Data analysis for next-generation gravitational-wave detectors

2026 Science Fair

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23 February 2026

GRAN SASSO SCIENCE INSTITUTE
SCHOOL OF ADVANCED STUDIES
Scuola Universitaria Superiore

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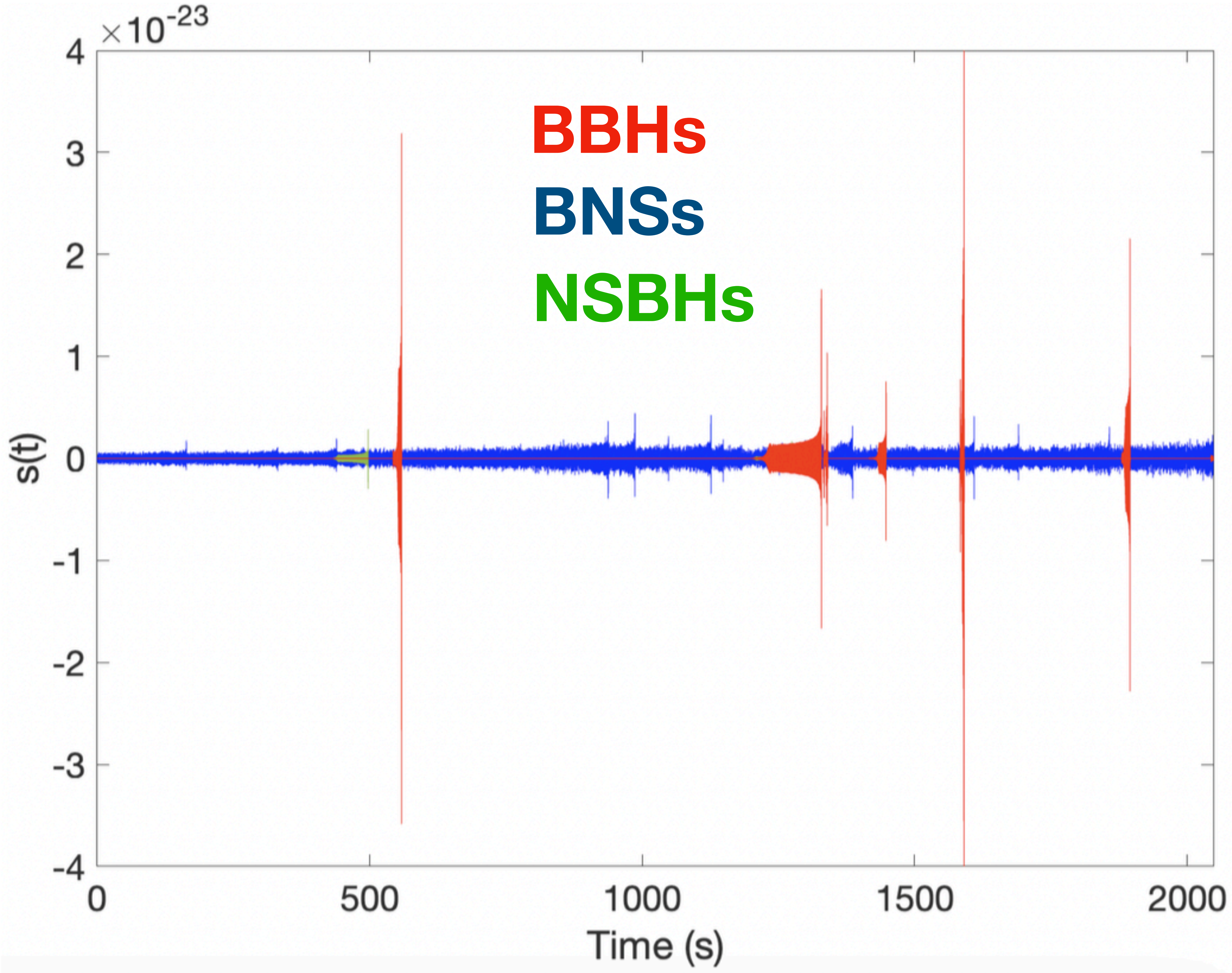
Next-generation challenges



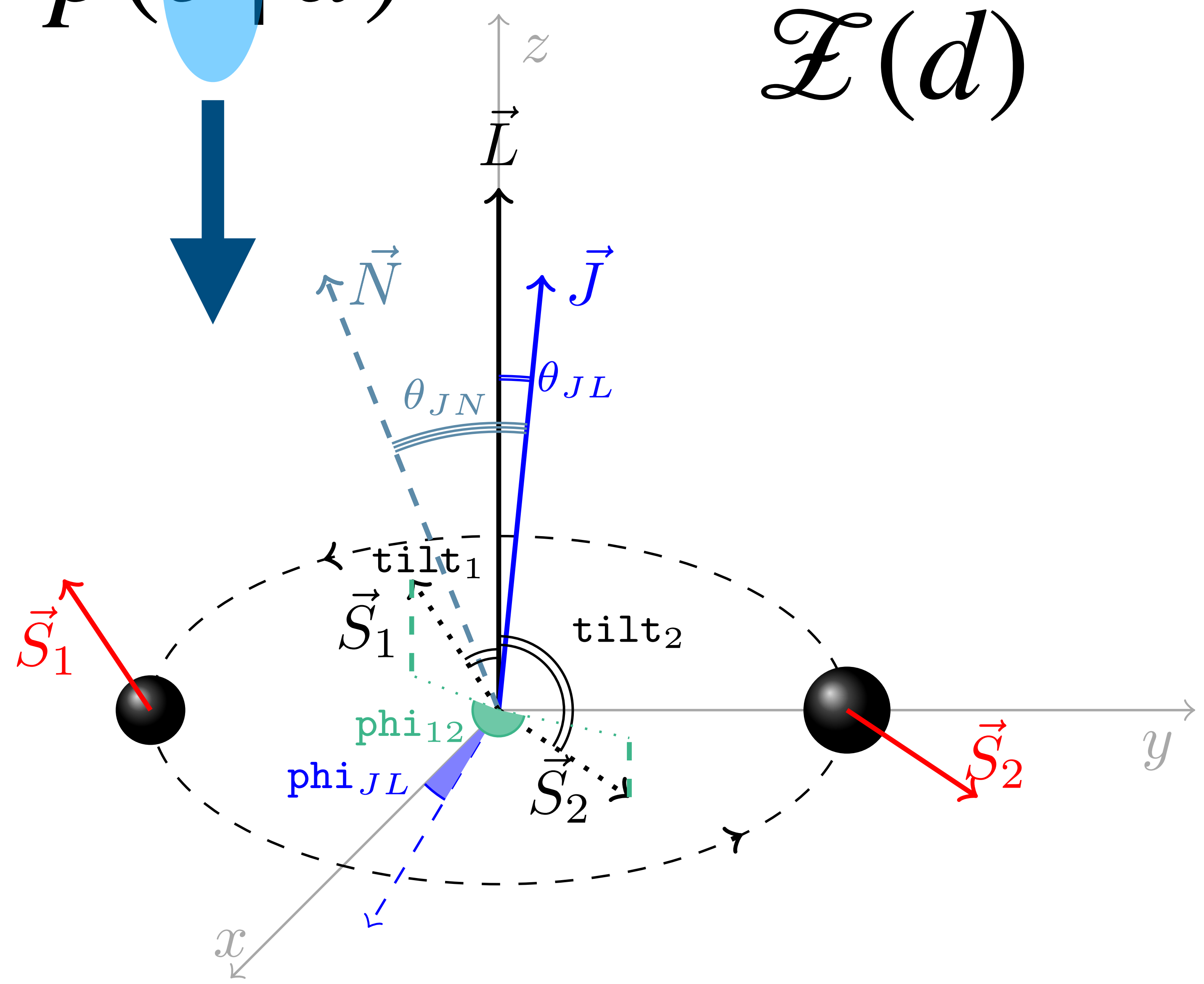
From a data-analysis perspective, **specific problems for ET** include:

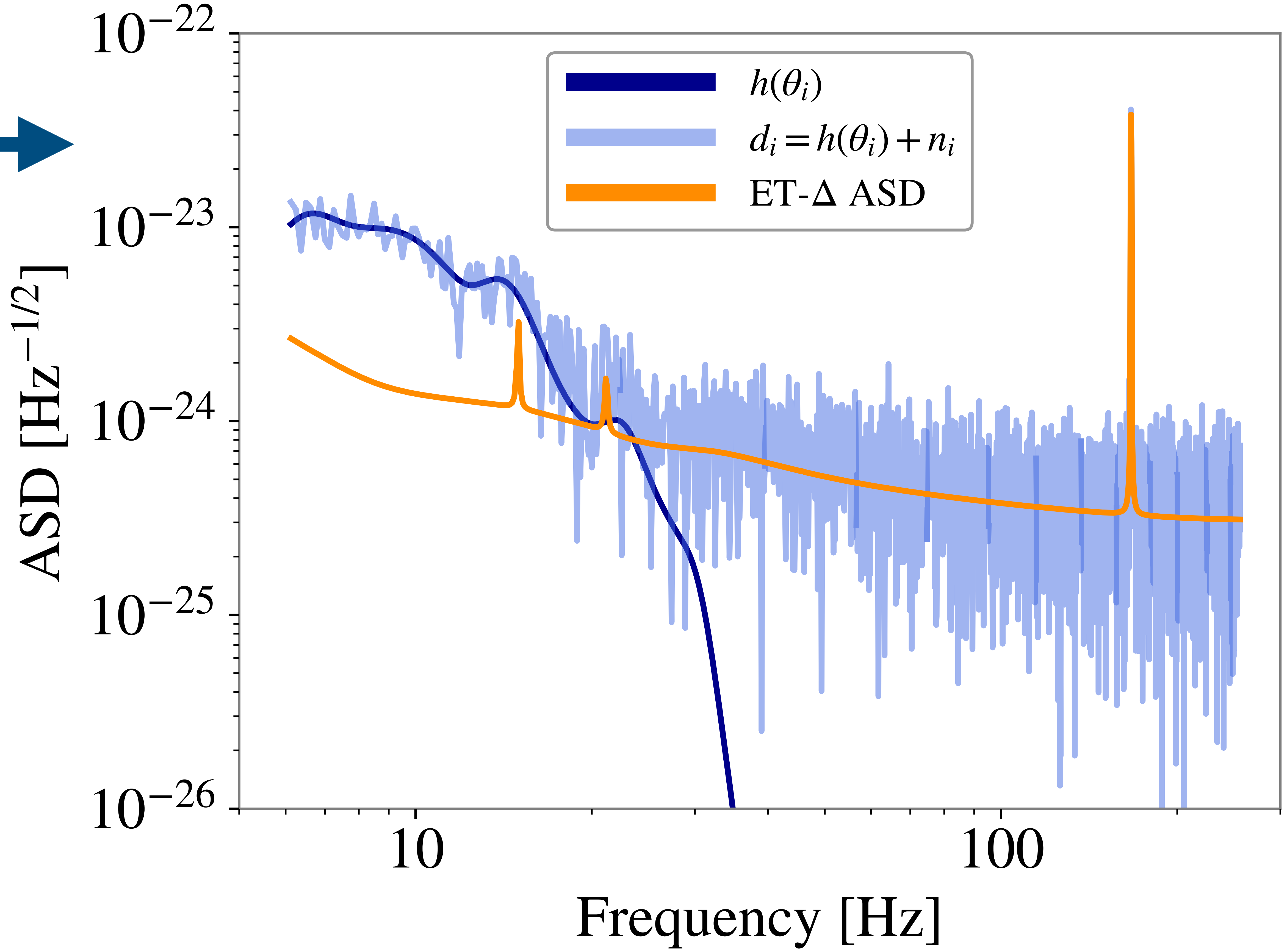
- **long signals** from the increase in frequency bandwidth
- the presence of a **very large number** 10^5 **of signals** per year within the sensitivity band
- **Overlapping signals** in the detector's band

Credits: Mock Data Challenge

Parameter estimation

$$p(\theta \mid d) = \frac{\mathcal{L}(d \mid \theta)\pi(\theta)}{\mathcal{Z}(d)}$$





$$\theta = \{\mathcal{M}_\mathrm{d},\, q,\, d_\mathrm{L},\, \mathrm{ra},\, \mathrm{dec},\, \theta_\mathrm{JN},\, \psi,\, \phi,\, t_\mathrm{geocent},\, \chi_1,\, \chi_2\}$$

Ref. Thrane et al. 2019, Christensen et al. 2022, Dupletsa et al. 2025

Likelihood-free inference

Sampling parameters θ from the prior $\theta \sim \pi(\theta)$ and **generating data** $d = h(\theta) + n$ is **fast**

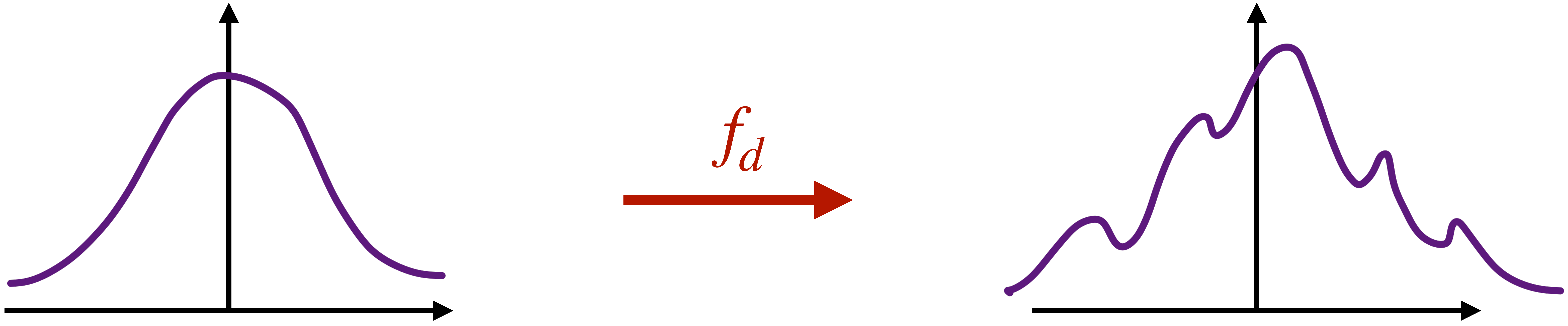
$$p(\theta | d) = \frac{\mathscr{L}(d | \theta)\pi(\theta)}{p(d)}$$

Using (θ, d) to construct with **deep learning** an estimator $q_\phi(\theta | d)$ of $p(\theta | d)$

Refs. Lueckmann et al. 2017, Greenberg et al. 2019, Cranmer et al. 2020, Chua et al. 2020, Dax et al. 2023

Normalising flows

They represent a complicated distribution q using a series of change of variables $f_d : u \rightarrow \theta$



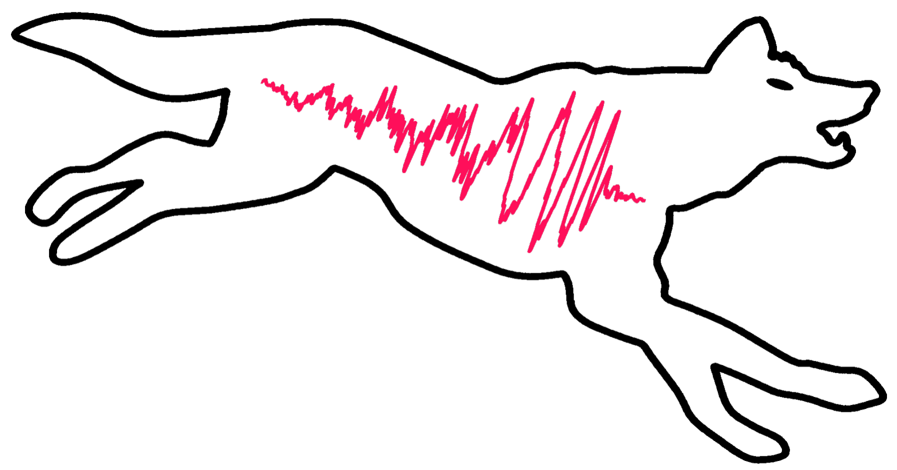
$$\mathcal{N}^D(0,1)$$

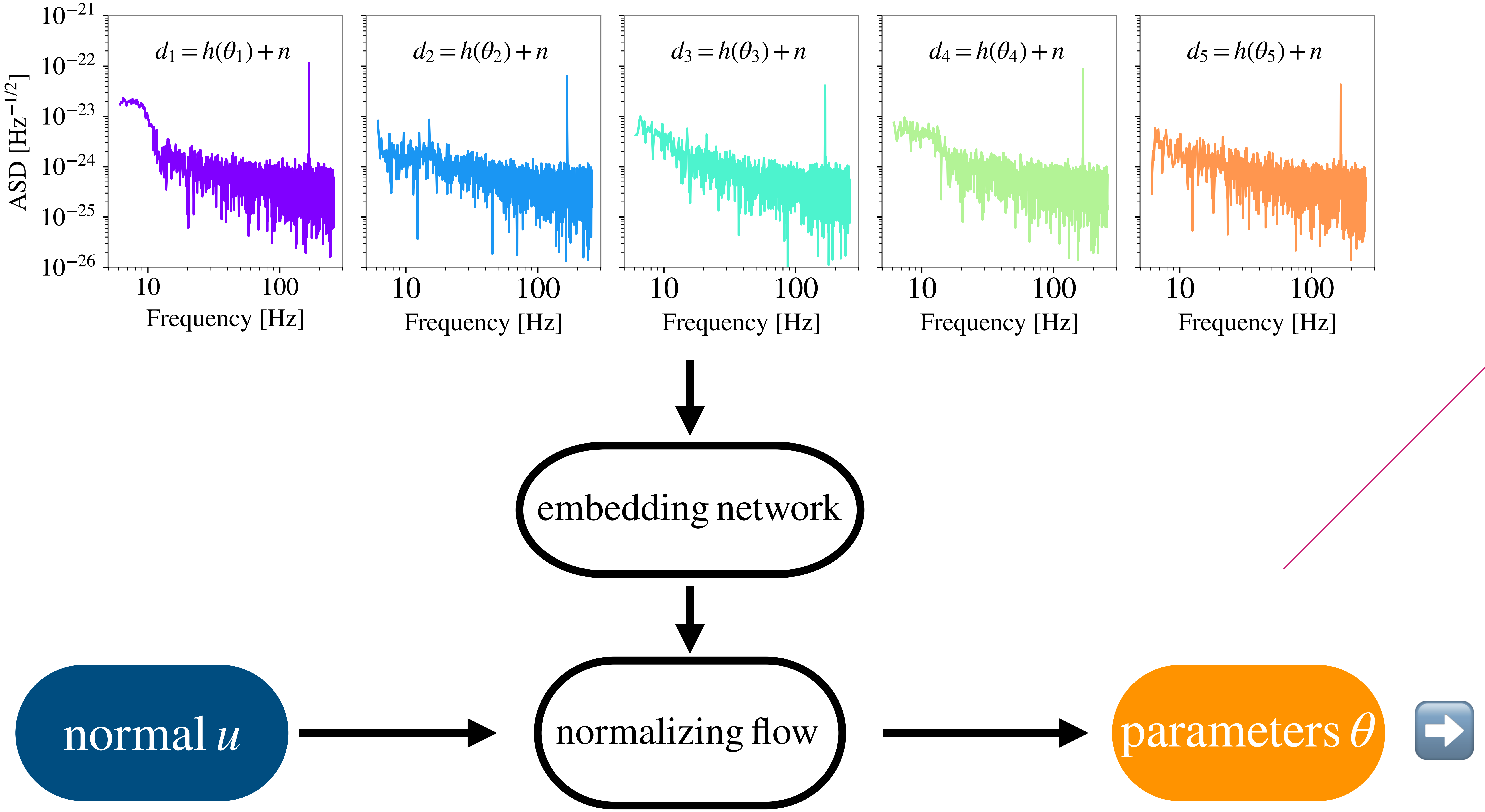
$$q_\phi(\theta \,|\, d) = \mathcal{N}^D(0,1)(f_d^{-1}(\theta))\,|\det J_{f_d}^{-1}\,|$$

Advantages:
rapidly evaluated and sampled from

Refs. Kobyzev et al. 2019, Durkan et al. 2019, Polanska et al. 2024

Dingo-IS





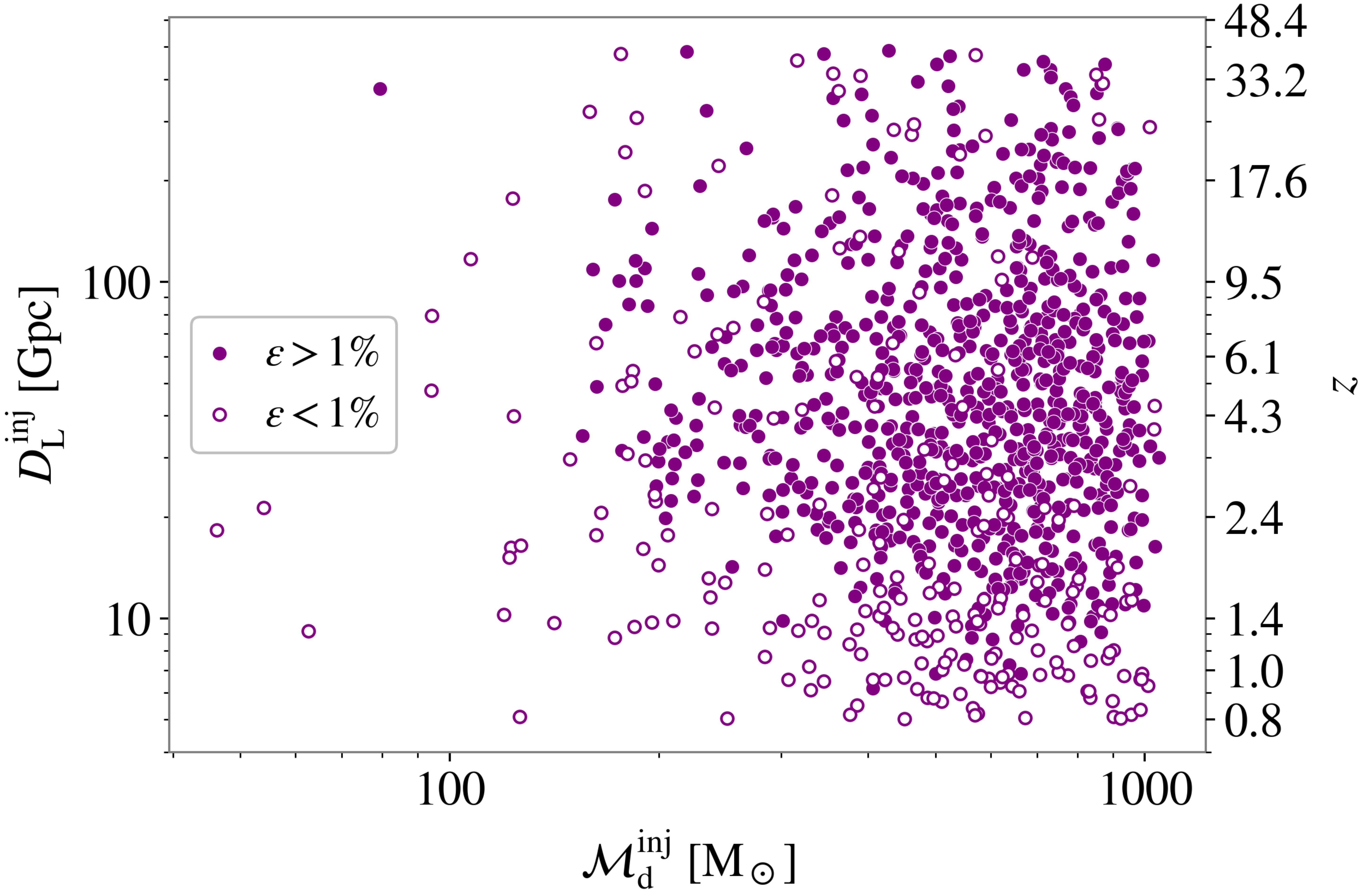
Importance sampling

$$w_i = \frac{\mathscr{L}(d|\theta)\pi(\theta)}{q_\phi(\theta|d)}$$

sample efficiency $\epsilon = \dfrac{\left(\sum_i w_i\right)^2}{N_s \sum_i w_i^2}$

Refs. Green et al. 2020, Green et al. 2021, Dax et al. 2021, Dax et al. 2022, Wildberger et al. 2022, Dax et al. 2023, Dax et al. 2024

Short-duration BBHs

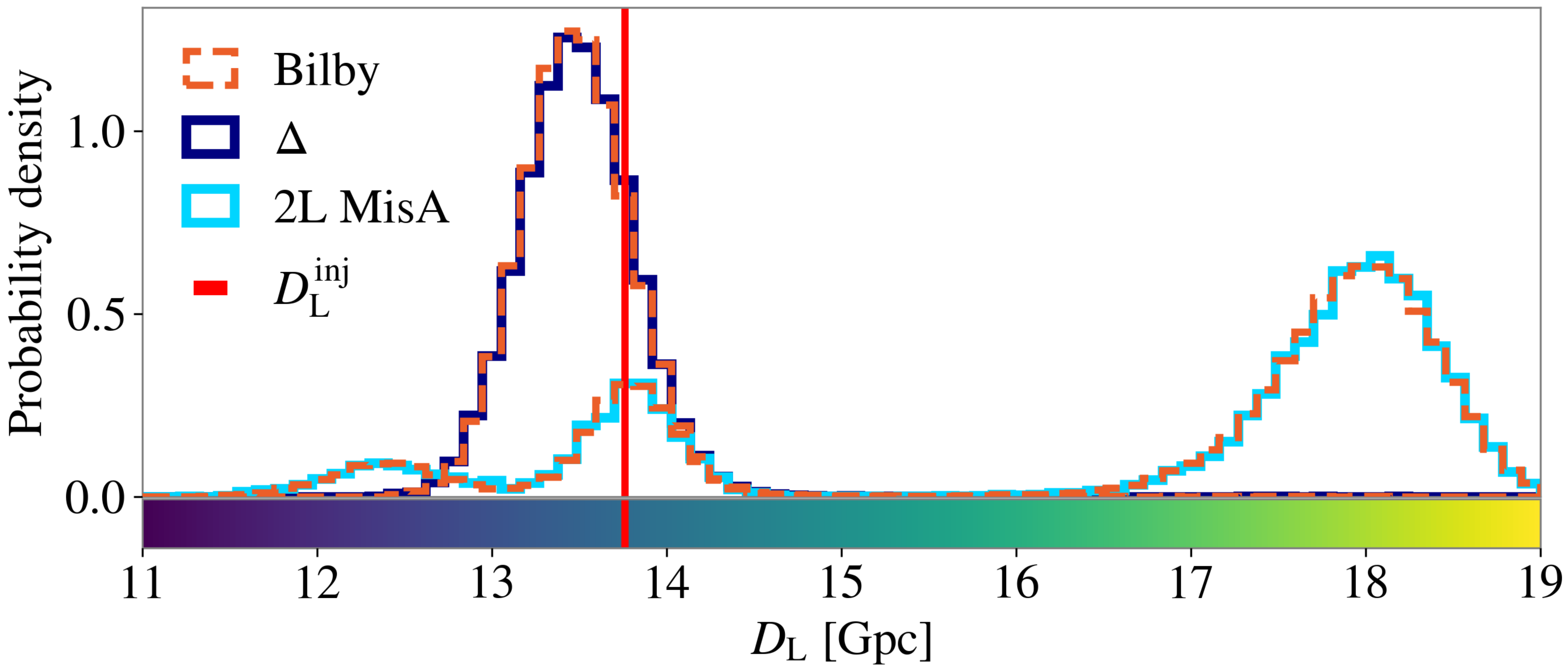


- **High-redshift BBHs**
  ➡️ Pop. III and Primordial

- **Intermediate-mass BBHs**

Refs. Santoliquido et al. 2023, Mestichelli et al. 2024, De Luca et al. 2020, Franciolini et al. 2022, Askar et al. 2023, Arca Sedda et al. 2023

Multimodal D_{L}

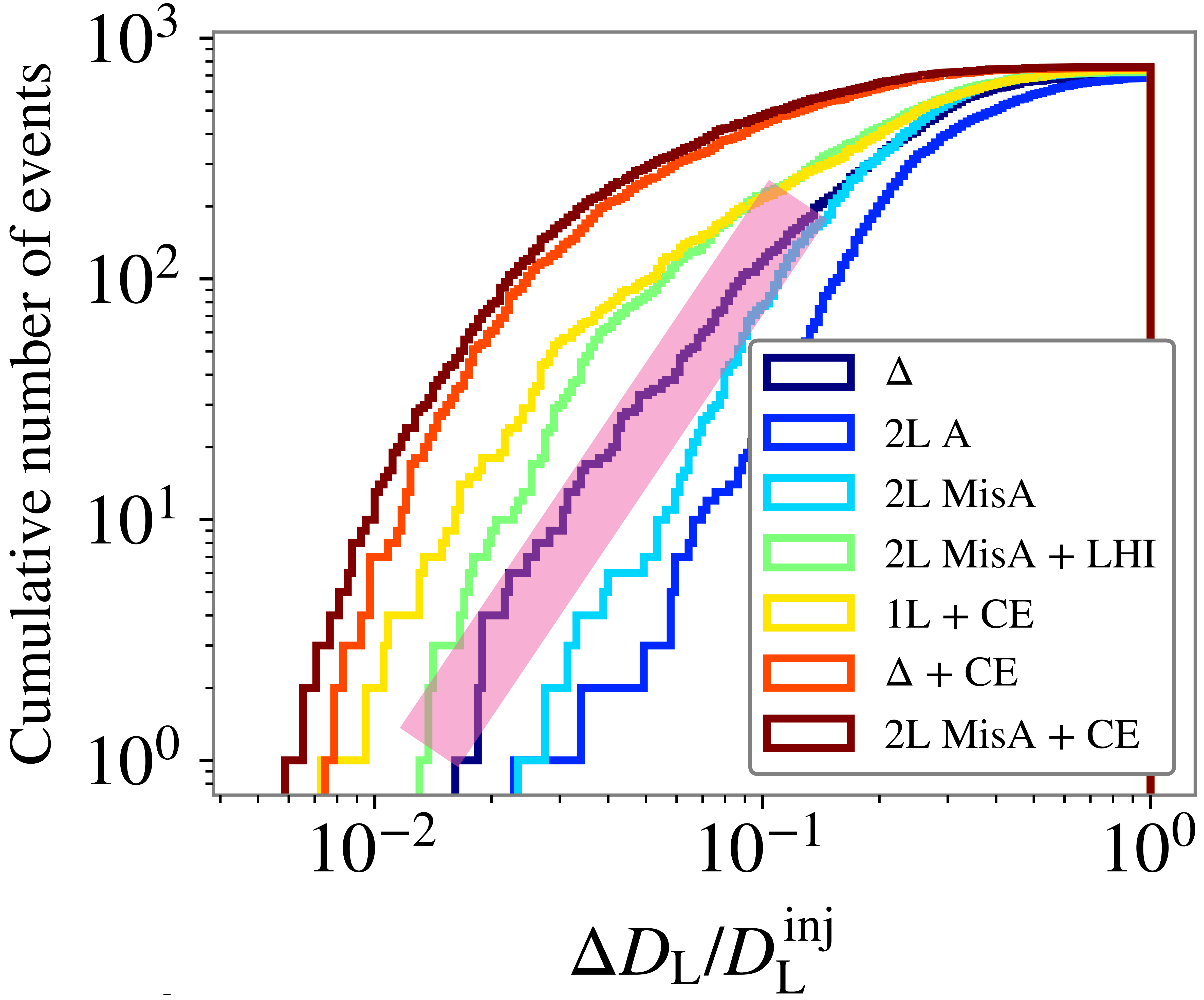


Multimodalities in luminosity distance for 2L MisA

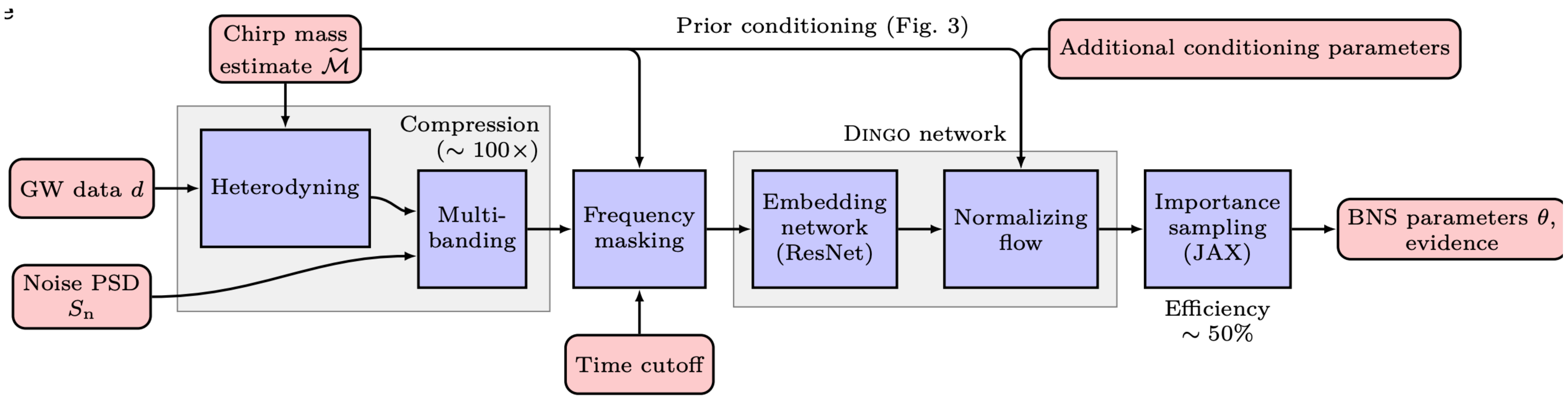
Perfect agreement between `Dingo-IS` and `Bilby`

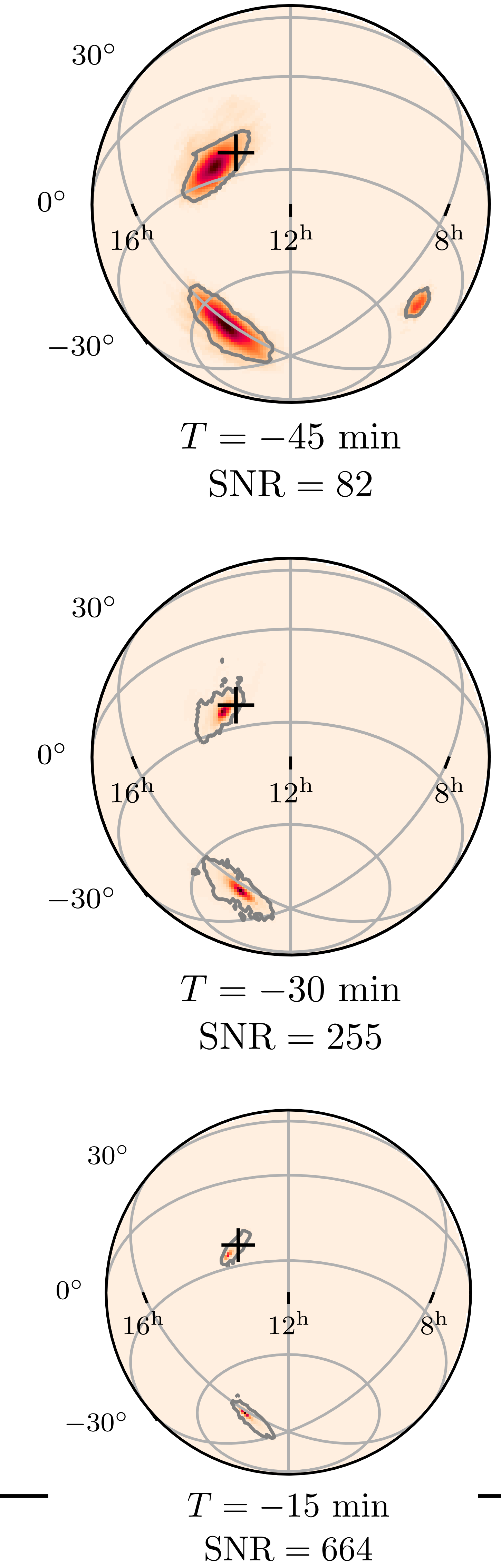
10 min vs. 50 hours

Luminosity distance performance



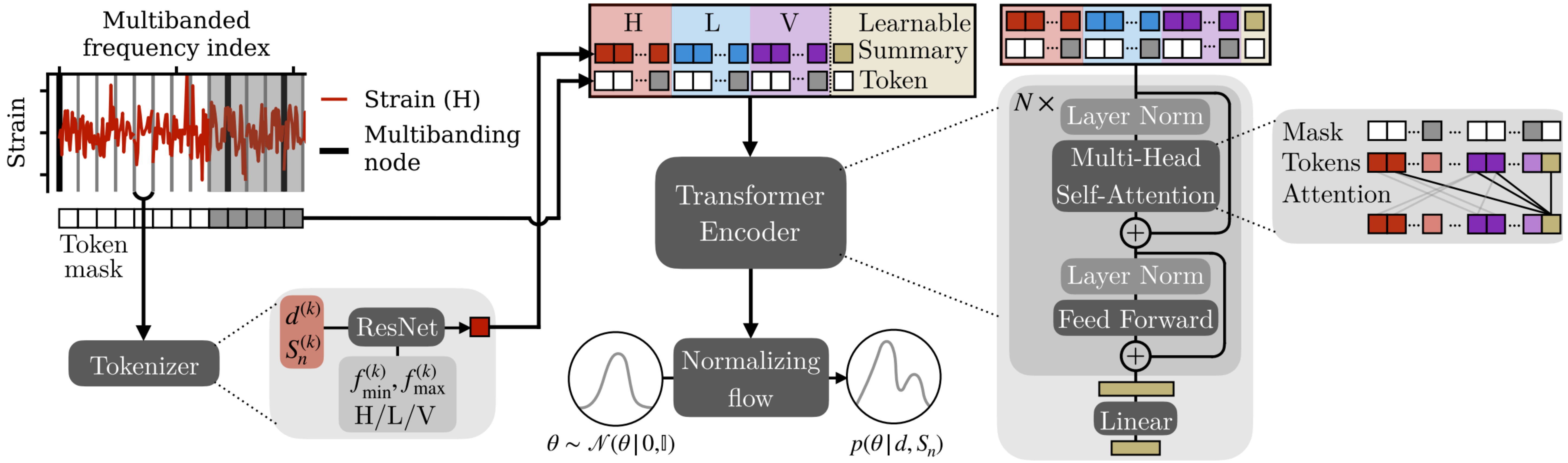
Dingo-BNS with Cosmic Explorer

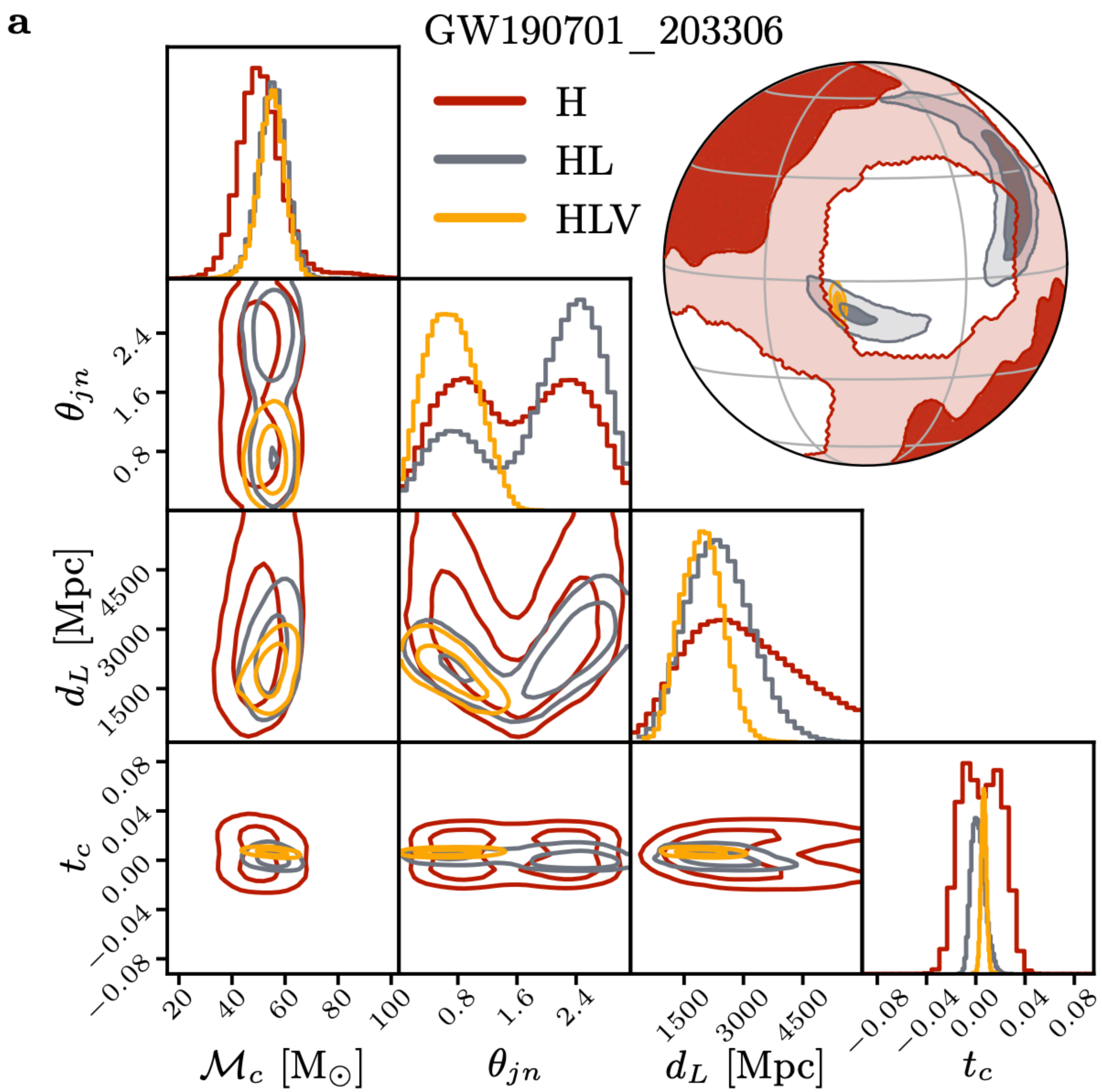




Areas of improvement: from $f_{\mathrm{min}} = 5$ Hz, neglecting Earth rotation, signal up to 15 minutes before merger

Dingo with transformers

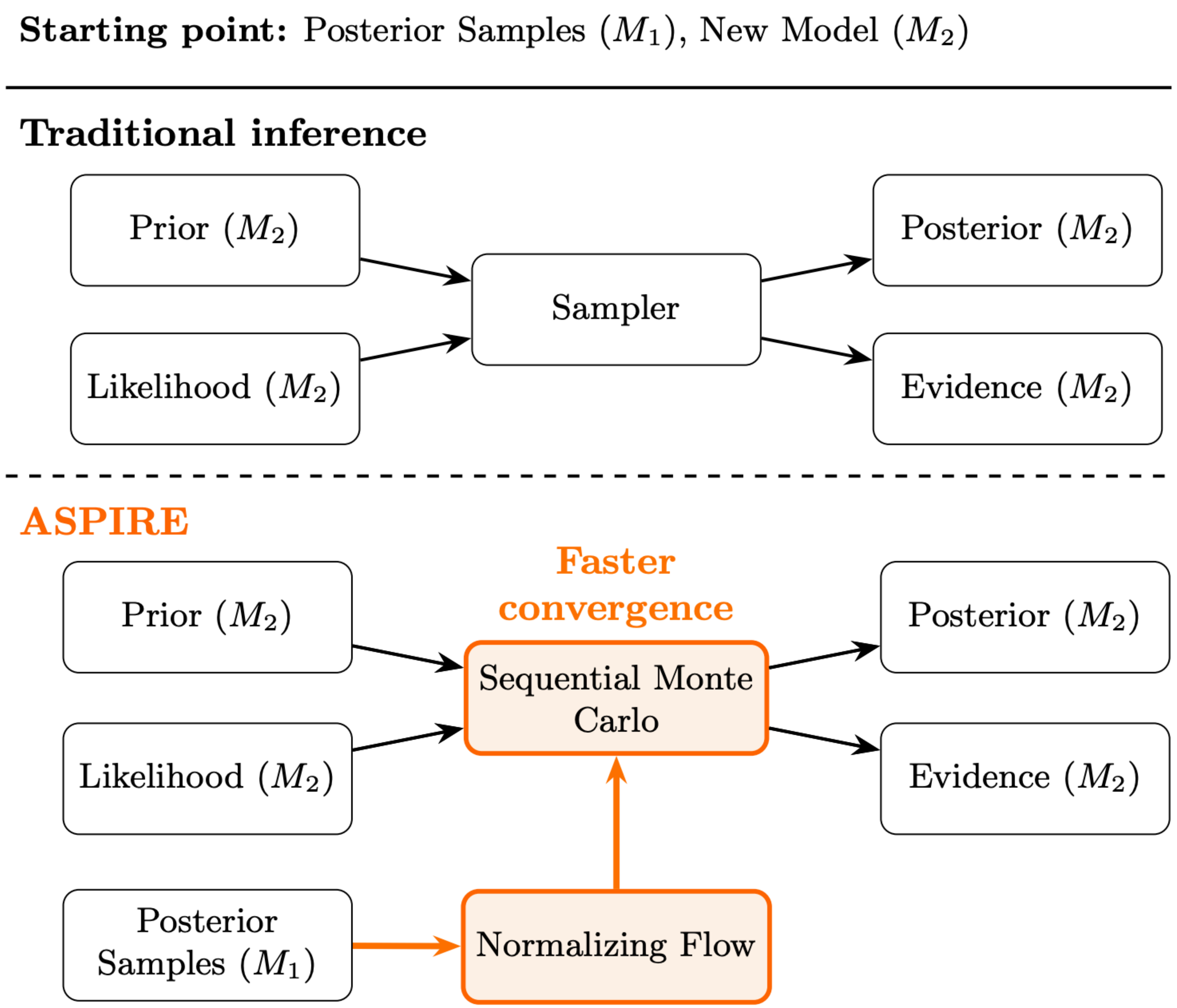




- Train `Dingo` directly with population priors
- Decrease $f_{\min} = 2$ Hz
- Expand the range of sources analysed

Credits: [Kofler et al. 2025]

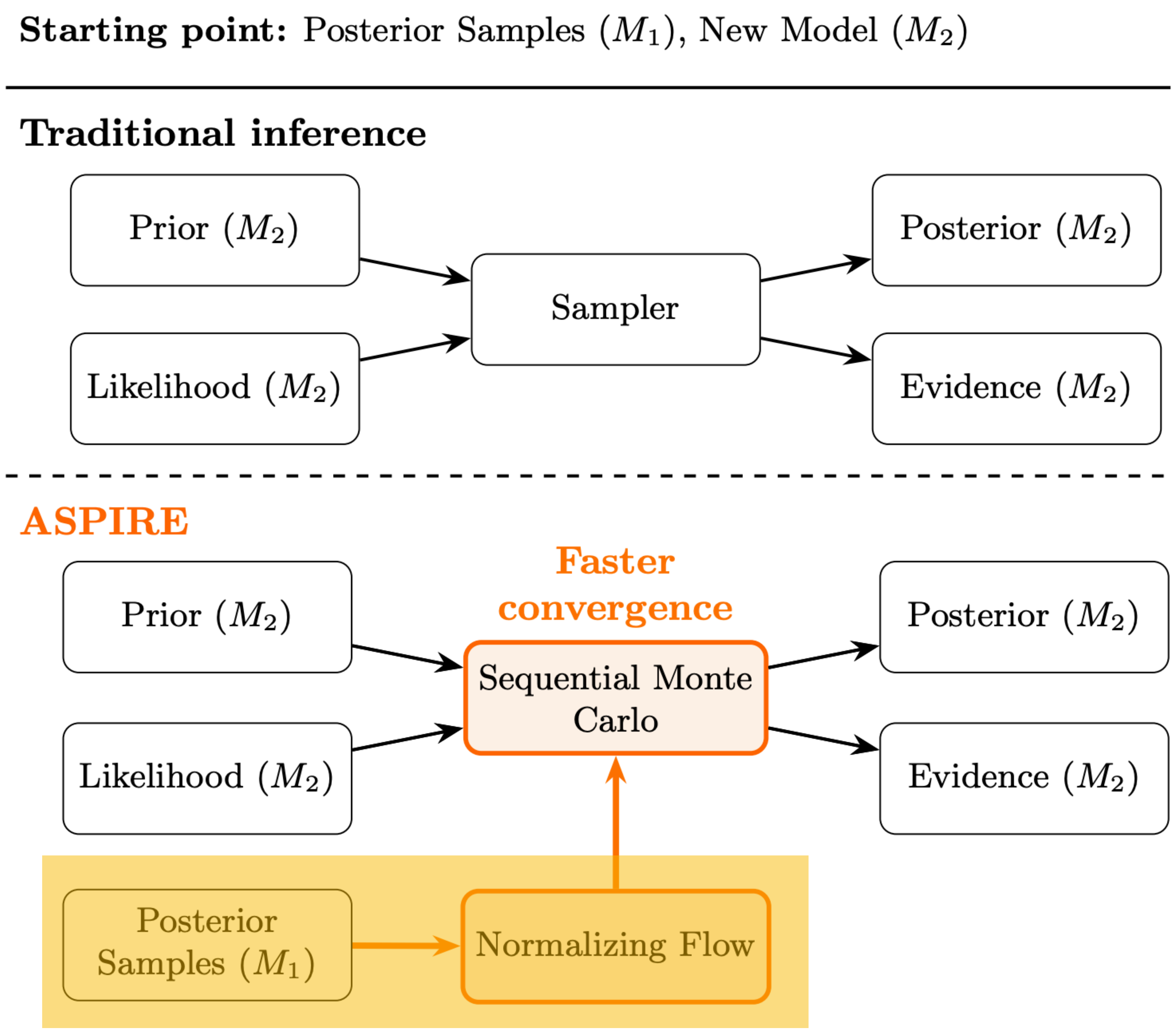
aspire-dingo



Refs. Williams et al. 2025b

aspire-dingo

We already have access to trained normalising flows!
Natural extension to make aspire work with `dingo`.
THIS IS GAME CHANGER!
Especially because aspire-dingo allows PE of high-SNR events ➡️



Refs. [Williams et al. 2025b]

Short course

- **“Foundations of gravitational-wave and multimessenger data analysis”**
- Filippo’s lectures: **13, 20, 22 May**
- Biswajit’s lectures: **11, 15, 16 June**
- This course provides a foundational **introduction to gravitational wave data analysis**, covering key concepts and standard Bayesian inference techniques used to analyse data from the LIGO, Virgo, and KAGRA detectors. We will also explore **analysis methods** recently developed **for next-generation observatories** such as the Einstein Telescope, including Fisher-matrix approximations and accelerated yet accurate **deep-learning– based approaches**. The course will also examine the multi-messenger opportunities for advancing our understanding of GRB physics. We will discuss observational strategies with current and future facilities, including the use of early-warning alerts. Particular emphasis will be placed on the largely unexplored high-energy gamma-ray domain (GeV–TeV) and its role in constraining jet physics and radiation mechanisms within the broader framework of multi-messenger astronomy. **The course will be highly hands-on**, with practical sessions designed to teach the essential Python tools commonly used in the gravitational wave community.

Contributions

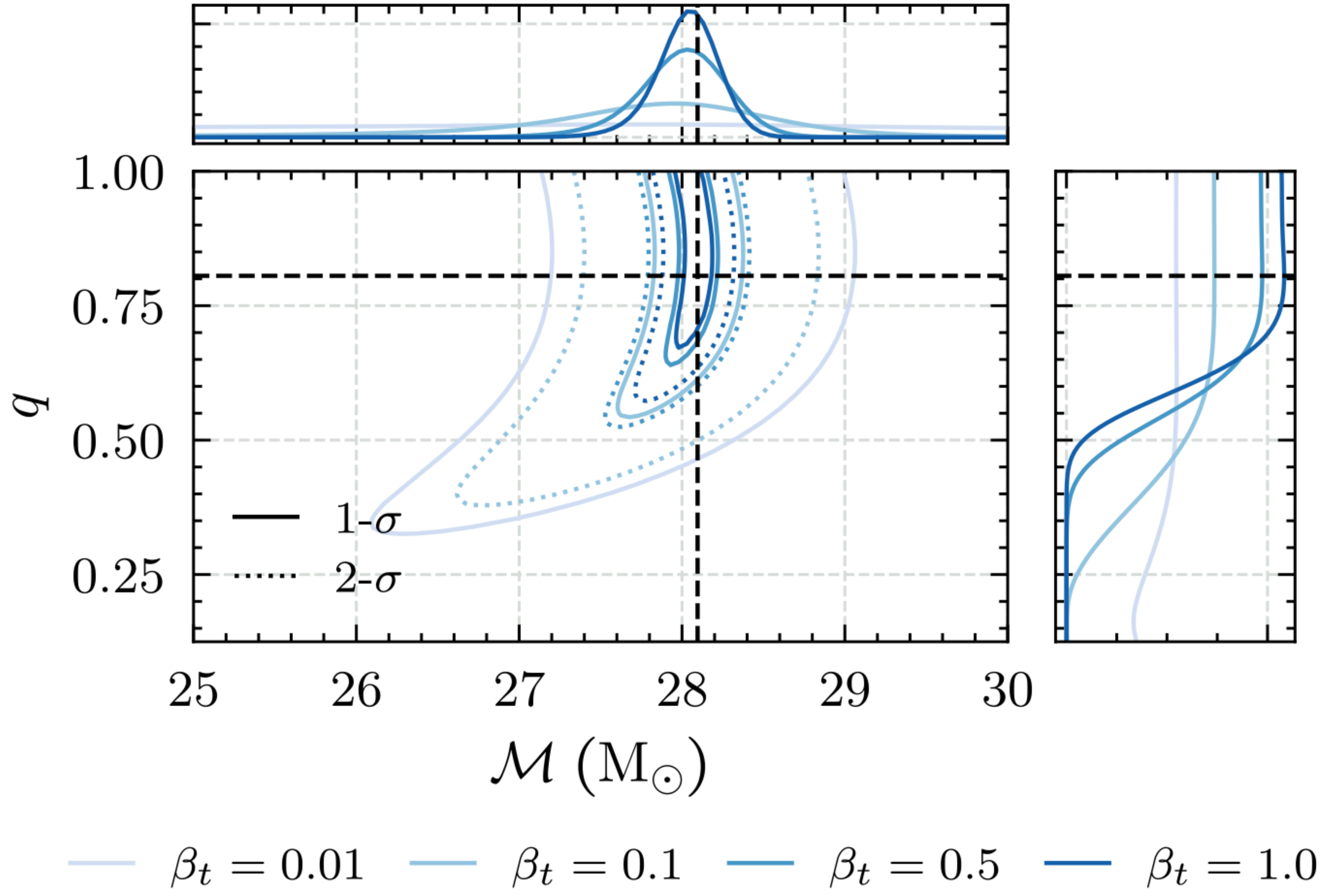
- The Einstein Telescope calls for a **pragmatic shift** in data analysis technique
- Addressing these challenges is **essential and feasible**
- We have the *unique* opportunity to **develop new technologies**

Backup slides

Solution: sequential Monte Carlo

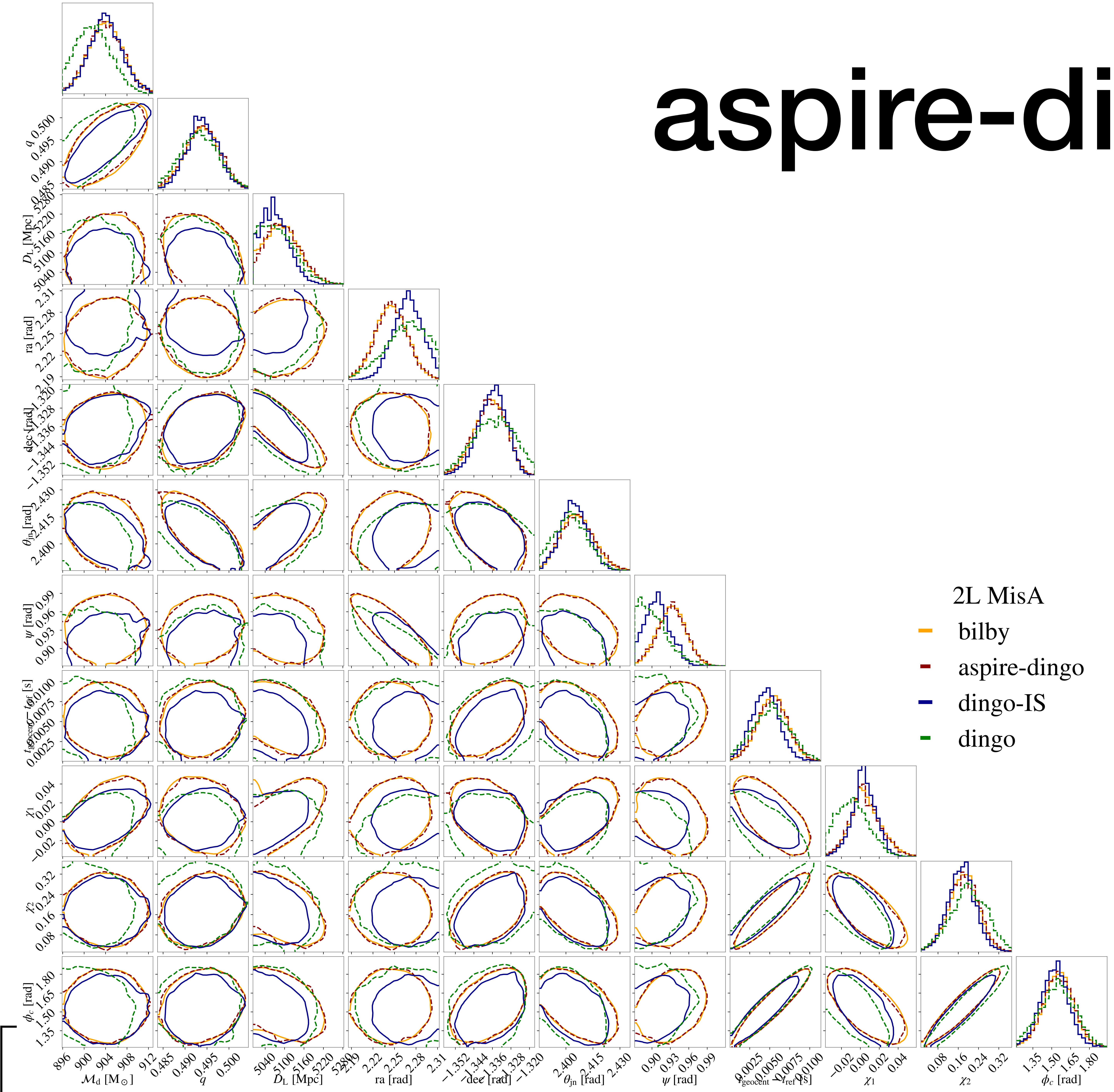
- $p_t(\theta \mid d) = \dfrac{\mathscr{L}(d \mid \theta)^{\beta_t} \pi(\theta)}{Z_t}$

- Where $\beta_t \in [0,1]$



Refs. Williams et al. 2025a

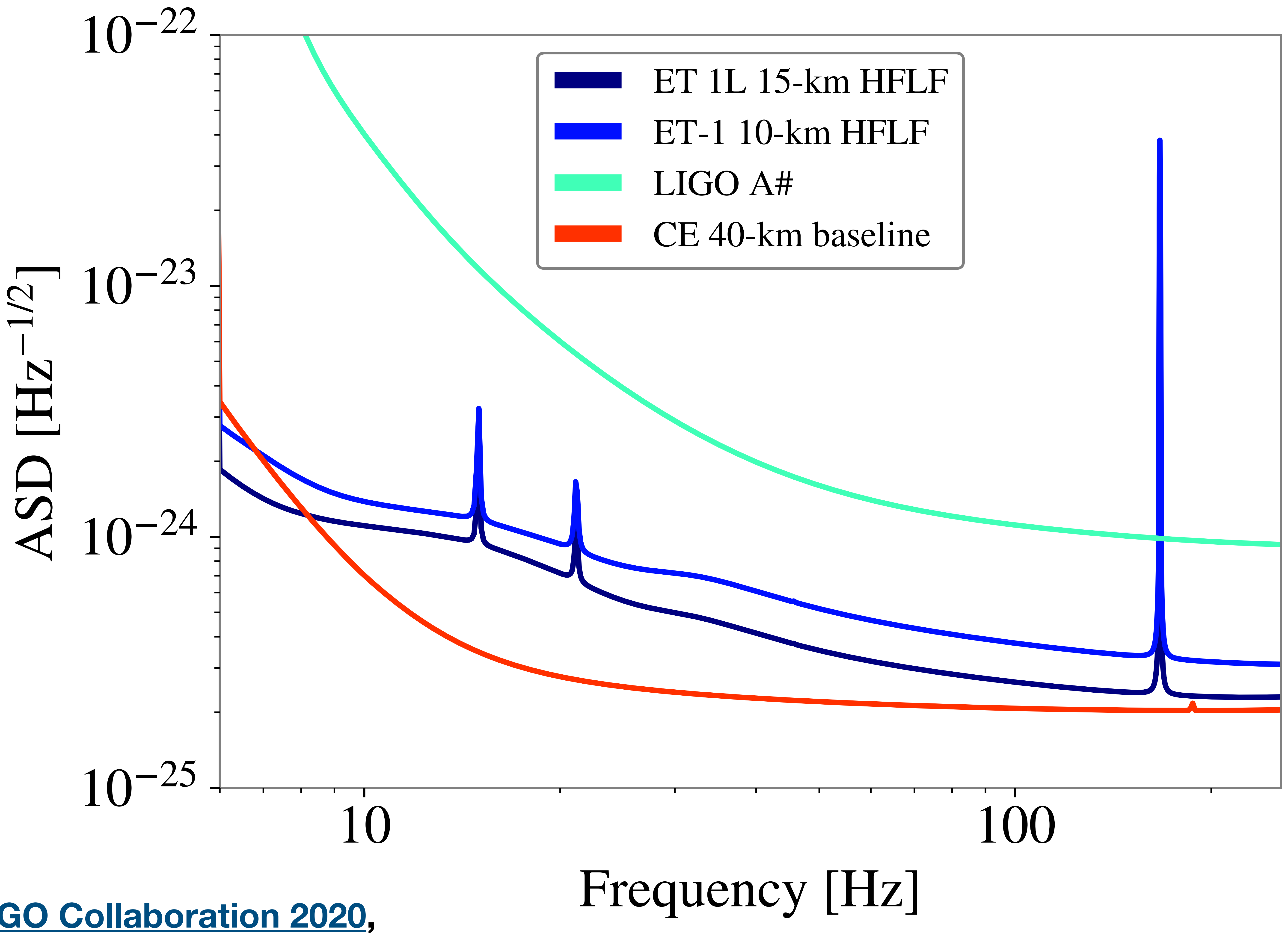
aspire-dingo



Sample efficiency very low ~0.02%
With very high SNR ~ 650

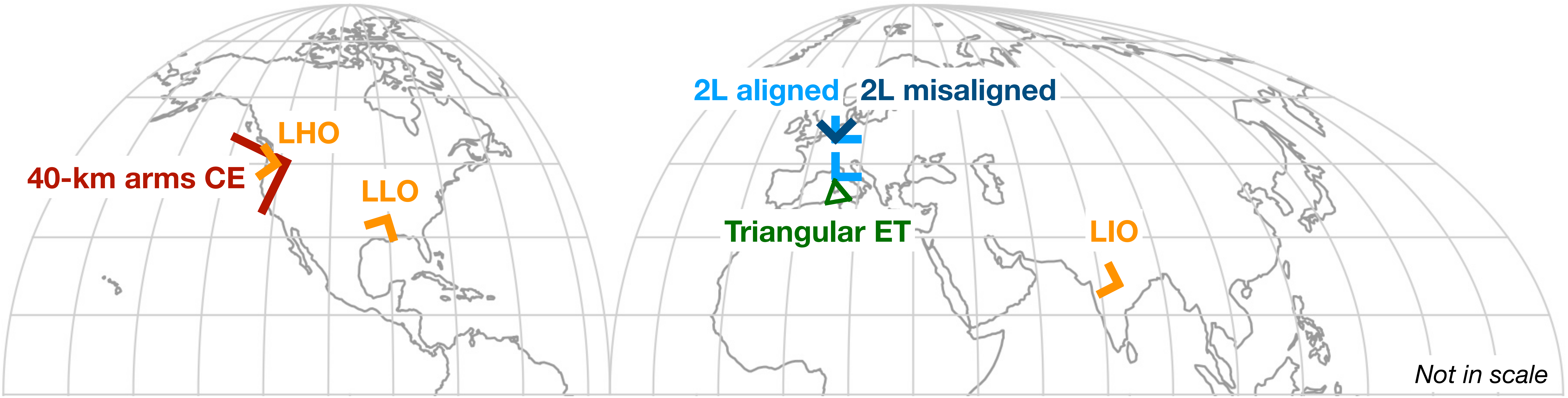
Computing times:
- dingo : < 1 s
- aspire-dingo: 7 hours
- bilby: 12 hours
- dingo-IS: 20 hours

Amplitude spectral densities



Refs. ET Collaboration 2023, LIGO Collaboration 2020, S. Kandhasamy & S. Bose 2020, CE Collaboration 2022

Configurations



Δ

2L A

2L MisA

2L MisA + LHI

1L + CE

2L MisA + CE

Δ + CE

Refs. Branchesi et al. 2023, D. Reitze et al. 2019, Unnikrishnan 2013

High-redshift sources

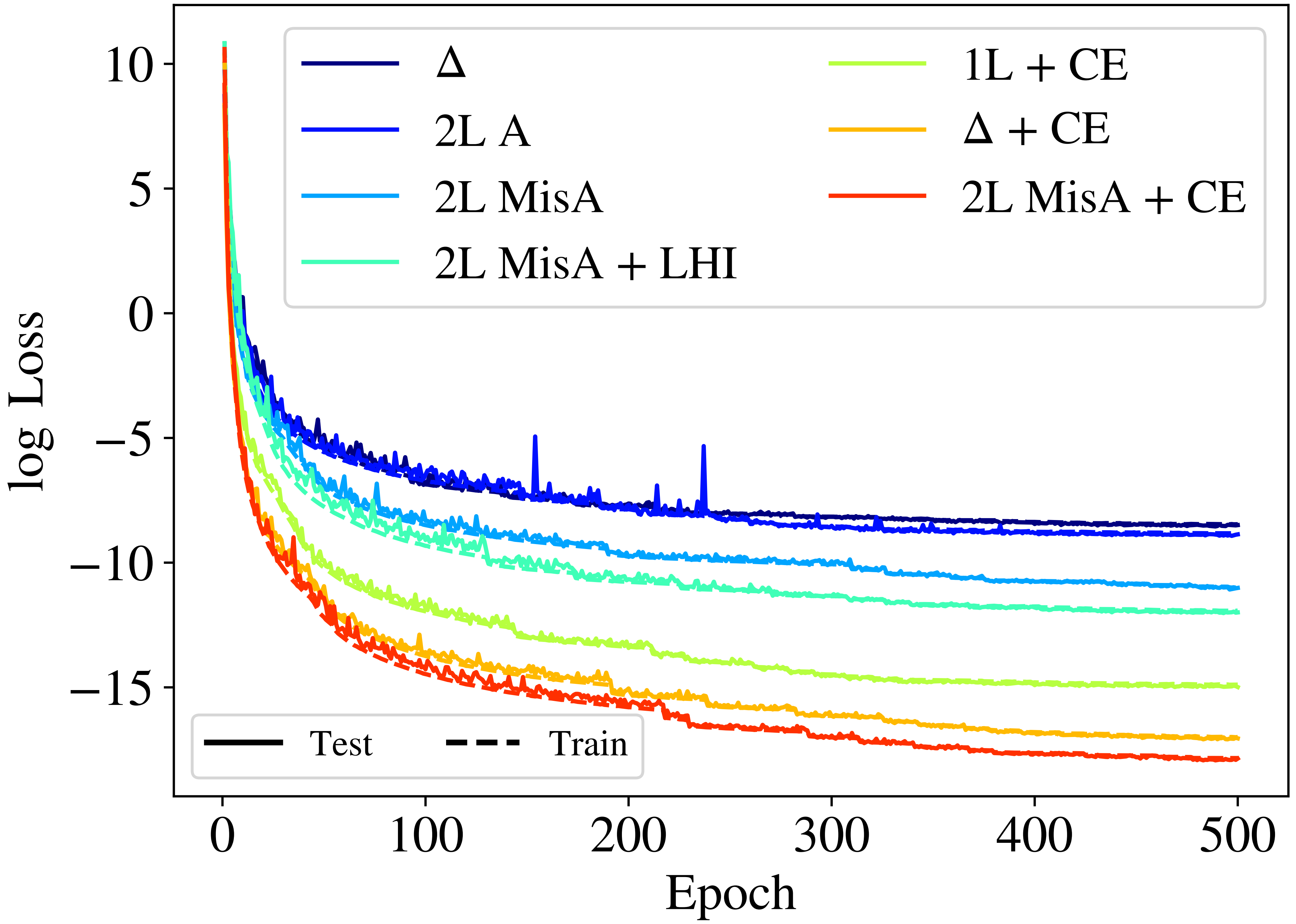
```
'chirp_mass': UniformInComponentsChirpMass(minimum=40, maximum=1100)

'luminosity_distance': UniformSourceFrame(minimum=5_000.0, maximum=500_000.0)
```

waveform approximant = `IMRPhenomXPHM`

Ref. Pratten et al. 2021

Training



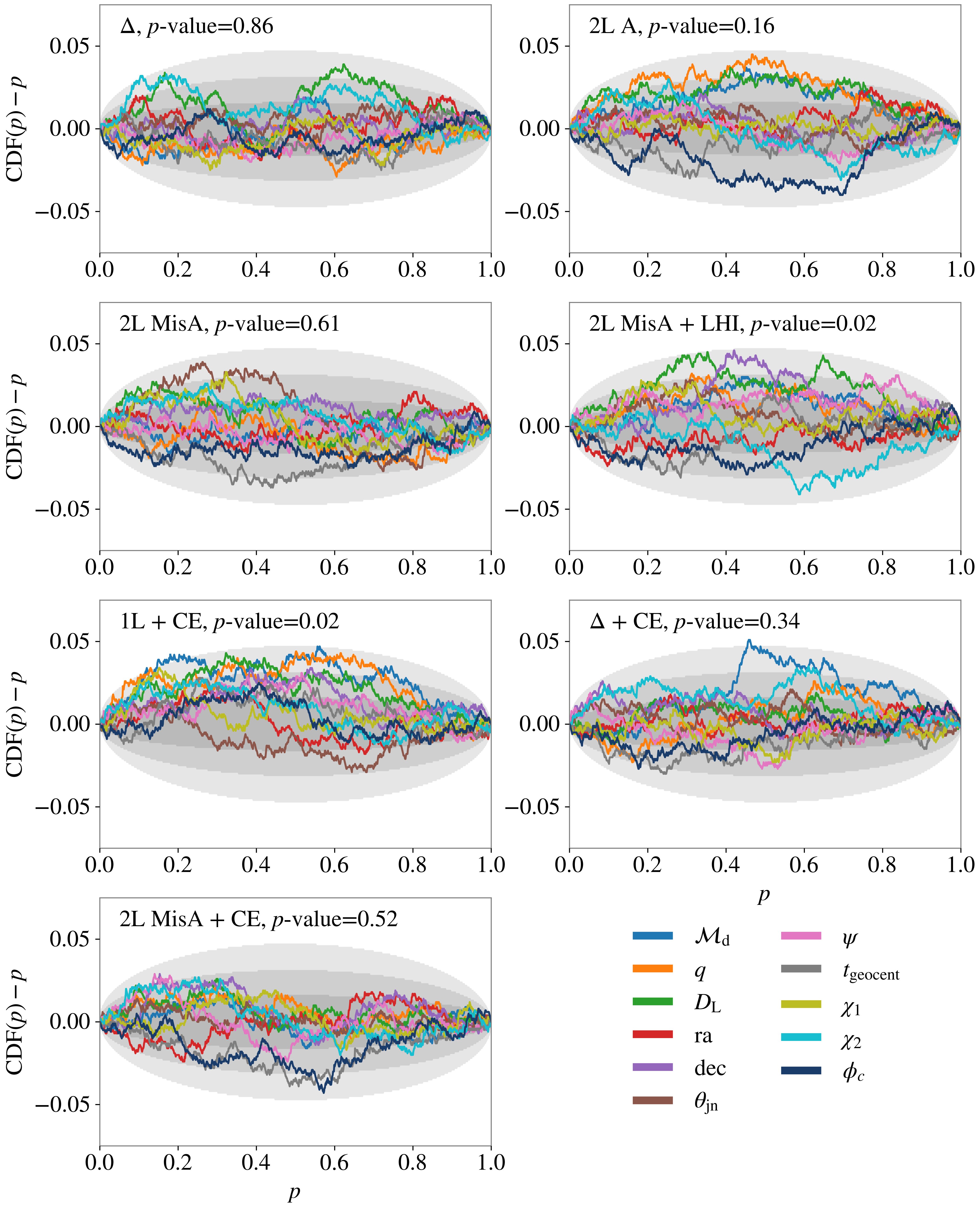
Injections

- Randomly sample 1000 BBHs from the priors
- Use the same injection parameters for all configurations.
- Obtain 10^5 posterior samples and importance weights for each injection.

P-P plots

	Δ	2L A	2L MisA	2L MisA + LHI	1L + CE	Δ + CE	2L MisA + CE
$\mathcal{M}_\mathrm{d}$	0.72	0.12	0.92	0.29	0.02	0.01	0.91
q	0.35	0.03	0.59	0.23	0.04	0.47	0.76
D_L	0.08	0.12	0.42	0.03	0.04	0.84	0.47
ra	0.79	0.53	0.73	0.59	0.71	0.90	0.57
dec	0.80	0.71	0.76	0.03	0.19	0.47	0.34
θ_jn	0.92	0.96	0.09	0.37	0.34	0.72	0.98
ψ	0.79	0.72	0.92	0.23	0.25	0.43	0.35
t_geocent	0.55	0.30	0.12	0.27	0.37	0.29	0.08
χ_1	0.55	1.00	0.21	0.41	0.19	0.61	0.83
χ_2	0.21	0.28	0.47	0.06	0.42	0.15	0.43
ϕ_c	0.89	0.07	0.50	0.33	0.50	0.44	0.04

Table 4. p-values (color-coded) for each GW parameter (rows) across different detector configurations (columns). See Figure 7 and Appendix C for details.

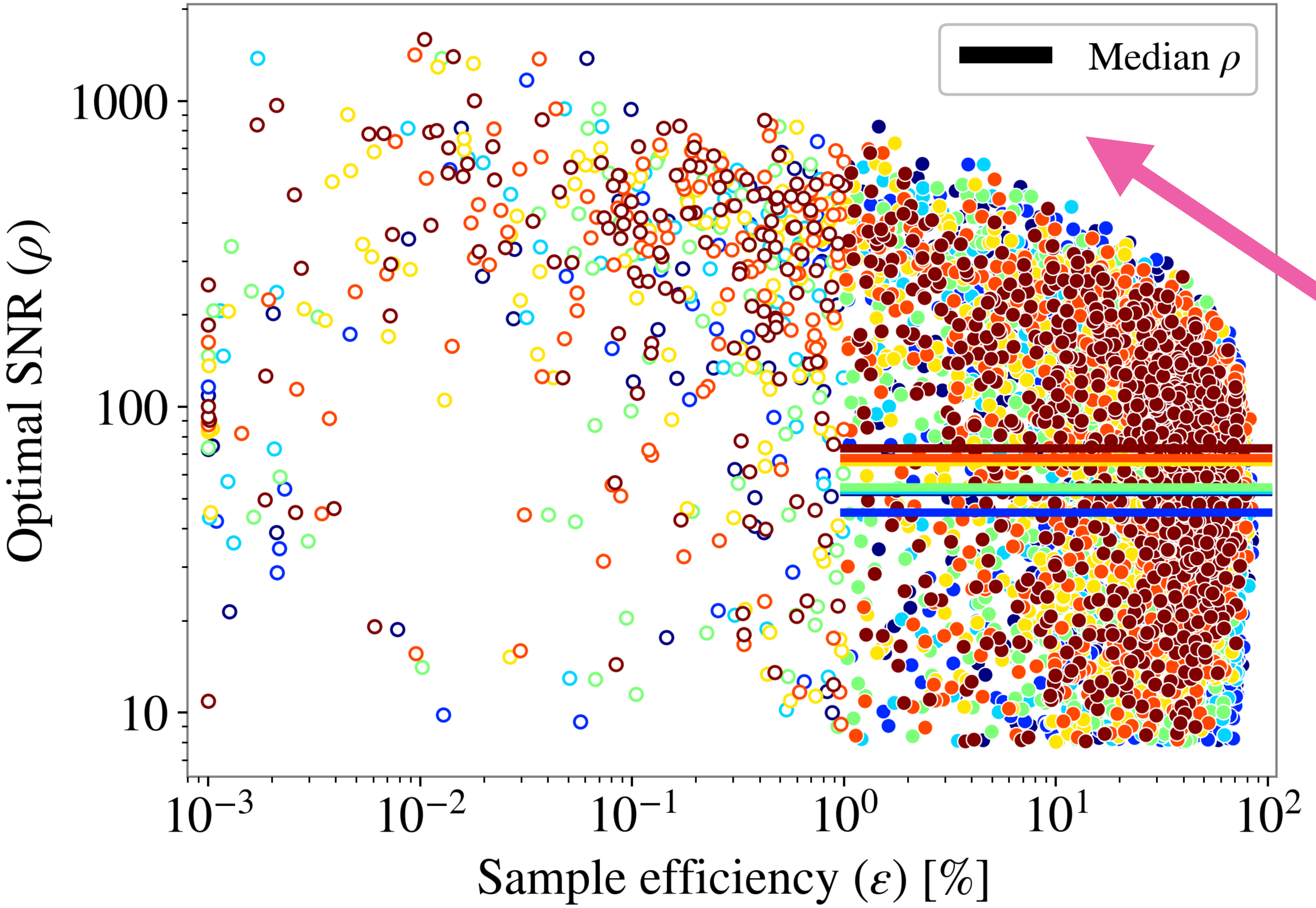


Refs. Santoliquido et al. 2025b

Sample efficiency

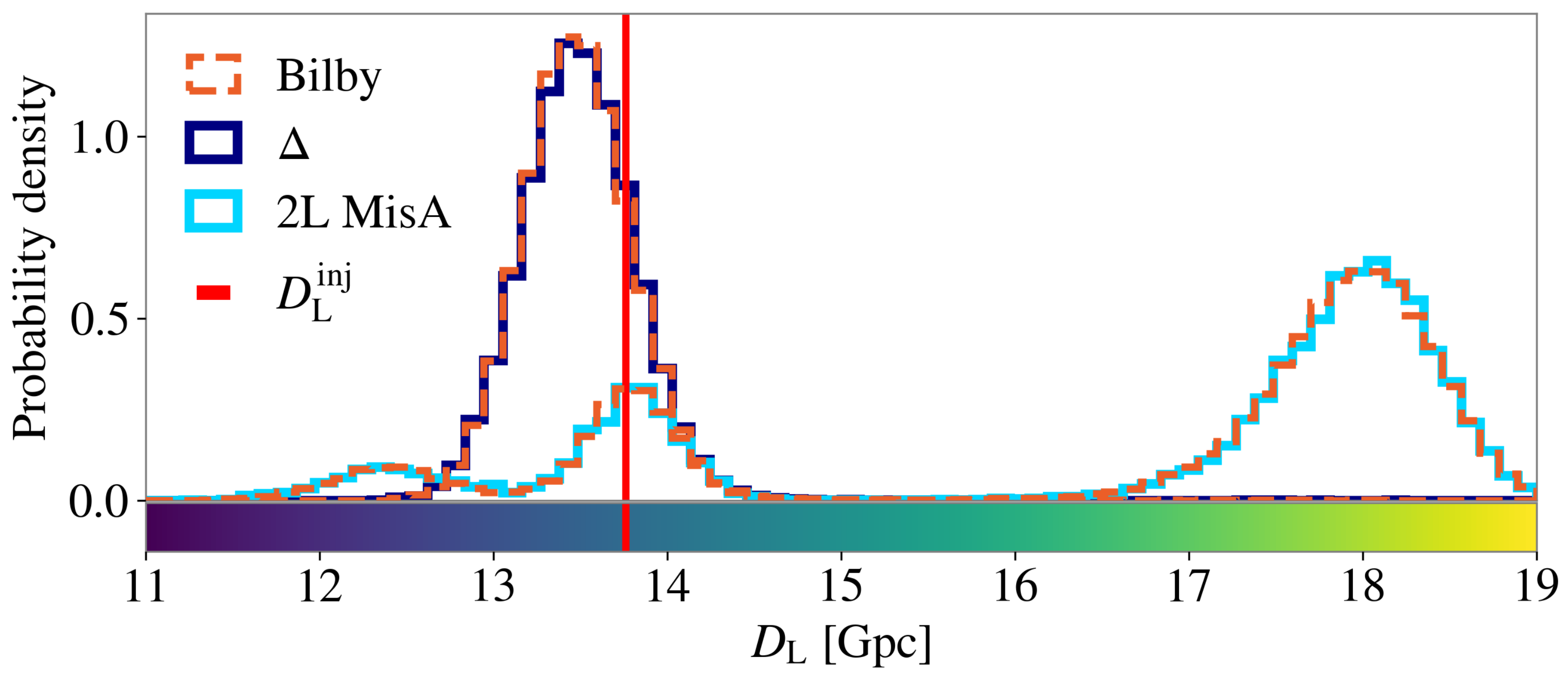
Higher sample efficiency wrt Santoliquido et al. 2025a

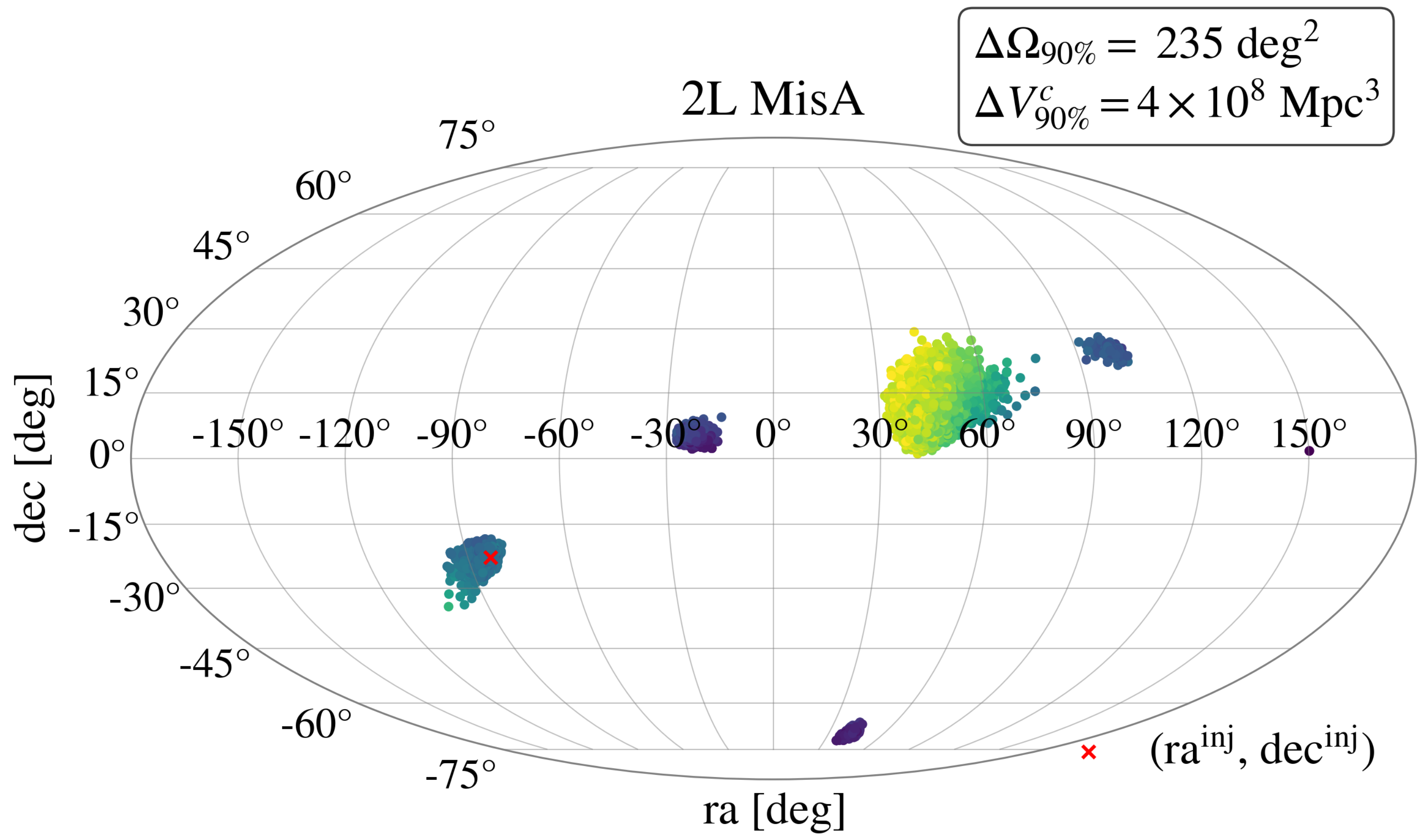
- 2L A (96%)
- Δ (96%)
- 2L MisA (94%)
- 2L MisA + LHI (93%)
- 1L + CE (89%)
- Δ + CE (88%)
- 2L MisA + CE (85%)

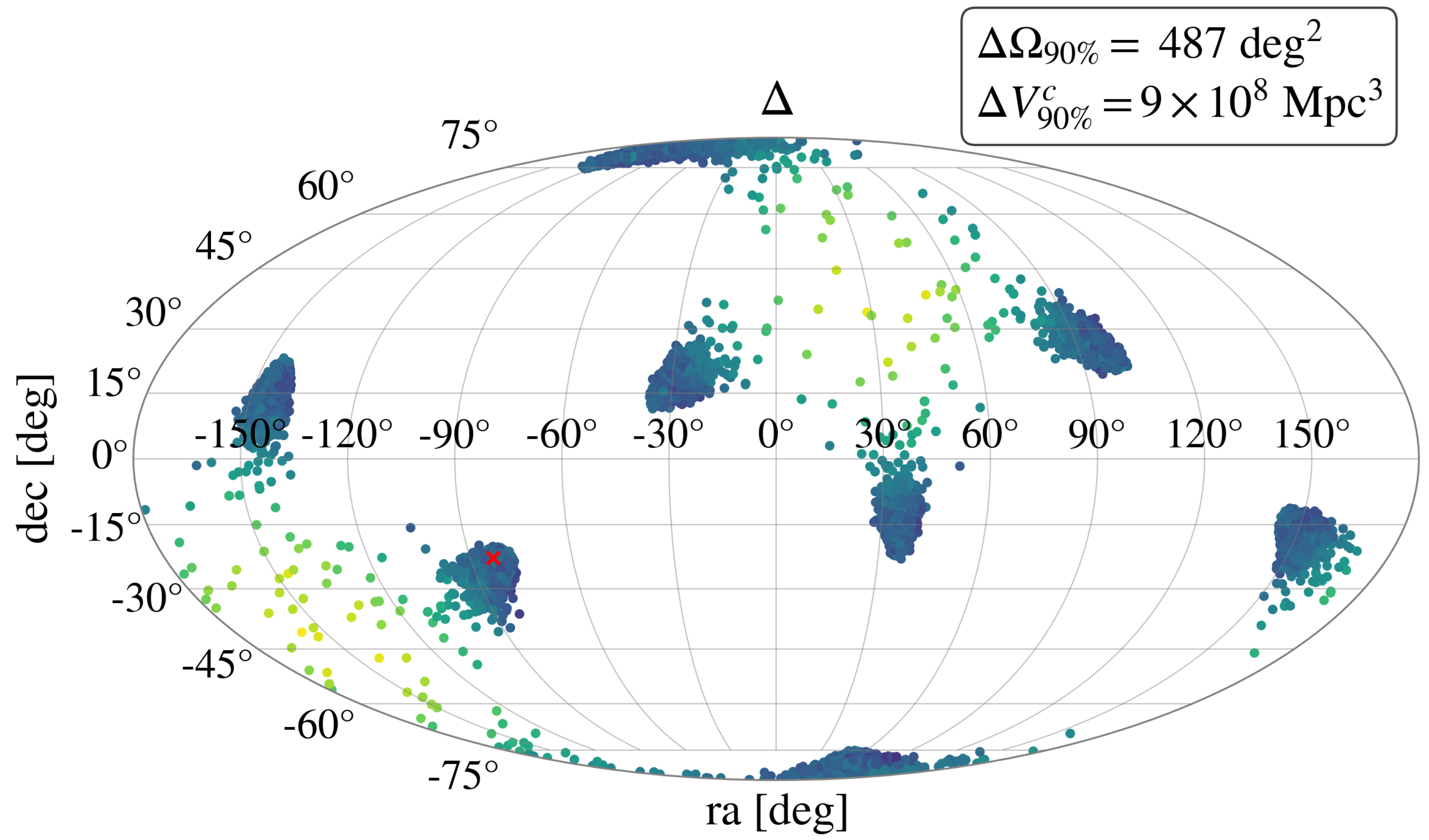


Median $\rho \in [\sim 40, \sim 70]$

Multimodal posteriors

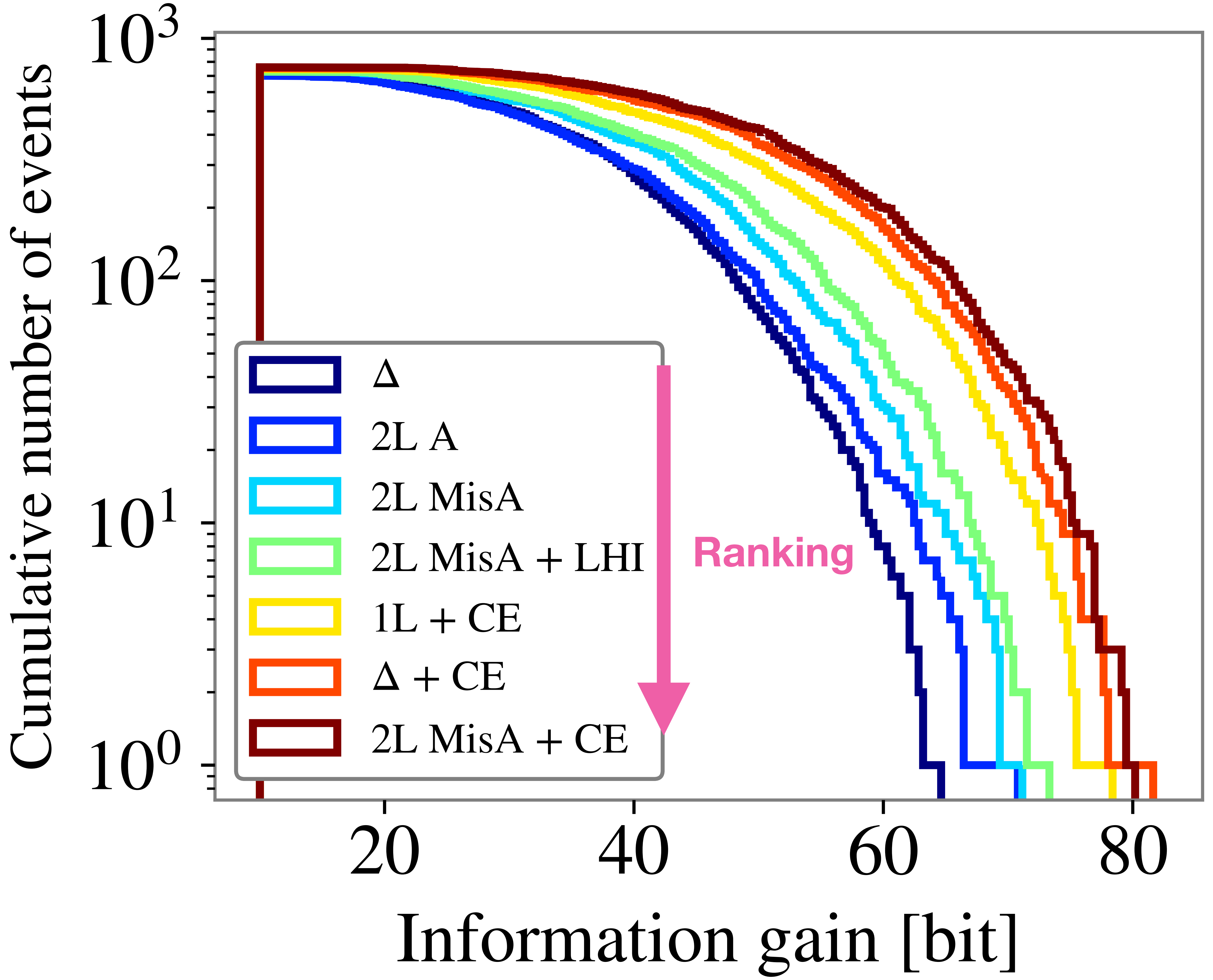






Eight-fold sky degeneracy extensively discussed in [Santoliquido et al. 2025a]

Parameter estimation performance

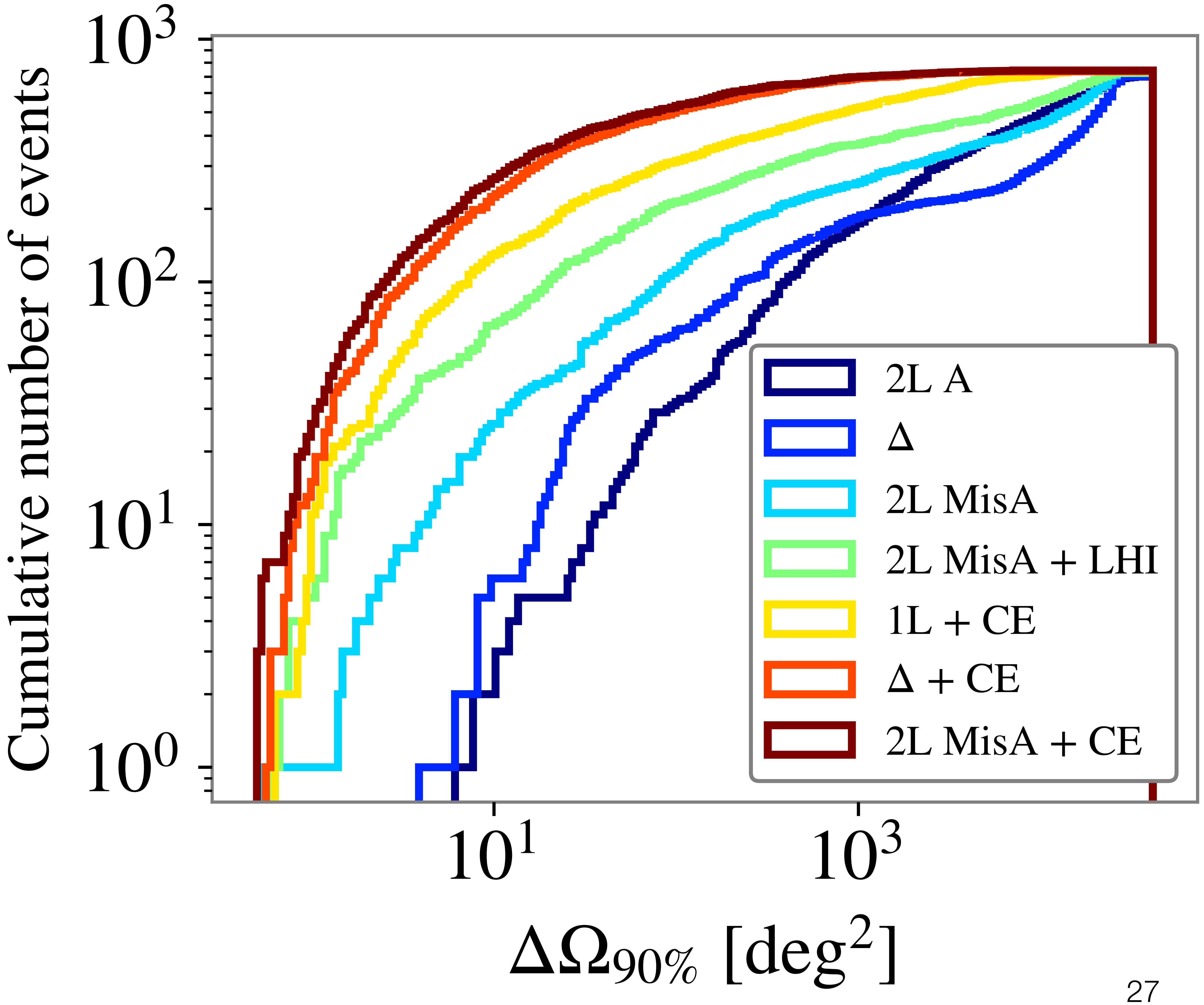


Kullback-Leibler divergence

$$I = \int \mathrm{d}\theta p(\theta \mid d) \log_2 \frac{p(\theta \mid d)}{\pi(\theta)}$$

Refs. Kullback & Leibler 1951, Buchner 2022

Sky localisation performance

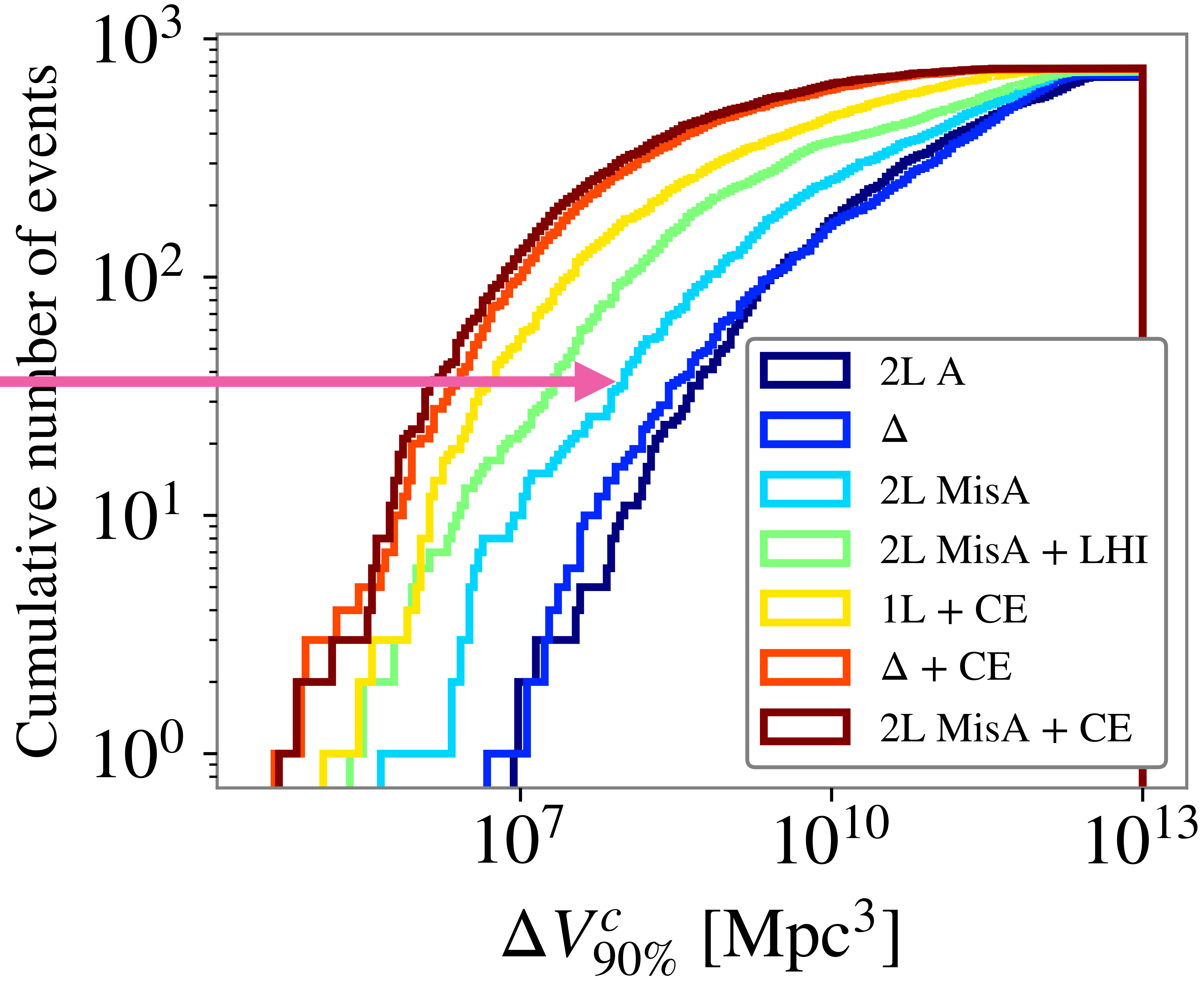


Improvement in sky localisation with **2L MisA** configuration wrt to Δ due to less sky modes

`ligo-skymap` (Singer et al. 2016a)

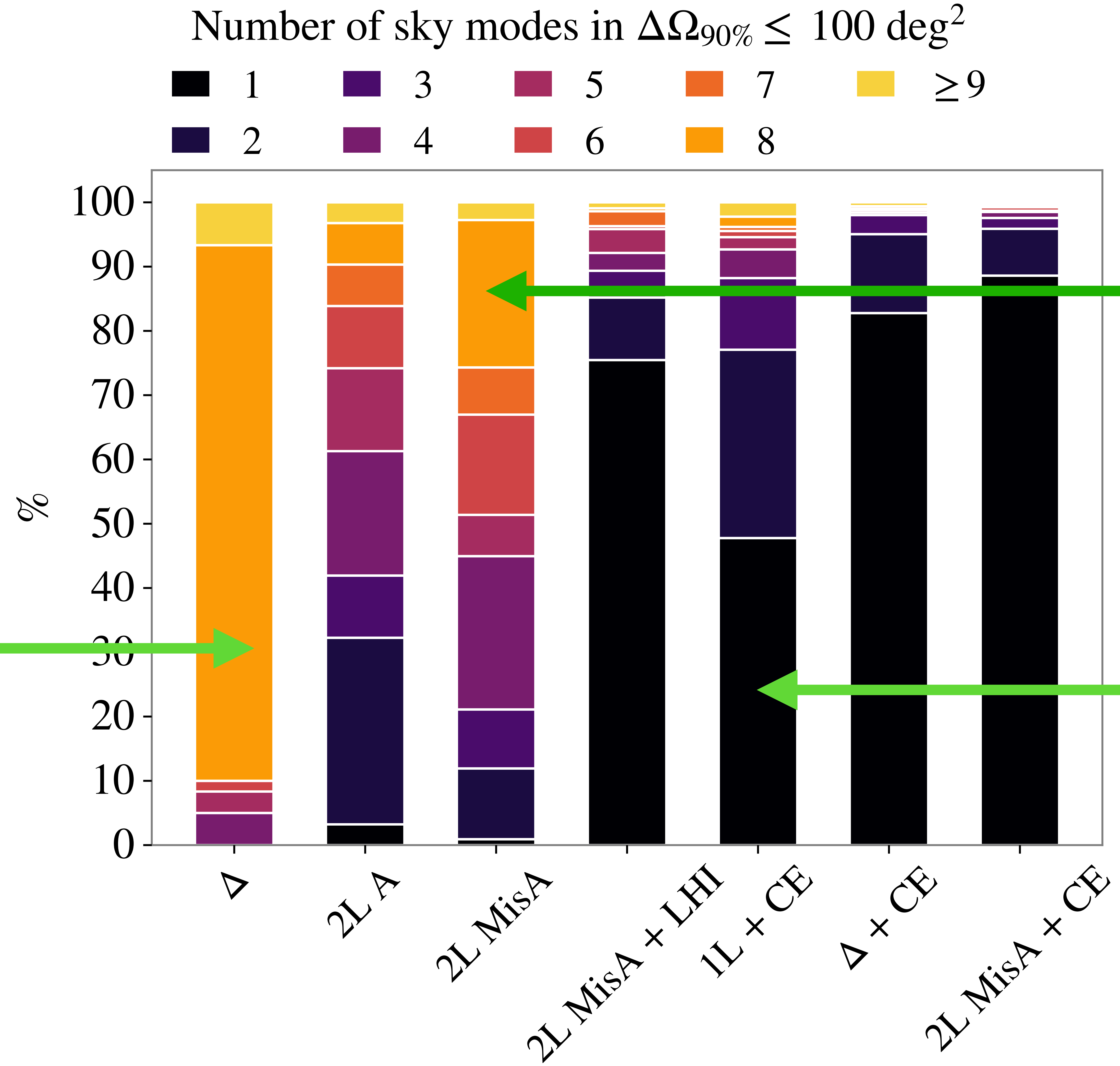
Volume localisation performance

Large **improvement in volume localisation** with **2L MisA** configuration. Impact on several science cases (e.g., dark siren cosmology)



Refs. Schutz 1986, Del Pozzo 2012, Libanore et al. 2021, Gair et al. 2023, Borghi et al. 2024

Sky modes

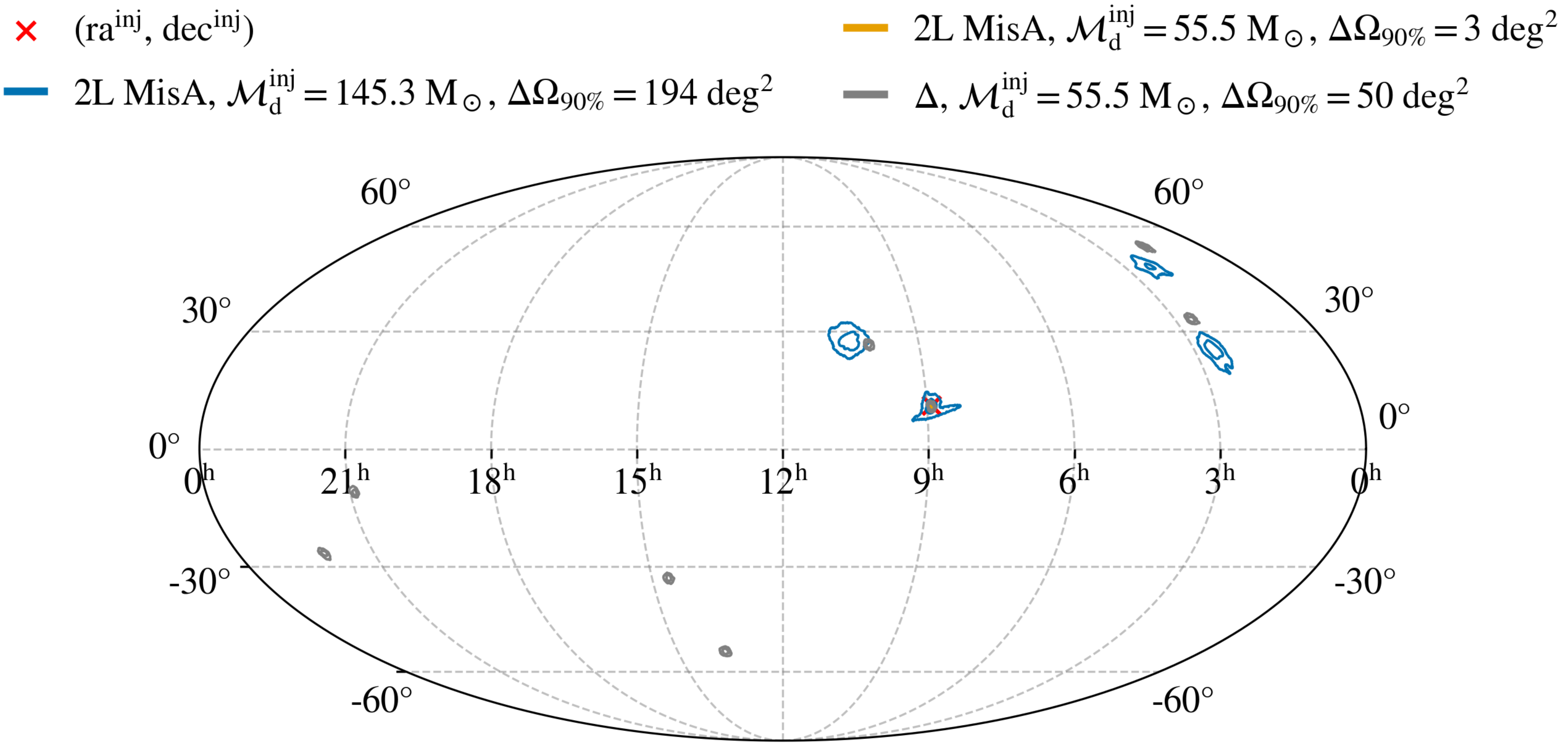


Δ, > 80% of sources with **eight sky modes**

2L MisA, ~ 20% of sources with **eight sky modes**

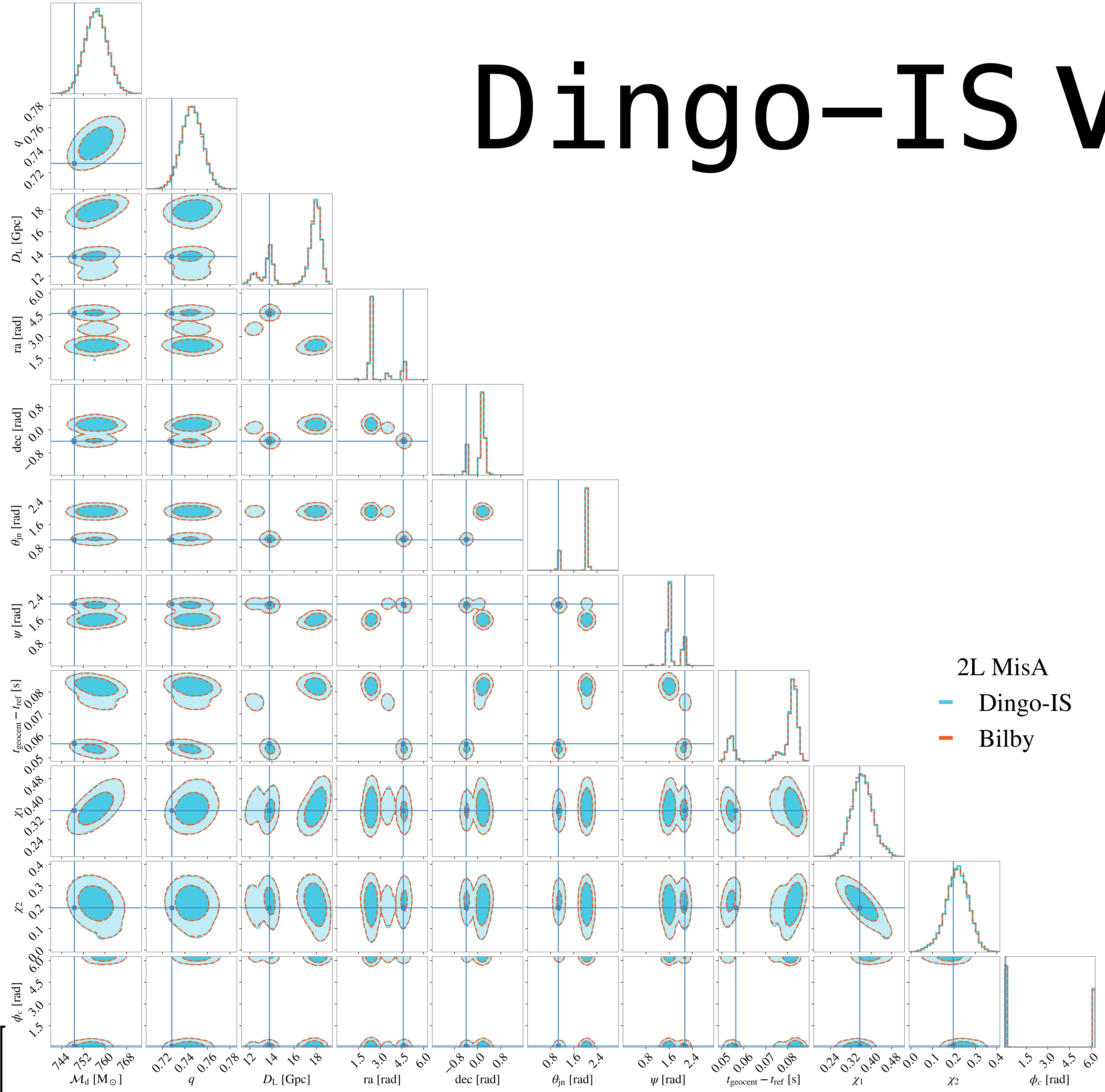
For 1L + CE, ~ 50% of sources with **one sky mode**

Sky modes



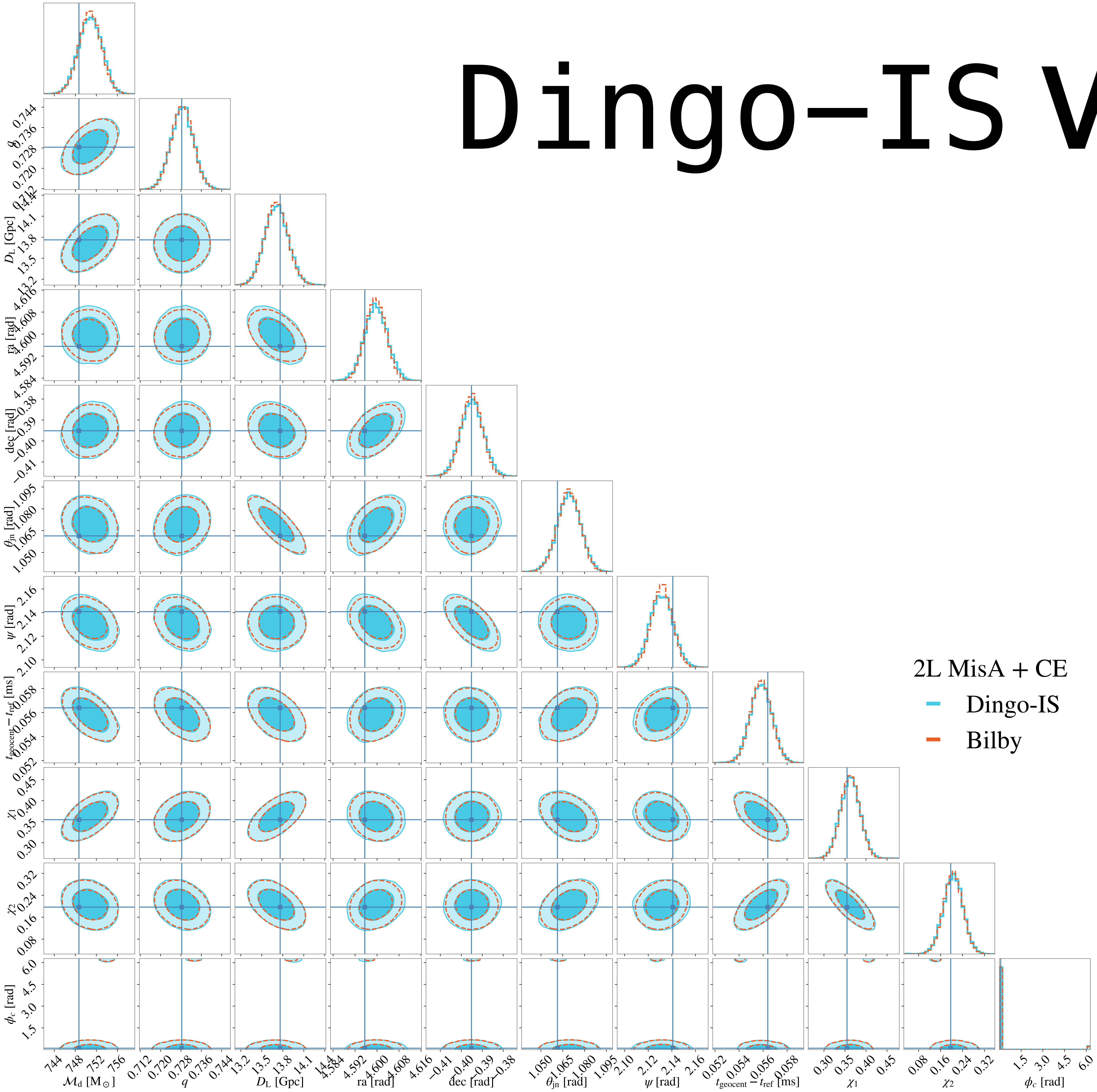
(ra^inj, dec^inj)
2L MisA, $\mathcal{M}_d^{inj} = 145.3\ M_\odot$, $\Delta\Omega_{90\%} = 194\ deg^2$
2L MisA, $\mathcal{M}_d^{inj} = 55.5\ M_\odot$, $\Delta\Omega_{90\%} = 3\ deg^2$
Δ, $\mathcal{M}_d^{inj} = 55.5\ M_\odot$, $\Delta\Omega_{90\%} = 50\ deg^2$
60°
30°
0°
-30°
-60°
0h
21h
18h
15h
12h
9h
6h
3h
0h

Dingo-IS VS Bilby



Refs. [Santoliquido et al. 2025b]

Dingo-IS VS Bilby



Refs. Santoliquido et al. 2025b

Parameter estimation performance