The hydrostatic-to-lensing mass bias from resolved X-ray and optical/IR data

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Outline

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- HSE-to-lensing mass bias
- HSE-to-lensing scaling relation
- Conclusions

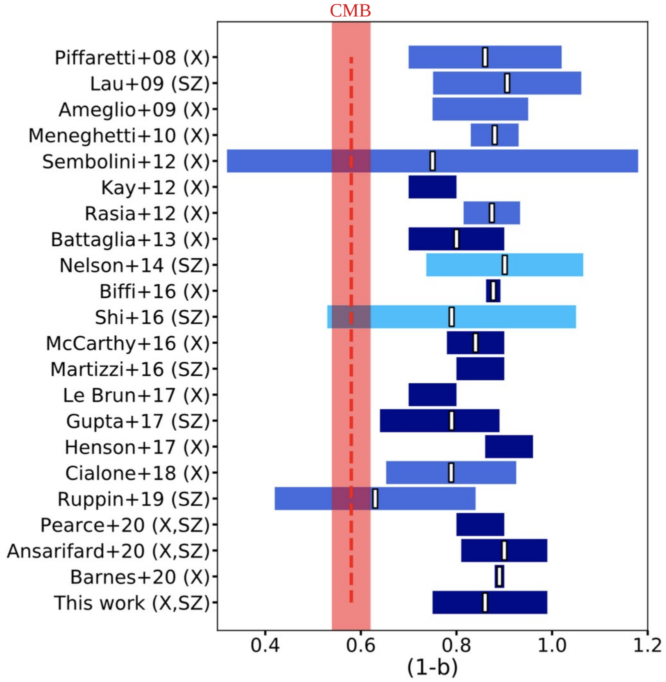
Motivation

Galaxy clusters masses estimated under hydrostatic equilibrium (HSE) hypothesis are biased

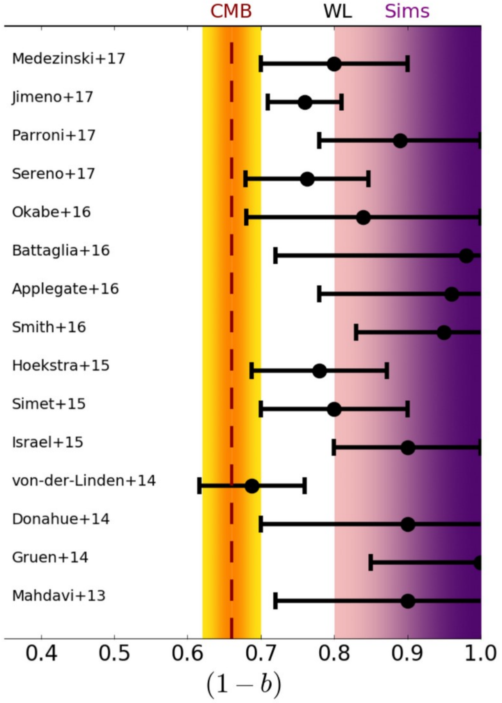
$$(1-b) = M_{500}^{\mathrm{HSE}} / M_{500}^{\mathrm{true}}$$

But not enough to conform to CMB power spectrum cosmology

Simulations [Gianfagna et al. 2021]



Observations [Salvati et al. 2018]



Motivation

Galaxy clusters masses estimated under hydrostatic equilibrium (HSE) hypothesis are biased

$$(1 - b) = M_{500}^{\mathrm{HSE}} / M_{500}^{\mathrm{true}}$$

- Which is the value of $(1 - b)$?
- Enough to match our understanding of baryonic physics?

→ Need of a **total mass estimate**
→ Need of a well **controlled cluster sample**

- Does the bias evolve with redshift?
- Are high redshift clusters more disturbed?

→ Need to cover a **large redshift range**

Data: X-ray hydrostatic masses and lensing masses

We will use masses estimated from individual mass profiles

$$(1-b) = M_{500}^{\mathrm{HSE}}/M_{500}^{\mathrm{true}} \sim M_{500}^{\mathrm{HSE}}/M_{500}^{\mathrm{lens}}$$

Hydrostatic masses obtained from X-ray data: $M^{\mathrm{HSE}}(<r) = -\frac{k_{\mathrm{B}} T_e(r) r}{\mu m_p G}\left(\frac{\mathrm{d}\ln n_e}{\mathrm{d}\ln r} + \frac{\mathrm{d}\ln T_e}{\mathrm{d}\ln r}\right)$

Estimator of true masses: masses from the lensing of background galaxies $M_{500}^{\mathrm{HSE}}/M_{500}^{\mathrm{true}} \sim M_{500}^{\mathrm{HSE}}/M_{500}^{\mathrm{lens}}$

[lensing effect presented in C. Payerne's talk]

→ Hydrostatic-to-lensing mass bias

Data: combination of cluster catalogues

Masses from resolved X-ray and lensing profiles (not from observable-mass scaling relations)

Reference sample:

XMM-*Newton* clusters [CEA/IRAP pipeline]

CoMaLit clusters [LC^2, Sereno 2015]

Sample used to calculate the bias

Comparison sample:

Other X-ray HSE masses

Other lensing masses

Sample used to estimate possible systematic on the reference masses

Reference X-ray and lensing masses

We match clusters on the basis of the coordinates in catalogues and check with the redshifts

Reference sample:

XMM-*Newton* clusters [CEA/IRAP pipeline]

53 clusters (+12)

CoMaLit clusters [LC^2, Sereno 2015]

Homogeneous method applied consistently to the full sample to reconstruct HSE masses

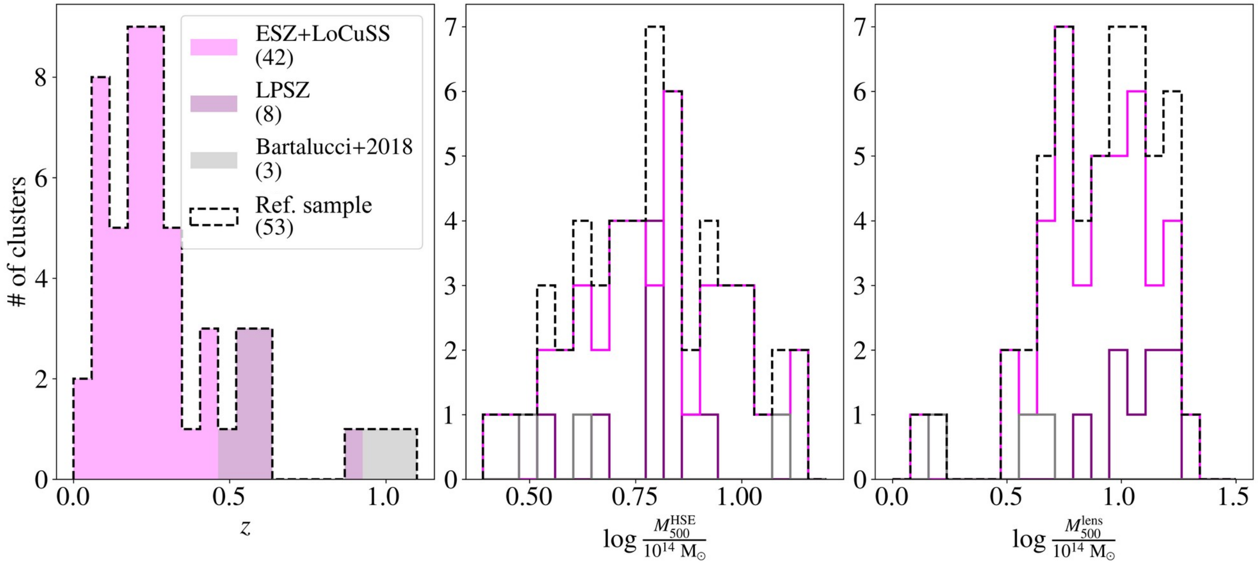
- $z < 0.5$, ESZ+LoCuSS [Planck Collaboration VIII. 2011, Planck Collaboration III. 2013]
- $0.5 < z < 0.9$, LPSZ sample
- $z > 0.9$, Bartalucci et al. 2018

A compilation of lensing masses for 806 clusters from the literature

Standardised to the same cosmology and definitions

Reference sample

53 clusters with XMM-*Newton* and CoMaLit masses



- Redshift range $0.05 < z < 1.07$, most of the clusters at $z < 0.5$
- Lensing masses centred at higher values than HSE masses

Direct HSE-to-lensing mass bias

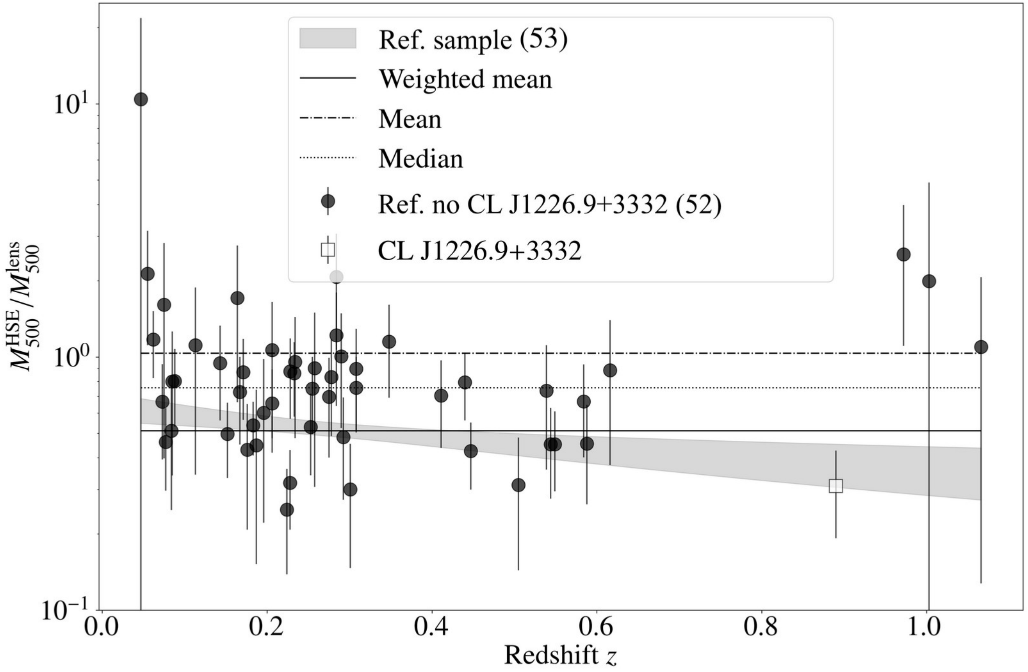
Fit a bias model with redshift evolution:
[Salvati et al. 2019, Wicker et al. 2023]

$$M_{500}^{\mathrm{HSE}}/M_{500}^{\mathrm{lens}}(z) = (1-b)(z) = (1-\mathcal{B})\left(\frac{1+z}{1+z_*}\right)^{\beta_z}$$

Conservative propagation of uncertainties:

$$\delta_{\mathrm{lens}}^2 = \delta_{M_{\mathrm{CoMaLit\ lens}}}^2 + \sigma_{\mathrm{sys\ lens}}^2$$
$$\delta_{\mathrm{HSE}}^2 = \delta_{M_{\mathrm{XMM\ HSE}}}^2 + \sigma_{\mathrm{sys\ HSE}}^2$$

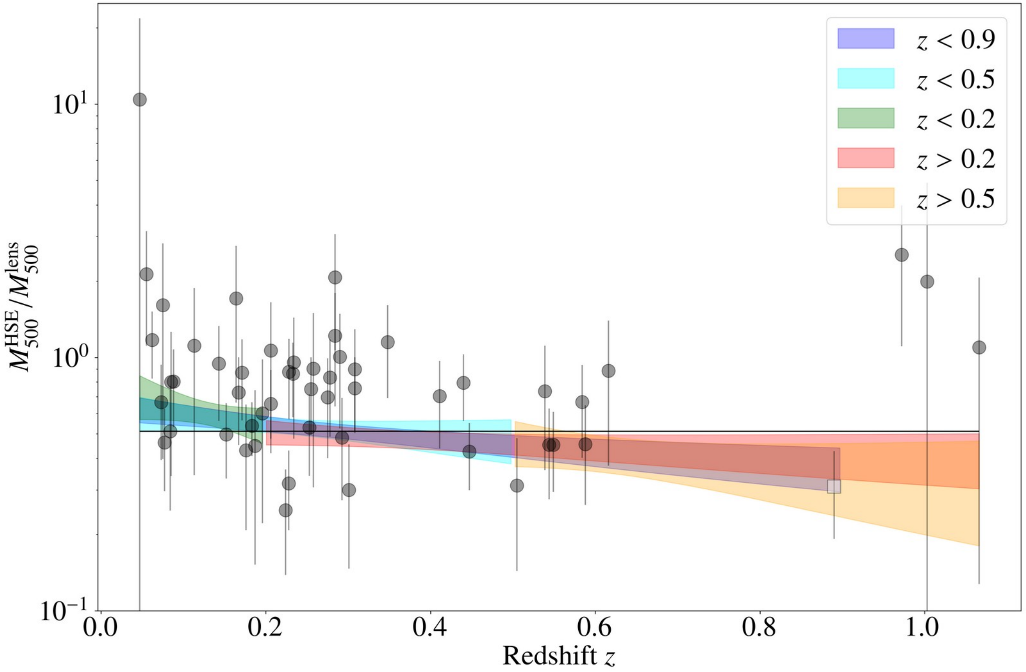
Add to the uncertainty of each mass (δ) the dispersion with respect to other mass estimates, σ_{sys}



→ Hints of redshift evolution

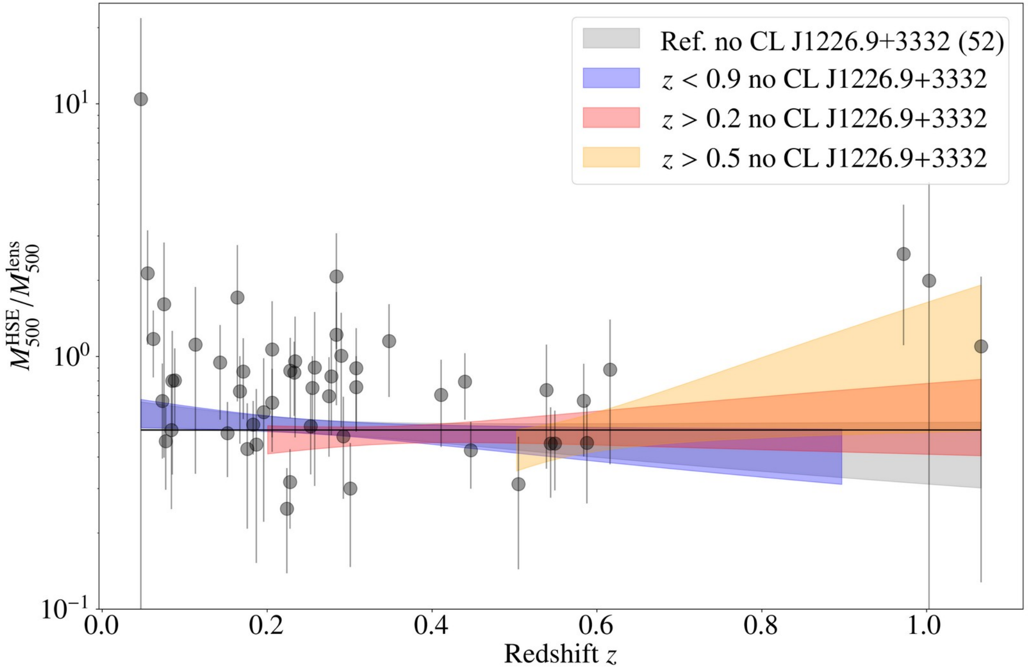
Direct HSE-to-lensing mass bias

Clusters with very different uncertainties
We distinguish subsamples in redshift



→ Compatible bias evolution model for all subsamples

At high redshift, very large uncertainties
Impact of excluding CL J1226.9+3332



→ Without CL J1226.9+3332, no evidence of redshift evolution

HSE-to-lensing scaling relation

HSE and lensing masses are scattered and biased with respect to the true mass

$$\ln M^{\text{lens}} \pm \delta_{\text{lens}} = \alpha^{\text{lens}} + \beta^{\text{lens}} \ln M^{\text{True}} \pm \sigma^{\text{lens}}$$

$$\ln M^{\text{HSE}} \pm \delta_{\text{HSE}} = \alpha^{\text{HSE}} + \beta^{\text{HSE}} \ln M^{\text{True}} \pm \sigma^{\text{HSE}} + \gamma^{\text{HSE}} \log\left(\frac{1+z}{1+z_{ref}}\right)$$

Mass estimates for individual clusters
and their corresponding uncertainties

HSE-to-lensing scaling relation

HSE and lensing masses are scattered and biased with respect to the true mass

$$\ln M^{\mathrm{lens}} \pm \delta_{\mathrm{lens}} = \alpha^{\mathrm{lens}} + \beta^{\mathrm{lens}} \ln M^{\mathrm{True}} \pm \sigma^{\mathrm{lens}}$$

$$\ln M^{\mathrm{HSE}} \pm \delta_{\mathrm{HSE}} = \alpha^{\mathrm{HSE}} + \beta^{\mathrm{HSE}} \ln M^{\mathrm{True}} \pm \sigma^{\mathrm{HSE}} + \gamma^{\mathrm{HSE}} \log\left(\frac{1+z}{1+z_{ref}}\right)$$

Redshift evolution
If $\gamma = 0$, no evolution

Intrinsic scatter

Deviation from linearity

If $\beta = 1$,
the bias $(1\text{-}b) = e^{\alpha}$

→ Fitting the HSE-to-lensing scaling relation we measure the mass bias accounting for the intrinsic scatter
We use LInear Regression in Astronomy (LIRA) [Sereno 2016] with the `pylira` wrapper [by F. Kéruzoré]

Scaling relation of reference

Linear scaling ($\beta = 1$) and no evolution with redshift ($\gamma = 0$)

$$\ln M^{\text{lens}} \pm \delta_{\text{lens}} = \alpha^{\text{lens}} + \beta^{\text{lens}} \ln M^{\text{True}} \pm \sigma^{\text{lens}}$$

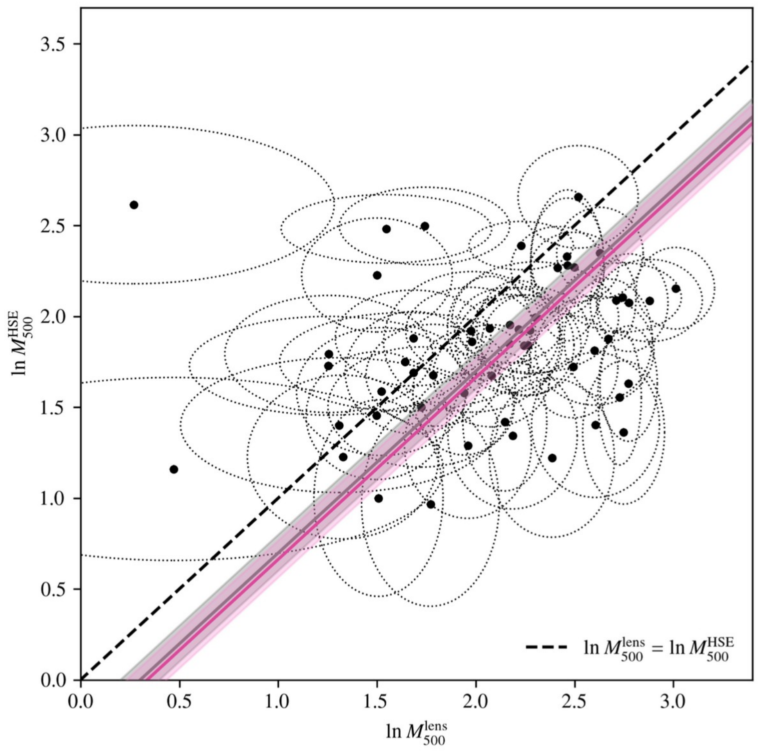
$$\ln M^{\text{HSE}} \pm \delta_{\text{HSE}} = \alpha^{\text{HSE}} + \beta^{\text{HSE}} \ln M^{\text{True}} \pm \sigma^{\text{HSE}} + \gamma^{\text{HSE}} \log\left(\frac{1+z}{1+z_{ref}}\right)$$

Intrinsic scatter

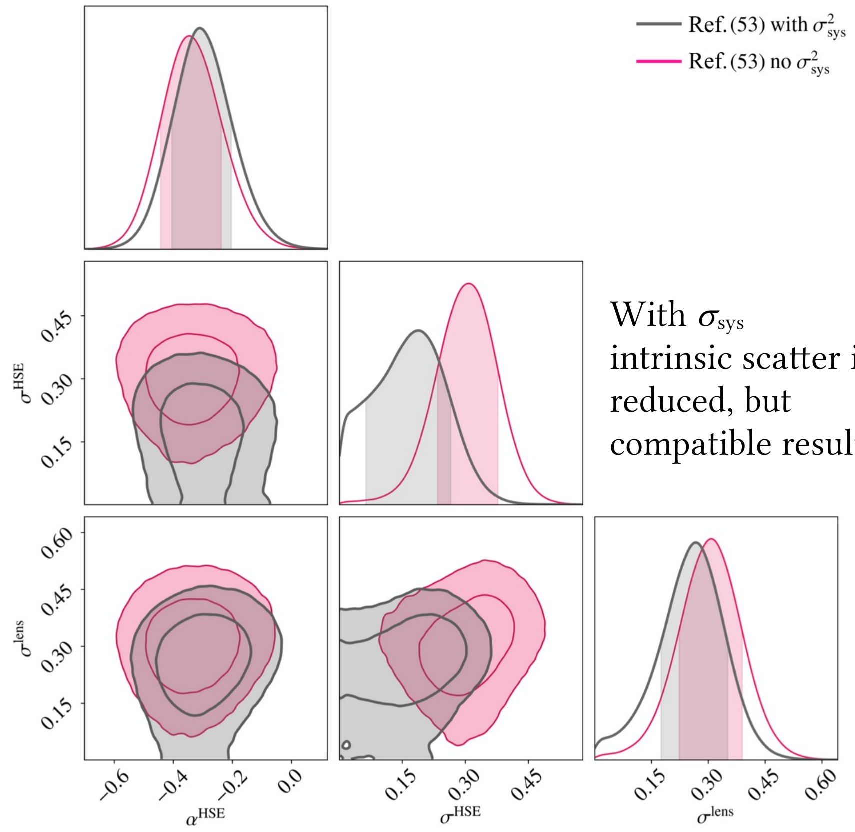
The bias (1-b) = e^{α}

Scaling relation of reference

Reference sample: XMM-*Newton* and CoMaLiT



→ We measure: $M_{500}^{\rm HSE}/M_{500}^{\rm lens} = (1-b) = 0.741 \pm 0.073$



With $\sigma_{\rm sys}$ intrinsic scatter is reduced, but compatible results

Evolution of the scaling relation with redshift

Linear scaling ($\beta = 1$) and evolution with redshift ($\gamma \neq 0$)

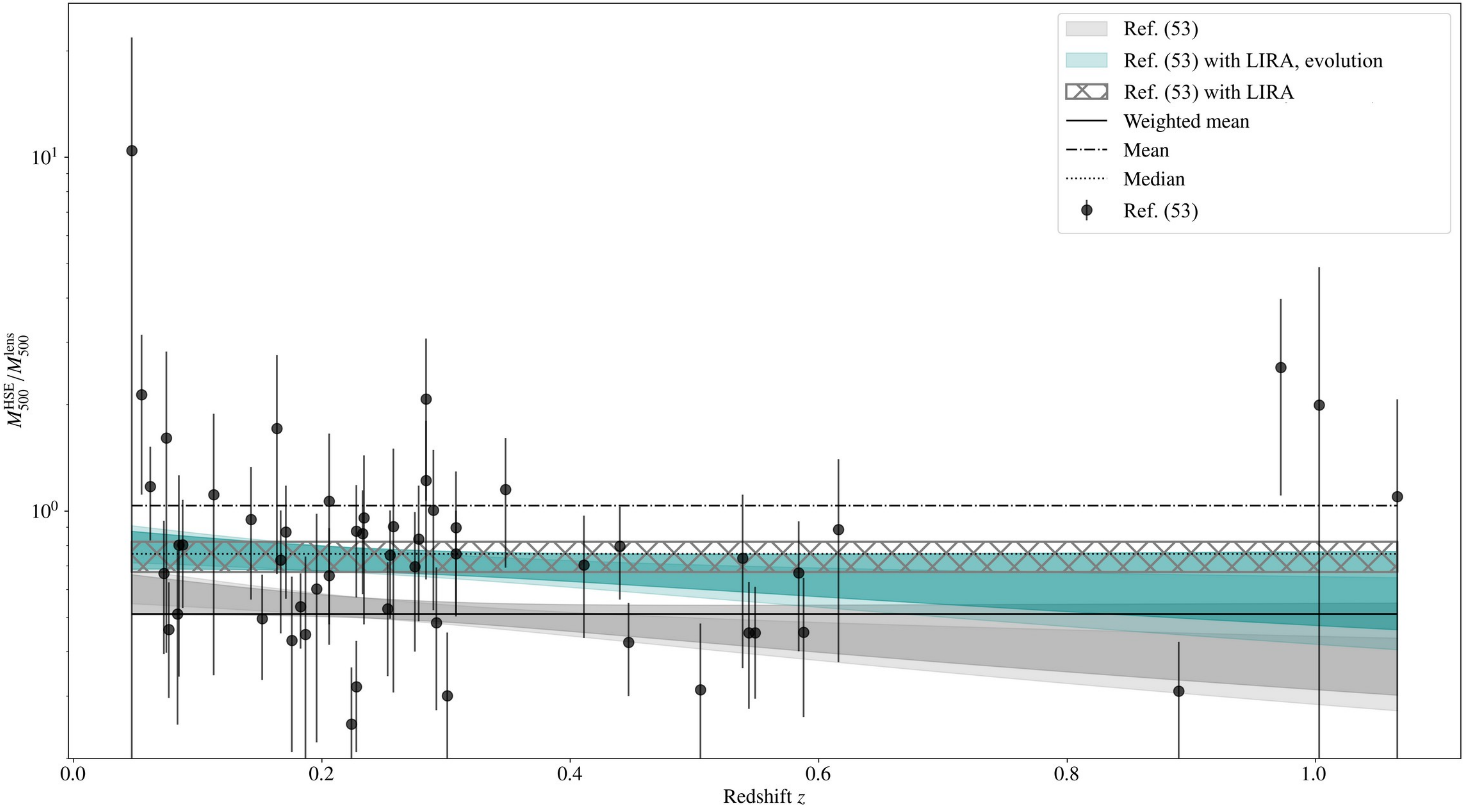
$$\ln M^{\mathrm{lens}} \pm \delta_{\mathrm{lens}} = \alpha^{\mathrm{lens}} + \beta^{\mathrm{lens}} \ln M^{\mathrm{True}} \pm \sigma^{\mathrm{lens}}$$

$$\ln M^{\mathrm{HSE}} \pm \delta_{\mathrm{HSE}} = \alpha^{\mathrm{HSE}} + \beta^{\mathrm{HSE}} \ln M^{\mathrm{True}} \pm \sigma^{\mathrm{HSE}} + \gamma^{\mathrm{HSE}} \log\left(\frac{1+z}{1+z_{ref}}\right)$$

Redshift evolution

Intrinsic scatter

Evolution of HSE-to-lensing bias with redshift



→ No evidence of evolution of the bias with redshift

→ Important impact of the intrinsic scatter on the bias estimate

Summary and conclusions

- After a careful **selection** of clusters: **53 clusters with redshifts 0.05 < z < 1.07**
- Measurement of the scatter of masses between different works
- Very **conservative propagation of uncertainties**
- Two methods to fit the bias: with and without intrinsic scatter

- Ignoring the **intrinsic scatter** introduces a **bias** in the HSE-to-lensing mass bias
- **No evidence of evolution with redshift**
- Strong impact of individual clusters with small uncertainties
- We measure (with $\sigma_{sys,}$ σ^{HSE}, σ^{lens}, $\beta = 1$, $\gamma = 0$): $M_{500}^{HSE}/M_{500}^{lens} = (1-b) = 0.741 \pm 0.073$