Image: Carl Knox, OzGrav-Swinburne University of Technology

LIGO-Virgo-KAGRAによる重力波観測の現状と展望

Soichiro Morisaki

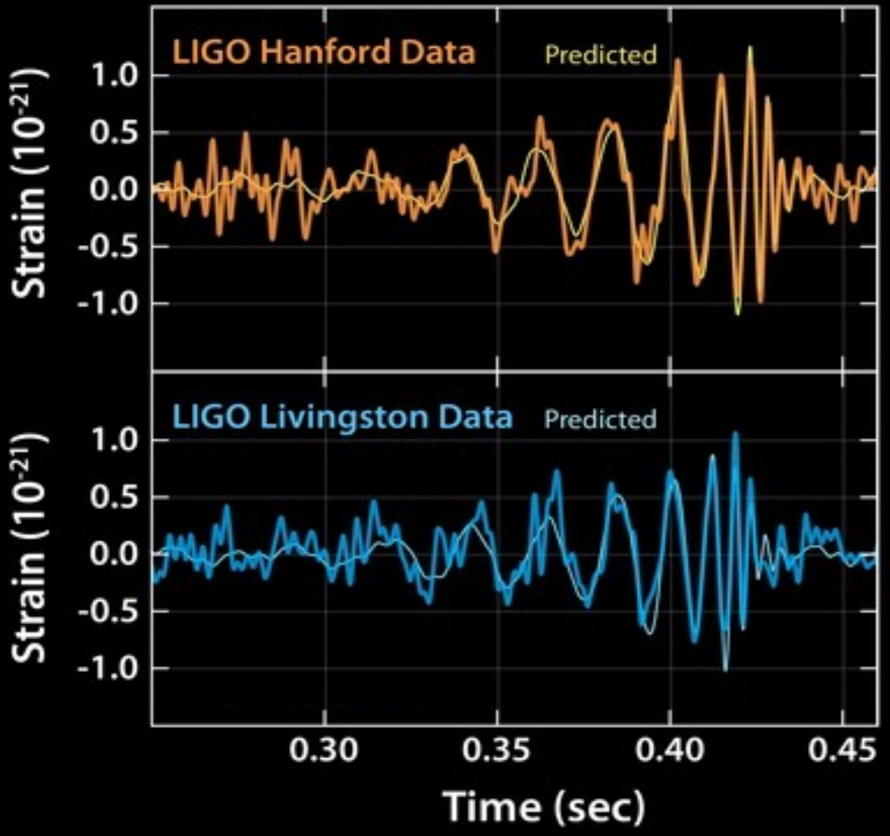
ICRR/University of Tokyo

2023年11月1日

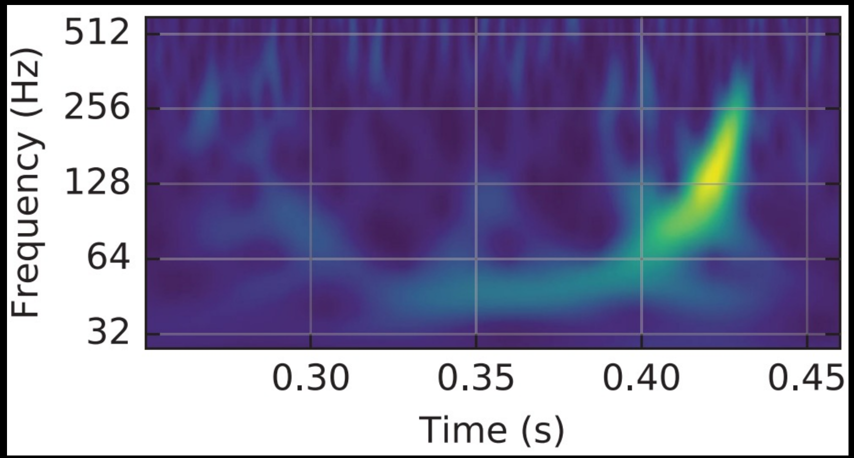
研究会「マルチメッセンジャー天文学の展開」

Credit: Caltech/MIT/LIGO Lab

LIGO achieved the first direct detection of gravitational waves 8 years ago.

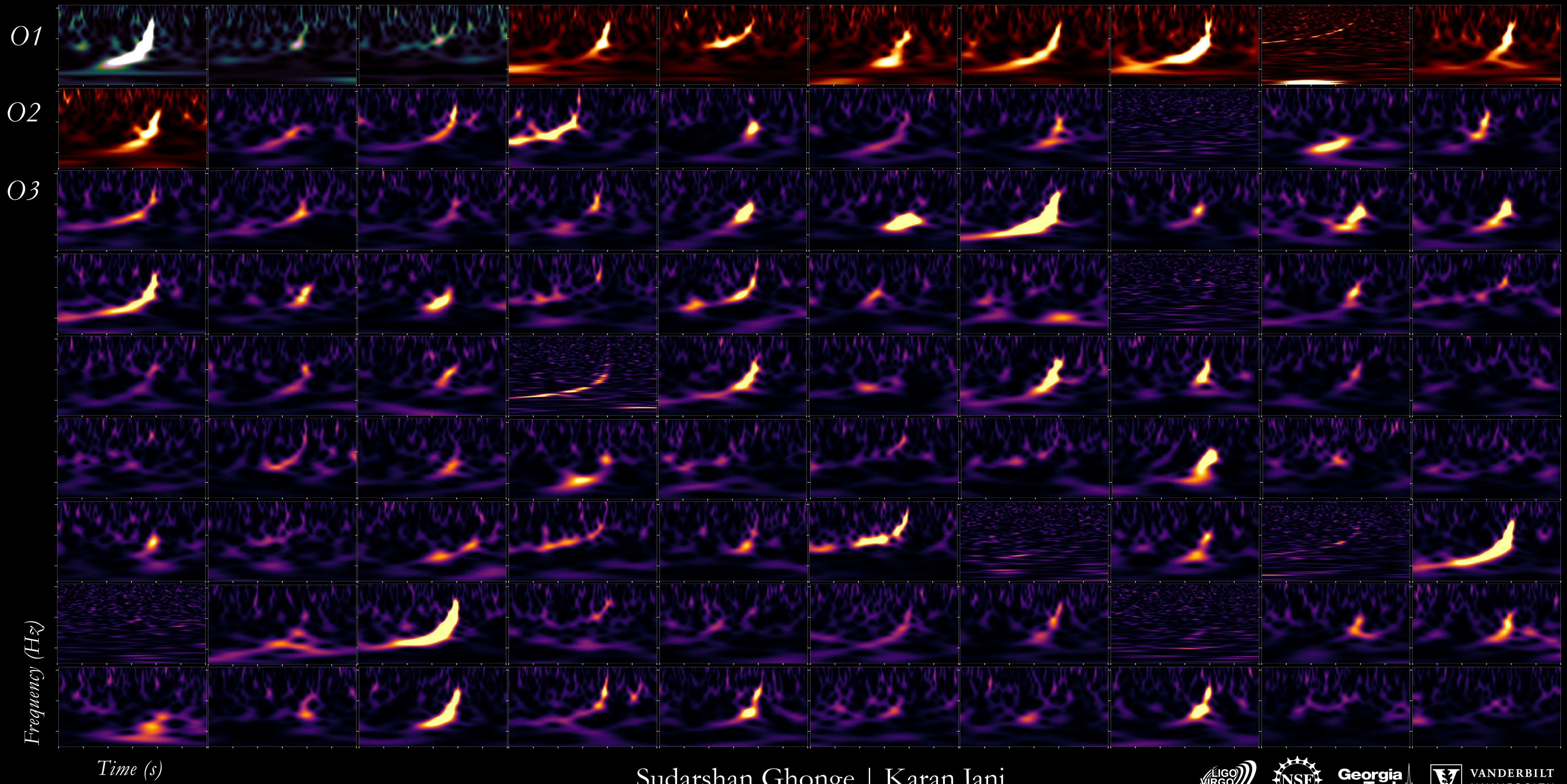


The signal is consistent with binary black hole merger with $m_1 = 36^{+5}_{-4}\,M_{\odot},\ m_2 = 29^{+4}_{-4}\,M_{\odot}$.



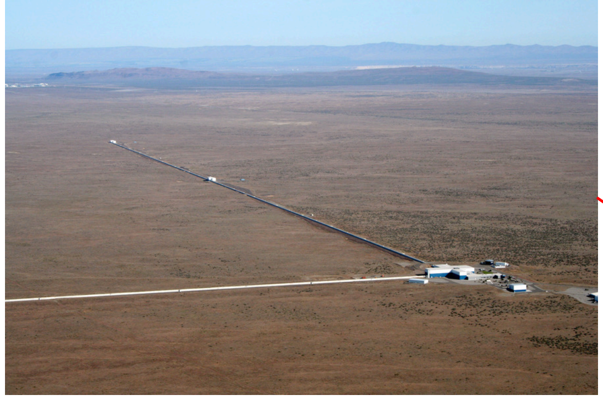
Gravitational-Wave Transient Catalog

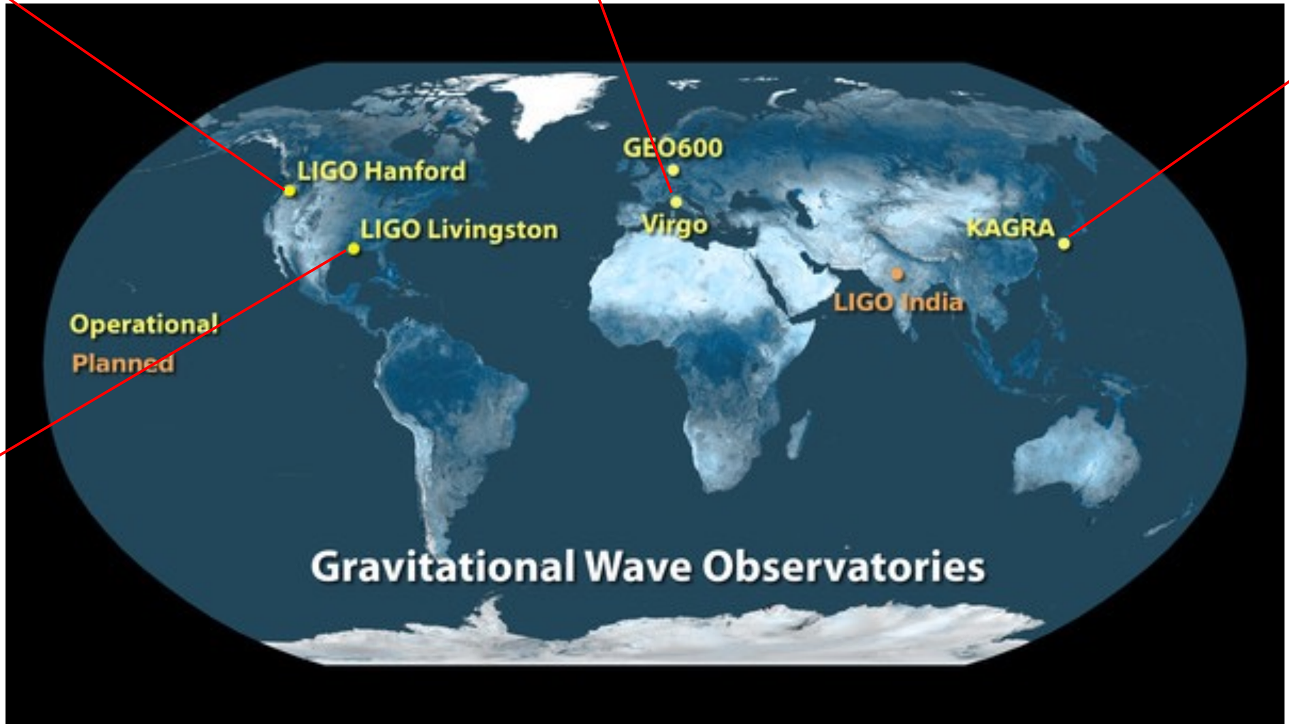
Detections from 2015-2020 of compact binaries with black holes & neutron stars



Sudarshan Ghonge | Karan Jani

Gravitational-wave observatories





LIGO-Virgo-KAGRA (LVK) collaboration

Figure credit:
Caltech/MIT/LIGO Lab/ICRR

Observing timeline

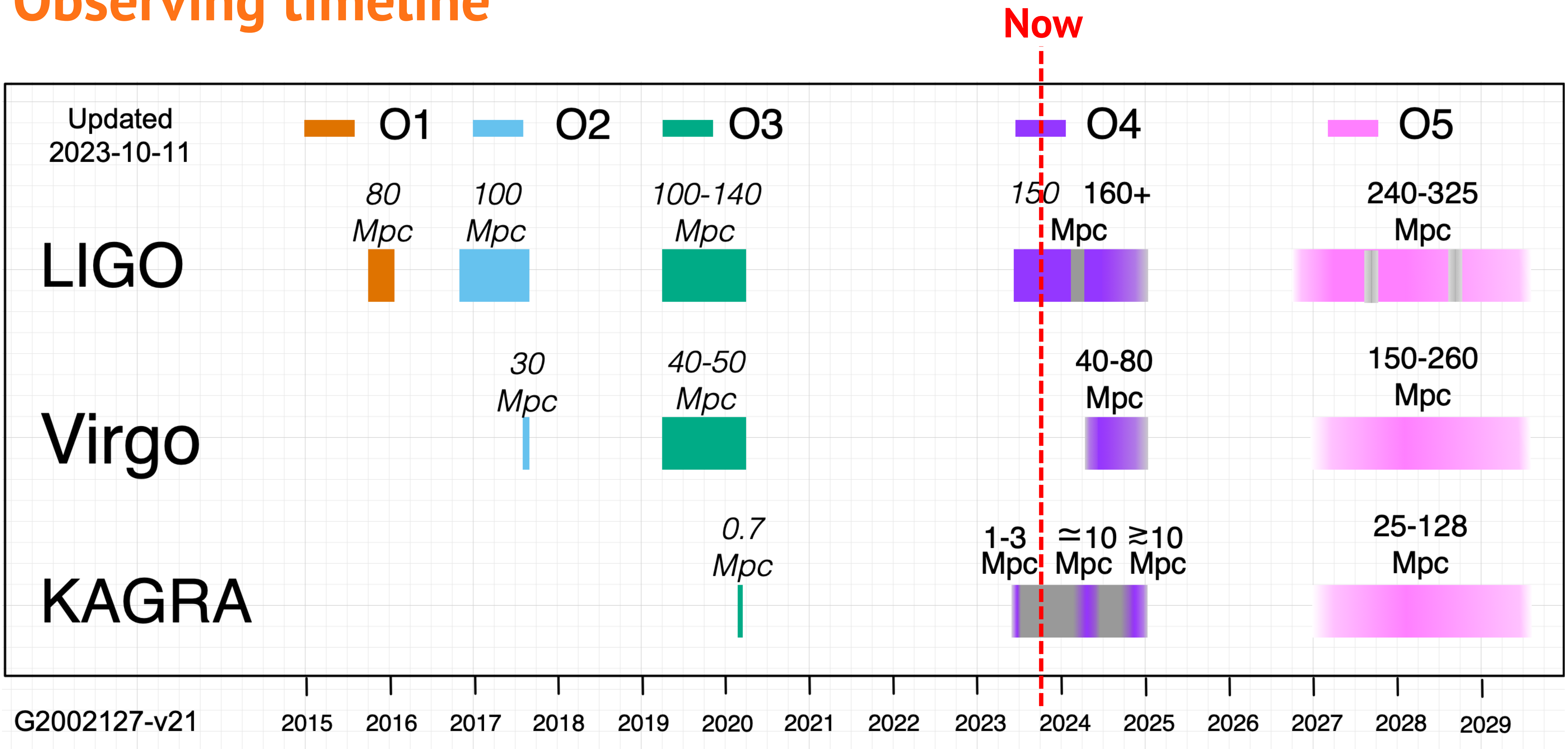
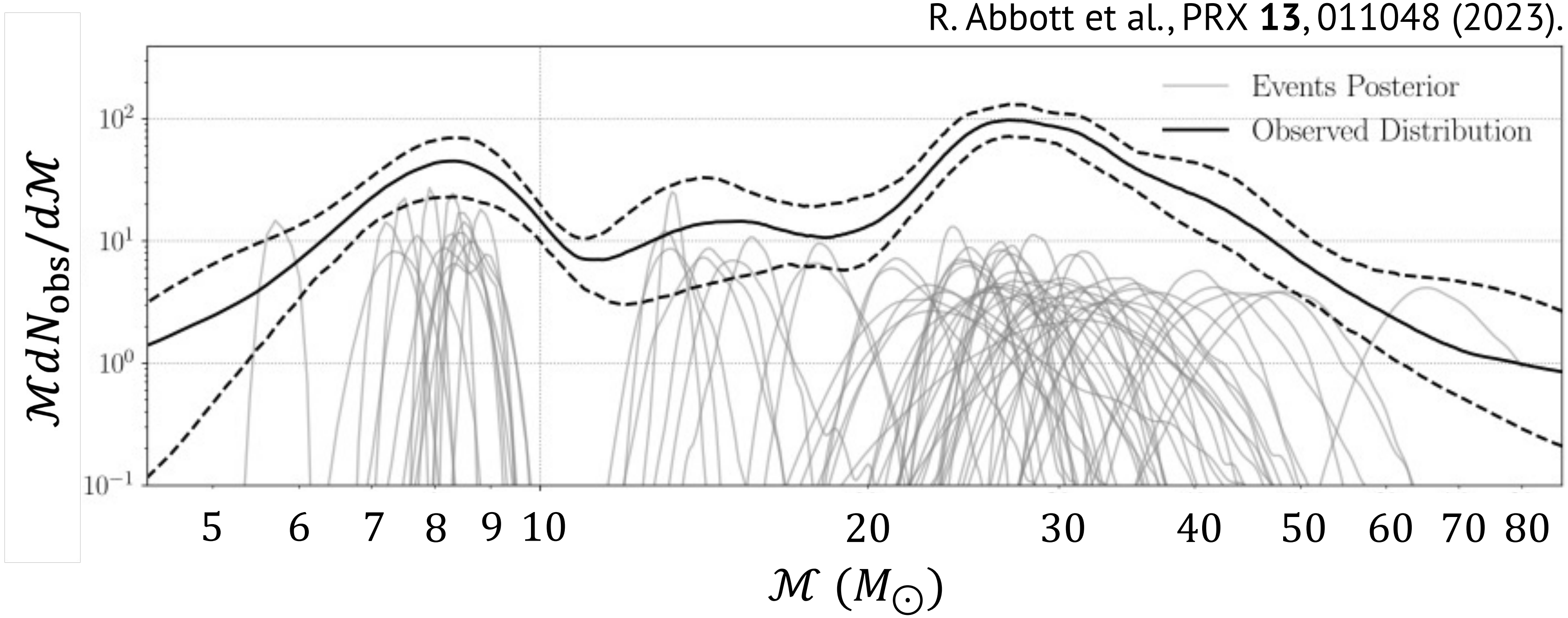


Figure: Observing plan (https://observing.docs.ligo.org/plan/)

Population properties of binary black holes

R. Abbott et al., PRX **13**, 011048 (2023).

"Observed" population



Chirp mass $\mathcal{M}$ is mass combination measured precisely with GWs:

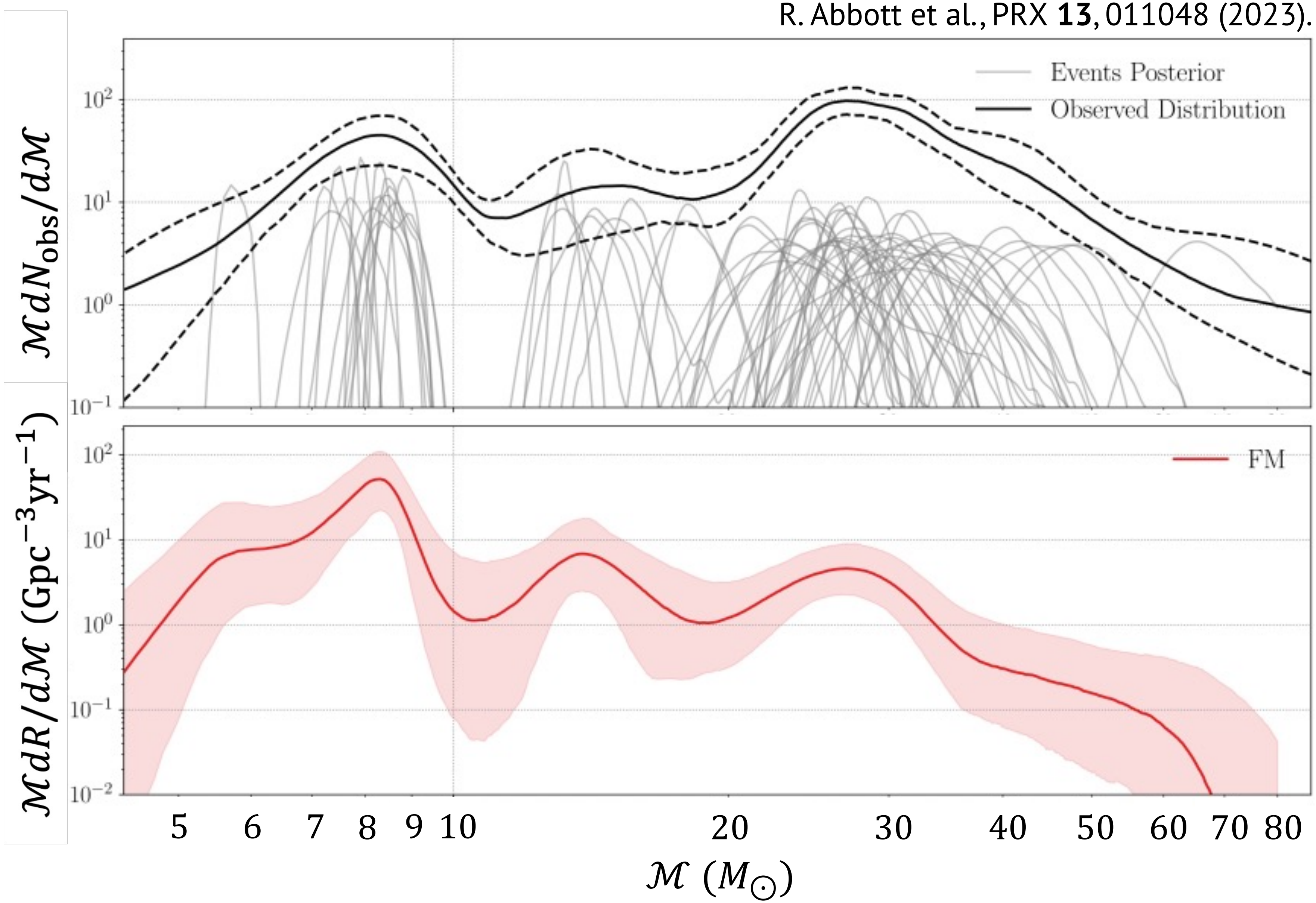
$$\mathcal{M} = \frac{(m_1 m_2)^{\frac{3}{5}}}{(m_1 + m_2)^{\frac{1}{5}}}.$$

Population properties of binary black holes

R. Abbott et al., PRX **13**, 011048 (2023).

"Observed" population

After correcting observation bias

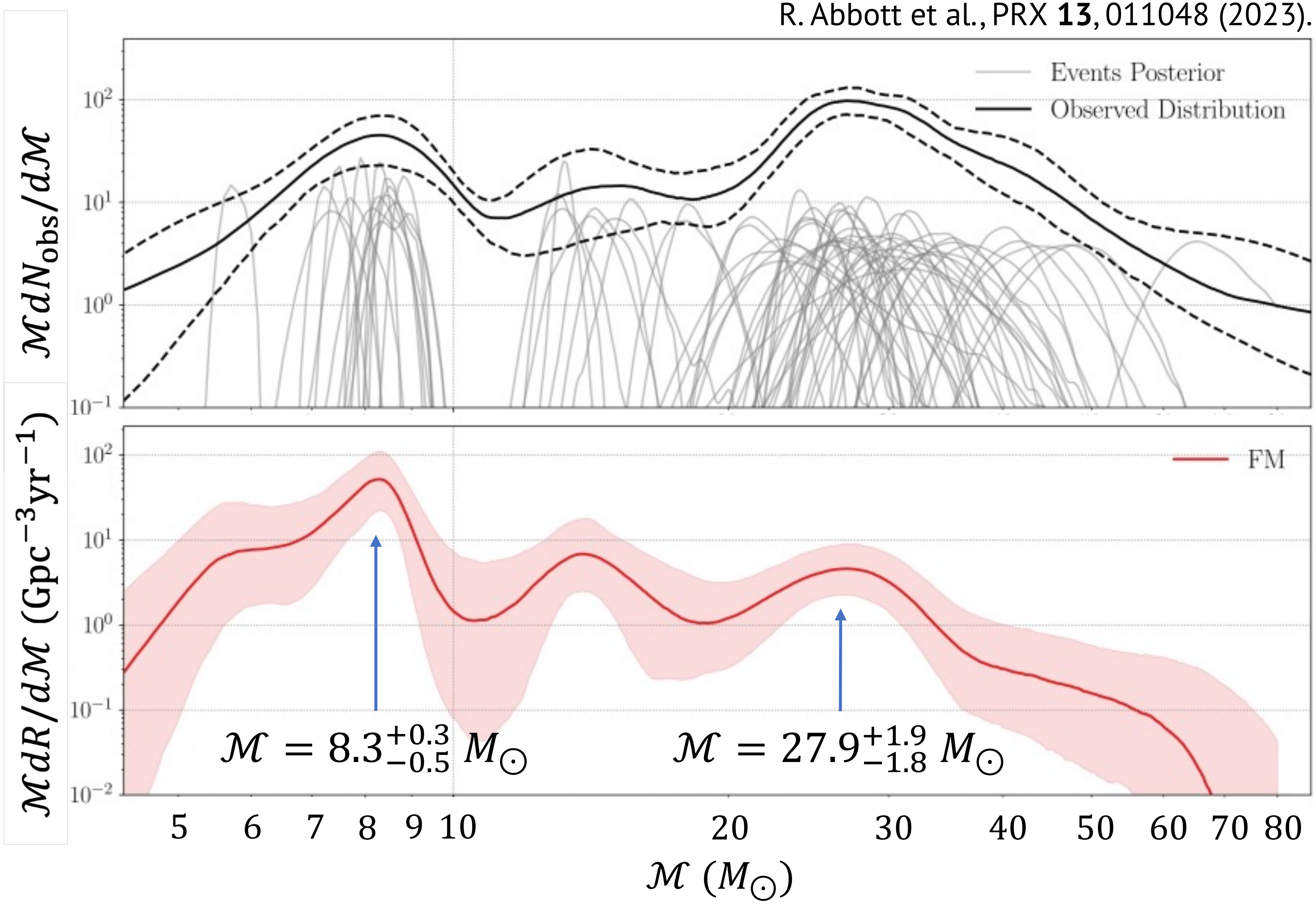


Population properties of binary black holes

R. Abbott et al., PRX **13**, 011048 (2023).

"Observed" population

After correcting observation bias



Heavy binary black holes

Reference: R. Abbott et al., PRL **125**, no.10, 101102 (2020),
R. Abbott et al., ApJL **900**, no.1, L13 (2020).

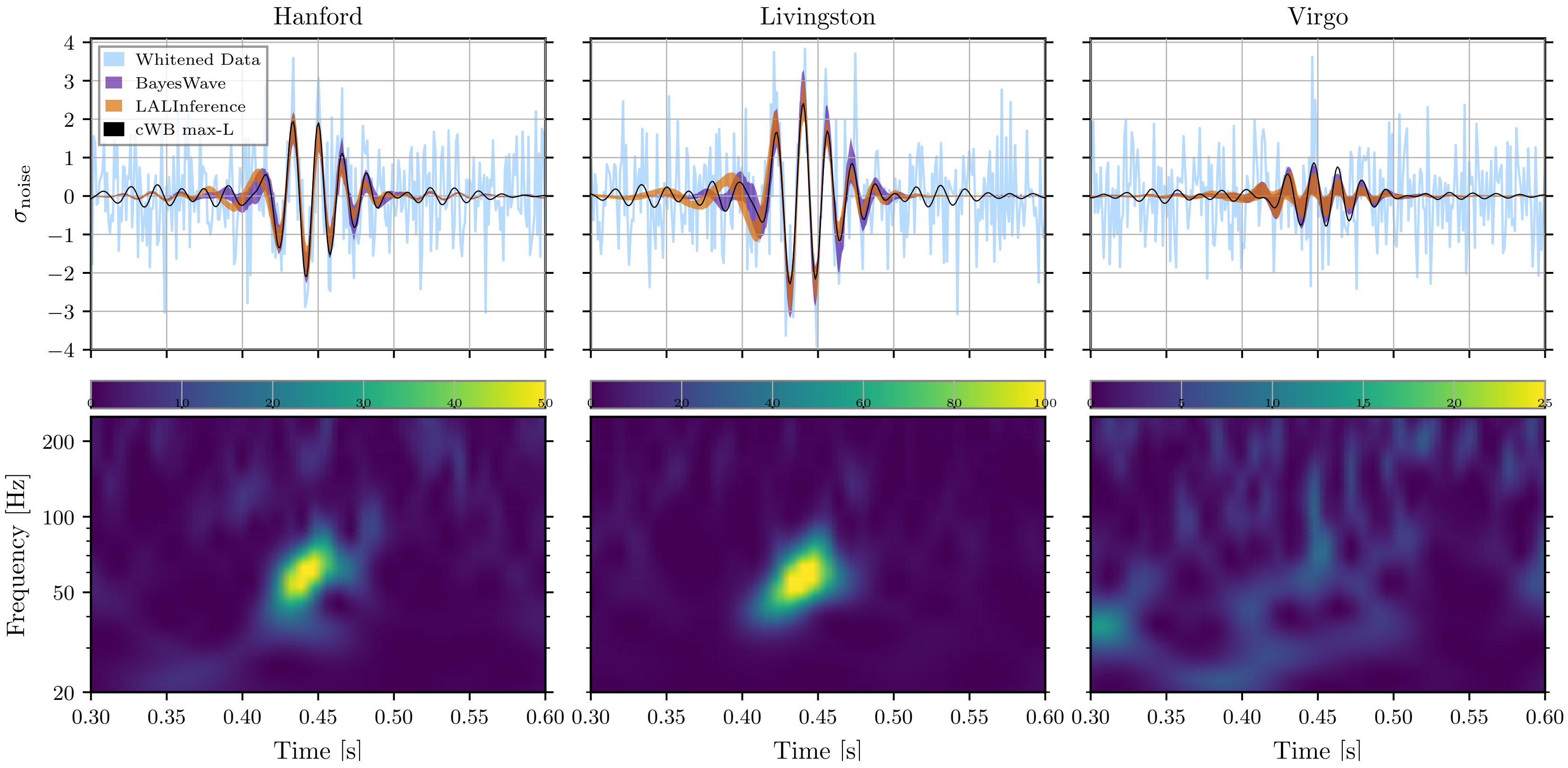


Figure: LIGO-Virgo data for GW190521

GW190521:

$m_1 = 85^{+21}_{-14} M_\odot$,

$m_2 = 66^{+17}_{-18} M_\odot$.

- The primary mass m_1 is in the pair-instability mass gap, $(65 - 120) M_\odot$.
- The remnant is an intermediate mass black hole: $M_f = 142^{+28}_{-16} M_\odot$.

Binary black holes with unequal masses

Reference: R. Abbott et al., PRD **102**, no. 4, 043015 (2020), R. Abbott et al., ApJL **896**, no.2, L44 (2020).

GW190412

- $m_1 = 30.1^{+4.6}_{-5.3} M_\odot$, $m_2 = 8.3^{+1.6}_{-0.9} M_\odot$.
- Strong evidence of higher GW multipoles ($p \leq 6 \times 10^{-4}$).

GW190814

- $m_1 = 23.2^{+1.1}_{-1.0} M_\odot$, $m_2 = 2.59^{+0.08}_{-0.09} M_\odot$.
- Strong evidence of higher GW multipoles ($p \leq 2.5 \times 10^{-4}$).
- The secondary mass is in "mass gap" between NS and BH.

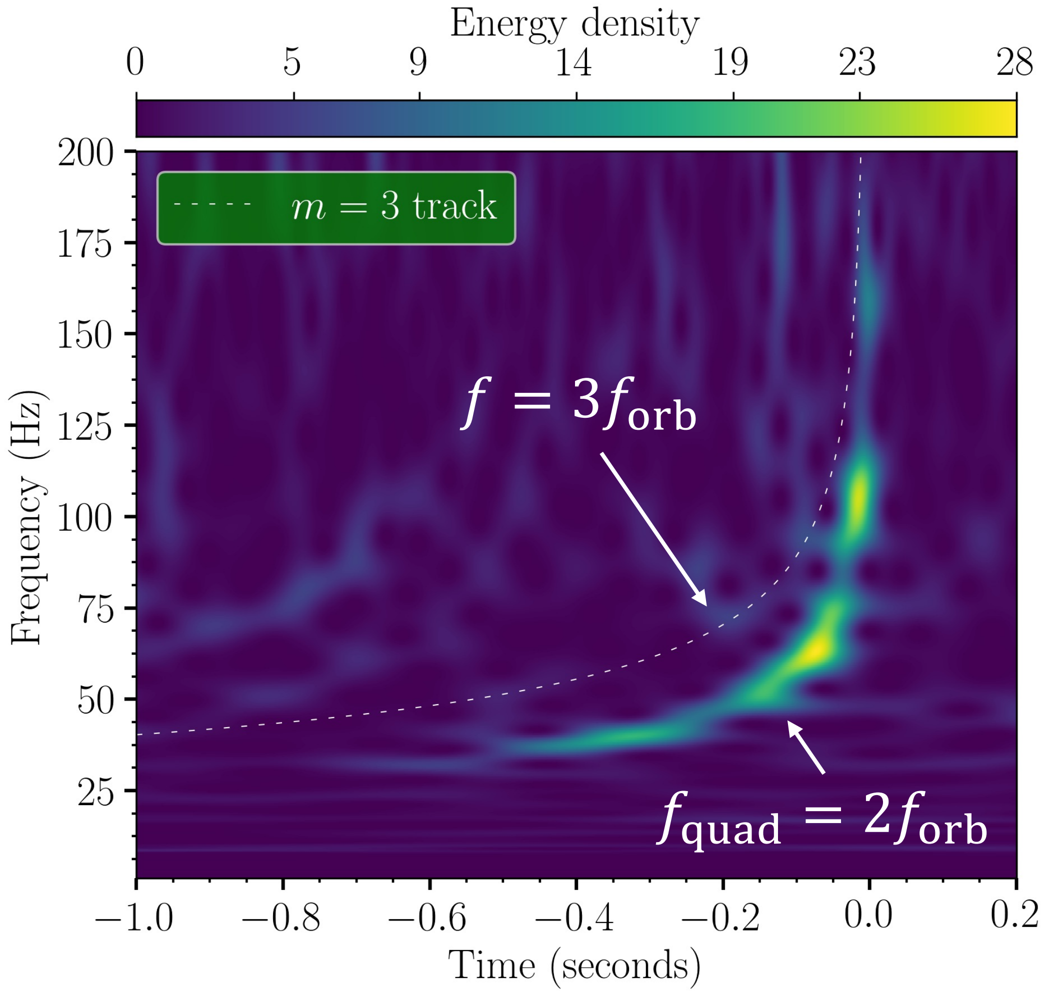
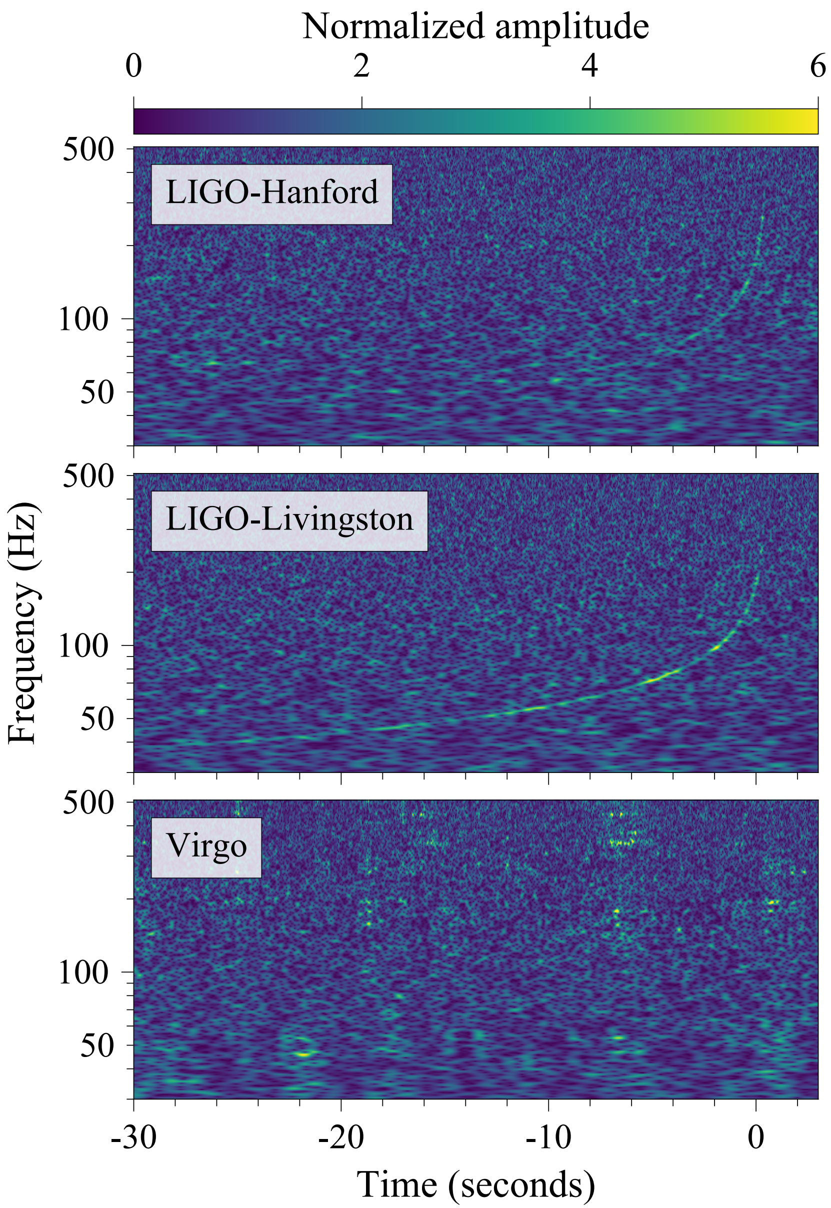


Figure: LIGO-Livingston data for GW190412

GW170817: The first observed GWs from binary neutron star



- Consistent with known neutron stars:

$$m_1 = (1.36—1.60)\ M_\odot,$$
$$m_2 = (0.86—1.36)\ M_\odot.$$

- Short gamma-ray burst detected ~1.7s after the coalescence (GRB 170817A).

Figure credit:
B. P. Abbott et al., PRL **119**, 161101 (2017).

GW170817: The first observed GWs from binary neutron star

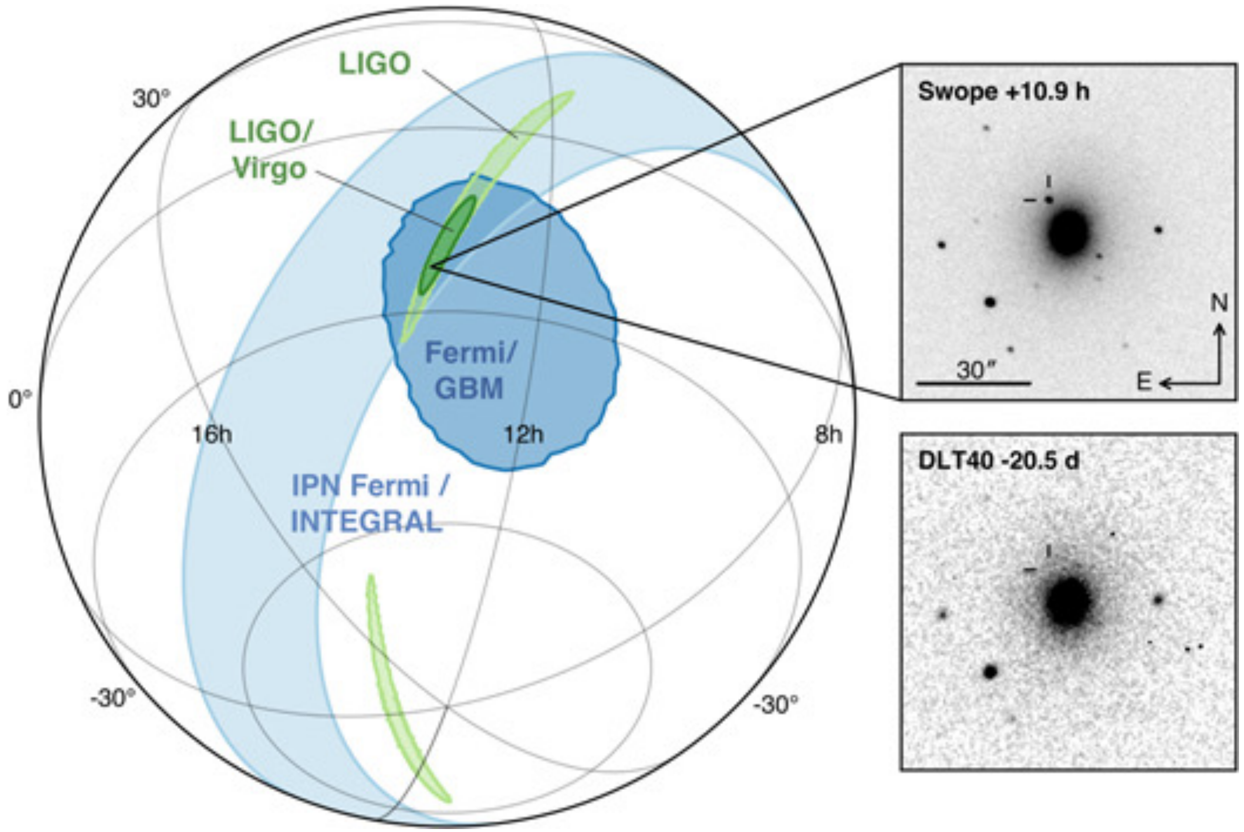


Figure: Localization from GWs and host galaxy location

Figure credit: B. P. Abbott et al., ApJL **848**, no.2, L12 (2017).

Sky localization from GWs

→ Identification of host galaxy

→ EM counterparts from radio to X-ray

Lessons from the first GW + EM obs.

- Origins of short gamma-ray bursts
- Speed of GWs
- Origin of heavy elements
- Measurement of Hubble constant

GW190425: Heavy binary neutron star

Figure credit:
B. P. Abbott et al., ApJL **892**, no.1, L3 (2020).

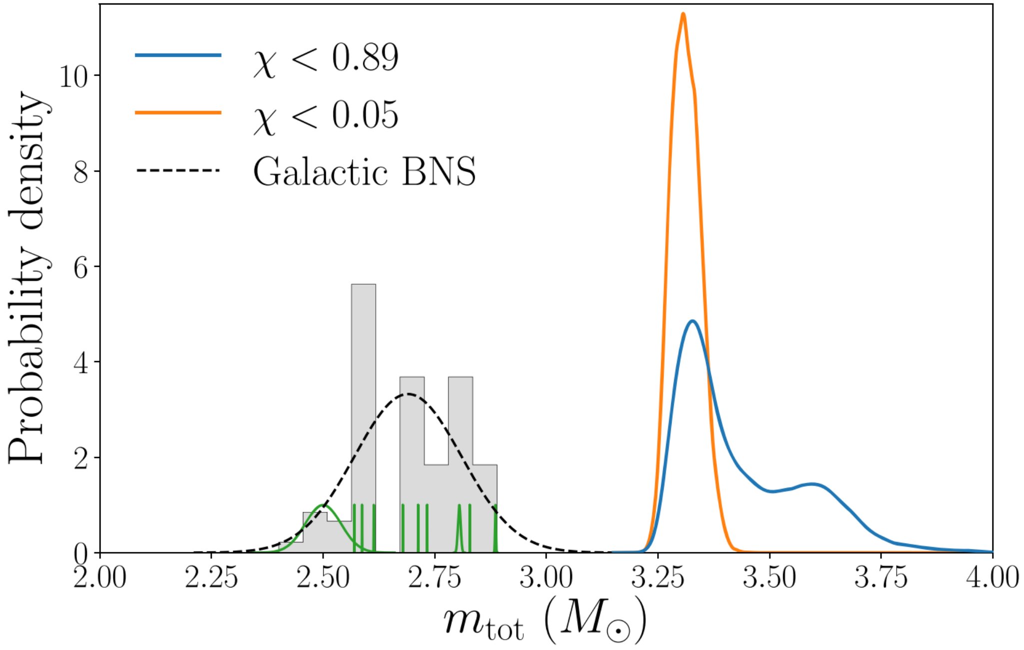


Figure: Total masses of GW190425 (orange, blue) and galactic merging binary neutron stars (gray)

- Heavier than galactic binary neutron stars:

$$m_1 = (1.61 — 2.52)\ M_\odot,$$
$$m_2 = (1.12 — 1.68)\ M_\odot.$$

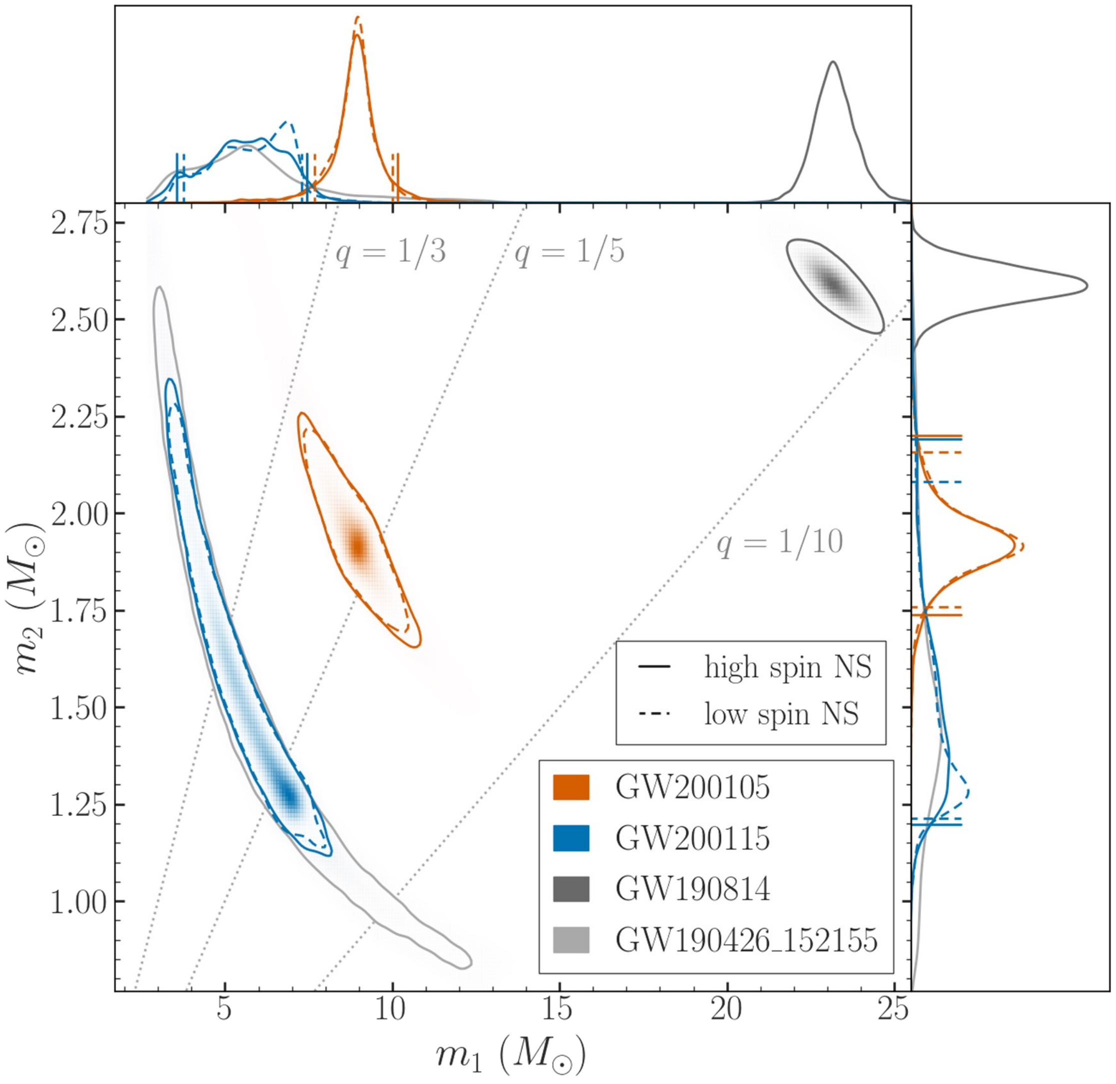
- LIGO-Hanford was not observing.
  → Large localization uncertainties
  (~ 16% of the whole sky)

- The source is also distant, (90— 230) Mpc.

- No EM or neutrino counterparts.

Neutron star – black hole candidates

Reference:
R. Abbott et al., ApJL **915**, no.1, L5 (2021).



	m_1	m_2
GW200105	$8.9^{+1.2}_{-1.5} M_\odot$	$1.9^{+0.3}_{-0.2} M_\odot$
GW200115	$5.7^{+1.8}_{-2.1} M_\odot$	$1.5^{+0.7}_{-0.3} M_\odot$

- Masses consistent with neutron star-black hole (NSBH)
- GW200105 does not pass the GWTC3 event criteria.
- No direct evidence of secondary objects being neutron stars (No EM counterparts, no tidal information)

O3GK

Reference:
R. Abbott et al., PTEP **2021**, 05A101 (2021).

- Joint observation of KAGRA and GEO600 from April 7 to 20 in 2020 (“O3GK”).

- Searches
  - All-sky CBC and burst searches
  - GRB-targeted searches

- No detections, but they demonstrate that analysis framework is ready.

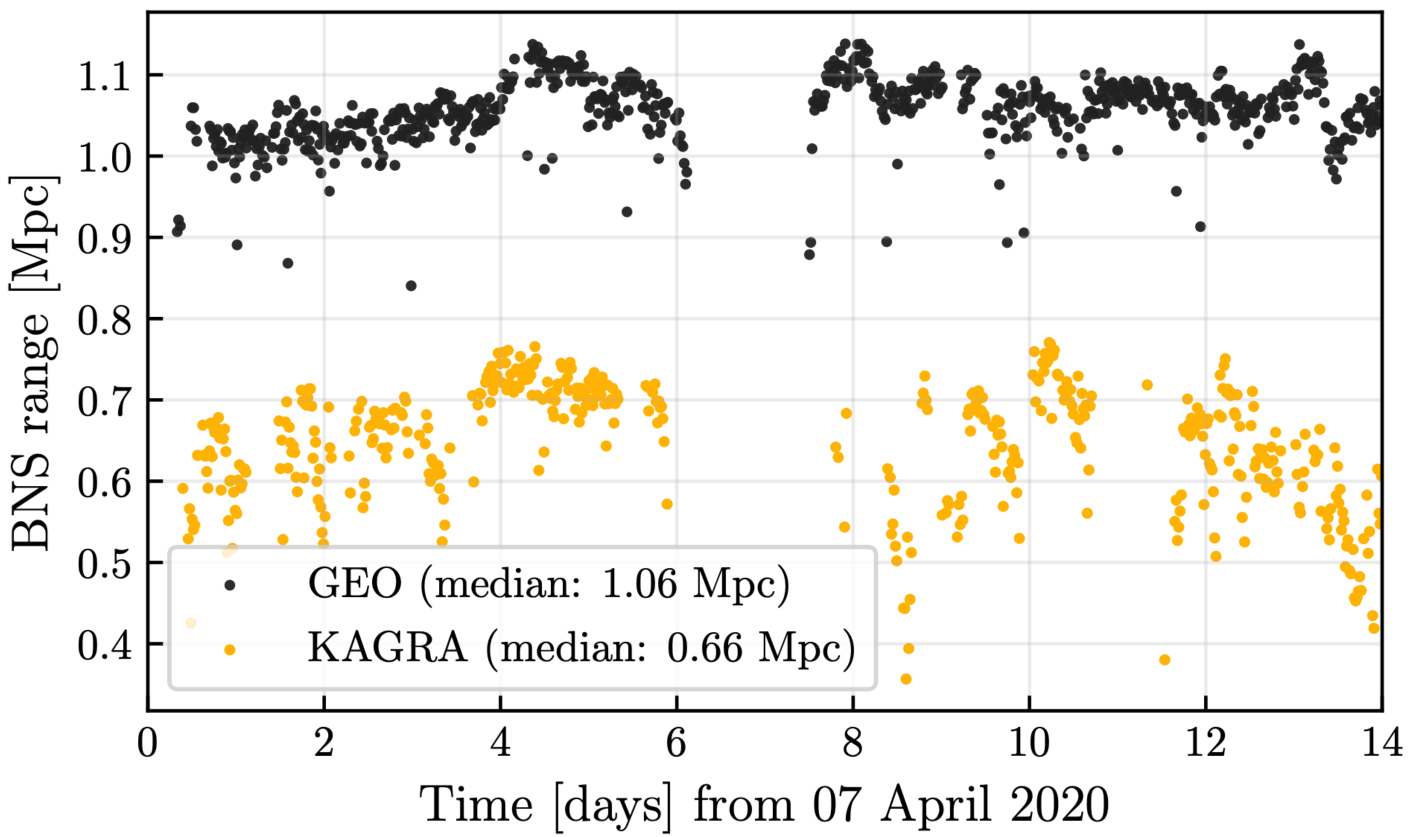


Figure: Binary neutron star range of GEO and KAGRA in O3GK

Observing timeline

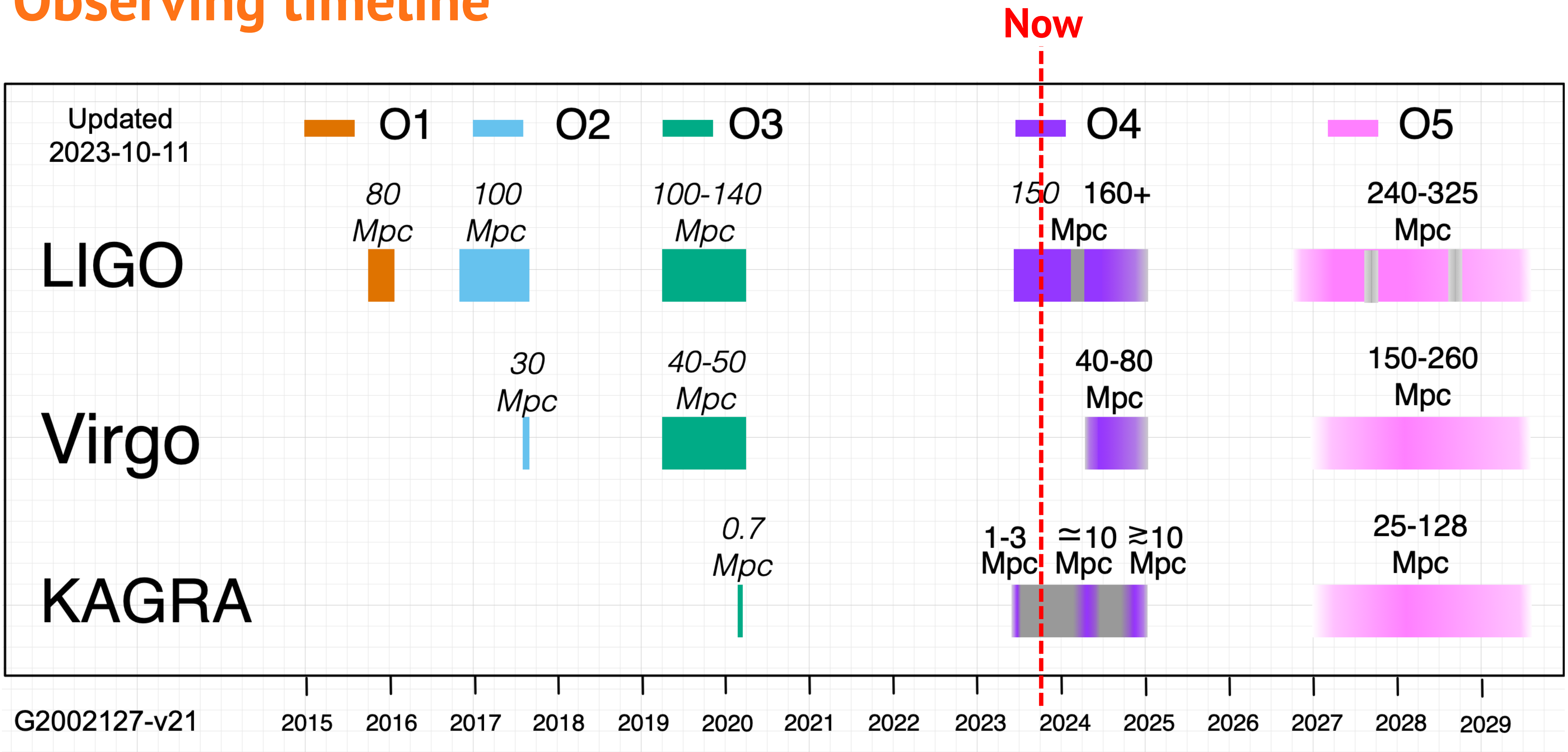


Figure: Observing plan (https://observing.docs.ligo.org/plan/)

KAGRA O4

Reference: Uchiyama-san's presentation at ASJ Spring Annual Meeting 2024

- KAGRA performed observation from May 24 to June 21 this year. = The first LIGO-KAGRA joint obs.
- Sensitivity improvement: 0.66 Mpc (O3GK) → 1.3 Mpc (O4a) in binary neutron star range.
- Duty cycle improvement: 53% (O3GK) → 80% (O4a)

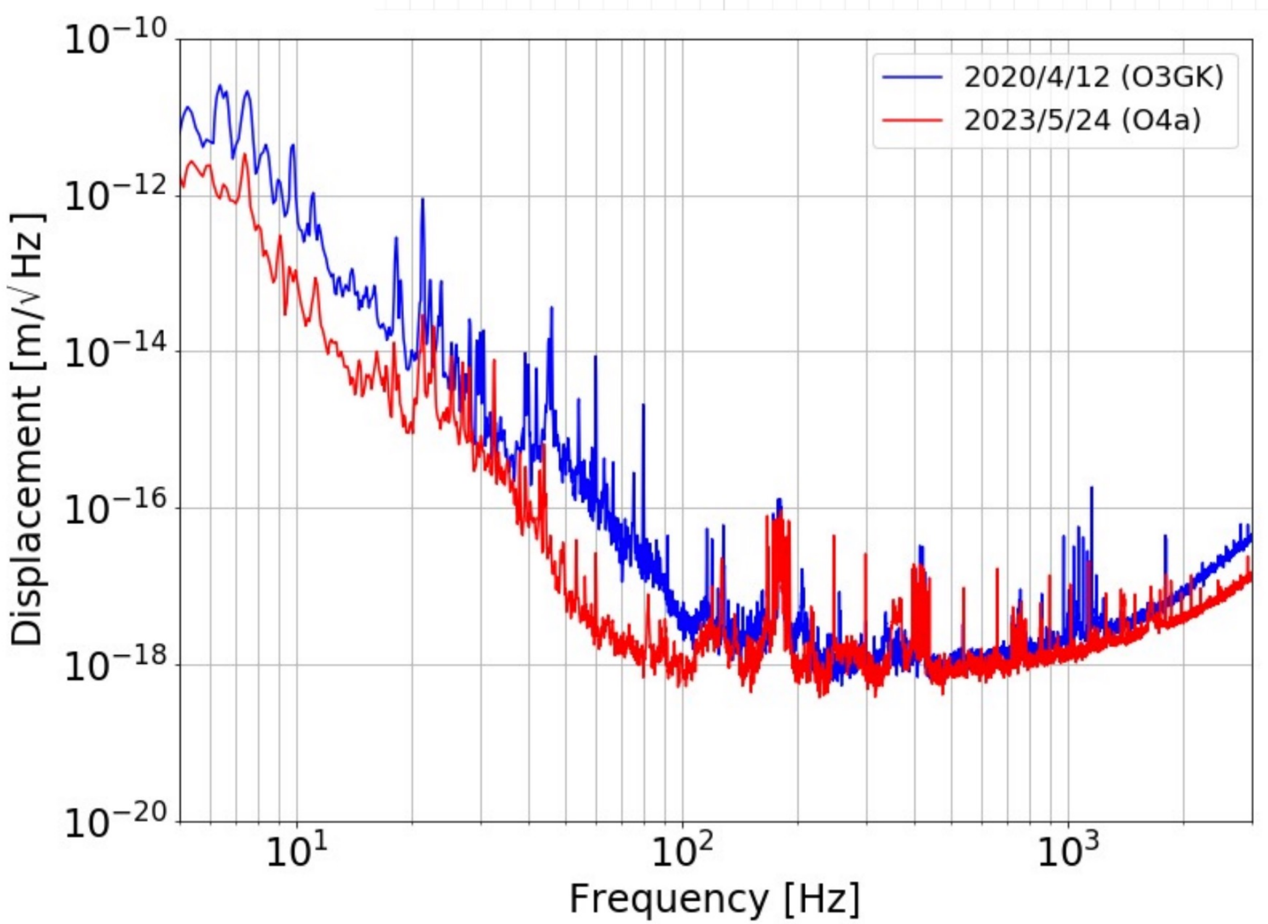
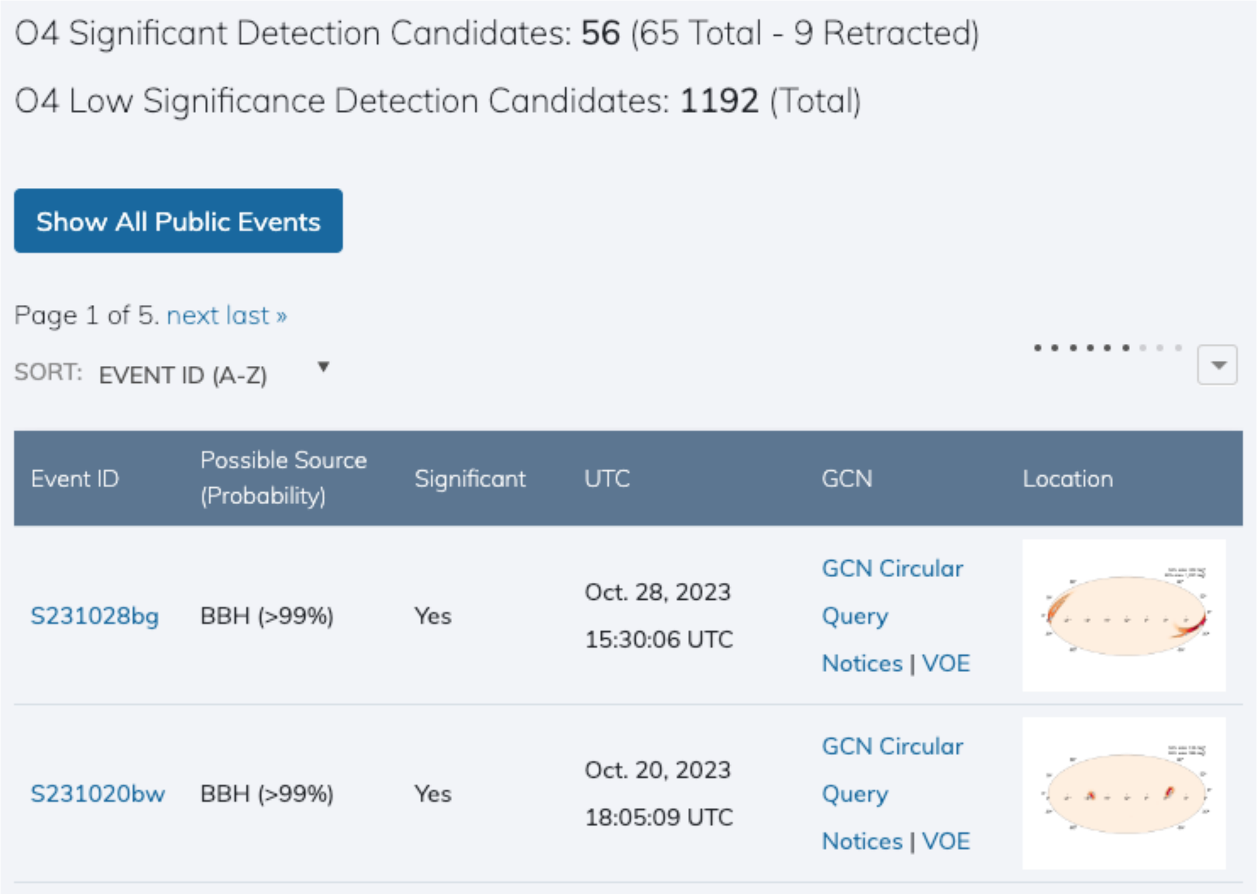


Figure: sensitivities in O3GK (blue) and O4a (red)

Current status of O4

- Significant candidates (as of Oct. 28): 56 detections (54 BBHs, 2 NSBHs)

- Virgo is commissioning to achieve its target sensitivity and will join the observation in spring next year.



O4 Significant Detection Candidates: **56** (65 Total - 9 Retracted)

O4 Low Significance Detection Candidates: **1192** (Total)

Show All Public Events

Page 1 of 5. next last »

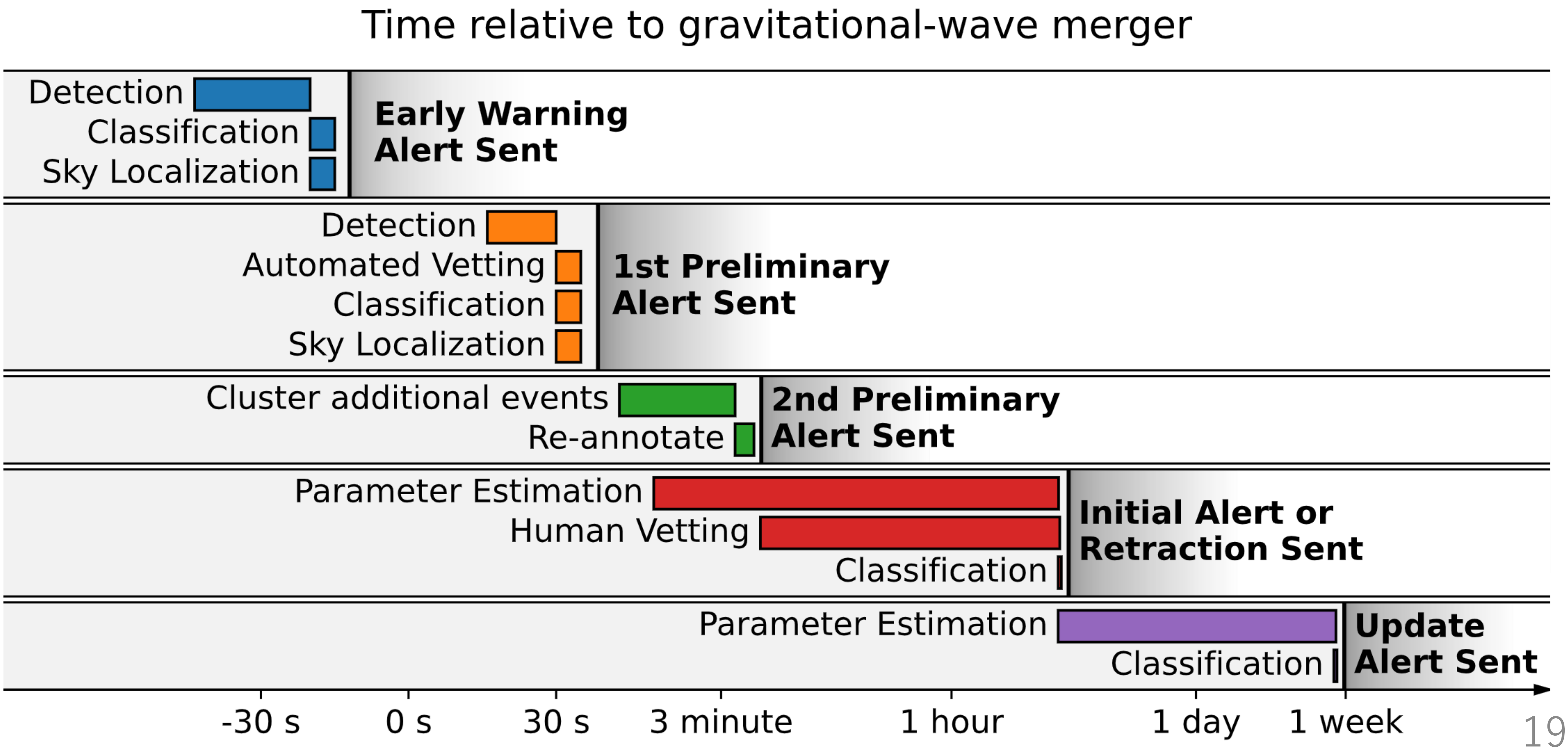
SORT: EVENT ID (A-Z)

Event ID	Possible Source (Probability)	Significant	UTC	GCN	Location
S231028bg	BBH (>99%)	Yes	Oct. 28, 2023 15:30:06 UTC	GCN Circular Query Notices | VOE	
S231020bw	BBH (>99%)	Yes	Oct. 20, 2023 18:05:09 UTC	GCN Circular Query Notices | VOE	

Event candidates public at GraceDB (https://gracedb.ligo.org/)

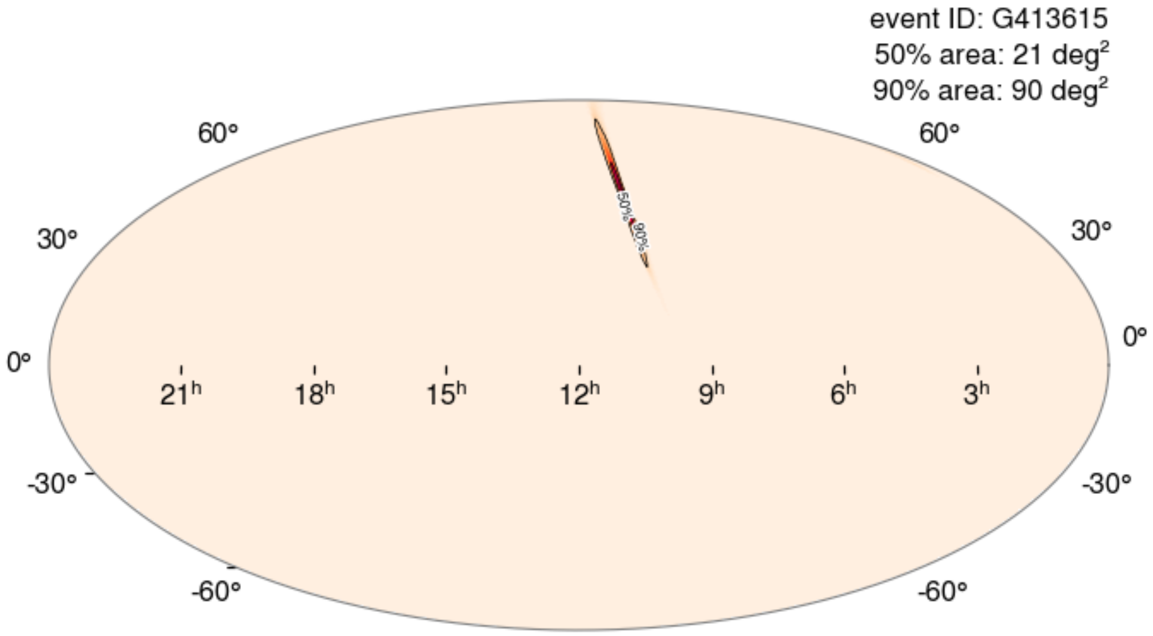
Low-latency alert in O4

Credit: Public Alerts User Guide
(https://emfollow.docs.ligo.org/userguide/index.html)

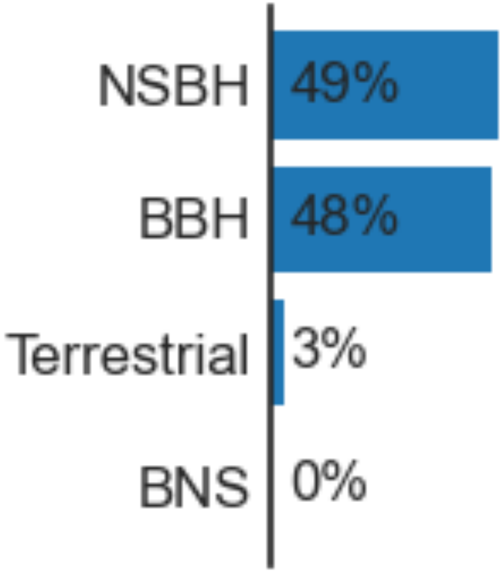


Public data products

All taken from https://gracedb.ligo.org/superevents/S230627c/view/



2D Skymap
(3D localization information also available)

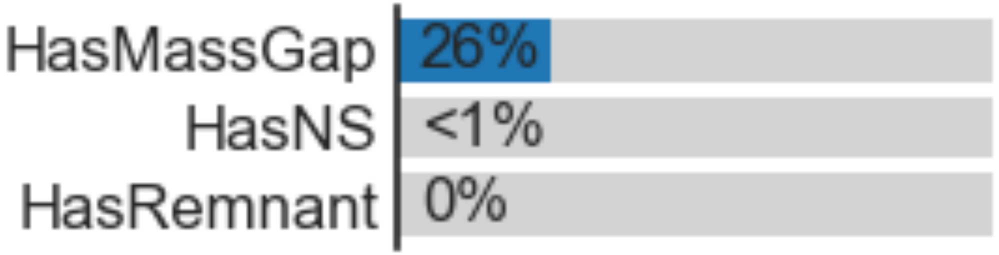


BBH=Binary Black Hole

NSBH=Neutron Star-Black Hole

BNS=Binary Neutron Star

Classification based on mass estimates



EM-Bright probabilities

Skymap improvements with detailed parameter estimation

GCN Circular 34087

Subject
LIGO/Virgo/KAGRA S230627c: Updated Sky localization and EM Bright Classification
Date
2023-06-27T04:37:12Z (3 months ago)
From
jgolomb@caltech.edu

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

We have conducted further analysis of the LIGO Hanford Observatory (H1) and LIGO Livingston Observatory (L1) data around the time of the compact binary merger (CBC) candidate S230627c (GCN Circular 34086). Parameter estimation has been performed using Bilby [1] and a new sky map, Bilby.multiorder.fits,0, distributed via GCN Notice, is available for retrieval from the GraceDB event page:

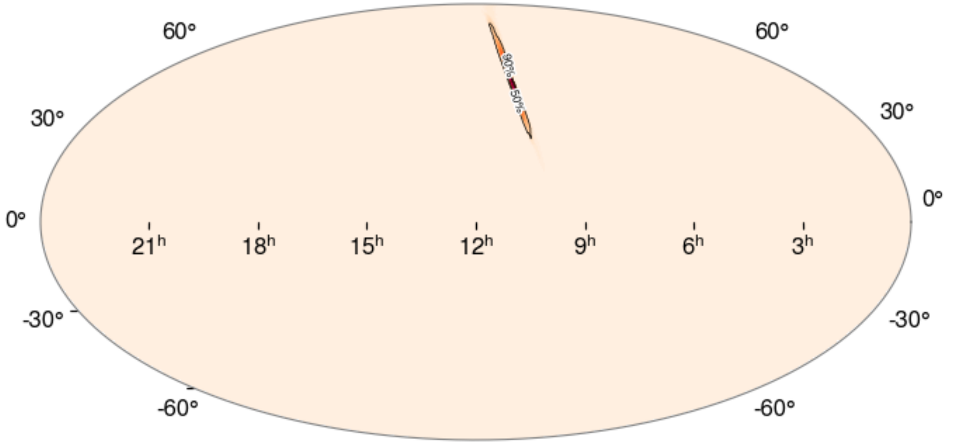
Update GCN circular for S230627c
https://gcn.nasa.gov/circulars/34087

Skymap is improved by rapid parameter estimation with the fROQ method [1, 2].

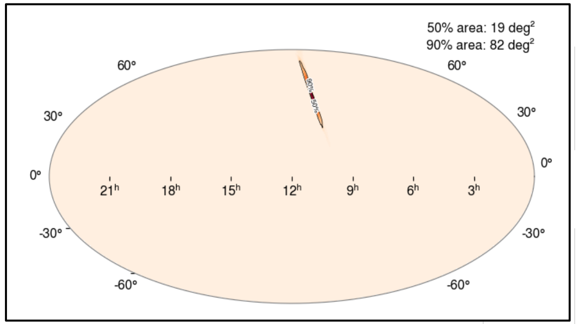
[1] **Morisaki** and Raymond, PRD **102**, 104020 (2020).
[2] **Morisaki** et al., arXiv: 2307.13380 (2023).

ex) For S230627c, updated skymap was sent ~2 hours after detection (c.f. it took ~60 hours at median in O3).

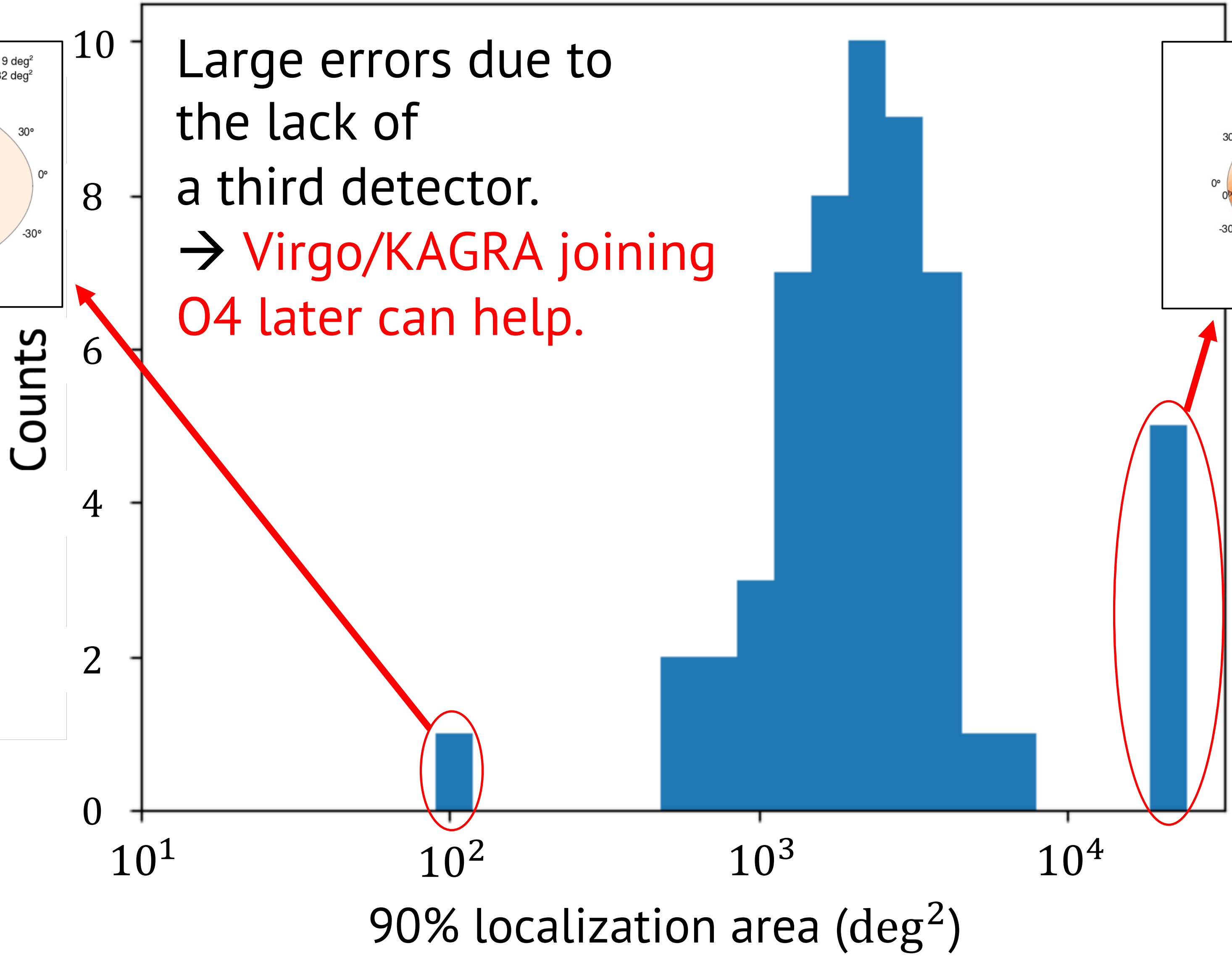
$90\ \mathrm{deg}^2 \rightarrow 82\ \mathrm{deg}^2\ (90\%)$



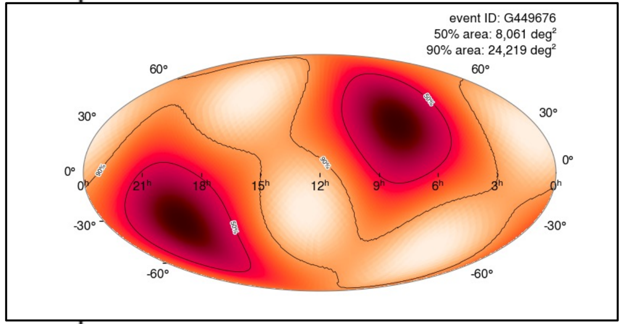
Localization accuracy in O4



S230627c



Large errors due to the lack of a third detector.
→ Virgo/KAGRA joining O4 later can help.



Single-detector detection

LIGO, VIRGO AND KAGRA OBSERVING RUN PLANS

https://observing.docs.ligo.org/plan/

We started the O4 Observing run on 24 May 2023. The observing run will last 20 calendar months including up to 2 months of commissioning breaks for maintenance.

The LIGO Commissioning break will begin on 16 January 2024, with a planned duration of two months. The main activities for this period have been determined; one of the corrective actions is

residual gap with design sensitivity. The Virgo Collaboration has set the ultimate date for Virgo to join O4 in March 2024, independently from the sensitivity achieved at that time. The exact date will be finalized in agreement with LVK partners and will be announced as soon as possible.

KAGRA restarted commissioning on 3 July 2023, and will rejoin the observing run in spring 2024, with a BNS range of around 10 Mpc.

Summary

- 90 compact binary coalescences were detected by the end of O3.
  - Population properties of binary black holes
  - GW + EM observation of binary neutron star
  - Neutron star-black holes
  - …

- O4 is currently ongoing.
  - 56 detections (54 BBHs, 2 NSBHs) as of Oct. 28
  - The first joint observation of KAGRA and LIGO
  - Large localization errors due to the lack of a third detector
  - Virgo will join O4 in March 2024.
  - KAGRA will rejoin the observation with a BNS range of ~10Mpc in spring 2024.