Mass and velocity anisotropy profiles of GOGREEN clusters

Andrea Biviano, INAF-OATs (Trieste, Italy)
& GOGREENers (most notably: van den Burg & Balogh)

Credits: “The incredible Hulk”, (partly) shot on location in Toronto

Motivation:

1) M(r): Cluster mass profile shape predicted to change with time

inner slope affected by adiabatic contraction (Blumenthal+86, Gnedin+04), accretion of subclusters (Laporte+12, Schaller+15), dynamical friction (El-Zant+01, +04), AGN feedback (Navarro+96, Ragone-Figueroa+12, Peirani+17)

outer slope affected by mass accretion (Diemer+Kratsov 14)

2) $\beta(r)$, velocity anisotropy profile ⇔ orbits of galaxies in clusters

Galaxy evolution (might) depend on the environment, that changes with time as the galaxy orbits the cluster

- ➔ ram pressure strength depends on a galaxy orbit (Tonnesen 19)
- ➔ galaxy morphology evolution depends on pericentric radius and number of pericentric passages (Joshi+20)

How to do this:

- Identify spectroscopic members
- Build stack cluster *(need samples of ≥200 galaxies)*
- Use MAMPOSSt to determine mass profile M(r)
- Use Jeans inversion to determine velocity anisotropy profile β(r)

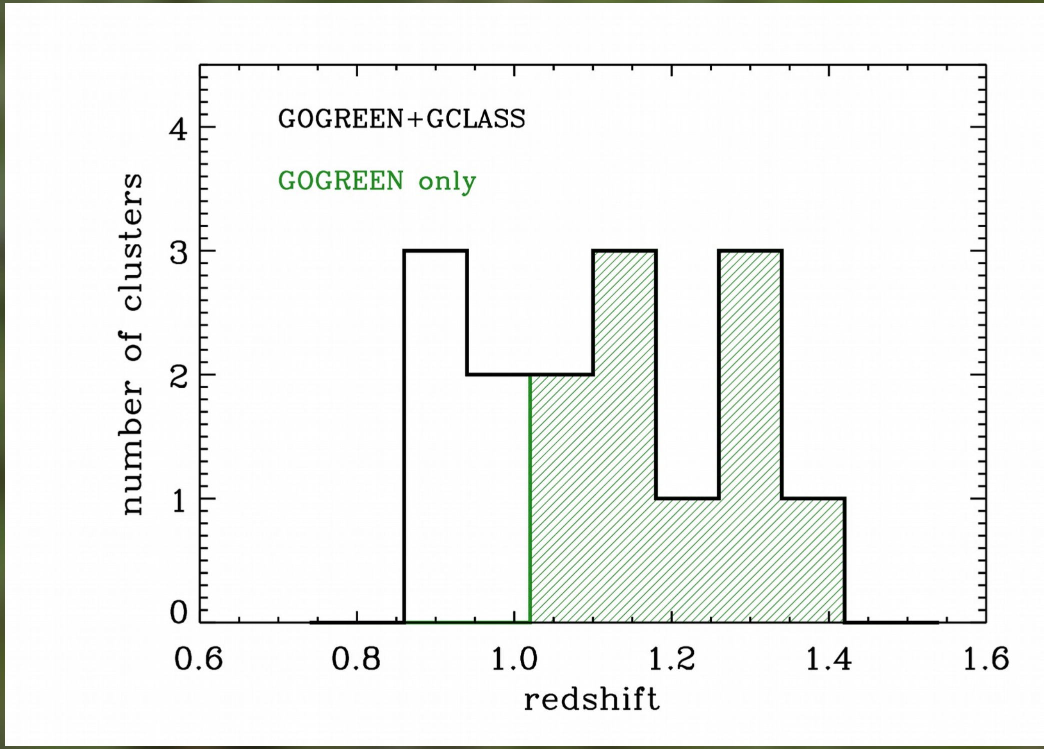
Data-set:

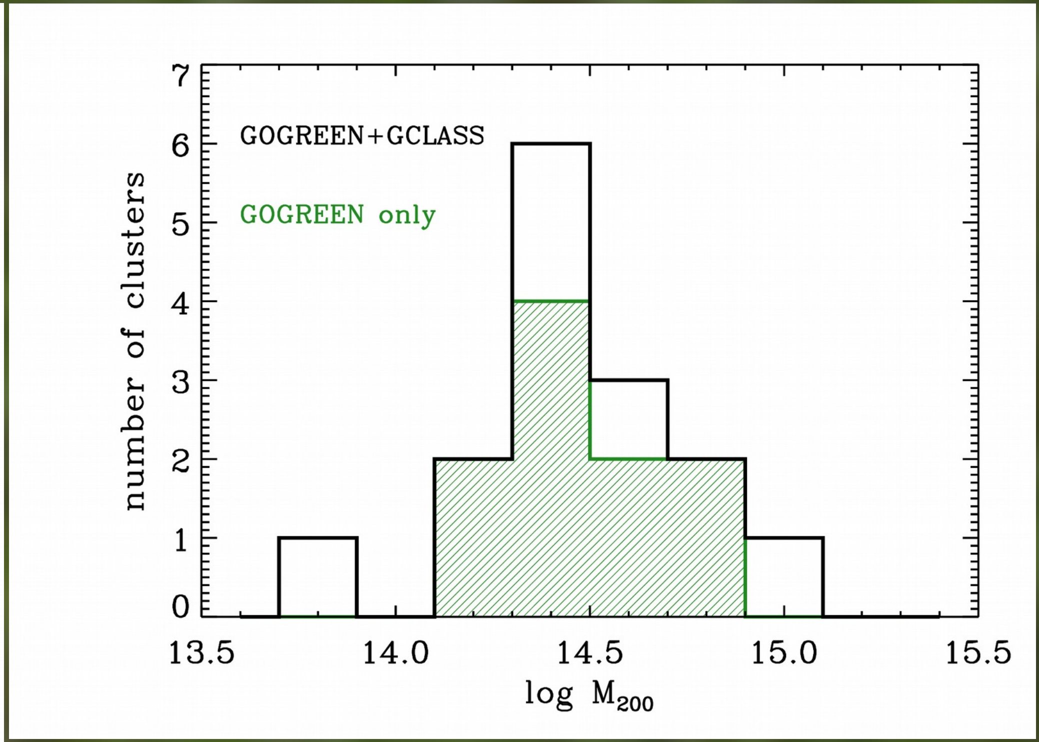
GOGREEN + GCLASS

+ literature (Stalder+13, Sifón+16, Nantais priv.comm.)

Data-set:

GOGREEN: SPT 205, 546, 2106; SpARCS 35, 219, 335, 1051, 1616, 1634, 1638
GCLASS: SpARCS 34, 36, 215, 1047, 1613





Masses M_{200} based on velocity dispersion
(more on this in following slides)

Membership:

Must define cluster center

In velocity space:

use peak of velocity distribution,
then iterate using biweight mean velocity

In coordinate space, 2 choices (so far):

1) BCG positions (van den Burg + Chan)

2) luminosity-weighted centers *(analysis to be completed)*

Membership:

Use KMM to identify main peak in z space,
then refine the identification by two methods:
CLEAN (Mamon, AB, Boué 13) & CLUMPS (Munari, priv. comm.)

The 2 methods are conceptually very different although both based on the location of a galaxy in its cluster projected phase space
(= line-of-sight rest-frame velocity vs. cluster-centric projected distance)

Assign weights: 1 = CLEAN and CLUMPS member
1/2 = CLEAN xor CLUMPS member
0 = neither CLEAN nor CLUMPS member

677 cluster members (sum of membership weights = 613.5)
in 15 clusters (3 SPT + 12 SpARCS) with $0.87 \leq z \leq 1.37$

Stacking:

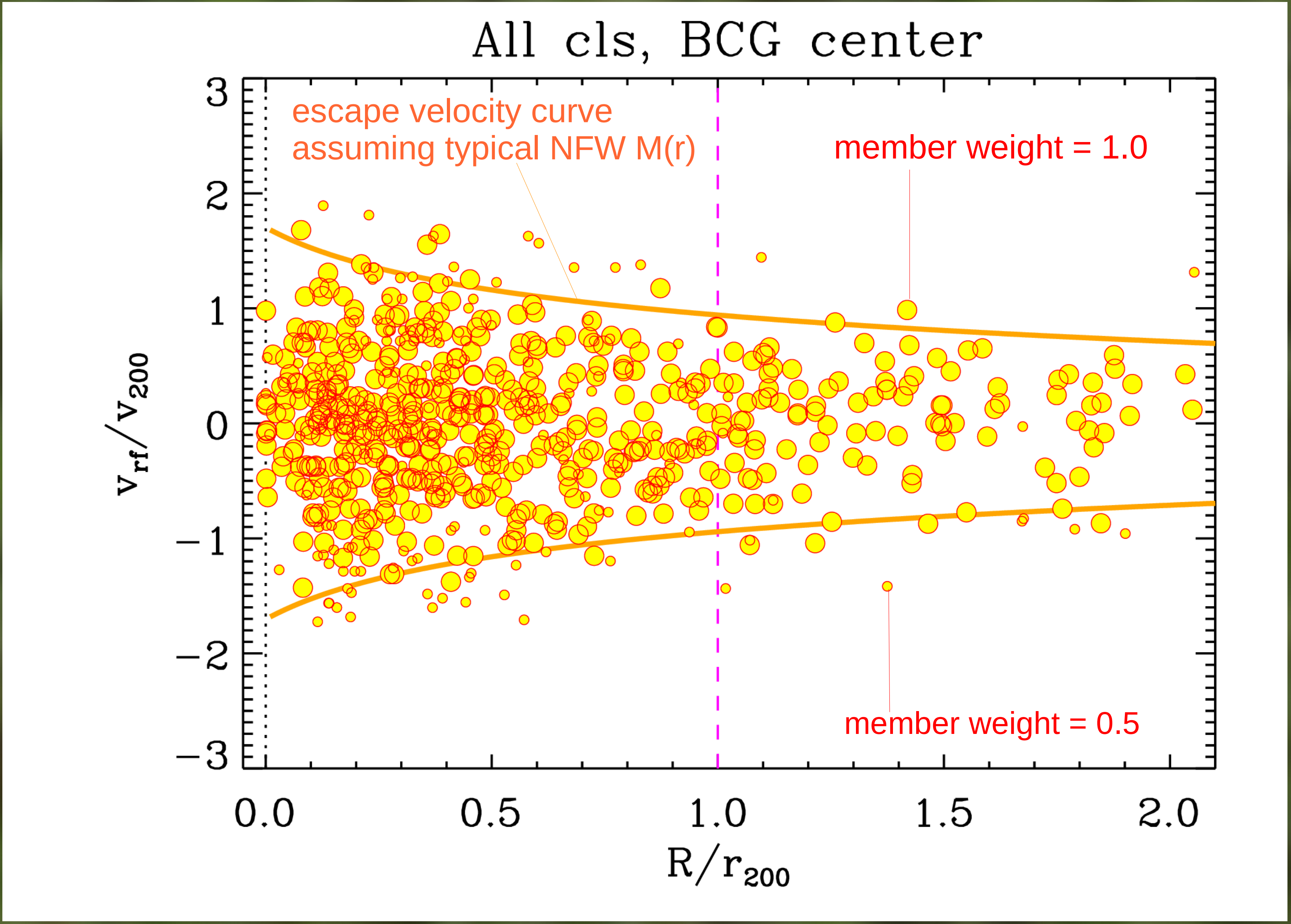
Limited statistics per cluster ⇒
need to stack clusters to determine <M(r)> and/or <β(r)>

Normalize galaxy cluster-centric projected distances (“radii” R) by r_{200}, and galaxy line-of-sight rest-frame velocities (v_{rf}) by v_{200}

Determine r_{200} *(hence also v_{200} and M_{200} given cluster <z> and cosmology)* from velocity dispersion **using 3 different prescriptions to check for systematics** *(no difference found among the 3 resulting stacked cluster projected phase-space distributions)*

Assume spherical symmetry – this is not a bad assumption for a stack cluster (van der Marel+00) as long as there is no selection bias for clusters elongated along the line-of-sight

Stacked projected phase-space



weighted average of clusters $\mathbf{r_{200}}$ *(using number of members as weights)*: **0.98 Mpc**

The Jeans equation

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

Velocity anisotropy profile

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

Mass profile

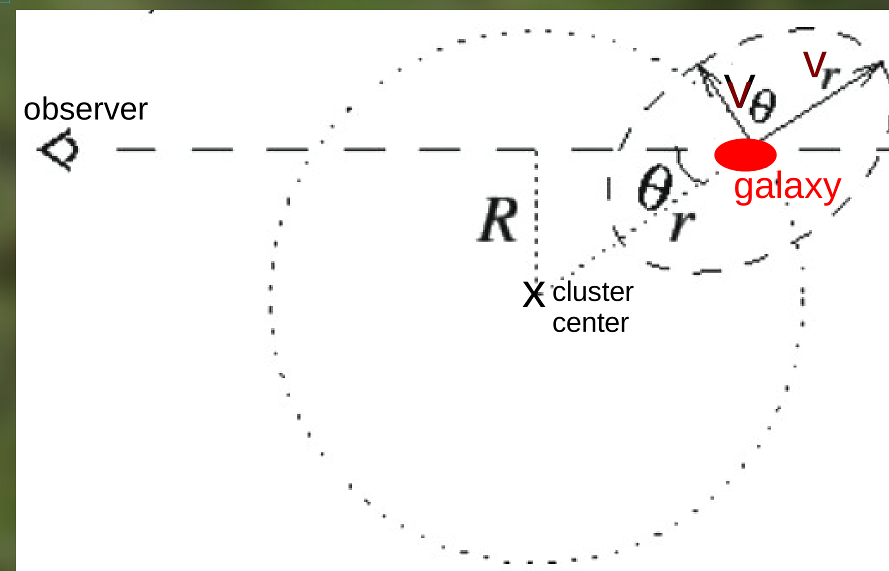
3D number density profile

Velocity dispersion profile along the radial direction, r

Velocity dispersion profile along the tangential direction

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

***M**ass-**A**nisotropy **D**egeneracy*
*(aka Jeans' **MAD**ness)*



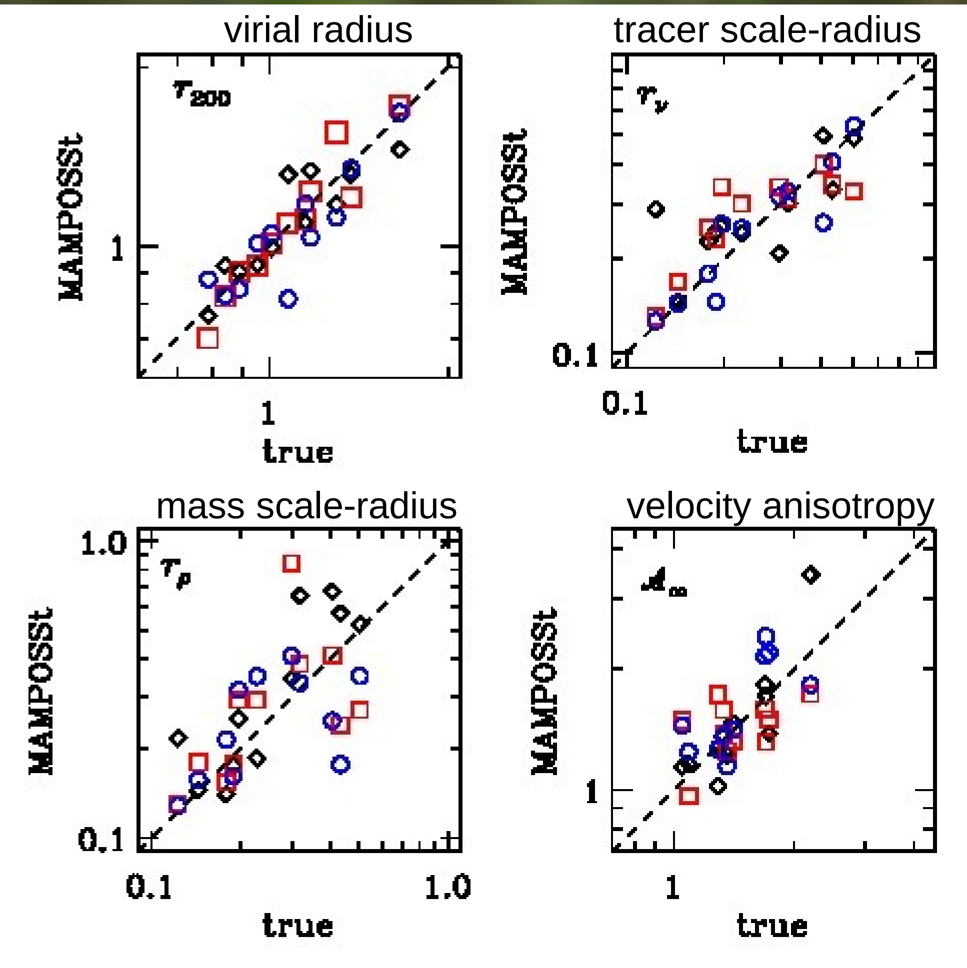
(courtesy of G. Mamon)

Solving the Jeans equation with observables:

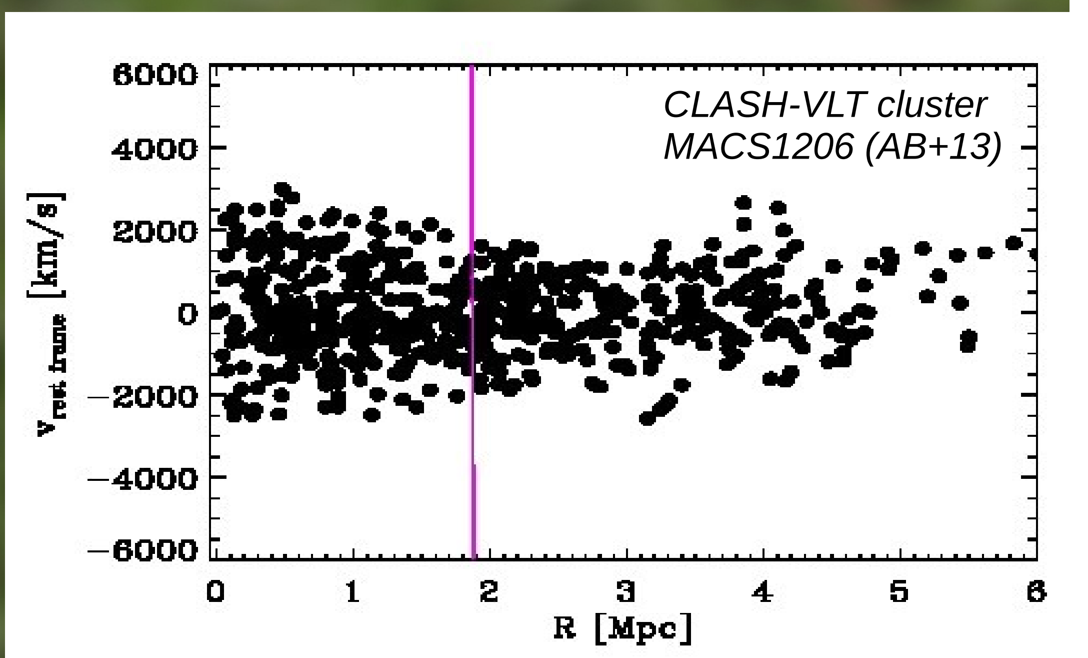
MAMPOSSt (Mamon, AB, Boué 13)

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

Modelling **A**nisotropy and **M**ass **P**rofiles of **O**bserved **S**pherical **S**ystems



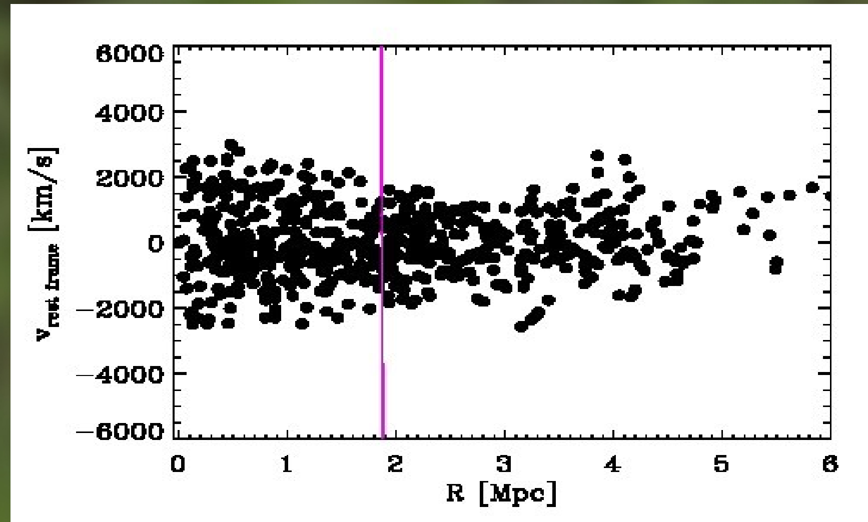
Cluster-size halos from numerical simulations



Using the full information available in projected phase-space...

MAMPOSSt cures Jeans' MADness!

Solving the Jeans equation with observables:



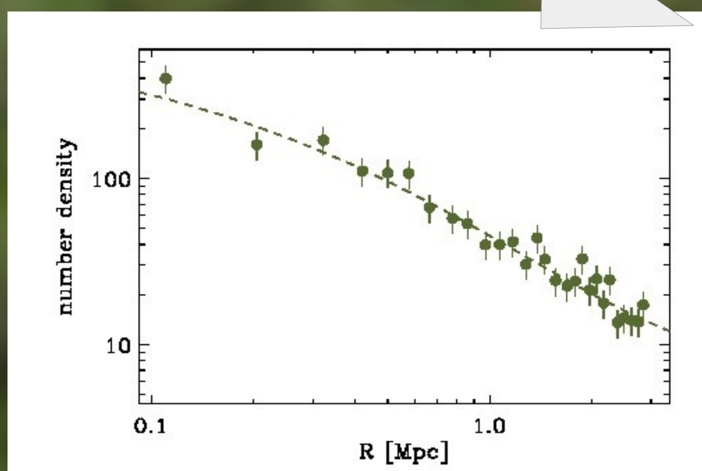
Projected phase-space distribution of cluster member galaxies

projected number density profile N(R)

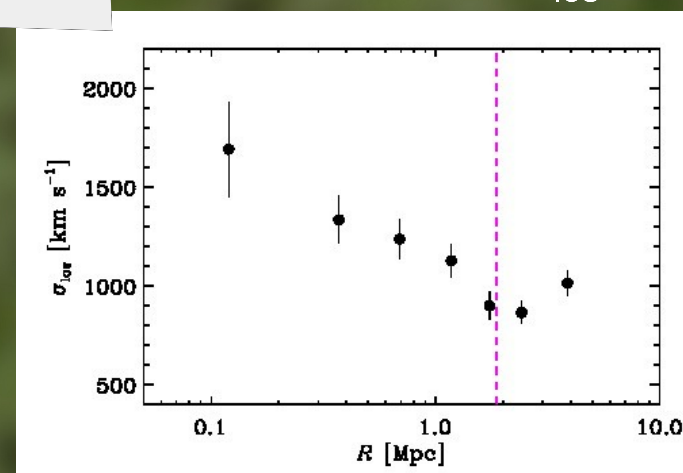
x y

line-of-sight velocity dispersion profile $\sigma_{los}(R)$

M(r) +



+



→ β(r)

If known, e.g. from lensing or MAMPOSSt

Inversion of the Jeans equation

(Binney & Mamon 82, see also Solanes & Salvador-Solé 90)

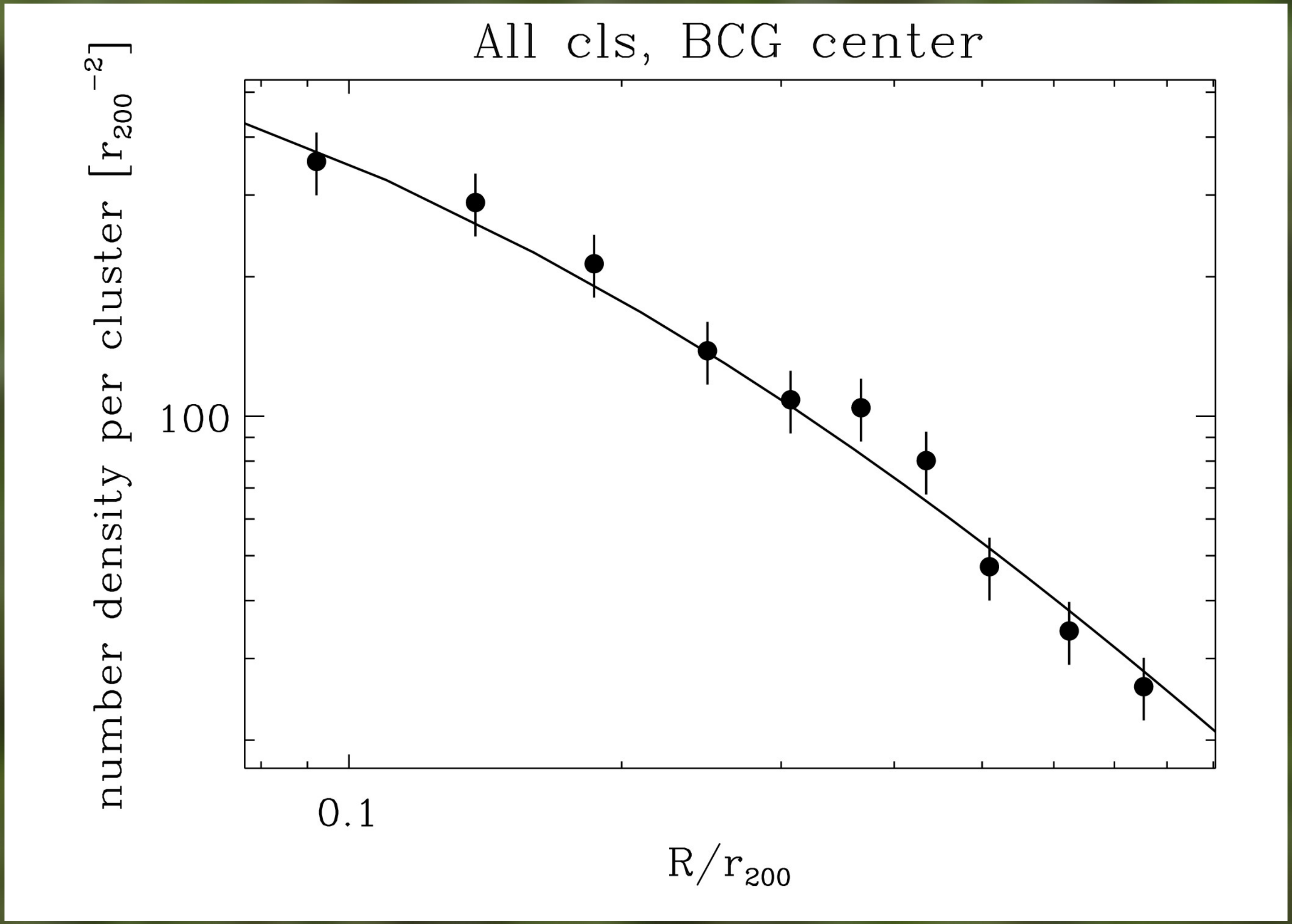
The number density profile

Use the photometric sample to correct for the spectroscopic sample incompleteness (van den Burg)

Best-fit with projected NFW profile:

$r_\nu = 0.24\ r_{200}$

$c_\nu = 4.1$



Running MAMPOSSt

Mass models considered *(γ, γ_{out} is the logarithmic inner/outer slope)*

gNFW: γ = 0.0, 0.5, 1.0 (NFW), 1.5; $\gamma_{\rm out}$ = 3

Burkert: γ = 0.0; $\gamma_{\rm out}$ = 3

Hernquist: γ = 1.0; $\gamma_{\rm out}$ = 4

Einasto: γ approaching 0.0 asimptotically; $\gamma_{\rm out}$ = 3

Velocity anisotropy models considered:

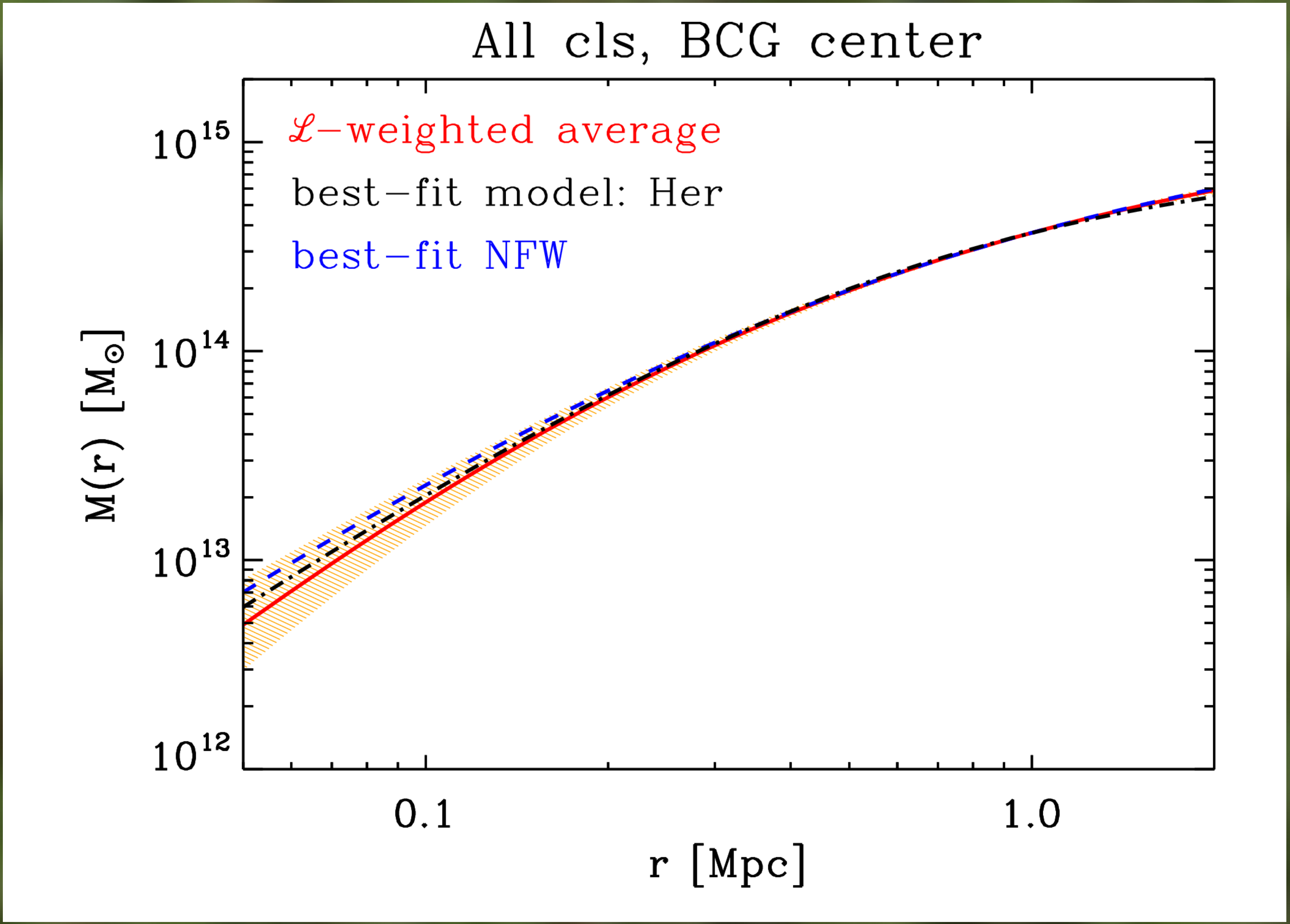
Constant with radius
Rising from isotropy to radial orbits with radius (3 different models)
Rising from tangential to radial orbits (or viceversa)

Use membership weights in the analysis

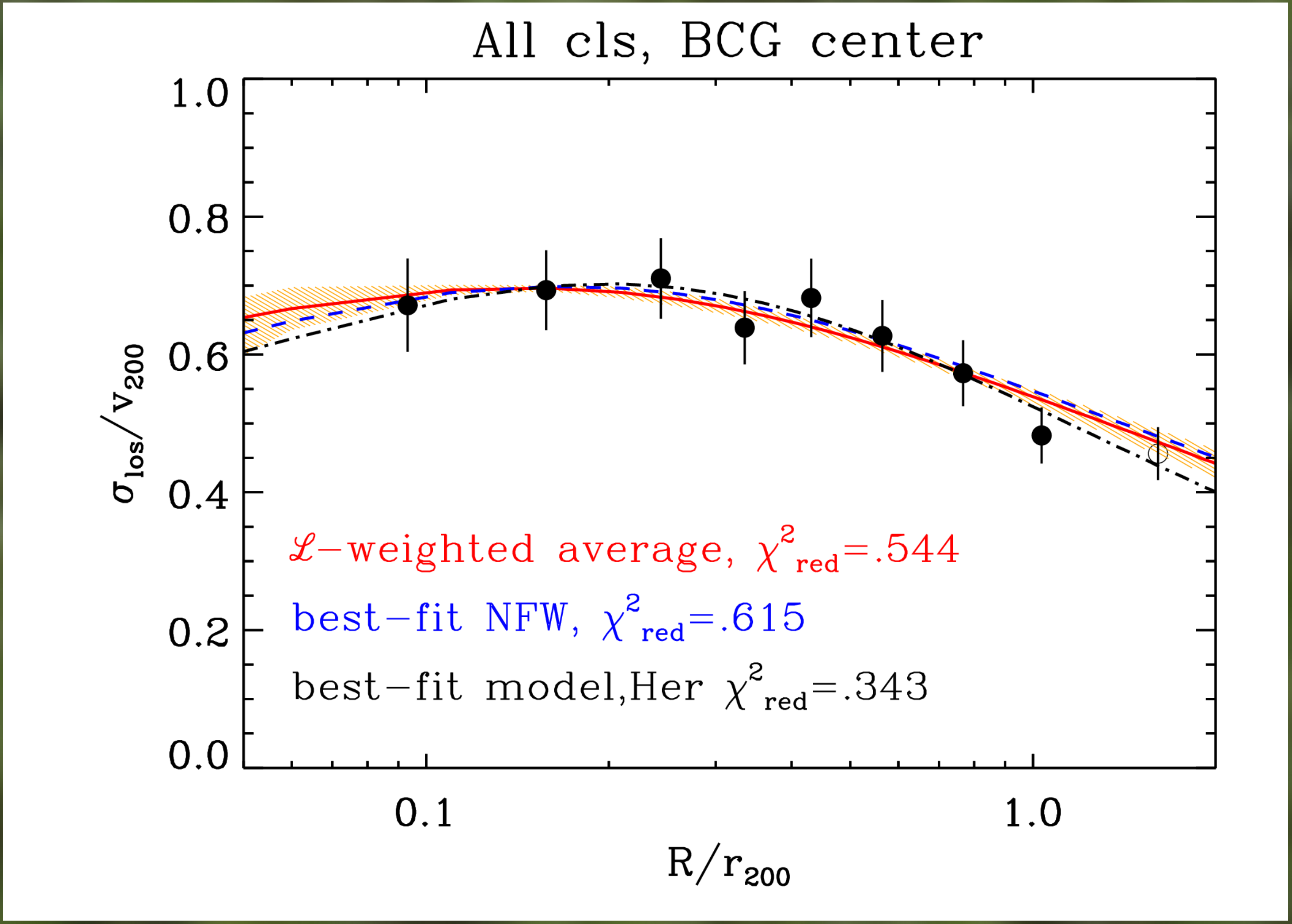
Mass profiles, M(r)

MAMPOSSt: results

All models are acceptable in terms or relative likelihoods

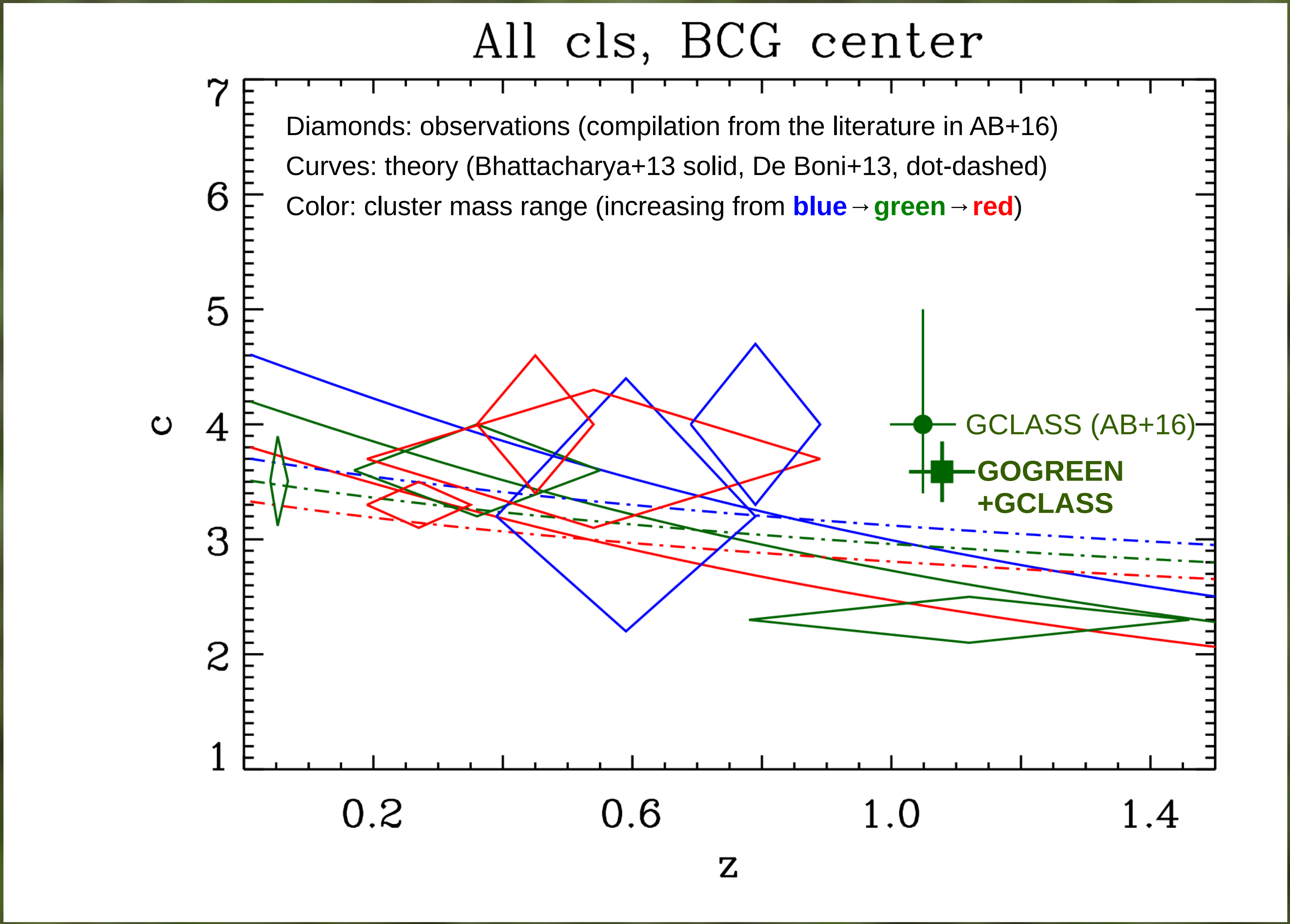


MAMPOSSt: predicted velocity dispersion profile



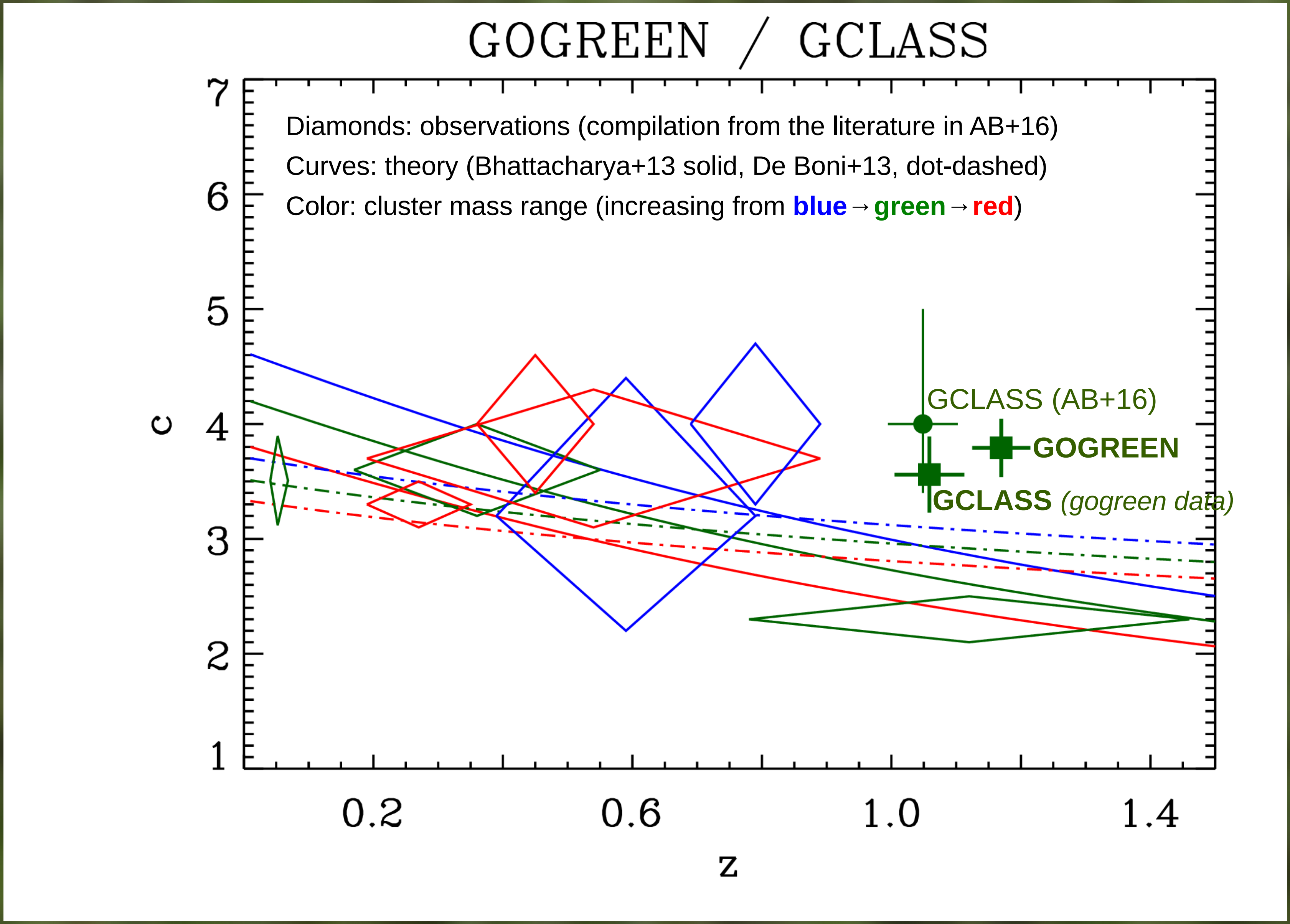
Model-likelihood weighted average M(r) projected onto the line-of-sight velocity dispersion profile (red) compared with the data (black dots)

MAMPOSSt: concentration of M(r)



Predicted and observed evolution of the total mass concentration

MAMPOSSt: concentration of M(r)

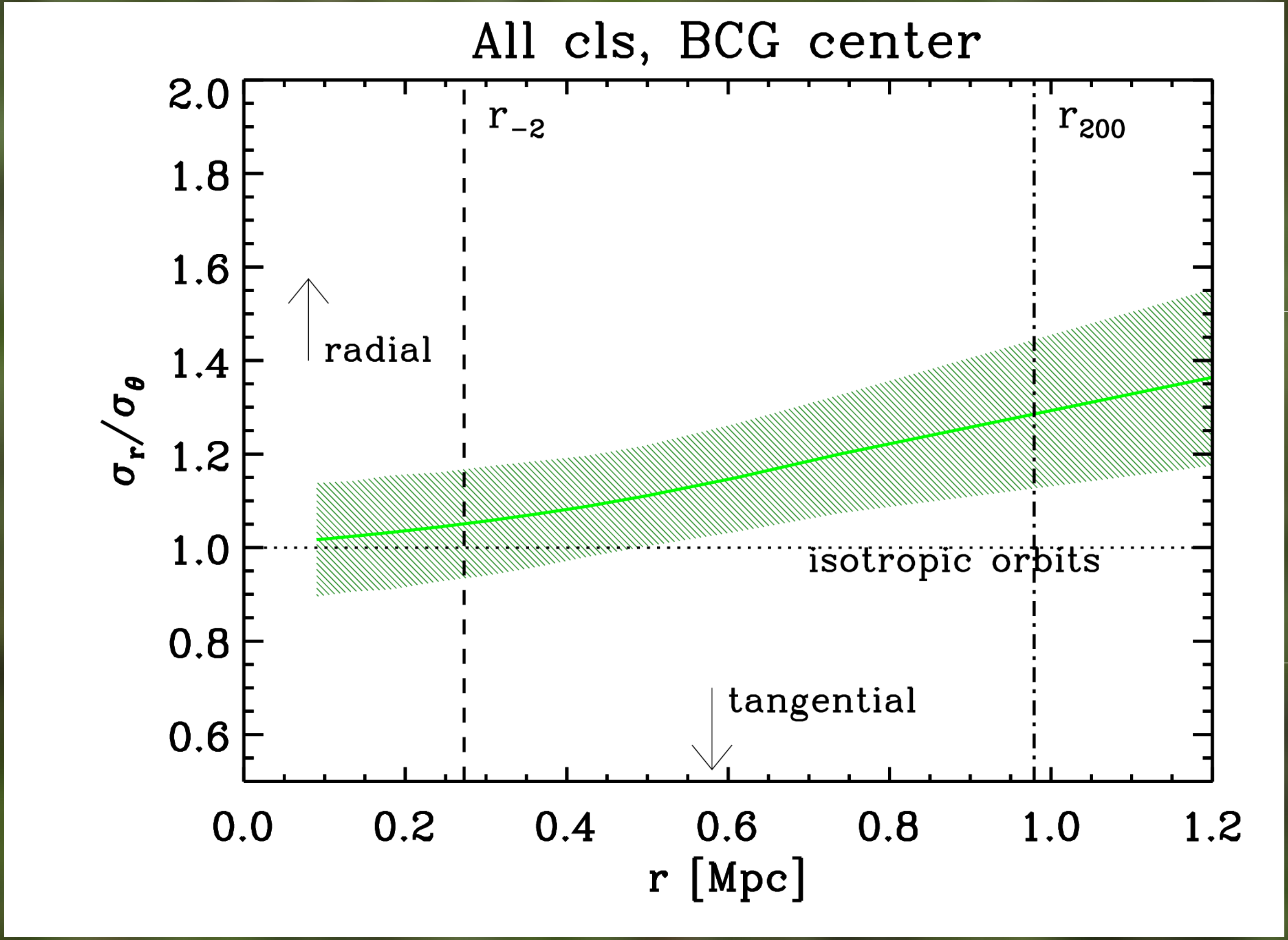


Extending the constraints on c to higher z: tension with theory
No redshift-dependence

Velocity anisotropy profiles, β(r)

Jeans inversion: velocity anisotropy

Use weighted average M(r) from MAMPOSSt analysis, observed (incompleteness-corrected) number density profile and observed velocity dispersion profile (using membership weights)

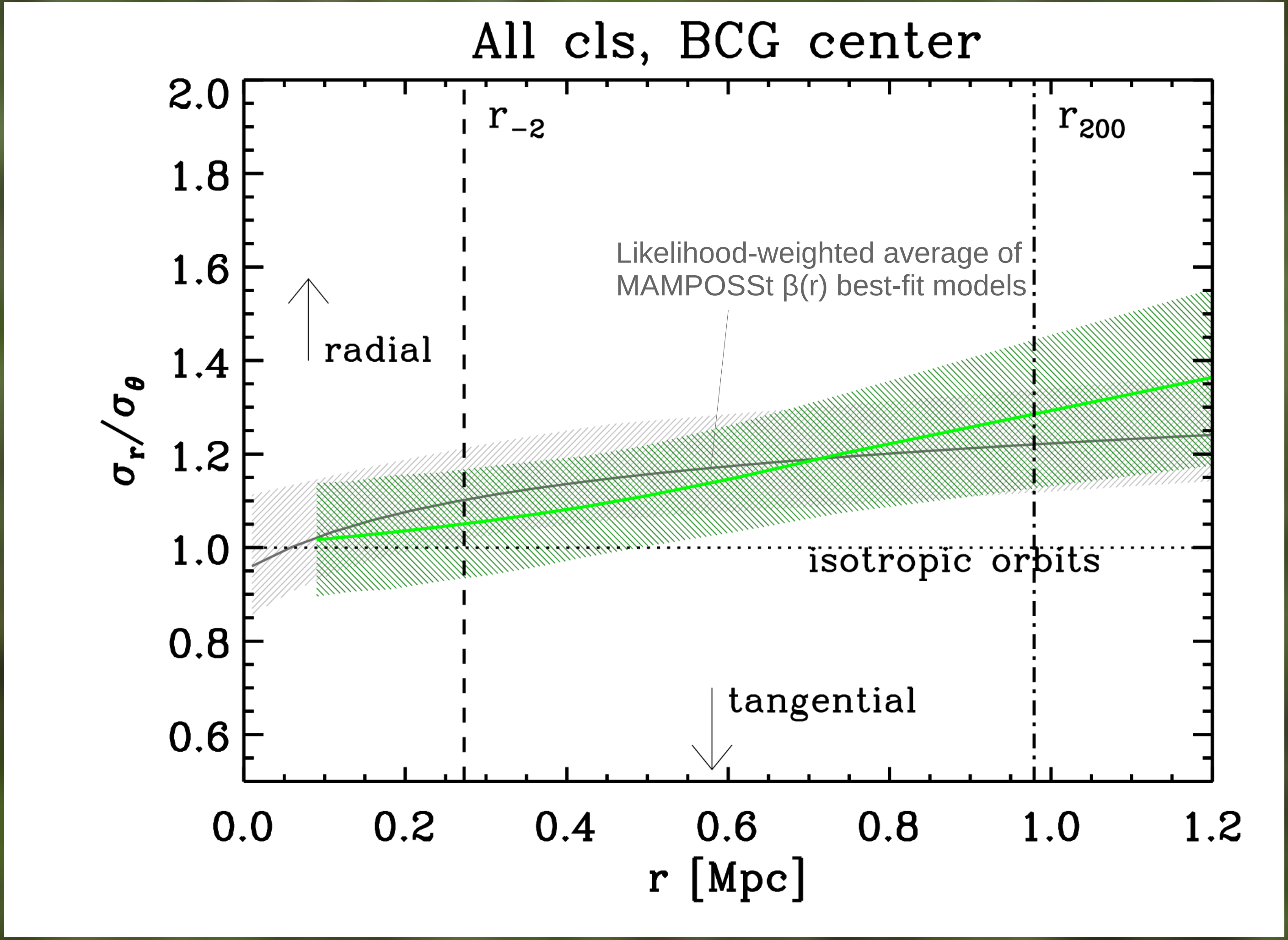


$$\beta(r) = 1 - \frac{\sigma_\theta^2(r)}{\sigma_r^2(r)}$$

Ratio between the radial and tangential components of the 3-d velocity dispersion vs. the 3-d cluster-centric distance

Jeans inversion: velocity anisotropy

Using MAMPOSSt M(r) to get β(r) from Jeans equation inversion gives consistent results with β(r) obtained directly from MAMPOSSt

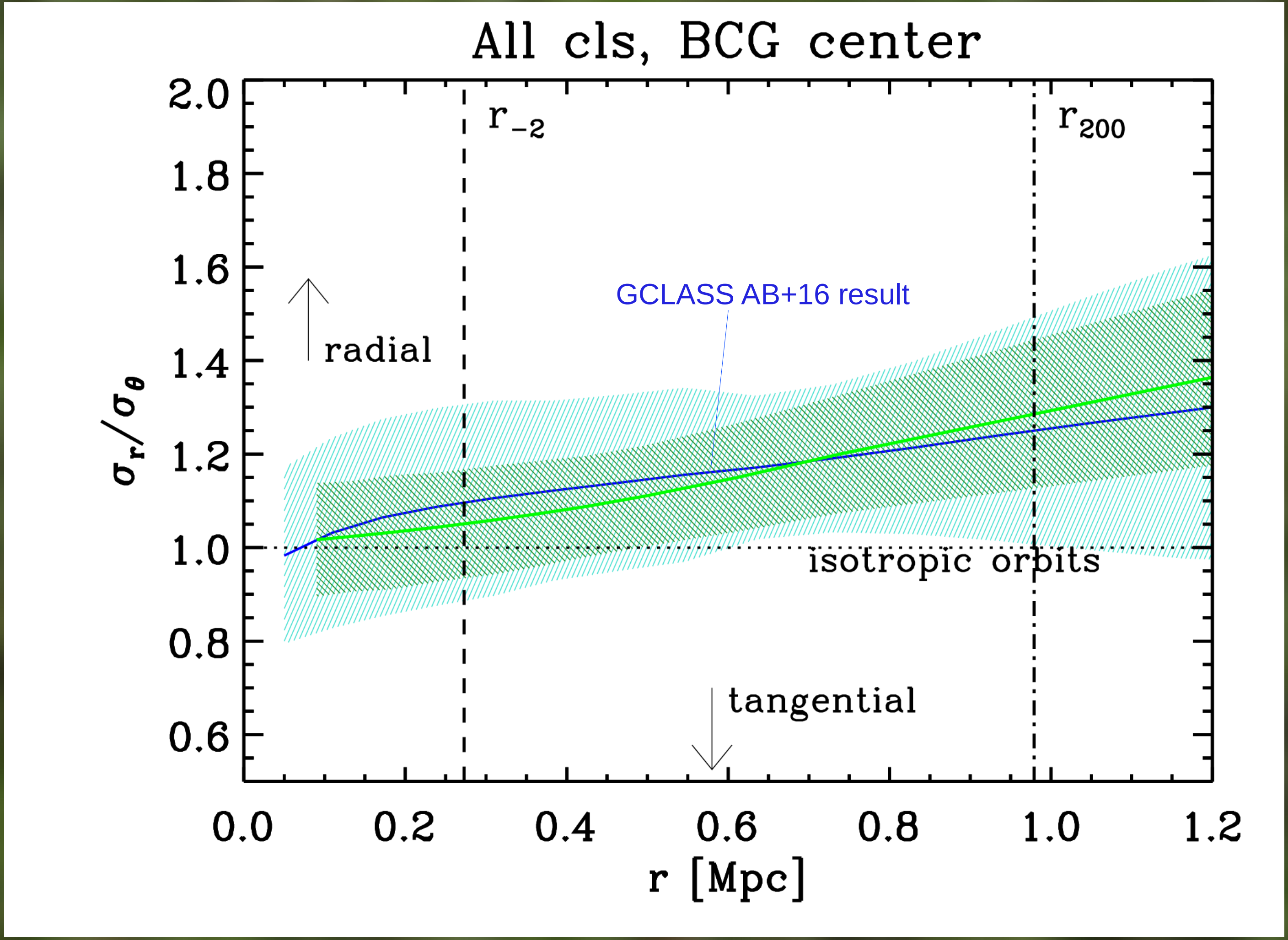


$$\beta(r) = 1 - \frac{\sigma_\theta^2(r)}{\sigma_r^2(r)}$$

MAMPOSSt β(r) error bars are smaller than for Jeans inversion because of the restricted range of models considered

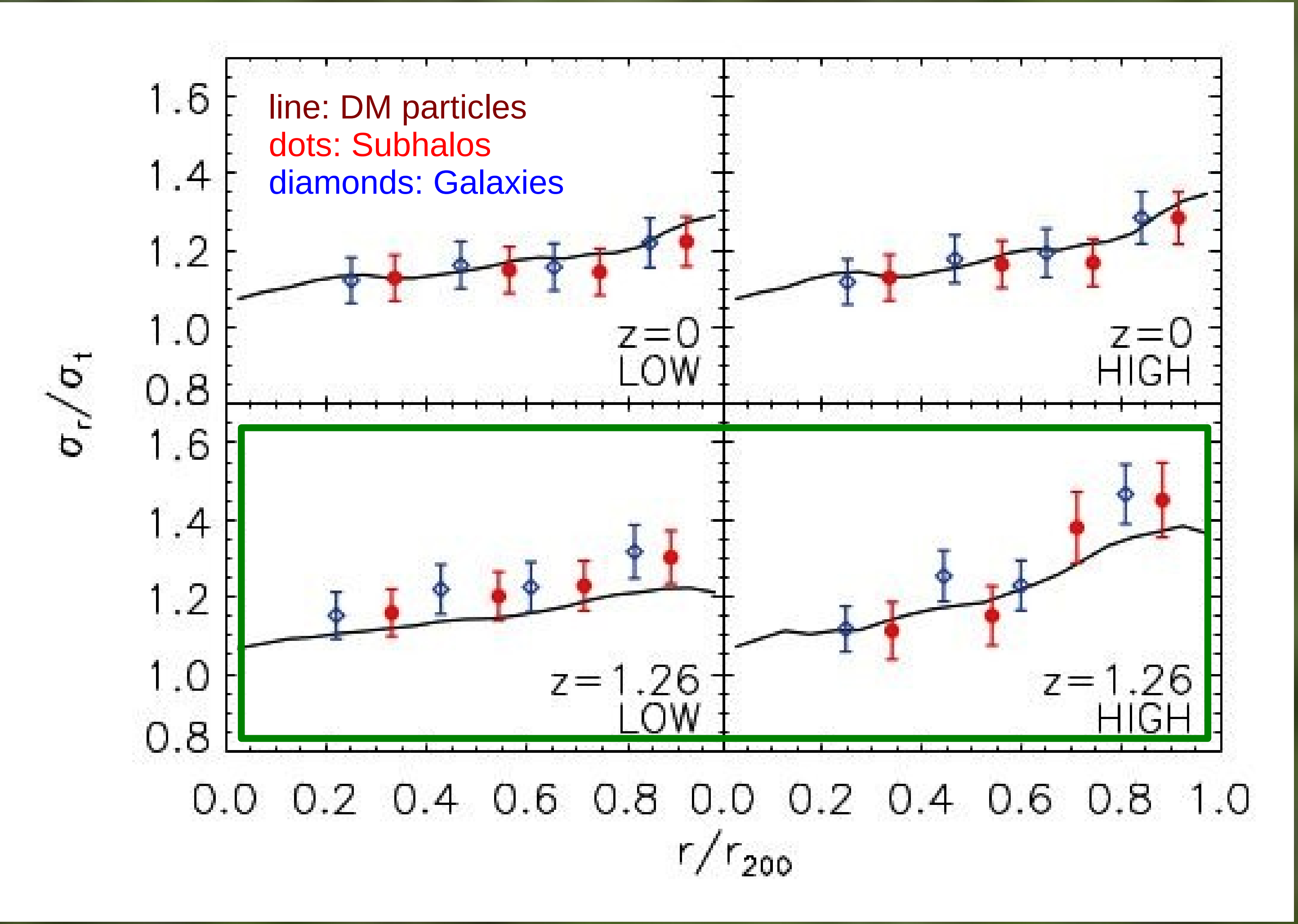
Jeans inversion: velocity anisotropy

Comparison with result of AB+16 based on the GCLASS sample:
no difference, but smaller error bars
⇒ orbits are now *inconsistent* with isotropy



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

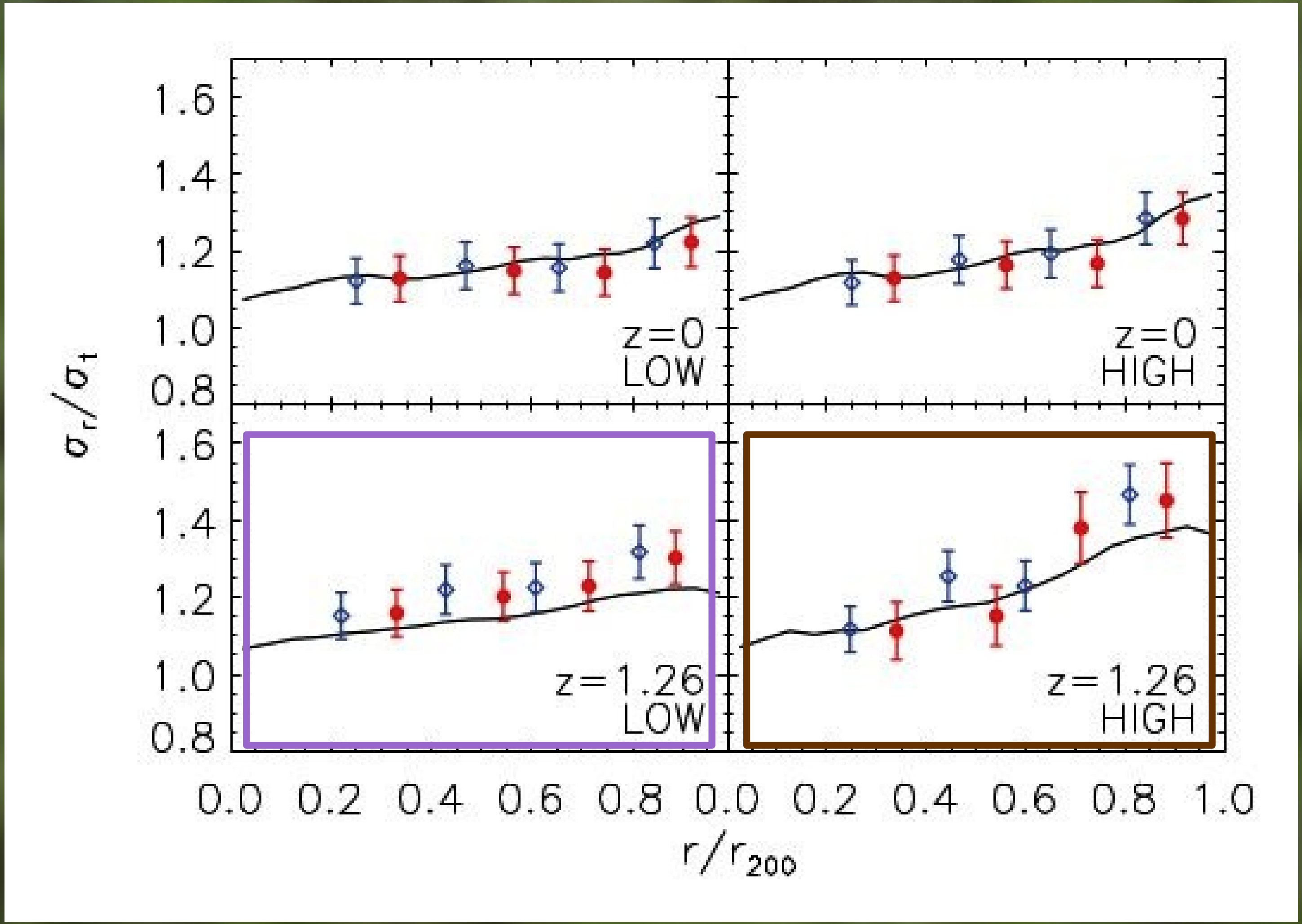
Orbits in numerical simulations



Munari, AB +13: orbits of dark matter particles, subhalos and "galaxies" are similar

Good agreement with GOGREEN velocity anisotropy profile

Orbits in numerical simulations

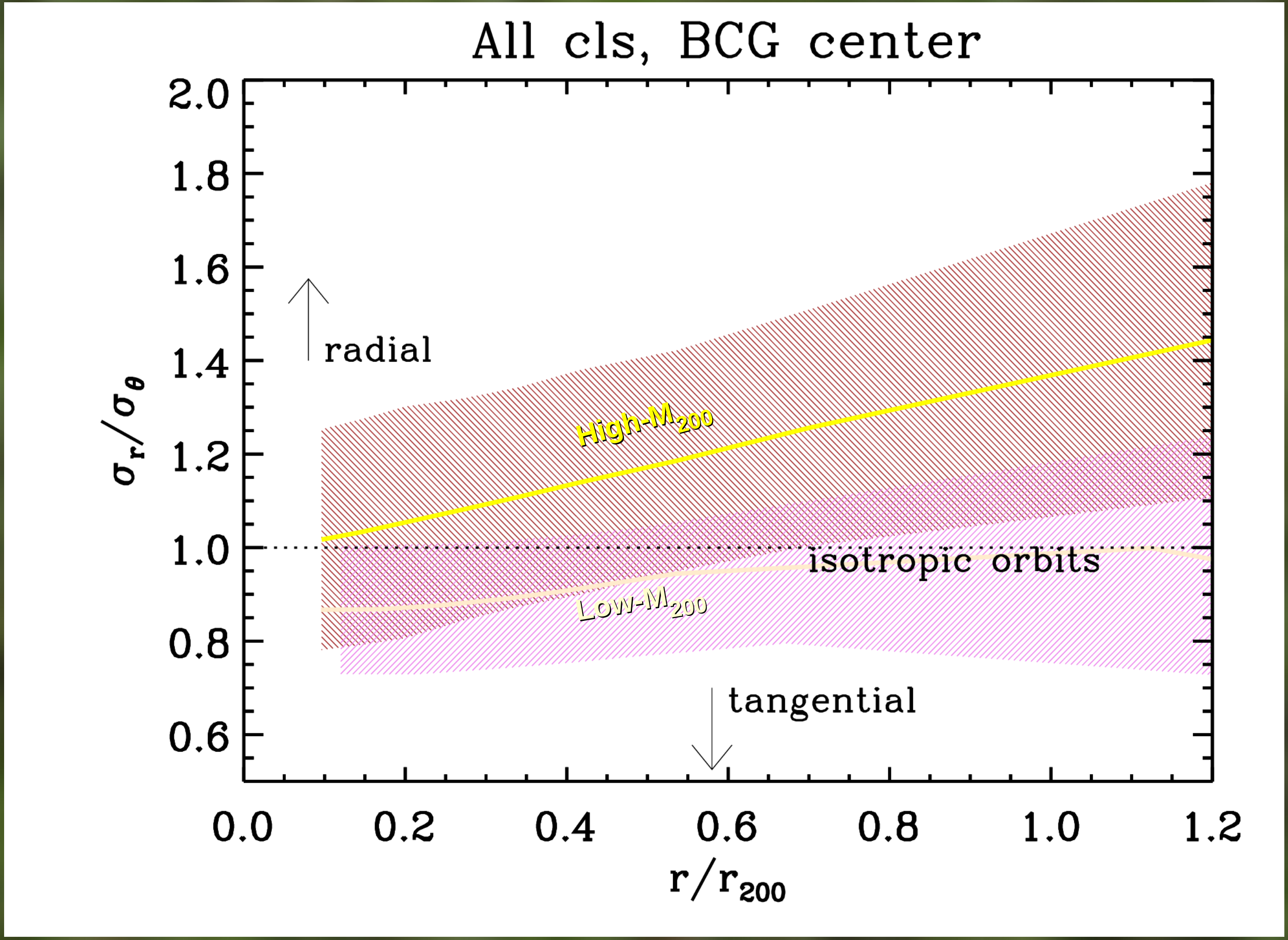


Munari, AB +13:
mild dependence on halo mass (LOW / HIGH) and redshift (z=0 / z=1.26).
Good agreement with observed velocity anisotropy profile

Jeans inversion: velocity anisotropy

Low-M_{200} vs. High-M_{200} GOGREEN+GCLASS clusters

no difference but trend consistent with results from simulations

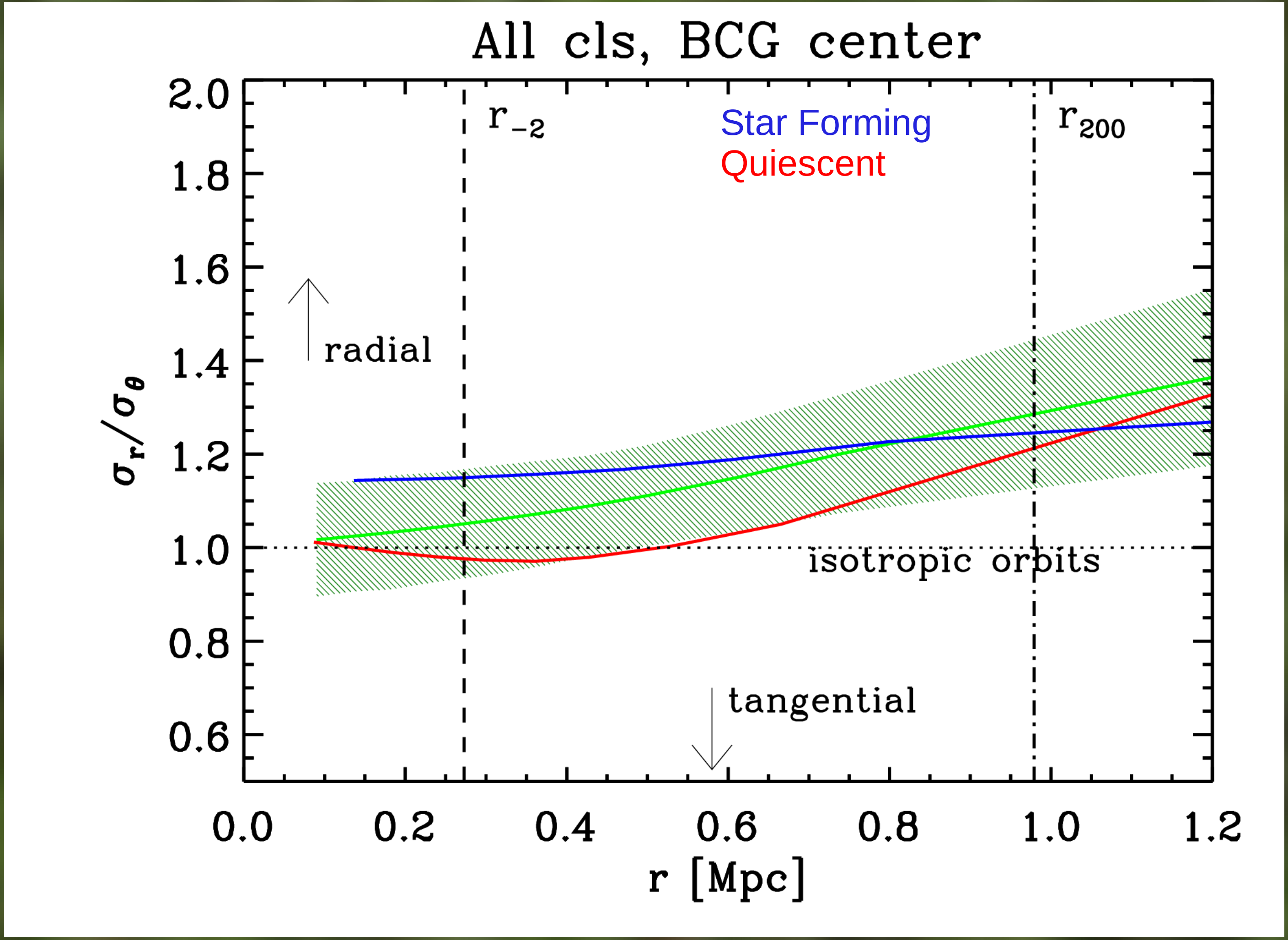


$$\beta(r) = 1 - \frac{\sigma_\theta^2(r)}{\sigma_r^2(r)}$$

Jeans inversion: velocity anisotropy

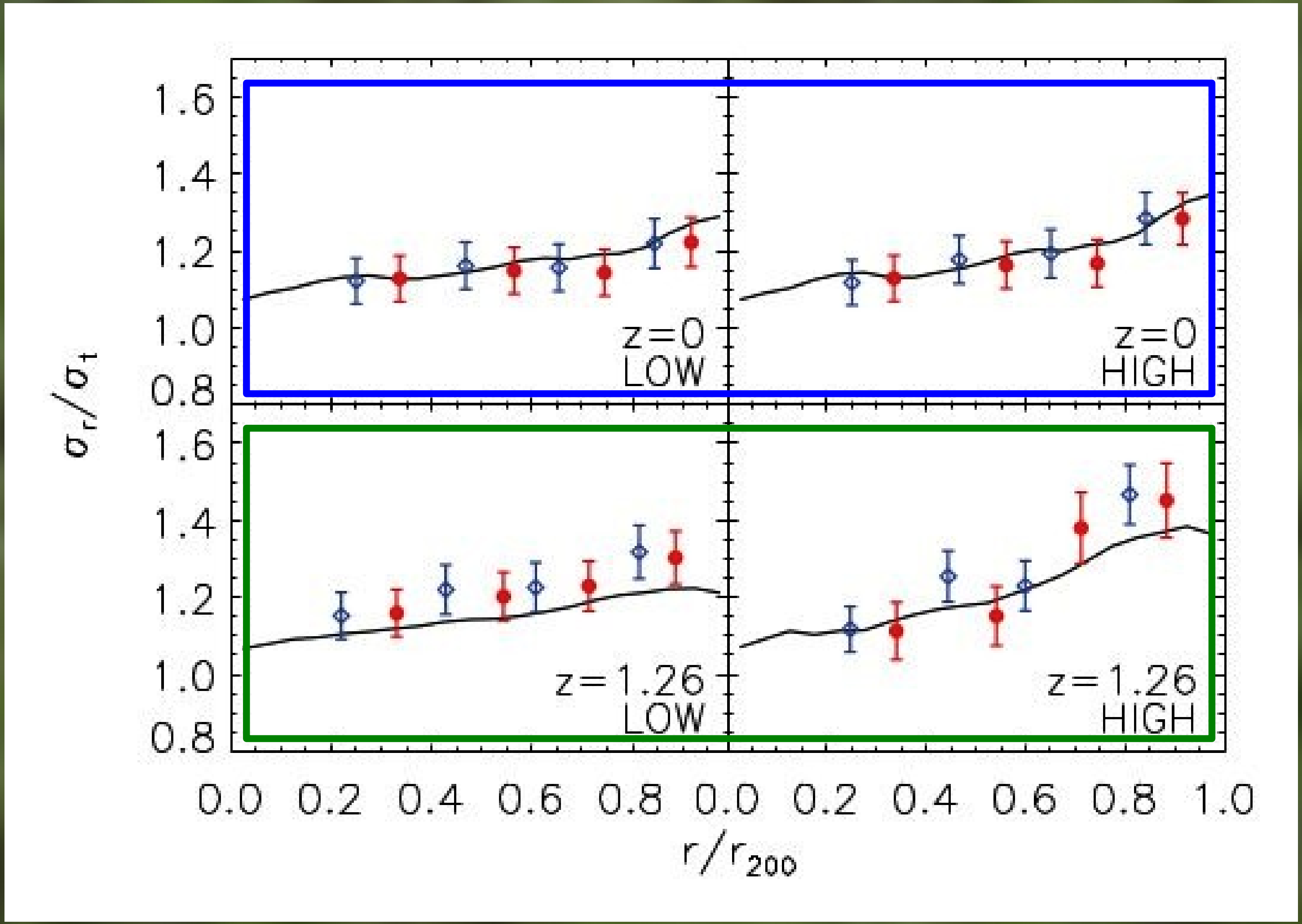
Quiescent vs. star-forming galaxies (with log $M_* \geq 9.0$):

no significant difference *(similar result as for GCLASS, AB+16)*



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

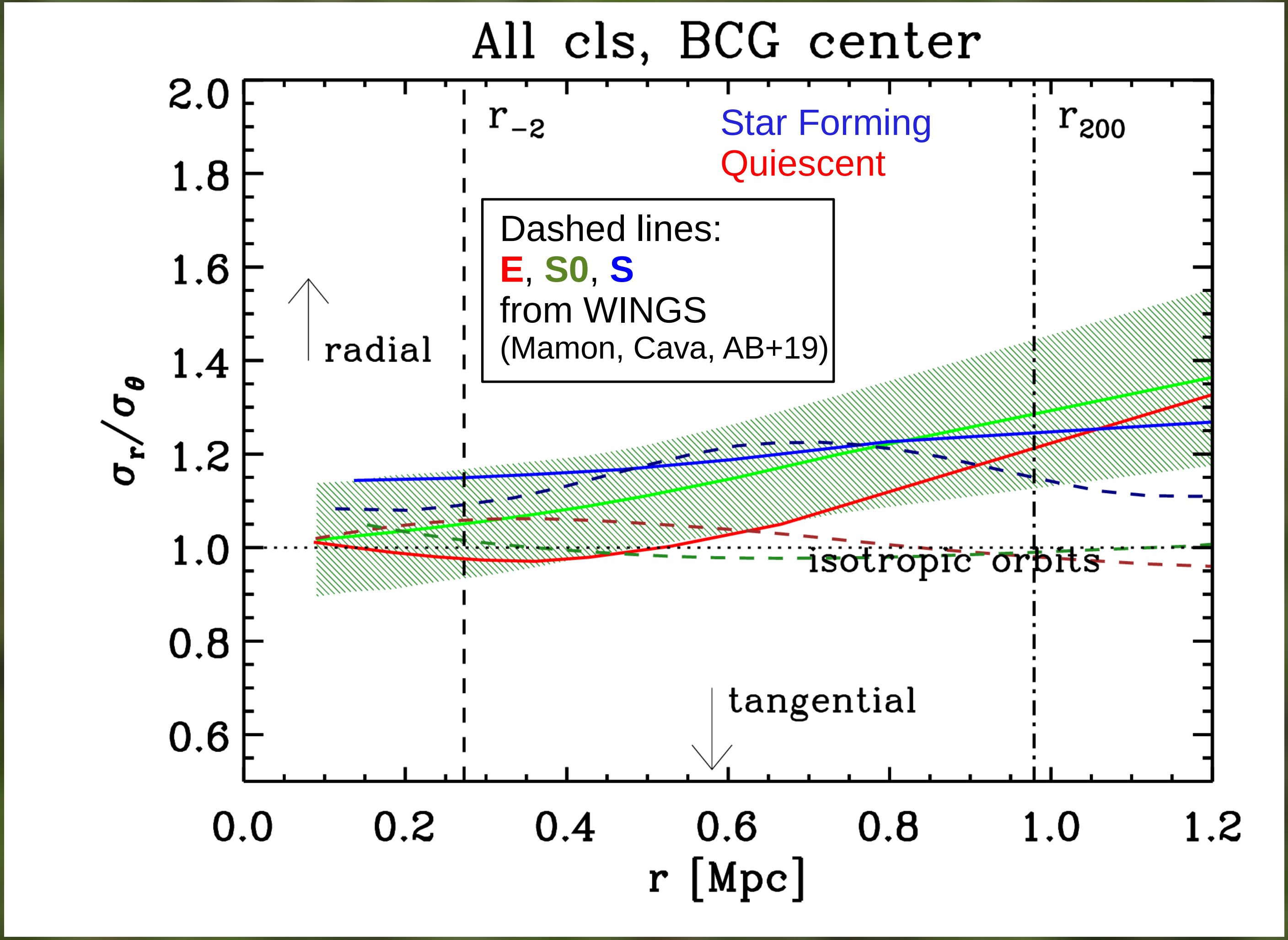
Orbits in numerical simulations



Munari, AB +13:
mild dependence on redshift (z=0 / z=1.26).
Good agreement with GOGREEN velocity anisotropy profile

Jeans inversion: velocity anisotropy

Quiescent vs. star-forming galaxies (with log $M_* \geq 9.0$):
comparison with nearby clusters (WINGS, 0.04<z<0.07)



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

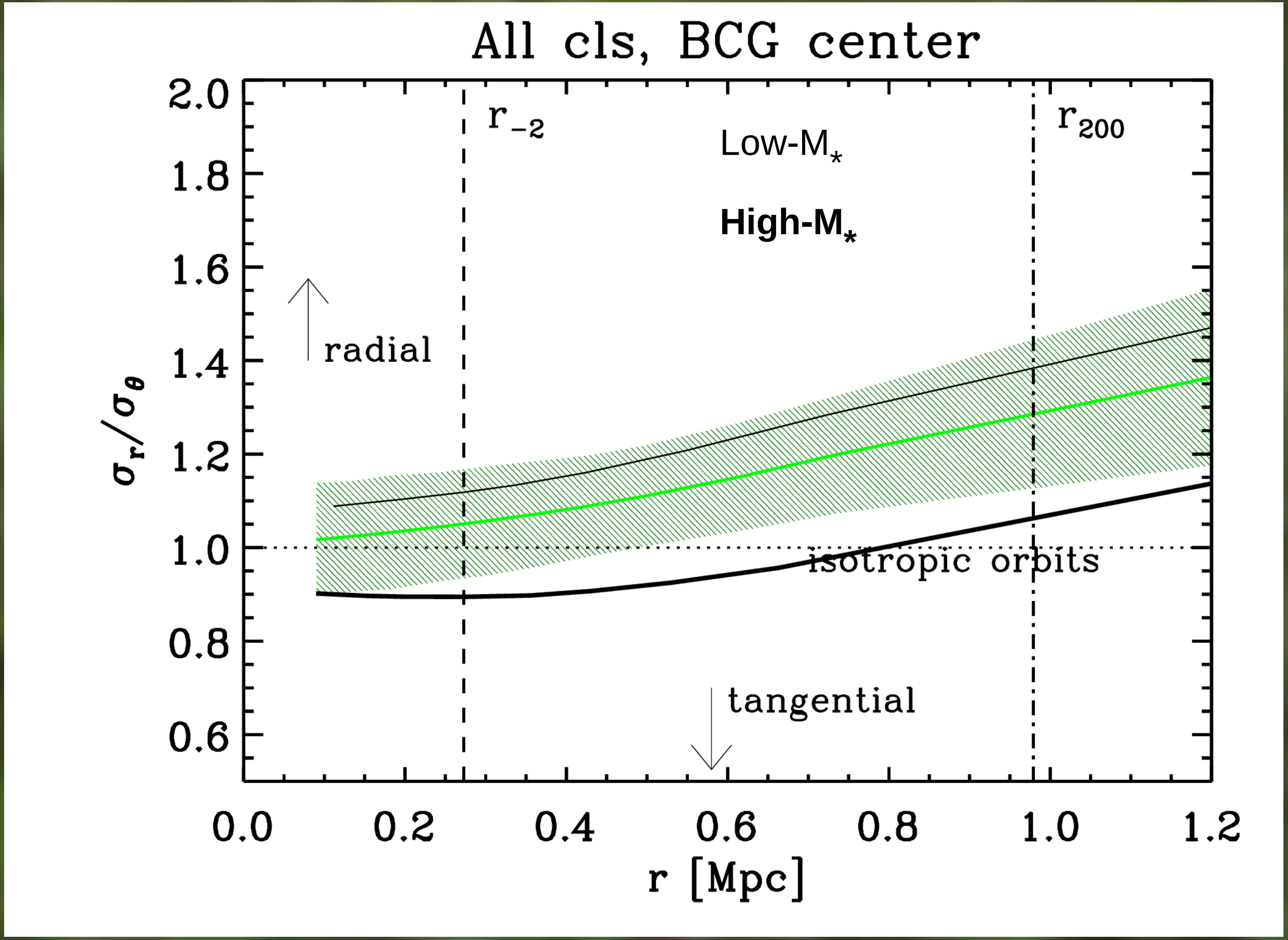
Star Forming:
no orbital evolution

Quiescent:
orbital isotropization beyond ≈ 0.5 r_{200}

Jeans inversion: velocity anisotropy

High-M_* vs. Low-M_* galaxies (with $\log M_* \geq 9.0$):

no significant difference, but stronger than between Q and SF



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

Orbital difference more related to stellar mass than to star-formation activity

Summary (1/2)

Mass profile, M(r):

- Highest-z cluster M(r) determination so far
- Statistics is not good enough to discriminate among different M(r) models
- Mass concentration significantly higher than predicted from simulations

  In better agreement with De Boni+13 hydro simulations than Bhattacharya+13 DM-only simulations; this suggests the discrepancy might be related to baryonic physics not correctly accounted for in the simulations.

Summary (2/2)

Velocity anisotropy profile (orbits), β(r):

- Highest-z cluster β(r) determination so far
- Orbits change from slightly tangential near the center to sligthly radial outside
- *More radial orbits for galaxies in more massive clusters*
- *Moderate evolution with z (more isotropic at low-z)*
- *Galaxies of lower stellar mass on more radial orbits*

Lacking significant statistical evidence

→ In agreement with predictions from numerical simulations