Image: Carl Knox, OzGrav-Swinburne University of Technology

Low-Latency Gravitational-Wave Alerts and Multimessenger Astronomy: O4 Results and Future Development

Soichiro Morisaki
ICRR/University of Tokyo

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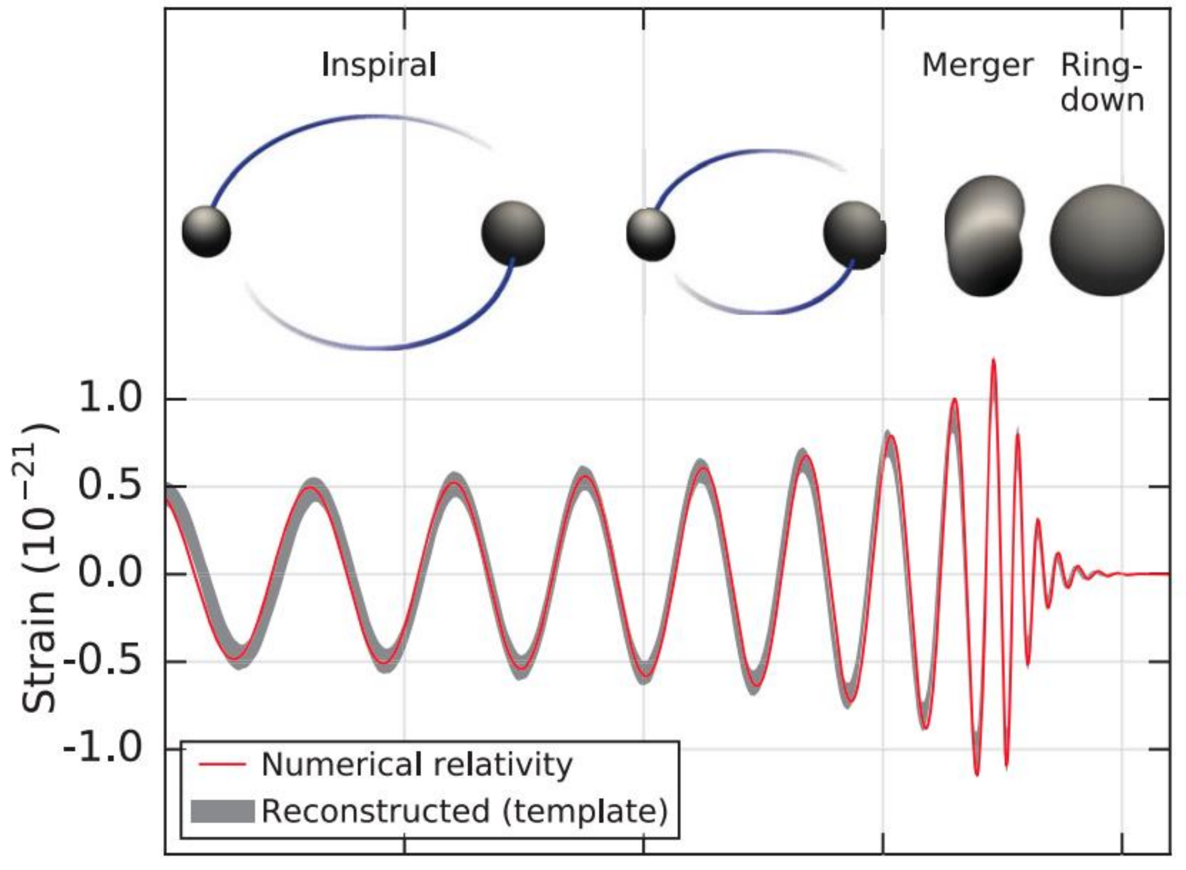
Multi-messenger pre-workshop

CREATION OF MULTI-MESSENGER ASTROPHYSICS

Gravitational Waves (in a single slide)

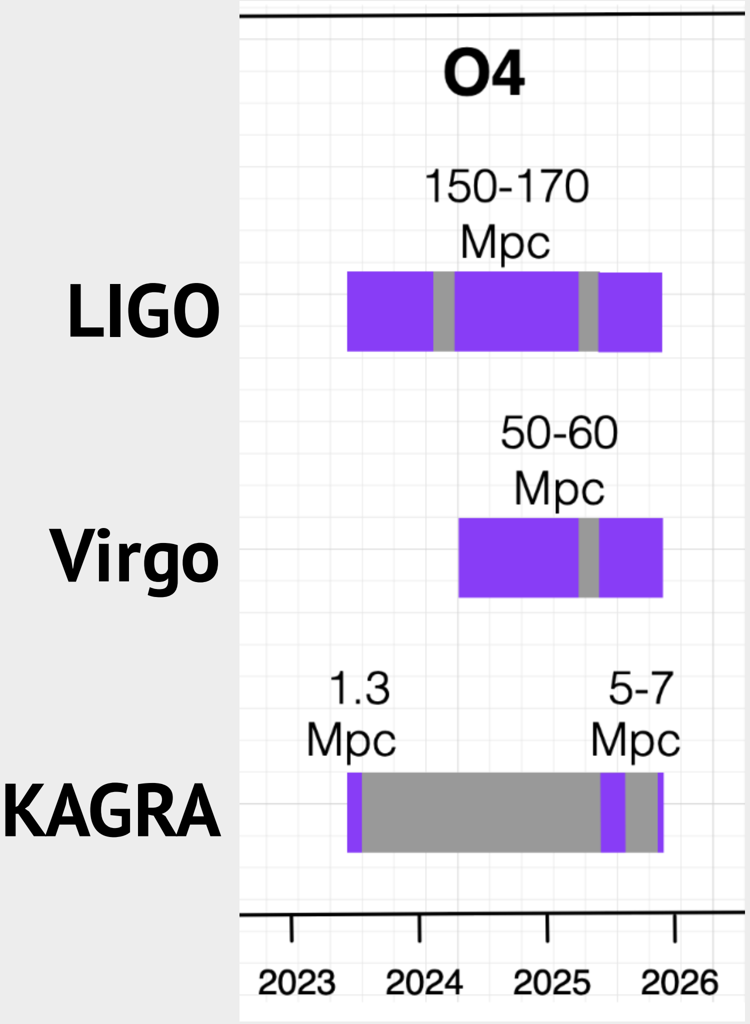
- **Primary (and so far only confirmed) source:** Compact Binary Coalescence (CBC)
- **Three CBC categories**
  - Binary Black Hole (BBH)
  - Neutron Star–Black Hole (NSBH)
  - Binary Neutron Star (BNS)
- **Four observing runs (O1, O2, O3, O4)** by **LIGO-Virgo-KAGRA** detector network
  - 90 CBC detections from O1–O3
  - O4 completed in November last year

Credit: Abbott+ PRL 2016



CBC waveform

O4 Real-Time Alerts



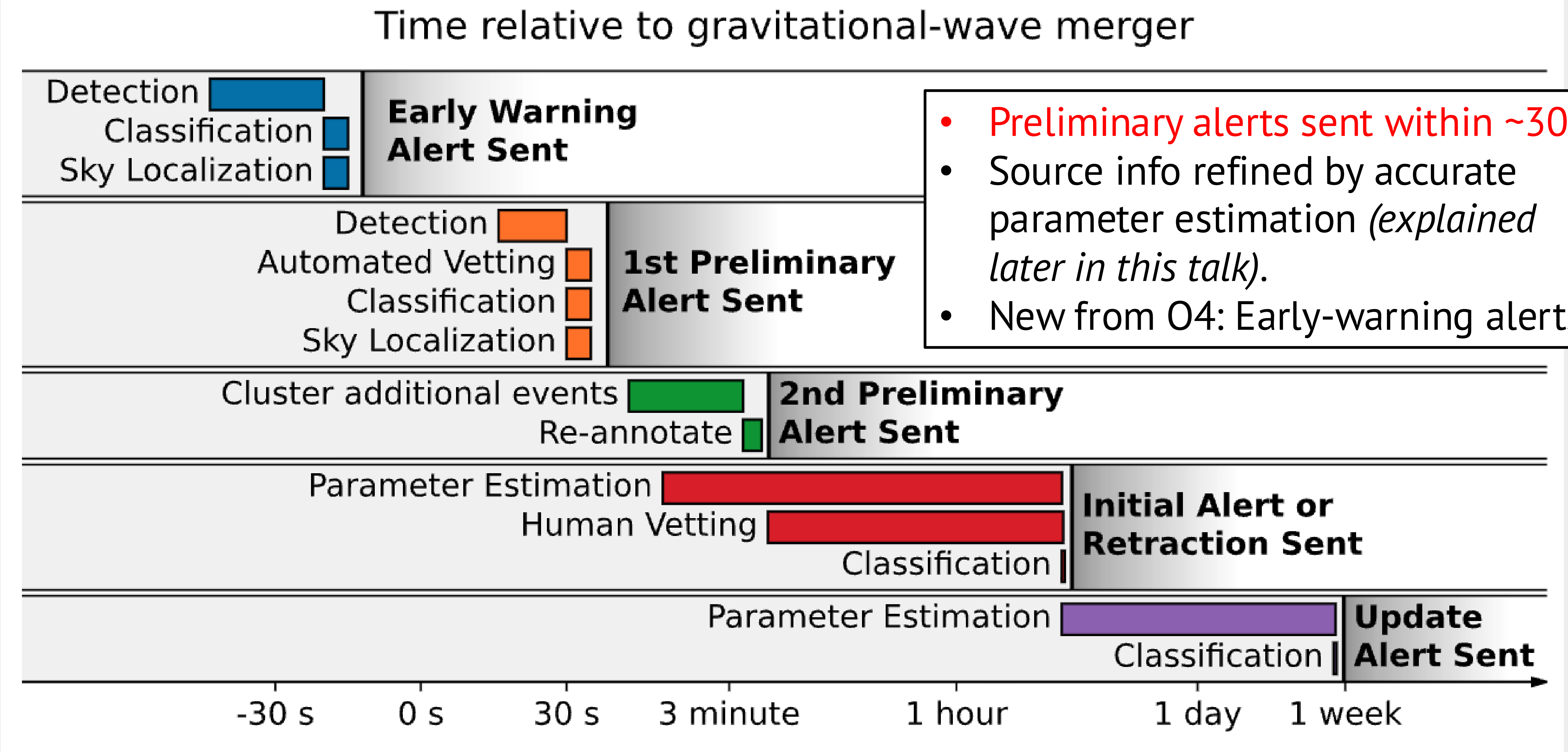
O4 Timeline

(taken from https://observing.docs.ligo.org/plan/)

- O4 conducted from May 2023 to November 2025
  - LIGO BNS range: 150-170Mpc
- 254 Significant Detection Candidates
  - FAR (False Alarm Rate) threshold: **1/month (CBC)** and **1/yr (unmodeled burst, sub-solar-mass CBC)** including trial factors
- 5,136 Low-Significance Detection Candidates (FAR<2/day)
- No electro-magnetic (EM)/neutrino counterparts confidently identified.

O4 Alert Timeline

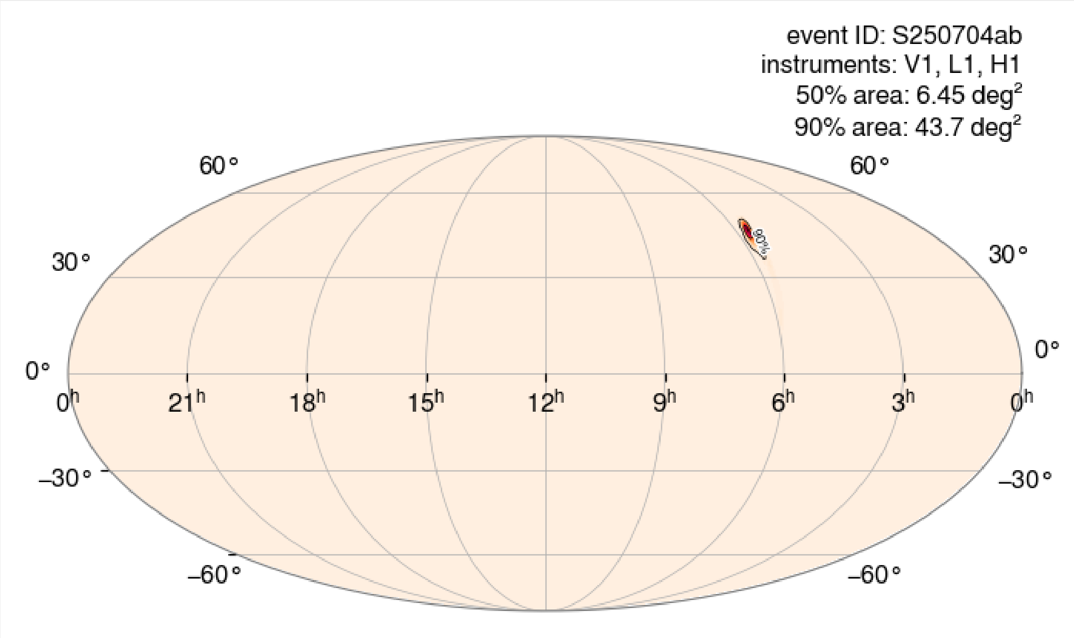
Credit: IGWN Public Alerts User Guide (emfollow.docs.ligo.org/userguide)



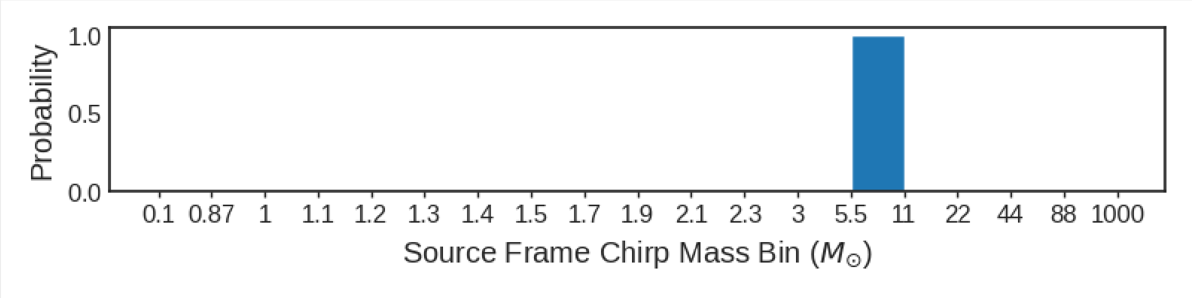
- Preliminary alerts sent within ~30s
- Source info refined by accurate parameter estimation *(explained later in this talk)*.
- New from O4: Early-warning alerts

Public Data Products

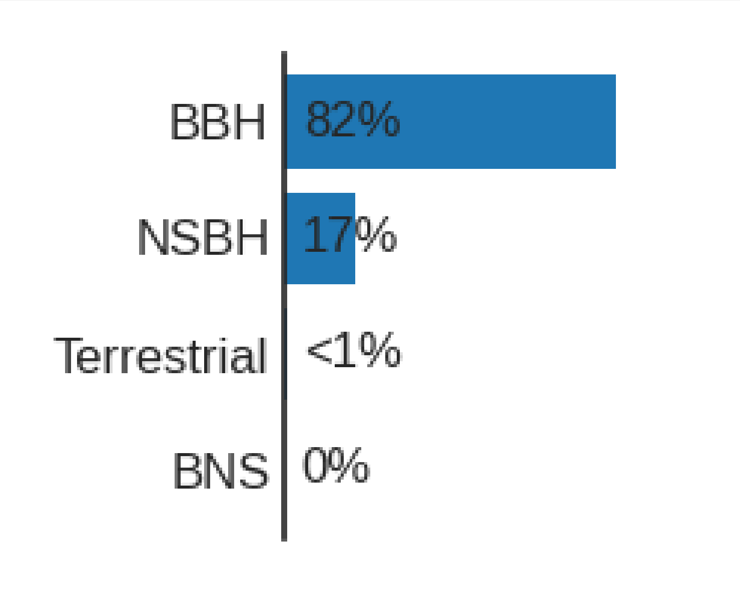
* All the figures are taken from [S250704ab]

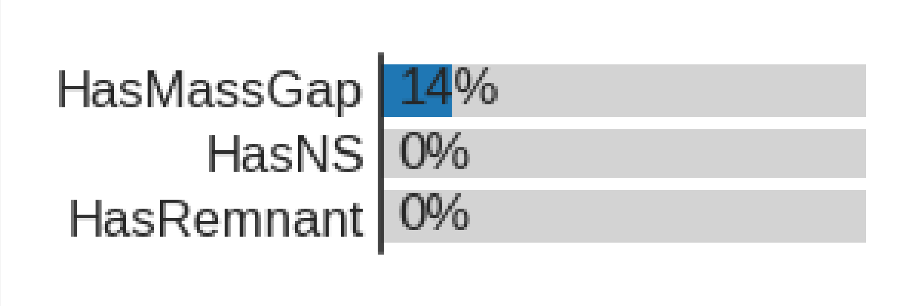


Source localization (2D and 3D)



Binned Source Chirp Mass





EM-Bright probabilities

Source classification

Interesting O4 Events for Multimessenger Astronomy

GW230529_181500 [LVK 2024]

Likely NSBH with a lower-mass-gap object ($3.6^{+0.8}_{-1.2}\ M_{\odot}$ - $1.4^{+0.6}_{-0.2}\ M_{\odot}$).

Single detector → poor localization

S250206dm

A high-significance BNS/NSBH candidate

50%/90% area: $38/547\ \mathrm{deg}^2$

Extensive EM/neutrino follow-up

S251112cm

A subsolar-mass event candidate

O4 start:
May 24, 2023

S231109ci [Niu+ 2025]

A sub-threshold BNS candidate

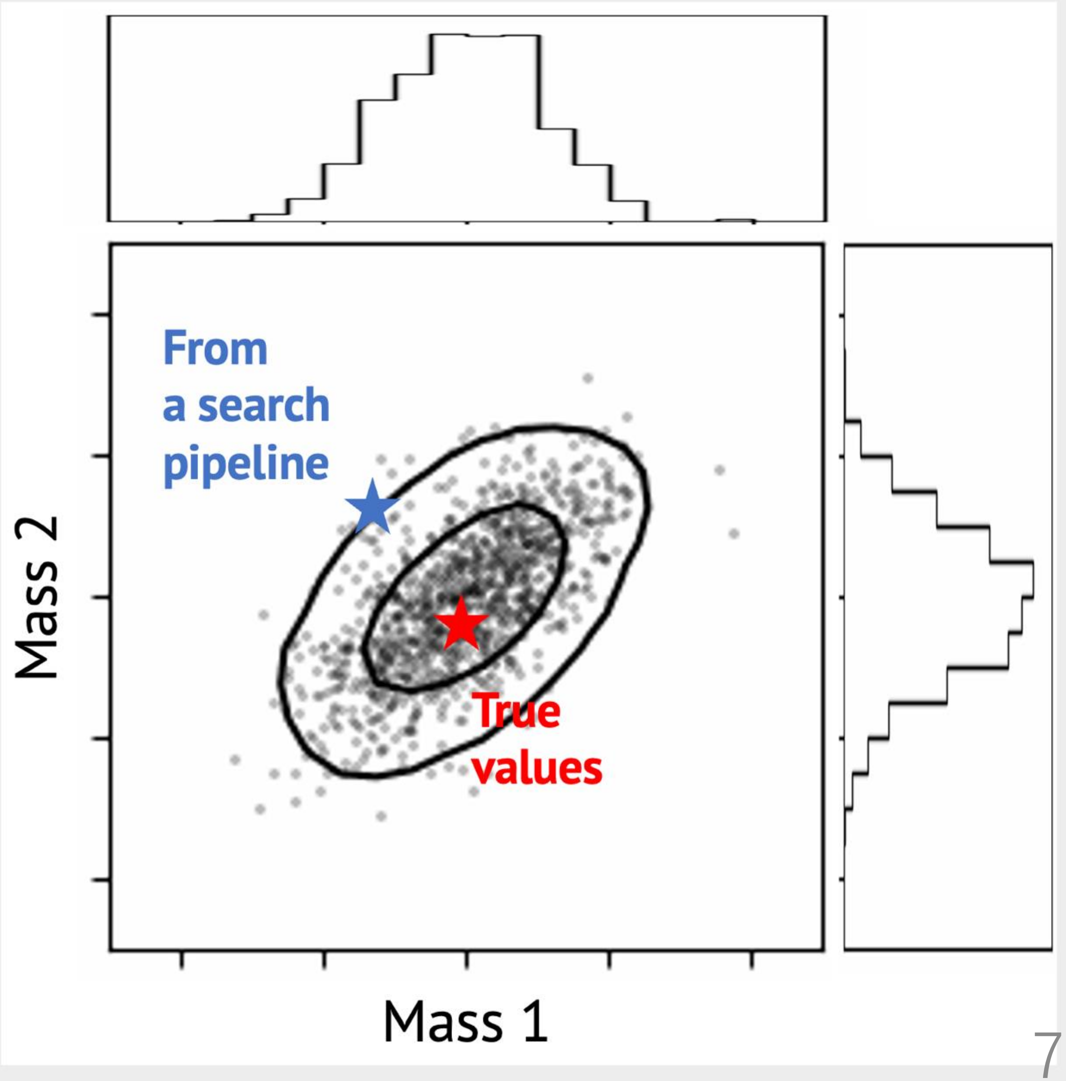
S250818k

A subthreshold subsolar mass candidate

AT2025ulz within the GW localization

Parameter Estimation Updates

- Initial products (BAYESTAR localization, EM-bright) rely on **point estimates of masses & spins from the search**
- Updated with accurate **parameter estimation:** detector calibration uncertainties, orbital precession etc.
- **In O3, the analyses took ~60 hours (median).**
- For O4, automated parameter estimation was performed with `Bilby`. [Ashton+ ApJS 2019; Romero-Shaw+ MNRAS 2020]

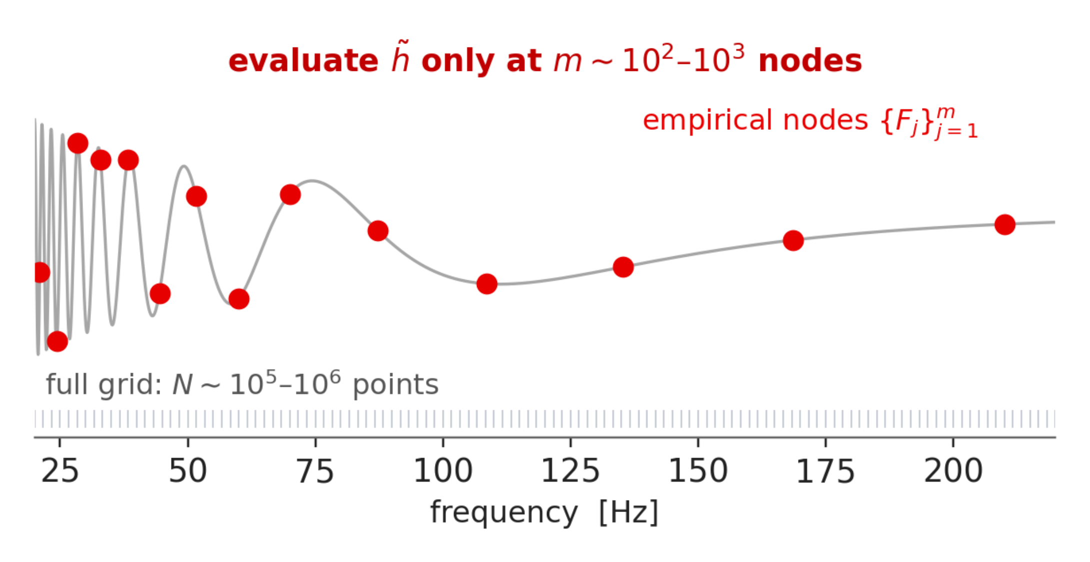


Reduced Order Quadrature (ROQ)

"Interpolate" the waveform from
$M \ll N$ frequency points:

$$\tilde{h}(f_n) \simeq \sum_{m=1}^{M} B_{nm}\tilde{h}(F_m)\,. \quad (n = 1,2,\dots,N)$$

→ **$\sim N/M$ speedup**



- **Greedy algorithm** to find out M *reduced basis vectors* $\{\vec{e}_m\}_{m=1}^{M}$ spanning the waveform space.

- **Empirical Interpolation Method** to map $\{\vec{e}_m\}_{m=1}^{M}$ to *interpolation nodes* $\{F_m\}_{m=1}^{M}$ and *coefficients* B_{nm}.

Ref: P. Canizares et al., Phys. Rev. Lett. **114**, 071104 (2015).
R. Smith et al., Phys. Rev. D **94**, 044031 (2016).

ROQ Improvements toward O4

Improved ROQ method accelerates likelihood evaluations by **O(100) for BNS and $O(10)$ for NSBH** [SM+ PRD 2023]

- **Union of targeted ROQ bases**, each constructed for a narrow chirp-mass range
- Bases are trained against amplitude & phase modulations from **detector calibration uncertainties**
- Chirping nature of the signal exploited to reduce the file size of ROQ bases [SM PRD 2021].

Low-mass, BNS

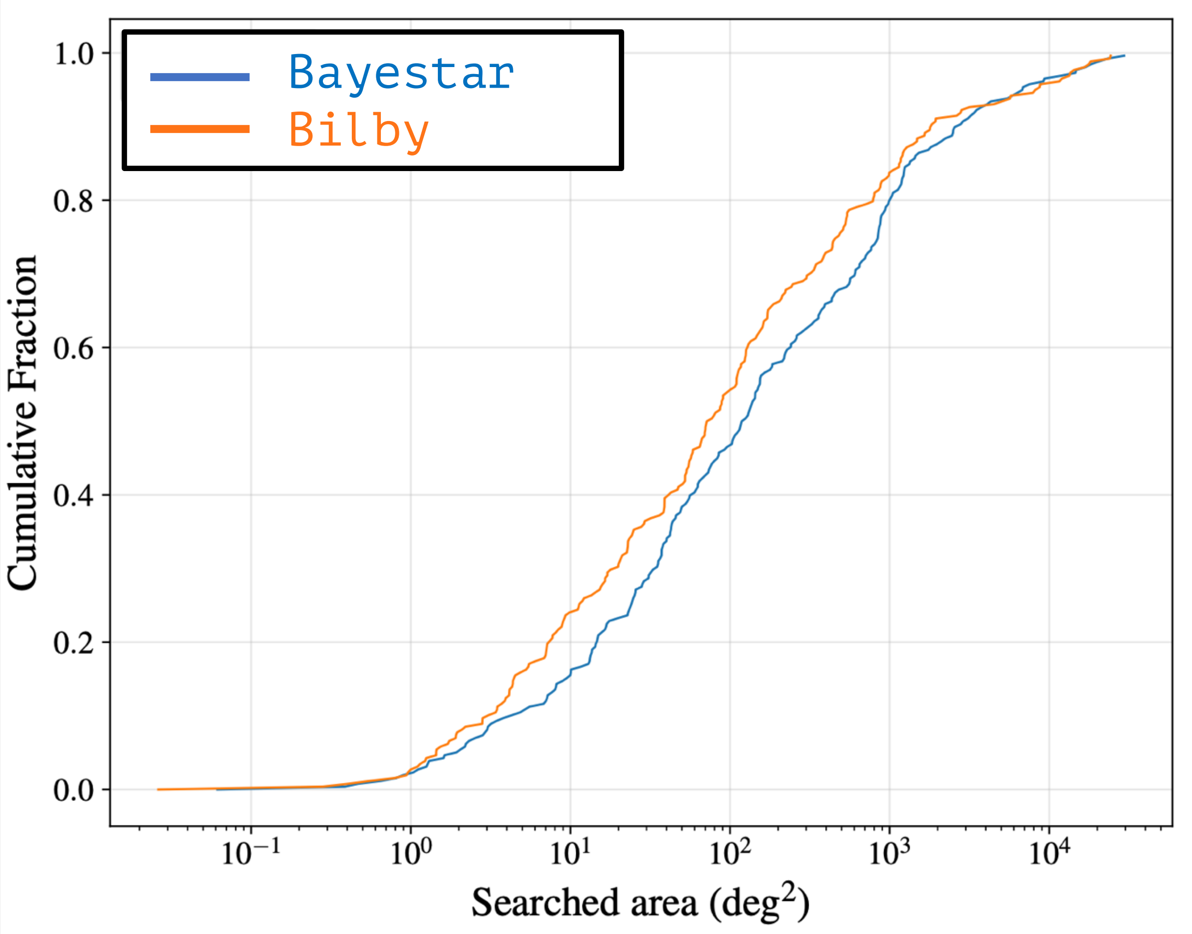
Waveform	$\mathcal{M}$ $(M_\odot)$ Min	$\mathcal{M}$ $(M_\odot)$ Max	Basis size Linear	Basis size Quadratic	Speedup
IMRPhenomD [Husa+ 2016, Khan+ 2016]	0.6	1.1	126–137	24	250–460
	0.92	1.7	120–130	25	110–210
	1.4	2.6	112–122	28	58–100
	2.1	4.0	109–117	32	29–43
IMRPhenomPv2 [Hannam+ 2014]	1.4	2.6	1540–1824	2808–3484	26–31
	2.1	4.0	1716–2092	3256–4034	11–14
	3.3	6.3	1979–2377	3840–4170	5.7–6.4
	5.2	11.0	2304–2404	3794–4056	3.0–3.2
	8.7	21.0	2062–2232	2525–3204	2.0–2.3
IMRPhenomXPHM [Pratten+ 2021]	10.02	19.05	1870–2092	2444–2619	14–19
	15.52	31.85	1886–3095	2463–3095	4.9–8.0
	26.54	62.86	1222–1836	1222–1836	2.4–3.8
	52.38	200.0	308–806	308–806	1.9–3.7

High-mass, BBH

The run time for a BNS is reduced to ~10 min.

Pre-O4 Rehearsal: End-to-End Mock Data Challenge

Credit: Chaudhary+ (including SM) PNAS 2024



Cumulative distribution of searched areas for simulated BNSs in the MDC

Automated parameter estimation was validated end-to-end in the production system before O4

Mock Data Challenge (MDC)

- 40 days of O3 data replayed in real time, with simulated CBC injections
- End-to-end tests from searches to PE

Initial (BAYESTAR) vs Updated (BILBY) Sky Maps

- Bilby systematically requires **less sky to scan before reaching the true position (searched area).**
- Quoted probabilities are confirmed to be well calibrated – 90% regions contain the true position ~90% of the time.

O4 Example: S230627c

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:

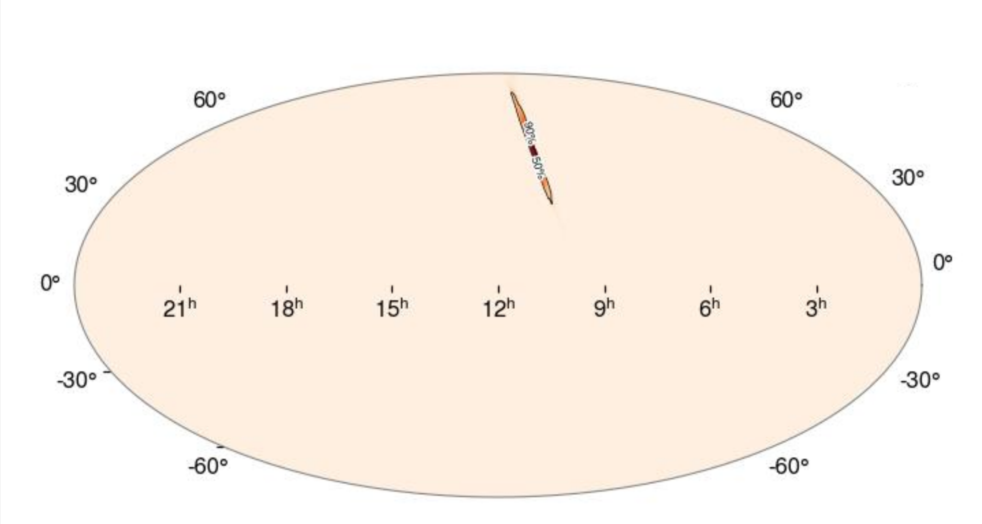
We have conducted further analysis of the LIGO Hanford Observatory (H1) and LIGO Livingston Observatory (L1) data around the time of the compact binary merger (CBC) candidate S230627c (GCN Circular 34086). Parameter estimation has been performed using Bilby [1] and a new sky map, Bilby.multiorder.fits,0,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

https://gcn.nasa.gov/circulars/34087

Estimated masses imply NSBH or BBH.

Automated parameter estimation ran on this event, and updated skymap was sent ~2 hours after detection.

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



Simulation-Based Inference

Train a neural posterior estimator $q_\phi(\theta|d)$ on simulated pairs $(\theta, d) \sim \pi(\theta)\mathcal{L}(d|\theta)$.

- **Amortized inference:** posterior samples in ~seconds per event after offline training
- **Normalizing flow** can represent the complex CBC posteriors.

$$q_\phi(\theta|d) = \mathcal{N}(0,1)^D \left(f_d^{-1}(\theta)\right) \left|\det J_{f_d}^{-1}\right|.$$

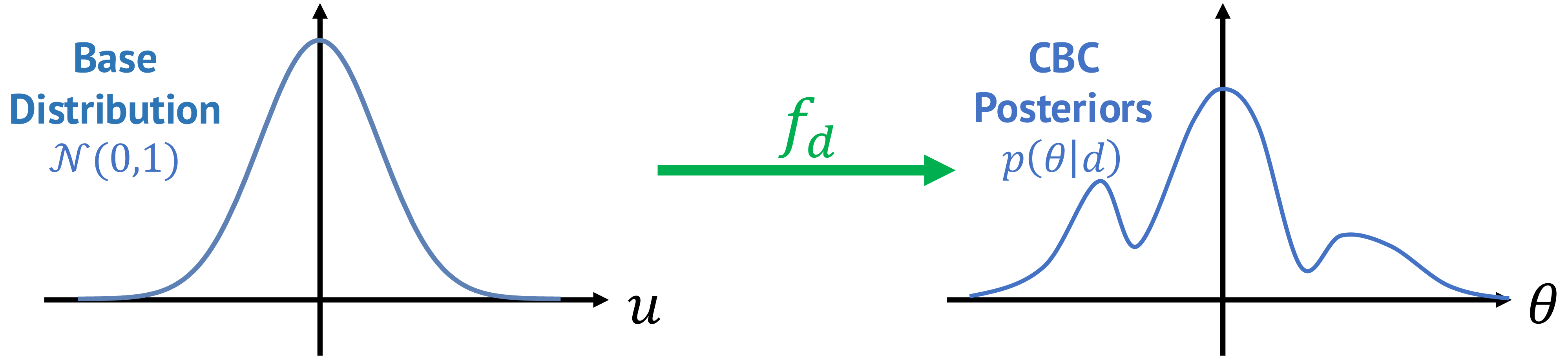


Figure: Schematics of normalizing flow

References: Dax+ PRL 2021; Gabbard+ Nat. Phys. 2022; Bhardwaj+ PRD 2023; Raymond+ MNRAS 2025; Marx+ PRD 2026; Roulet+ PRD 2026.

Data Compression

Credit: Zackay+ 2018

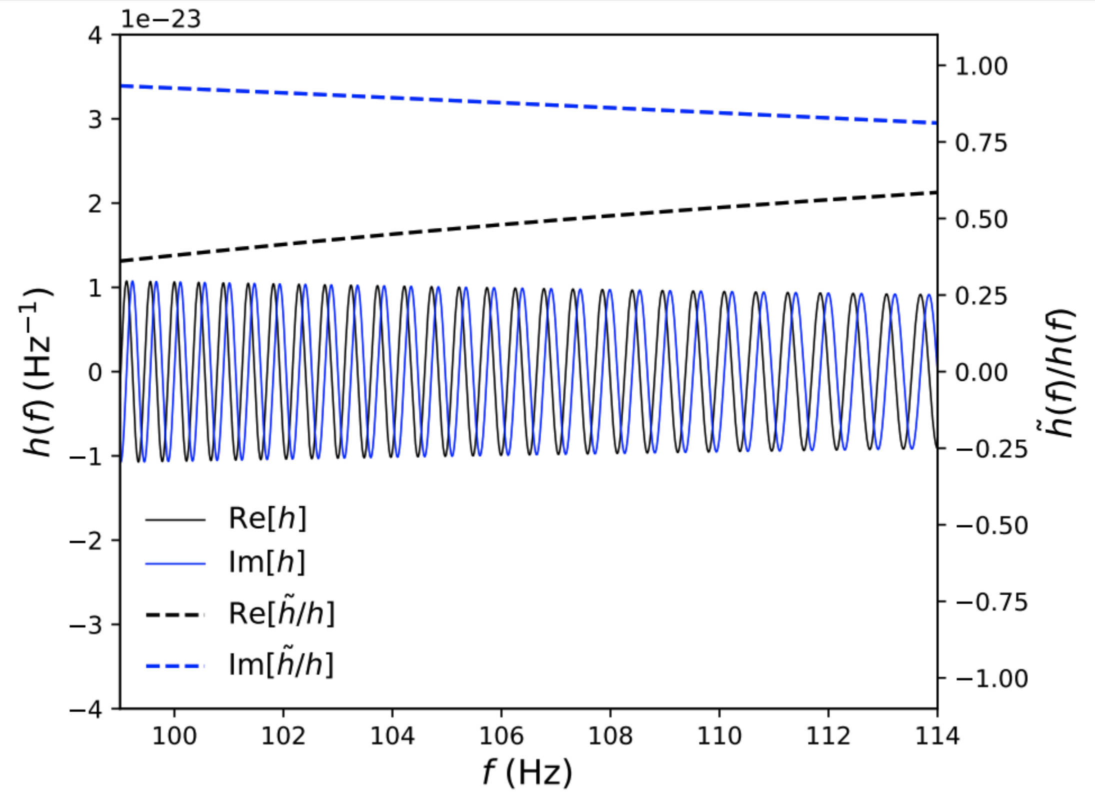


Figure: The original waveform $\tilde{h}(f)$ (rapidly oscillating) and the ratio $\tilde{h}(f)/h(f)$ (smooth)

Are the classical acceleration efforts wasted?
→ **No!**

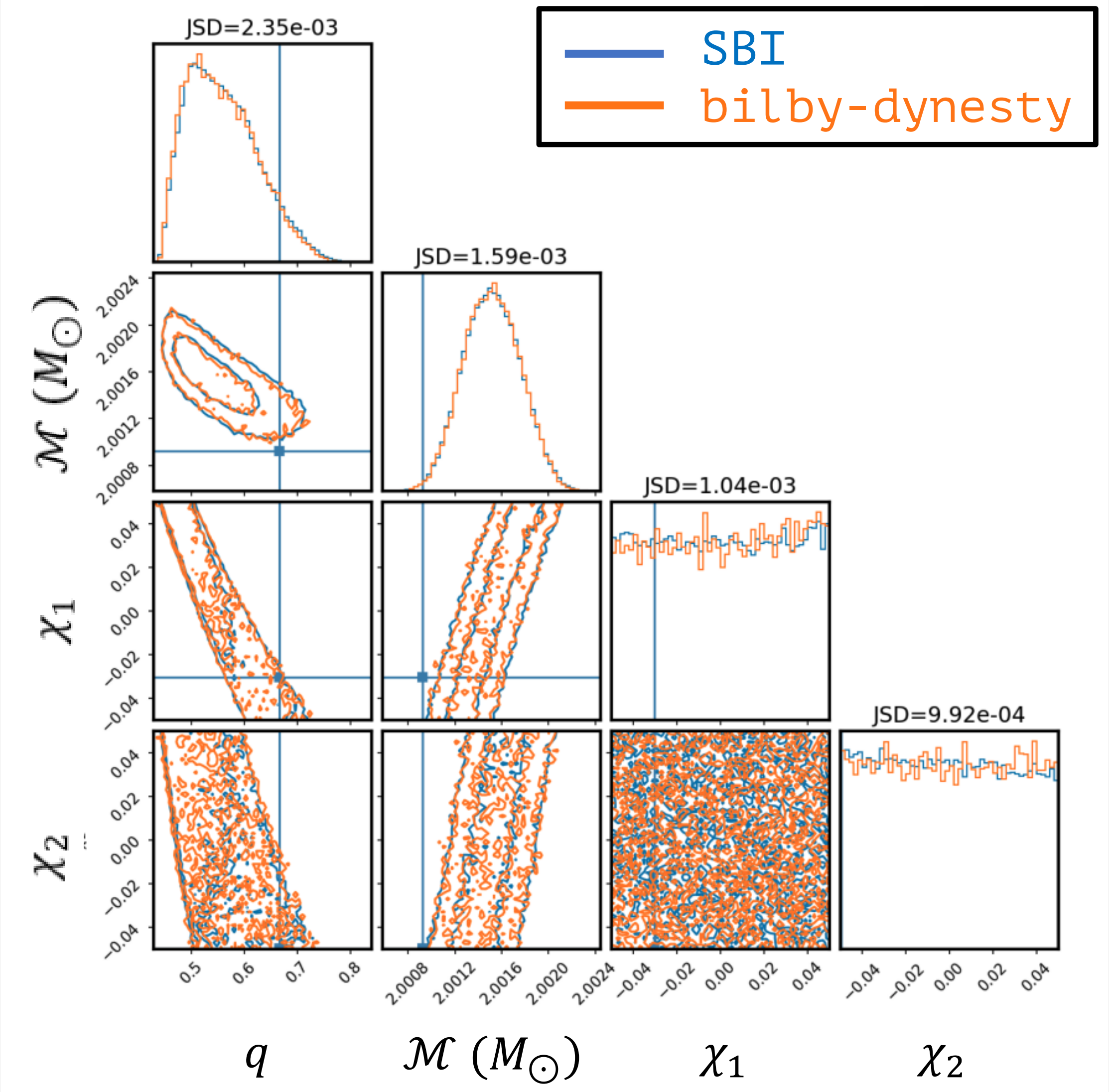
Waveform-acceleration techniques reduce the dimension of training data and simplify its structure [Dax+ Nature 2024; Hu+ ApJL 2025; Roulet+ PRD 2026]

We formulated a method to train **directly on the summary data** of relative binning / heterodyning [Cornish 2010; Zackay+ 2018]

→ Compression factor > 200;
BNS training data generated from only $O(10^3)$ waveform samples.
[Iwaya, Raymond, SM, Takada 2026]

Data Compression

Credit: Iwaya, Raymond, SM, Takada arXiv:2604.22380.



Consistent with the conventional sampling method (`bilby-dynesty`)

- Median JSD $\sim 10^{-3}$ bits for mass ratio & spins
- Median JSD $\gtrsim 10^{-2}$ bits for chirp mass; can be corrected with importance sampling
- Well-calibrated P-P plot over 1024 injections

~10^6 posterior samples in 80 s

Figure: Posteriors from simulation-based inference (SBI, blue) and `bilby-dynesty` (orange)

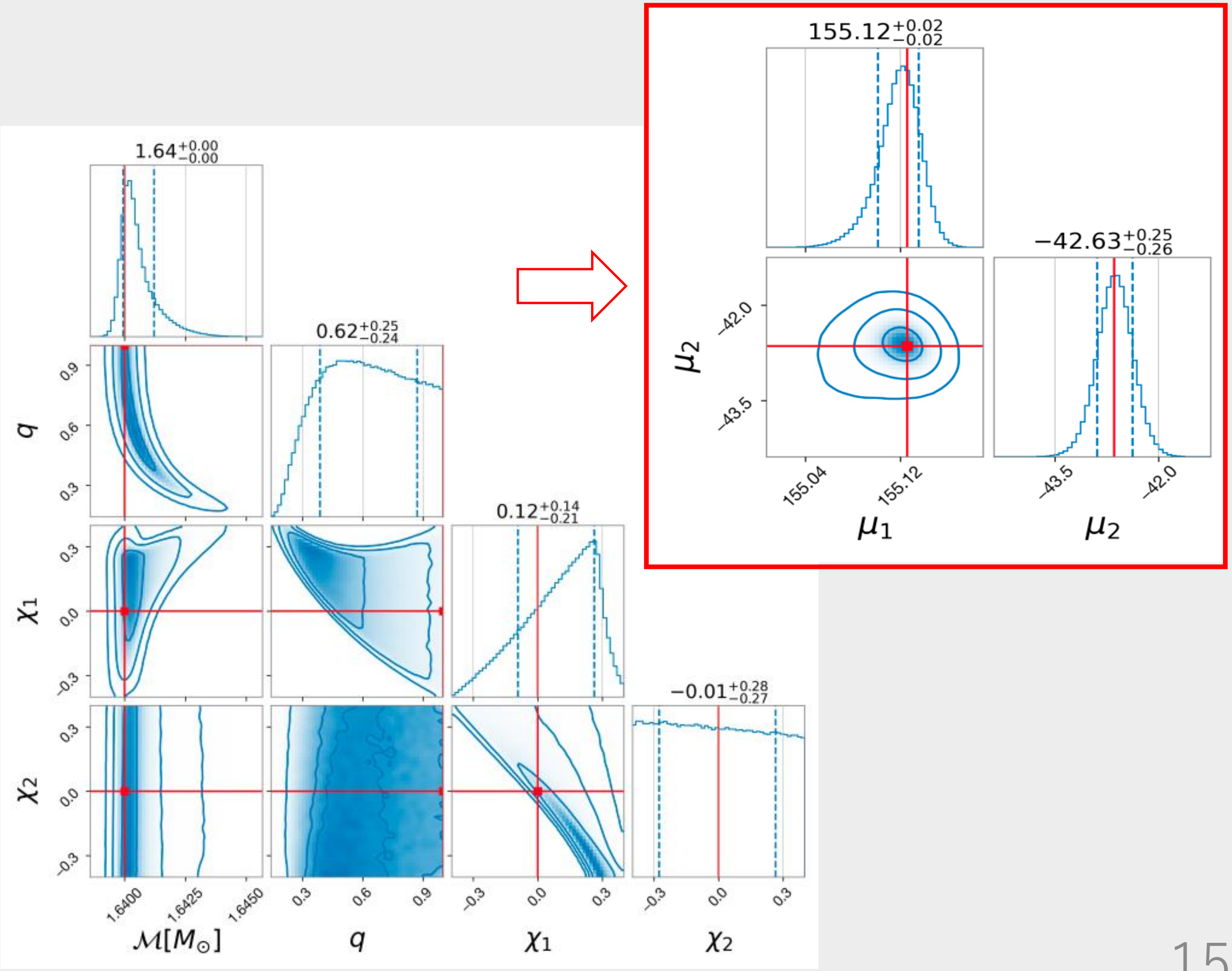
Efficient Parameterization

Move to coordinates where posterior becomes **nearly Gaussian**:

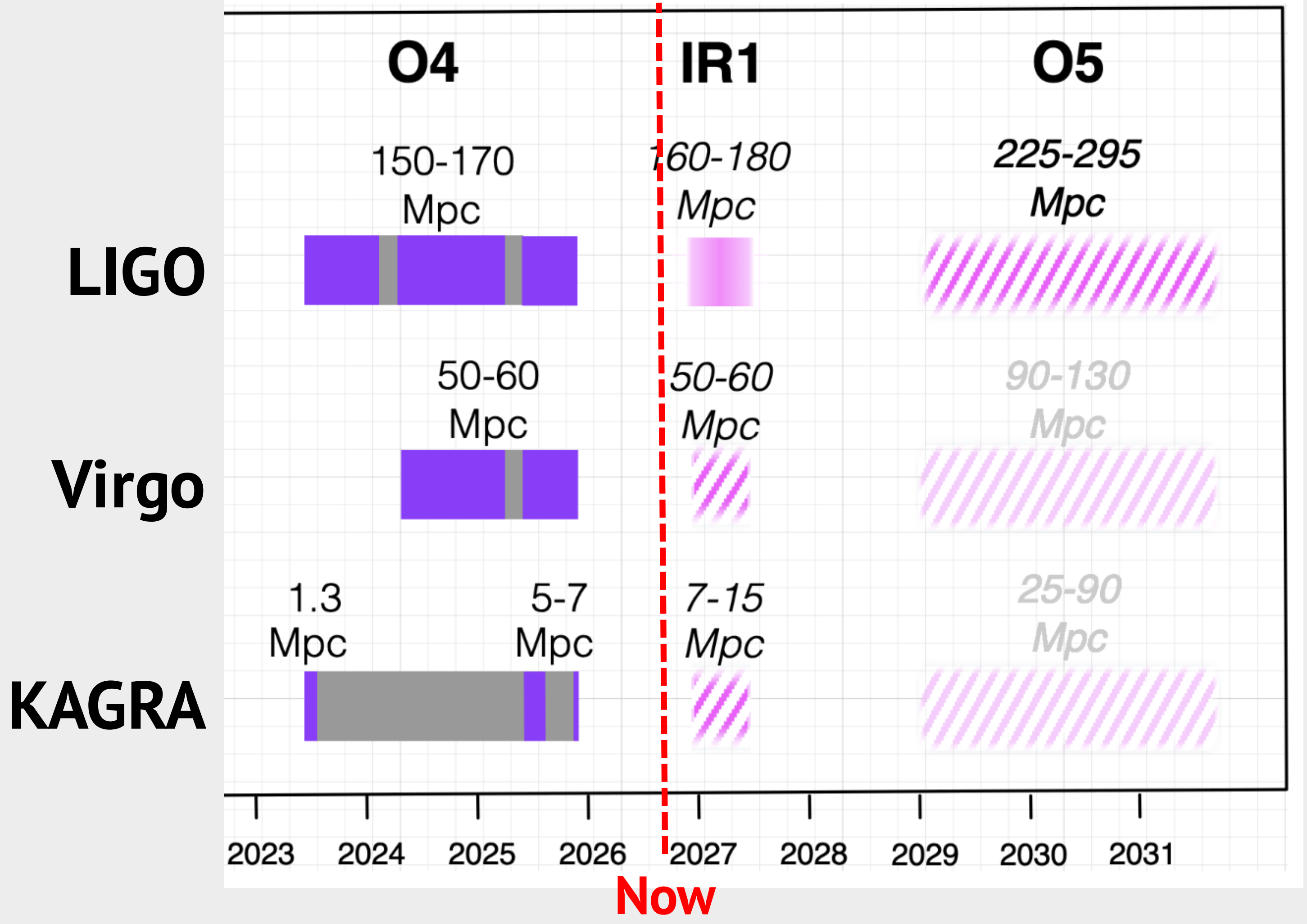
- **Waveform-based parameterization** for masses and spins **[Lee, SM+ PRD 2022]**
- **Well-measured combinations and folding** for extrinsic parameters **[Roulet+ PRD 2022]**

Implemented in `labrador` **[Roulet+ PRD 2026]**

See also *Kazuki Takada's talk* tomorrow!



Future Observations



LIGO-Virgo-KAGRA Observing Plans
(taken from https://observing.docs.ligo.org/plan/)

IR1 will start late Oct – mid Nov 2026

- **LIGO:** Both detectors observing throughout
- **Virgo:** observing with possible interruptions for maintenance & upgrade
- **KAGRA:** joins later in the run – after signal-recycling (DRFPMI) lock & laser power increase (10W → 30W)

O5 timeline being refined.

Multimessenger Prospects for IR1 and O5

	BNS	NSBH	BBH
Public alerts / yr (Rate uncertainty * Poisson uncertainty)			
O4 (HL)	1^{+4}_{-1}	3^{+7}_{-3}	210^{+250}_{-120}
O4 (HLV)	2^{+4}_{-2}	4^{+9}_{-4}	240^{+290}_{-140}
O5a	5^{+9}_{-5}	11^{+17}_{-8}	520^{+620}_{-290}
O5b	10^{+15}_{-8}	21^{+28}_{-14}	760^{+910}_{-420}
O5c	15^{+20}_{-11}	25^{+33}_{-16}	890^{+1060}_{-490}
Median 90% credible area [deg^2] (Monte Carlo uncertainty)			
O4 (HL)	1900^{+520}_{-470}	1860^{+520}_{-340}	2277^{+61}_{-58}
O4 (HLV)	1420^{+310}_{-250}	2150^{+380}_{-310}	1837^{+55}_{-48}
O5a	1260^{+130}_{-280}	1540^{+140}_{-400}	1238^{+27}_{-31}
O5b	1350^{+240}_{-240}	1710^{+170}_{-120}	1472^{+31}_{-32}
O5c	1150^{+240}_{-170}	1320^{+130}_{-190}	1155^{+29}_{-25}

Assumptions

- Simulated populations with GWTC-4 merger rates (BNS: $45^{+53}_{-24}\ \mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$)
- Network SNR > 8; duty cycle 70%

More NS-merger alerts, but with larger localization areas and fainter counterparts.

- Median luminosity distance for BNSs is ~ 300-500 Mpc for O5.

Table: Summary statistics for O4 and O5
(values taken from IGWN Public Alerts User Guide)

Conclusion

- **O4 (May 2023 – Nov 2025):** 254 significant alerts, preliminary alerts within ~30 s of merger.
  - Interesting events for multi-messenger astronomy, but **no confirmed EM/neutrino counterparts.**

- **Parameter estimation updates dramatically accelerated with Bilby + ROQ:**
  ~10 min (BNS) / ~1 hour (NSBH); validated end-to-end with O3 replay MDC

- **Toward parameter estimation updates within ~seconds:**
  amortized machine-learning inference + classical acceleration techniques

- **IR1 starts late Oct – mid Nov 2026**; O5 will bring several times more NS-merger alerts at ~300–500 Mpc.

Implications of Low BNS Rates

Credit: Fishbach+ ApJL 2026