# Realtime pre-merger localization of BNS in 3G GW detectors

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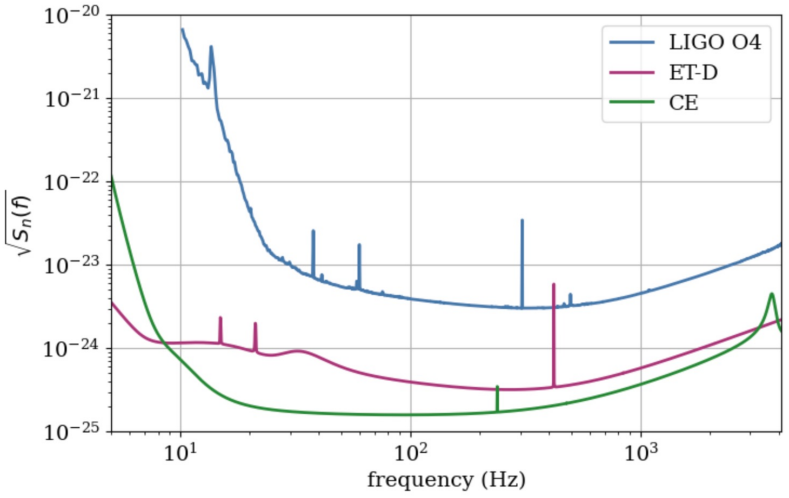
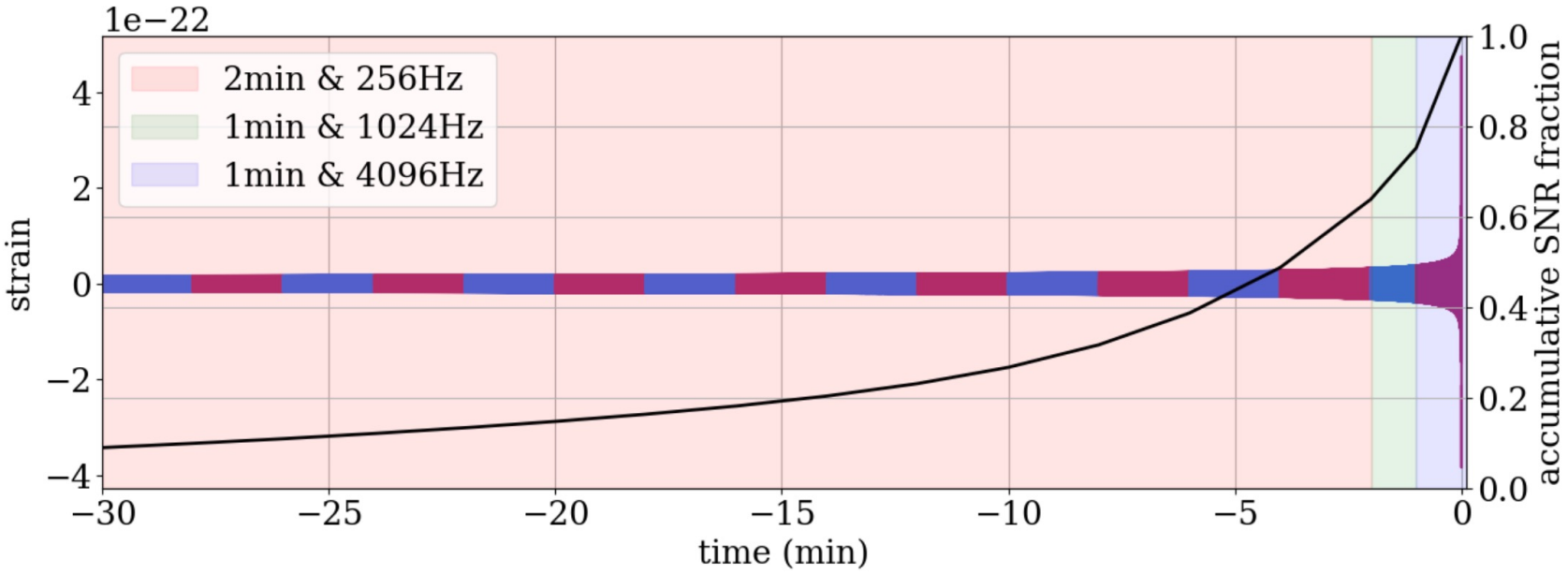
# Early warning detection

- 3G detector network can detect and localize BNS ~30min before merger (Nitz+ 2021 ApJL) -> EM observations-> nucleosynthesis, ejecta, remanent,…
- Long signal issues: matched filtering speed, antenna response change, …
  - Chop waveforms to segments for matched filtering (Cannon+ 2012 ApJ)



# SealGW

SEmi-Analytical Localization for Gravitational Waves, PRD 104, 104008 (2021)

- Bayesian posterior for extrinsic parameters:

nuisance parameters

$$p(\vartheta \mid \mathbf{d}) \propto p(\mathbf{d} \mid \vartheta) p(\vartheta), \qquad \vartheta = \{\alpha, \delta, t_c, r, \iota, \phi_c, \psi\}$$

- Bayestar (Singer+ 2016): five-fold numerical integral over nuisance parameters
- SealGW: parameter conversion + analytical integral

$$h^{(i)} = (G_+^{(i)}, G_\times^{(i)})\mathbf{A_c} h_c + (G_+^{(i)}, G_\times^{(i)})\mathbf{A_s} h_s,$$

$$\mathbf{A} = \begin{pmatrix} \mathbf{A_c} & \mathbf{A_s} \end{pmatrix} = \begin{pmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{pmatrix}$$

$$= \frac{1\mathrm{Mpc}}{r} \begin{pmatrix} \cos 2\psi & \sin 2\psi \\ -\sin 2\psi & \cos 2\psi \end{pmatrix} \begin{pmatrix} \frac{1+\cos^2 \iota}{2} & \\ & \cos \iota \end{pmatrix} \begin{pmatrix} \cos \phi_c & \sin \phi_c \\ -\sin \phi_c & \cos \phi_c. \end{pmatrix}$$

numerical marginalized

analytical integrable

$$\vartheta = \{\alpha, \delta, t_c, r, \iota, \phi_c, \psi\} \xrightarrow{A_{ij} = A_{ij}(r, \iota, \phi_c, \psi)} \vartheta = \{\alpha, \delta, t_c, A_{11}, A_{12}, A_{21}, A_{22}\}$$

- SealGW has been implemented into SPIIR pipeline: https://git.ligo.org/spiir-group/SealGW

# Combination of segments

- Measurements from different segments should be combined
- Combining SNR timeseries directly? – phase drift due to the earth rotation

$$\rho(t) = \frac{1}{\sigma}\left[(h_c \mid d) + i(h_s \mid d)\right] \qquad \phi_0 = \arctan\left(\frac{F_\times \cdot (2\cos\iota)}{F_+ \cdot \left(1+\cos^2\iota\right)}\right) - \phi_c.$$

- Combining likelihood
  - Segments have little overlap -> independent measurements
  - Multiplying likelihood from different time segments:

$$p(\alpha, \delta|d) = \int dt_c \int \boldsymbol{d^4A}\ p(\boldsymbol{A}) \prod_{i=0}^{N_{seg}} \mathcal{L}_i\left(\alpha, \delta, t_c, \boldsymbol{A}\right)$$

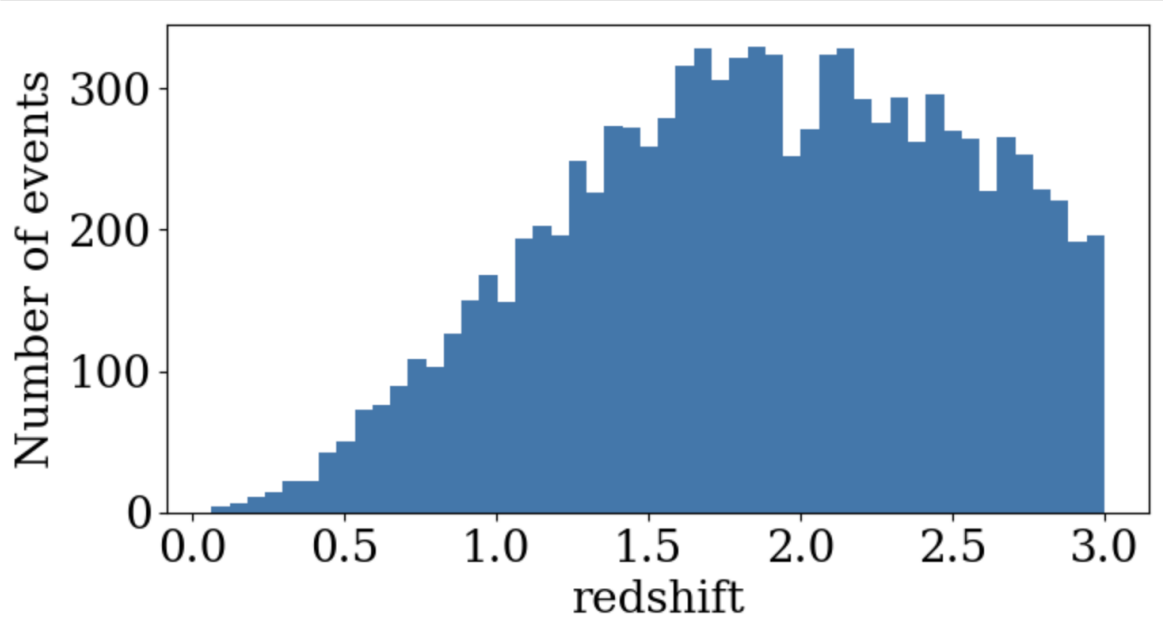
analytical integral; combined likelihood; numerical integral; prior

  - Can be seen as different detectors at different frequency bands

# Catalog study

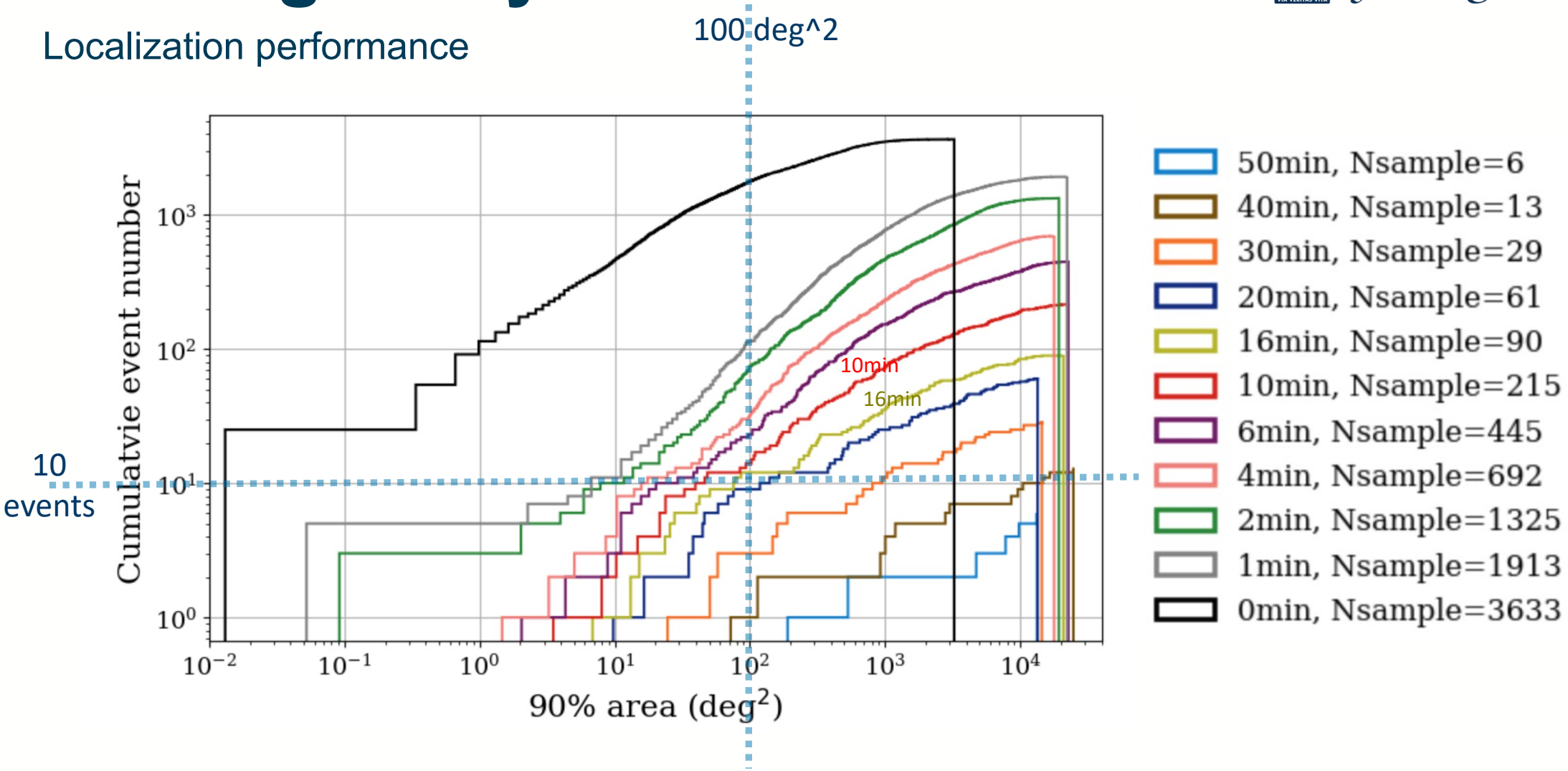
Catalog simulation & detection

- Detector network: ET at Italy + CE at Hanford + CE at Livingston
- Source:
  - BNS, component mass 1.1-2 Msun, zero spin
  - Within 16Gpc (z~2), astrophysical distribution (Oguri 2018 MNRAS)
  - Isotropic distribution in the sky, isotropic inclination
  - 14200 sources (~ 10 days)
- Detection criterion: accumulative SNR > 12. ~3600 are detected



# Catalog study

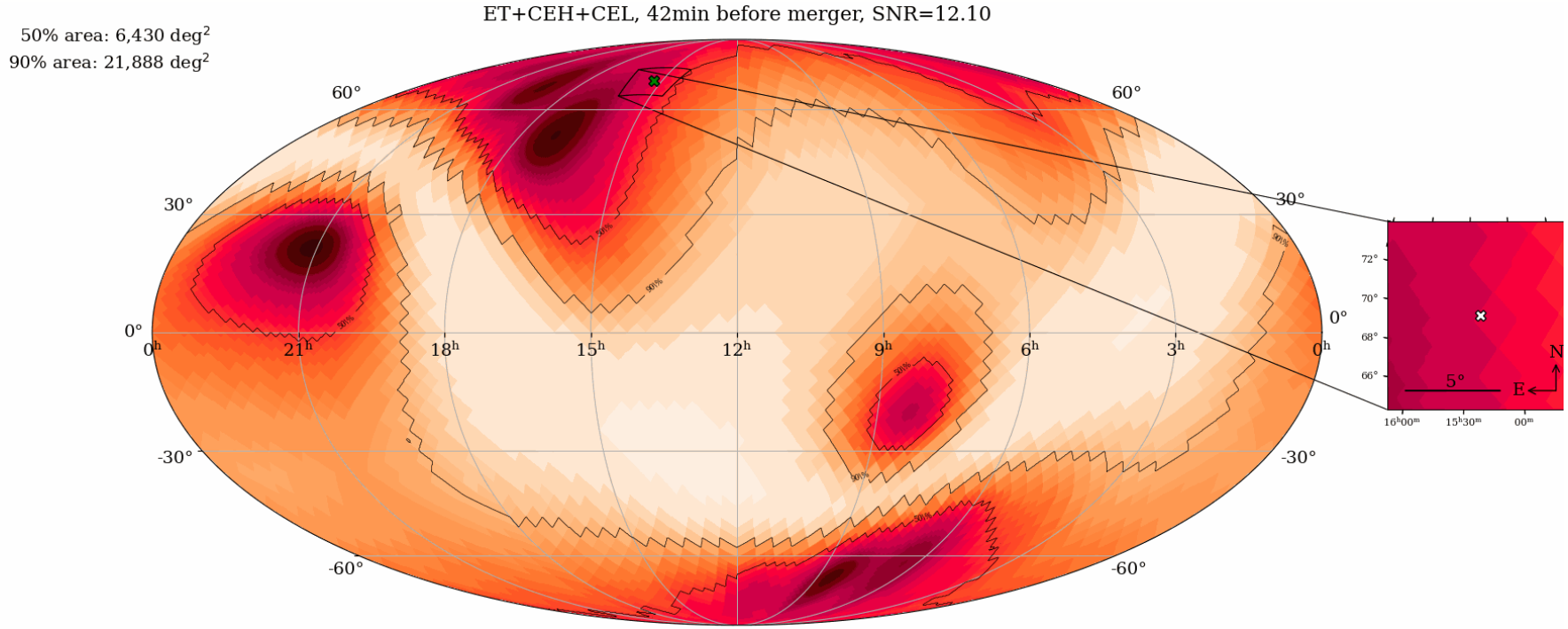
Localization performance

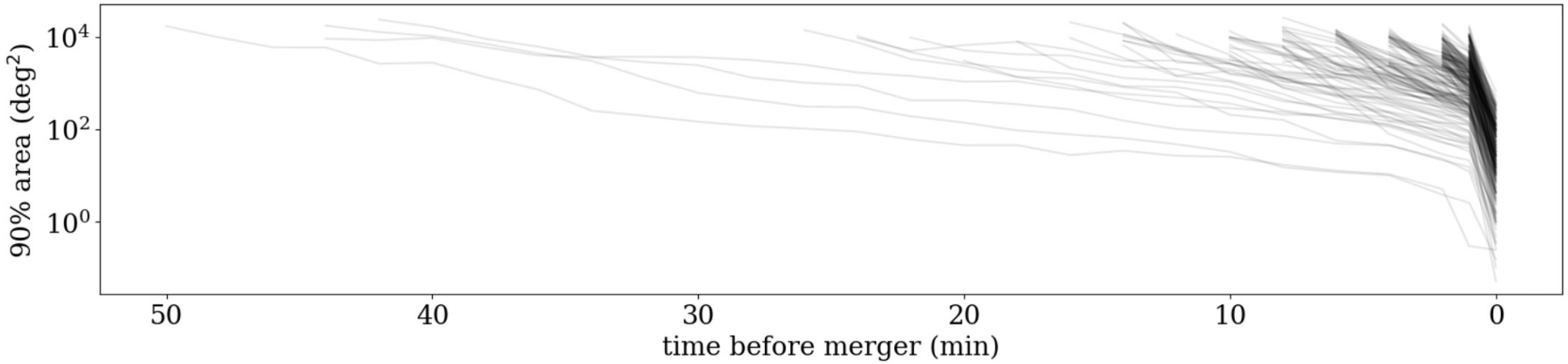



- ~1-10 well-localized early warning BNS 10 days, ~10 minutes before merger (dependent on astrophysical population and detector sensitivity)

# Catalog study

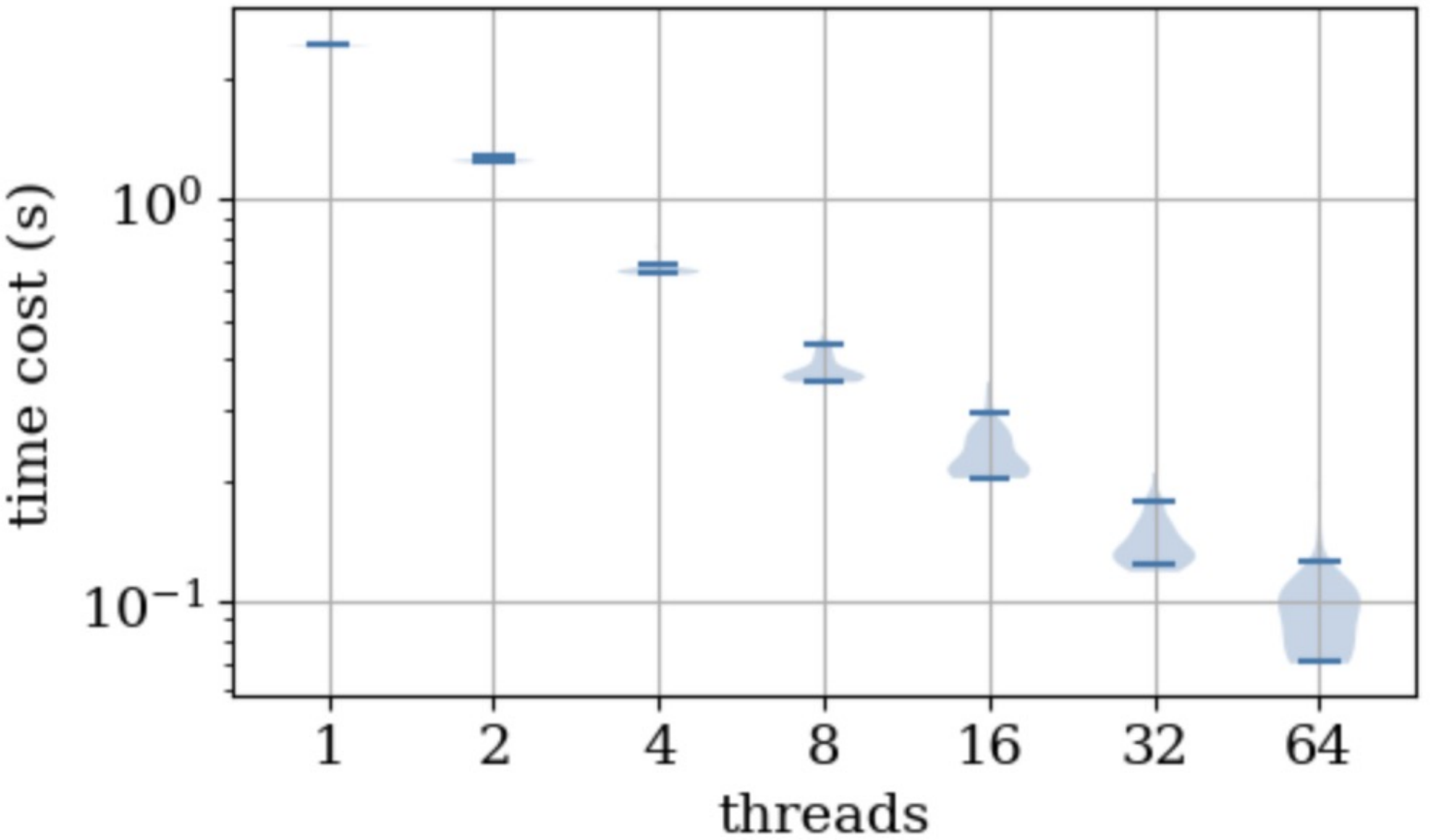
## Skymap evolution



# Time cost

- Time costs of skymap calculation (doesn't include data conditioning)
- Tested on AMD EPYC 7763 (2.44 GHz)
- 4 threads ~ 0.5s; 32 threads ~ 0.1s (~30x faster than Bayestar)
- Efficient and cheap for large amount of detections



# Summary

- SealGW: SEmi-Analytical Localization for Gravitational Waves
  - https://github.com/MarinerQ/SealGW, https://git.ligo.org/spiir-group/SealGW
  - arXiv:2110.01874, PRD 104, 104008 (2021)
- Long signal detection: matched filtering for waveform segments
- Long signal localization: multiplying likelihoods
- A demonstration of fast and accurate early warning localization based on SealGW:
  - 1~10 well-localized early warning BNS every 10 days, ~10 minutes before merger
  - 4 threads ~ 0.5s, capable of processing large amount of events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