Rapid Parameter Estimation Using Reduced Order Quadrature

10th KAGRA International Workshop (KIW-10)

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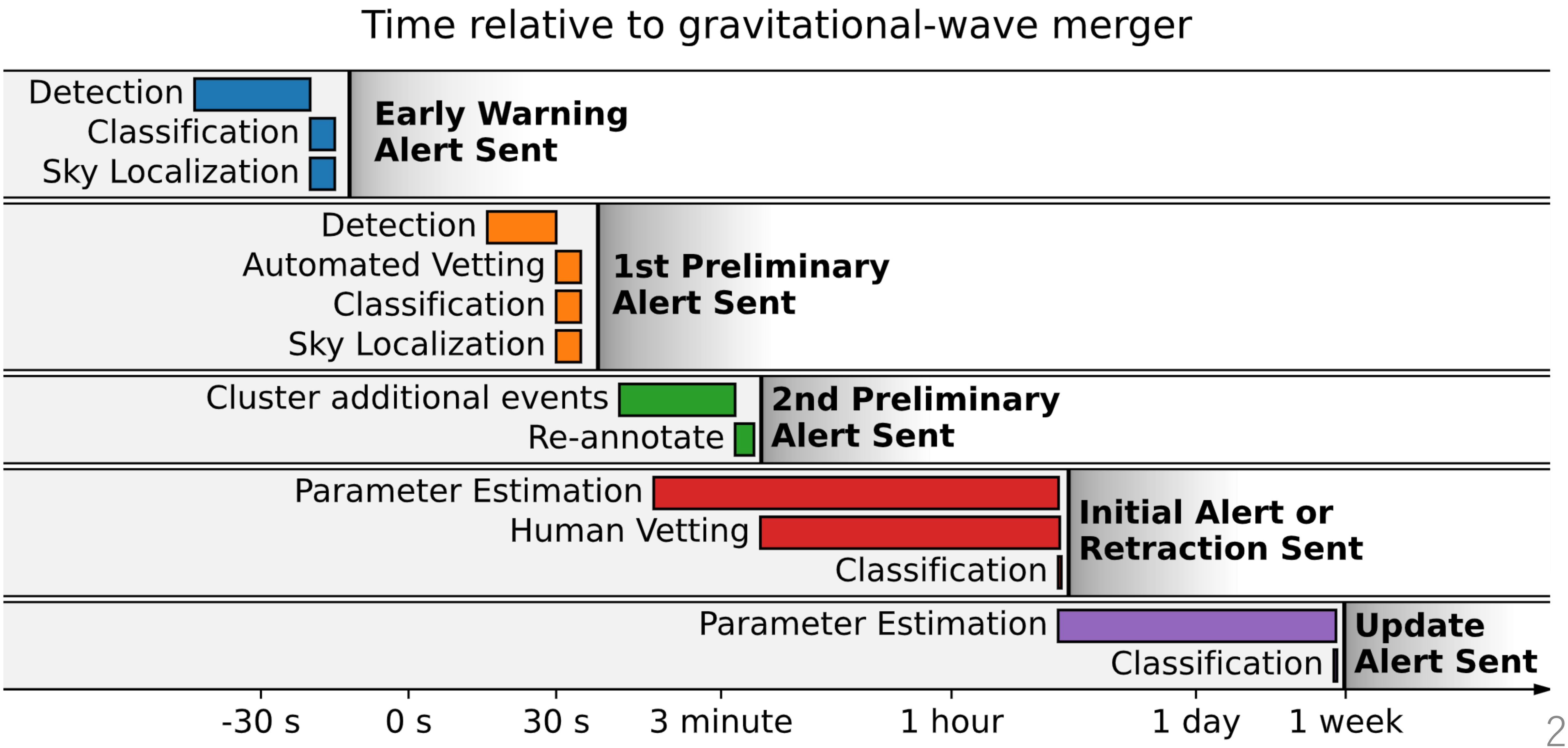
Low-latency alert in O4

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



Low-latency alert in O4

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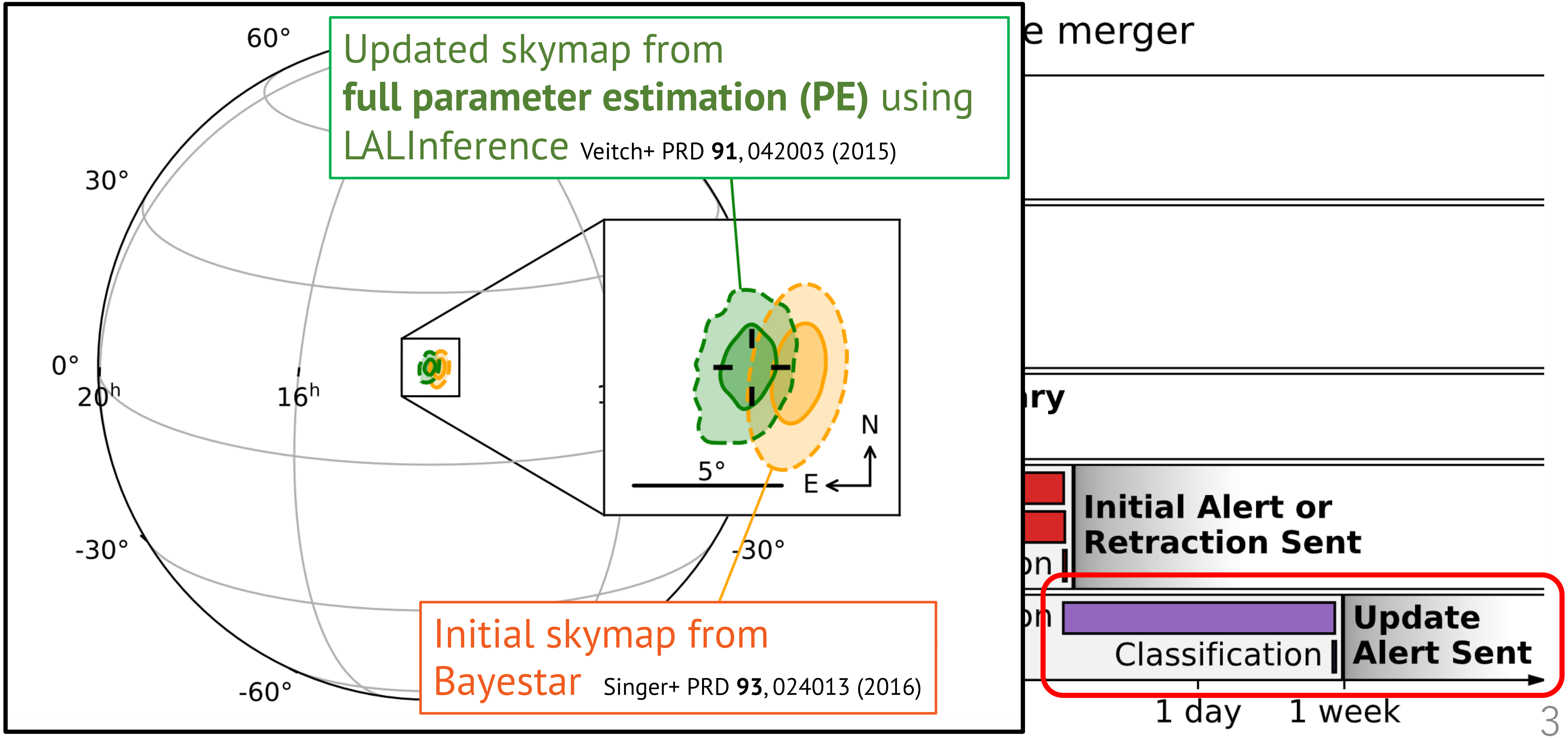
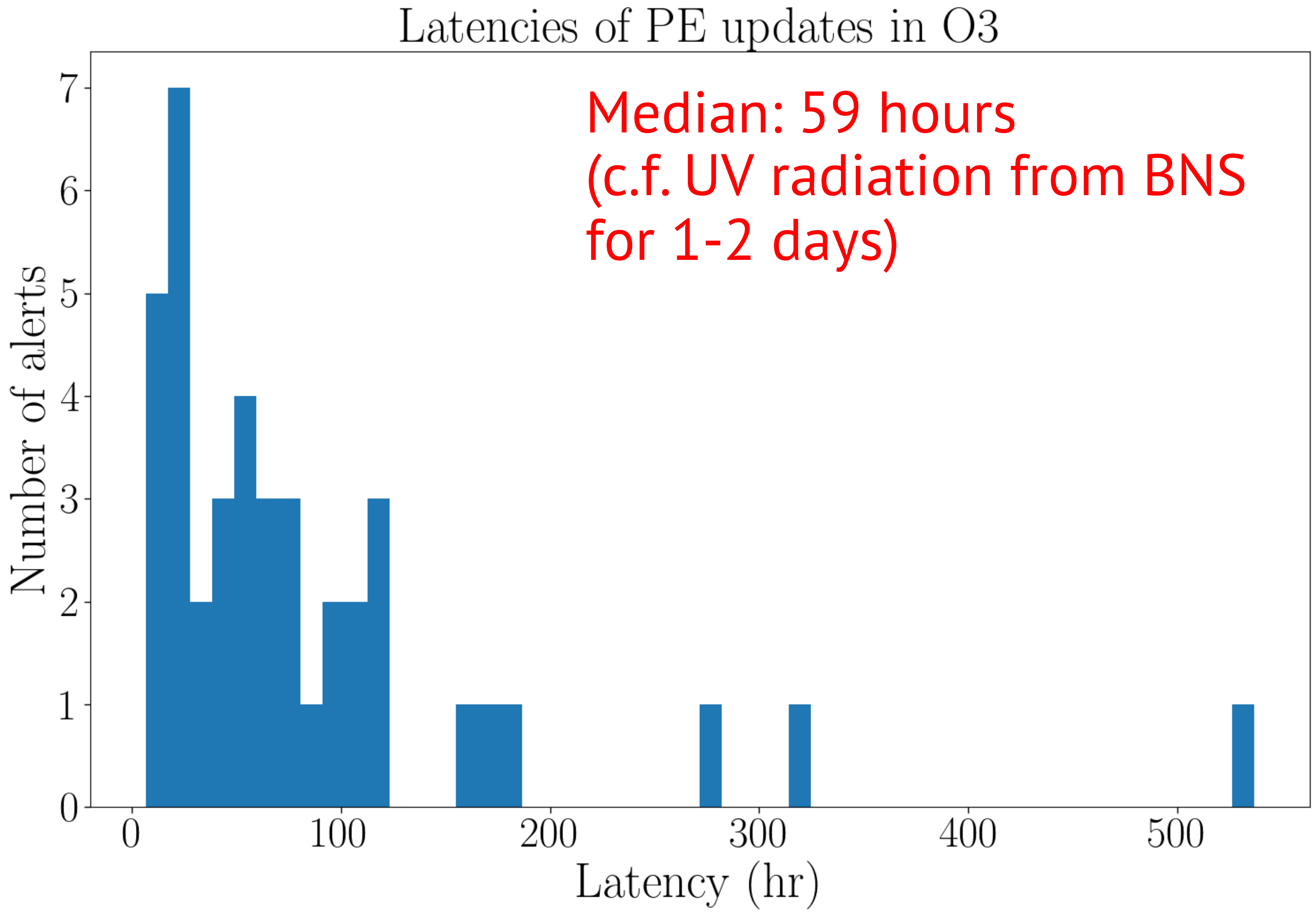


PE latency in O3



Reduced Order Quadrature (ROQ)

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

- PE requires more than millions of waveform generation.
- Its cost is proportional to L, the number of frequency points $\{f_l\}_{l=1}^{L}$.
- Interpolate waveform values at $K \ll L$ interpolation nodes $\{F_k\}_{k=1}^{K}$,

$$\tilde{h}(f_l) \simeq \sum_{k=1}^{K} \tilde{h}(F_k) \underline{B_k(f_l)}. \quad (l = 1,2,\dots,L)$$

ROQ basis

→ Speed-up by L/K

Optimizing ROQ for O4

- Significant speed-up if bases are constructed for targeted mass-spin space.

  See **SM** and Vivien Raymond, Phys. Rev. D **102**, 104020 (2020).

  → Use multiple ROQ bases, each constructed for targeted chirp-mass range.

- Adaptive frequency resolution to speed up pre-computation of ROQ weights.

$$\langle d, h \rangle = \frac{4}{T} \sum_{l=1}^{L} \frac{\tilde{d}^*(f_l)\tilde{h}(f_l)}{S(f_l)} = \sum_{k=1}^{K} \tilde{h}(F_k)\omega_k, \qquad \omega_k \equiv \frac{4}{T} \sum_{l=1}^{L} \frac{\tilde{d}^*(f_l)B_k(f_l)}{S(f_l)}.$$

See **SM**, Phys. Rev. D **104**, 044062 (2021).

Those improvements were implemented in **Bilby**, one of the LVK PE libraries.

Ashton+ ApJS **241** 27 (2019),
Romero-Shaw+ MNRAS **499** 3 (2020).

ROQ bases for low-latency PE of BNS

- Waveform model: **IMRPhenomD** Husa+ PRD **93**, 044006 (2016), Khan+ PRD **93**, 044007 (2016).
- Frequency range: $20\text{Hz} < f < 1024\text{Hz}$
- Parameter range
  - Chirp mass: $0.6M_{\odot} < \mathcal{M} < 4M_{\odot}$
  - Mass ratio: $Q \equiv m_1/m_2 < 8$
  - Spins: $\mathbf{a_1}, \mathbf{a_2} < \mathbf{0.05}$ **(based on BNS observations)**
- Trained against calibration errors of $< 20\%$ in amplitude and $< 15\text{deg}$ in phase.
- Speed-up gain: **400 - 3500**
- Run time: ~7min for SNR~25

ROQ bases for NSBH and BBH

Both cover **mass ratio up to 20** and **spin magnitude up to 0.99**.

<u>NSBH</u>

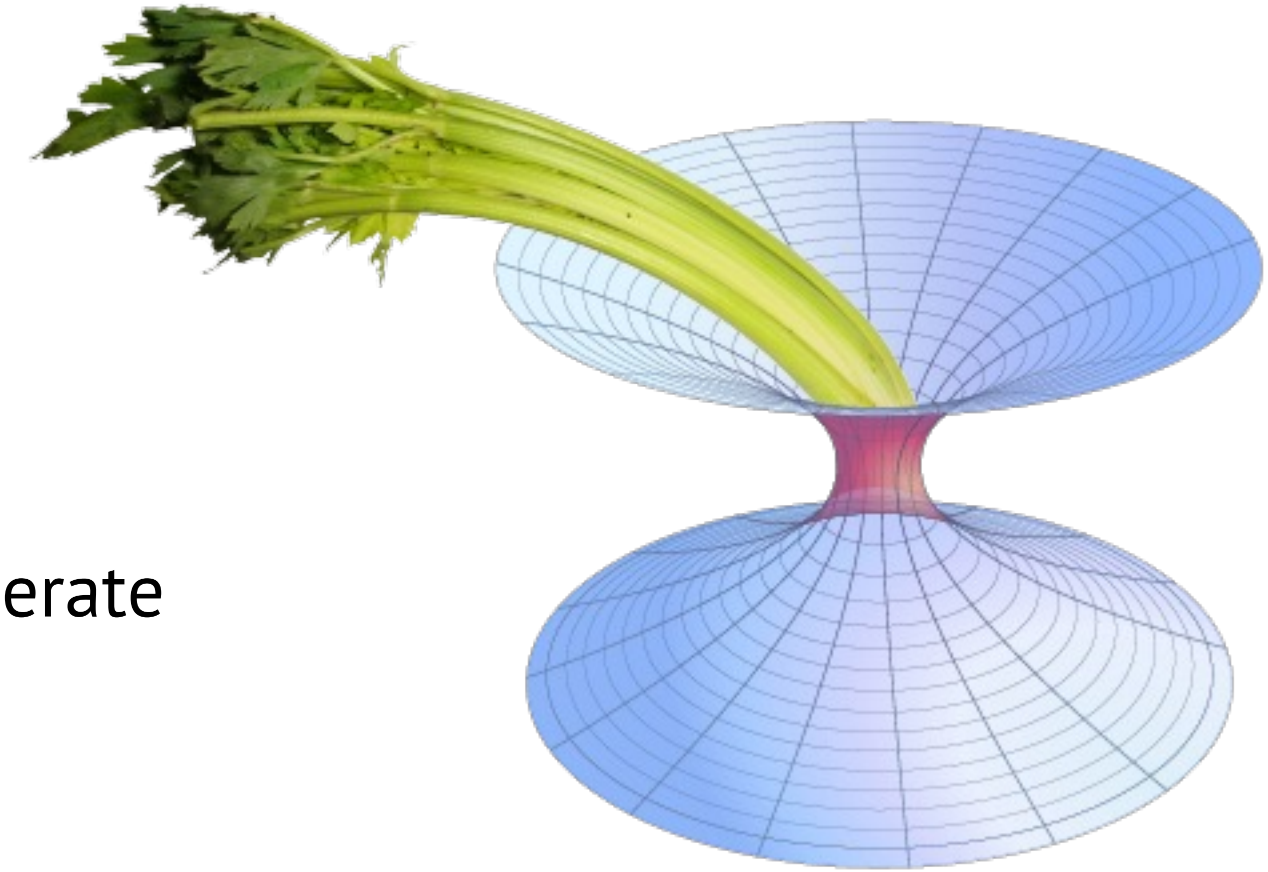
- Waveform model: **IMRPhenomPv2** Hannam+ PRL **113**, 151101 (2014)
- Chirp-mass range: $1.4M_{\odot} < \mathcal{M} < 21M_{\odot}$
- Run time: ~3 hours for SNR~20

<u>BBH</u>

- Waveform model: **IMRPhenomXPHM** Pratten+ PRD **103**, 104056 (2021)
- Chirp-mass range: $10M_{\odot} < \mathcal{M} < 200M_{\odot}$
- Run time: ~4 hours for SNR~30

Automation with GWCelery https://git.ligo.org/emfollow/gwcelery

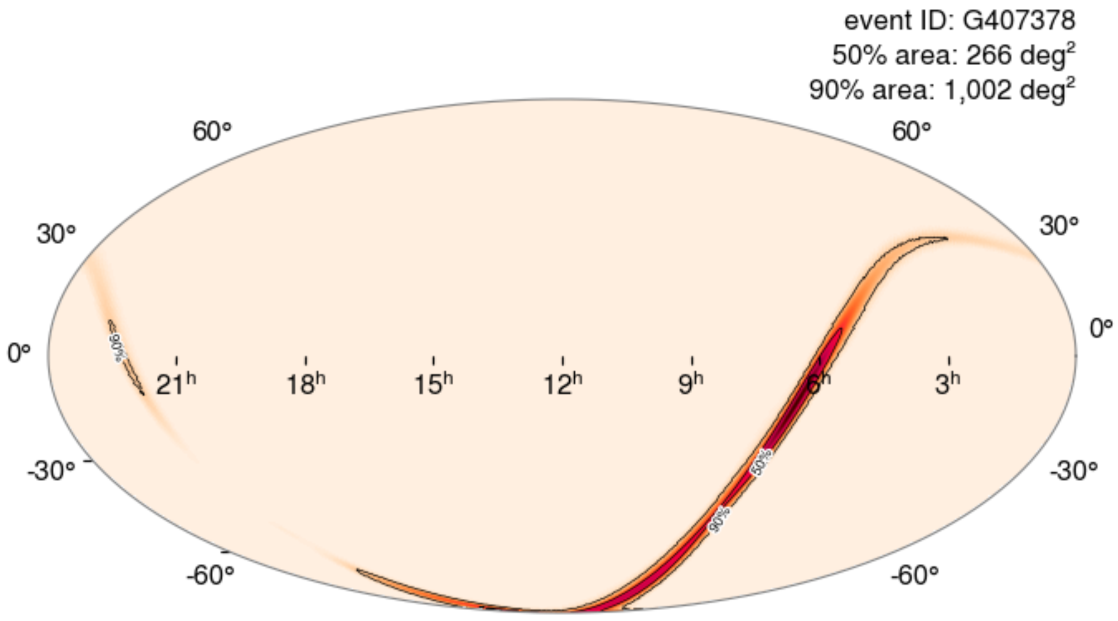
Parameter estimation is automated by **GWCelery**, the LIGO-Virgo-KAGRA alert pipeline.



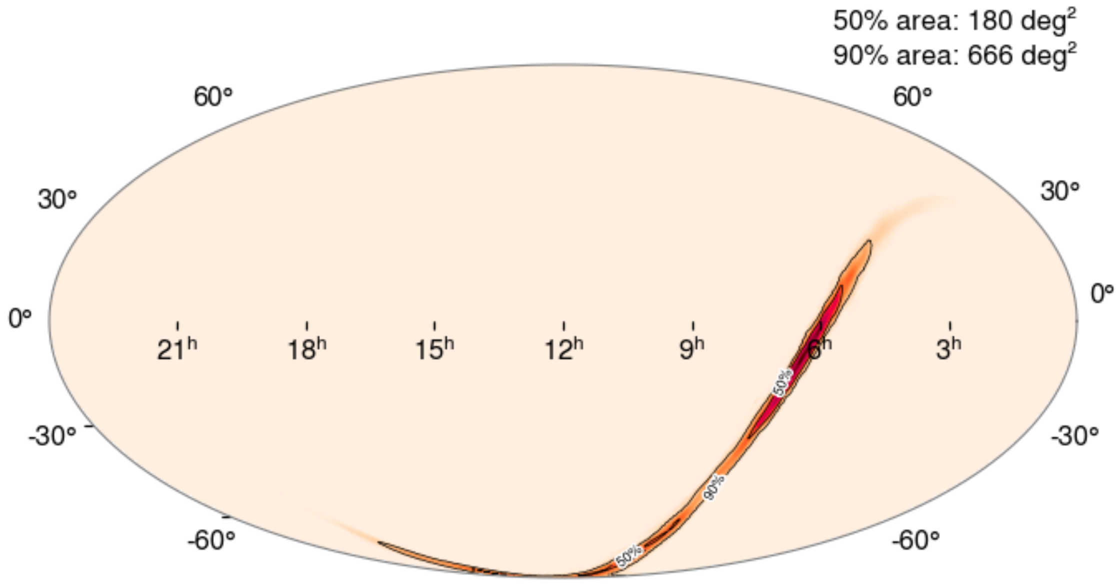
- Submit and monitor PE jobs automatically.
- Postprocess PE results to generate skymap and EM-bright probs.

S230518h

The updated skymap was sent in ~4 hours after the detection, reducing 90% area from $1002 deg^2$ to $666 deg^2$ (See GCN circular 33816).



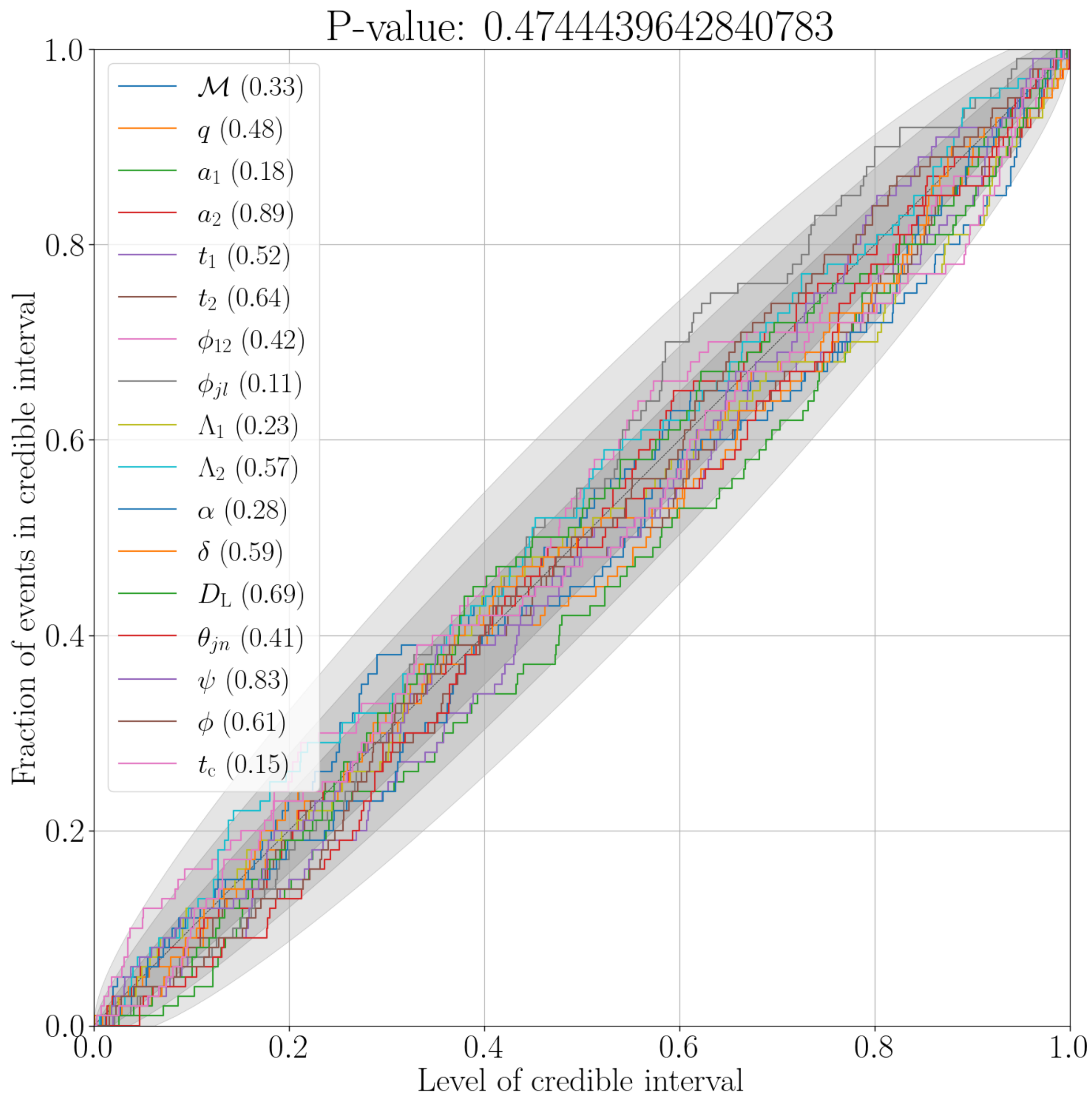
Bayestar skymap



Bilby skymap

ROQ bases for BNS incorporating tides

- Waveform model: **IMRPhenomPv2_NRTidalv2**
  Dietrich+ PRD 100, 044003 (2019)
- Parameter range
  - Chirp mass: $0.6M_{\odot} < \mathcal{M} < 4M_{\odot}$
  - Mass ratio: $Q \equiv m_1/m_2 < 8$
  - **Spins: $\mathbf{a_1, a_2 < 0.99}$**
  - **Tides: $\boldsymbol{\Lambda_1, \Lambda_2 < 5000}$**
- Trained against calibration uncertainties.
- Enable sampler tests within a few hours.



Summary

- Optimization to reduced order quadrature (ROQ) for O4
  - Multiple ROQ bases in a single parameter estimation (PE) run
  - Adaptive frequency resolution to speed up pre-computation

- Improved ROQ enables rapid (minutes-hours) updates of skymap in O4.

- Can be applied to test sampler for more detailed PE.