

On the impact of lensing on standard siren measurements

Lensing of standard sirens

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Gravitational waves (GWs) from merging binaries of compact objects

- From the GW amplitude: luminosity distance of the source,

$$d_L(z) = \frac{c(1+z)}{H_0} \int_0^z \frac{dz}{\sqrt{\Omega_m(1+z)^3 + \Omega_{DE}}}$$

→ Constraints on H_0 and Ω_m

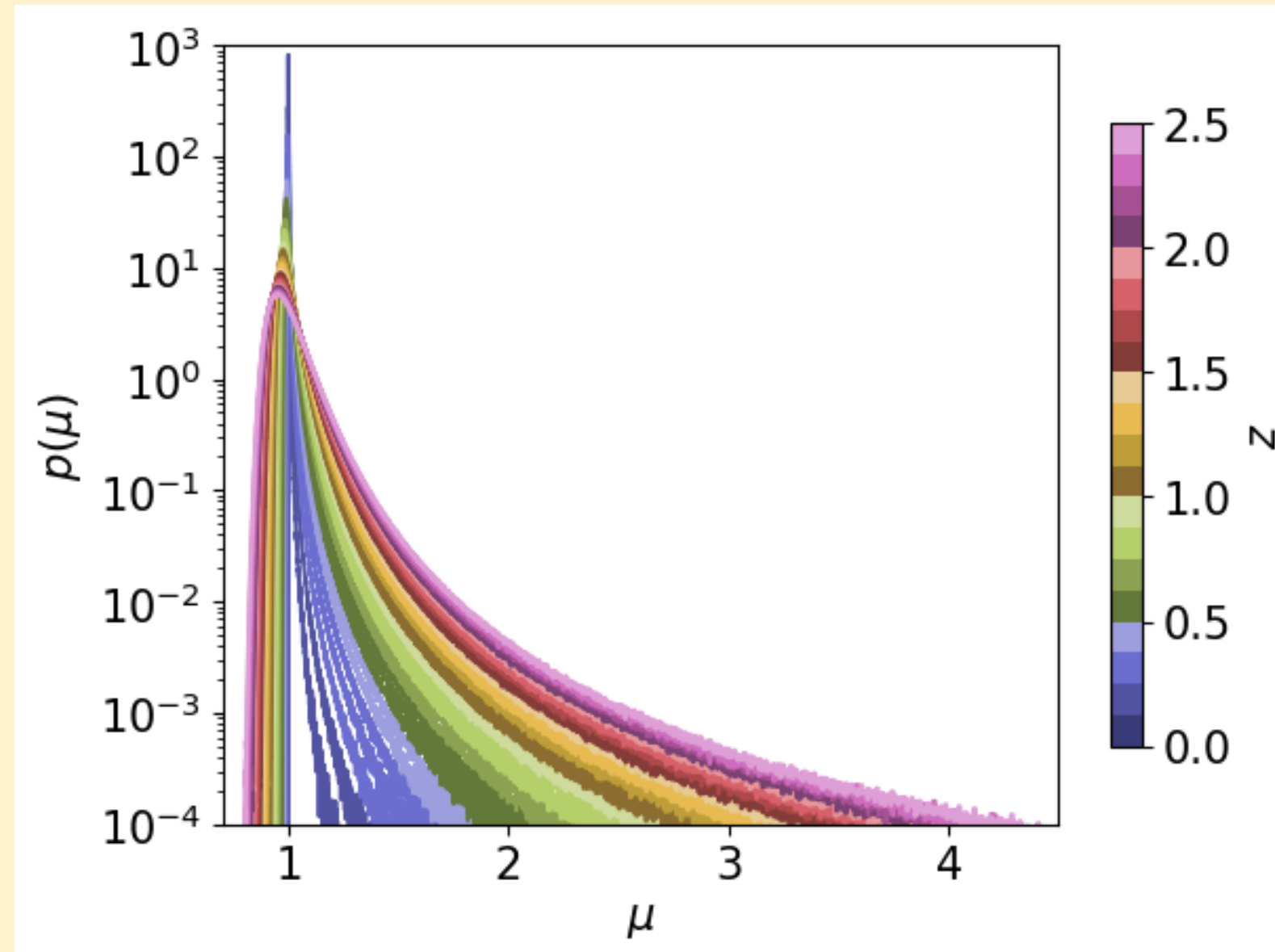
- From the GW phase: redshifted chirp mass, $\mathcal{M}_z = (1+z)\mathcal{M}$

In the geometric optic approximation ($\lambda_{GW} \ll M_L$) lensing induces a frequency-independent modification of the GW amplitude

→ Observed luminosity distance,

$$d_L^{obs} = \frac{d_L}{\sqrt{\mu}}$$

with μ the lensing magnification



Hadzhiyska B., et al., MNRAS, 525, 4367 (2023)

Mock catalogues of binary neutron star events

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Mock catalogues of binary neutron star events detectable by the *Einstein Telescope* (ET)

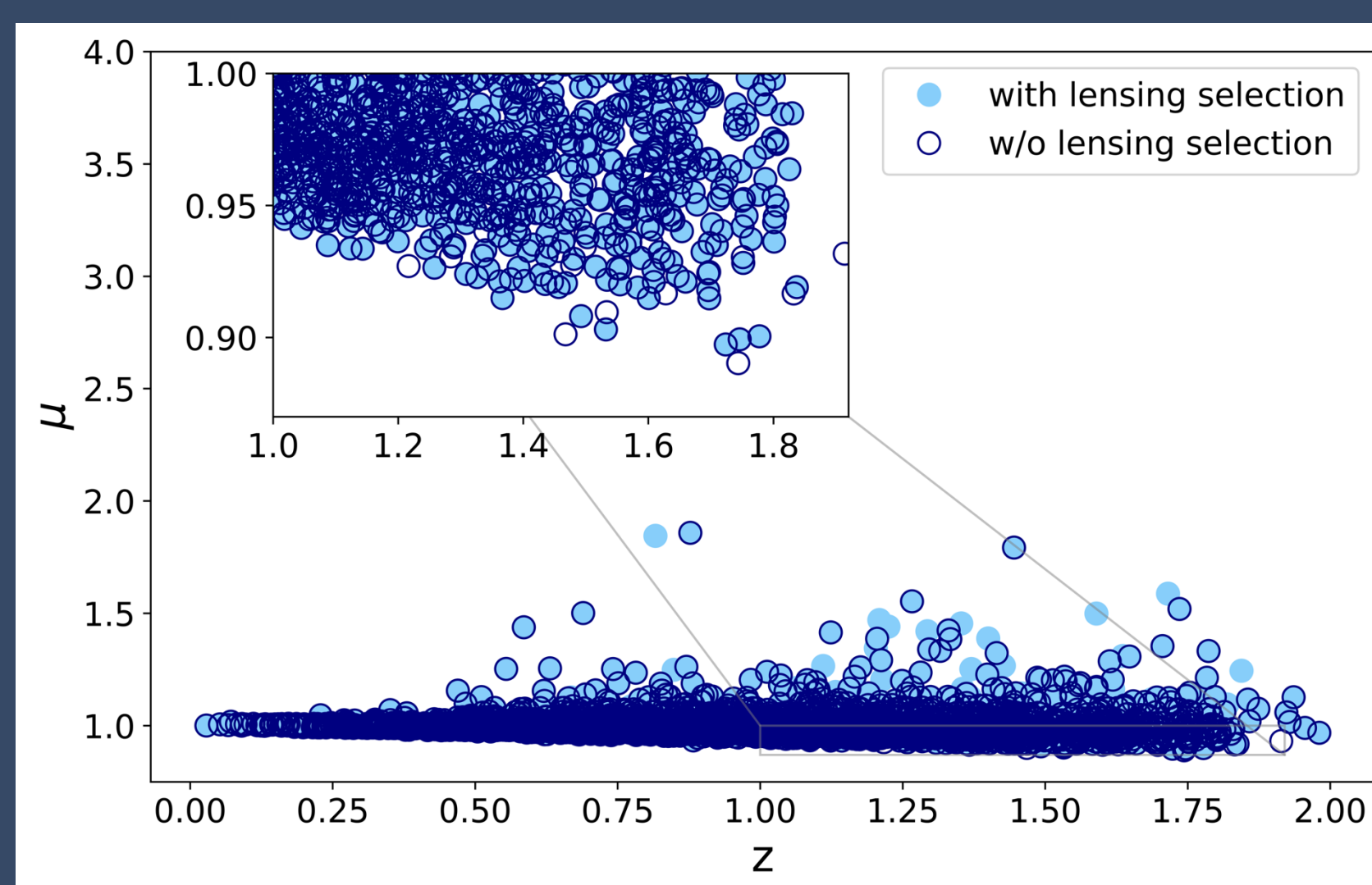
- Drawing a collection of redshifts, masses, angles and lensing magnifications
- Computing the signal-to-noise ratio (SNR) of each event,

$$\rho^2 = \mu \frac{5}{6} \frac{(GM(1+z))^{5/3}}{c^3 \pi^{4/3} d_L^2} F^2(\vartheta, \iota, \varphi) \int df \frac{f^{-7/3}}{S_n(f)}$$

Including μ in the SNR accounts for the *lensing selection effect*

Bright sirens

- GW with an electromagnetic counterpart, redshift can be measured
- Cut-off at $z = 2$, based on the coverage of future spectroscopic galaxy surveys
- Assuming 3000 multi-messenger events in ~ 10 years



Catalogues publicly available:



Dark sirens

- Without electromagnetic counterpart
- Observationally-motivated intrinsic distributions for neutron star masses
- Assuming 10^6 binary neutron stars in ~ 10 years

Bias on cosmological parameters: method

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Considering bright sirens and neglecting lensing in the analysis,

$$\Delta d_L = d_L^{obs} - d_L = \left(\frac{1}{\sqrt{\mu}} - 1 \right) d_L \rightarrow b_{\theta_i} = \hat{\theta}_i - \theta_i^{true}$$

with $\theta_i = (H_0, \Omega_m, \dots)$.

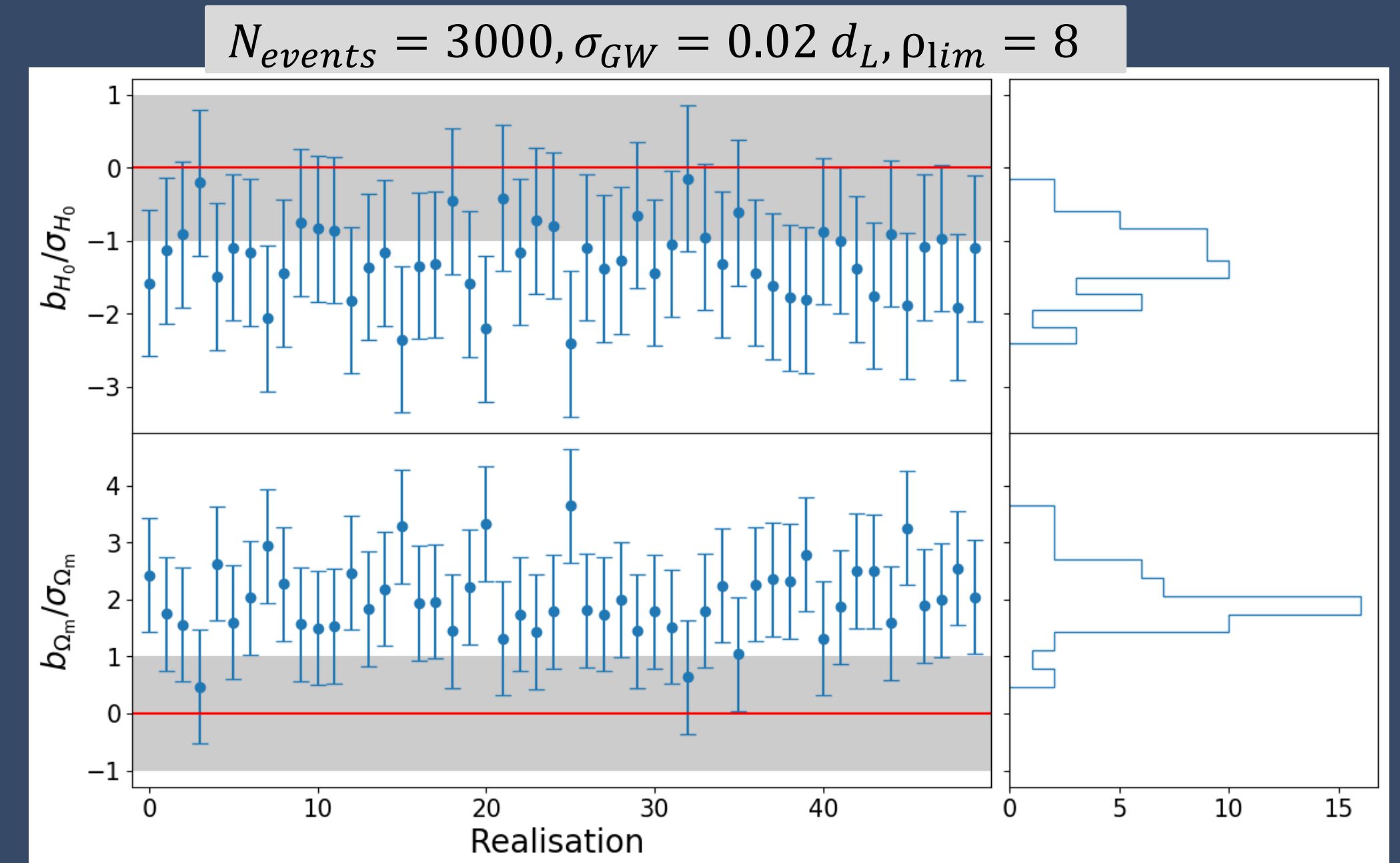
- Fisher matrix formalism extended to include systematic errors
- Full likelihood Monte Carlo Markov Chain analysis

Check our paper:

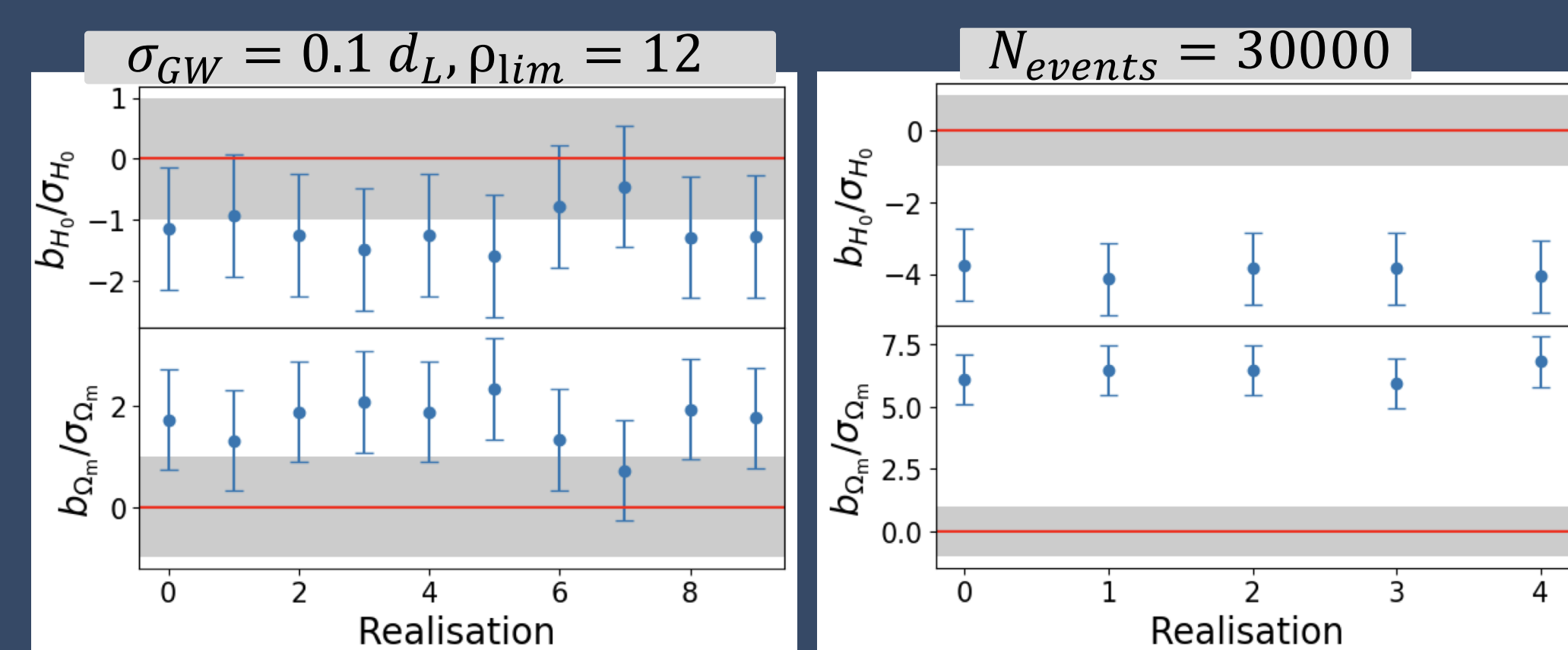


Bias on the cosmological parameters: results

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Assumptions on the catalogue affect the amount of bias



Assumption	$\langle \frac{b_{\theta}}{\sigma_{\theta}} \rangle$
Increasing σ_{GW}	↓
Increasing N_{events}	↑
Increasing z_{max}	↑
Restricting ι	↓
Increasing ρ_{lim}	↑
Log-Normal $p(\mu)$	↓

Canevarolo S. & Chisari N. E., arXiv:2310.12764 (2023)

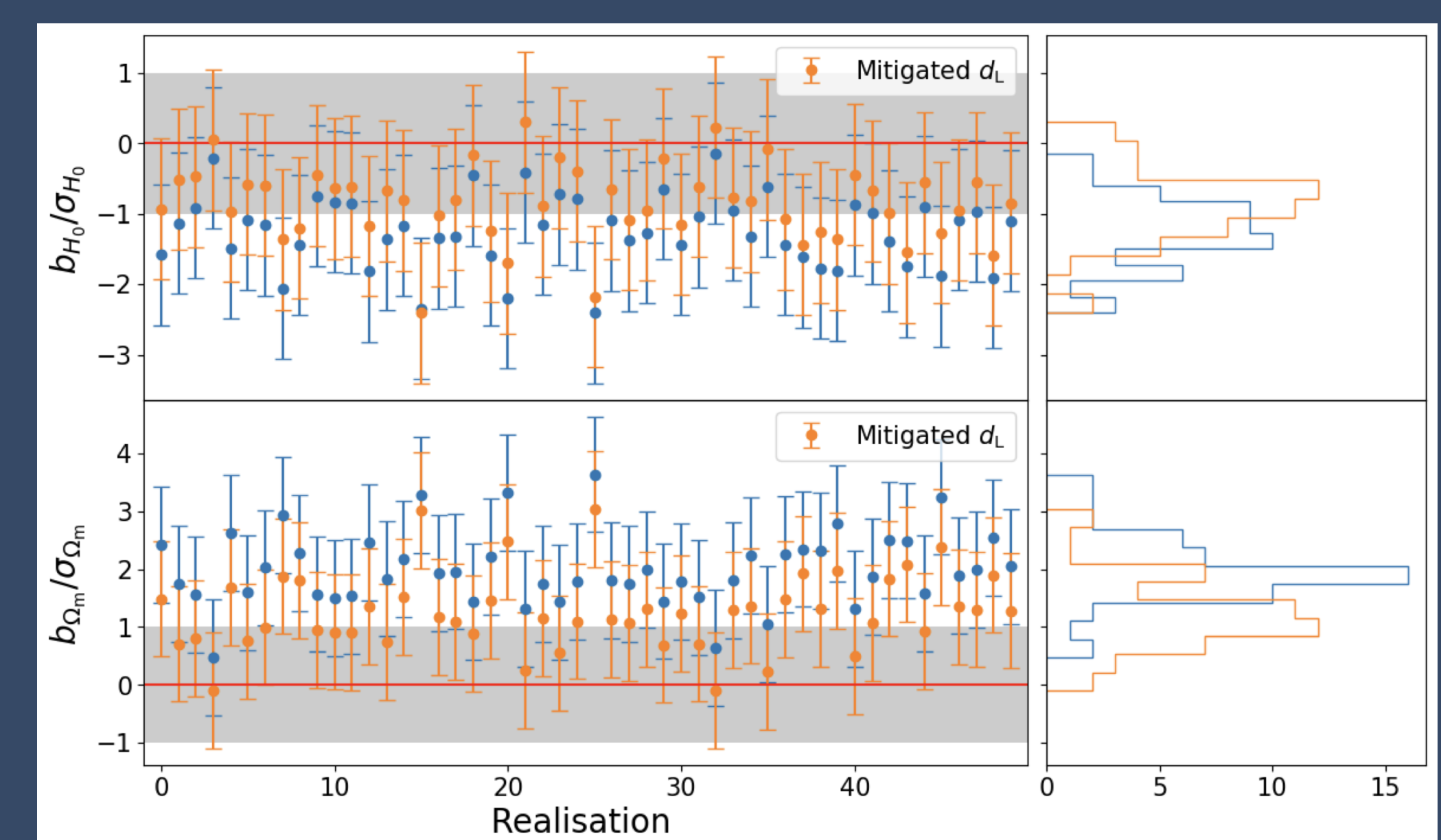
Mitigation

5

Statistical mitigation of the bias,

$$d_L^{MIT} = d_L \sqrt{\frac{\mu_M}{\mu}}$$

→ Additional work needed to fully correct the effect

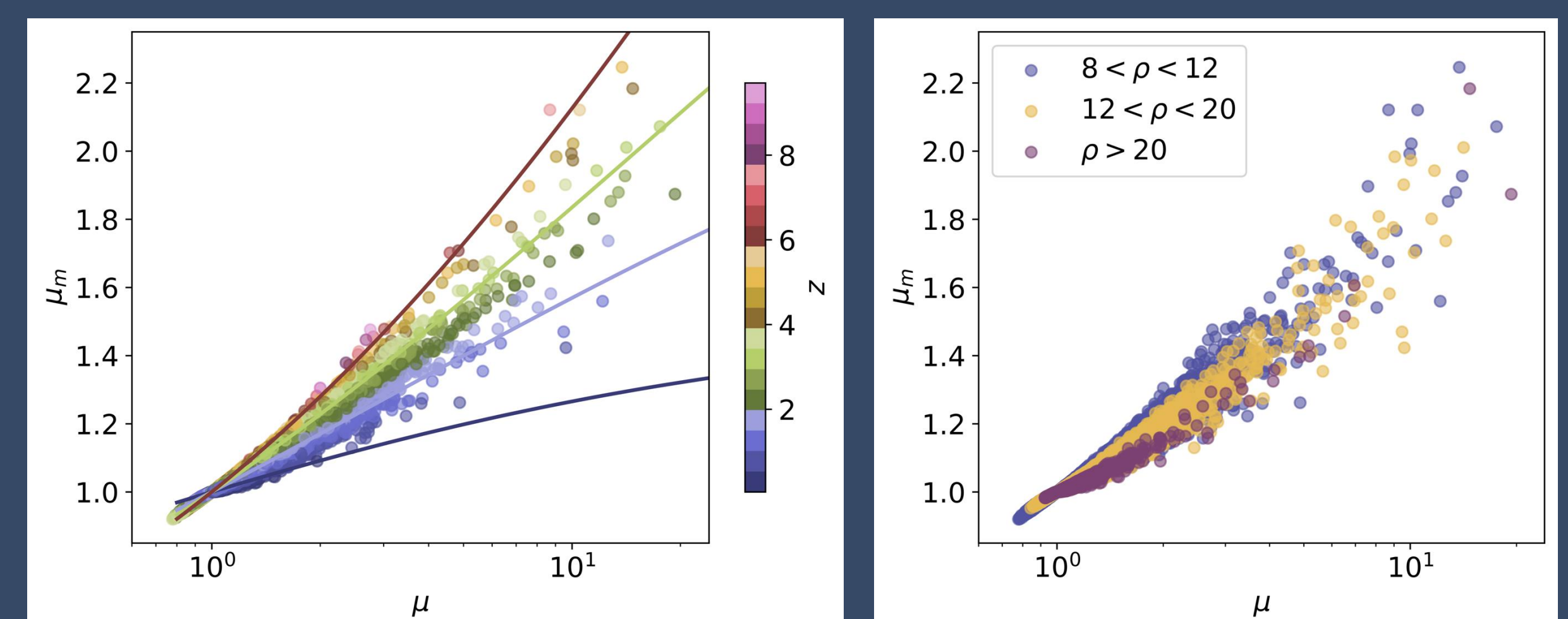


Impact on the neutron star mass distribution

6

- Bright and dark sirens events
- Mass-redshift degeneracy broken using $d_L^{obs}(z, \mu) \rightarrow$ Biased masses,

$$m_{1,2}^{obs} = \frac{1+z}{1+z^{obs}} m_{1,2} \equiv \mu_m m_{1,2}$$



Canevarolo S., van Vonderen L., Chisari N.E. (2024)

Main Messages

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- Lensing impacts the luminosity distance inferred from GW events. This will likely become relevant for ET.
- For bright sirens, lensing acts as a *systematic error* in the inference of the *cosmological parameters*.
- High precision estimates needed to appreciate this effect, whose magnitude depends on specific assumptions.
- Lensing also affects the *observed neutron star mass distribution* obtained from dark siren events, especially the *high-mass tail*.