Università di Pisa

INFN

MUR
Ministero dell'Università e della Ricerca
PRIN 2022

Boosting Inference for Gravitational-Wave Astrophysics

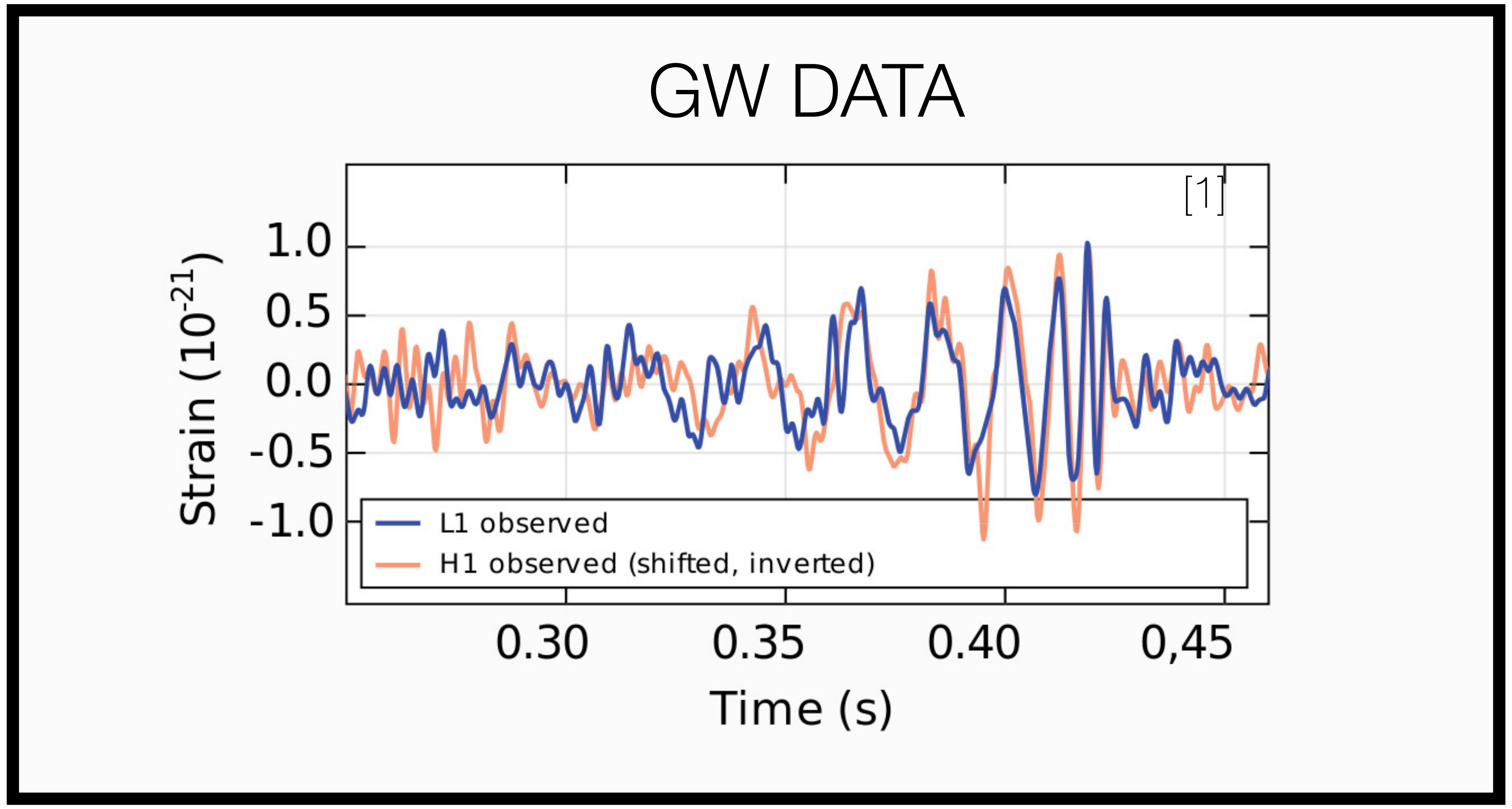
GRAWITA-METE Meeting - Padova, 10-12 Feb 2026

Giulia Capurri *(University of Pisa)*

Gravitational-wave inference

[1] The LIGO Scientific Collaboration, the Virgo Collaboration (2016) arXiv:1602.03839

[2] GW150914 posterior samples from SHARPy Demasi et al. 2026 arXiv:2601.02336

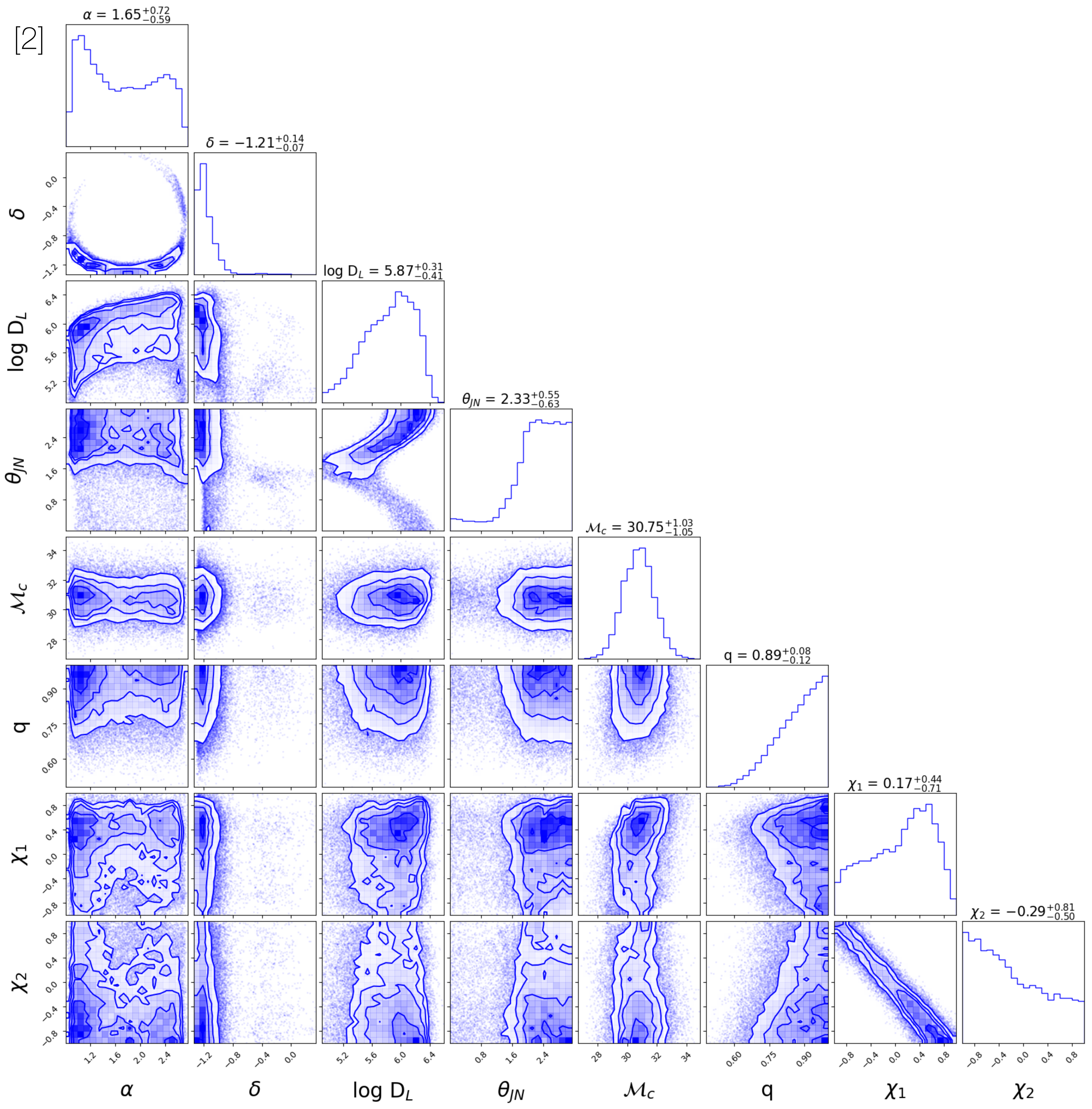


Posterior distribution of source parameters
(~11-15 depending on models)

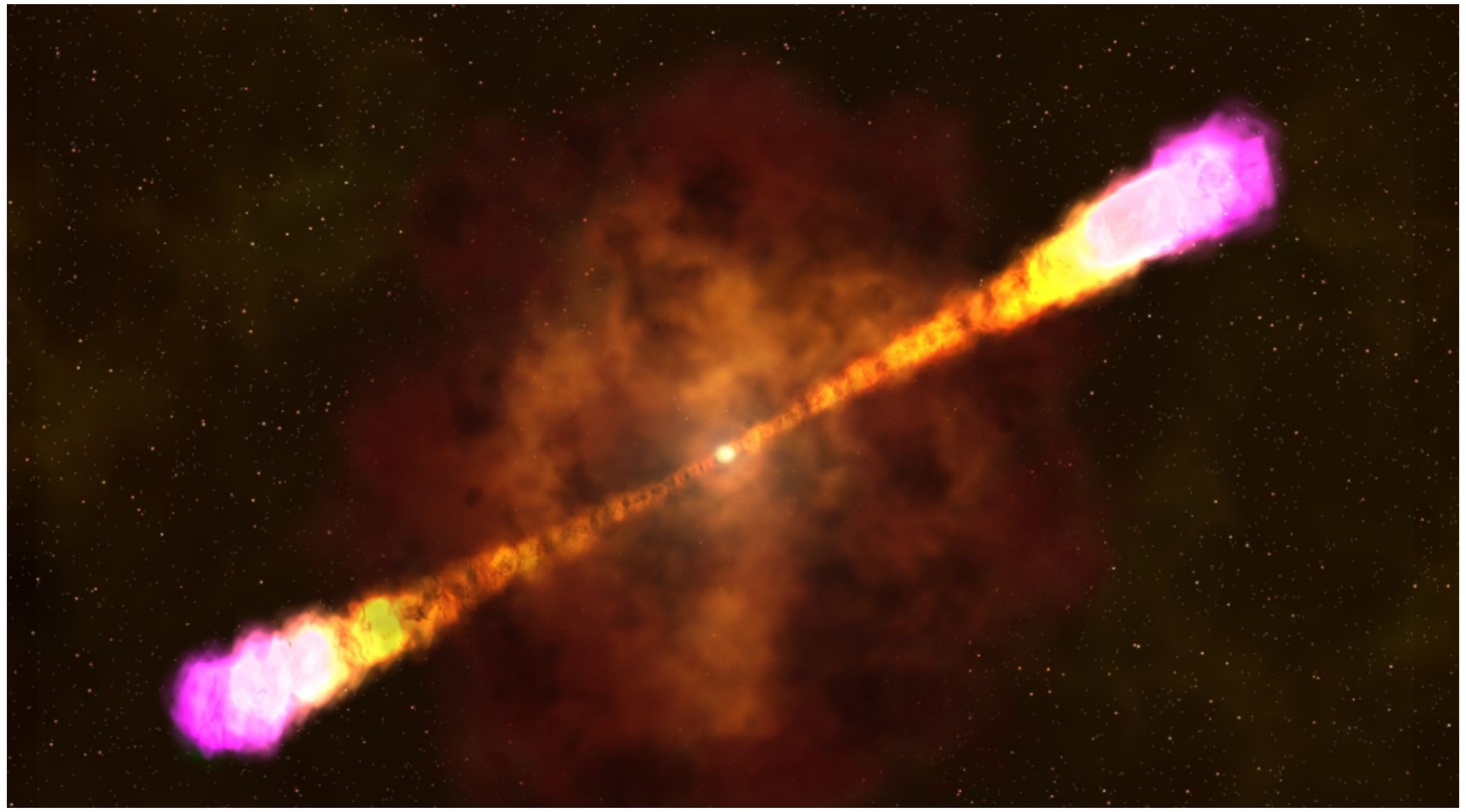
$\mathcal{M}_c, q, \chi_1, \chi_2,$

$\alpha, \delta, d_L, \theta_{jn}, t_c, \Psi, \Phi_{ref}$

Most relevant for multi-messenger astronomy



From GW inference to EM follow-up: what do we need?



[1]

EM emission after BNS/NS-BH mergers:

- Short Gamma-Ray Burst
  - Prompt emission: **< 2 s**
  - Afterglow emission: **minutes —> months**
- Kilonova: **days —> weeks**

Short timescales

Beamed emission

[1] Illustration of GRB jets. Credits: NASA Goddard Space Flight Center

From GW localization to EM follow-up: what do we need?

GOAL

Develop tools to optimize GW data analysis and maximize the chances of identifying the EM counterpart.

Two crucial factors:

- **Rapid and accurate localization** of the GW event
- **Inclination angle information**

GW event localization

GW trigger

BAYESTAR[1] skymap

~ sec/min

First full parameter estimation results

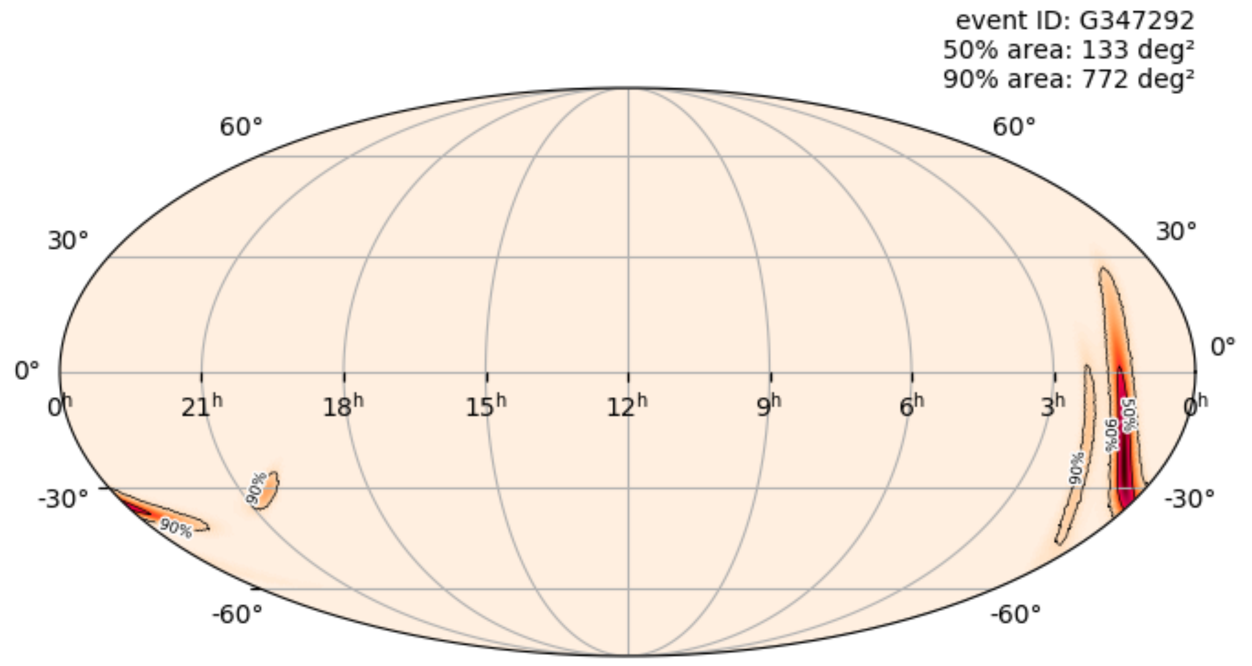
~ 10 minutes

Refined parameter estimation results

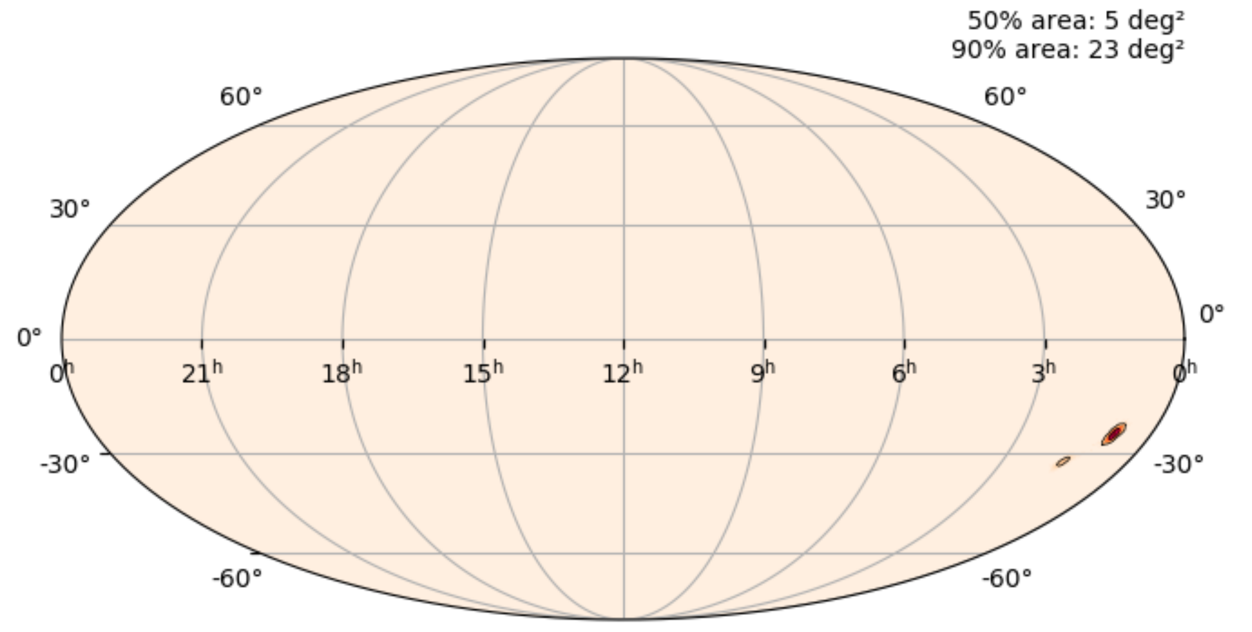
~ hours/days

ACCURACY

First public alert



Alert updates



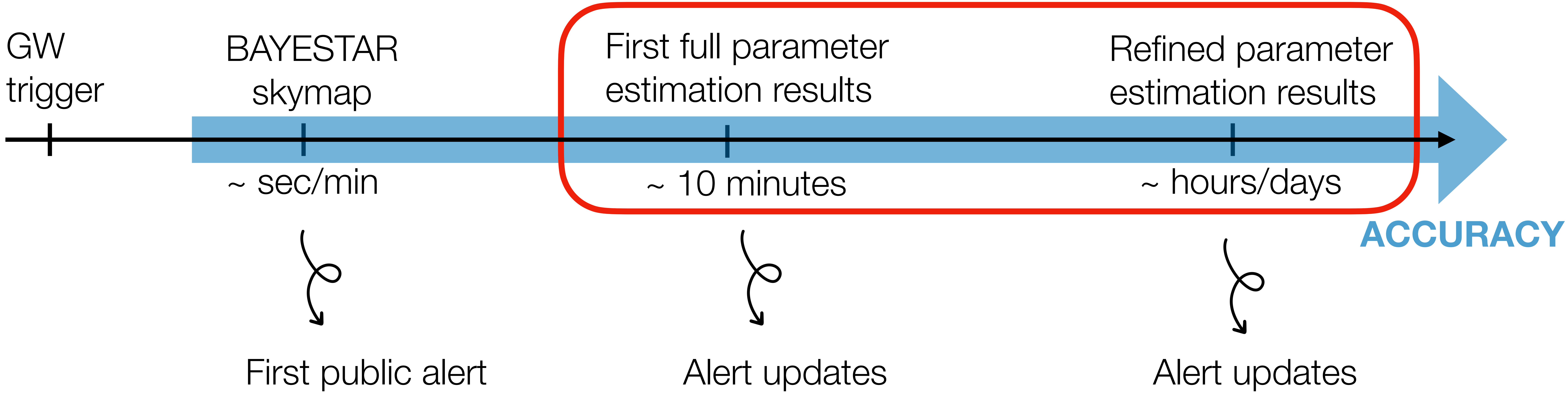
Alert updates

[1] Singer and Price 2016 arXiv:1508.03634

Can we do better?

① We can improve PE:

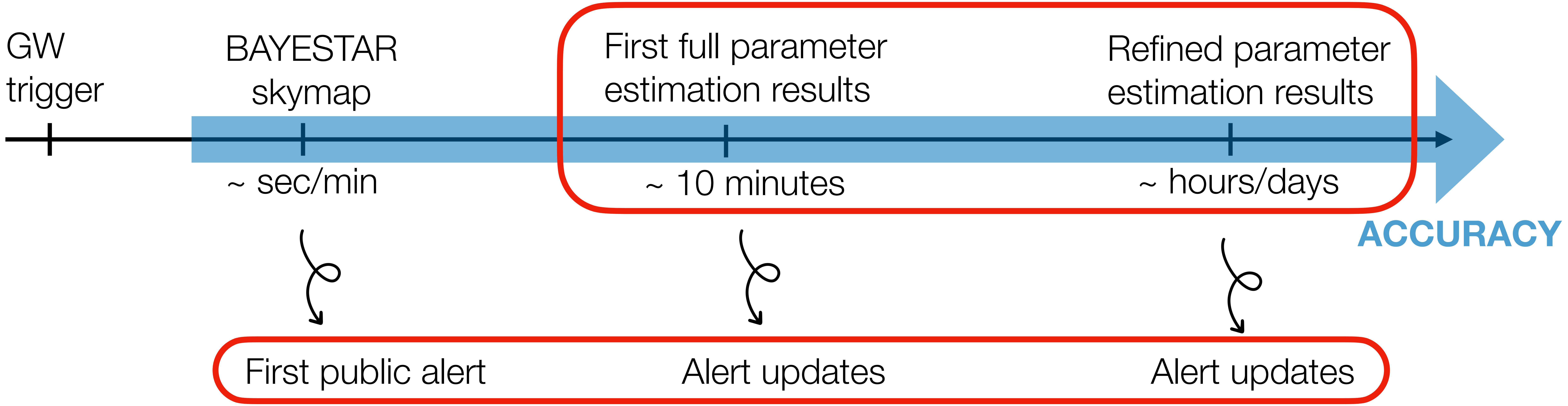
- faster
- more robust
- reduced computational cost



Can we do better?

1 We can improve PE:

- faster
- more robust
- reduced computational cost

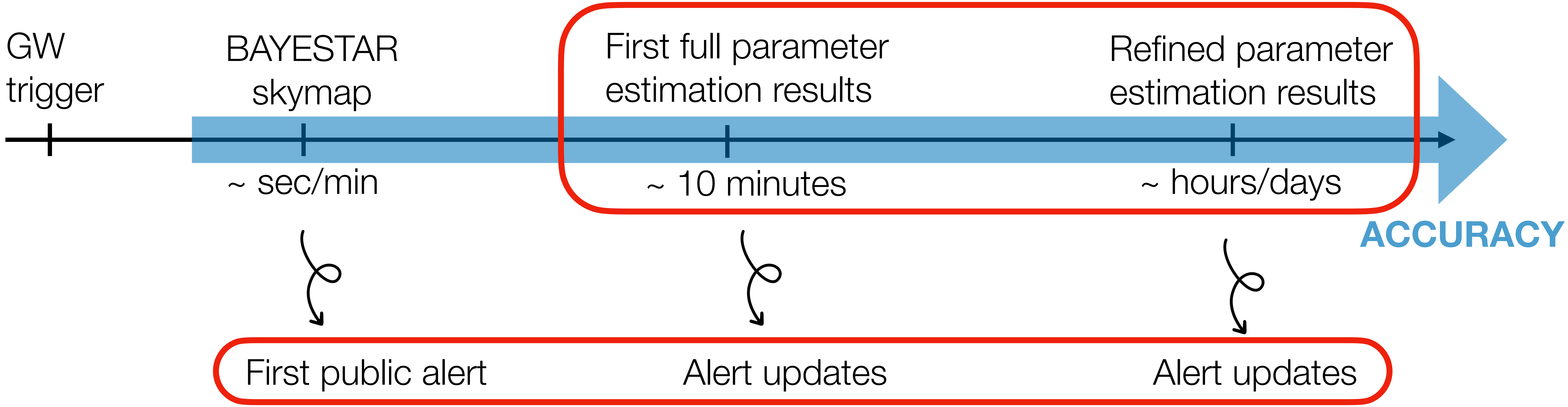


2 We have the ability to produce more information (e.g., inclination angle) at all alert timescales

Can we do better?

1 We can improve PE:

- faster
- more robust
- reduced computational cost



2 We have the ability to produce more information (e.g., inclination angle) at all alert timescales

3 We can strengthen the interface with EM communities (e.g. by integrating galaxy catalogs into the workflow)

Boosting **I**nference for **G**ravitational-wave **A**stronomy

University of Pisa, INFN Pisa

Giulia Capurri, Barbara Patricelli, Angelo Ricciardone, Walter Del Pozzo

University of Firenze, INFN Firenze

Gabriele Demasi, Massimo Lenti

University of Urbino, INFN Firenze

Saul Albuquerque, Gianluca Guidi

INAF Bologna, INFN Bologna

Giulia Stratta

Sapienza University of Rome, INFN Rome

Lorenzo Piccari, Adriano Mascioli, Francesco Pannarale

BIGA

Ministero dell'Università e della Ricerca

PRIN

Progetti di Ricerca di Rilevante Interesse Nazionale

SHARPy[1] **GPU-accelerated PE pipeline** using a **Sequential Monte Carlo** scheme

MLGW-JAX[2] **rapid waveform generation** using **machine learning,** implemented in **JAX**

SKYFAST[3] **rapid galaxy host localization** and **inclination angle information**

[1] Demasi et al. 2026 arXiv:2601.02336, [2] Mascioli et al. (in prep), [3] Demasi et al. 2025 arXiv:2407.13695

Boosting Inference for Gravitational-wave Astronomy

University of Pisa, INFN Pisa

Giulia Capurri, Barbara Patricelli, Angelo Ricciardone, Walter Del Pozzo

University of Firenze, INFN Firenze

Gabriele Demasi, Massimo Lenti

University of Urbino, INFN Firenze

Saul Albuquerque, Gianluca Guidi

INAF Bologna, INFN Bologna

Giulia Stratta

Sapienza University of Rome, INFN Rome

Lorenzo Piccari, Adriano Mascioli, Francesco Pannarale

BIGA

SHARPy[1] **GPU-accelerated PE pipeline** using a **Sequential Monte Carlo** scheme

MLGW-JAX[2] **rapid waveform generation** using **machine learning,** implemented in **JAX**

SKYFAST[3] **rapid galaxy host localization** and **inclination angle information**

Ministero dell'Università e della Ricerca

PRIN
Progetti di Ricerca di Rilevante Interesse Nazionale

[1] Demasi et al. 2026 arXiv:2601.02336, [2] Mascioli et al. (in prep), [3] Demasi et al. 2025 arXiv:2407.13695

Analytical posterior reconstruction with DPGMM

input

Posterior samples for
$\alpha, \delta, d_L, \theta_{jn}$

output

Analytical posterior
$p(\alpha, \delta, d_L, \theta_{jn})$

SKYFAST

$$p(\boldsymbol{x}) = \sum_{k=1}^{\infty} w_k \mathcal{N}(\boldsymbol{x} \,|\, \boldsymbol{\mu}_k, \boldsymbol{\sigma}_k)$$

$\boldsymbol{x} = \{\alpha, \delta, d_L, \theta_{jn}\}$

Gaussian mixture:
$\{w_k, \boldsymbol{\mu}_k, \boldsymbol{\sigma}_k\}$

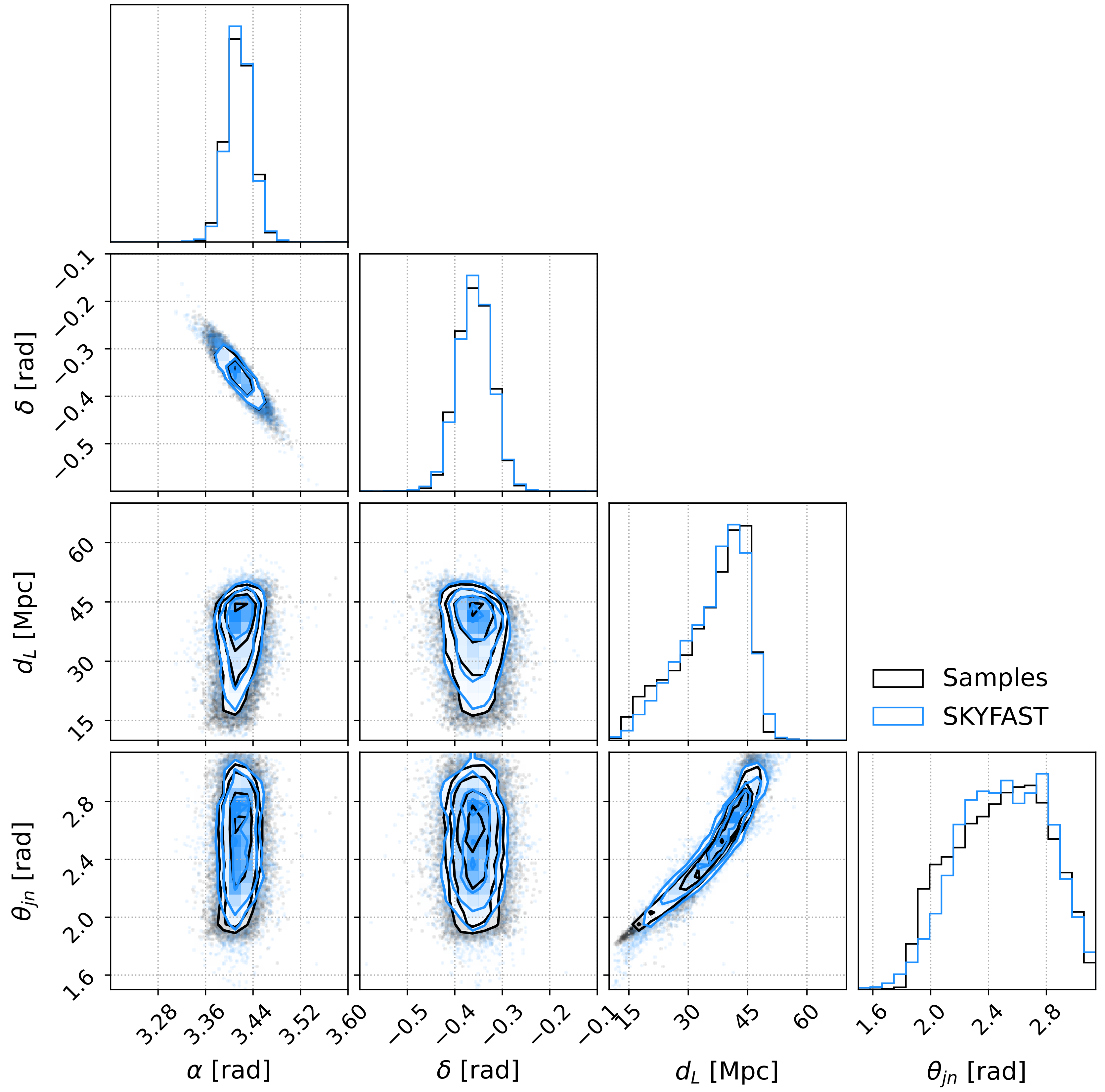
Dirichlet process gaussian mixture model
FIGARO[1]

[1] Rinaldi & Del Pozzo 2021 arXiv:2109.05960,
Rinaldi & Del Pozzo 2022 arXiv:2205.07252,
Del Pozzo et al. 2018 arXiv:1801.08009

Why is this useful?

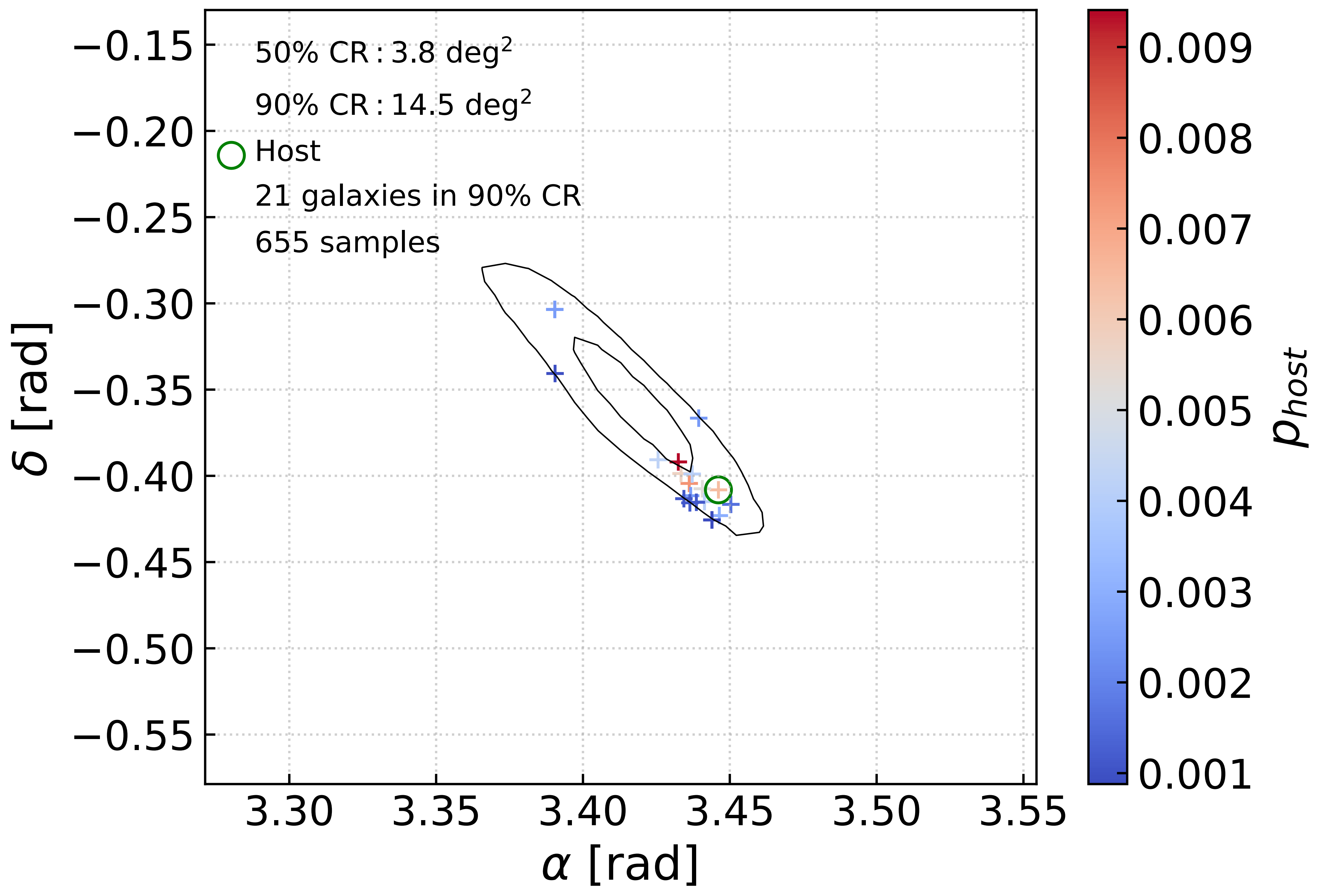
Raw output:

Analytical posteriors for $\{\alpha, \delta, d_L, \theta_{jn}\}$



Test with GW170817 samples

- **Sky and volume maps** with credible regions
- **Ranked list** of potential **galaxy hosts** from **any galaxy catalog**
- **Conditioned** probability distributions



Host galaxy ranking with inclination angle information

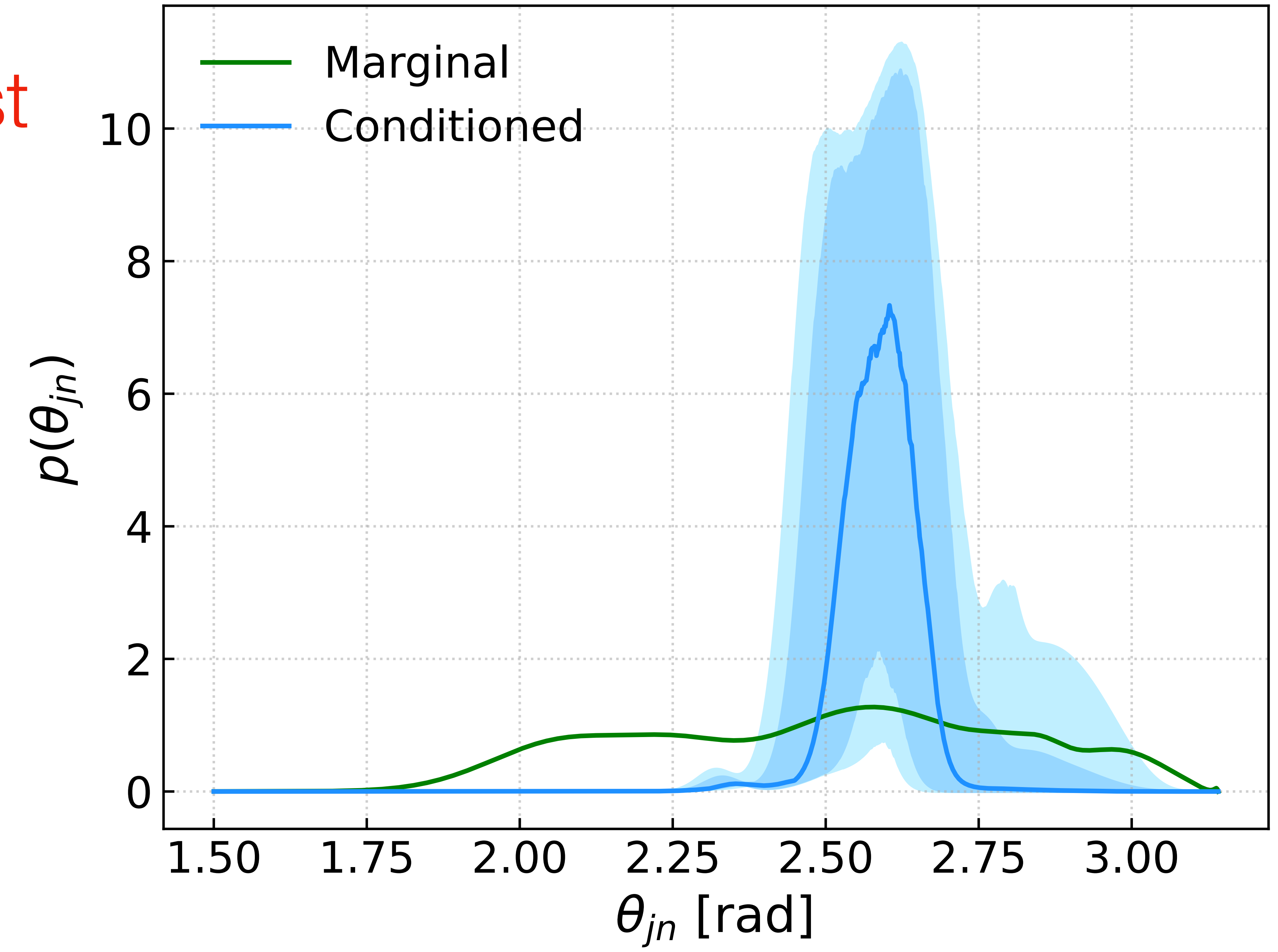
Galaxies from the GLADE+[1] catalog within the 90% credible volume of GW170817:

Galaxy	α [rad]	δ [rad]	d_L [Mpc]	logP	θ_{jn} [rad]
ESO 575-055	3.43248	-0.39193	45.30372	-4.18092	$2.82^{+0.21}_{-0.18}$
ESO 508-014	3.44065	-0.40749	44.53725	-4.51669	$2.78^{+0.18}_{-0.18}$
NGC 4993	3.44613	-0.40812	41.16691	-4.75818	$2.63^{+0.20}_{-0.15}$
J131045.95-235156.6	3.45037	-0.41654	40.30587	-5.29308	$2.59^{+0.19}_{-0.13}$
PGC 803966	3.43619	-0.40440	39.46450	-5.34645	$2.56^{+0.16}_{-0.13}$

True host

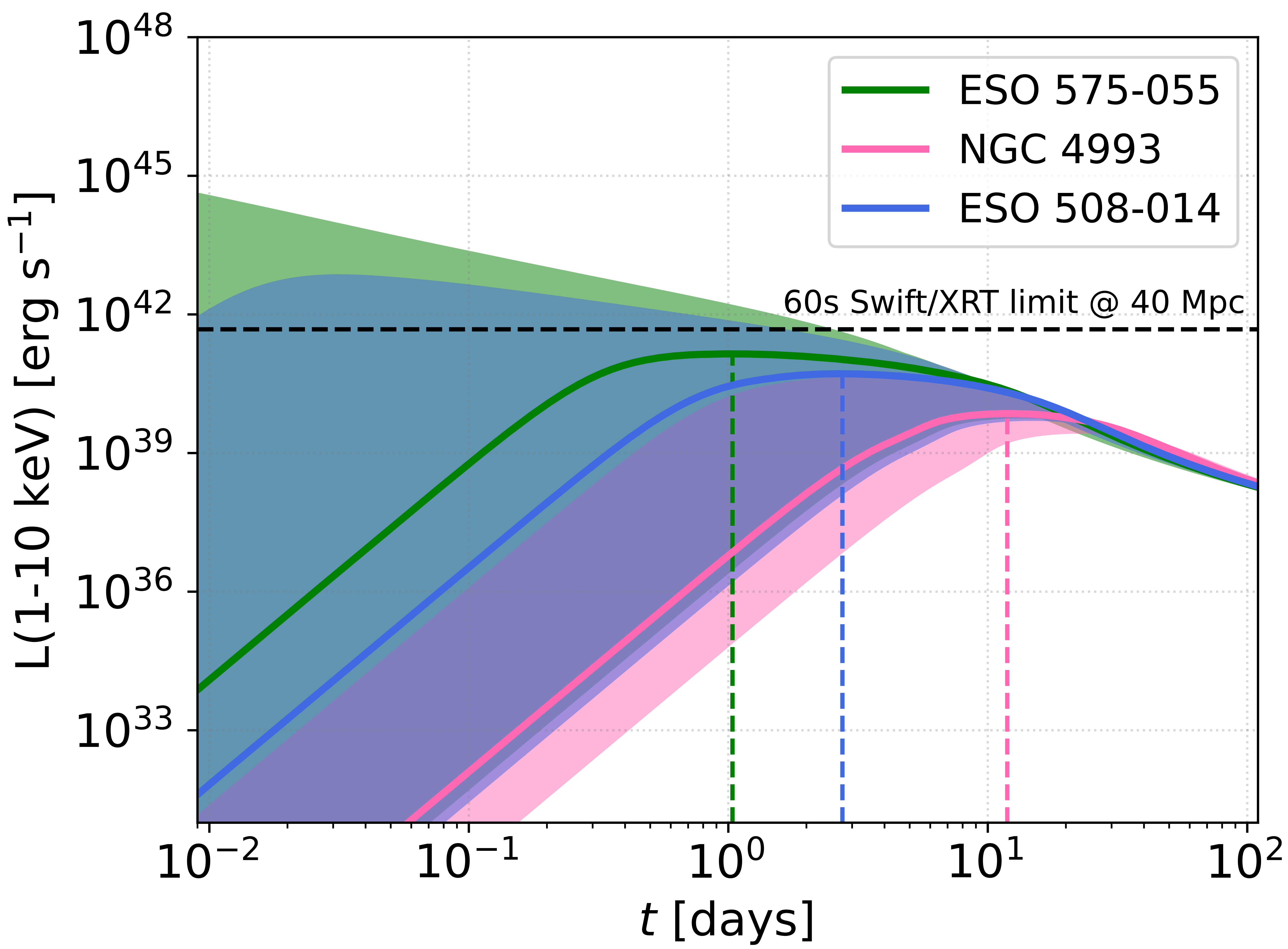
Probability of being host based on the galaxy 3D position

Inclination angle distribution conditioned to the position of the galaxy.



[1] Dálya et al. 2022 arXiv:2110.06184

The importance of inclination angle information



Impact of different conditioned inclination angle posteriors on the expected GRB afterglow light curve in the X-ray band.

The light curves are computed assuming a Gaussian profile for the structured GRB jet and the best-fit GRB parameters obtained for GW170817[1].

Ryan at al. (2020), arXiv:1909.11691

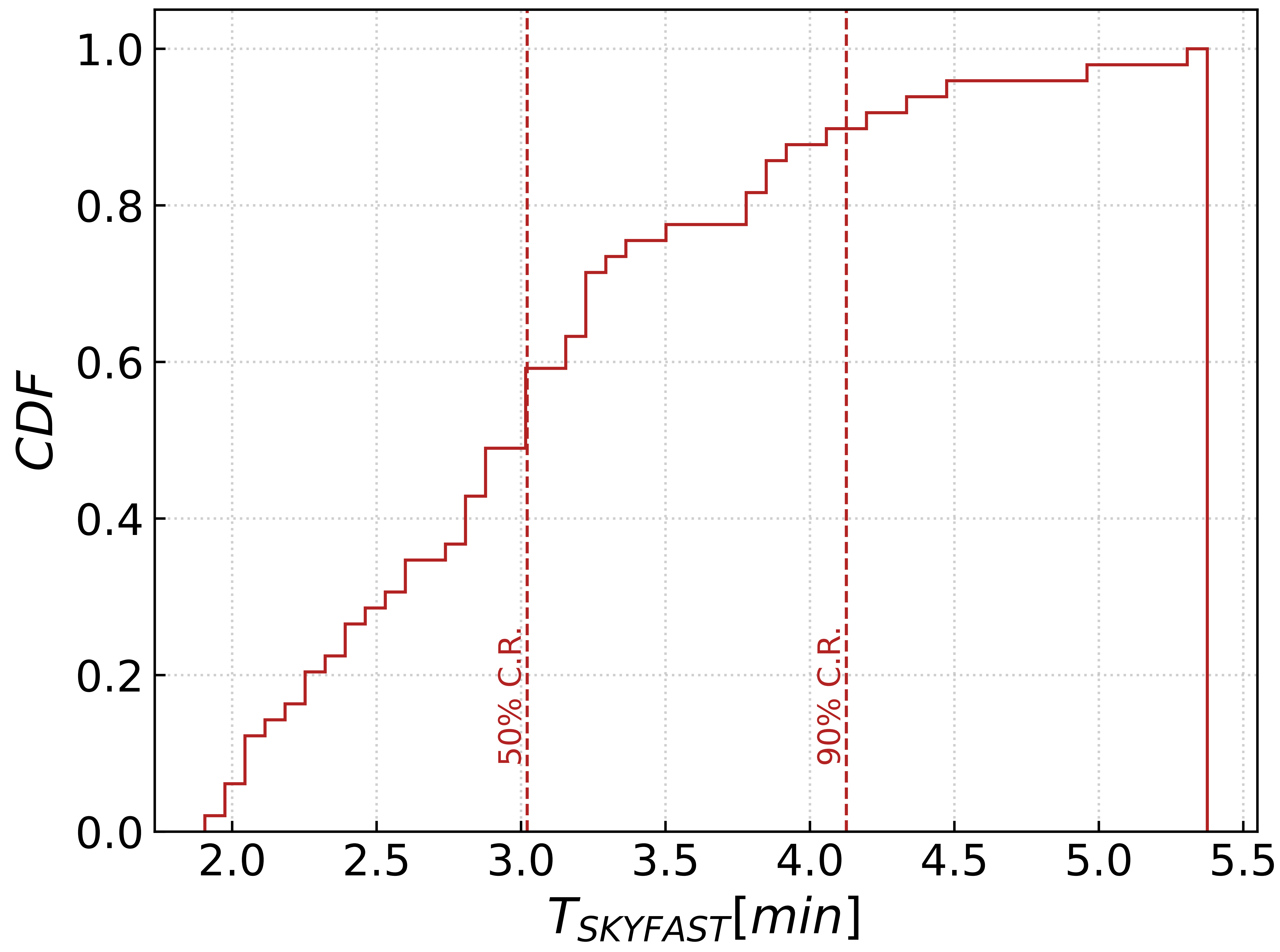
Galaxy ranking validation

Test on a population of 100 BNSs

- Position randomly extracted from GLADE+
- Max d_L = 100 Mpc, median d_L = 67 Mpc

SKYFAST results:

- Median number of galaxies in 90% CL: 30
- True host galaxy average position: 5th

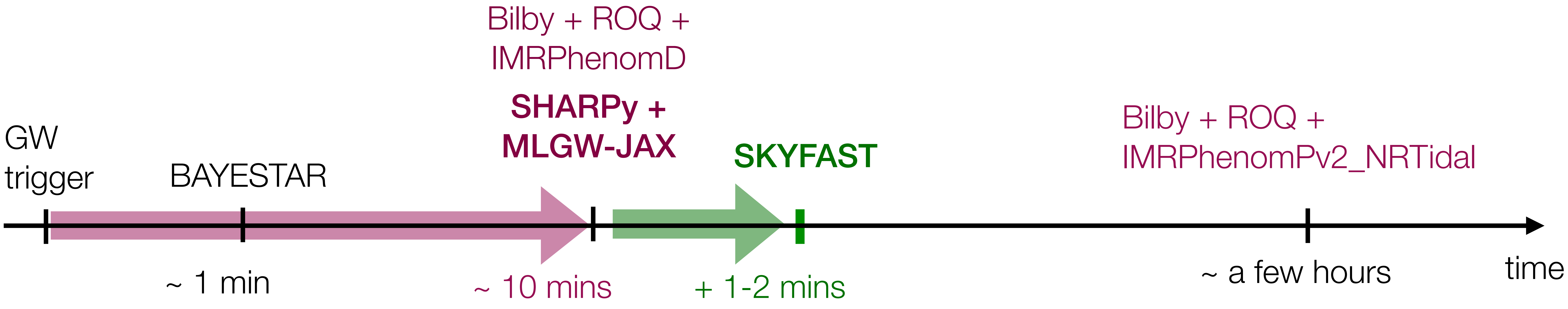


Runtimes on a cluster with 2.5 GHz CPUs

Much faster on a recent laptop (~1 min!)

Combination with PE pipelines

- BILBY[1] with sampler DYNESTY[2] and ROQ approximation[3], ~100 CPUs, used in O4
- **SHARPy + MLGW-JAX waveform generation, 1 GPU**



[1] Ashton et al. 2018 arXiv:1811.02042
[2] Speagle 2020 arXiv:1904.02180
[3] Morisaki et al. 2023 arXiv:2307.13380

Conclusions

Boosting GW inference for multi-messenger astrophysics:

- Faster PE (robust, less computationally expensive) —> **SHARPy**
- Fast waveform generation —> **MLGW-JAX**
- Rapid host localization + inclination angle information —> **SKYFAST**

SKYFAST:

- Analytic posteriors for $\{\alpha, \delta, d_L, \theta_{jn}\}$ from PE samples
- Fast host-galaxy ranking —> **Please reach out to formulate better ranking strategies!**
- Works with **any** galaxy catalog —> **Share your favourite catalogs!**
- **Inclination angle** conditioned on each candidate host

Thank you for your attention!

Feel free to reach out for any question:
giulia.capurri@df.unipi.it

SKYFAST is publicly available!
https://github.com/gabrieledemasi/skyfast