Status of the gravitational-wave interferometers LIGO-Virgo-KAGRA

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on behalf of LVK collaborations

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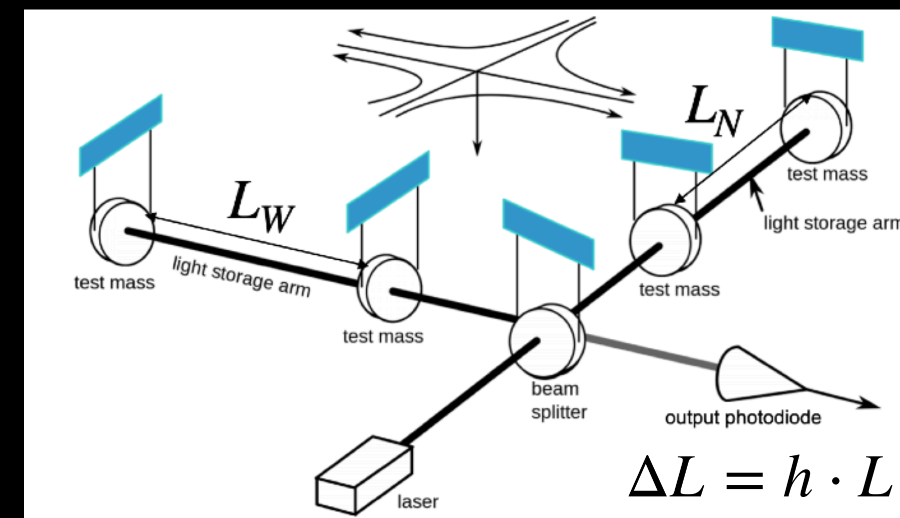
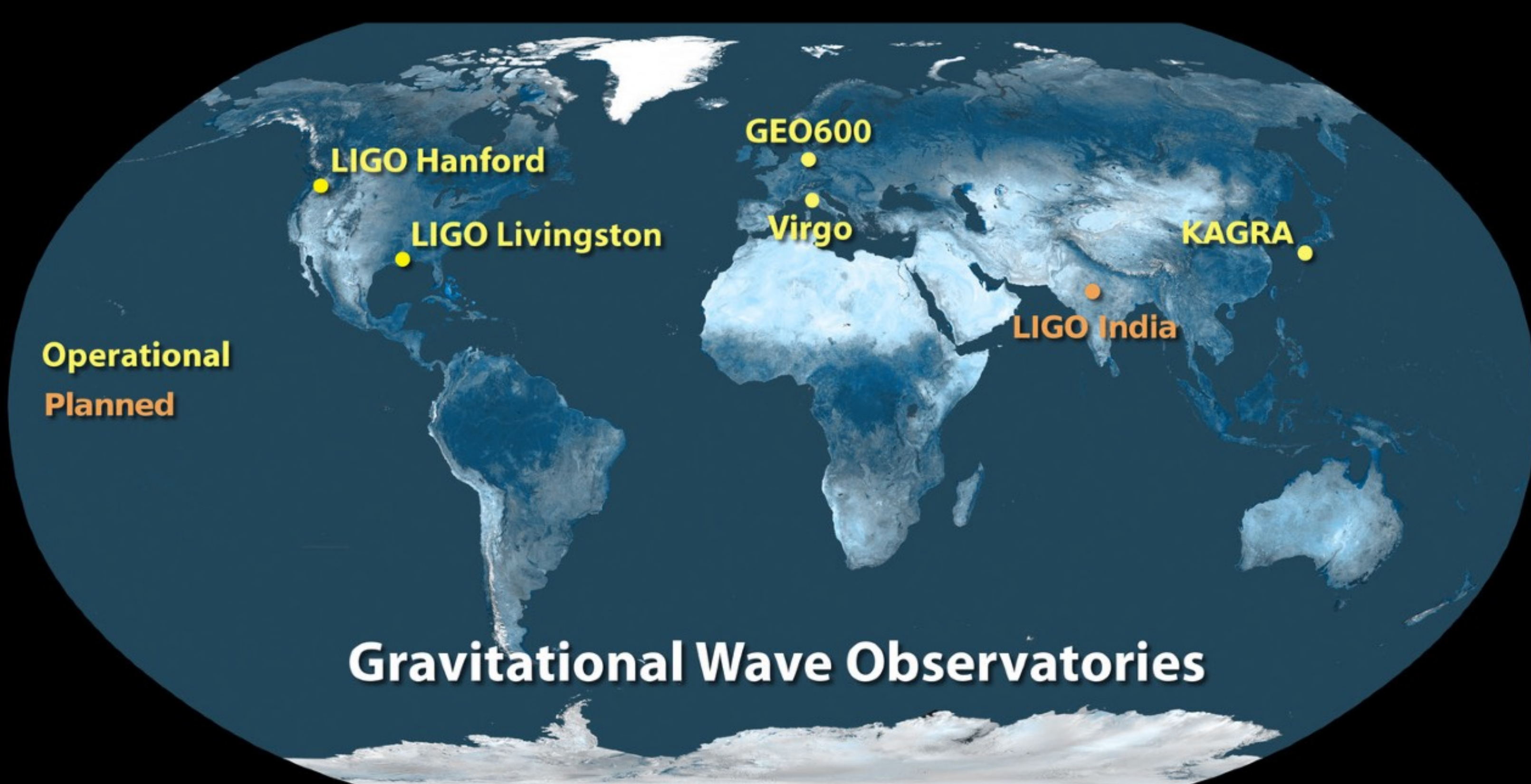
Astro-COLIBRI workshop, 17 September 2024

Numerical relativity simulation of a BH-NS merger, where the NS is tidally disrupted by the BH (as GW200105, GW200115)
Modified from Deborah Ferguson (UT Austin), Bhavesh Khamesra (Georgia Tech), and Karan Jani (Vanderbilt University).

2nd generation interferometers

- Current laser interferometers: slightly different design (optically, cryo/not, underground/not, etc)
  - **Michelson interferometer** of ~several km of baseline
  - Input **infrared laser** (1064nm) of ~tens of W
  - Resonant **Fabry-Perot cavities** used to enhance the response of interferometers
  - **Recycling cavities** (power and signal recycling mirrors)
  - Very **reflective coatings** on **high purity tens of kg mirror** substrates

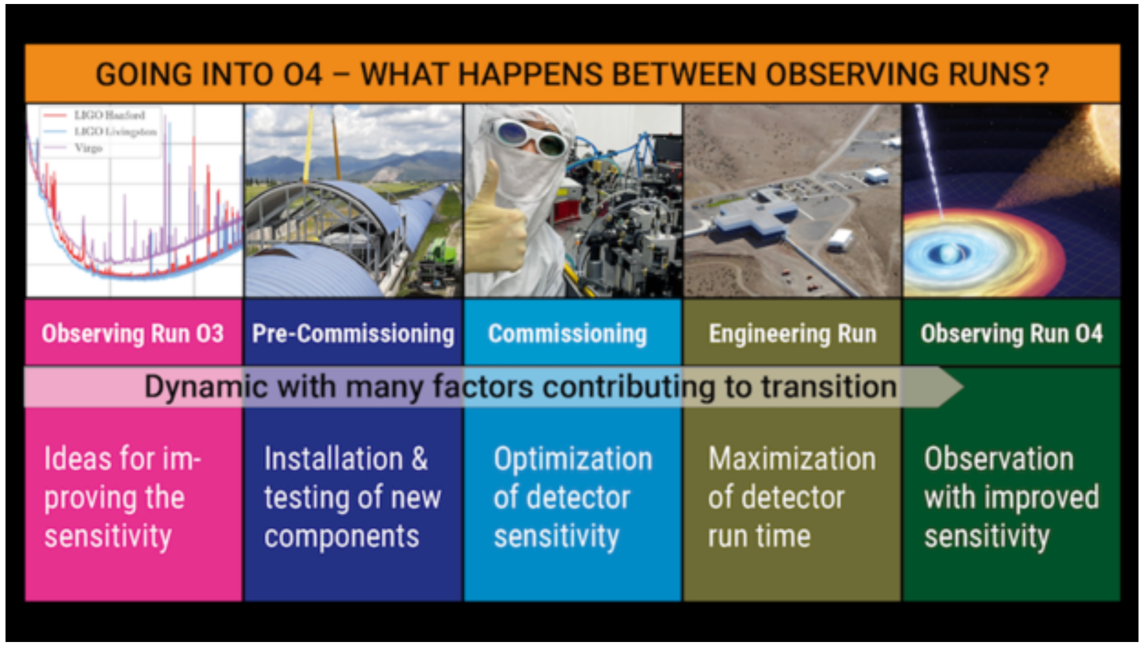


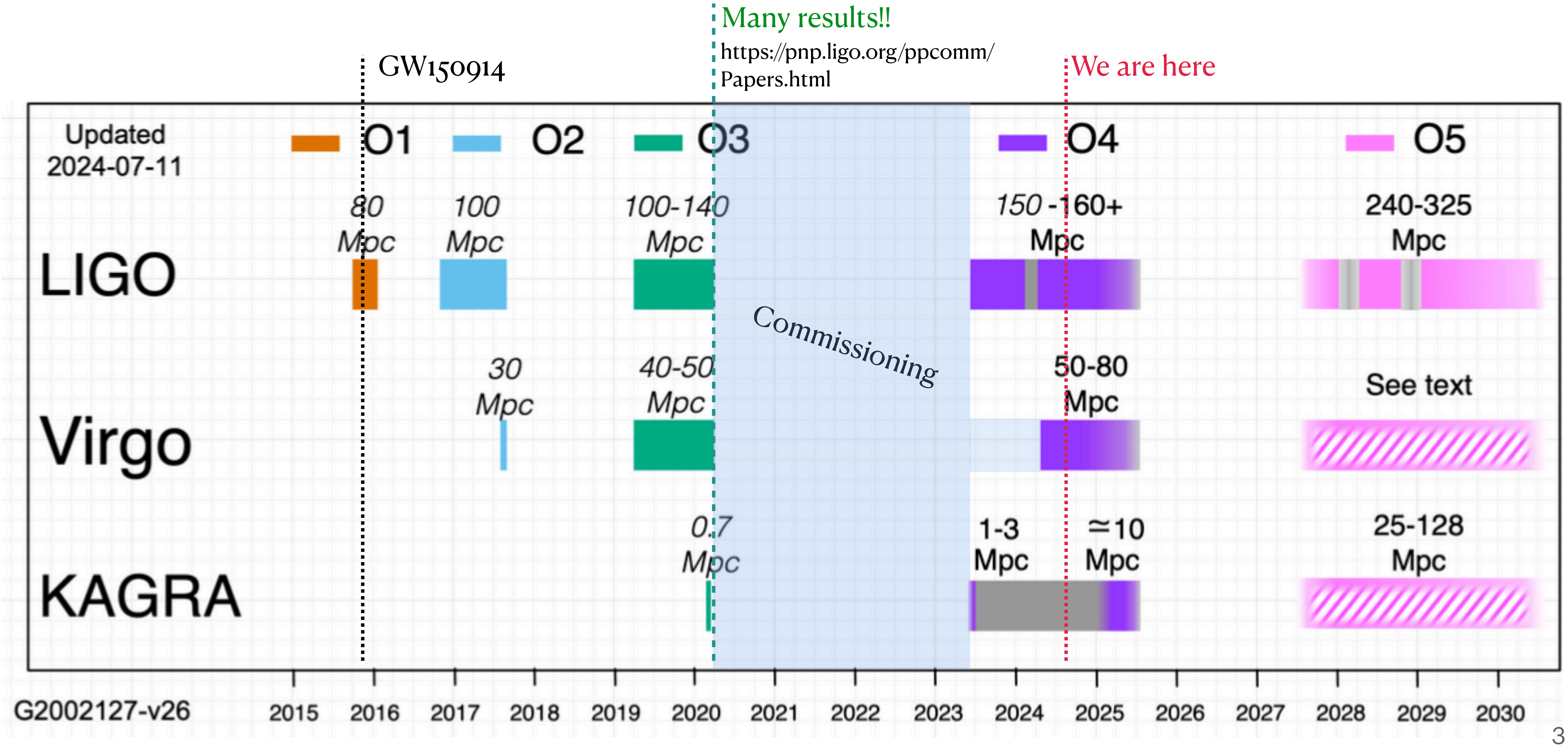


*Sensitivity range expressed in terms of **BNS inspiral range, for a 1.4+1.4M$_\odot$ system on-axis at single-detector SNR=8**

The LVK observing runs

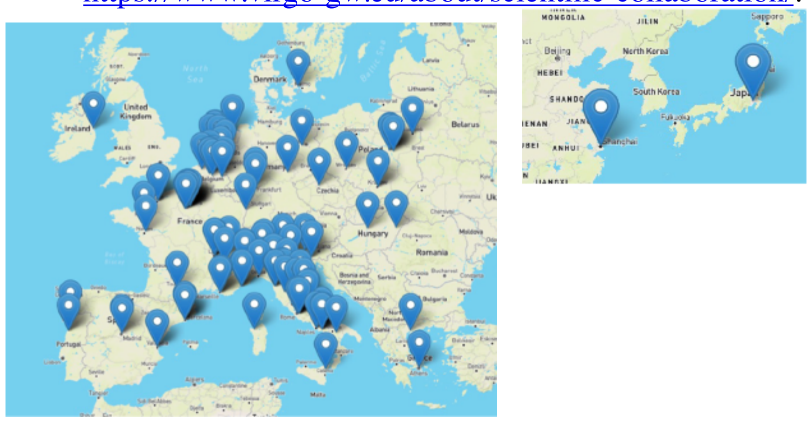
- The O4 observing run started on **May 2023**
  - O4a with LIGO-L and LIGO-H: **10 months**
  - O4b started in **April 2024**: LIGO-L LIGO-H and Virgo
  - Observing run extended until **9 June 2025**: **14 months**



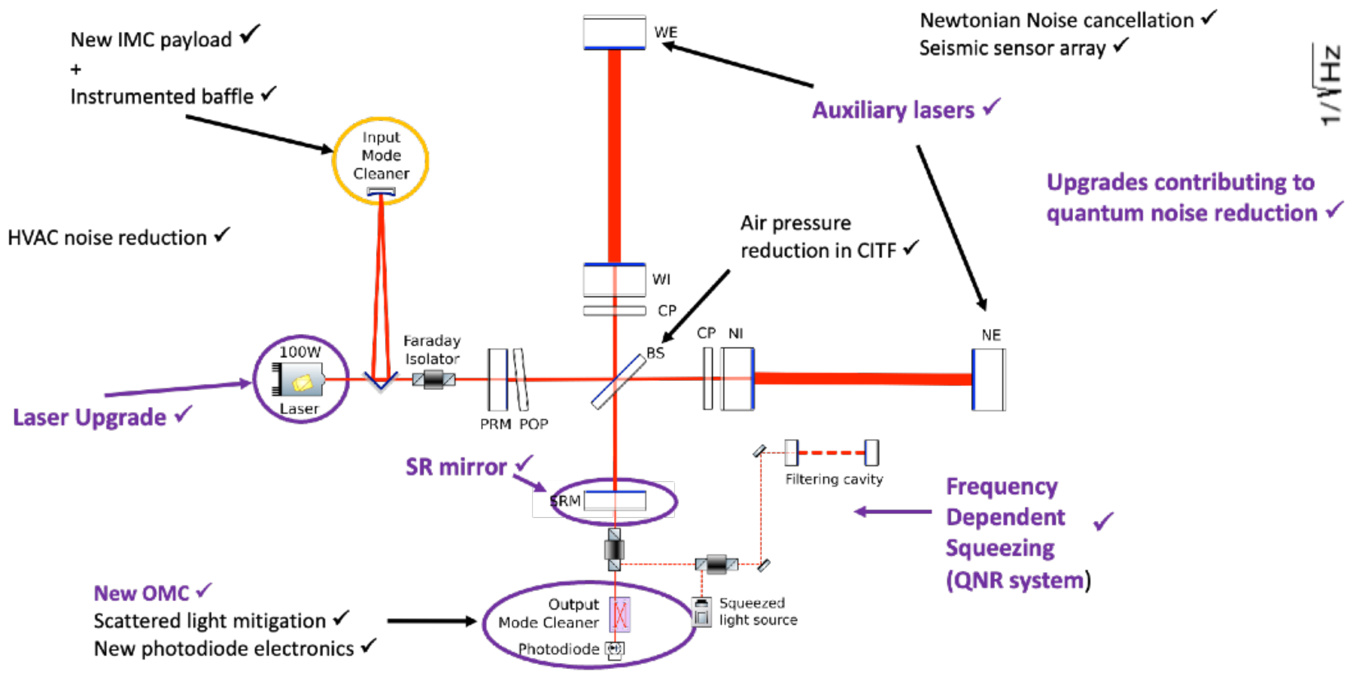


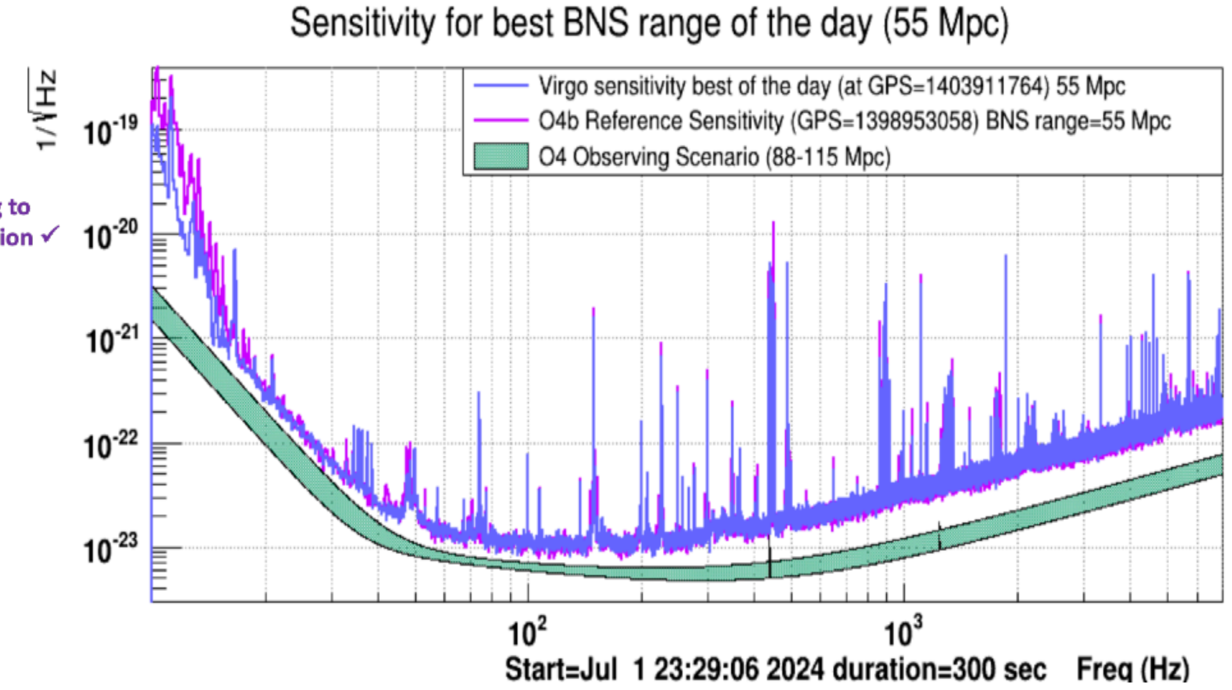
https://www.virgo-gw.eu/about/scientific-collaboration/.

Virgo



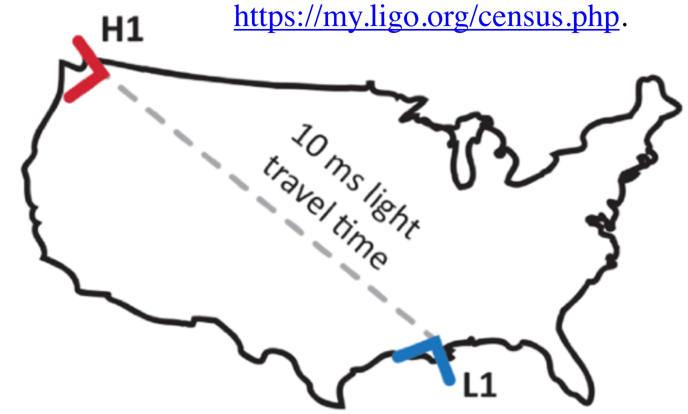
- 880 members from 152 institutions in 17 different (mainly European) countries.
- The European Gravitational Observatory (EGO) hosts the 3-km interferometer detector near in Cascina, Pisa (Italy)
- The Advanced Virgo+ Phase I upgrade focuses on **quantum noise reduction**





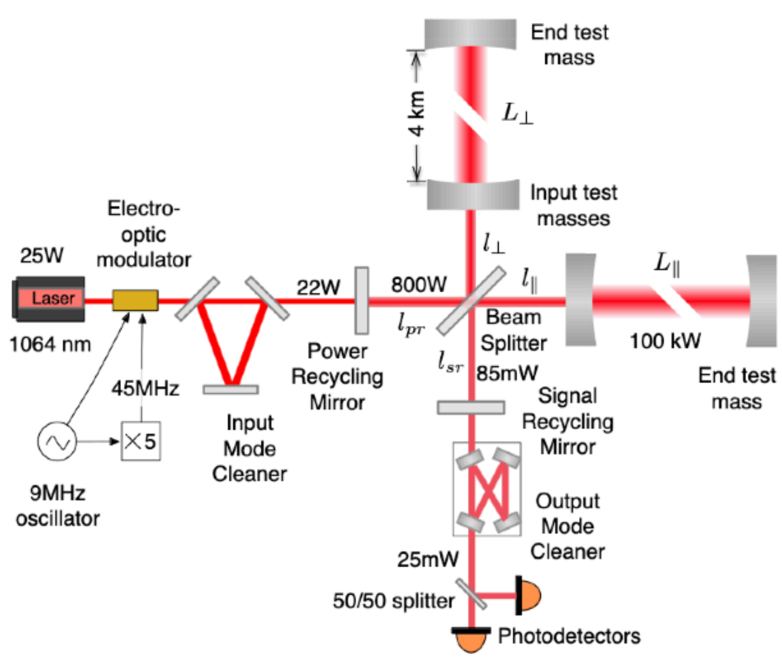
- Stable and reproducible control of interferometer mostly achieved in Fall 2022: Lowering input power from nominal 40 W to 18 W (currently), new thermal actuator to correct power-recycling mirror curvature, deal with signal-recycling cavity with resonating higher-order modes....
- Several challenges to reach the expected sensitivity for O4 (80-115 Mpc) **are being tackled**
  - Noise in the bucket limiting the sensitivity
  - Detector **very sensible** to thermal defects and aberrations due to the design of the recycling cavities

https://my.ligo.org/census.php.

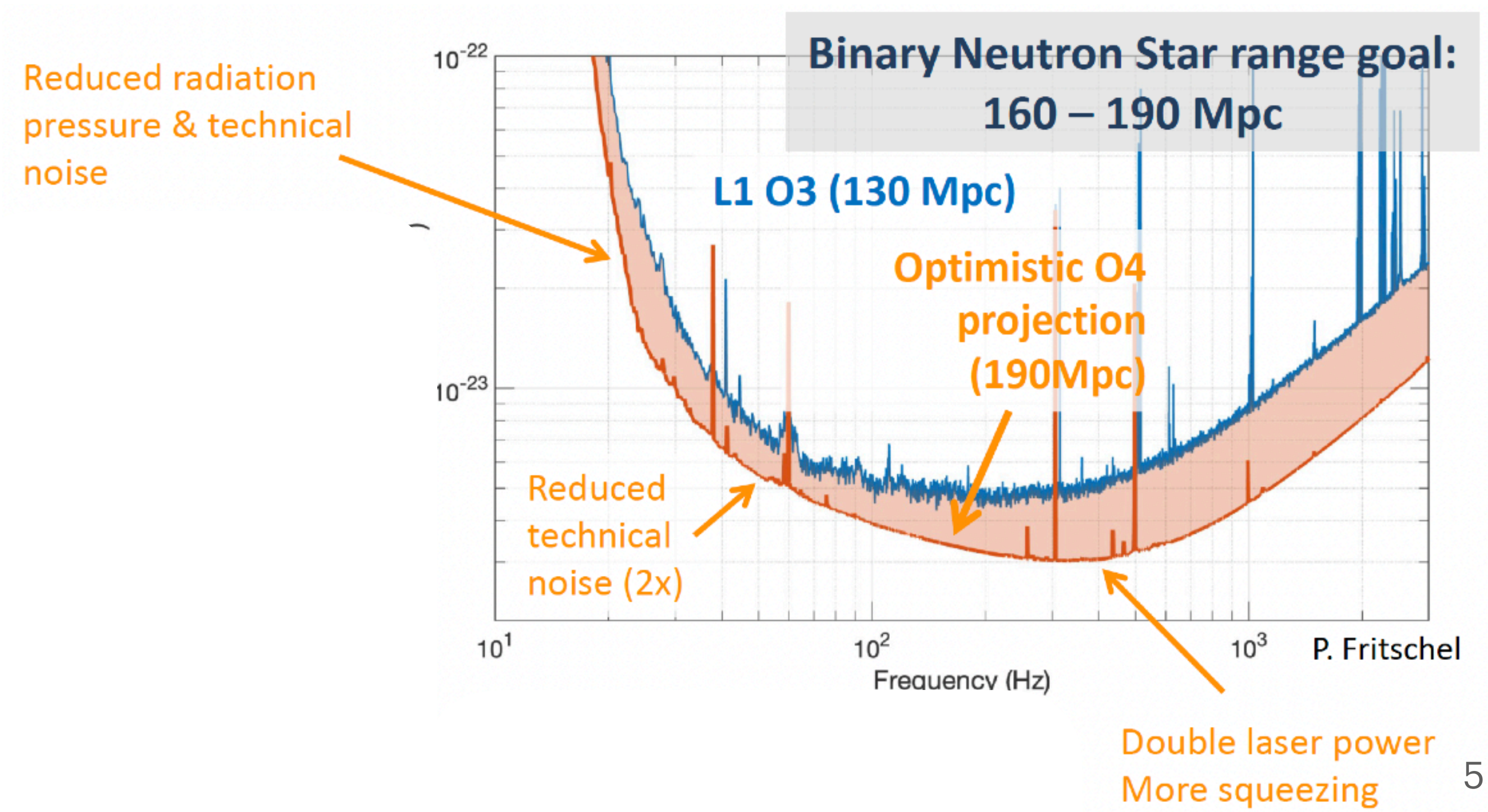


LIGO

- Two 4-km interferometric gravitational wave detectors in USA
- Funded by US NSF, operated by Caltech and MIT, with contributions from Germany, UK and Australia
- More than 1,600 scientists from around the world participate in the effort through the LIGO Scientific Collaboration, which includes the GEO Collaboration.
- Some of the O4 goals:
  - **400 kW circulating arm power** (Compare to 200 kW in O3)
  - **Squeezed light efficacy: 4.5 dB** (2-3 dB in O3)
  - **300 m filter cavity** for frequency dependent squeezing
  - **Low frequency technical noise reduction** (below 100 Hz): Scattered light, control, electronics
- LIGO–H down for 8 weeks July-August for in-vacuum intervention: replacement of a damaged crystal

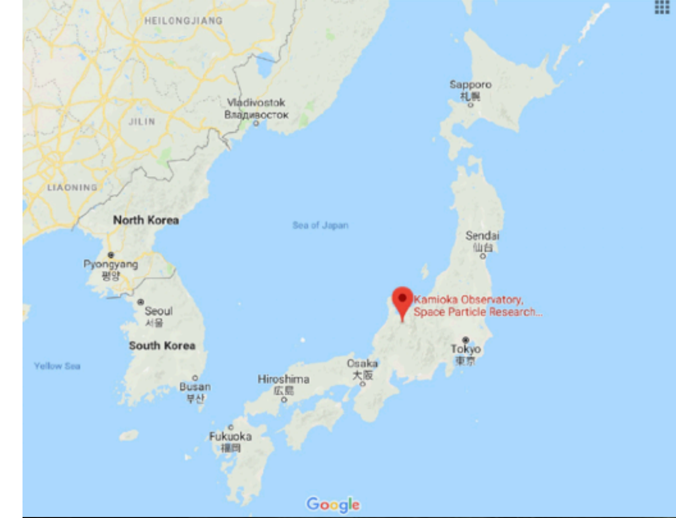


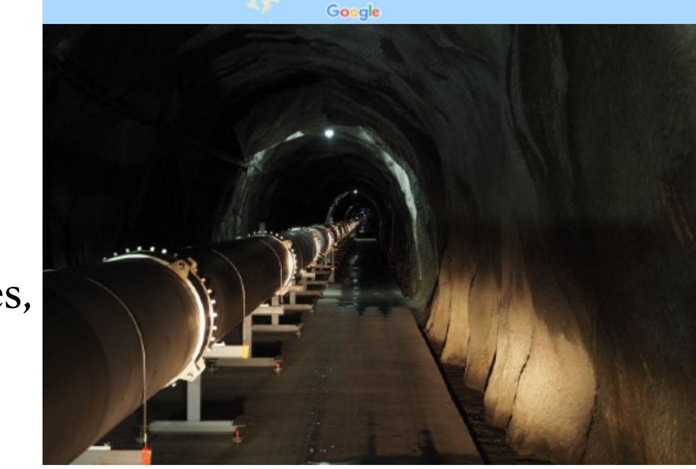
Phys. Rev. D 93, 112004

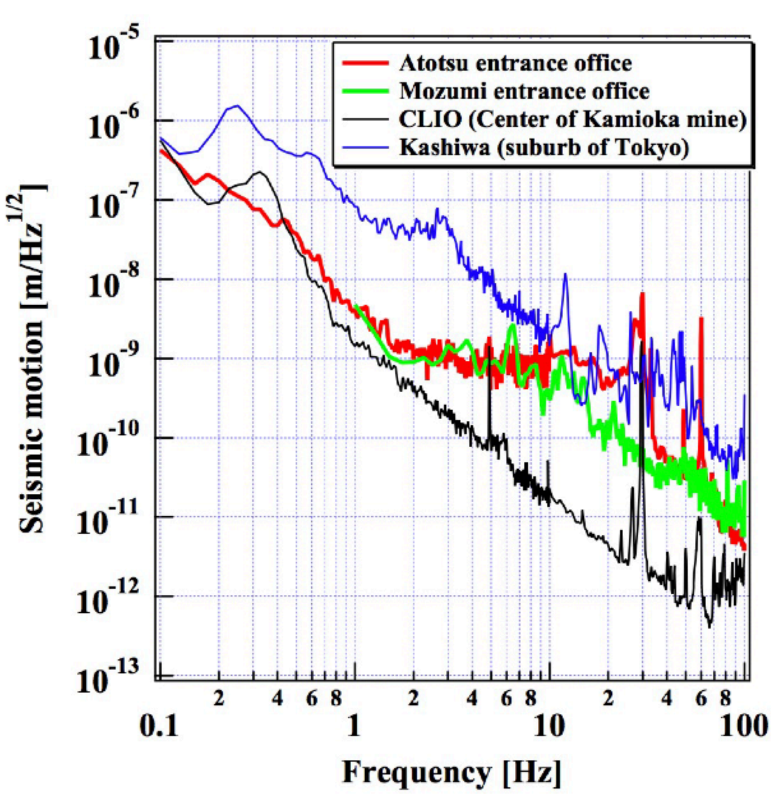


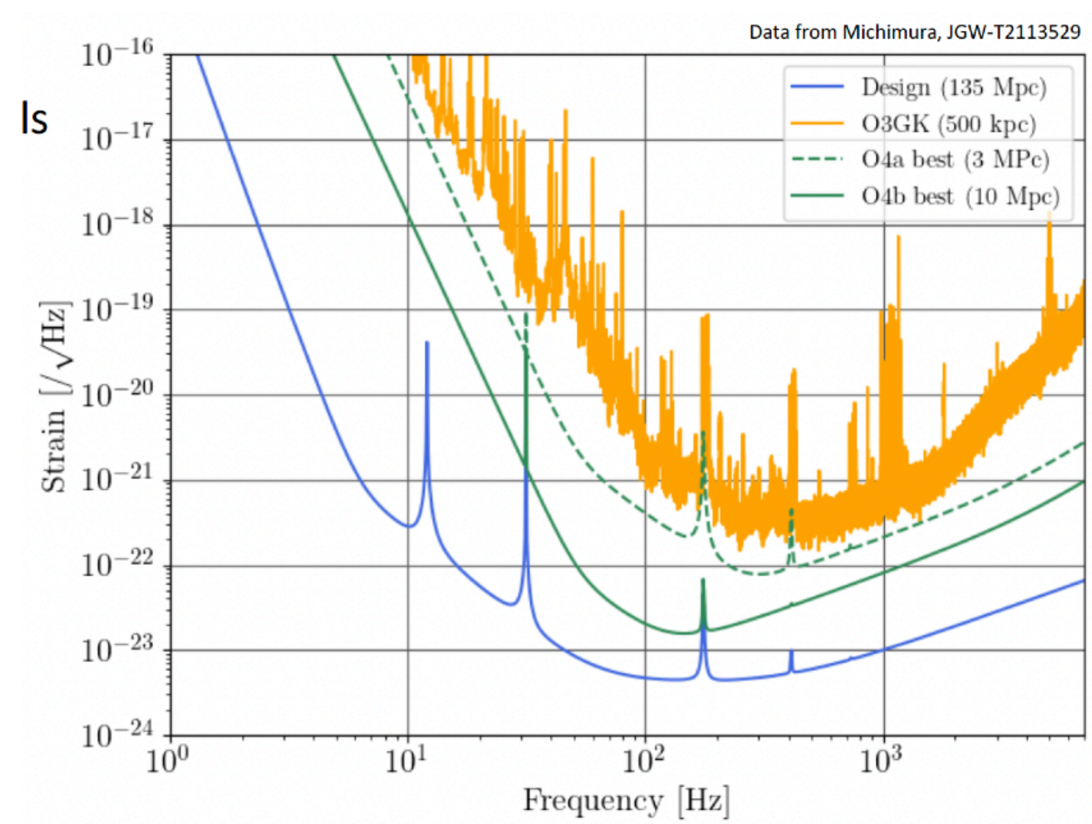
KAGRA

- 3 km arm-length interferometer, placed deep under the Kamioka mines : **underground to reduce seismic motion**
- Host institute is ICRR, co-hosted by NAOJ and KEK
- ~400 members from 128 institutes in 17 countries/regions
- Test masses: Sapphire at~20K (**cryonenic**). Auxiliary mirrors fused silica (room temperature)
- **Some of the goals for O4**: Suspension sensing and control, suppressing scattered light with baffles, SRM replacement, improve low-frequency region, cool down below 100
- Joined O4a for a month before going back to commissioning.
- Currently **recovering from damage** caused by the magnitude 7.6 earthquake that struck the Noto peninsula (120 km from KAGRA site) on January 1, 2024 => ~10 Mpc expected when recovery achieved









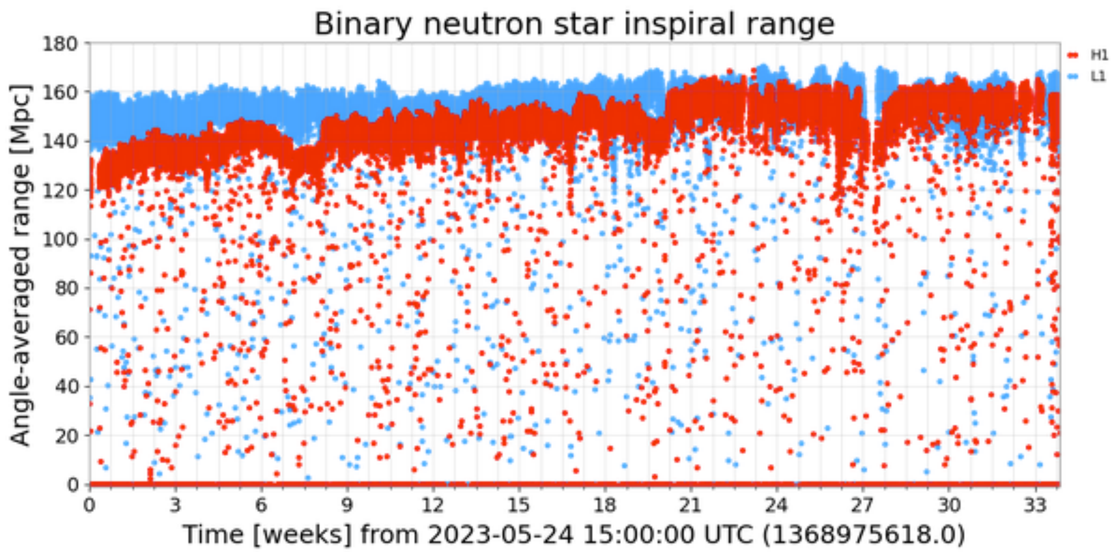
From K. Kokeyama

https://gwosc.org/detector_status/
https://online.ligo.org

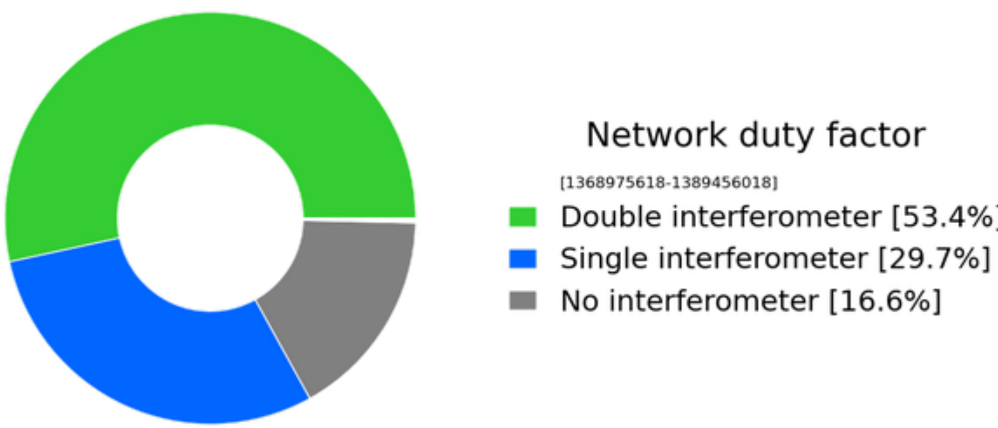
Duty cycle of the LVK network

O4a (LH + first 4 weeks with KAGRA) : 10 months of data

- BNS range increase over the observing run

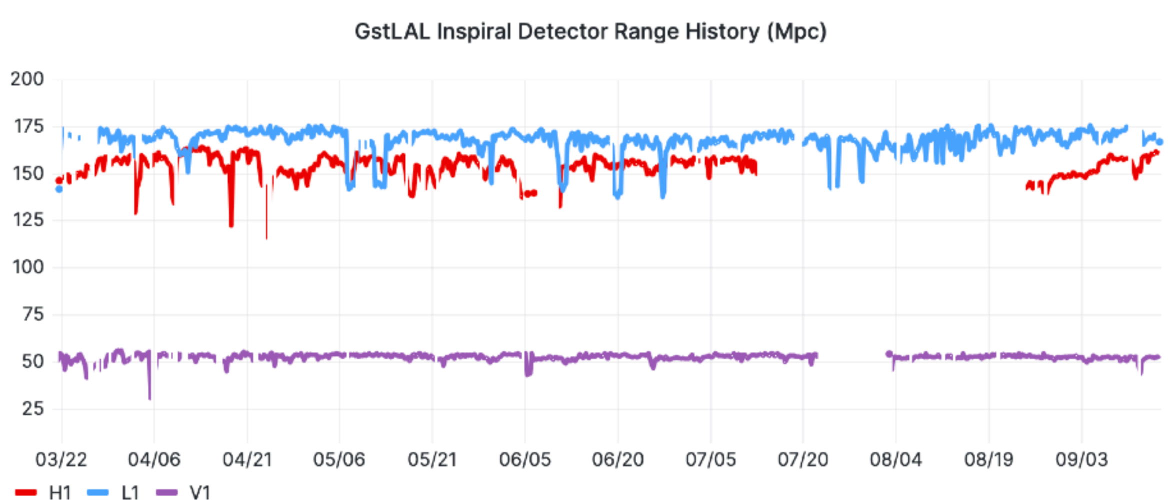


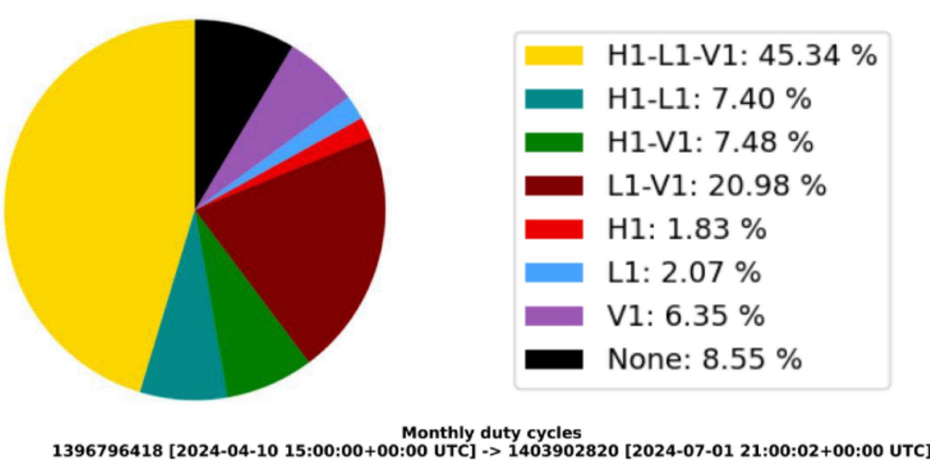
- 2 interferometers 53% of the time!



O4b (LHV): 14 months, ongoing

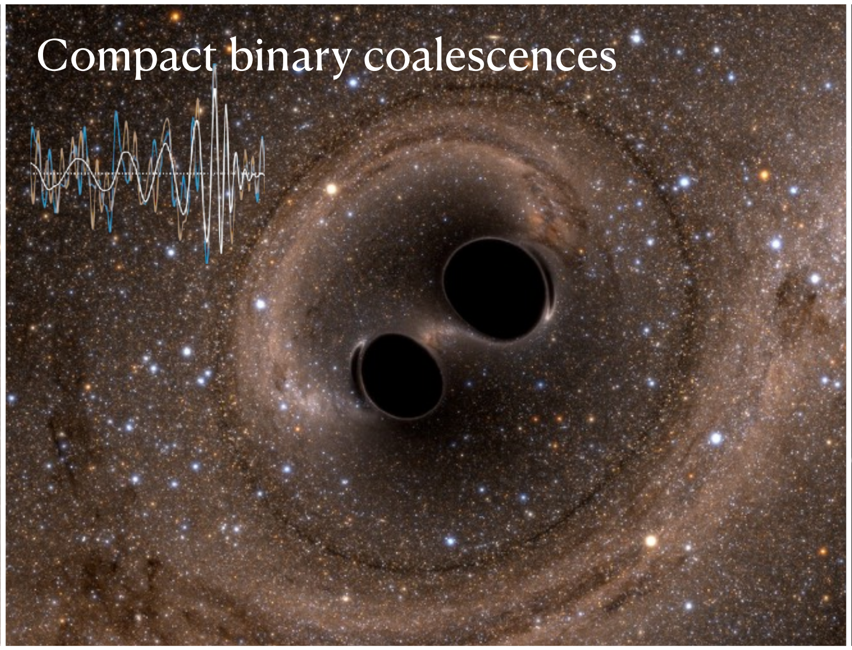
- Strategy: maximising 3 ITF operations for improved sky localisations (~80% uptime with >1 ITFs)
- Continuous coordination effort in downtimes at LVK level

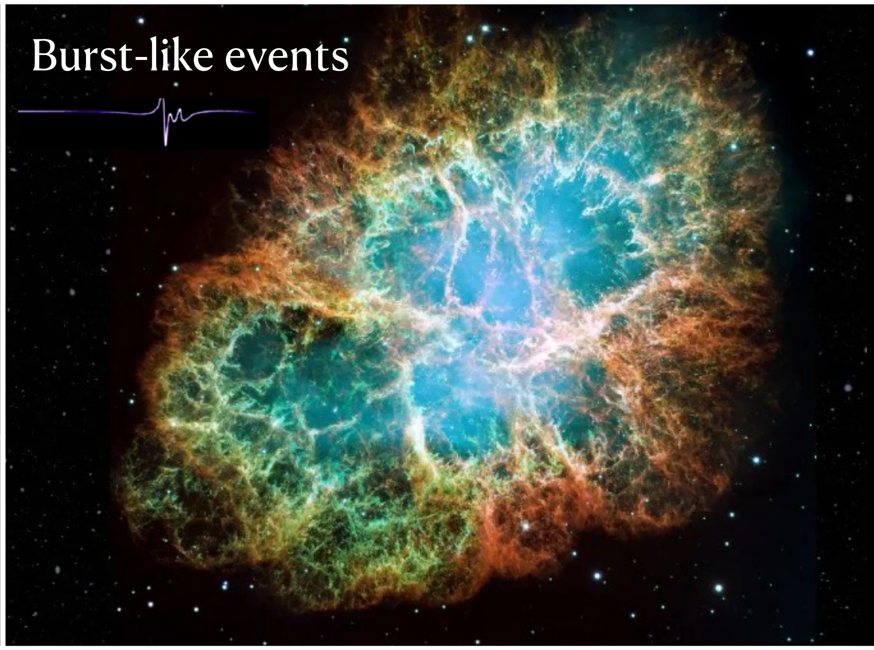


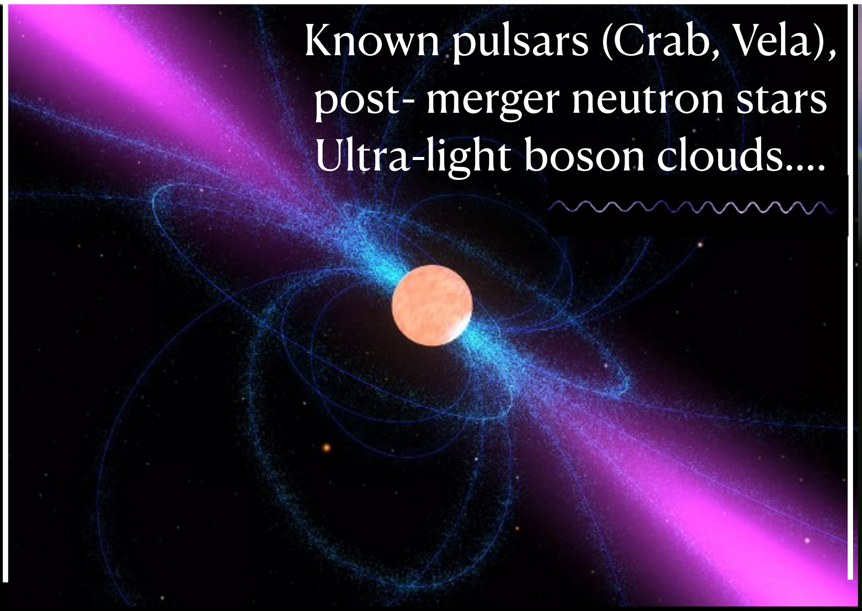


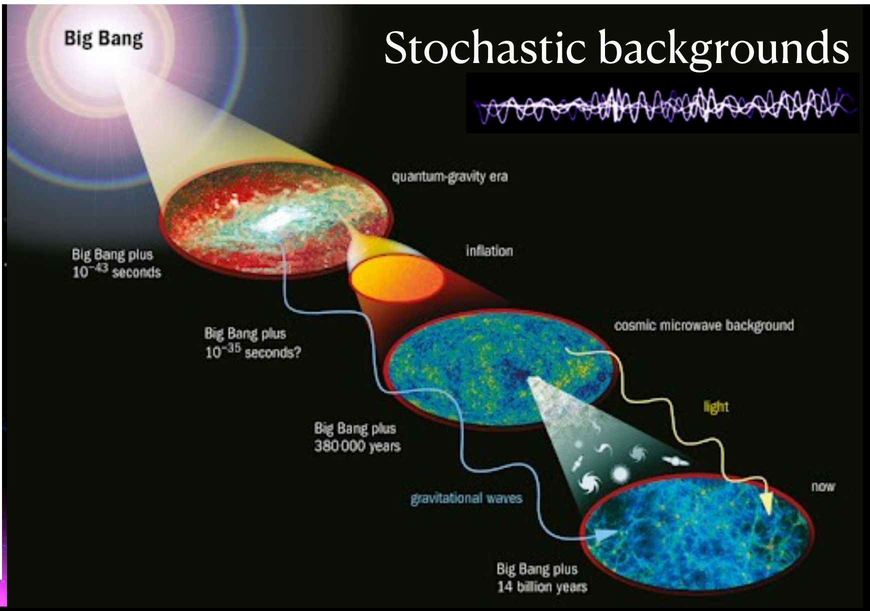
Gravitational wave sources at Hz-kHz

	Modeled searches	Unmodelled searches
Short-lived (transients)	Compact binary coalescences	Burst-like events
Long-lived	Known pulsars (Crab, Vela), post- merger neutron stars Ultra-light boson clouds....	Stochastic backgrounds









https://pnp.ligo.org/ppcomm/Papers.html

Online detections during observing run O4

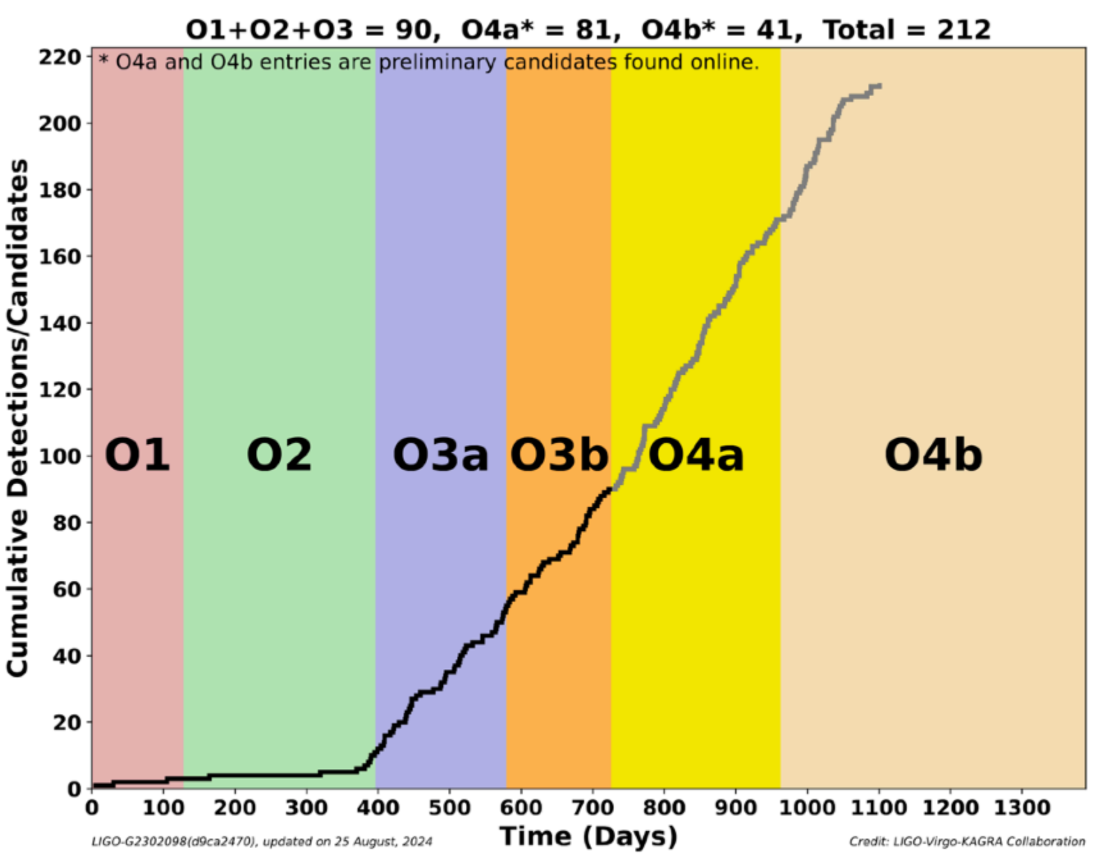
- Separation between **significant candidates (1/month for CBC events, 1/year for burst events)** and **non-significant candidates** (interesting in joint sub-threshold searches)
- Rate of significant candidates:~ **1 every 3 days** (compared to 1 every 6 days in O3b)

O4a (LH)

- **Total 80 (92**, Retracted: 11)
- 80 BBH and 1 NSBH Significant Candidates
- Non-significant Detection candidates ~1600

O4b (LHV)

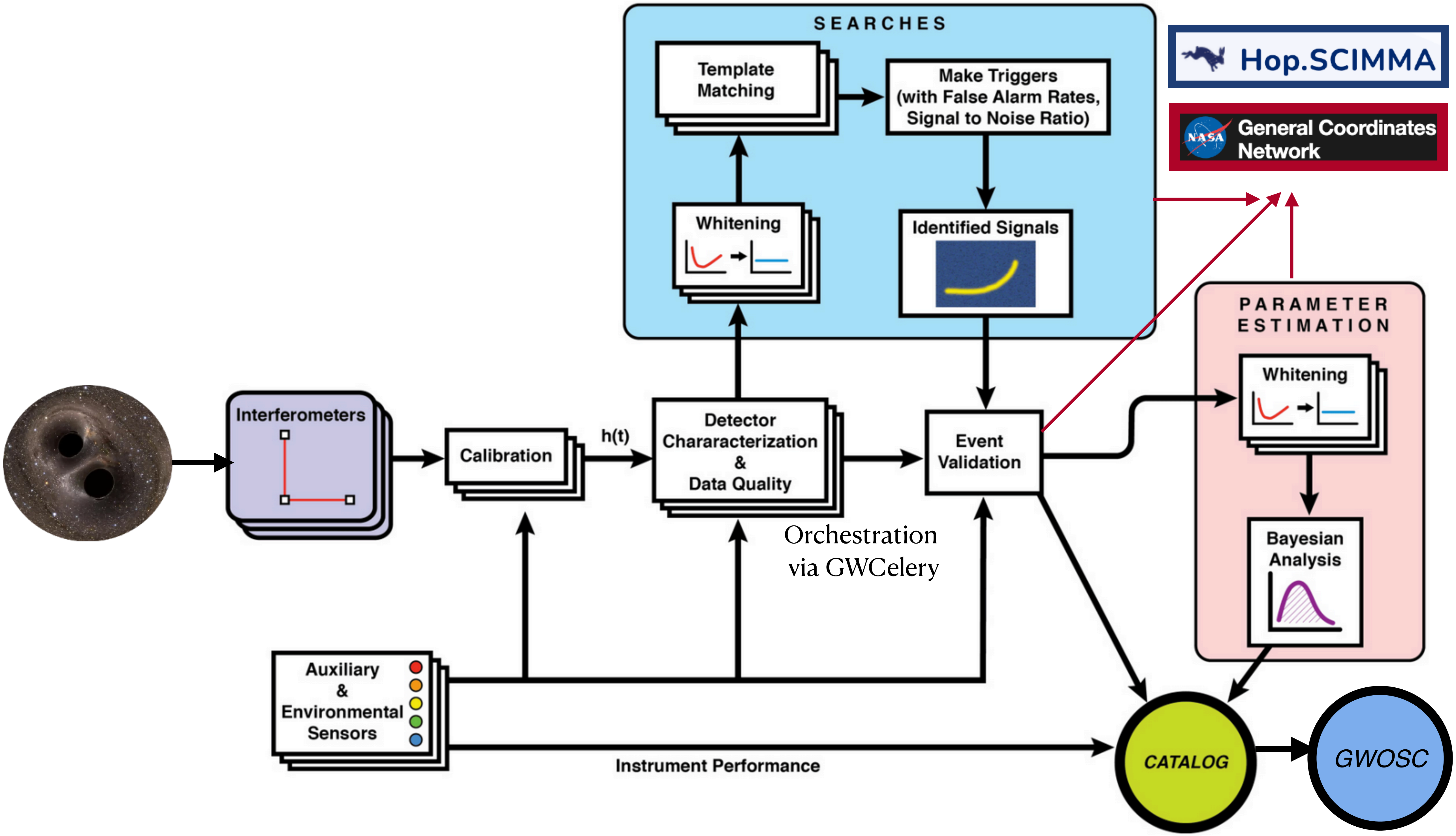
- **Total** 49 (54 Retracted: 5)
- 49 BBH Significant Candidates
- Non-significant Detection candidates ~758



More than ~300 detections by the end of O4!

*Online searches. Final numbers in GWTC catalogs

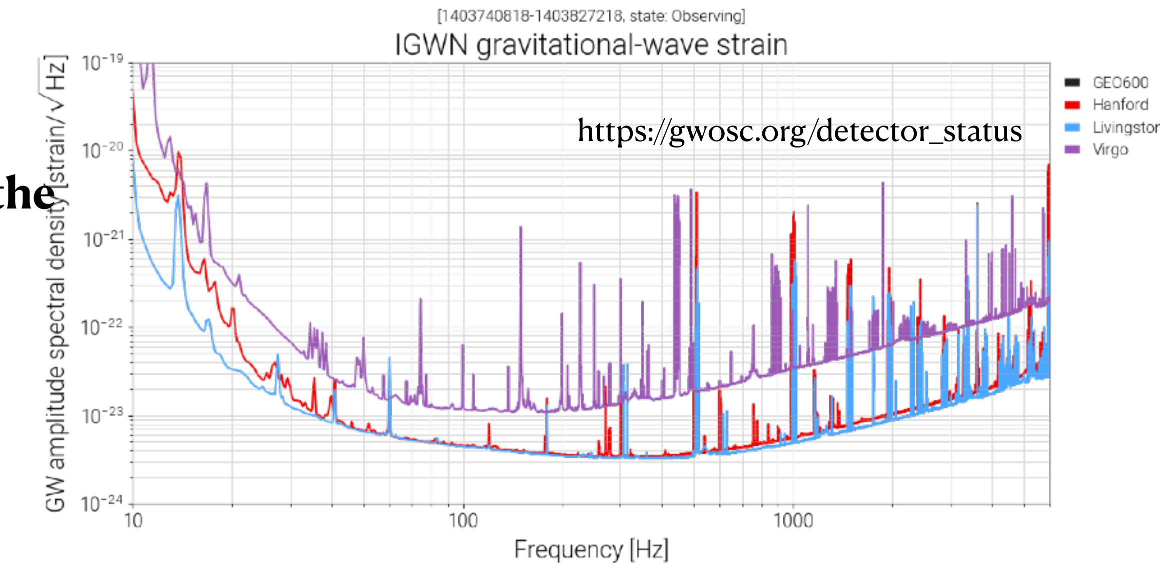
Simplified LVK workflow



Modified from Davis, D.; Walker, M., *Galaxies* **2022**, *10*, 12.

Calibration and detector characterization

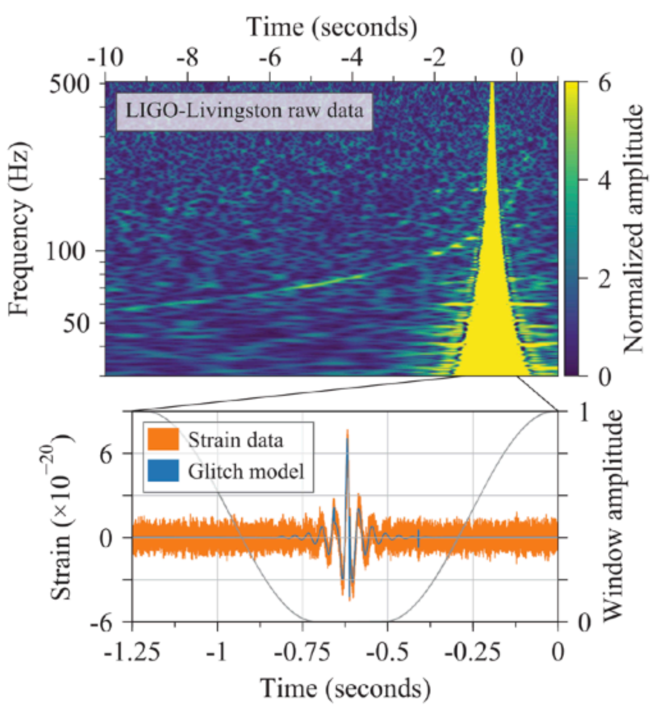
- The ITF is controlled via control loops to be kept on a working point
- The interferometer needs to be calibrated to go from e**xcess power in the output photodiode** to **mirror displacement** caused by GW passage
- Total h(t) uncertainties during O3b for LIGO/Virgo in the most sensitive frequency band 20–2000 Hz
  - **5- 10% in magnitude** and **2-9 deg in phase** (depending on the ITF, *CQG* 37.22 (2020): 225008., *CQG*39.4 (2022): 045006)



https://gwosc.org/detector_status

- **Data quality can be impacted by noises with very different morphologies!**

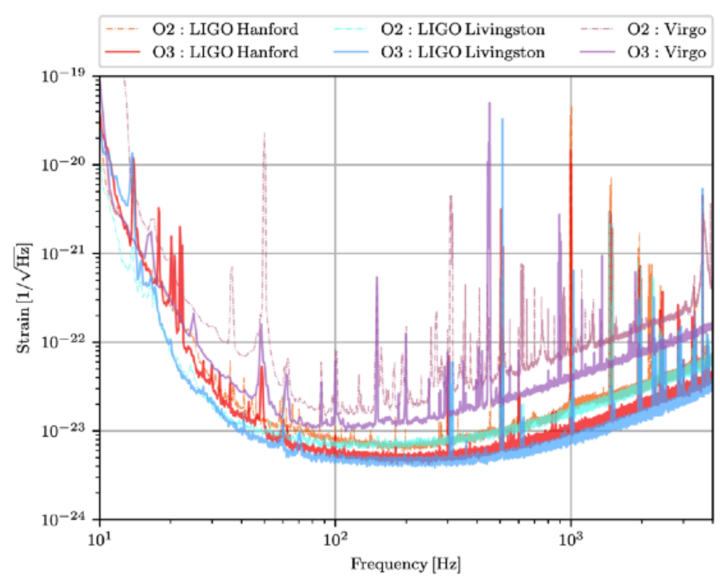
Glitches



GW170817, *PRL*, 119.16 (2017): 161101

Lines

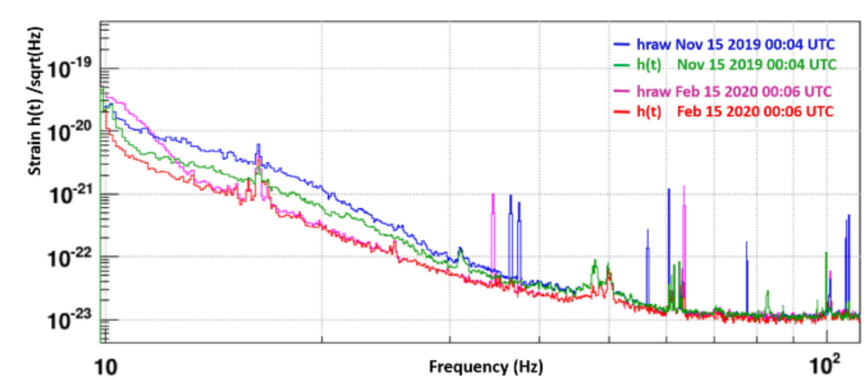
Identification of lines as part of noise hunting effort



*CQG*38.13 (2021): 135014

Broadband

~7 Mpc improvement with linear noise subtraction (O3, Virgo)



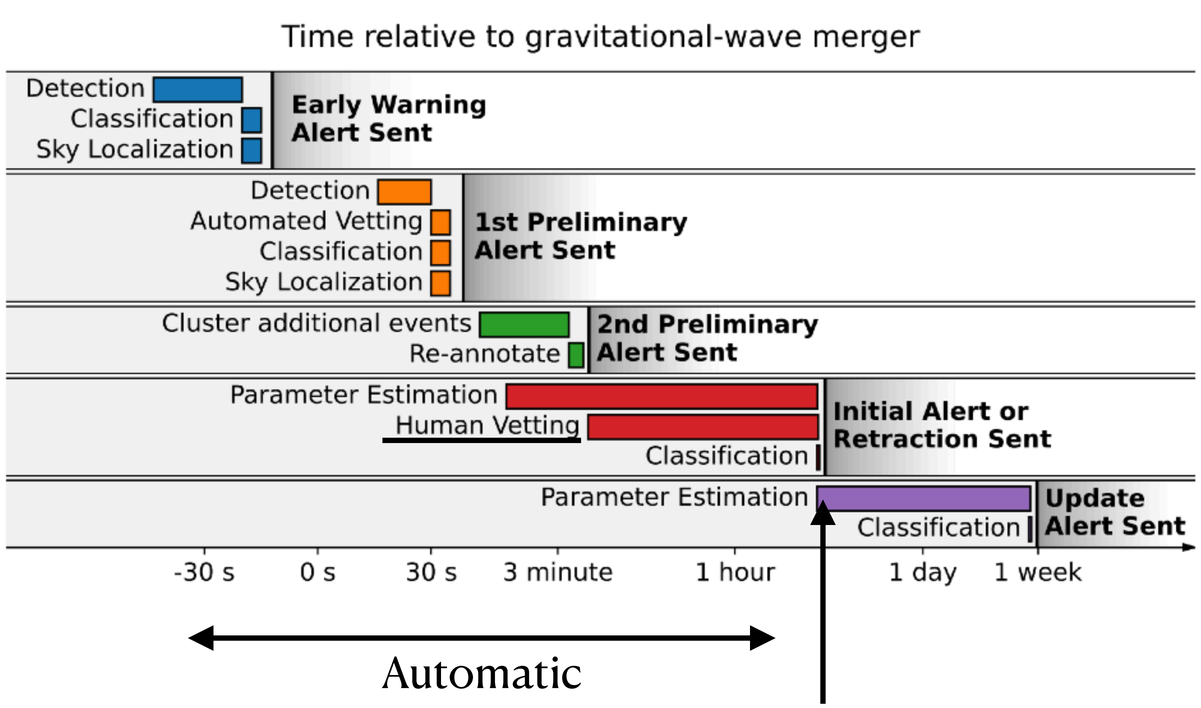
CQG 39.4 (2022): 045006

Rapid Response Team

- Composition of the RRT team ("Humans in the loop"): **commissioning, computing, and calibration experts** from each of the detector sites, pipeline experts, detector characterization experts, and follow-up advocates.
- Role: Check results of the Data Quality Report, lead the discussion, write the Initial GCN or Retraction
  - All processes are highly automated (DQ checks, GCN templates)
  - Optimized rota: 2-3 people on three different timezone (Asia, Europe, America)

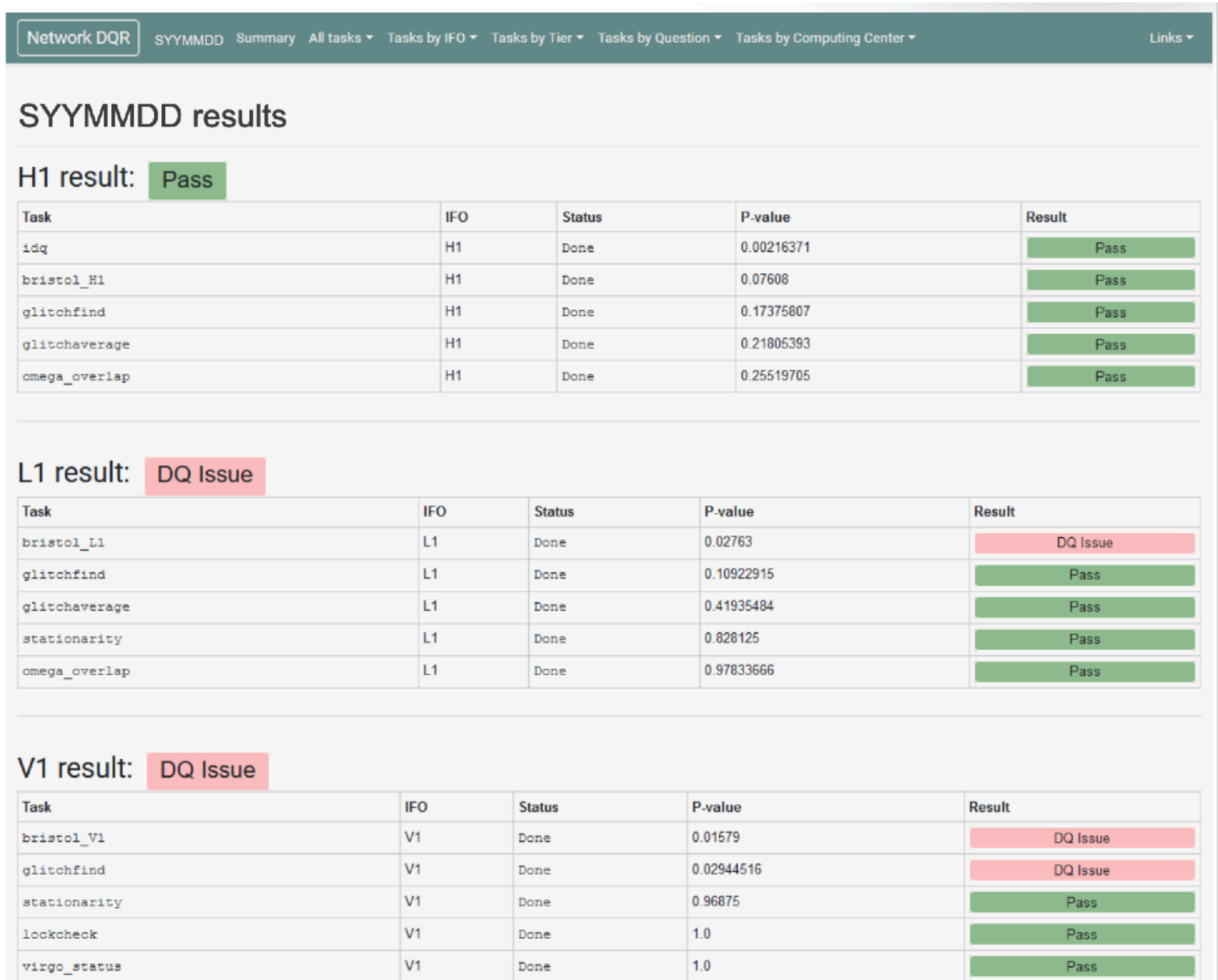
Main DQ checks:

- Status of the detector and subsystems
- Data Quality flags
- Noise characterization: stationarity and Gaussianity, glitches and their distribution; correlation with auxiliary channels; status of the environment,



Data Quality Report

F Di Renzo, ICHEP 2024


Network DQR | SYYMMDD | Summary | All tasks | Tasks by IFO | Tasks by Tier | Tasks by Question | Tasks by Computing Center | Links

SYYMMDD results

H1 result: Pass

Task	IFO	Status	P-value	Result
idq	H1	Done	0.00216371	Pass
bristol_H1	H1	Done	0.07608	Pass
glitchfind	H1	Done	0.17375807	Pass
glitchaverage	H1	Done	0.21805393	Pass
omega_overlap	H1	Done	0.25519705	Pass

L1 result: DQ Issue

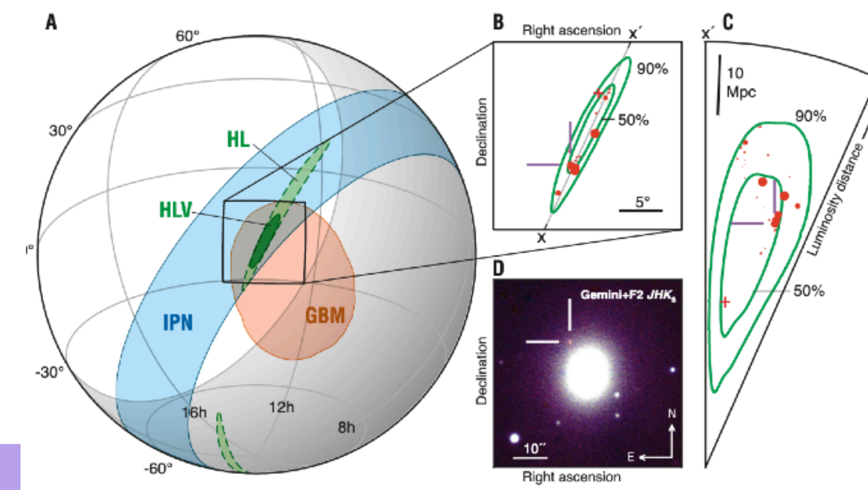
Task	IFO	Status	P-value	Result
bristol_L1	L1	Done	0.02763	DQ Issue
glitchfind	L1	Done	0.10922915	Pass
glitchaverage	L1	Done	0.41935484	Pass
stationarity	L1	Done	0.828125	Pass
omega_overlap	L1	Done	0.97833666	Pass

V1 result: DQ Issue

Task	IFO	Status	P-value	Result
bristol_V1	V1	Done	0.01579	DQ Issue
glitchfind	V1	Done	0.02944516	DQ Issue
stationarity	V1	Done	0.96875	Pass
lockcheck	V1	Done	1.0	Pass
virgo_status	V1	Done	1.0	Pass

GW alerts: distribution and content

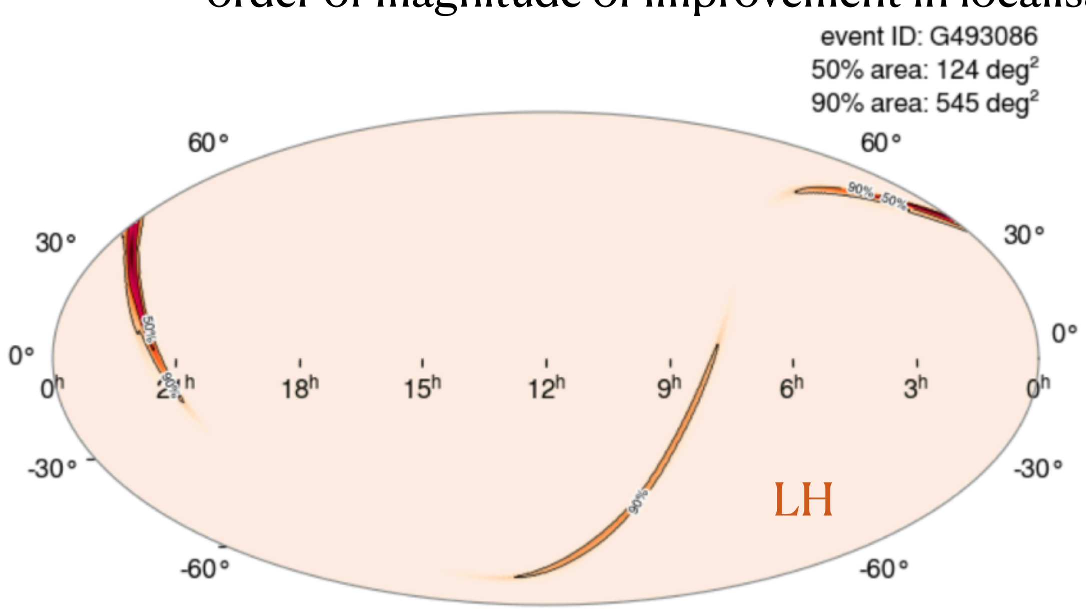
Kasliwal, Nakar, Singer+ 2017, Science



- **Types**: GW candidates , GW+ Coincidences: Fermi, Swift, INTEGRAL, SNEWS, LLAMA (IC)
- Notices distributed via:
  - JSON-serialized Kafka Notices (via GCN)
  - Avro-serialized Kafka Notices (via SCIMMA)
  - VOEvent Notices (via GCN Classic)
- Information inferred for the GWs:
  - Properties of the signal
  - False Alarm Rate
  - Detectors

CBC (with EW)	Burst
Classification (BH, NSBH, BNS, Terrestrial)	Duration
HasNS, HasRemnant, HasMassGap	Central frequency

  - Localization: Remarkably good sky localisations in many recent 3-interferometer events!
    - **Loud events with favourable source position**
    - ~ order of magnitude of improvement in localisation: from ~thousands to tens of squared degrees!



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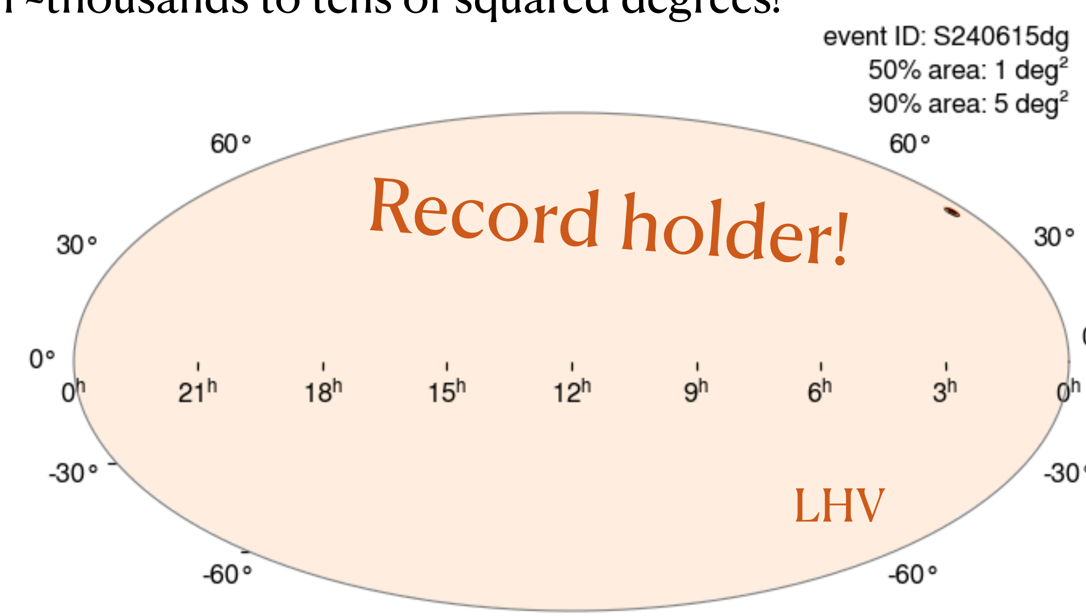
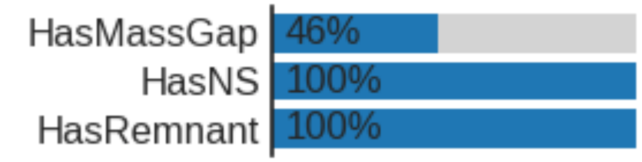


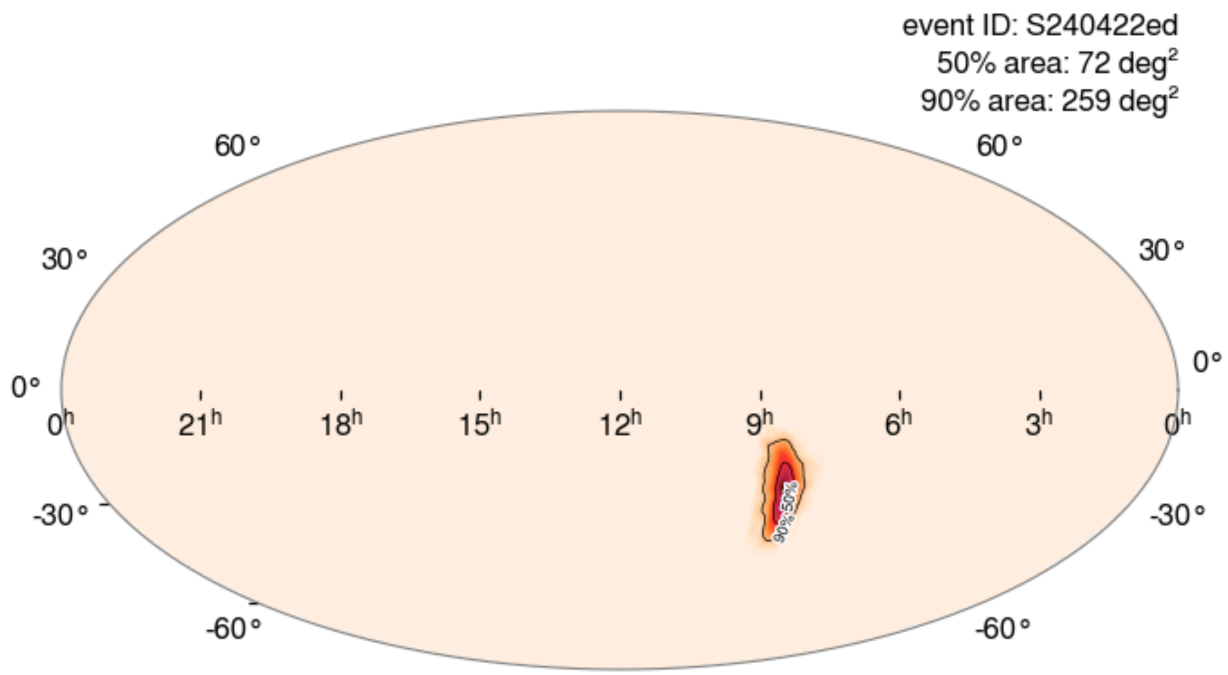
https://emfollow.docs.ligo.org

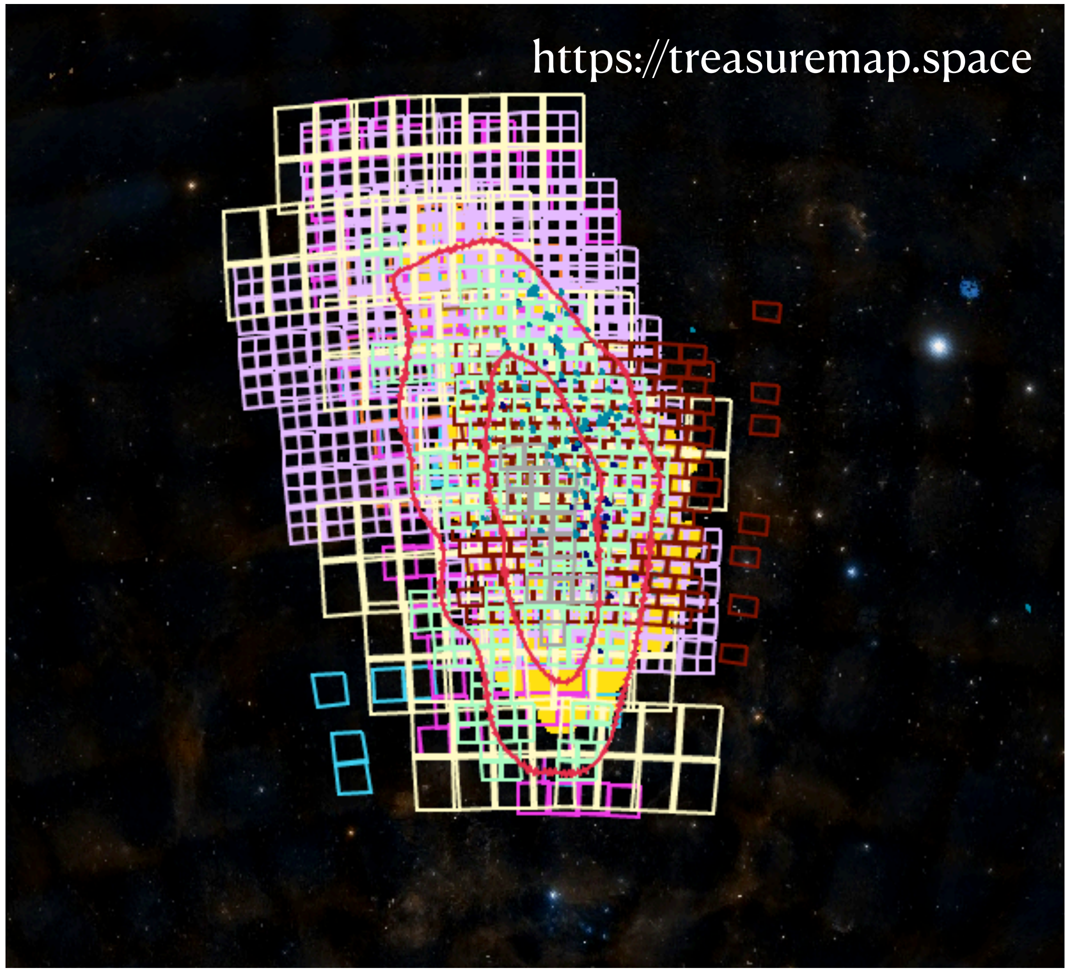
Multi-messenger campaign on NSBH during in O4b



- GW S240422ed (LHV): FAR 1/10^{5}years, distance 188+-43Mpc
  - NSBH, candidate to to show tidal disruptions and potentially power an EM counterpart
- Galaxy host identification:
  - Galaxy catalogs quite complete at this distance (GLADE+ ~85% in K-band Schechter function)
  - BUT! Localisation is on the GP: very incomplete regions in galaxy catalogs
- Very extensive multi-messenger campaign: **93 Circulars in GCN.** Several candidates in x-rays, optical, none confirmed

RETRACTED :(

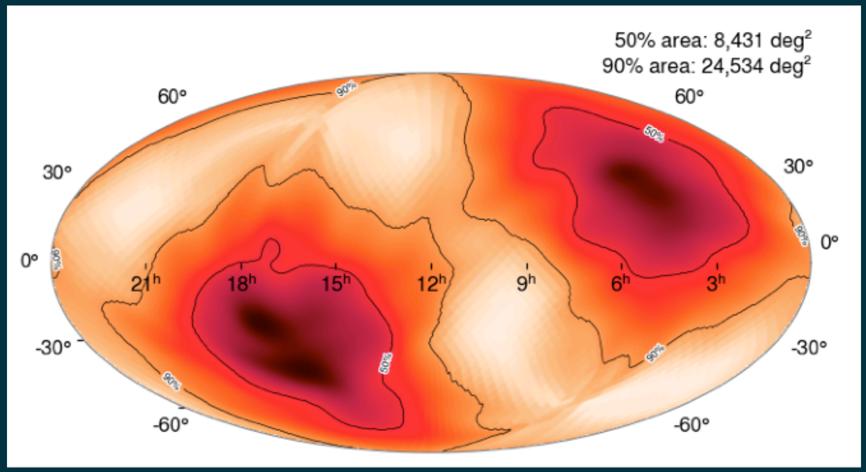


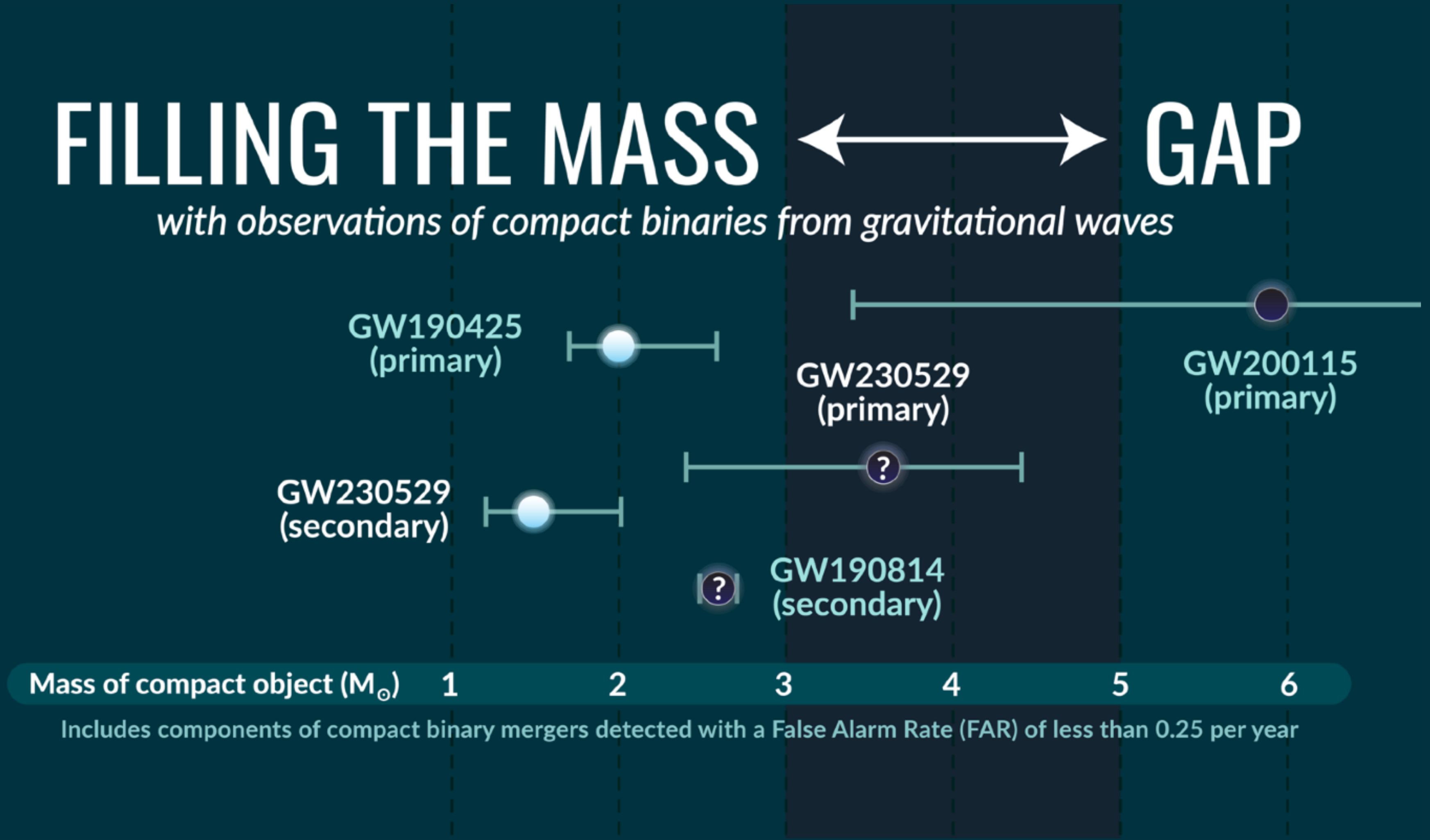


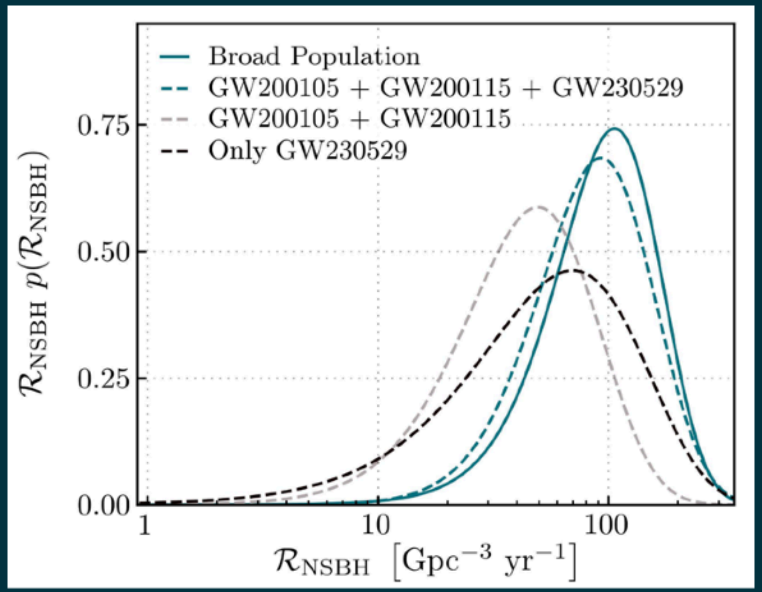
Early science results from O4: NSBH GW230529

- Coalescing compact binary with component masses 2.5–4.5 M⊙ and 1.2–2.0 M⊙ (90% credible level)
- Most symmetric NSBH so far!
- Livingston-only event: 50% of ~8000 sq.deg, FAR <1/1000 yr
- Evidence for compact objects existing within the lower mass gap
- Increase in the expected rate of NSBH with potential EM counterparts

Astrophys. J. Lett. **970**, L34 (2024)





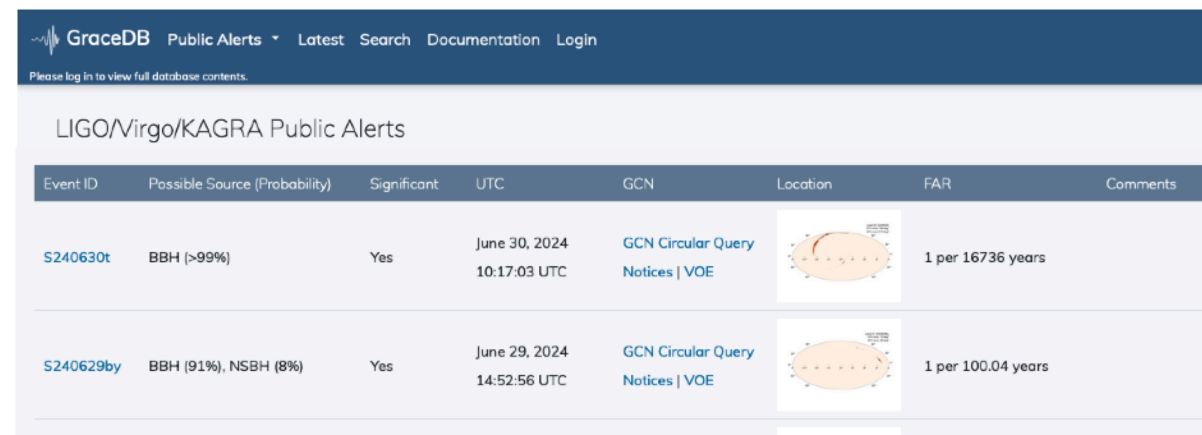


Stay tuned for results!

- *In preparation*: **Gravitational Wave Transient Catalog-4 (GWTC-4)** including results from O4a.
  - Offline analysis of data segments
  - Coordination between papers using same data sample: GRBs, astrophysical populations, isotropic backgrounds..
- Separated publications expected for special events.

GraceDB

- Information sent via GCN to the astro community
- **High-level** data uploaded by analysis pipelines
- Skymaps, ITF that provides data, FAR, event time, probabilities (pHasMassGap, pRemnant, pHasNS)
- Search engine allows for detailed queries



https://gracedb.ligo.org/

GWOSC: Gravitational Wave Open Science Center

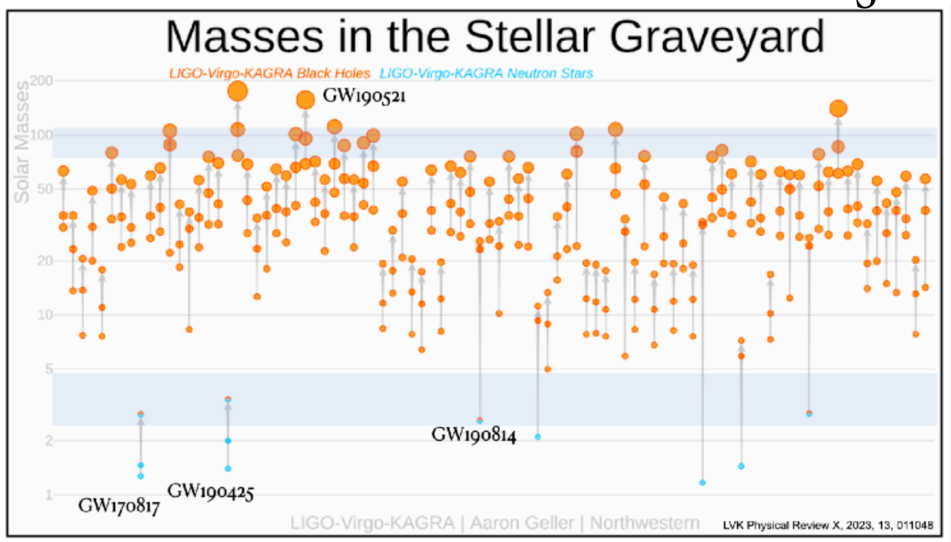
- Mid-level data: **Strain h(t) data passing quality cuts available from all LVKG interferometers after proprietary period**
- Release of data contact to specific publications
- Tutorials and Software for GW data analysis available
- 7th GW Open Data Workshops (hybrid): April 2024 edition hosted in Taiwan

https://www.gw-openscience.org

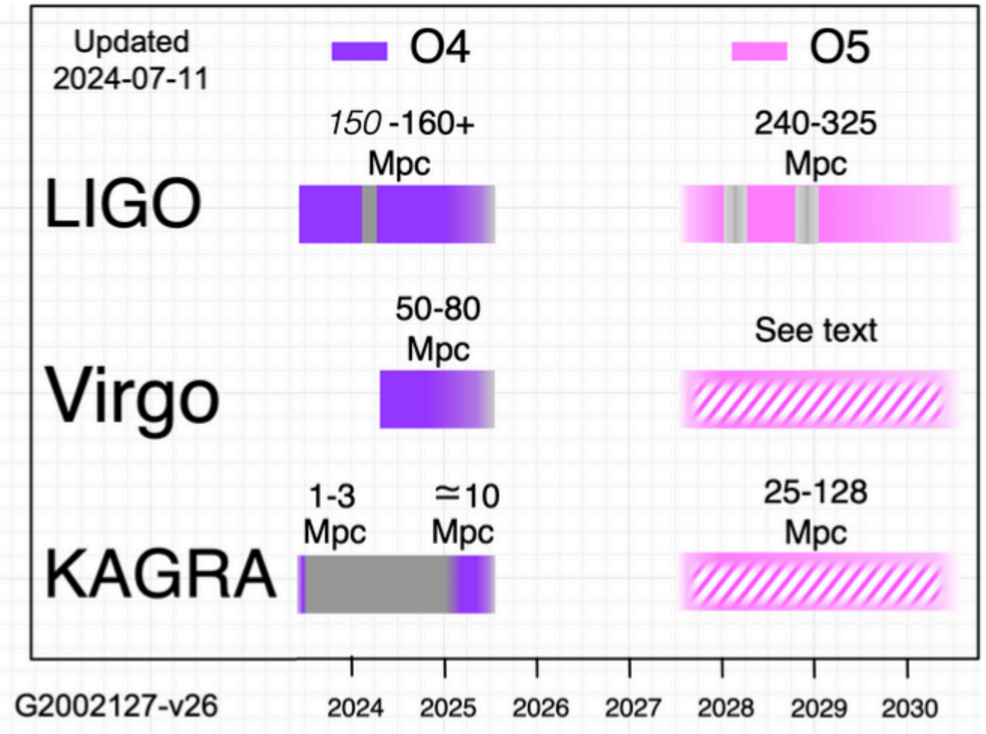
What's next?

- From O1- nowadays: **LVK unveiling the GW sky between 10's Hz-kHz!**
- O4 commissioning : **GW interferometers are very complex machines!**
- O4: **total of 24 months of data!**
  - **O4b ~ year of 3-ITF, eventually 4-ITF network!**

GWTC-3-1



- Goal for O5: Long observing run of ~3 **years** with commissioning gaps
- Current best understanding of the long-term observing schedule (note 26 versions of the plot !)
- Virgo interferometer: Marginally-stable recycling cavities (Signal Recycling and Power Recycling) are a structural weakness
  - LIGO&KAGRA run with stable recycling cavities
  - Stable recycling cavities: Assessment of the best optical layout modification **ongoing**
- **PostO5**: push the infrastructure as much as possible (x2 BNS range) with very good duty cycle



Acknowledgements

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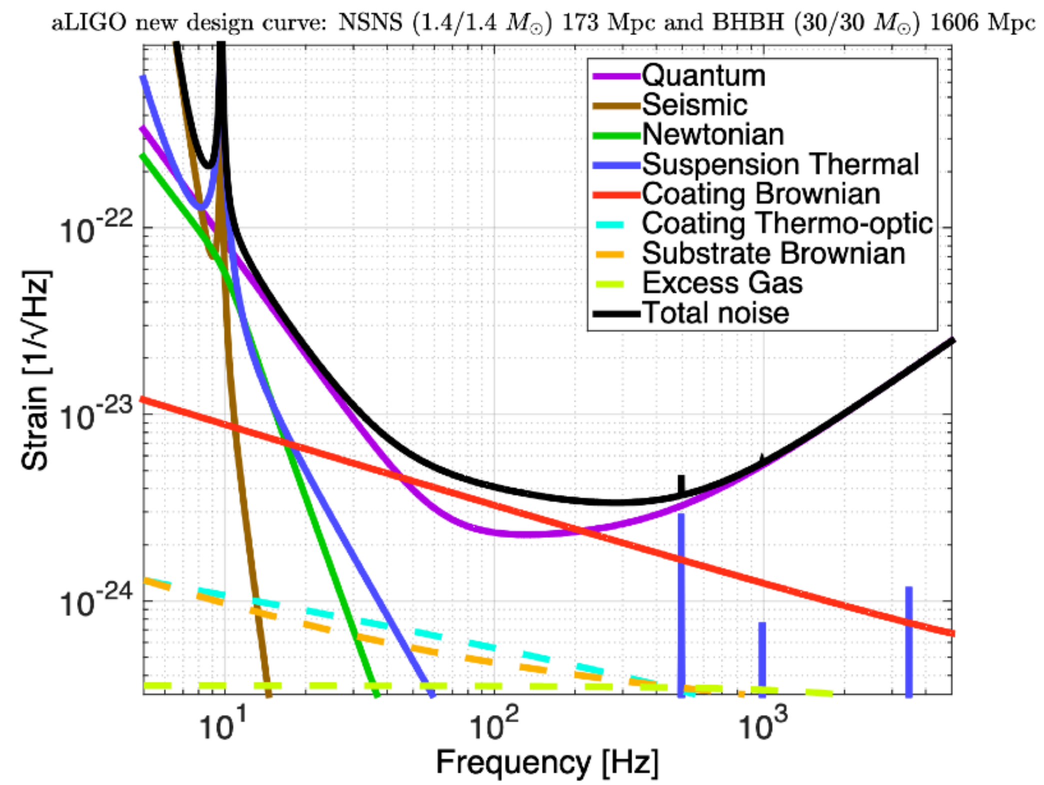
Thanks for your attention!

Back-up

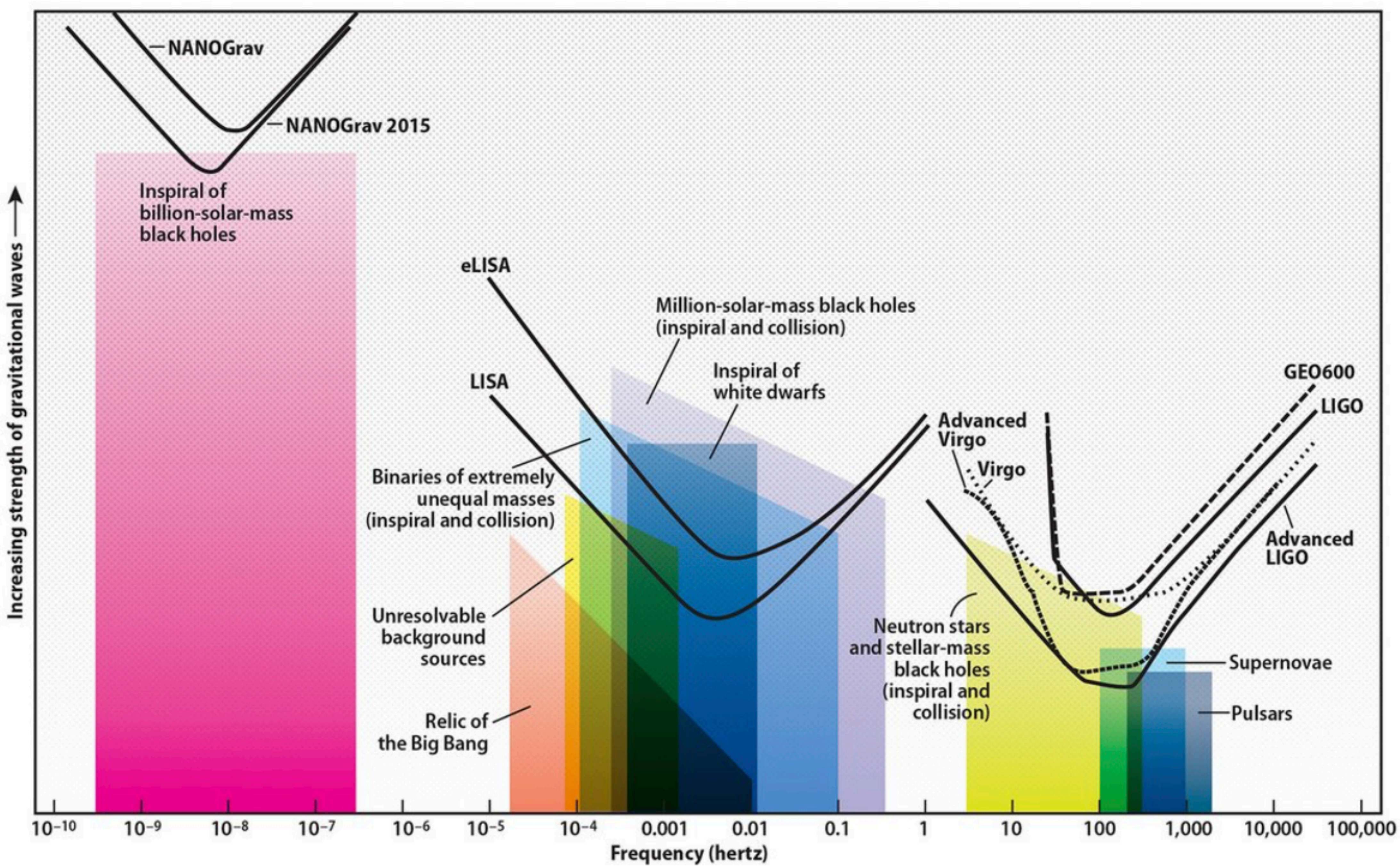
Limiting set of noises of ground-based ITF

- **The sensitivity curve: sum of fundamental and technical noises**
- **Quantum noise:** shot noise (dominant at high f) and radiation pressure (dominant at low f)
- **Seismic noise:** Movement coming from ground motion.
- **Newtonian noise** is instead produced by the tiny fluctuations of the Earth's gravitational field
- **Thermal noise:** Brownian motion at ambient temperature of all the material in the detector, mostly coming from suspensions and test masses, causing random vibrations of the mirror surface.
- **Excess gass**: residual particules in the ultra-high vacuum interact with laser
- **Technical noises:**
  - Scattered light, magnetic, controls, laser frequency and power,, air molecules in the tubes, electronic noises of photodiodes and electronics, natural environment (earthquakes, high wind, sea activity..)
  - Tackled during **noise hunting campaigns**.

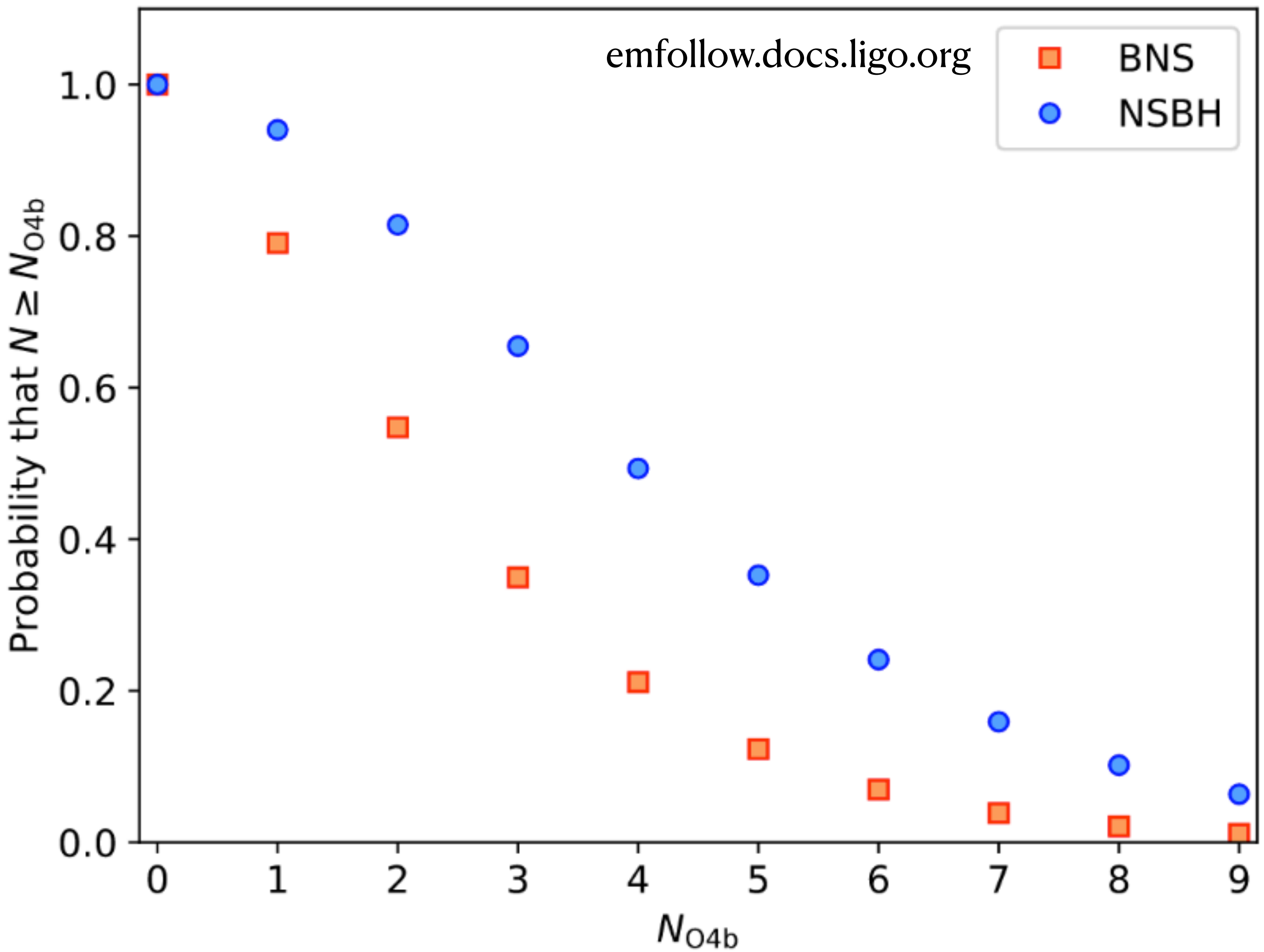


https://dcc.ligo.org/LIGO-T1800044/public

Sensitivity



Where are the BNS?



CBC analysis pipelines

From F Di Renzo, ICHEP 2024

Search type	Pipeline	Description
Modeled	gstlal	Matched-filter pipeline that evaluates the ratio of the likelihood of a given signal SNR and noise residual over the same quantity for noise only data
	MBTA	Uses the matched filter technique, but splits it in two frequency bands to reduce the computational cost.
	PyCBC	Matched reweighted by imposing the consistency of the signal over various frequency bands. Time-slides method for the background estimate
	SPIIR	Applies GPU empowered summed parallel infinite impulse response (IIR) filters to approximate matched-filtering results
Unmodeled	WB	Searches for coincidences in multiple detectors on the time-frequency data obtained with a wavelet transform
	oLIB	Time-frequency domain search over planes of constant Q factor
Coincident searches	RAVEN	Coincidences between GW events and GRBs and galactic SN alerts
	LLAMA	Combines GW triggers with High Energy Neutrino (HEN) triggers from IceCube

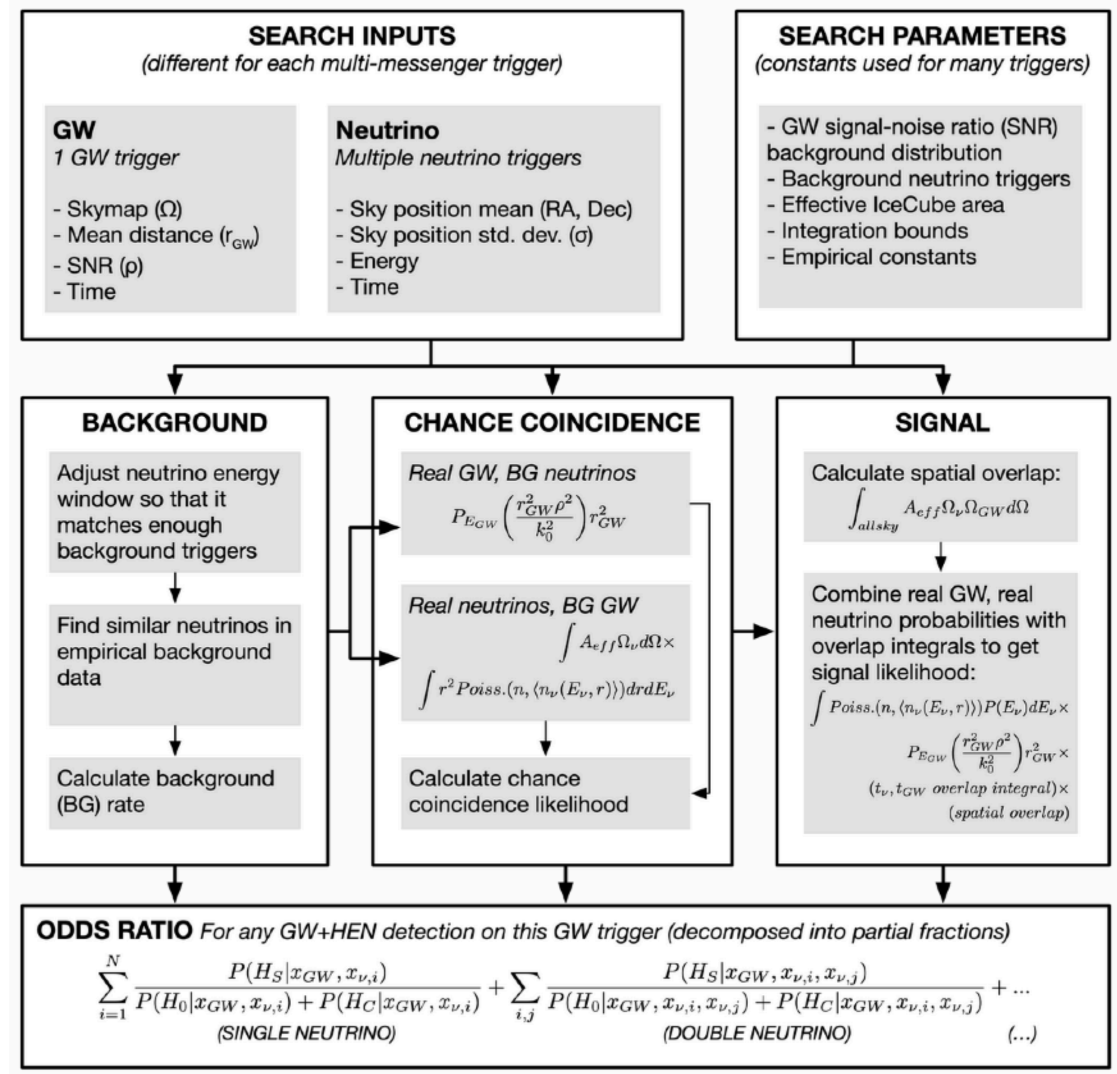
+ **MLy**, the machine-learning-based burst search pipeline

About coincidences

RAVEN

Event Type	Time window (s)		Notice Type Considered (see full list)
	CBC	Burst	
GRB (*Fermi*, *Swift*, *INTEGRAL*, *AGILE*)	[-1,5]	[-60,600]	FERMI_GBM_ALERT FERMI_GBM_FIN_POS FERMI_GBM_FLT_POS FERMI_GBM_GND_POS SWIFT_BAT_GRB_ALERT SWIFT_BAT_GRB_LC INTEGRAL_WAKEUP INTEGRAL_REFINED INTEGRAL_OFFLINE AGILE_MCAL_ALERT
SubGRB (*Fermi*)	[-1,11]	[-1,11]	FERMI_GBM_SUBTHRESH
SubGRBTargeted (*Fermi*)	[-1,11]	[-1,11]	via Kafka alert
SubGRBTargeted (*Swift*)	[-10,20]	[-10,20]	via Kafka alert
Low-energy Neutrinos (*SNEWS*)	[-10,10]	[-10,10]	SNEWS

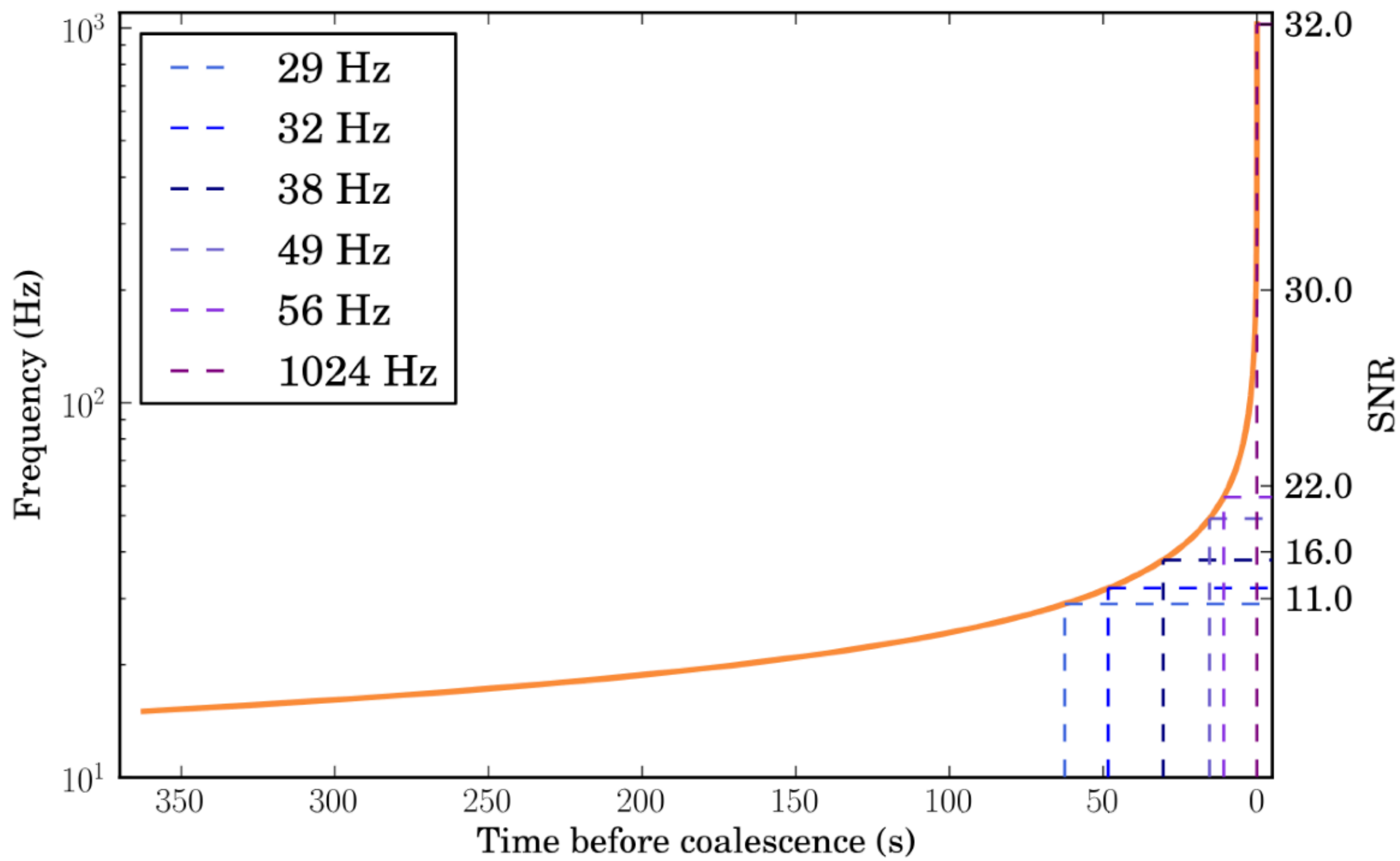
LLAMA

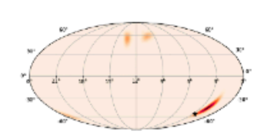
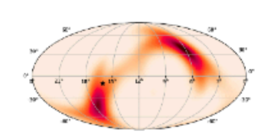
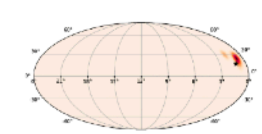


Flowchart describing the significance calculation used in the O3 version of the pipeline.

Early Warning Alerts

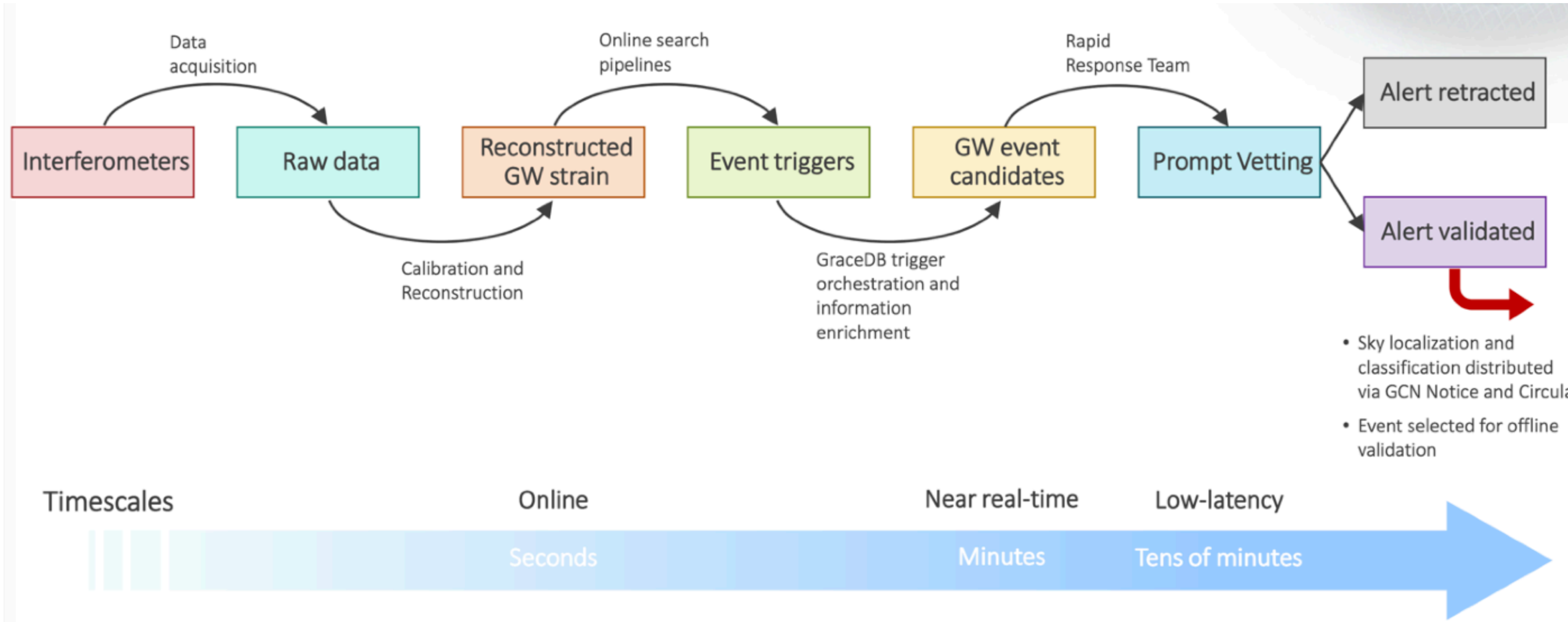
All CBC search pipelines (GstLAL [2], MBTA, PyCBC [3], and SPIIR [4])



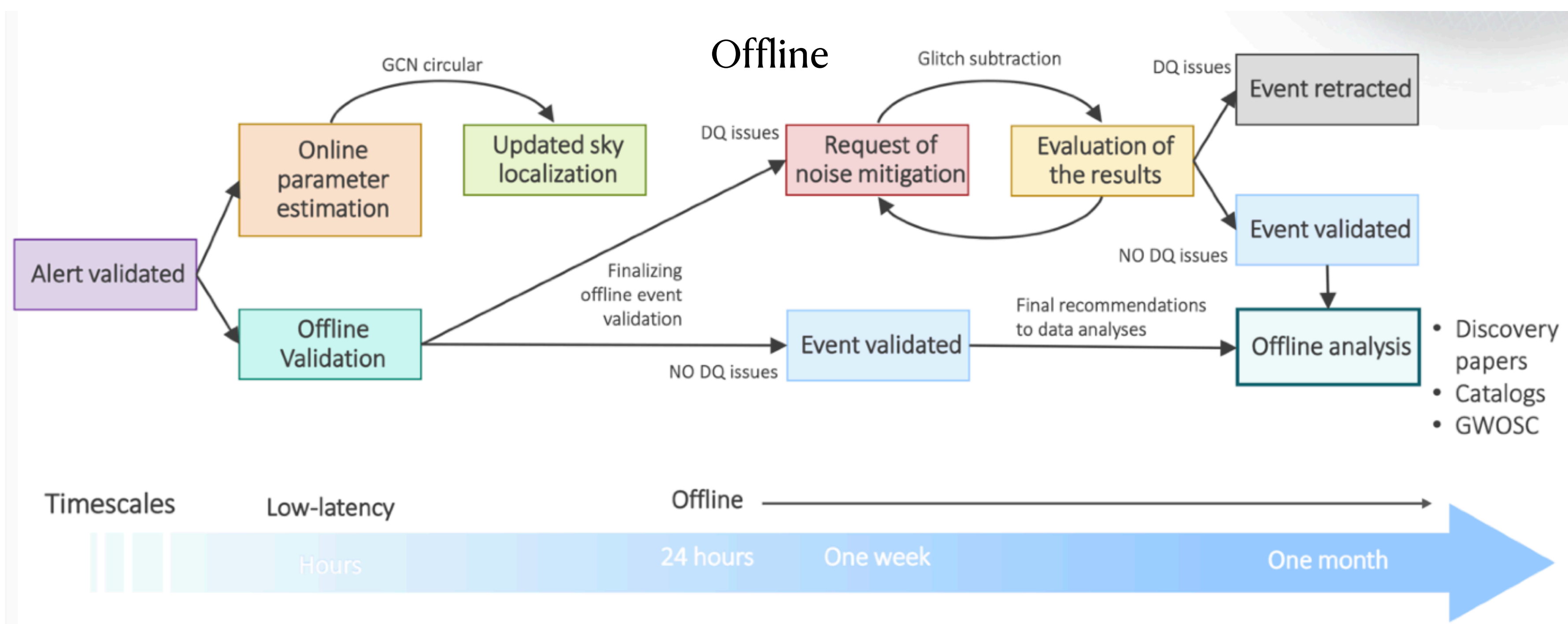
Final SNR	**11**	**18**	**25**
Distance	**250 Mpc**	**210 Mpc**	**160 Mpc**
Sky map (animated GIF)			
Frequency	**Localization accuracy** (90% credible area)		
29 Hz	Not detected	Not detected	12000 deg^2
32 Hz			10000 deg^2
38 Hz		9200 deg^2	8200 deg^2
49 Hz	2300 deg^2	1000 deg^2	730 deg^2
56 Hz	1000 deg^2	700 deg^2	250 deg^2
1024 Hz	10 deg^2	31 deg^2	5.4 deg^2

Latency of online/offline searches

Online



Offline



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