Gravitational wave observations with LIGO, Virgo and KAGRA: status and prospects

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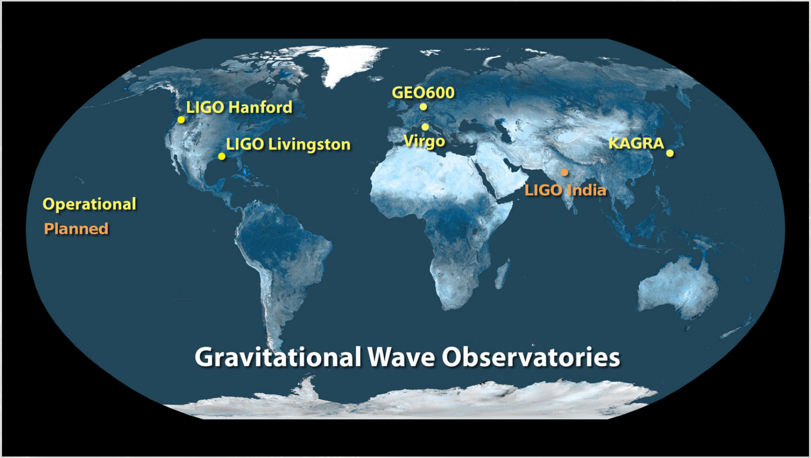
Outline

The 2nd generation GW detector network



Where do we stand?

Credit: LIGO-Virgo-KAGRA

- *O1: September 2015 - January 2016*

  LIGO operating
- *O2: November 2016 - August 2017*

  Virgo joined the network on August 1
- *O3a: April 2019 - September 2019*

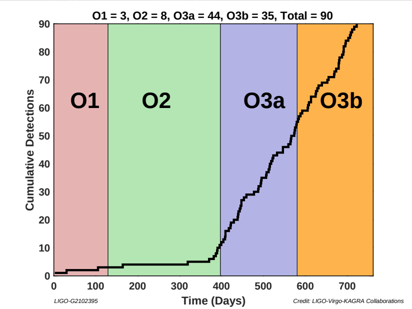
  O3b: November 2019 - March 2020

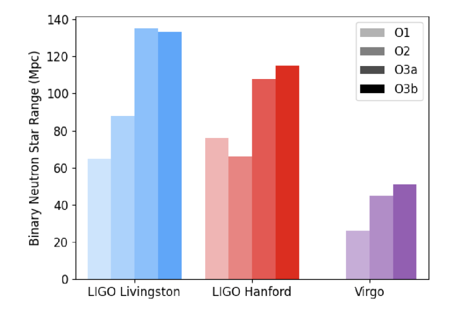
  Virgo and LIGO operating
- *O4a: May 2023 - January 2024*

  LIGO operating; KAGRA operating for 1 month
- *O4b: April 2024 - now*

  LIGO and Virgo operating; KAGRA expected to join before the end of the run

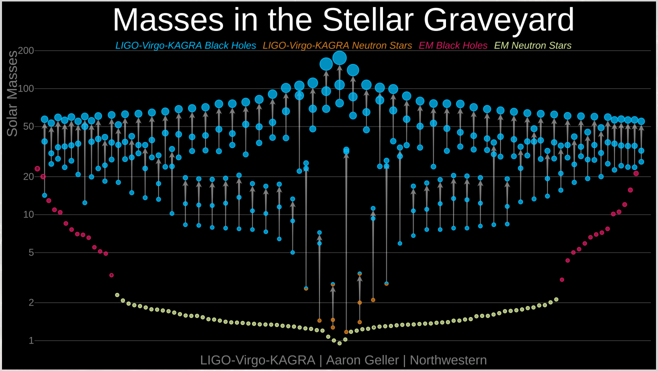
GW detections: O1+O2+O3 summary





Credits: LIGO-Virgo-KAGRA Collaborations/Hannah Middleton/OzGrav

GW detections: O1+O2+O3 summary

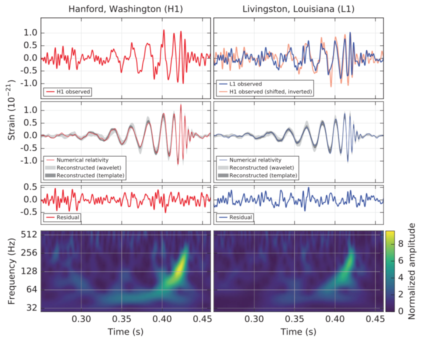


- Total number of candidates: 90
- Most are binary black holes (BBHs); some are neutron star - black hole (NSBH) binaries; two are binary neutron stars (BNSs)
- Four GW catalogs: GWTC-1 (O1+O2), GWTC-2 and GWTC-2.1 (O3a), GWTC-3 (O3b)

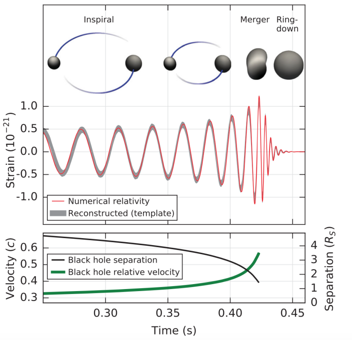
LVK Collaboration 2019, PRX, 9, 031040; LVK Collaboration 2021, PRX, 11, 021053; LVK Collaboration 2023, PRX, 13, 041039; LVK Collaboration 2024, PRD, 109, 022001

GW150914: the birth of GW astronomy

The observation



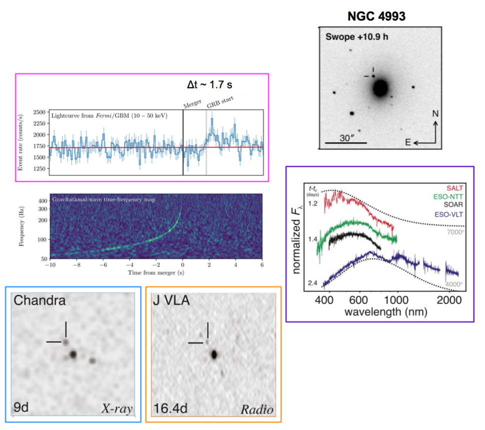
The model



- BBHs can form in nature and merge within the age of the Universe
- The two BH masses are $\sim 30\ M_\odot \Rightarrow$ First direct evidences for "heavy" stellar mass BHs ($> 25\ M_\odot$)

LVC 2016, PRL, 116, 061102

GW170817: the beginning of multi-messenger astronomy with GWs



- GW170817: **first observation of a binary neutron star inspiral**
- coincident short GRBs detected in γ rays

  $\Rightarrow$ first direct evidence that at least some **BNS mergers are progenitors of short GRBs**
- identification of the **host galaxy**: NGC 4993

  $\Rightarrow$ new, independent estimate of the Hubble constant
- an optical/infrared/UV counterpart has been detected

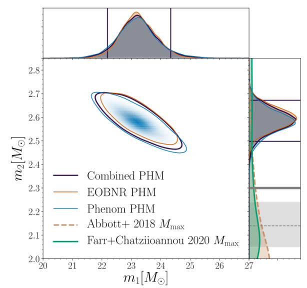
  $\Rightarrow$ first spectroscopic **identification of a kilonova**
- An X-ray and a radio counterparts have been identified

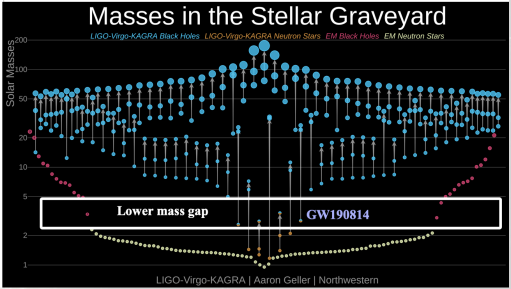
  $\Rightarrow$ GRB afterglow from a **structured jet** seen off-axis (Ghirlanda et al. 2019, Mooley et al. 2018)

see LVC 2017, ApJ Letters, 848, 2 and refs. therein

GW190814: lower mass gap

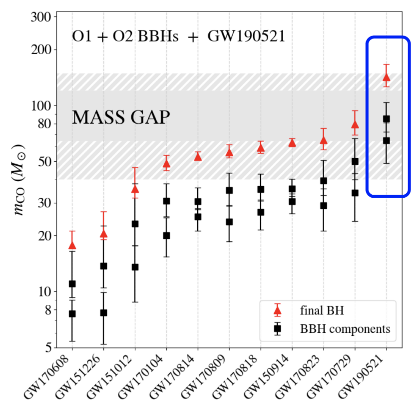
- GW event observed by the two LIGO detectors and Virgo
- m_1: $23.2^{+1.1}_{-1.0}$ $M_\odot$
- **m_2: $2.59^{+0.08}_{-0.09}$ $M_\odot$ $\Rightarrow$ BBH or NS-BH?**





LVC 2020, ApJL, 896, 44

GW190521: upper mass gap



- GW event observed by the two LIGO detectors and Virgo
- m_1: 85^{+21}_{-14} $M_\odot$, m_2: 66^{+17}_{-18} $M_\odot$
- The primary falls in the mass gap by (pulsational) pair-instability SN

Challenge for stellar evolution

- Isolated binary evolution is disfavoured
- **Dynamical scenario?** e.g., hierarchical mergers in an AGN disk

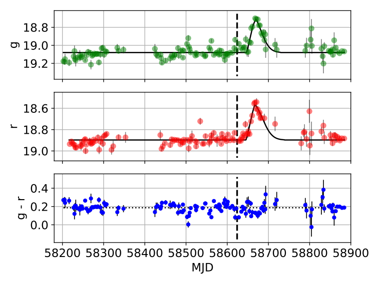
LVC 2020, PRL, 125, 101102

LVC Collaboration 2020, ApJL, 900, 13

GW190521: an EM counterpart?

The Zwicky Transient Facility (ZTF) detected a candidate optical counterpart in AGN J124942.3+344929

- GW sky localization: 765 deg^2 (90% C.R.)
- ZTF observed 48% of the 90% C.R. of the GW skymap
- An EM flare observed $\sim$ 34 days after the GW event
- It is consistent with expectations for a **BBH merger in the accretion disk of an AGN** (see McKernan et al. 2019, ApJL, 884, 50)

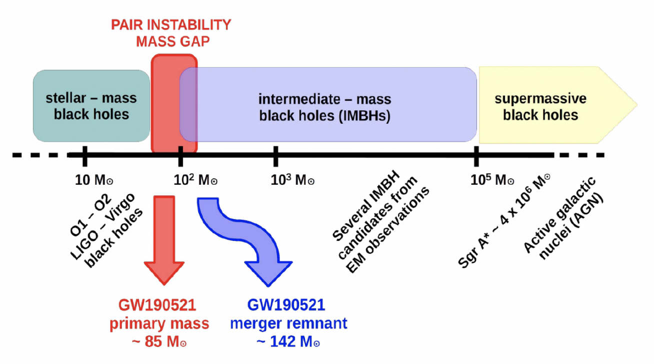


Graham et al. 2020, PRL, 124, 251102

Common origin of the two transients seems to be preferred with respect to random coincidence (Morton et al. 2023; see, however, Ashton et al. 2021, Palmese et al. 2021)

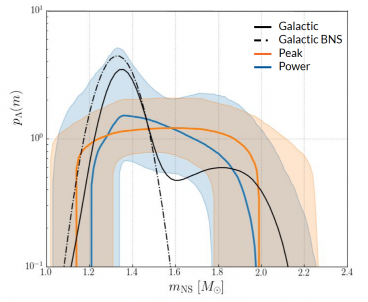
GW190521: the birth on a intermediate massive BH

The remnant BH mass is $\sim 142\ M_\odot \Rightarrow$ **First strong observational evidence for an intermediate-mass BH**: the missing link between stellar and supermassive BHs



The astrophysical population of NSs

The mass distribution of NSs

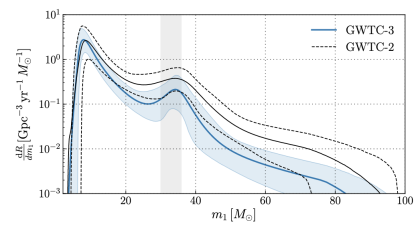


- The mass distribution of NSs observed in GWs is broader and has greater support for high-mass NSs with respect to the Galactic population
- Difference could result from:
  - distinct formation channels;
  - strong selection effects;
  - overlap of NS and BH mass distributions

LVK Collaboration 2023, PRX, 13, 011048

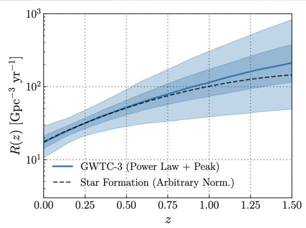
The population of BBH merging systems

Primary BH mass distribution



- BH mass distribution is non-uniform, with overdensities at BH masses of 10 M$_\odot$ and 35 M$_\odot$; tail up to 80 M$_\odot$

BBH merger rate



- BBH merger rate is observed to increase with redshift

LVK Collaboration 2023, PRX, 13, 011048; LVC 2021, ApJL, 913, L7

Astrophysical implications: the merger rates

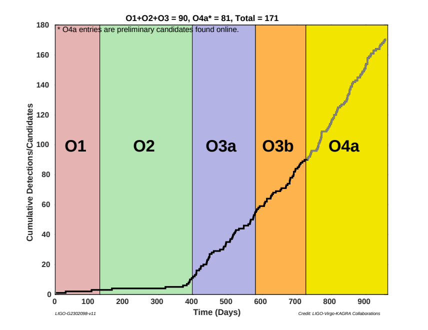
O1+O2+O3:

- BBH merger rate (z=0.2): 17.3 - 45 Gpc^{-3} yr^{-1}
- BNS merger rate: 13 - 1900 Gpc^{-3} yr^{-1}
- NS-BH merger rate: 7.4 - 320 Gpc^{-3} yr^{-1}

LVK Collaboration 2023, PRX, 13, 011048

→ Helpful to constrain population synthesis models

O4a: summary

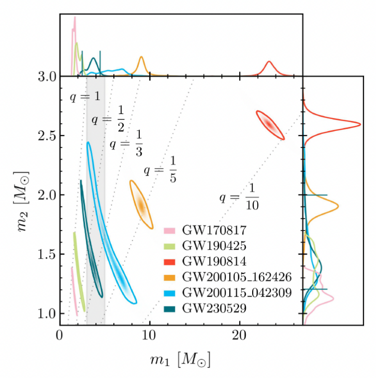


- $\sim$ 8 months of data taking
- LIGO detectors running with:
  - sensitivity of 120-160 Mpc (H1) and 140-160 Mpc (L1)
  - duty cycles of $\sim$ 70%
- 81 significant[a] detection candidates (92 Total - 11 Retracted)
- Almost all BBHs; no BNS; a couple of possible NS-BHs
  - **S230627c** - GraceDB
  - **GW230529**

[a] Significant GW alerts: false alarm rate $<$ 1/month for CBC and 1/year for bursts

GW230529

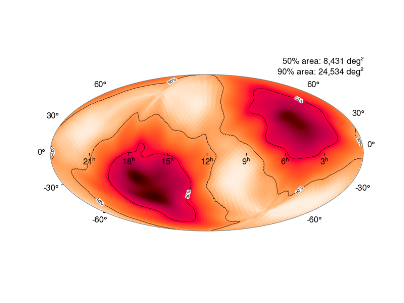
- Single-detector signal found by LIGO Livingston
- Primary: (2.5 - 4.5) $M_\odot$; Secondary: (1.2 - 2.0) $M_\odot$
- Most probable interpretation: merger of a NS with a BH with mass in the "lower mass gap" (3 - 5 $M_\odot$)
- GW230529 data release



LVK Collaboration 2024, arXiv:2404.04248

GW230529

- Significantly more symmetric than other NSBHs
- More symmetric masses → more susceptible to tidal disruption ⇒ EM counterpart
- 90 % C.R. $\sim 2 \times 10^4$ deg^2
- $D_L = 201^{+102}_{-96}$ Mpc
- No EM counterpart reported so far

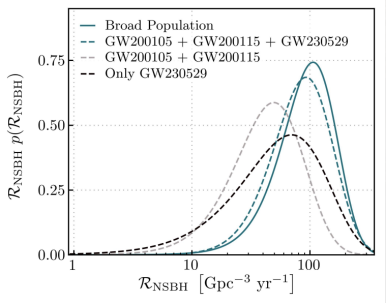


LVK Collaboration 2023, GCN 34148
LVK Collaboration 2024, arXiv:2404.04248

GW230529: the merger rate

NSBH merger rate updated using two different methods:

- GW230529 is representative of its own class of event (event-based)
- GW230529, GW200105, GW200115, and less-significant triggers treated as one source class (population-based)



Event-based: **GW230529-like systems merge at a similar (or even higher) rate to the more asymmetric NSBHs identified so far**

LVK Collaboration 2024, arXiv:2404.04248

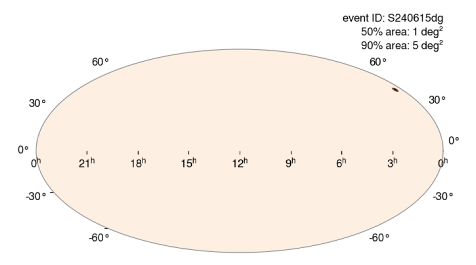
O4b: summary

- The two LIGO detectors are now running with a sensitivity of 140-180 Mpc, and with duty cycles of 60-75%
- Virgo is running with a sensitivity of 50-55 Mpc, and with duty cycle of $\sim$ 80%
- O4b Significant Detection Candidates*:

  27 (30 Total - 3 Retracted); No BNS so far; 1 NSBH
- **Virgo** can have a **significant impact on network localization capabilities**

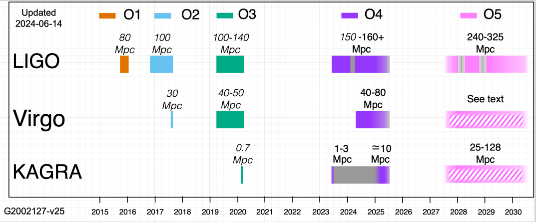
Example:

- S240615dg
- BBH
- Luminosity Distance: 1420 ± 236 Mpc
- GraceDB
- GCNs: 36669 and 36704



*Updated on June 21, 2024 at 23:00 CEST

Current and next GW observing runs



- O4b will run until June 9, 2025
- KAGRA will possibly join the network by the end of the run
- A fifth observing run (O5) is planned to start in a few years

Updated observing run plans at https://observing.docs.ligo.org/plan/

In the future 2nd generation GW detectors will operate with high sensitivity, in synergy with current and future EM facilities (e.g. SVOM, CTA, Vera Rubin Observatory etc)

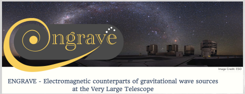
Many other GW and multi-messenger discoveries are expected in the near future... stay tuned!

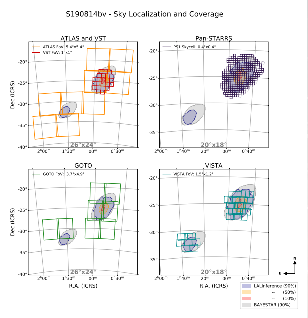
Backup

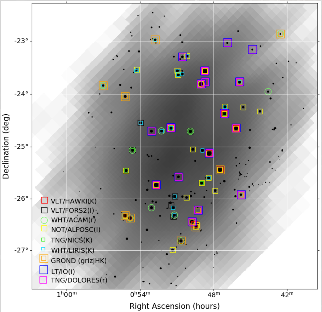
Backup Slides

GW190814: the EM follow-up

Example: optical counterpart searches by ENGRAVE



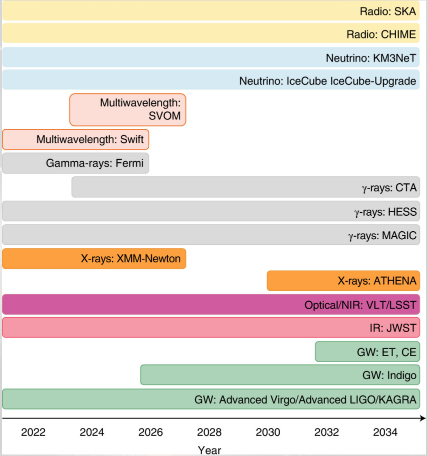




No EM counterpart has been observed

Ackley et al. 2020, A&A, 643, 113

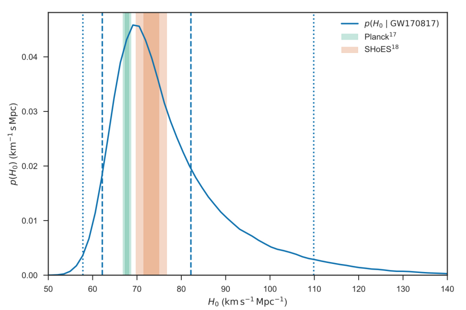
Multi-messenger facilities in the next years



Cuoco, Patricelli et al. 2022, Nat Comput Sci 2, 479

GW-NGC4993 association: implications for Cosmology

GW170817 as a standard siren:
the association with the host galaxy NGC 4993 and the luminosity distance directly measured from the GW signal have been used to determine the **Hubble constant**



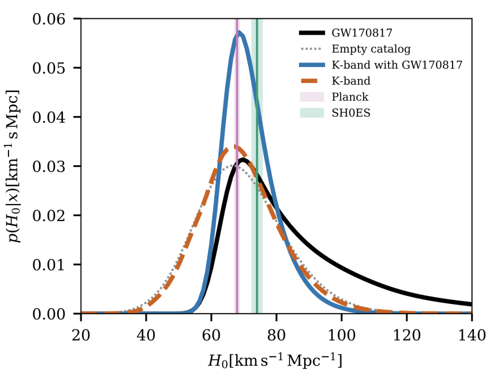
- $H_0 = 70.0^{+12.0}_{-8.0}$ km s^{-1} Mpc^{-1}*
- $H_0 = 67.74^{\pm 0.46}$ km s^{-1} Mpc^{-1}
- $H_0 = 73.24^{\pm 1.74}$ km s^{-1} Mpc^{-1}

Abbott et al., Nature, 551, 85 (2017)

* More recent estimates, obtained assuming a priori that the GW source is in NGC 4993, are:
- $H_0 = 70^{+13}_{-7}$ km s^{-1} Mpc^{-1} (high-spin case)
- $H_0 = 70^{+19}_{-8}$ km s^{-1} Mpc^{-1} (low-spin case)

LVK Collaboration 2019, PRX, 9, 011001

Hubble constant estimate with GWTC-3

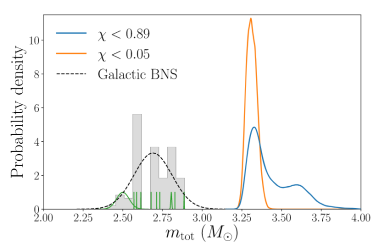


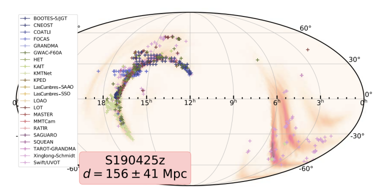
BBHs + galaxy catalogs + GW170817: $\mathrm{H_0} = 68^{+8}_{-6}$ km s^{-1} Mpc^{-1}

$\Rightarrow$ improvement of $\sim$ 40 % with respect to the result obtained using only GW170817

LVK Collaboration 2023, ApJ, 949, 76

GW190425: the second BNS merger





- GW event observed by LIGO-Livingston and Virgo
- The total mass is significantly larger than that of the other BNS systems...

  ... different formation channel?

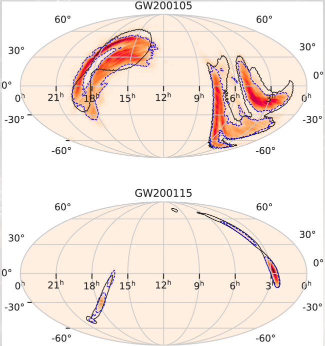
- 90 % C.R.: 8284 deg^2;

  $D_L = 159^{+69}_{-72}$ Mpc
- No EM counterpart (see, e.g., Hosseinzadeh et al. 2019)

LVC 2020, ApJL, 892, 3

GW200105 and GW200115

	m_1	m_2	D_L	90 % C.R.
GW200105*	$8.9^{+1.2}_{-1.5}$ $M_\odot$	$1.9^{+0.3}_{-0.2}$ $M_\odot$	280^{+110}_{-110} Mpc	7200 deg^2
GW200115	$5.7^{+1.8}_{-2.1}$ $M_\odot$	$1.5^{+0.7}_{-0.3}$ $M_\odot$	300^{+150}_{-100} Mpc	600 deg^2

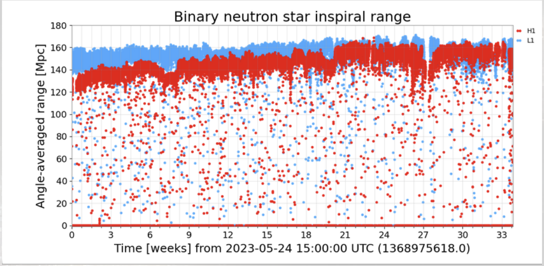


- No EM counterpart has been found...
- ... However, EM emission would have been difficult to detect, given the large distances and large error in the sky localization

LVK Collaboration 2021, ApJL, 915, L5

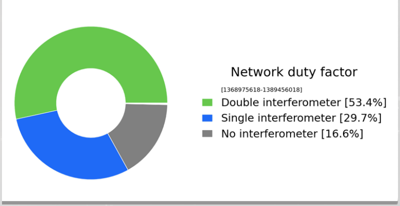
* In the GWTC-3 analysis, GW200105 is found to have $p_{\rm astro}$ <0.5, but it remains a candidate of interest (Abbott et al. 2023, PRX, 13, 041039

O4a: detector status



Individual duty cycle:

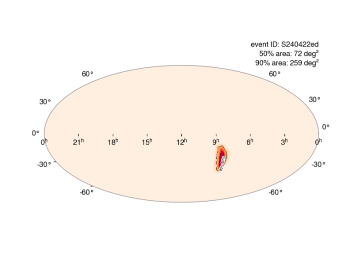
- LIGO-Hanford: 67.5 %
- LIGO-Livingston: 69.0 %



https://gwosc.org/detector_status/O4a/

S240422ed

- NSBH (> 99 %)
- HasRemnant* > 99 %
- Luminosity Distance: (188 ± 43) Mpc
- GraceDB
- GCNs: 36236 and 36240
- No confirmed EM counterpart so far



*Probability of having a non-zero amount of NS material outside the final remnant compact object