Astrophysical Searches in the LIGO-Virgo-KAGRA O4 Observational Campaign

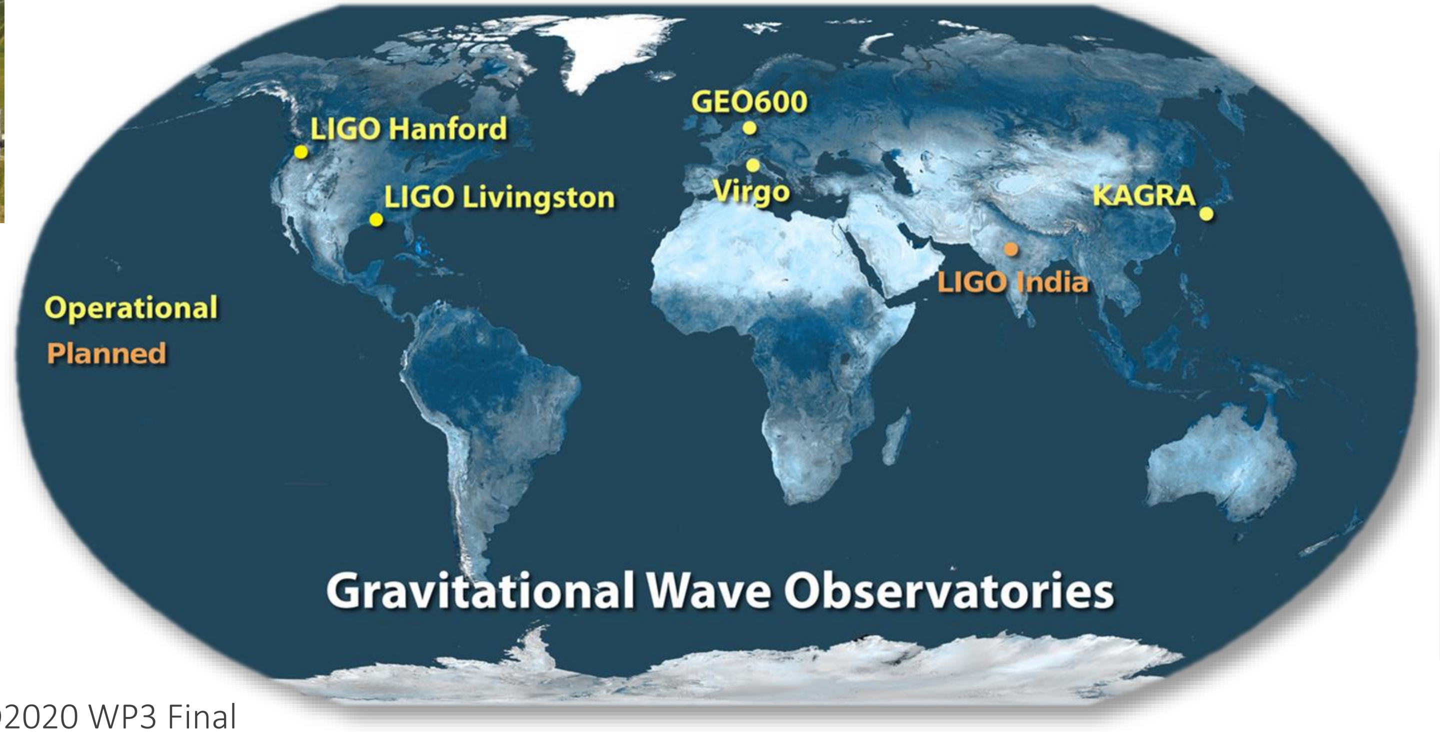
Francesco Di Renzo, IP2I Lyon
f.di-renzo@ip2i.in2p3.fr

AHEAD 2020
HIGH ENERGY ASTROPHYSICS

Aerial view of the Virgo interferometer
Credit: Virgo Collab.

LIGO VIRGO KAGRA
cnrs
iP2i LES 2 INFINIS LYON

The global network of gravitational-wave detectors



The LVK in numbers

LIGO Scientific Collaboration

- Founded in 1989
- 127 institutions
- 1600 individuals
- 19 countries

Virgo Collaboration

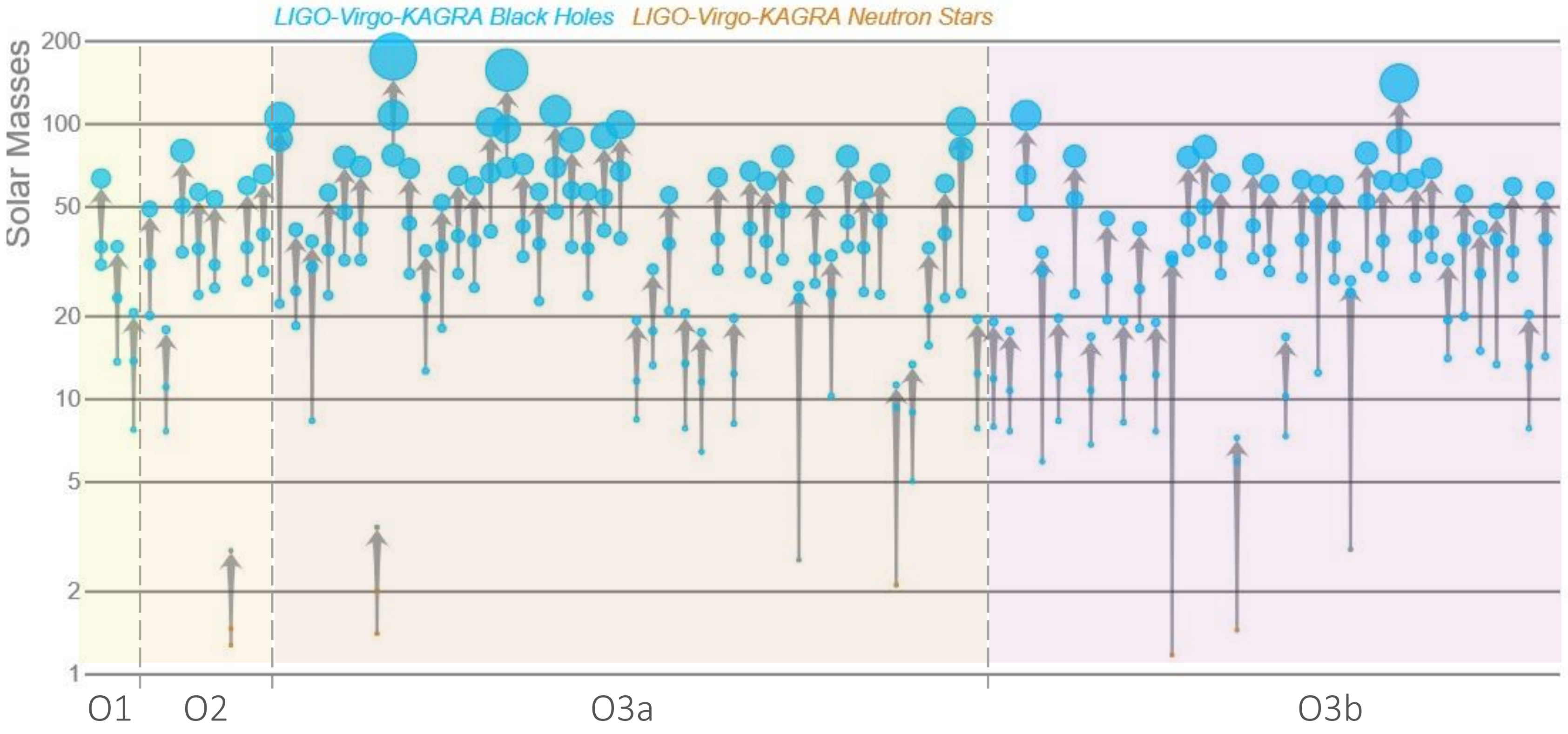
- Founded in 1993
- 150 institutions
- 900 individuals
- 17 countries

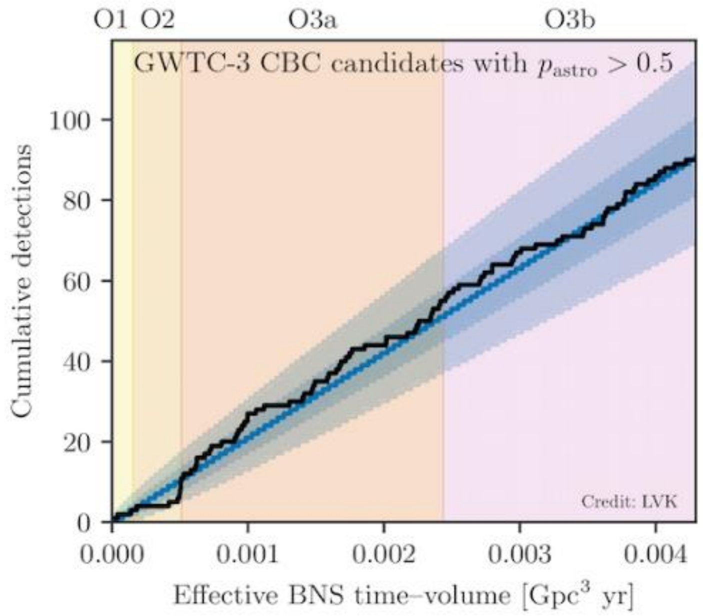
KAGRA Collaboration

- Founded in 2010
- 130 institutions
- 400 individuals
- 17 countries

Compact binary observations by LIGO and Virgo

Masses in the stellar graveyard

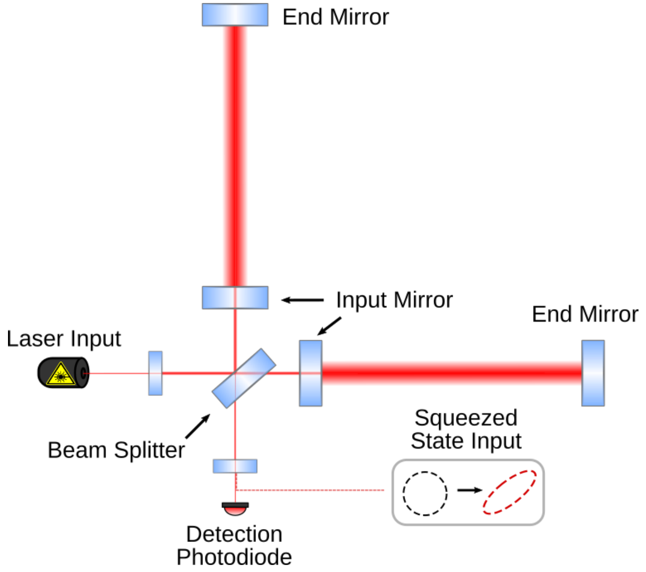


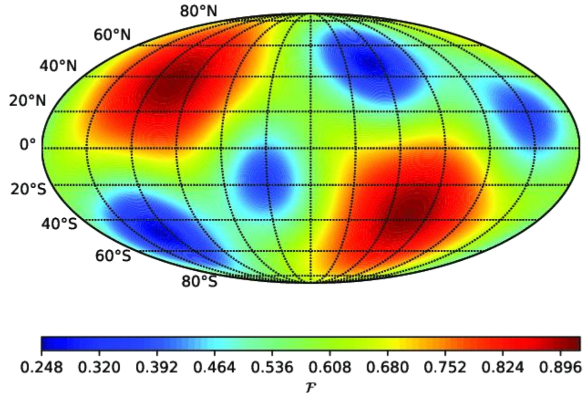


arXiv:2111.03606

Credit: Visualization: LIGO-Virgo-KAGRA / Aaron Geller / Northwestern

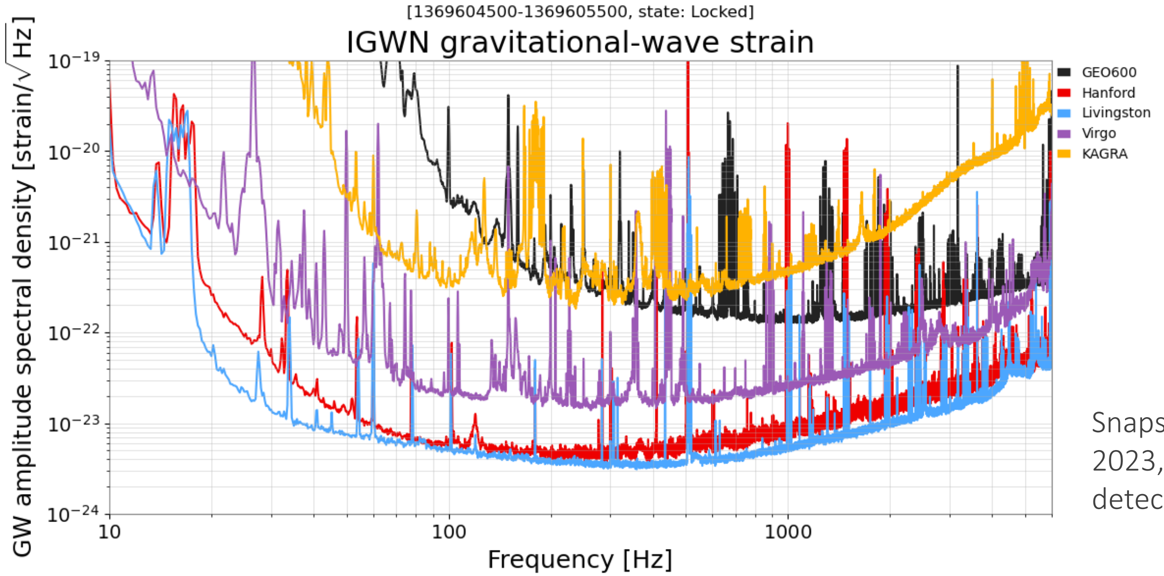
Ground-based interferometric GW detectors





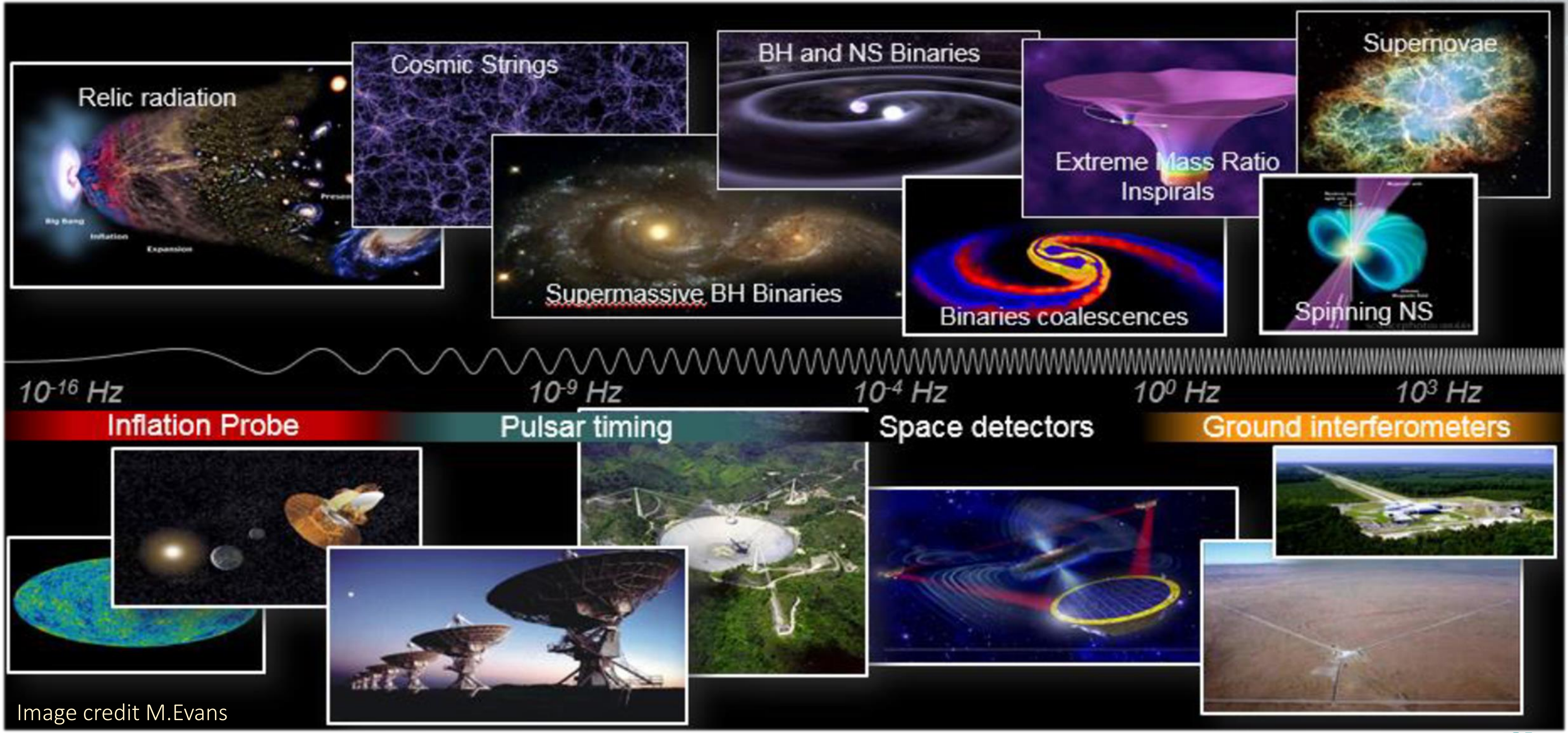
Antenna pattern function of a single detector

- **Modified Michelson interferometer** optical layout: they measure the perturbation of spacetime of an incoming GW from the differential **strain** ($\delta L/L \sim 10^{-21}$) induced on the detector arms and the corresponding phase shift
- The detector sensitivity is determined by their **noise sources**, namely everything of no astrophysical origin that can produce a strain
- These **detectors are non-directional**. We need a network of detectors to triangulate the sky localization of the GW signal source.



Snapshot of May 31, 2023, with three detectors

Sources and detectors

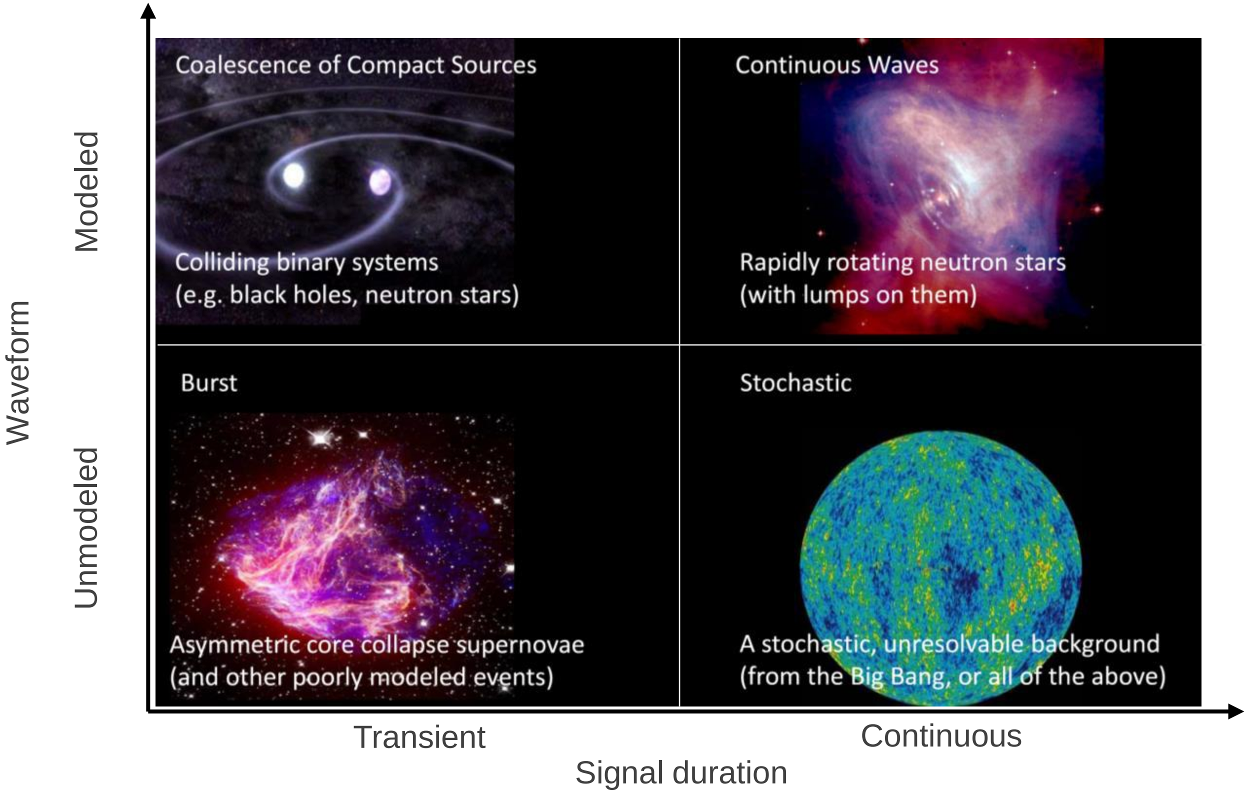


Sources for ground-based detectors

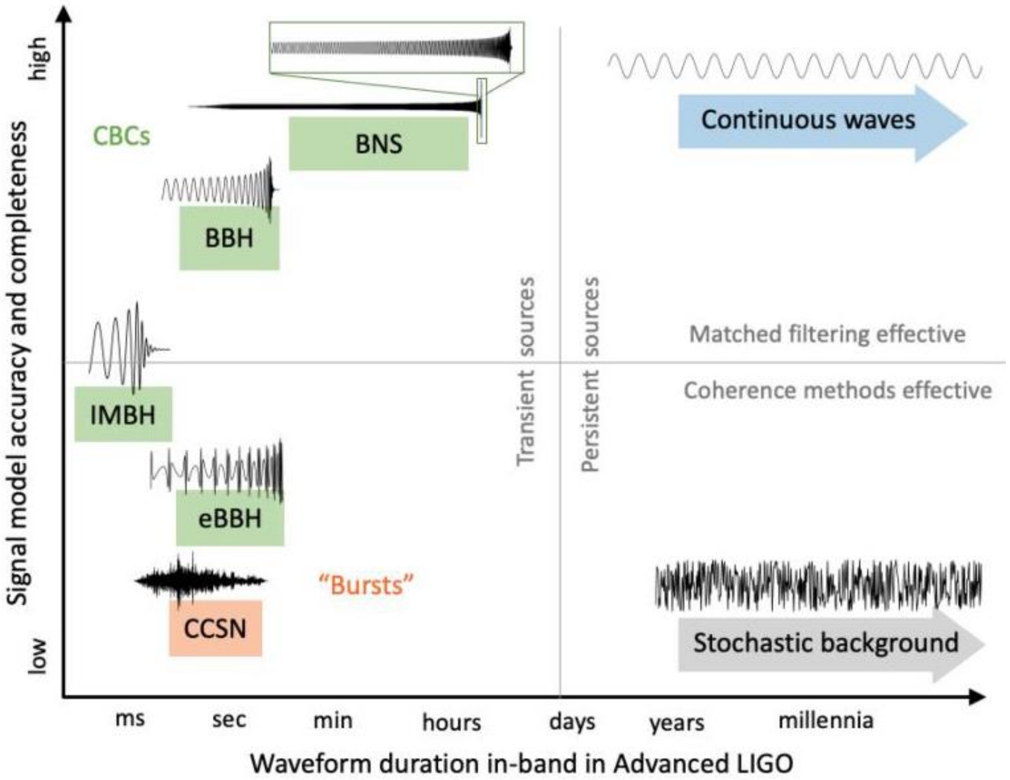
Typical search strategies:

- **Matched filter** based for well modeled sources
- Excess energy identification and **coherence** of the signal among multiple detectors for poorly modeled ones.

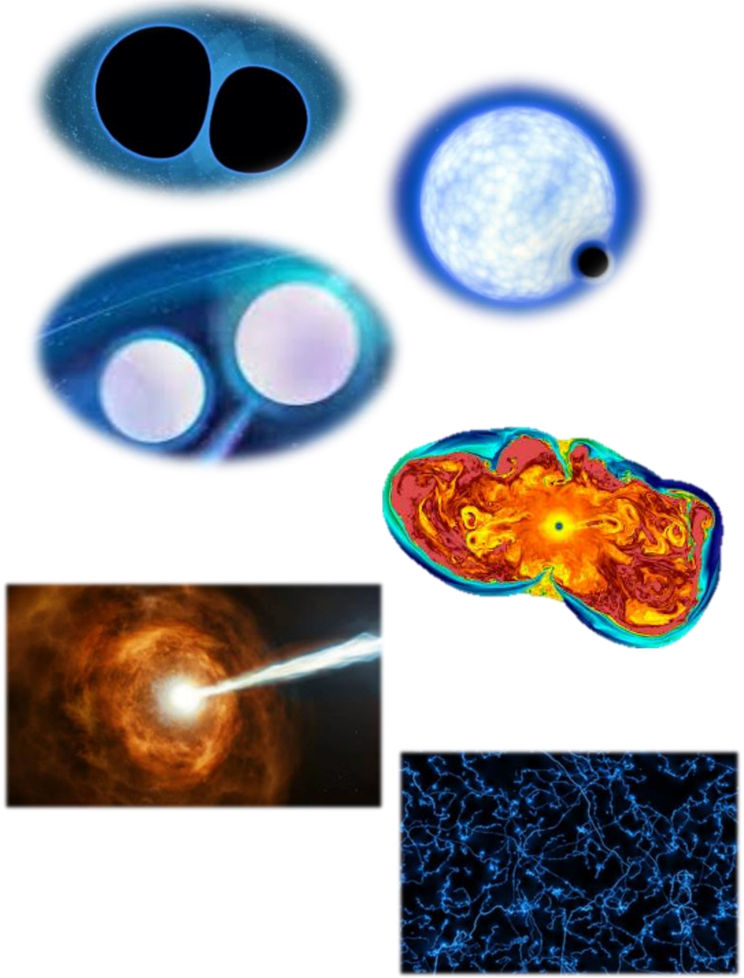
GW sources (rough) classification



GW source waveform classification



Transient sources



Compact Binary Coalescences

- Binary star systems made of black holes (BHs) and neutron stars (NSs): BBH, NSBH, BNS. GWTC-3
- Sub-Solar Mass (SSM) objects, MNRAS **524**, 5984 (2023)

Unmodeled or poorly modeled burst signals

- Core-collapse supernovae (CCSNe)
- Magnetar bursts
- Signals associated with fast radio bursts or gamma-ray bursts
- Cosmic strings cusps and kinks
- …

Online GW transient search pipelines

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 Multi-Band Template Analysis	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	cWB	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
	MLy PIPELINE	Machine-learning based search for coincident, simultaneous transient signals
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

The low-latency pipeline:
Be prepared for the next GW170817-like event!

The **Low-Latency** workflow, in brief:

A *significant* GW **signal candidate** is found by online search pipelines

→

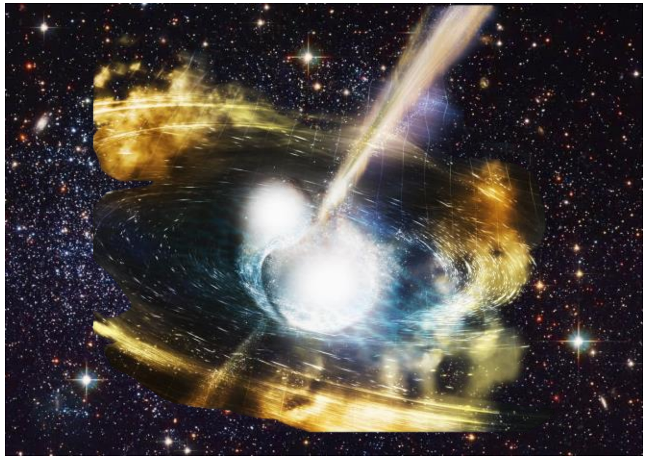
A **GCN alert** is sent to astronomers in order to search for counterparts (EM waves or neutrinos)

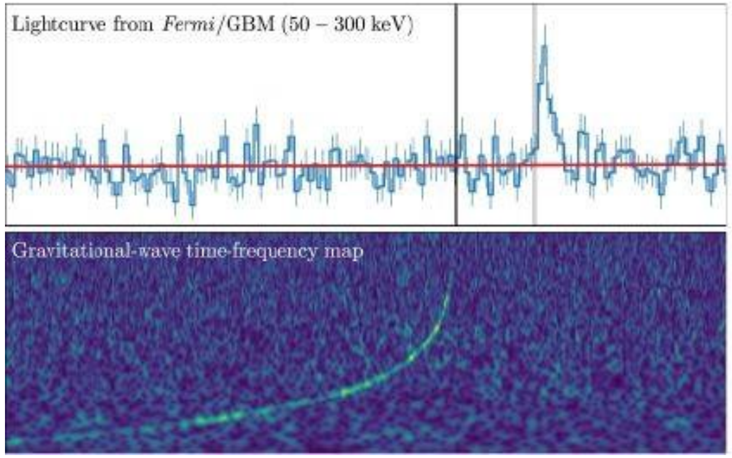
→

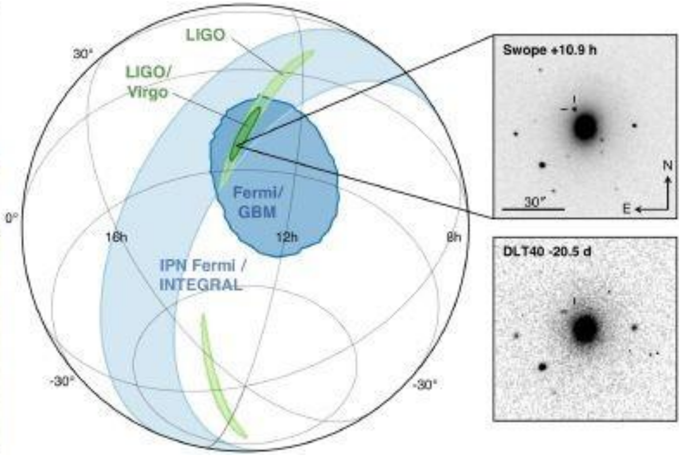
The **Rapid Response Team** provides rapid human vetting of low-latency alerts

→

- Foster multimessenger searches
- Trigger event validation and all downstream analyses







Astrophys.J.Lett. 848 (2017) 2, L12

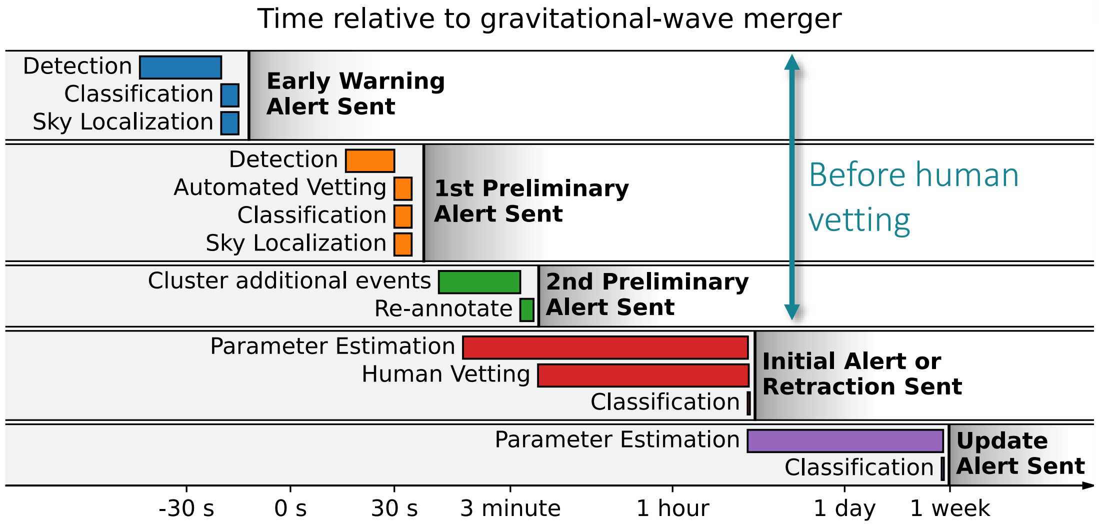
Event triggers, Superevents and alerts

- Search pipelines produce Events, with associated **SNR** and false alarm rate (**FAR**), which are uploaded to GraceDB
- **GWCelery** clusters events, possibly from different pipelines, on the basis of coalescence time for modeled searches, and trigger time for unmodeled searches, to Superevents
- The **preferred event** is identified on the base of FAR, SNR and search kind.

Alerts:

- **Low-significance:** preferred event FAR is < 2 per day; a “preliminary alert” is sent out but no human vetting
- **Significant event:** FAR < 1 per month* for modeled CBC candidates and < 1 per year* for unmodeled burst candidates.

Alert timeline



LVK Public Alerts Open Guide

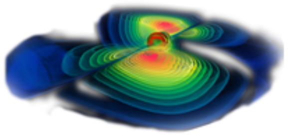
* **Alert threshold after trials factor:** to account for the trials factor from the different searches with statistically independent FARs, the event thresholds are corrected to 1 per 6 months and 1 per 4 years for CBC and bursts respectively.

The rapid response team and human vetting timeline

Rapid Response Team (RRT)

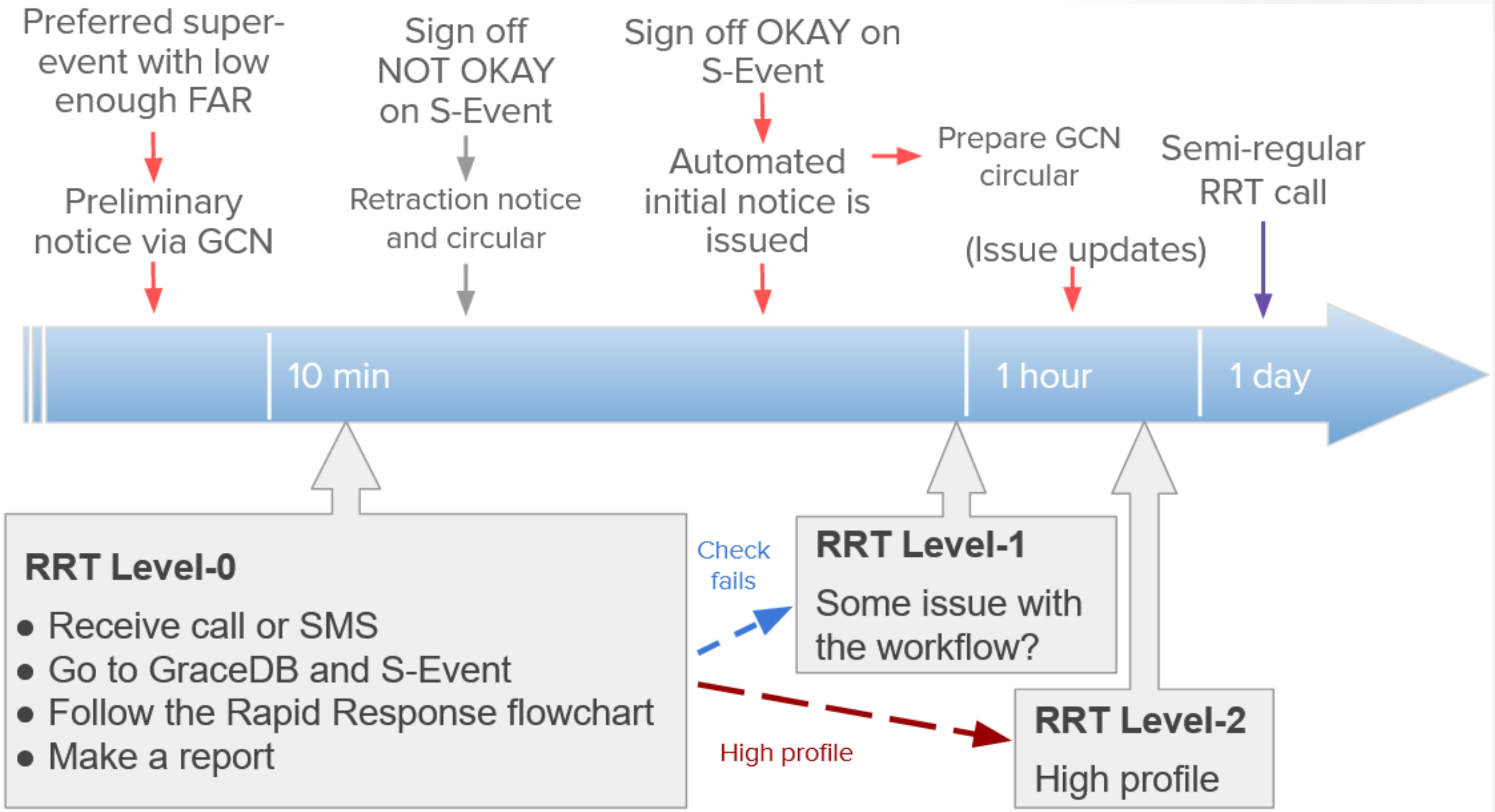
A joint LVK effort to provide human vetting to event alerts:

- Foster multimessenger searches
- Vet candidates with evidence of noise artefacts



Three tier system

- Level-0 shifters, online 24/7 over three shifts per day (almost 300 participants total)
- Level-1 experts of data quality and all the parts of the low-latency pipeline
- Level-2: all the above, called for vetting **high profile events.**



Notices and circulars, content of a GCN alert

```
//////////////////////////////////////////////////////////////////////
TITLE:            GCN/LVC NOTICE
NOTICE_DATE:      Thu 18 May 23 13:38:21 UT
NOTICE_TYPE:      LVC Preliminary
TRIGGER_NUM:      S230518h
TRIGGER_DATE:     20082 TJD;   138 DOY;   2023/05/18 (yyyy/mm/dd)
TRIGGER_TIME:     46748.000000 SOD {12:59:08.000000} UT
SEQUENCE_NUM:     1
GROUP_TYPE:       1 = CBC
SEARCH_TYPE:      1 = AllSky
PIPELINE_TYPE:    15 = pycbc
FAR:              3.219e-10 [Hz]  (one per 35957.2 days)  (one per 98.51 years)
PROB_NS:          1.00 [range is 0.0-1.0]
PROB_REMNANT:     0.00 [range is 0.0-1.0]
PROB_BNS:         0.00 [range is 0.0-1.0]
PROB_NSBH:        0.86 [range is 0.0-1.0]
PROB_BBH:         0.03 [range is 0.0-1.0]
PROB_MassGap:     -1 [range is 0.0-1.0]   VALUE NOT ASSIGNED!
PROB_TERRES:      0.09 [range is 0.0-1.0]
TRIGGER_ID:       0x10
MISC:             0x189A003
SKYMAP_FITS_URL:
https://gracedb.ligo.org/api/superevents/S230518h/files/bayestar.multiorder.fits
EVENTPAGE_URL:    https://gracedb.ligo.org/superevents/S230518h/view/
COMMENTS:         LVC Preliminary Trigger Alert.
COMMENTS:         This event is an OpenAlert.
COMMENTS:         LIGO-Hanford Observatory contributed to this candidate event.
COMMENTS:         LIGO-Livingston Observatory contributed to this candidate event
```

- Trigger time
- Search type
- Source classification
- EM-bright properties
  More details in the EM-follow guide
- Sky localization

GCN Circular 33813

Subject LIGO/Virgo/KAGRA S230518h: Identification of a GW compact binary merger candidate
Date 2023-05-18T14:06:25Z (5 months ago)
From f.di-renzo@ip2i.in2p3.fr

The LIGO Scientific Collaboration, the Virgo Collaboration, and the KAGRA Collaboration report:

We identified the compact binary merger candidate S230518h during real-time processing of data from LIGO Hanford Observatory (H1) and LIGO Livingston Observatory (L1) at 2023-05-18 12:59:08.167 UTC (GPS time: 1368449966.167). The candidate was found by the PyCBC Live [1], GstLAL [2], and MBTAOnline [5] analysis pipelines.

The LIGO detectors are currently operating in an "engineering run" mode prior to the start of the O4 observing run. The data being collected at the time of this candidate is believed to be of good quality based on preliminary checks, but requires further investigation. A decision was made to alert the community promptly, with this caveat, due to the potential significance of this candidate.

S230518h is an event of interest because its false alarm rate, as estimated by the online analysis, is 3.2e-10 Hz, or about one in 98 years. The event's properties can be found at this URL:
https://gracedb.ligo.org/superevents/S230518h

The classification of the GW signal, in order of descending probability, is NSBH (86%), Terrestrial (10%), BBH (4%), or BNS (<1%).

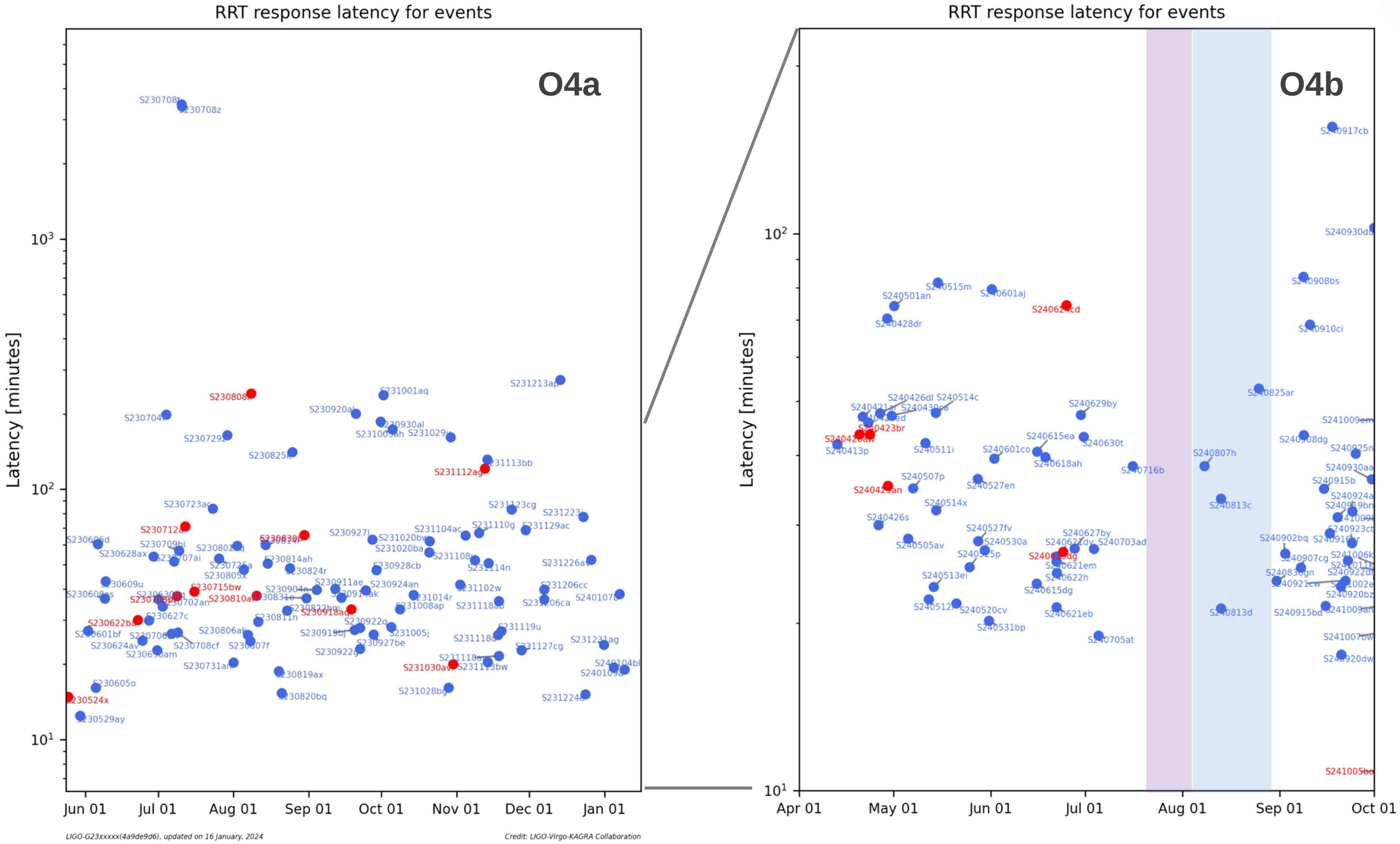
Assuming the candidate is astrophysical in origin, the probability that the lighter compact object is consistent with a neutron star mass (HasNS) is >99%. [3] Using the masses and spins inferred from the signal, the probability of matter outside the final compact object (HasRemnant) is < 1%. Both HasNS and HasRemnant consider the support of several neutron star equations of state. The probability that any one of the binary components lie between 3 to 5 solar mass (HasMassgap) is < 1%.

One sky map is available at this time and can be retrieved from the GraceDB event page:
* bayestar.multiorder.fits, an initial localization generated by BAYESTAR [4], distributed via GCN Notice about 39 minutes after the candidate event time.

For the bayestar.multiorder.fits sky map, the 90% credible region is 1002 deg2. Marginalized over the whole sky, the a posteriori luminosity distance estimate is 276 +/- 79 Mpc (a posteriori mean +/- standard deviation).

GCN Circular 33813

O4 alert latency and event distribution



Alert vetting:

- Confirmed
- Retracted

Latency to sign-off:

O3 35’

O4a 38’

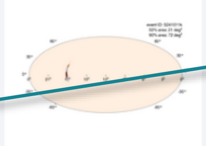
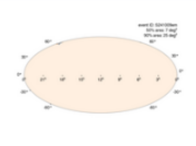
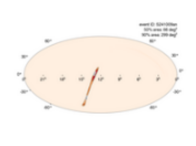
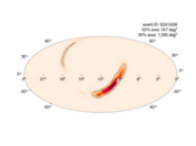
O4b 30’

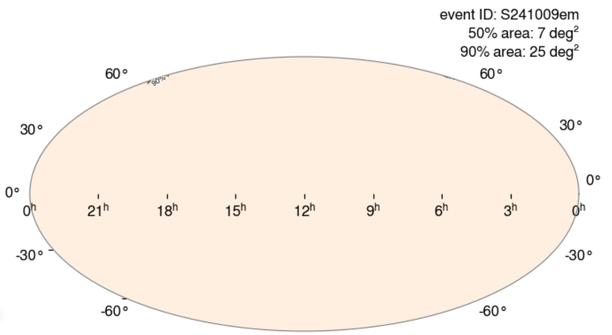
The Gravitational-Wave Candidate Event Database

- O4 Significant Detection Candidates: **149** (166 Total - 17 Retracted)
- O4 Low Significance Detection Candidates: **2561** (Total)

GraceDB Public Alerts Latest Search Documentation Login

Please log in to view full database contents.

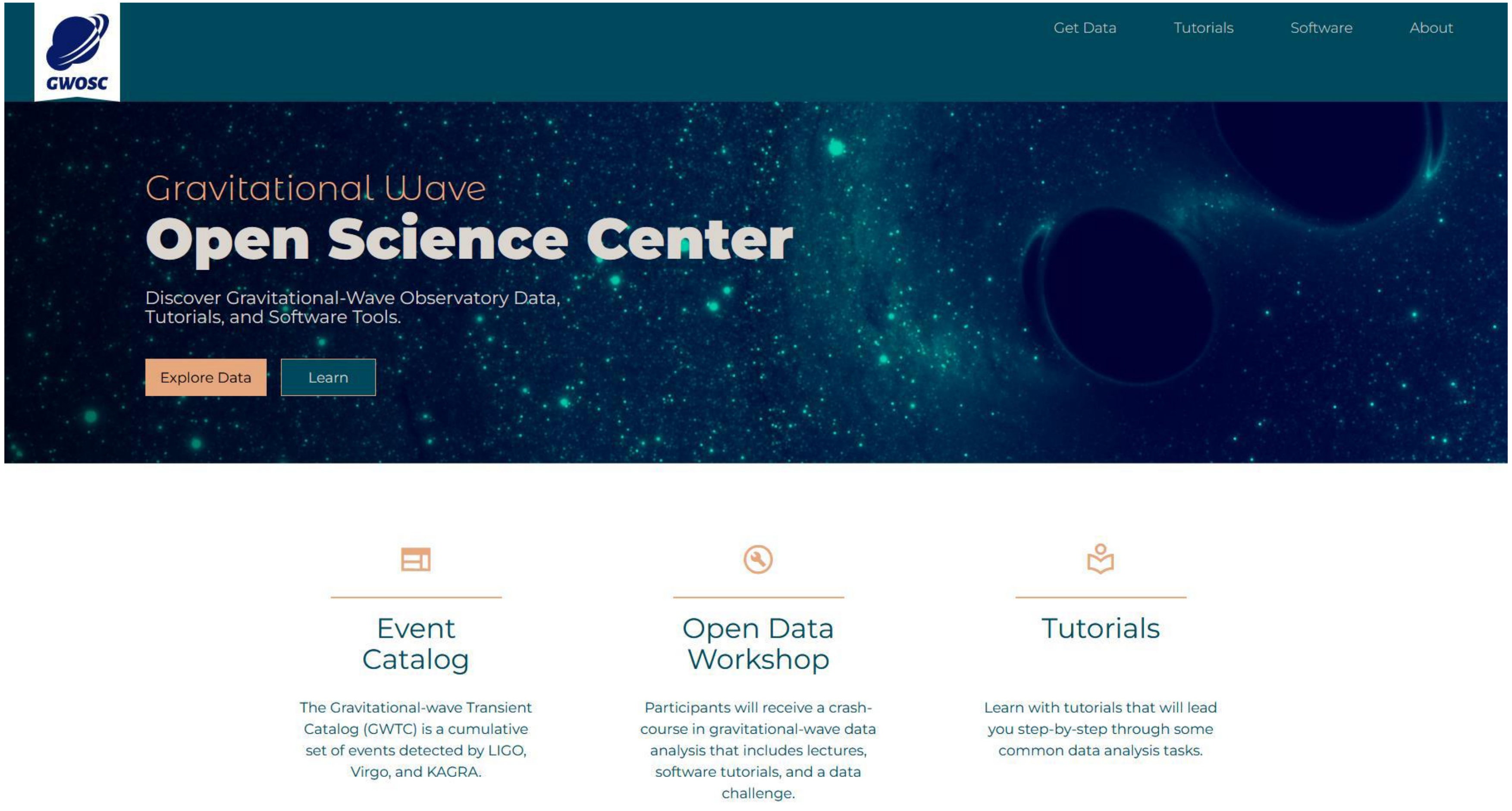
Event ID	Possible Source (Probability)	Significant	UTC	GCN	Location	FAR	Comments
S241011k	BBH (>99%)	Yes	Oct. 11, 2024 23:38:34 UTC	GCN Circular Query Notices | VOE		1 per 1.252e+26 years	
S241009em	BBH (>99%)	Yes	Oct. 9, 2024 22:04:55 UTC	GCN Circular Query Notices | VOE		1 per 11.246 years	
S241009an	BBH (>99%)	Yes	Oct. 9, 2024 08:48:16 UTC	GCN Circular Query Notices | VOE		1 per 16402 years	
S241009l	BBH (98%), Terrestrial (2%)	Yes	Oct. 9, 2024 02:28:35 UTC	GCN Circular Query Notices | VOE		1.0446 per year	



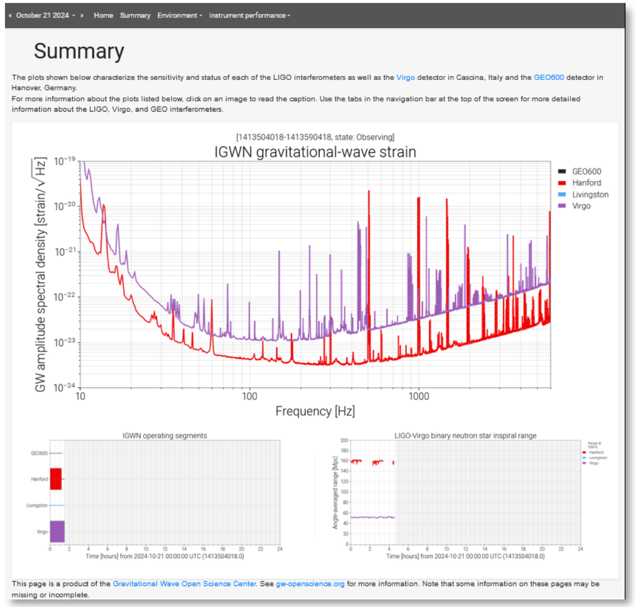
p_astro p_BBH= 0.99755,
p_BNS= 0.0,
p_NSBH= 0.0,
p_Terrestrial= 0.00245

HasMassGap	0%
HasNS	0%
HasRemnant	0%

Gravitational Wave Open Science Center



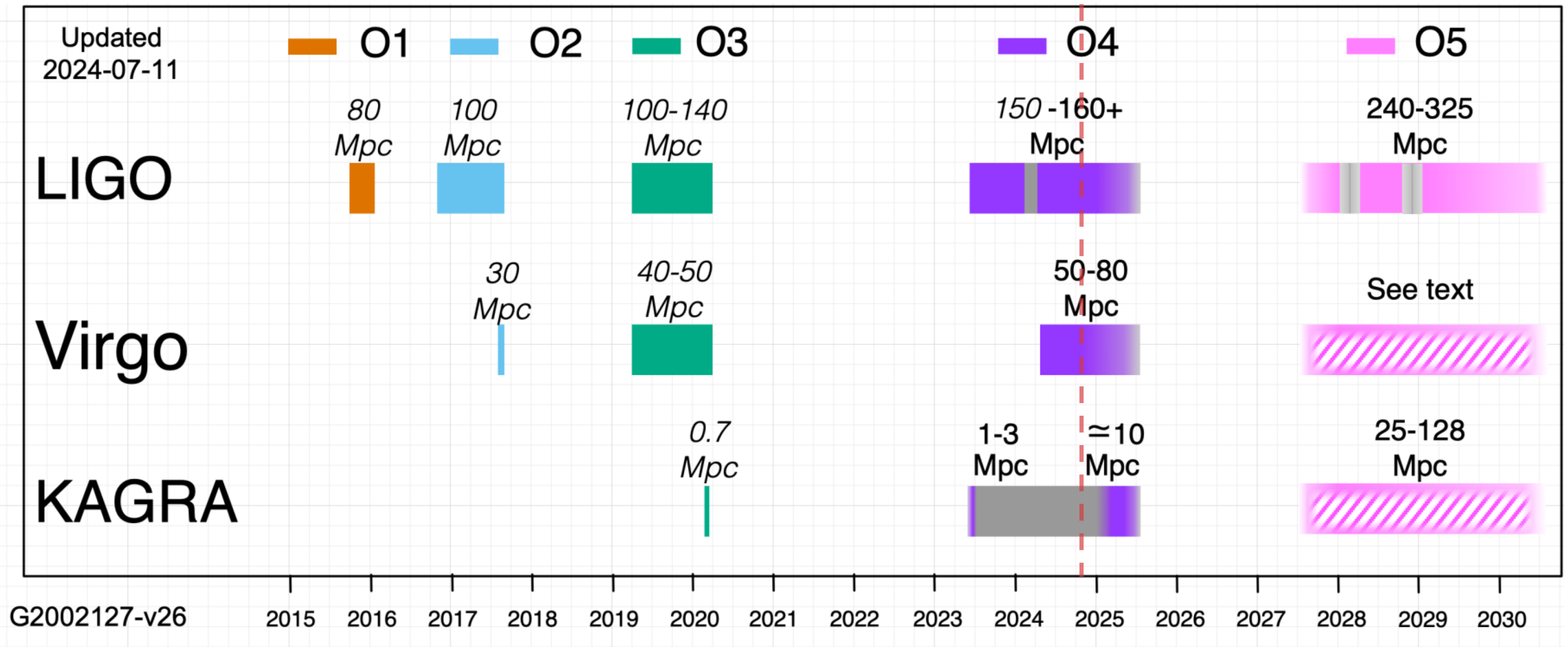
Name	Version	Release	GPS	Mass 1 ($M_\odot$)	Mass 2 ($M_\odot$)
GW200322_091133	v1	GWTC-3-confident	1268903511.3	38^{+130}_{-22}	$11.3^{+24.3}_{-6.0}$
GW200316_215756	v1	GWTC-3-confident	1268431094.1	$13.1^{+10.2}_{-2.9}$	$7.8^{+2.0}_{-2.9}$
GW200311_115853	v1	GWTC-3-confident	1267963151.3	$34.2^{+6.4}_{-3.8}$	$27.7^{+4.1}_{-5.9}$
GW200308_173609	v1	GWTC-3-confident	1267724187.7	60^{+166}_{-29}	24^{+36}_{-13}
GW200306_093714	v1	GWTC-3-confident	1267522652.1	$28.3^{+17.1}_{-7.7}$	$14.8^{+6.5}_{-6.4}$
GW200302_015811	v1	GWTC-3-confident	1267149509.5	$37.8^{+8.7}_{-8.5}$	$20.0^{+8.1}_{-5.7}$
GW200225_060421	v1	GWTC-3-confident	1266645879.3	$19.3^{+5.0}_{-3.0}$	$14.0^{+2.8}_{-3.5}$
GW200224_222234	v1	GWTC-3-confident	1266618172.4	$40.0^{+6.7}_{-4.5}$	$32.7^{+4.8}_{-7.2}$
GW200220_124850	v1	GWTC-3-confident	1266238148.1	$38.9^{+14.1}_{-8.6}$	$27.9^{+9.2}_{-9.0}$
GW200220_061928	v1	GWTC-3-confident	1266214786.7	87^{+40}_{-23}	61^{+26}_{-25}
GW200219_094415	v1	GWTC-3-confident	1266140673.1	$37.5^{+10.1}_{-6.9}$	$27.9^{+7.4}_{-8.4}$
GW200216_220804	v1	GWTC-3-confident	1265926102.8	51^{+22}_{-13}	30^{+14}_{-16}



The LIGO, VIRGO and KAGRA observing run plans

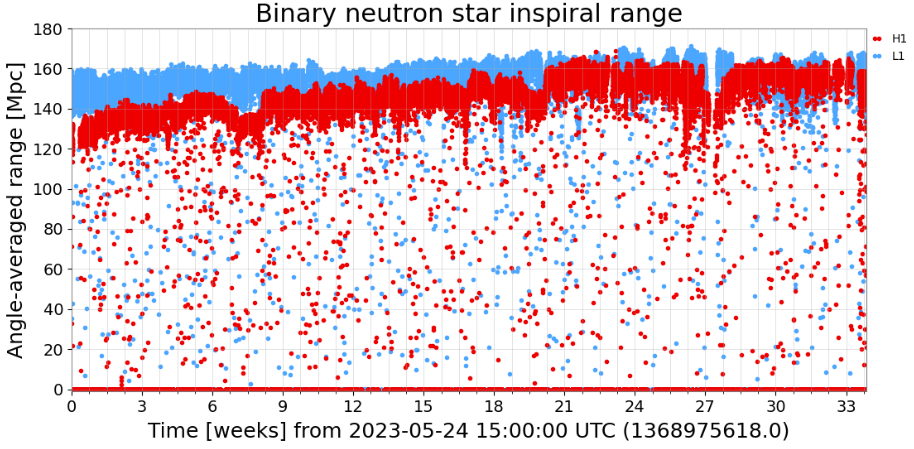
The LIGO, Virgo and KAGRA (LVK) collaborations operate as a network to maximize the scientific output of their searches:

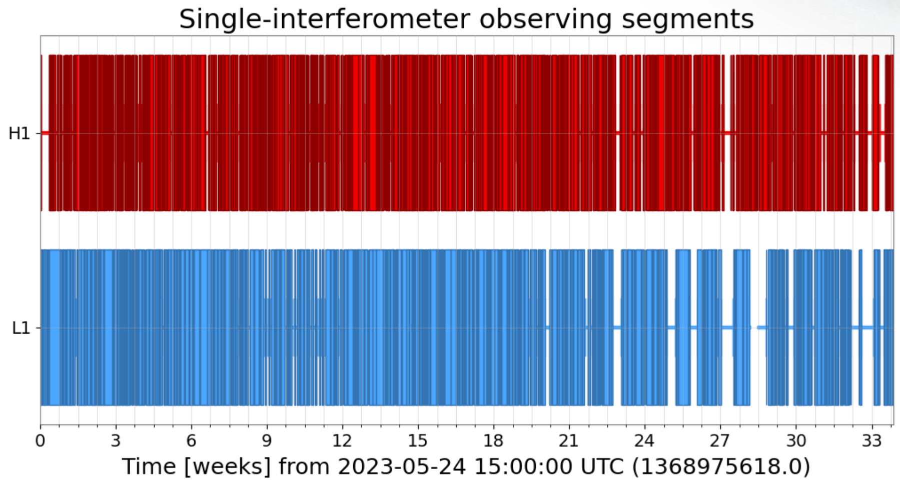
- Joint strategy for observational campaigns: On, with $n = 1, \ldots, 5$, plus finer division into sub-runs
- LVK observing run plans receive monthly updates: link

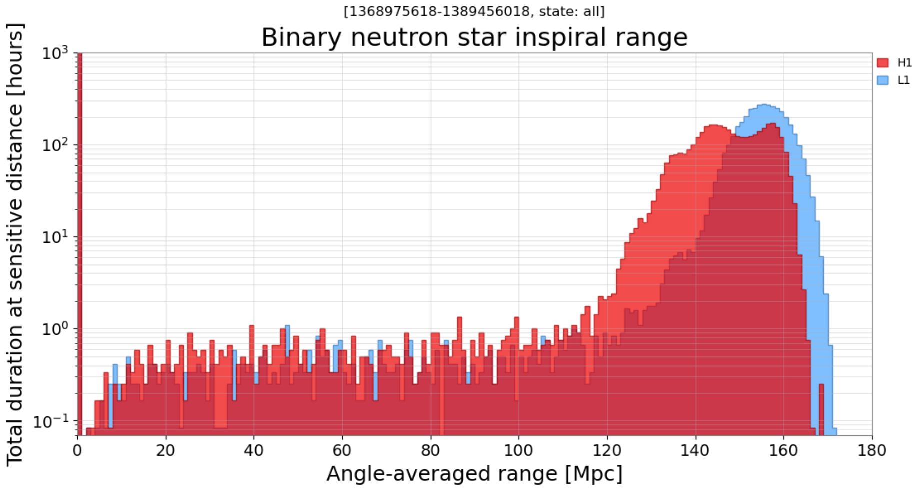


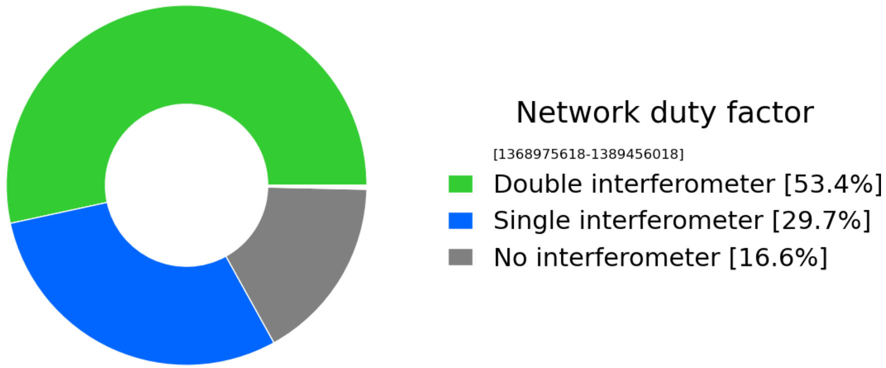
Summary of the O4a run

May 24, 2023 – January 16, 2024



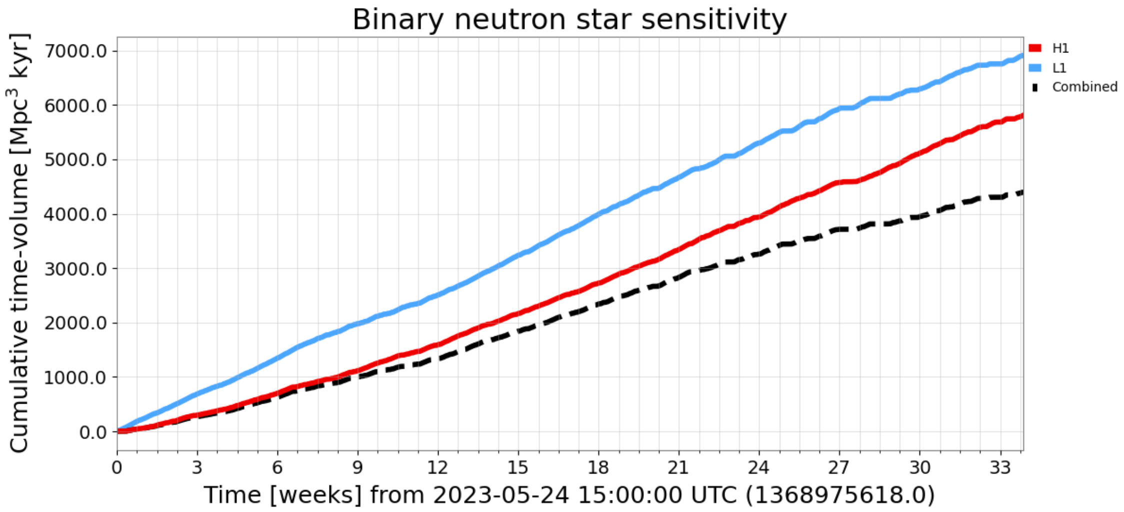


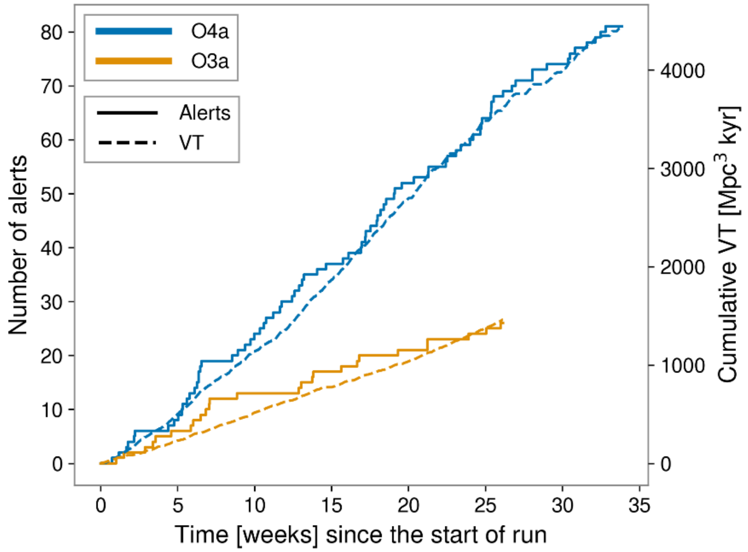


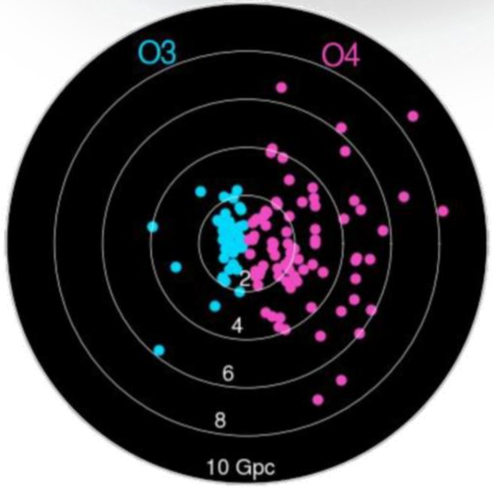


Summary of the O4a run

May 24, 2023 – January 16, 2024





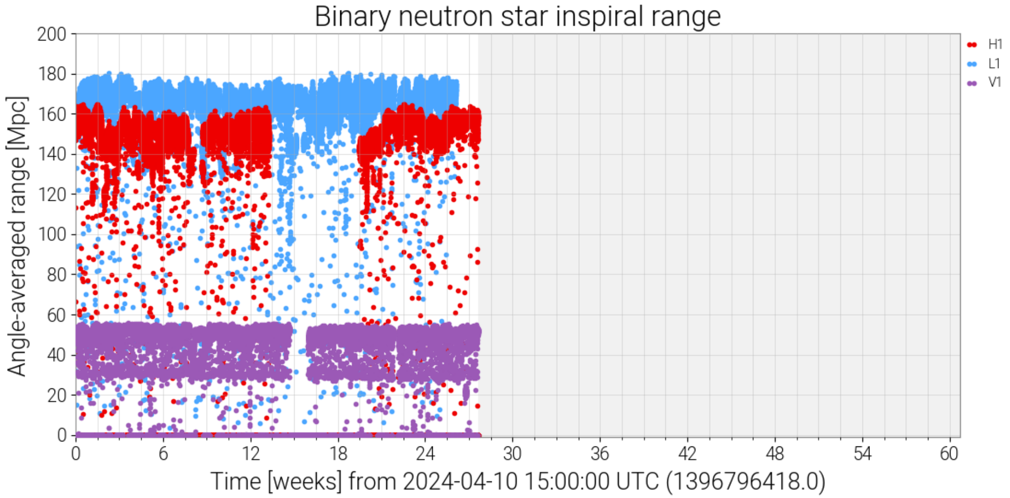


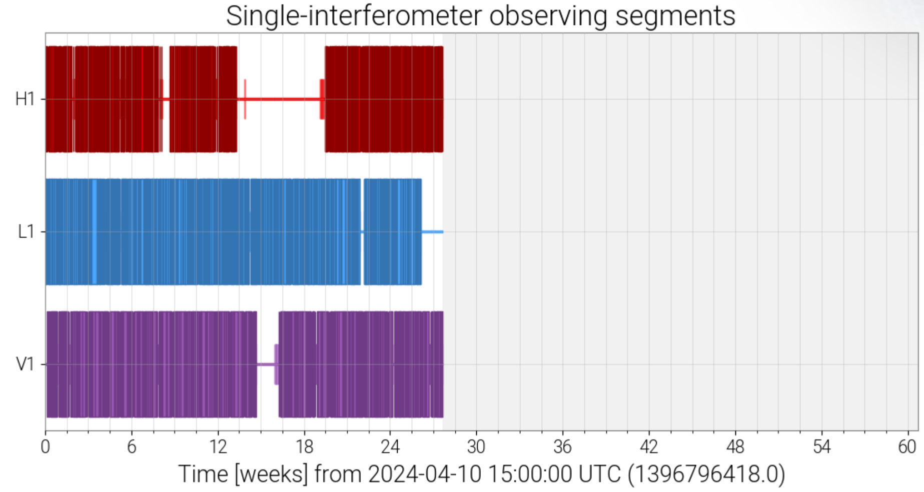
81 significant detection candidates (92 Total - 11 Retracted) found online in O4a. More to come from offline searches

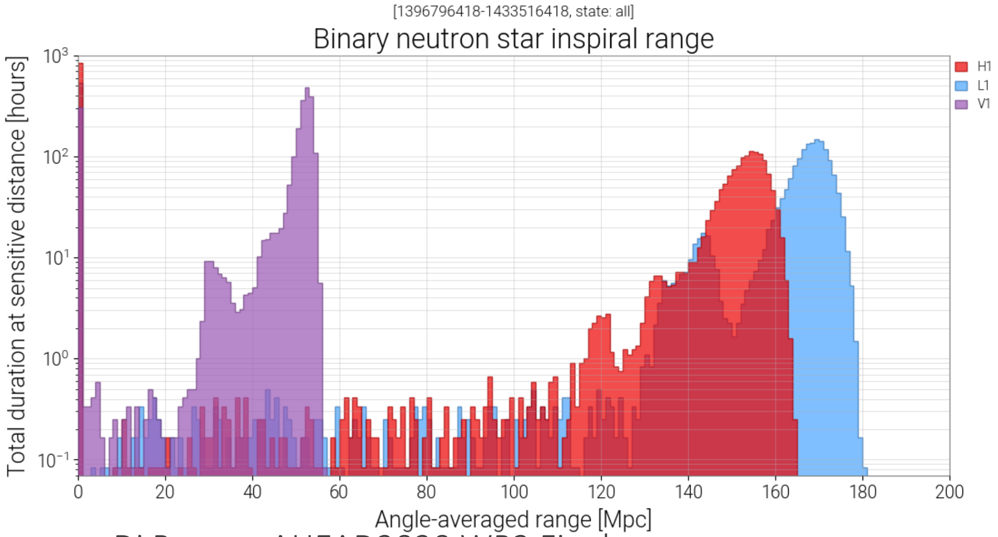
- More candidates/alerts than in O3
- Larger SNRs
- More distant sources

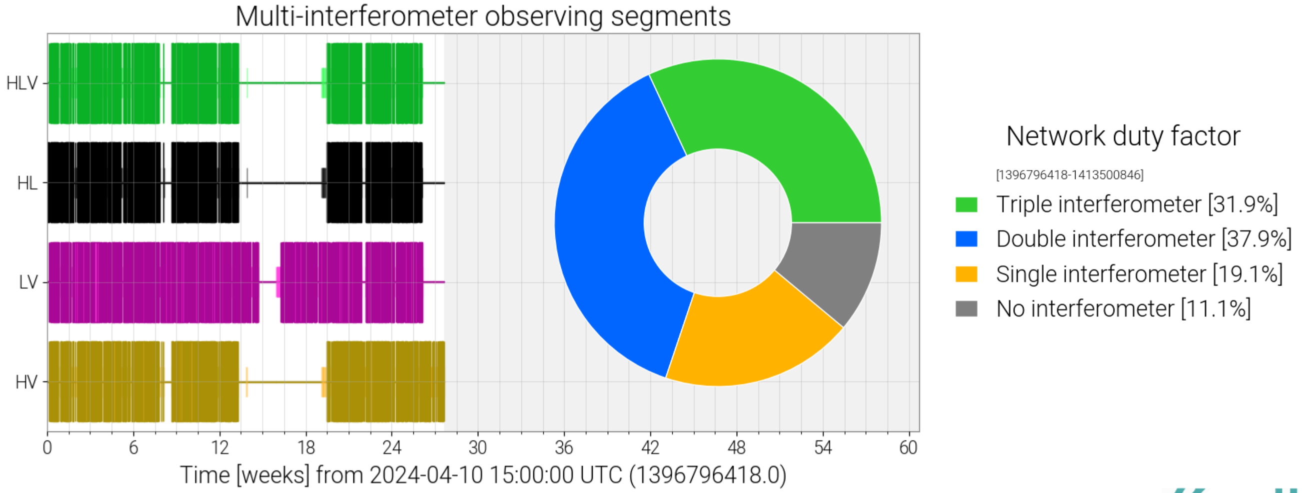
Summary of the O4b run so far

April 10, 2024 – June 9, 2025







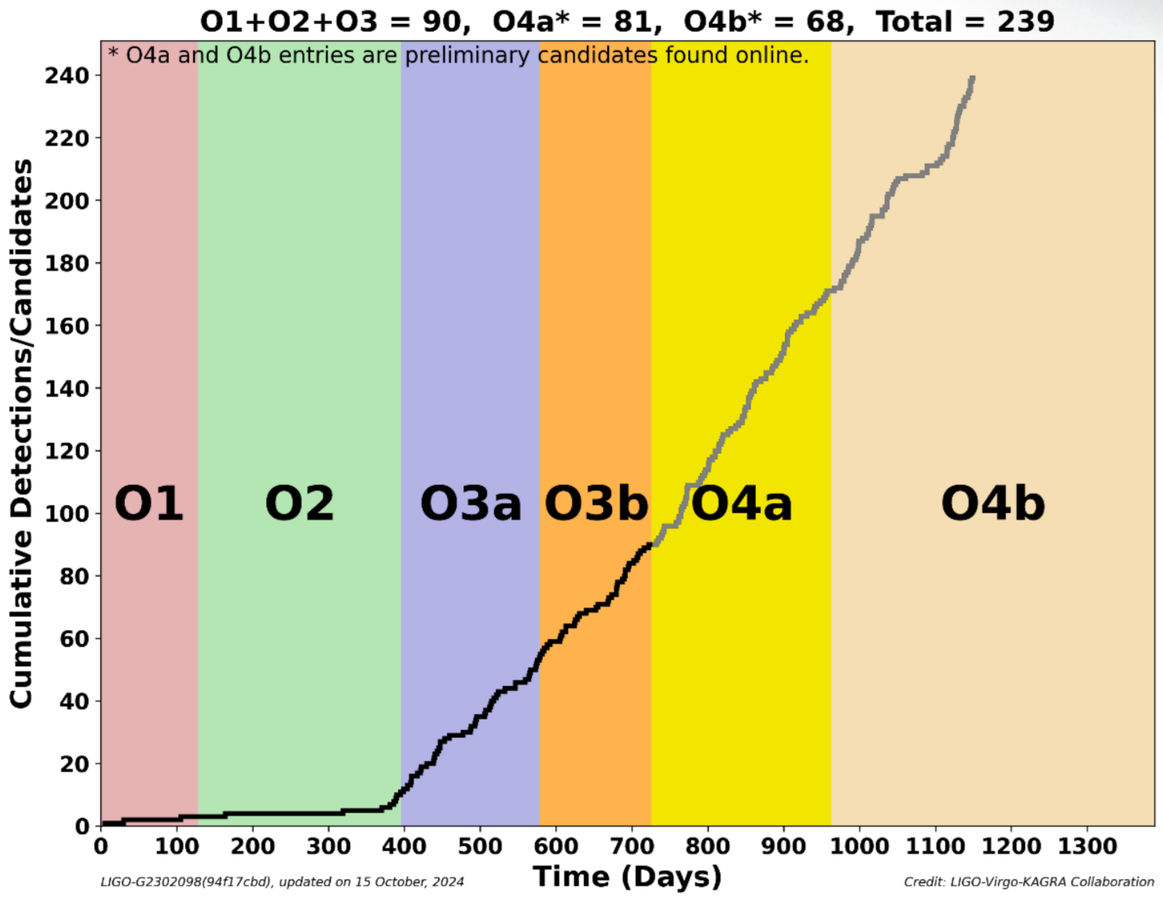


Summary of the O4b run so far

April 10, 2024 – June 9, 2025

68 significant detection candidates in O4b (74 Total - 6 Retracted)

- Virgo data used for triggering (assessment of trigger significance) only by the gstlal pipeline
- Used for sky localization and parameter estimation by all the others.



Improved sky localization from the inclusion of Virgo

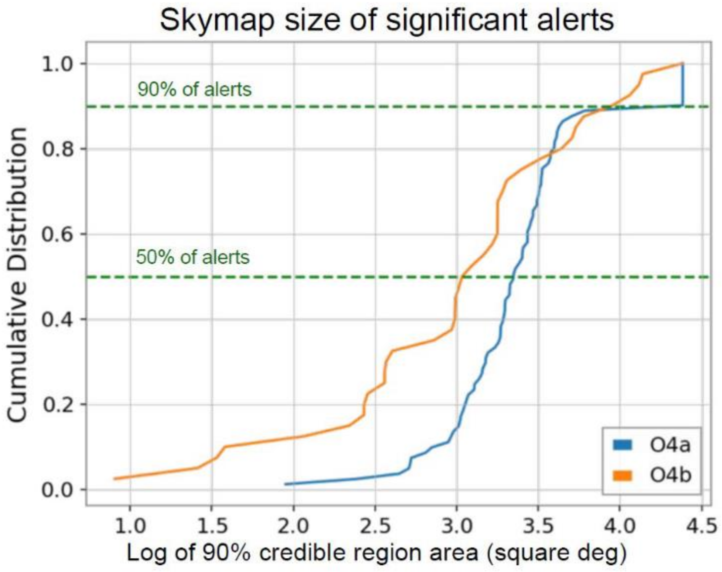
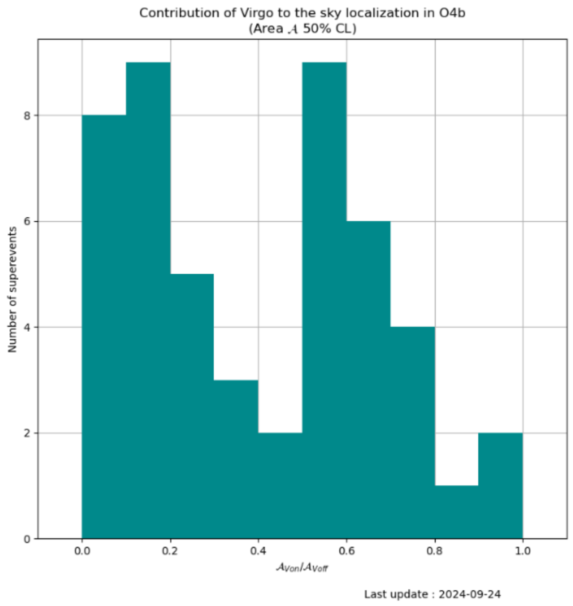
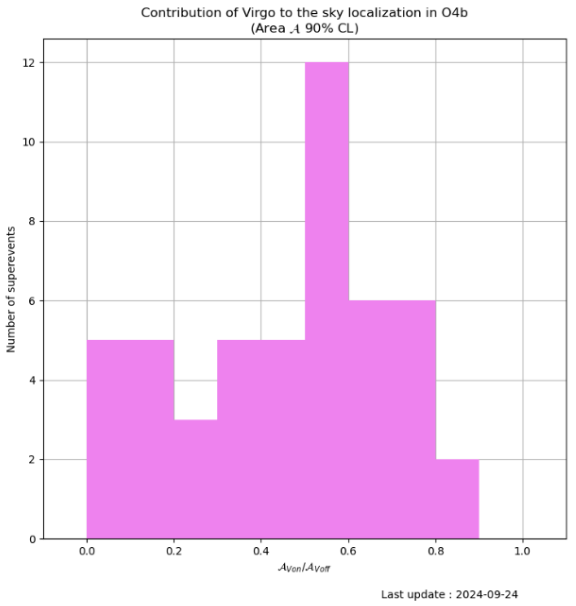


Figure produced by M.Chan (UBC)

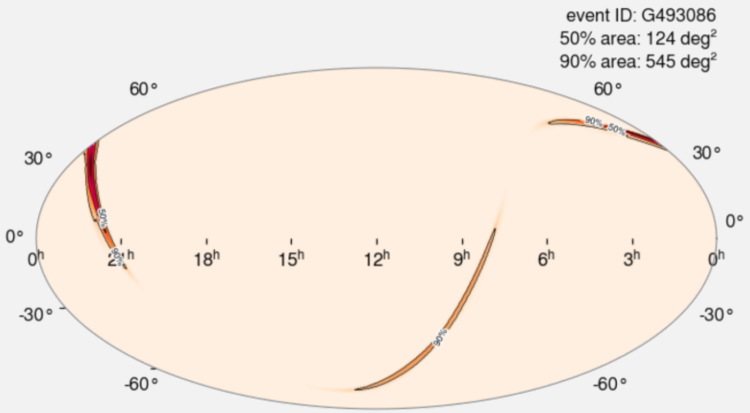




Plot credit
I.Bentara

Example: [S240615dg]

LIGO L1 and H1 only



+ Virgo

Summary and outlook

- The fourth joint observational campaign (O4) is proceeding well
  - More event candidates than the total of the past 3 campaigns
  - Sustained level of performance from the detectors. Some exceptional down times due to interventions but overall the longest continued data taking
  - Improved pipelines and infrastructure to cope with the increased rate of candidate events, and to deliver alerts to the astronomical partners in a timely manner
  - KAGRA will join observations in the coming months. Stay tuned for updates: link
- O5 preparation is ongoing
  - Various detector upgrades planned (better mirror coatings, increase laser power, improved optical configuration…)
  - The goal is to reach a ×1.5 in astrophysical range, that is 3+ times more detections. The low-latency infrastructure will need to be revised to cope with a rate of events larger than one-per-day. Many progress on automation ha already been done.
  - The post-O5 (Virgo-nEXT and LIGO A#) will serve as a bridge between the next generation of detectors, to test new technologies and push to the limits the current infrastructures.

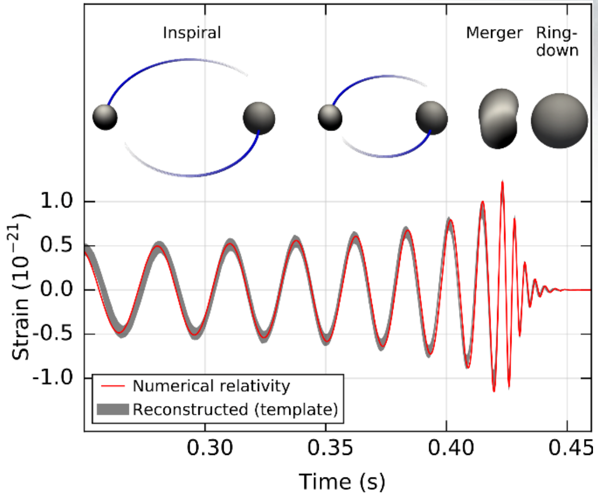
Thanks for the attention!

Backup slides

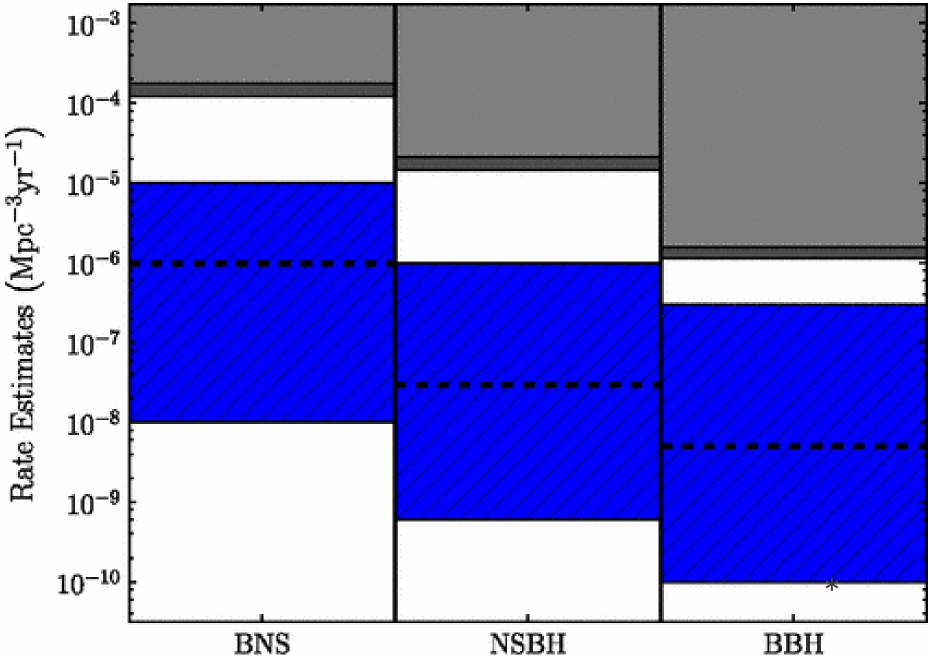
The rate density of compact binary coalescences

Compact binary star systems can emit detectable Gravitational Waves (GW) in the last stages of their inspiral motion.

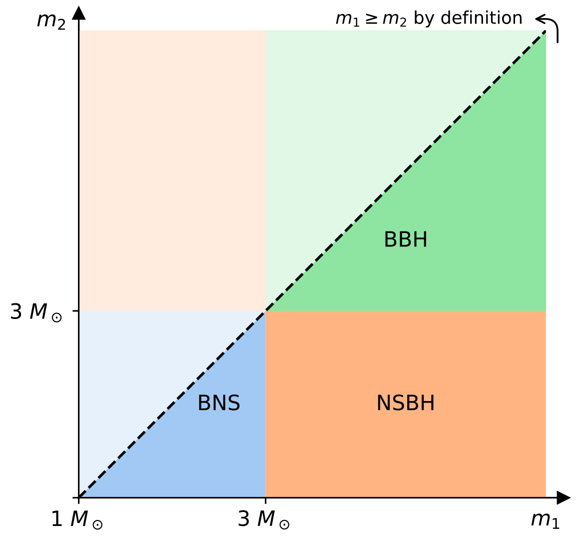
- **BNS**: two Neutron Stars (NSs) system, *e.g.* GW170817;
- **NSBH**: binary formed by one Neutron Star and one Black Hole (BH), *e.g.* GW200105 and GW200115;
- **BBH**: two Black Holes (BHs) system, *e.g.* GW150914.



PhysRevLett.116.061102



Abadie2010



Abbott2013

*Updated inference on BBH population arXiv2010.14533

The effective BNS Volume-Time

Euclidean sensitive volume of the second-most sensitive detector in the network at a given time, multiplied by the **live time** of that network configuration.

The **network Euclidean sensitive volume** is the volume of a sphere with a radius given by the **BNS inspiral range.**

⇒ Multiplying the BNS Volume-Time by the **CBC density rate** we get an estimate of the expected number of detections. (ignoring cosmological corrections)

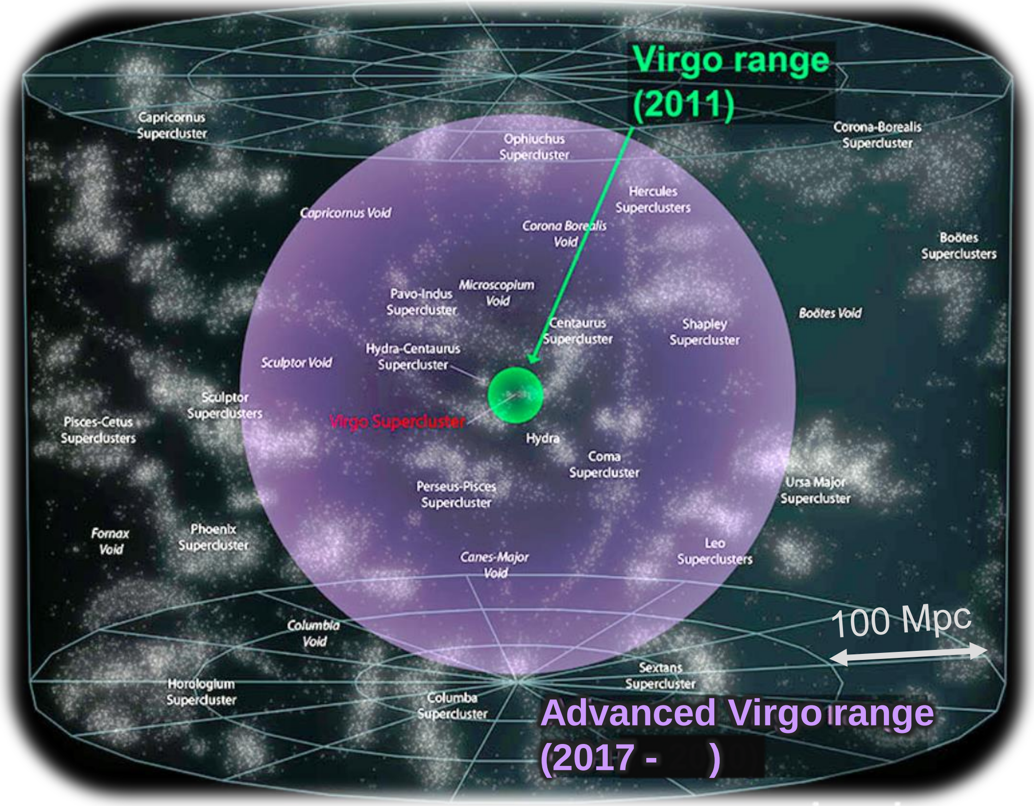
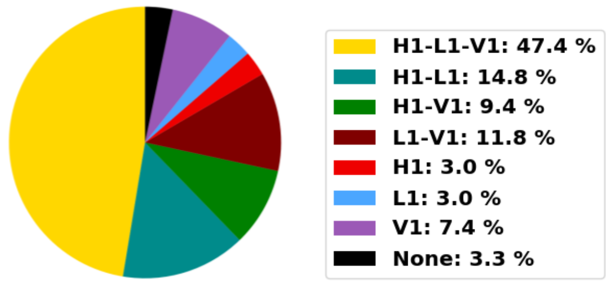
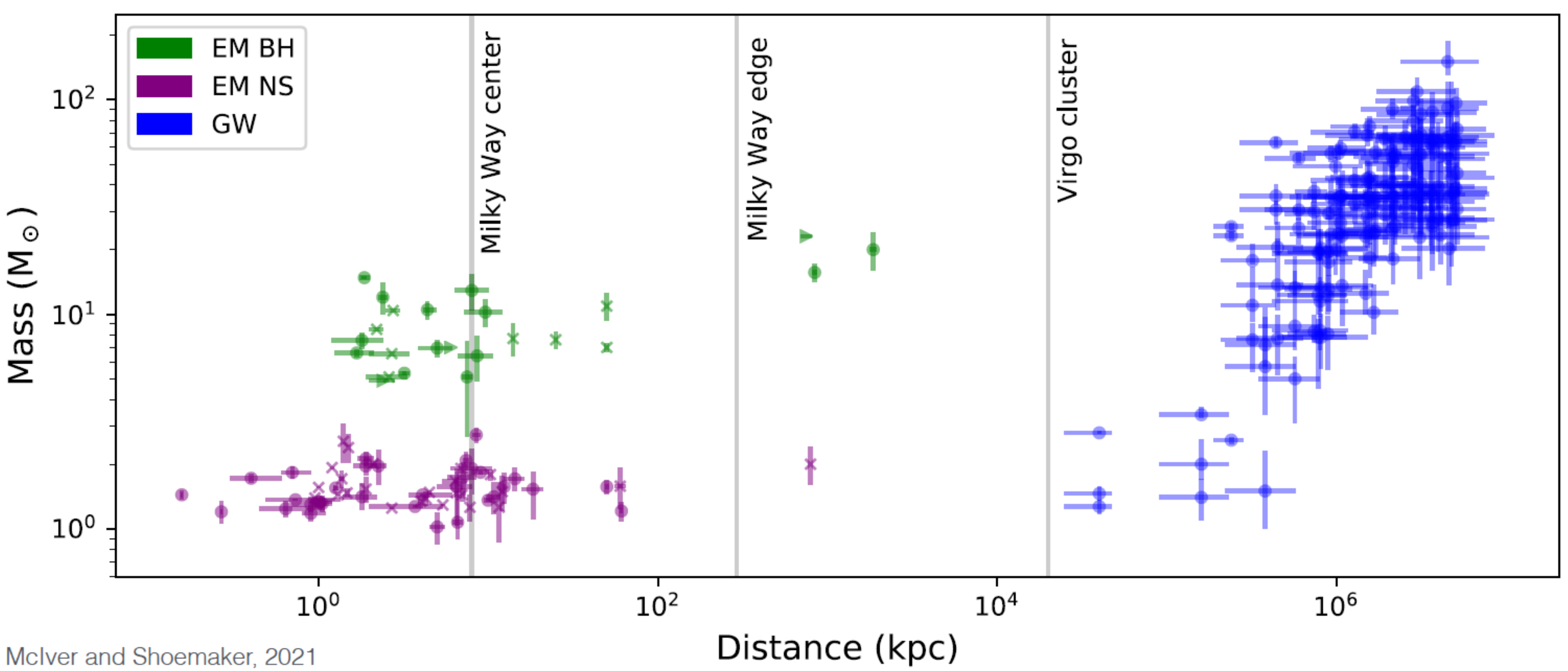


Image Credit: [Virgo Collab.]



LIGO-Virgo Network duty cycle during O3

Known compact object masses vs. estimated distance

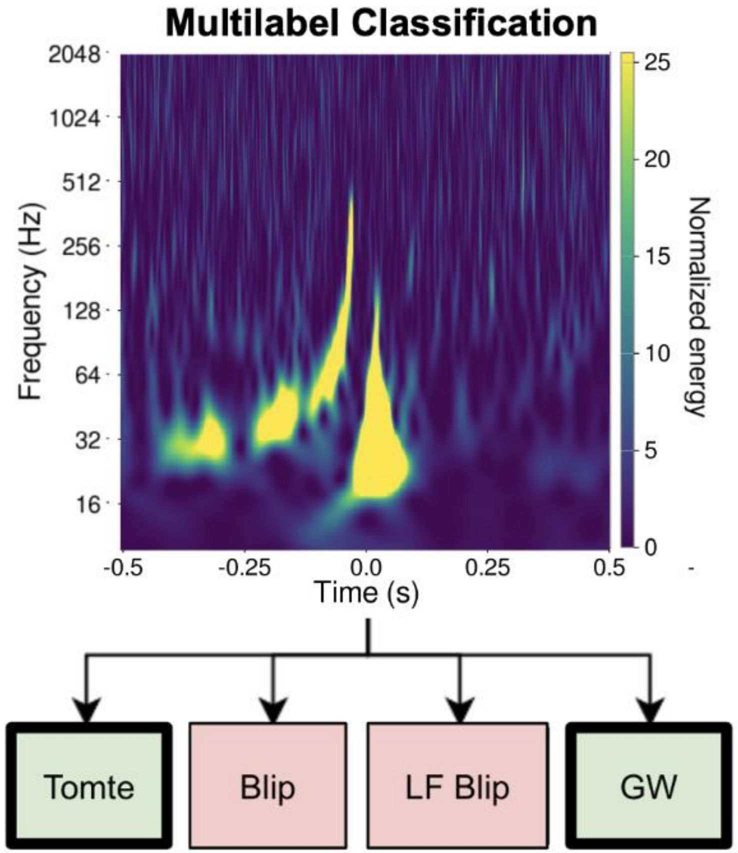


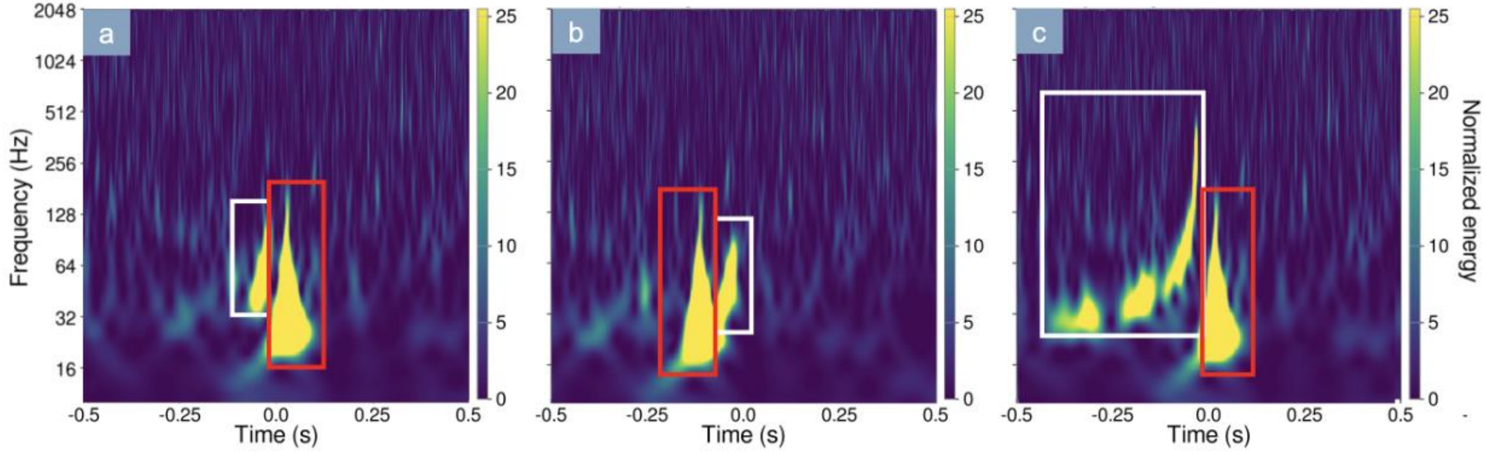
McIver and Shoemaker, 2021

Using Deep Learning to distinguish signal and noise

Multilabel classifier to label excess energy in the spectrogram images and distinguish noise artefacts from GW transients.

- Refer also to [Gravity Spy] and [GWitchHunters] projects on Zooniverse





https://arxiv.org/abs/2304.09977

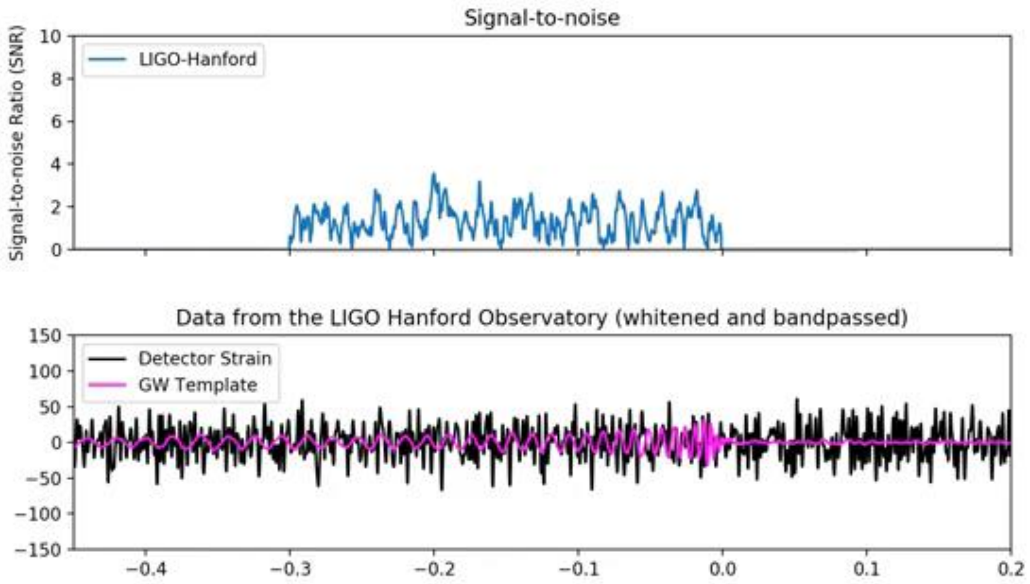
SNR for matched-filter based searches

Given a signal plus noise model, $\underbrace{x(t)}_{\text{detector data}} = \underbrace{n(t)}_{\text{noise}} + \underbrace{s(t)}_{\text{signal}}$, and a signal model $s(t) \approx \varrho h(t)$

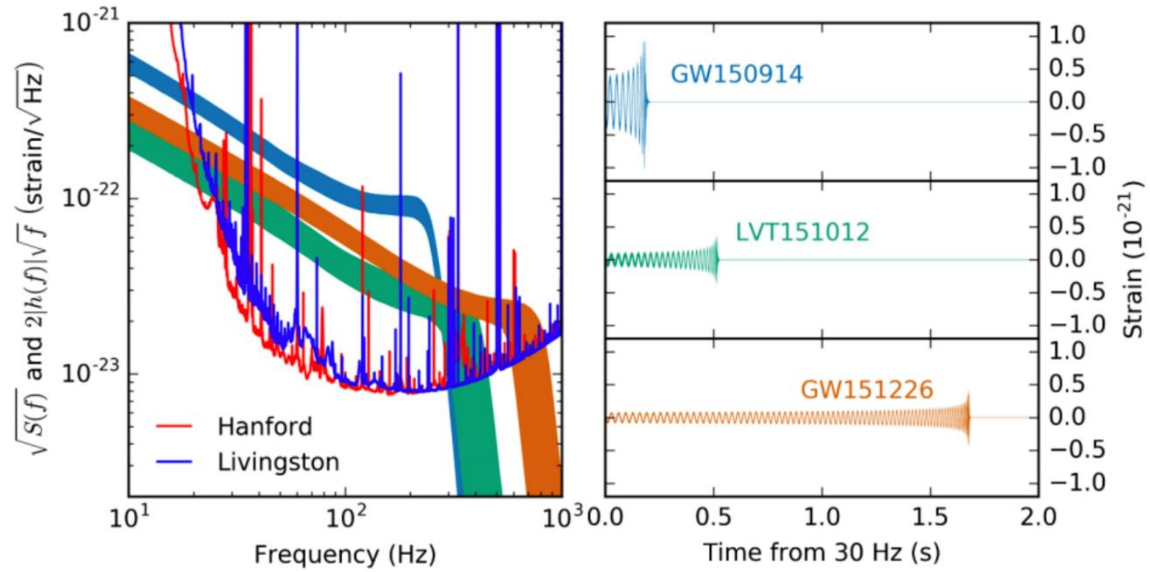
with ϱ the amplitude and $h(t) = h(t;\boldsymbol{\theta})$ the waveform model ($(\boldsymbol{h}|\boldsymbol{h}) = 1$).

Optimal detection statistic: likelihood ratio, in stationary and Gaussian noise equivalent to:

$$(\boldsymbol{x}|\boldsymbol{h}) = 4\,\Re \int_0^\infty \frac{\tilde{x}(f)\tilde{h}^*(f)}{S(f)}\,df$$

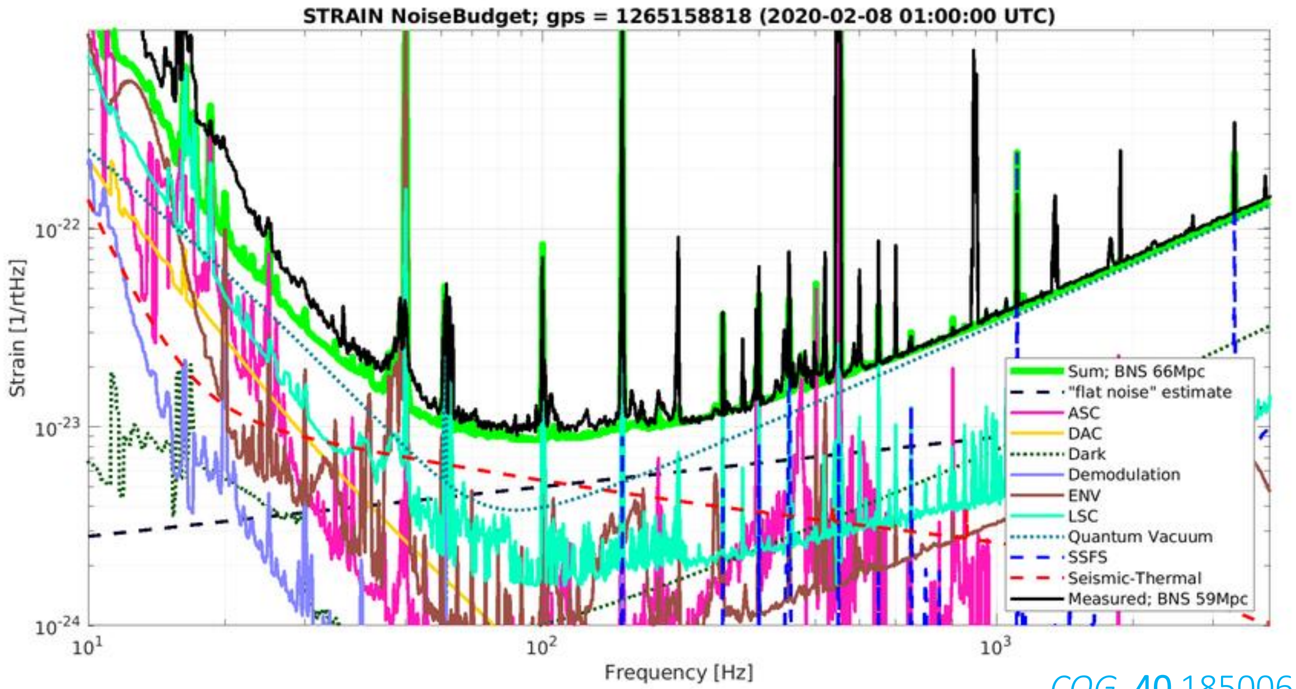


Credit Alex Nitz



PRX 8 039903

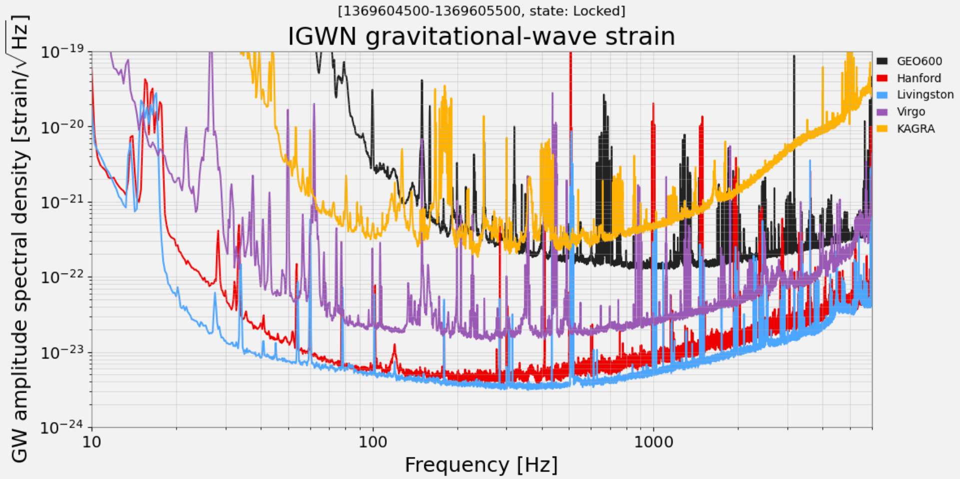
Real gravitational wave detectors



[CQG. 40 185006](#)

Snapshot of May 31, 2023

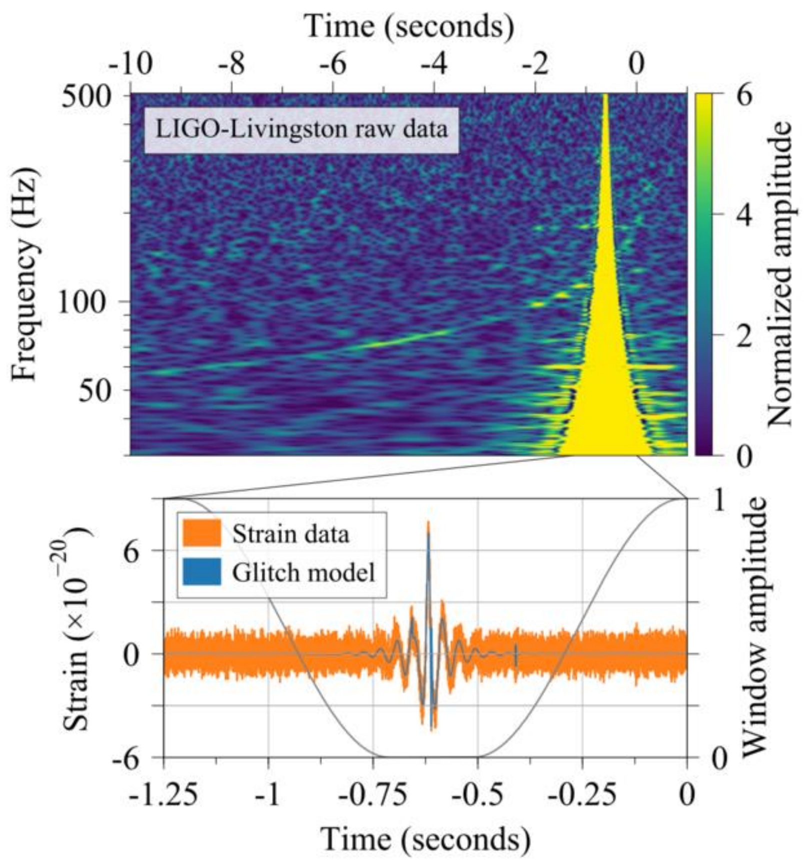
Five GW detectors simultaneously observing for the first time



Many *non-astrophysical* sources can produce an effect similar to a strain at the detector output: **noise**

- **Fundamental noise:** intrinsic in the detection principle and its practical implementation
- **Technical noise:** from components and controls that are not optimal
- **Environmental noise:** from the detector physical environment

The validation of gravitational-wave events



PRD 98, 084016 (2018)

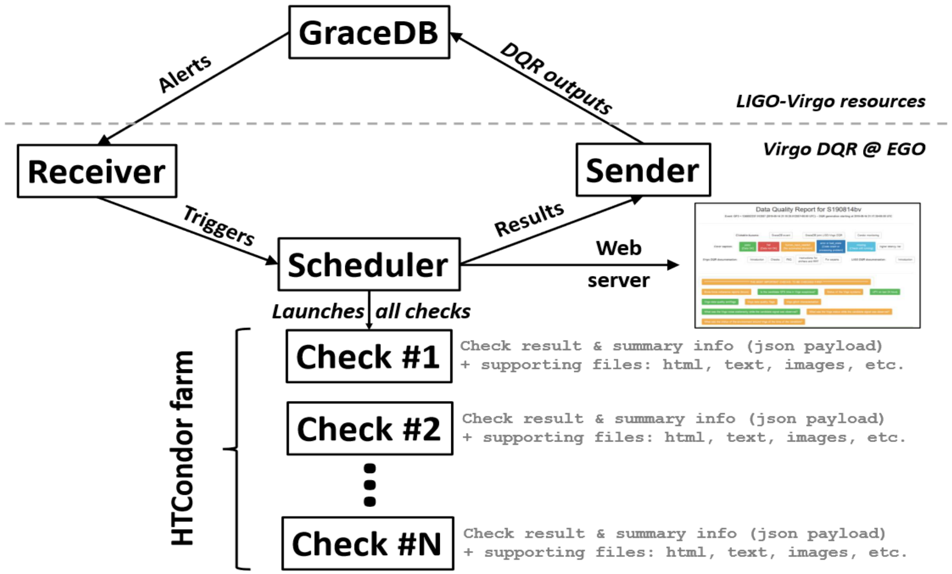
- **Event validation** consists of a set of procedures to verify if data quality (DQ) issues, such as instrumental artifacts, environmental disturbances, or anomalies in the search pipelines, can impact the analysis results and **decrease the confidence of a detection**;
- It is applied to all gravitational-wave transient candidate events found by both *online* and *offline* search pipelines;
- Typically, candidate events undergo **two stages of validation**:
  - **Prompt validation (RRT, online triggers only)**:

    Accompanies every public alerts and is typically completed within $\mathcal{O}(10\ \mathrm{min})$ from the data acquisition. It has the role to **vet** an event trigger if there is evidence of terrestrial origin or other severe DQ issues;
  - **Offline validation (all)**:

    Completed as a final check before publication for all events found by online and/or offline pipelines. The typical timescale is days or even months after the time of the event.

The Data Quality Report framework

Schematics of the Virgo O3 DQR architecture, from CQG **40**, 185006 (2023)



Snapshot from the “LIGO DQR” (credit Areeda, Davis)

H1 result: Pass Observing

Task	IFO	Status	P-value	Result
glitchaverage	H1	Done	0.14768264	Pass
stationarity	H1	Done	0.375	Pass
pemcheck	H1	Done	0.51362564	Pass
rayleigh	H1	Done	0.609375	Pass
omega_overlap	H1	Done	0.6546039	Pass
glitchfind	H1	Done	0.91762616	Pass
gspynettree	H1	Done	0.9683	Pass

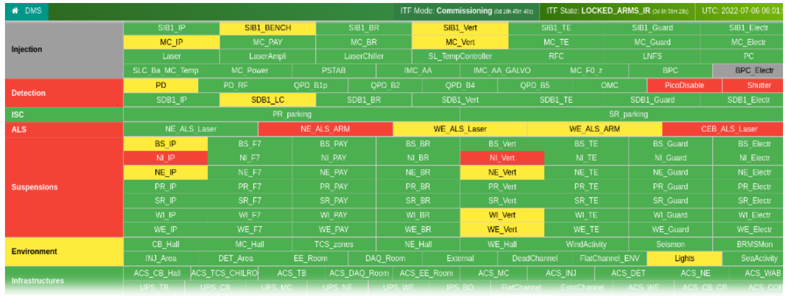
- A **Data Quality Report** (DQR) is a framework developed by LIGO and Virgo consisting in a set of DQ checks;
- Two parallel implementations: “Virgo DQR” and “LIGO DQR”
- It is automatically prompted after each gravitational-wave candidate trigger with false alarm rate (FAR) of $1/\mathrm{day}$ is being generated on GraceDB;
- The results are uploaded back to GraceDB and used by the **Rapid Response Team** to validate or vet the associated event, and afterwards for the final event validation.

Table: Performance of Virgo DQR during O3b, from CQG **40**, 185006 (2023)

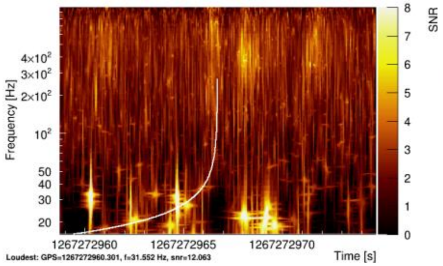
Operation	Time taken [s]		
	Median	Mean	95^{th} percentile
Data acquired → Candidate on GraceDB	52	166	331
Candidate on GraceDB → `LVAlert` trigger	4	4	11
`LVAlert` trigger → Virgo `DQR` configured	331	339	383
Virgo `DQR` configured → Virgo `DQR` started	8	10	21

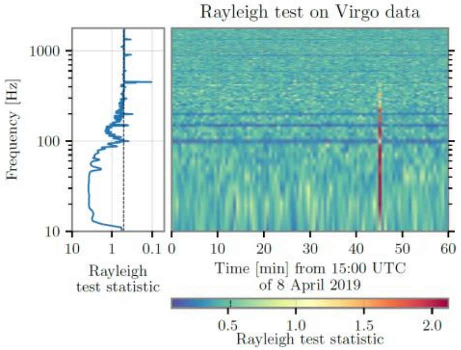
Operation	Time from start [s]		
	Median	Mean	95^{th} percentile
Quick key checks	374	383	619
Adding `Omicron` trigger distributions	868	816	935
Adding full `Omicron` scans	1740	2159	4690
End	5185	4954	6330

Prompt event validation of low-latency alerts



Example of **Virgo DMS**. From [Virgo logbook entry #56363] (NOT a candidate event) [VIR-0191A-12]





[*CQG* **40** 185005]

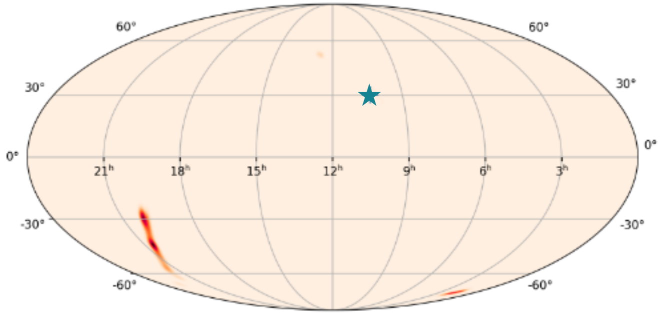
166.88	SDB1_LC_TZ_fb (0.24)	SDB1_LC_TZ_corr (0.24)	SDB1_LC_TZ_err (0.24)	SDB1_LC_TZ (0.24)	SDB1_LC_COIL_FL_V (0.24)
167.00	SDB1_LC_TZ_fb (0.32)	SDB1_LC_TZ_corr (0.32)	SDB1_LC_COIL_FL_V (0.32)	SDB1_LC_COIL_BL_V (0.32)	SDB1_LC_COIL_BR_V (0.32)
167.12	SDB1_LC_COIL_FR_V (0.45)	SDB1_LC_COIL_BL_V (0.45)	SDB1_LC_COIL_FL_V (0.45)	SDB1_LC_COIL_BR_V (0.45)	SDB1_LC_TZ_err (0.45)

- This stage has the role to **vet those event triggers with severe noise contamination**, for which an astrophysical origin should be excluded;
- Otherwise, it serves to enforce the confidence in the event type and **sky-localization** to support multimessenger follow-up.
- The **main DQ checks** based on the DQR are:
  - Operational **status of the detector** and its subsystems at the time of the trigger and around it;
  - Scan of the **main DQ flags**: h_{rec} correctly computed, detector observational intent and working condition, injections of spurious signals, etc.
  - **Noise characterization**: stationarity and Gaussianity, including the presence of glitches and their distribution; correlation with auxiliary channels; status of the environment, etc.

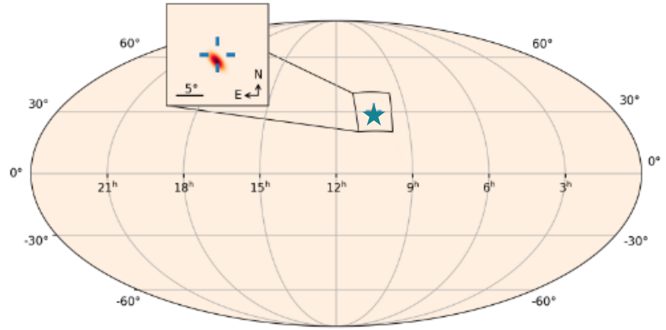
Final validation before publications

- **Every LVK publications** (catalogs and exceptional events) undergo a final, comprehensive validation procedure before data analysis reruns;
- This includes all the events found online and pre-validated and those found by offline pipelines;
- An event validation team is in charge of this procedure. Each event requires $\mathcal{O}(1\ \mathrm{hour})$ per person involved if no DQ issue is found;
- The goal is to assess whether the parameter estimation of the astrophysical source can be affected by noise artifacts; [*CQG* 35 (2018) 15, 155017]()
- If no DQ issue is found, the candidate event is considered validated;
- For those events where noise artifacts are found in the vicinity of the putative GW signal, or even overlapping with it, a procedure of **noise mitigation** is implemented. This requires additional time and person power.

Glitch: 90% credible region 137 deg^2

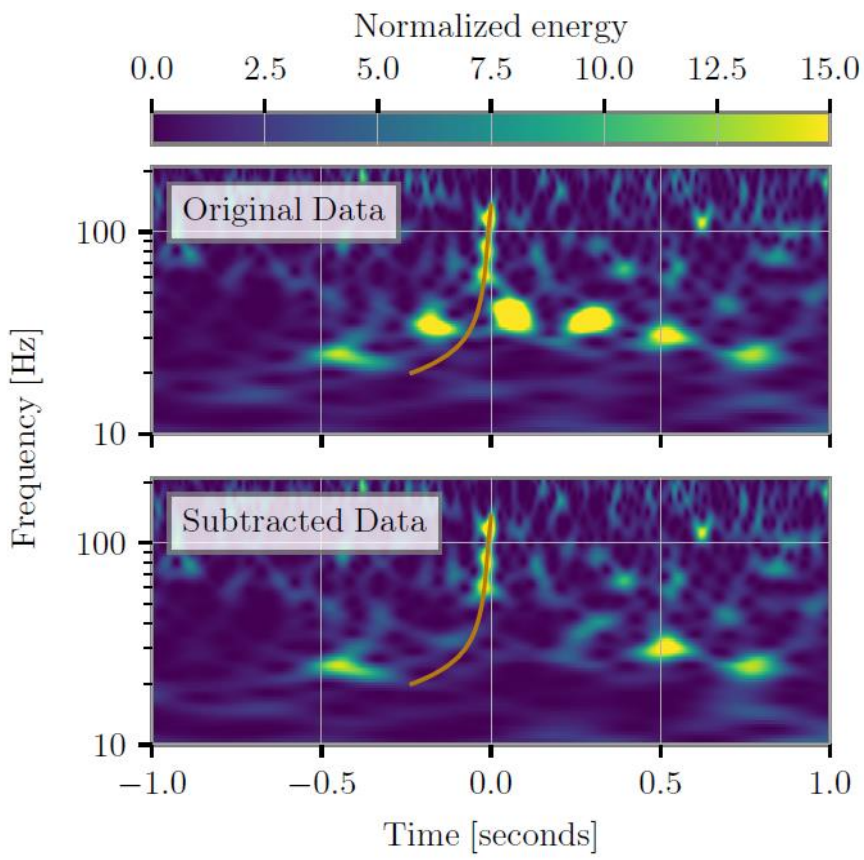


No glitch: 90% credible region 8 deg^2



Effect on sky-localization of a blip glitch 30 ms after a GW150914-like event. PRD 105 (2022) 103021

Noise artifacts mitigation of gravitational-wave detector data



PRX 11, 021053 (2021)

- Applied to those events flagged to have DQ issues: transient noise, namely **glitches**, superimposing the putative astrophysical signal (orange curve);
- Metric based on the PSD variation to assess the extent of each non-stationary region identified [CQG 37 (2020) 21];
- Deglitched frames mostly produced with BayesWave pipeline [CQG 32 (2015) 13];
- Assessment of subtraction by means of the previous stationarity metric. Parameter Estimation comparison tests to check for bias and systematics;
- **16 events** (≈20%) required glitch subtraction during O3. This process involves lots of human input and slows down downstream analyses.