GW and multimessenger astronomy in the era of second generation GW detectors: recent results and future prospects

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Multimessenger astronomy in the Einstein Telescope Era

Padova

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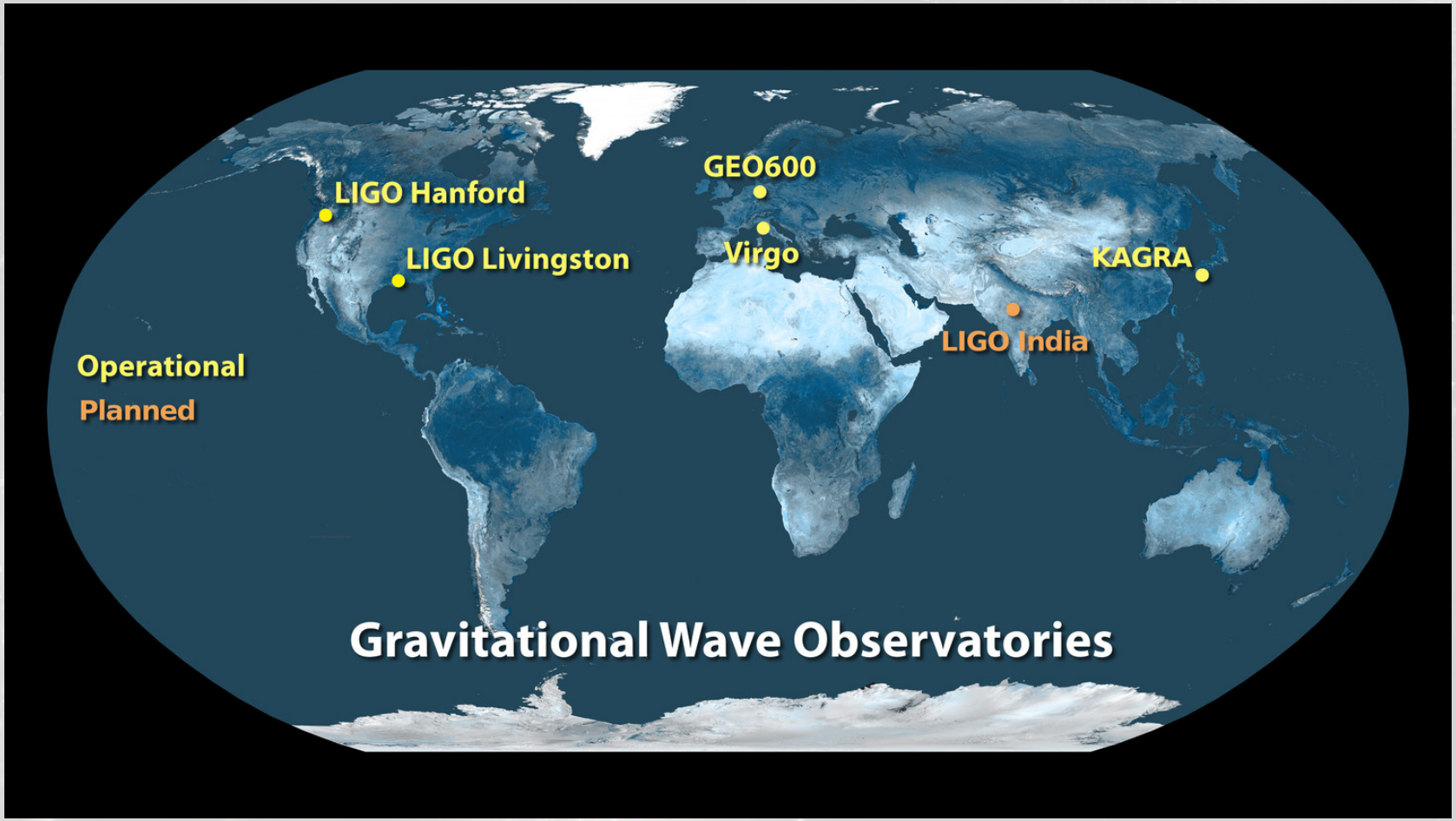
Outline

The 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

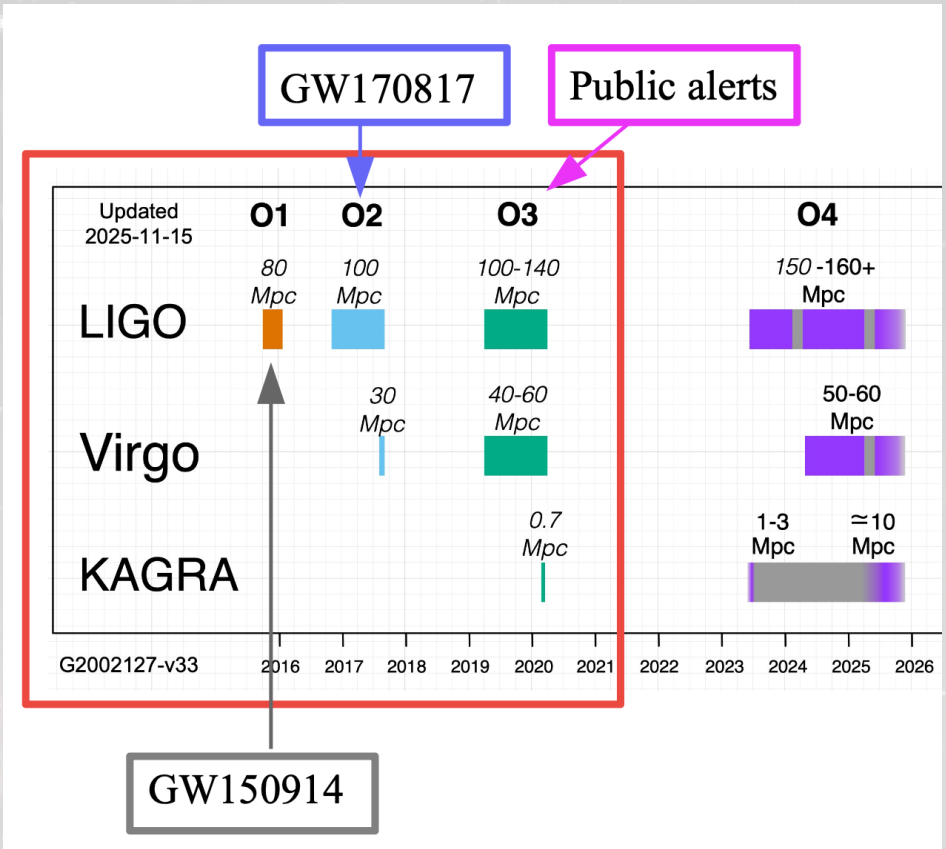
  O4b: April 2024 - January 2025

  LIGO and Virgo operating; KAGRA under commissioning

  O4c: January 2025 - November 2025

  LIGO, Virgo and KAGRA operating

Highlights from O1+O2+O3



- O1 - first direct detection of GWs: **GW150914**

  LVC 2016, PRL, 116, 061102

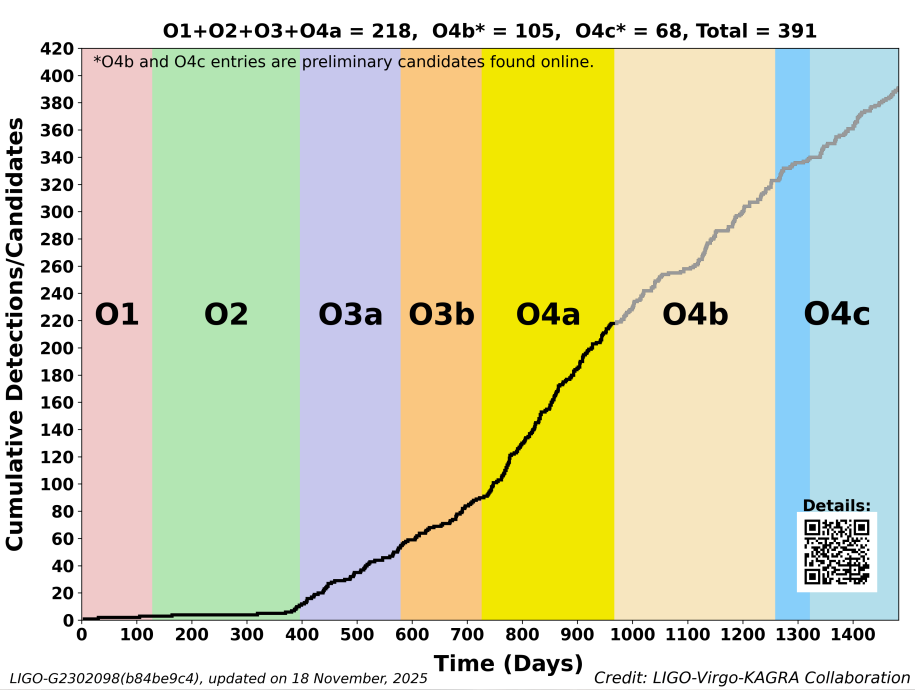
- O2 - first multimessenger observation of a binary neutron star (BNS) merger: **GW170817** $\Rightarrow$

  LVC 2017, ApJ, 848, 13

- O3 - second BNS merger: GW190425 (LVC 2020, ApJL, 892, 3); **Public alerts**

- Total number of candidates (O1+O2+O3): 90

GW detections: O4 summary



- **O4a**: 128 new candidates
- **O4b**: 105 significant* candidates (114 Total - 9 Retracted)
- **O4c**: 68 significant candidates (77 Total - 9 Retracted)
- Almost all BBHs; no BNS; one NS-BH: **GW230529** (O4a)
- An interesting low significant* candidate: **S250818k** (O4c)

* For CBC searches:

Significant GW alerts: false alarm rate $<$ 1 per month;

Low significant GW alerts: 1 per month $<$ FAR $<$ 10 per day

O4a data: GWTC-4 catalog

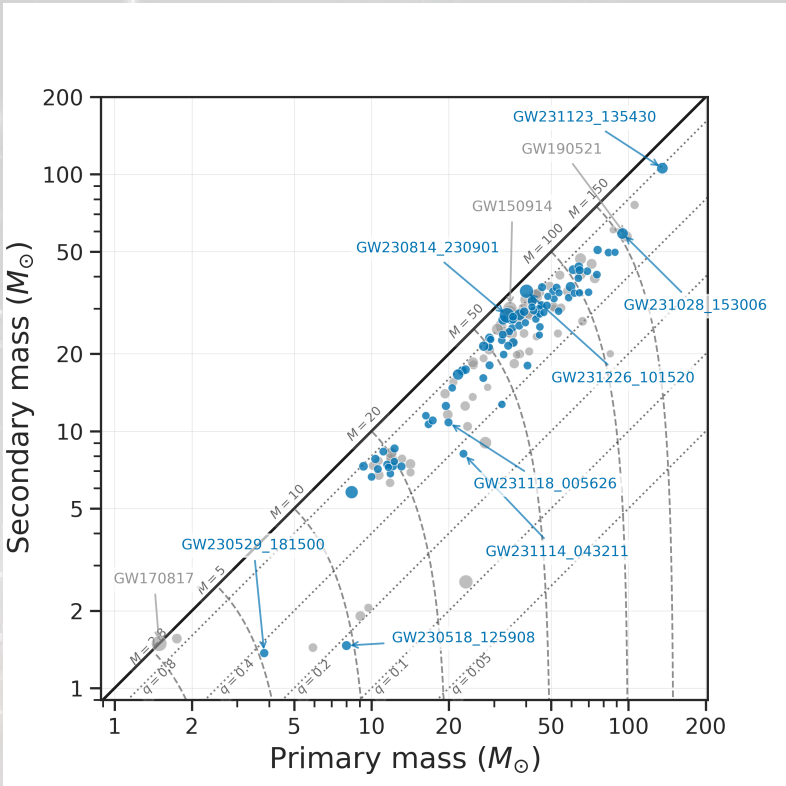


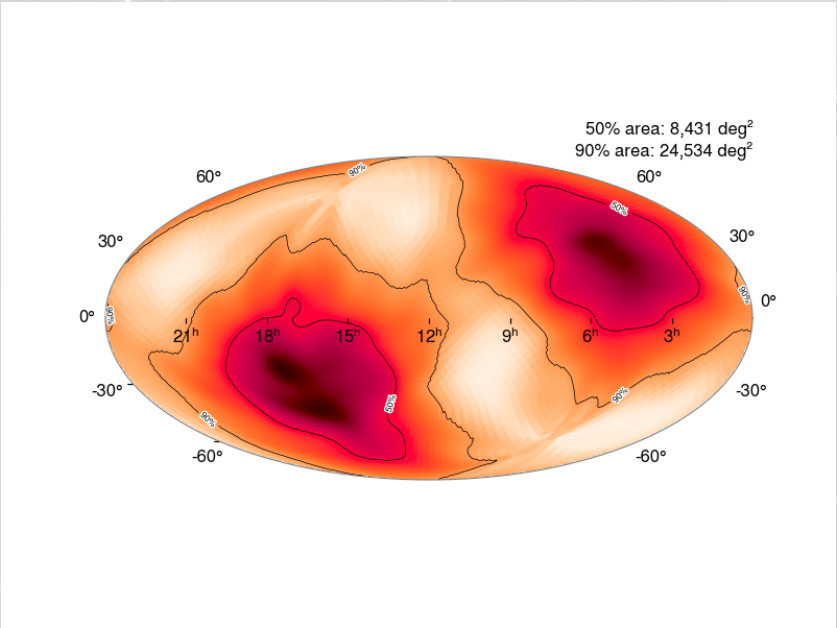
Image Credit: G. Ashton

- GWTC-4.0: An Introduction
  https://arxiv.org/abs/2508.18080
- GWTC-4.0: Methods
  https://arxiv.org/abs/2508.18081
- GWTC-4.0: Update
  https://arxiv.org/abs/2508.18082
- GWTC-4.0: Population
  https://arxiv.org/abs/2508.18083
- Open Data from O4a
  https://arxiv.org/abs/2508.18079
  Data available in GWOSC

GW230529

- Single-detector signal found by LIGO Livingston
- Primary: (2.5 - 4.5) $M_\odot$; Secondary: (1.2 - 2.0) $M_\odot$ $\Rightarrow$ NS-BH merger!
- Significantly more symmetric than other NS-BHs

- More symmetric masses $\rightarrow$ more susceptible to tidal disruption $\Rightarrow$ EM counterpart
- 90 % C.R. $\sim 2 \times 10^4$ deg^2
- $D_L = 201^{+102}_{-96}$ Mpc
- No EM counterpart reported



LVK Collaboration 2023, GCN 34148
LVK Coll. 2024, ApJL 970 L34

S250818k

- Low-significant candidate; it has the highest probability of being a NS-NS among all candidates observed in O4 ($p_{NS-NS} = 29\%$)
- Luminosity Distance (D_L): 259 $\pm$ 74 Mpc*
- H, L and V online
- Only automated data quality checks for low-significant events, but ...

- ... Possible EM counterpart observed by ZTF: ZTF25abjmnps/AT2025ulz (GCN 41414)
- Further observations with Keck (GCN 41436)
  - z=0.0848, consistent with the GW distance;
  - initial data consistent with a kilonova

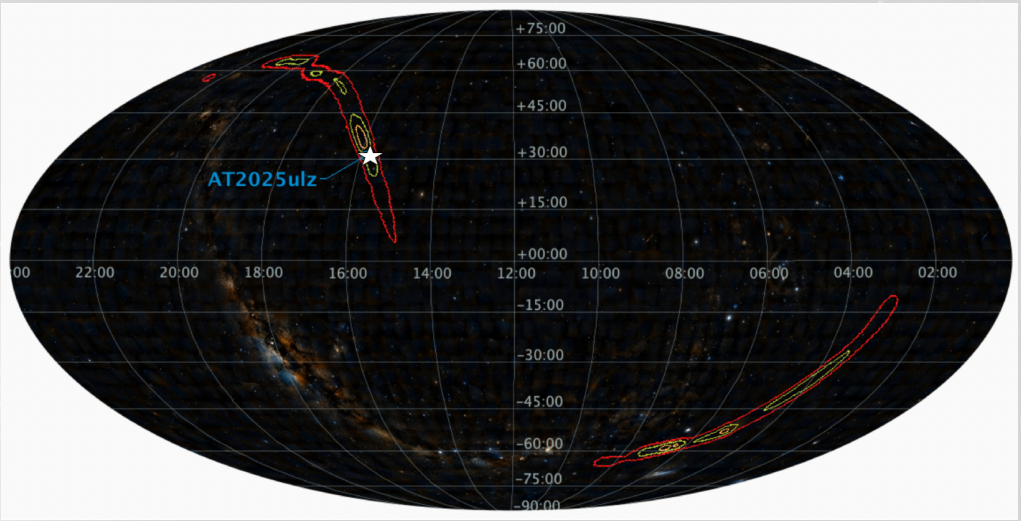


Image Credit: G. Greco

* Preliminary notice's value

S250818k

- Given the **special science case**, LVK released an Initial GCN Circular: GCN 41437
  - No evidence for glitches or data quality issues
- Update GCN Circular: GCN 41440
  - Updated 3D GW skymap; $D_L = 237 \pm 62$ Mpc
  - AT2025ulz position still consistent

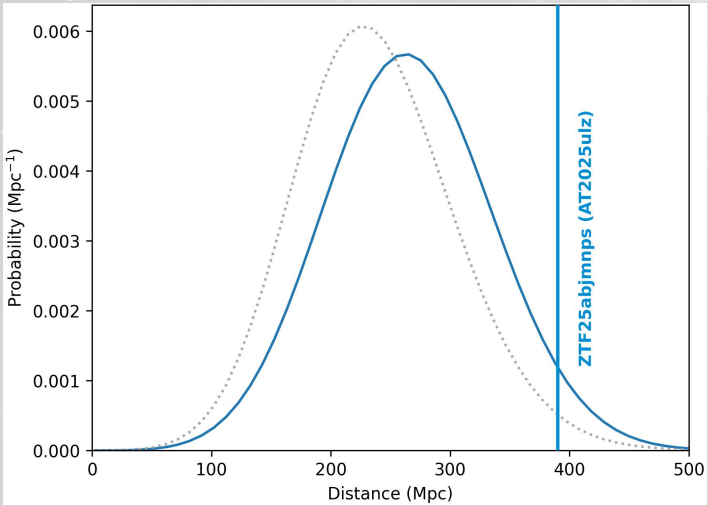
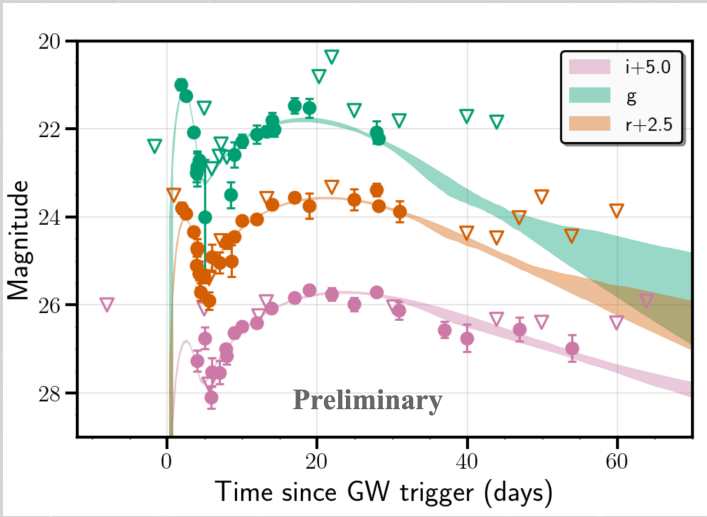


Image Credit: G. Greco

ENGRAVE - Electromagnetic counterparts of gravitational wave sources at the Very Large Telescope



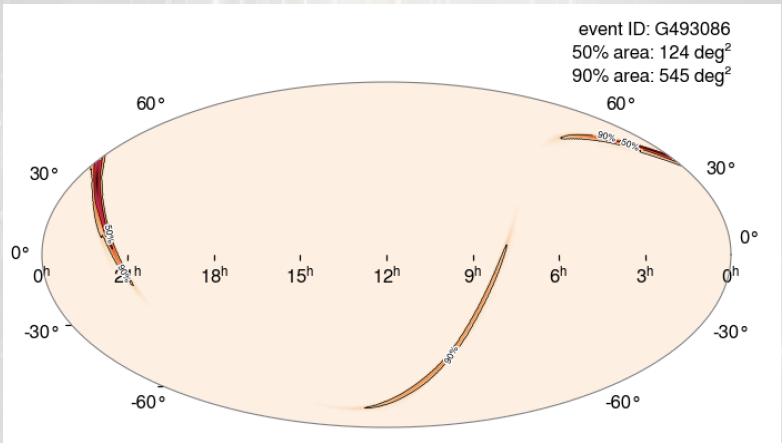
- Later EM observations suggest AT2025ulz is a type IIb supernova (ENGRAVE Collaboration, in preparation)...

(see Om's talk)

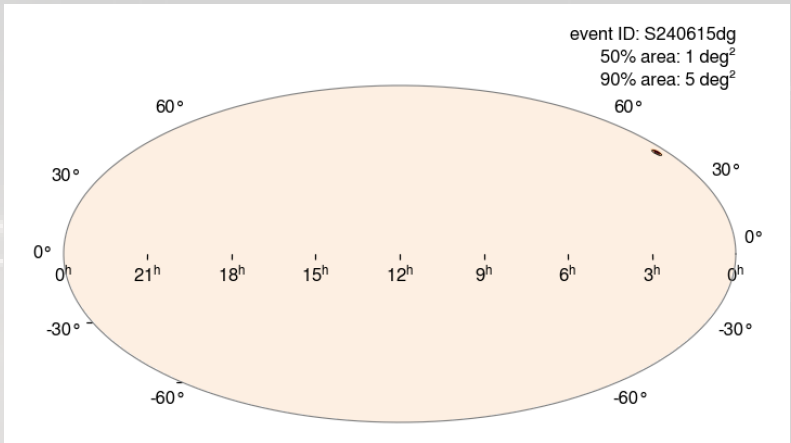
Virgo contribution in O4

- Virgo joined the GW detector network in O4b
- 138 out of 173 total O4b+c events detected by online pipelines received contributions from the Virgo detector (credits: F. Di Renzo)
- **Virgo** can have a **significant impact on network localization capabilities**

Example: S240615dg (BBH, GraceDB, GCNs 36669 and 36704)

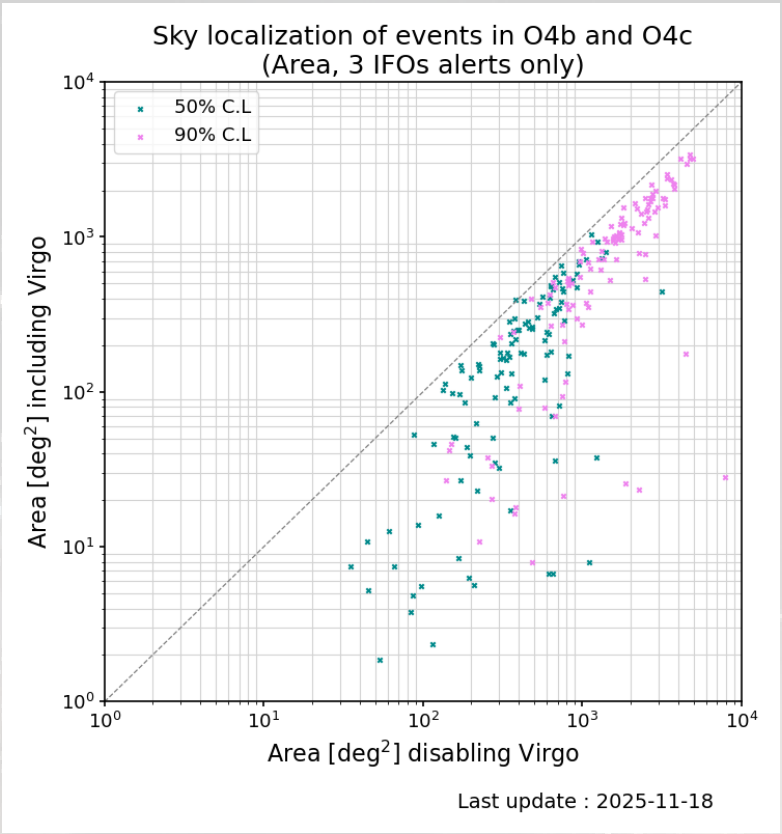


Early sky localization, Bayestar



Offline sky localization, Bilby

Virgo contribution to sky localization: O4b and O4c



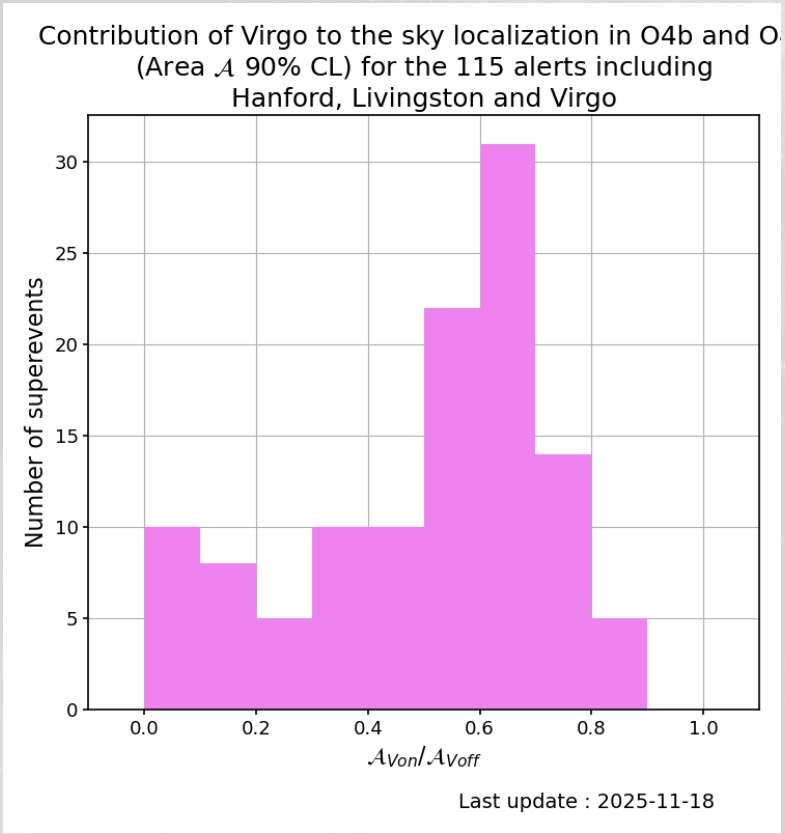


Image Credits: I. Bentara

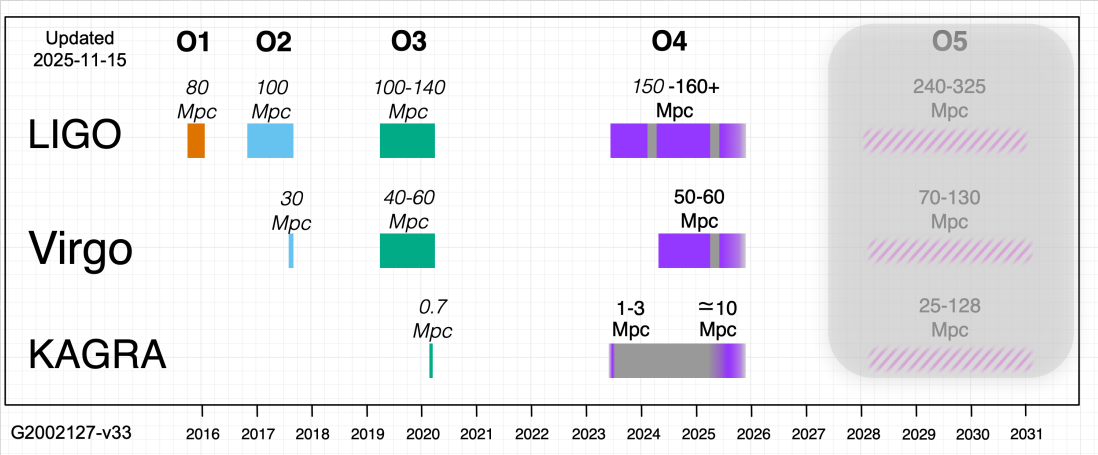
LVK O4b and O4c data release

O4b and O4c data release this year

Data set	Date range	Months of data	Release date
O4b	2024-04-10 to 2025-01-28	9.5	2026-05-26
O4c	2025-01-28 to 2025-11-18	10	2026-12-16

Many new interesting results to come!

Current and next GW observing runs



- A six-month observing run should begin in the early fall of this year, with detectors participating as available
- A fifth observing run (O5) is planned to start in a few years

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

The six-month observing run will probably be under **"IGWN"** and not LVK

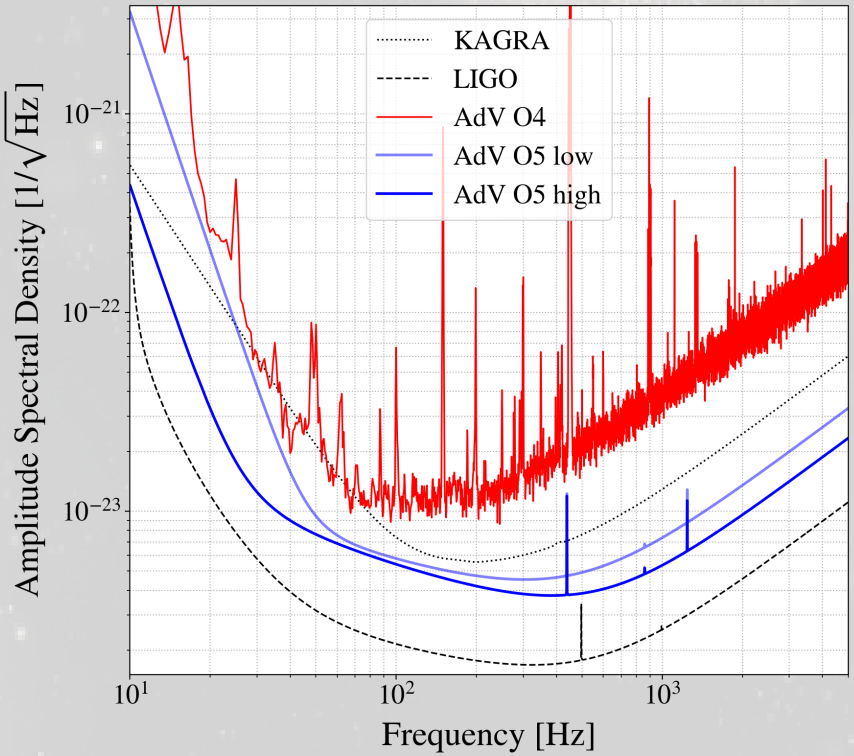
Transition to IGWN

- **What is IGWN?** The International Gravitational-Wave Observatory Network (IGWN) is an organization anchored by the current network of LIGO, Virgo and KAGRA gravitational-wave observatories
- **Why IGWN?** A unified collaboration, with a single governance structure and a single set of policies and procedures
- **When?** LVK groups are expected to join IGWN by May-June 2026; IGWN expected to be fully operational by October 2027, so **O5 will be an IGWN run**. The next six-months observing run falls in the transition period

Prospects for compact binary merger detection in O5

- We generated sample of synthetic compact binary merging systems
  - MOBSE population-synthesis code (Mapelli et al. 2017, Giacobbo et al. 2018)
  - COSMO$\mathcal{R}$ATE code (Santoliquido et al. 2020, 2021)
- We simulated the associated GW signal and estimated the GW detection rates with the HLVK network
  - LIGO[1] Livingston and Hanford: 325 Mpc;
  - KAGRA[1]: 80 Mpc;
  - Virgo[2] in three configurations:

    AdV O4 (50 Mpc), AdV O5 high (138 Mpc) and AdV O5 low (108 Mpc)



[1] https://dcc.ligo.org/LIGO-T2000012/public
[2] https://tds.virgo-gw.eu/ql/?c=21980

Muccillo, Patricelli & Razzano, submitted to JHEAP

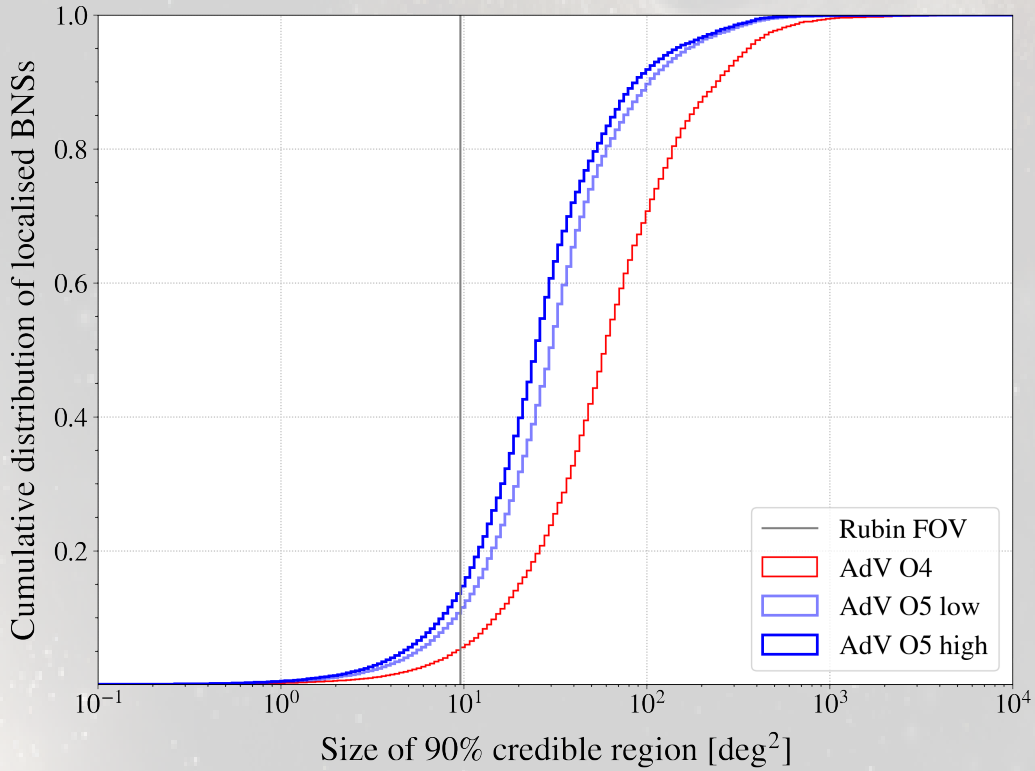
Prospects for compact binary merger detection in O5

Virgo configuration	$\mathcal{R}_{\rm BBH}$ events/year	$\mathcal{R}_{\rm NSBH}$ events/year	$\mathcal{R}_{\rm NSNS}$ events/year
AdV O4	260^{+230}_{-130}	$9.5^{+5.3}_{-3.6}$	$2.0^{+1.2}_{-0.8}$
AdV O5 low	270^{+240}_{-130}	$9.7^{+5.4}_{-3.6}$	$2.1^{+1.3}_{-0.8}$
AdV O5 high	280^{+240}_{-130}	$10.0^{+5.6}_{-3.8}$	$2.2^{+1.3}_{-0.8}$

Muccillo, Patricelli & Razzano, submitted to JHEAP

Prospects for compact binary merger detection in O5

- **Vera Rubin observatory**: a key instrument for discovering EM counterparts to GWs
  (see Silvia's talk)
- Given its high sensitivity, it will be able to detect kilonovae up to $\sim$ 300 Mpc
- It will use a dedicated Target of Opportunity (ToO) program to rapidly follow up GW triggers
- Rubin ToO trigger criteria for deeper* observations:
  $\Delta\Omega < 100$ deg^2
  (Andreoni et al. 2024)



Muccillo, Patricelli & Razzano, sub. to JHEAP

MoU between LVK and Rubin TVS-MMA signed on November 2025

Patricelli & Piranomonte, LVK and Rubin liaisons

* multi-filter observations with longer exposure times

Conclusions

- Four LVK observing runs have been completed
- We had the first multi-messenger (GWs+photons) observation of a binary system of NSs
- Other multi-messenger sources still to be detected (supernovae, pulsars...)
- O5 will start in a few years, with GW detectors operating with increased sensitivity
- Many EM facilities will operate in synergy with 2nd (and 3rd) generation GW detectors

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