Dianoga Simulation (OATs)

On Hydrostatic Equilibrium and Mass Bias in (Simulated) Galaxy Clusters

Veronica Biffi (INAF OATs)

w/ S. Borgani, E. Rasia, S. Planelles + OATs group + TheThreeHundred collab.;
K. Dolag + USM/eROSITA collab.; J. ZuHone

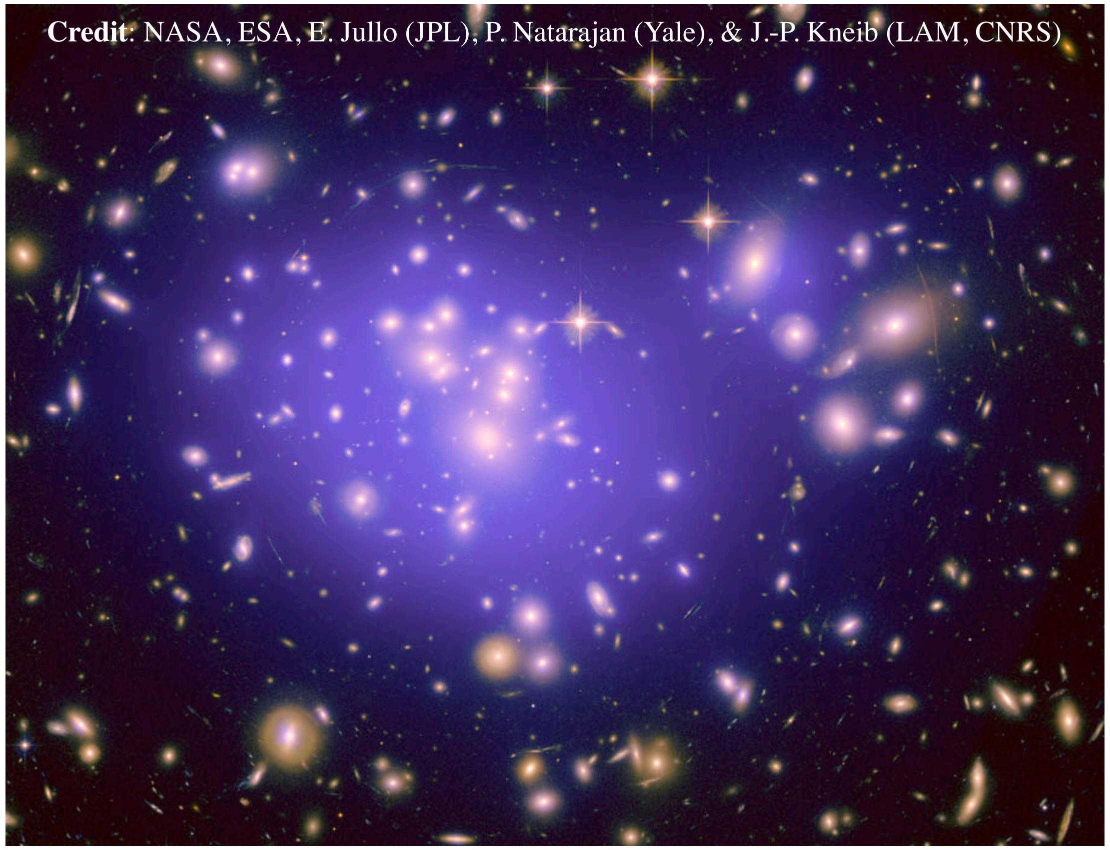
Pic by V.Biffi

Starting from the ICM...

- Clusters are **X-ray bright extended** sources
  X-ray obs.: ICM thermodynamical properties

- Multi-wavelength obs.: combined to study cluster physics (chemical and energy feedback, relation ICM-stellar population, plasma micro-physics, ...)

- **ICM traces the underlying DM potential well:**
  allows to reconstruct the total mass (DM-dominated)
  - **Hydrostatic mass estimate**
    (thermal pressure from X-ray & SZ)
  - **Scaling laws** between ICM observables and total mass calibrated on small sample w/ precise mass estimates (via HE or WL)



Hydrostatic Mass (...bias)

"Simplest" assumption:
ICM is in Hydrostatic Equilibrium (HE)

\+ **spherical symmetry**

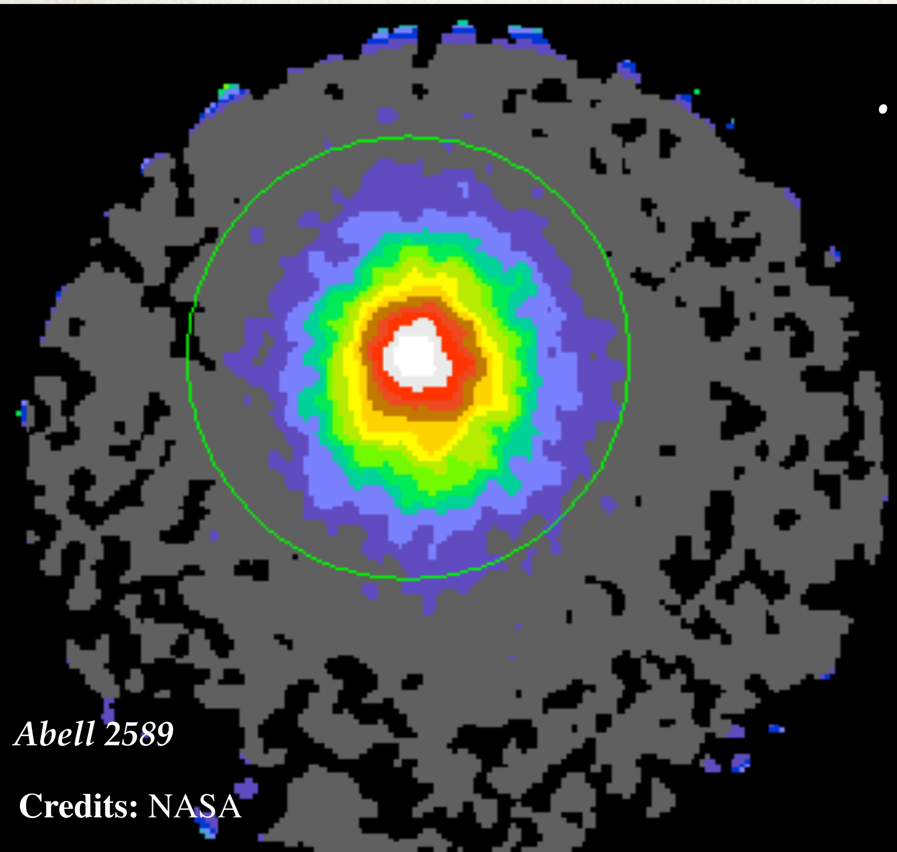
\+ purely **thermal pressure** support ($P = P_{ther}$)

$$0 = -\nabla\Phi - \frac{1}{\rho}\nabla P$$

Hydrostatic Mass Estimate

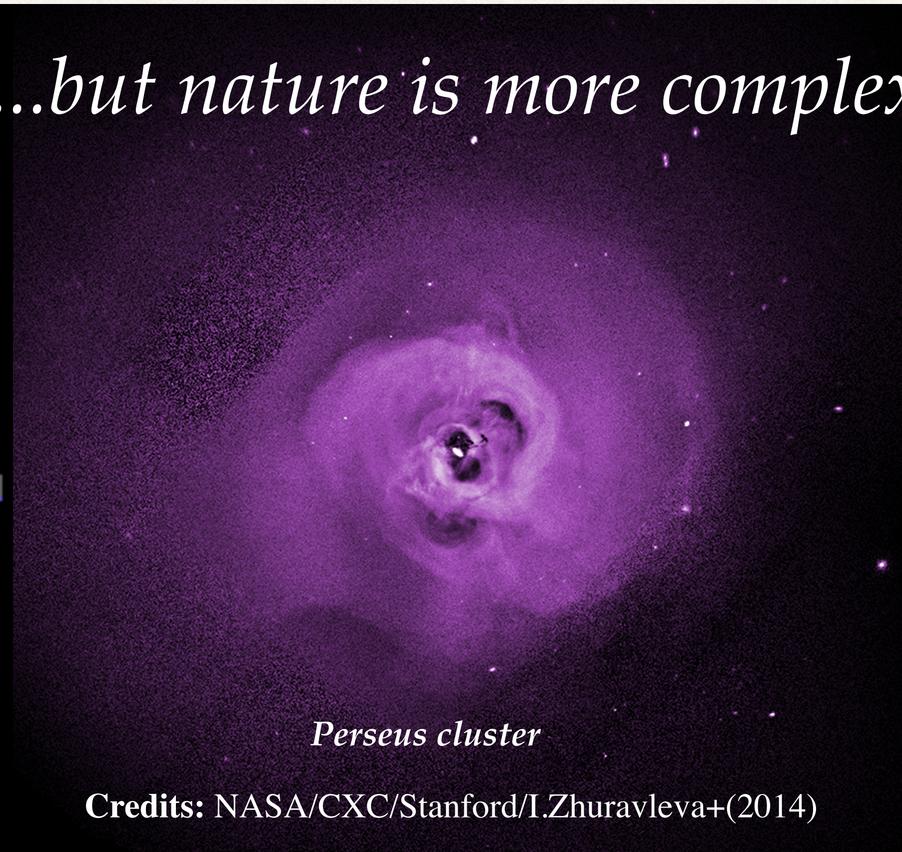
$$M_{HE}(< r) = -\frac{k_B T(r) r}{\mu G m_p}\left[\frac{d\log\rho(r)}{d\log r} + \frac{d\log T(r)}{d\log r}\right]$$

...but nature is more complex



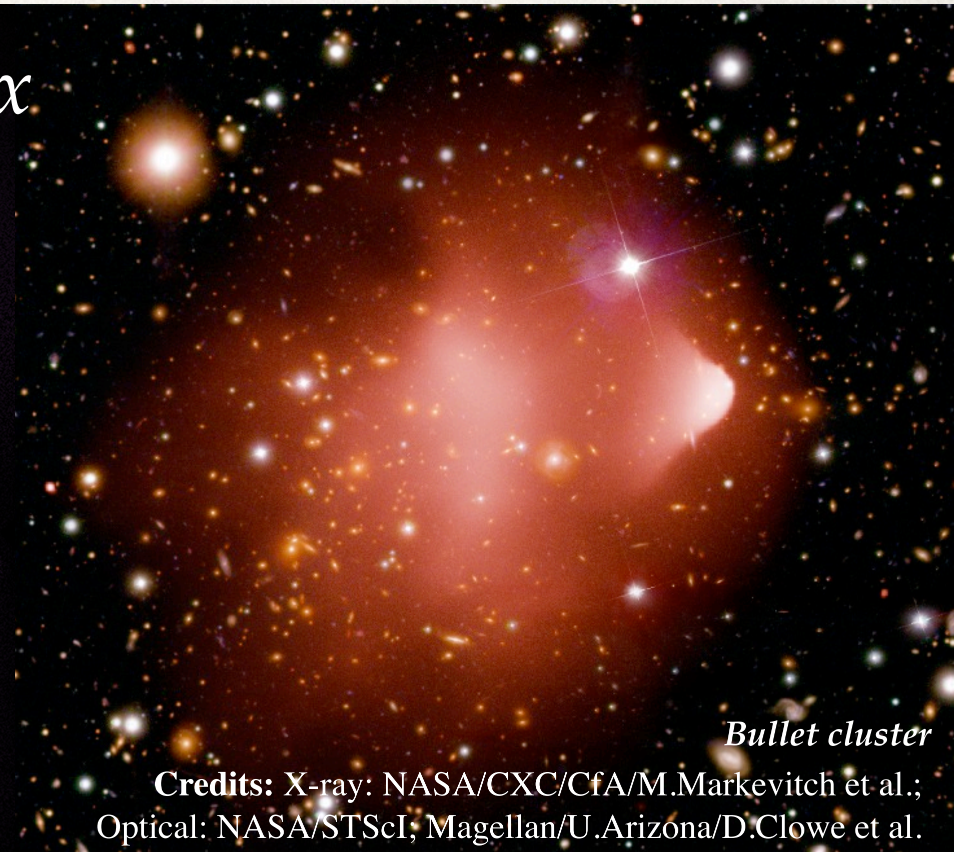
Abell 2589

Credits: NASA



Perseus cluster

Credits: NASA/CXC/Stanford/I.Zhuravleva+(2014)



Bullet cluster

Credits: X-ray: NASA/CXC/CfA/M.Markevitch et al.;
Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.

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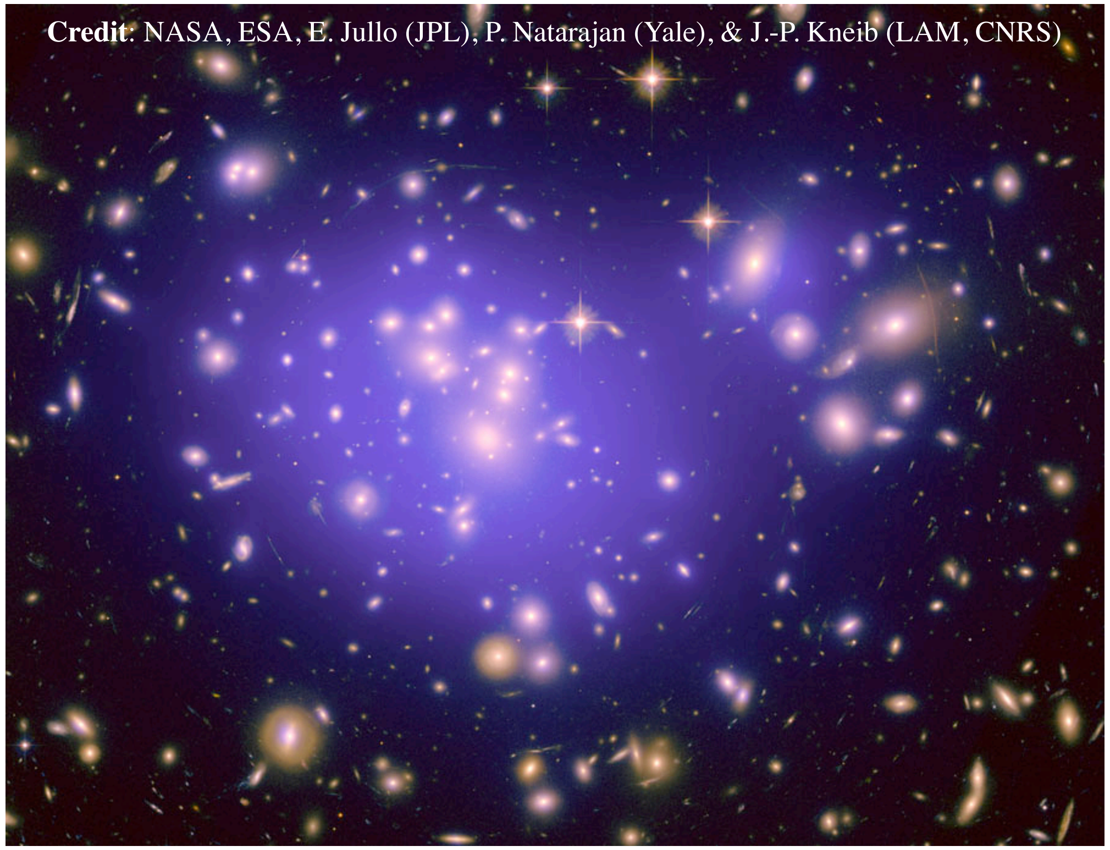
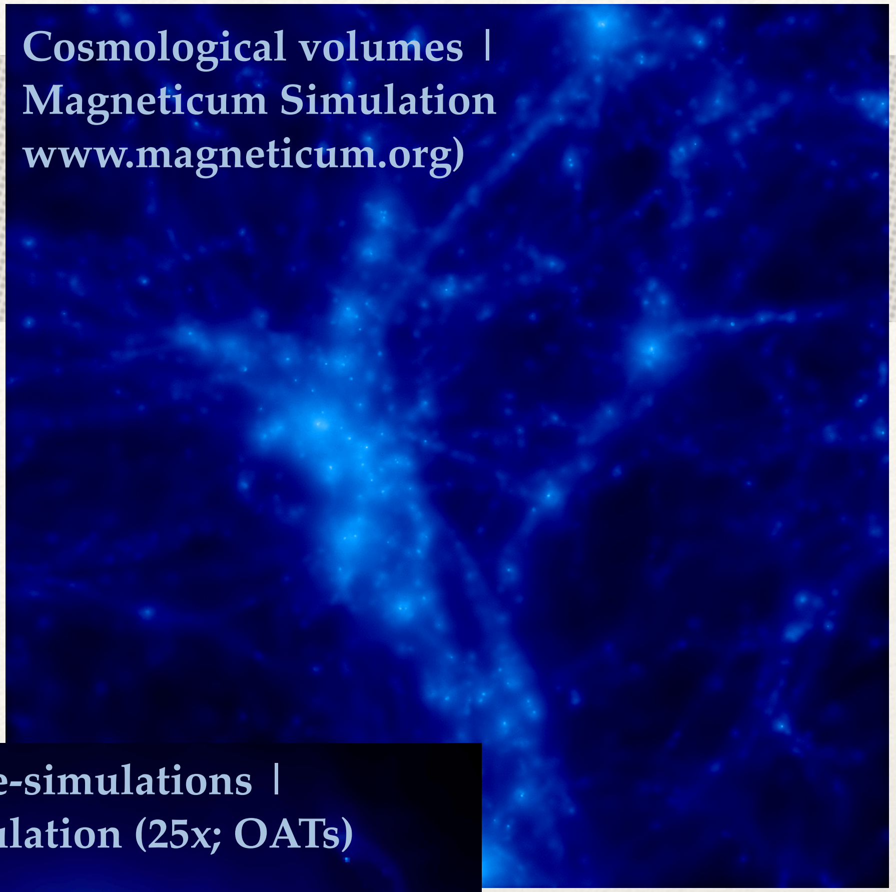


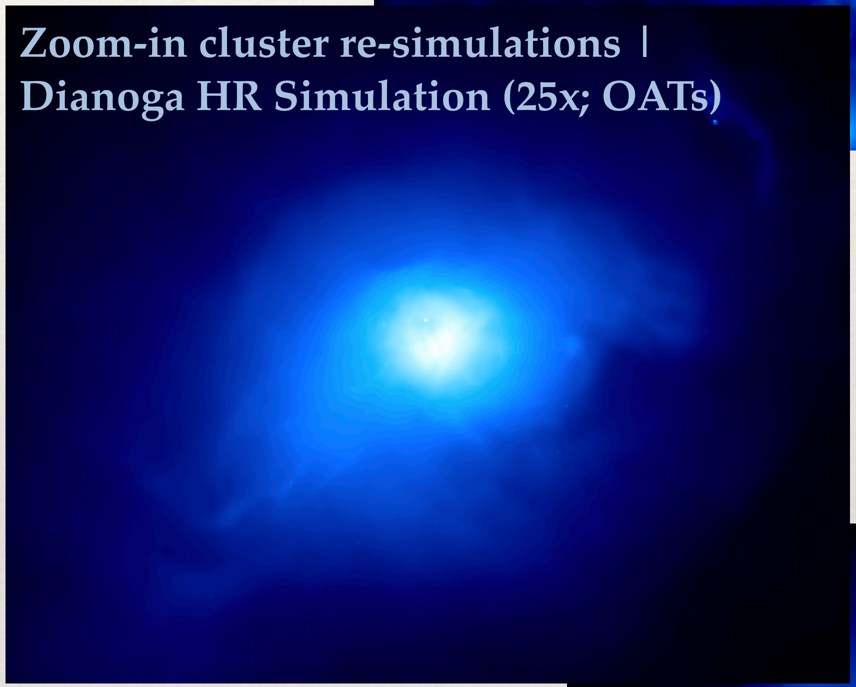
This can be well studied in simulations!

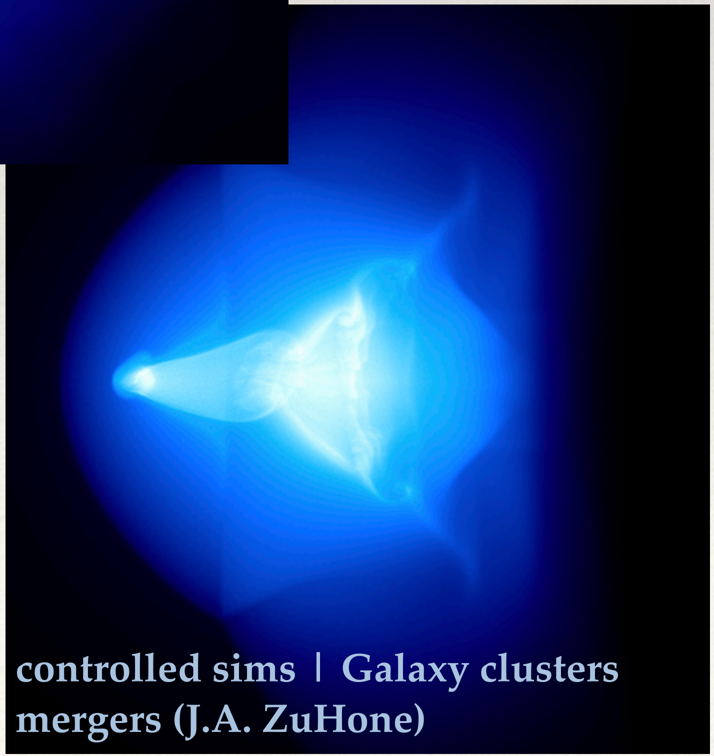
Rasia+06; Nagai+07; Piffaretti+08; Fang+09; Lau+09,13; Vazza+09; **VB**+11,16; Suto+13; Zhuravleva+13; Nelson+14; Shi+15,16; Vazza+18; Pratt+19; Ansarifard+20; Angelinelli+20; Gianfagna+23

Why Numerical Simulations?

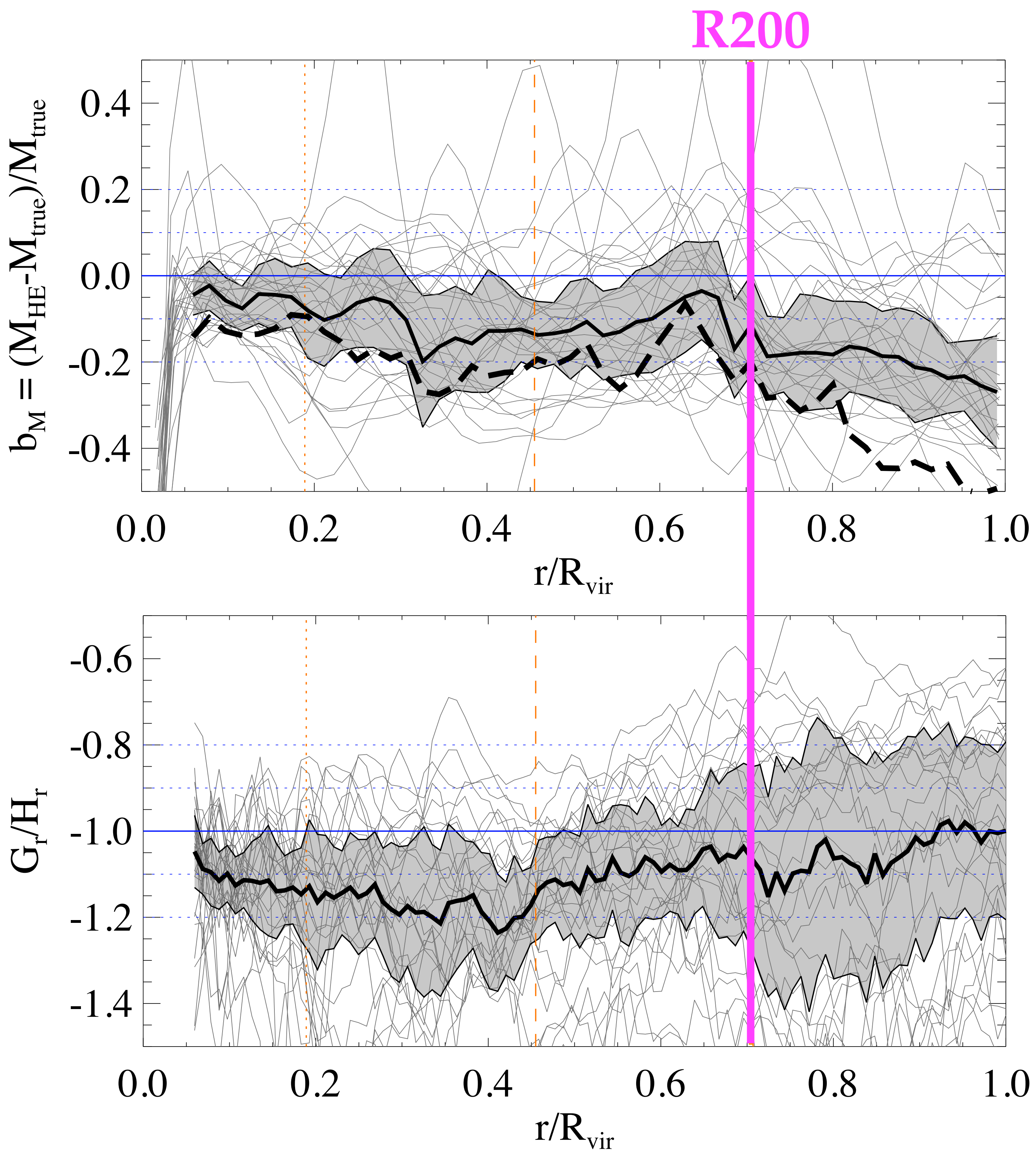
- cosmological volumes, zoom-in re-simulations of galaxy clusters or idealized controlled simulations
- follow DM & baryonic component evolution
- direct access to 3D structure of systems and time evolution
- can validate or constrain model assumptions and make predictions
- help interpretation of observational data...
- *... provided a reliable comparison* (mock obs? choice of most-suitable observables/proxies?...)







Relation between HE-deviation and M-bias



Biffi et al. (2016)

$$\delta_{HE} = \mathcal{G}_r/\mathcal{H}_r + 1$$

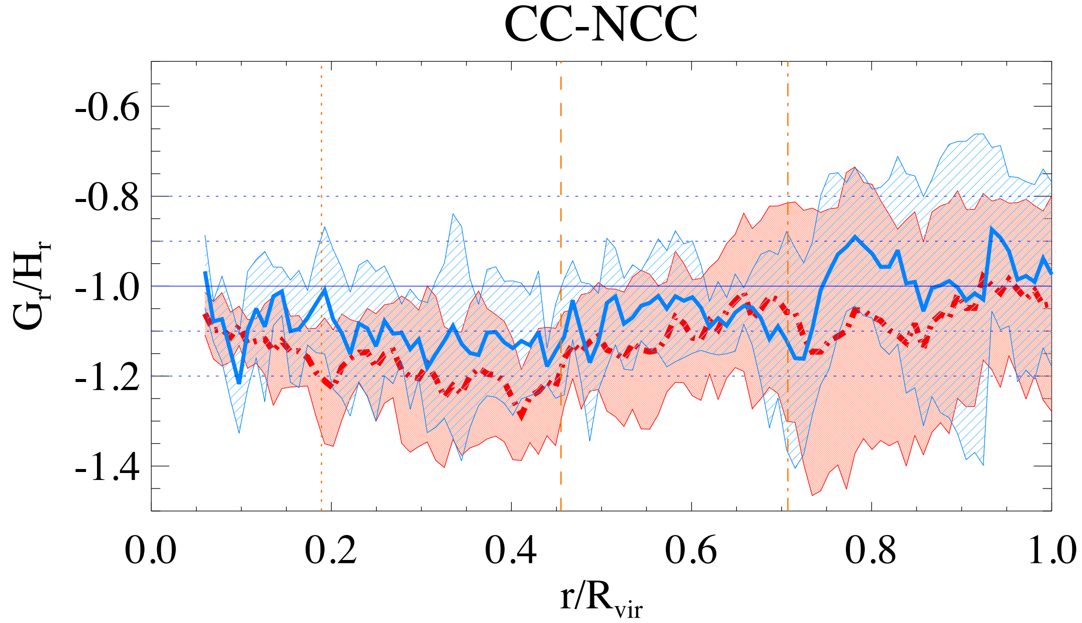
M-bias = (M_{HE} - M_{true})/M_{true}

- ✦ Average mass-bias <20% out to R_{200} (~20% for T_{sl})
- ✦ M-bias <10% within the core (< R_{2500})
- ✦ *Individual profiles very noisy*
- ✦ large scatter in the outskirts
- ✦ Average HE-deviation within 20%
- ✦ Median stacked profile tracing mass-bias out to R_{200}

HE-deviation & M-bias: CC/NCC vs. Relaxed/Disturbed

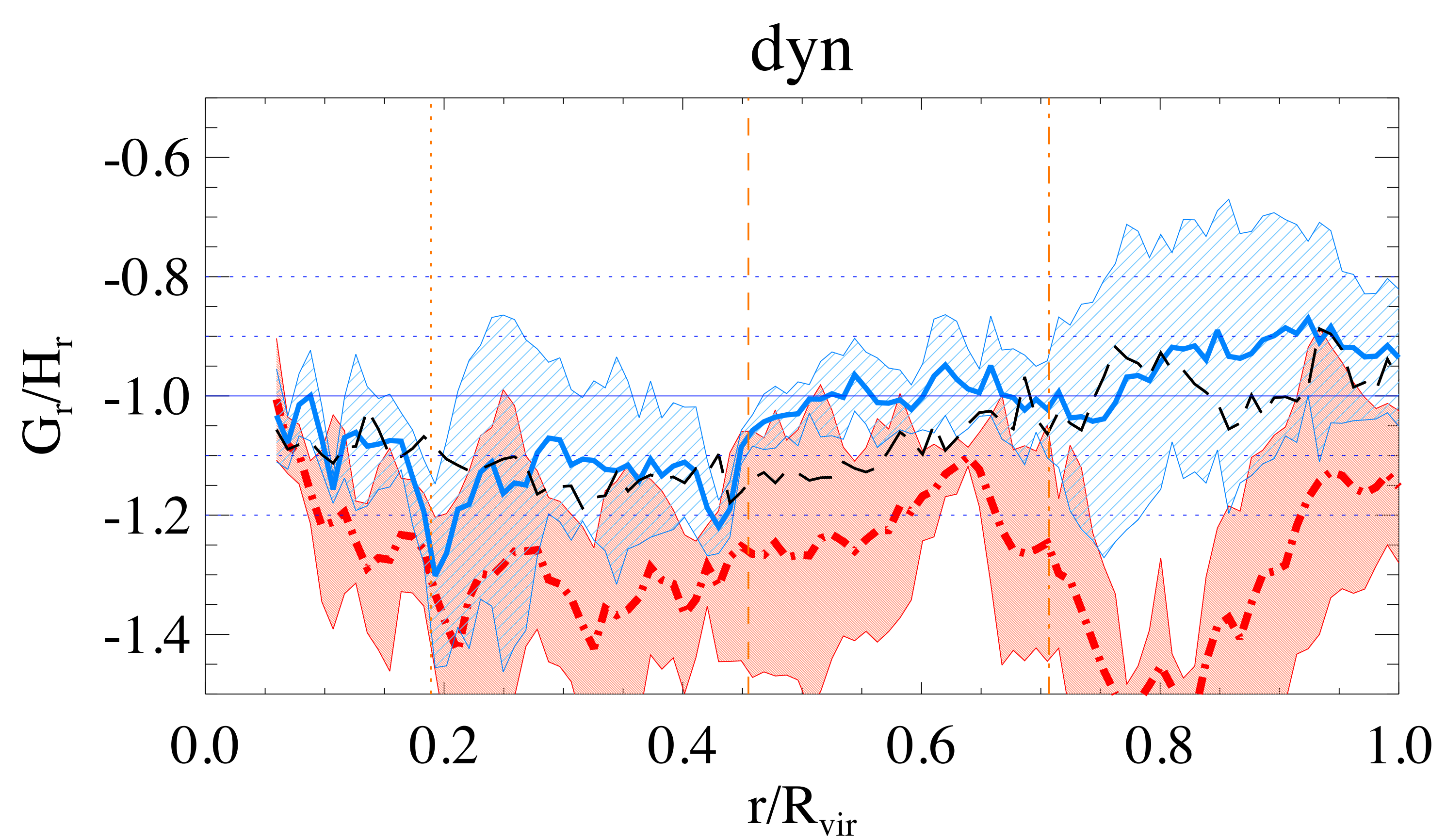
$$\delta_{HE} = \mathcal{G}_r/\mathcal{H}_r + 1$$

M-bias = (M_{HE} - M_{true})/M_{true}



- HE-violation does not correlate with CC/NCC distinction

- dynamically regular clusters show less deviation from HE than disturbed systems
  - severe lack of HE in outskirts of disturbed clusters: accretion of substructures, significant gas motions etc.



Biffi et al. (2016)

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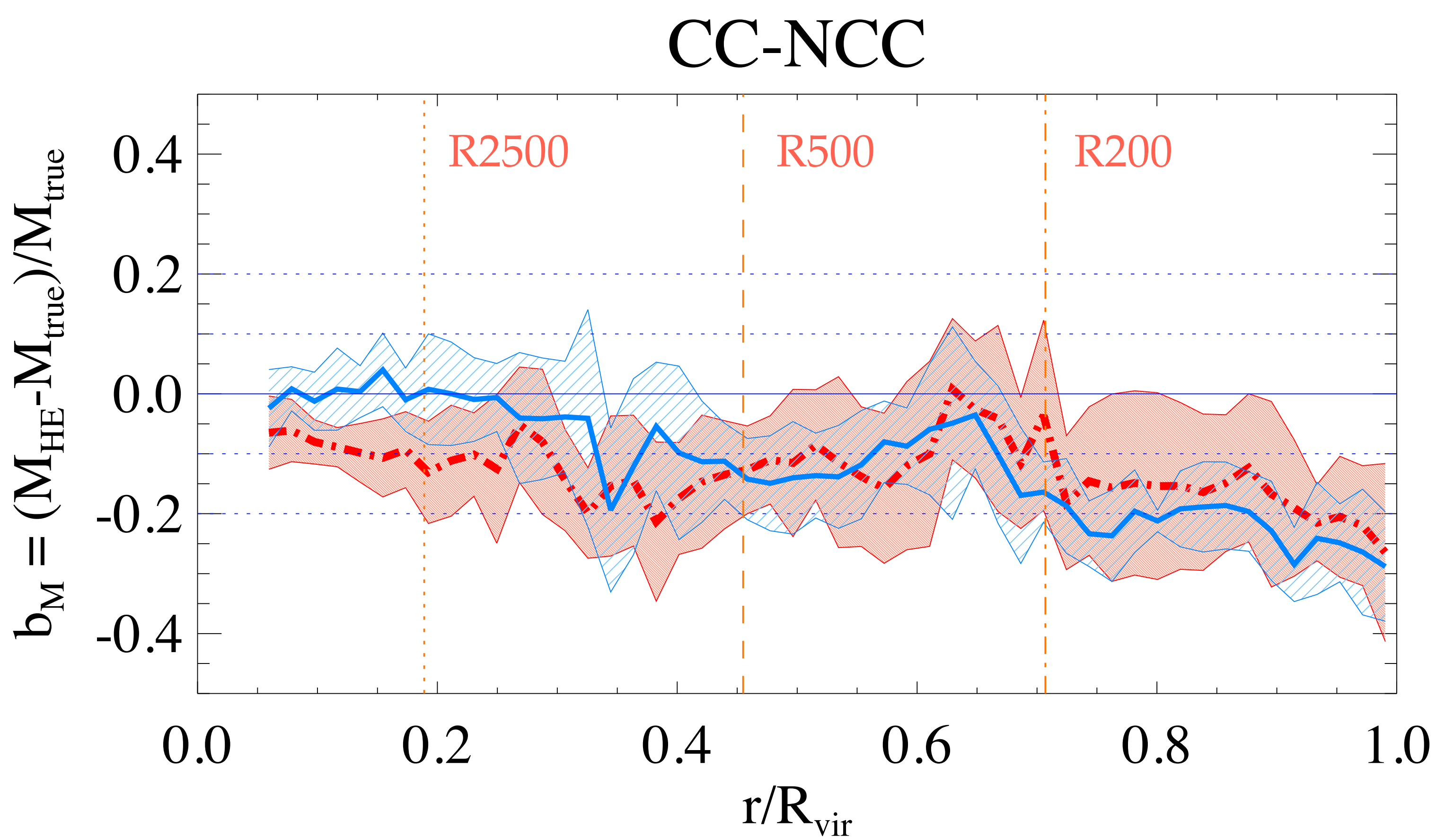
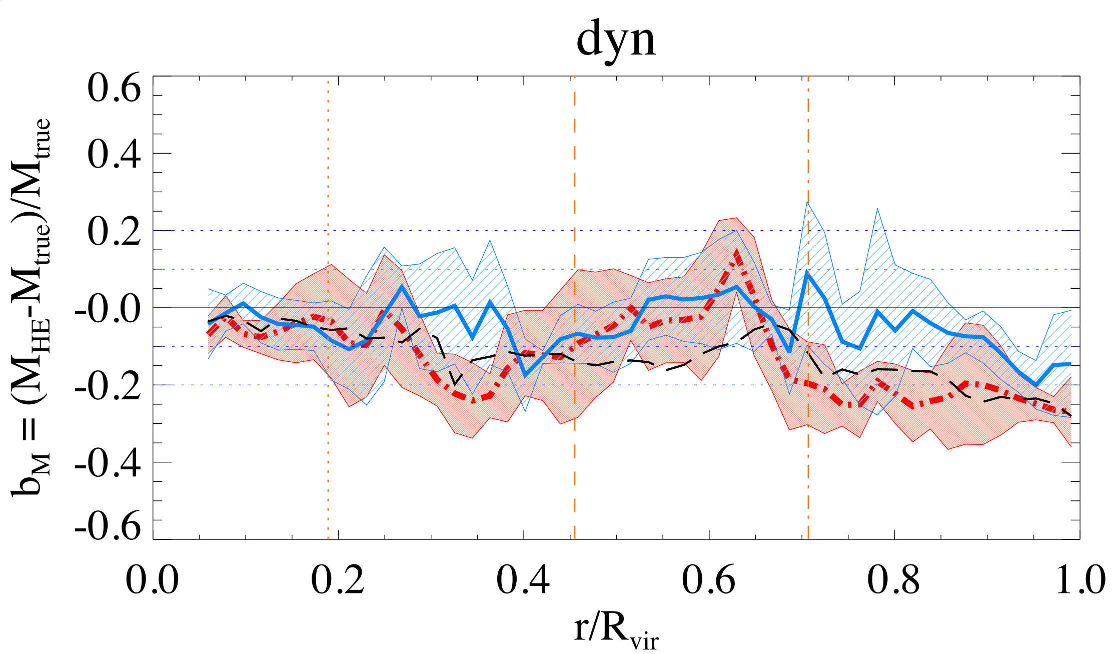


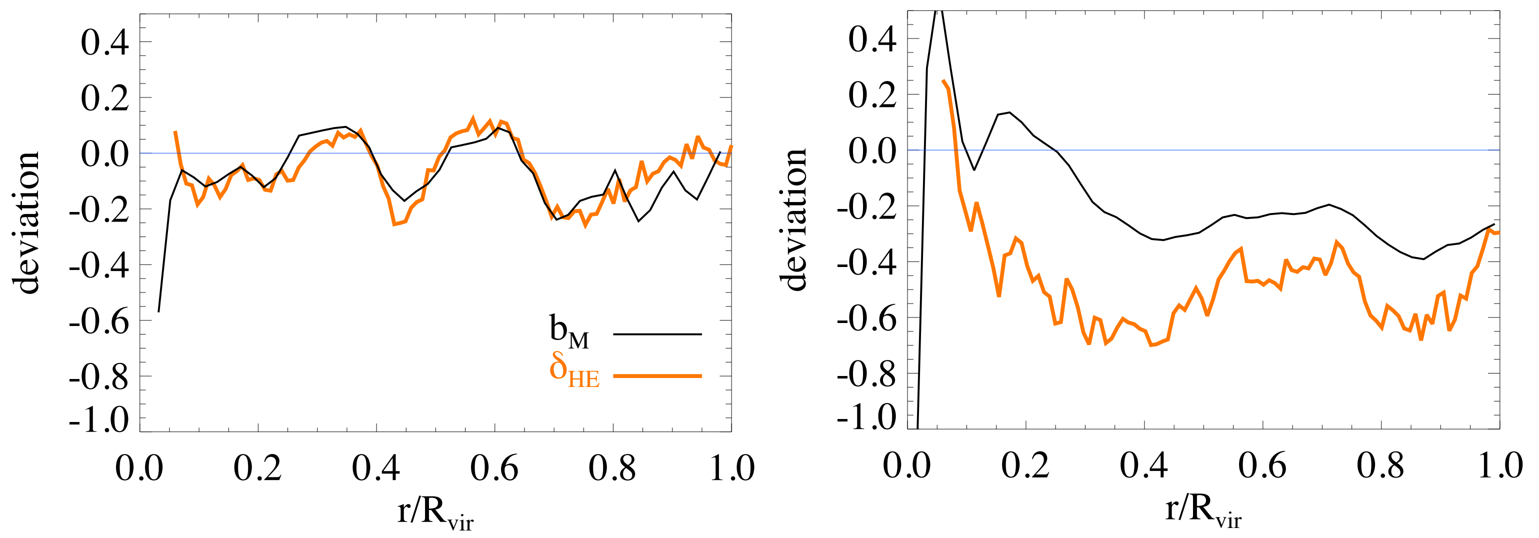
- For similar depth of potential well, CC have larger thermal pressure support than NCC in the core --> smaller mass bias



- no strong dependence of M-bias on large-scale dynamical state, except in the very outskirts

Biffi et al. (2016)

Relation between HE-deviation and M-bias

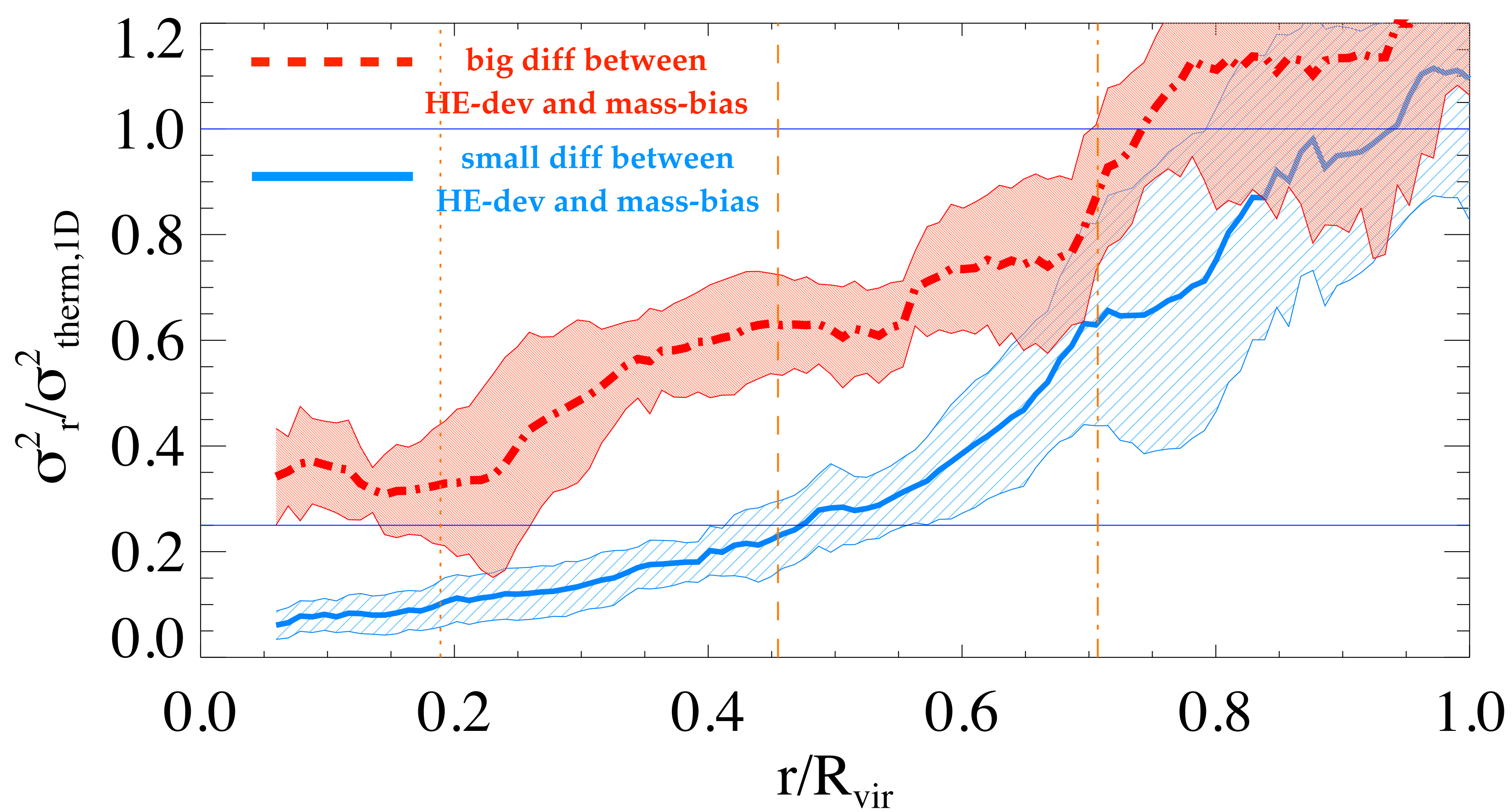


$\delta_{HE} = \mathcal{G}_r/\mathcal{H}_r + 1$

M-bias = (M_{HE} - M_{true})/M_{true}

- **very different case-by-case**

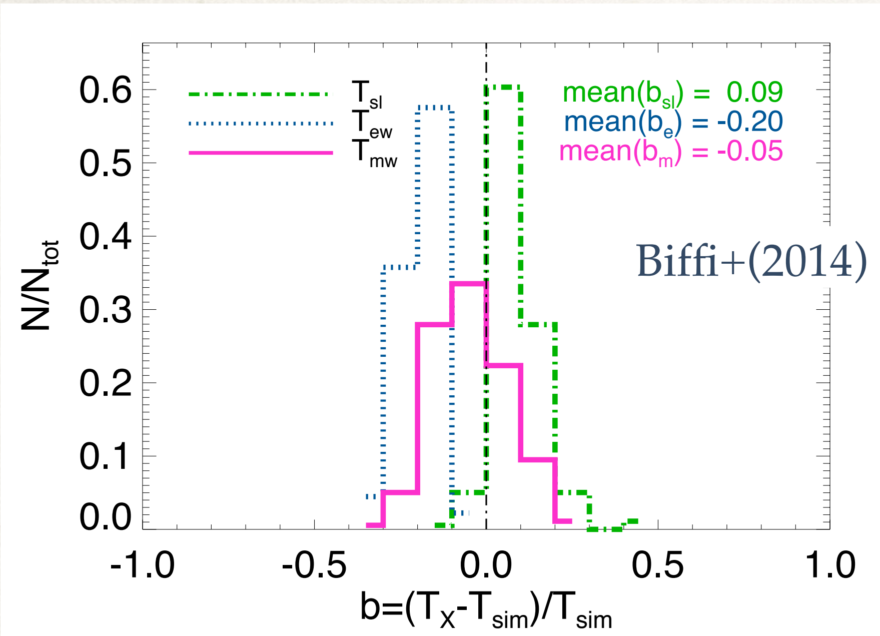
- on average,
  large differences between HE-deviation and M-bias correspond to significant gas motions
  $(\sigma_r^2 \gtrsim 0.3\sigma_{therm,1D}^2)$

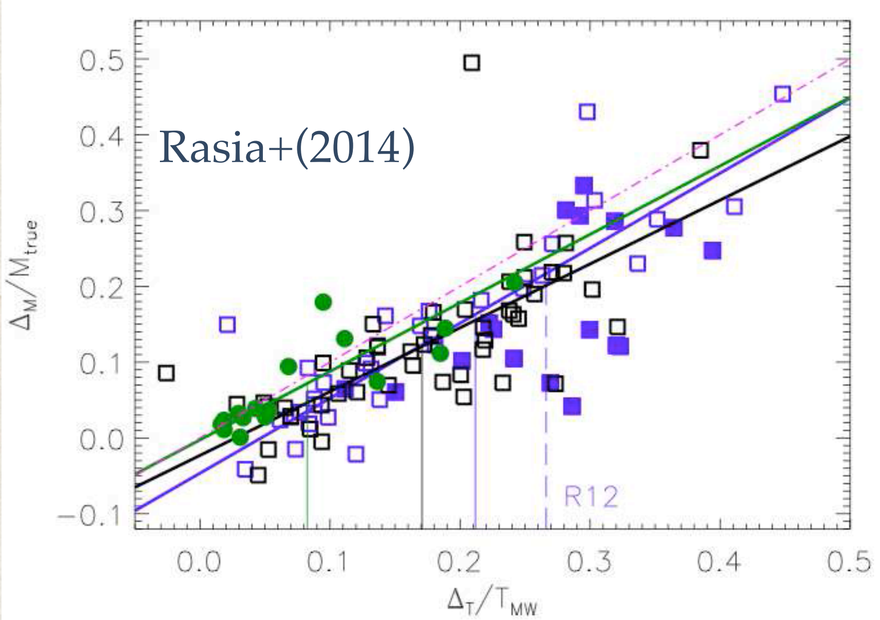


Biffi et al. (2016)

Numerous sources of possible bias: asymmetry, gas multi-phase structure, gas motions…

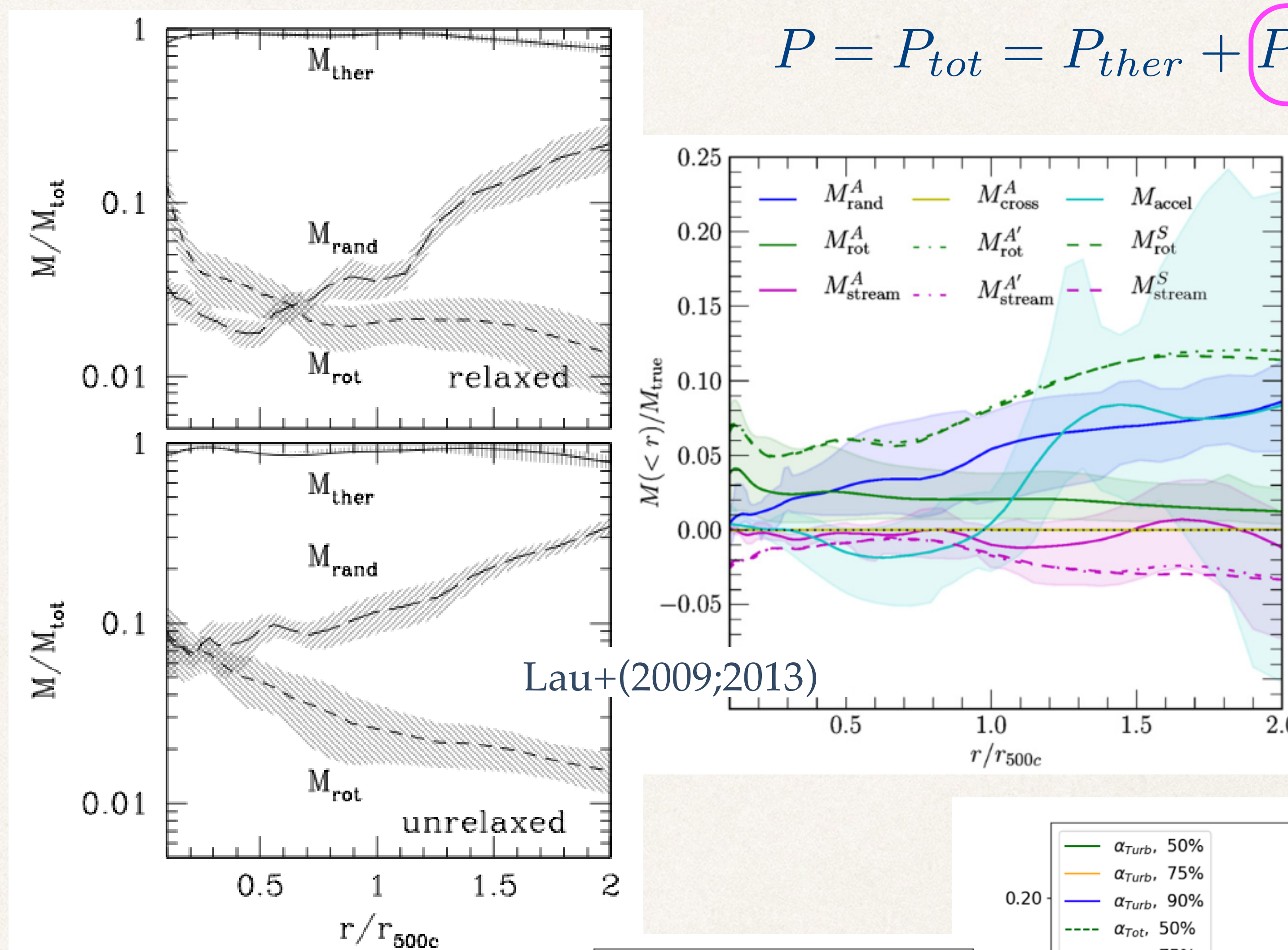
T-bias: $T_X\,,\ T_{sl} \neq T_{mw}$

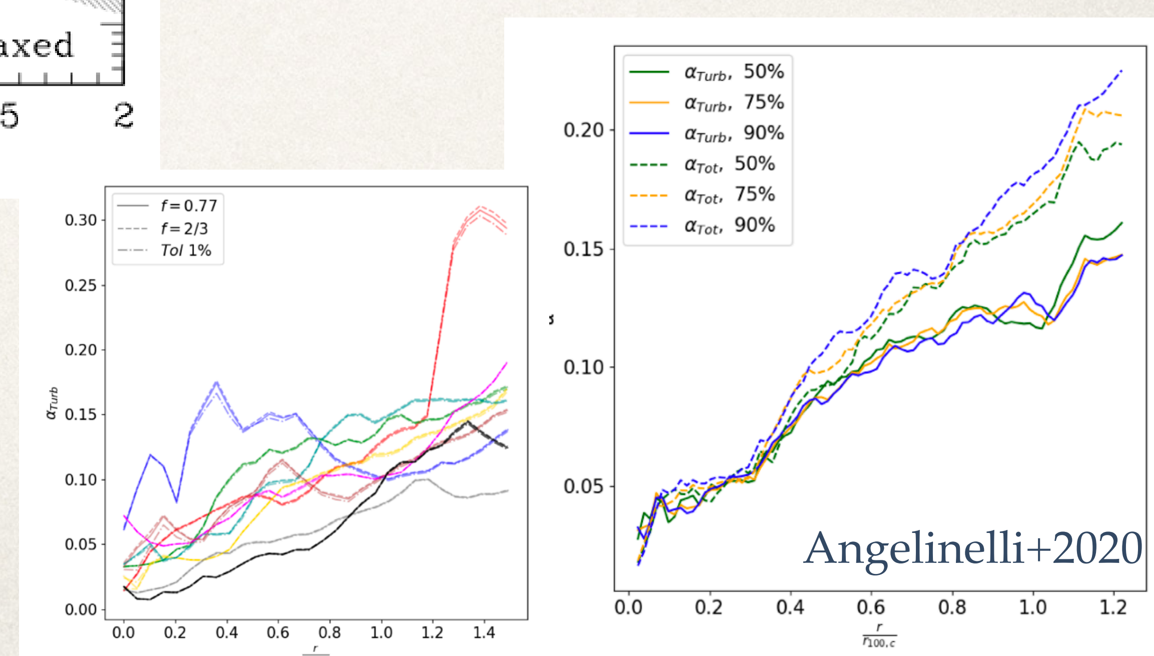




Additional pressure support from: magnetic fields, cosmic rays, rotational / turbulent / streaming gas motions and gas acceleration:

$$P = P_{tot} = P_{ther} + P_{non-ther}$$





Clumpiness: gas density inhomogeneities

(e.g. Zhuravleva+13; Angelinelli+20; Ansarifard+2020)

How to correct for mass bias

The Three Hundred Project: Correcting for the hydrostatic-equilibrium mass bias in X-ray and SZ surveys

S. Ansarifard, E. Rasia, V. Biffi et al., A&A (2020)

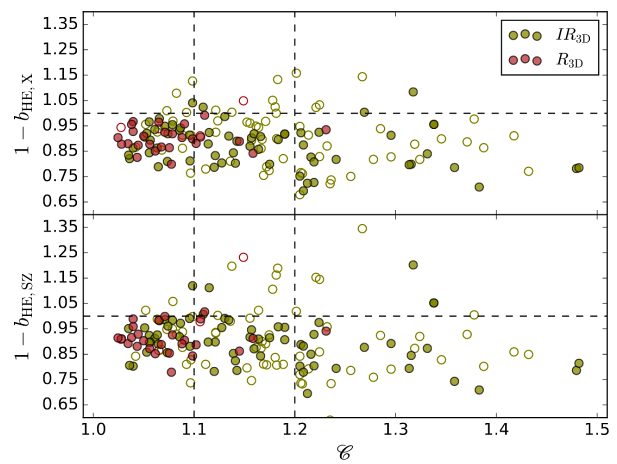


Fig. 13. Mass bias as a function of clumpiness. All quantities are considered at R_{500}. Empty and filled circles refer to clusters whose thermodynamical profiles are either poorly or well fitted with the assumed analytic function, respectively (Sect. 4.3.4). The R_{3D} objects are show in brown and the IR_{3D} clusters in olive green.

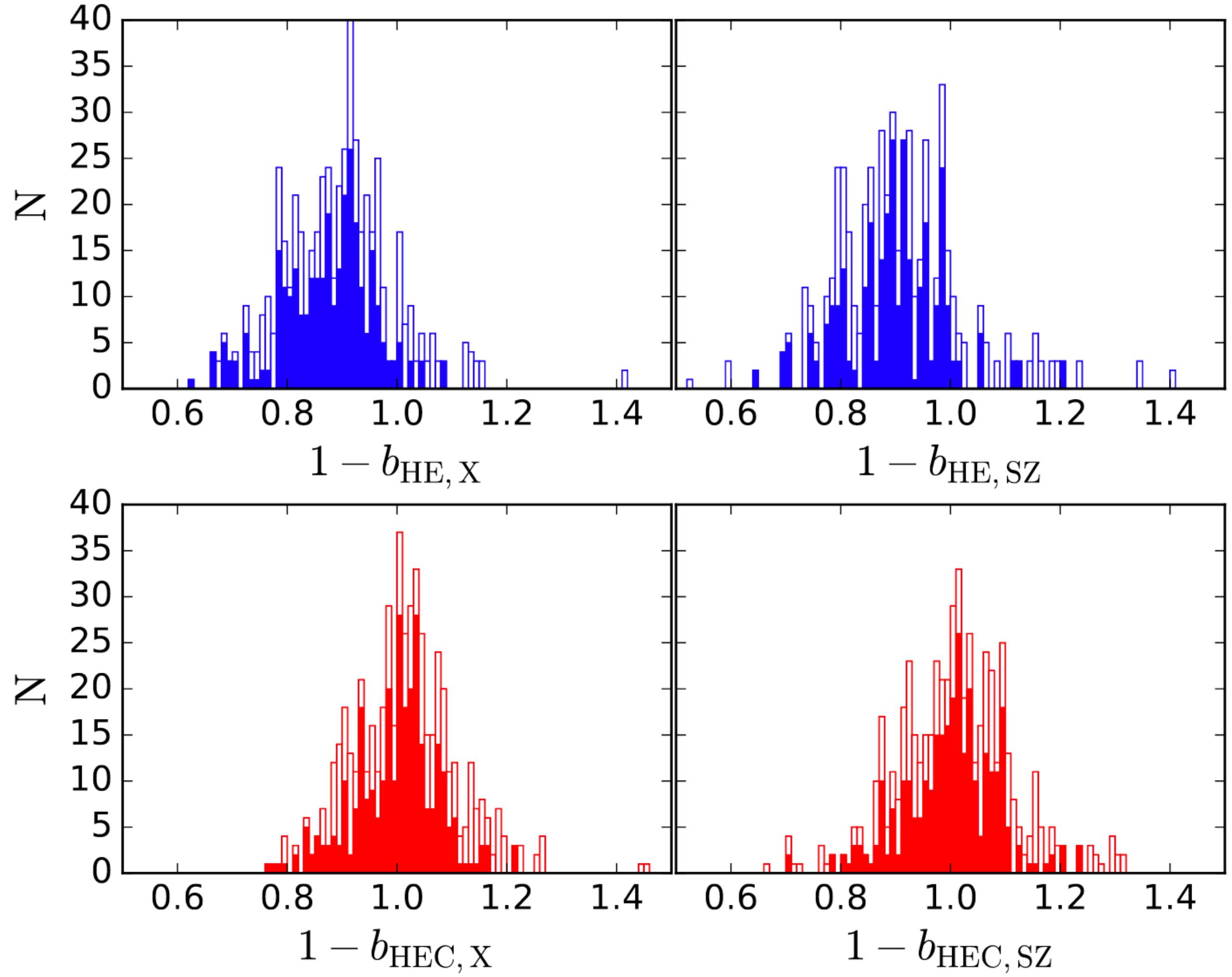


Fig. 16. Distribution of the mass biases, $(1-b_{HE,X})$, on the *left*, and $(1-b_{HE,SZ})$, on the *right*, before (*top panels*) and after (*bottom panels*) the corrections expressed respectively in Eqs. (16) and (17). The empty histograms show the overall distribution of all the 175 clusters, the filled histograms are restricted to the 97 well-fitted objects. The parameters characterizing the histograms are reported in Table 2.

- Regular clusters, less-clumped, w/ low-azimuthal scatter and well-behaved gas profiles have lower bias and a reduced scatter
- No strong correlation between bias and parameters explored (e.g. clumpiness, azimuthal scatter), but...
- corrections can be done to **reduce scatter (10-15%) and skewness (by factor of 3)** of bias distribution

Reconstruction of hydrostatic masses: sims & mock X-ray obs

Hydrostatic mass profiles of galaxy clusters in the eROSITA survey

Dominik Scheck[1,2], Jeremy S. Sanders[1], Veronica Biffi[3,4], Klaus Dolag[4,5], Esra Bulbul[1], and Ang Liu[1]

A&A (2023)

TEST of reconstruction procedure:

- Idealized clusters in perfect HE
  - idealized eROSITA mocks
    - reconstruction of HE mass with deviations ~1% (max 7%)

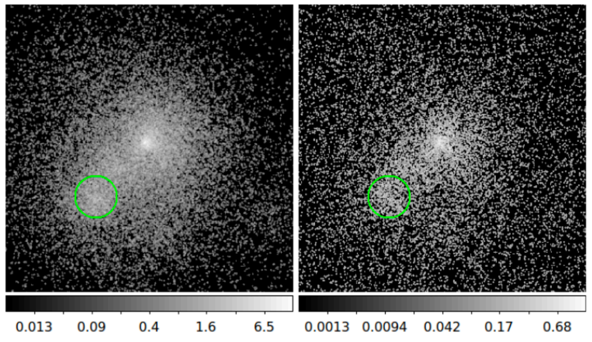


Fig. 12. Cluster 384 in snap 140 from the Magneticum Pathfinder simulations. The images use a logarithmic scale, cover energies from 0.6 keV to 1.1 keV, and are smoothed with a Gaussian. The numbers on the scales of the colorbars show the numbers of counts per pixel; they differ for idealized and realistic observations because of the relative exposure times. The green circles have a radius of about 3.1 arcmin and indicate the masked region.

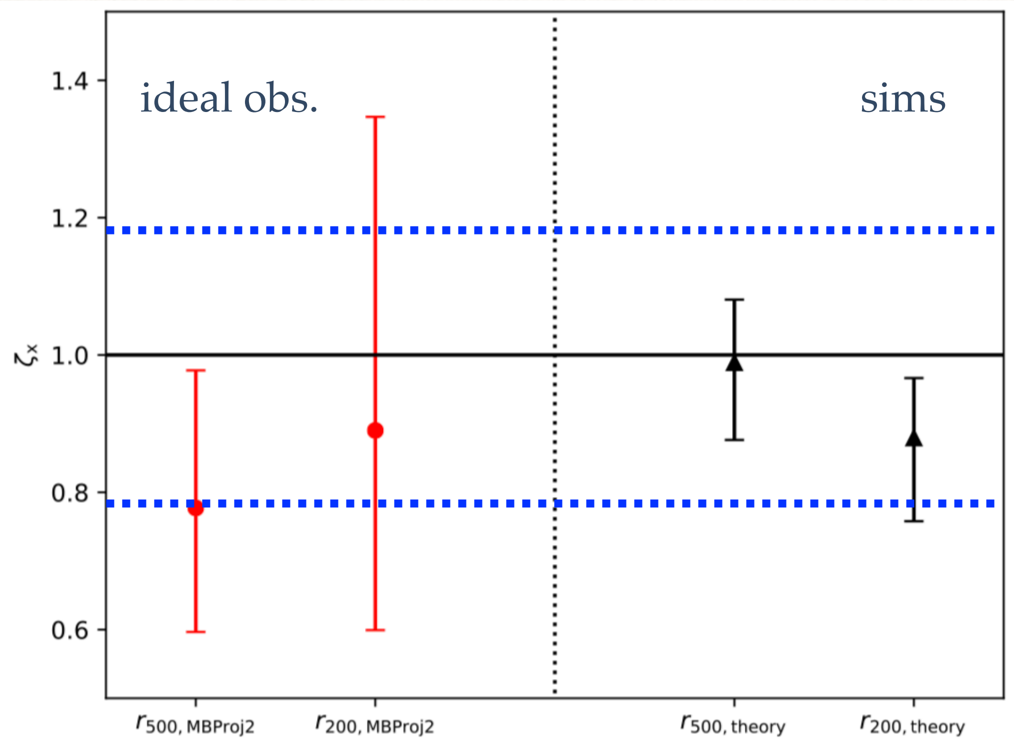


Fig. 5. Idealized observations: medians and 1σ intervals of ζ_x for the profiles fitted with MBProj2 (left side) and for the hydrostatic mass according to theory (right side).

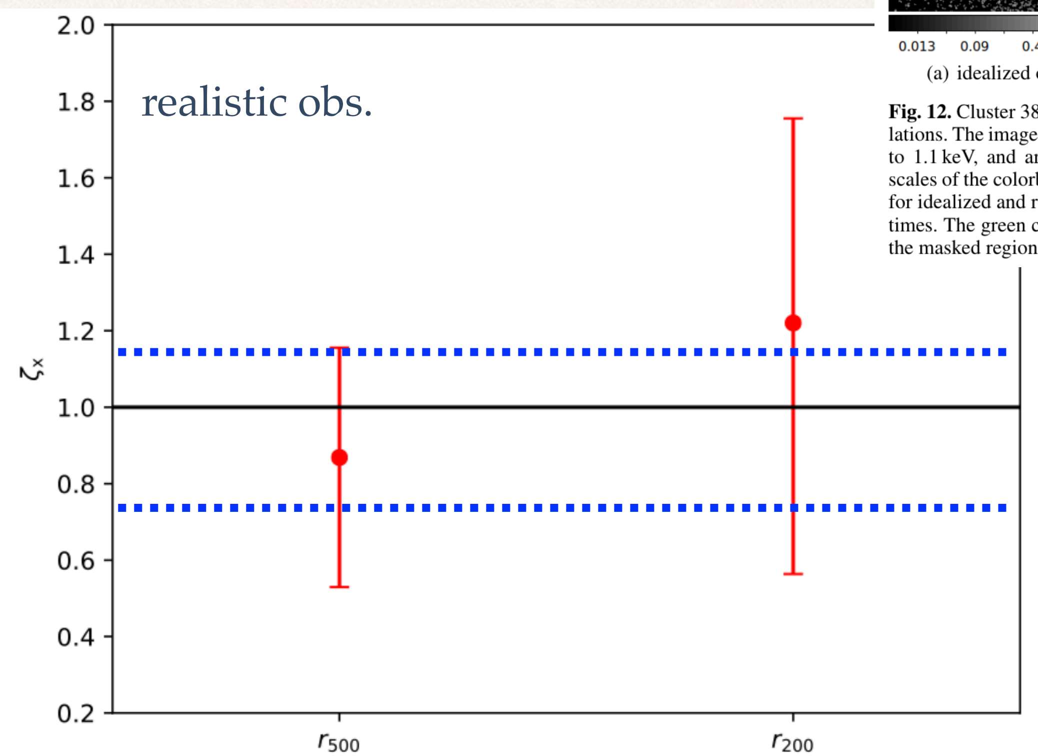


Fig. 14. Realistic observations: medians and 1σ intervals of ζ_x, according to the fits with MBProj2.

- Sample of 93 simulated GCs from Magenticum lightcone
  1. theoretical estimates
  2. idealized eROSITA mocks
  3. realistic eROSITA mocks

- Scatter increases going from 1. to 3. & depends on mass
- No strong dependence on radius nor on center shift
- Average bias within expectations for idealized obs. ($0.77 < M_{HE}/M_{true} < 0.9$)
- larger deviations and errorbars for realistic mocks
- *too steep reconstructed mass profiles*

Mass bias dependence on cluster properties and redshift

...common findings from simulations

- Typical values of Hydrostatic M-bias are around 20%
- Disturbed clusters show on average larger biases compared to regular / well-behaved / relaxed clusters
- M-bias shows little or no dependence on
  - redshift
  - true mass
  - dynamical-state indicators
  - concentration
  - ICM physics implemented in sims (see tests by LeBrun+2017)
- Introducing X-ray mock reconstruction increases bias and scatter (LeBrun+2017; Scheck+2023)

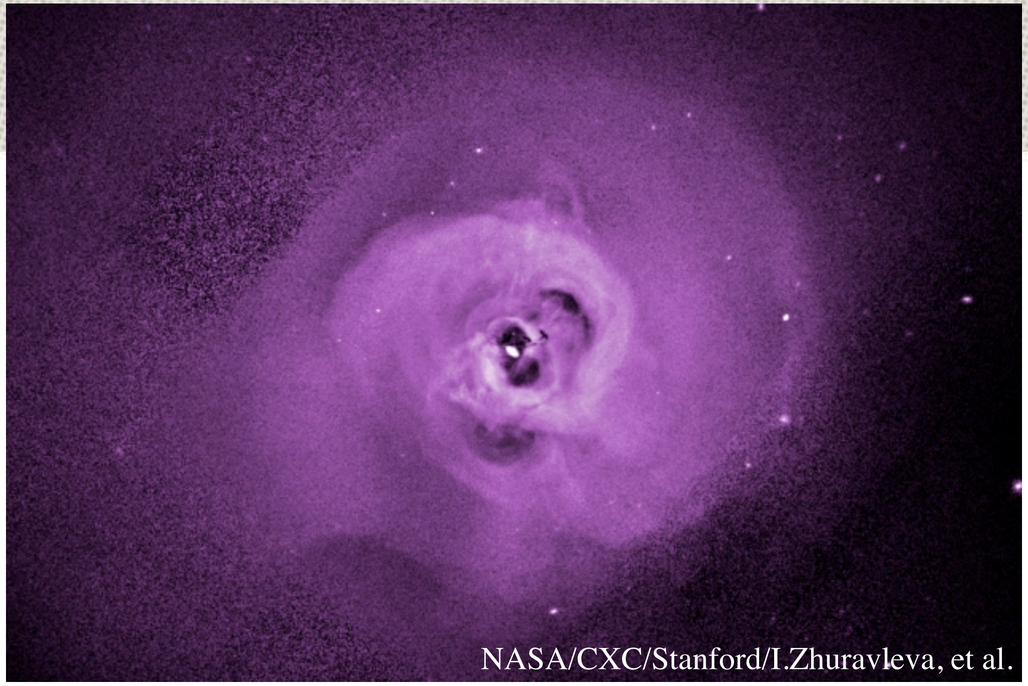
A study of the hydrostatic mass bias dependence and evolution within The Three Hundred clusters

G. Gianfagna, E. Rasia, et al., MNRAS (2023)

The M-bias can have negative or positive values, depending on the combination of density and temperature and their derivatives

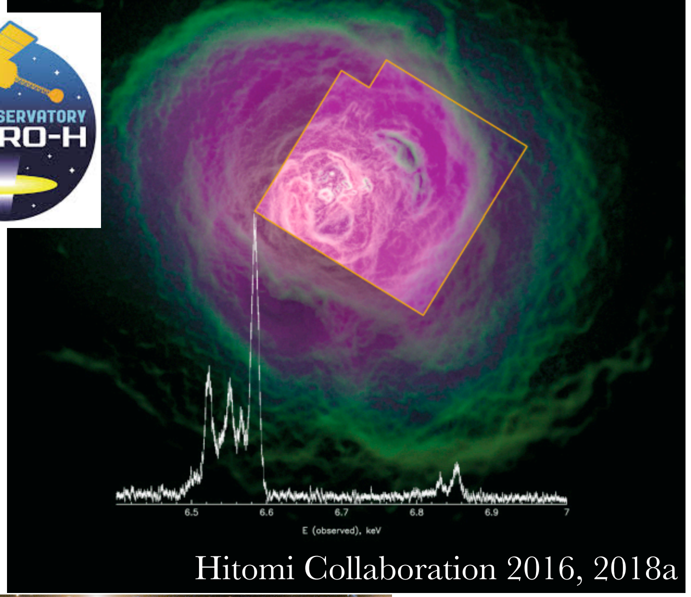
During major mergers the cluster get disturbed and the bias tends to increase

Issue: ICM motions


NASA/CXC/Stanford/I.Zhuravleva, et al.

- ICM carries signatures of accretion, merging events, energetic/ chemical feedback, interaction with member galaxies - *most of it derivable from X-ray obs.*
  - ✳ **Gas motions are present in the ICM**: **turbulence**, AGN activity, large scale accretion, **<u>mergers</u>**, shocks, cold fronts, infalling substructures
  - ✳ Important contribution to **non-thermal pressure** support (refine mass estimates -> cosmology)
- **Direct measurements** from shifting & broadening of X-ray spectral lines of emitting gas (IGM, ICM): require **high energy resolution X-ray spectroscopy** (`XRISM`, *`ATHENA`*, ...)

Copyright: Background: NASA/CXO; Spectrum: Hitomi Collaboration/JAXA, NASA, ESA, SRON, CSA


Hitomi Collaboration 2016, 2018a

X-ray energy resolution of few eV

See review by Simionescu et al. 2019

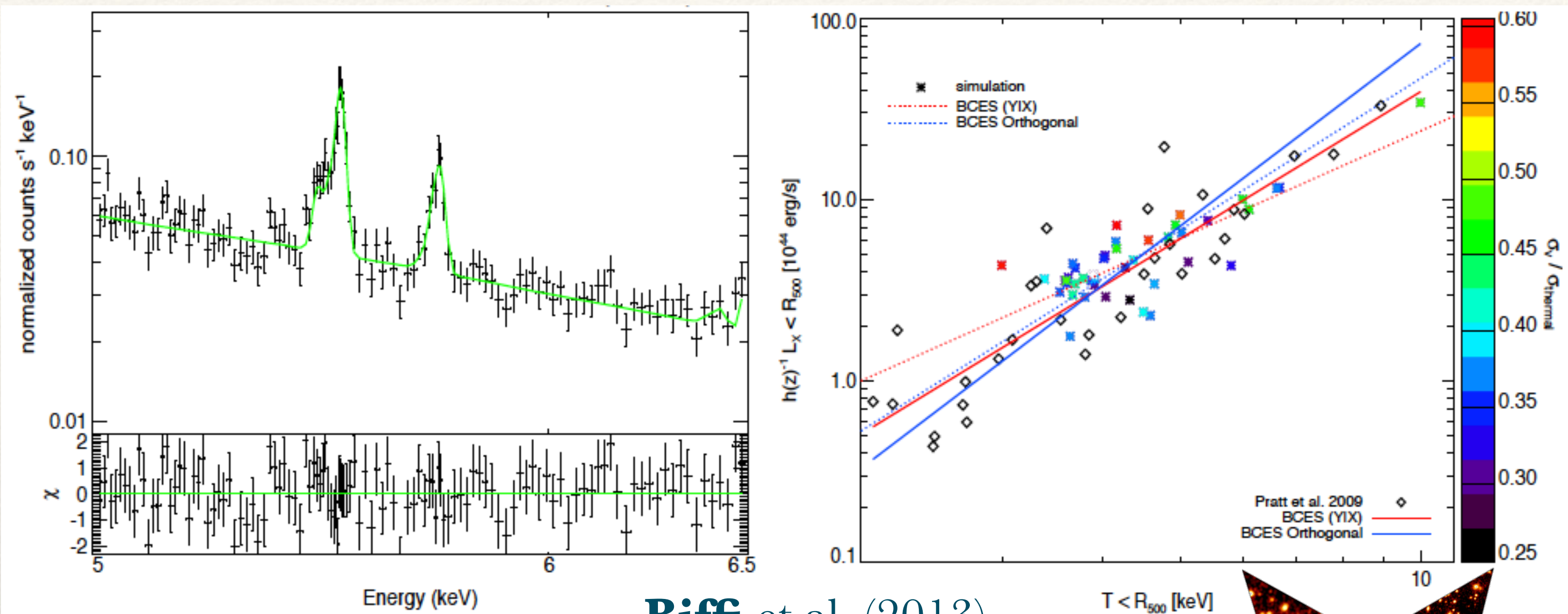
Mock observations from hydro-sims:
e.g. **VB**+13,22; ZuHone+16a,16b,18; Roncarelli+18

ATHENA

ICM Velocity Diagnostics from high-res. X-ray spectra: sims

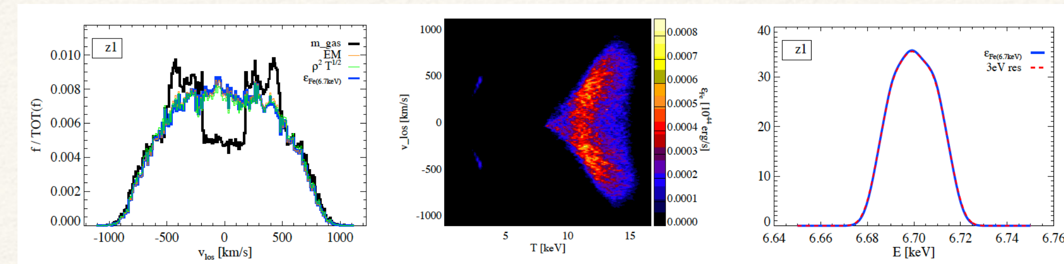
Mock observations from hydro-sims:

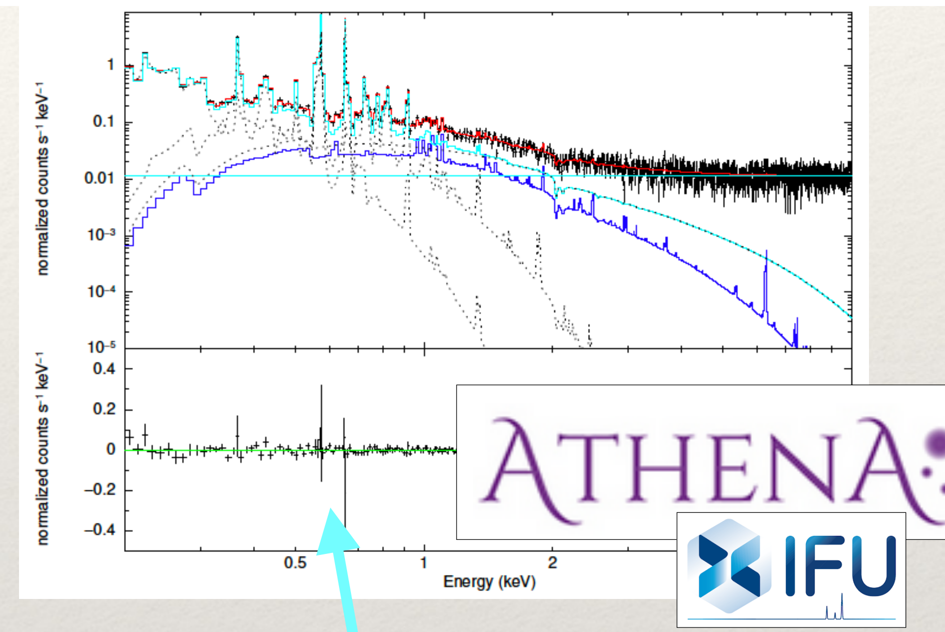
e.g. ZuHone+16a,16b,18 (XRISM); Roncarelli+18 (ATHENA X-IFU)

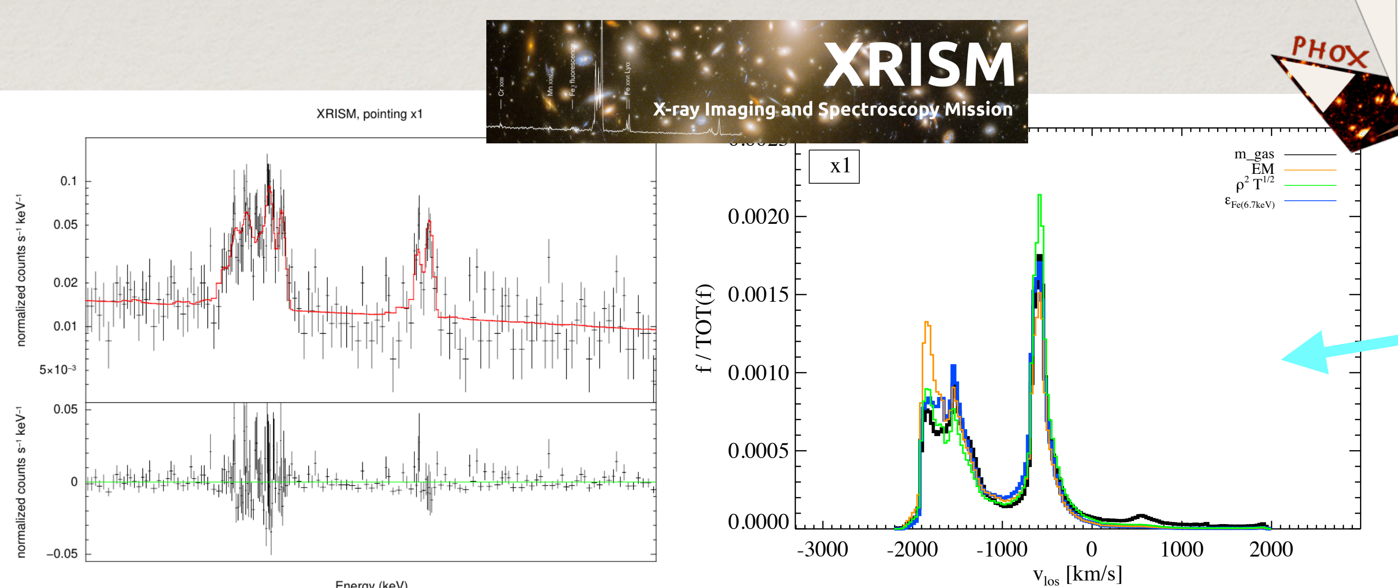


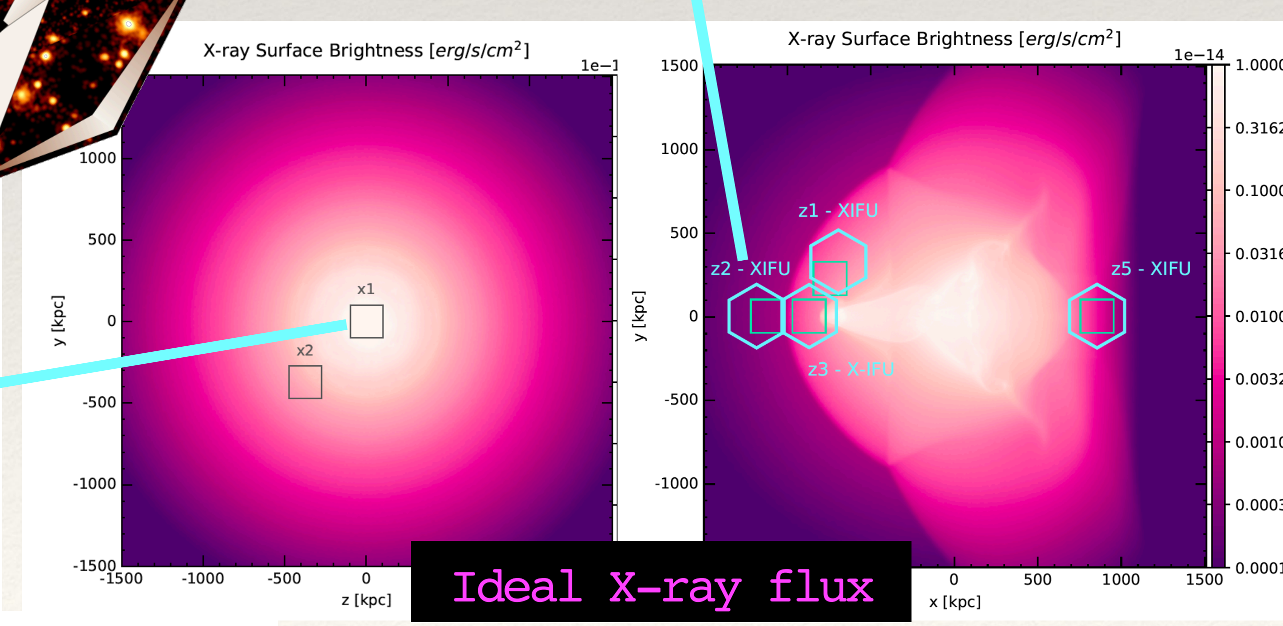
Biffi et al. (2013)

ATHENA precursor









Biffi et al. (2022)