The orbits of galaxies in clusters

Andrea Biviano
(INAF - Oss. Astr. Trieste & IFPU)

Outline of this talk:

- Introduction:
  - why studying galaxy orbits in clusters?
  - how to determine galaxy orbits in clusters?
  - what do we know so far?
- A new analysis of 9 massive clusters at z~0.35
  - the data-set and the methods of analysis
  - results
- Summary, discussion and conclusions

Introduction:
why studying cluster galaxy orbits?

Why studying the orbits of galaxies in clusters?

1. Understanding the evolution of galaxy clusters

Theory predicts two evolutionary phases:

1) early, fast collapse; 2) late, slow accretion

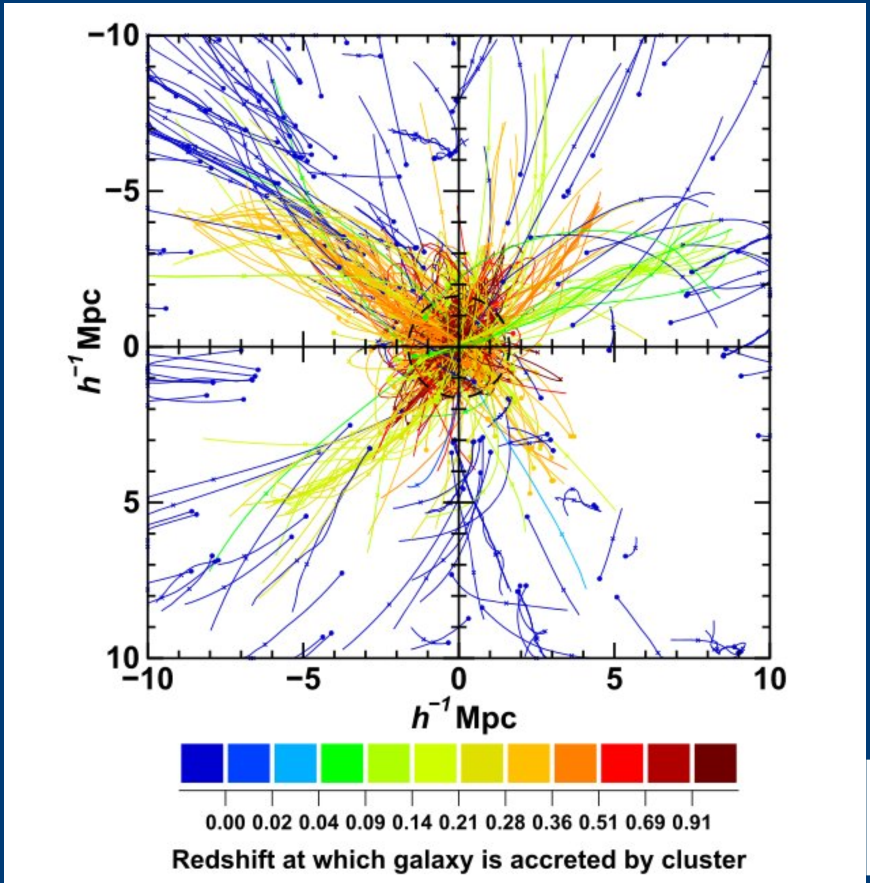
the orbits of galaxies inside the cluster are shaped by the way the cluster achieves its dynamical equilibrium, i.e. via collective collisions ("violent relaxation") and/or slow inside-out growth (mass accretion from the surrounding field)

➔ the shape of the galaxy orbits is a measure of the clumpiness of the collisions by which the cluster grows its mass with time

(Lapi & Cavaliere 11)

Why studying the orbits of galaxies in clusters?

2. Understanding the evolution of cluster galaxies

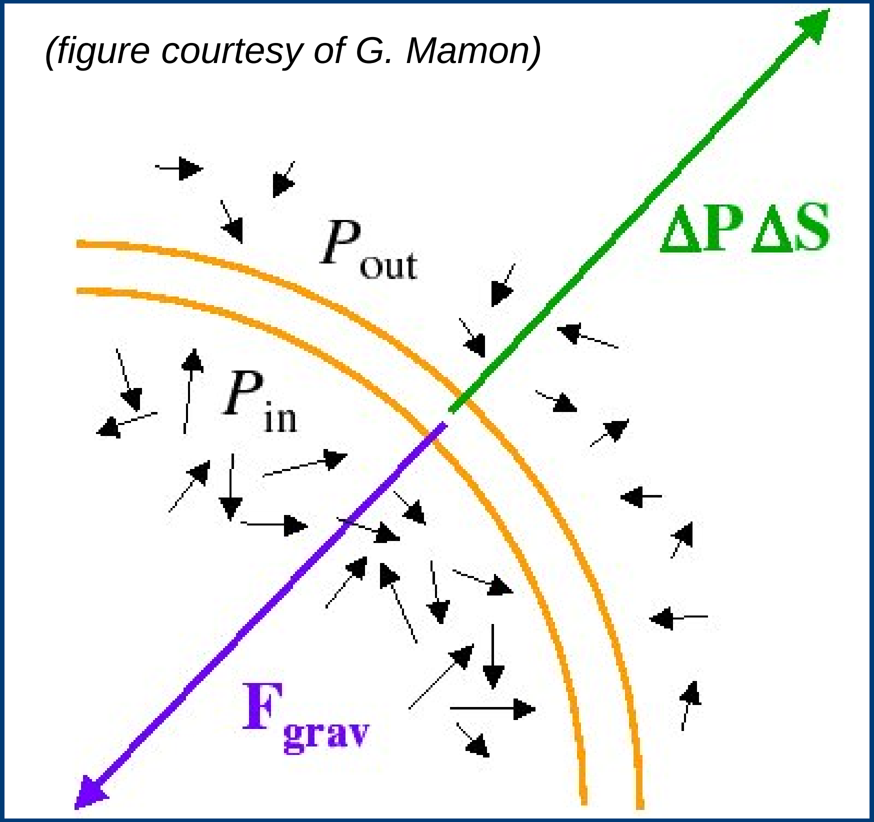


Galaxies on different orbits pass different amount of times in regions of different densities, hence they are more or less affected by density-related evolutionary processes *(e.g. ram-pressure, see Tonnesen 19)*

Haines et al. 15: Individual galaxy orbits in a massive halo from the Millennium simulation

Why studying the orbits of galaxies in clusters?

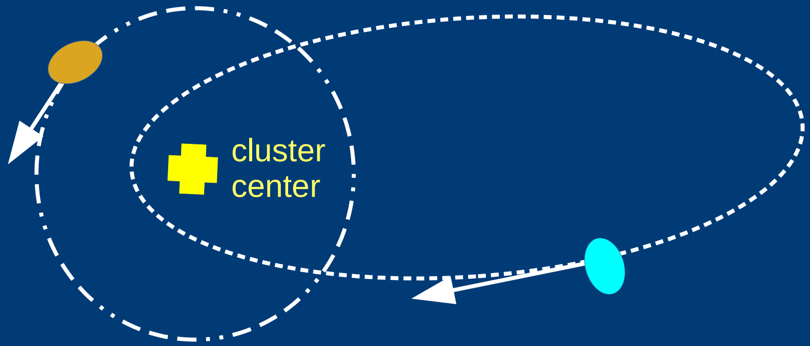
3. Estimating the cluster mass (profile)



Cluster mass ⇒ Gravitational pull

Number density + velocity distribution of galaxies
⇒ Pressure against gravitational pull

Pressure is different if the velocity vector is aligned with or orthogonal to the gravitational pull, i.e. it depends on the galaxy orbital shape



Introduction:
how to determine cluster galaxy orbits?

How to determine galaxy orbits in clusters?

$$M(<r) = -\frac{r\sigma_r^2}{G}\left(\frac{d\ln\nu}{d\ln r}+\frac{d\ln\sigma_r^2}{d\ln r}+2\beta\right)$$

Mass profile

3D number density profile

Velocity dispersion profile along the radial direction, *r*

Velocity anisotropy profile

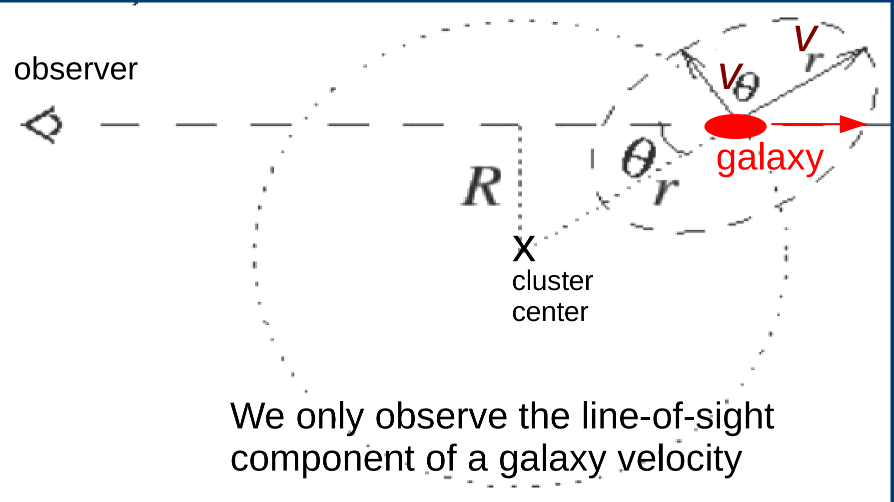
$$\beta(r) = 1 - \frac{\sigma_\theta^2(r)}{\sigma_r^2(r)}$$

Velocity dispersion profile along the tangential direction

The Jeans equation in spherical symmetry

β(r) is related to the orbital distribution of cluster galaxies:
β(r)<0 tangentially elongated
β(r)>0 radially elongated

The solution for the mass profile M(<r) is degenerate with the solution for the velocity anisotropy profile β(r)



(figure courtesy of G. Mamon)

How to determine galaxy orbits in clusters?

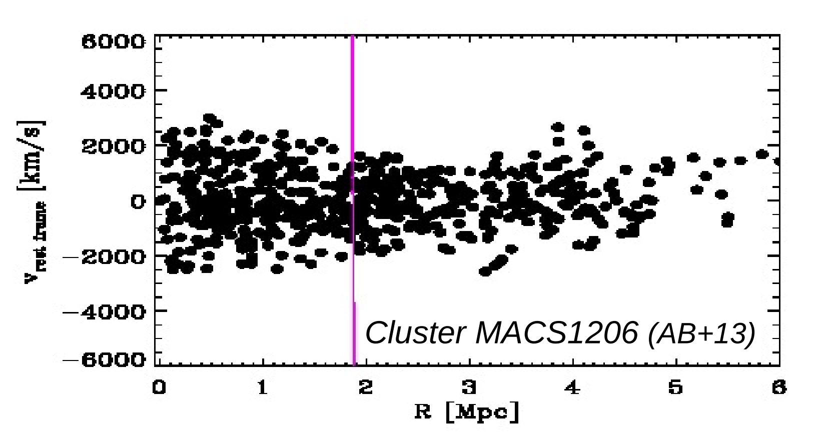
It performs a maximum likelihood fit of model M(<r) and model β(r) to the projected phase-space distribution of cluster galaxies

MAMPOSSt *(Mamon+13)*

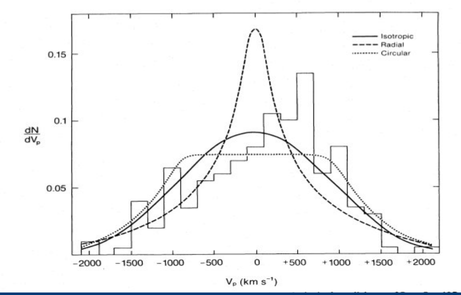
Modelling
Anisotropy and
Mass
Profiles of
Observed
Spherical
Sys**t**ems

MAMPOSSt breaks the mass-anisotropy degeneracy of the Jeans equation by using the full information available in the spatial and velocity distributions of cluster galaxies, and constrains M(<r) and β(r) at the same time

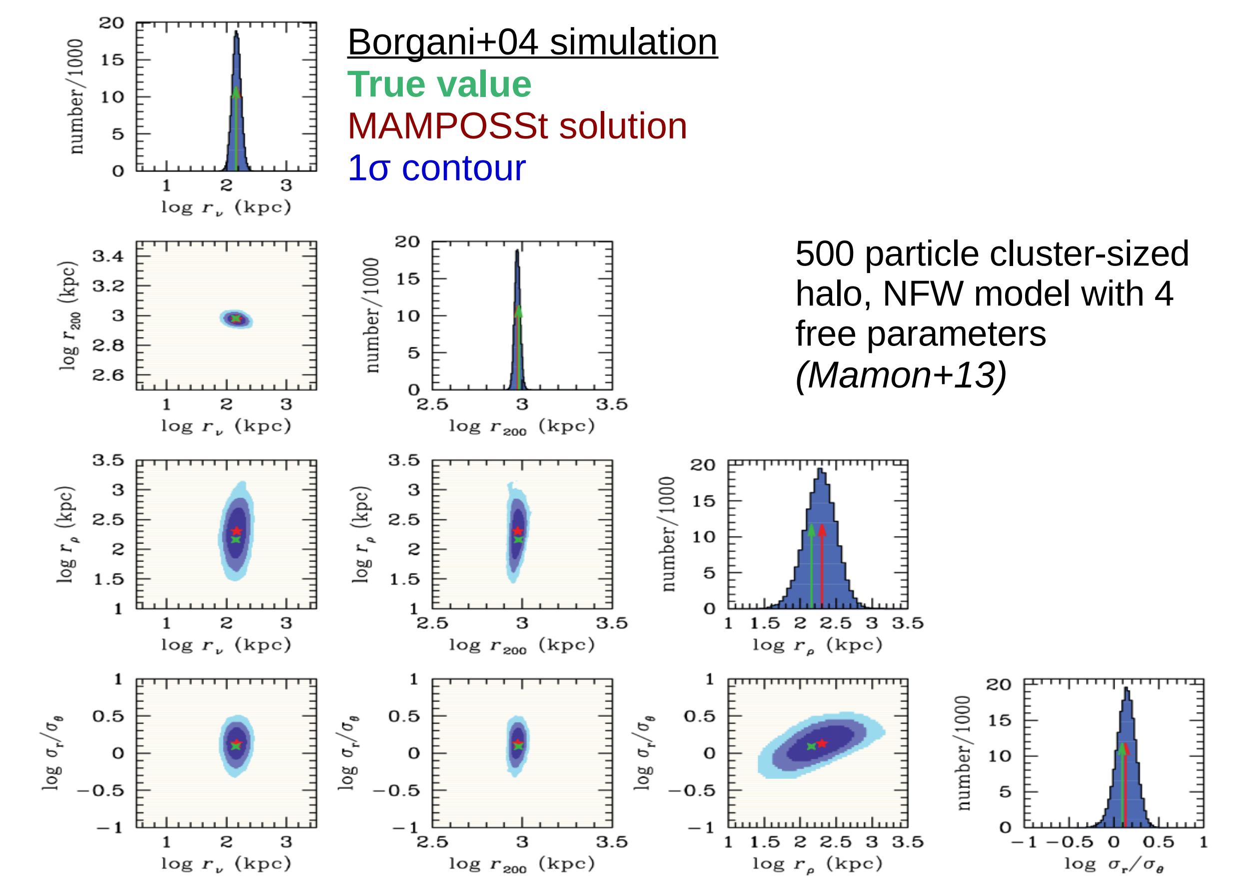
Fortran+python code available on GitHub (Pizzuti+23)

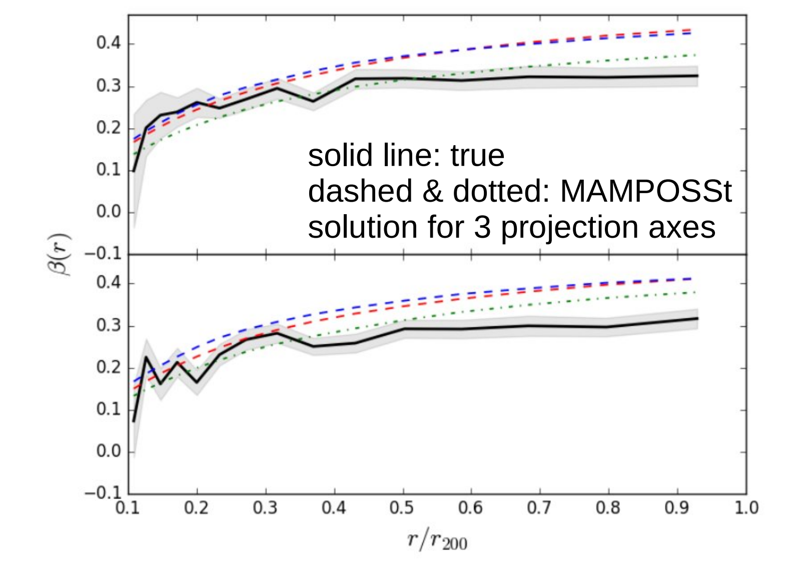


(...following up an original idea by Merritt 87, and by no means the only method available in the literature)



MAMPOSSt has been tested on cluster-sized halos in numerical simulations (hydrosim and semi-analytic), including projection effects (interlopers)





MAMPOSSt solution ⟨β(r)⟩ for 100 simulated clusters along 3 projection axes (two simulations: GAEA and De Lucia & Blaizot; *Aguirre Tagliaferro + 21)*

How to determine galaxy orbits in clusters?

JEI: JEANS EQUATION INVERSION

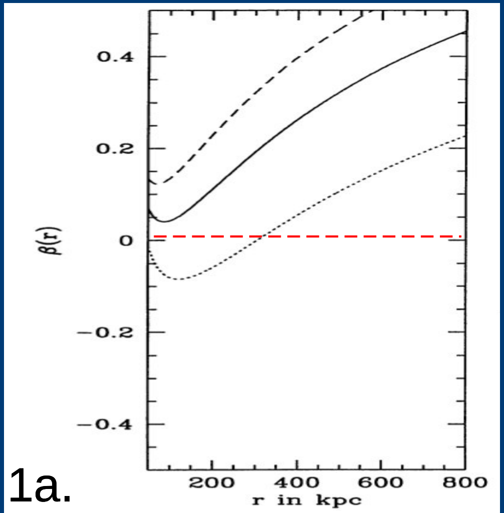
$$M(<r) = -\frac{r\sigma_r^2}{G}\left(\frac{d\ln\nu}{d\ln r} + \frac{d\ln\sigma_r^2}{d\ln r} + 2\beta\right)$$

If M(<r) is known, the mass-anisotropy degeneracy is broken; given the observables: projected number density profile N(R) and the line-of-sight velocity dispersion profile $\sigma_{los}(R)$, we can get the 3D number density profile ν(r), and both the radial and tangential velocity dispersion profiles $\sigma_r(r)$, $\sigma_\theta(r)$ (and hence β(r); *Binney & Mamon 82, Solanes & Salvador-Solé 90)*

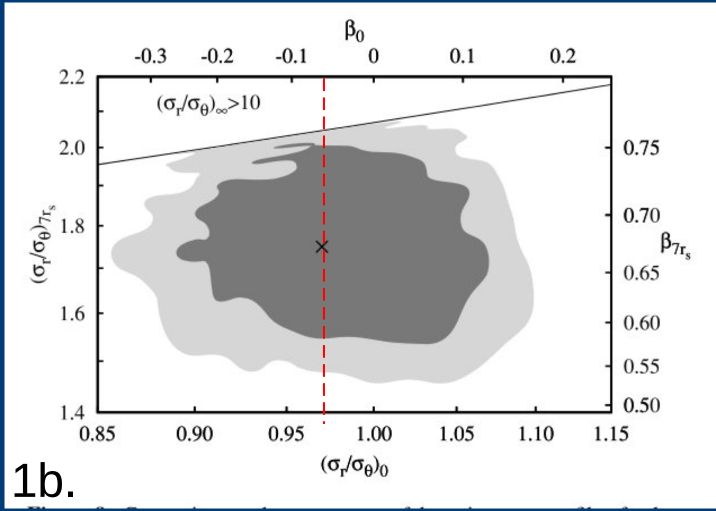
I developed a JEI procedure that, unlike MAMPOSSt, does not require assuming models; given M(<r), the observed profiles N(R) and $\sigma_{los}(R)$ are smoothed and the set of integro-differential equations solved numerically to provide a non-parametric solution for β(r) *(AB & Katgert 04 and subsequent modifications, see, e.g., AB+24)*

Introduction:
what do we know so far?

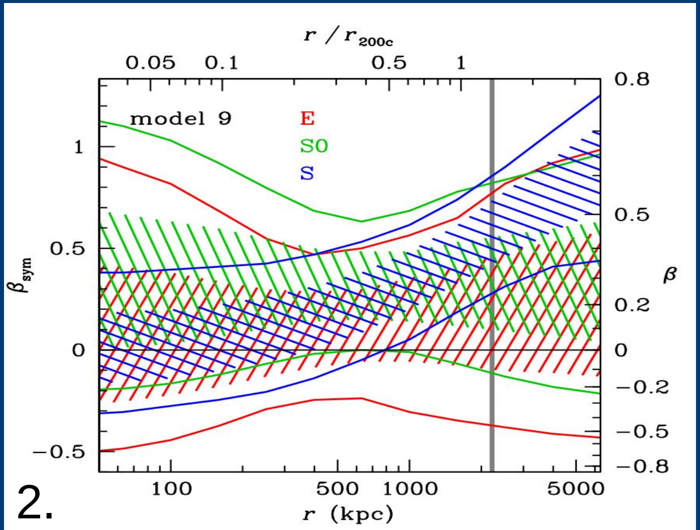
What do we know so far? *(z<0.25)*



(Natarajan & Kneib 96)



(Wojtak & Łokas 10)

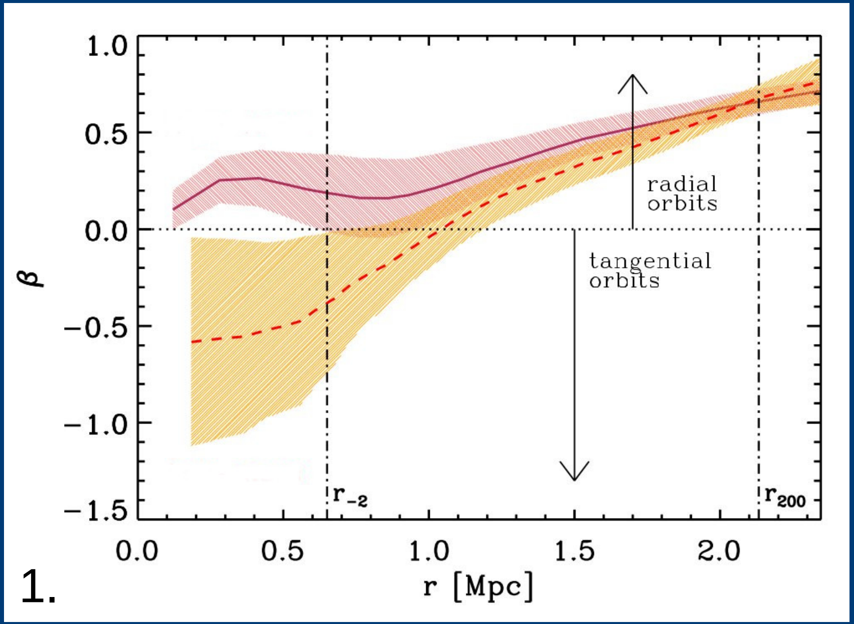


(Mamon+19)

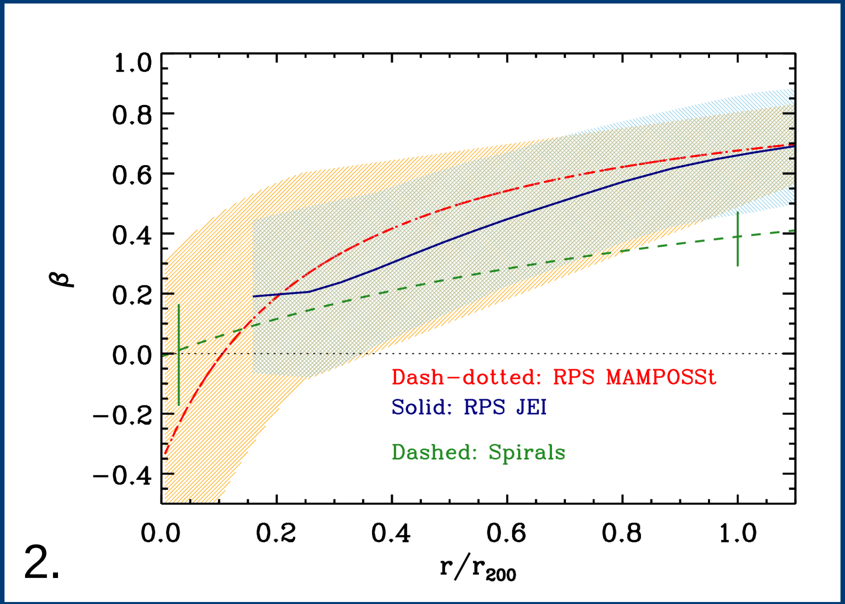
1. The velocity anisotropy profile is: β(0)≈0, gently increasing with r
(i.e. orbits are isotropic near the cluster center, becoming more radial outside)

2. The orbits of blue/star-forming/late-type galaxies are more radially elongated than those of Red/passive/early-type galaxies.

What do we know so far? *(z<0.25)*



(Annunziatella+16)

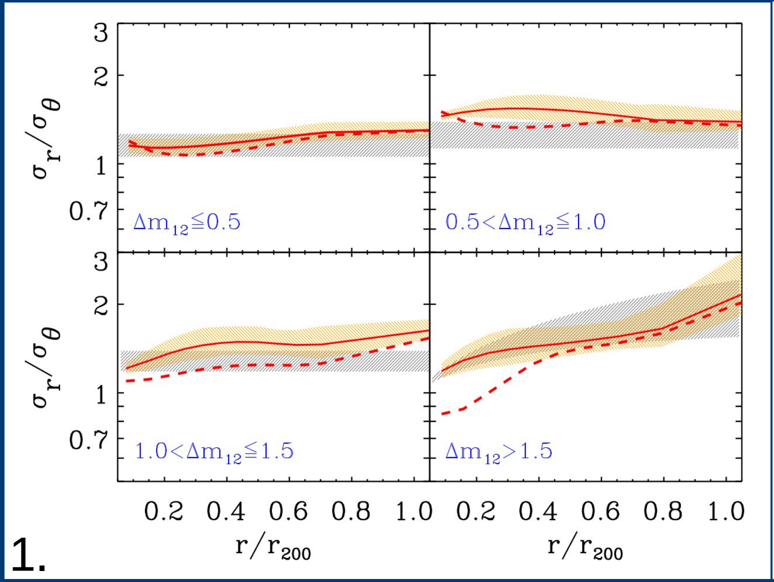


(AB+25)

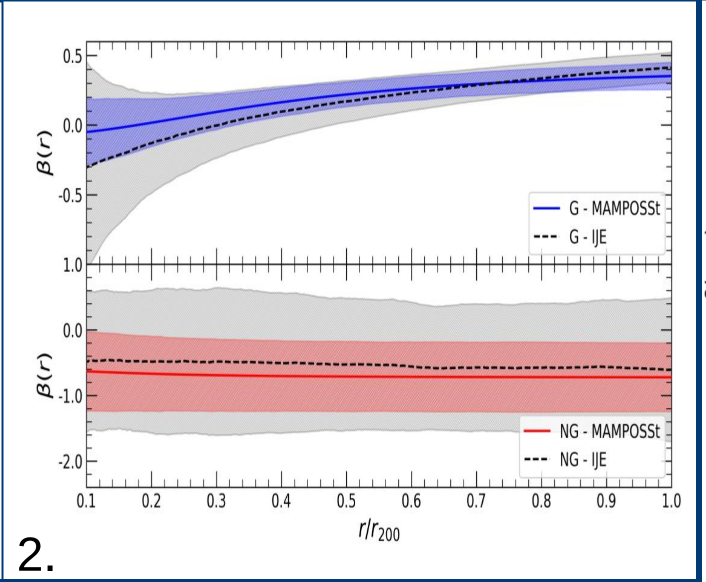
Other galaxy properties than their morphology or color define their orbits:

1. *The orbits of red galaxies depend on their stellar mass (based on one z=0.2 cluster only)*
2. The orbits of jellyfish (Ram-Pressure Stripped) galaxies in low-z clusters are very radial

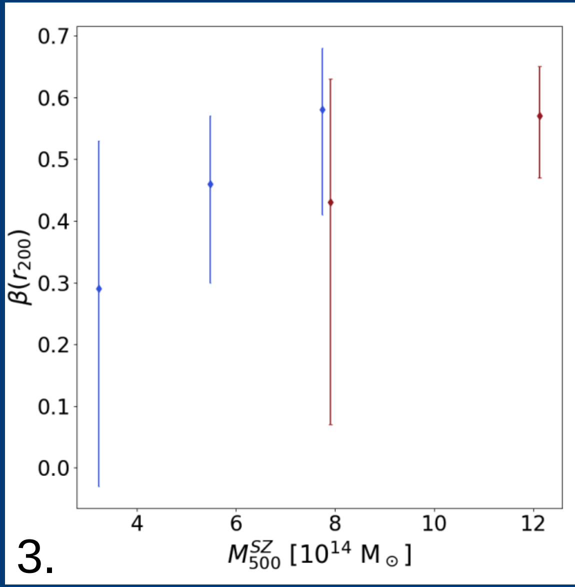
What do we know so far? *(z<0.25)*



(Zarattini+21)



(Valk & Rembold 25)

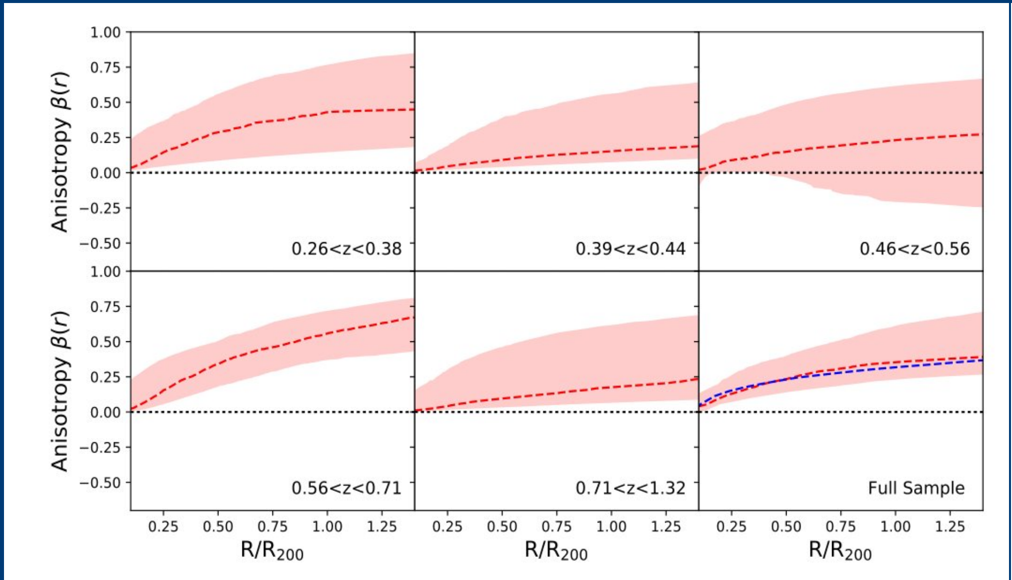


(Pizzuti+25)

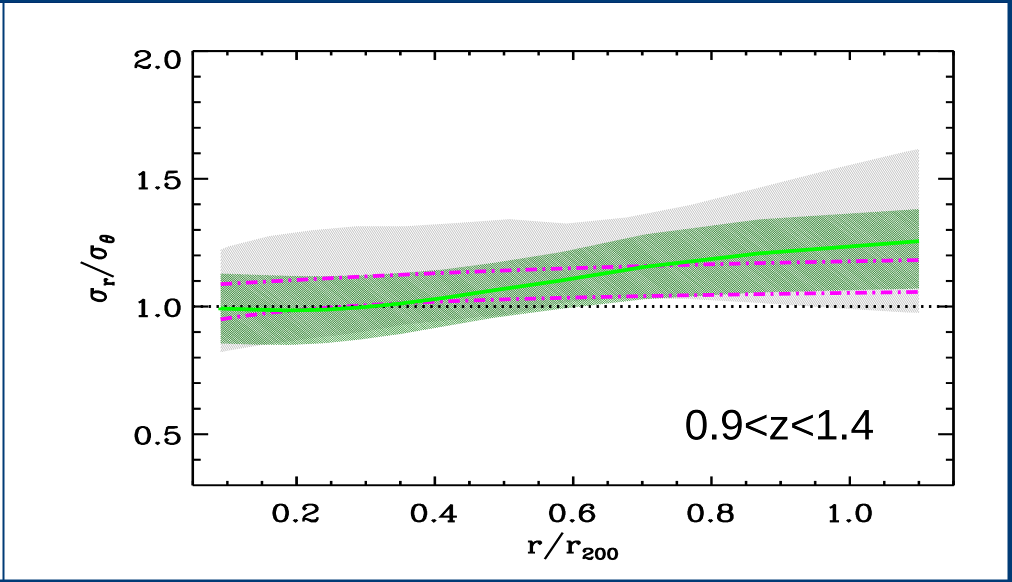
The orbits of galaxies also depend on their cluster characteristics:

1. In fossil groups: galaxy orbits are more radial
2. In dynamically disturbed clusters: galaxy orbits are less radial (or even tangential)
3. *Orbits at large radii are more radial in more massive clusters*

What do we know so far? *(z>0.25)*



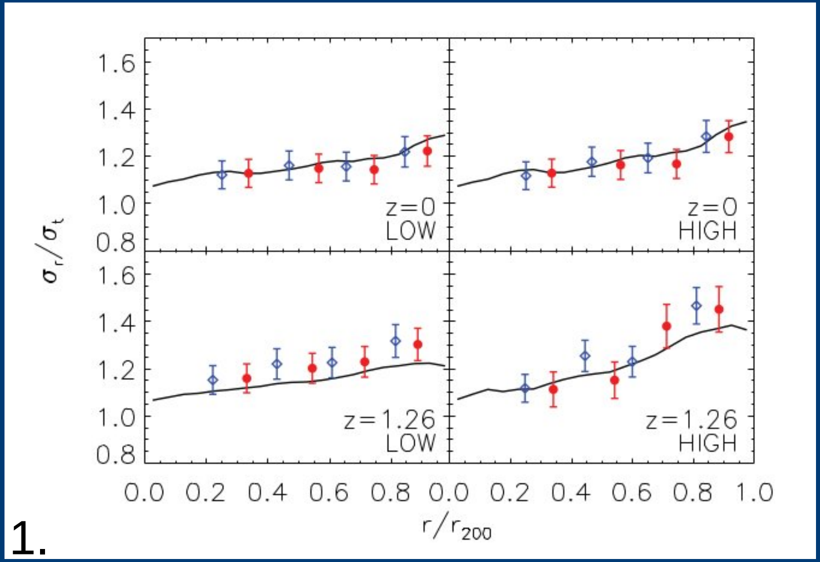
(Capasso+19)



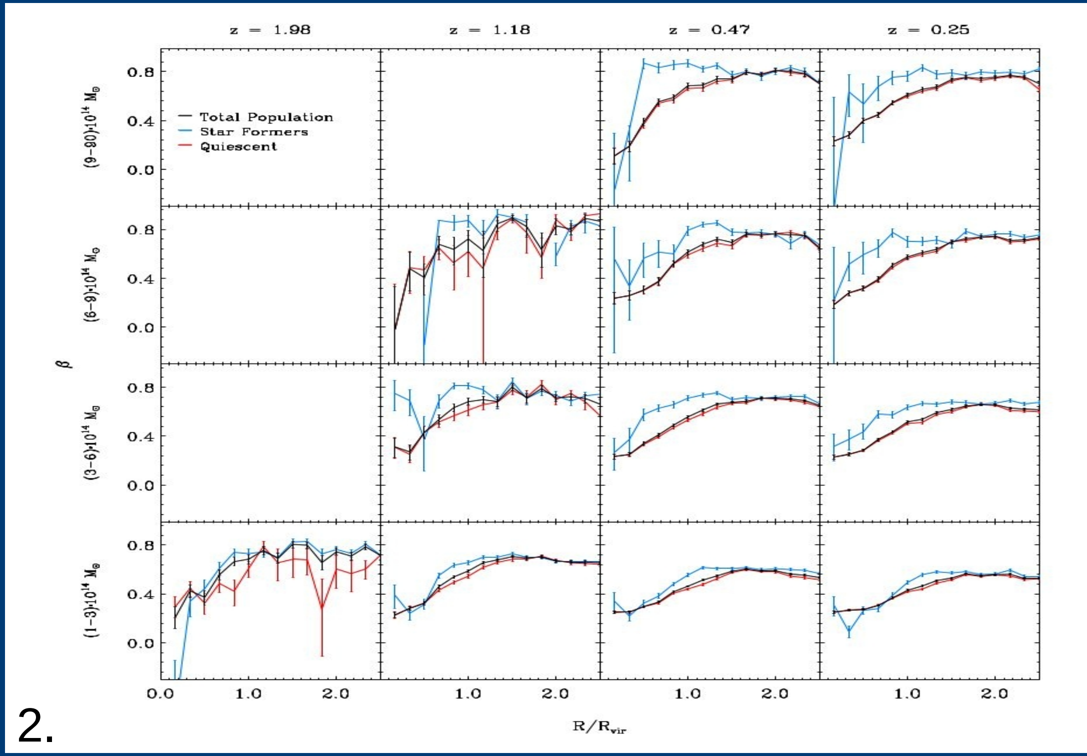
(AB+21)

β(r) has similar shape at z>0.2 as in low-z clusters, with no clear evolution up to z≈1.4,
but there is no evidence that the orbits depend on the galaxy nor on the cluster properties

What do we know so far? *(simulations)*



(Munari+13)



(Lotz+19)

1. The orbits of galaxies are more radial in more massive clusters and at higher-z

2. Blue galaxies have more radial orbits than red galaxies *(but see, e.g., Iannuzzi & Dolag 12)*

A new analysis: the data set and the methods of analysis

CLASH-VLT: The variance of the velocity anisotropy profiles of galaxy clusters

A. Biviano[1,2], E. A. Maraboli[3], L. Pizzuti[4], P. Rosati[5], A. Mercurio[6,7], G. De Lucia[1,2], C. Ragone-Figueroa[8,1,2], C. Grillo[3,9], G. L. Granato[1,2,8], M. Girardi[10,1], B. Sartoris[11,1], and M. Annunziatella[12]

A&A, submitted (under first revision)

Aims:

Quantify the cluster-to-cluster variance in the velocity anisotropy profiles β(r) and identify the main driver of this variance

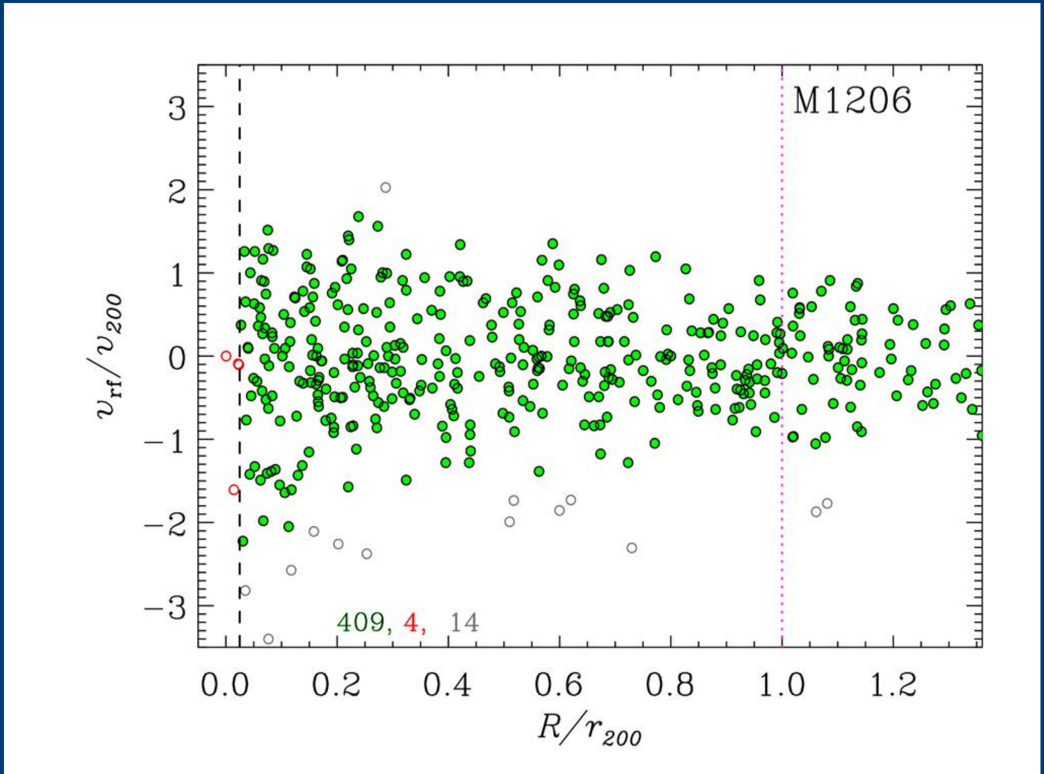
All cluster galaxy populations together; the analysis of β(r) for different cluster galaxy populations is the topic of another paper in preparation (Maraboli+26)

The data set

Nine M_{200}>7 10^{14} $M_\odot$ clusters at 0.19<z<0.44 from CLASH *(Postman+12)* with extensive spectroscopic follow-up at ESO VLT *(Rosati+14)*

Cluster membership established with CLUMPS (AB+21) in projected phase-space
+ a conservative cut based on the escape velocity curve
(method calibrated on simulations from GAEA, DeLucia+24)

From 159 to 954 spectroscopic members per cluster (~500 on average) within 0.05 Mpc ≤ R ≤ 1.36 r_{200} ≈(r_{vir}+r_{ta})/2
and down to m_R≈23.0 (±0.5)



The MAMPOSSt analysis

We run MAMPOSSt on each cluster data-set with the following models:

NFW for the mass profile M(<r): **two** parameters, r_{200} and r_s

King or projected-NFW for the number density profile N(R): **one** parameter, r_ν

Tiret or Osipkov-Merritt for β(r): **two** parameters β_0 and β_∞

$$\beta(r) = \beta_0 + (\beta_\infty - \beta_0)\frac{r^\delta}{r^\delta + r_\beta^\delta}$$

δ=1 Tiret model
δ=2 Osipkov-Merritt

<u>Note:</u>

- We run 25,000 MCMC steps, adopting flat priors within wide ranges for all parameters
- r_ν is estimated outside MAMPOSSt (‘split mode’) to account for spectroscopic incompleteness
- r_ν and r_s are independent parameters, no “mass-follows-light” hypothesis

The MAMPOSSt analysis

The MAMPOSSt posteriors for the M(<r) parameters r_{200} and r_s, are compared with the values obtained by Umetsu+18’s gravitational lensing analysis and found to be in agreement within 1.5 σ for eight of our nine clusters.

For MACS1115 we find a significant smaller value for r_{200} than Umetsu+18’s, in better agreement with the results of the X-ray dynamical analysis by Donahue+14.

We therefore re-run MAMPOSSt on eight of our clusters (except MACS1115) by adopting Umetsu’s independent estimates of r_{200} and r_s as Gaussian priors, thereby reducing the uncertainties in the posteriors of the MAMPOSSt analysis.

Note: Umetsu+18’s values are obtained for elliptical mass models, while we are assuming spherical symmetry. However, Umetsu+18’s mass profiles are in excellent agreement with Umetsu+14’s, that were derived under the spherical symmetry assumptions, M_{ell}/M_{sph}=0.97 with rms=0.08, 0.13, 0.17 at the Δ=500, 200, 100 overdensities, resp.

The JEI analysis

The advantage of JEI wrt MAMPOSSt is that the solution for $\beta(r)$ is not bound to follow a specific model profile.

We adopt the MAMPOSSt posteriors for $M(<r)$ and *LOWESS*-smoothed versions of the binned $N(R)$ and l.o.s. velocity dispersion profile $\sigma_{los}(R)$ to solve for $\beta(r)$

We determine the uncertainties on $\beta(r)$ by running JEI 1,500 times, each time:

- randomly selecting the $M(<r)$ parameters from the MAMPOSSt MCMC steps,
- re-evaluating $N(R)$ and $\sigma_{los}(R)$ on a bootstrap sample of the projected phase-space,
- using a random choice of the *LOWESS* smoothing parameter

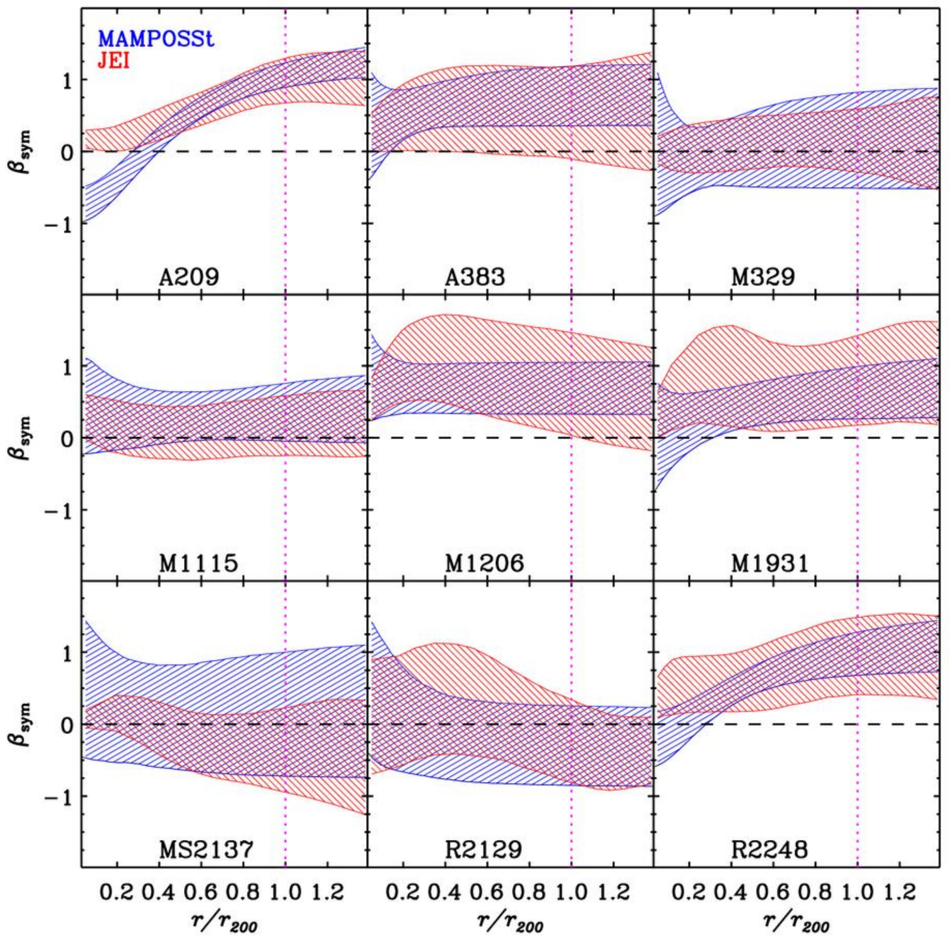
We checked for convergence.

Finally, we checked for consistency between the JEI and MAMPOSSt $\beta(r)$.

A new analysis:
results

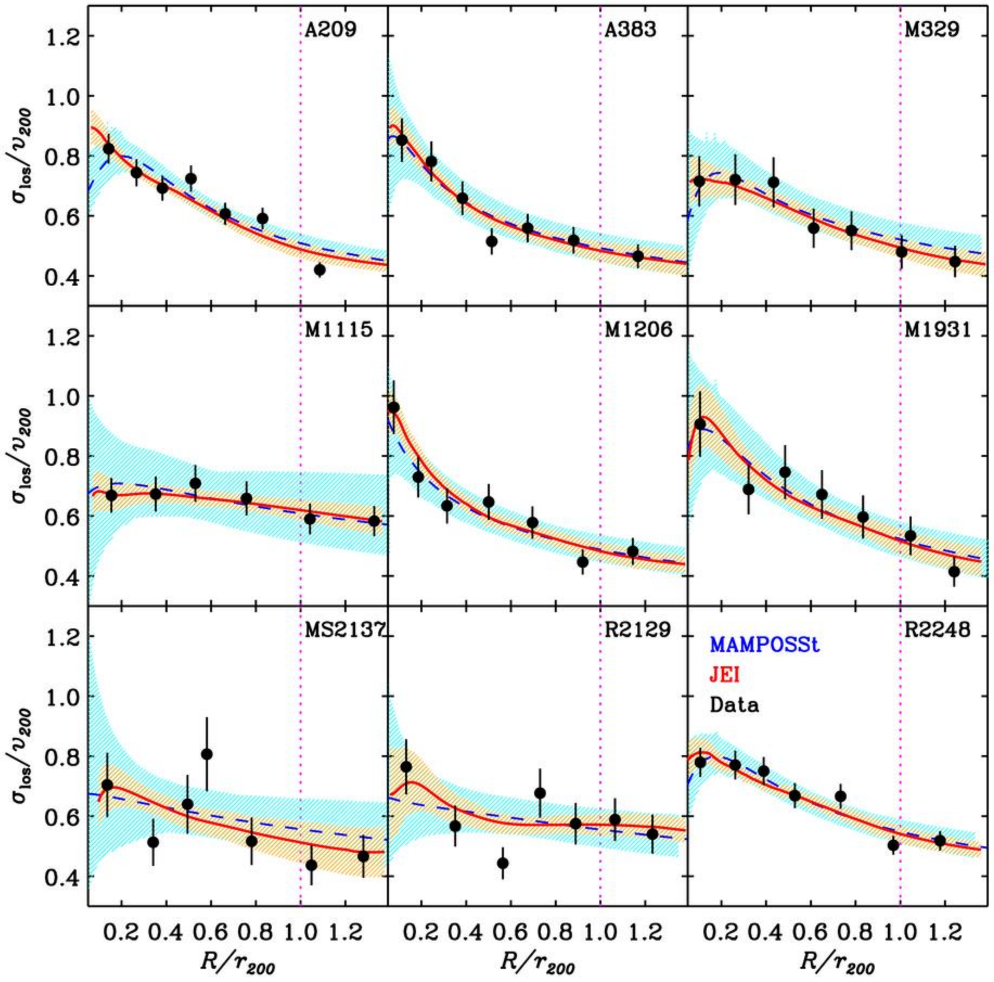
MAMPOSSt vs. JEI $\beta_{sym}(r)$

Results are consistent
(68% confidence levels shown),
except for A209 near the center
(the only cluster showing a core
in the galaxy distribution, i.e. better
fit by a King than a NFW N(R))



We adopt Mamon+19's $\beta_{sym} \equiv \frac{\beta}{1-\beta/2}$

- =+2: purely radial orbits
- = 0 : isotropic orbits
- =-2 : purely tangential orbits



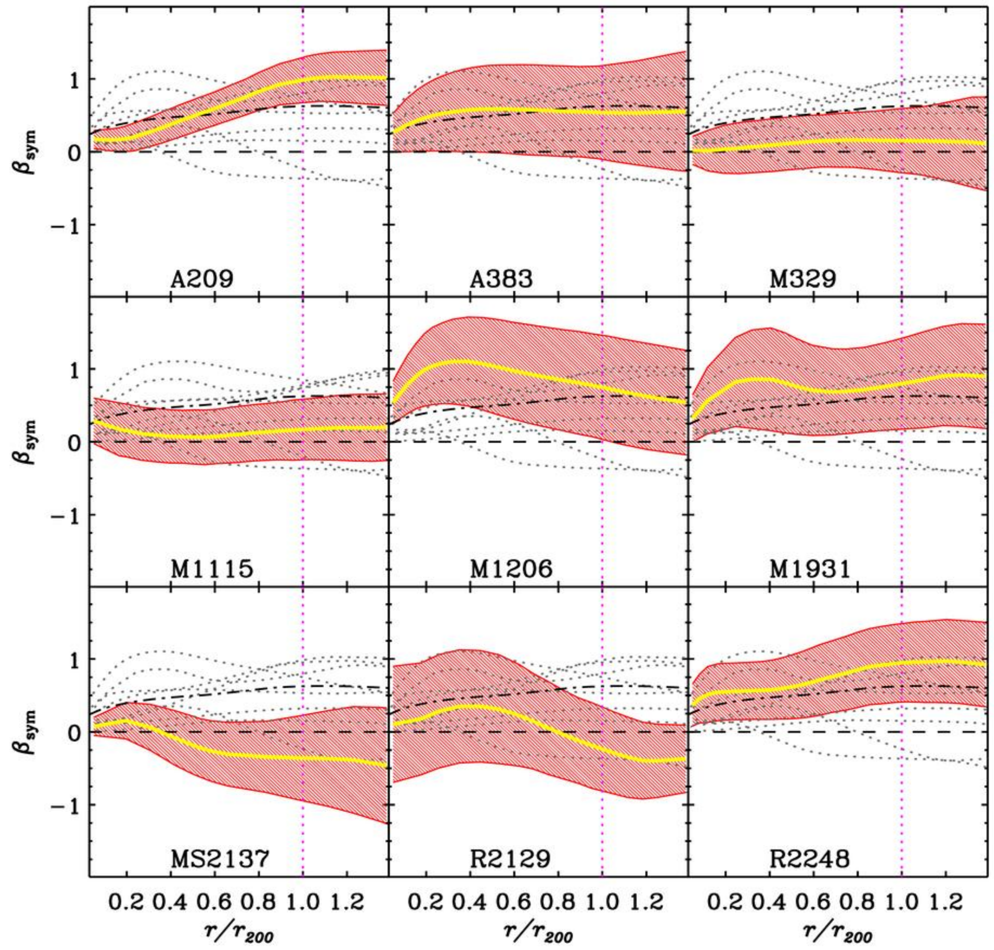
MAMPOSSt vs. JEI: checking the β(r) solutions in the space of observables

Given M(<r), β(r) and N(R), we predict $\sigma_{los}(R)$ and compare it with the observed profile.

The MAMPOSSt-predicted $\sigma_{los}(R)$'s fit the observed profiles well (not a-priori guaranteed, MAMPOSSt will always provide a posterior).

The JEI-predicted and the observed $\sigma_{los}(R)$ coincide only if the JEI solution for β(r) is physical (i.e. there is a solution of the Jeans equation for dynamical equilibrium).

The agreement between predicted and observed $\sigma_{los}(R)$ suggests our nine clusters are in dynamical equilibrium



The 9 cluster β_{sym}(r) from JEI

Yellow line and red shadings:
β_{sym}(r) and 68 % confidence region, resp.

In each panel we show the β_{sym}(r) of all nine clusters (dotted lines), the mean $\langle\beta_{sym}(r)\rangle$, weighted on the number of members (dash-dotted line), and the isotropic case (dashed horizontal line).

There is significant variance in the cluster-to-cluster β_{sym}(r)'s.

We adopt Mamon+19's

$$\beta_{\rm sym} \equiv \frac{\beta}{1-\beta/2}$$

- =+2: purely radial orbits
- = 0 : isotropic orbits
- =-2 : purely tangential orbits

The origin of the variance in the cluster β(r)'s

We define the deviation $d\beta$ of each cluster $\beta_{sym}(r)$ from the mean as:

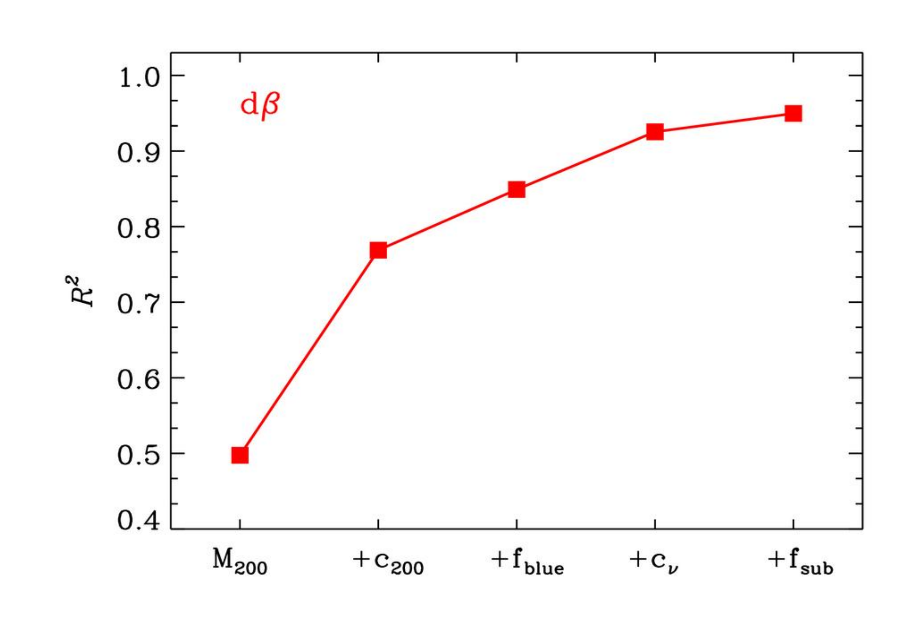
$$d\beta \equiv \sum_{i=1}^{50} \beta_{\rm sym}(r_i) - \langle \beta_{\rm sym}(r_i) \rangle$$

evaluated in 50 equally spaced radial bins

We search for correlation of $d\beta$ with other cluster properties:

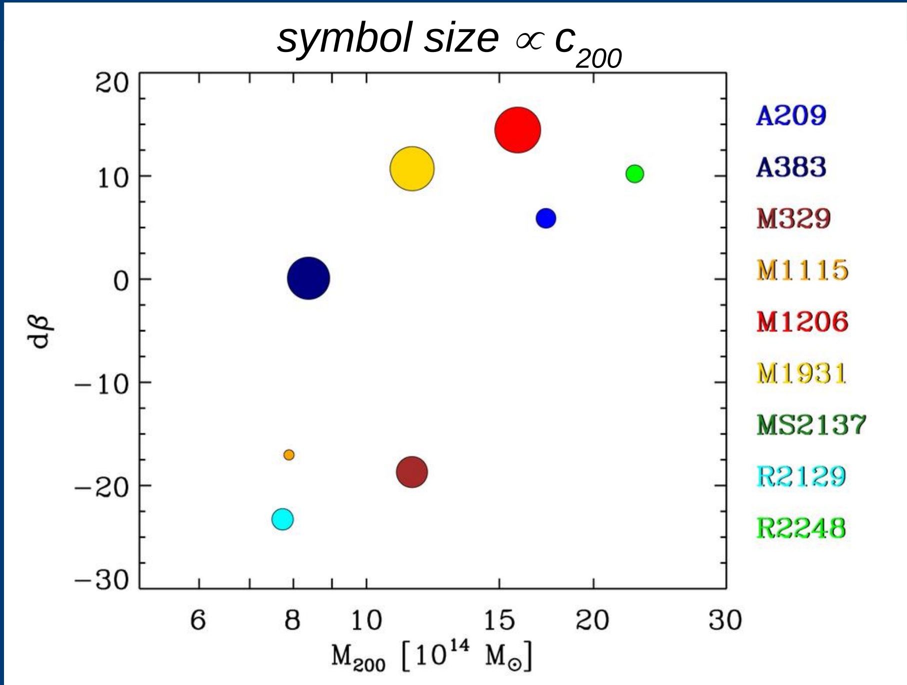
- M_{200}, the cluster mass
- $c_{200} \equiv r_{200}/r_s$, the concentration of the mass distribution
- $c_\nu \equiv r_{200}/r_\nu$, the concentration of the galaxy distribution
- f_{blue}, the fraction of blue galaxies among the cluster members
- f_{sub}, the fraction of galaxies in subclusters, as identified by the DS+ method *(Benavides+23)*

The origin of the variance in the cluster β(r)'s



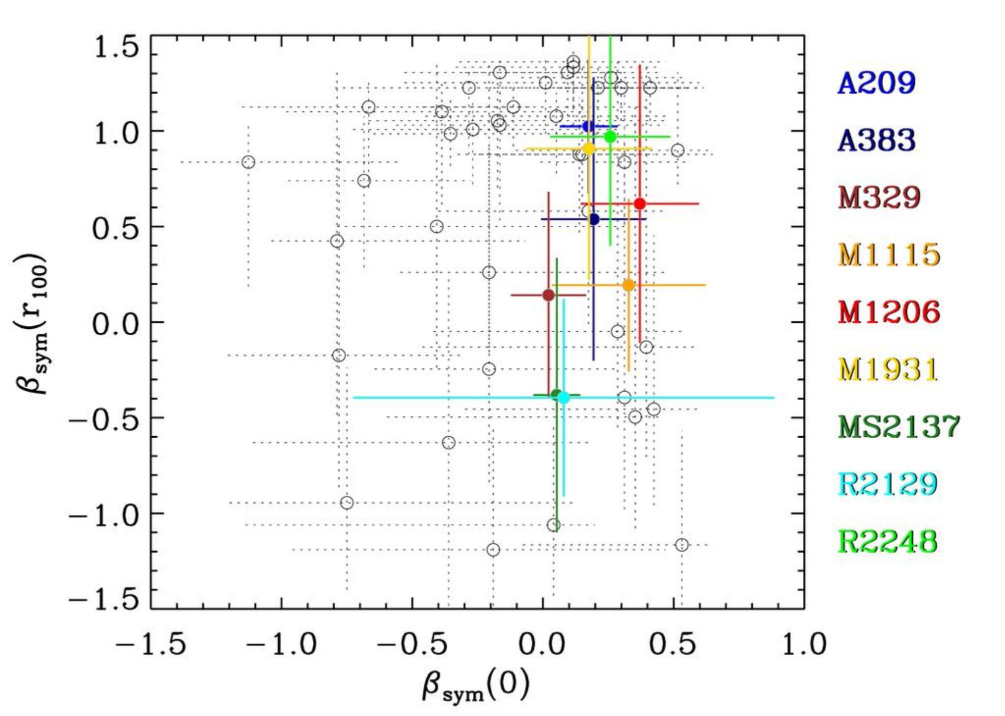
We perform a stepwise regression analysis with forward selection to identify the most predictive cluster properties for dβ:

M_{200} and c_{200}

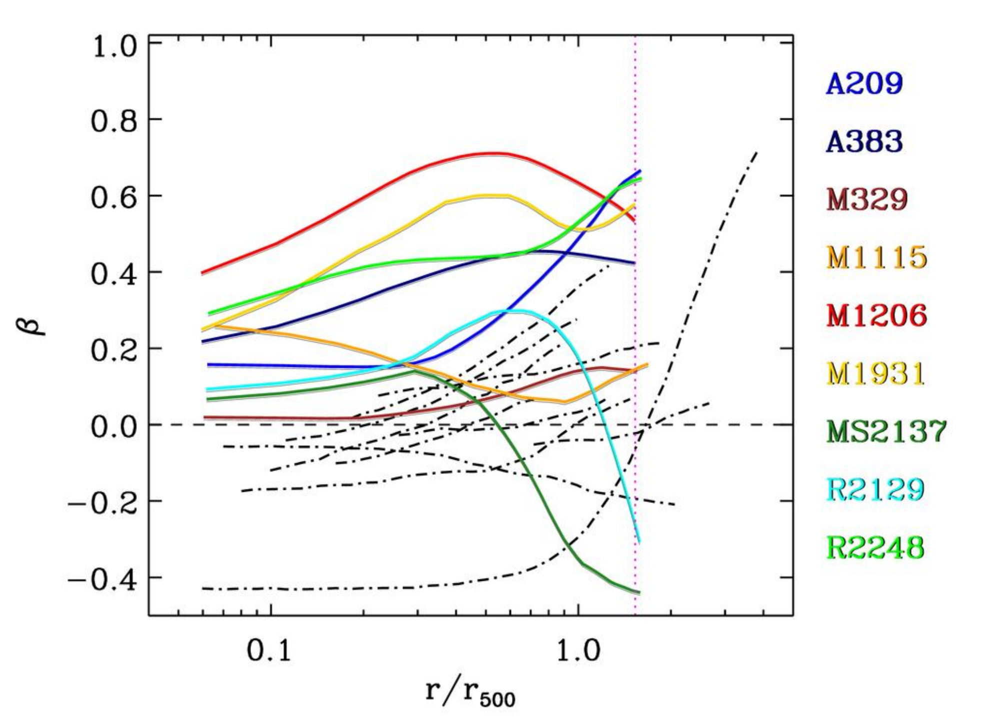


Clusters of higher M_{200}, as well as clusters of high-c_{200} at given M_{200}, tend to have more radial orbits ($d\beta>0$)

Comparison with lower-z clusters



(cmp to Wojtak & Łokas 10)



(cmp to Li+23)

The orbits of galaxies in our clusters *(in color in the figures)* are, on average, more radial than those of galaxies in low-z clusters *(in black in the figures)*

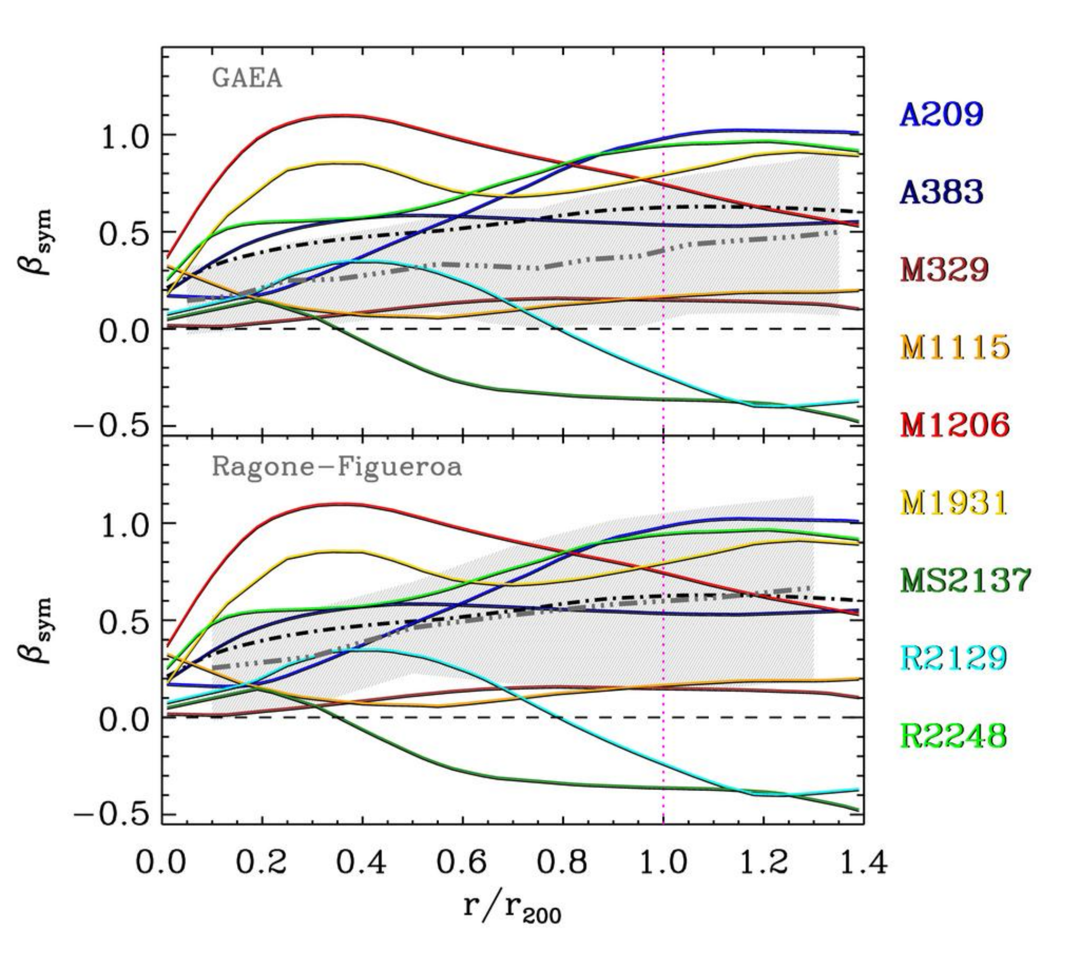
Comparison with simulations

We compare our nine cluster $\beta_{sym}(r)$'s with:

- 112 halos from the semi-analytical model simulation GAEA *(DeLucia+24)*
- 25 halos from the hydrodynamical simulation of *Ragone-Figueroa+18*

Halos matched in mass and redshift with our nine clusters sample

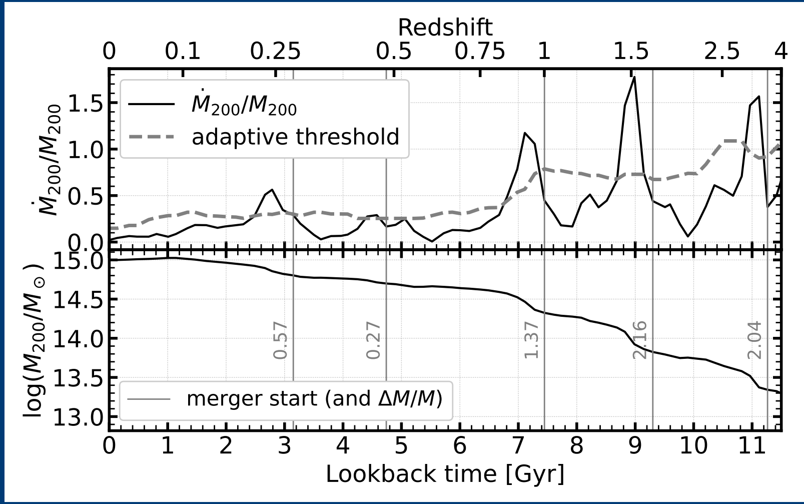
There is good agreement on the average but the variance of β(r) is larger among observed clusters than among simulated halos *(even after accounting for observational uncertainties)*

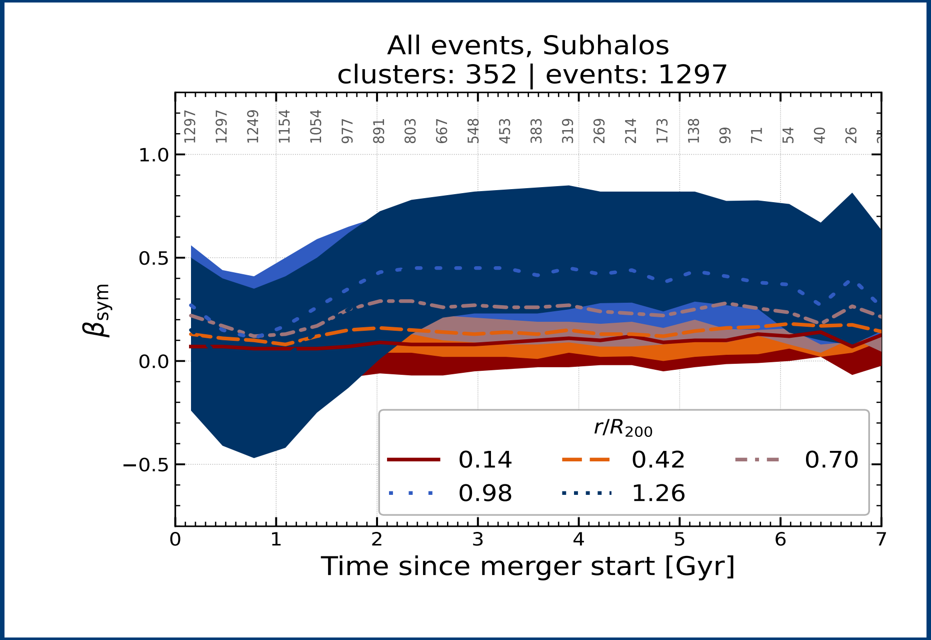


Comparison with simulations

What causes the variance in cluster β(r)'s? We look at halos in the TNG-Cluster simulation *(Nelson+24)*: 352 halos with z=0 masses $2 \le M_{200}/[10^{14}\ M_\odot] \le 25$

We *(Ragone-Figueroa+26, in prep.)* reconstruct the mass assembly history of these halos and flag merger events with $\Delta M_{200}/M_{200}>0.05$ above a z-dependent accretion rate threshold





Stacking together all the significant merger events of all halos we then evaluate how β(r) for subhalos and DM particles change after a merger event

Following a merger, $\beta_{sym}(r > 0.7 r_{200})$ drops to ≈0, then radial orbits are recovered after 2 Gyr

Summary,
discussion & conclusions

Summary

Previous observations indicate that:

- orbits of $0 \leq z \leq 1.4$ cluster galaxies are isotropic near the center, and more radial outside *(Natarajan & Kneib 96, Wojtak & Łokas 10, Capasso+19, AB+21, ...many others)*

- *at low-z, early-type/red/passive galaxies have more isotropic orbits than late-type/blue/star-forming ones (AB+Katgert 04, Mamon+19, ...but see, e.g., Aguerri+17)*
  and jellyfish galaxies have very radial orbits (AB+24)

- orbits are more radial in very concentrated clusters (“fossil groups”; *Zarattini+21*)

- orbits are more isotropic in dynamically disturbed clusters *(Valk & Remboldt 25)*

- *orbits tend to be more radial in more massive clusters (Pizzuti+25, not statistically significant)*

Summary

- ✔ We investigate a limited sample of nine massive clusters ($M_{200}>7\ 10^{14}\ M_{\odot}$ $0.19<z<0.44$), each one with a large spectroscopic data set (≈500 members per cluster, on average, and up to ≈1000) that allows us to determine β(r) with improved precision wrt previous works.

- ✔ We take advantage of previous gravitational lensing M(<r) determinations to assist our kinematic analysis based on the spherical Jeans equation (MAMPOSSt)

- ✔ We go beyond model assumptions for β(r), using our non-parametric Jeans Equation Inversion (JEI) technique

Summary

Based on our observational data set we find that:

- $\langle\beta_{sym}(r)\rangle$ increases from 0.25 near the center to 0.55 at the virial radius
- there is significant variance in the orbital distributions of galaxies across different clusters
- orbits are more radial in more massive clusters, and in more concentrated clusters at given mass
- *we do not distinguish among different cluster galaxy populations but we do not find a dependence on f_{blue} (stay tuned: Maraboli+26 in prep.)*

Comparing to simulations we find that:

- $\langle\beta_{sym}(r)\rangle$ of the observed clusters and simulated halos matched in mass and redshift are very similar, but the variance is larger among our clusters than among simulated halos
- merger events isotropize radial orbits in the outer cluster regions (while they remain isotropic near the center)

Discussion and conclusions

Our results confirm the average β(r) found in previous investigations but find significant variance among the different clusters → it is inappropriate to assume a universal β(r) in solving for M(<r).

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Our results confirm the average β(r) found in previous investigations but find significant variance among the different clusters → it is inappropriate to assume a universal β(r) in solving for M(<r).

We identify cluster mass and concentration as the main drivers of this variance. Some dependence of β(r) on cluster mass has been found previously in observations *(Pizzuti+25)* and in simulations *(Munari+13)*. Our (ongoing) analysis of TNG300-cluster numerical simulations indicate mergers cause transition from radial to isotropic orbits (in line with theoretical predictions by *Lapi & Cavaliere 11*, and also supported observationally by *Valk & Rembold 25*). We must look for connections among these cluster properties (e.g. clusters undergoing mergers are less concentrated, more massive clusters have undergone more merger events...) and identify the best observational indicators of merger events.

Discussion and conclusions

Our results confirm the average β(r) found in previous investigations but find significant variance among the different clusters → it is inappropriate to assume a universal β(r) in solving for M(<r).

We identify cluster mass and concentration as the main drivers of this variance. Some dependence of β(r) on cluster mass has been found previously in observations *(Pizzuti+25)* and in simulations *(Munari+13)*. Our (ongoing) analysis of TNG300-cluster numerical simulations indicate mergers cause transition from radial to isotropic orbits (in line with theoretical predictions by *Lapi & Cavaliere 11*, and also supported observationally by *Valk & Rembold 25*). We must look for connections among these cluster properties (e.g. clusters undergoing mergers are less concentrated, more massive clusters have undergone more merger events...) and identify the best observational indicators of merger events.

We find more radial orbits than in lower-z clusters. Based on the simulations results, the isotropy of galaxies in low-z clusters suggests that most of these galaxies have had their orbits re-shaped by a merger event (i.e. the fraction of recently smoothly accreted galaxies is small). We should try to determine the cluster accretion rates (e.g. by identifying the splashback radius).

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Nine clusters are clearly not a large data set. To extend our analysis we will consider stacking more clusters, although with a lower amount of spectroscopic data each, in bins of cluster properties.