The importance of population assumptions for gravitational-wave dark sirens cosmology

Konstantin Leyde

Work with Simone Mastrogiovanni, Daniele Steer, Eric Chassande-Mottin, Christos Karathanasis, Rachel Gray, Jonathan Gair, Archisman Ghosh, Stefano Rinaldi

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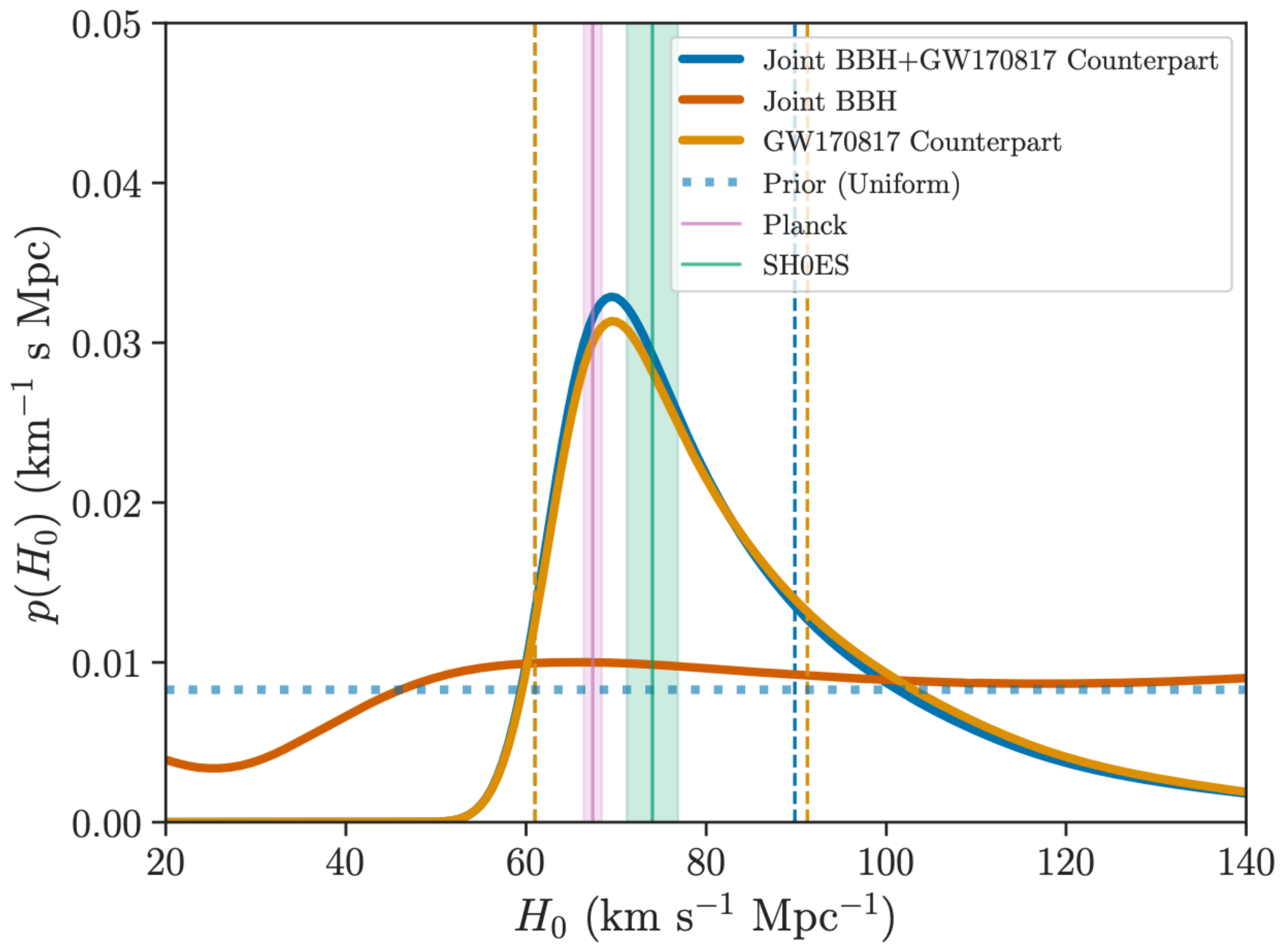
Cosmology with gravitational waves

- Gravitational waves provide us with **luminosity distance information**, to constrain the cosmology we also need **redshift information**

$$d_L(z) = \frac{(1+z)c}{H_0} \int_0^z \frac{dz'}{[\Omega_M (1+z')^3 + \Omega_\Lambda (1+z')^{3(1+w)}]^{1/2}}$$

- There are **several approaches** to GW cosmology (*Schutz 1986*):
  - Electromagnetic counterpart (GW170817)
  - Statistical association of an event with redshift information from galaxy catalogs
- Currently, the BNS horizon is at 130 Mpc, the BBH horizon is at 1200 Mpc
- **For a large fraction of events, we do not expect any observable EM counterpart** (if any generated)



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Cosmology with GW dark sirens

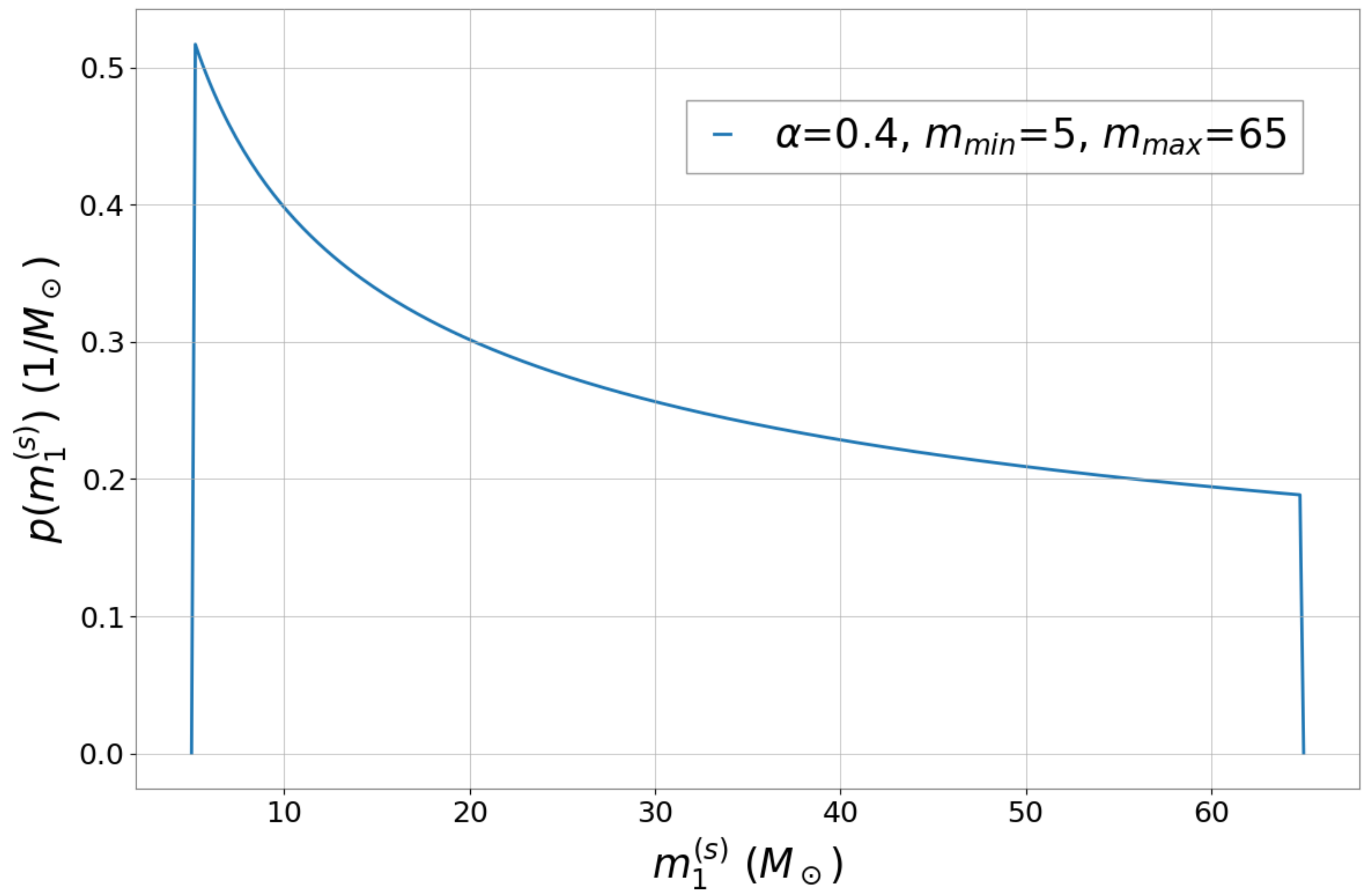
- A priori the signal carries no redshift information, we cannot distinguish between a source of higher mass in a low H_0 universe from a source with low source mass in a universe with large H_0

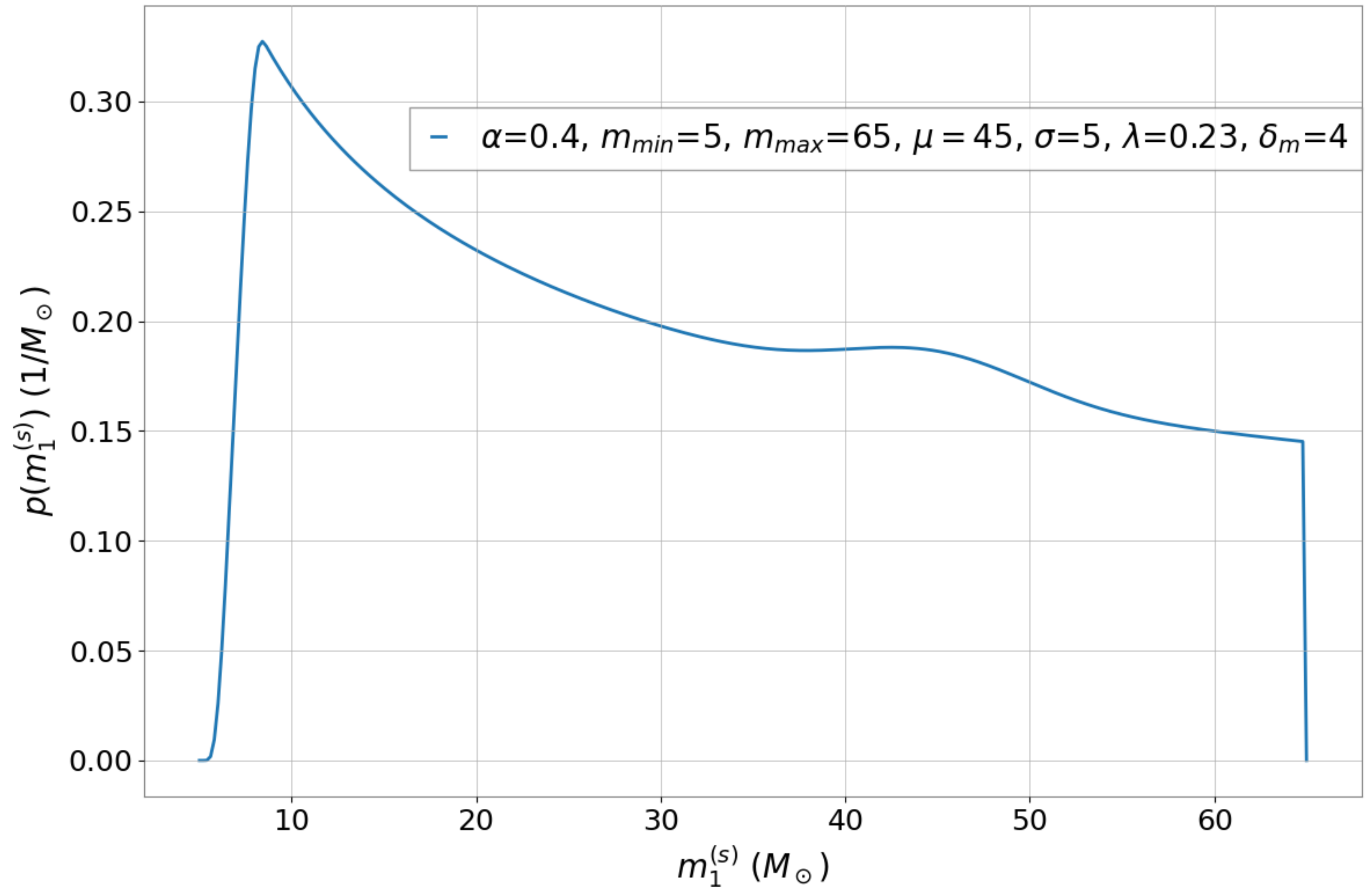
$$m^{(d)} = m^{(s)}(1+z)$$

- **If we assume a mass population model**, we can obtain a statistical measurement of the redshift (*Taylor et al. 2012, Taylor and Gair 2012, Farr et al. 2019, You et al. 2020*)
- Perform a **joint parameter estimation** Λ
    - Λ_m source mass parameters ($m_{\rm min}, m_{\rm max}, \alpha, \beta, \ldots$)
    - Cosmological parameters (H_0, Ω_M)
- We **validate this new approach with simulations and identify important factors when estimating the cosmology**

The source mass population model

- **Various astrophysical mechanisms** shape the BH mass distribution
- The simplest model: power law: mass range and two power law slopes, the PISN mass gap is a sharp cutoff
  - Motivation from **pair instability supernova** (PISN, *J. R. Bond, W. D. Arnett, and B. J. Carr* 1984) for the upper mass cutoff
- **More complex models**:
  - power law gaussian peak (excess of BHs due to PISN, accumulation point)
  - broken power law (include dynamical formation channels such as in globular clusters)





Statistical framework

Bayesian analysis with selection effects

$$p(\Lambda|\{x\}, N_{\rm obs}) \propto p(\Lambda) \prod_i^{N_{\rm obs}} \frac{\int p(x_i|\Lambda,\theta)p(\theta|\Lambda)d\theta}{\int p_{\rm det}(\theta,\Lambda)p(\theta|\Lambda)d\theta}$$

- The source parameters are θ, the GW data $\{x\}$, Λ are the population parameters and the cosmology, $p_{\rm det}$ is the detection probability

- The population assumption (mass model + cosmology + source rate's redshift evolution) is $p(\theta\,|\,\Lambda)$

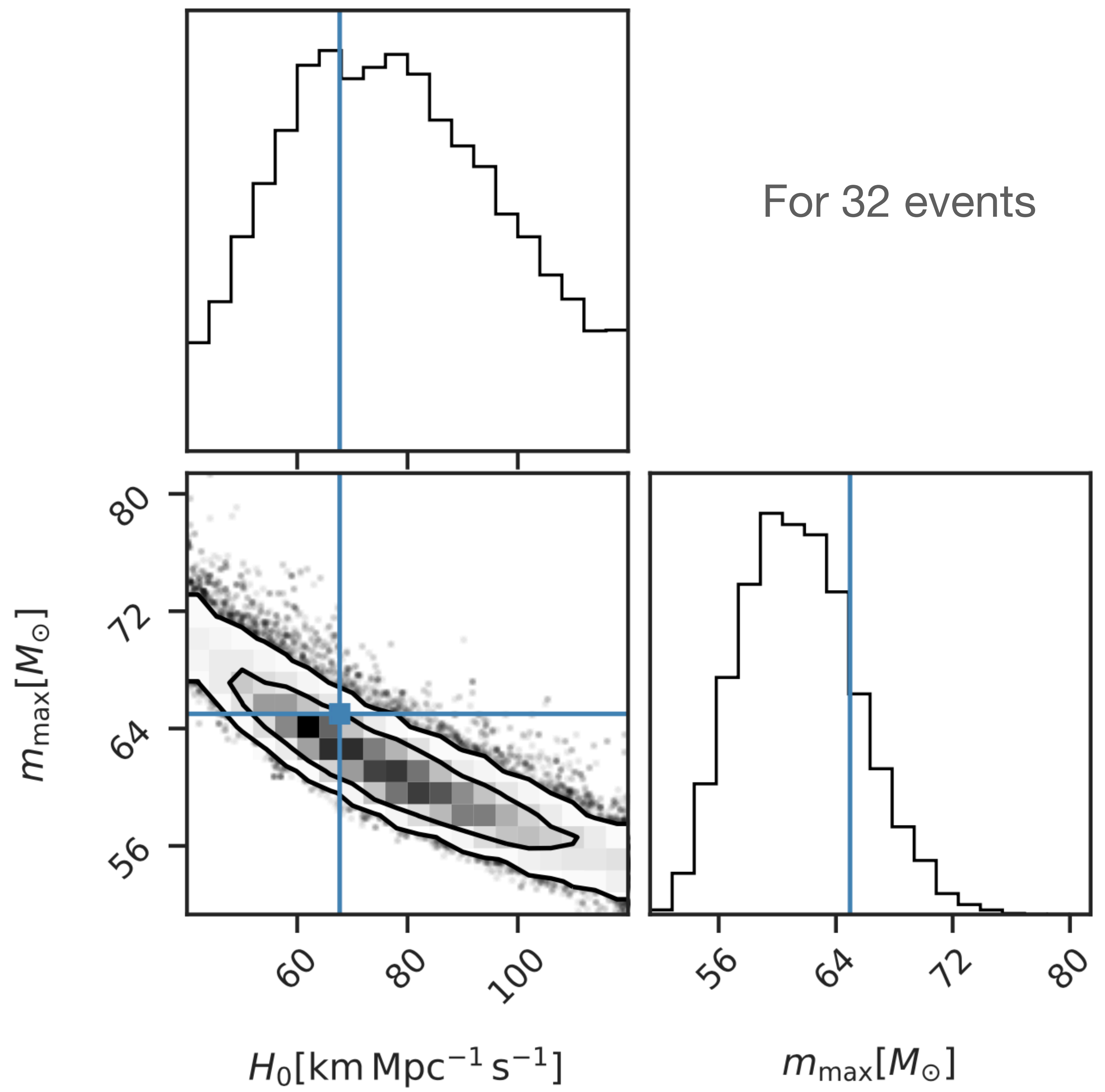
- The GW likelihood $p(x_i\,|\,\Lambda, \theta)$ is obtained **from posterior samples**

- **Noisy measurements** force us to introduce a criterion to distinguish between real events and noise (threshold on signal to noise ratio or the false alarm rate). We are subject to **selection effects**.

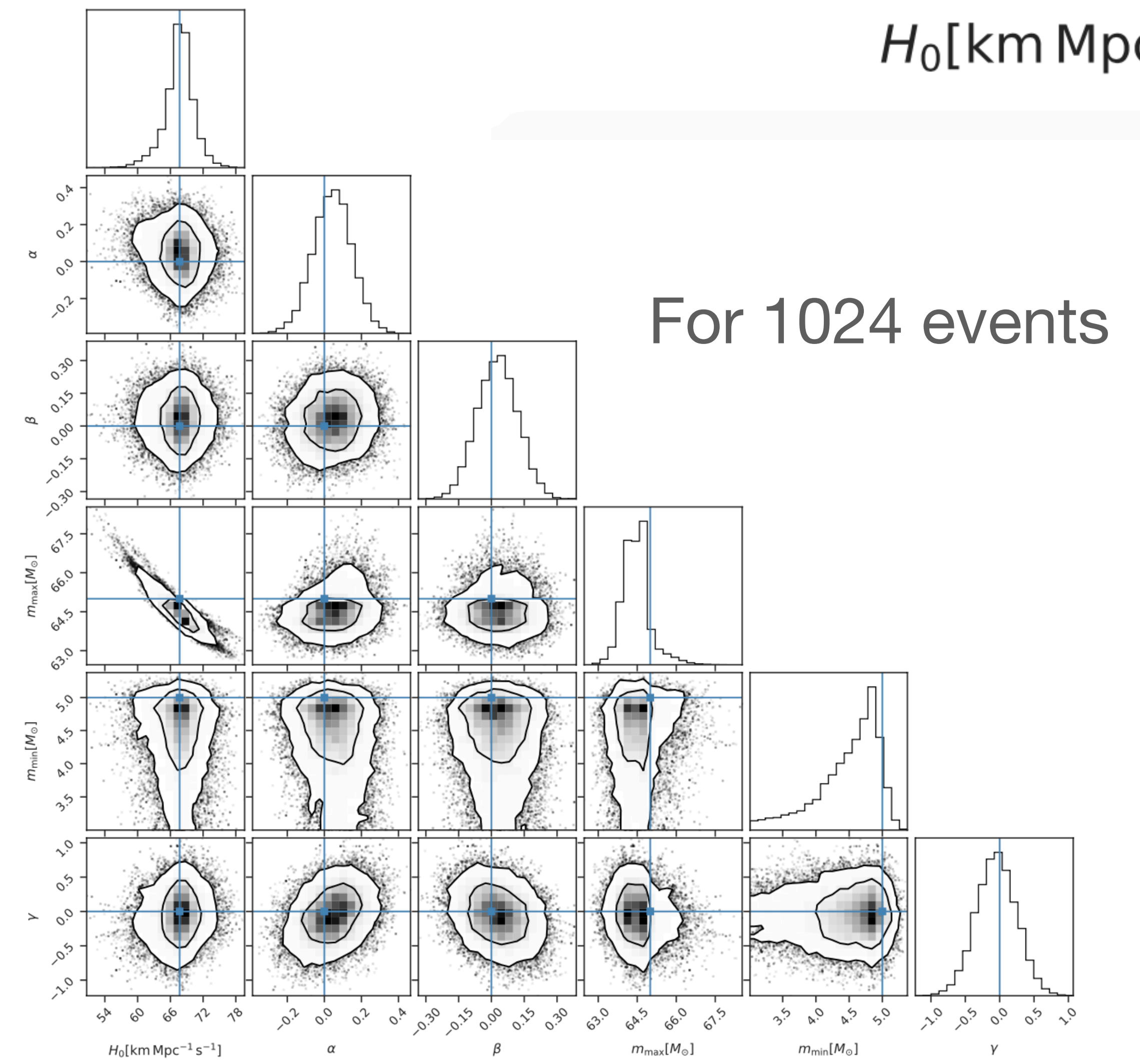
Results for an O3a scenario

Using simulated samples

- Assume a LIGO/Virgo network
- Generate a catalog with $m_{\rm min} = 5M_{\odot}, m_{\rm max} = 65M_{\odot}, \alpha = 0, \beta = 0$ of O3a like scenario with 1024 detected events
- Results **from an analytical likelihood approximant** (*Farr, Fishbach et al. 2019*).
- This model assumes **very optimistic uncertainties** on masses and luminosity distance
- **Strong correlation** between H_0 and $m_{\rm max}$



For 32 events

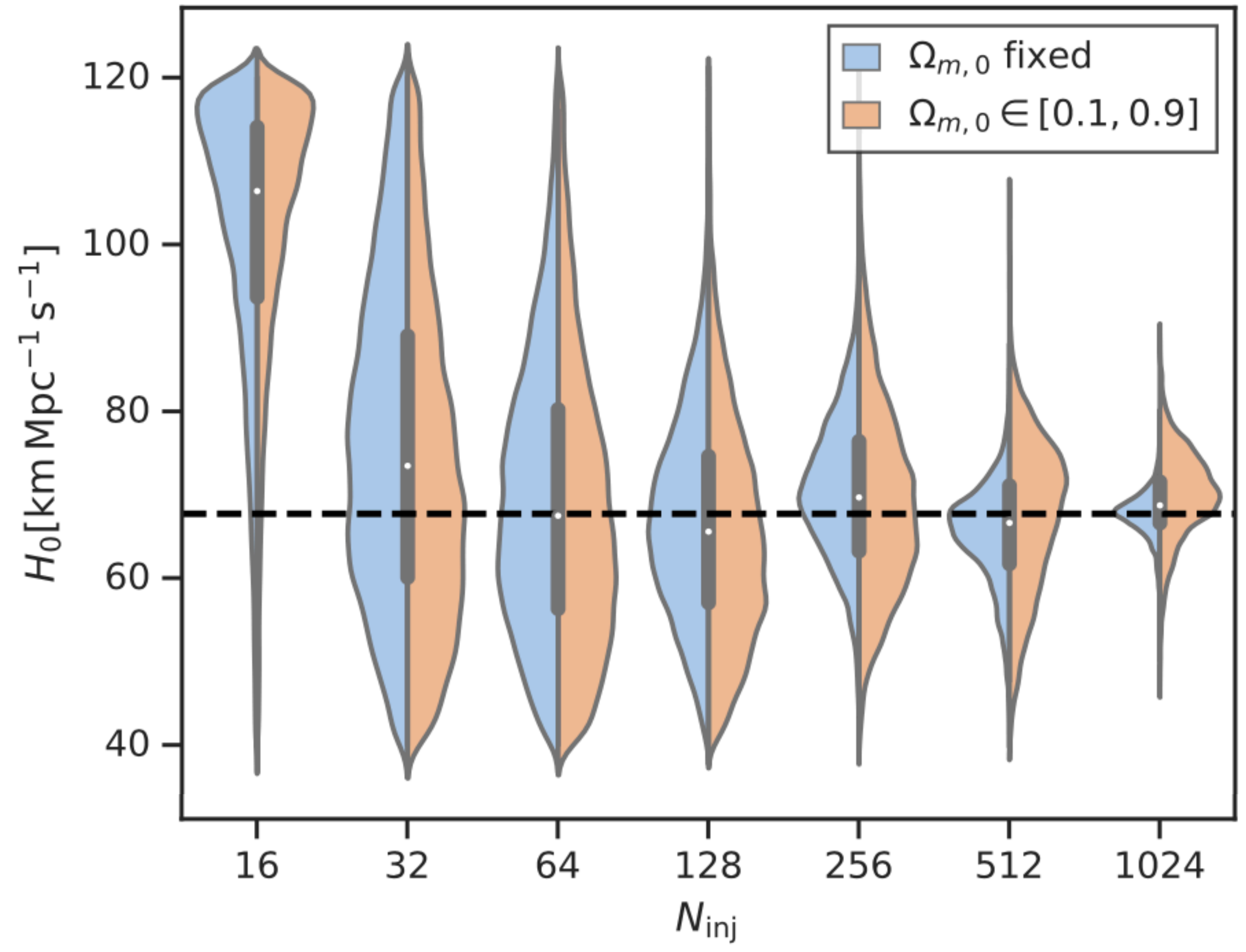


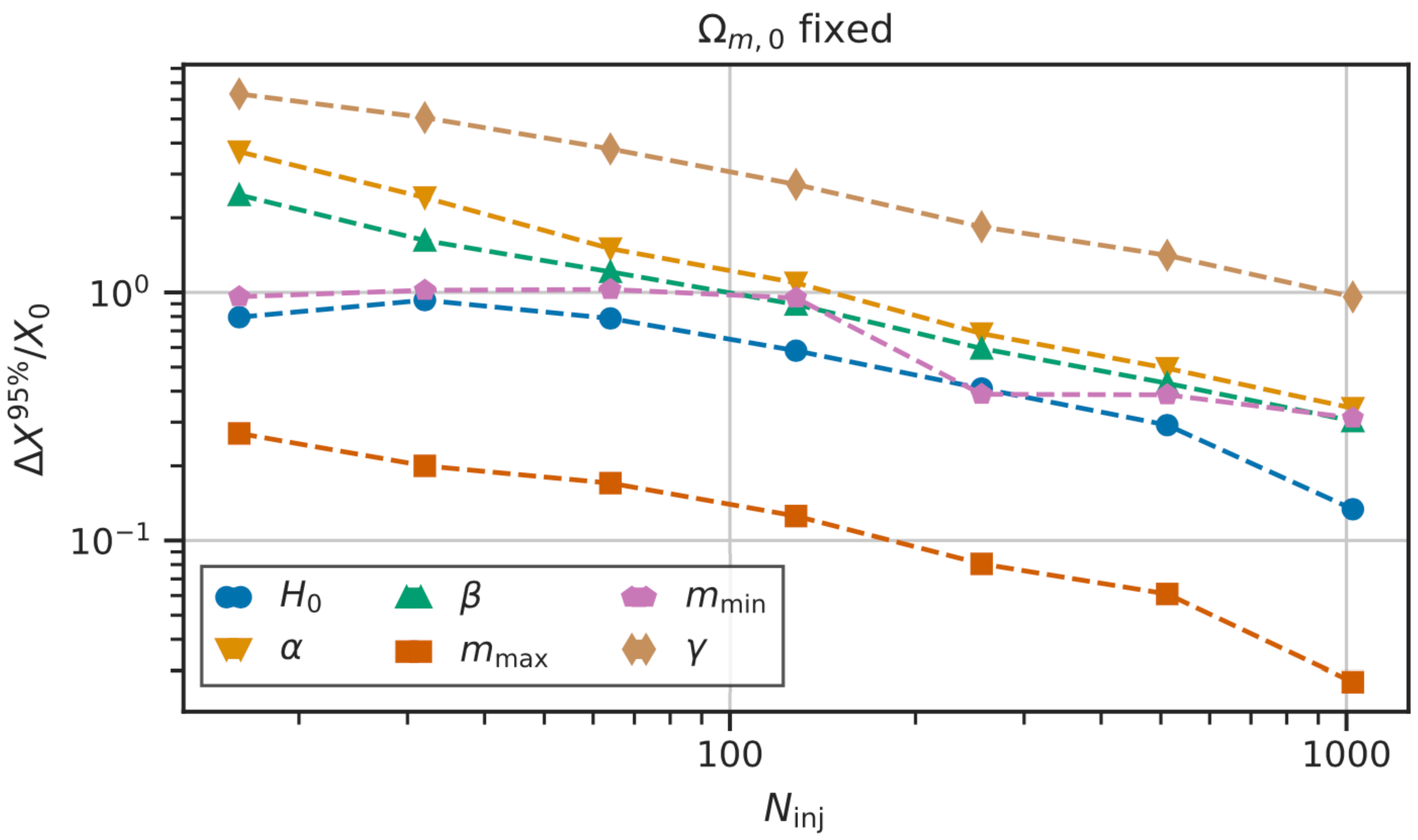
For 1024 events

Results for an O3a scenario

Using simulated samples

- For 1024 events, H_0 accuracy is at 10%
- If Ω_M is jointly estimated, H_0 accuracy is at 20%, but Ω_M is not constrained
- Uncertainty of model parameters falls towards $1/\sqrt{N_{\rm inj}}$ if the number of sources is large enough

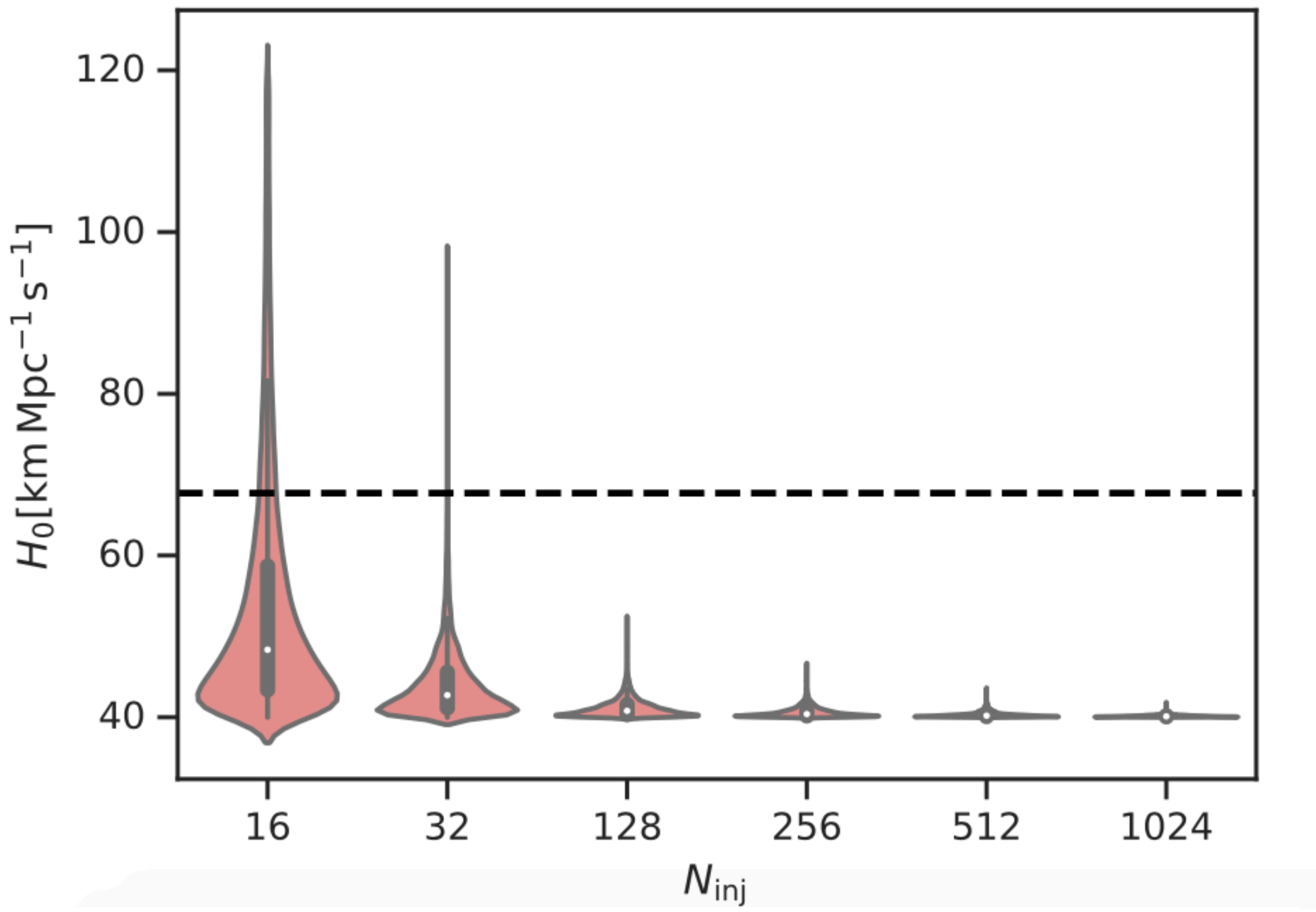


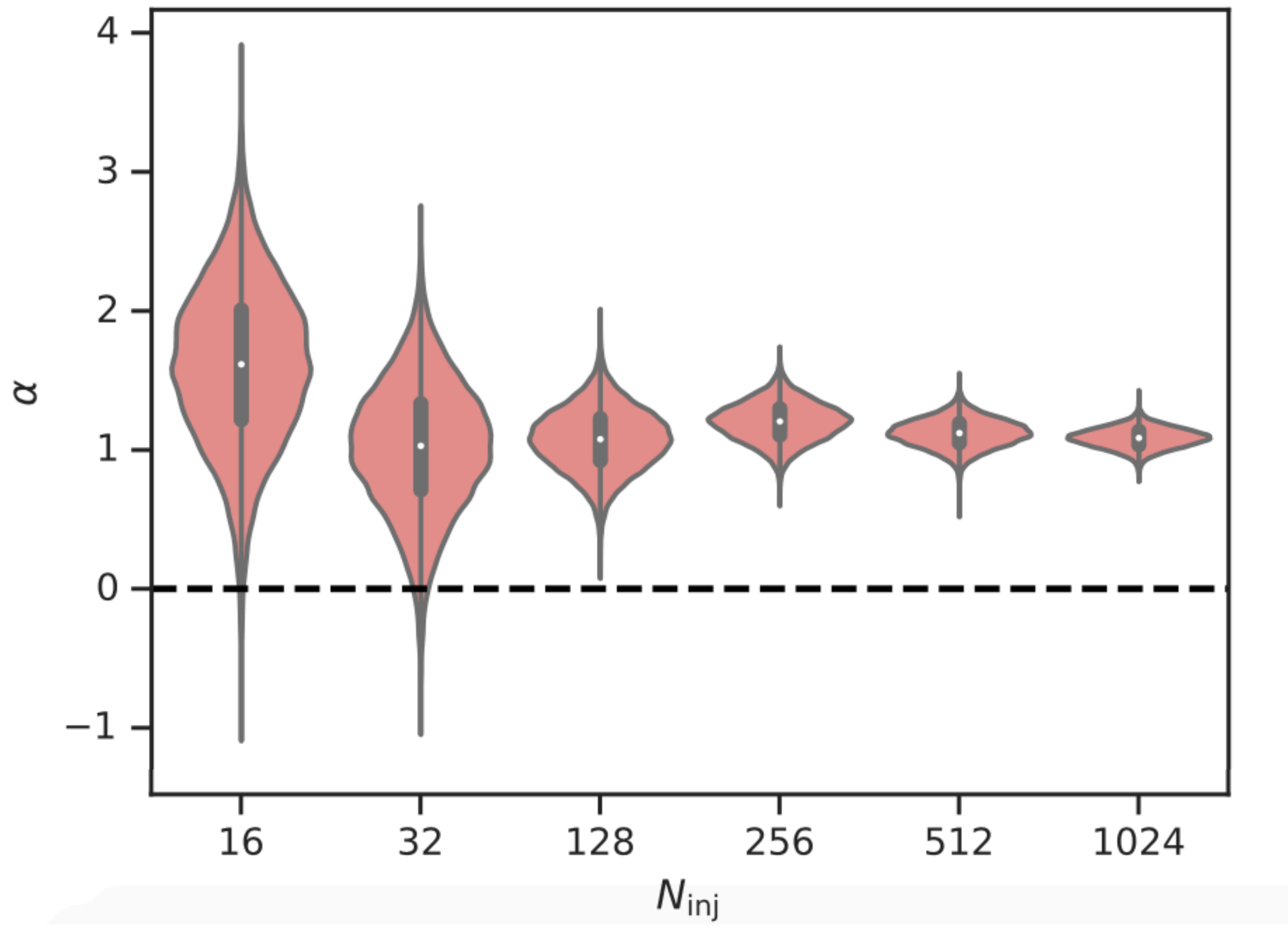


Results for an O3a scenario

Fixing the population parameters to incorrect values

- Leads to a **bias in the cosmological parameters** (which becomes more important for a large number of events)
- This is **particularly pronounced for fixing the maximum mass** to an incorrect value (recall that H_0 and $m_{\rm max}$ are strongly correlated)
- Example here: Fix $m_{\rm max}$ to 85$M_{\odot}$ (true value 65 $M_{\odot}$) and study the evolution of the bias with the number of events



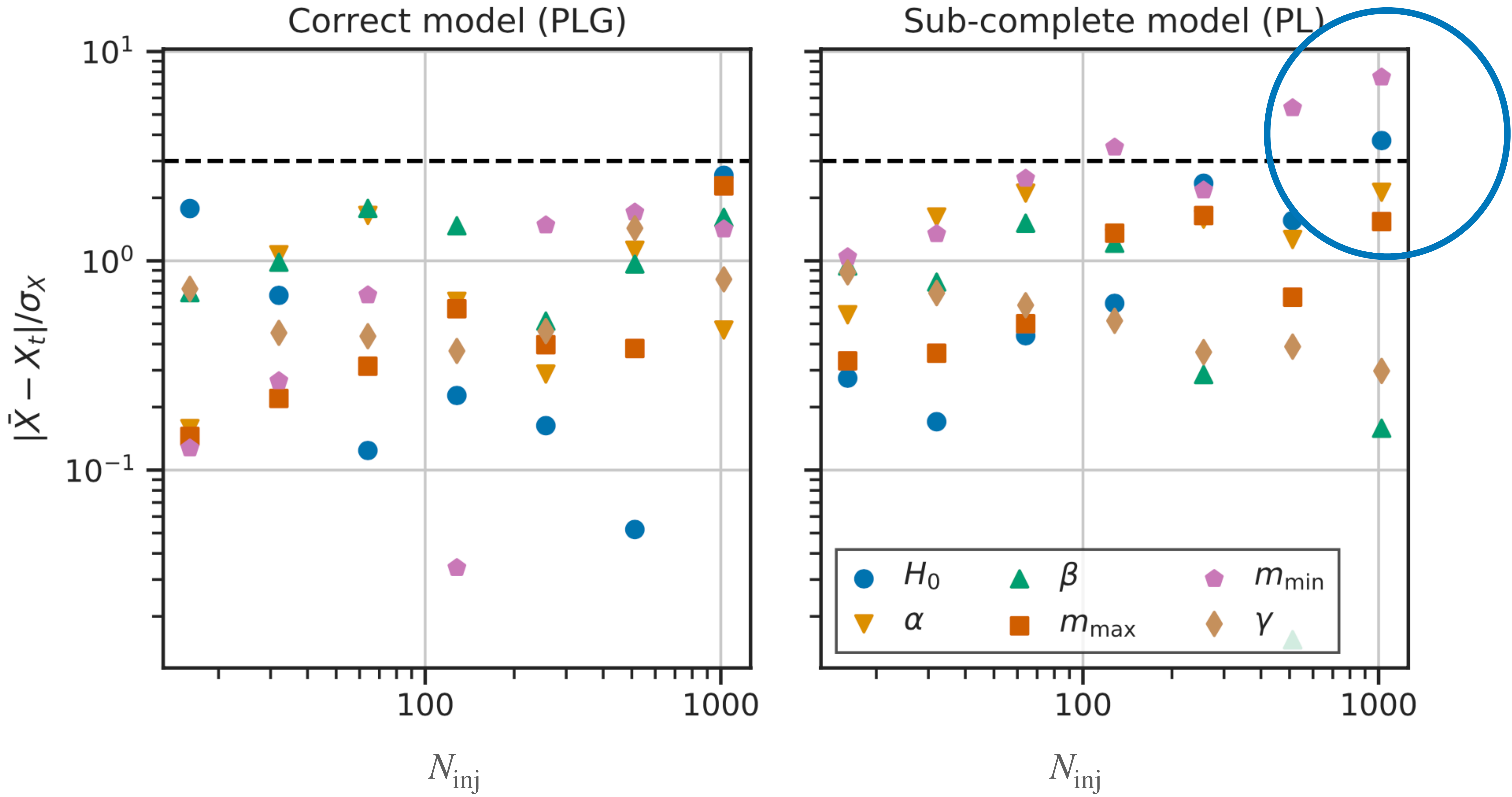


Results for an O3a scenario

Using a subcomplete model

- Ignoring the gaussian component leads to drastic difference between injected and recovered parameters

- It is **important to calculate the Bayes factor** of the two models to compare the goodness of fit



Summary

- Dark sirens will become more and more frequent in the future (from the increased sensitivity, especially for third generation GW detectors)
- This method allows one to **constrain astrophysics and cosmology at the same time** (and they should be estimated jointly)
- **Assuming the correct mass distribution is important for estimating the cosmology** — fixing incorrect population parameters (here m_{max}) will bias H_0 (up to 40%). Subcomplete models can significantly impact the estimation of the cosmology
- Paper should be appearing soon