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Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA
ICSC Centro Nazionale di Ricerca in HPC, Big Data and Quantum Computing

Lessons learned in O4 and future perspectives

MG17 / Parallel Session: *New frontier of multi messenger astrophysics*

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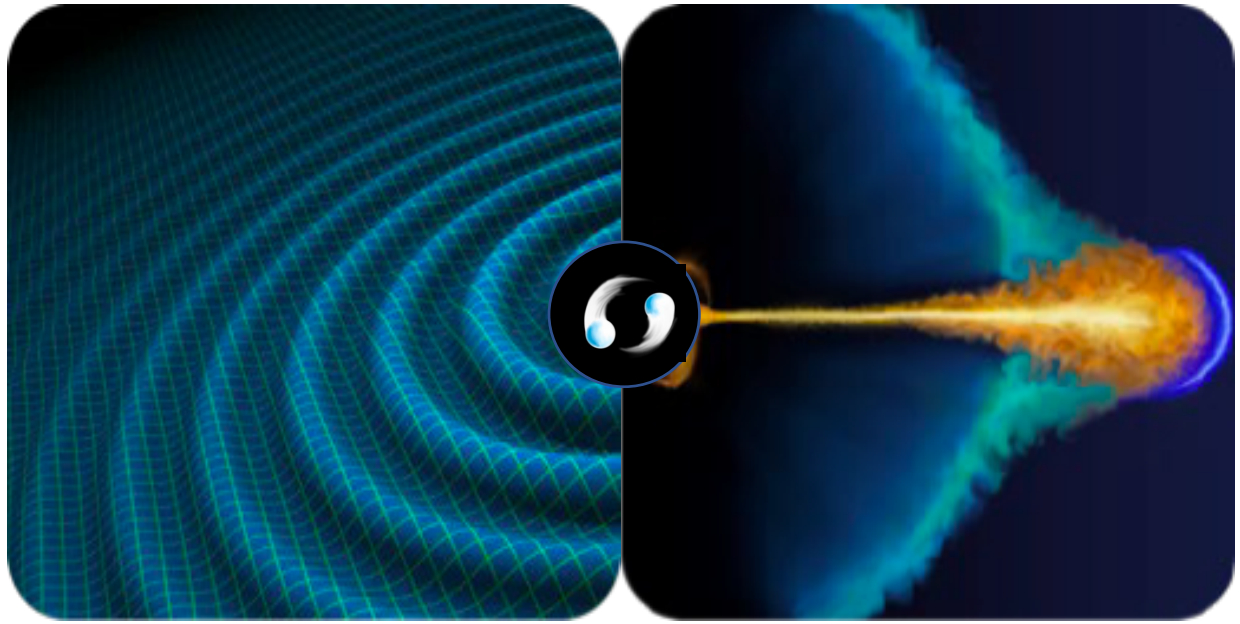
University of Trieste, Trieste, Italy; INFN-Trieste, Trieste, Italy; IRA-INAF, Bologna, Italy;

*on behalf of the LIGO scientific, Virgo and KAGRA collaborations

Outline

1. **O4a LVK observing run**
   - O4a summary
   - GW230529
2. **O4b LVK observing run**
   - O4b properties
   - S240422d (NSBH candidate)
   - O4b expectations
3. **O5 LVK observing run**
4. **Multi-messenger (MM) expectations**
   - Third generation GW detectors and MM synergies
5. **Outlook**



Fourth observing run of LVK network

O4a

24 May 2023 - 16 January 2024

- 81 significant alerts
- (only LIGO detectors) poor event localisation

O4b

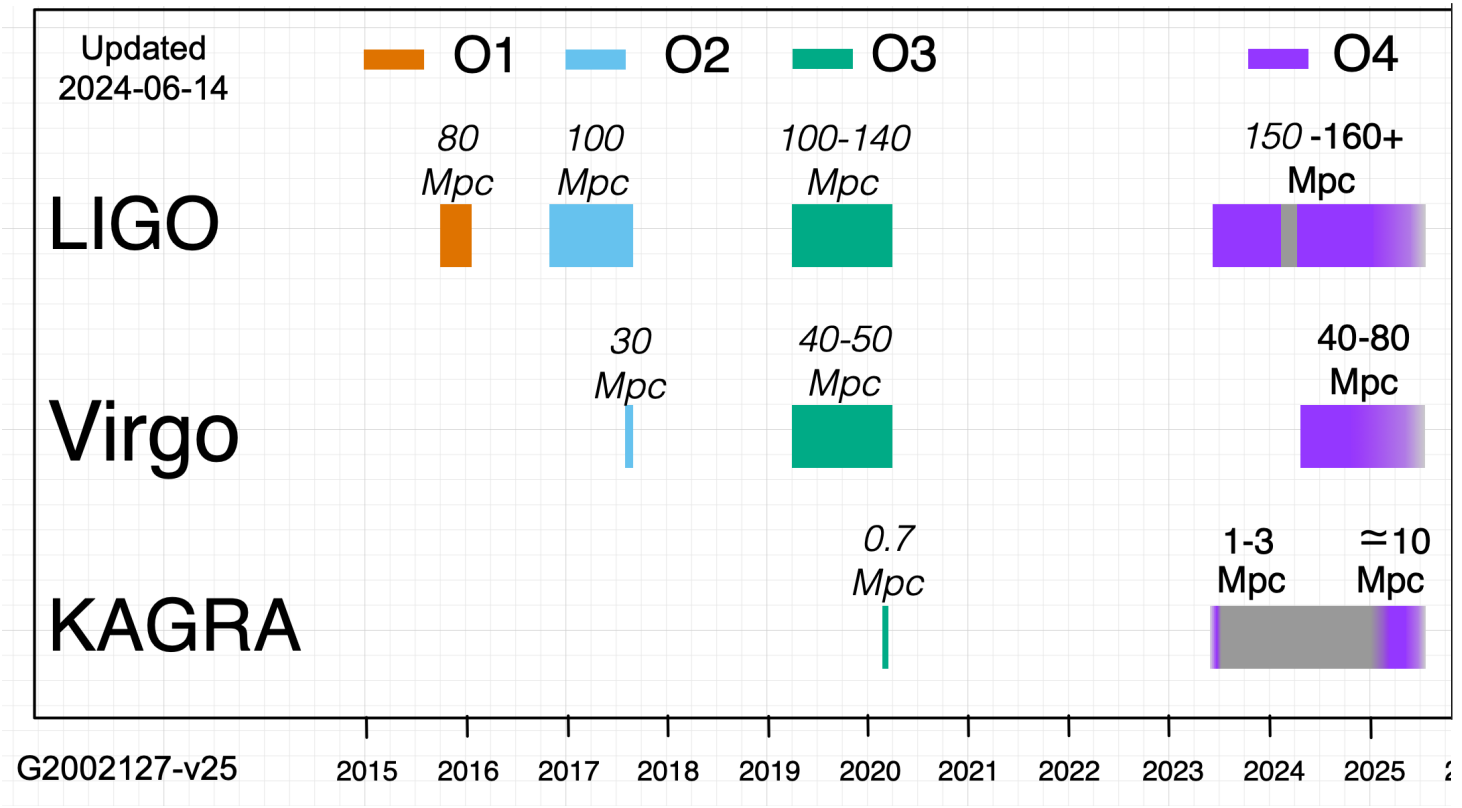
(ER16 25 April - 24 May)

24 May 2024 - **9 June 2025***

KAGRA will join only at the end of O4b**

*Previously set as February (4 months extension)

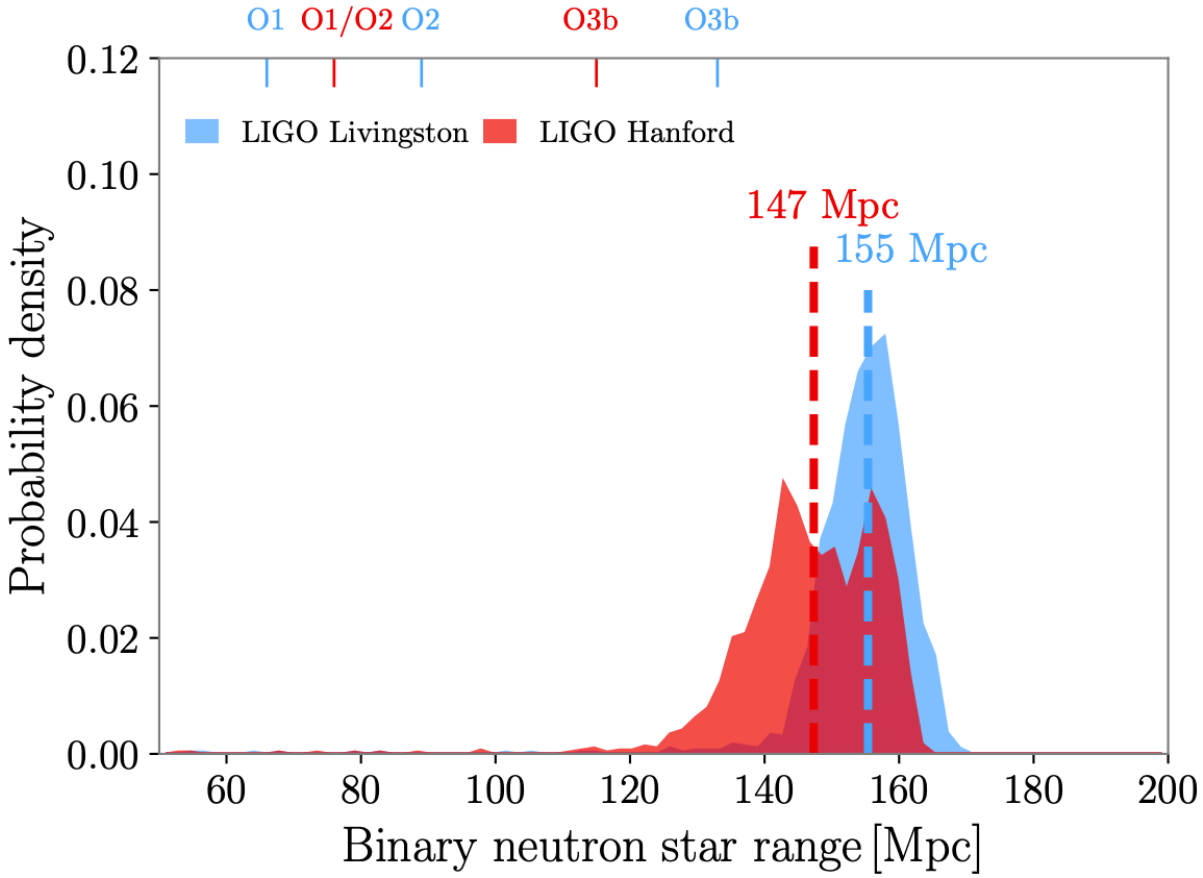
**On Jan. 1 2024, a 7.6 magn. earthquake near the KAGRA site.



Complete observing plans can be found at https://observing.docs.ligo.org/plan/

O4a sensitivity and early warning pipelines

O4a sensitivity

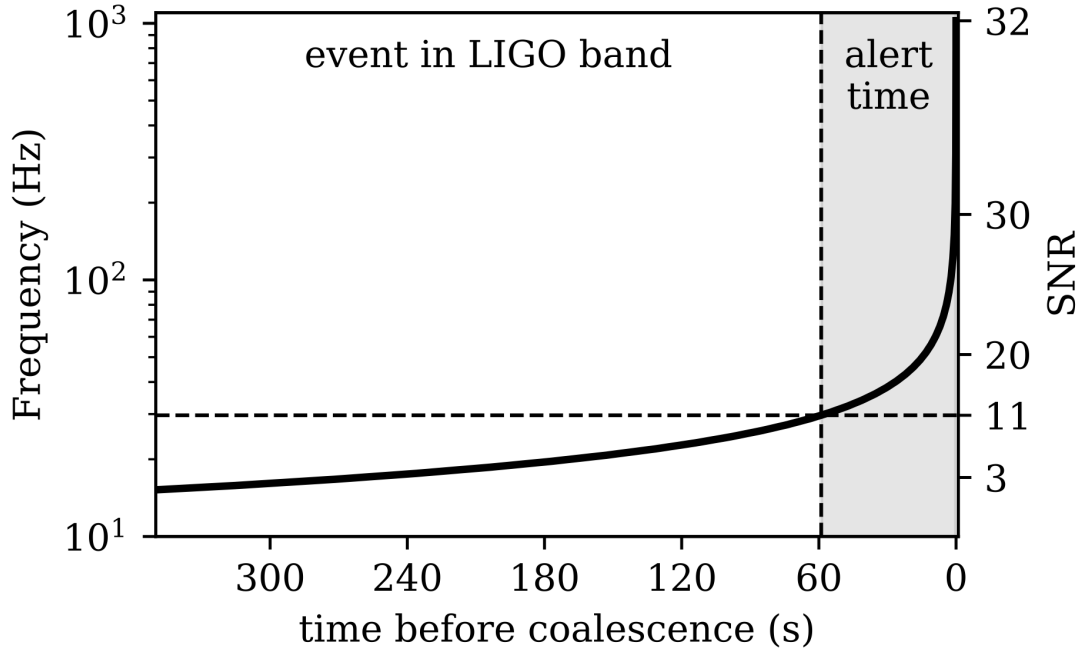


Credit: Derek Davis

New in O4: early warning pipelines

CBC pipeline can produce *Early-warning alerts:*

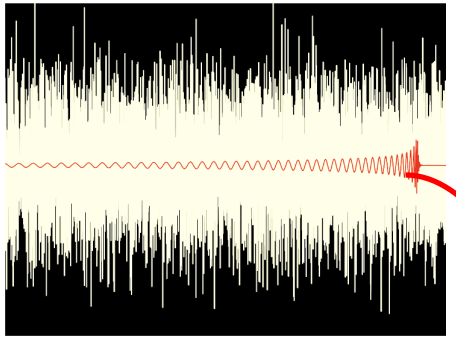
- early as 60 s before merger (for ideal case)
- accompanied by source localization



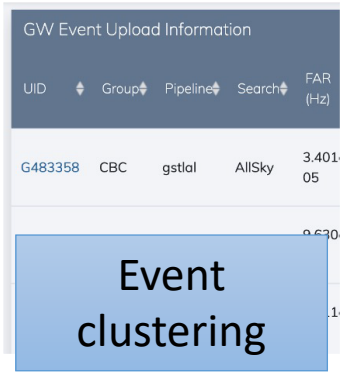
https://emfollow.docs.ligo.org/userguide/early_warning.html

O4 GW alerts

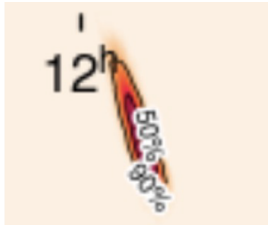
GraceDB: https://gracedb.ligo.org



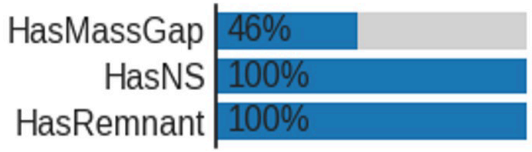
Search pipelines



Event clustering



Localisations

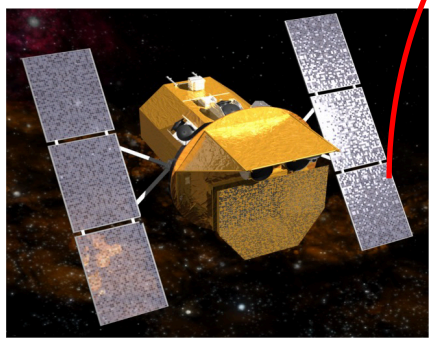


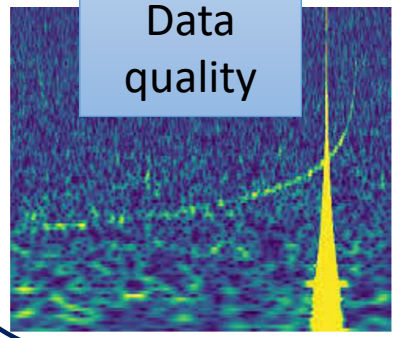
Prob (EM bright)

GraceDB

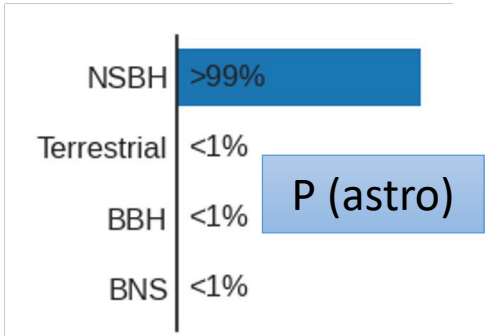
Coincidence

External events

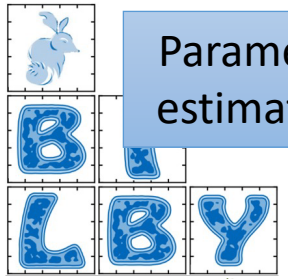




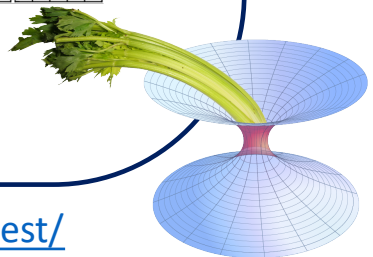
Data quality

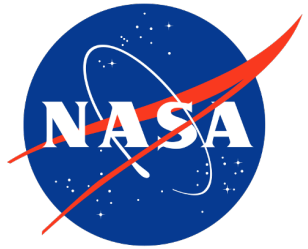


P (astro)



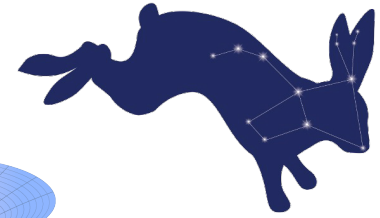
Parameter estimation





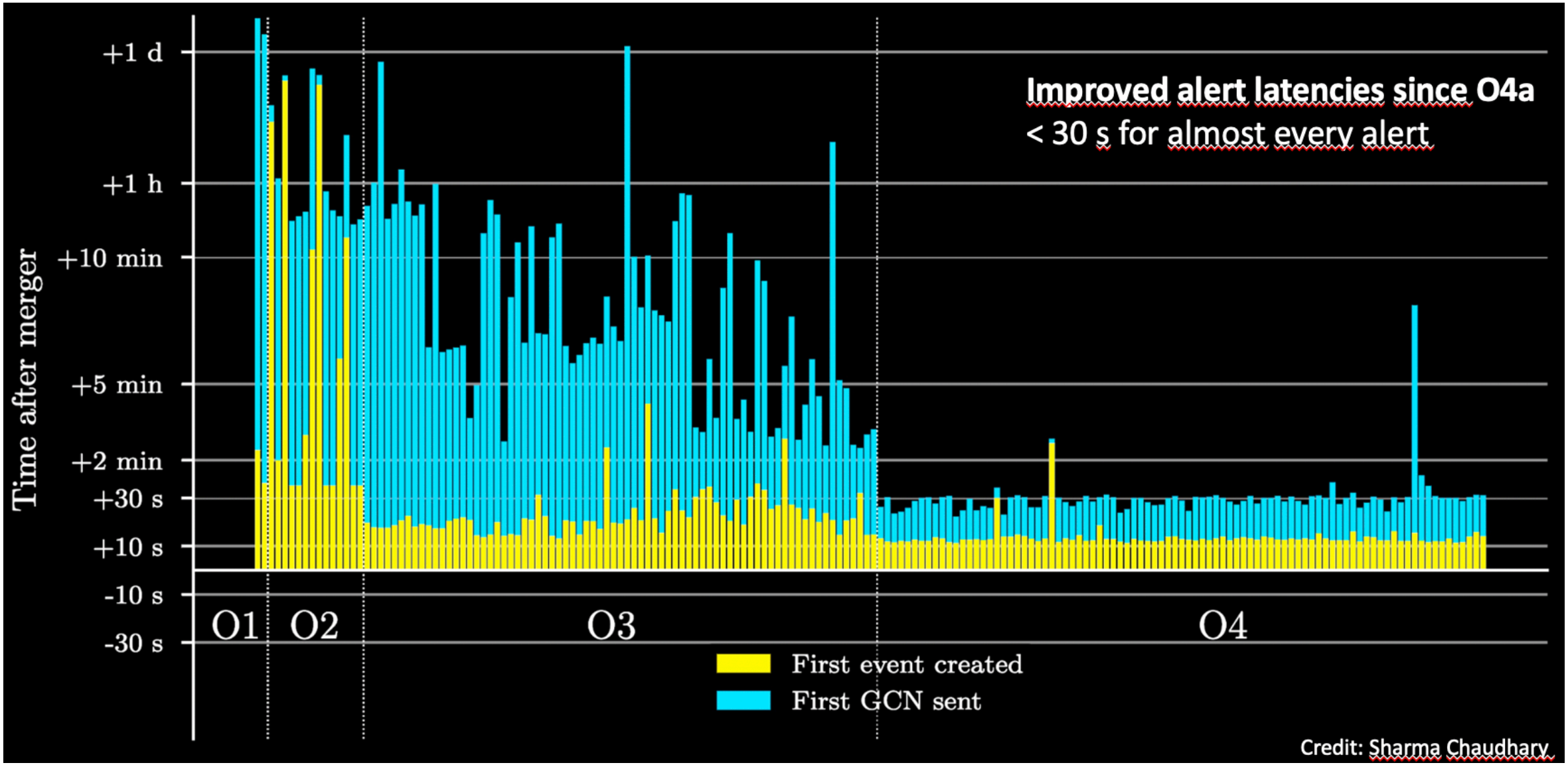
GCN

SCIMMA



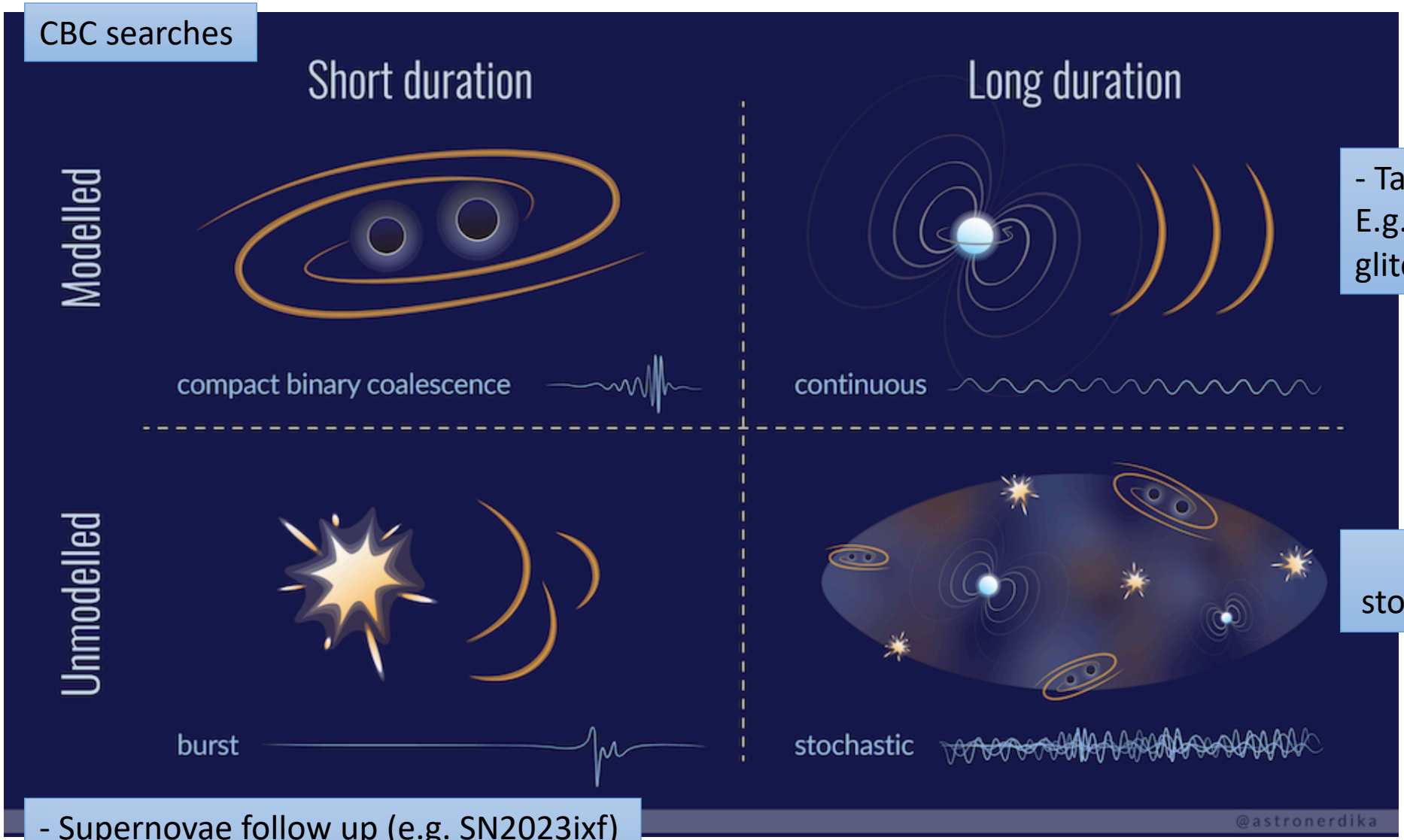
https://rtd.igwn.org/projects/gwcelery/en/latest/

O4 Alert latencies



Gravitational wave searches during O4

CBC searches

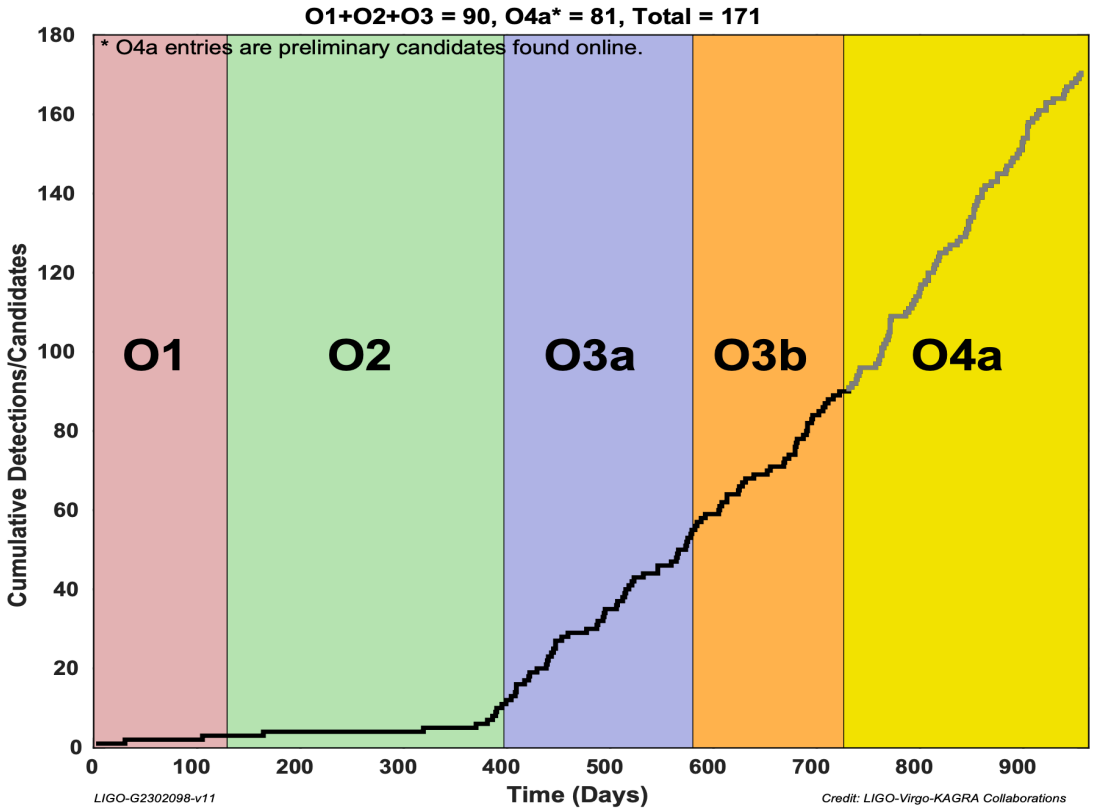


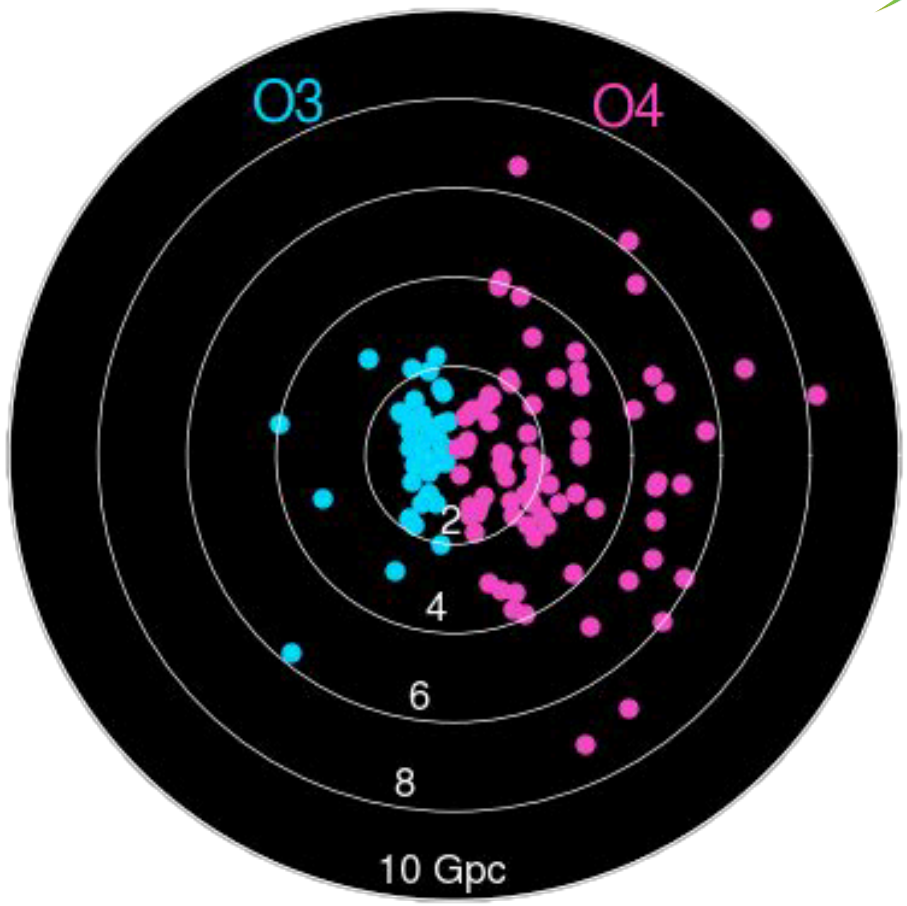
- Targeted search
E.g. Vela-pulsar glitch follow up

Search for stochastic GW bkg

- Supernovae follow up (e.g. SN2023ixf)
- Magnetar flares, FRBs follow up

O4a CBC events





Online Results for O4a:

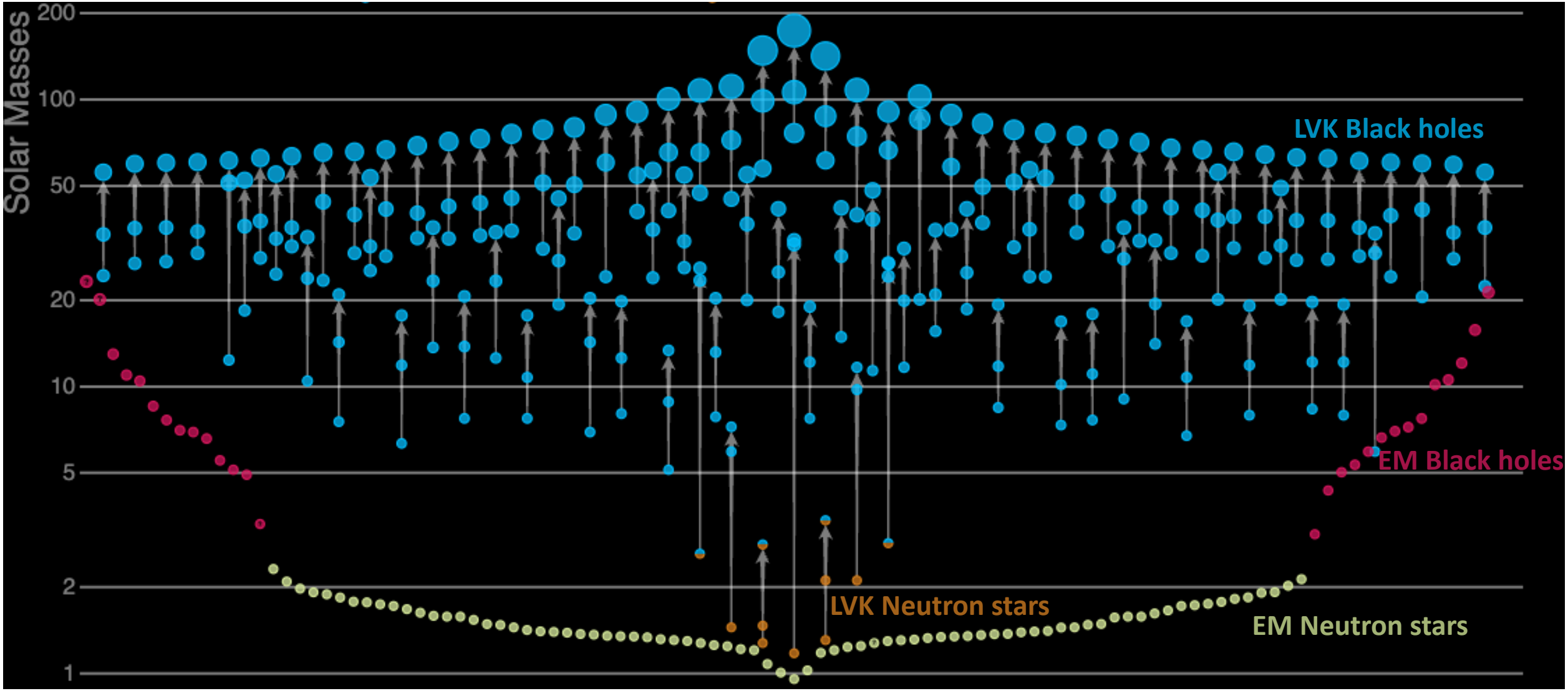
-> 81 significant (FAR< 1/6 months) Detection Candidates

- Mostly BBH events
- 1-2 candidate consistent with containing a NS
- 2-3 candidates consistent with an object in the lower mass gap

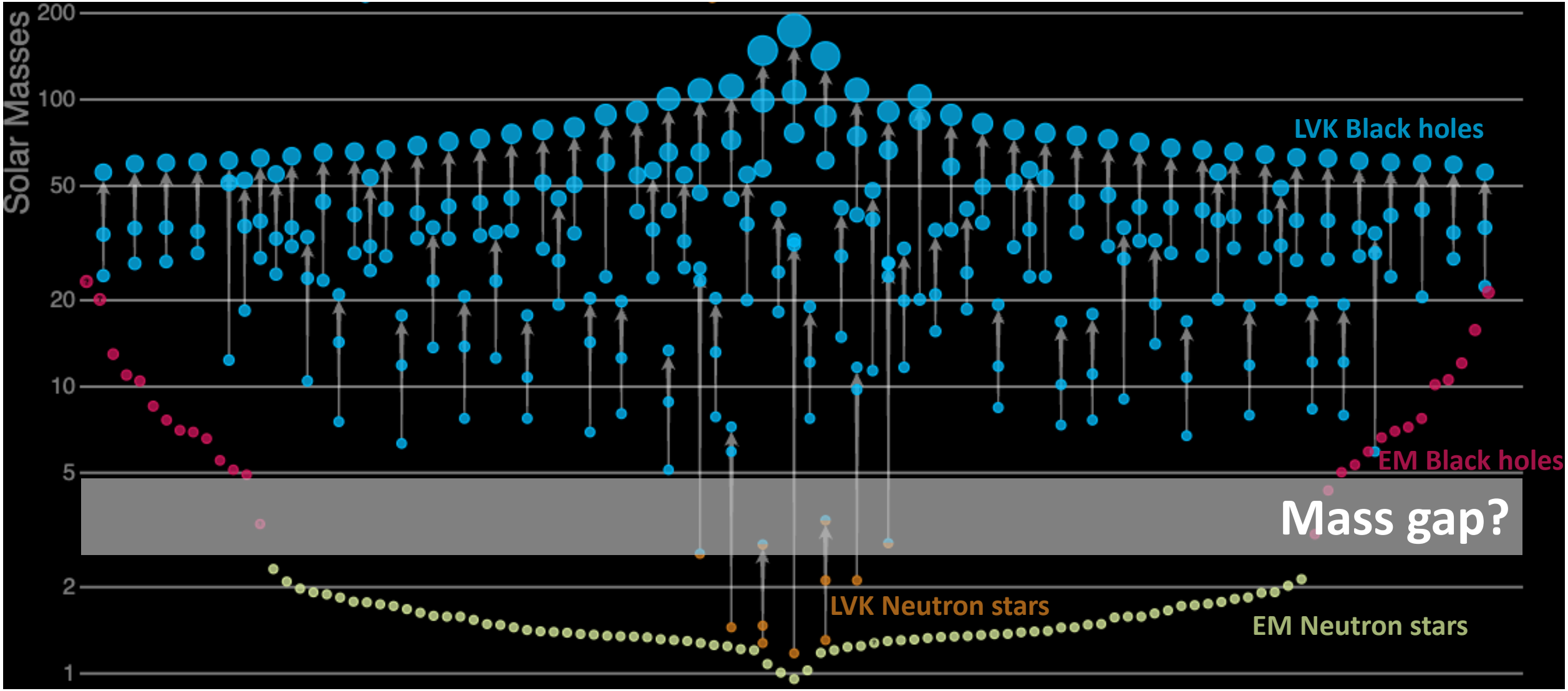
We are observing signals further away!

A couple of events at > 8 Gpc

Masses in the stellar Graveyard

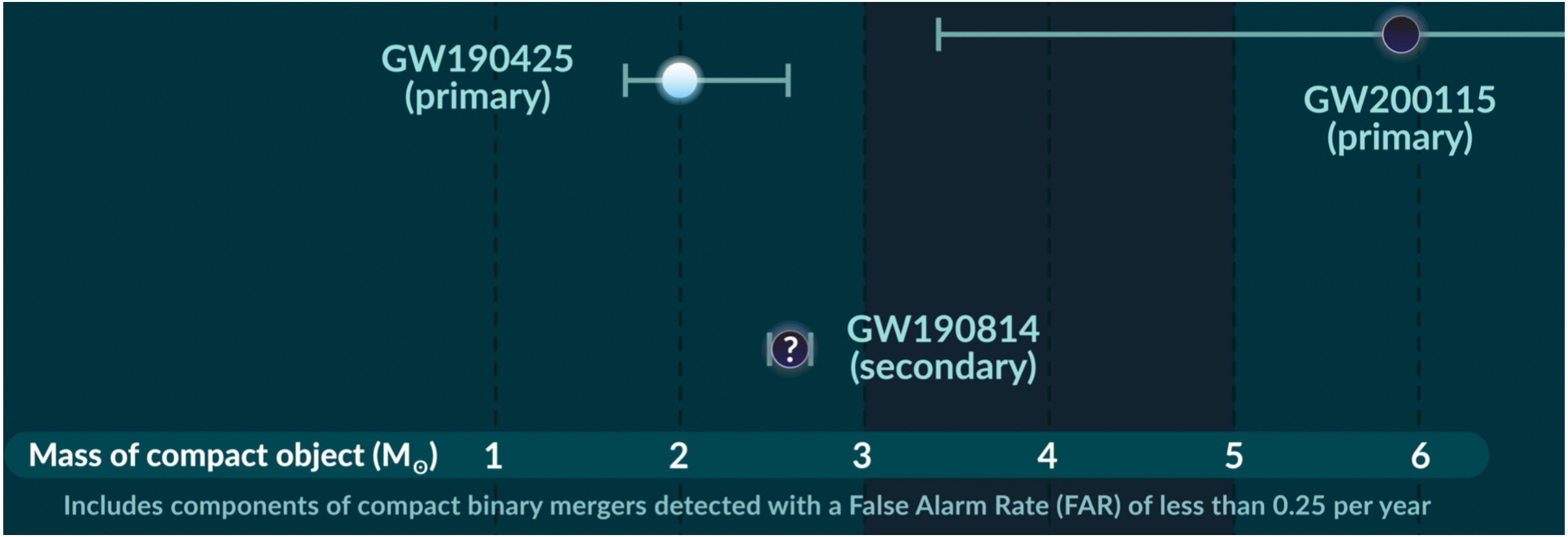


Masses in the stellar Graveyard



The mass gap

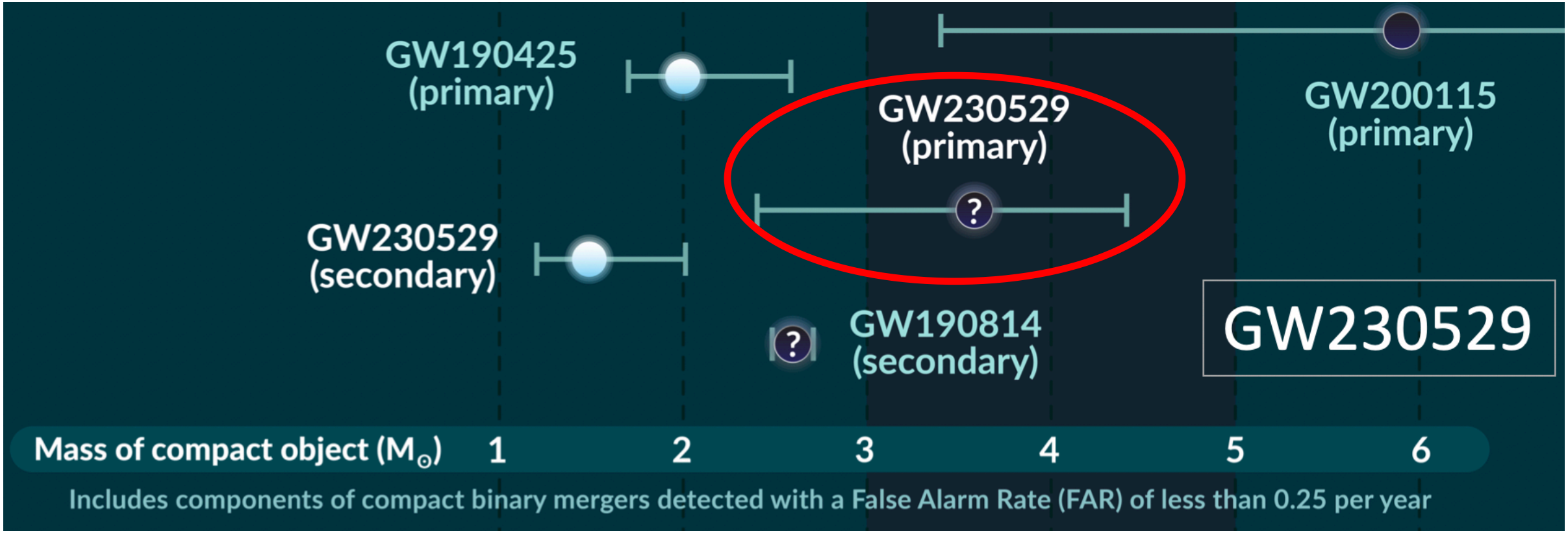
Observations of compact binaries from gravitational waves



GW230529 - Filling the mass gap

GW230529 provides best evidence of compact objects existing in the lower mass gap

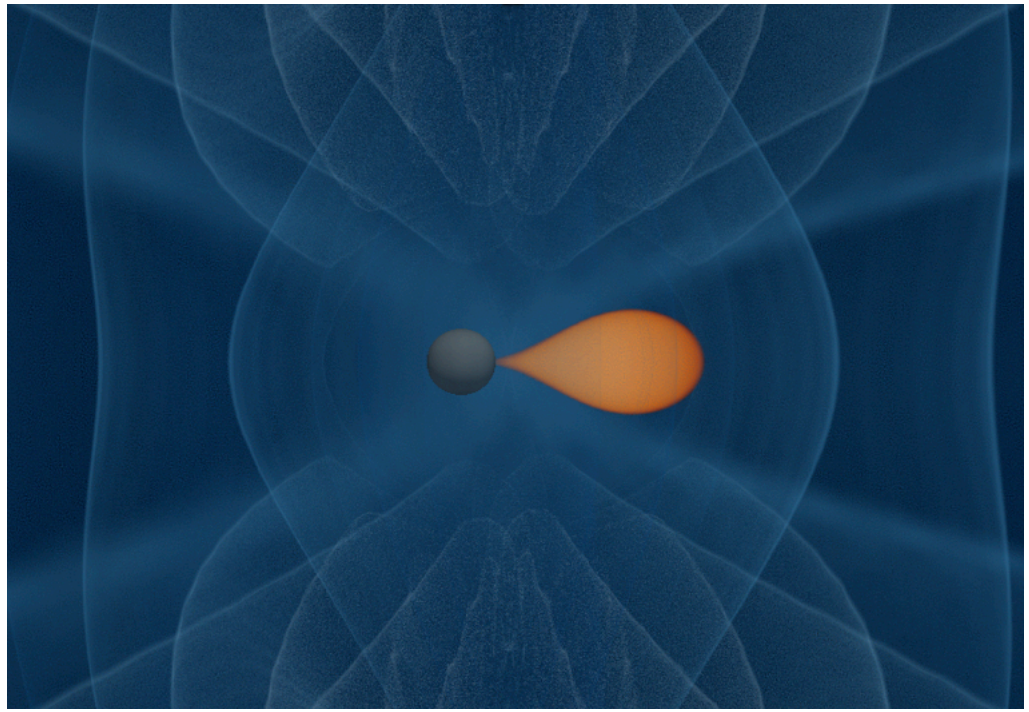
Observations of compact binaries from gravitational waves



Paper: https://dcc.ligo.org/P2300352/public

GW230529

GW from the coalescence of a neutron star with a mass-gap compact object* (2.5-4.5 $M_\odot$): the primary component of the source has a mass less than 5 $M_\odot$ at 99% credibility

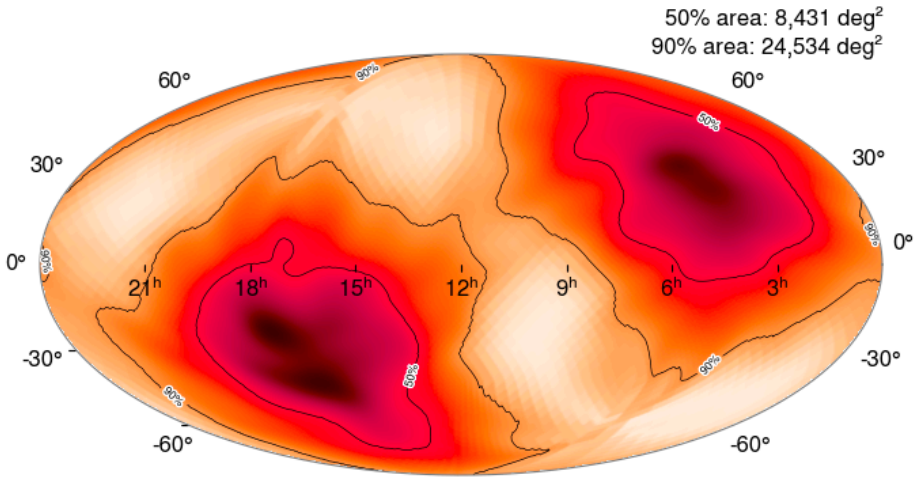


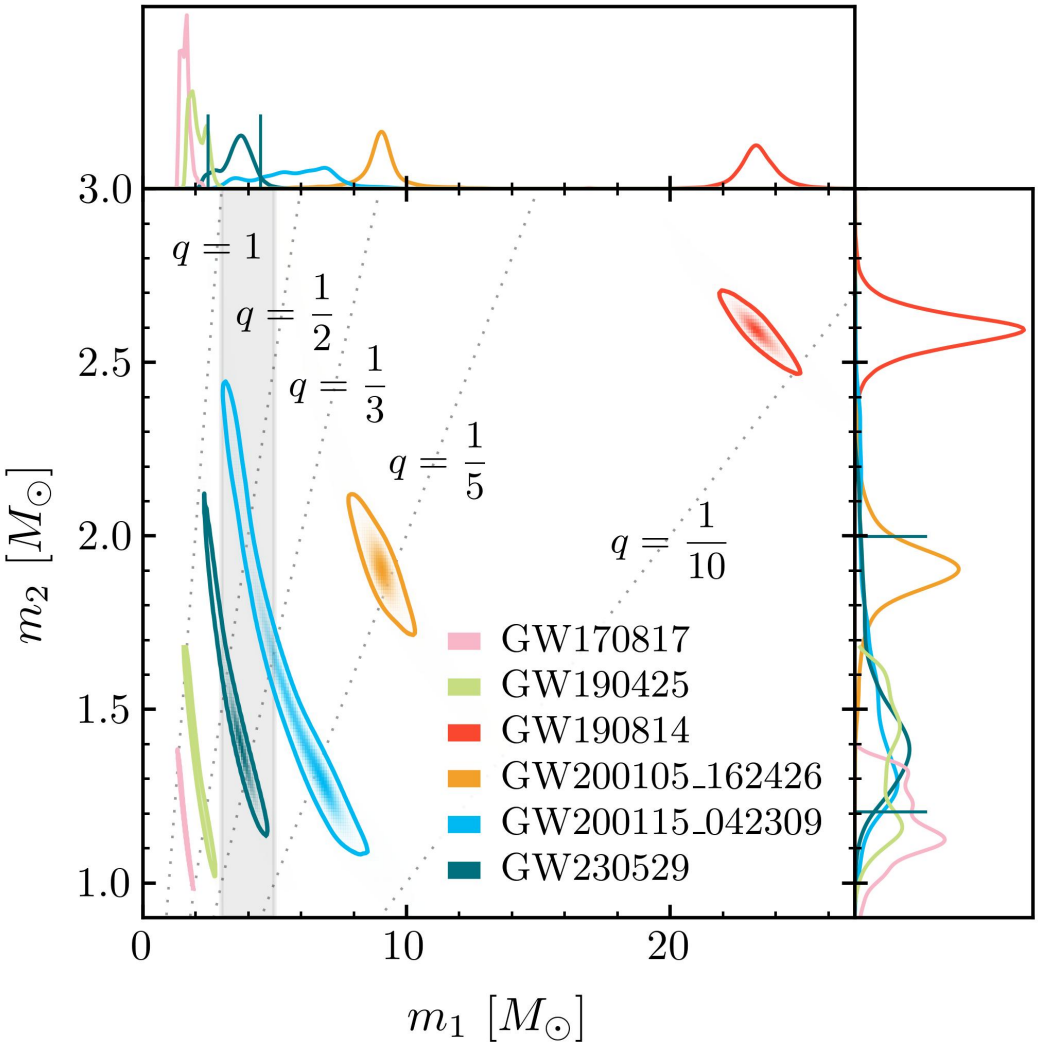
*most likely a black hole, but caveats to follow

Primary mass $m_1/M_\odot$	$3.6^{+0.8}_{-1.2}$
Secondary mass $m_2/M_\odot$	$1.4^{+0.6}_{-0.2}$
Mass ratio $q = m_2/m_1$	$0.39^{+0.41}_{-0.12}$
Total mass $M/M_\odot$	$5.1^{+0.6}_{-0.6}$
Chirp mass $\mathcal{M}/M_\odot$	$1.94^{+0.04}_{-0.04}$
Detector-frame chirp mass $(1+z)\mathcal{M}/M_\odot$	$2.026^{+0.002}_{-0.002}$
Primary spin magnitude χ_1	$0.44^{+0.40}_{-0.37}$
Effective inspiral-spin parameter $\chi_{\rm eff}$	$-0.10^{+0.12}_{-0.17}$
Effective precessing-spin parameter $\chi_{\rm p}$	$0.40^{+0.39}_{-0.30}$
Luminosity distance $D_{\rm L}$/Mpc	201^{+102}_{-96}
Source redshift z	$0.04^{+0.02}_{-0.02}$

GW230529

- Observed on May 29 2023 at 18:15:00 UTC
- Only observed by LIGO Livingston**:**
  No EM counterpart: **poor sky localization** (~25,000deg^2)
- most probable detected NSBH to have undergone tidal disruption (increased symmetry in its component masses)
- **Updated local NSBH merger rate: 30- 200 Gpc^{-3} yr^{-1}**





GW230529: astrophysical implications

How did GW230529's source form?

1. Isolated binary evolution

Incomplete understanding of core collapse in massive stars, but possible formation of mass-gap objects through:

- stochasticity in remnant masses
- supernova fallback
- delayed explosion timescales

2. Dynamical assembly

- Primary of GW230529 may be the product of a *hierarchical merger* between two neutron stars in a dense stellar environment or a triple system
- rates of such mergers expected to be multiple orders-of-magnitude too low

GW230529 shows a compact objects existing in the lower mass gap urging a change in the NS-BH paradigm

O4b online properties

Duration

- 24 May 2024 - *9 June 2025* (recently extended)*

Sky localisation

- Having 3+ detectors is crucial for localising our events

(e.g., SN240615dg: 50% area ~1 deg^2; 90% area ~5 deg^2)

(current) BNS sensitivity and duty cycles:

- LIGO (H1~150 Mpc, L1~170 Mpc): 60-75%
- Virgo (V1~55 Mpc): 80% or higher

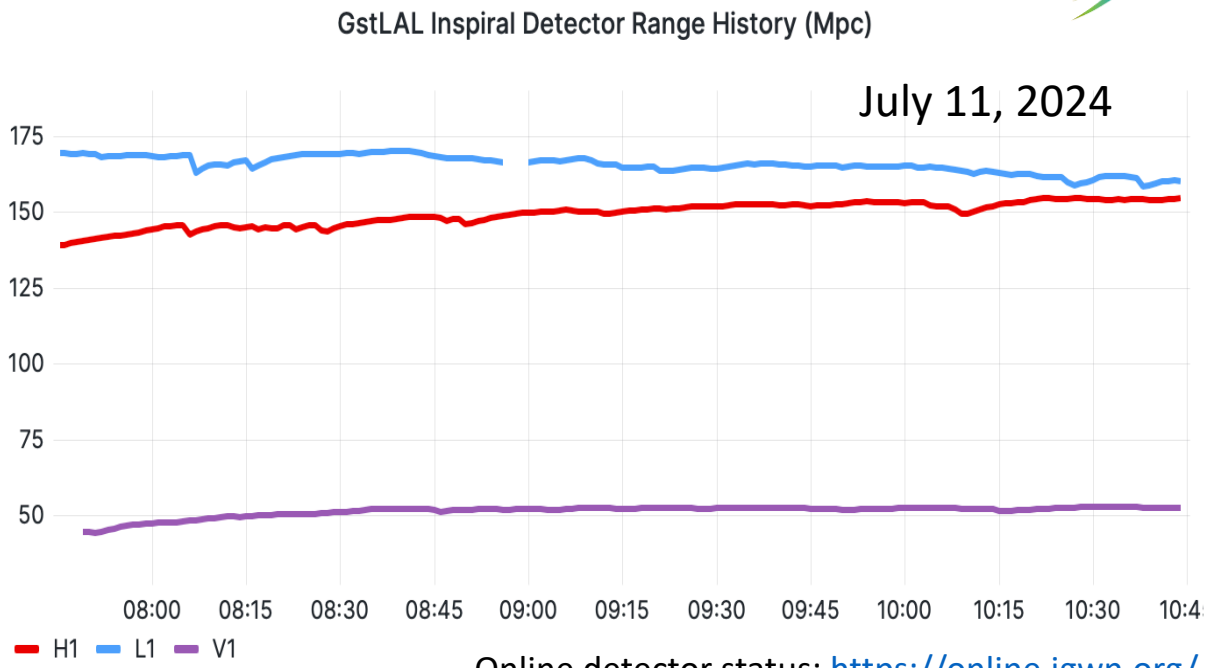
Events

36 events so far (up to July 11)

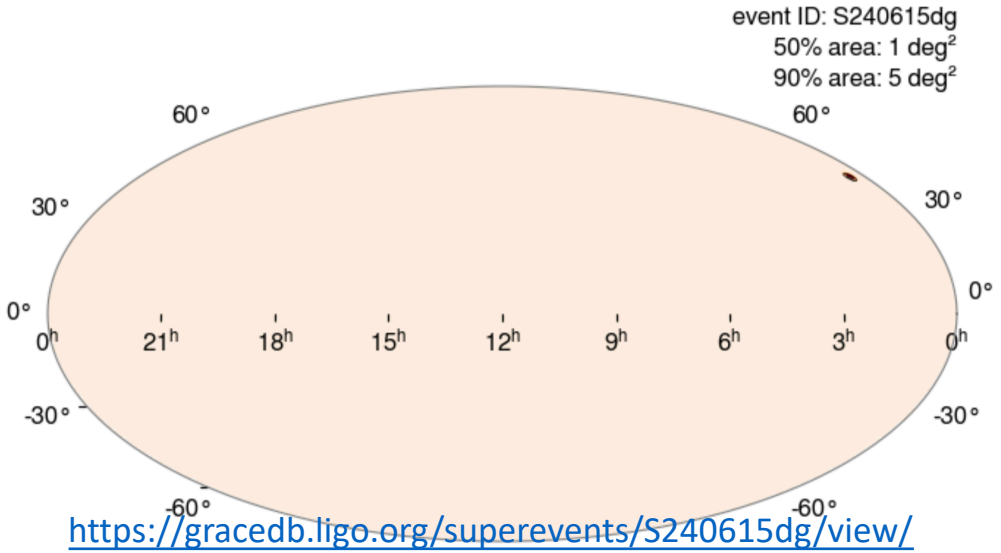
(41 in total - 5 retracted)

- Mostly BBH events
- S240422ed: candidate NSBH (see next slide)
- **Tot O4**: 117 events (133 in total – 16 retracted)

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



Online detector status: https://online.igwn.org/

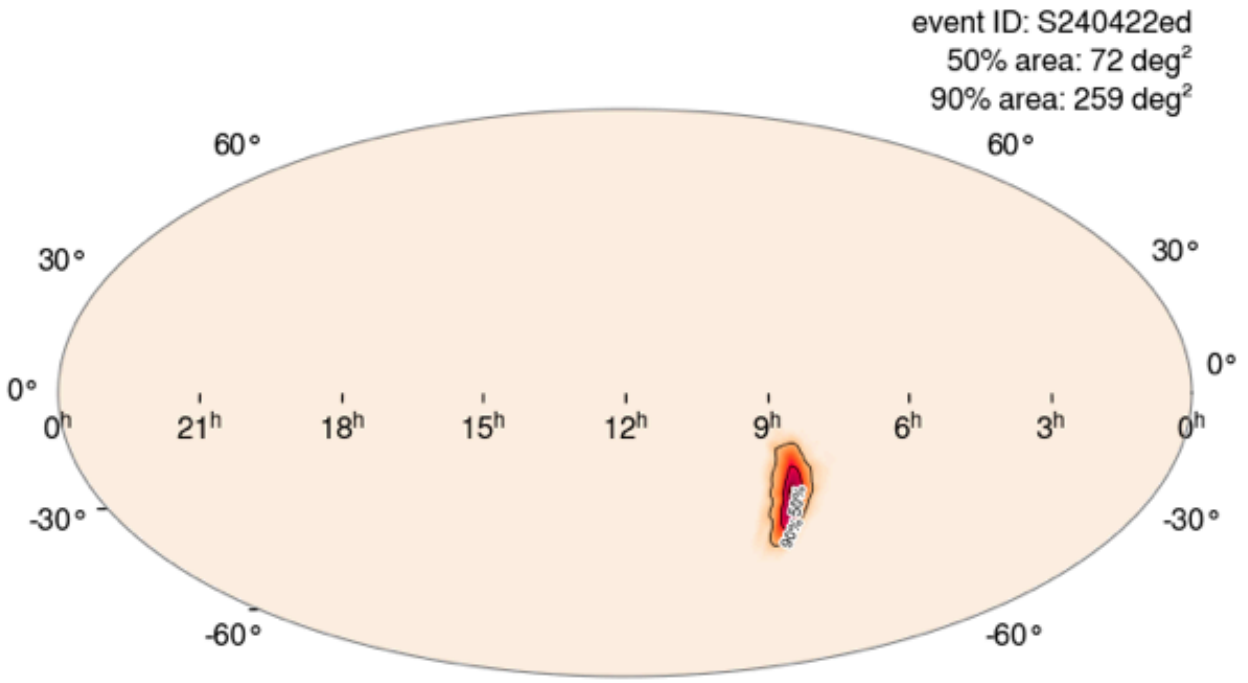


https://gracedb.ligo.org/superevents/S240615dg/view/

S240422ed – candidate NSBH event

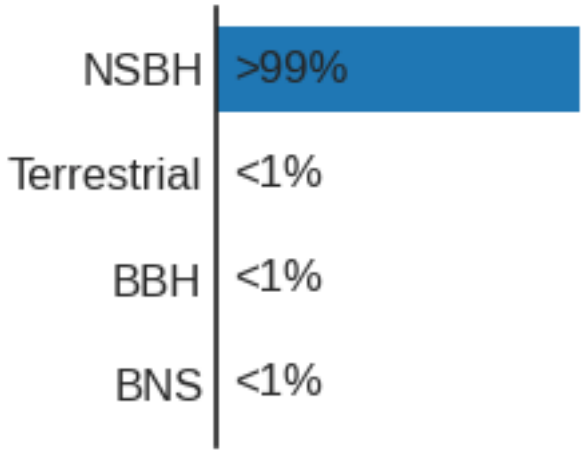
S240422ed A candidate **NSBH** event
https://gracedb.ligo.org/superevents/S240422ed/view/

Event time: 2024-04-22 21:35:13 UTC
Instruments: H1, L1, V1
FAR: 3.095e-13 (1 per 1.03e+05 years)

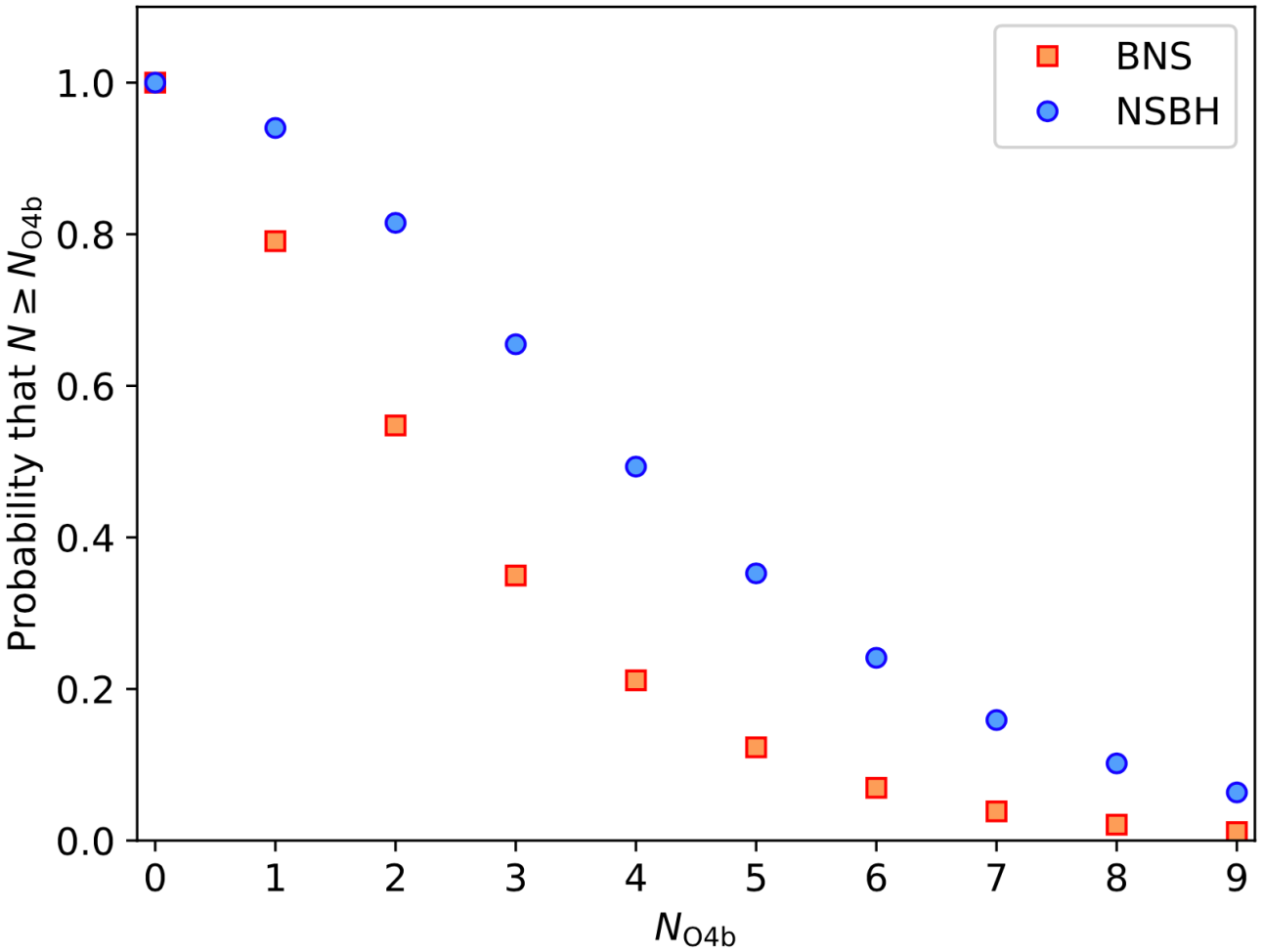


>80 follow up observations (GCN reported)
(from radio to gamma-rays, to neutrinos searches).
No counterpart found

(Potential counterparts initally reported – none of them presenting transient phenomena
https://gcn.nasa.gov/circulars?query=S240422ed&startDate=&endDate=&sort=circularID



O4b expectations

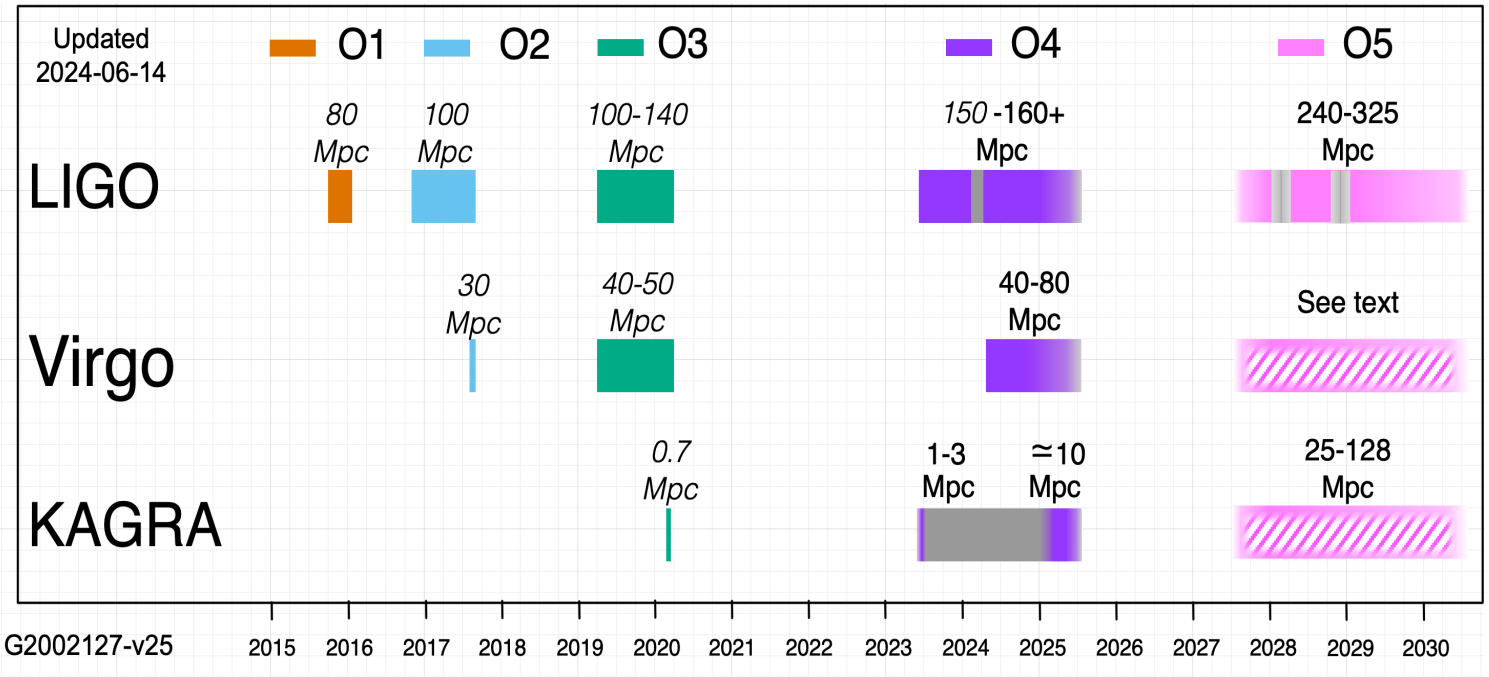


- The probability of having at least one **BNS** detection is around 80%.
  BNS rate: 5 - 920 Gpc^{-3} yr^{-1}
- The probability of having at least one **NSBH** detection is 94%

Not revised yet for the extended duration of O4b as well as for the detection of S240422ed (NSBH event)
https://emfollow.docs.ligo.org/userguide/capabilities.html

O5

O5 dates: start of O5 was recently shifted to *June 2027*, as consequence of the O4b extension (O4b end in June 2025).



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

O5 expectations

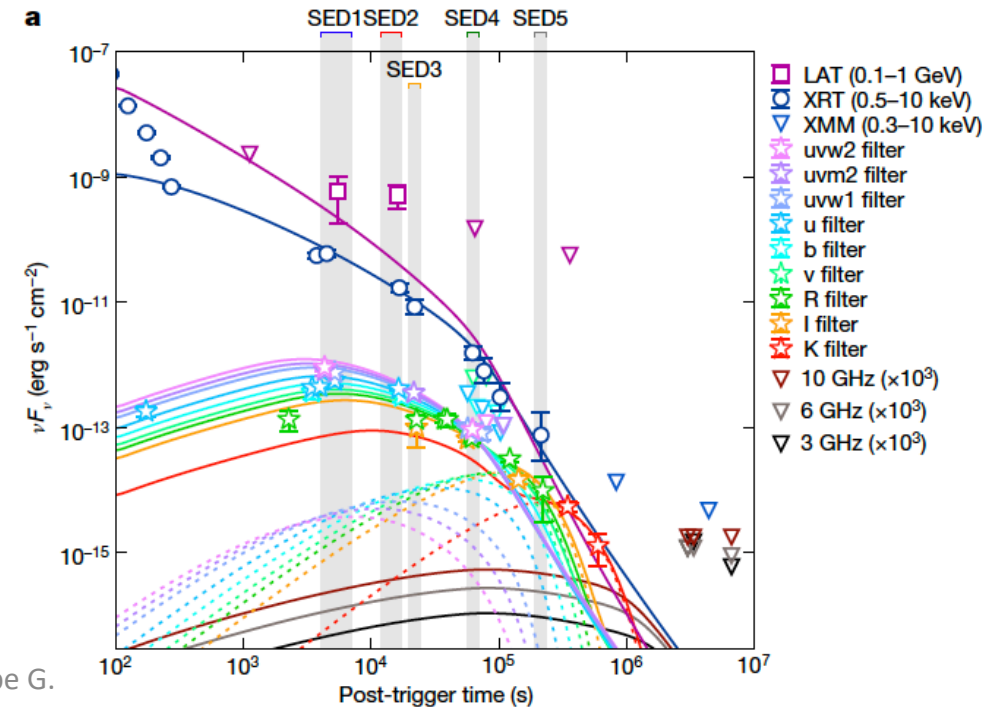
Observing run	Network	Source class	Predicted before start of O4	
		BNS	NSBH	BBH
Merger rate per unit comoving volume per unit proper time (Gpc^{-3} year^{-1}, log-normal uncertainty)				
		210^{+240}_{-120}	$8.6^{+9.7}_{-5.0}$	$17.1^{+19.2}_{-10.0}$
Sensitive volume: detection rate / merger rate (Gpc^3, Monte Carlo uncertainty)				
O4	HKLV	$0.172^{+0.013}_{-0.012}$	$0.78^{+0.14}_{-0.13}$	$15.15^{+0.42}_{-0.41}$
O5	HKLV	$0.827^{+0.044}_{-0.042}$	$3.65^{+0.47}_{-0.43}$	$50.7^{+1.2}_{-1.2}$
Annual number of public alerts (log-normal merger rate uncertainty × Poisson counting uncertainty)				
O4	HKLV	36^{+49}_{-22}	6^{+11}_{-5}	260^{+330}_{-150}
O5	HKLV	180^{+220}_{-100}	31^{+42}_{-20}	870^{+1100}_{-480}

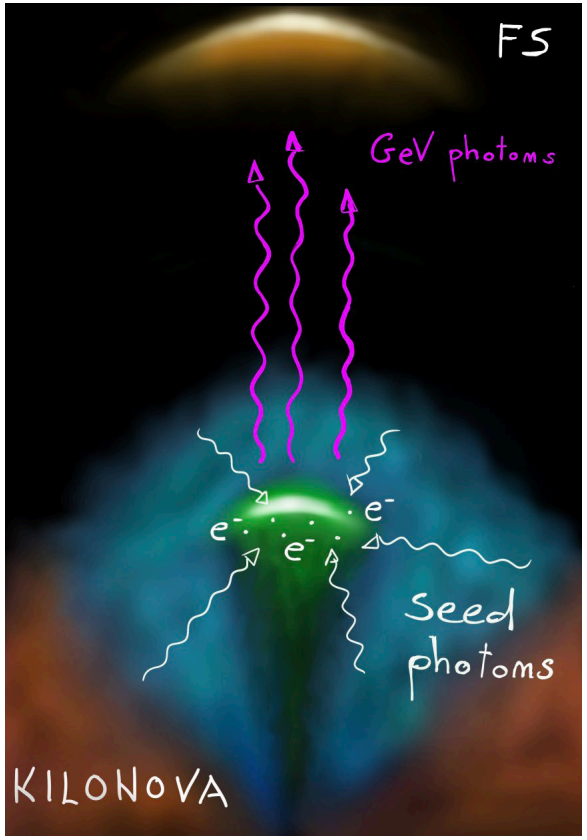
https://emfollow.docs.ligo.org/userguide/capabilities.html

Multi-messenger expectations

- *NO multi-messenger (MM) event after GW170817*
- **BNS mergers are there!**

- *Expected a few MM detections per year with the current GW detectors up to z = 0.2*
- Two long GRBs with kilonova emission, GRB 211211A (350 Mpc; Rastinejad+22, Mei+22, Troja+22) and GRB 230307A (300 Mpc ?, Levan+23) close to the current GW detector reach!



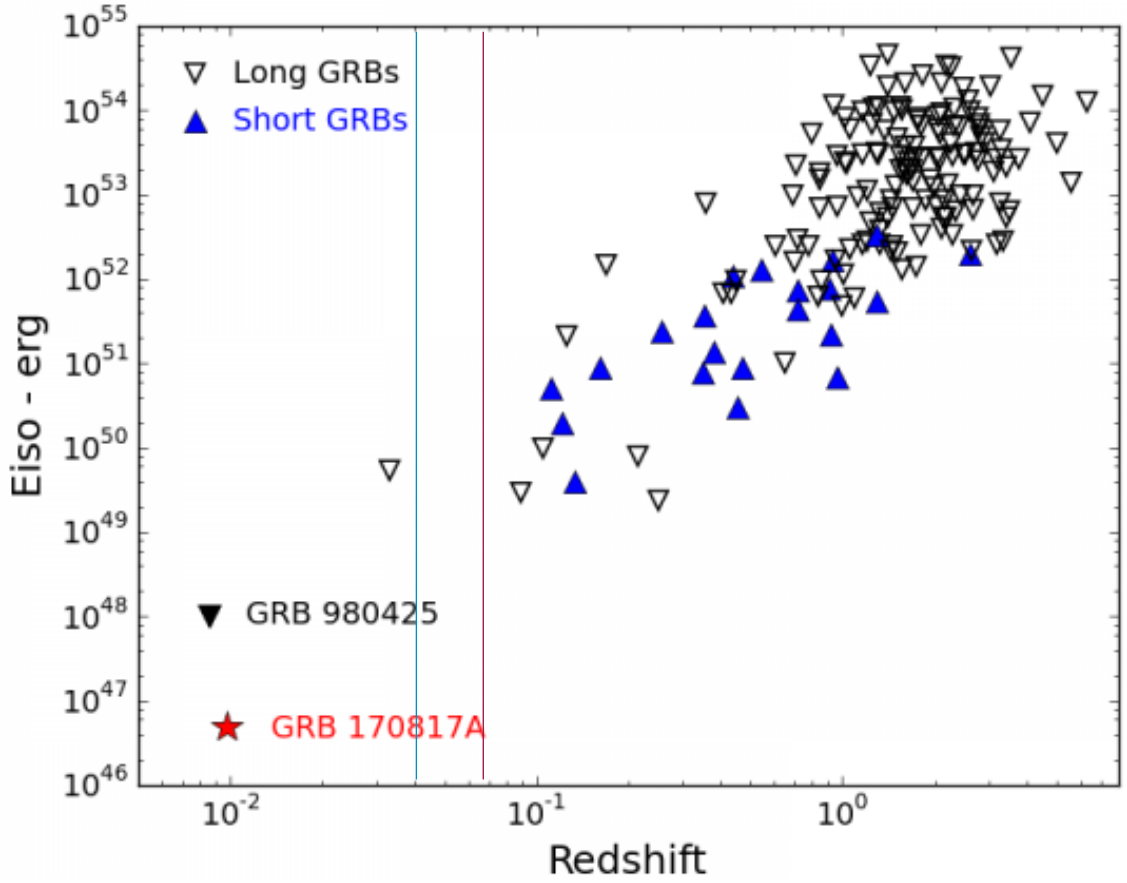


Multi-messenger expectations

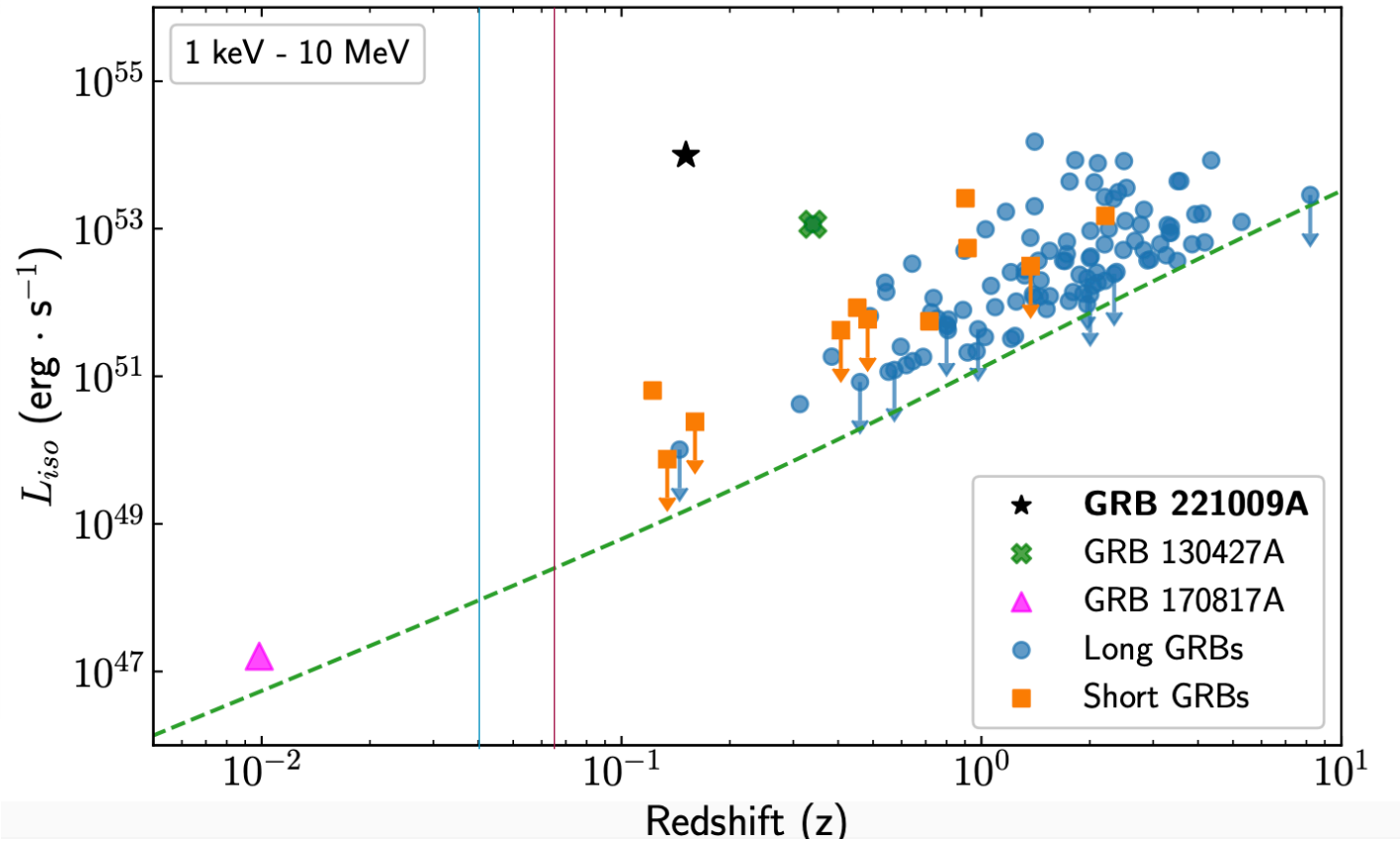
GRBs with known redshift

LIGO-L O4b (170 Mpc) z~0.04

LIGO O5 (300 Mpc) z~0.065



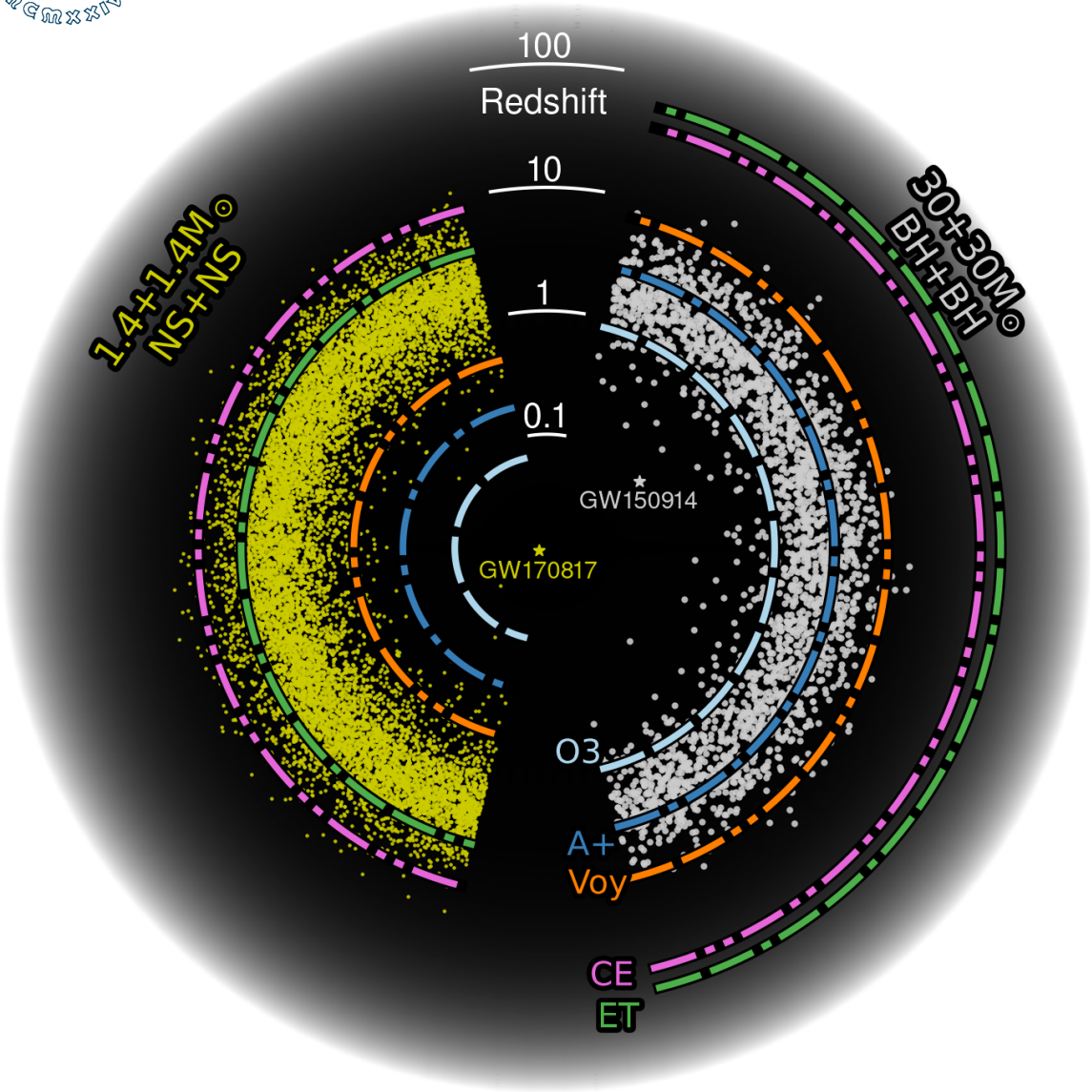
SVOM white paper, 2022

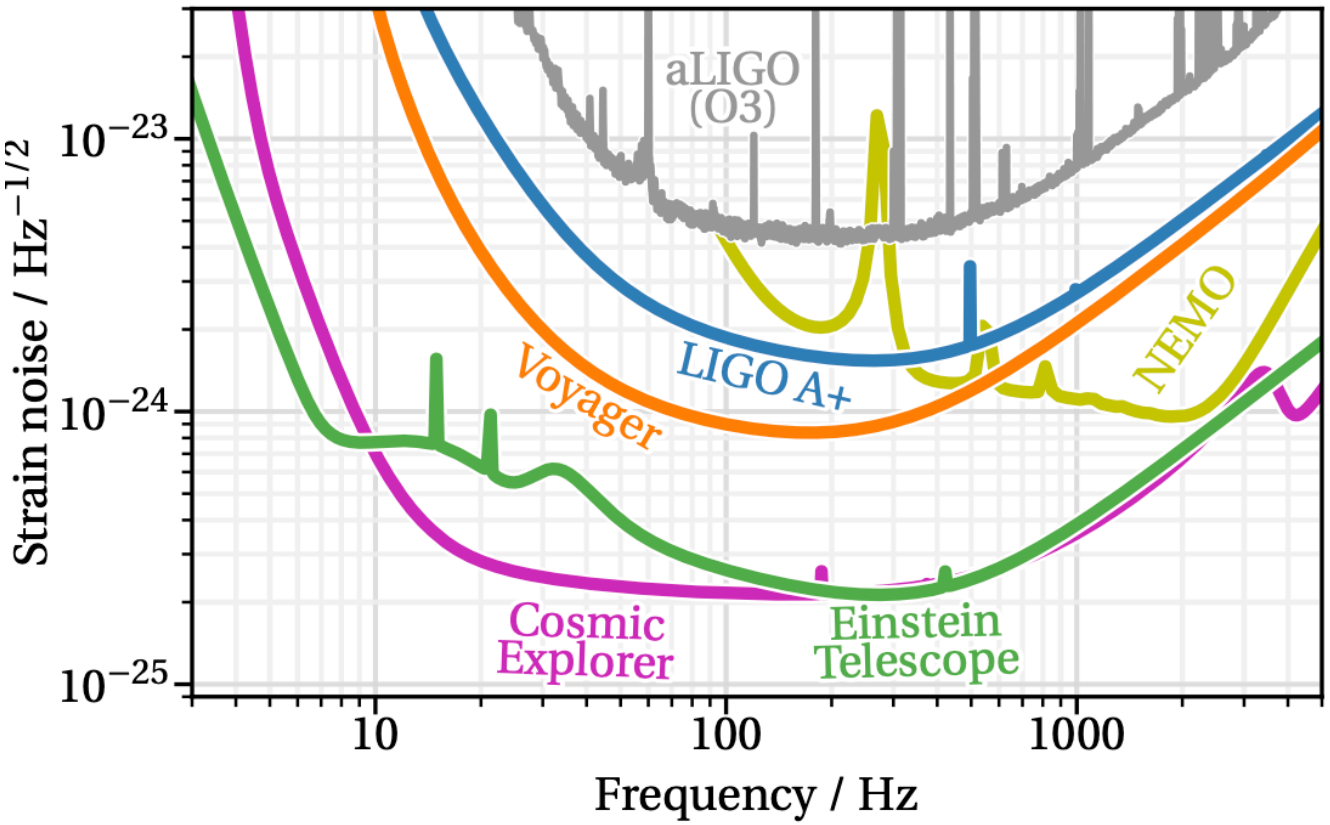


Fermi GBM GRBs

Lesage et al., 2023

Third generation GW interferometers

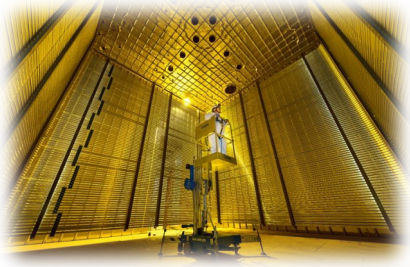




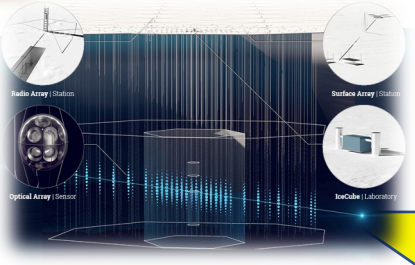
https://cosmicexplorer.org/sensitivity.html

See next talks by: ***Ulyana Dupletsa, Sofia Bisero and Eleonora Loffredo***

Multi-messenger synergies



Galactic core-collapse supernova



Gamma-ray bursts from neutron star mergers

Neutrino:

DUNE, KMN3Net, IceCube Gen 2

Radio:

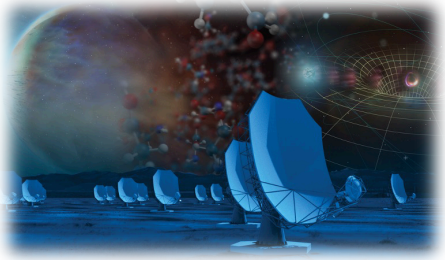
ng VLA, SKA

X-ray / Gamma-ray:

Einstein Probe, Athena, THESEUS, HERMES, CTA

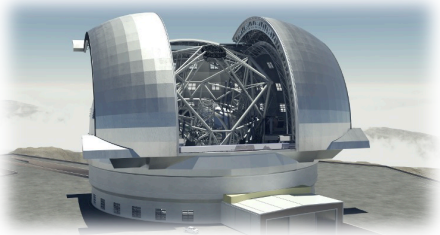
Optical/IR:

Nancy Grace Roman, ELT, VRO LSST



Elliptical, single, rapidly-rotating neutron stars

Kilonova, GRB afterglow



Outlook

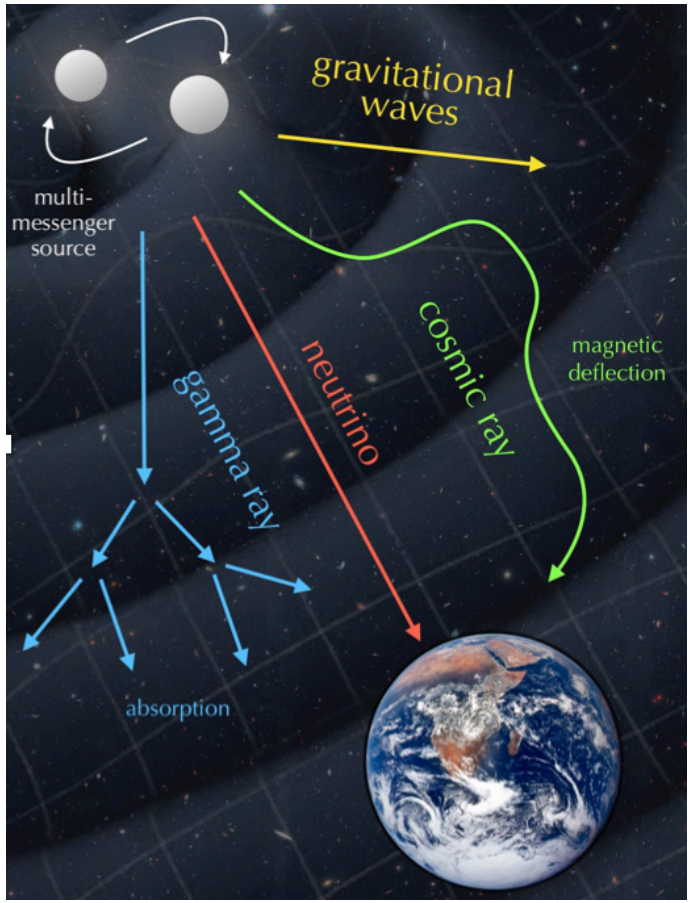
- Ongoing O4 obs. run with LIGO-Virgo-KAGRA

- Improved alerts (shorter low-latency better sky localisation) to enable Multi-Messenger follow up

- Preliminary results from O4a:
  - 81 significant alerts
  - GW230529 compact objects existing in the lower mass gap

- O4b LIGO-Virgo (KAGRA*) detectors are currently taking data
  - 36 significant events
  - S240422ed: candidate NSBH
  - probability of having at least one BNS detection during O4b is 80%

- Next-generation ground-based detectors will enable a *multimessenger revolution!*



Thanks you for your attention!

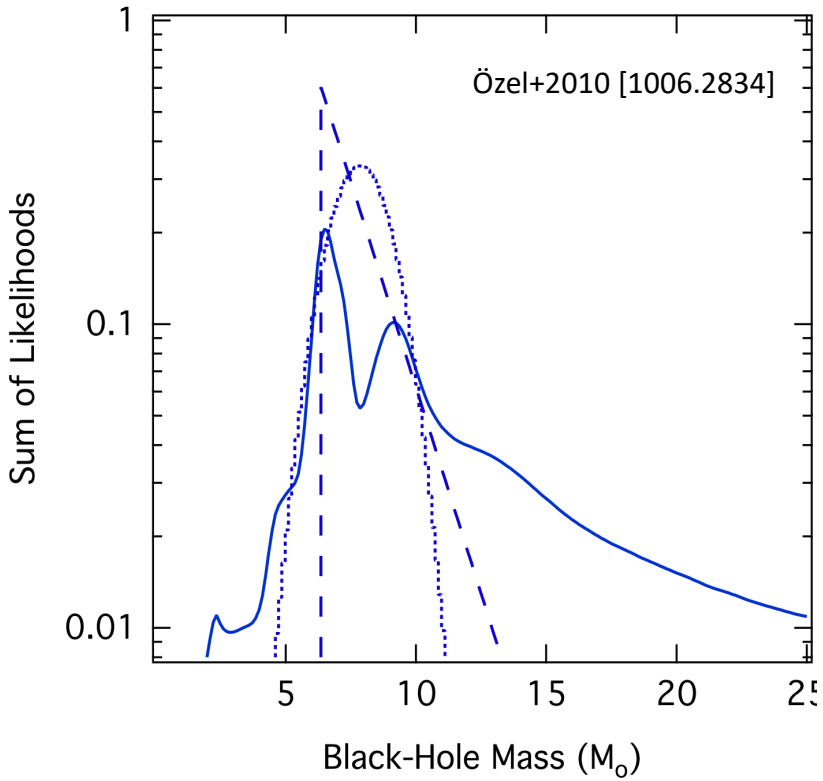
ICSC
Centro Nazionale di Ricerca in HPC, Big Data and Quantum Computing

Backup

Investigating the ‘lower mass gap’

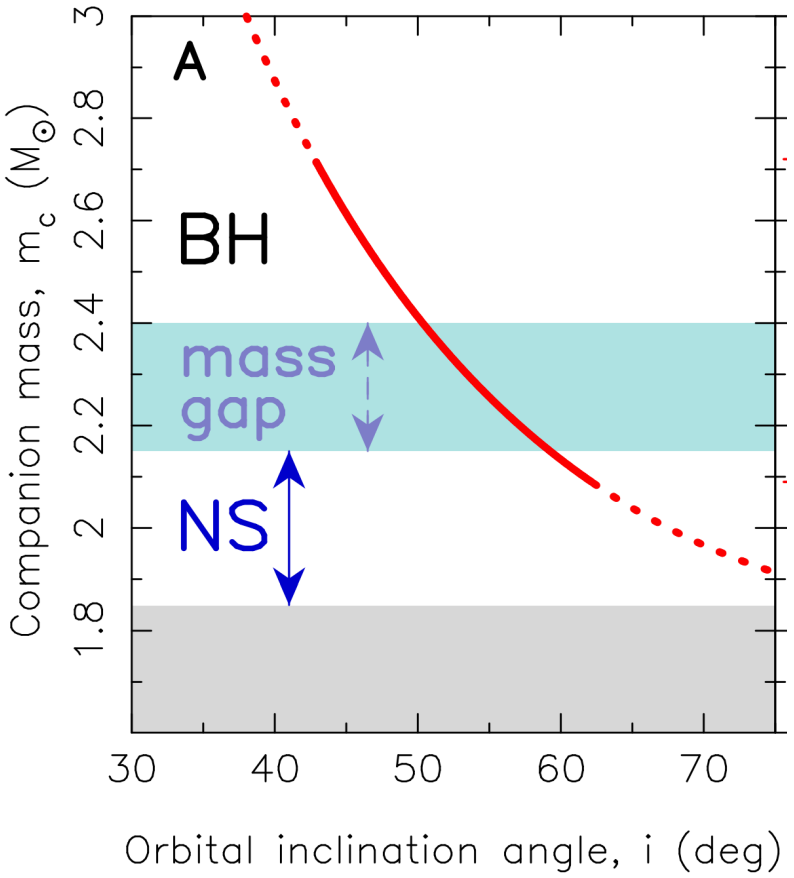
Dearth of $\sim 3-5\ M_{\odot}$ compact objects observed in the Milky Way… evidence of “lower mass gap” between heaviest neutron stars and lightest black holes?

X-ray binaries



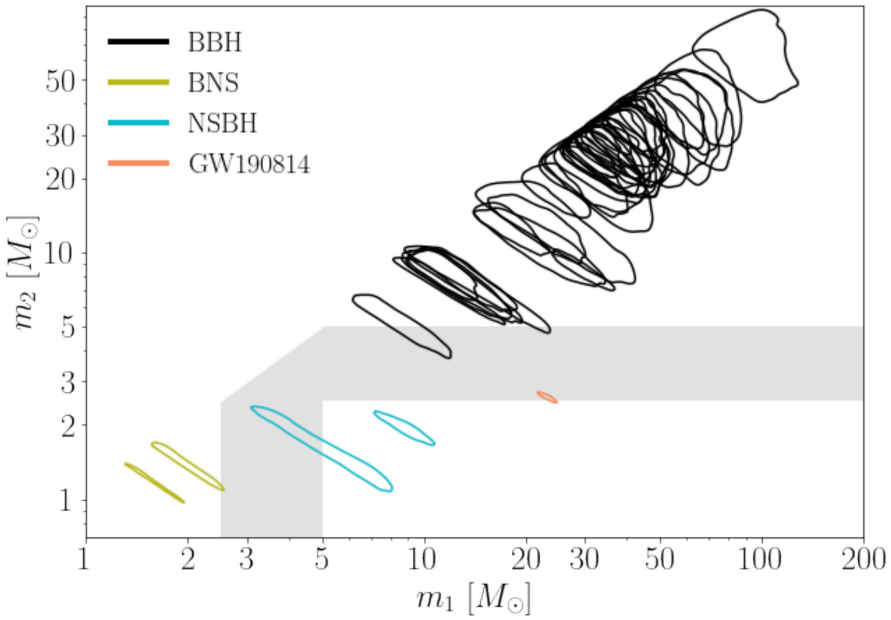
Bailyn+1998 [astro-ph/9708032], Özel+2010 [1006.2834], Farr+2011 [1011.1459]

Detached Galactic binaries



Thompson+2019 [1806.02751], Jayasinghe+2021 [2101.02212], Barr+2024 [2401.09872]

Gravitational waves

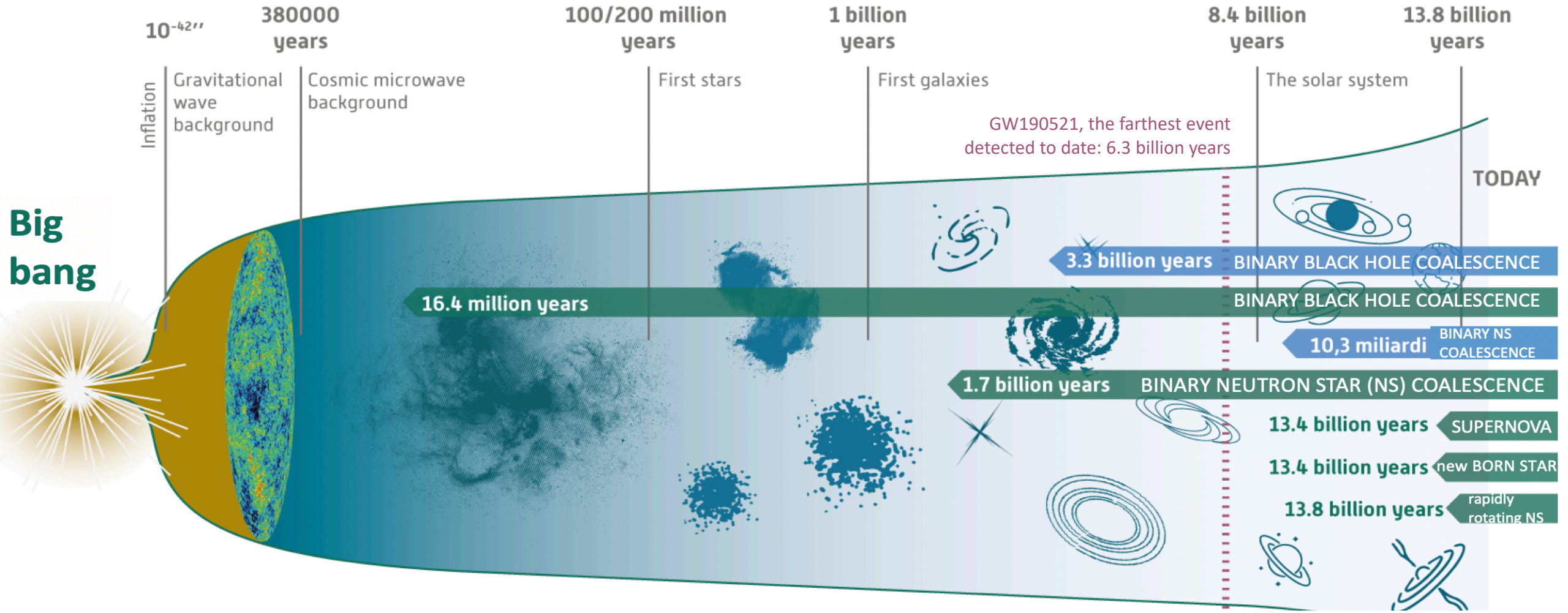


Fishbach, Essick, & Holz [2006.13178], Farah+2022 [2111.03498], LVK 2023 [2111.03634]

What we have learned so far?

- Binary black holes (including heavy “30 Msun”), neutron-star black holes exist
- We have discovered BHs in both mass gaps, although it is not clear if these BHs were formed via conventional mechanisms
- BBH mass distribution shows several sub-features of potentially different formation mechanisms, possibly some of them being formed in dynamical environments
- NS in compact binaries mass distribution is different from that of NSs observed in the galaxy
- GWs can be used to measure the Hubble constant and possibly resolve the tension
- No evidence of sub-solar mass / primordial black holes yet
- No violations of GR have been observed
- No matter effects have been conclusively measured, though some equation of states have been ruled out

Third generation GW interferometers



Einstein Telescope | Advanced LIGO-Virgo+

Neutrino connection

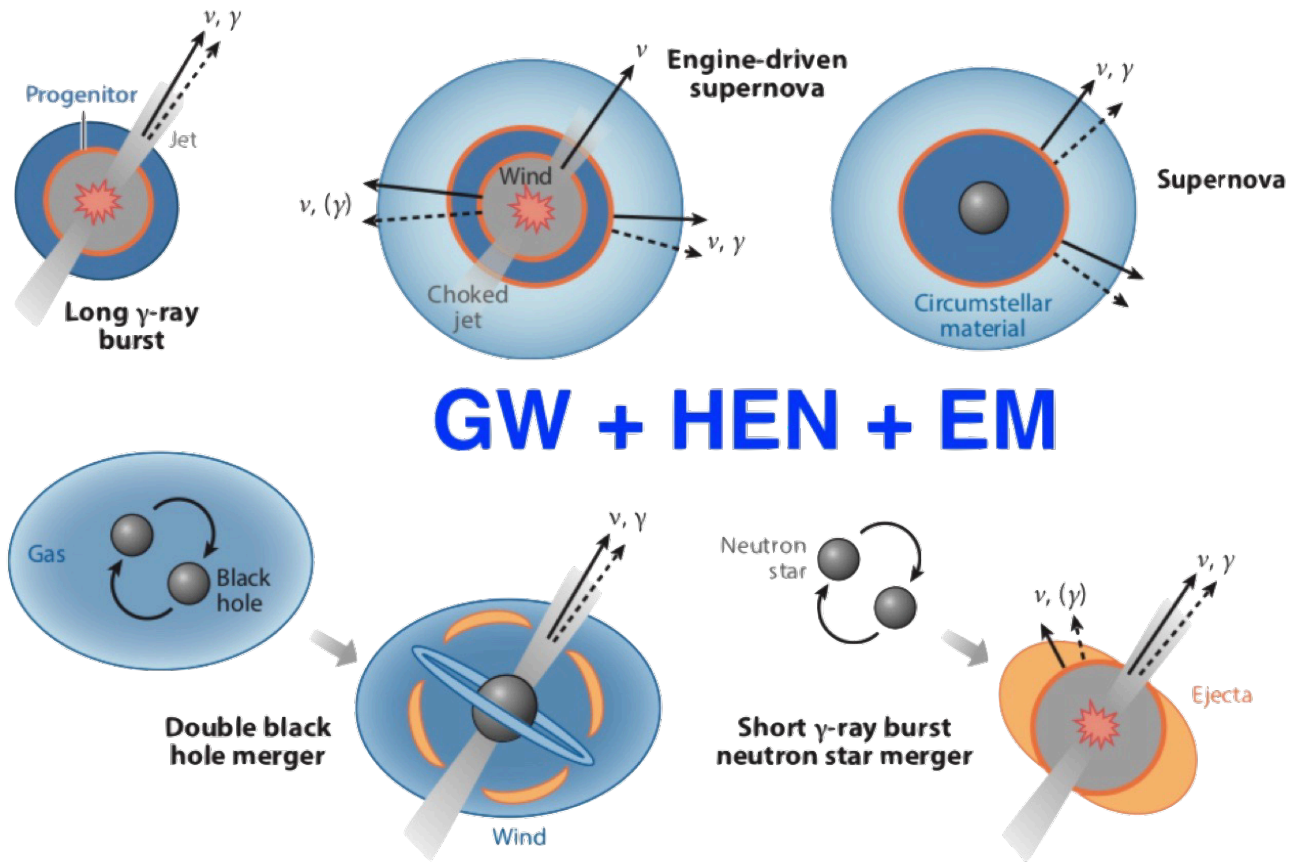
Upper limits on the neutrino flux spatially and temporally coincident with public GW alerts from O3:

- *Super-K (ApJ 2021), IceCube (ApJ 2023), ANTARES (JCAP 2023), KM3Net (JCAP 2024)*

Realtime IceCube follow-up of GW public alerts

Future possibilities in development:

- LVK RAVEN pipeline search for GraceDB coincidences between GW and IceCube public alerts
- Joint GW + neutrino sub-threshold search using IceCube and KM3Net
- Reranking GW candidates based on external neutrino coincidence

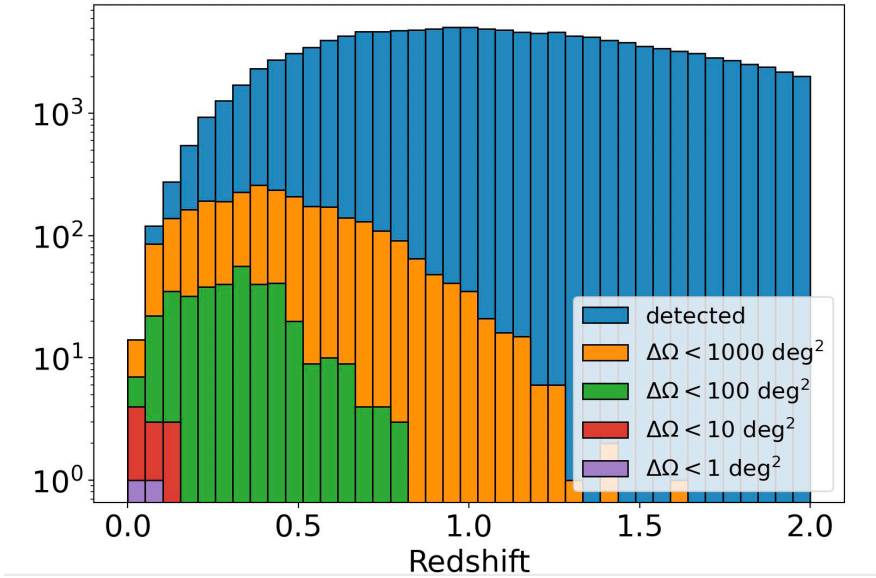


Credit: Thierry Pradier

Talk by Cristoph Raab (IceCube)

Multi-messenger expectation and sky localization

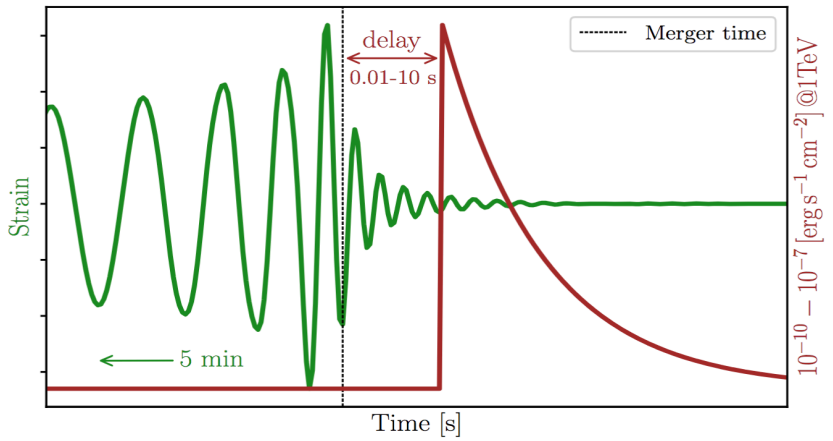
- O(100) detections per year with sky-localization (90% c.r.) < 100 sq. deg
- ET low frequency sensitivity make it possible to localise BNS!
- Early warning alerts!
- A few tens of alerts per hour -> overlapping signals
- Almost all detected short GRB will have a GW counterpart around 70% ET and 95% ET+CE
- Depending on the satellites, we will have **tens to hundreds** of detections per year
- Crucial instruments able to localize at arcmin-arcsec level to drive the ground-based follow-up!



Dupletsa et al. 2023, Ronchini et al. A&A 2022

- 10^5 BNS alerts per year
- 10^5 BBH alerts per year

Branchesi, Maggiore et al 2023, JCAP



Electromagnetic counterparts

Fate of the merger remnant and electromagnetic counterpart depends on the properties of the component objects

1. Gamma-ray burst
- Jet geometry, Lorentz factor -> central engine

2. Kilonova
- Ejecta mass, composition, geometry -> neutron star equation of state