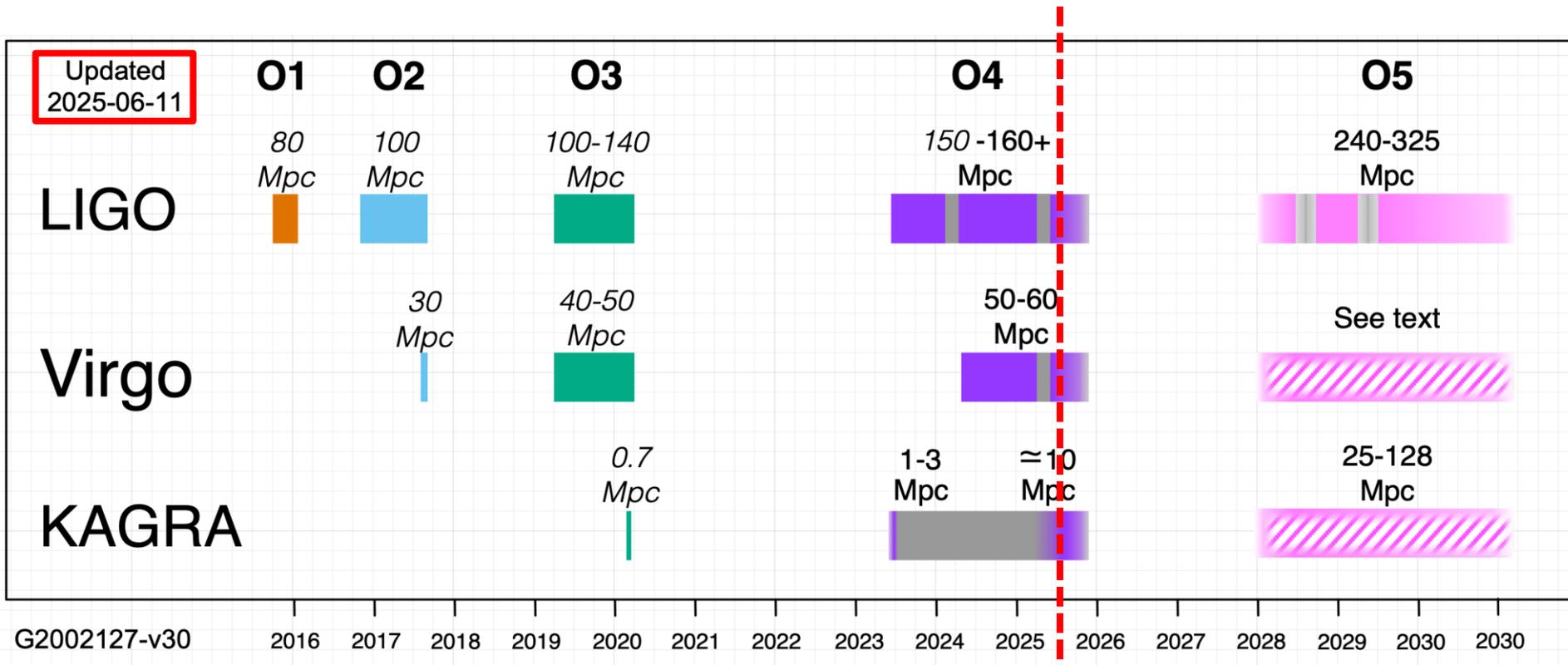
Amaldi 2025, Glasgow – July 14th, 2025

VIR-0061A-25

G2500125

LVK Observing runs

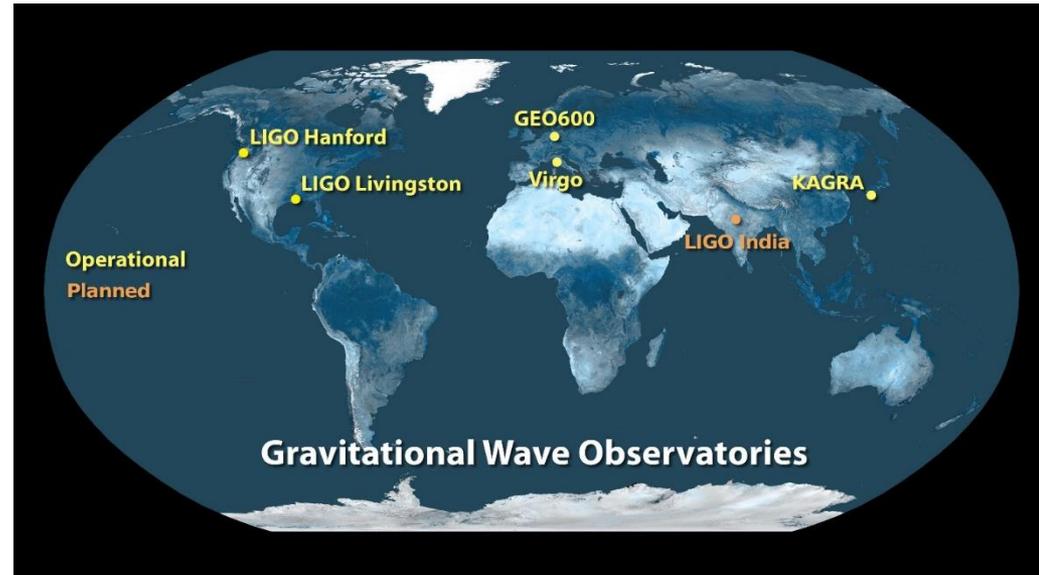
- **LIGO-Virgo-KAGRA (LVK) Observing plans** updated at least monthly on the 15th
 - <https://observing.docs.ligo.org/plan>
 - Latest update on June 11th – **next one expected tomorrow**
 - ◆ When the LVK data taking restarted after a 10-week break



Today

LVK network of detectors

- A **worldwide network** of ground-based GW interferometric detectors
 - Each detector responsible of its own data taking
→ **Global coordination**
 - **Joint data analyses & publications**
- **GEO600** [Germany]
 - Astrowatch, R&D
- **LIGO Hanford (H1)** [WA, USA]
LIGO Livingston (L1) [LA, USA]
 - **LIGO India**: planned



- **Virgo** [Italy]
- **KAGRA** [Japan]
 - **Underground and cryogenic**
- **Gravitational Wave Open Science Center (GWOSC)**:



<https://www.gw-openscience.org>

LVK O4 run in a nutshell

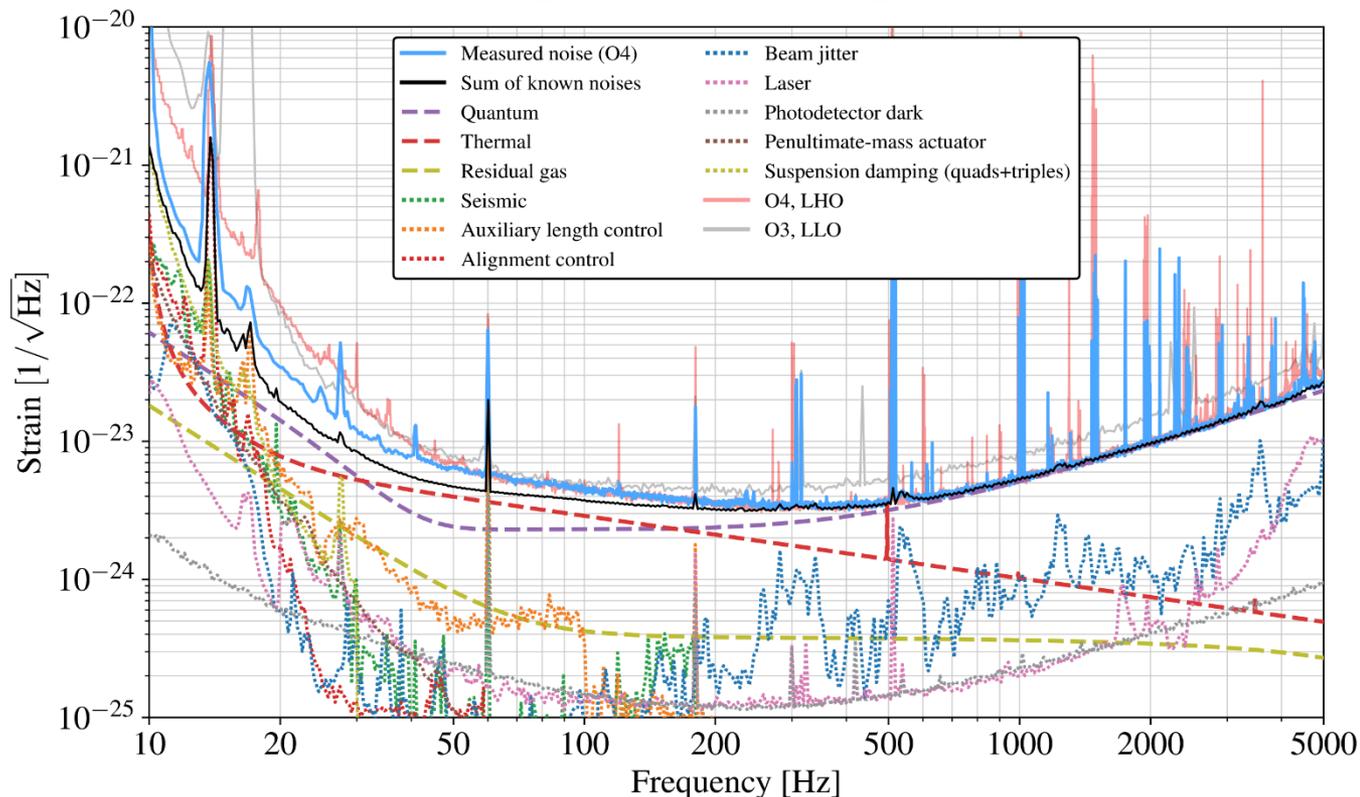
- **O4a**: 24 May 2023 @ 15:00 UTC → 16 January 2024 @ 16:00 UTC
 - **The two LIGO detectors**
 - ◆ **Virgo** decided to continue **commissioning** to work further on improving the sensitivity and the stability of the detector for O4b
 - ◆ **KAGRA** took data for **four weeks**, before moving back to commissioning
- **O4b**: 10 April 2024 @ 15:00 UTC → 28 January 2025 @ 1700 UTC
 - **The two LIGO detectors + Virgo** for the full data taking period
 - ◆ **Scheduled downtimes aligned to maximize the 3-detector uptime**
 - **KAGRA** continued **commissioning** with the goal to be ready for O4c
 - ◆ **Site significantly impacted** by a 7.6-magnitude earthquake on 01 January 2024
- **No detector break between O4b and O4c**
 - Transition driven by the schedule to release public data by chunks
 - ◆ Clean cut: all detectors down at the time of the change
- **O4c**: 28 January 2025 @ 1700 UTC → 18 November 2025 @ 16:00 UTC (currently)
 - **Four detectors** for the first time: **the two LIGO + Virgo + KAGRA**
 - ◆ **KAGRA** data not used in **low latency** for public alerts
 - **10-week detector break** from 01 April to 11 June

LIGO detectors status update

- **Major changes from O3**
 - Frequency-dependent squeezing: better than 4dB @ H1 / close to 6dB @ L1
 - More power in the arms, ~200 kW → 380 kW @ H1 / 280 kW @ L1
 - Some scatter sources and control noises mitigated
- **Current issues**
 - **Cannot easily power up more**, instabilities and unclear gain in sensitivity
→ Buildups do not scale, more noise, etc.
 - **Mystery noise** thought to be scatter, working hard to understand (to fix for O5)
→ L1: Added extra baffles in recent O4c vent as a test – unclear results so far
- **Near future improvements (to be tested early before O5)**
 - Better suspension local damping sensors
 - Install big beam splitter
 - Input jitter mitigation (new, small input cavity, JAC)
 - Front surface heater for input test masses (CHETA)
 - Better output losses (partial BHD)
 - Better test masses: improved coating thermal noise
 - ◆ A bit delayed, but still planned for O5

LIGO Livingston O4 noise budget

- Blue trace: measured sensitivity
- Black trace: sum of all known noises
 - Some mystery noise remains in the low- and mid-frequency ranges
- Red dashed trace: thermal noise
 - To be improved (better coating for O5 test masses) alongside the quantum noise
 - Otherwise not much gain at mid. frequencies



Reference:
[Phys. Rev. D 111, 062002 \(2025\)](#)

Virgo detector status update

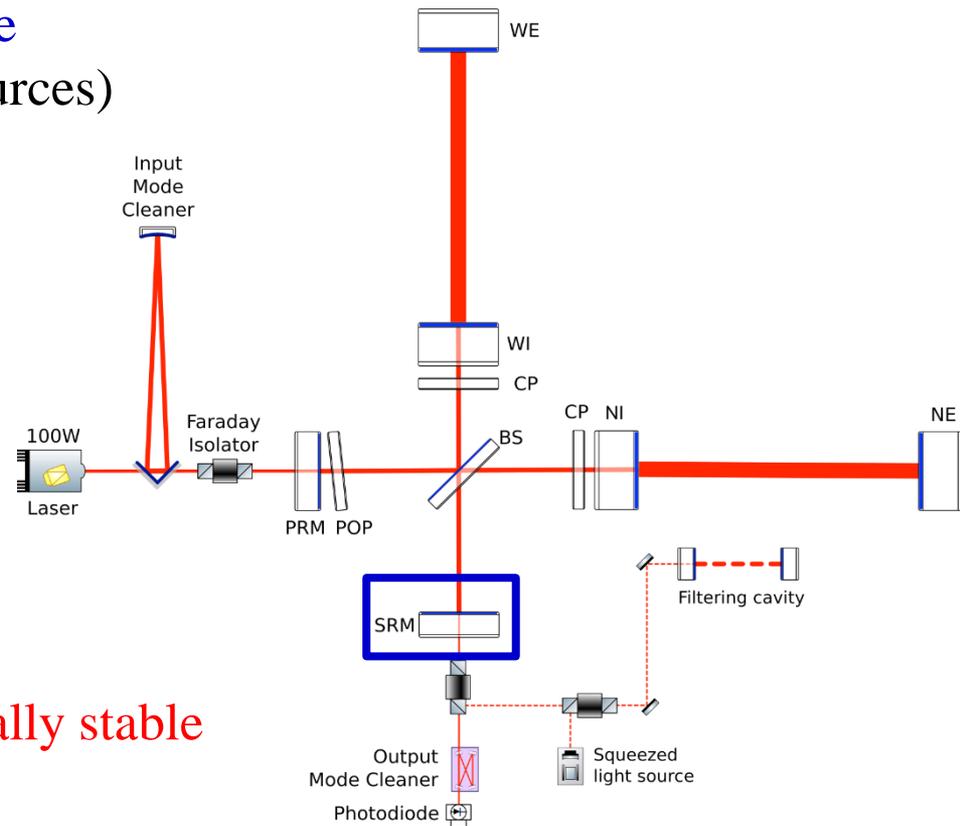
- **Main O3 → O4 upgrade**: addition of the **signal recycling mirror (SRM)**
 - **Improve and shape the sensitivity curve** in a given frequency band (specific sources)
 - ◆ **Mirror reflectivity** ↔ **Bandwidth**
 - ◆ **Position** ↔ **Resonance frequency**

→ **Additional cavity to control**

- **Longitudinal and angular degrees of freedom**

→ Need to **redesign** the procedure leading to the global control of the full detector

- **Virgo recycling cavities** are **only marginally stable**
 - **Space constraints**
 - **More sensitive to optical defects** (cold & thermal)
 - **Mirror radius of curvature tuned for high power**: more instabilities at lower power
 - A lot of **control** and **stability issues**



Virgo detector status update

- “Mystery” noise scaling like $1/f^{2/3}$ is limiting BNS range around 55 Mpc
 - Exact origin still unknown, in spite of numerous studies and hypothesis testings
 - Possibly coming from high-order modes
 - ◆ Larger contributions due to the marginally-stable cavities
- New direction for the post-O4 upgrade of the Virgo detector
 - Priority is to install stable cavities
 - ◆ Requires a complete redesign of the central interferometer area and some related civil engineering work
- Technical Design Report submitted to funding agencies
 - Review process in progress
- Virgo-specific upgrade planning to be discussed with LIGO and KAGRA
 - In the framework of the joint preparation for the O5 run and beyond

KAGRA detector status update

- **History**

- April, 2020: **Joint O3GK run with GEO600**. BNS range: ~ 0.66 Mpc (median)
- May, 2023: Took data during first month of O4a. Sensitivity: ~ 1.3 Mpc (prelim.)
- October 2024: **full recovery** from January 1st, 2024 earthquake (epicenter ~ 100 km)
- June, 2025: **Observing in the second part of O4c**. Sensitivity: ~ 7 Mpc (prelim.)

- **Major improvements** since O3GK

- **Enhanced test mass cooling**: $1@300\text{K} + 3@250\text{K} \rightarrow 2@40\text{K} + 1@60\text{K} + 1@90\text{K}$
- Implemented Wavefront Sensing in **Alignment Sensing and Control**
- Increased input laser power: ~ 1 W \rightarrow 10 W
- Upgraded suspension controls + vibration isolation for output optics
- Stray light mitigation

- **Current issues**: unidentified noise source around 100 Hz + beam jitter

- **Near-Future improvements** (toward O5)

- Implementation of **Resonant Sideband Extraction**
- Replacement of **Input Mirrors**
- **Photodiodes** put into vacuum
- **High-power laser**: targetting 30 W at the input mode-cleaner output

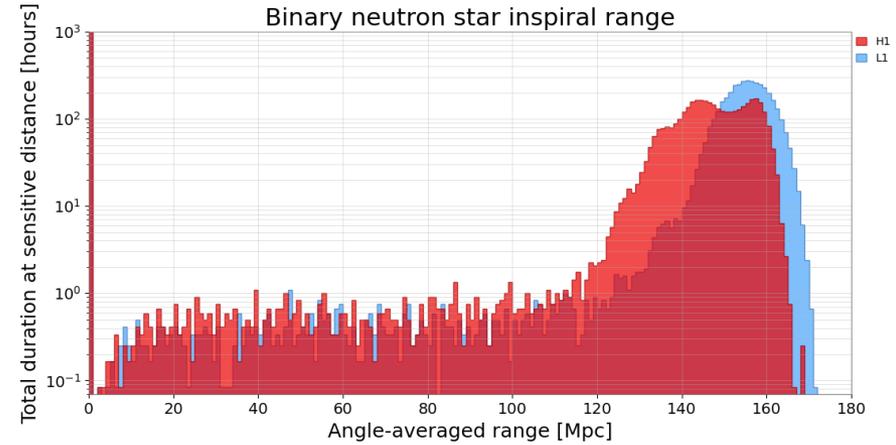
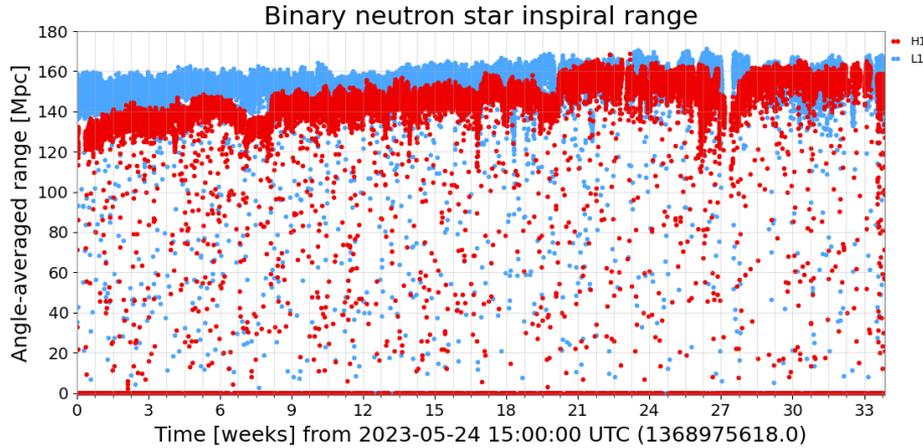
More LVK detector talks this week

[That was this morning]

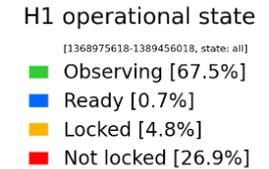
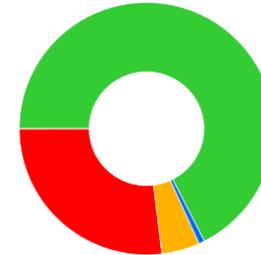
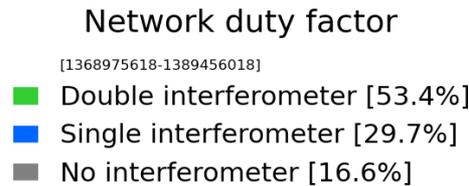
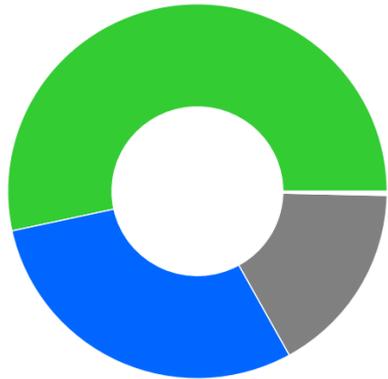
- Mon. Session 2 – Plenary Talks: A new chapter of gravitational wave observations with ground-based laser interferometers
- Mon. Session 3 - C2: Gravitational wave astronomy: searches, data analysis, parameter estimation and multi-messenger astronomy
 - Evan Goetz, Characterizing LIGO detector data in the fourth observing run
 - Didier Verkindt, Virgo $h(t)$ reconstruction for O4 and O5
- Tue. Session 3 - C3: Progress and challenges in advanced ground-based detectors
 - Diego Bersanetti, Interferometer Configuration and Commissioning of the Virgo Detector during the O4b/c Run
 - Matthieu Gosselin, Injection system improvement for AdV+ phase II
 - Cervane Grimaud, From the Virgo interferometer calibration to the bias and uncertainty of the $h(t)$ detector strain during the O4 run
 - Pierre Van Hove, Absolute Calibration of the Virgo Interferometer Using a Newtonian Calibrator
 - Eilidh Mackenzie, Hunting for new glitches in LIGO data using community science
 - Thejas Seetharamu, A+ LIGO Output Mode Cleaner Cavities and Investigation of Polarisation Balanced Homodyne Detection
- Wednesday Session 4 - C4: Concept and research towards next-generation detectors
 - Mattia Boldrini, Simulations of Sensing & Control for Advanced Virgo+ phase II
- Friday Session 4 - C3: Progress and challenges in advanced ground-based detectors
 - Paul Lagabbe, Adaptive optic for mode matching correction
 - Lorenzo Aiello, High power demands high precision: addressing challenges with innovative solutions in GW detector's aberration control
 - Valentina Mangano, Mitigation of Parametric Instabilities in Gravitational Wave Detectors using Mechanical Dampers
 - Maddalena Mantovani, Methodological approach to evaluate control requirements for gravitational wave detectors
- And possibly more...

The O4a run

BNS range



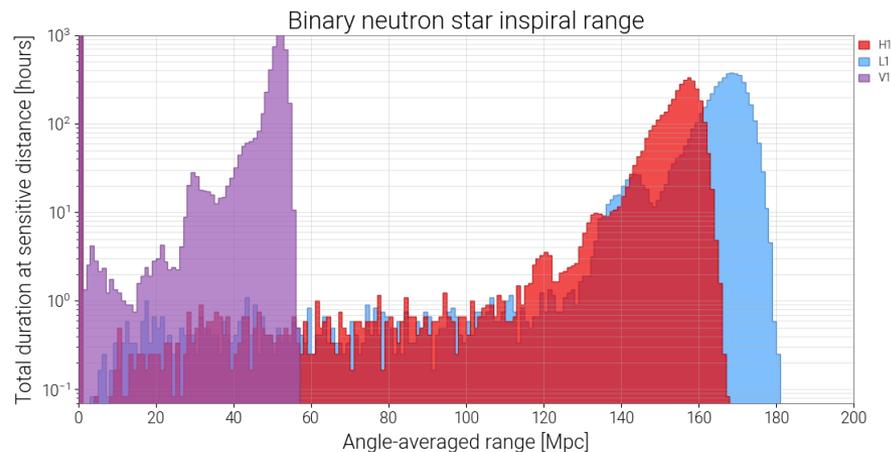
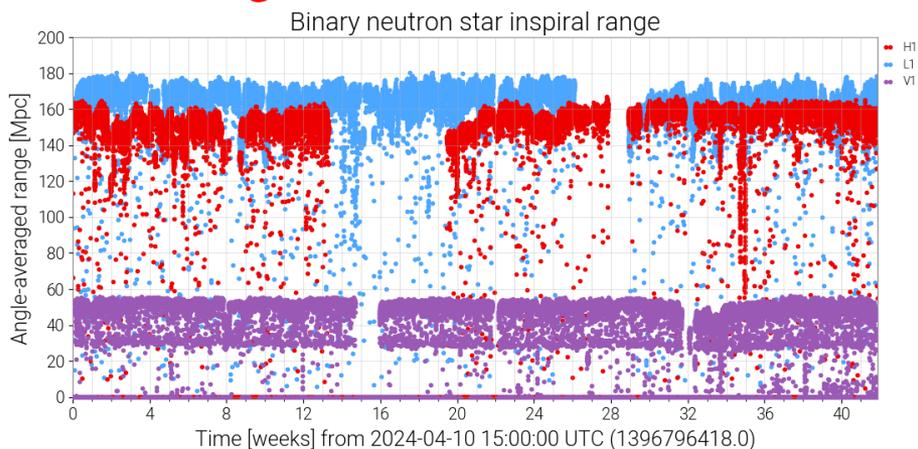
Duty cycles



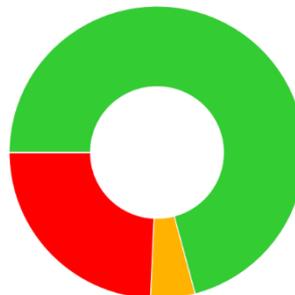
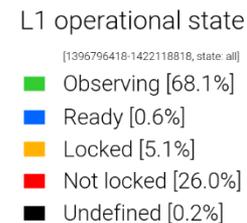
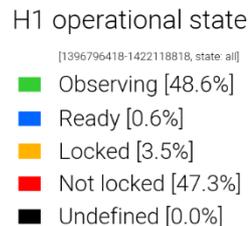
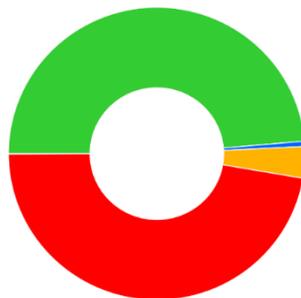
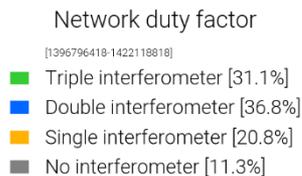
Public monitoring plots: https://gwosc.org/detector_status/O4a

The O4b run

BNS range



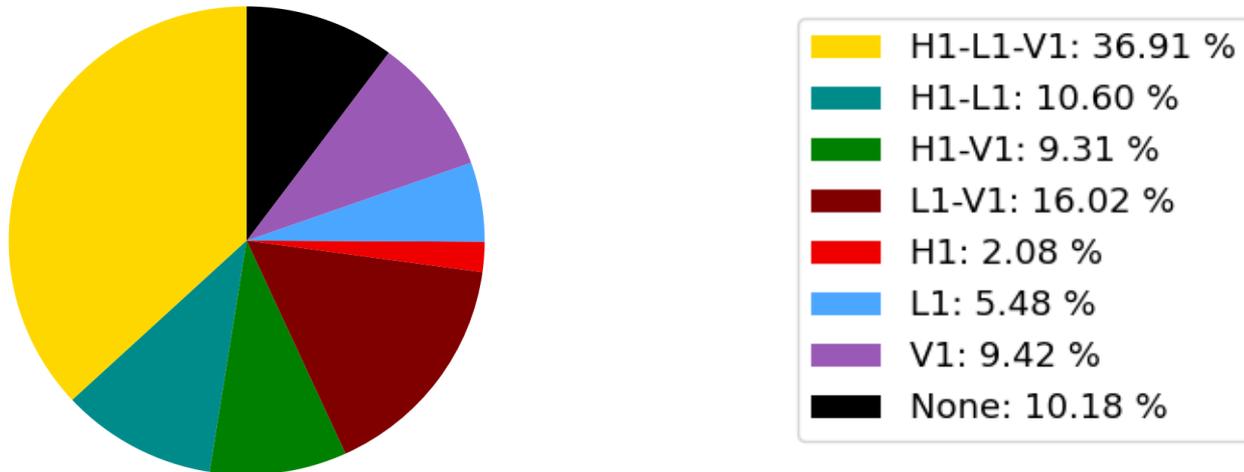
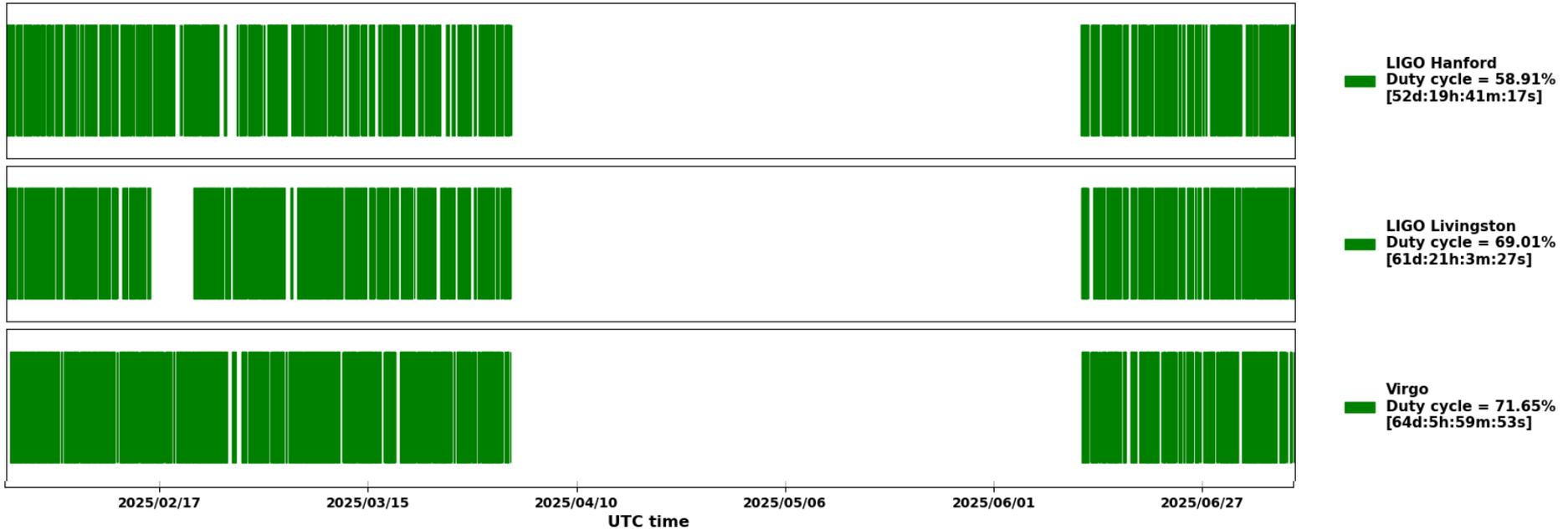
Duty cycles



Public monitoring plots: https://gwosc.org/detector_status/O4b

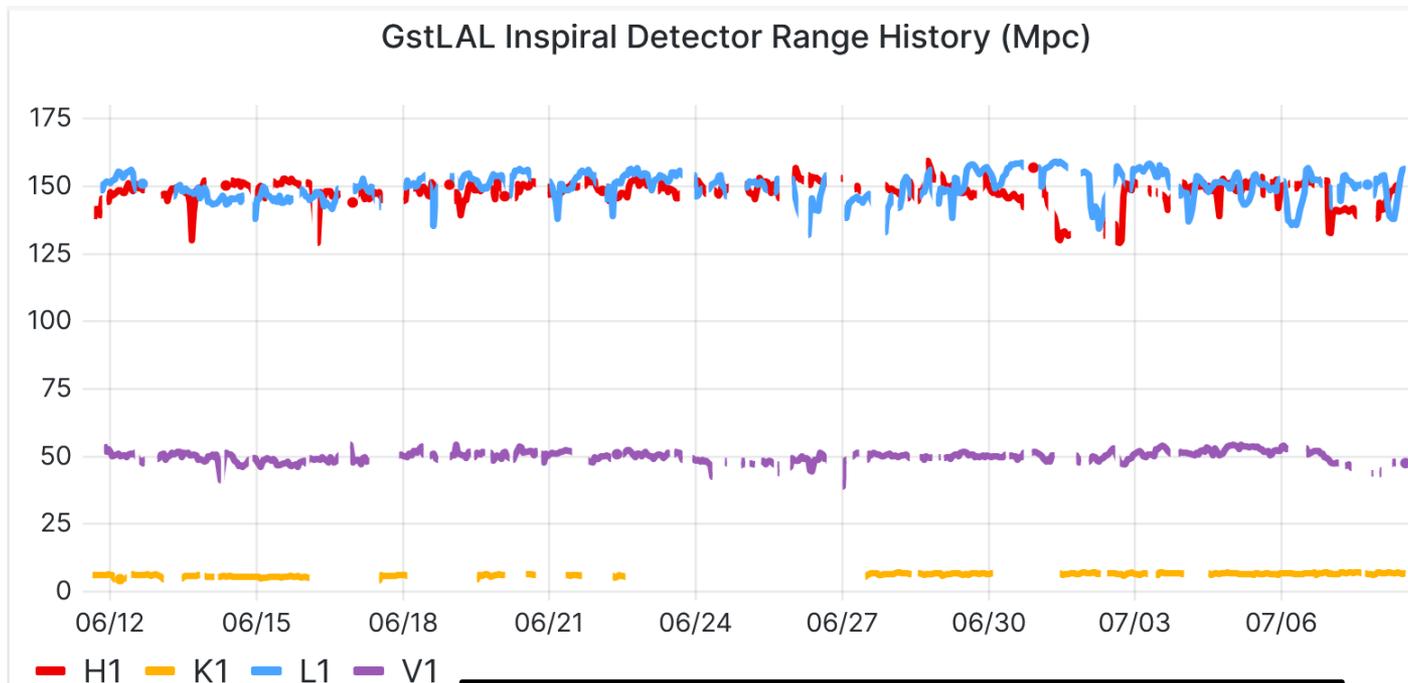
The O4c run

- Duty cycle excluding the 10-week detector break



The O4c run

- **BNS range** evolution
 - From the **gwistat** public website: <https://online.igwn.org>



- Screenshot: **five detectors** observing simultaneously

Gravitational Wave Detector Network

Operational Snapshot as of Jun. 11, 2025 20:50:53 UTC

Detector	Status	Duration [hh:mm]
GEO600	Observing	04:13
LIGO Hanford	Observing	00:00
LIGO Livingston	Observing	03:07
Virgo	Observing	01:03
KAGRA	Observing	03:27

Low latency alerts

- **General Coordinates Network (GCN)**

- <https://gcn.nasa.gov>

- **Real-time processing of LVK data**

- Dedicated data analysis pipelines searching for **transient GW events**

- **Latency is the main challenge**

for the public alert

- **The lower, the better**

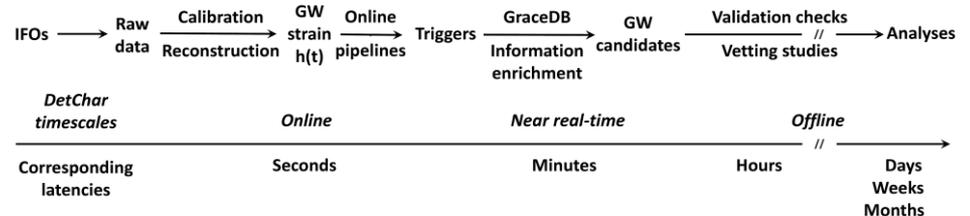
- An alert must be **informative** for the **astronomy community**

- Automated alerts later found not to originate from the cosmos are **retracted**

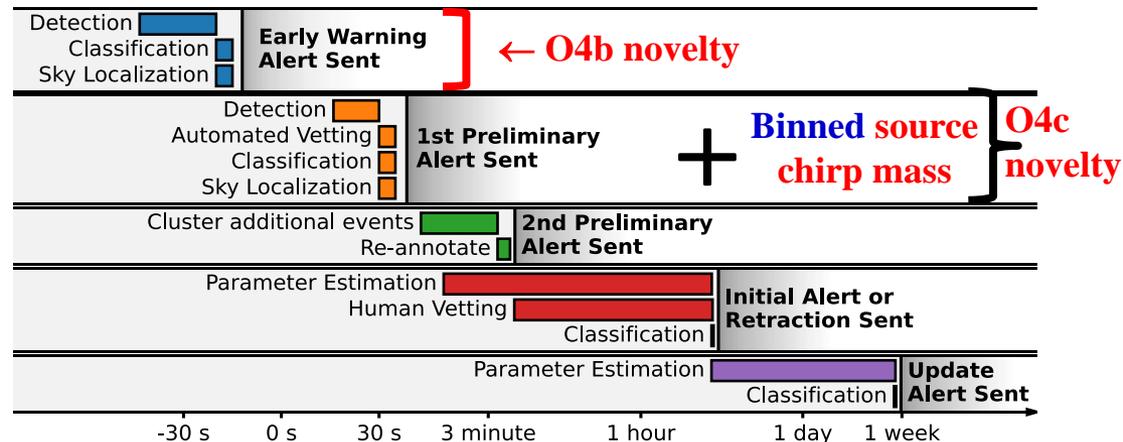
- Central database: **GraceDB**

- **Gravitational wave candidate event DataBase**

→ **Public portal:** <https://gracedb.ligo.org/superevents/public/O4>



Time relative to gravitational-wave merger



[O4a] [O4b]

[O4c]

Binned source chirp mass

- From <https://emfollow.docs.ligo.org/userguide/content.html#inference>

Binned Source Chirp Mass: Probabilities for the chirp mass of the source binary \mathcal{M} to lie within predefined bins, i.e., a coarse-grained histogram. As for the Properties above, we assume in calculating these probabilities that the event is astrophysical, i.e., not noise. The apparent chirp mass including the effect of redshift on the GW signal, $\mathcal{M}_{\text{det}} = (1+z)\mathcal{M}$, is precisely measured for many CBC sources, with the dominant uncertainty in \mathcal{M} generally due to the uncertain redshift of the source.

For events from the cWB-BBH [unmodeled search](#) a distance estimate is not available in low latency, therefore we set the redshift equal to zero for the purpose of calculating binned probabilities. For Burst events detected by neither modeled CBC pipelines nor cWB-BBH, a chirp mass is not provided.

The bin edges are given by $B = (0.1, 0.87, 1.0, 1.1, 1.2, 1.3, 1.4, 1.5, 1.7, 1.9, 2.1, 2.3, 3, 5.5, 11, 22, 44, 88, 1000)$. The value in bin i is the probability that $B_i \leq \mathcal{M}/M_{\odot} < B_{i+1}$.

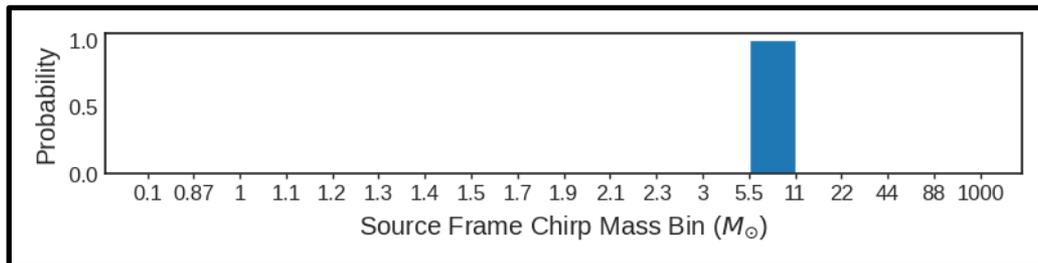
Notes:

- The lowest-mass bin up to $0.87 M_{\odot}$ covers cases where at least one component is [sub-solar mass](#).
- For $\mathcal{M}/M_{\odot} \geq 44$, the source total mass is above $\sim 100 M_{\odot}$ while for $\mathcal{M}/M_{\odot} \geq 88$ at least one component mass is above $\sim 100 M_{\odot}$.

These binned probabilities are available at [GraceDB](#) as a file with JSON format data named either `mchirp_source.json` for a preliminary alert, or `mchirp_source_PE.json` for later updates. An example of the format is below:

- Example:

<https://gracedb.ligo.org/superevents/S250704ab/view>



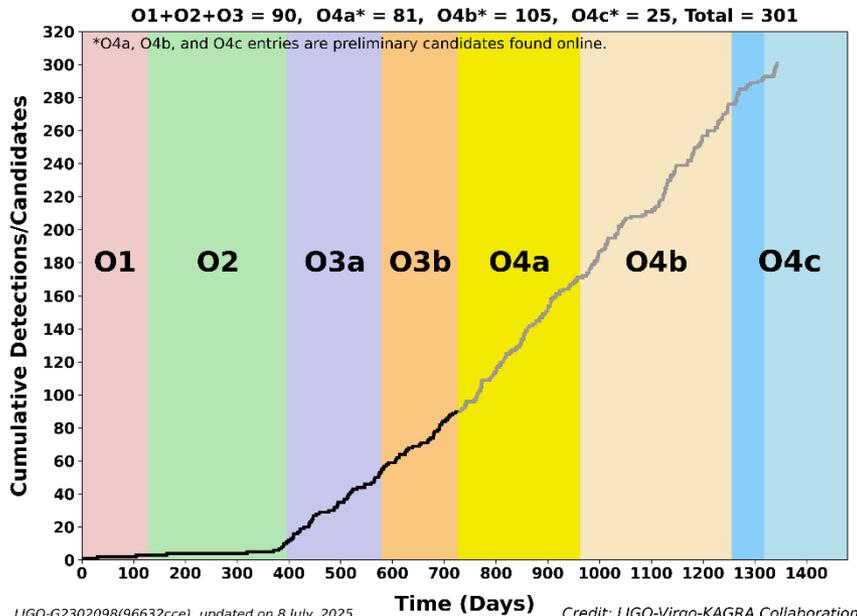
```
bin_edges:
0: 0.1
1: 0.87
2: 1.0 JS:1
3: 1.1
4: 1.2
5: 1.3
6: 1.4
7: 1.5
8: 1.7
9: 1.9
10: 2.1
11: 2.3
12: 3.0 JS:3
13: 5.5
14: 11.0 JS:11
15: 22.0 JS:22
16: 44.0 JS:44
17: 88.0 JS:88
18: 1000.0 JS:1000

probabilities:
0: 0.0 JS:0
1: 0.0 JS:0
2: 0.0 JS:0
3: 0.0 JS:0
4: 0.0 JS:0
5: 0.0 JS:0
6: 0.0 JS:0
7: 0.0 JS:0
8: 0.0 JS:0
9: 0.0 JS:0
10: 0.0 JS:0
11: 0.0 JS:0
12: 7.771561172376096e-15
13: 0.9999874724740854
14: 0.0 JS:0
15: 0.0 JS:0
16: 0.0 JS:0
17: 0.0 JS:0
```

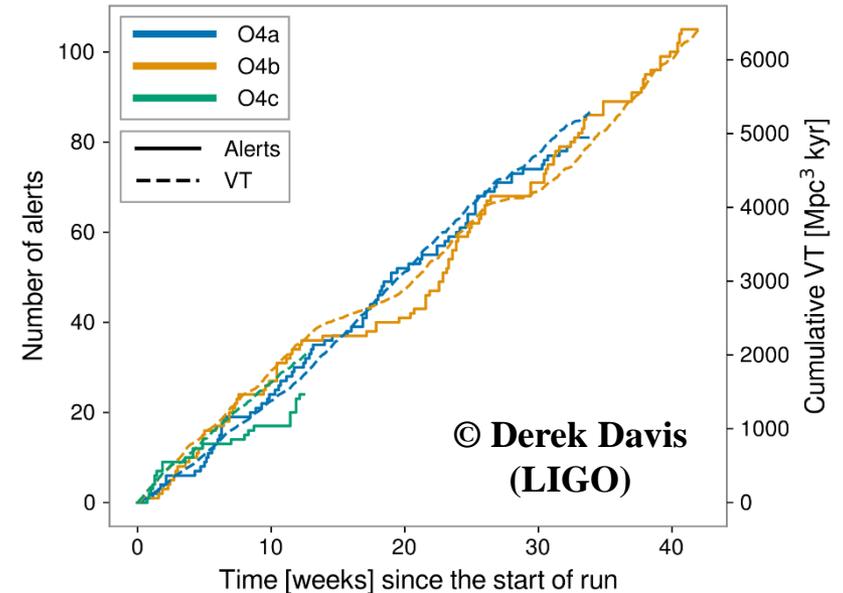
Public alerts

- Cumulative number of (non-retracted) public alerts

- Versus calendar



- Versus integrated Volume \times Time

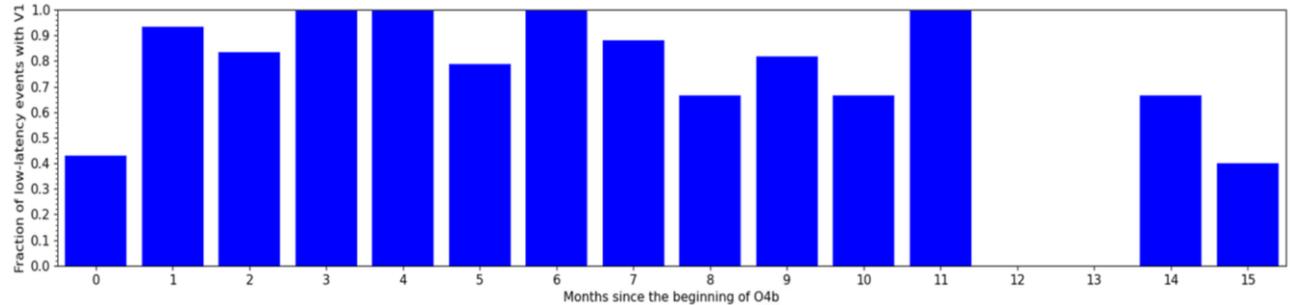


- 211 public alerts in O4 + 25 more retracted
- 301 events integrating over O1 + O2 + O3 (published detections) + O4 (public alerts)
 - The O4a part of this cumulative plot will change when GWTC-4 is released

→ For more information about the LVK low-latency alert system, see talk by Andrew Toivonen in Tuesday Session 3 - C7: MMA of GW sources

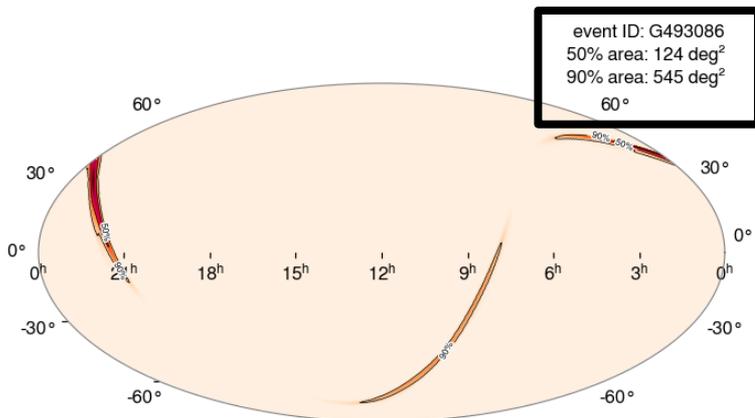
Sky localization

- O4{b+c}: 130 public alerts
→ 80% (104/130) include Virgo data
◆ Fraction per month:

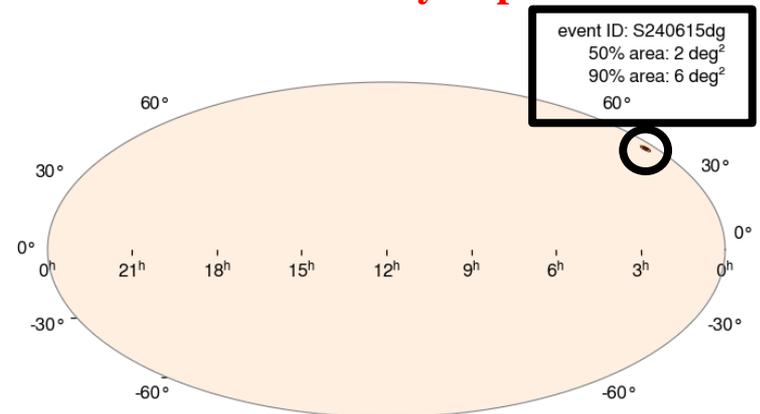


- Sky localization greatly improved in some cases
■ Example: [S240615dg](#)

LIGO-only skymap



3-detector skymap



- No counterpart identified for any event in O4 so far

The Rapid Response Team

- **Joint LVK vetting of low-latency alerts** since the beginning of O4: the **Rapid Response Team (RRT)**
 - **24/7 shift** coverage
 - Shared coordination: **3 geographical regions**, covering **8 hours** each
 - ◆ Europe (+ Africa): Virgo
 - ◆ Asia/Pacific: KAGRA
 - ◆ Americas: LIGO
 - **3-tiered system**
 - ◆ Level 0: shifters
 - ◆ Level 1: experts
 - ◆ Level 2: full team



Level 0: collaboration wide contributions

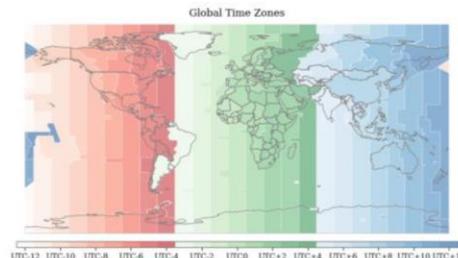


Level 1: experts and problem solvers



RRT coordinators:

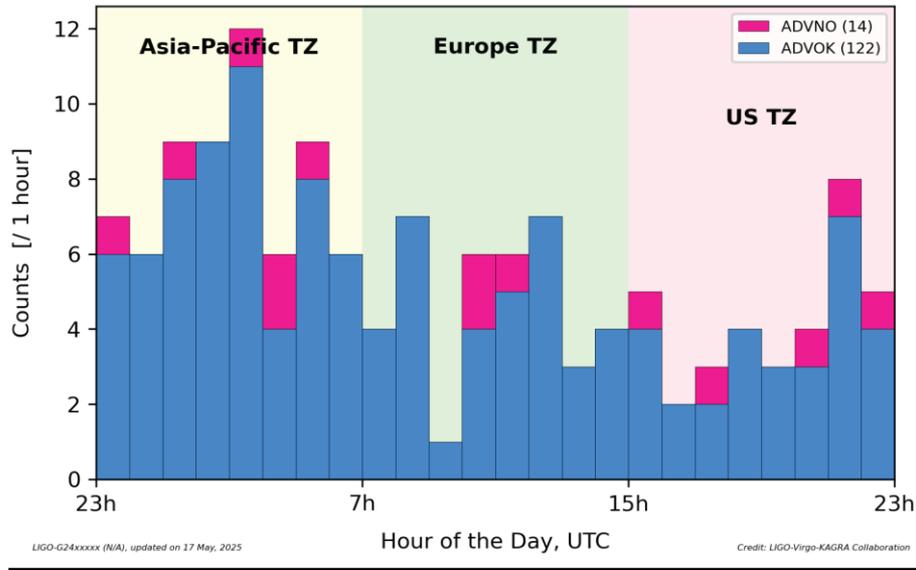
- **The RRT in numbers**
 - **4000+ Shifts** completed
 - **600+ Level-0 shifters**
 - **54 Level-1 shifters**
 - **13 Site advocates**
 - **4 RRT shift managers**



Asia-Pacific	Central- Europe	Americas
UTC 22:45-1-07:00	UTC 6:45-15:00 CEST 8:45-17:00	UTC 14:45-23:00

The RRT: vetting low-latency alerts

- Distribution of **O4b+c** alerts by hour

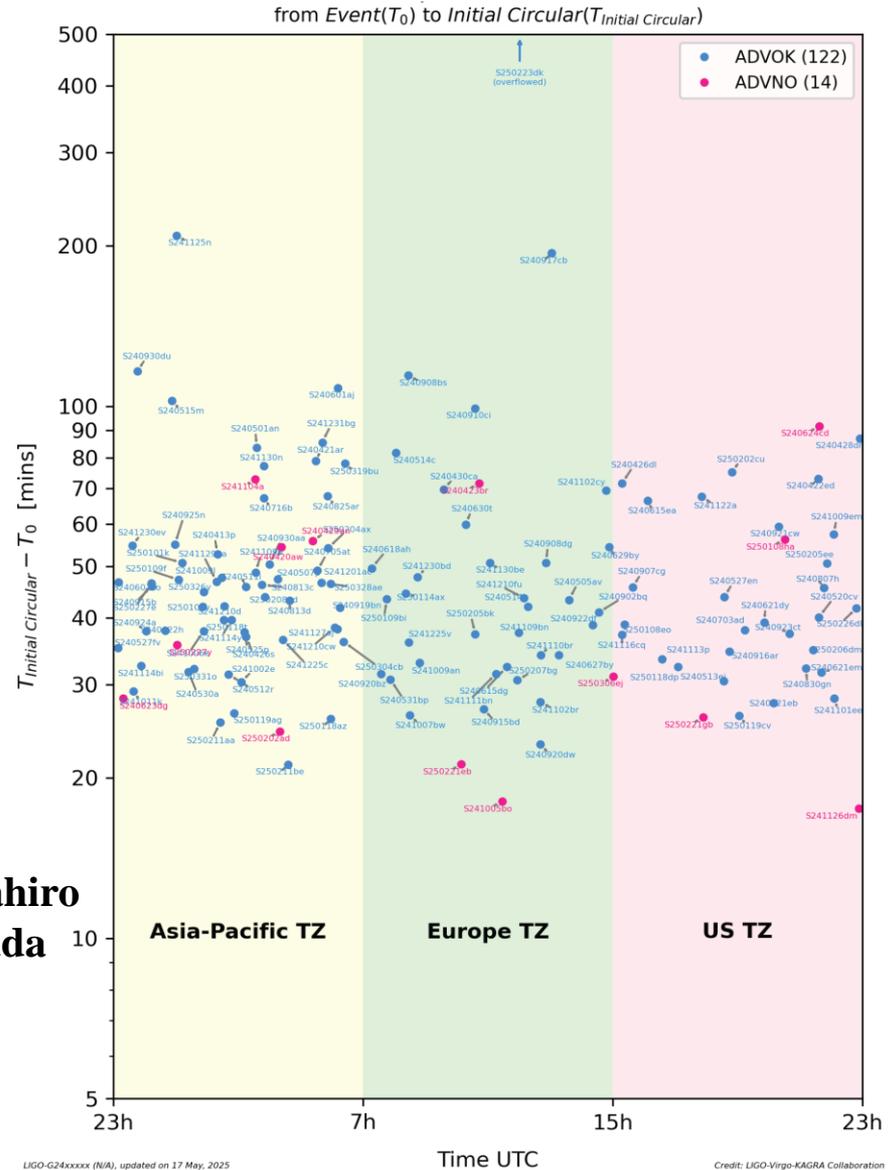


- **Latency** measured from event time t_0
→ Includes all the steps upstream of

Rapid Response Team (RRT)

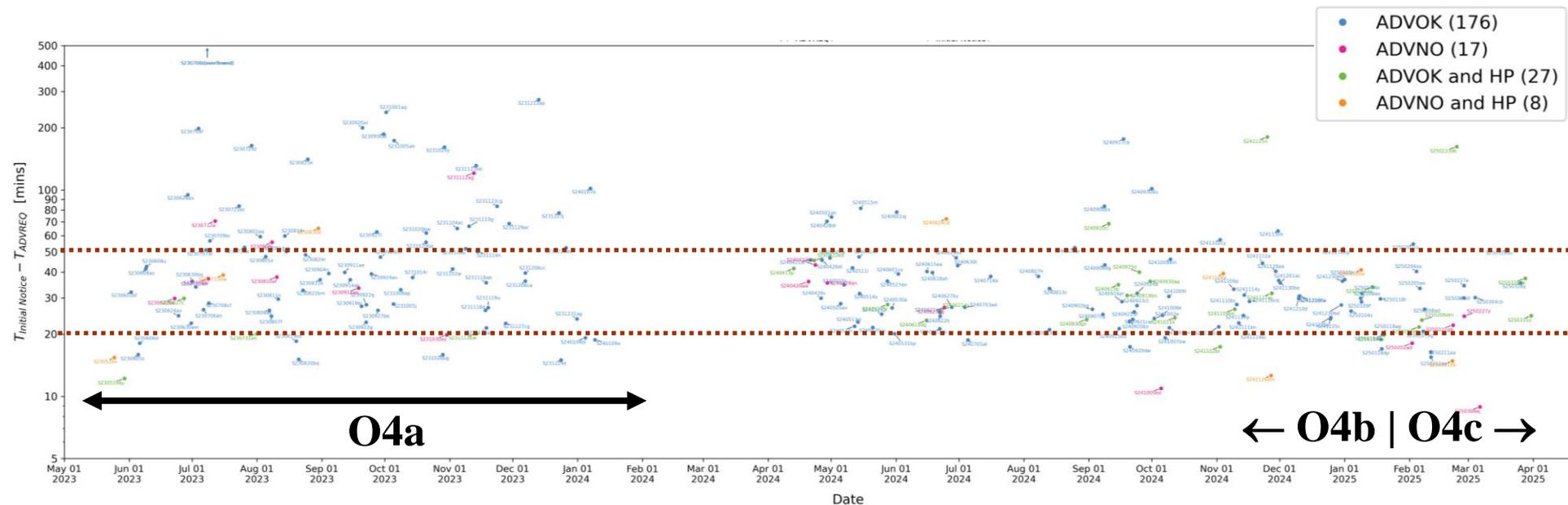
© Takahiro Sawada

- DAQ
- GW strain channel reconstruction
- Data transfer
- Online pipelines processing
- Candidate vetting by **RRT** – including the initial circular writing



The RRT: vetting low-latency alerts

- Evolution of the **time taken to vet the candidate**
 - **From** when the RRT has been triggered automatically, **to** when the RRT decision about the event is sent
- Evolution of the (global) **RRT latency** over O4
 - From the **automated alert** to the **human decision**
→ (**ADV**)OK or retract (**ADVNO**)
 - **HP = High Profile** (events potentially highly interesting: **BNS candidates**, etc.)



Outlook

- **O4 is significantly better than O3**
 - Number of public alerts
 - Integrated $V \times T$

→ A **major LVK success** overall

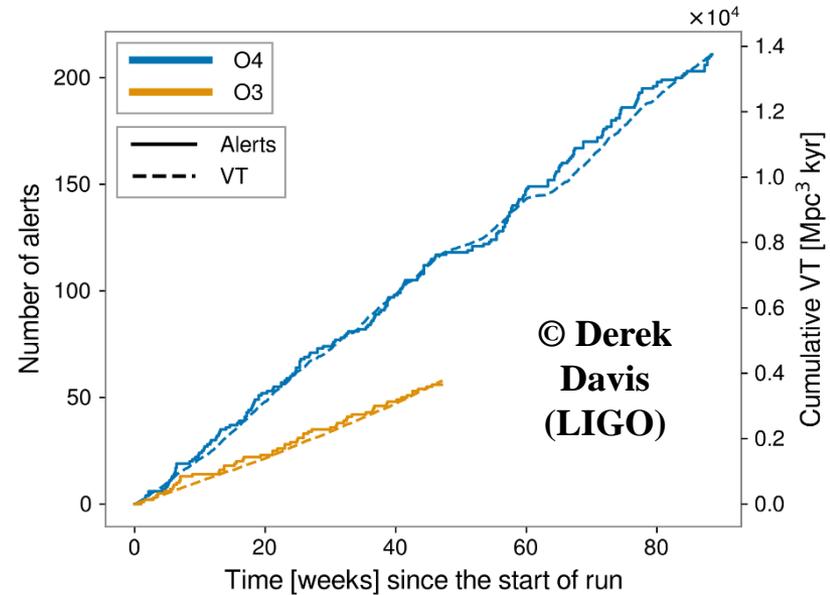
- The result of the **dedication** and **effort** of all the **scientists** involved in the **global network of ground-based interferometric detectors**

→ Still missing a “big” EM-bright event though...

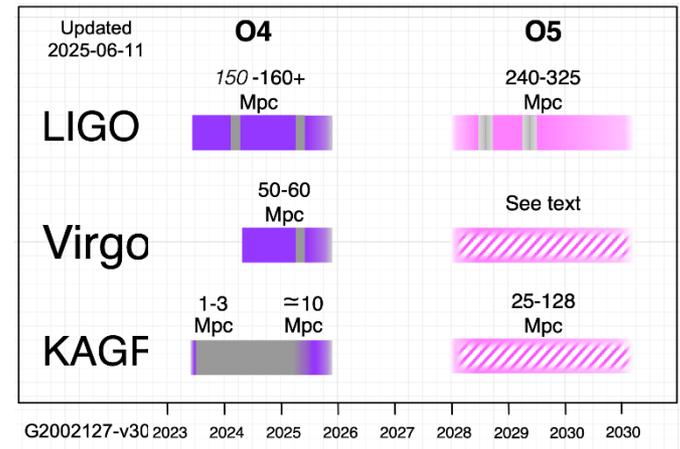
- **10 years after GW150914**, the **LVK**
 - continues **making discoveries**
 - shows the **power of the network and of collaborating work**

→ **We are looking to continue this forward, after O4 and for the years to come**

- **Stay tuned to the public LVK Observing plans webpage for updates**



Updated 2025-07-07



Acknowledgements

This material is based upon work supported by NSF's LIGO Laboratory which is a major facility fully funded by the National Science Foundation. The authors also gratefully acknowledge the support of the Science and Technology Facilities Council (STFC) of the United Kingdom, the Max-Planck-Society (MPS), and the State of Niedersachsen/Germany for support of the construction of Advanced LIGO and construction and operation of the GEO600 detector. Additional support for Advanced LIGO was provided by the Australian Research Council. The authors gratefully acknowledge the Italian Istituto Nazionale di Fisica Nucleare (INFN), the French Centre National de la Recherche Scientifique (CNRS) and the Netherlands Organization for Scientific Research (NWO), for the construction and operation of the Virgo detector and the creation and support of the EGO consortium. The authors also gratefully acknowledge research support from these agencies as well as by the Council of Scientific and Industrial Research of India, the Department of Science and Technology, India, the Science & Engineering Research Board (SERB), India, the Ministry of Human Resource Development, India, the Spanish Agencia Estatal de Investigación (AEI), the Spanish Ministerio de Ciencia e Innovación and Ministerio de Universidades, the Conselleria de Fons Europeus, Universitat i Cultura and the Direcció General de Política Universitaria i Recerca del Govern de les Illes Balears, the Conselleria d'Innovació, Universitats, Ciència i Societat Digital de la Generalitat Valenciana and the CERCA Programme Generalitat de Catalunya, Spain, the National Science Centre of Poland and the European Union – European Regional Development Fund; Foundation for Polish Science (FNP), the Swiss National Science Foundation (SNSF), the Russian Foundation for Basic Research, the Russian Science Foundation, the European Commission, the European Social Funds (ESF), the European Regional Development Funds (ERDF), the Royal Society, the Scottish Funding Council, the Scottish Universities Physics Alliance, the Hungarian Scientific Research Fund (OTKA), the French Lyon Institute of Origins (LIO), the Belgian Fonds de la Recherche Scientifique (FRS-FNRS), Actions de Recherche Concertées (ARC) and Fonds Wetenschappelijk Onderzoek – Vlaanderen (FWO), Belgium, the Paris Île-de-France Region, the National Research, Development and Innovation Office Hungary (NKFIH), the National Research Foundation of Korea, the Natural Science and Engineering Research Council Canada, Canadian Foundation for Innovation (CFI), the Brazilian Ministry of Science, Technology, and Innovations, the International Center for Theoretical Physics South American Institute for Fundamental Research (ICTP-SAIFR), the Research Grants Council of Hong Kong, the National Natural Science Foundation of China (NSFC), the Leverhulme Trust, the Research Corporation, the Ministry of Science and Technology (MOST), Taiwan, the United States Department of Energy, and the Kavli Foundation. The authors gratefully acknowledge the support of the NSF, STFC, INFN and CNRS for provision of computational resources.

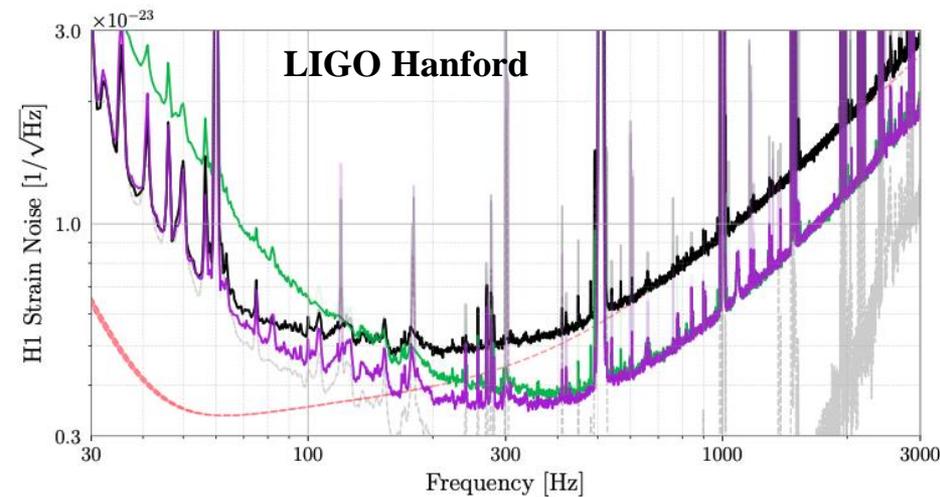
This work was supported by MEXT, JSPS Leading-edge Research Infrastructure Program, JSPS Grant-in-Aid for Specially Promoted Research 26000005, JSPS Grant-in-Aid for Scientific Research on Innovative Areas 2905: JP17H06358, JP17H06361 and JP17H06364, JSPS Core-to-Core Program A. Advanced Research Networks, JSPS Grant-in-Aid for Scientific Research (S) 17H06133 and 20H05639, JSPS Grant-in-Aid for Transformative Research Areas (A) 20A203: JP20H05854, the joint research program of the Institute for Cosmic Ray Research, University of Tokyo, National Research Foundation (NRF) and Computing Infrastructure Project of KISTI-GSDC in Korea, Academia Sinica (AS), AS Grid Center (ASGC) and the Ministry of Science and Technology (MoST) in Taiwan under grants including AS-CDA-105-M06, Advanced Technology Center (ATC) of NAOJ, Mechanical Engineering Center of KEK.

LVK public data releases

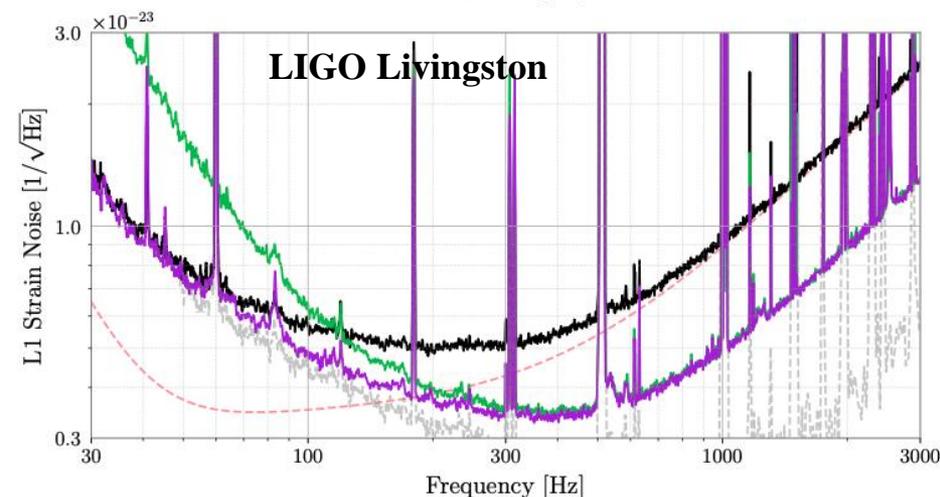
Data set	Data collection date range	Months of data	h(t) release date
O4a	2023-05-24 to 2024-01-16 16:00:00 UTC	7.7	2025-08-26
O4b	2024-04-10 to 2025-01-28 17:00:00 UTC	9.5	2026-05-26
O4c	2025-01-28 17:00:00 UTC to 2025-11-18 17:00:00 UTC	10	2026-12-16

LIGO detectors status update

- Major changes from O3
 - Frequency independent squeezing: better than 4dB @ H1 / close to 6dB @ L1



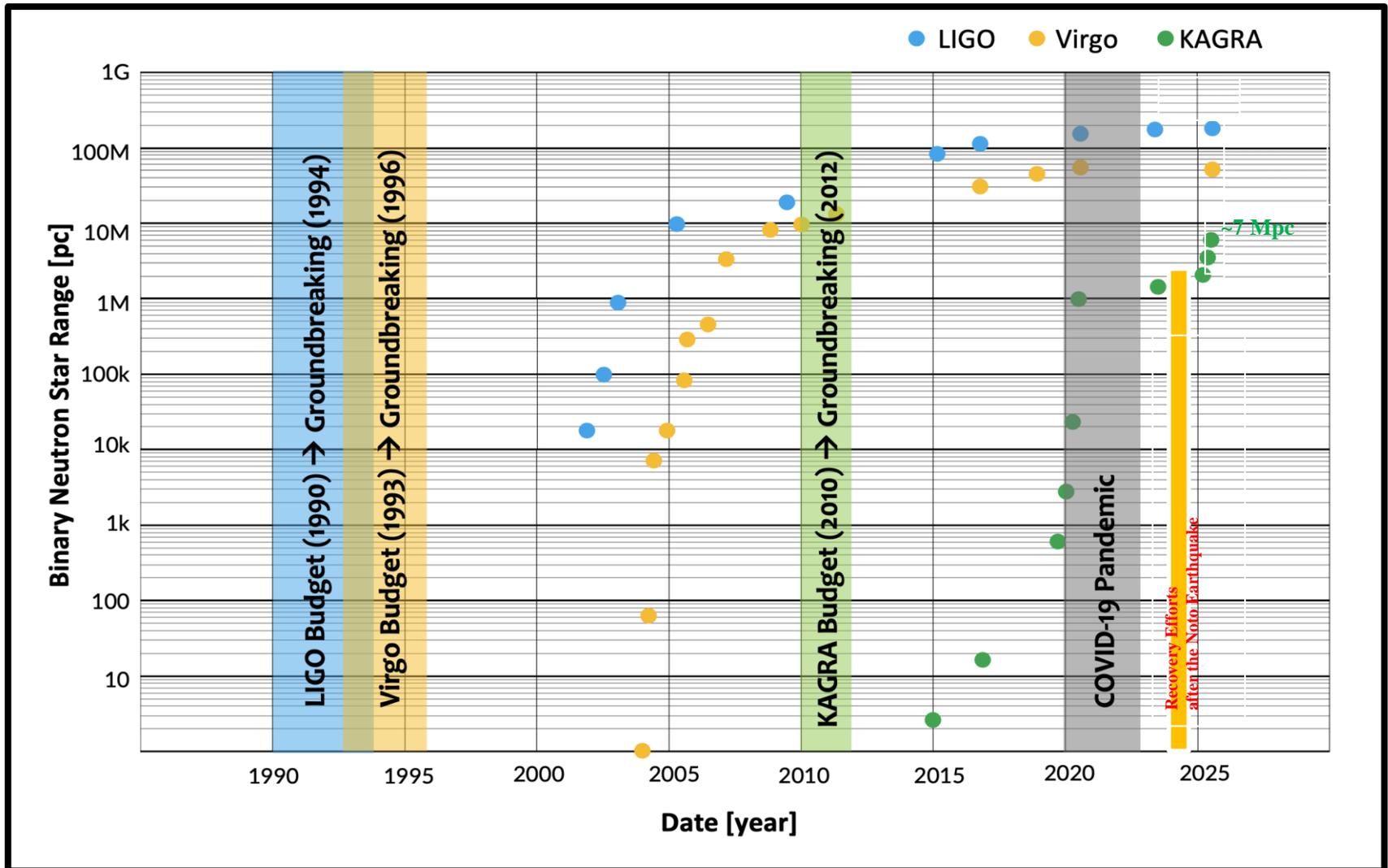
- Reference (No Squeezing)
- Frequency-Independent Squeezing
- Frequency-Dependent Squeezing
- Quantum Noise Model
- Classical Noise Estimate



- Reference:
[Phys. Rev. X **13**, 041021 \(2023\)](#)

KAGRA detector status update

- Performance evolution over time – compared with LIGO and Virgo

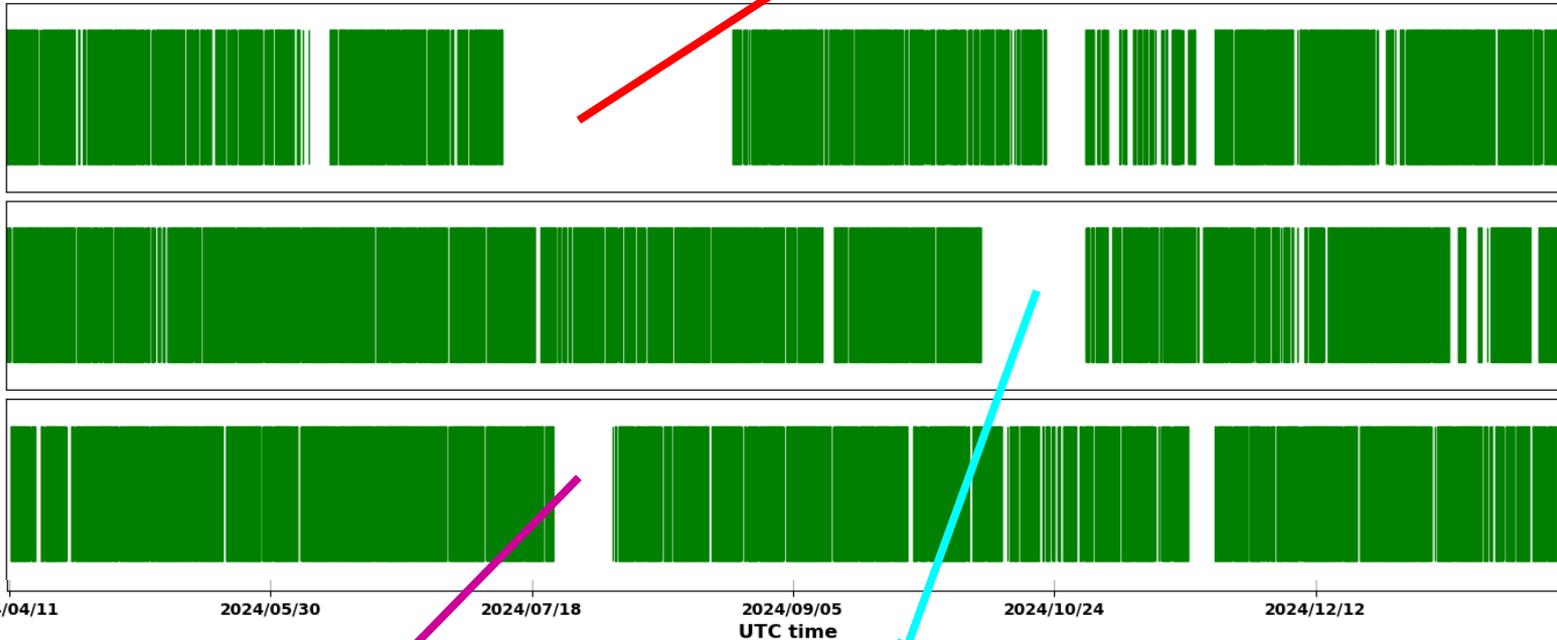


The O4b run



Damaged output Faraday isolator

- Main downtimes



LIGO Hanford
Duty cycle = 48.64%
[142d:13h:9m:49s]

LIGO Livingston
Duty cycle = 68.13%
[199d:16h:20m:26s]

Virgo
Duty cycle = 70.84%
[207d:14h:49m:38s]

Opportunistic detector work while H1 down



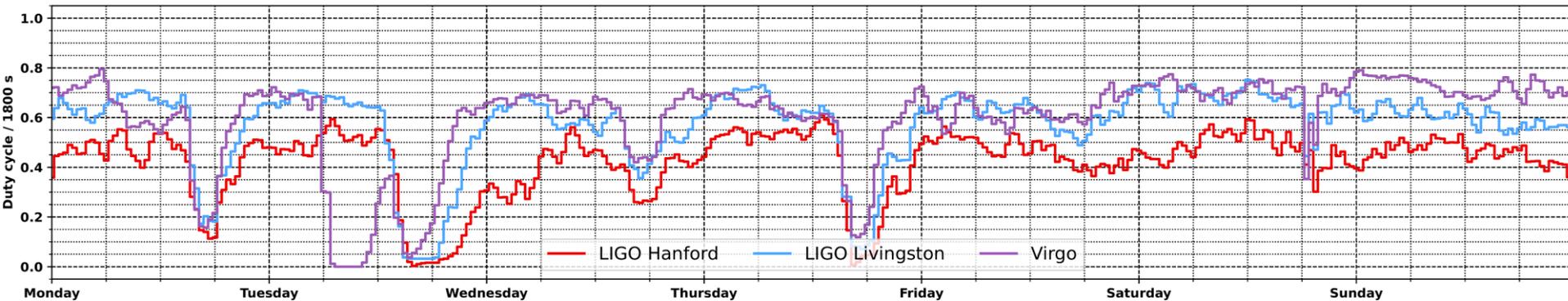
Kink of almost broken wire; the viton casing was removed from the wire, but placed at the side to show that the kink developed where it was just exiting.

Fast shutter issue [Dark fringe photodiode protection system]

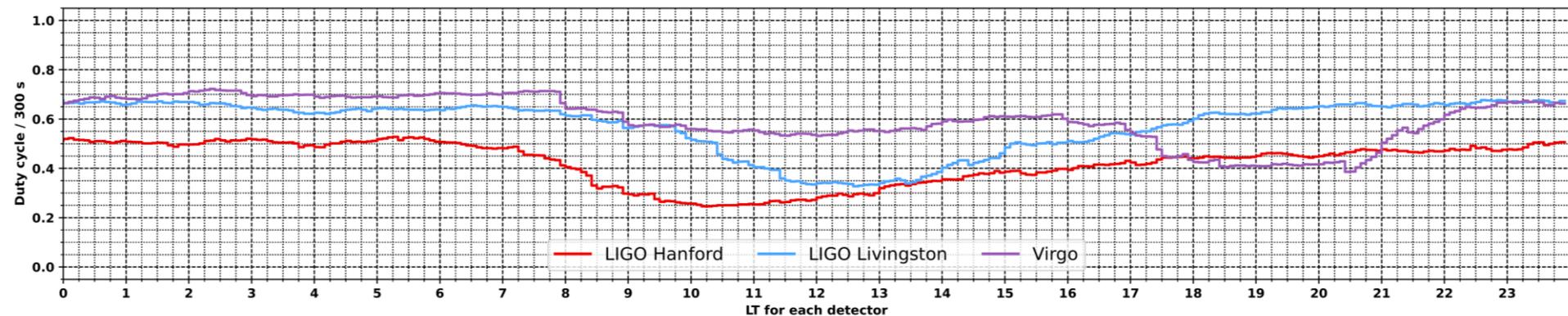
O4{b+c} LVK network duty cycle

- Weekly, UTC timezone

Comparing H1, L1 and V1, average duty cycles
1396796418 [2024-04-10 15:00:00+00:00 UTC] -> 1434459620 [2025-06-20 13:00:02+00:00 UTC]



- Daily, local timezones for each detector



LIGO Livingston O4 noise budget

- **Red trace:** sensitivity curve based on all known noises
→ Some **mystery noise** remains
- **Light green trace:** all technical noises
 - **Dark green trace:** all known technical noises
- Thermal coating noise to be improved (new O5 test masses) with the quantum noise
→ Otherwise not much gain at mid. frequencies

