The LIGO-Virgo-KAGRA Observing Run 4:

May 2023 – June 2025

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European Gravitational Observatory

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

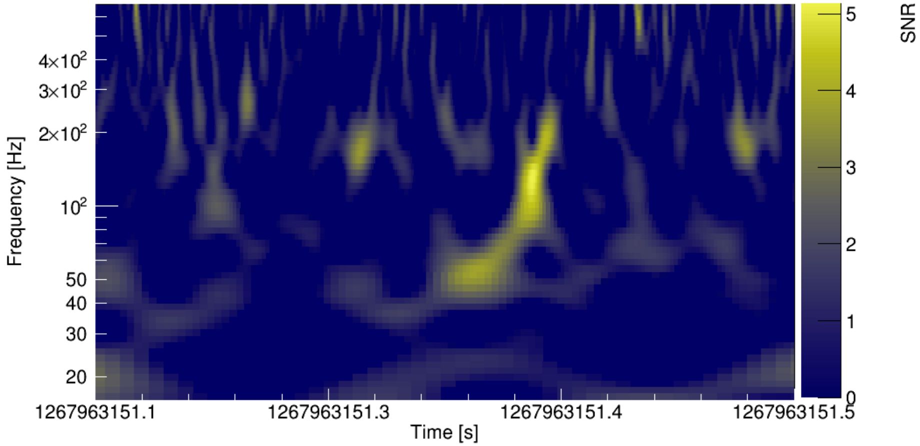
ICHEP 2024, Prague – July 18th, 2024

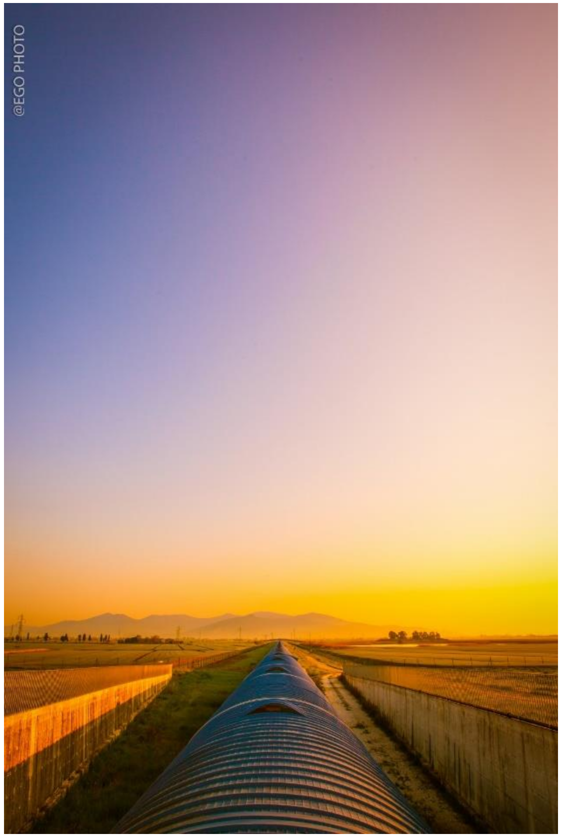
VIR-0080B-24 G2400232

Outline

- Detecting gravitational waves with the LIGO-Virgo-KAGRA network of giant, ground-based, suspended interferometric detectors

- The path to the O4 run
  - 90 detections between 2015 and 2020 during the O1-O3 runs





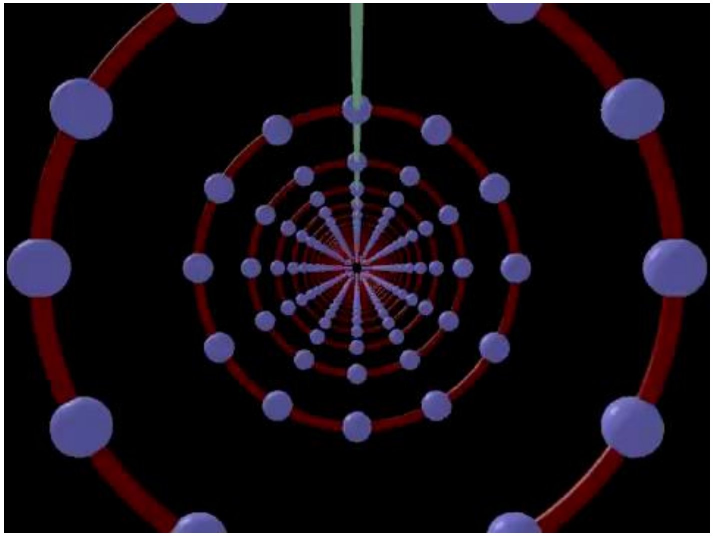
- The O4a run
  - GW230529

- The ongoing O4b run

- Outlook

Gravitational waves (GW) in a nutshell

- One of the first predictions of general relativity (GR, 1916)
  - Accelerated masses induce perturbations of the fabric of the spacetime, propagating at the speed of light – and of gravity
- Traceless and transverse (tensor) waves
  - 2 polarizations in GR: « + » and « × »
  - Quadrupolar radiation
    $\rightarrow$ Deviation from axisymmetry to emit GW

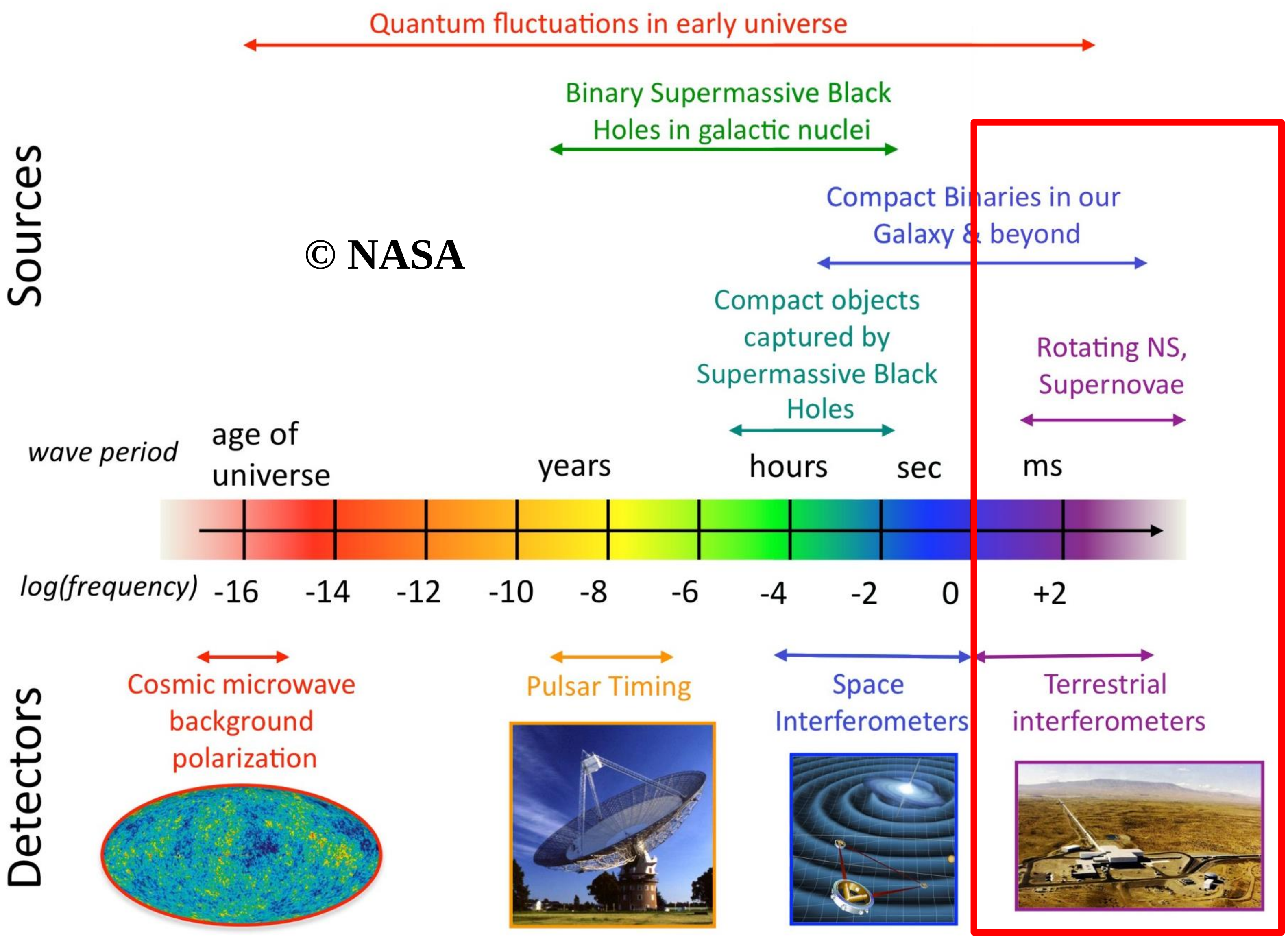


- GW strain h
  - Dimensionless, scales like 1/distance
  - Differential length change: $h = \Delta L / L$
- Detectors directly sensitive to h
  $\rightarrow$ Small sensitivity gains can lead to large improvements in event rate
- Rough classification
  - Signal duration
  - Frequency range and evolution

  } Detectable by the instruments

  - Known/unknown waveform
  - Any/no counterpart (electromagnetic spectrum, neutrinos, etc.) expected

Gravitational wave spectrum



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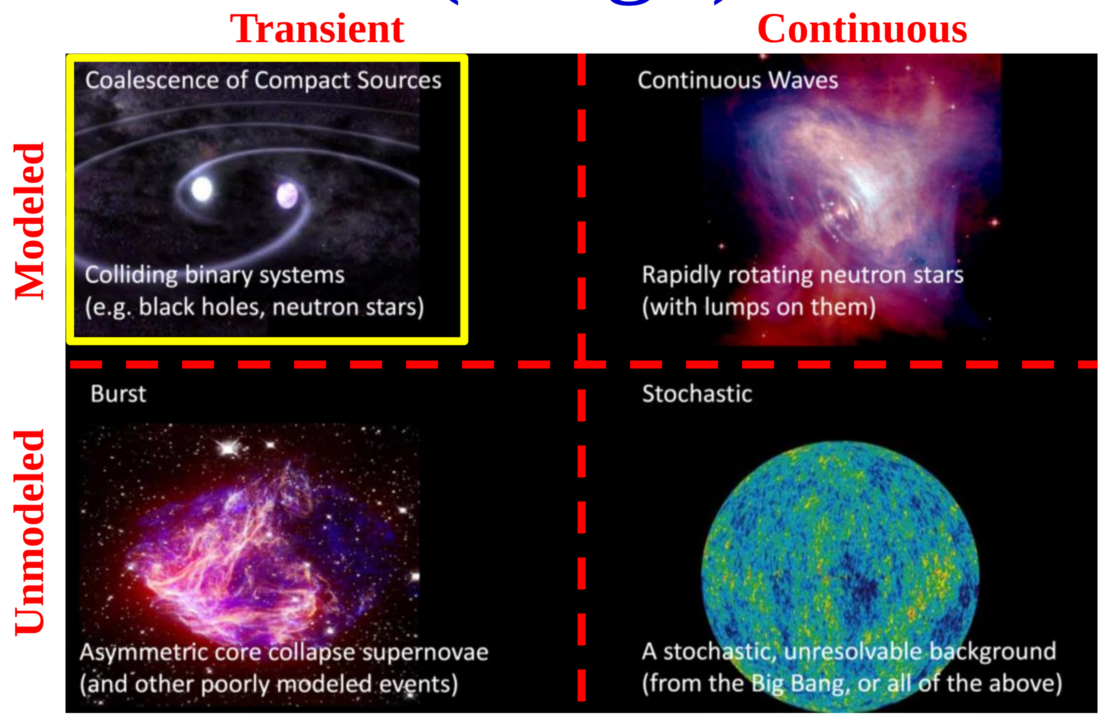
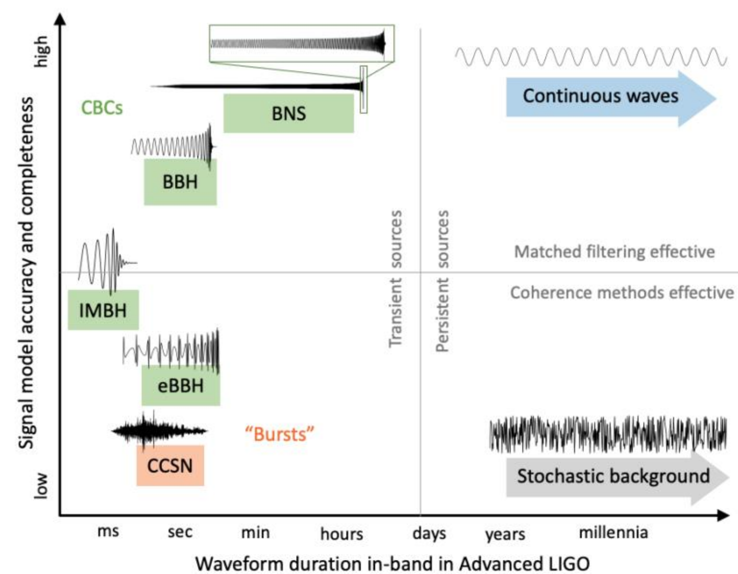
LIGO, Virgo, KAGRA

GW sources (rough) classification



→ Drives the choice of the data analysis methods

- Matched filtering when waveform known
- Coherence methods otherwise



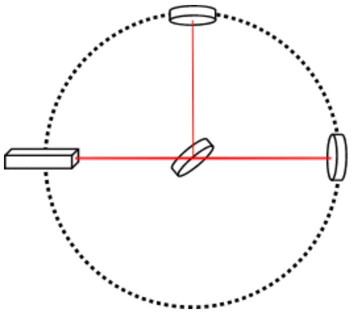
Detectors

- Gravitation very weak ↔ Spacetime extremely rigid

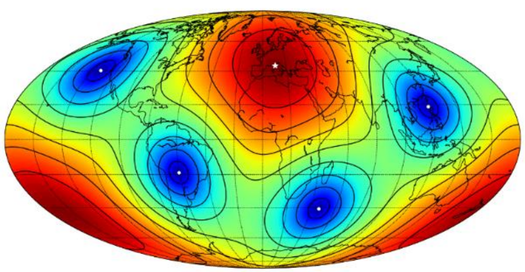
→ Only GW sources from the cosmos can be powerful enough to be detected
- Sources very far away: GW signals received on Earth are extremely tiny
  - $h \approx 10^{-22} \Leftrightarrow \Delta L \approx 10^{-19}$ m

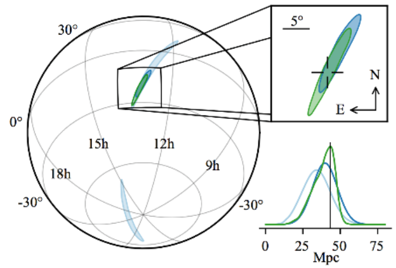
→ Extremely sensitive detectors required

- Giant ground-based interferometric detectors
  - A passing GW distorts spacetime locally, thus changes the interference pattern → Signal at the interferometer output port

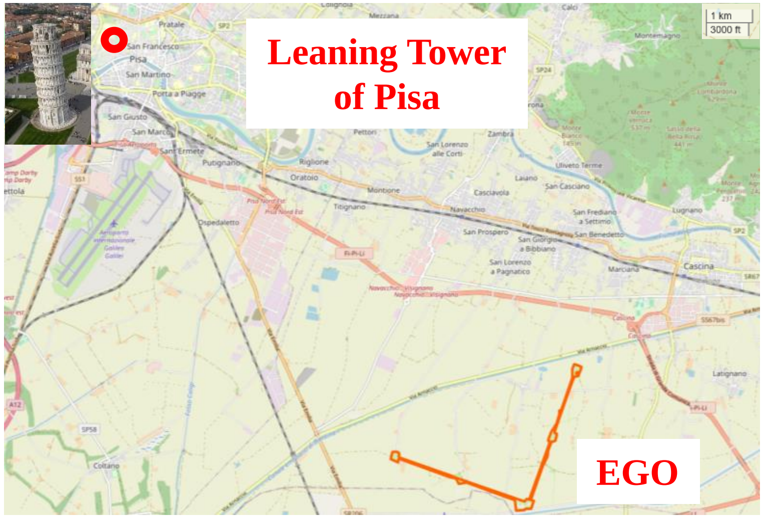


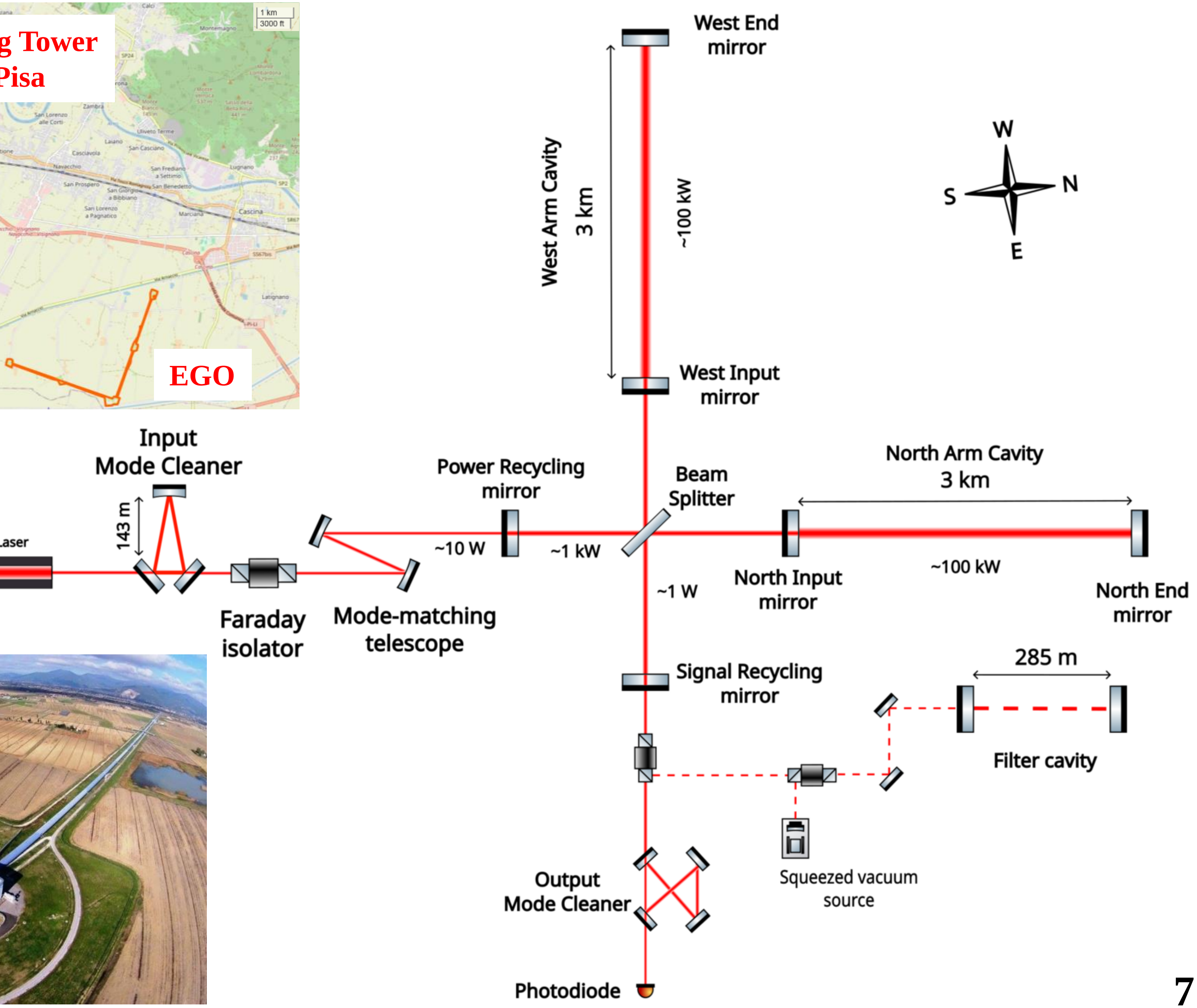
- Detectors non directional: see more or less the whole sky
  → Network of instruments analyzing data jointly are much more powerful
  → Sky localization of the source





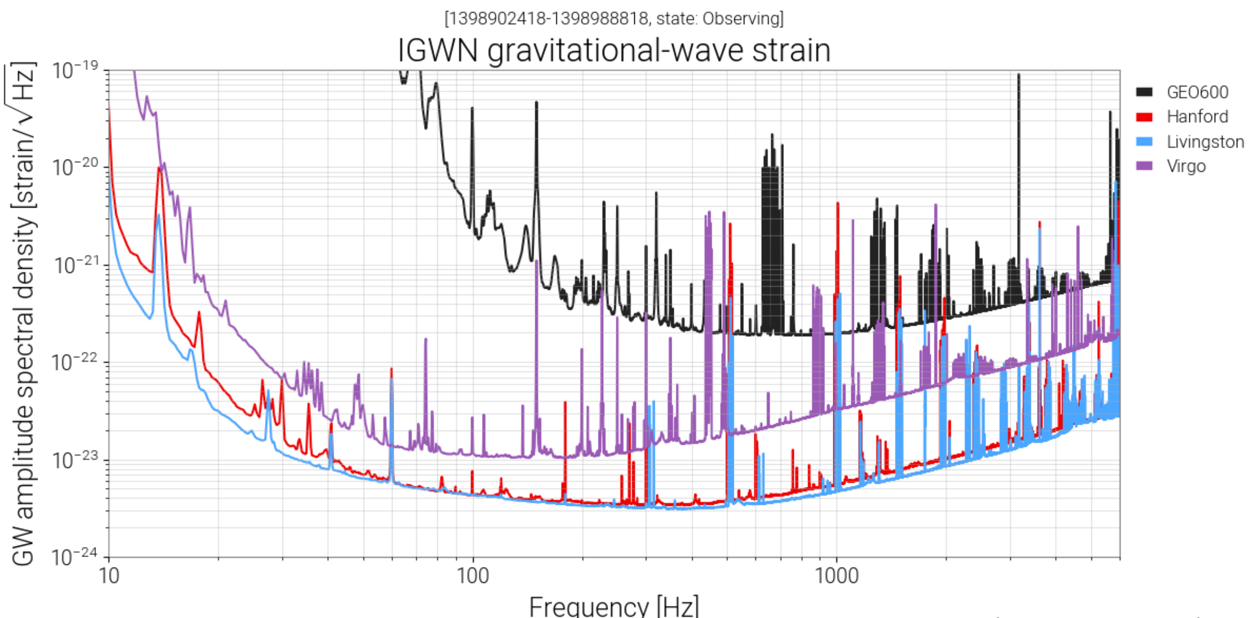
Example: the Advanced Virgo Plus detector





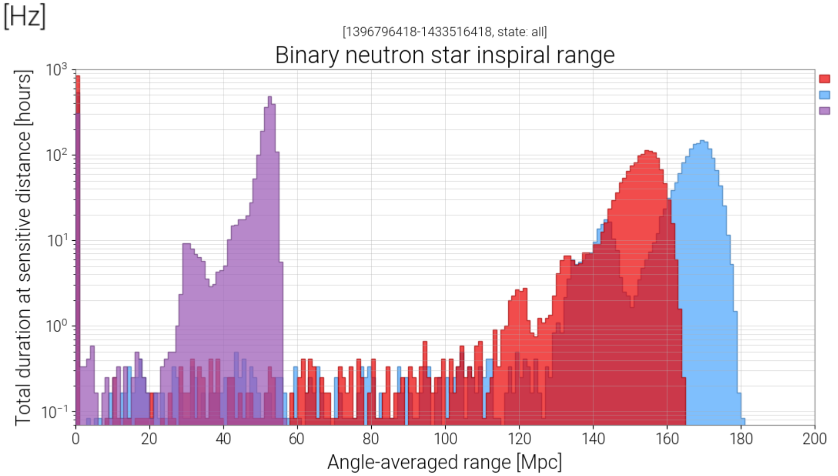
Detector sensitivity and BNS range

- Sensitivity: noise amplitude spectrum density [Unit: 1/√Hz] vs. frequency
  - Complex curve full of features, summing up contributions from many noise sources



→ Useful (simplifying) figure of merit: the BNS range

- Averaged (sky and binary inclination) distance [Mpc] up to which a "typical" merging Binary Neutron Star system can be detected (signal-to-noise ratio of 8)

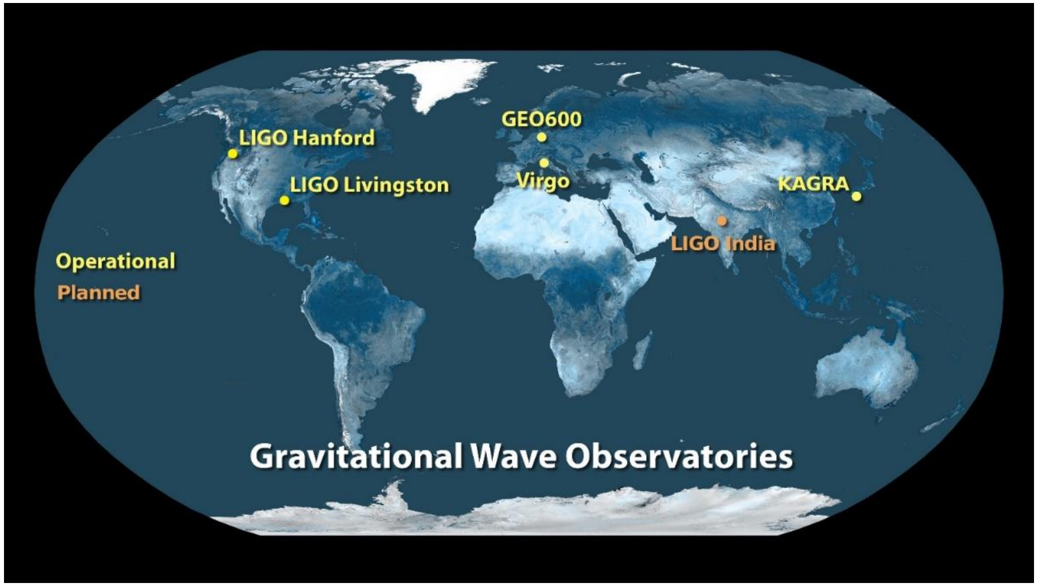


LVK: LIGO-Virgo-KAGRA collaboration

- LIGO
  - LIGO Labs: funded by NSF, operated by Caltech and MIT
    → Conceived and built the project
  - Advanced LIGO: USA + Germany + UK + Australia
    → Significant commitments and contributions
  - LIGO Scientific Collaboration (⊃ GEO Collaboration)
    → 1,600+ scientists
    More info: https://my.ligo.org/census.php
- Virgo Collaboration
  - ~900 members from 150+ institutions
    17 countries – mainly European
    More info: https://www.virgo-gw.eu/about/scientific-collaboration
  - European Gravitational Observatory hosts the Virgo detector
    → Funded by France, Italy and The Netherlands
- KAGRA Collaboration
  - 400+ members from ~130 institutions
    17 countries/regions
    More information: https://gwcenter.icrr.u-tokyo.ac.jp/en

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 [WA, USA]
  LIGO Livingston [LA, USA]
  - Advanced detectors online since September 2015
  - LIGO India: planned for end of decade
- Advanced Virgo : since August 2017
- KAGRA [Japan]
  - Underground and cryogenic
- Gravitational Wave Open Science Center (GWOSC): https://www.gw-openscience.org

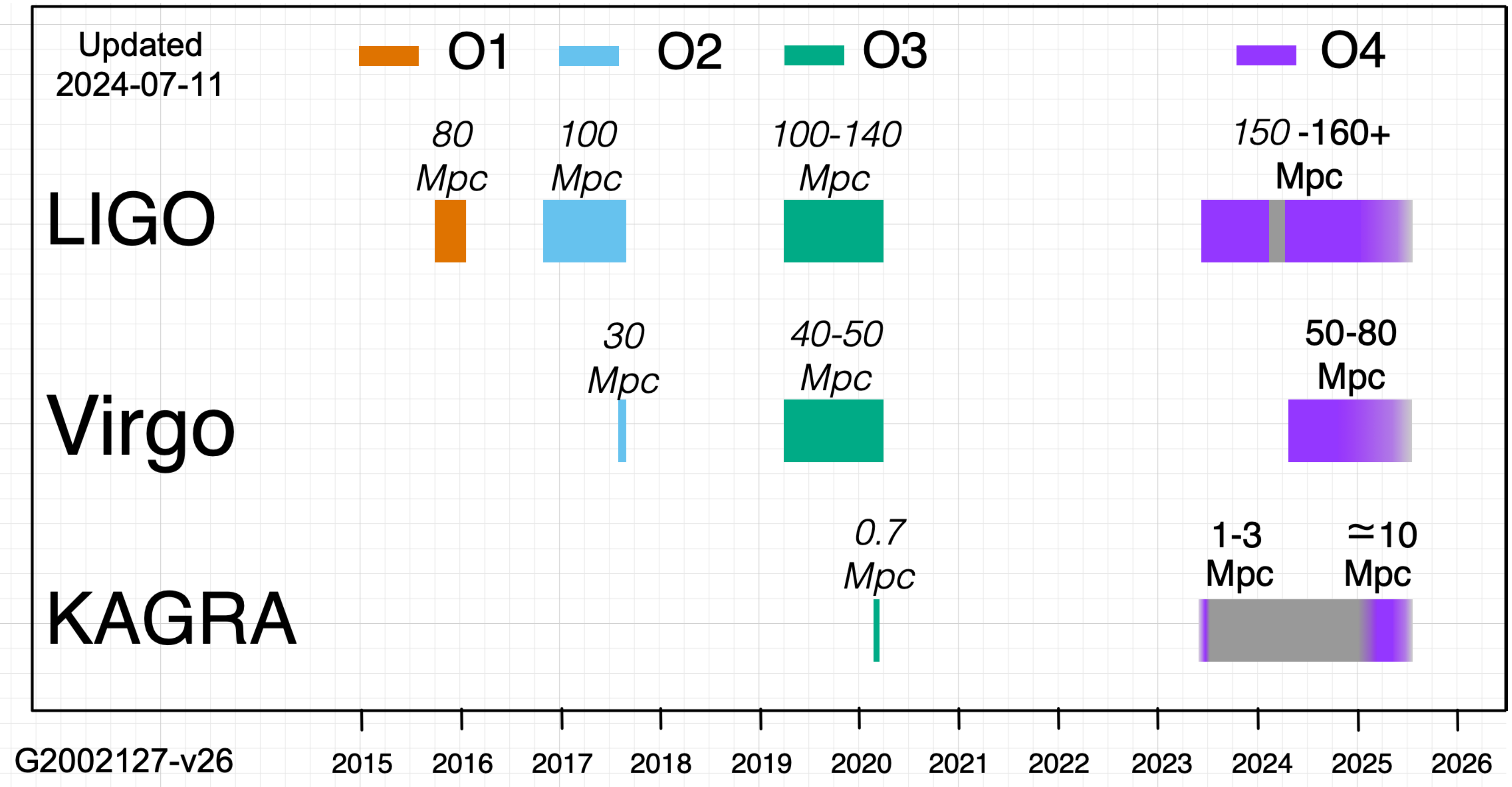
Of data taking periods and upgrades

- LVK is a meta-collaboration aiming at optimizing the global yield of the network
  - Joint strategy

    → Data taking periods:

    Observing Runs (O*n*) Past: *n*=*1, 2, 3* Current: *n*=*4* Future: *n*=5, *etc.*

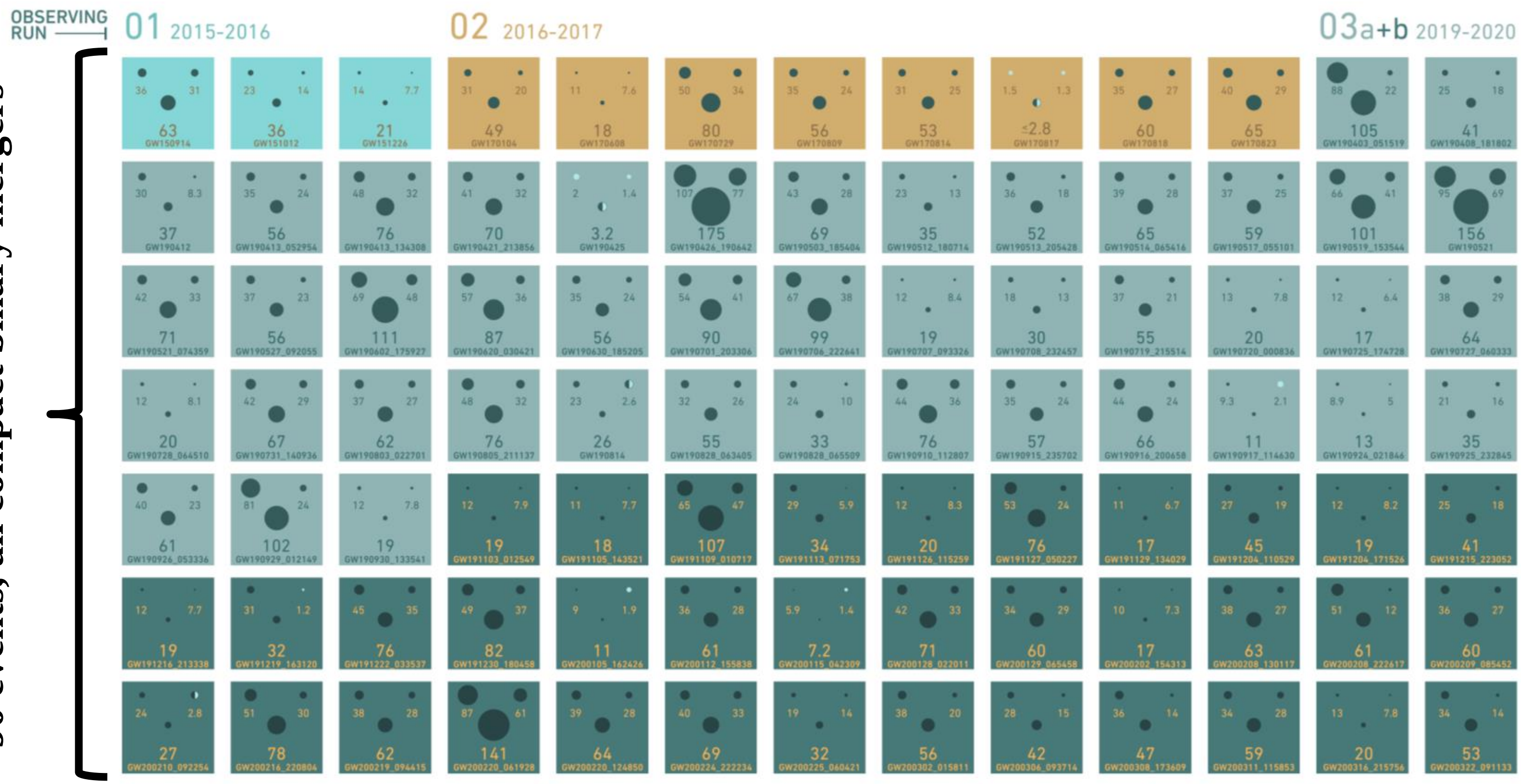
    → Upgrades: lead to (much) more detections during the next run

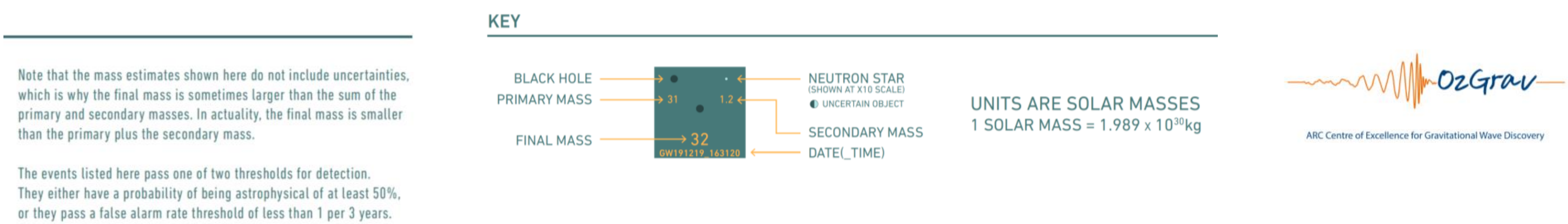


LVK catalog of GW transient detections

- Latest issue: GWTC-3, covering O1, O2 and O3 – Phys. Rev. X 13, 041039 (2023)

90 events, all compact binary mergers

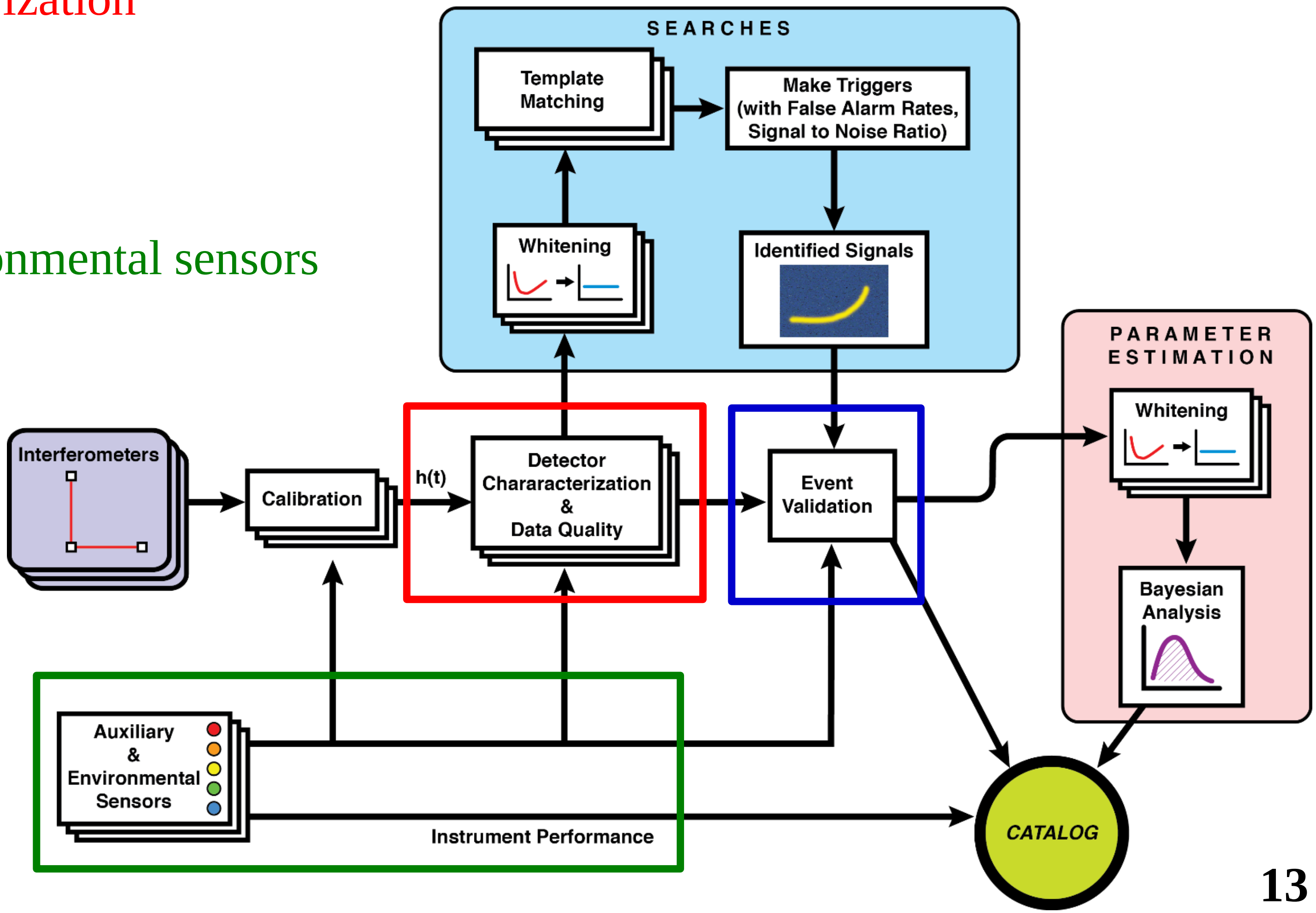




LVK dataflow

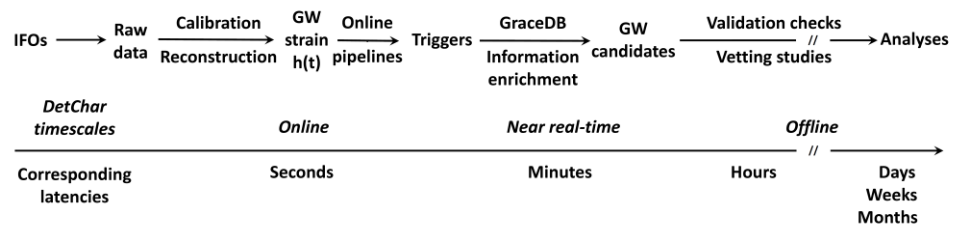
- From: **A guide to LIGO-Virgo detector noise and extraction of transient gravitational-wave signals**
  - B. P. Abbott *et al.*, 2020 *Class. Quantum Grav.* **37** 055002

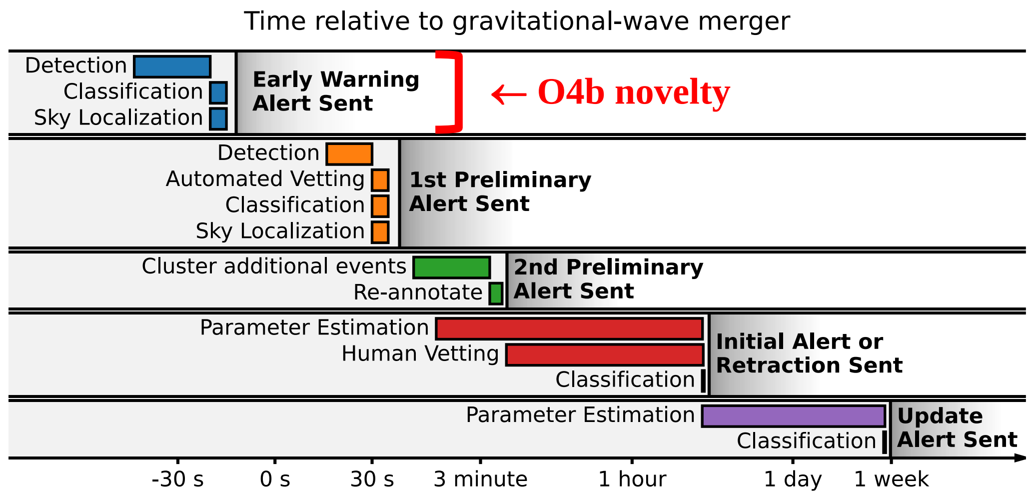
- Detector Characterization & Data Quality
- Event validation
- Auxiliary & environmental sensors
- Different latencies
  - Online
  - Offline
  - On-demand
- Many monitoring levels
  - Detector
  - Network
  - Analyses



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 [O4a] [O4b]





From O3 to O4

- Ambitious program of upgrades for all detectors in the network
  - Slowed down (at best) by the covid-19 pandemic
    → O3b stopped a month earlier and detectors shut down a few days later
    → O4 should have been over before the date it actually started! ☹

- Manifold goals
  - Increase binary merger detection rate from ~1/5 days to ~1/2 days
  - Improve public alerts: latency + localization + classification
  - Improve SNR of detected GWs

- LIGO
  A+ project: improvements in various frequency bands to address dominant (limiting) noises

- Virgo
  First stage of a 2-step upgrade: Advanced Virgo +
  - O3-O4 break: quantum noise + technical noises
  - O4-O5: thermal noise

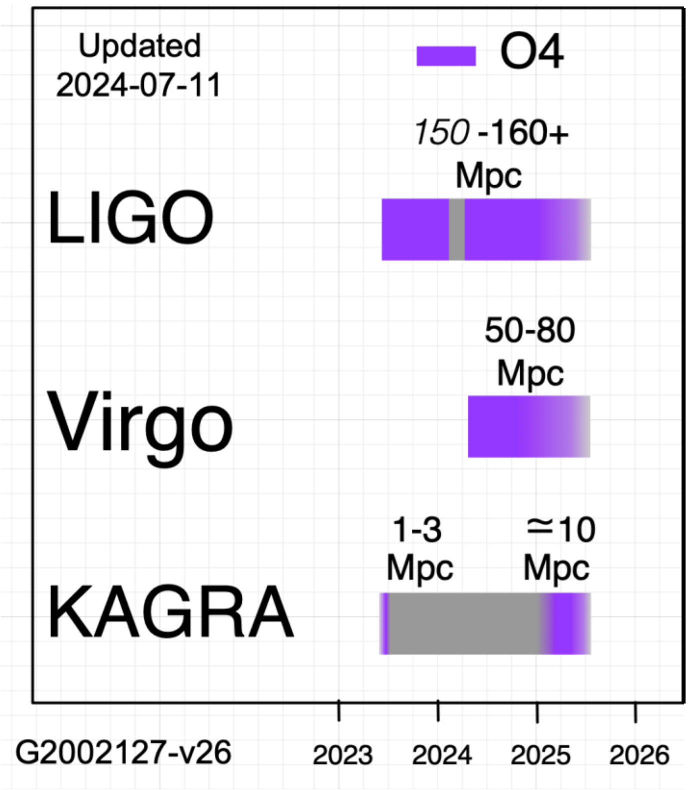
- KAGRA
  - 2-week run with GEO600 in April 2020: "O3GK"
  - Then about 1 year of repair and installations, followed by some commissioning to be ready for O4

The O4a run

- May 2023 → January 2024
  - Followed by a commissioning break of a few weeks, before starting O4b

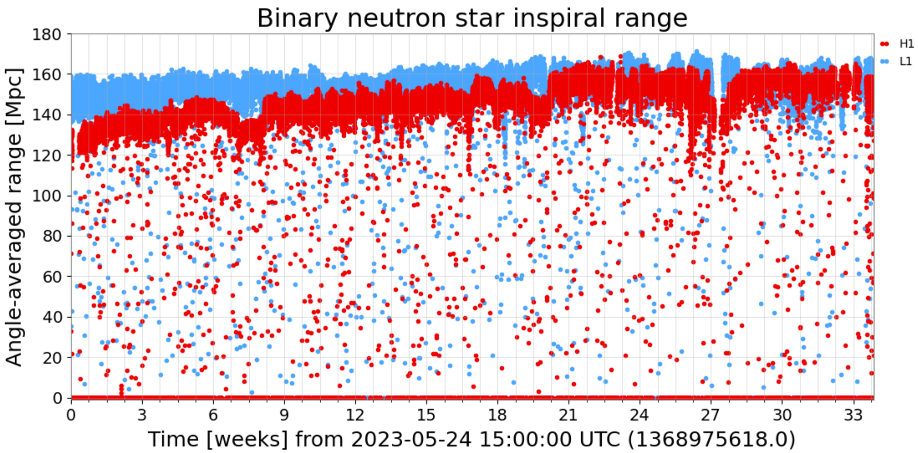
- Data taking by the two LIGO detectors only
  - As planned, KAGRA has taken data with a limited sensitivity for a few weeks, before moving back to commissioning with the goal of participating to the final part of O4b with a improved sensitivity
  - Virgo has decided to keep on commissioning, in order to work further on improving the sensitivity and the stability of the detector
    - Recycling cavities are only marginally stable: that makes the interferometer control difficult
      Plus some technical noises impacting the sensitivity

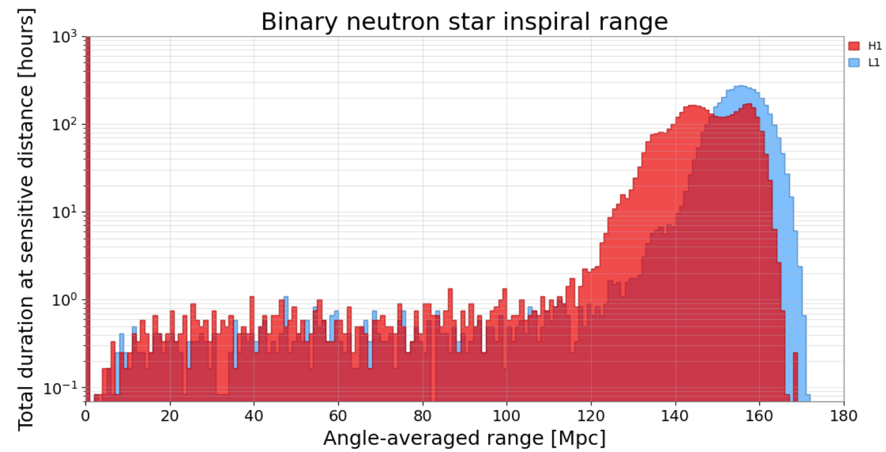
  → After a few months, it was decided that Virgo would join O4b directly



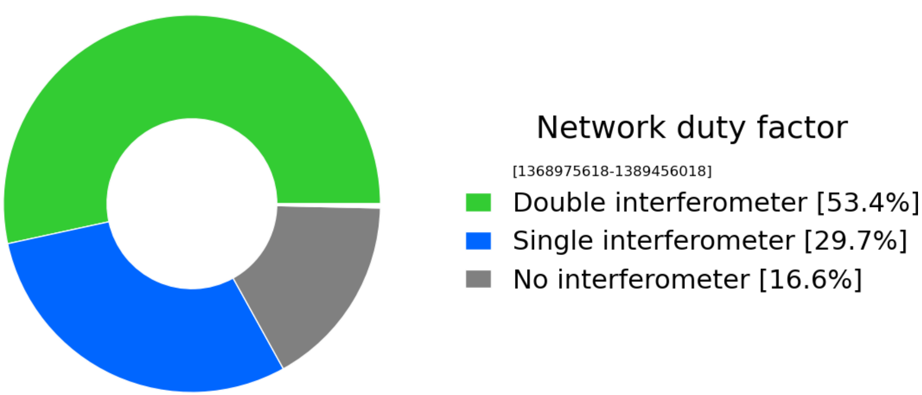
The O4a run

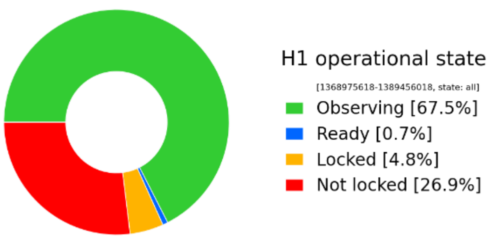
- BNS range

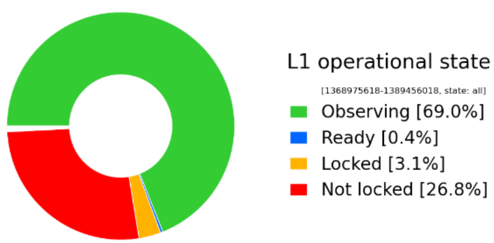




- Duty cycles







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

The O4a run

- Public alerts
  - https://gracedb.ligo.org/superevents/public/O4a

Larger rate than in O3

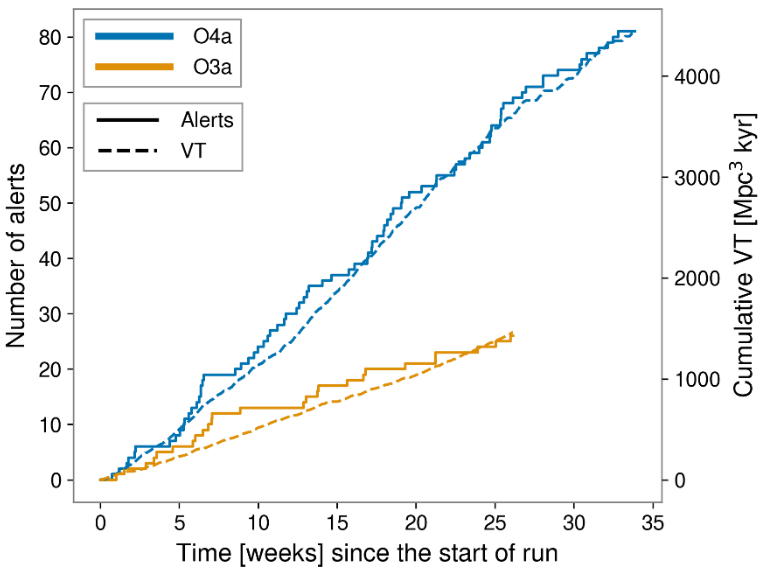
Lower rate than in O3

O4a Significant Detection Candidates: **81** (92 Total - 11 Retracted)

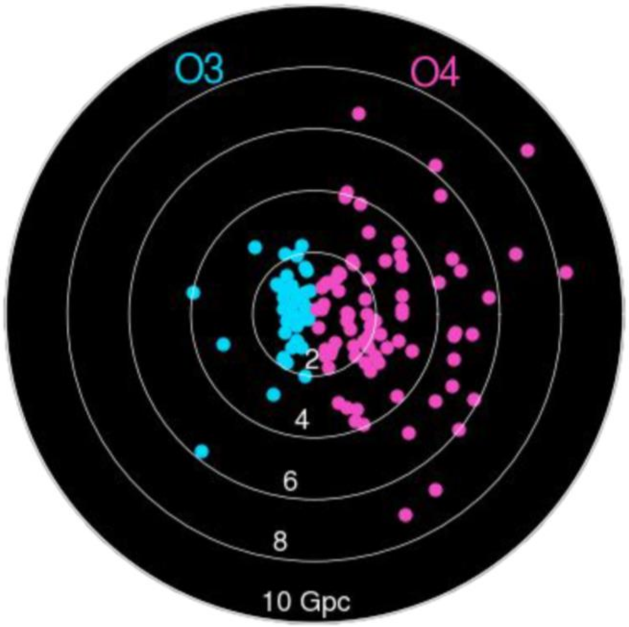
O4a Low Significance Detection Candidates: **1610** (Total)

O4b novelty

- Number of significant alerts scales well with integrated V×T

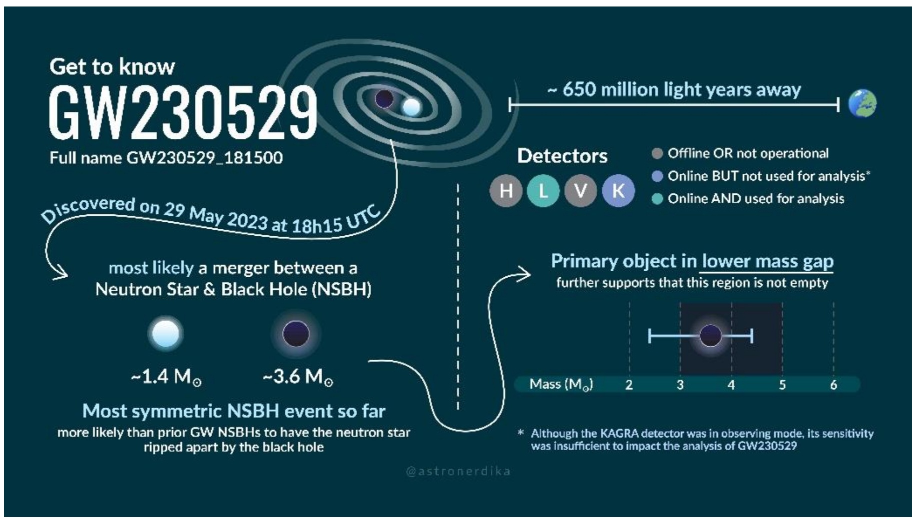


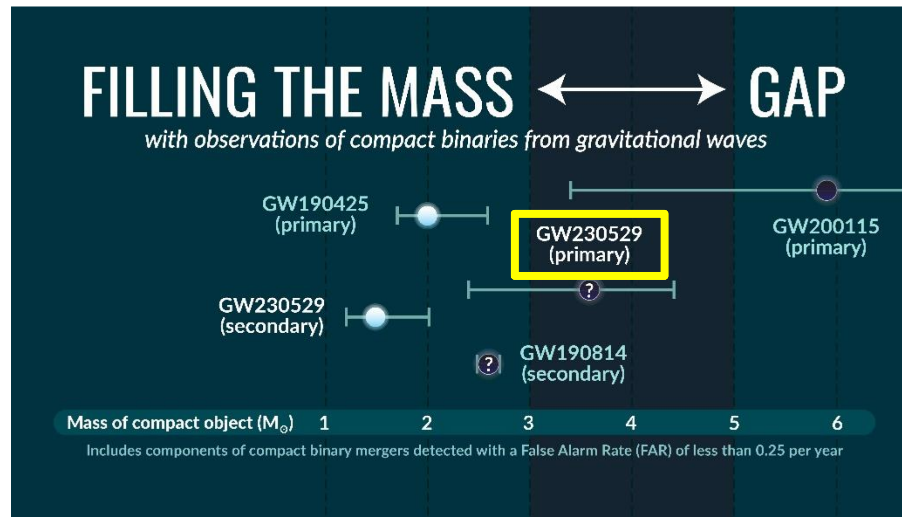
- More distant sources are found



First O4a detection published: GW230529

- Single detector (LIGO Livingston) significant event
- A neutron star merging with a likely black hole
- Lower mass gap: dearth of 3-5 $M_\odot$ compact objects in the Milky Way
  → Separation between heaviest neutron stars and lightest black holes?





→ Best-yet evidence of compact objects existing in the lower mass gap

- Reference: arXiv – accepted for publication in ApJ Letters

- Data release: **https://gwosc.org/eventapi/html/O4_Discovery_Papers/GW230529_181500**

The O4b run

- April 2024 → June 2025
  - 3-month break after O4a, including a 3-week preparatory engineering run
  - O4b recently extended from February to June 2025
    - More time for the preparation of the O4-O5 upgrades

    → The longest data taking period in the Advanced detectors era: 14 months!
- Virgo joining O4b from day 1 and for the whole run
  - Sensitivity similar to the O3b one – BNS range ~ 55 Mpc
    - Impacted by some noise of unknown origin so far
  - Limitation due to the Virgo optical configuration

    → To be addressed between O4 and O5
  - Good stability overall: high duty cycle
- KAGRA status
  - 7.6-magnitude earthquake near the KAGRA site on January 1st
    - Most significant in the area in the past century

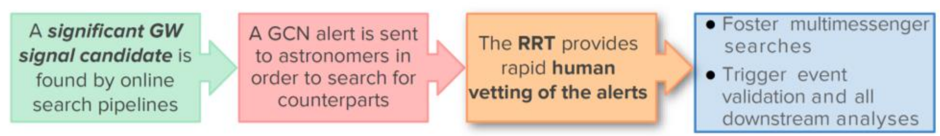
    → No serious infrastructure damage (tunnel, facility, vacuum, cryogenics)

    → About 10 mirror suspension systems needed repair
  - Work in progress and mostly completed: commissioning to restart soon

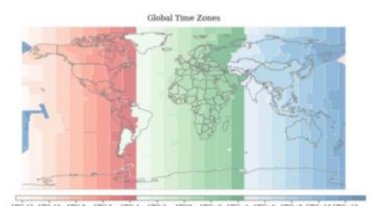
    → Goal remains to join the run before the end of O4b (BNS range ~ 10 Mpc)

The O4b run

- Virgo data usage in low latency
  - ☒ Not for triggering: sensitivity gap + computing resources
  - ☑ For sky localization: a third detector can significantly reduce the skymap size
    - → Virgo data vet in low latency exactly like LIGO ones
      - ▪ Corresponding framework works fine and is integrated with LIGO
    - → O4b overall strategy: maximize 3-detector uptime – 0 detector downtime ~10%
      - ▪ Requires continuous coordination within the LVK
        - ◆ In particular: align known, weekly recurring, downtimes



→ Joint LVK vetting of low-latency alerts since the beginning of O4: the Rapid Response Team (RRT)
- ▪ 24/7 shift coverage
- ▪ 3 regions covering 8 hours each
- ▪ 3-tiered system
  - ◆ Level 0: shifters
  - ◆ Level 1: experts
  - ◆ Level 2: full team

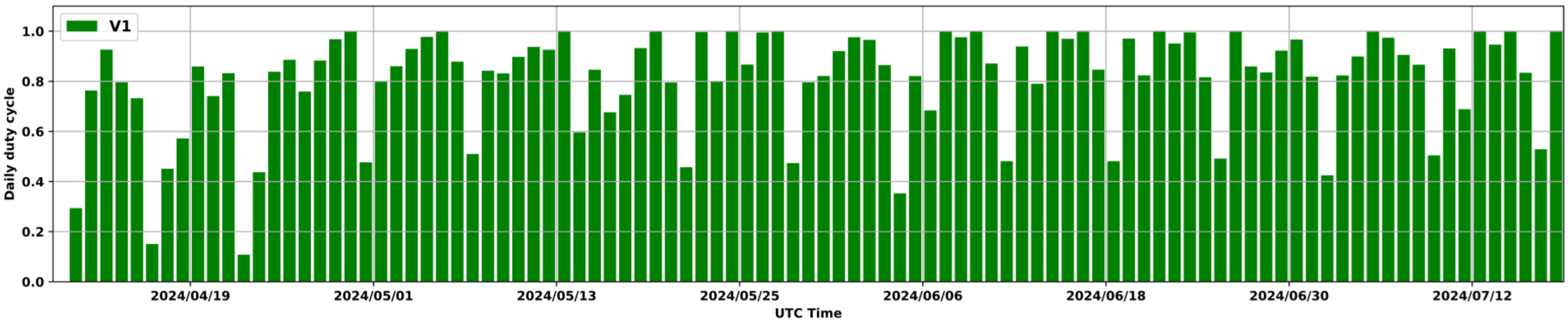


Asia-Pacific	Central- Europe	Americas
UTC 22:45-1- 07:00	UTC 6:45-15:00 CEST 8:45-17:00	UTC 14:45- 23:00

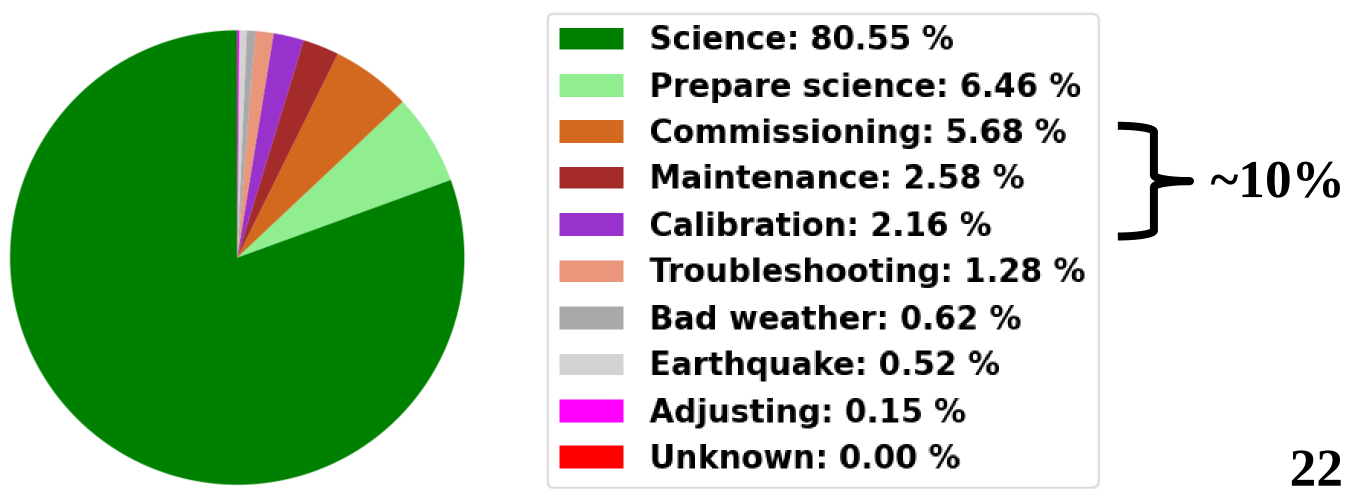
- Public monitoring plots: https://gwosc.org/detector_status/O4b

The O4b run

- Single detector duty cycle: the example of Virgo
- Daily duty cycle histogram
  - Lower on Tuesdays: maintenance in the morning + commissioning in the evening [LIGO maintenance]

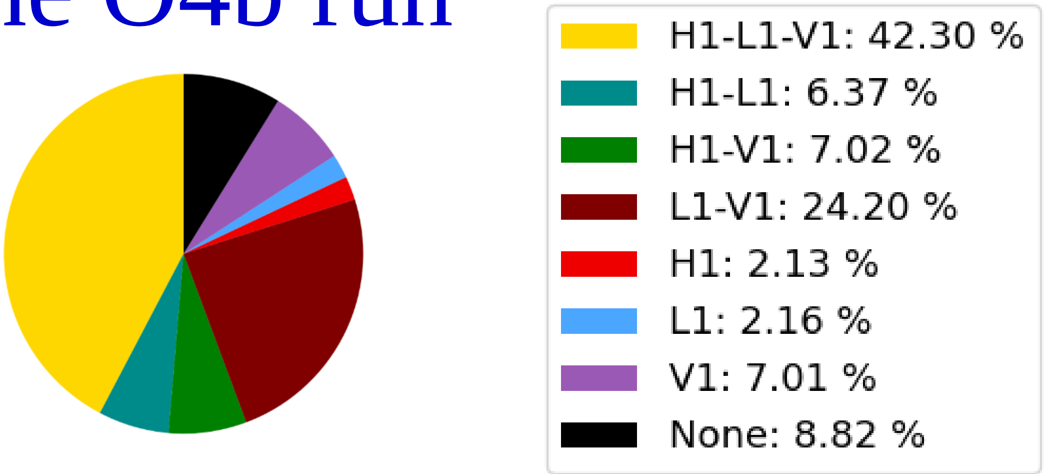


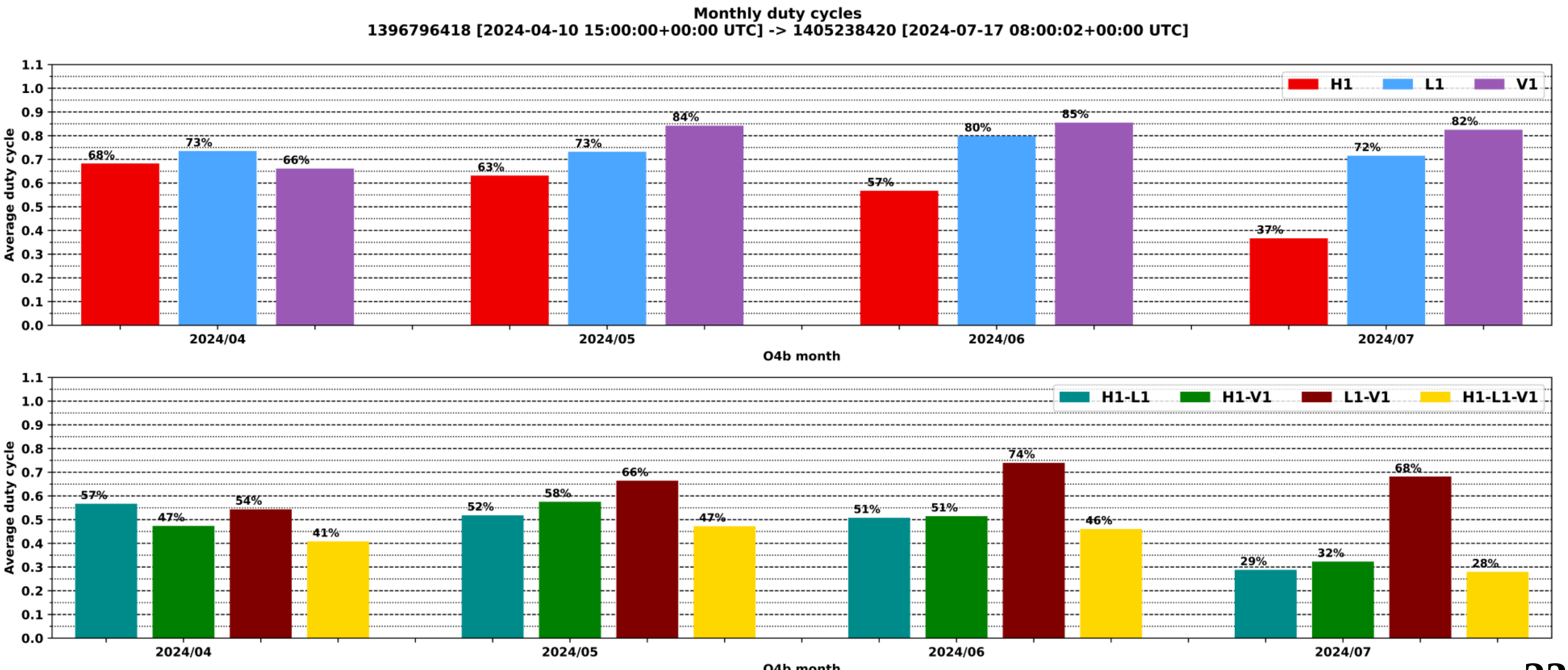
- Activities breakdown



The O4b run

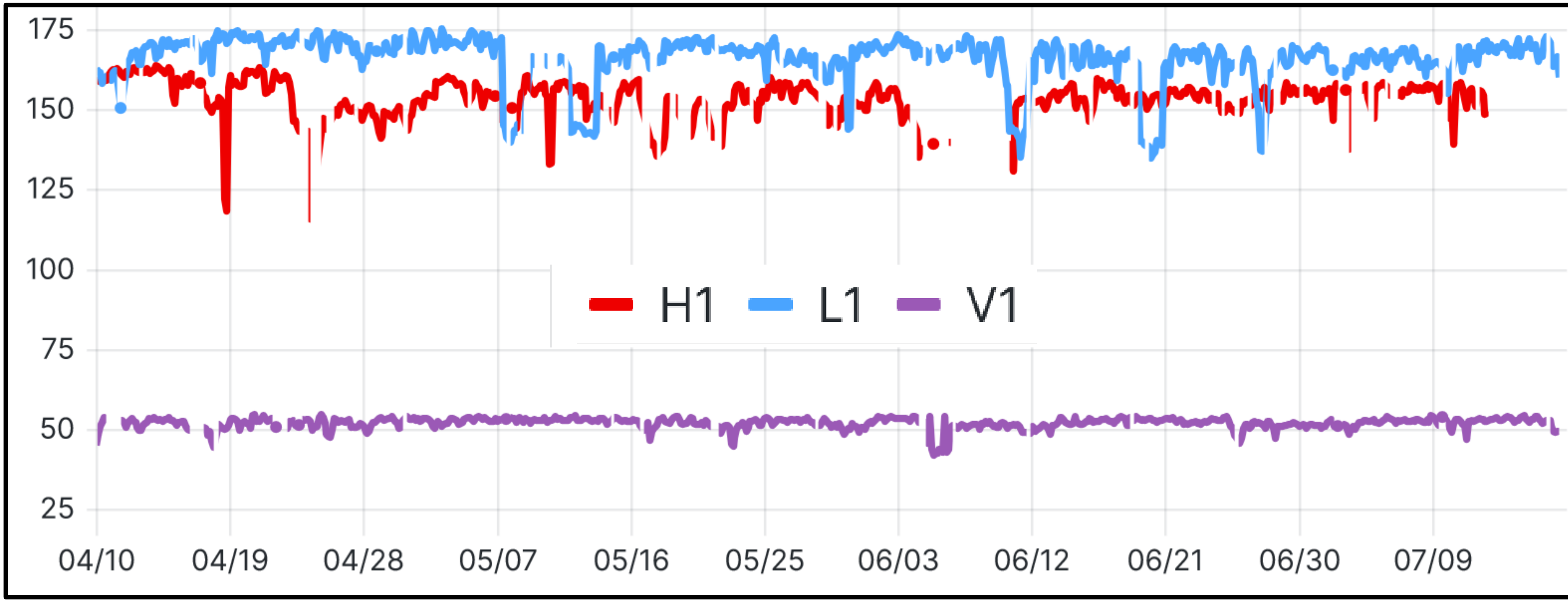
- Network duty cycle





The O4b run

- Network sensitivity
  - Data from the public website online.igwn.org



→ Alongside a live status of the LVK detectors

Gravitational Wave Detector Network

Operational Snapshot as of Jul. 11, 2024 12:55:09 UTC

Detector	Status	Duration [hh:mm]	Latency [s]
GEO600	Unlocked	>99:00	48
LIGO Hanford	Observing	07:32	58
LIGO Livingston	Observing	05:53	70
Virgo	Observing	03:31	44
KAGRA	Down	>99:00	75

The O4b run

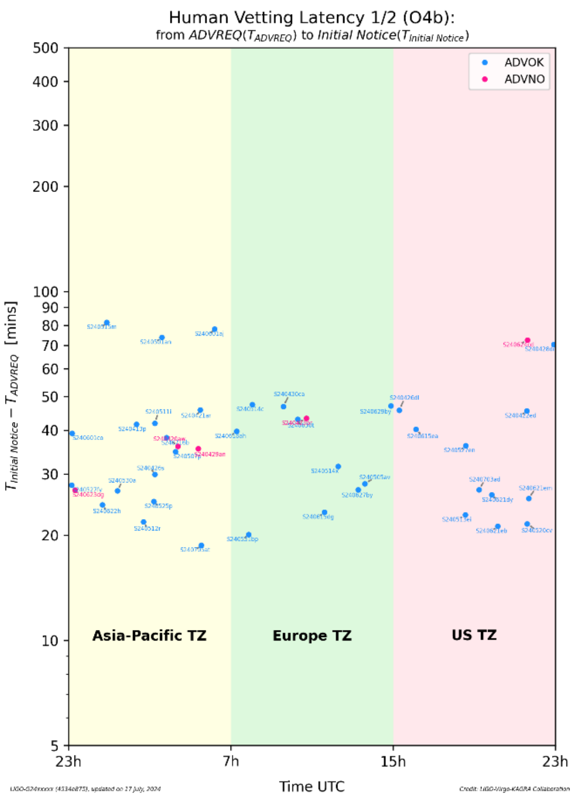
- Low-latency alerts
  - Number of candidates

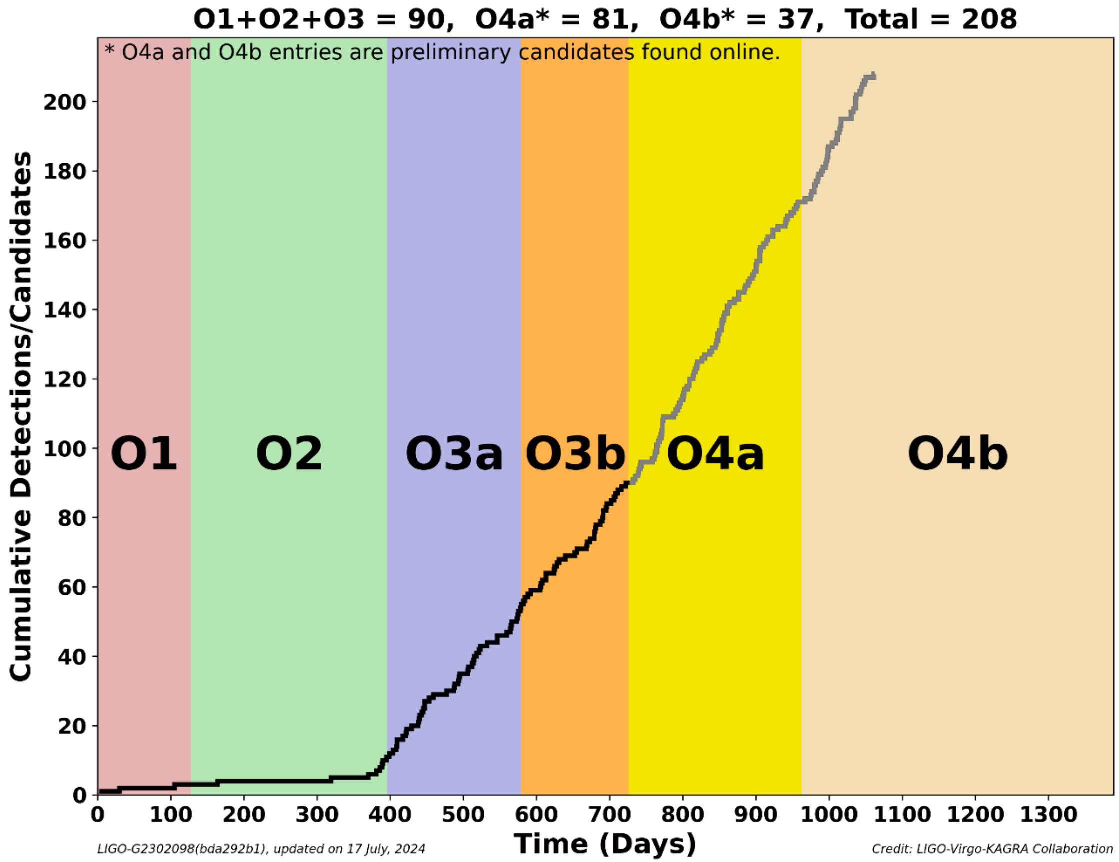
O4b Significant Detection Candidates: **37** (42 Total - 5 Retracted)

O4b Low Significance Detection Candidates: **557** (Total)

  - Cumulative plot vs. number of days of data taking

- RRT vetting latency



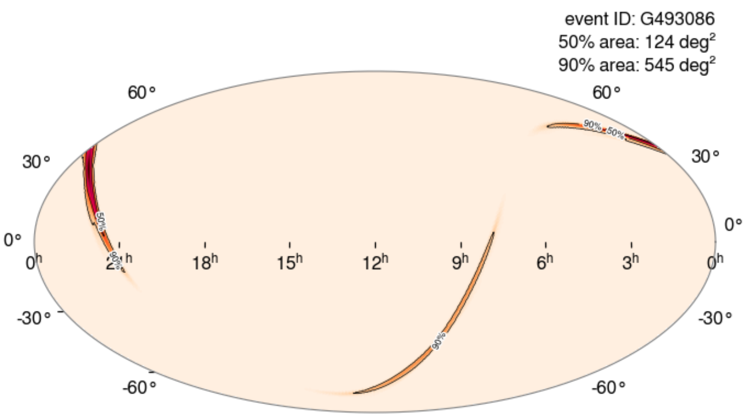


The O4b run

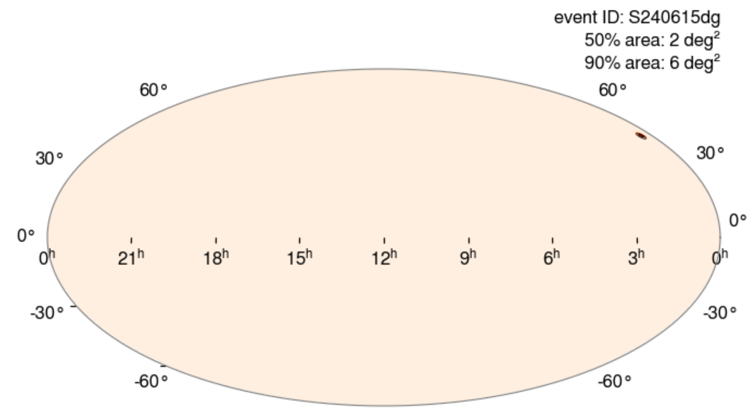
- Virgo data available for 90% of the LIGO triggers
  - Triggers missed: Virgo maintenance or attempt to control again the detector

- Sky localization greatly improved in some cases
  - Example: S240615dg

LIGO-only skymap



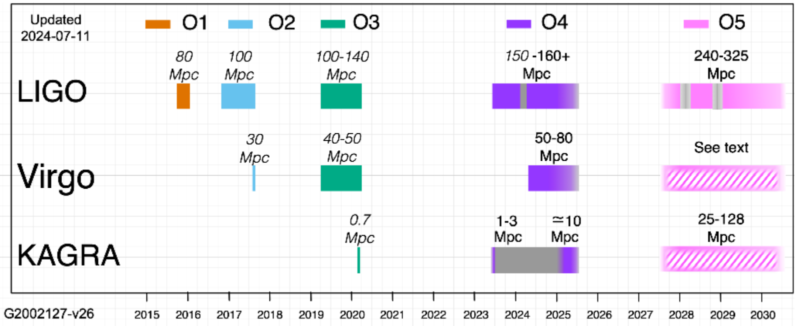
3-detector skymap



→ Statistical studies planned to assess the actual improvement
  - No counterpart identified for all events: real source locations unknown

Outlook

- Still ~11 months of data taking to complete the O4b run
  - KAGRA is recovering from the earthquake: goal remains to join at the end of O4b
- In the meantime, preparation of upgrades between O4 and O5
  - Major work foreseen at Virgo to install stable recycling cavities
    → While preserving its participation to at least part of the O5 run

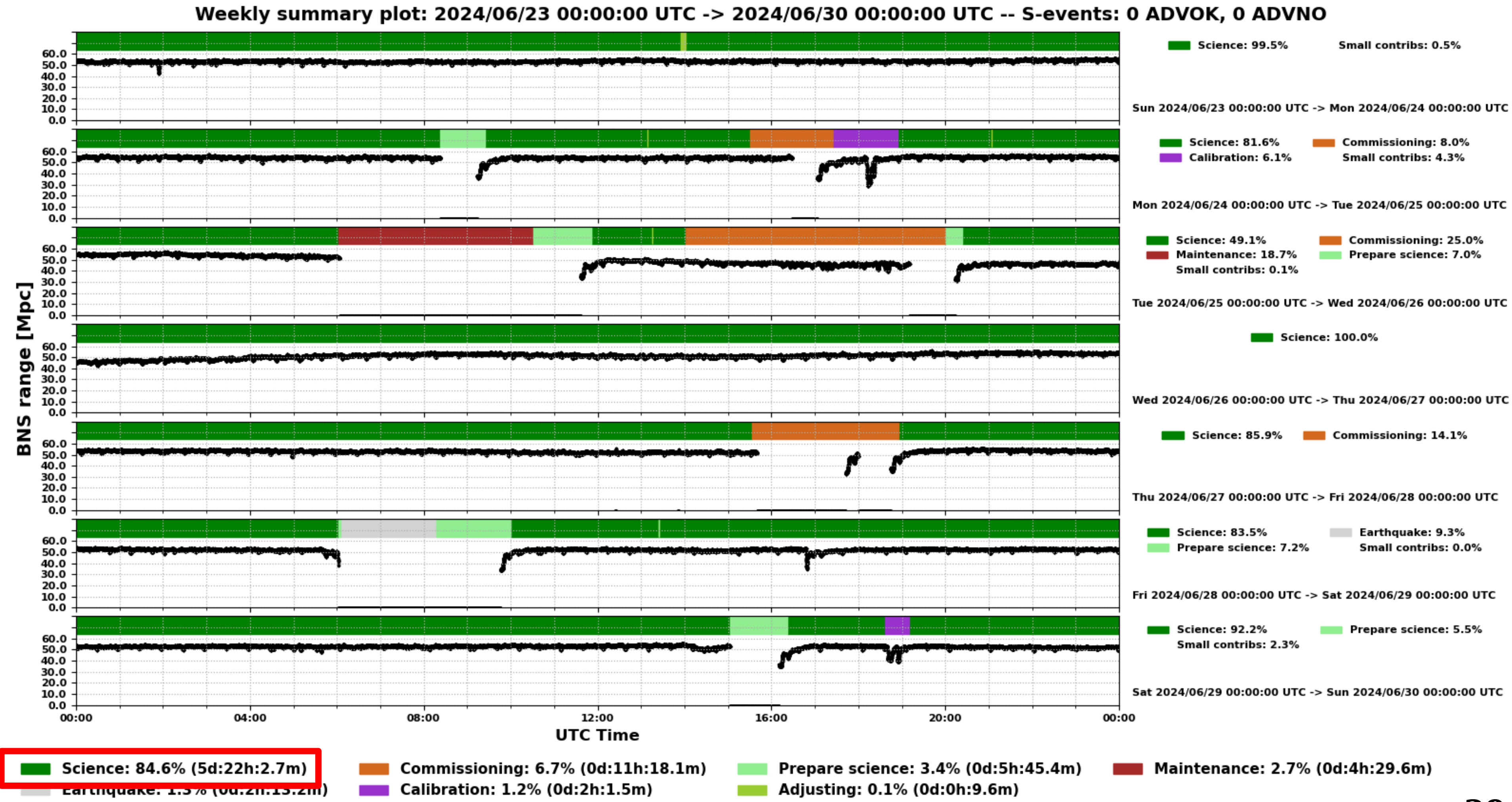


LIGO, Virgo and KAGRA observing plans *[monthly updates]*
https://observing.docs.ligo.org/plan

- Post-O5 projects being developed in LIGO (A#) and Virgo (V_nEXT)
  - At least a decade before 3rd generation detectors come online (CE & ET)
  - Test future technologies, train a new generation of scientists, bridge the gap between current (2nd generation) and future detectors, make more discoveries
- LIGO India will join the network
  - Possibly as early as the end of the decade

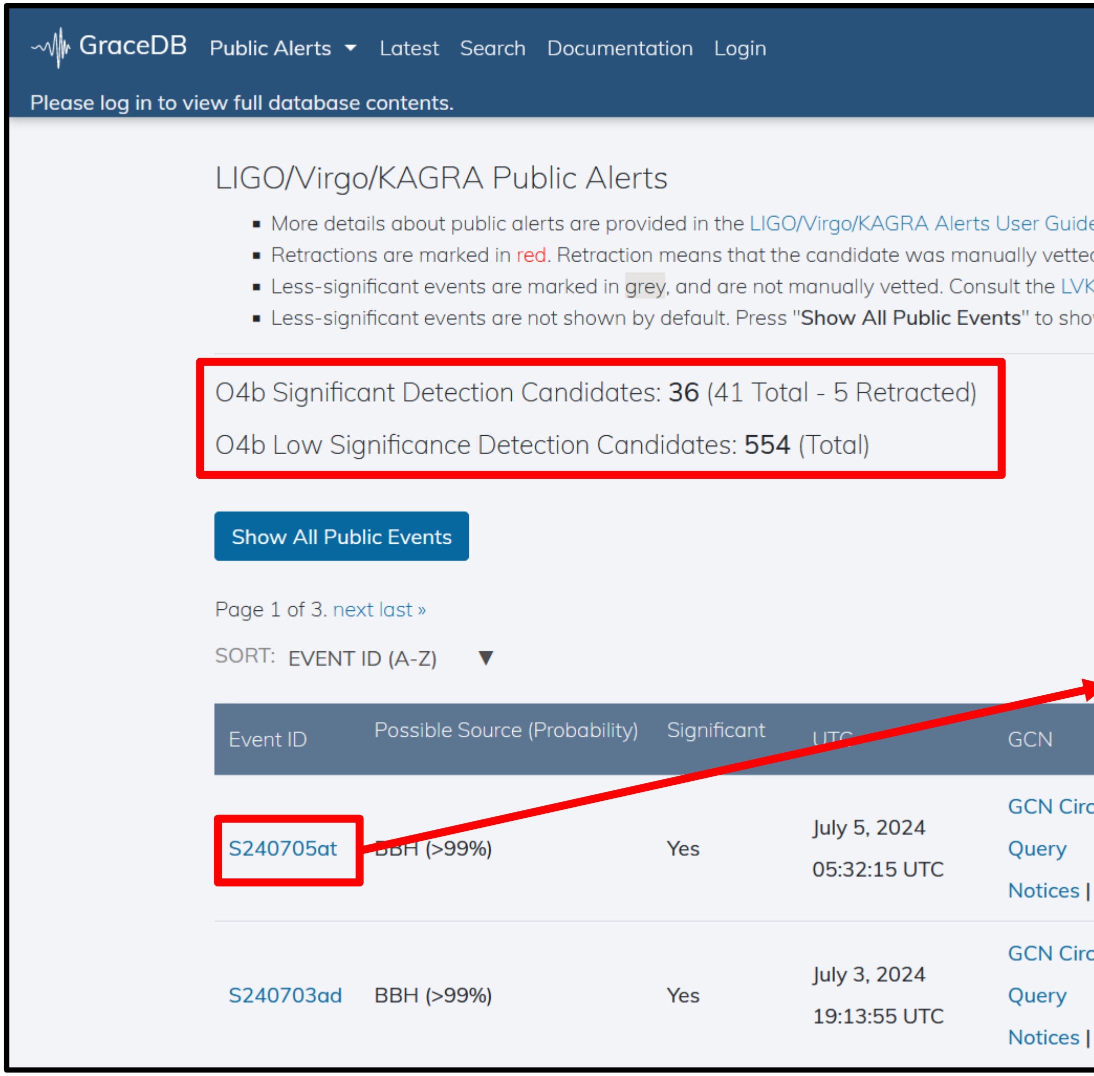
A typical O4b week

- High duty cycle: > 80%
- Expected downtime pattern: Monday, Tuesday, Thursday and Saturday



GraceDB

- https://gracedb.ligo.org/superevents/public/O4



GraceDB Public Alerts Latest Search Documentation Login

Please log in to view full database contents.

LIGO/Virgo/KAGRA Public Alerts

- More details about public alerts are provided in the LIGO/Virgo/KAGRA Alerts User Guide.
- Retractions are marked in red. Retraction means that the candidate was manually vetted
- Less-significant events are marked in grey, and are not manually vetted. Consult the LVK
- Less-significant events are not shown by default. Press "**Show All Public Events**" to show

O4b Significant Detection Candidates: **36** (41 Total - 5 Retracted)

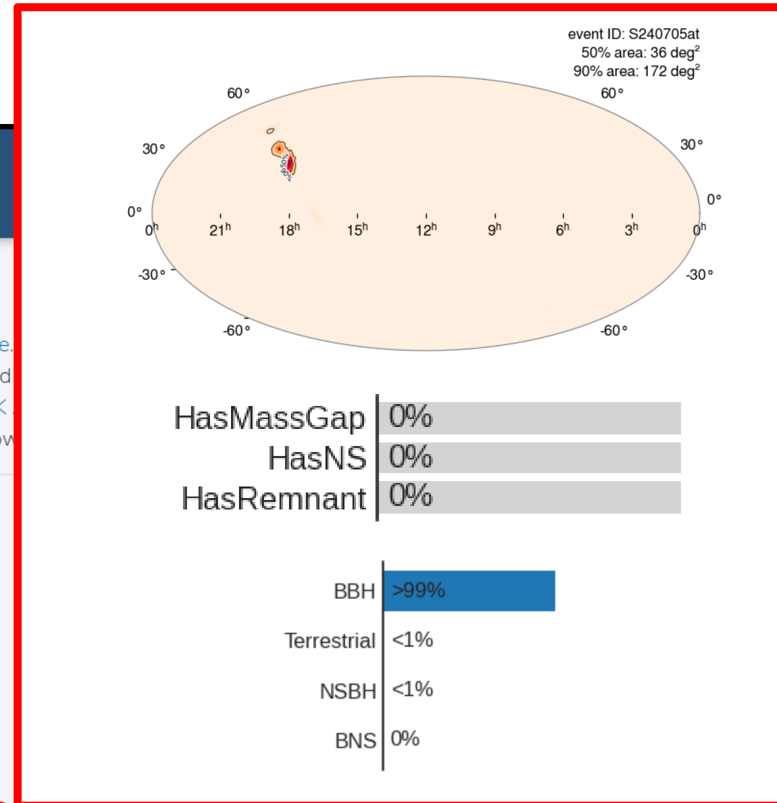
O4b Low Significance Detection Candidates: **554** (Total)

Show All Public Events

Page 1 of 3. next last »

SORT: EVENT ID (A-Z) ▼

Event ID	Possible Source (Probability)	Significant	UTC	GCN	Location	FAR	Comments
S240705at	BBH (>99%)	Yes	July 5, 2024 05:32:15 UTC	GCN Circular Query Notices | VOE		1 per 4.4755e+07 years	
S240703ad	BBH (>99%)	Yes	July 3, 2024 19:13:55 UTC	GCN Circular Query Notices | VOE		1 per 2.6751e+05 years	



GWOSC

- Gravitational Wave Open Science Center: https://www.gw-openscience.org