

# THE SIGNATURE OF MAJOR MERGERS ON THE HYDROSTATIC MASS BIAS OF GALAXY CLUSTERS

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**16th International Workshop on the Identification of Dark Matter**  
**June 2026, Zaragoza**



# The signature of major mergers on the hydrostatic mass bias of galaxy clusters

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Received 25 July 2025 / Accepted 13 November 2025

## ABSTRACT

**Context.** While the masses and abundances of galaxy clusters are key observables for Cosmology, mass determinations based on intra-cluster medium observations often rely on the hydrostatic equilibrium assumption. This assumption introduces a systematic bias that is expected to be more noticeable during strong assembly episodes, such as major mergers.

**Aims.** We aim to study in detail how mergers shape the variability in the hydrostatic mass bias values through the evolutionary history of clusters, identify the primary mechanisms driving such evolution, and assess its potential dependence on dynamical state and merging history.

**Methods.** Using a moderate-sized adaptive mesh refinement Eulerian plus  $N$ -Body cosmological simulation, we identified a sample of galaxy cluster mergers in the redshift interval  $1.5 \geq z \geq 0$ . We compared true and hydrostatic masses within the virial volume. We derived the latter from gas density and temperature radial profiles. The evolution was assessed in relation to the merging history extracted from halo merger trees.

**Results.** At  $z = 0$ , the hydrostatic mass bias shows a mild correlation with dynamical state. During major mergers, the bias follows a characteristic trend: a sharp negative dip around the merger time, a transient positive peak, and a gradual return to pre-merger levels. This behaviour is primarily driven by morphological and dynamical reconfigurations of the gas density within the ICM, while thermodynamic processes play a secondary role. The pattern shows no strong dependence on secondary parameters, such as mass ratio or impact parameter, but it can be fitted to a simple time-dependent functional form. This trend is present at radii  $r \leq R_{\text{vir}}$ , although with reduced amplitude and shorter timescales as the radius decreases.

**Conclusions.** Hydrostatic mass bias is closely linked, albeit in a non-trivial way, with the merging history of galaxy clusters. We find that the bias values are weakly correlated with the dynamical state of clusters. Nevertheless, our results give a robust estimation of the hydrostatic mass bias values in the pre-merger, merging, and post-merger phases. These findings highlight the importance of delving deeper into the observational assessment of cluster assembly state in order to improve mass estimations for cosmological analyses.

**Key words.** hydrodynamics – methods: numerical – galaxies: clusters: intracluster medium – cosmology: theory – dark matter – large-scale structure of Universe





# GALAXY CLUSTERS AS DARK MATTER HALOS



**The Coma galaxy cluster – NASA**

Galaxy clusters are the pinnacle of the hierarchical formation of structures in the Universe:

- ~ 85% of their total mass consists of Dark Matter
- Their mass function constrains directly cosmological parameters
- Masses typically  $10^{13} M_{\odot} \leq M \leq 10^{15} M_{\odot}$



# THE HYDROSTATIC MASS BIAS PROBLEM



- Mass is not an observable
- Observational techniques (X-ray, SZ) to reconstruct the mass profile require:



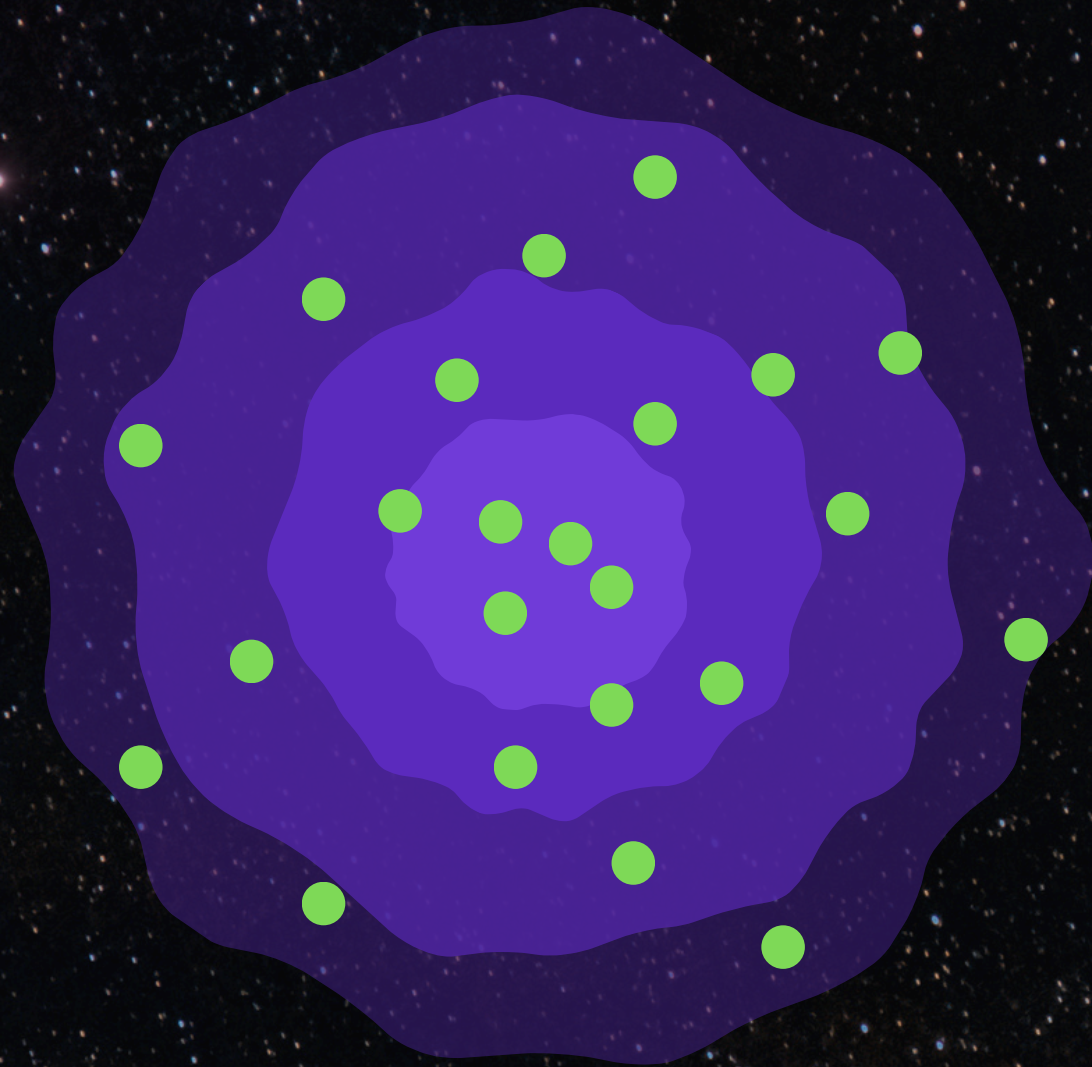
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- Mass is not an observable
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  - **Spherical symmetry**



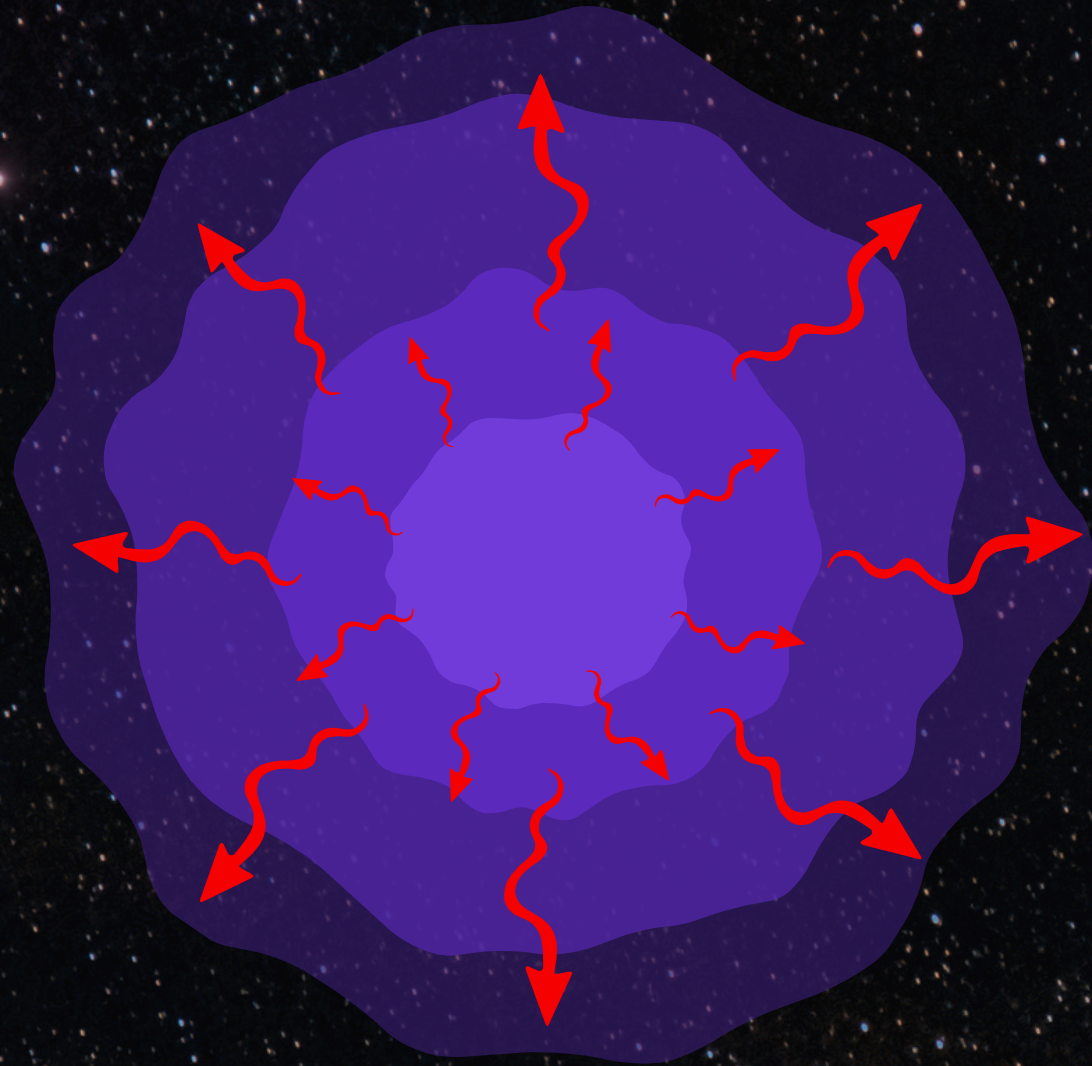
# THE HYDROSTATIC MASS BIAS PROBLEM



- Mass is not an observable
- Observational techniques (X-ray, SZ) to reconstruct the mass profile require:
  - Spherical symmetry
  - **Ideal gas with constant mean molecular weight**



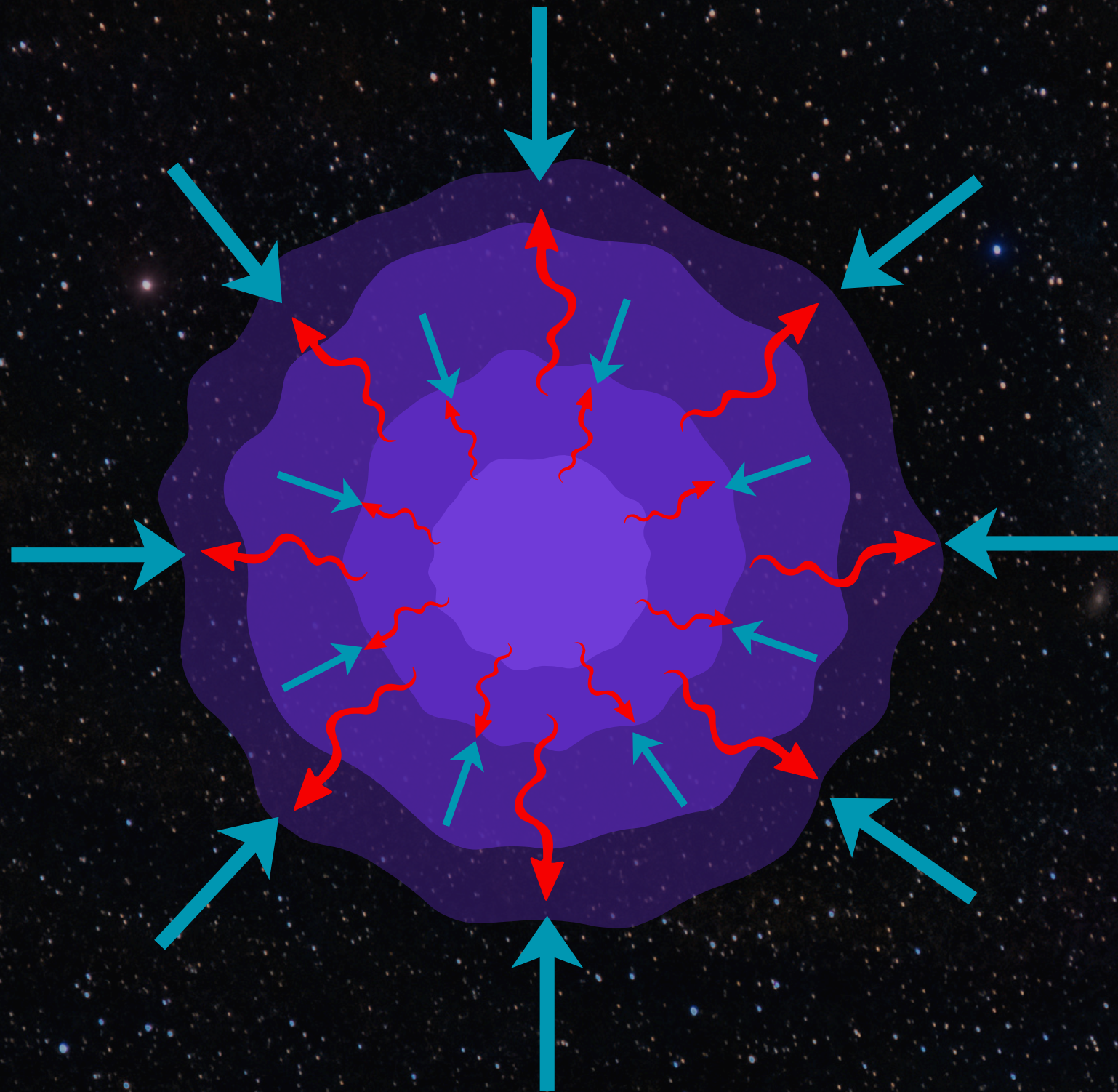
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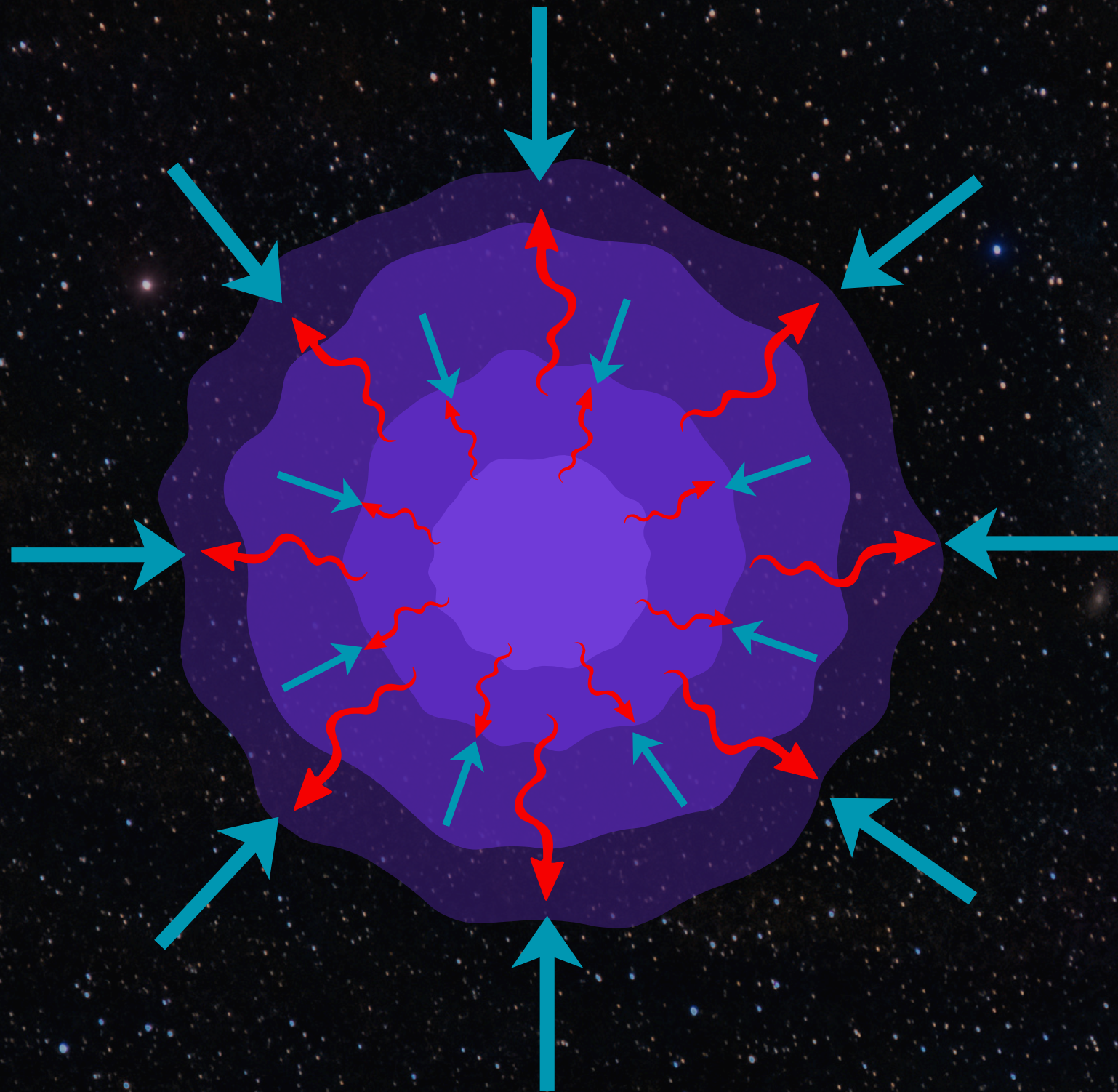
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- Mass is not an observable
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  - Spherical symmetry
  - Ideal gas with constant mean molecular weight
  - Thermal pressure
  - **Hydrostatic equilibrium** (baryons) and virial equilibrium (DM)



# THE HYDROSTATIC MASS BIAS PROBLEM



$$M_{HE}(r) = -\frac{k_B T(r)r}{\mu G m_p} \left( \frac{d \log(\rho(r))}{d \log(r)} + \frac{d \log(T(r))}{d \log(r)} \right)$$





# THE HYDROSTATIC MASS BIAS PROBLEM

- If any assumption is not met:

$$b = \frac{M_{HE} - M_{true}}{M_{true}}$$

- A negative bias means HE underestimates the true mass (DM + baryons) – a **direct systematic error in DM mass inference**



On average, HE is expected to underestimate galaxy cluster masses by ~20% at virial radius – even in relaxed systems

## Why?

Dynamic and morphological disturbances

Non-thermal contributions to the pressure

Strong merging and accretion events





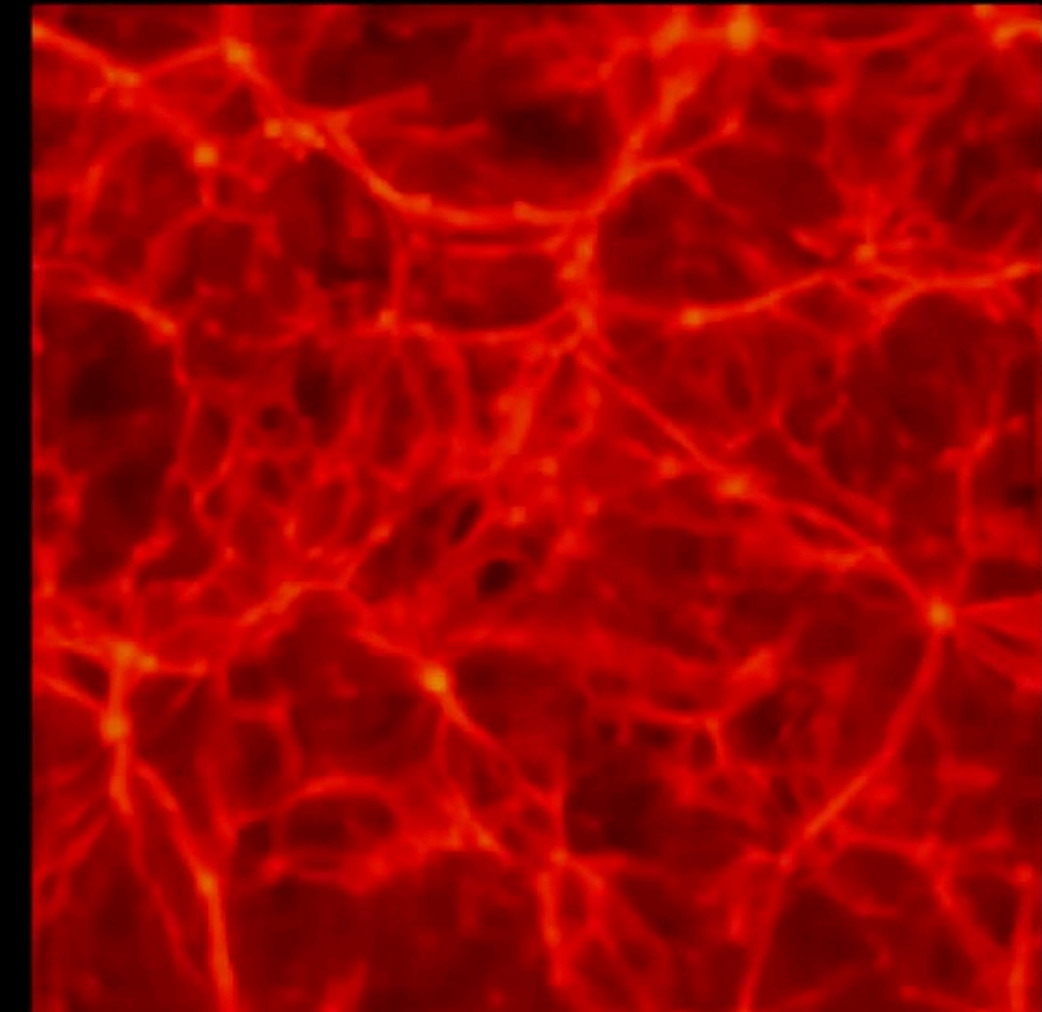
# SIMULATING GALAXY CLUSTERS

## Simulation details

- Magneto-hydrodynamic and N-body AMR cosmological code (**MASCLET**)
- flat  $\Lambda$ CDM:  $\Omega_m = 0.31$ ,  $\Omega_b = 0.048$ ,  $\Omega_\Lambda = 0.69$  and  $h = 0.678$ .
- $L = 147.5$  Mpc with a peak resolution of 9kpc
- Clusters are identified with ASOHF

## Sample selection

- Galaxy clusters with  $M \geq 4 \cdot 10^{13} M_\odot$
- Merger events with more than 20% of mass rate
- Mergers sufficiently isolated in time
- We focus on the range from  $z=1.5$  to  $z=0$





# DYNAMIC STATE AND MASS BIAS

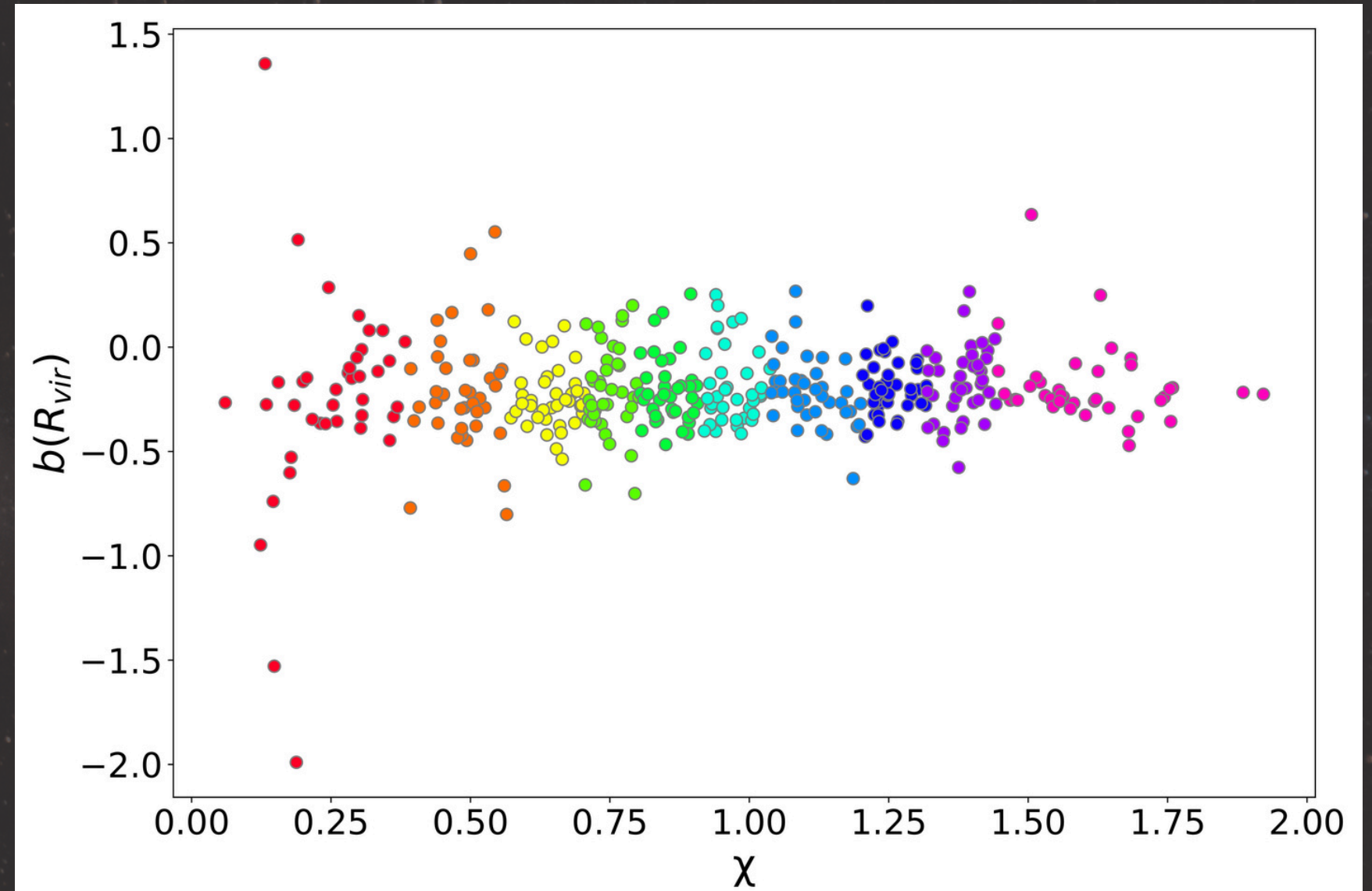
## Dynamic state indicator

- We use a **integrated relaxedness indicator** presented on [Vallés-Perez et al. \(2025\)](#):

- Centre offset
- Virial ratio
- Mean radial velocity
- Ellipticity
- Sparsity
- Substructure mass fraction

}  $\chi$

## Hydrostatic mass bias as a relaxedness indicator function

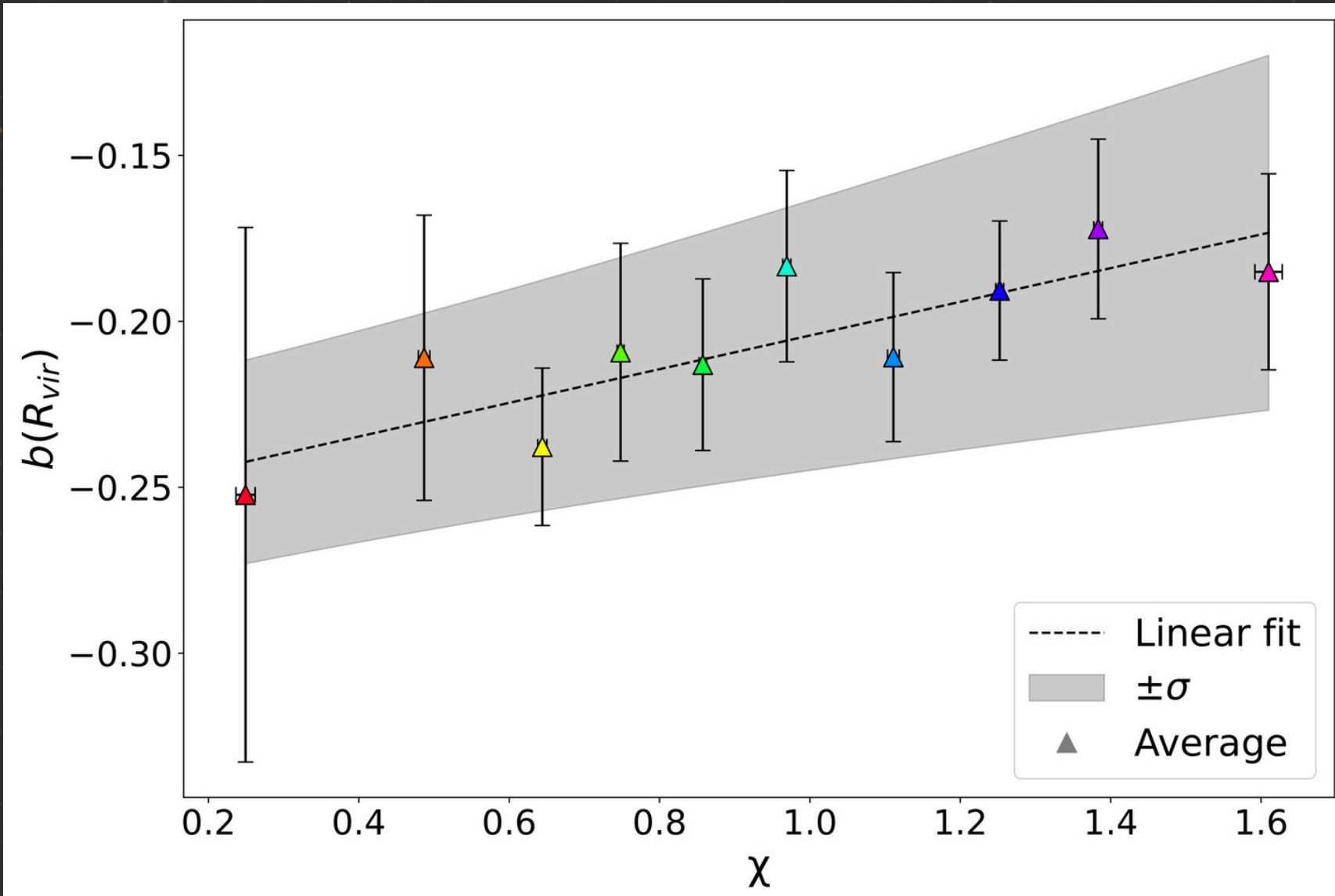


Hydrostatic mass bias evaluated at  $R_{\text{vir}}$  as a function of the combined dynamical state indicator,  $\chi$ , for all the clusters in our sample at  $z = 0$ . [Barranco-Llorca et al. \(2026\)](#)



# DYNAMIC STATE AND MASS BIAS

## Hydrostatic mass bias as a relaxedness indicator function



Average bins of hydrostatic mass bias evaluated at  $R_{vir}$  as a function of the combined dynamical state indicator,  $\chi$ , at  $z = 0$ .

[Barranco-Llorca et al. \(2026\)](#)

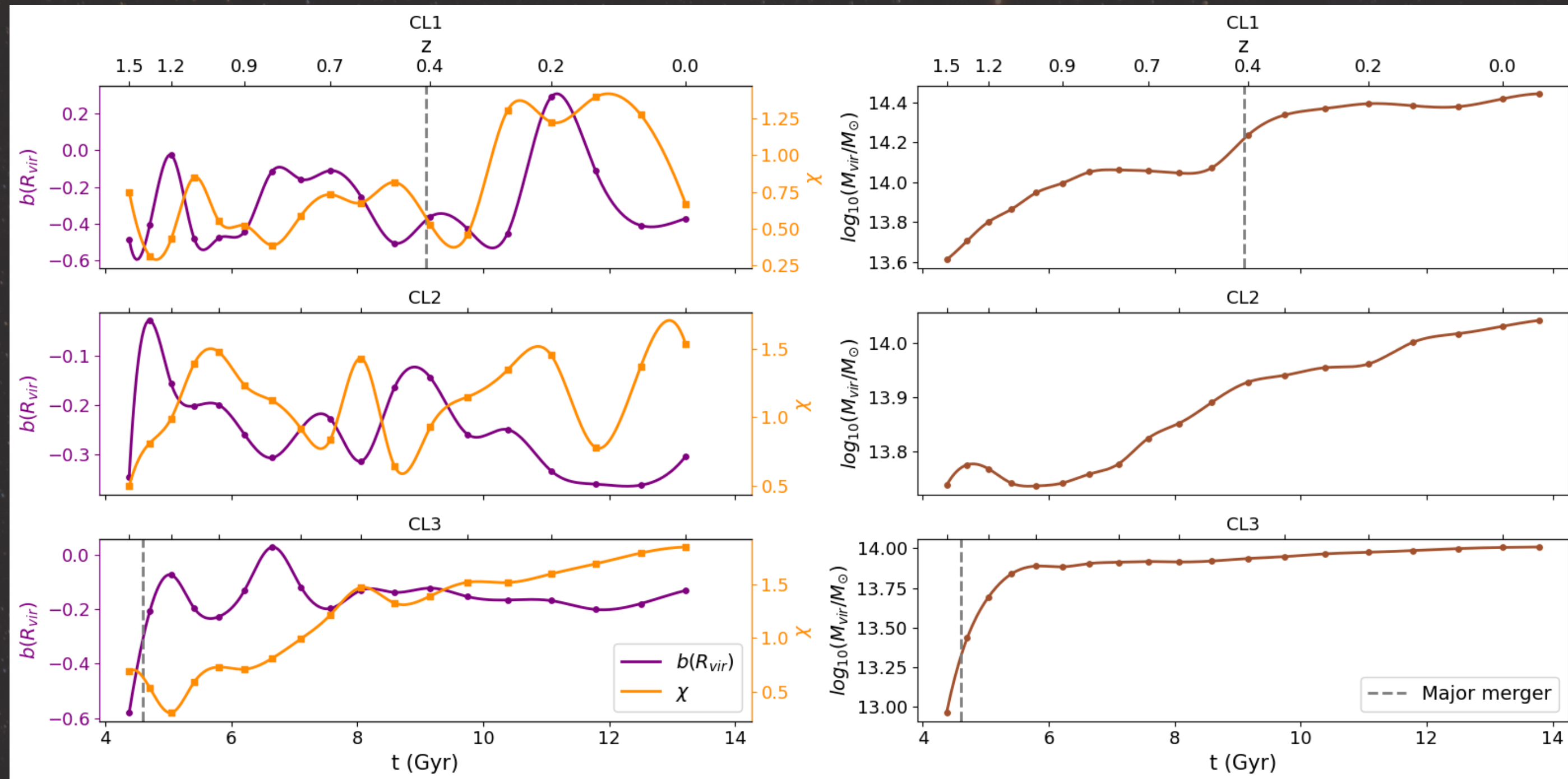
**More relaxed galaxy clusters show smaller average mass bias**

**Dynamical state alone is insufficient to predict the bias cluster by cluster.**



# MASS BIAS EVOLUTION OVER CLUSTERS LIFETIME

Evolution of three different prototypical galaxy clusters



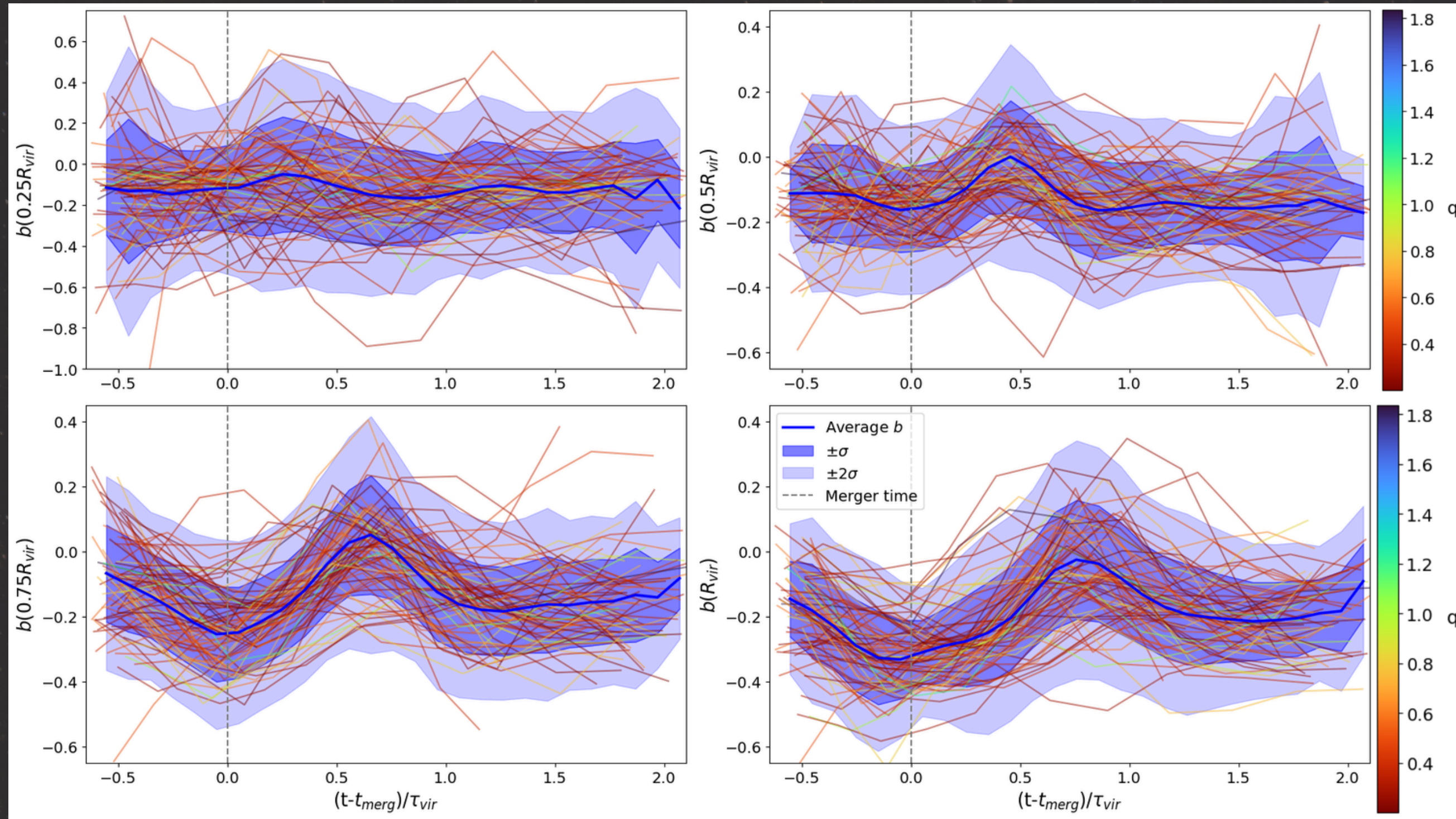
Left panels: Hydrostatic mass bias evaluated at the virial radius,  $b(R_{vir})$  (purple), and of the dynamical state indicator,  $\chi$  (orange). Right panels: Logarithmic mass growth history. [Barranco-Llorca et al. \(2026\)](#)





# THE MERGER SIGNATURE ON THE MASS BIAS

Mas bias evolution as a function of time for different appertures



$$\tau_{vir}(z) = \frac{1}{\sqrt{G\Delta_{vir}(z)\rho_c(z)}}$$

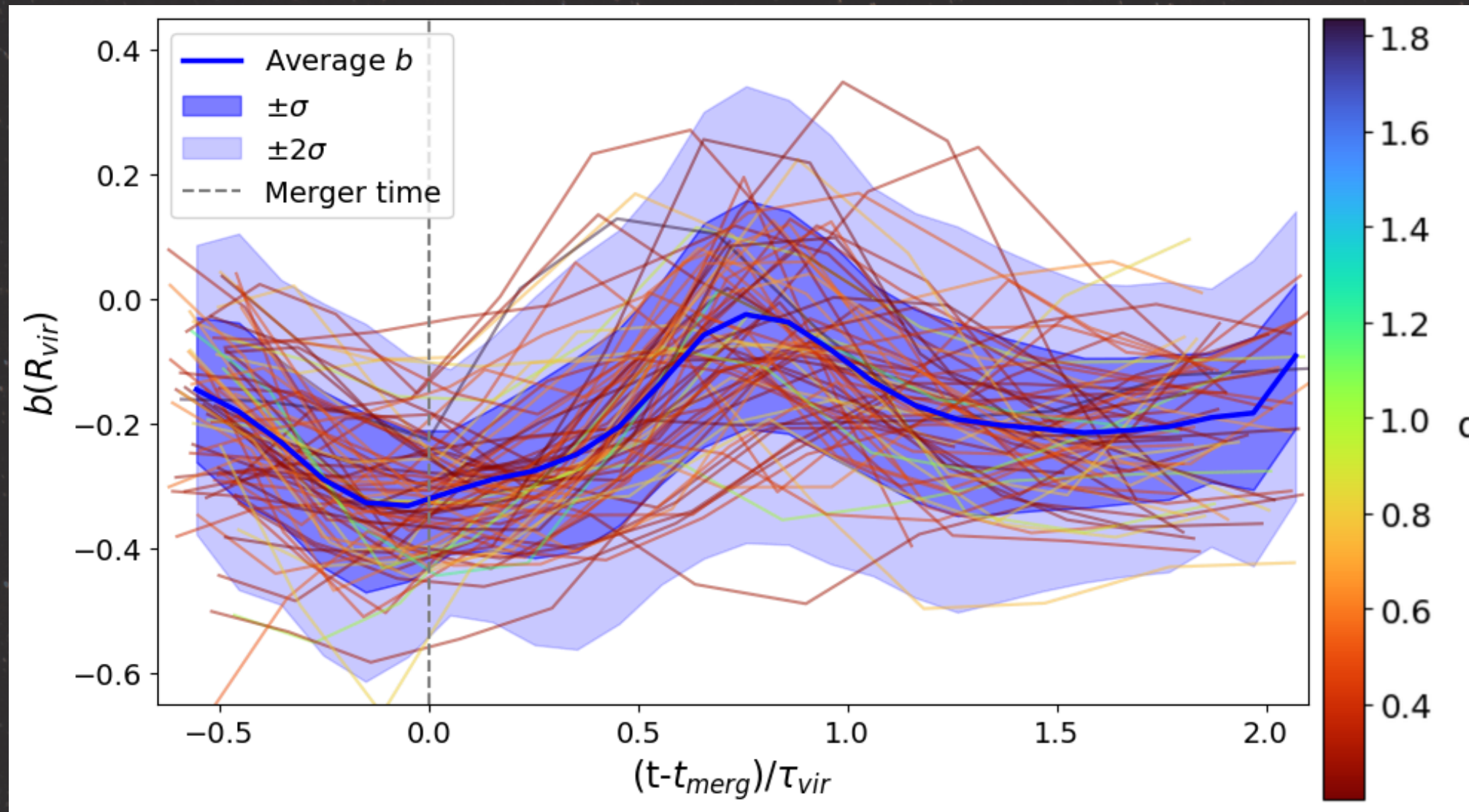
$$q = \frac{M_{infalling}}{M_{host}}$$





# THE MERGER SIGNATURE ON THE MASS BIAS

Mas bias evolution as a function of standardised time



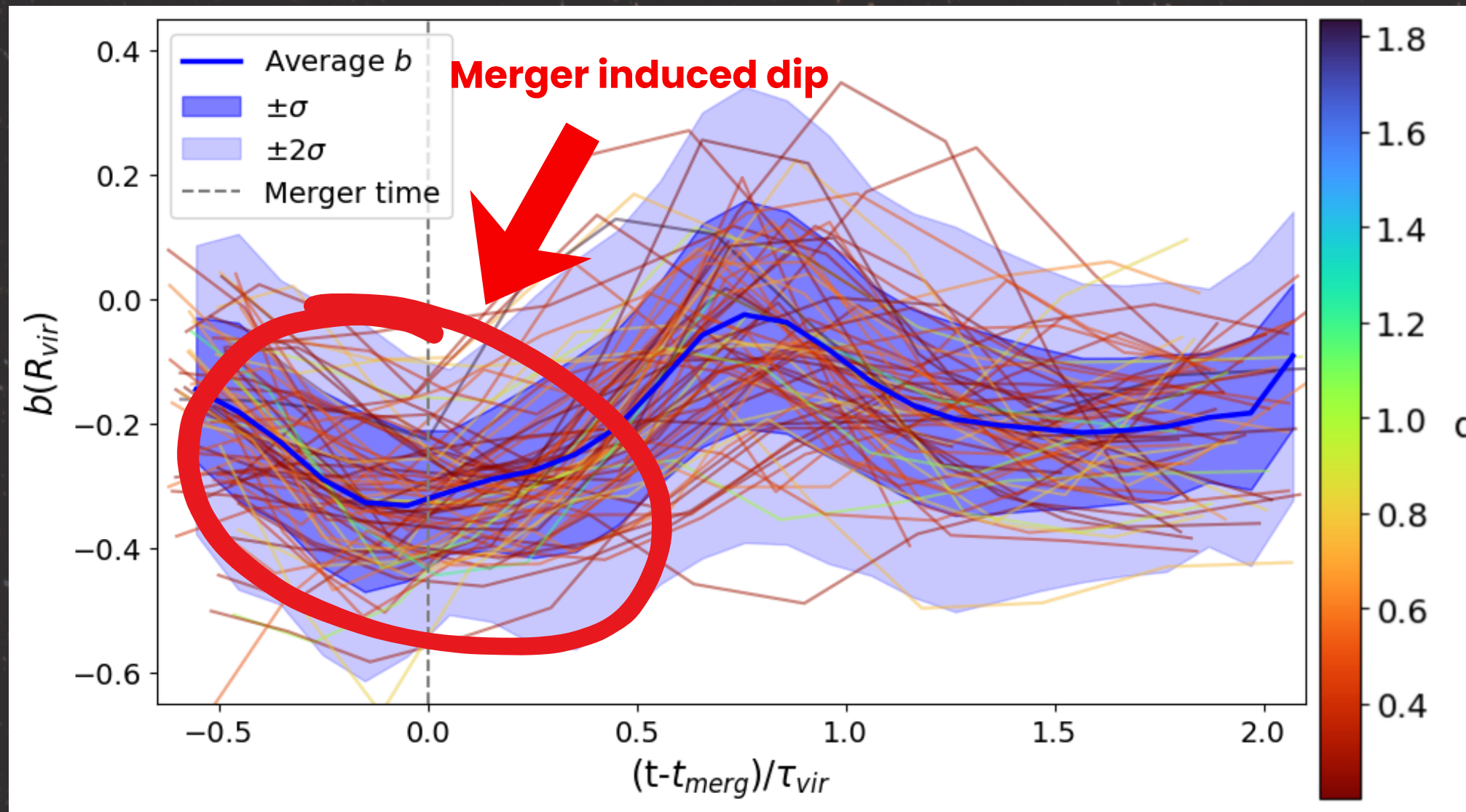
Standardised evolution of the hydrostatic mass bias, evaluated at several radii for the sample of isolated major merger events. The colour bar illustrates the magnitude of the merger mass ratio. [Barranco-Llorca et al. \(2026\)](#).

i A consistent trend is present during major merger events



# THE MERGER SIGNATURE ON THE MASS BIAS

Mas bias evolution as a function of standardised time



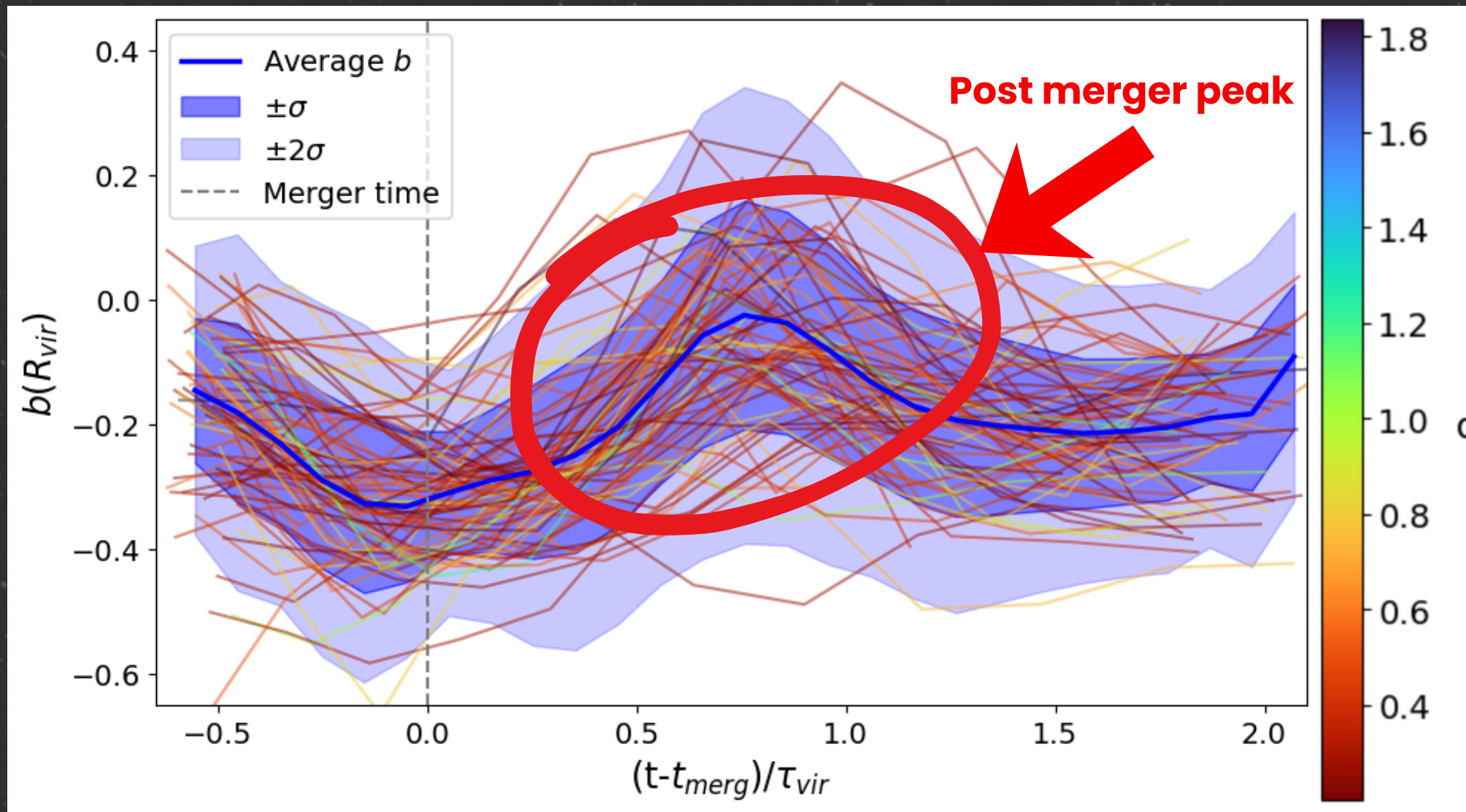
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- i** A consistent trend is present during major merger events:
- **Infall phase**: a negative dip in the bias occur as the secondary halo approaches the host



# THE MERGER SIGNATURE ON THE MASS BIAS

Mas bias evolution as a function of standardised time



Standardised evolution of the hydrostatic mass bias, evaluated at several radii for the sample of isolated major merger events. The colour bar illustrates the magnitude of the merger mass ratio. [Barranco-Llorca et al. \(2026\)](#).

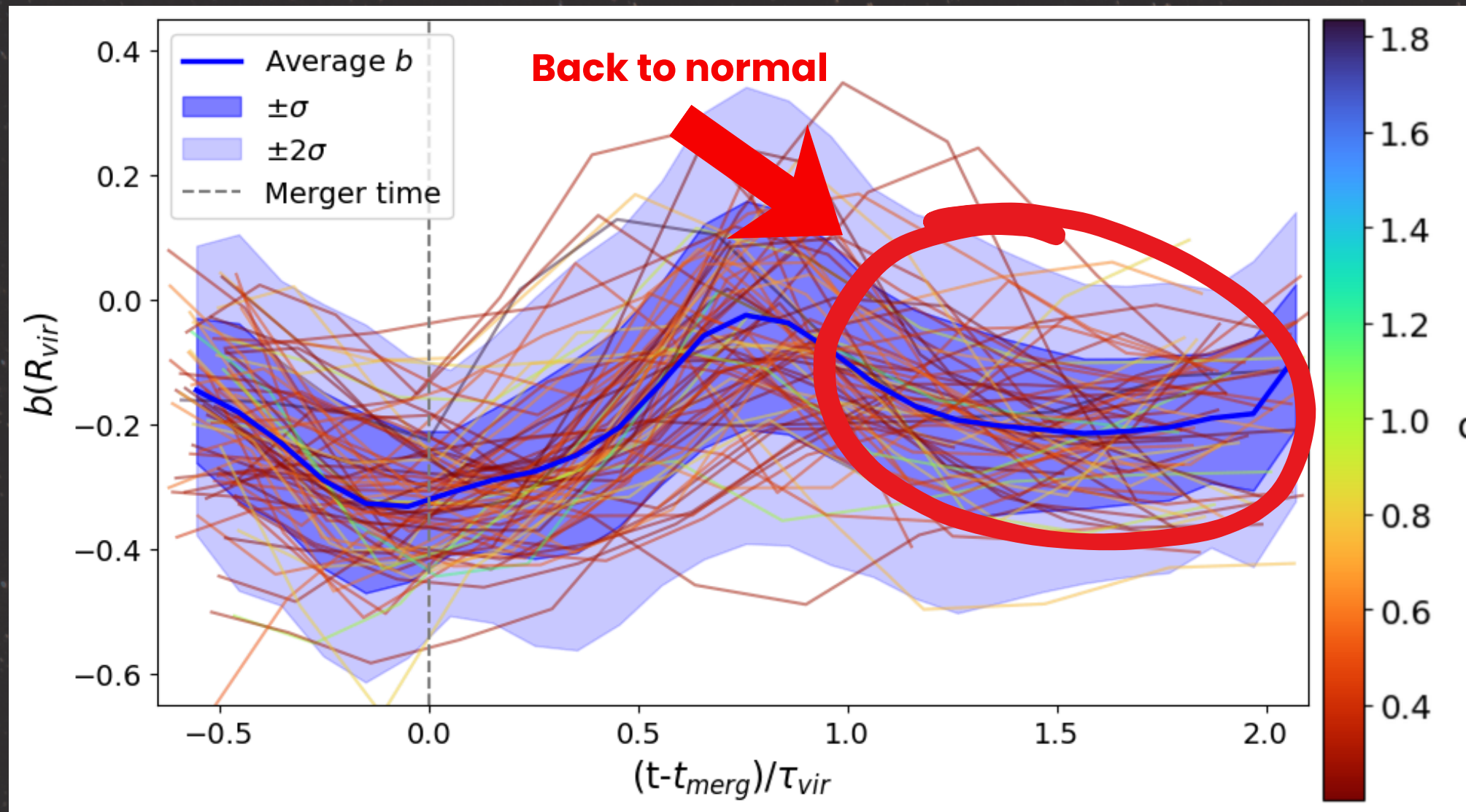
**i** A consistent trend is present during major merger events:

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- **Merger assimilation**: the bias peaks as the infalling halo passes through the pericentre



# THE MERGER SIGNATURE ON THE MASS BIAS

Mas bias evolution as a function of standardised time



Standardised evolution of the hydrostatic mass bias, evaluated at several radii for the sample of isolated major merger events. The colour bar illustrates the magnitude of the merger mass ratio. [Barranco-Llorca et al. \(2026\)](#).

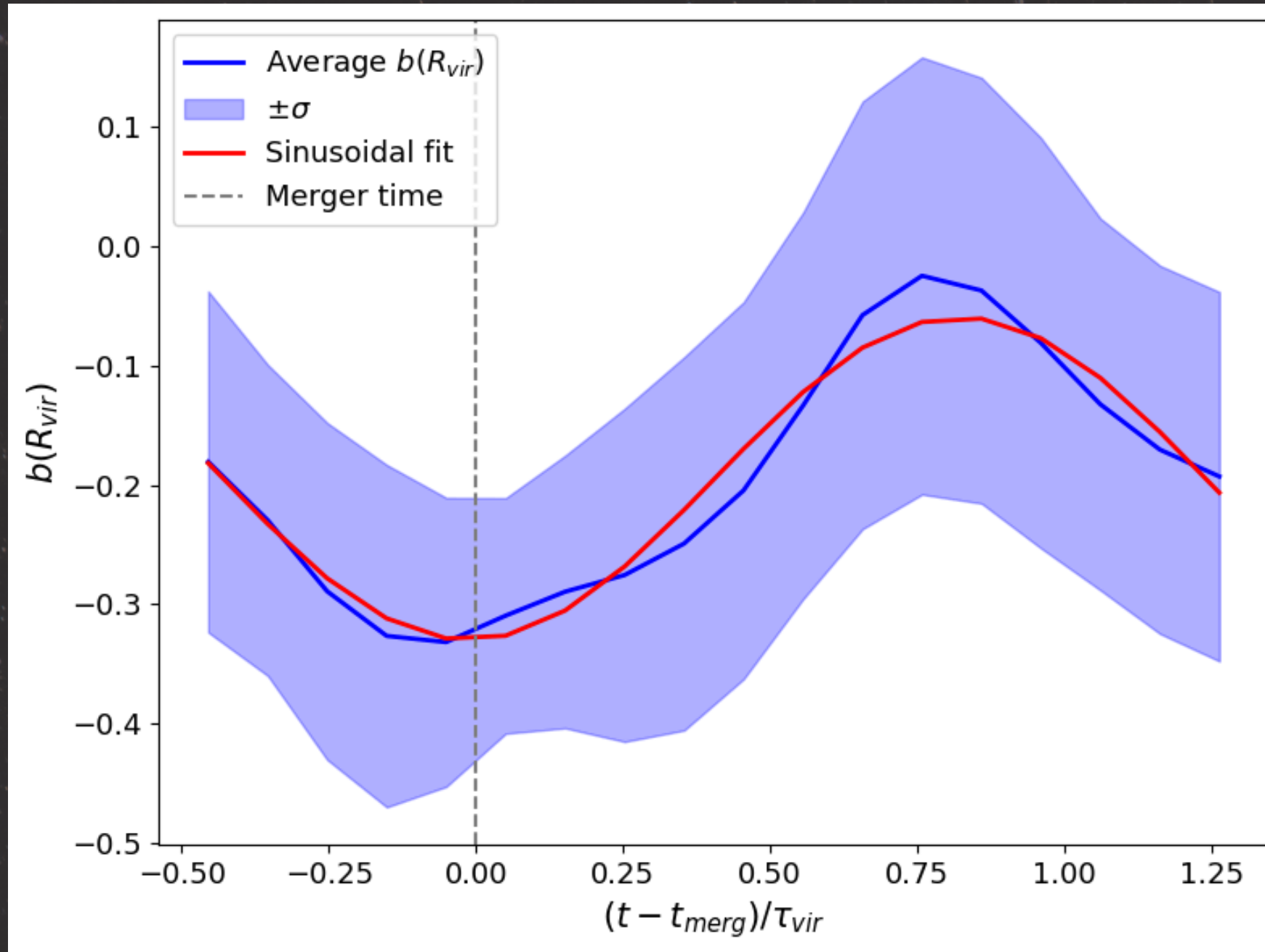
**i** A consistent trend is present during major merger events:

- **Infall phase**: a negative dip in the bias occur as the secondary halo approaches the host
- **Merger assimilation**: the bias peaks as the infalling halo passes through the pericentre
- **Relaxation phase**: The bias decreases to pre-merger levels



# MASS BIAS ESTIMATION AS A TIME FUNCTION

Hydrostatic mass bias fit for one oscillation



Sinusoidal fit (red) over the average mass bias trend evolution evaluated at  $R_{vir}$  during major mergers (blue), with the corresponding  $1\sigma$  shadowed area. [Barranco-Llorca et al. \(2026\)](#)

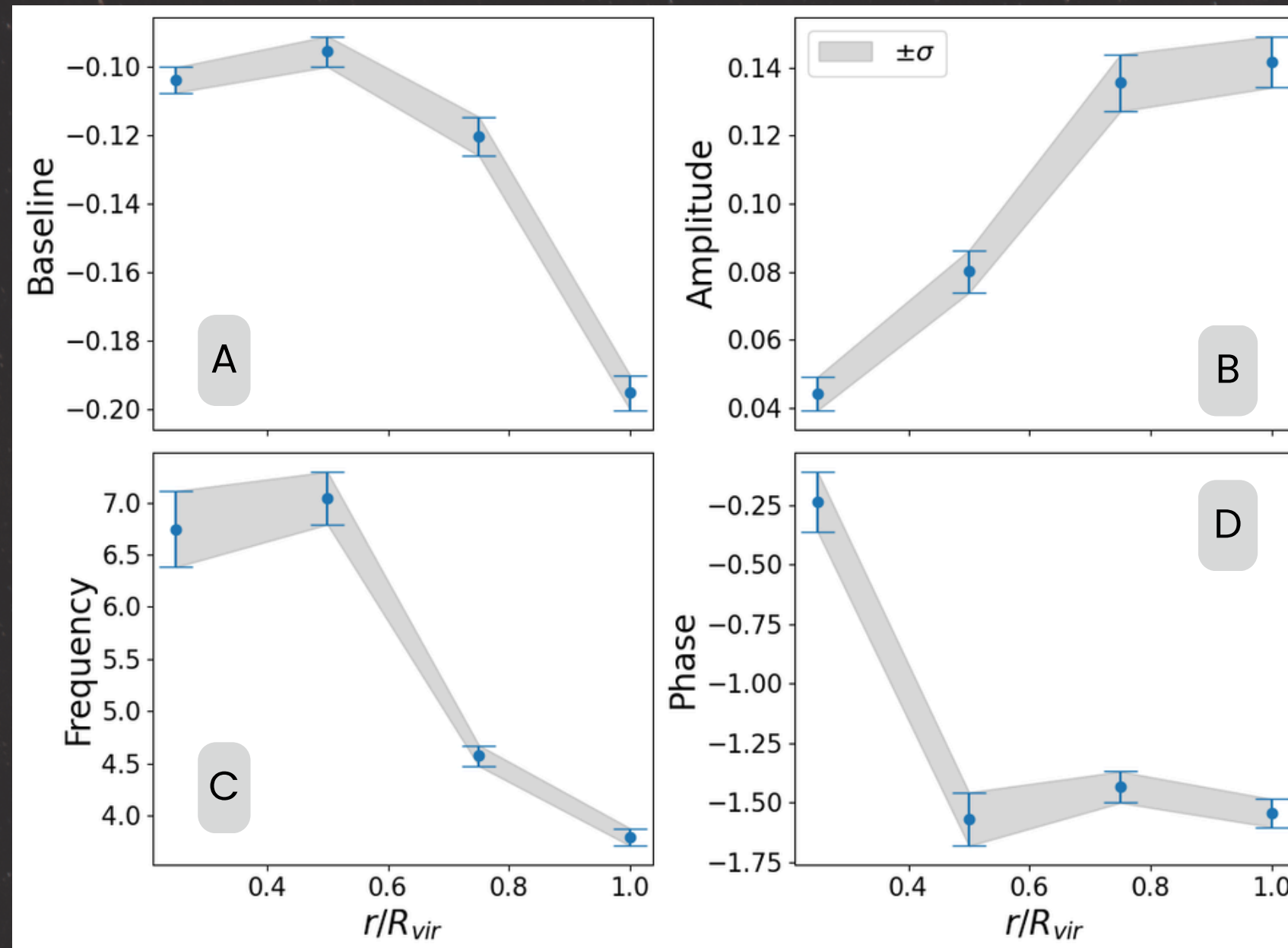
The trend can be fitted within one mass bias oscillation as a simple functional form:

$$b_r(\tau) = A + B \sin(C\tau + D)$$



# MASS BIAS ESTIMATION AS A TIME FUNCTION

Radial variation of the mass bias fit parameters



Radial variation of the parameters of the sinusoidal fit for the bias oscillation. [Barranco-Llorca et al. \(2026\)](#)

The trend can be fitted within one mass bias oscillation as a simple functional form:

$$b_r(\tau) = A + B \sin(C\tau + D)$$



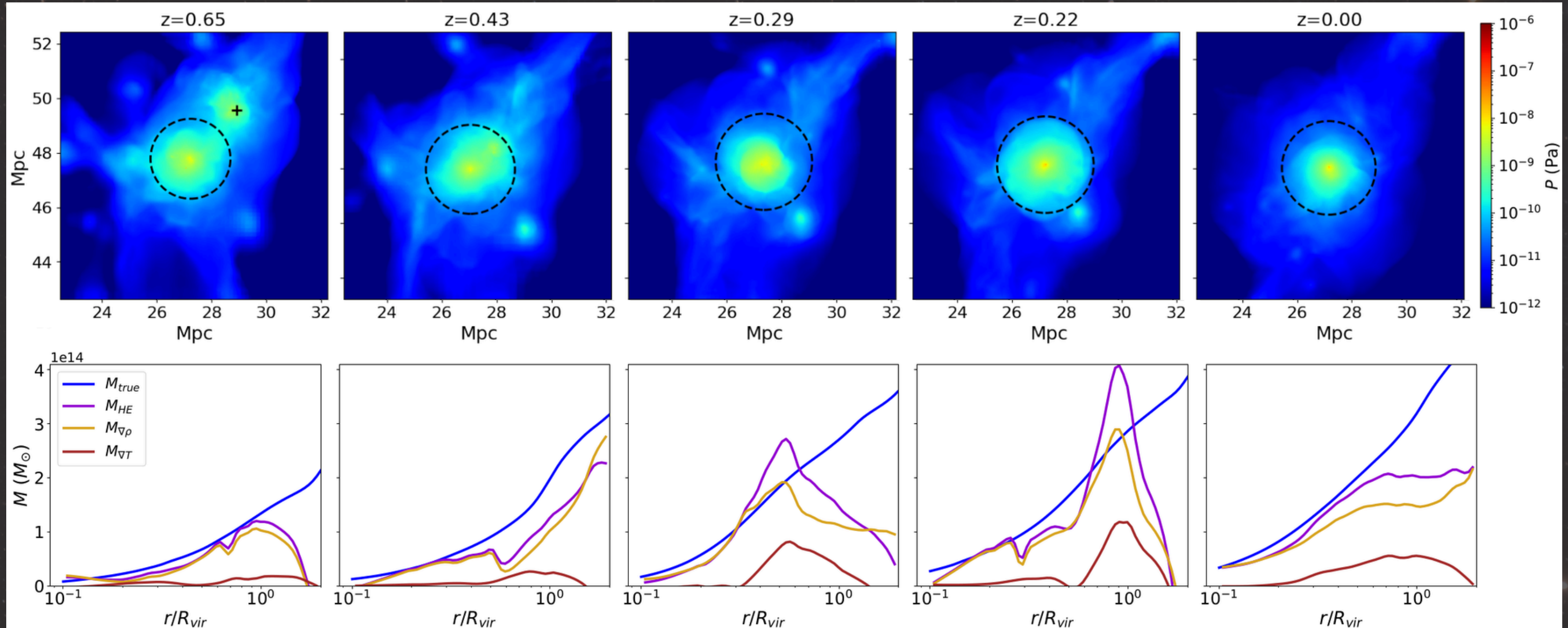
The fit parameters show that the effect of the merger propagates outwards, varying radially as we approach the outskirts





# MAIN DRIVER OF THE MERGER EFFECT ON THE BIAS

Thermal and density contributions to the hydrostatic mass estimation during a merger



Temporal evolution of a merging event between two galaxy clusters with  $q=0.5$ . Top panels represent pressure maps, bottom panels represent different mass radial profiles. [Barranco-Llorca et al. \(2026\)](#).



# CONCLUSIONS

- Major mergers induce a predictable track on the bias: a sharp drop , a positive overshoot post-collision, and final stabilization.
- Merger impacts expands radially toward the outskirts. The core is shielded, but a residual bias persists at the virial radius for gigayears.
- The bias evolution during major mergers is dominated by the geometric and morphological deformation of gas density profile, not by purely thermal changes.
- Tracking the merging stage allows using a sinusoidal/step-wise model to mitigate errors and recover the true Dark Matter mass.





# THANK YOU!



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Barranco-Llorca et al. (2026)



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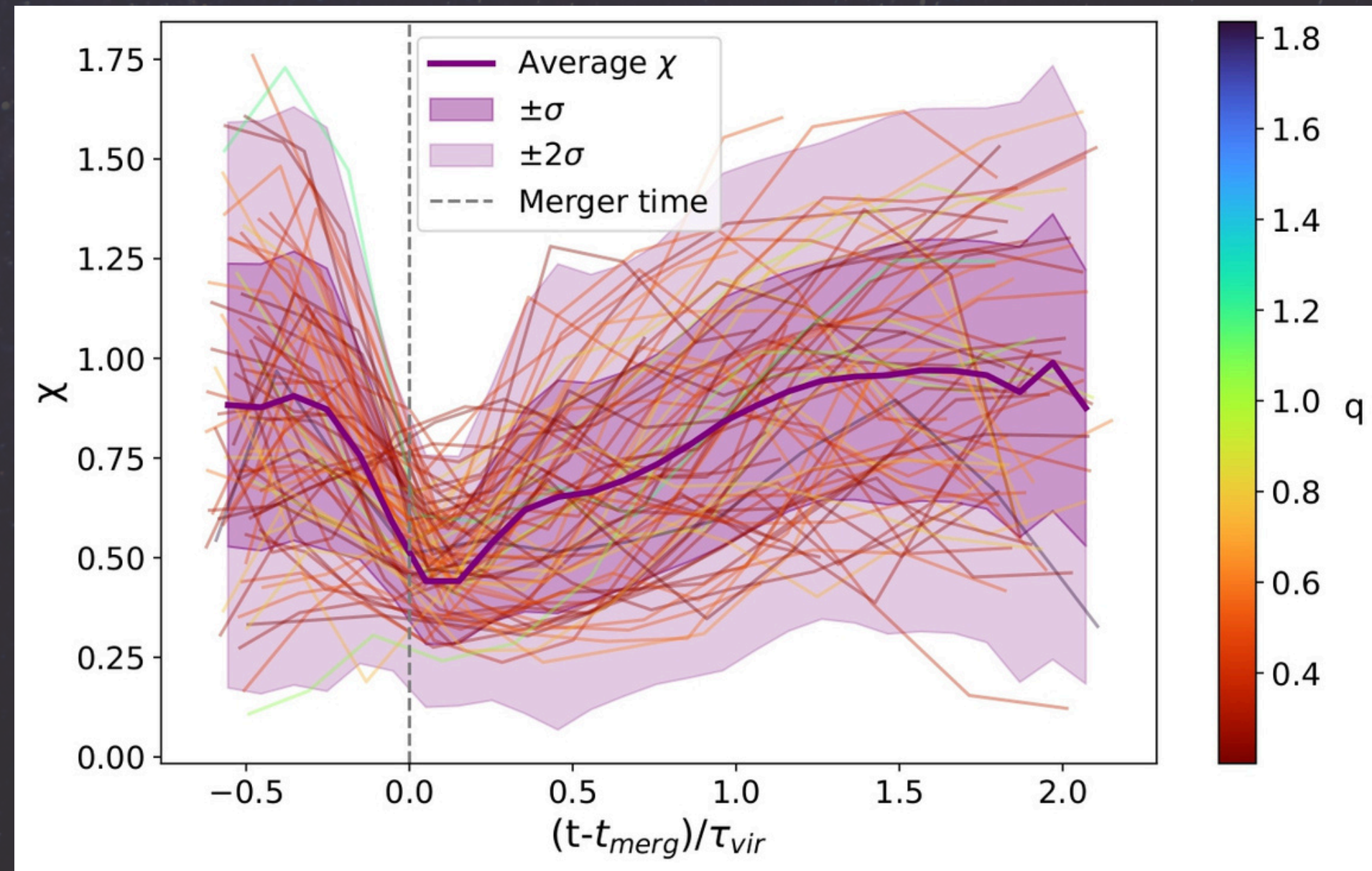


# ADDITIONAL SLIDES



# VARIATION OF THE DYNAMIC STATE DURING MERGERS

Variation of the relaxedness indicator during major mergers

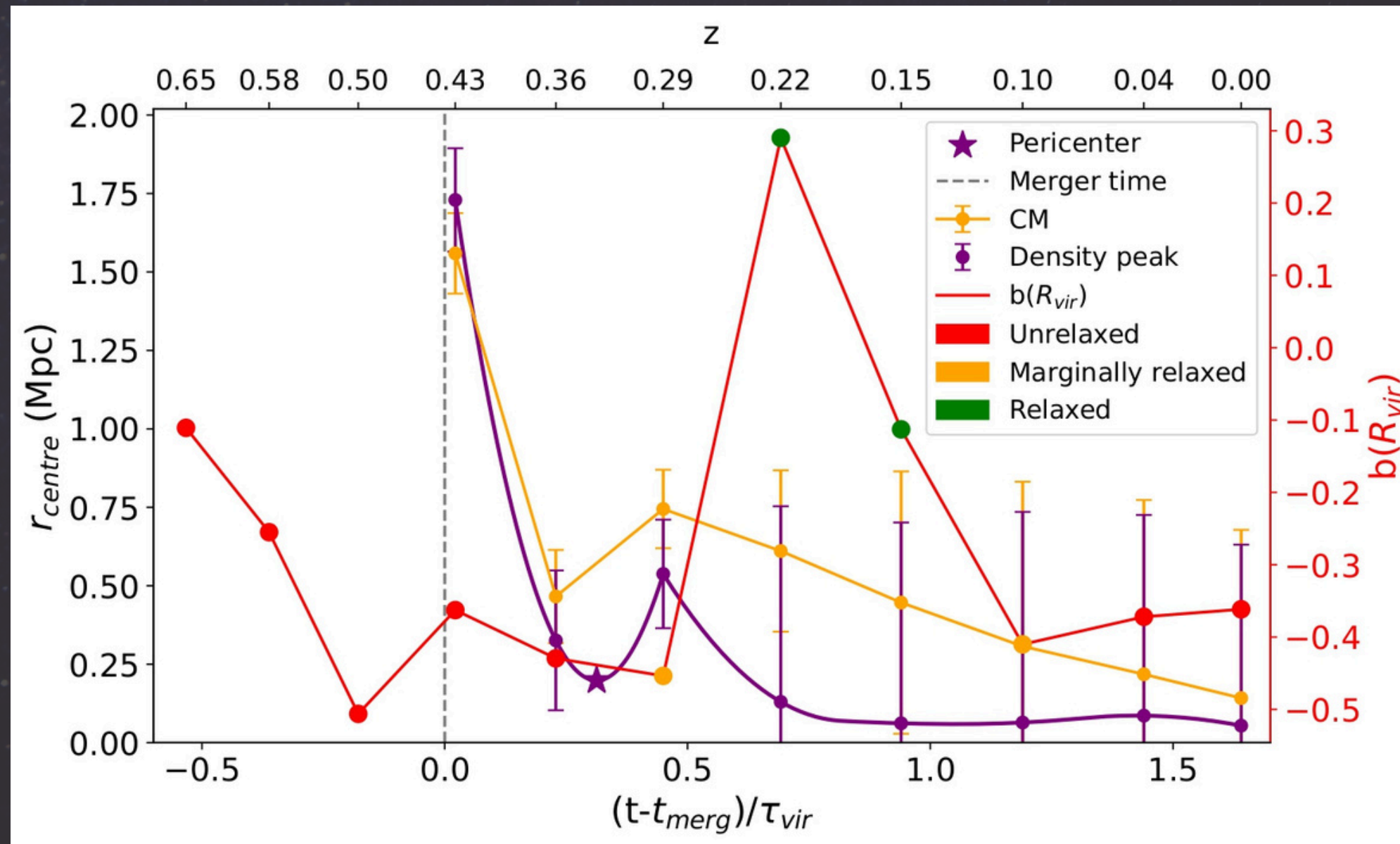


Temporal evolution of the relaxedness indicator as a function of time.  
[Barranco-Llorca et al. \(2026\)](#)



# TRACKING THE INFALLING HALO

Variation of the relaxedness indicator during major mergers

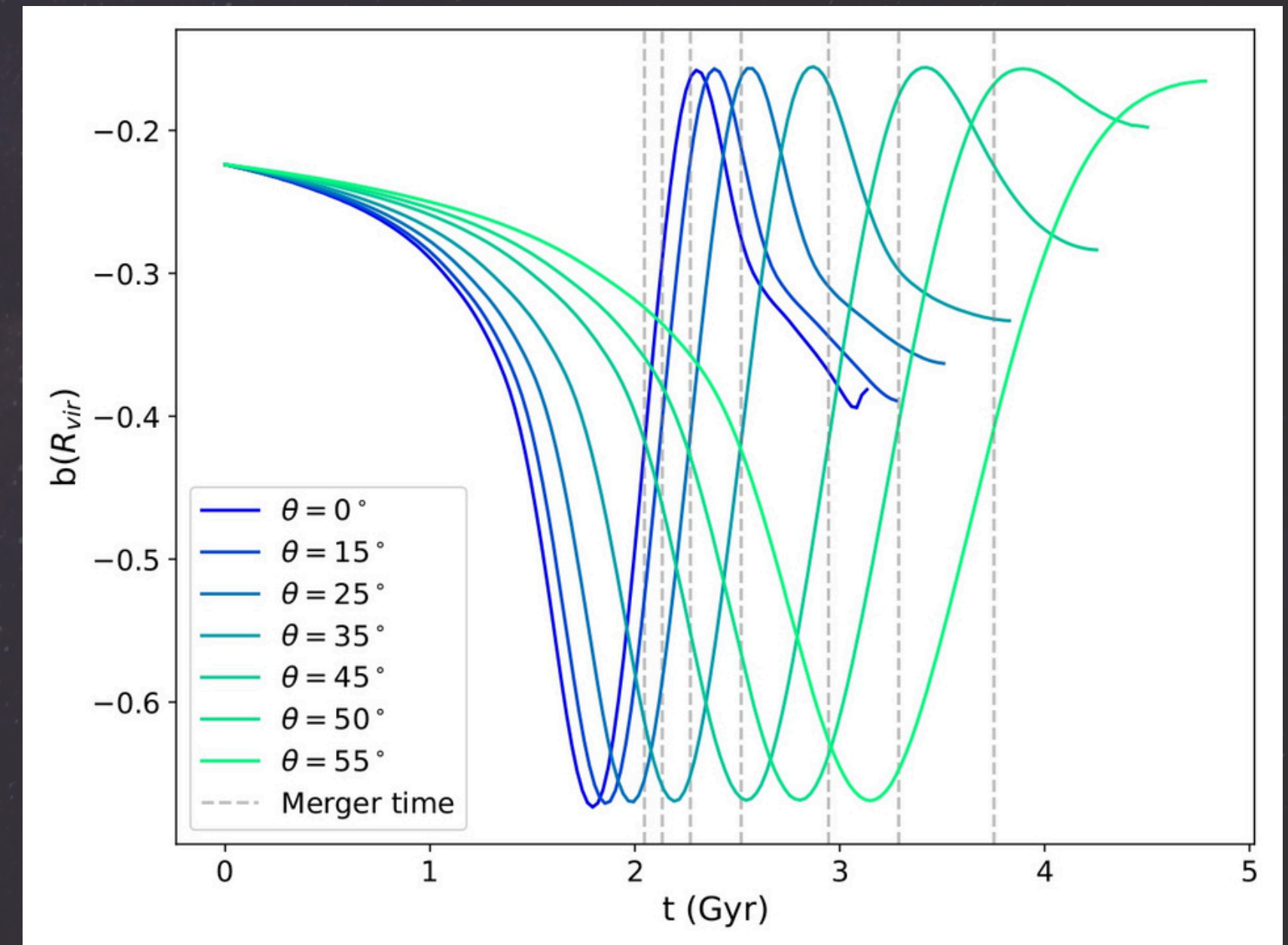
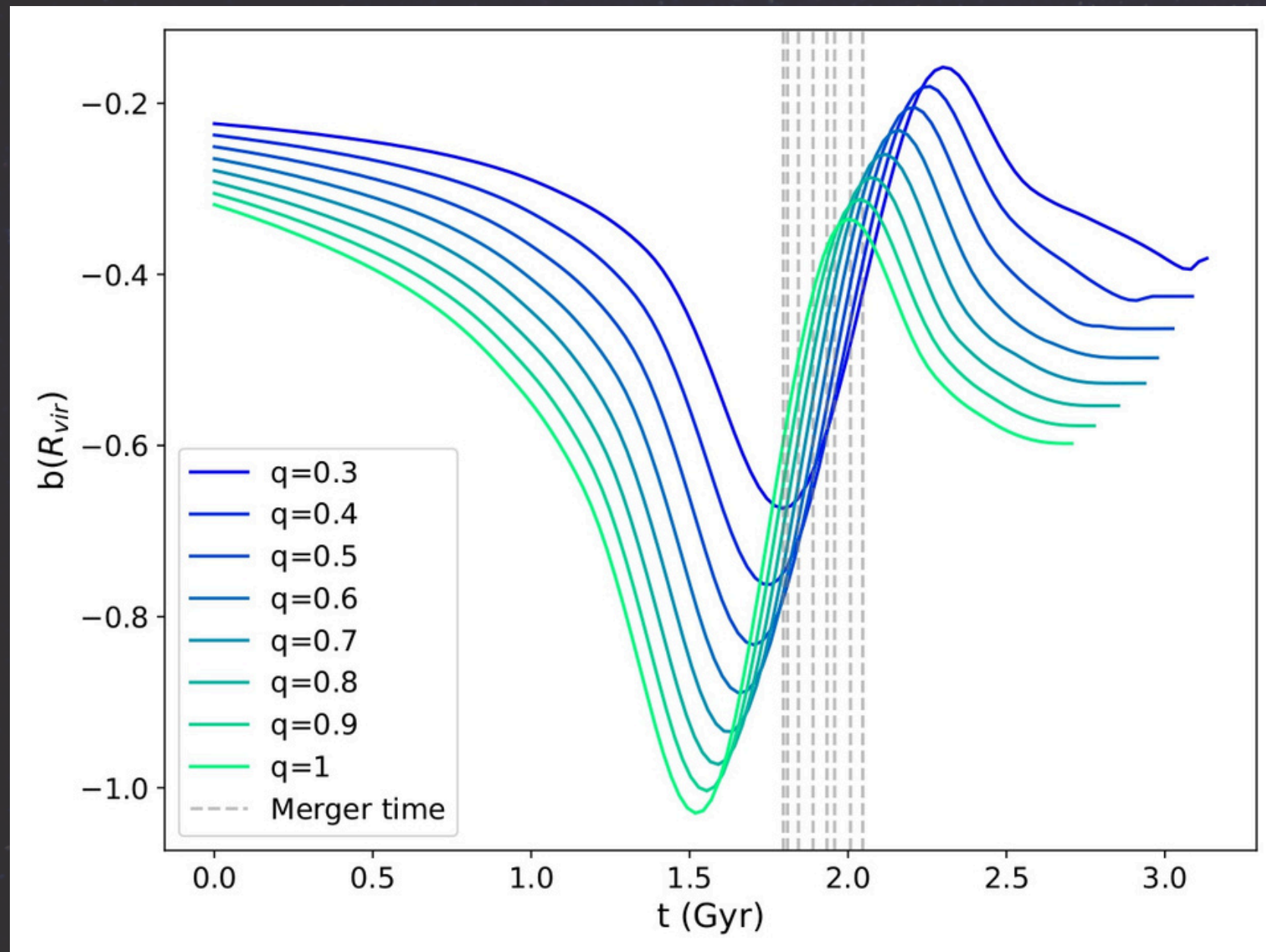


Temporal evolution of the mass bias, the position of the infalling halo centre and the dynamic state. [Barranco-Llorca et al. \(2026\)](#)



# MOCK TEST OF A MAJOR MERGER

Variation of the mass ratio and the impact parameter in a toy model merger

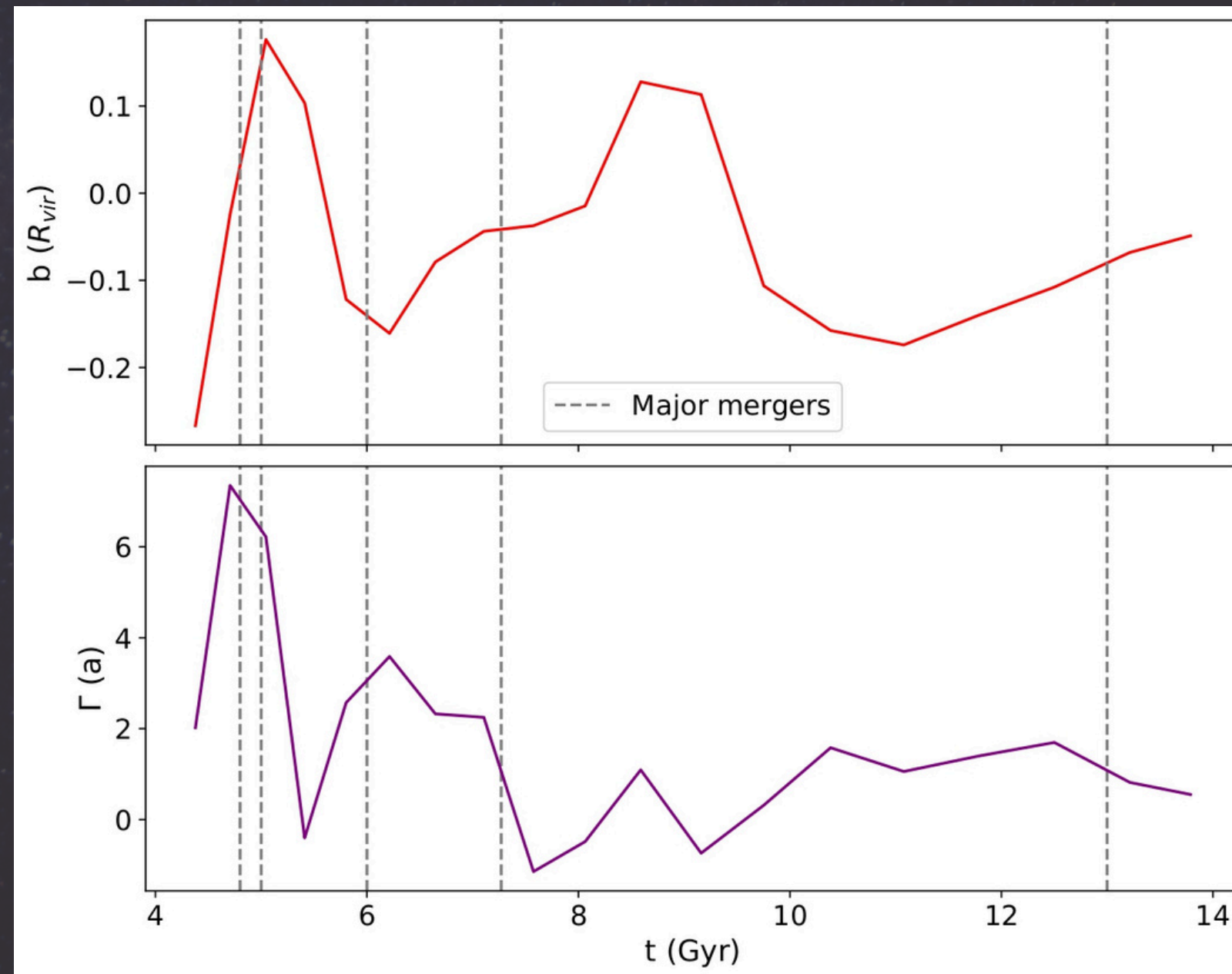


Variation of the mass ratio between host and infalling halo and the impact parameter (initial relative angle of the infall trajectory). [Barranco-Llorca et al. \(2026\)](#)



# NON ISOLATED MAJOR MERGERS

Bias and mass variation with cumulative merger effects



Temporal evolution of the hydrostatic mass bias and the gamma function (temporal derivative of mass). [Barranco-Llorca et al. \(2026\)](#)



