Cluster density profiles and orbits of galaxies from dynamical analysis

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Collaborators & papers:

on the observational side:

A.B. & M. Girardi 2003,
P. Katgert, A.B. & A. Mazure 2004,
A.B. & P. Katgert 2004,
A.B. & P. Salucci 2006,
A.B., G. Mamon,T. Ponman in prep.,
A.B., A. Diaferio, K. Rines in prep.

on the numerical side:

A.B., G. Murante, S. Borgani, A. Diaferio, K. Dolag,
& M. Girardi 2006 & in prep.

Aims:

1. Constrain M(r) of galaxy systems
   - central cusp or core?
   - external slope?
   - influence of baryons?

2. How do galaxies move in their systems?
   - evidence of infall?
   - relaxation processes?

Tracers of the grav. potential: ***galaxies***

Observables:

R_i radial distance of i-th galaxy from the cluster center

V_i rest-frame l.o.s. velocity wrt the cluster $\langle V \rangle$

Because of poor sampling of single clusters and deviation from spherical symmetry...

→ Combine many clusters using M_{200}

$R_n = R/r_{200}$ & $V_n = (V - \langle V \rangle)/\, v_{200}$

M_{200} from σ_v (virial theorem)

or T_X (scaling relations) when N_{gal} small

Why using the cluster galaxies to determine the total mass profile?

- less direct than lensing and X-ray $\downarrow$

- sample mass profile to larger radii $\uparrow$
- IC gas not fully thermalized (?) $\uparrow$

  (Rasia et al. 2004, Faltenbacher et al. 2005)
- lensing inefficient for nearby clusters $\uparrow$

  (Natarajan & Kneib 1997)

…and in any case, 3 is better than 1!

METHODS

An example of YDS climbing class 1

M(<r): methods:

1. Jeans analysis

(e.g. Binney & Tremaine 1987; see also Mamon & Boué 2007

- Works better in central cluster regions
- Degeneracy mass profile - velocity anisotropies

2. Caustic method

(Diaferio & Geller 1997; see also Diaferio 1999)

- Works better in external cluster regions
- Only mild dependence on velocity anisotropies

$M(<r)$ from the Jeans analysis

Assumes dynamical equilibrium of the system

$I(R)$ and $\sigma_p(R) \leftrightarrow \nu(r)$, $\sigma_r(r)$, $M(<r)$, through $\beta(r)$

or, more generally: $f_p(R,v) \leftrightarrow \Phi(r) + f(E,L^2)$

Mass – orbits degeneracy:

given R,v the $M(<r)$ solution depends on $\beta(r)$

($\beta(r) \equiv 1 - \sigma_t^2/\sigma_r^2$, velocity anisotropy profile)

Our adopted solutions to this problem:

- analysis of the shape of the velocity distribution
- Use ≥ 2 independent tracers of the cluster potential

The Jeans equation

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

r, clustercentric radial distance

$<v_r^2>$, or σ_r, radial component of velocity dispersion

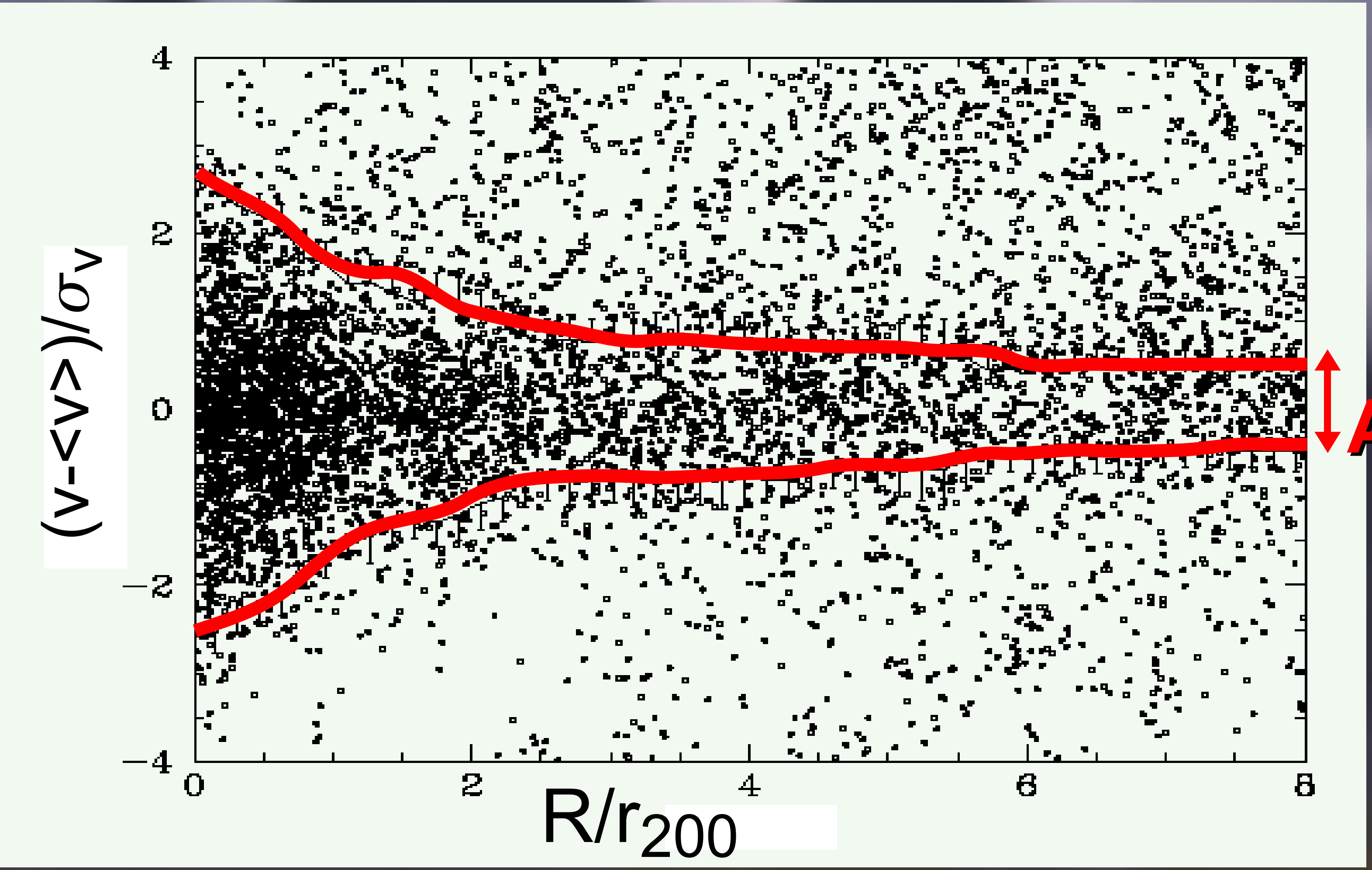
ν, number density of cluster galaxies

β, velocity anisotropy:

$$\beta(r) \equiv 1 - \frac{< v_t^2 >}{< v_r^2 >}$$

M(<r) from the caustic method:

Based on num.sims.: from caustic amplitude A(r) → Φ(r) through F(Φ,β,r)≈const ...*outside the center, indipendent of dynamical status of the cluster*



Galaxy orbits: methods:

1. Inverse Jeans analysis

(Binney & Mamon 1982, see also Solanes & Salvador-Solé 1990)

Given M(r), invert Jeans eq. $\Rightarrow$ $\beta(r)$

2. Moments of velocity distribution

(e.g. Merritt 1987, see also van der Marel et al. 2000)

Determine 4th and 6th moments by Gauss-Hermite polynomial decomposition

SAMPLES

An example of YDS climbing class 2

Samples *(all at $\langle z \rangle \approx 0$)*:

1. ENACS *(Katgert et al. 1996)*

   59 clusters, $\langle \sigma_v \rangle$=699 km/s, ≈2700 gal.s within r_{200}

2. CIRS *(based on SDSS; Rines & Diaferio 2006)*

   65 clusters, $\langle \sigma_v \rangle$=617 km/s, ≈3300 gal.s within r_{200}

3. 2dFGRS *(B. & Girardi 2003)*

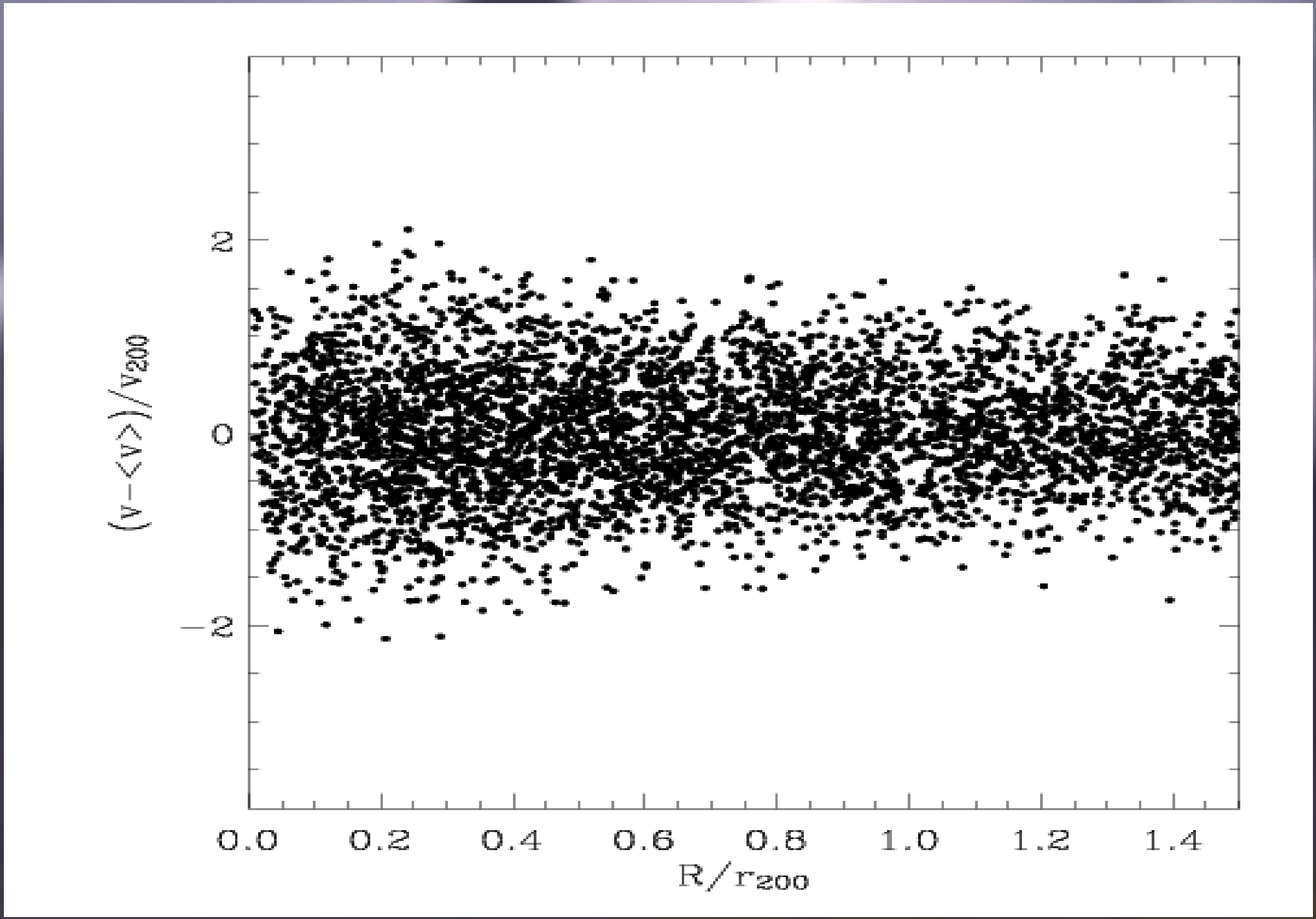
   43 clusters, $\langle \sigma_v \rangle$=490 km/s, ≈700 gal.s within r_{200}

4. GEMS *(Osmond & Ponman 2002)*

   31 groups with measured T_X,

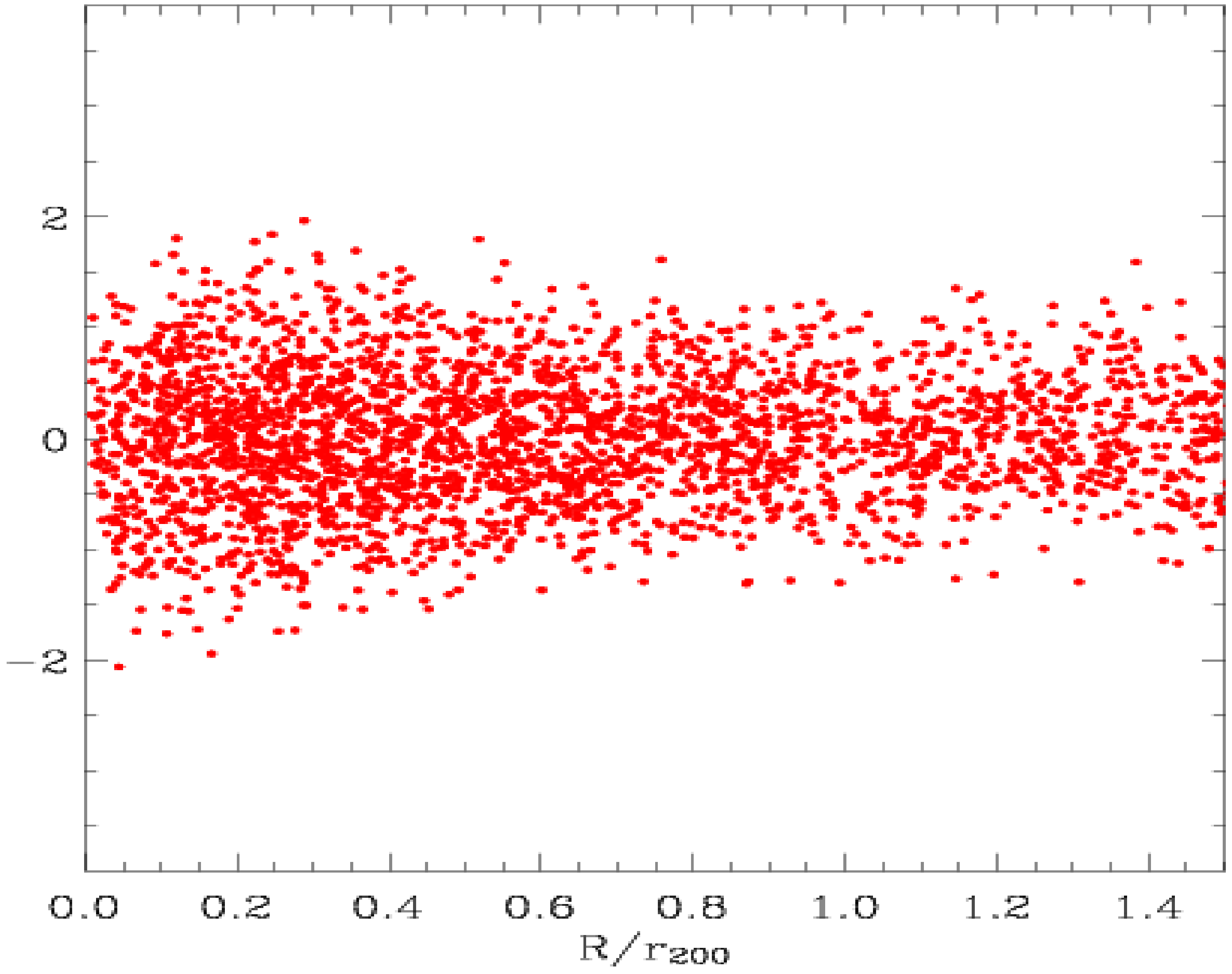
   $\langle \sigma_v \rangle$=370 km/s, ≈700 gal.s within r_{200}

Stacked CIRS cluster in R_n,V_n space

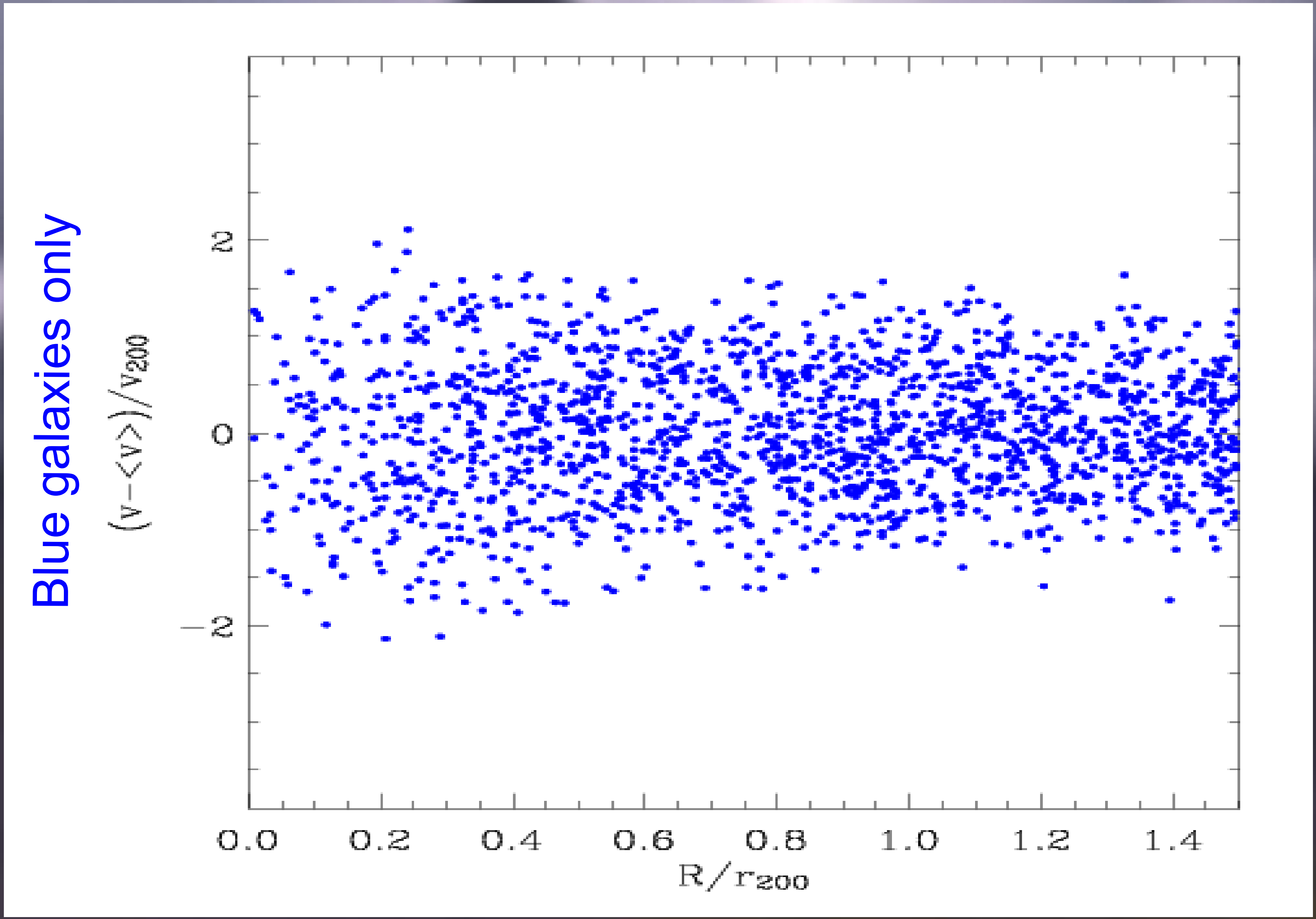


Stacked CIRS cluster in R_n, V_n space

Red (CM sequence) galaxies only



Stacked CIRS cluster in R_n,V_n space



MASS PROFILES

cored or cuspy? external slope?

An example of YDS climbing class 3

Fit models to the $V_c(r)$ profiles

The cuspy model of NFW, motivated by cosmological num. simulations with CDM:

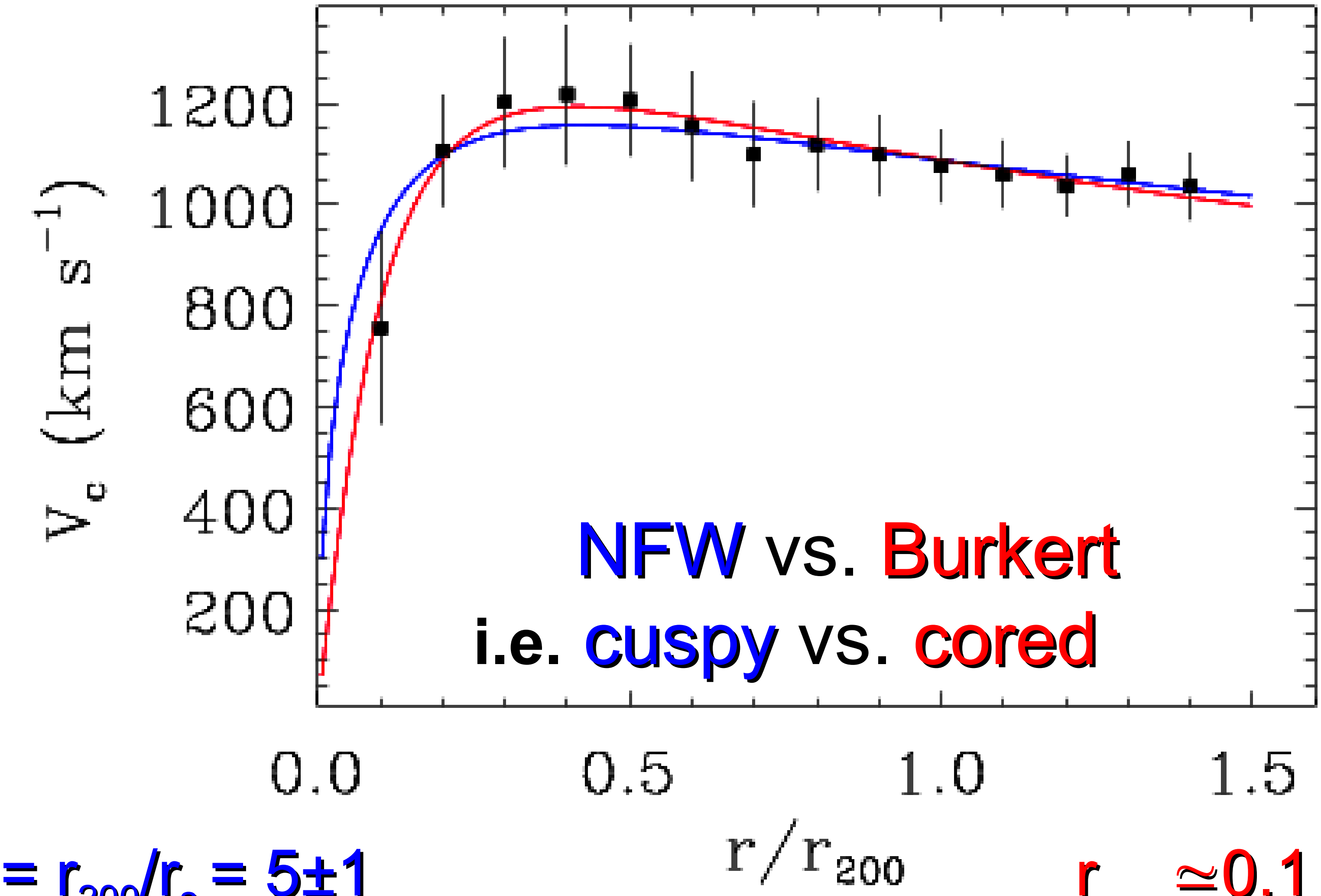
$$\rho_{NFW}(r) = \frac{\rho_0}{(r/r_s)(1+r/r_s)^2}$$

…vs. the cored model of Burkert (1995), motivated by the problems of NFW on galactic scales (e.g., de Blok et al. 2003, Gentile et al. 2004):

$$\rho_{Burkert}(r) = \frac{\rho_0}{(1+r/r_0)[1+(r/r_0)^2]}$$

ENACS

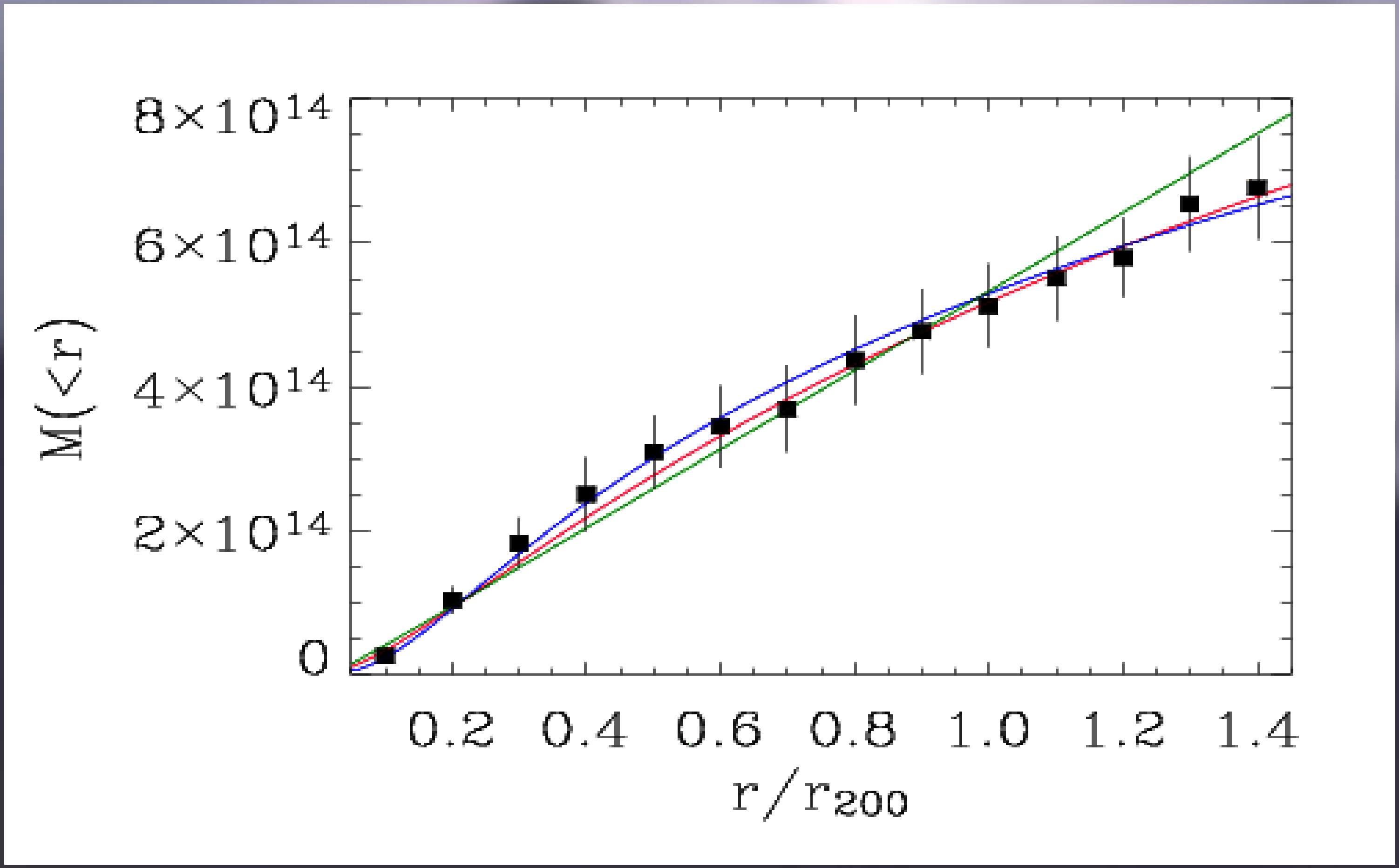
$$V_c(r) \equiv \sqrt{\frac{G\,M(r)}{r}}$$



$c = r_{200}/r_s = 5 \pm 1$

$r_{core} \simeq 0.1\, r_{200}$

ENACS: $\rho(r) \propto r^{-2.4\pm0.4}$ at $r=r_{200}$



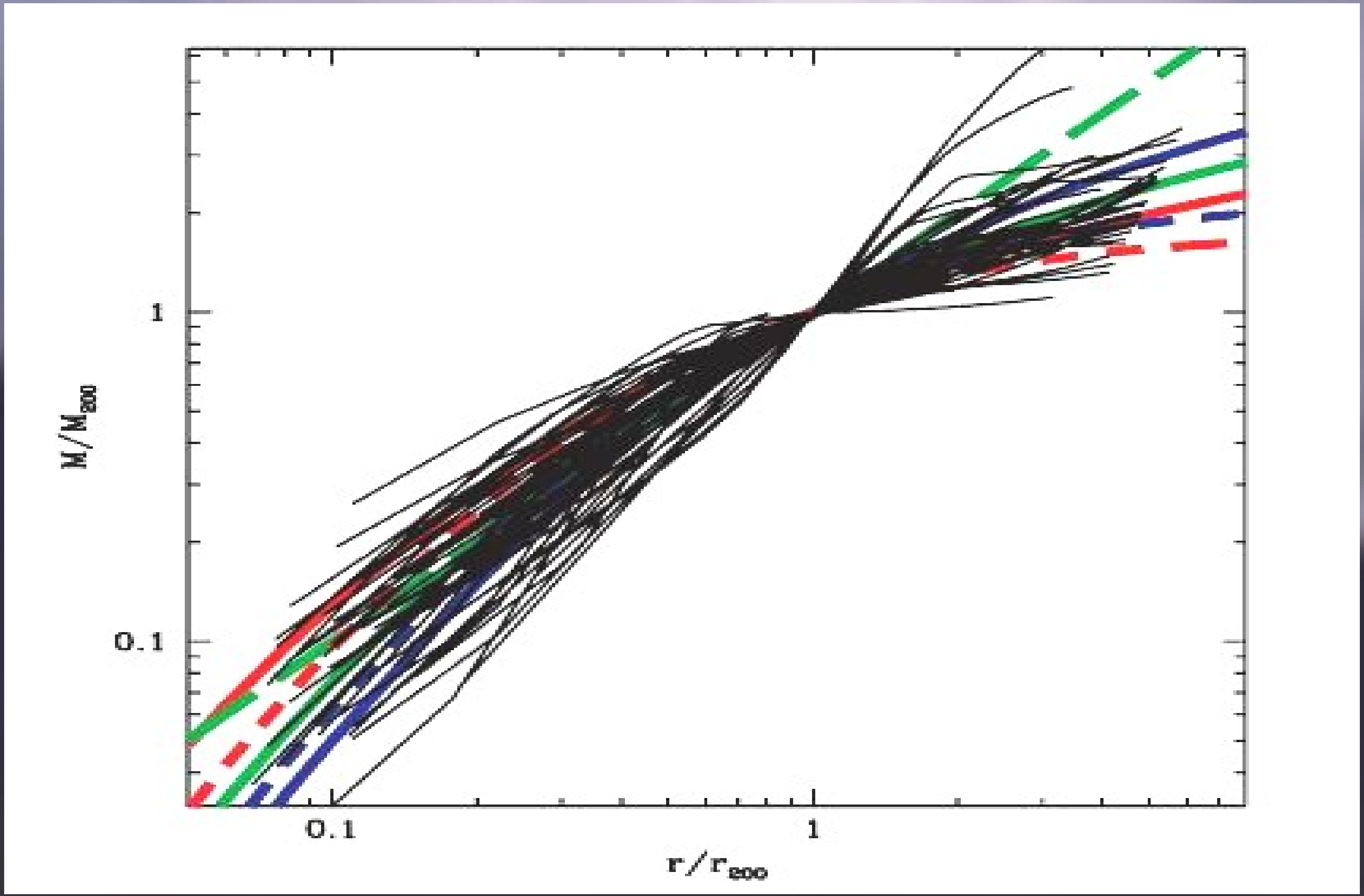
Fitting models: **NFW**

Burkert 95

Isothermal *gives poor fit*

CIRS: individual cluster mass profiles

From Rines & Diaferio (2006)

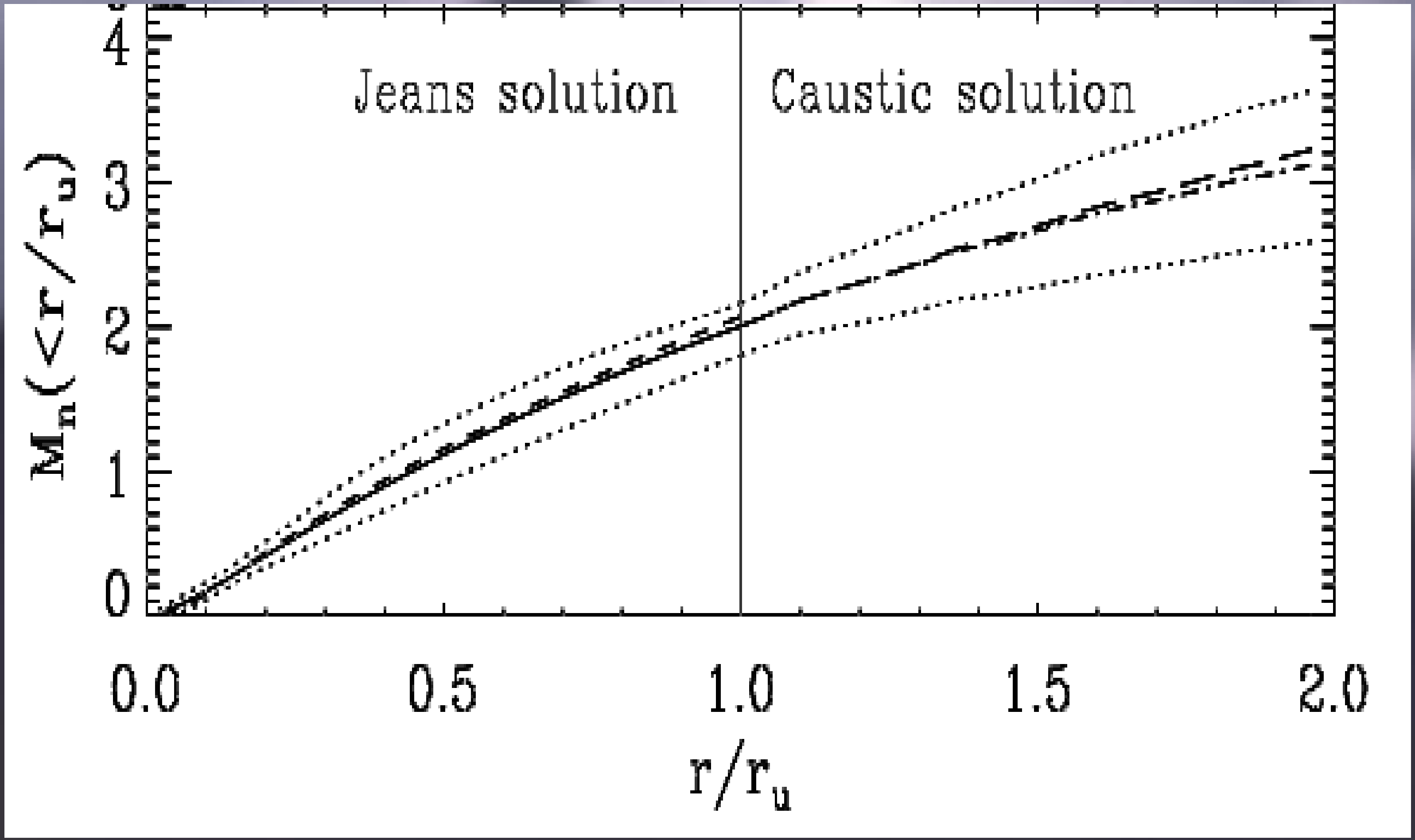


Fitting models: Solid lines: NFW c=3,5,10

Short dashed: Hernquist

Long dashed: SIS

2dFGRS: combine the two methods:



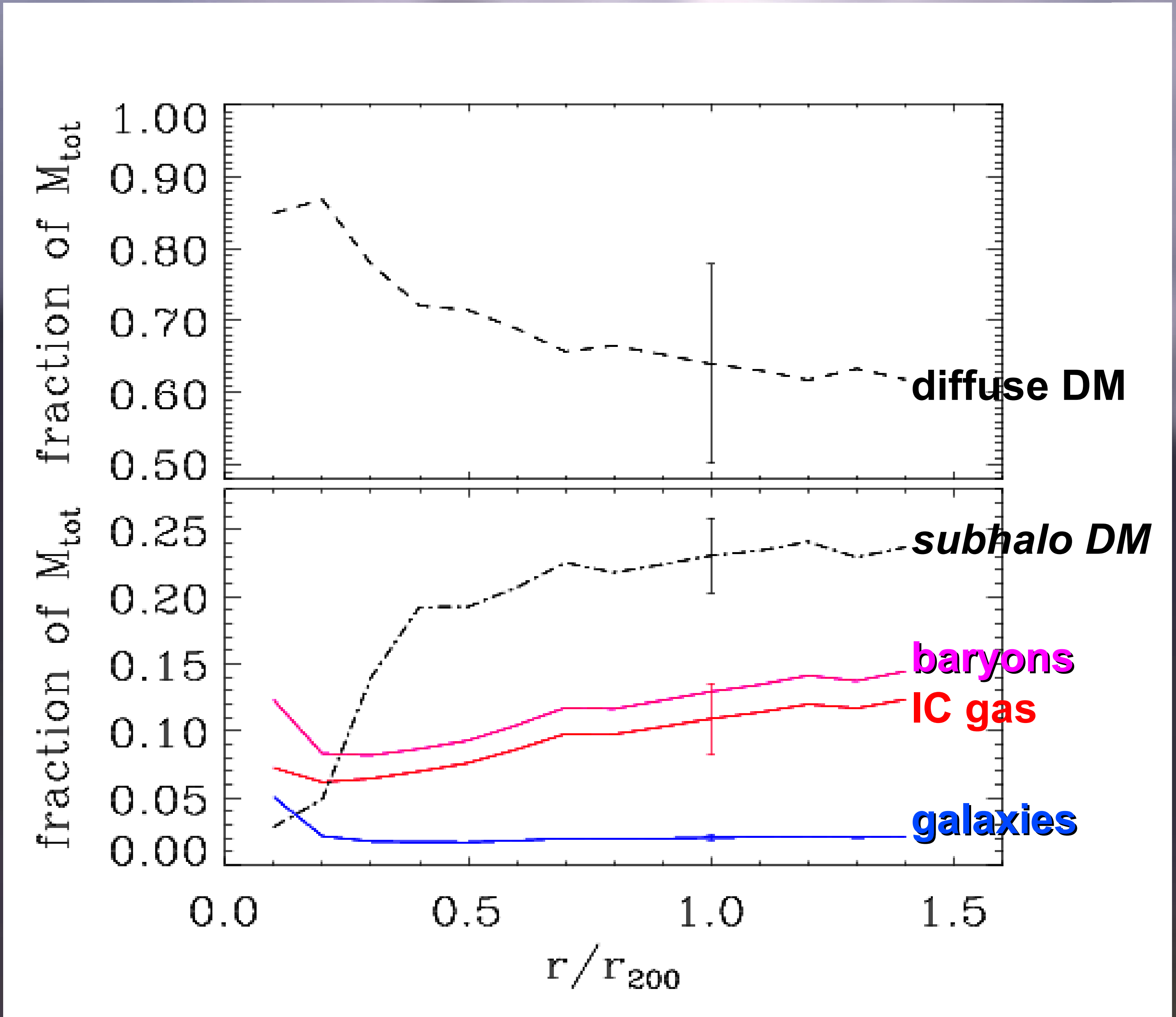
The caustic M(r) nicely continue the M(r) found with the Jeans solution, $\rho(r) \sim r^{-3}$ at large r

MASS PROFILES

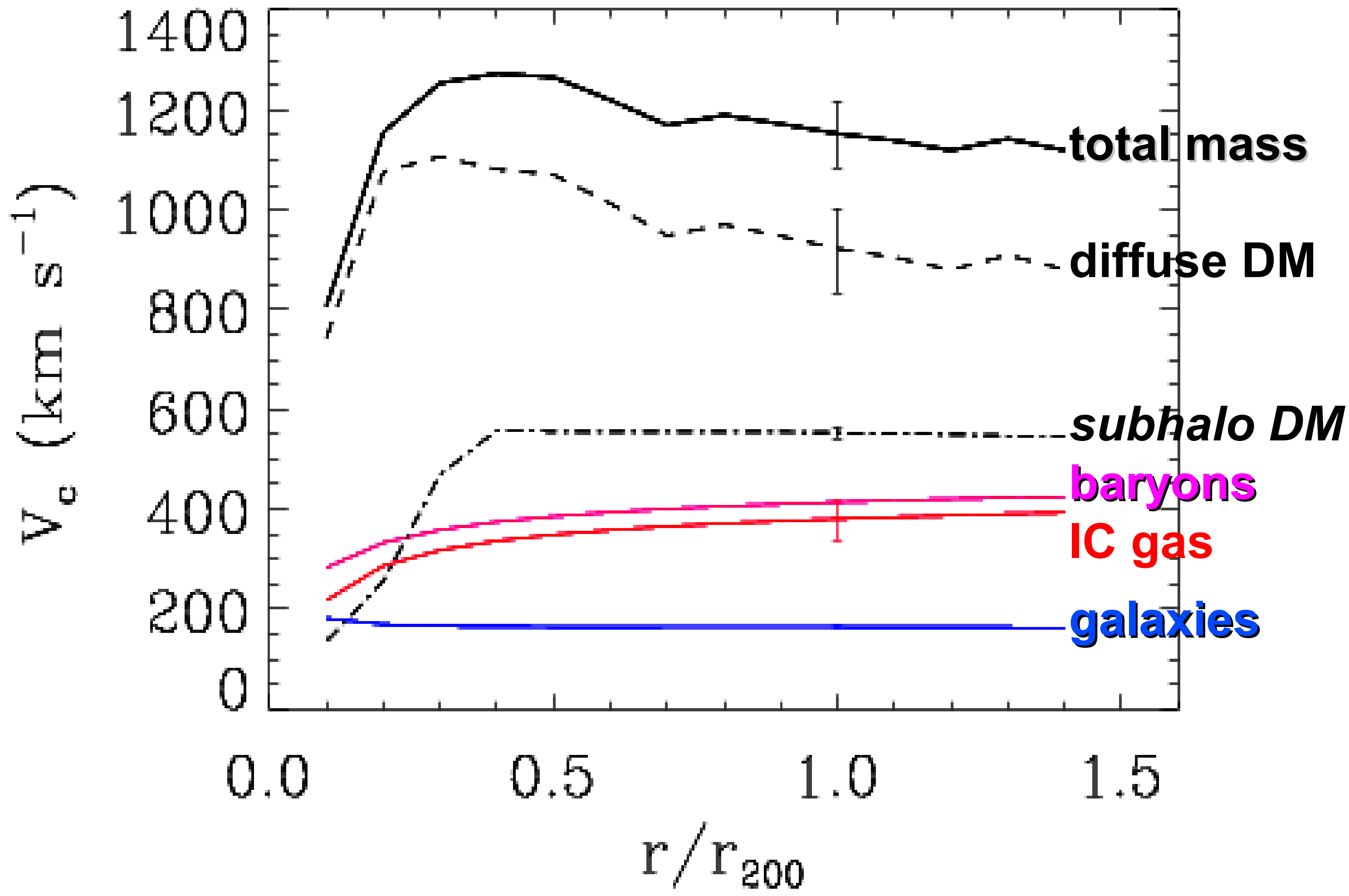
the baryonic components

An example of YDS climbing class 4

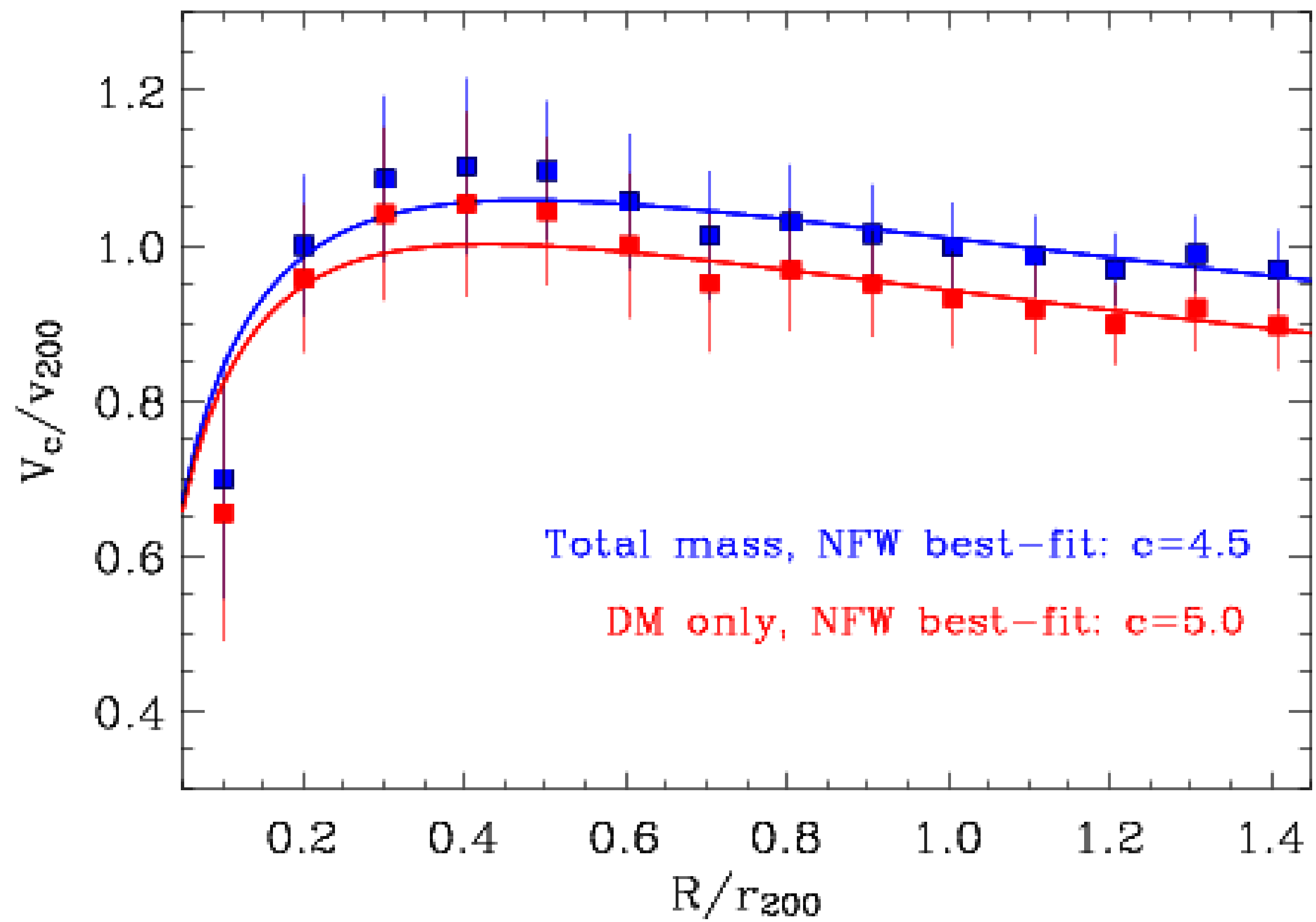
ENACS: M(<r) subdivided into its components



c for DM only > c for total M(r) *(but only slightly)*

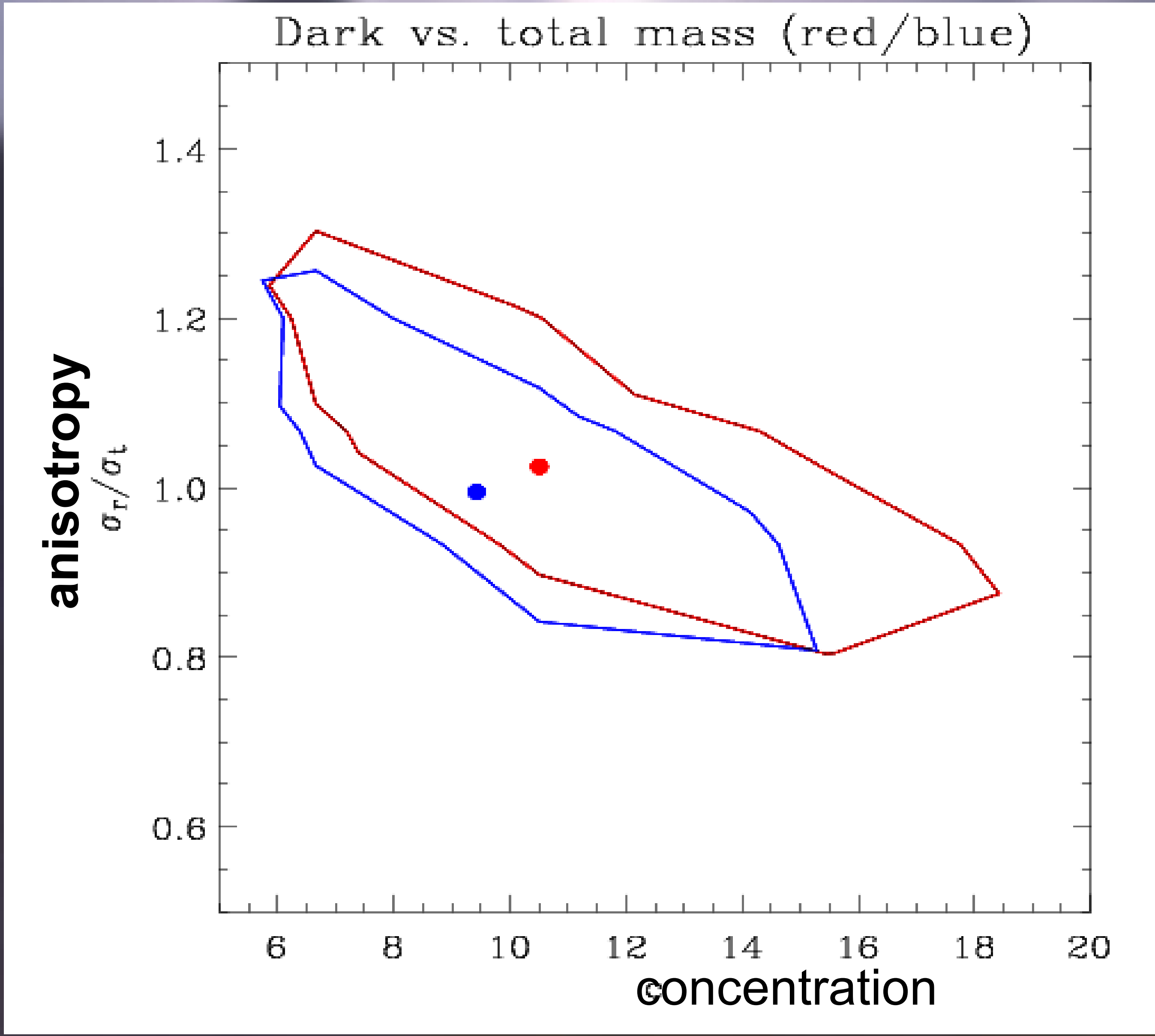


c for DM only > c for total M(r) *(but only slightly)*



c for DM only > c for total M(r) *(but only slightly)*

GEMS

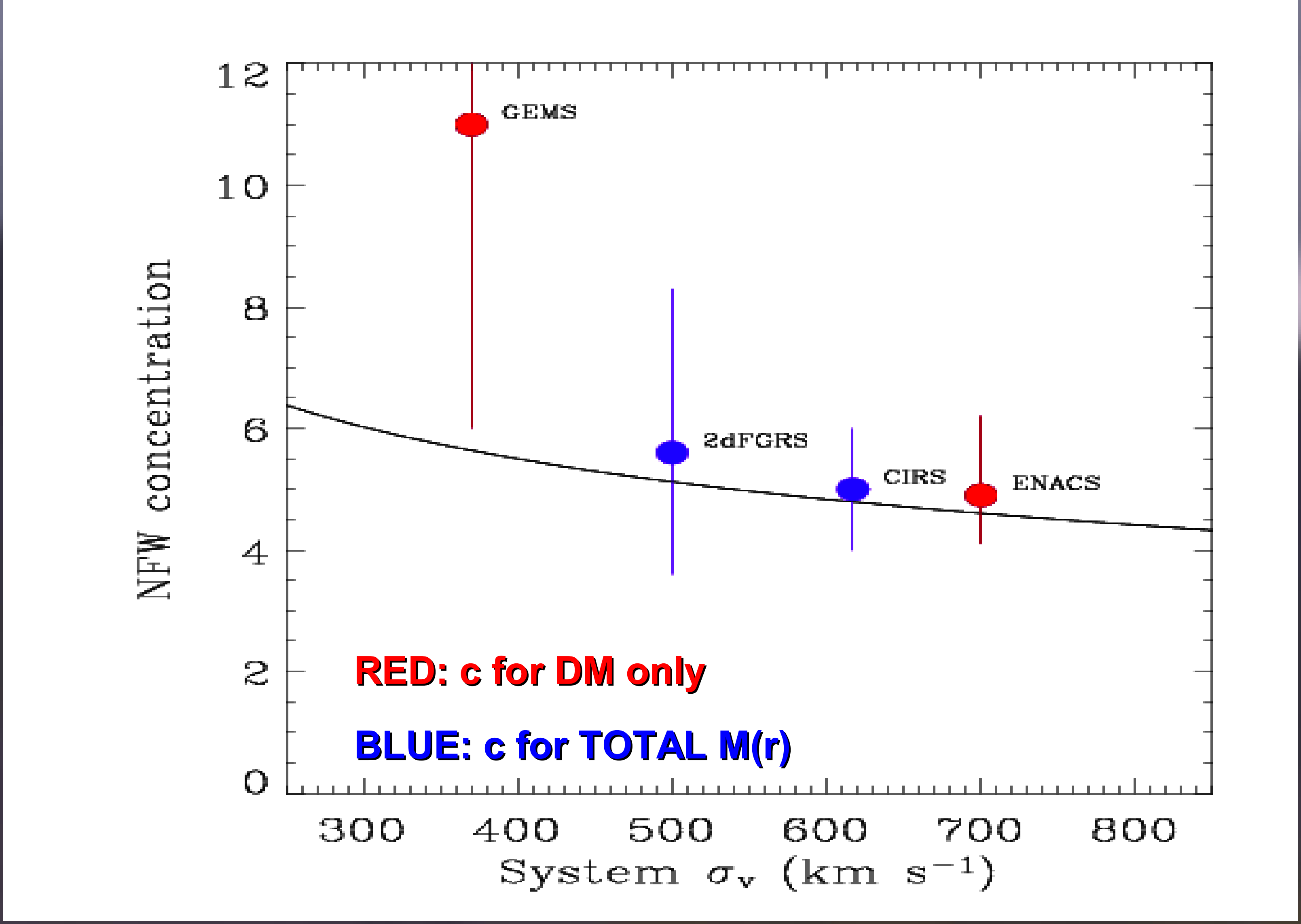


MASS PROFILES

c=c(M)

An example of YDS climbing class 5

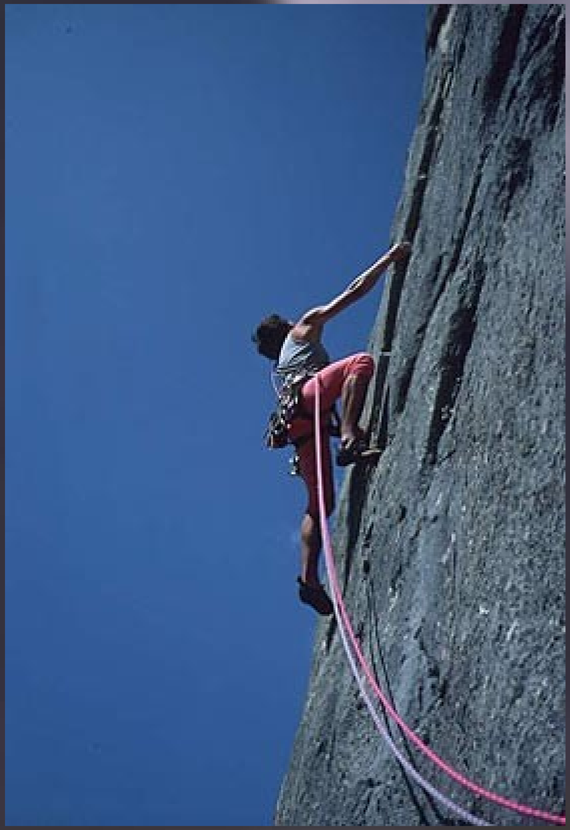
NFW c=c(M): *observations vs. theoretical predictions* (*ΛCDM;* Dolag et al. 2004)



GALAXY ORBITS

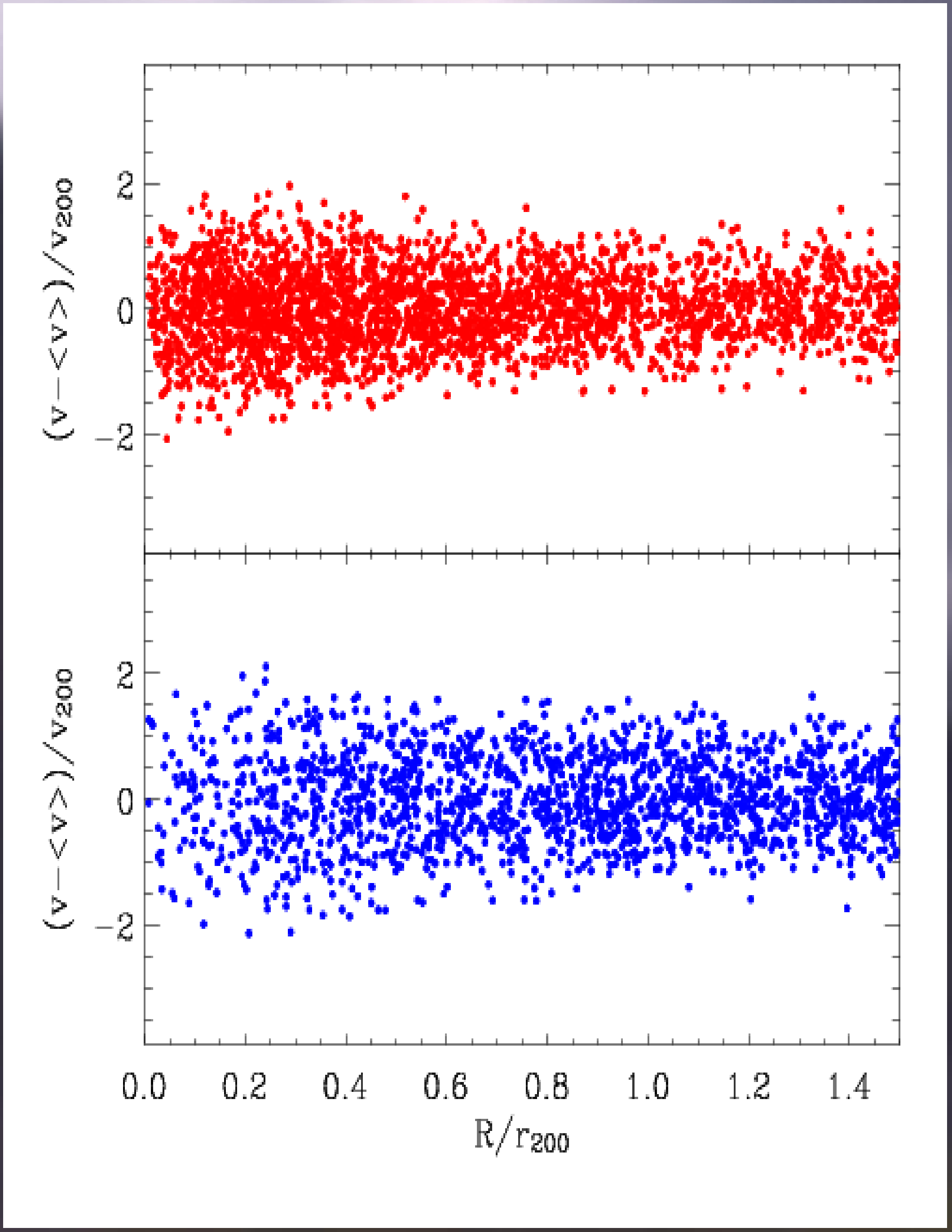
i.e. velocity anisotropy profiles

$\beta'(r) \equiv \sigma_r(r)/\sigma_t(r)$



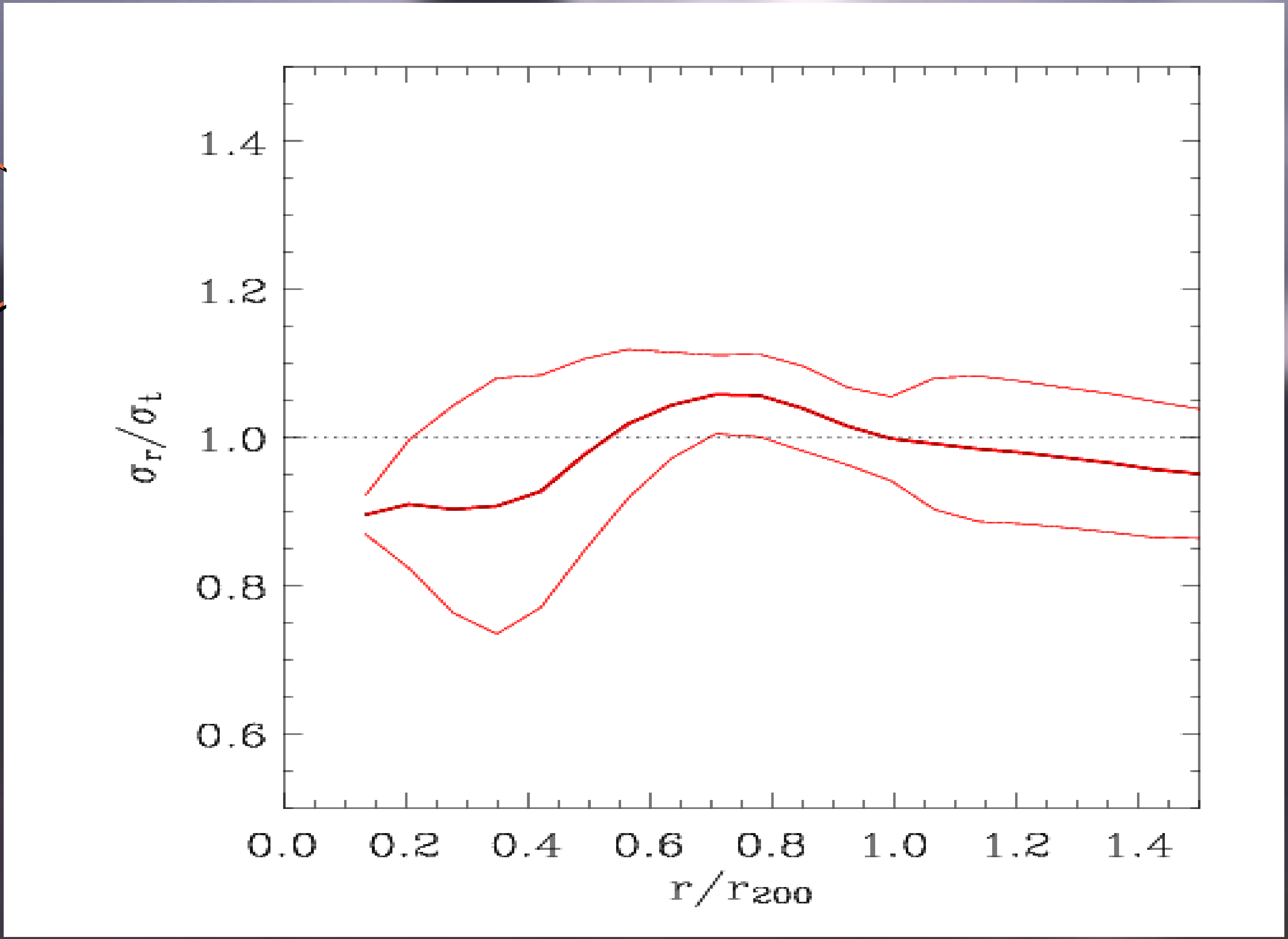
An example of YDS climbing class 5.3

Must distinguish red (early-type) from blue (late-type) galaxies because they have different R_n, V_n distributions (hence different orbits may be expected given the same mass profile)



CIRS

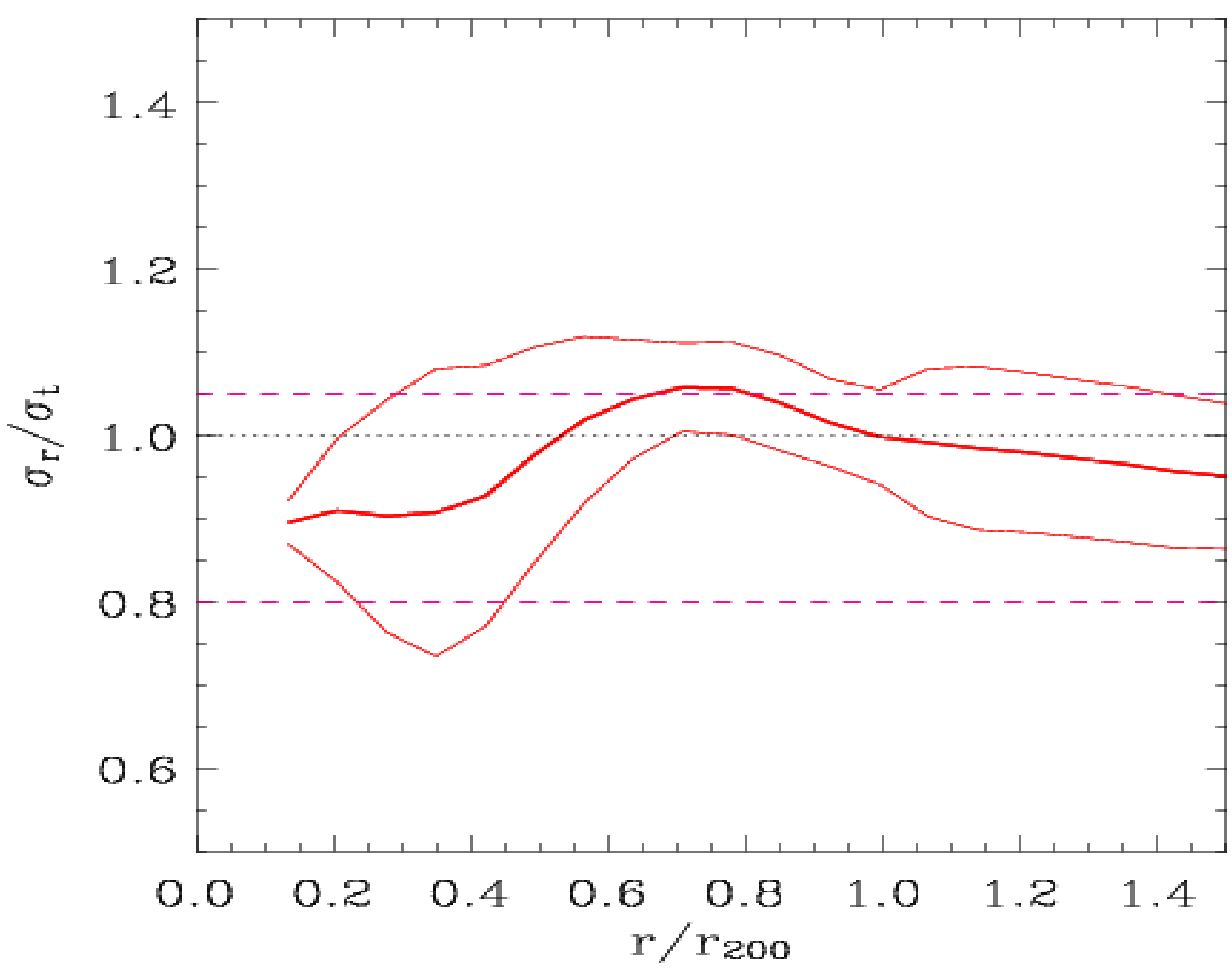
Red galaxies move on ≈ isotropic orbits



CIRS, caustic M(r) from
Rines & Diaferio (2006)

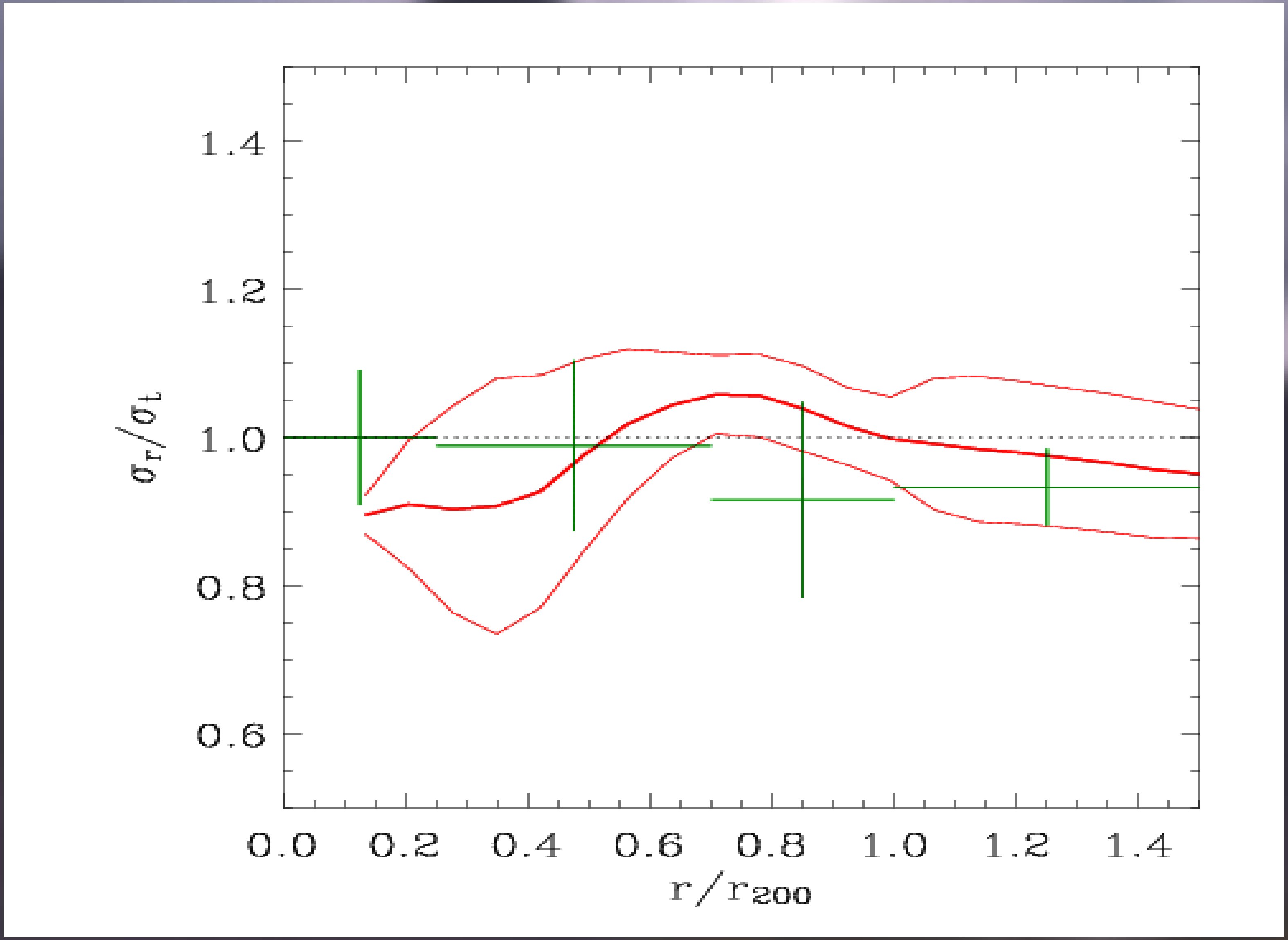
Isotropic orbits for red gal.s: ≠ samples

CIRS vs. ENACS



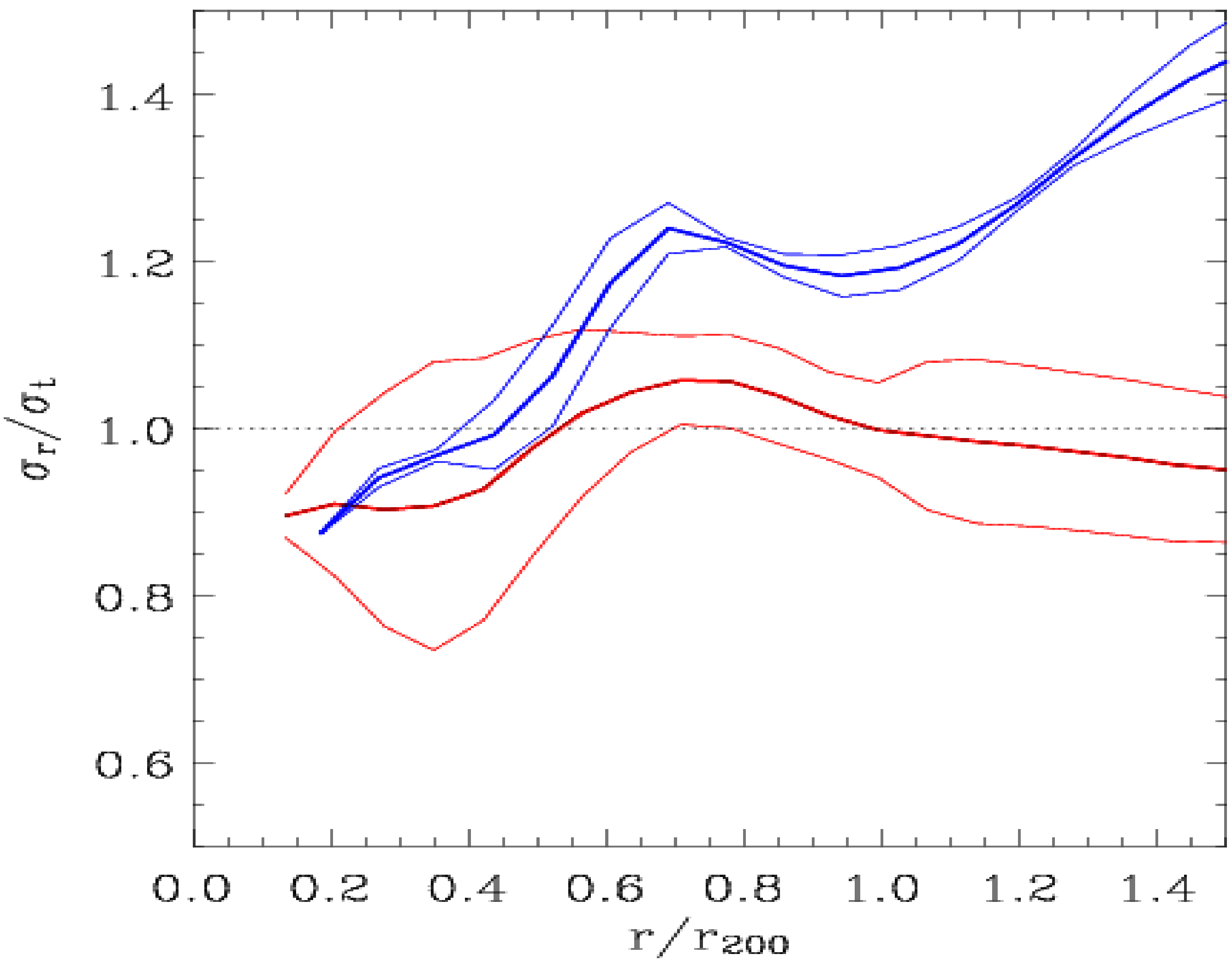
Isotropic orbits for red gal.s: ≠ methods

CIRS: Jeans vs. Gauss-Hermite



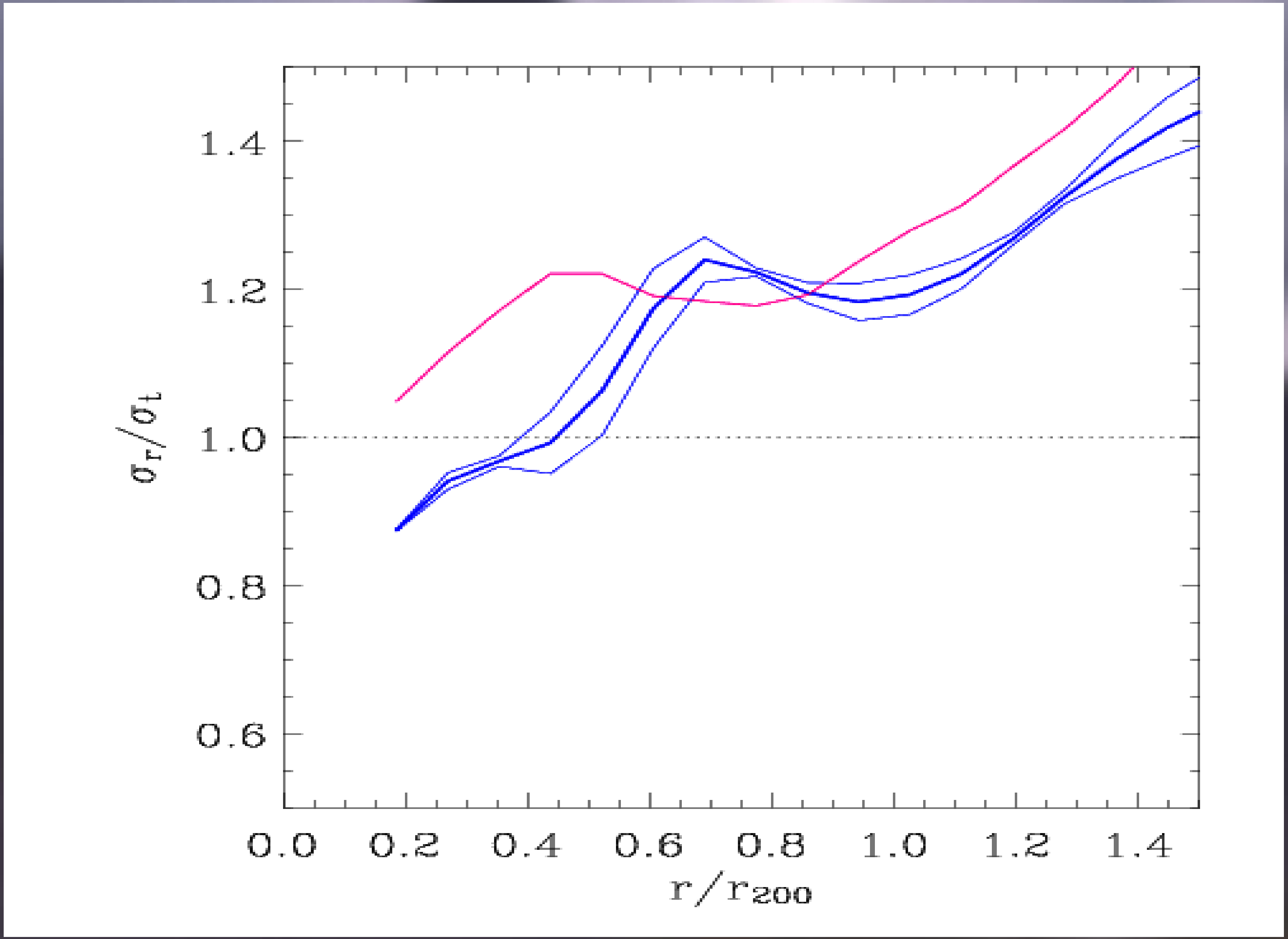
Blue galaxies move on more radial orbits

CIRS: red vs. blue galaxies



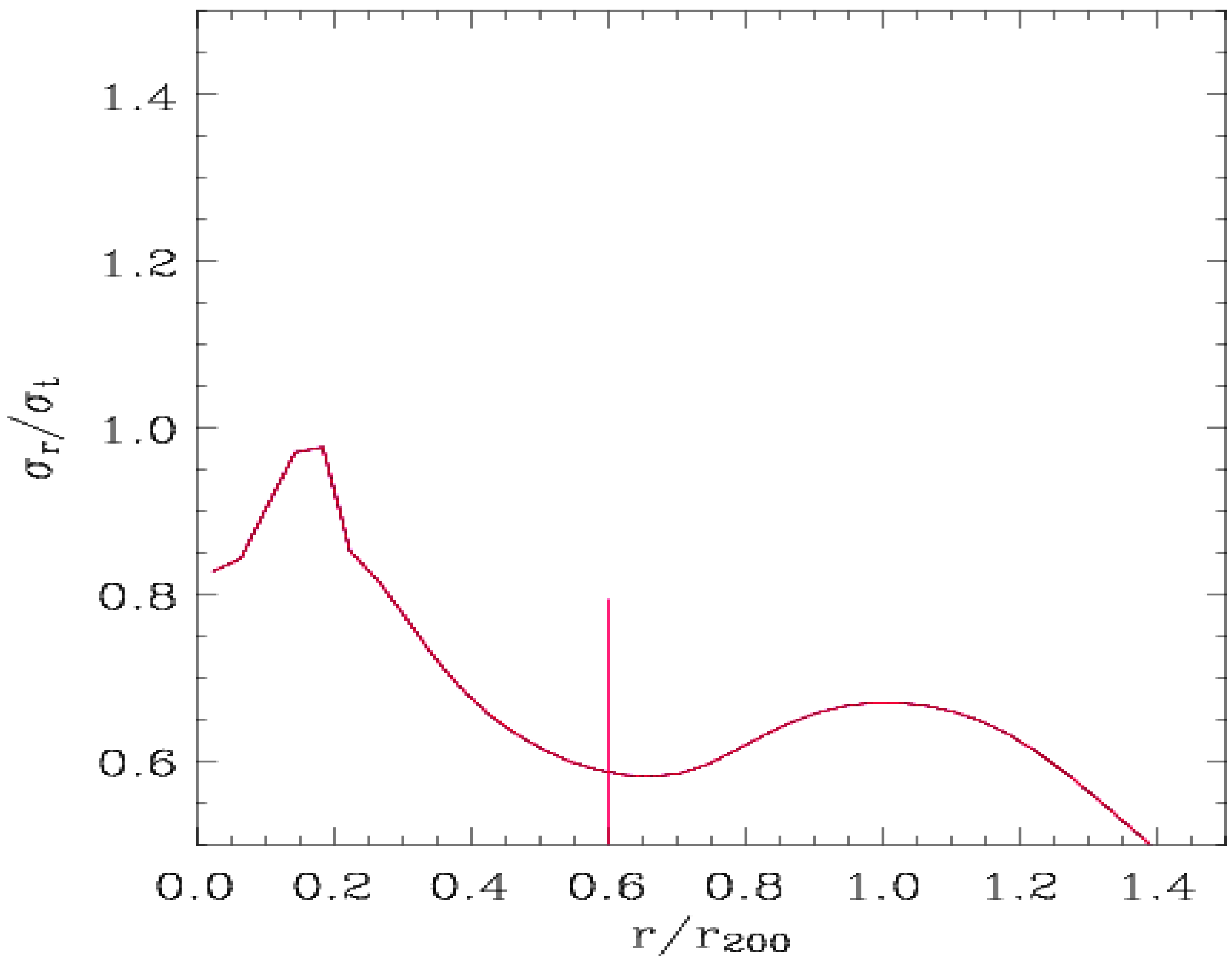
Radial orbits for blue gal.s: ≠ samples

CIRS vs. ENACS



Substructures (groups in clusters): *tangential anisotropy*

ENACS

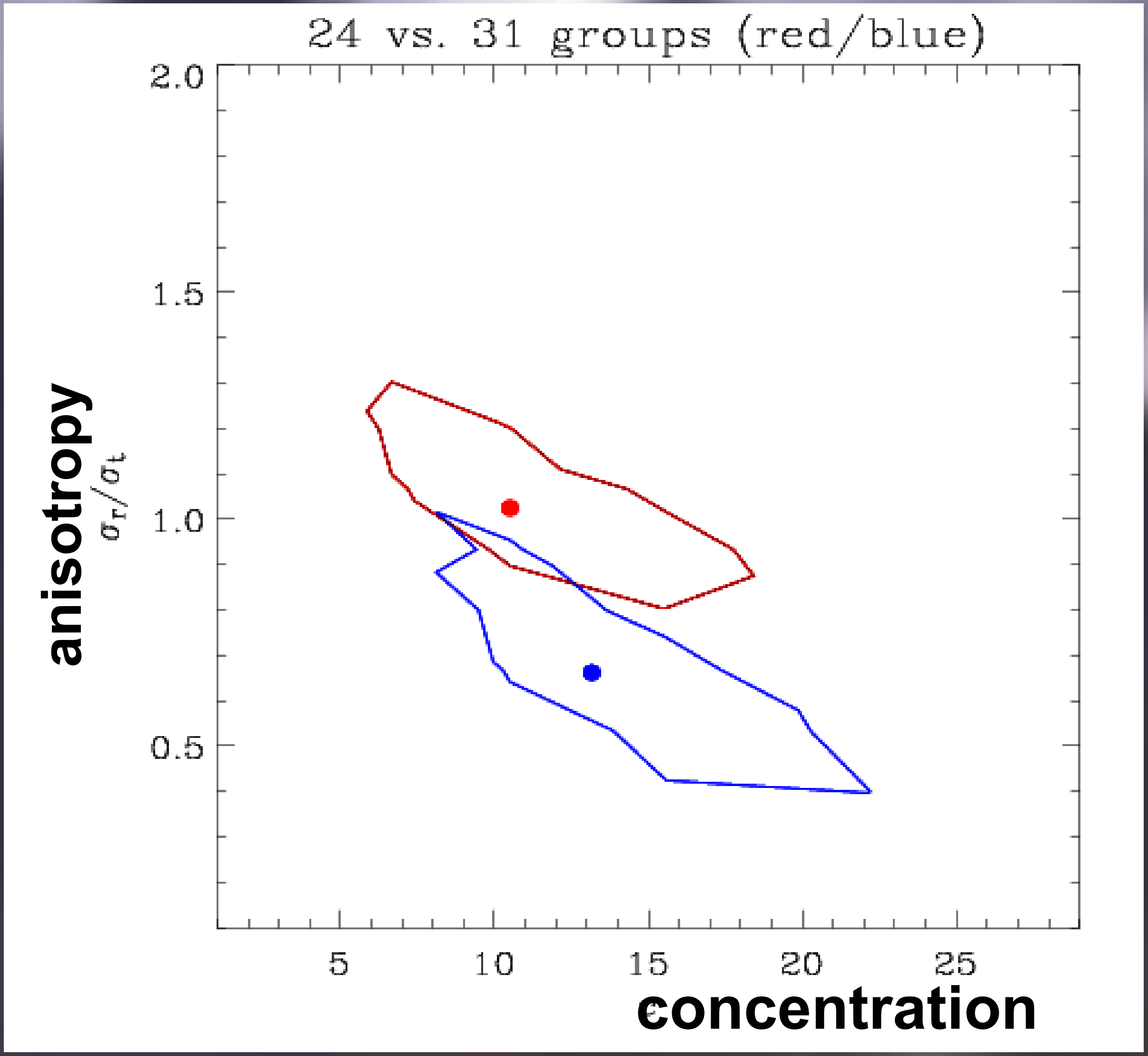


Gal.s in small σ_v groups: energy dissipation?

GEMS:

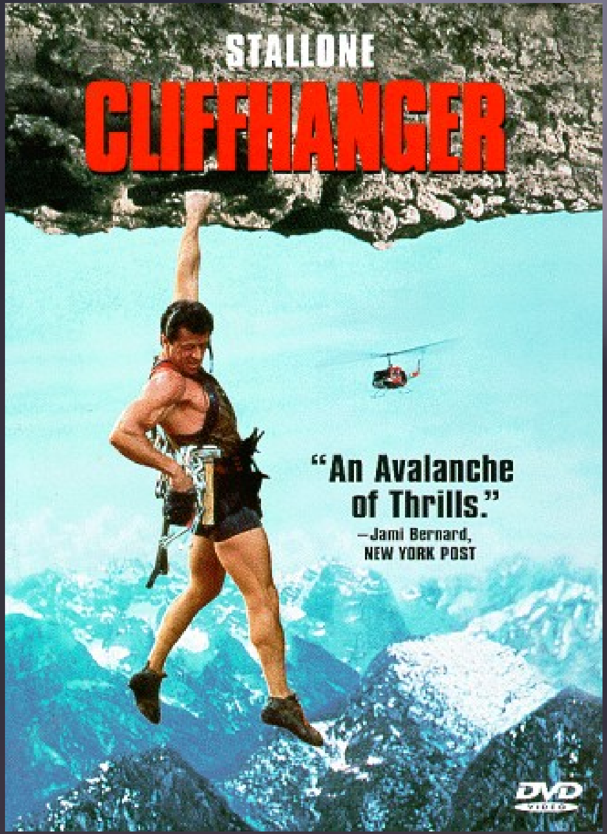
7 out of 31 groups have very small σ_v given their T_X:

their galaxies move on slightly tangential orbits



SHOULD WE TRUST THESE RESULTS?

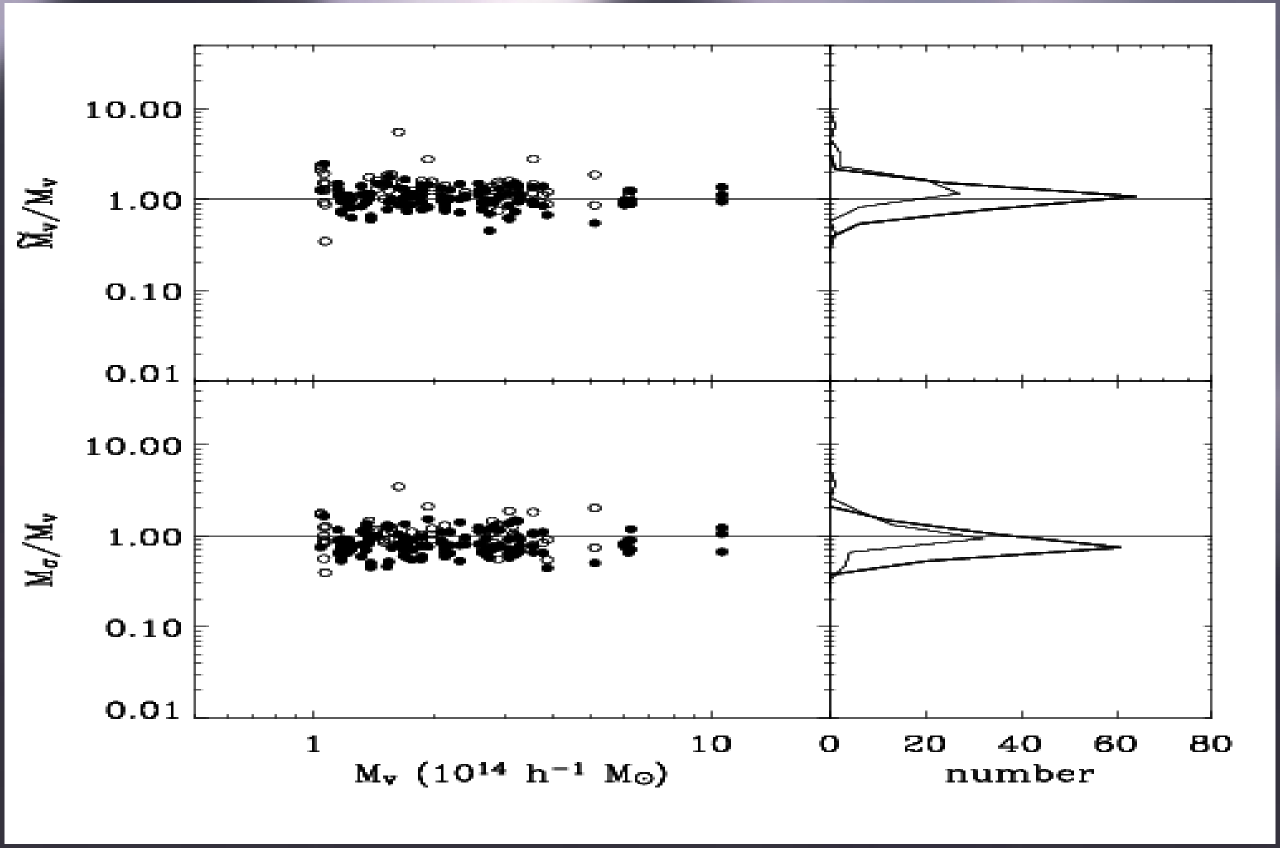
cmp with numerical simulations: masses and mass profiles



An example of YDS climbing class 5.6

⇒ compare to clusters extracted from cosmological simulations *(from Borgani et al. 04)* and projected

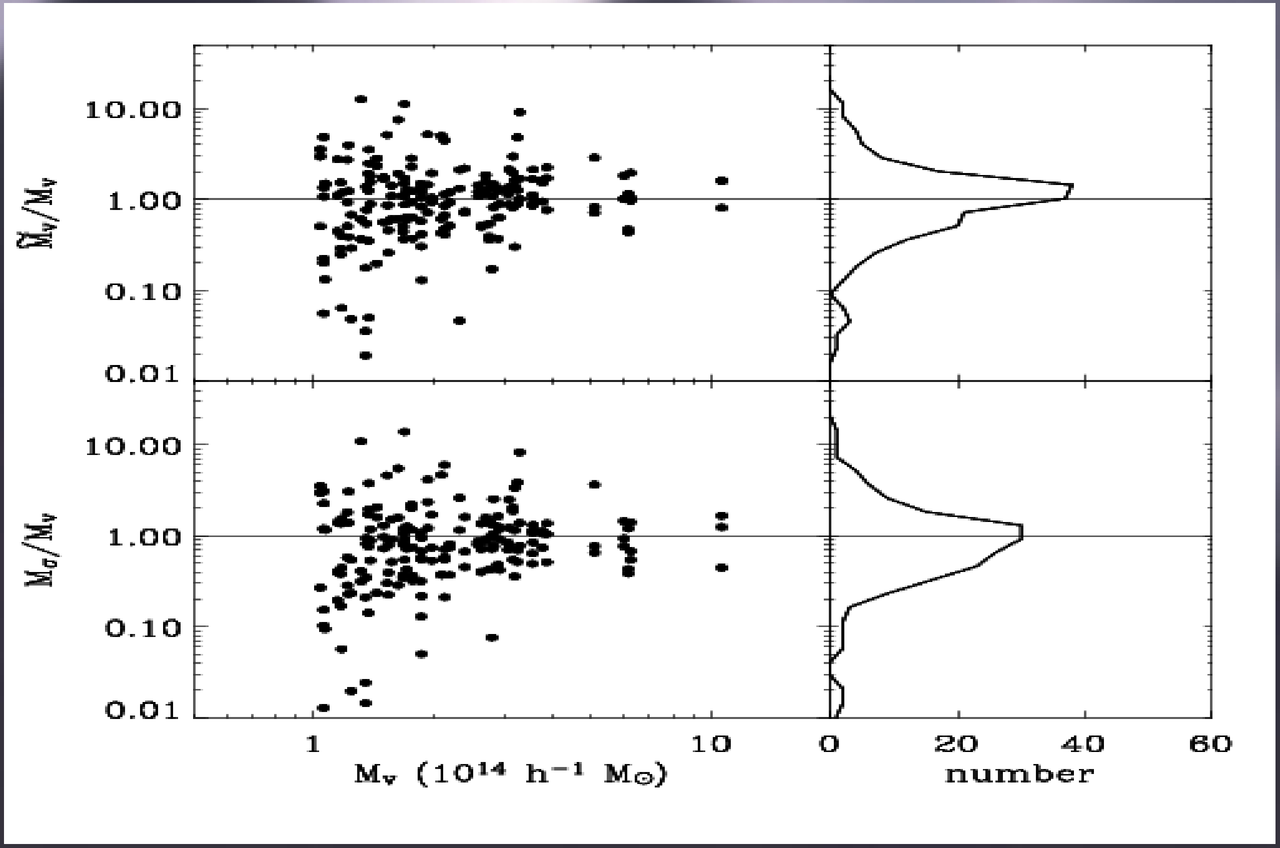
Virial mass estimates ≈unbiased for $N_{part} \geq 60$



⇒ compare to clusters extracted from cosmological simulations and projected

Virial mass estimates ≈unbiased for $N_{part} \geq 60$

For smaller N_{gal} select 'old' (red) galaxies

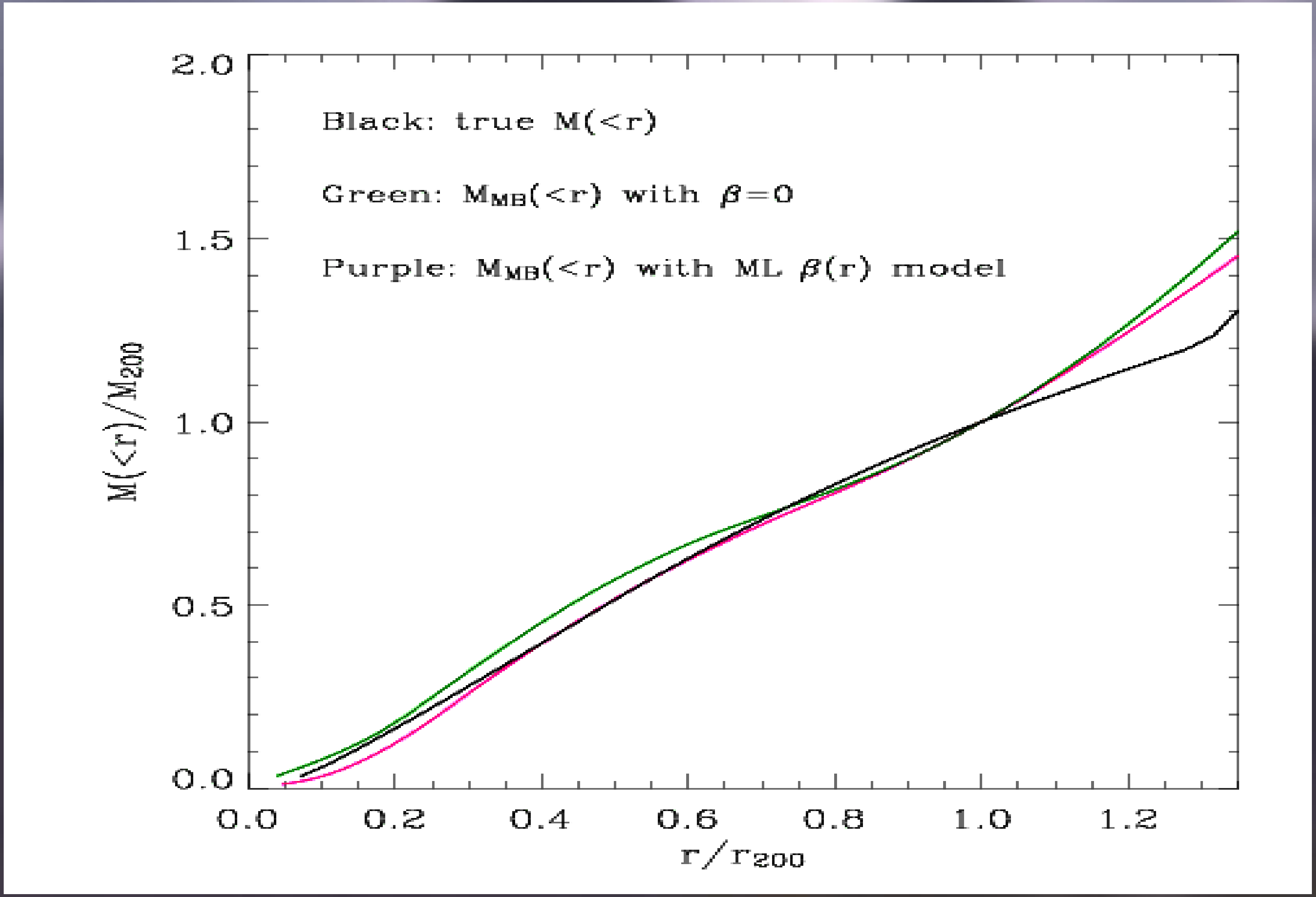


⇒ *Global dynamical estimates for clusters are OK:*

M_{200} can be used for scaling vel.s and radii

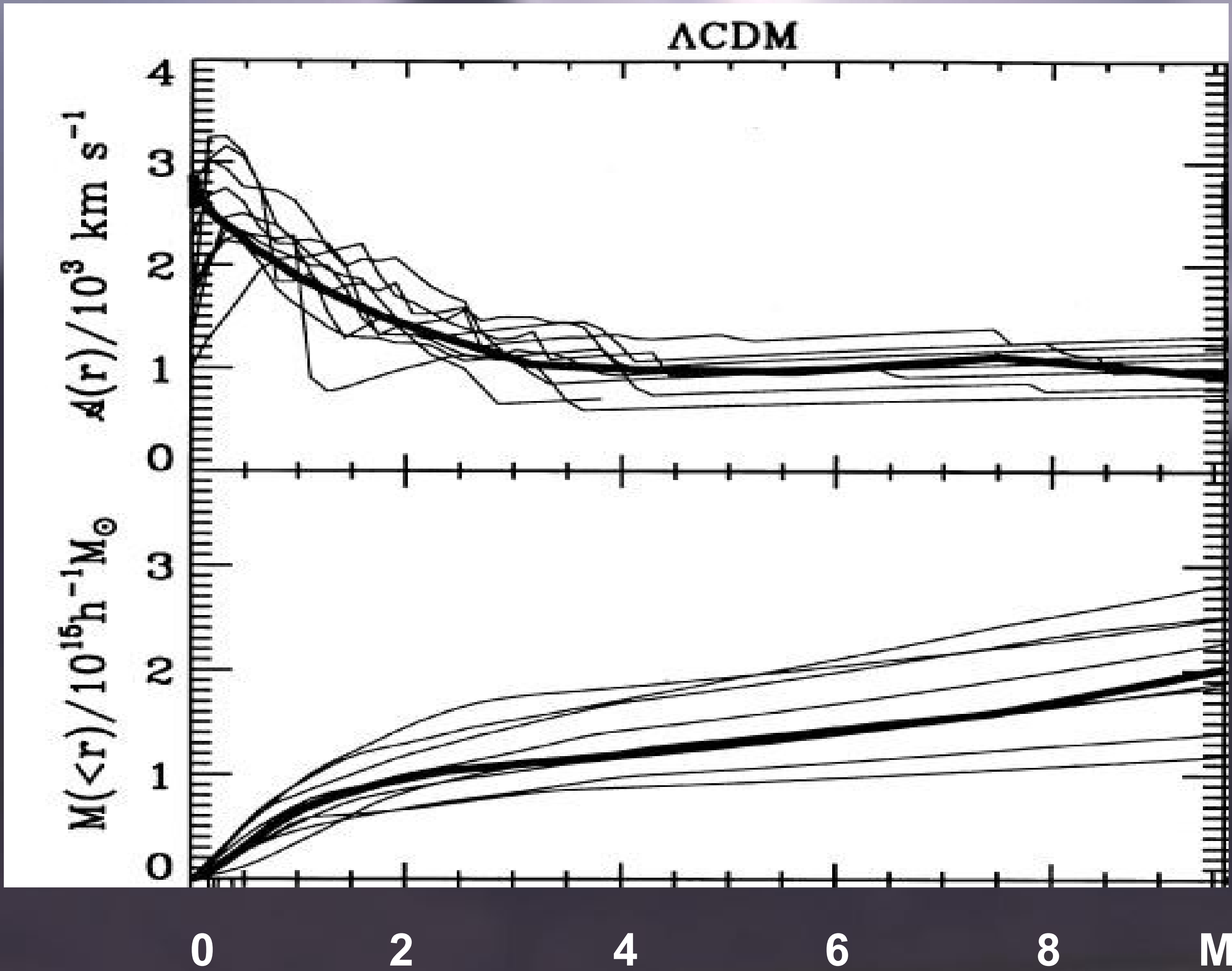
(unless N_{gal} very small: groups; use T_X)

Apply the Jeans method to projected data: M(r) (β(r) from projected velocity distribution moments)



Stacked cluster from Borgani's simulations, ≈4000 objs

Determine M(r) with the caustic method:

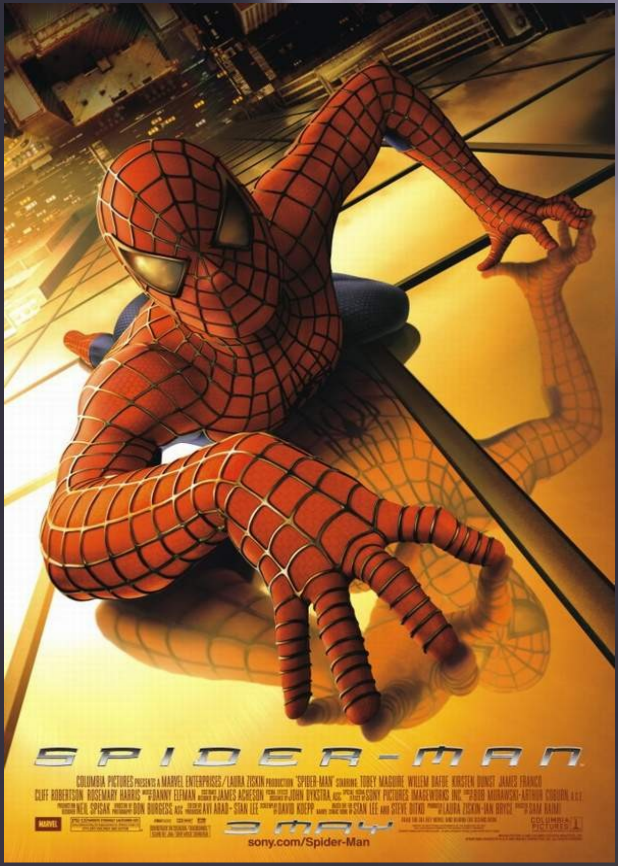


From Diaferio (1999)

Single cluster from GIF simulations, 9 ≠ projections

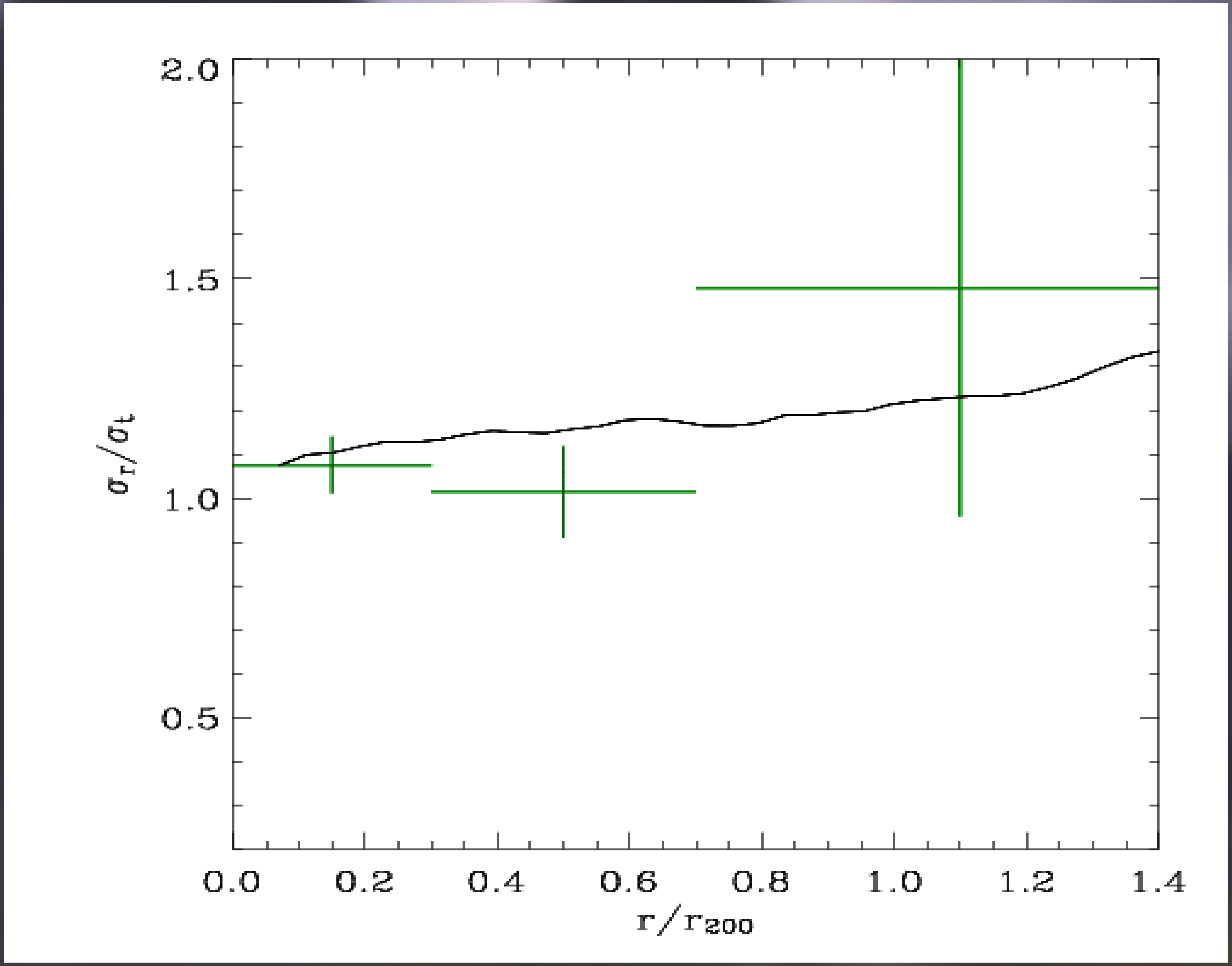
SHOULD WE TRUST THESE RESULTS?

cmp with numerical simulations:
velocity anisotropy profiles (orbits)

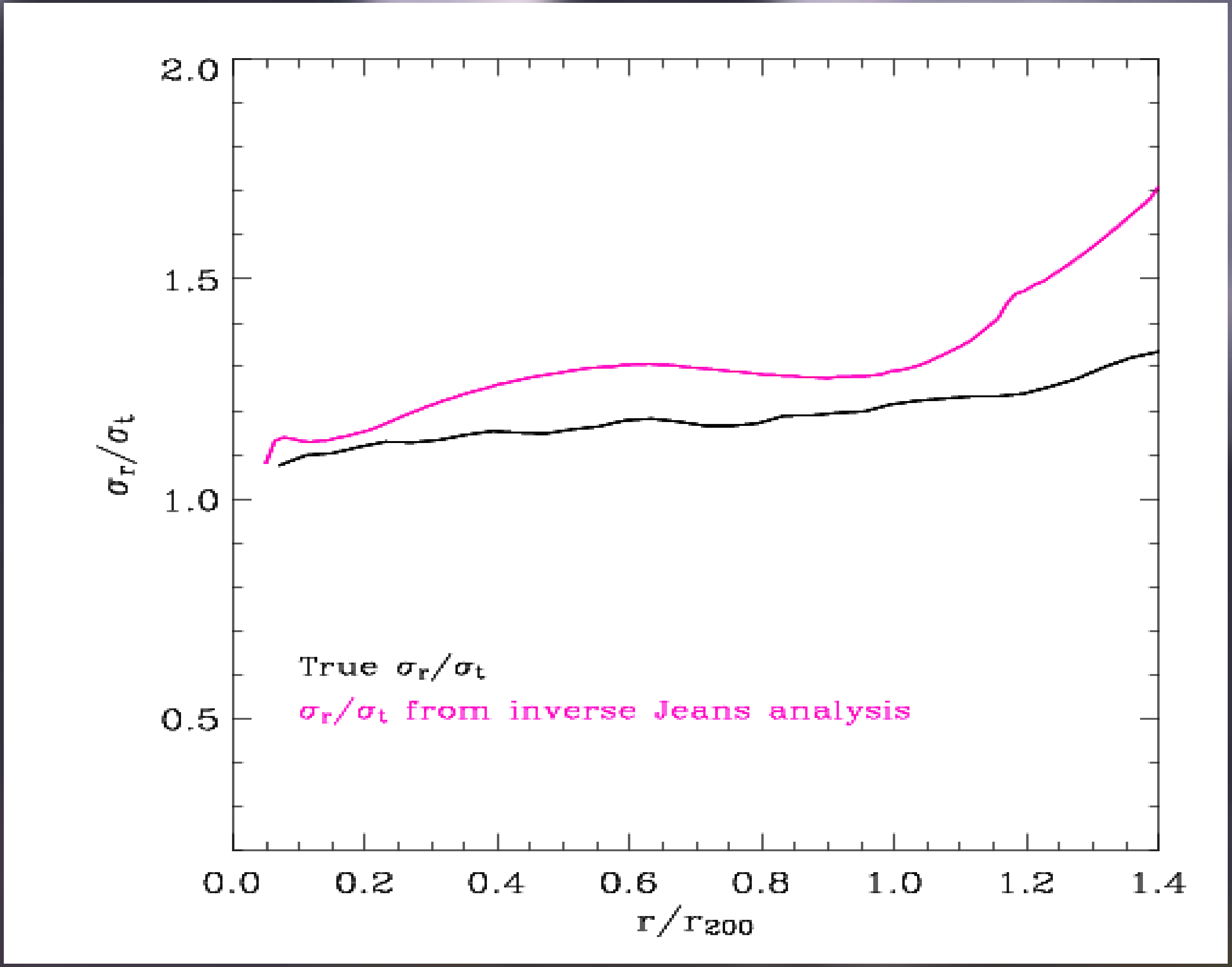


An example of YDS climbing class 5.9

Stacked cluster from Borgani et al.'s simulations: true velocity anisotropy profile cmpd to profile obtained from the analysis of the velocity moments of projected data *(Gauss-Hermite)*

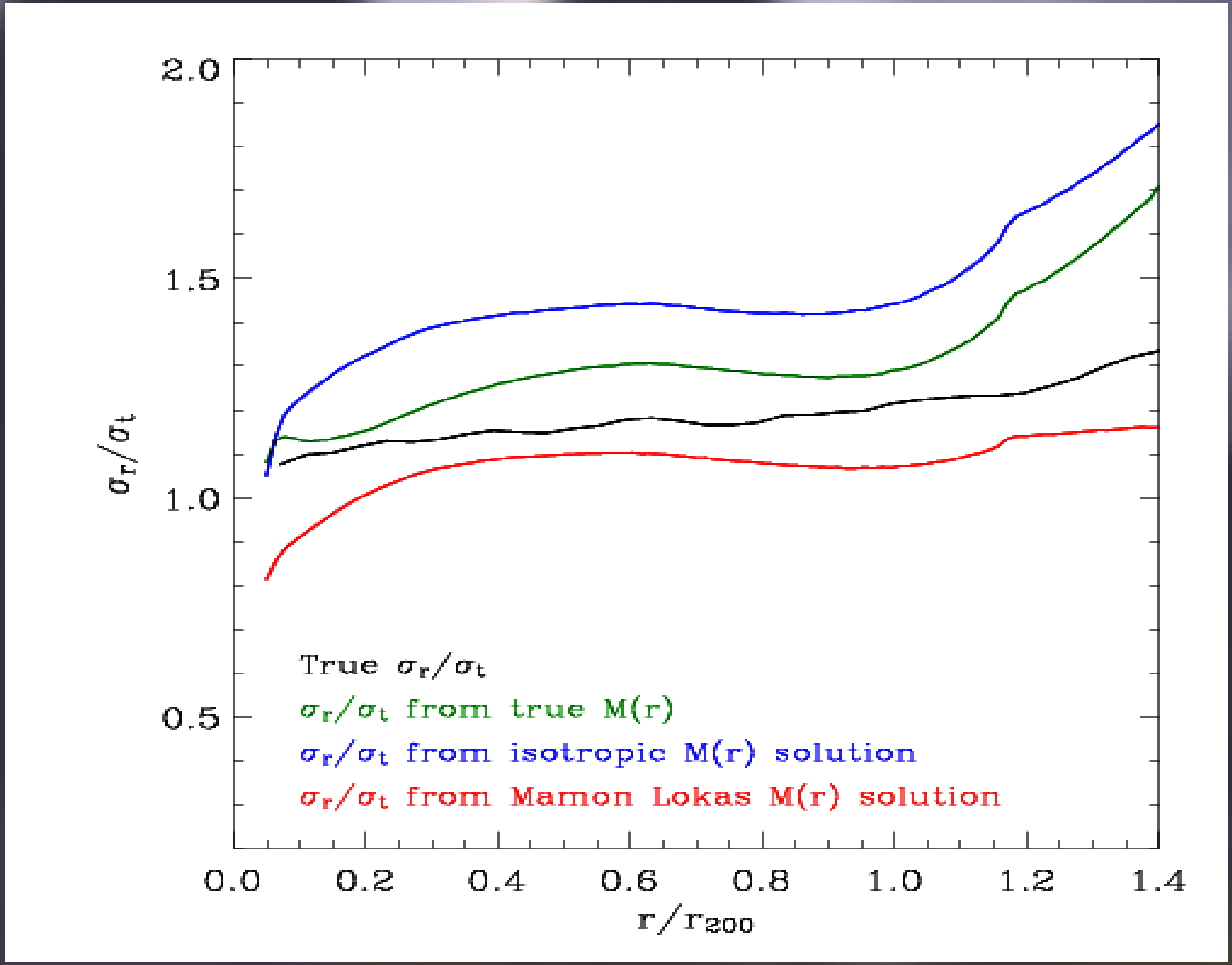


Stacked cluster from Borgani et al.'s simulations: true velocity anisotropy profile cmpd to profile obtained from Jeans analysis of projected data, given M(r)



Overestimate probably due to unidentified interlopers in (R,v) space

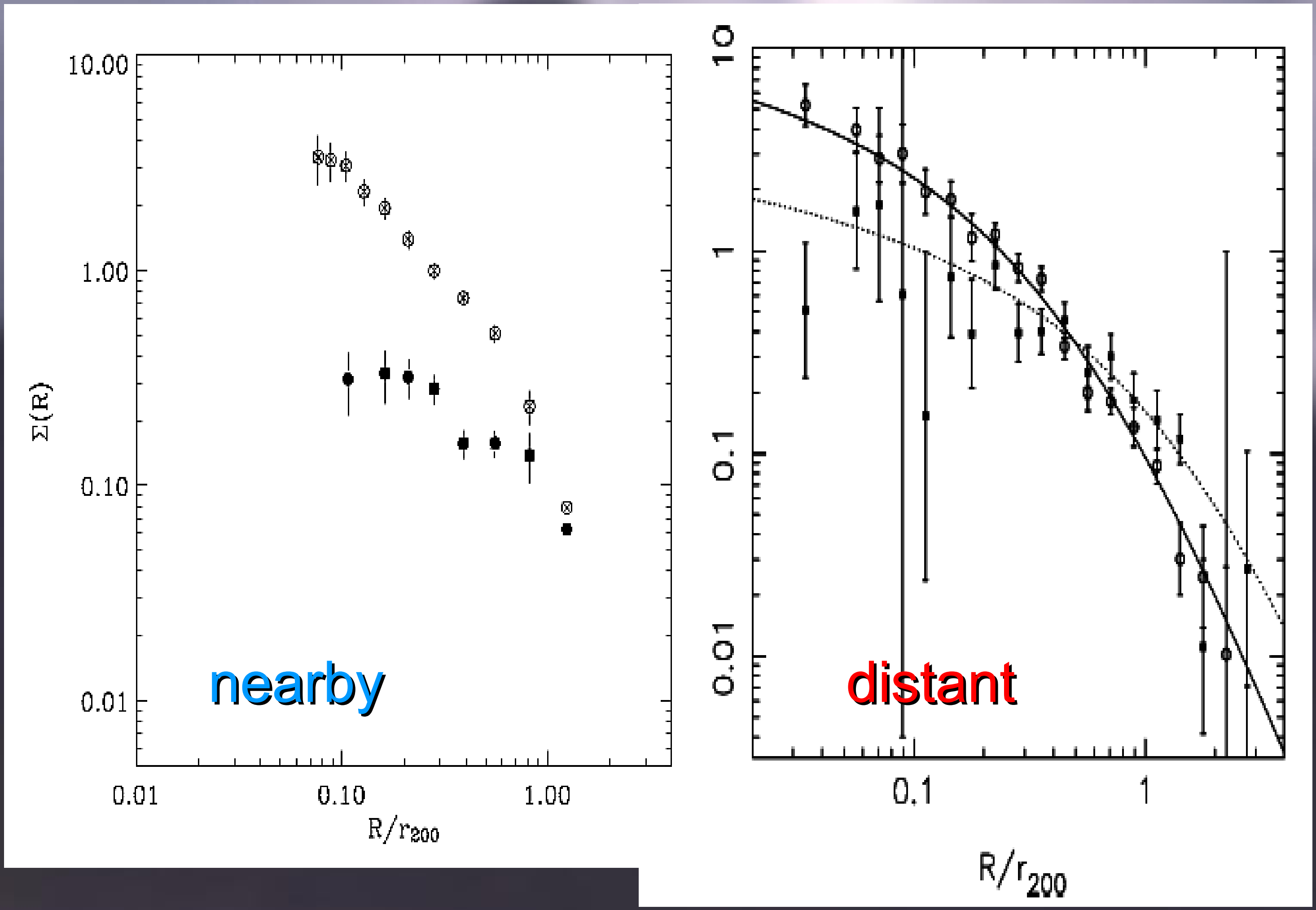
True velocity anisotropy profile *cmpd to profiles obtained from Jeans analysis, using* true M(r), isotropic M(r) Jeans solution, *and* anisotropic M(r) Jeans solution *(as obtained from Gauss-Hermite analysis)*



→Accurate β'(r) determination requires accurate M(r) determination

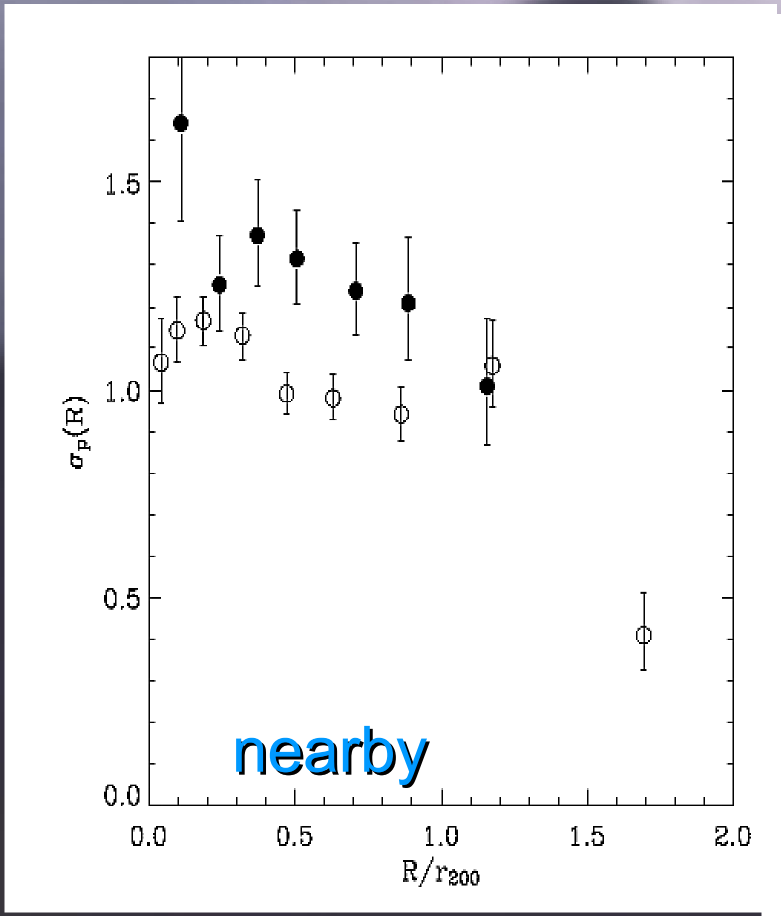
ORBITS OF GALAXIES IN CLUSTERS: EVOLUTION

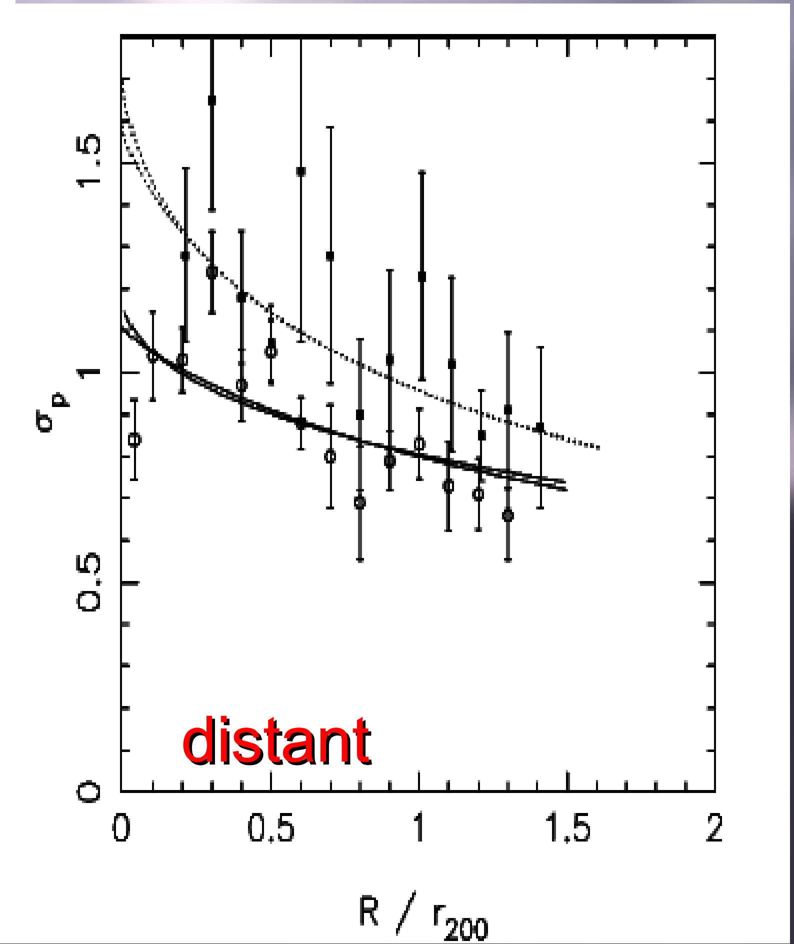
Compare ENACS vs. CNOC



Number density profiles for early- (empty symbols) and late- (filled symbols) cluster galaxies

Compare ENACS vs. CNOC





$\sigma_p(R)$ profiles for early- (empty symbols) and late- (filled symbols) cluster galaxies

Early-type galaxies at z≈0 & z≈0.3: isotropic orbits

(Katgert, B. & Mazure 04; van der Marel et al. 00)

Late-type galaxies at z≈0: radial orbits *(B. & Katgert 04)*

No evolution of (R,v) distributions
of early- and late-type galaxies from z≈0 to z≈0.3

(Carlberg et al. 97 vs. B. & Katgert 04)

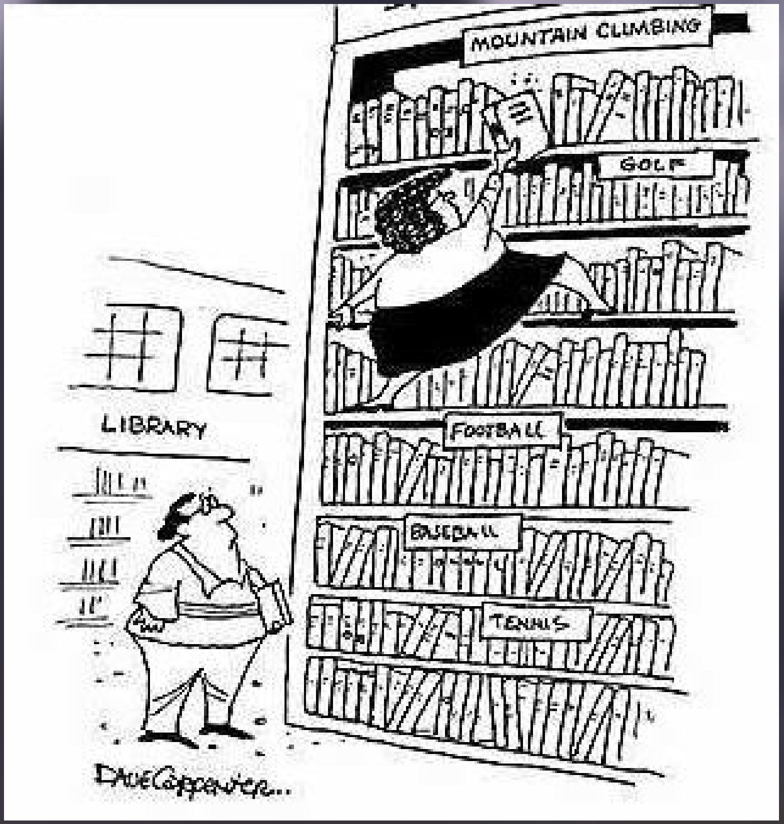
⇒ late-type galaxies at z≈0.3 must also be on radial orbits like late-type galaxies at z≈0

The late-type -galaxy fraction increases with z,
hence more cl. galaxies are on radial orbits at higher z

⇒ the infall rate increases with z

(in agreement with Ellingson et al. 2001)

CONCLUSIONS



An example of YDS climbing class 6

Density profiles of clusters are as predicted by ΛCDM models; if cored, core $\simeq 0.1\ r_{200} \sim$ cD size

(→DM particles cross-section)

DM more concentrated than baryons

(→effectiveness of dyn. friction & adiabatic contraction)

Groups: higher concentration than predicted by ΛCDM?

dissipation processes at work?

(...TBC: need better statistics)

Red (early-type) galaxies move on isotropic orbits,
Blue (late-type) galaxies move on slightly radial orbits
Substructures move on tangential orbits

(→cluster accretion history, galaxy evolution in clusters)

Density profiles of clusters are as predicted by ΛCDM models; if cored, core $\simeq$ 0.1 r_{200} ~ cD size

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Groups: higher concentration than predicted by ΛCDM? dissipation processes at work?

(...TBC: need better statistics)

Red (early-type) galaxies move on isotropic orbits,
Blue (late-type) galaxies move on slightly radial orbits
Substructures move on tangential orbits

(→cluster accretion history, galaxy evolution in clusters)

- The best fitting Burkert core-radius is small,
  0.1 r_{200} ~ size of central cD
  → DM scattering cross section <2 $cm^2\,g^{-1}$

(By comparison with simulation res. of Meneghetti et al. 2001)

Much smaller than the 5 cm^2g^{-1} needed to fit dwarf galaxy mass density prof., *Davé et al. (2000)*

- DM is *more* concentrated than the total matter

Dynamical friction mechanism ineffective in transferring galaxy energy to DM in clusters or counteracted by adiabatic contraction

(e.g. Zappacosta et al. 2006)

Future work

Num.simulations: investigate physics of evolution of orbits of galaxies in clusters and find optimal algorithm for M(r), β(r)

(ongoing collaboration with Borgani, Dolag, Mamon, Murante et al.)

More data: Improve current constraints on cluster M(r) and β(r) by combining existing data-bases and using new ones

*(e.g.: W I N G S, **see A. Cava's poster**, ongoing collaboration with Bettoni, Cava, D'Onofrio, Fasano, Moles, Poggianti, Ramella, Varela)*

Higher z: Evolution of M(r) and β(r), extend the analysis to higher-z cluster samples

(e.g.: I C B S, possible collaboration with Dressler, Poggianti et al.)

Thank you for your attention!

An example of YDS climbing class 7
(...my favorite!)