LENSING BIAS ON COSMOLOGICAL PARAMETERS FROM BRIGHT STANDARD SIRENS

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in collaboration with Elisa Chisari

Based on arXiv:2310.12764

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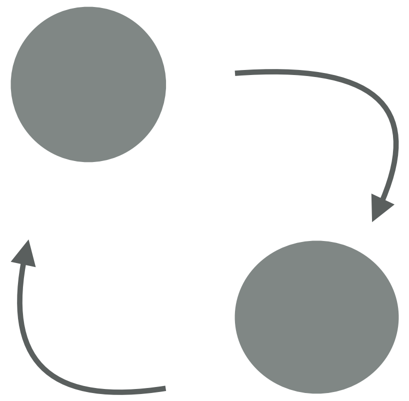
COSMOLOGY WITH STANDARD SIRENS

Gravitational waves (GWs) from merging binaries of compact objects.



(Schutz 1986)

- Amplitude: luminosity distance d_L
- Electromagnetic (EM) counterpart: redshift z → Bright standard sirens

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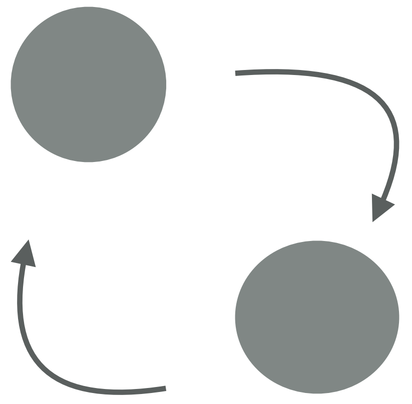


(Schutz 1986)

* Amplitude: luminosity distance d_L

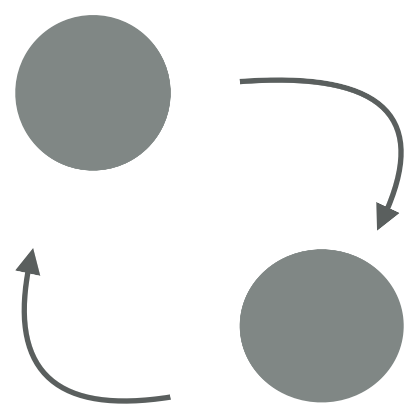
* Electromagnetic (EM) counterpart: redshift z → Bright standard sirens

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

Einstein Telescope (ET) era?

Expected 10^5 Binary Neutron Stars merger per year, up to $z \sim 2-3$

(Maggiore et al. 2020)

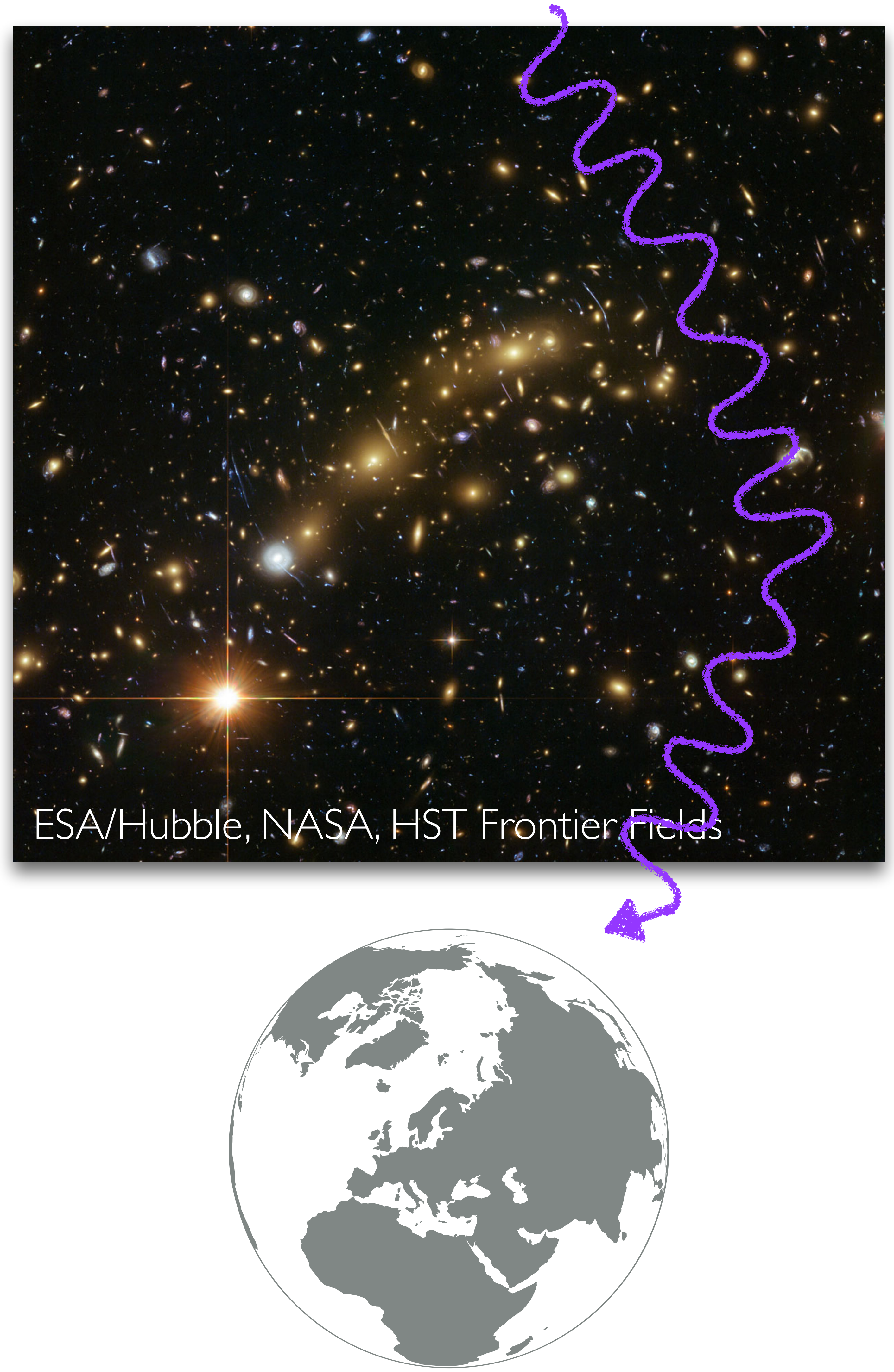


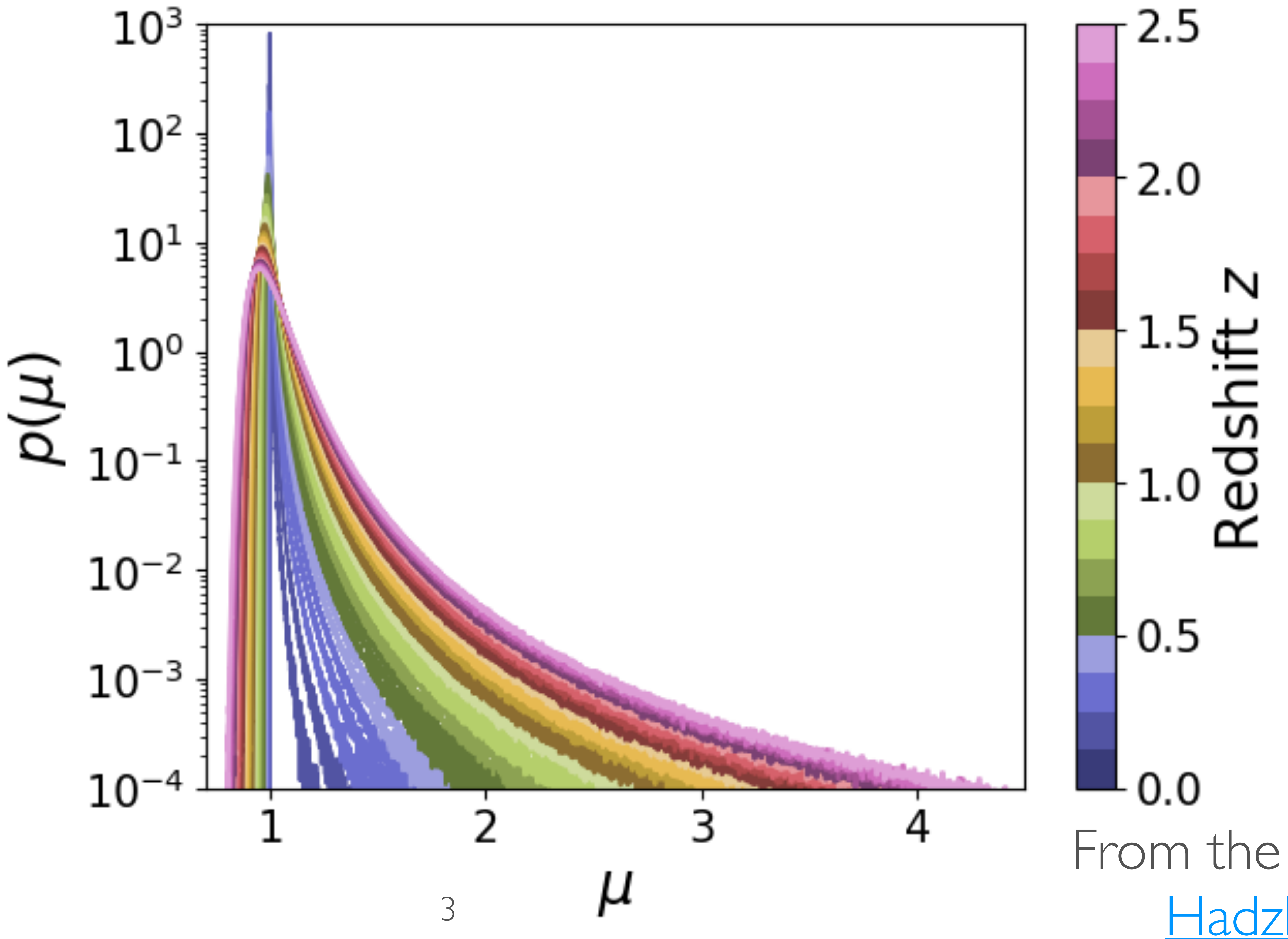
GW LENSING

Geometric optics ($\lambda_{\rm GW} \ll M_{\rm L}$):

- A few events will be strongly lensed
- All events will be weakly lensed

$$d_{\rm L}^{\rm bias}(z,\mu) = \frac{d_{\rm L}(z)}{\sqrt{\mu}}$$

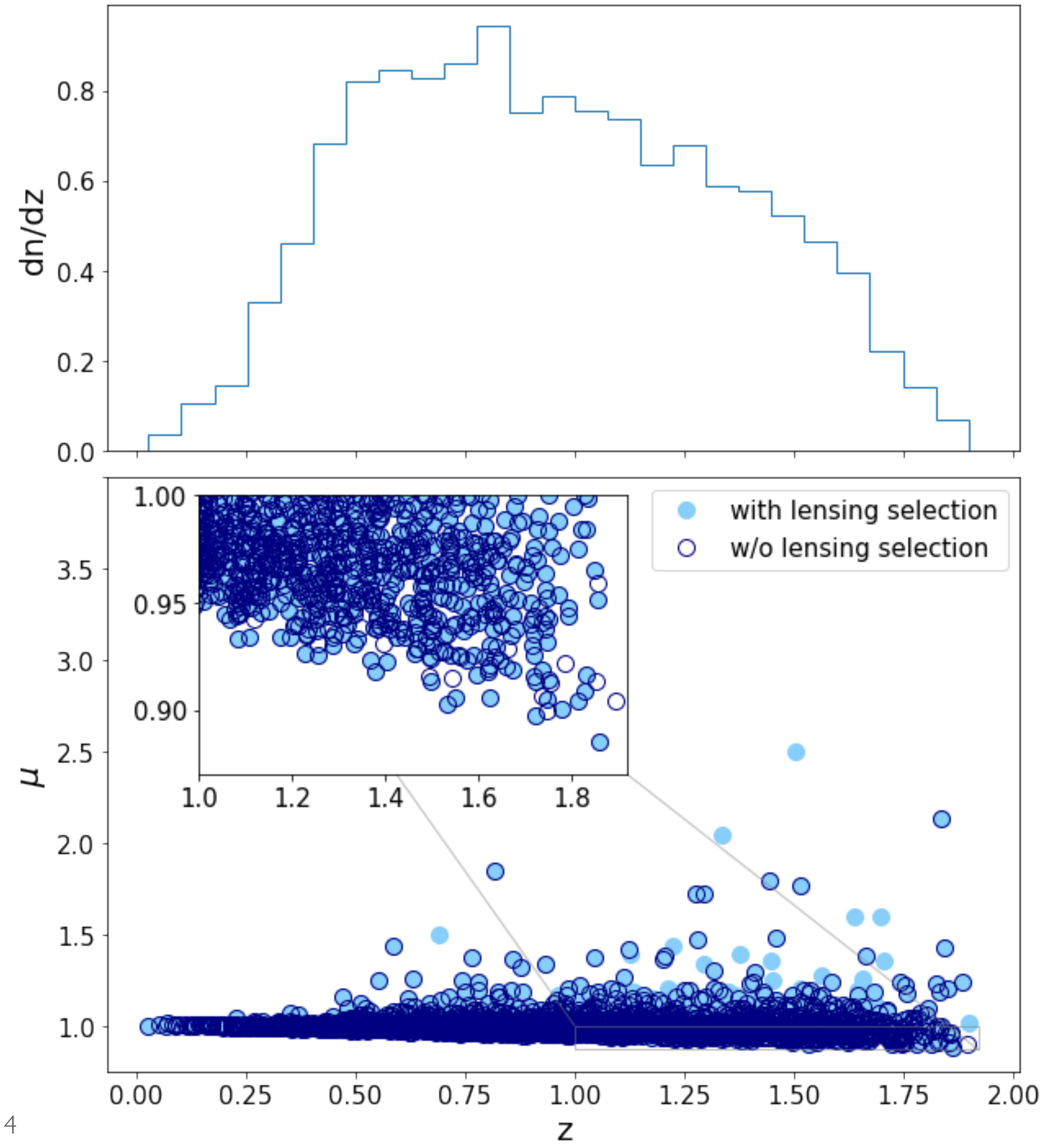




From the N-body simulations of
[Hadzhiyska et al. (2023)]

MOCK CATALOG

- Draw a collection of redshifts z, masses (m_1, m_2), angles $(\theta, \varphi, \psi, \iota)$ and lensing magnifications μ.
- Apply a cut-off at $z_{\rm max} = 2$, due to EM selection effects. (Mpetha et al. 2023)
- Calculate SNR for each event, *including μ (lensing selection effect)* (Cusin et at. 2019)



CAN LENSING INDUCE A SYSTEMATIC ERROR?

* Fisher matrix Γ for the cosmological parameters $\overrightarrow{\theta} = (H_0, \Omega_m, \dots)$.

* Include systematic error: $\Delta d_{\mathrm{L}}^{\mathrm{sys}} = d_{\mathrm{L}}^{\mathrm{bias}} - d_{\mathrm{L}} = \left(\frac{1}{\sqrt{\mu}} - 1\right) d_{\mathrm{L}}$.

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$$b_{\theta_i} \equiv \hat{\theta}_i - \theta_i^{\rm true} \simeq (\Gamma^{-1})_{ij} \left(\sum_{\rm events} \frac{1}{(\sigma_{d_{\rm L}})^2} \Delta d_{\rm L}^{\rm sys} \frac{\partial d_{\rm L}}{\partial \theta_j} \right)$$ for small systematics.

(Amara & Réfrégier 2008)

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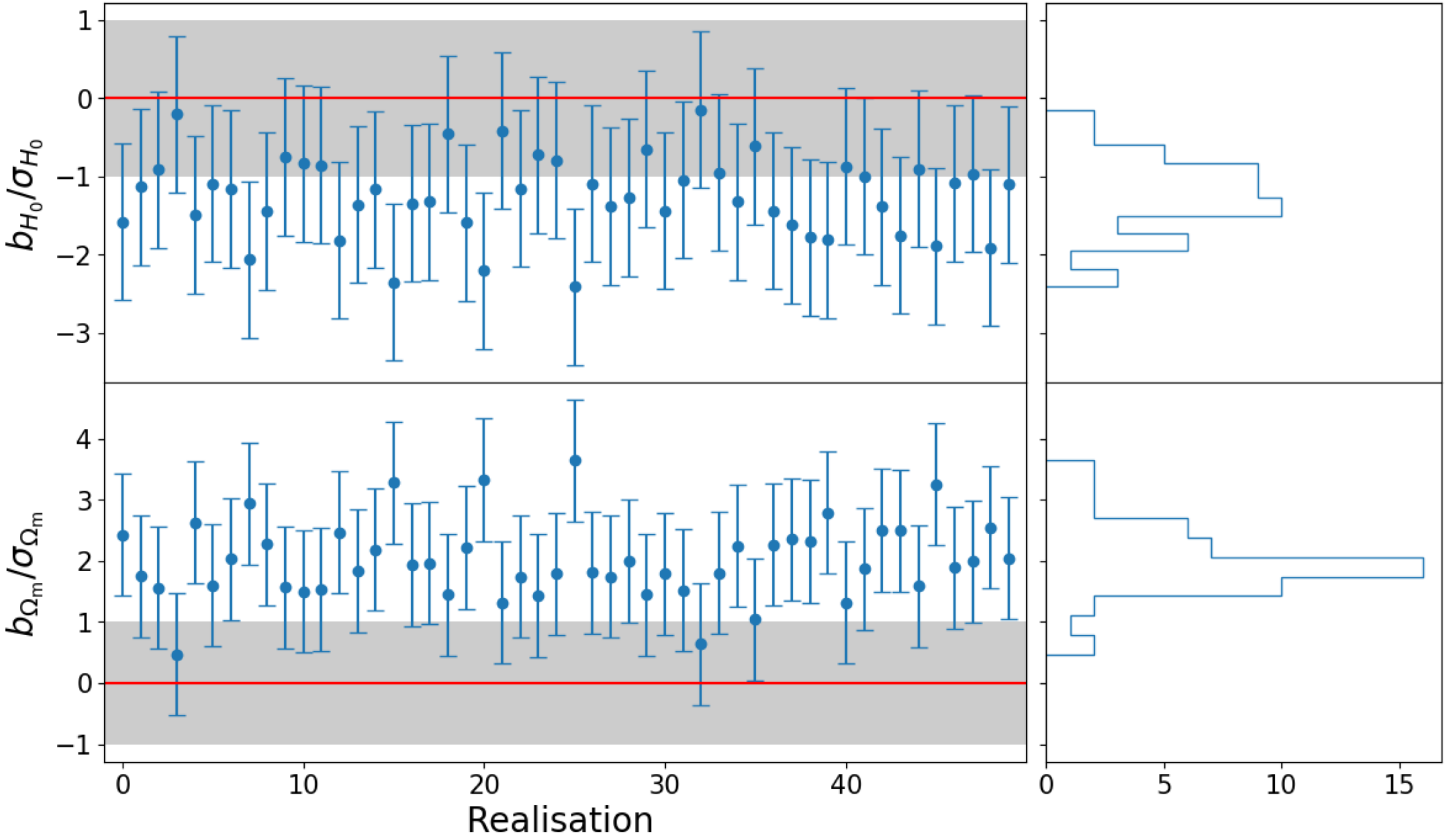
☑ Validate the results with the full likelihood Monte Carlo Markov Chain analysis.

FIDUCIAL SCENARIO

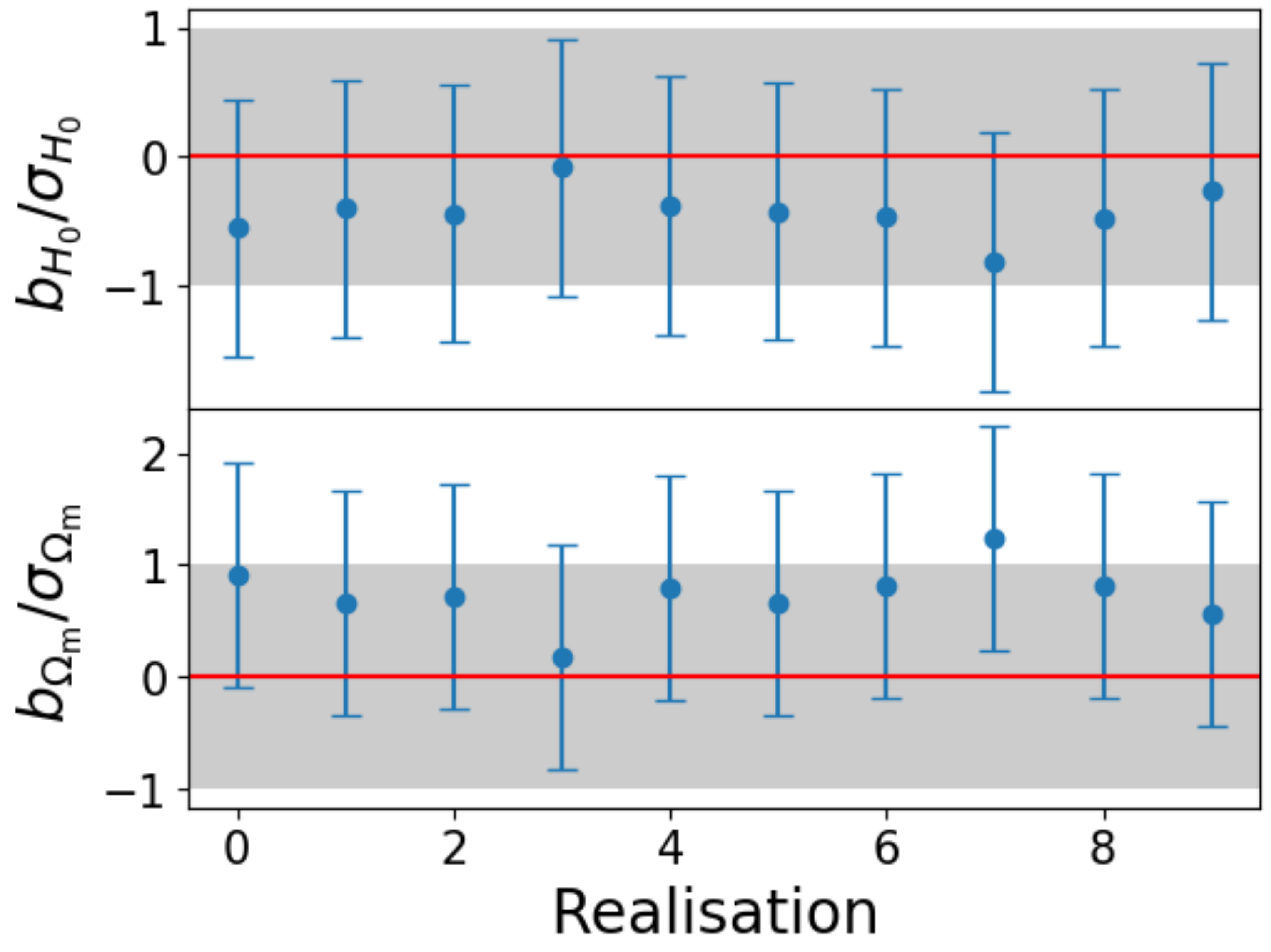
- $N_{\mathrm{events}} = 3\,000$
- $\sigma_{\mathrm{GW}} = 0.02 d_{\mathrm{L}}$
- $z_{\mathrm{max}} = 2$
- $\rho_{\mathrm{lim}} = 8$



ASSUMPTIONS MATTER!

$\rho_{\rm lim} = 8, \;\; \sigma_{\rm GW} = 0.1 d_{\rm L}$

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



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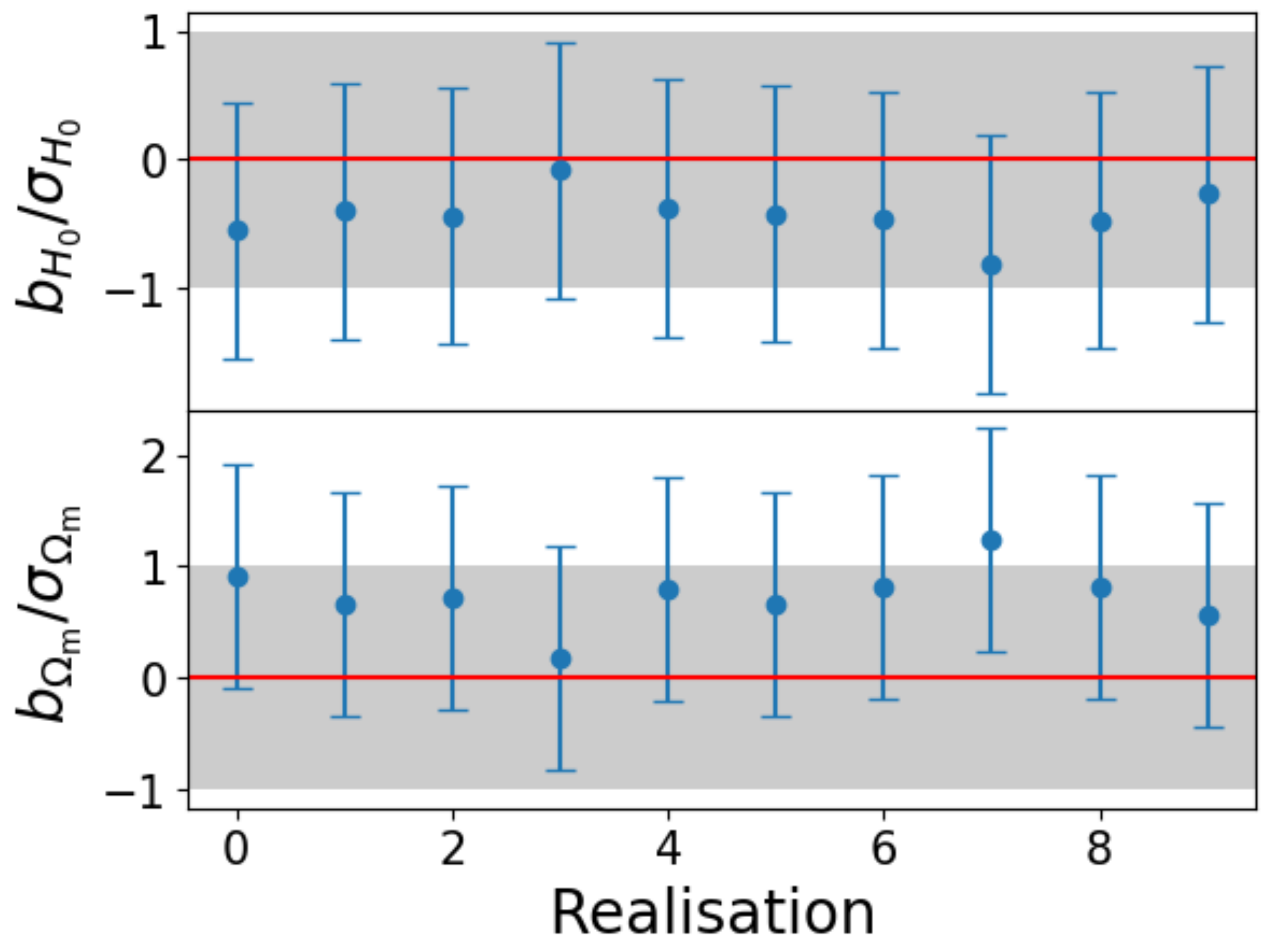
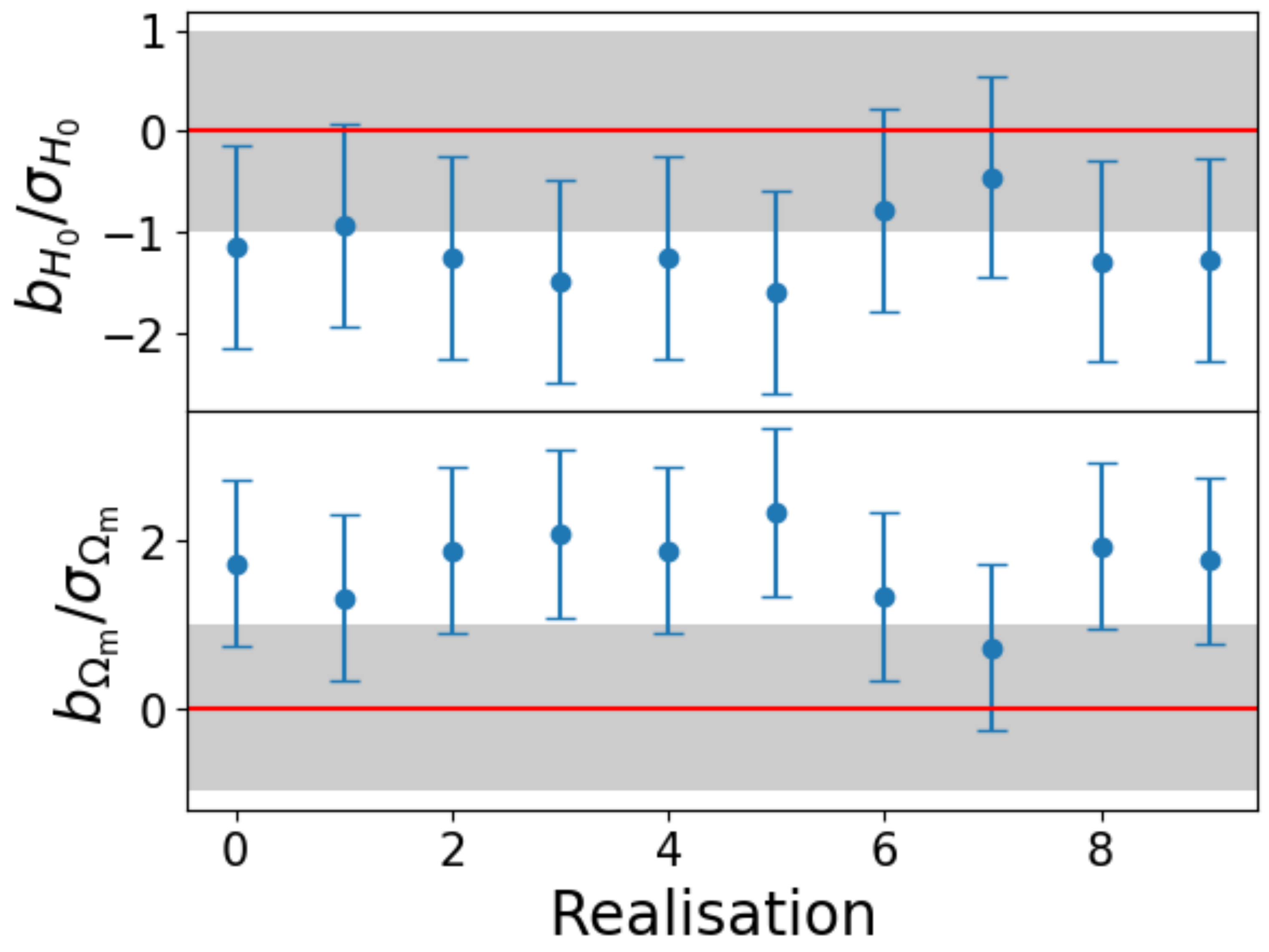


$\rho_{\rm lim} = 12, \ \sigma_{\rm GW} = 0.1 d_{\rm L}$



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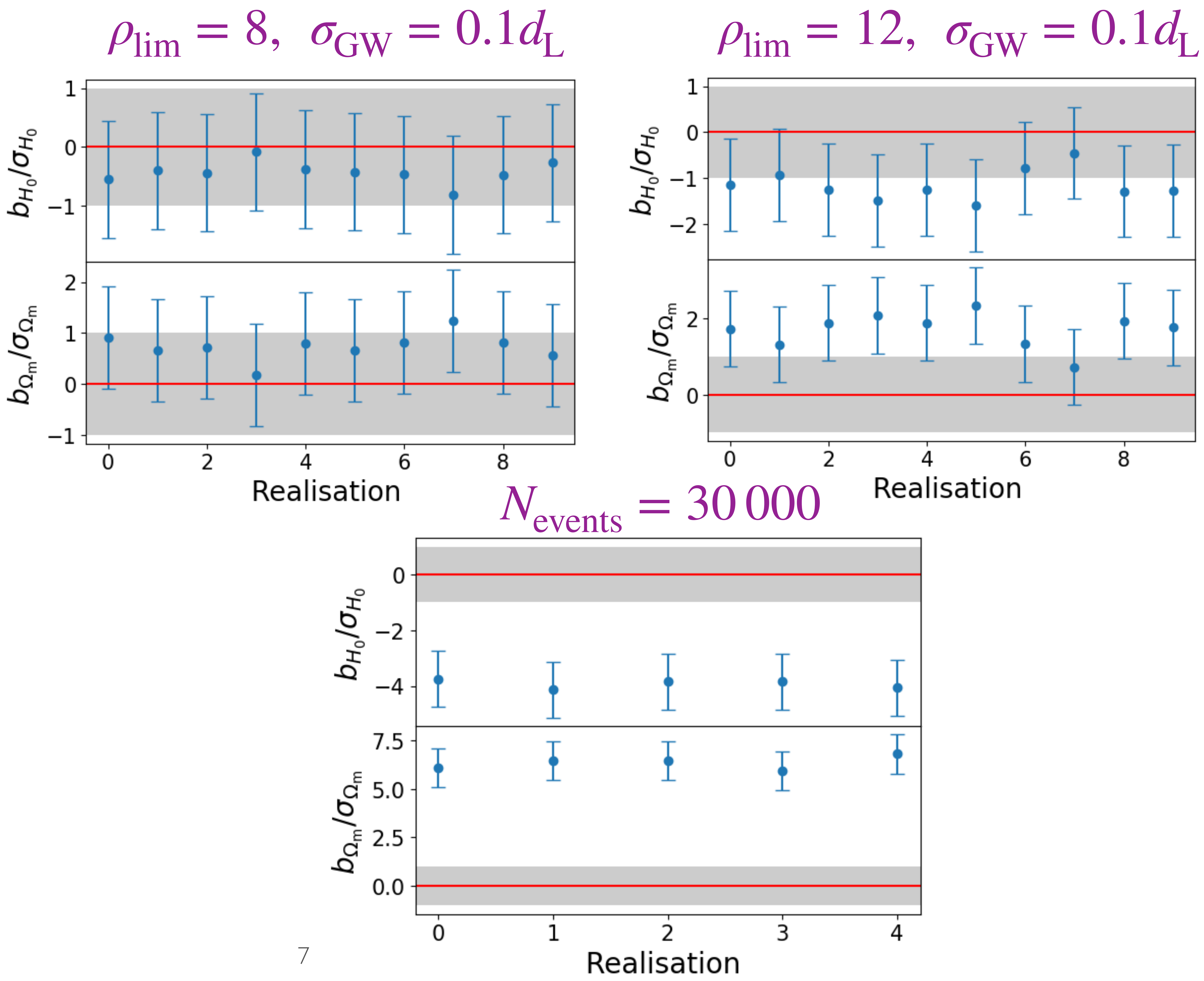

IS IT POSSIBLE TO REDUCE THE BIAS?

* “Delensing” GWs, event-by-event procedure (Shapiro et al. 2010; Hilbert et al. 2011; Wu et al. 2023)
* Remove all strongly lensed events
* Consider only high-SNR sub-group
* Statistical mitigation

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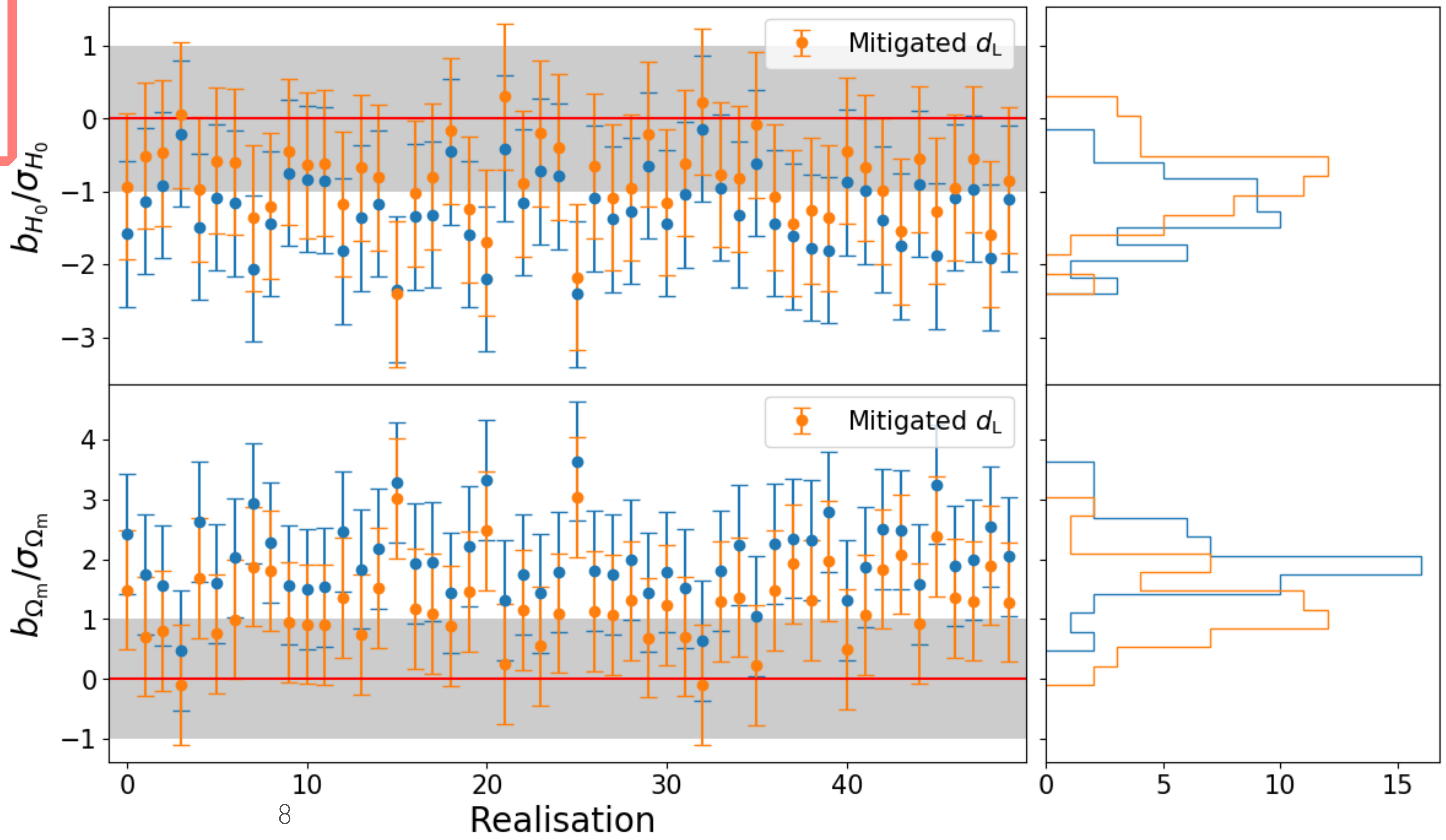
- Consider only high-SNR sub-group
- Statistical mitigation:

$$d_{\rm L}^{\rm MIT} = d_{\rm L}^{\rm bias}(\mu)\sqrt{\mu_{\rm M}} = d_{\rm L}^{\rm true}\sqrt{\frac{\mu_{\rm M}}{\mu}}$$



CONCLUSIONS

* Bright Standard Sirens might open the era of precision GW cosmology.
* GW lensing will be not only an additional source of noise but also a possible systematic error in the cosmological parameters' inference.
* Amount of bias depends on the characteristics of future data but, in general, high-precision estimates of the cosmological parameters are needed to appreciate the effect.
* *Future works* can investigate possible degeneracy between the lensing bias and dark energy effect, as well as, improve the mitigation strategies.

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Thank you for your attention!

UNCERTAINTY ON d_L

$$\sigma_{d_L}^2 = \sigma_{GW}^2 + \sigma_{WL}^2 + \left(\frac{\partial d_L}{\partial z}\right)^2 (\sigma_z^2 + \sigma_{v_{pec}}^2)$$

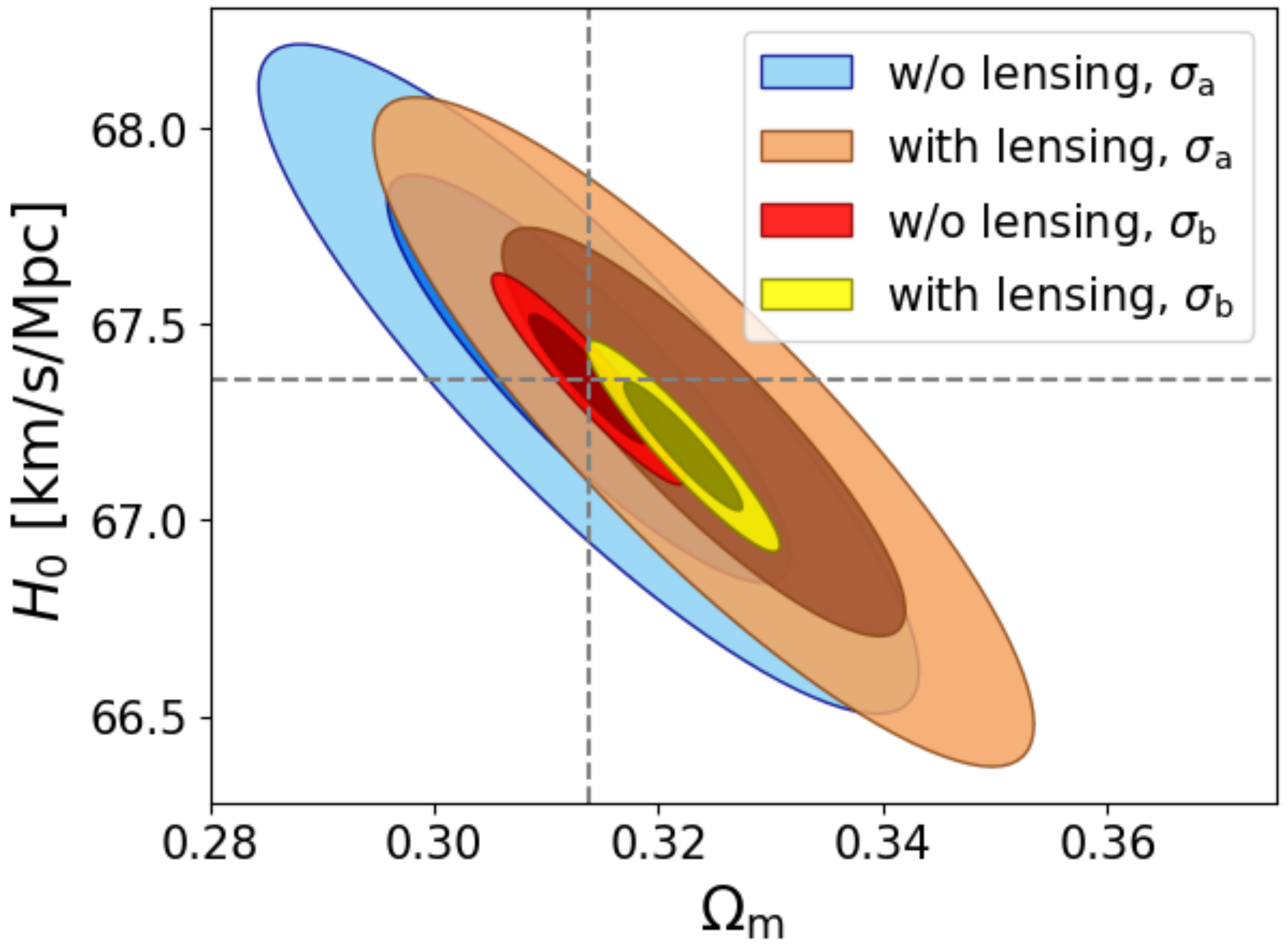
(Mpetha et al. 2023)

With:

$$\sigma_z = 0.001(1+z)$$

$$\sigma_{v_{pec}} = \sqrt{\langle v_{pec}^2 \rangle}(1+z)/c$$

$$\sigma_{WL} = 0.066\left(\frac{1-(1+z)^{-0.25}}{0.25}\right)^{1.8} d_L$$



$$\sigma_a = 2d_L/\rho$$

$$\sigma_b = 0.02d_L$$

REDSHIFT DISTRIBUTION

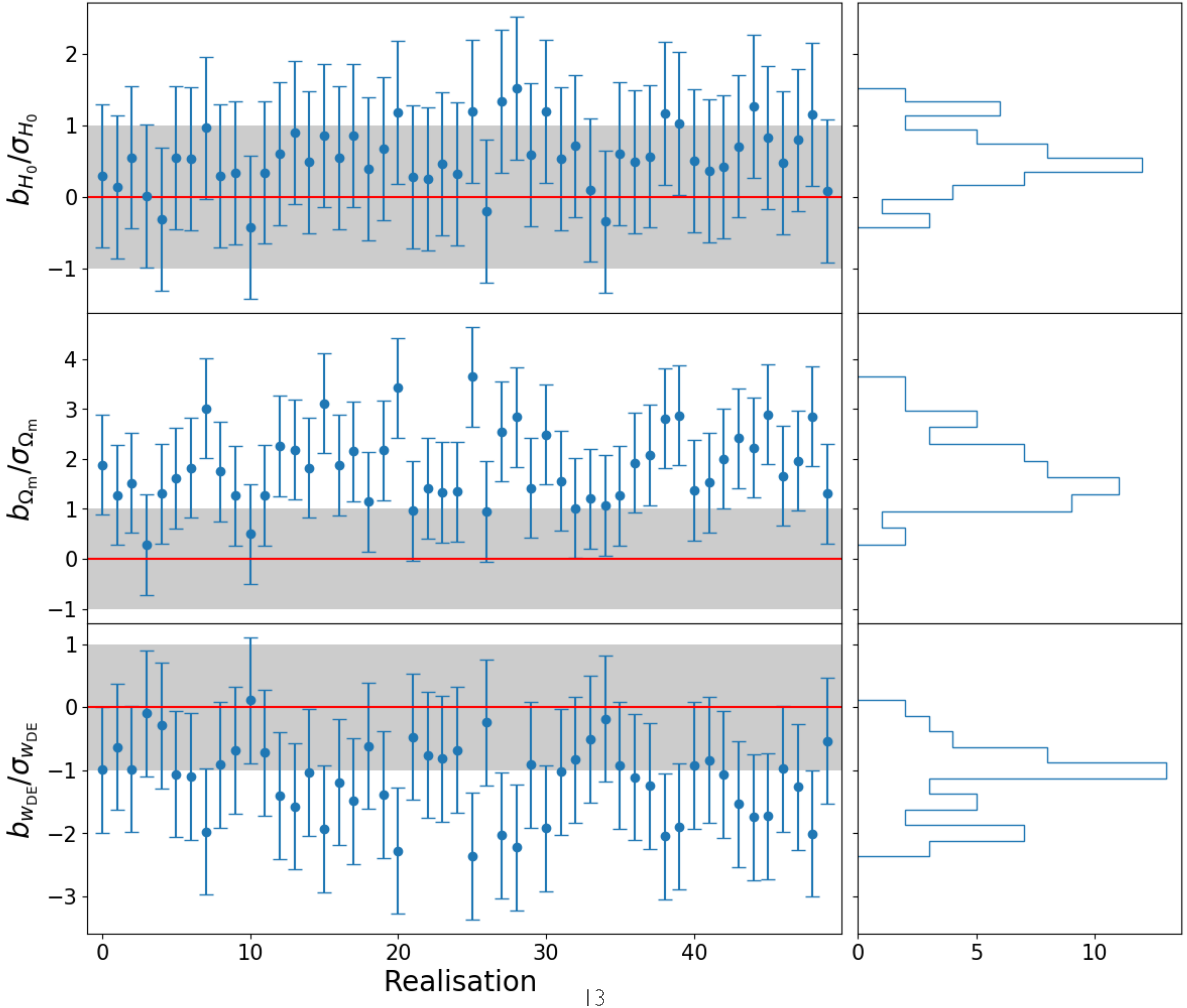
$$p(z) = p^{(\mathrm{th})}(z) f(z)$$

With:

$$p^{(\mathrm{th})}(z) = \frac{1}{1+z}\frac{4\pi c \chi^2(z)}{H(z)} \int_{t_\mathrm{d}^\mathrm{MIN}}^{t_\mathrm{d}^\mathrm{MAX}} dt_\mathrm{d} \Psi(z_\mathrm{f}(z, t_\mathrm{d})) \times \left(\log\left(\frac{t_\mathrm{d}^\mathrm{MAX}}{t_\mathrm{d}^\mathrm{MIN}}\right) t_\mathrm{d}\right)^{-1}$$

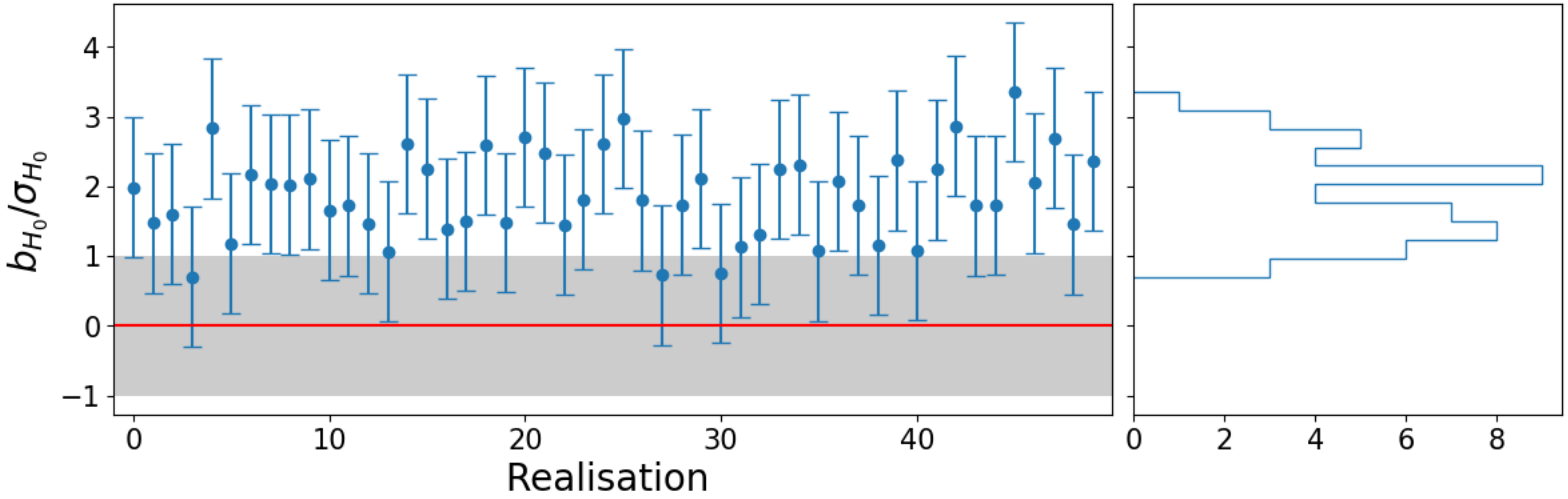
$$f(z) = \frac{0.9}{2}\left(1 - \tanh\left(\frac{z - z_\mathrm{pivot}}{w z_\mathrm{pivot}}\right)\right), \quad w = \frac{z_\mathrm{max} - z_\mathrm{pivot}}{2 z_\mathrm{max}}$$

(Mpetha et al. 2023)



b_{H_0}/σ_{H_0}
$b_{\Omega_m}/\sigma_{\Omega_m}$
$b_{w_{DE}}/\sigma_{w_{DE}}$
Realisation

Assuming Ω_m is perfectly known



AbacusSummit suite of N-body simulations by Hadzhiyska et al. (2023)

Base box:

- Box of $2 \ \mathbf{Gpc/h}$, mass resolution $2.1 \ 10^9 \ h^{-1}\mathrm{M}_\odot$
- Coverage of an octant of the sky, up to $z \sim 0.8$ then reduced to $1800 \ \mathrm{deg}^2$
- 47 maps of the convergence fields κ ranging from $z = 0.15$ to $z = 2.45$
- Pixel resolution of $0.21 \ \mathbf{arcmin}$

Following Takahashi et al. 2011:

$$\mu = \frac{1}{(1-\kappa)^2}$$