Galaxy Systems in the Optical and Infrared

Andrea Biviano
INAF/Oss.Astr.Trieste

Plan of the lectures:

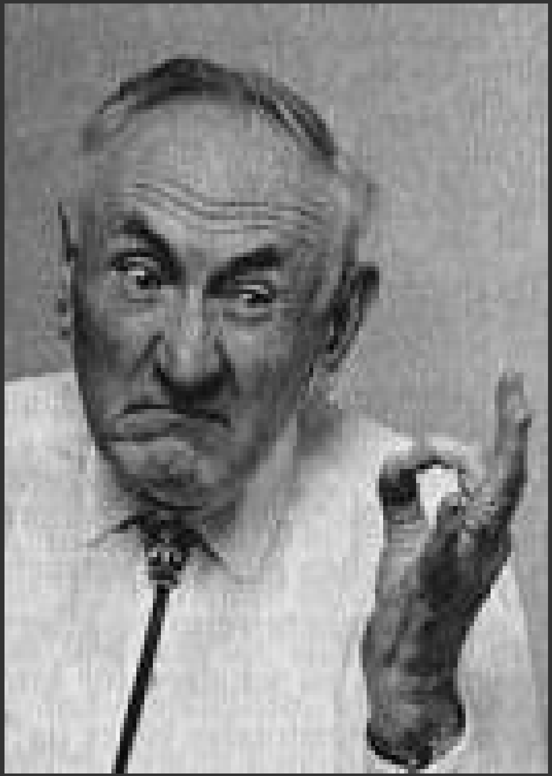
I. Identification, global properties, and scaling relations

II. Structure and dynamics

III. Properties of the galaxy populations

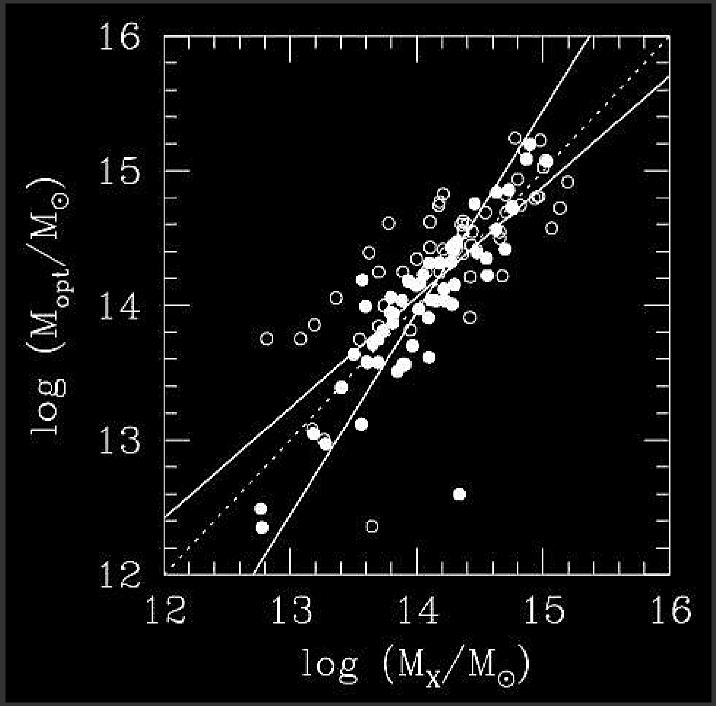
Introduction

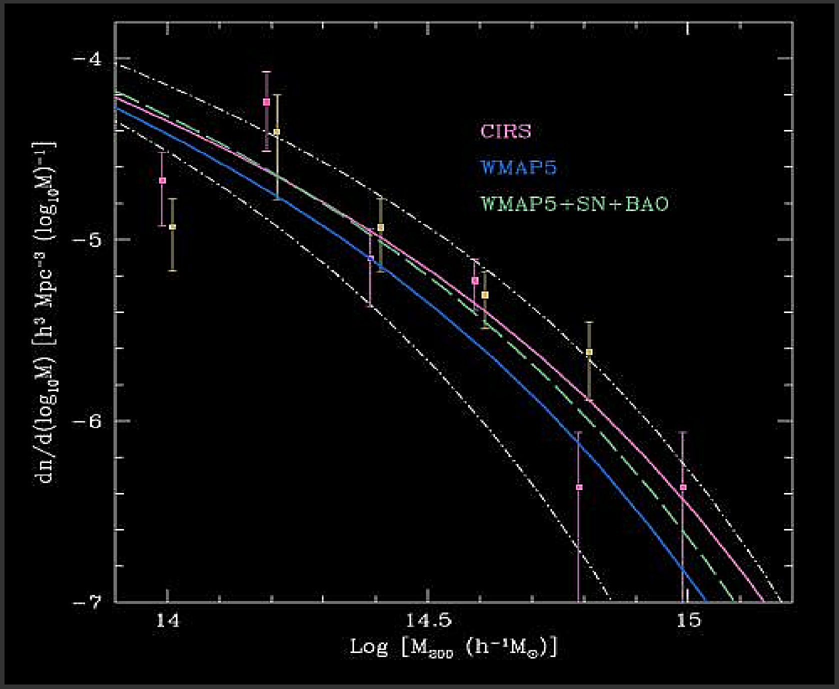
Early cluster mass determinations based on the *light traces mass* hypothesis



Early cluster mass determinations based on the *light traces mass* hypothesis

Indirect evidence supports this hypothesis





Early cluster mass determinations based on the *light traces mass* hypothesis

Indirect evidence supports this hypothesis

Must **prove** it by direct comparison of the TRACER and MASS distributions

M(r) determination $\Rightarrow$ clues on:

- nature of DM

- formation and evolution of galaxy clusters

Cold DM:

halo density profiles have central cusp

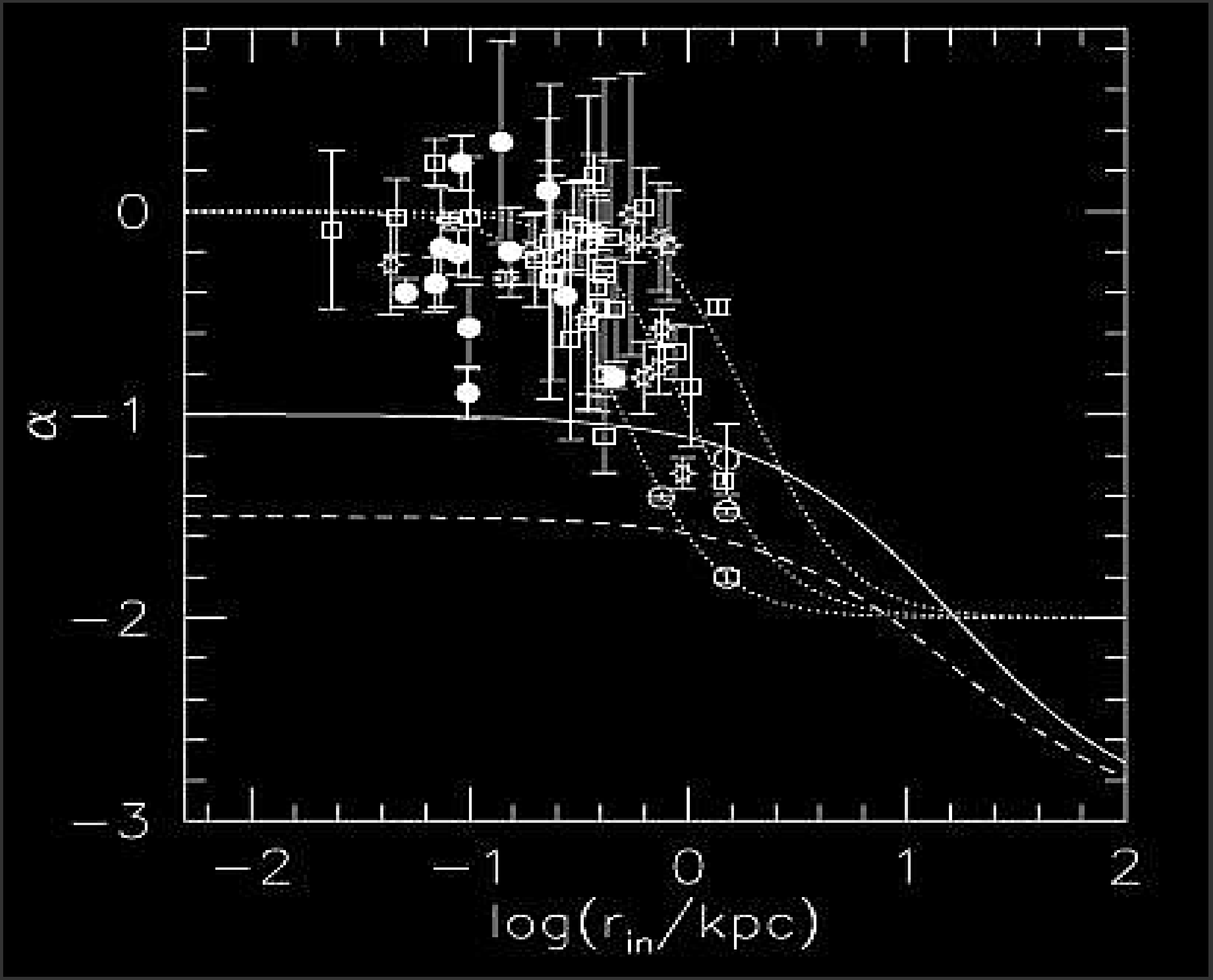
$$\rho_{NFW} = \frac{\rho_0}{(cr/r_{200})(1 + cr/r_{200})^2}$$

from cosmological numerical simulations

$$\rho_{Hernquist} = \frac{\rho_0}{r\left(r + r_H\right)^3}$$

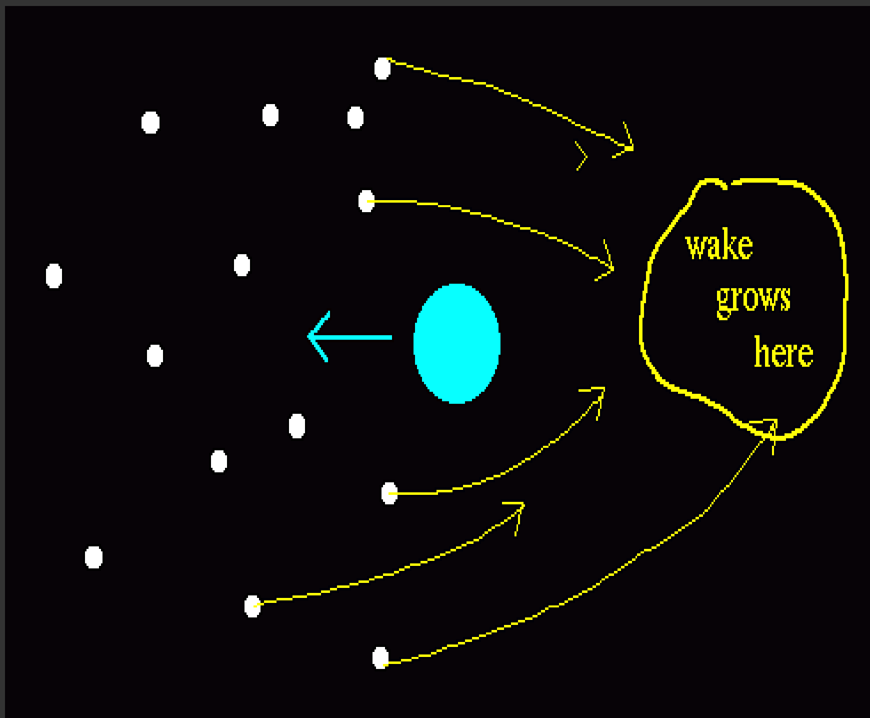
used in theoretical modelling; note steeper slope

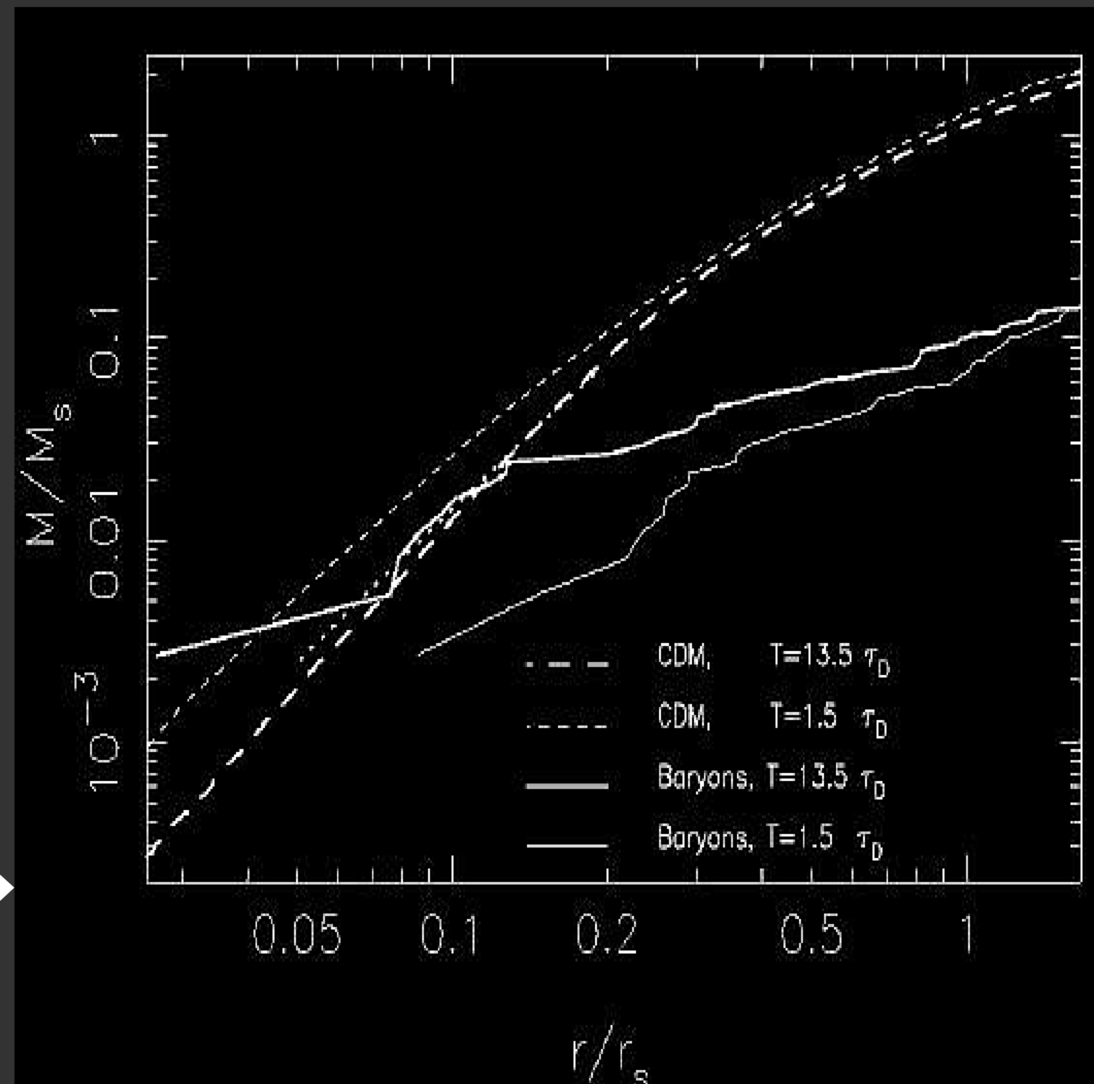
Galaxy rotation curves: no central cusp?



(de Blok & Bosma 02)

Central cusp erased by dynamical friction?





(El Zant+04)

Halo density profiles with central core

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

Note: same asymptotic slope as NFW

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

Note: shallower asymptotic slope

Dynamical analysis: methods

The Jeans equation

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

$$\beta(r) \equiv 1 - \frac{<\mathrm{v}_\mathrm{t}^2>(\mathrm{r})}{<\mathrm{v}_\mathrm{r}^2>(\mathrm{r})}$$

The Jeans equation

$$\frac{d(\nu\sigma_r^2)}{dr} + 2\beta\frac{\nu\sigma_r^2}{r} = -\nu\frac{d\phi}{dr}$$

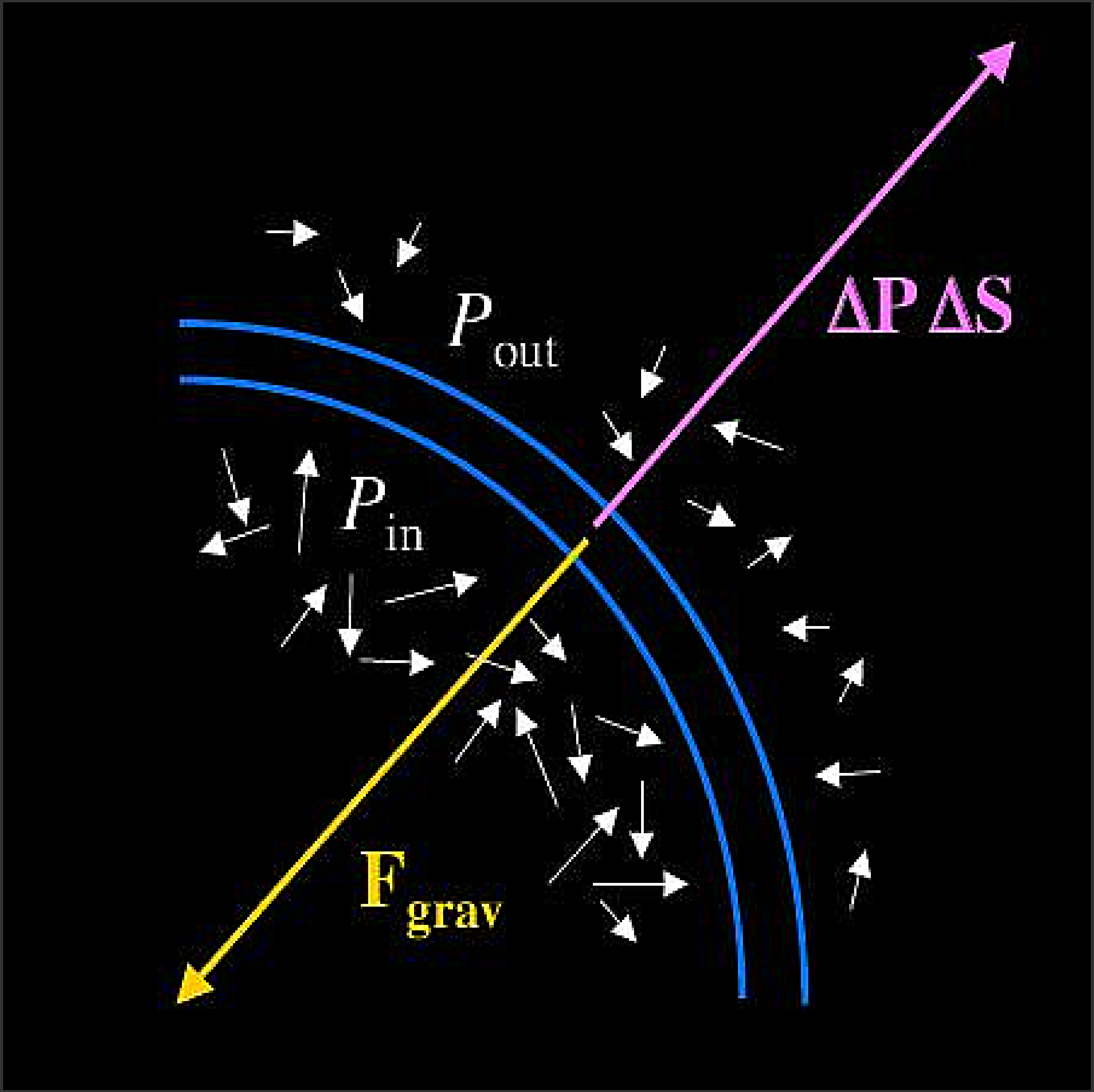
$$\beta(r) \equiv 1 - \frac{\langle \mathrm{v}_t^2 \rangle(\mathrm{r})}{\langle \mathrm{v}_r^2 \rangle(\mathrm{r})}$$

The Jeans equation

$$\frac{d(\nu\sigma_r^2)}{dr} + 2\beta\frac{\nu\sigma_r^2}{r} = -\nu\frac{d\phi}{dr}$$

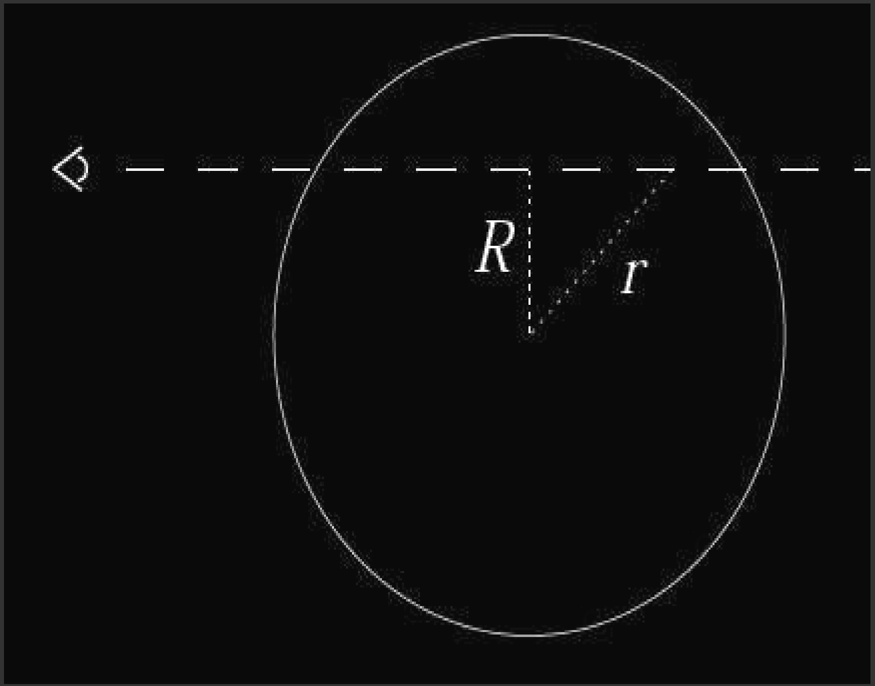
Dynamical pressure gradient

Gravitational potential gradient



(from Gary Mamon's University lectures)

3-d profiles enter the Jeans equation but only projected profiles are observable



(from G. Mamon's lectures)

$$\nu(r) = -\frac{1}{\pi}\int_r^\infty \frac{dN}{dR}\frac{dR}{\sqrt{R^2-r^2}}$$

$$N(R) = 2\int_R^\infty \frac{\nu\, r\, dr}{\sqrt{r^2-R^2}}$$

Spherical symmetry:

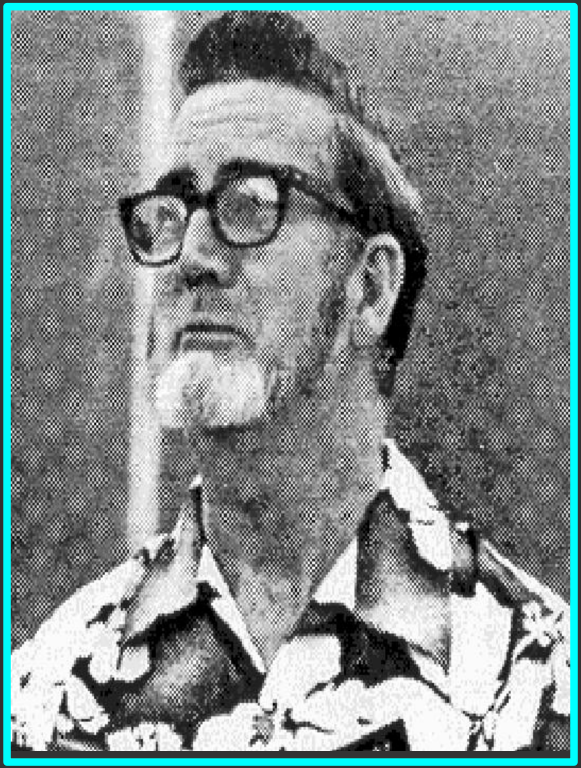
direct Abel inversion of density profile

Note:

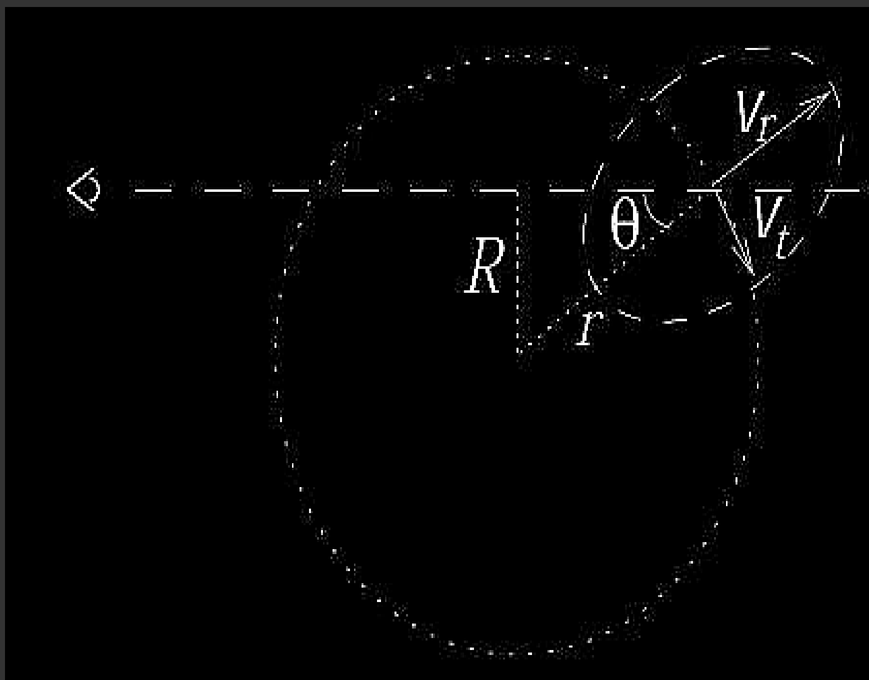
Niels Henrik Abel (∗1802 ✝1829)

is not

George Ogden Abell (∗1927 ✝1983)



3-d profiles enter the Jeans equation but only projected profiles are observable



(from G. Mamon's lectures)

$$\sigma_r^2 = -\frac{1}{\pi \nu(r)} \int_r^\infty \frac{d[N \times \sigma_p^2]}{dR} \frac{dR}{\sqrt{R^2 - r^2}}$$

$$N(R)\sigma_p^2(R) = 2 \int_R^\infty \left(1 - \beta \frac{R^2}{r^2}\right) \frac{\nu\, \sigma_r^2(r)\, r\, dr}{\sqrt{r^2 - R^2}}$$

β needed to invert the velocity dispersion profile; not a simple Abel inversion (Mamon & Boué 08)

Playing the Jeans game:

Observables
N(R), σ_p(R)

+β(r)

→ M(r)

Mamon & Boué 08

Observables
N(R), σ_p(R)

+M(r)

→ β(r)

Binney & Mamon 82

Observables
N(R), σ_p(R)

←

M(r)+β(r)

Bacon+83

$$\nu\,\sigma_r^2 = -G\int_r^\infty \nu(\xi)\frac{M(<\xi)}{\xi^2}\exp\left[2\int_r^\xi \frac{\beta dx}{x}\right]d\xi$$

van der Marel 94

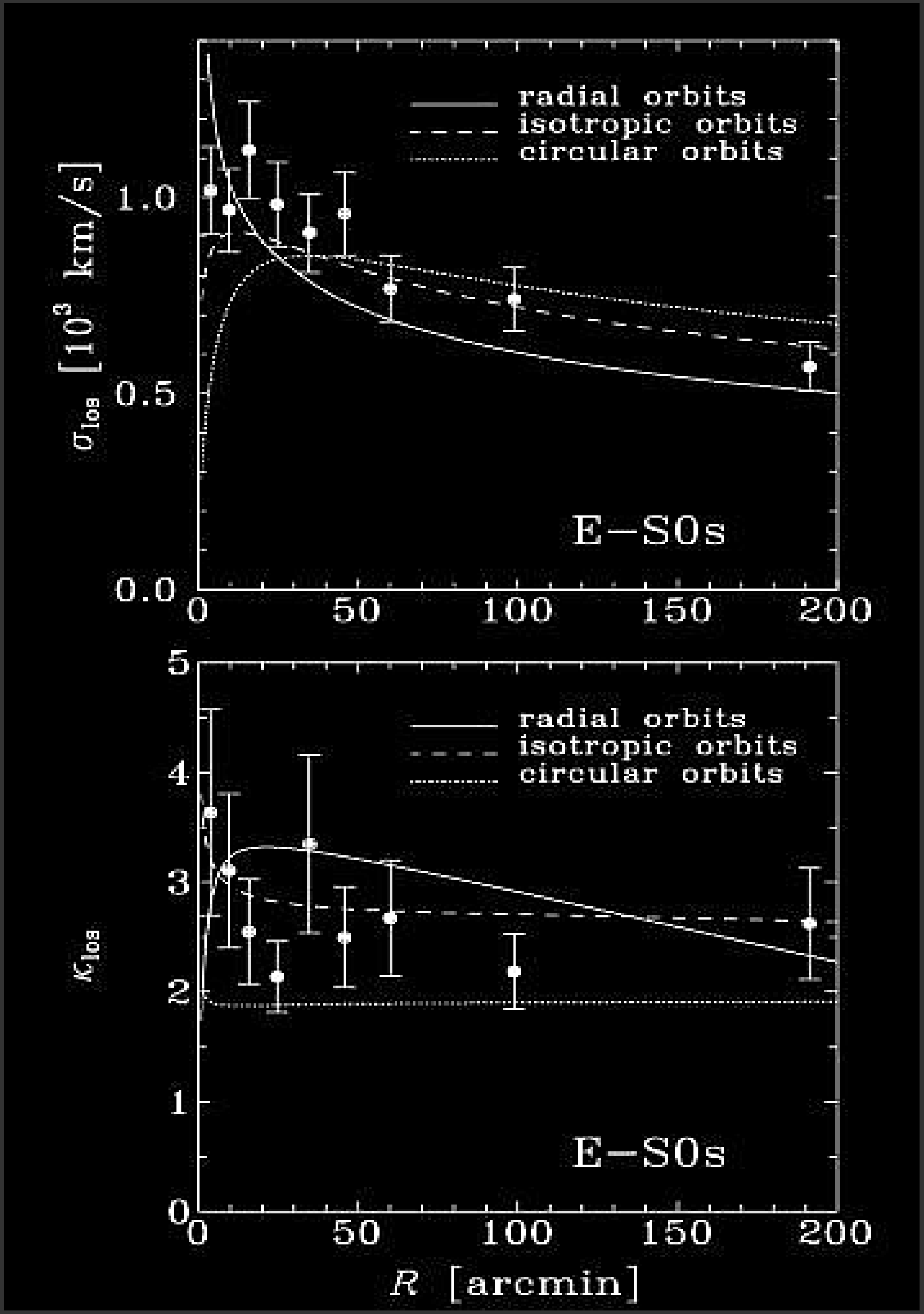
Breaking the M-β degeneracy

- D.F. models cmpd to proj. phase-space distrib. via Maximum Likelihood analysis

- Fit the whole velocity distribution, not only $\sigma_p(R)$

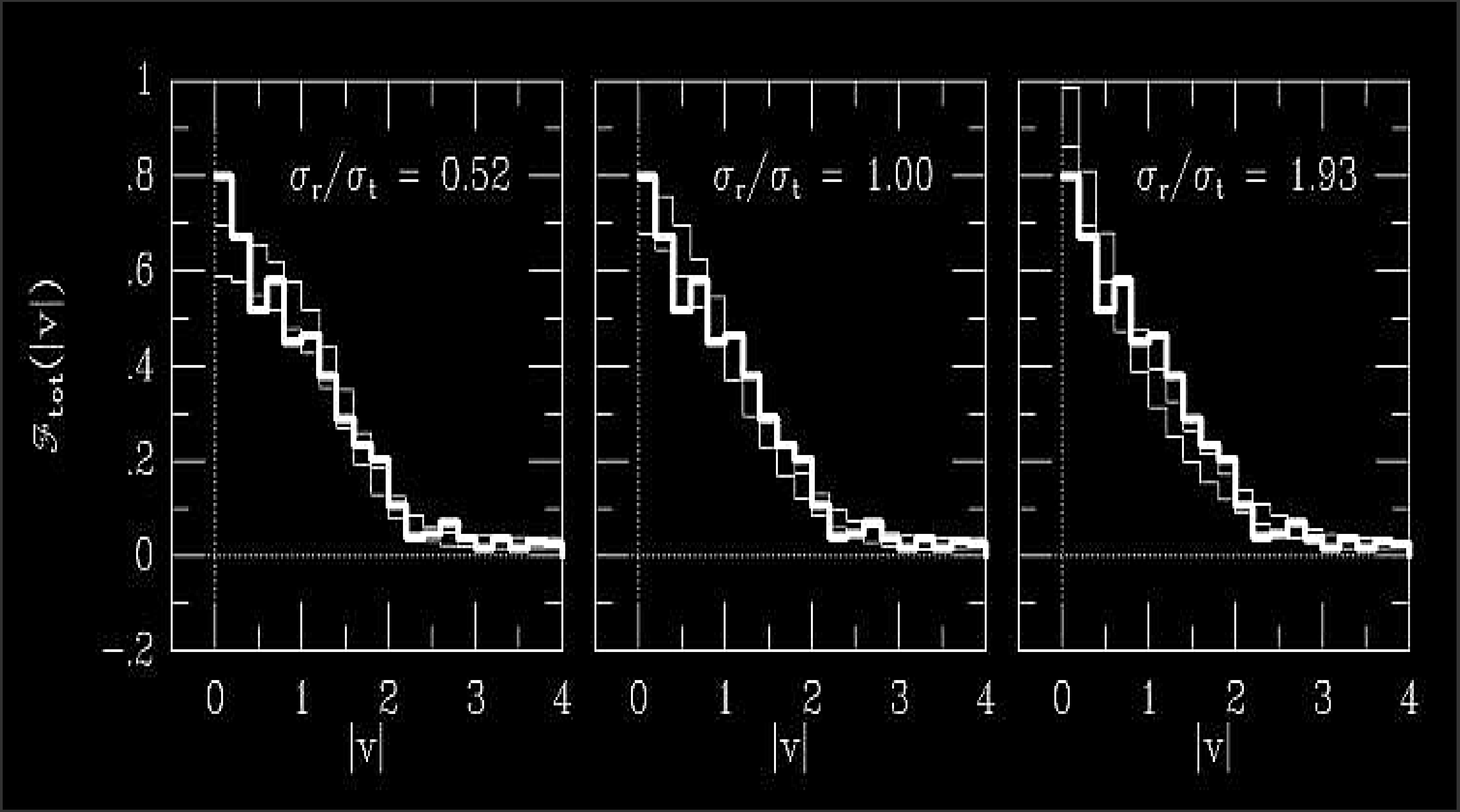
- Use several tracers of the gravitational potential

E.g., use
Kurtosis profile
to constrain $\beta(r)$
of the Coma cluster
(Łokas & Mamon 03)



Velocity dispersion

Velocity kurtosis



E.g. fit the whole velocity distribution of a stacked of several clusters from the CNOC survey (van der Marel + 00)

Additional problems:

- clusters are not closed systems

...but almost: 8% total mass in last 0.1 t_H

Intense accretion phase seen as subclustering

More problems for groups and high-z systems

- no net rotation assumed

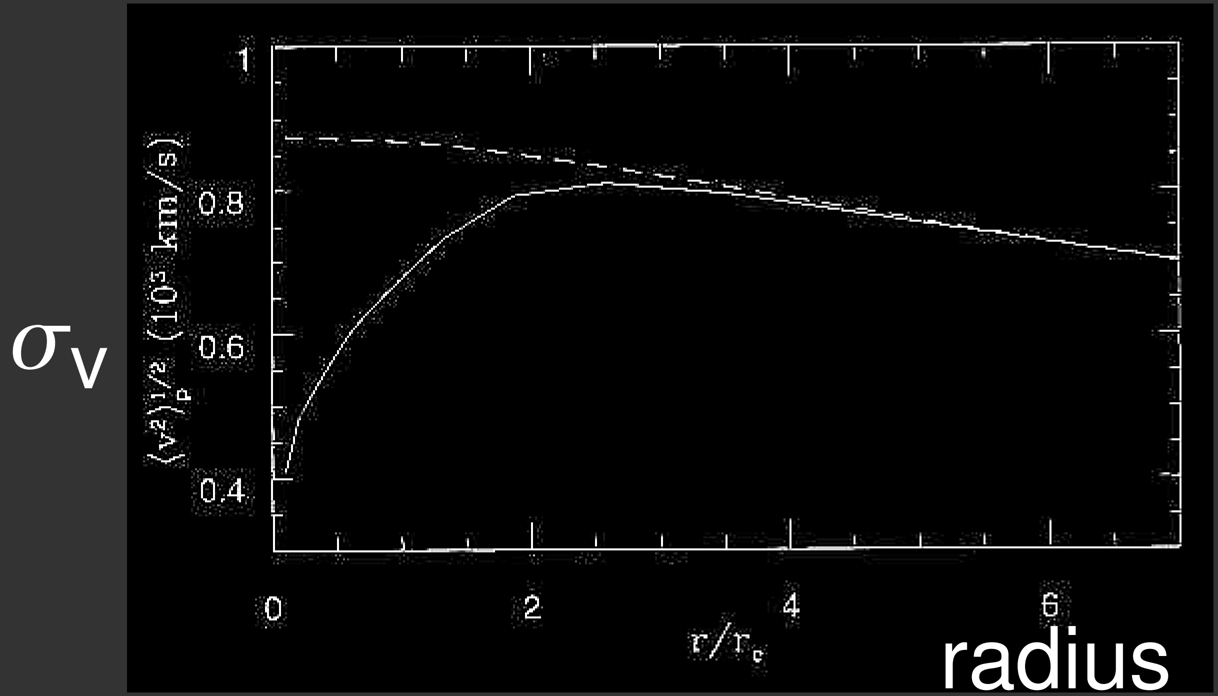
...OK, little if any evidence for rotation

Additional problems:

- collisionless systems?

...high-$\sigma_V \Rightarrow$ no mergers, no dissipation

BUT beware of groups & dynamical friction!



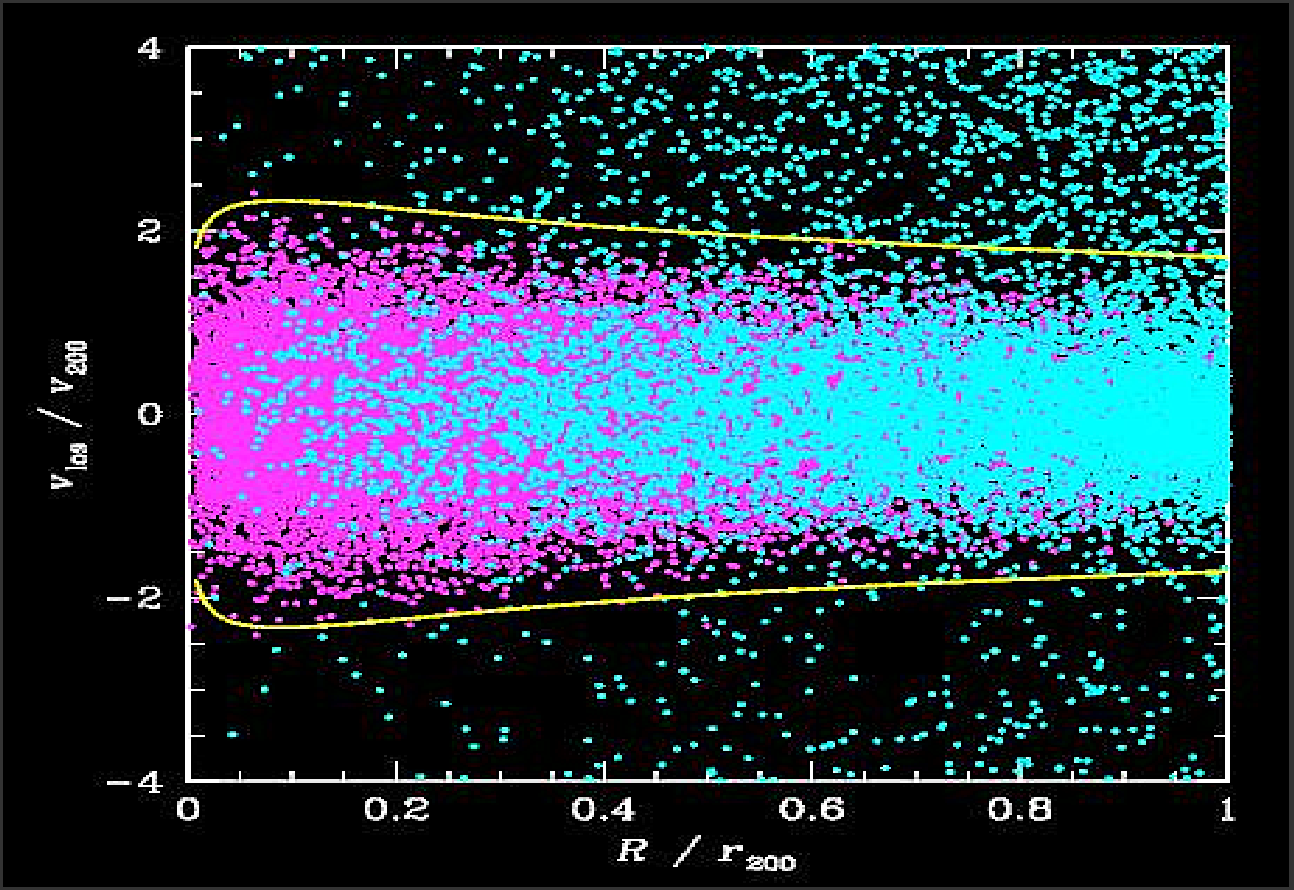
(Menci & Fusco-Femiano 96)

Additional problems:

- interlopers

...several techniques, they work pretty well

Velocity



(Mamon+08)

Radius

(Wojtak & Łokas 07)

Additional problems:

- small number statistics

...few clusters with N_z>500 ➔ STACK MANY

Scale R and V with virial quantities (r_{200}, v_{200})

(clusters quasi-homologous family of objects)

Samples of (stacked) clusters

- CNOC, 16 clusters, $\langle z \rangle$=0.17-0.55, $\langle \sigma_v \rangle \approx$900 km/s, $\approx$1000 gals out to $r<r_{200}$ (Carlberg+97)
- ENACS, 59, 700 km/s, 2700 gals (Katgert+96)
- CAIRNS, 9, 700 km/s, 800 gals (Rines+03)
- CIRS, 65, 600 km/s, 3300 SDSS gals (Rines & Diaferio 06)
- EDisCS, 16, $0.4<z<0.9$, 600 km/s, 500 gals (White+05)
- 2dFGRS, 43, 500 km/s, 700 gals (Biviano & Girardi 03)
- GEMS, 31 X-ray, 350 km/s, 700 gals (Osmond & Ponman 02)

\+ WINGS (Fasano+06) + LARCS (Pimbblet+01)

\+ ICBS (Dressler+09)

An alternative to Jeans: the Caustic technique

A(r)

↓

ϕ(r)

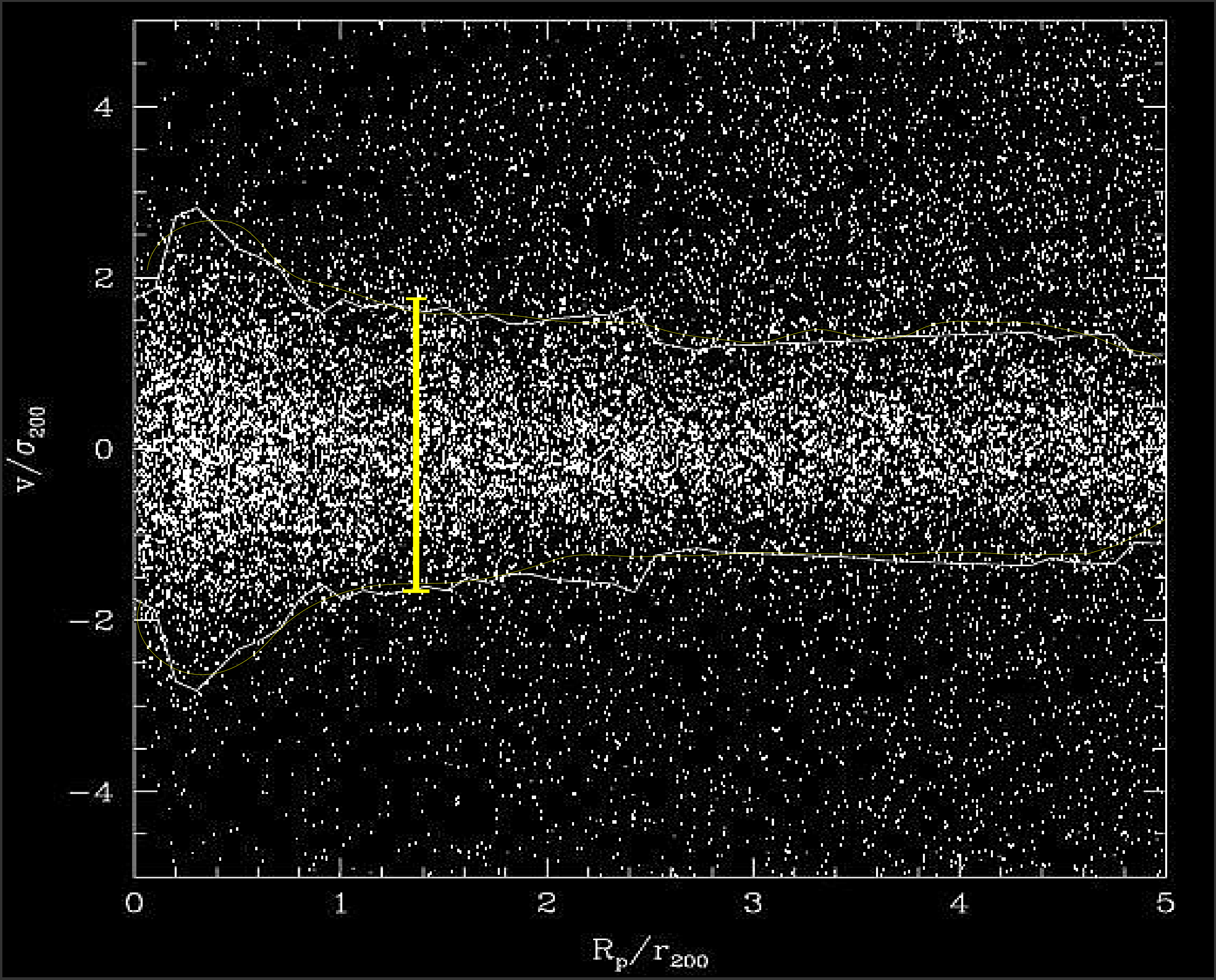
through

F(r;β,ϕ)

$\approx$ const

outside

the center

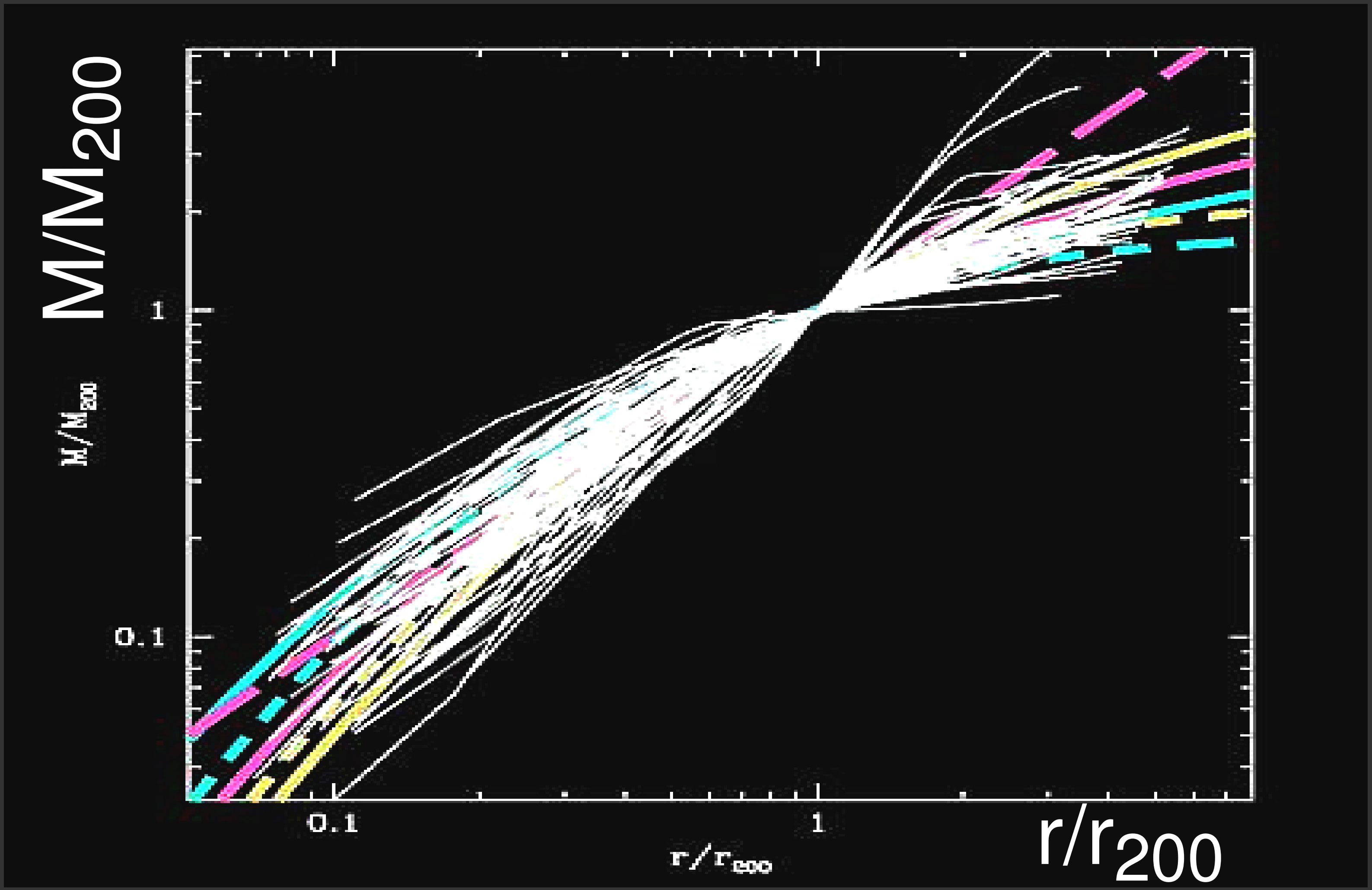


(Diaferio 99; Rines & Diaferio 06)

Mass profiles

CIRS cluster mass profiles (Caustic)

(Rines & Diaferio 06)



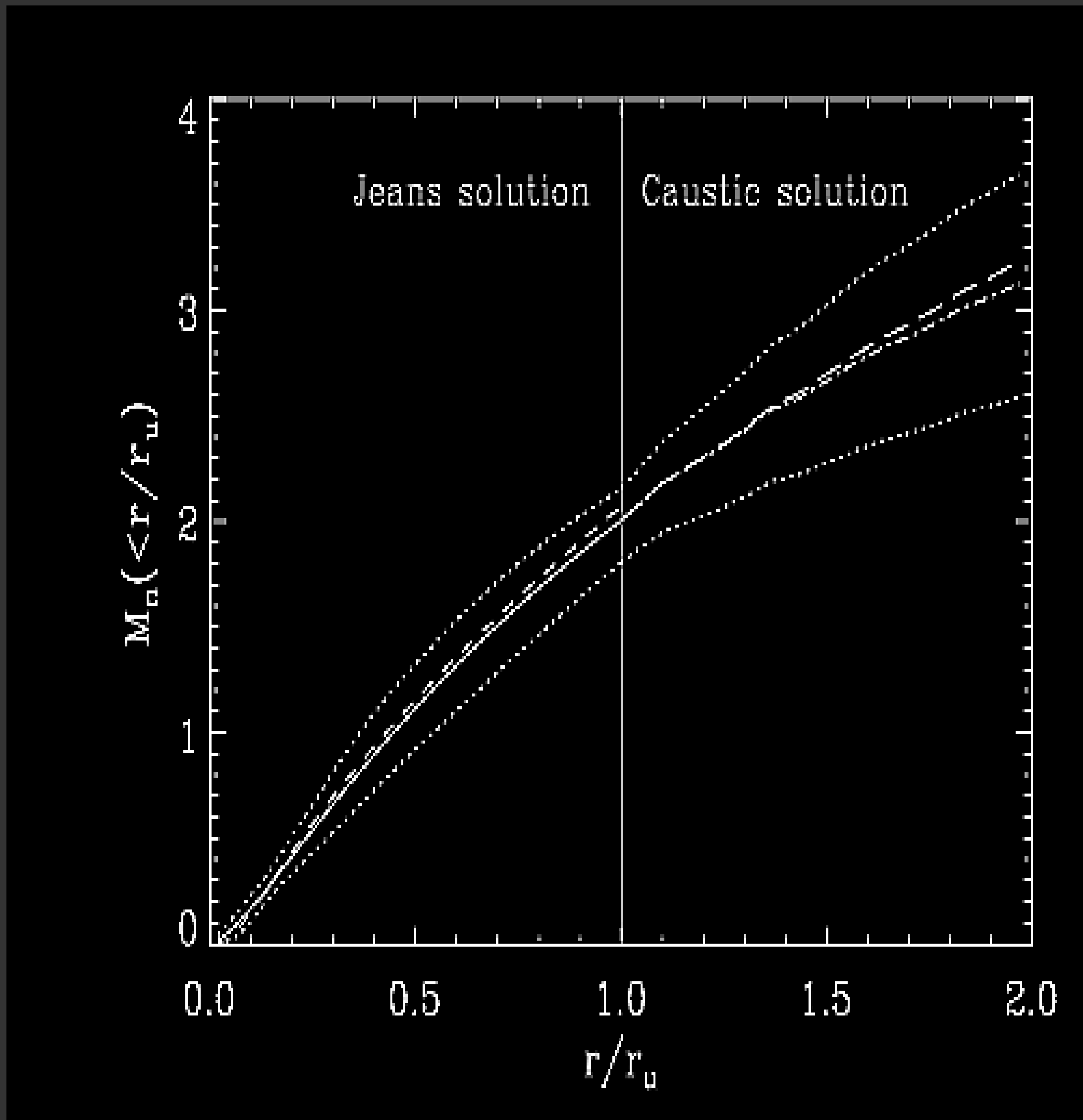
Fitting models: Solid lines: NFW c=3,5,10

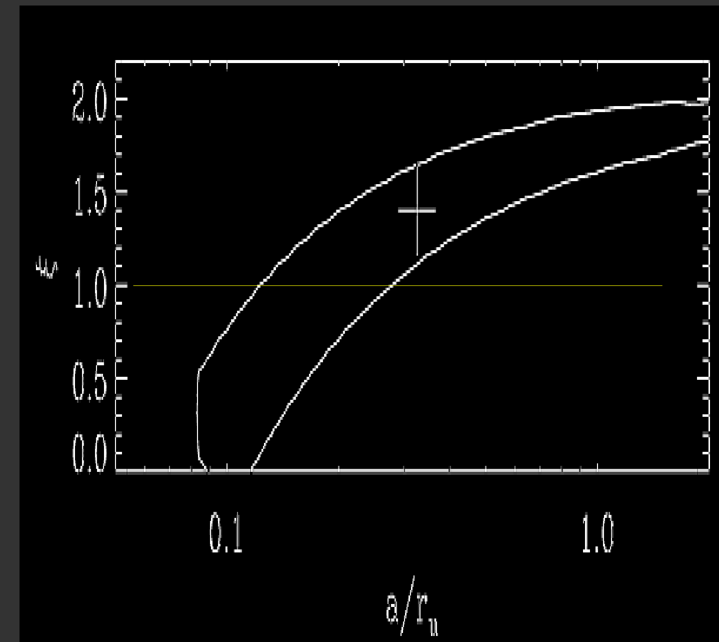
Short dashed: Hernquist

Long dashed: Isothermal sphere

2dFGRS (Jeans + caustic)

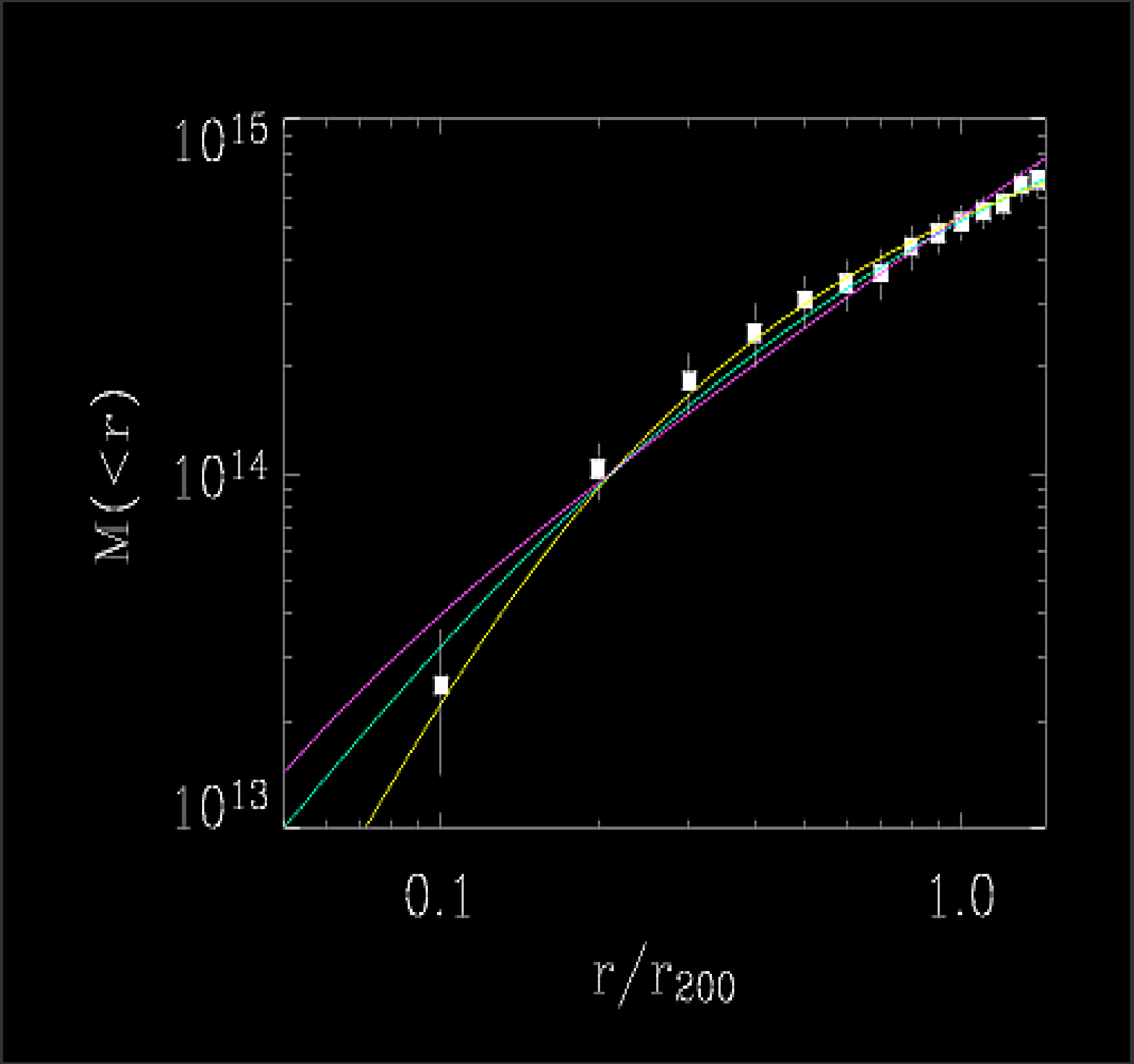
(B. & Girardi 03)





Best-fit inner slope consistent with NFW

ENACS (Jeans)



Burkert

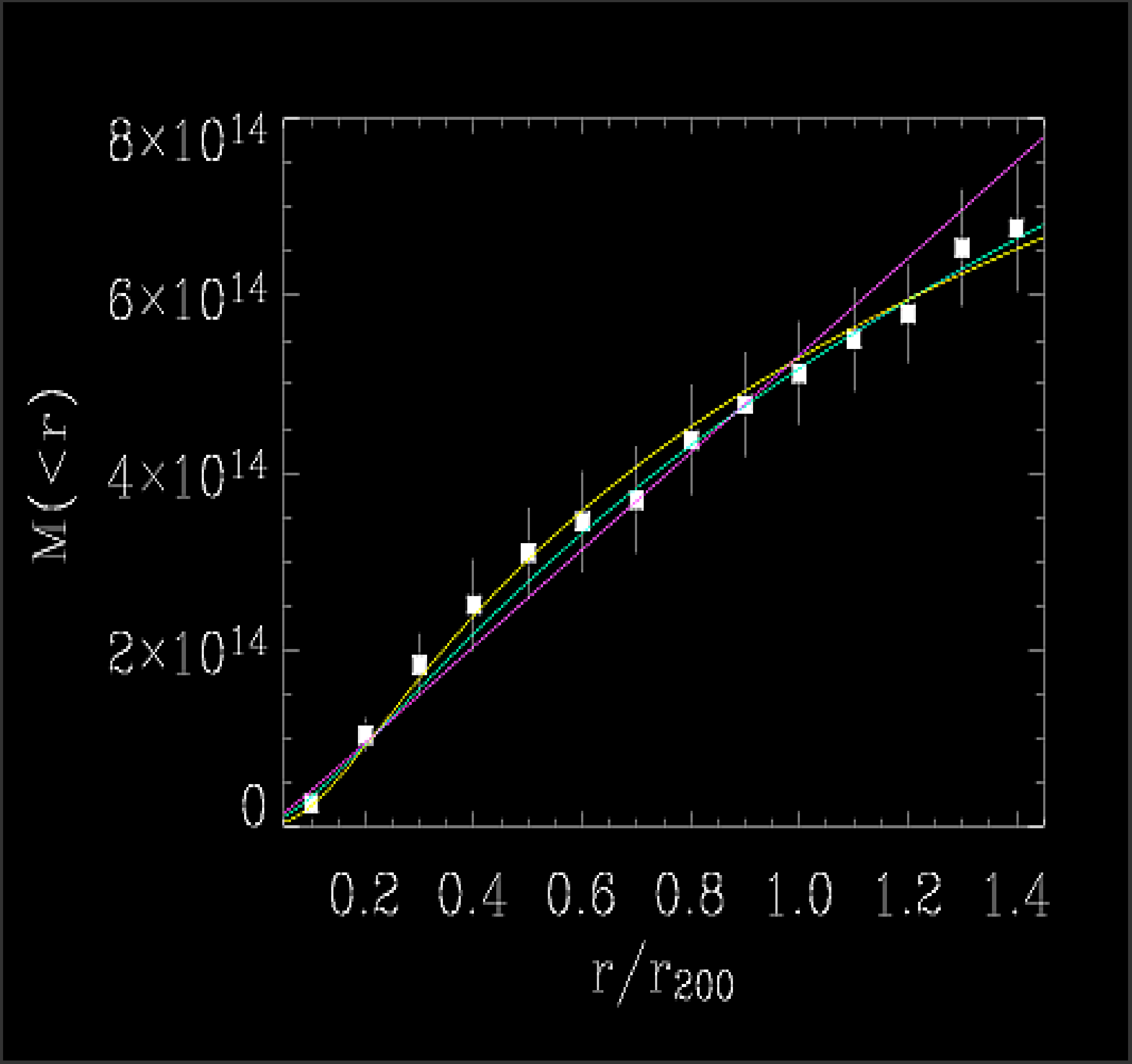
r_c/r_{200}=0.15

NFW c=4±2

SIS

(Katgert+04)

ENACS (Jeans)



Burkert
r_c/r_{200}=0.15

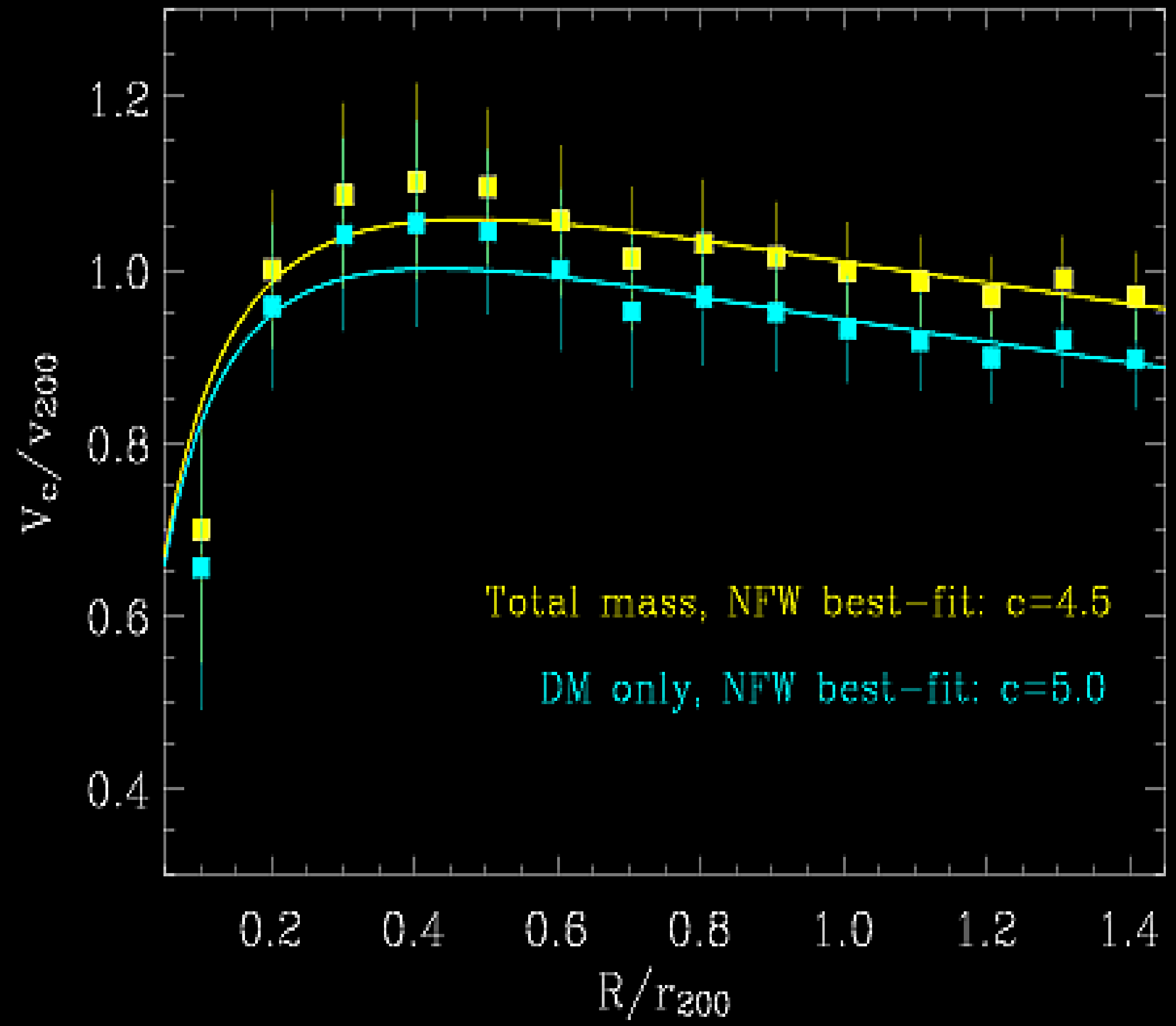
NFW c=4±2

SIS

(Katgert+04)

ENACS (Jeans)

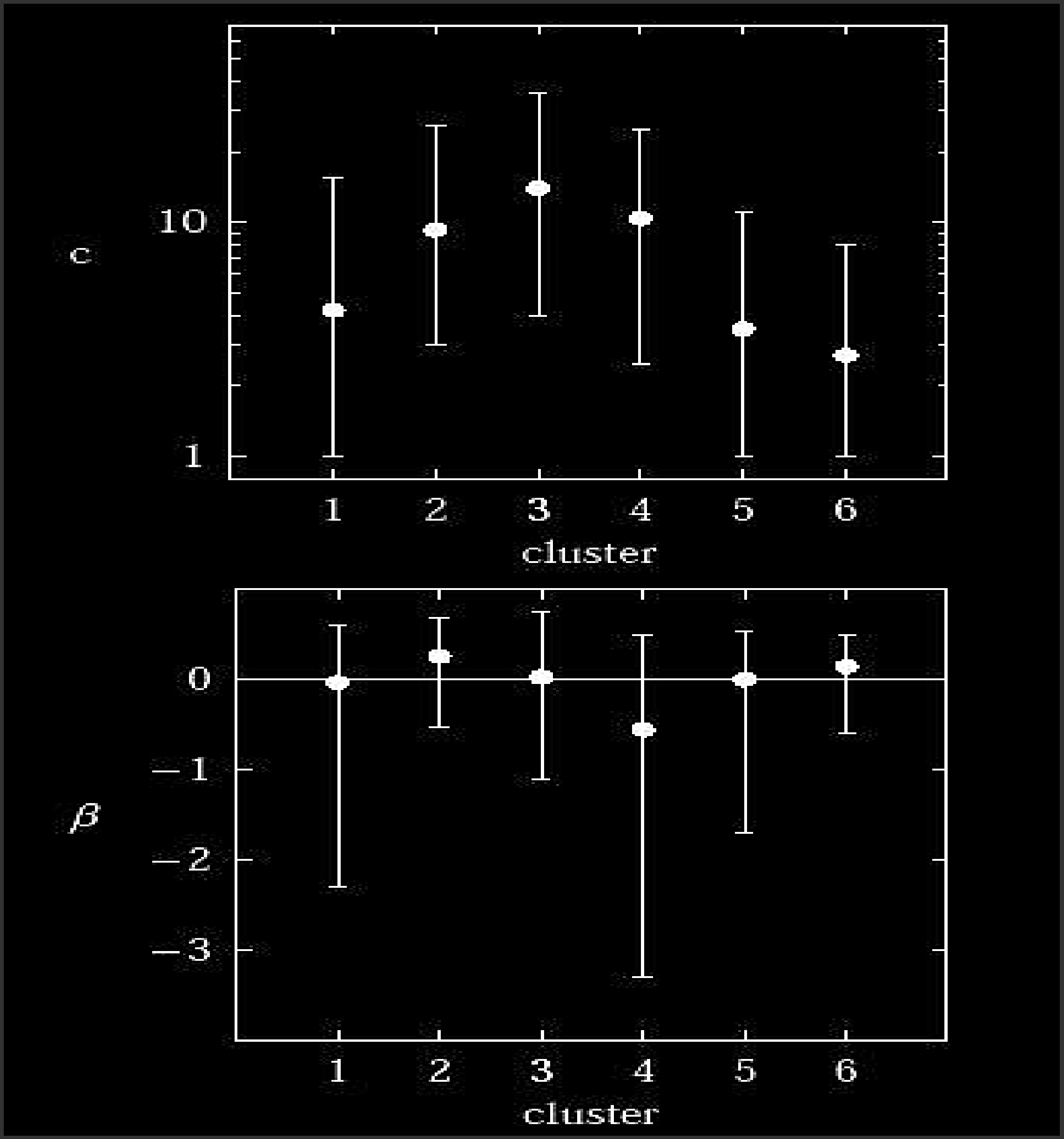
(B. & Salucci 06)



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

Individual clusters (Jeans)

(Łokas+06)



NFW concentration

Velocity constant anisotropy, β

Cluster low-z M(r): NFW OK

Cluster low-z M(r): NFW OK

Core allowed, but r_c ~ size BCG

Cluster low-z M(r): NFW OK

Core allowed, but r_c ~ size BCG

→ DM scattering cross section <2 cm^2 g^{-1}

(by cmp w. num. sims. Meneghetti+01)

5 cm^2 g^{-1} required on galaxy scales (Davé+00)

Cluster low-z M(r): NFW OK

Core allowed, but r_c ~ size BCG

→ DM scattering cross section $<2\ cm^2\ g^{-1}$

(by cmp w. num. sims. Meneghetti+01)

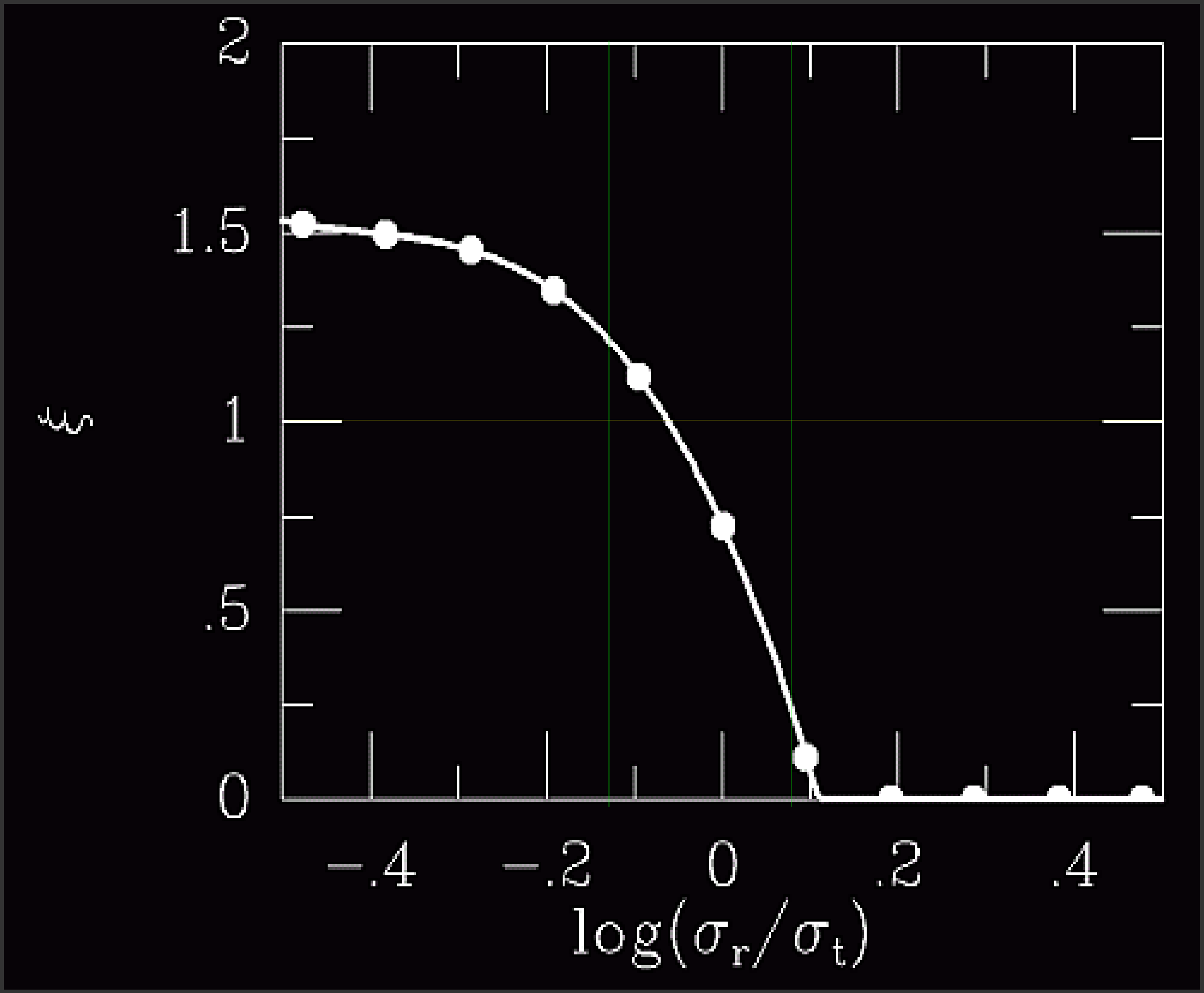
$5\ cm^2\ g^{-1}$ required on galaxy scales (Davé+00)

→ Dynamical friction not very effective

or counteracted by adiabatic contraction

(baryonic infall, Blumenthal+86)

Cluster medium-z M(r): NFW still OK



(van der Marel+00)

Group M(r): controversial results

Hernquist (Mahdavi+99)

Power-law (Mahdavi & Geller 04)

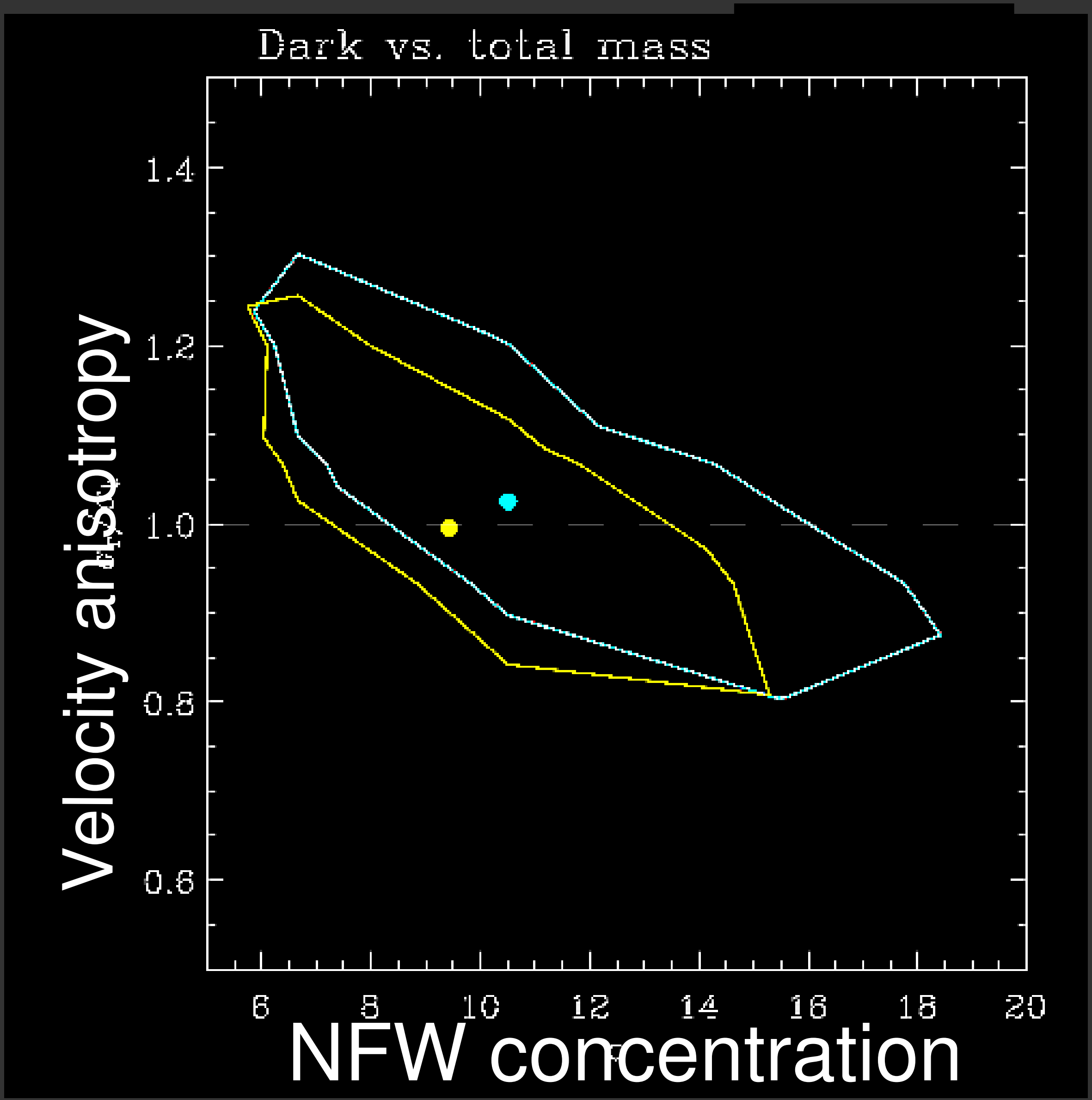
Core (Carlberg+01)

Not all groups are virialized systems

Different samples → different results

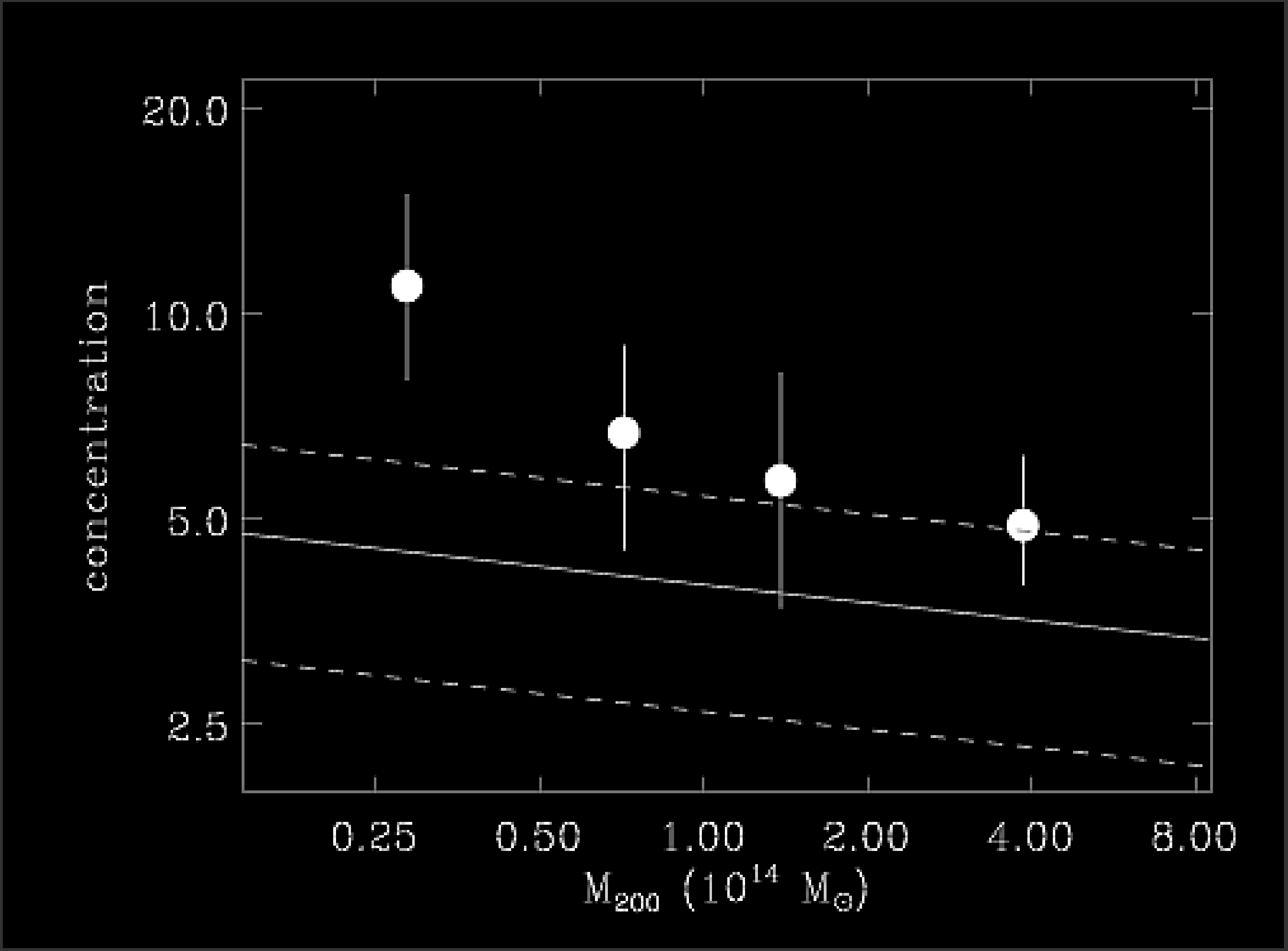
GEMS: X-ray luminous groups

(more likely to be in a virialized state)



(B., Mamon, Ponman, in prep.)

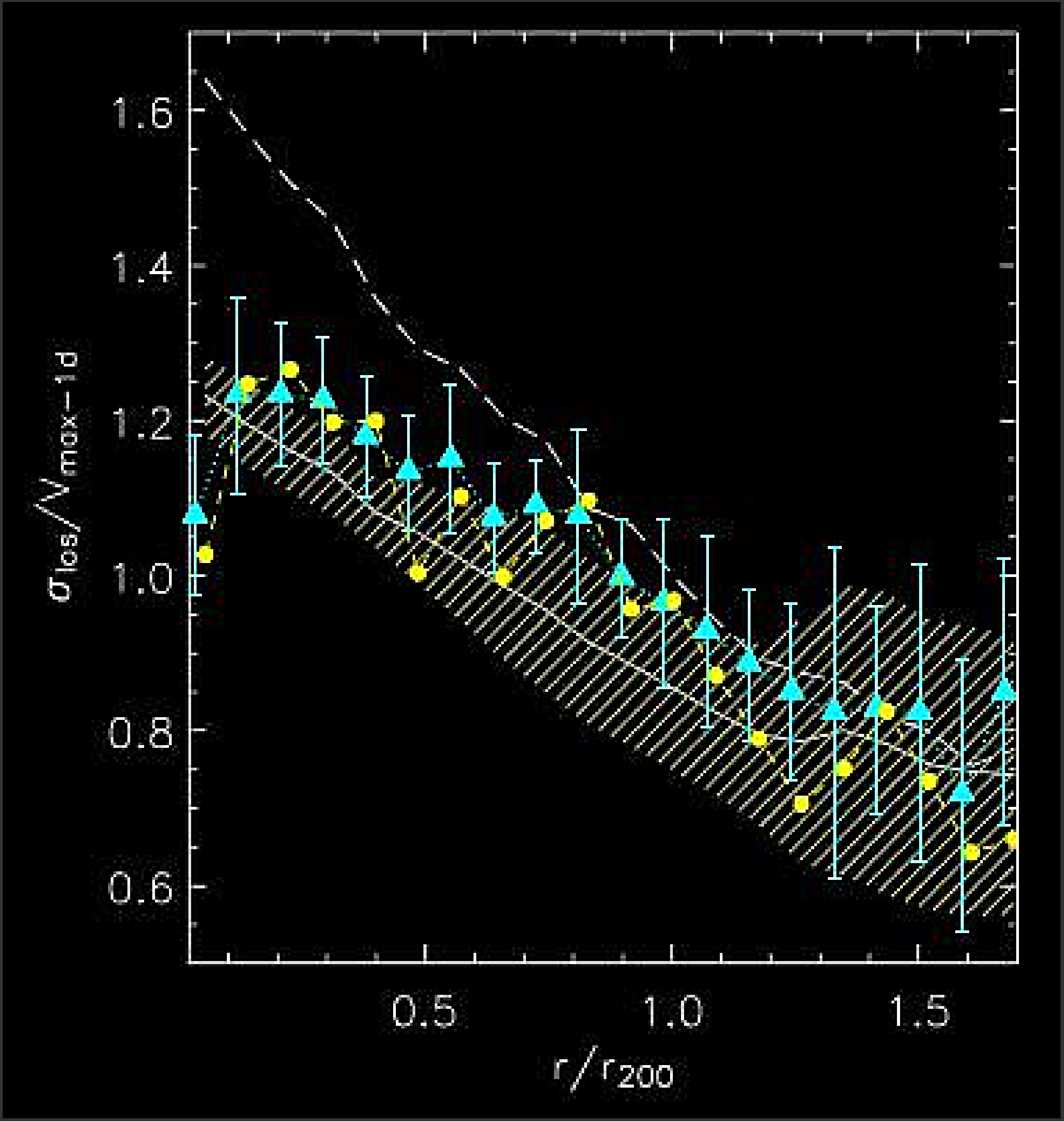
NFW c vs. M



Model from Duffy+08

4 samples: B.+09, Mahdavi+99, B. & Girardi 03, B. & Salucci 06

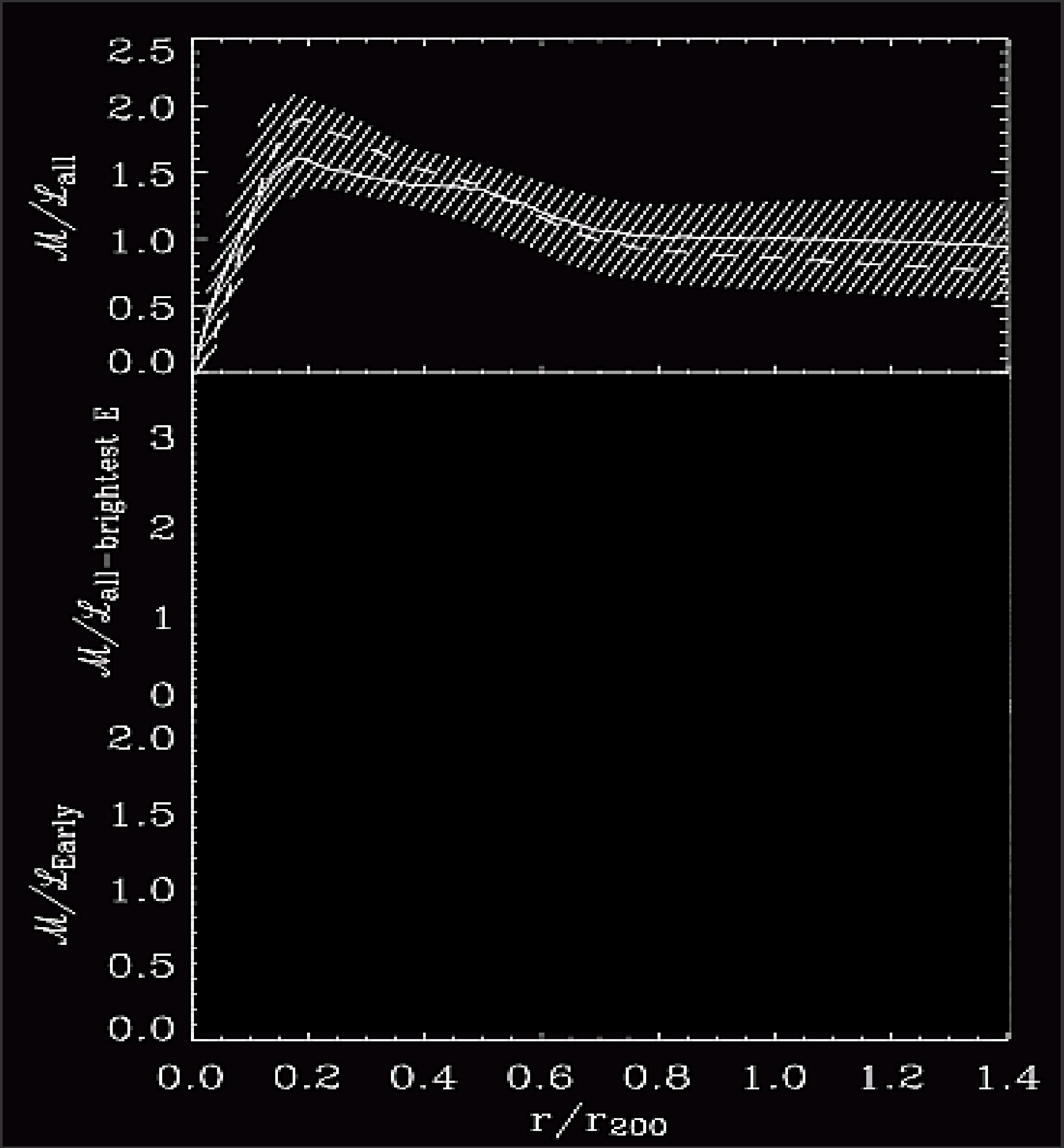
The relative distribution of dark and baryonic matter



Theoretical expectation

(Gao+04)

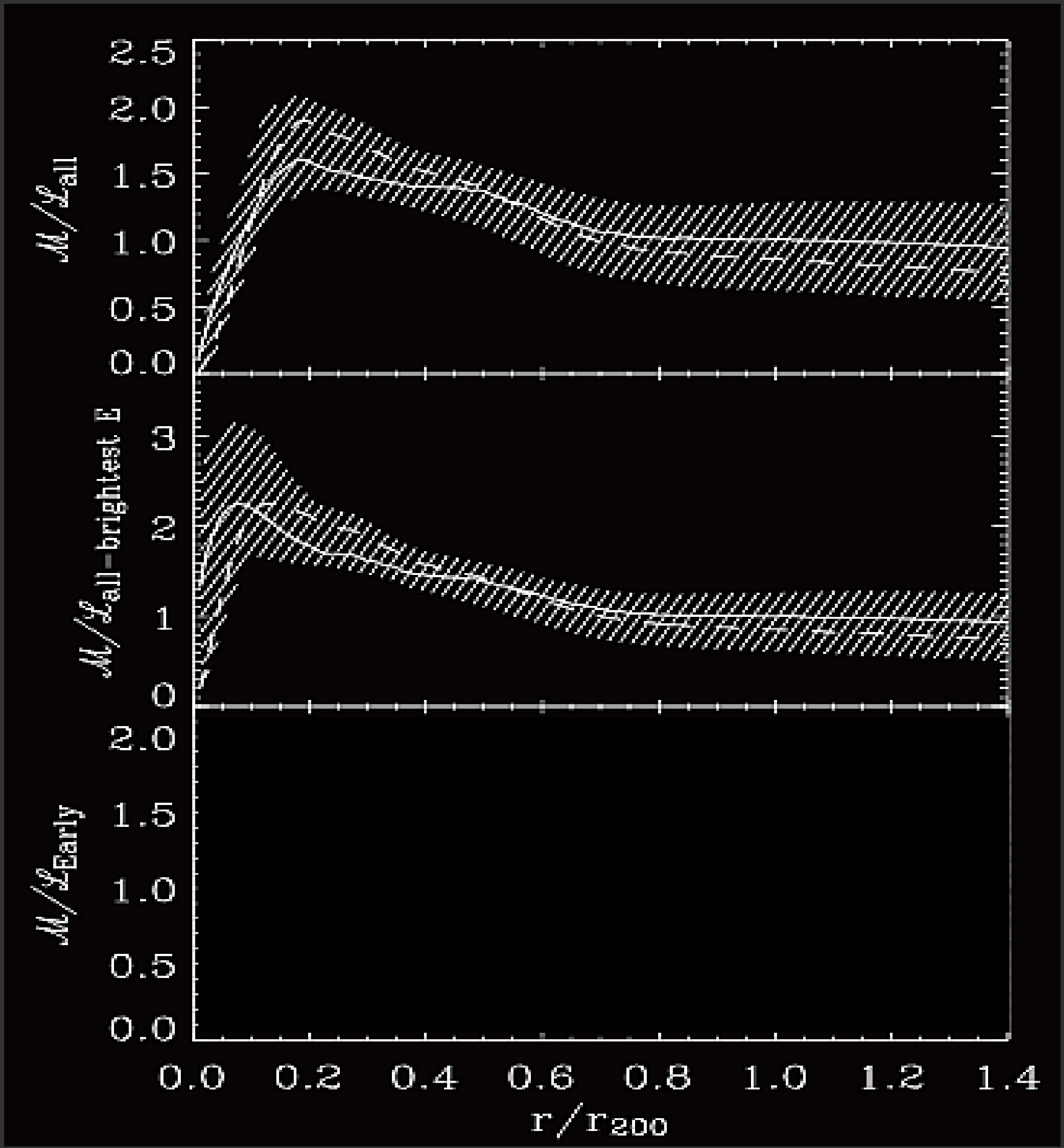
velocity dispersion profiles of subhalos vs. galaxies vs. DM



ENACS

(Katgert+04)

Mass density divided by Luminosity density vs. distance from cluster center



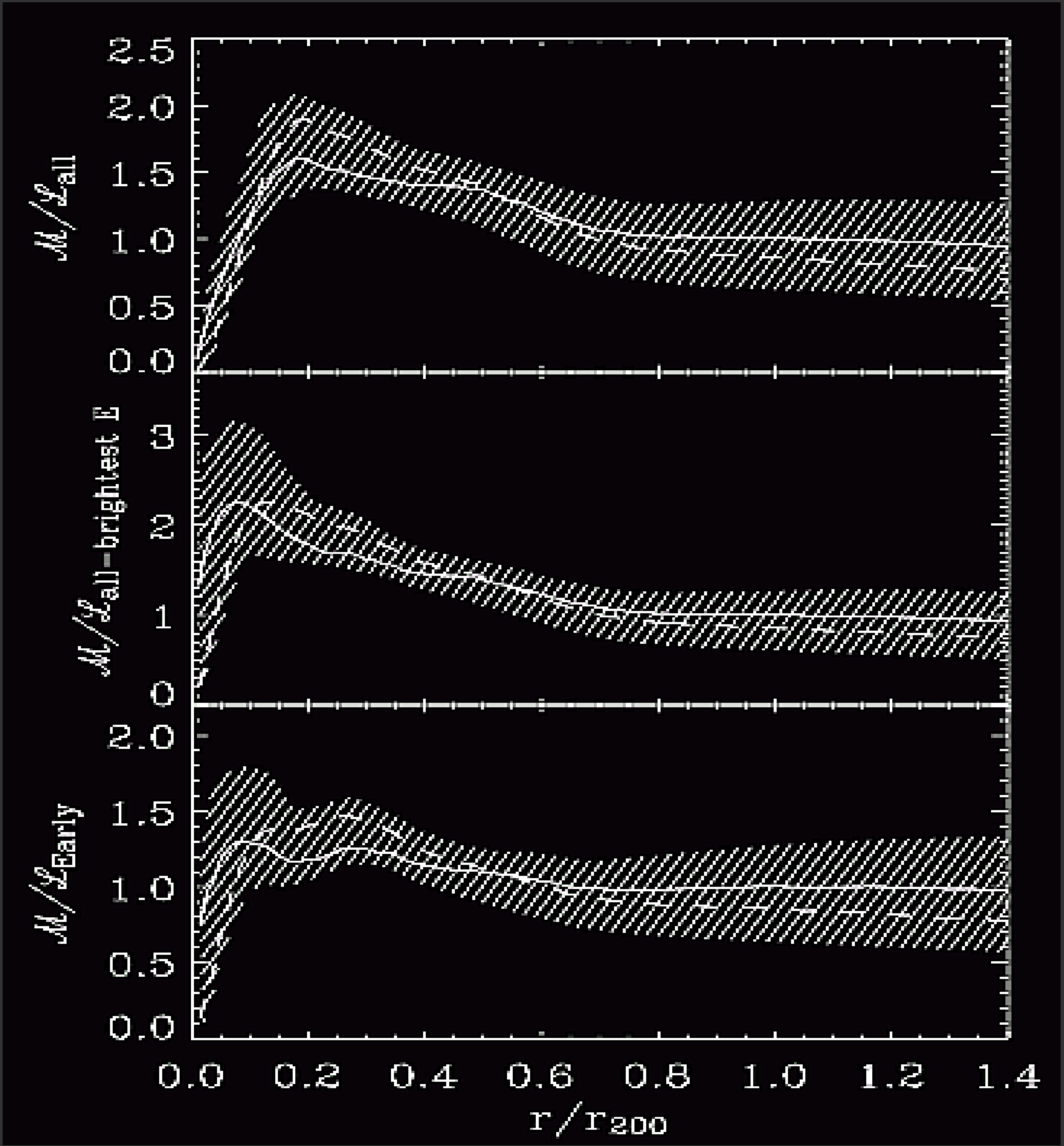
ENACS

(Katgert+04)

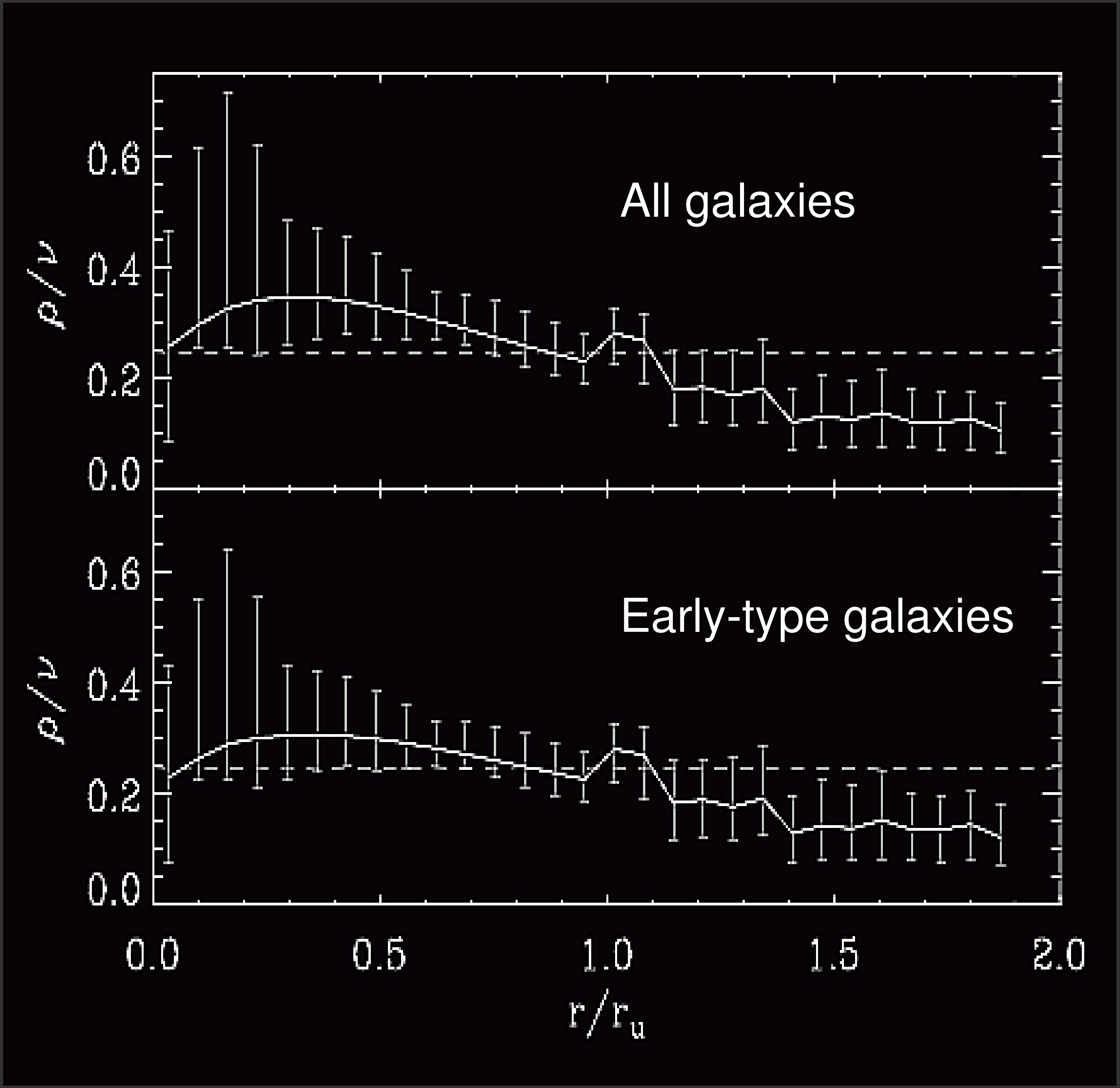
Mass density divided by Luminosity density vs. distance from cluster center

ENACS

(Katgert+04)



Mass density divided by Luminosity density vs. distance from cluster center

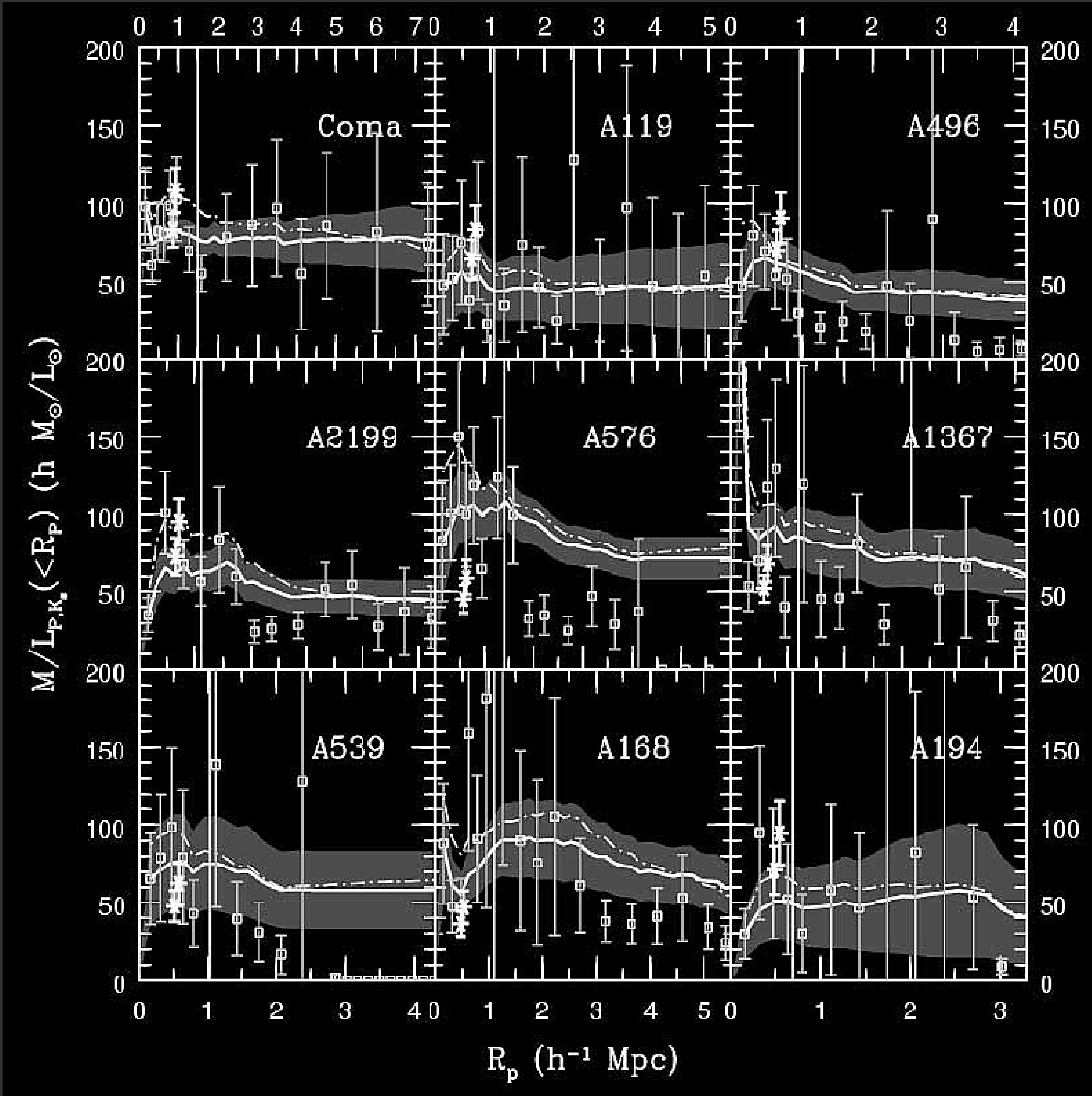


2dFGRS

(B. &

Girardi 03)

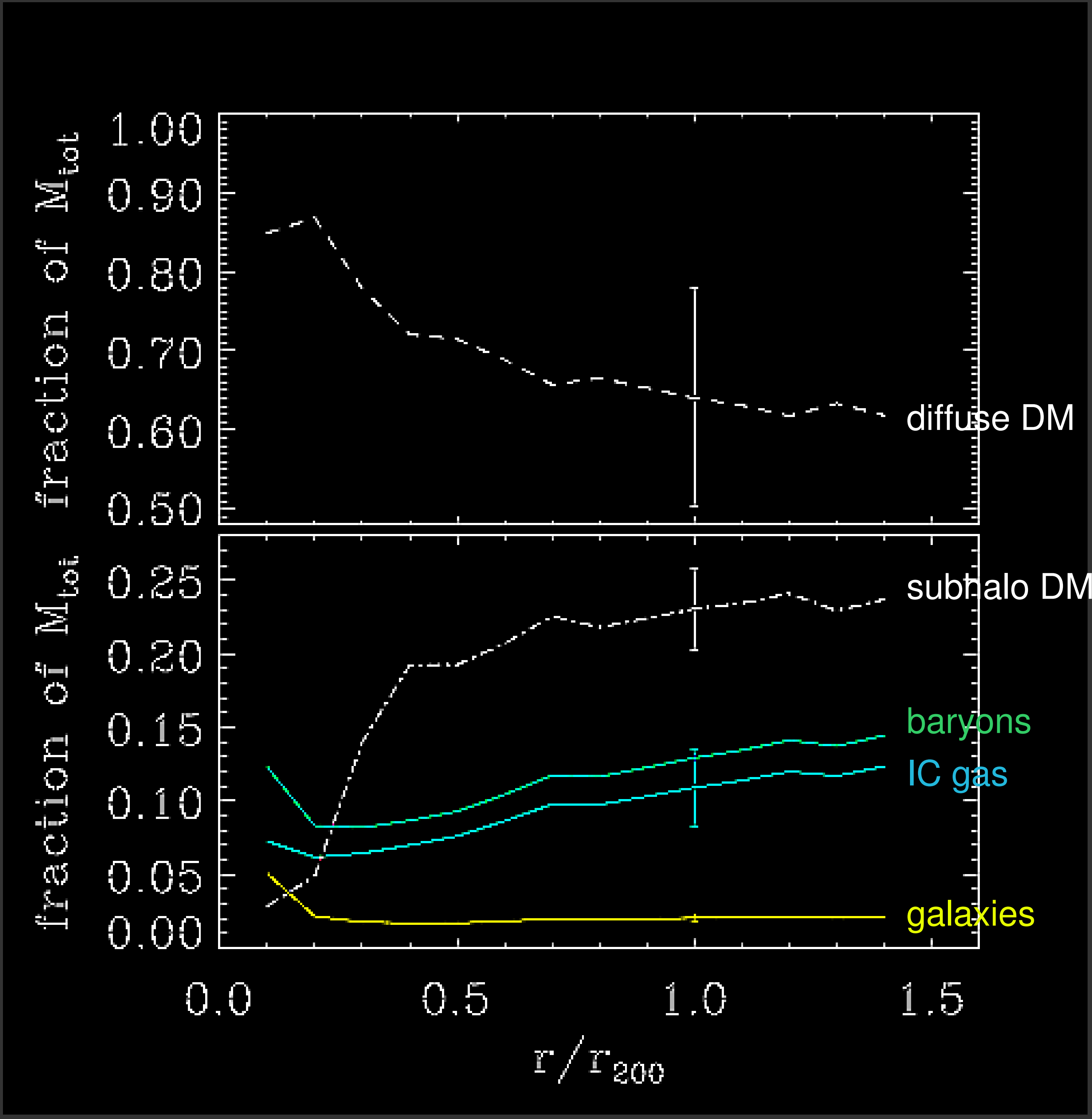
Mass density divided by Number density vs. distance from cluster center



CAIRNS

(Rines+04)

M(<r) divided by K-band L(<R) vs. distance from cluster center



ENACS

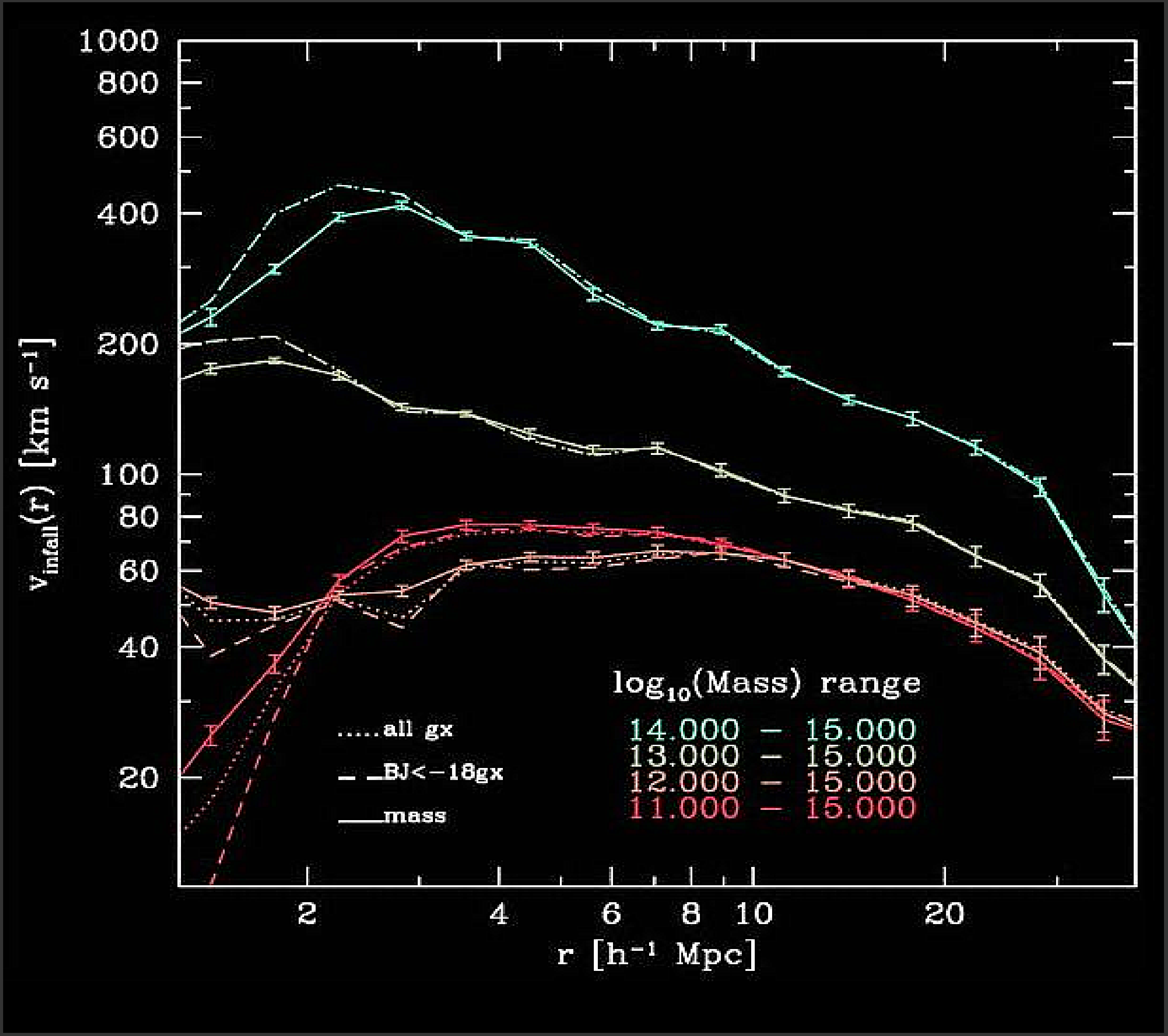
(B.

& Salucci 06)

The mass budget in clusters of galaxies

Mass accretion

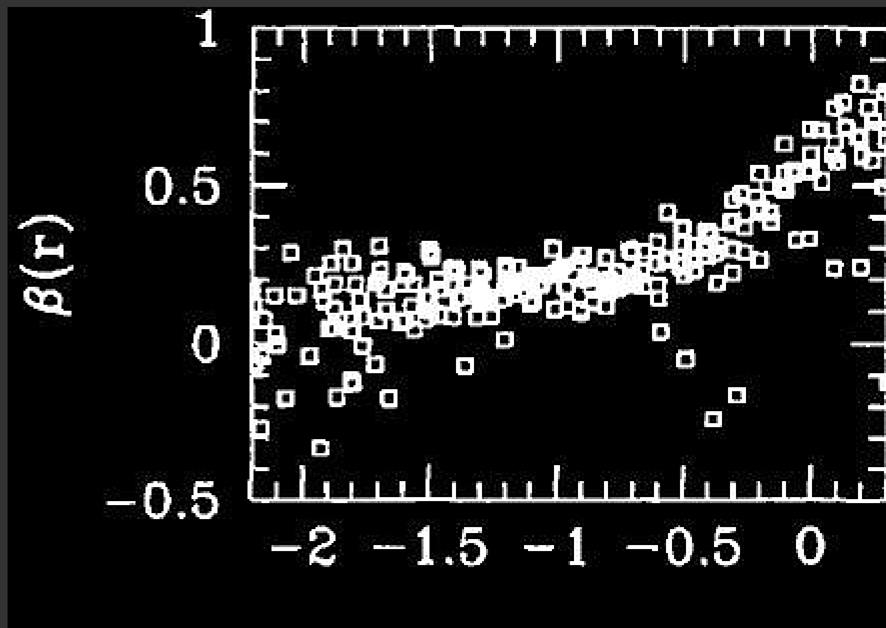
Direct test of hierarchical clustering: evidence for infall?

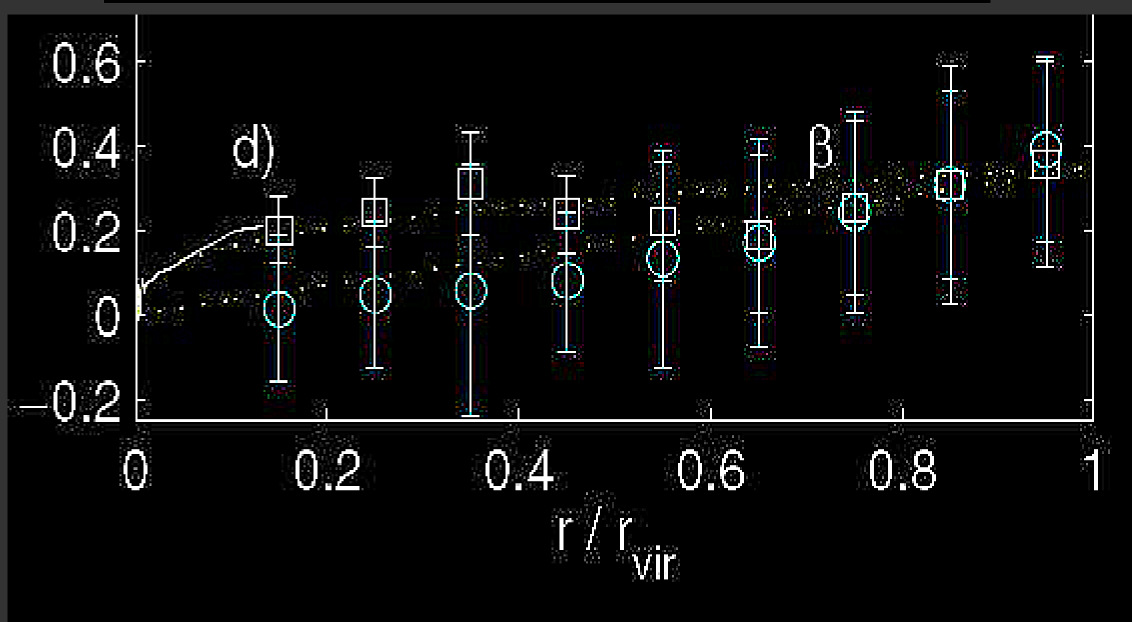


Theoretical predictions

(Ceccarelli+05)

Direct test of hierarchical clustering: evidence for infall?



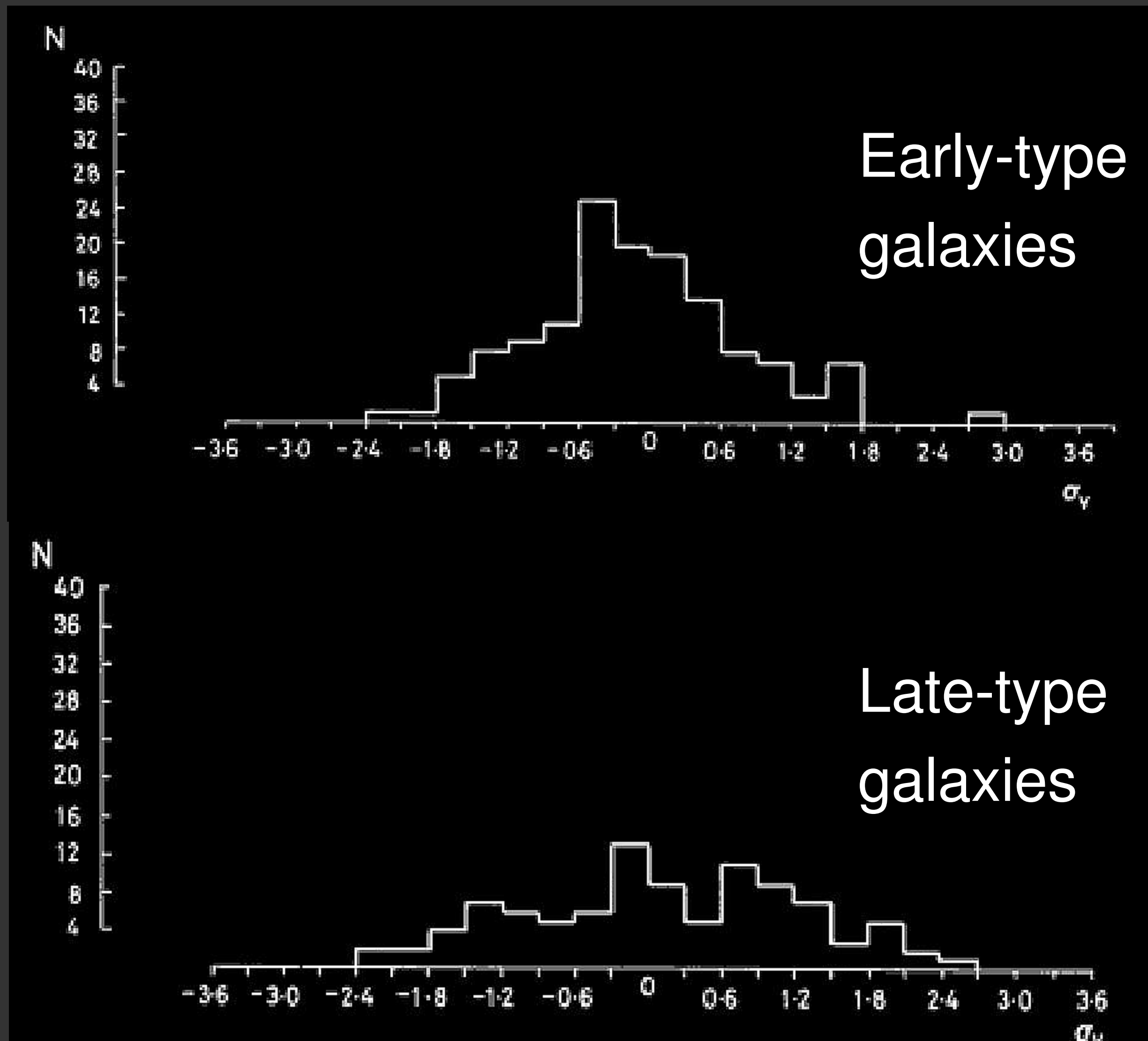


Theoretical predictions

(Tormen+97)
(Diemand+04)

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

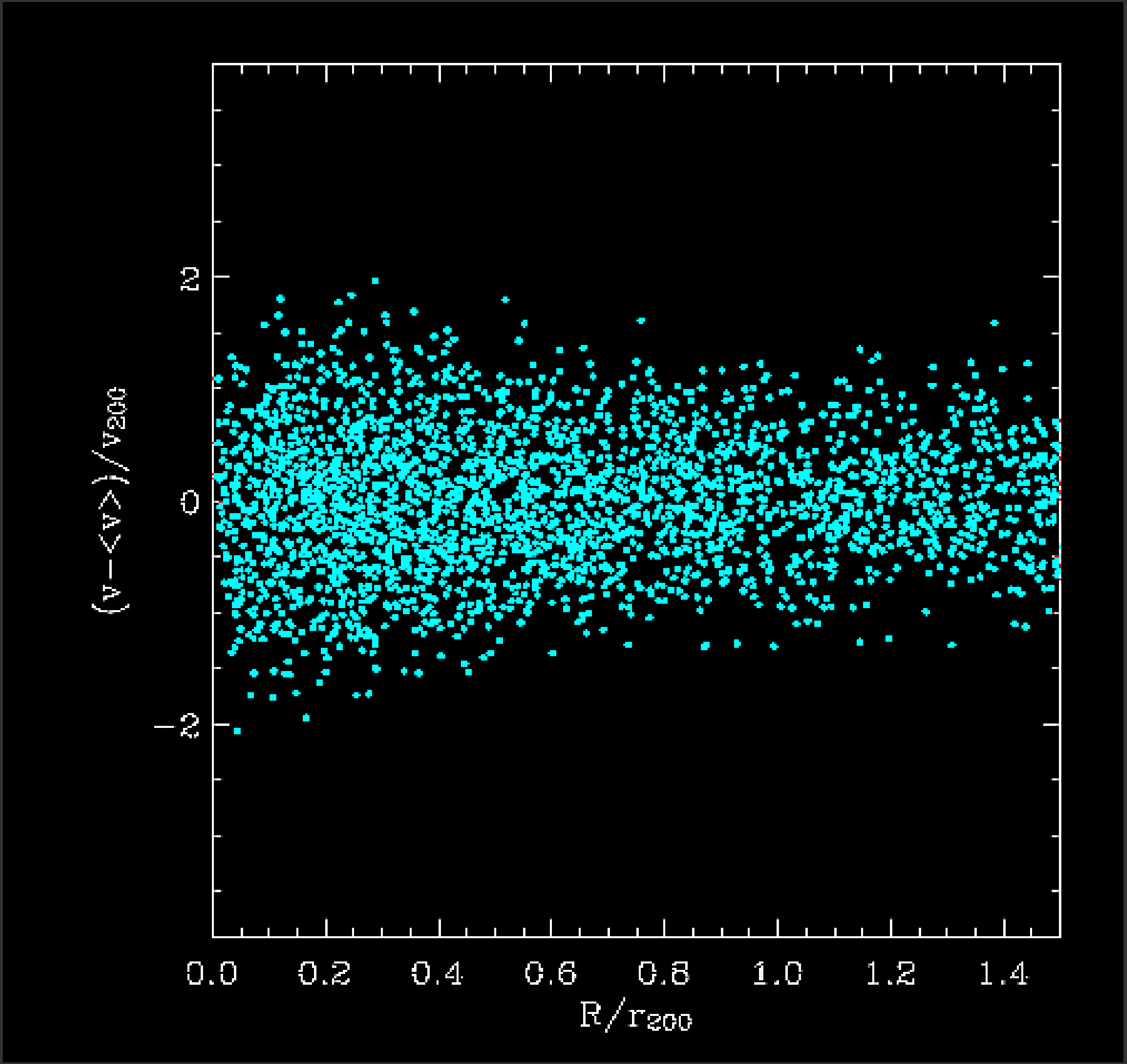
Early- and Late-type gals: different distributions



(Moss & Dickens 77)

Velocity wrt cluster mean

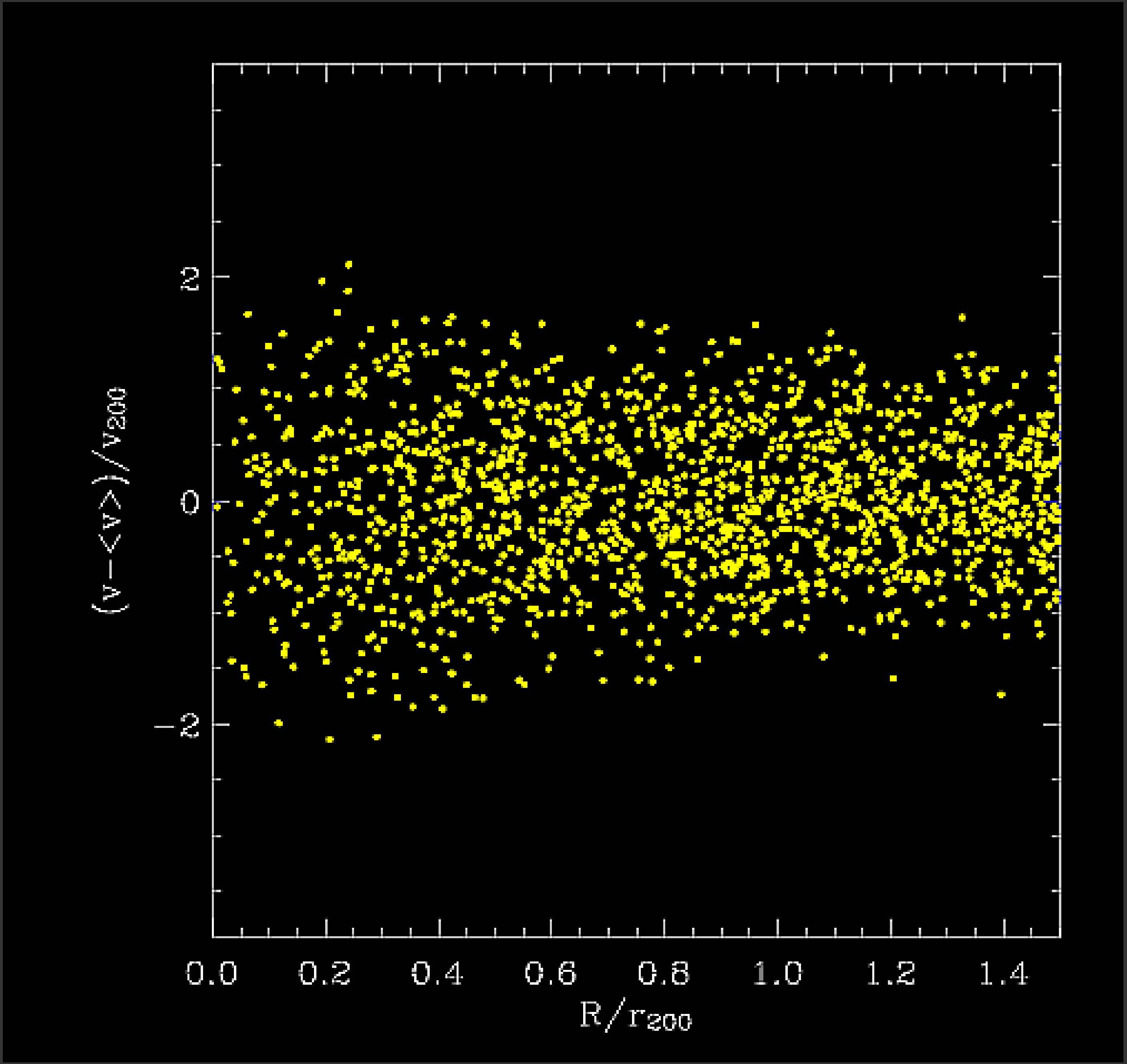
Early- and Late-type gals: different distributions



Early-type galaxies

(CIRS; B., Diaferio, Rines, in prep)

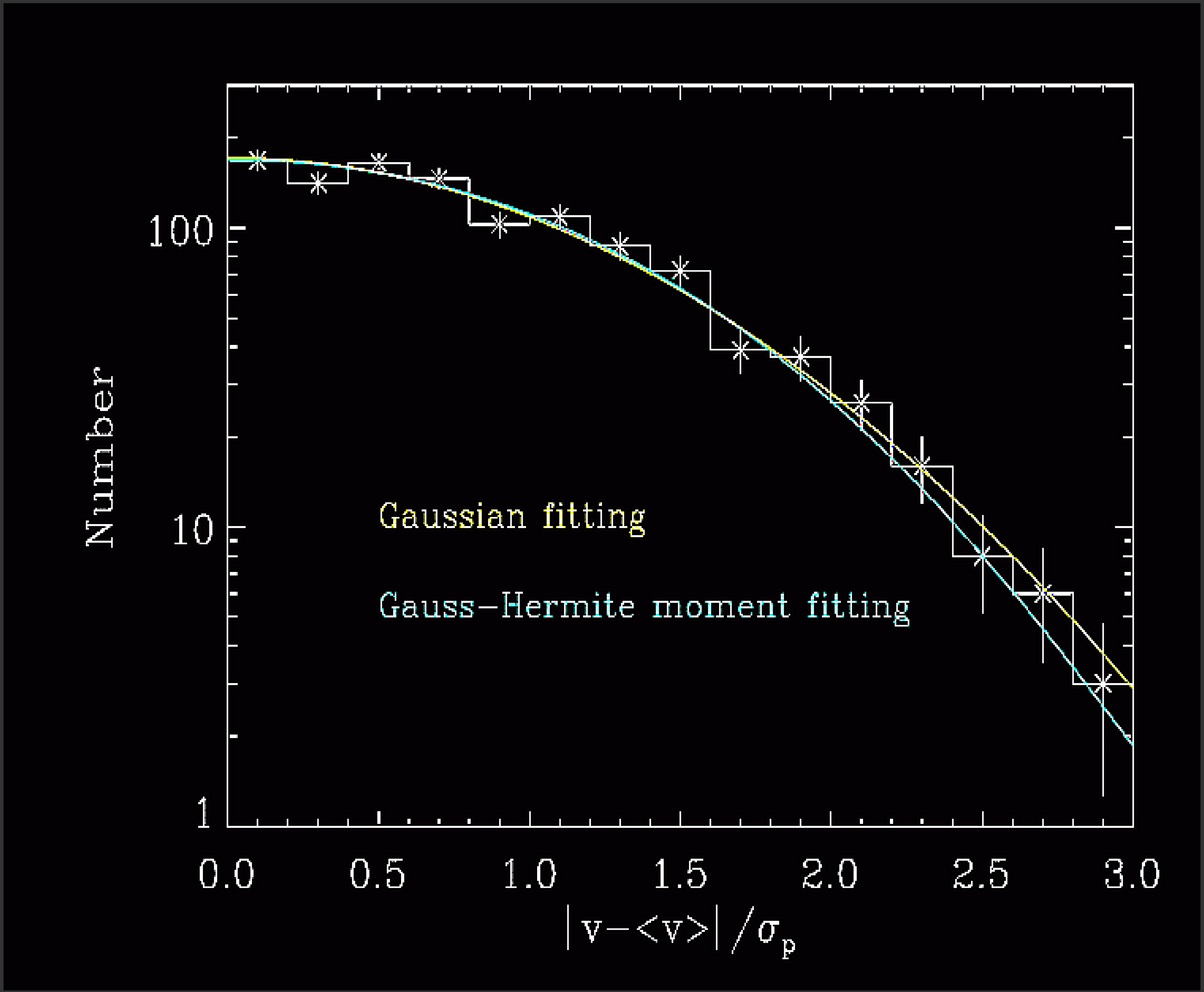
Early- and Late-type gals: different distributions



Late-type galaxies

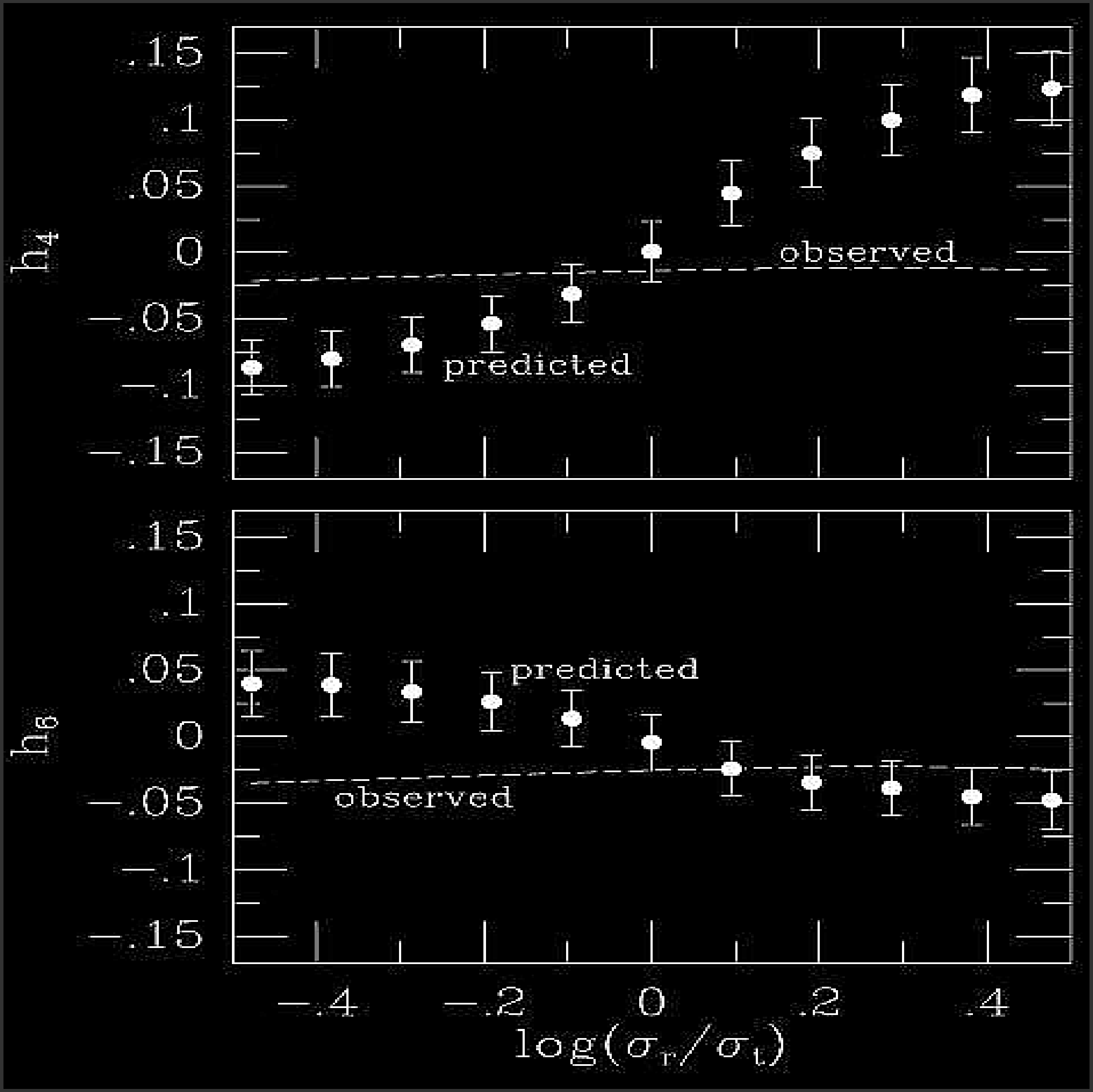
(CIRS; B., Diaferio, Rines, in prep)

Early-type gals: ~isotropic orbits, $\beta \approx 0$



ENACS
(Katgert+04)

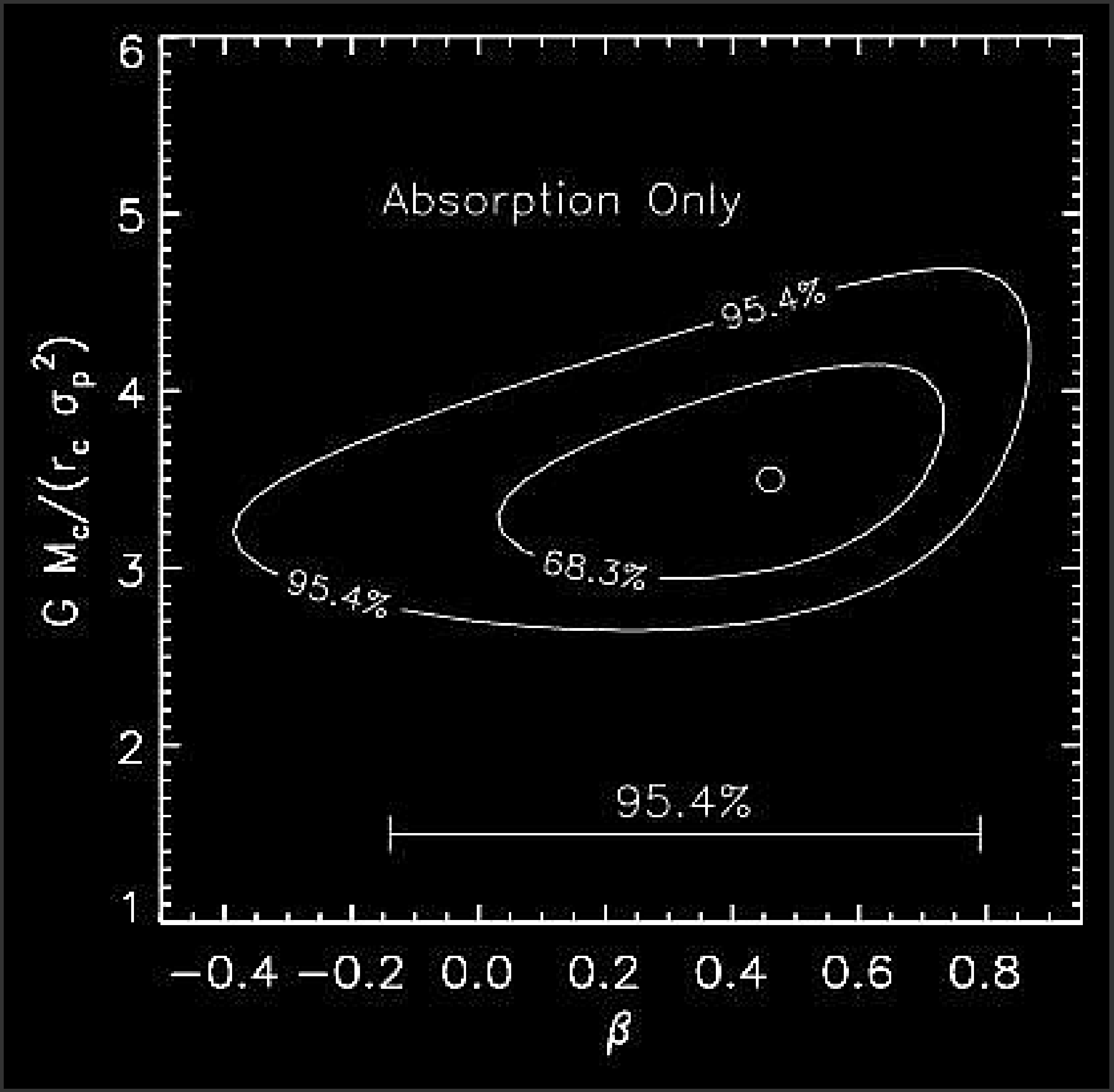
Early-type gals: ~isotropic orbits, $\beta \approx 0$



CNOC

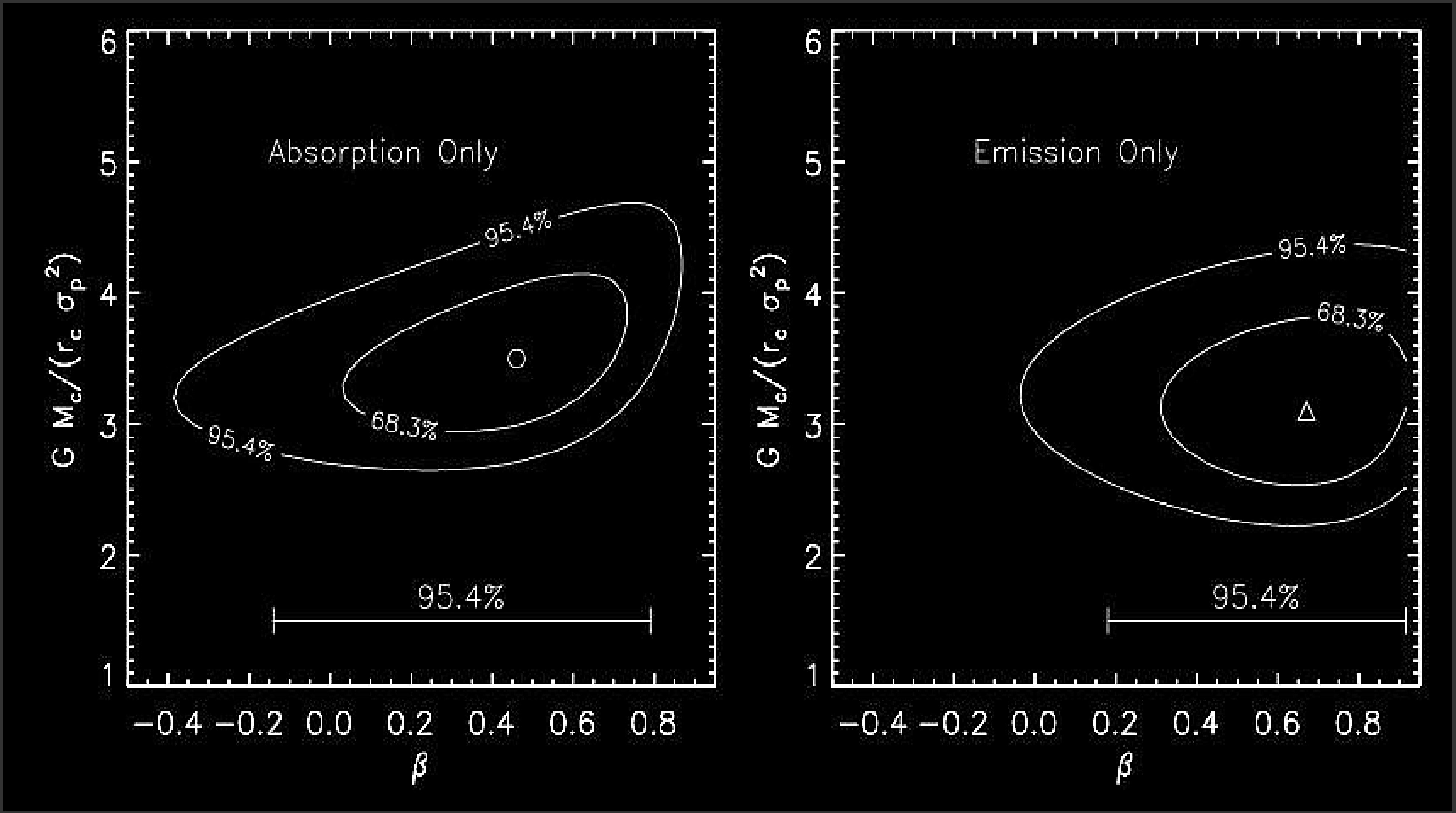
(van der Marel+00)

Early-type gals: ~isotropic orbits, $\beta \approx 0$



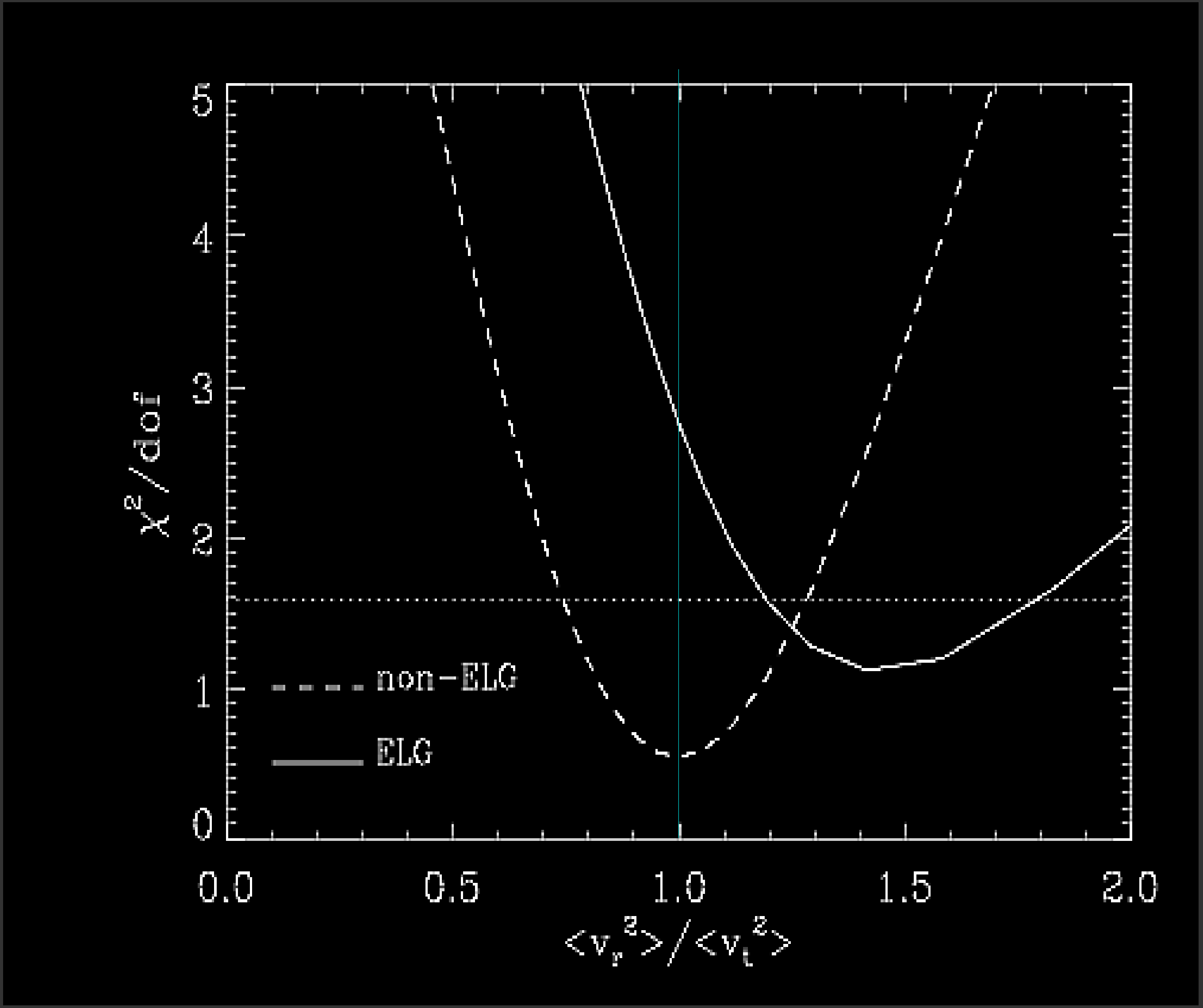
Poor clusters
(Mahdavi+99)

Late-type gals: mildy radial orbits, β>0



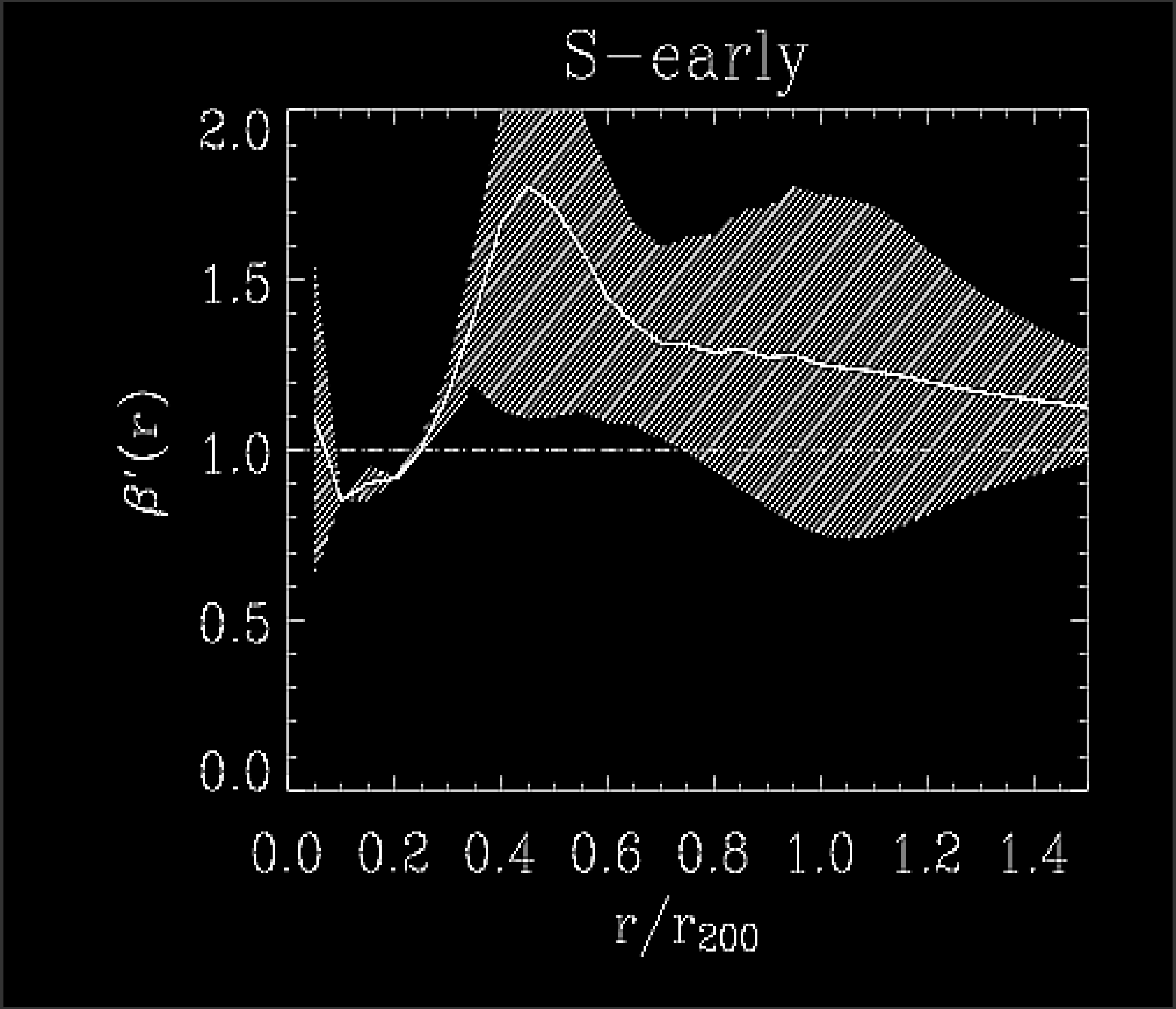
Poor clusters (Mahdavi+99)

Late-type gals: mildy radial orbits, $\beta>0$



ENACS
(B. 01)

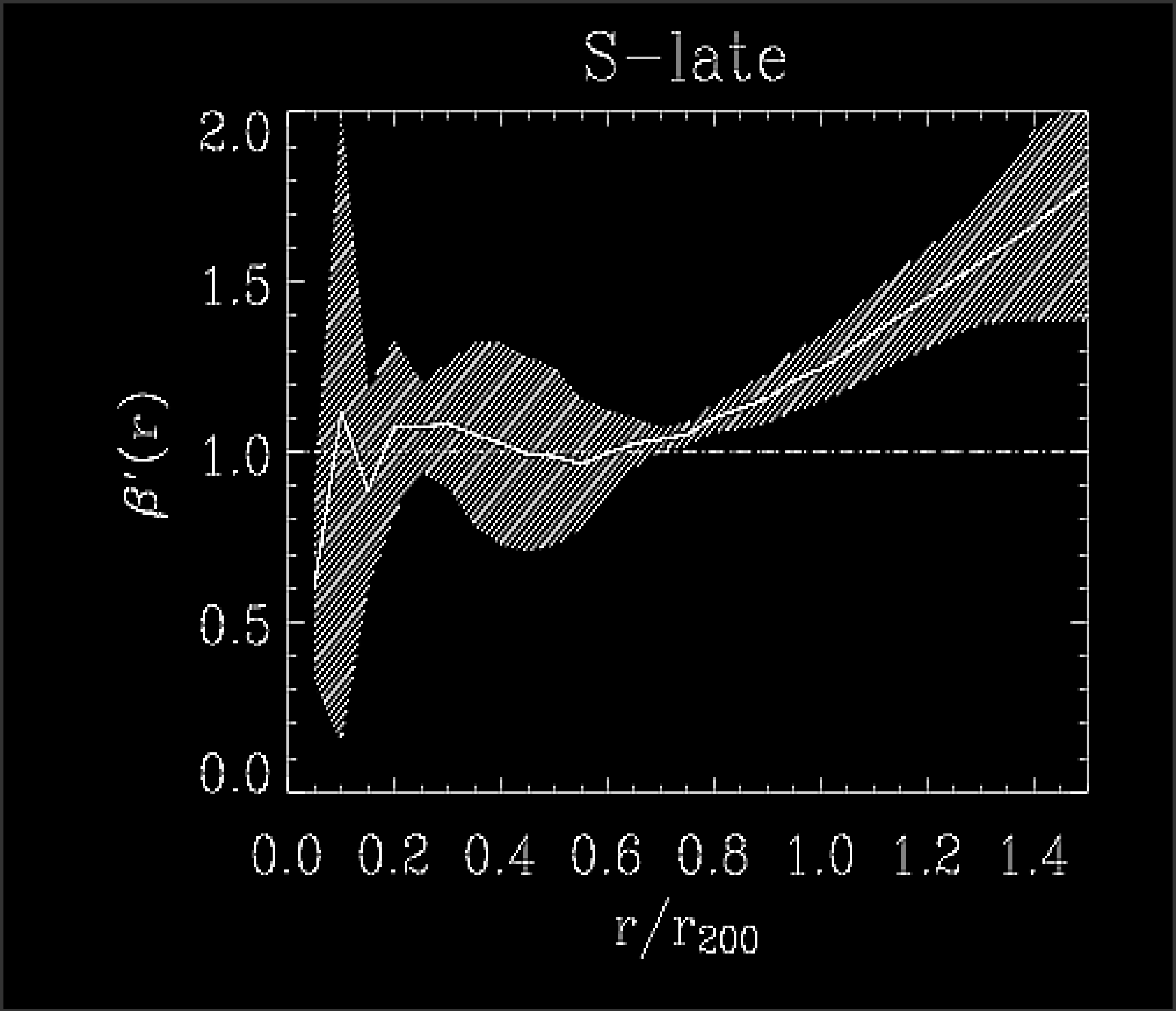
Late-type gals: $\beta \approx 0$ for Sa→Sb



ENACS
(B. &
Katgert 04)

$$\beta'(r) = \left(\frac{< v_r^2 >}{< v_t^2 >} \right)^{1/2}$$

Late-type gals: β>0 at large r for Sbc→Irr

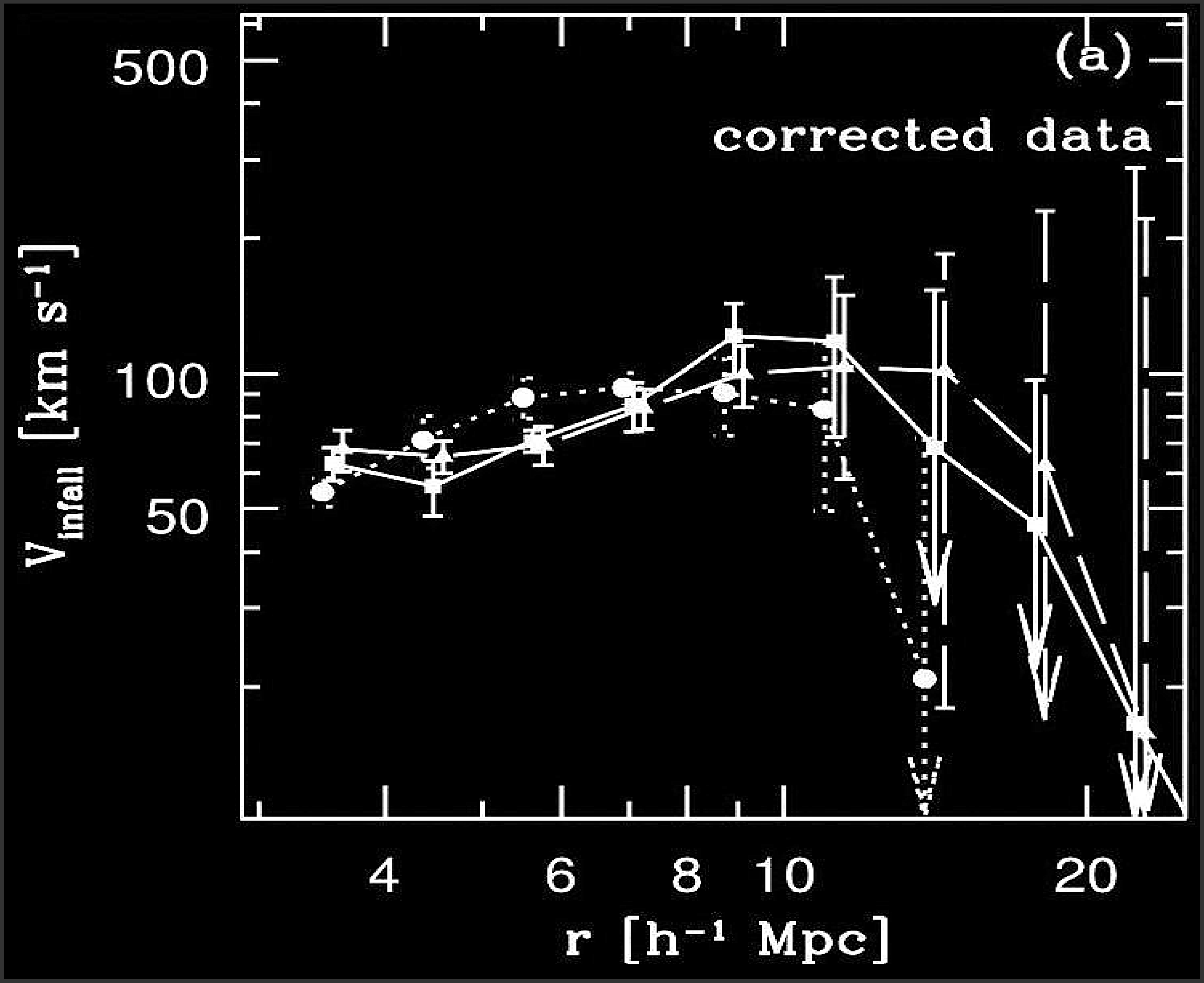


ENACS
(B. &
Katgert 04)

$$\beta'(r) = \left(\frac{< v_r^2 >}{< v_t^2 >}\right)^{1/2}$$

Direct evidence of Spiral infall into clusters

l.o.s. velocities vs. Tully-Fisher distances



(Ceccarelli+05)

Estimates of dM/dt from $M(r>r_{200})$:

$dM/dt \approx 0.06\ M_{200}/\mathrm{Gyr}$ (Rines & Diaferio 06)

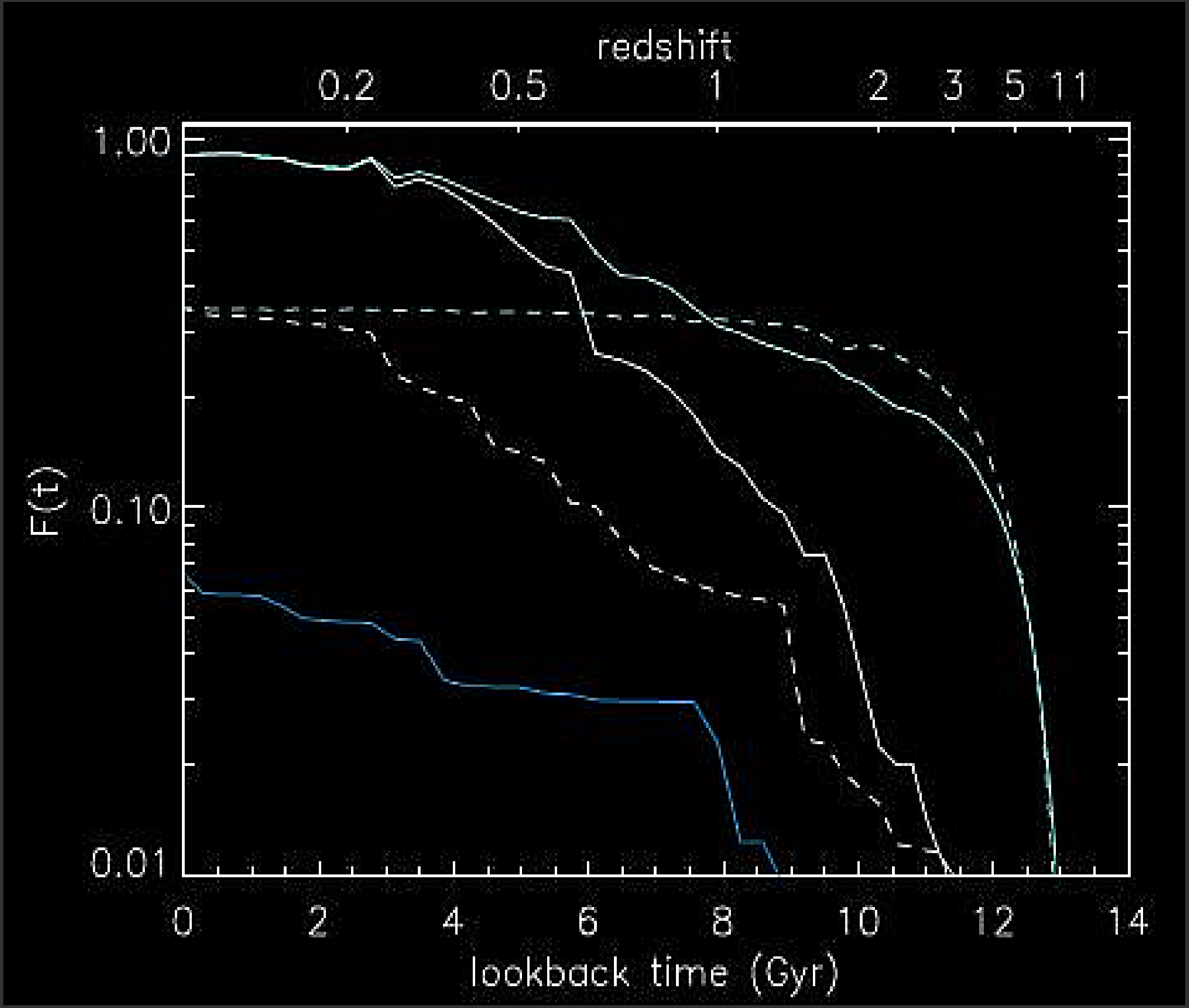
$\approx 0.02\text{-}0.11\ M_{200}/\mathrm{Gyr}$ (Adami+05)

If late-type gals are infalling population, their decreasing number density with time ⇒ also dM/dt decreases with time (x2 from z=0.45 to 0.20) (Ellingson+01)

Estimates of dM/dt from $M(r>r_{200})$

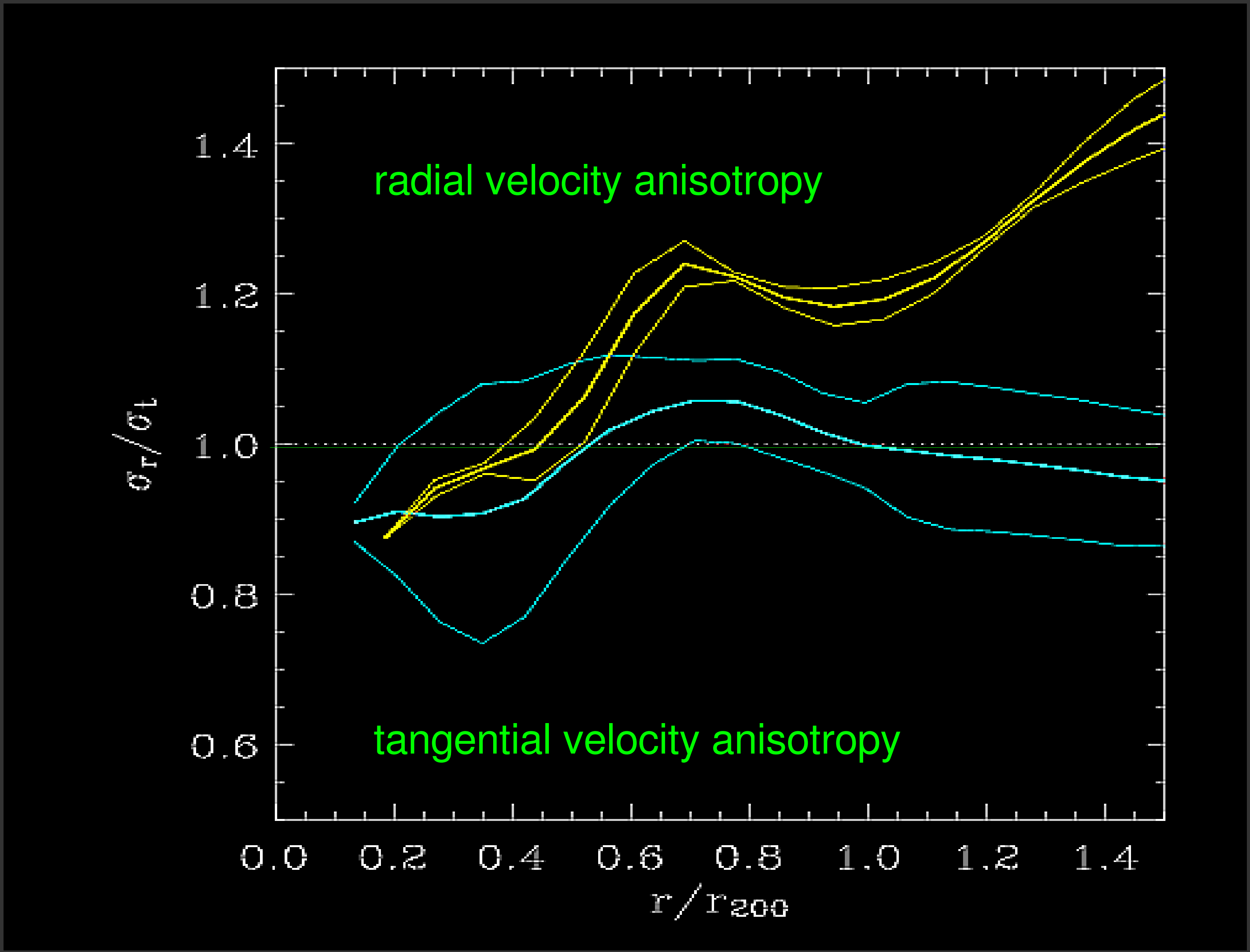
in agreement with ΛCDM num. sims.

(De Lucia & Blaizot 06)



Early- and late-type gals: different β(r)

(CIRS; B., Diaferio, Rines, in prep)



Isotropic orbits of early-type galaxies:

violent relaxation, phase- and chaotic-mixing

(Hénon 64, Lynden-Bell 67, Kandrup+Siopis 03)

at cluster formation and during major mergers

(Manrique+03, Peirani+06, Valluri+07)

secular growth of cluster mass (Gill+04)

Isotropic orbits of early-type galaxies:

violent relaxation, phase- and chaotic-mixing

(Hénon 64, Lynden-Bell 67, Kandrup+Siopis 03)

at cluster formation and during major mergers

(Manrique+03, Peirani+06, Valluri+07)

secular growth of cluster mass (Gill+04)

Radial orbits of late-type galaxies:

similar to DM particles in num. sims.

recent infall (they still have gas)

after last major merger

Subclusters

Theoretical expectations (De Lucia + 04)

- Halos accrete subhalos

- Subhalo survival = f(orbit,mass)
  regulated by dyn. friction + tidal truncation

- Shape of subhalo f(M) independent of M_{halo}

- Most massive subhalos avoid the halo center

Theoretical expectations (De Lucia + 04)

- Halos accrete subhalos

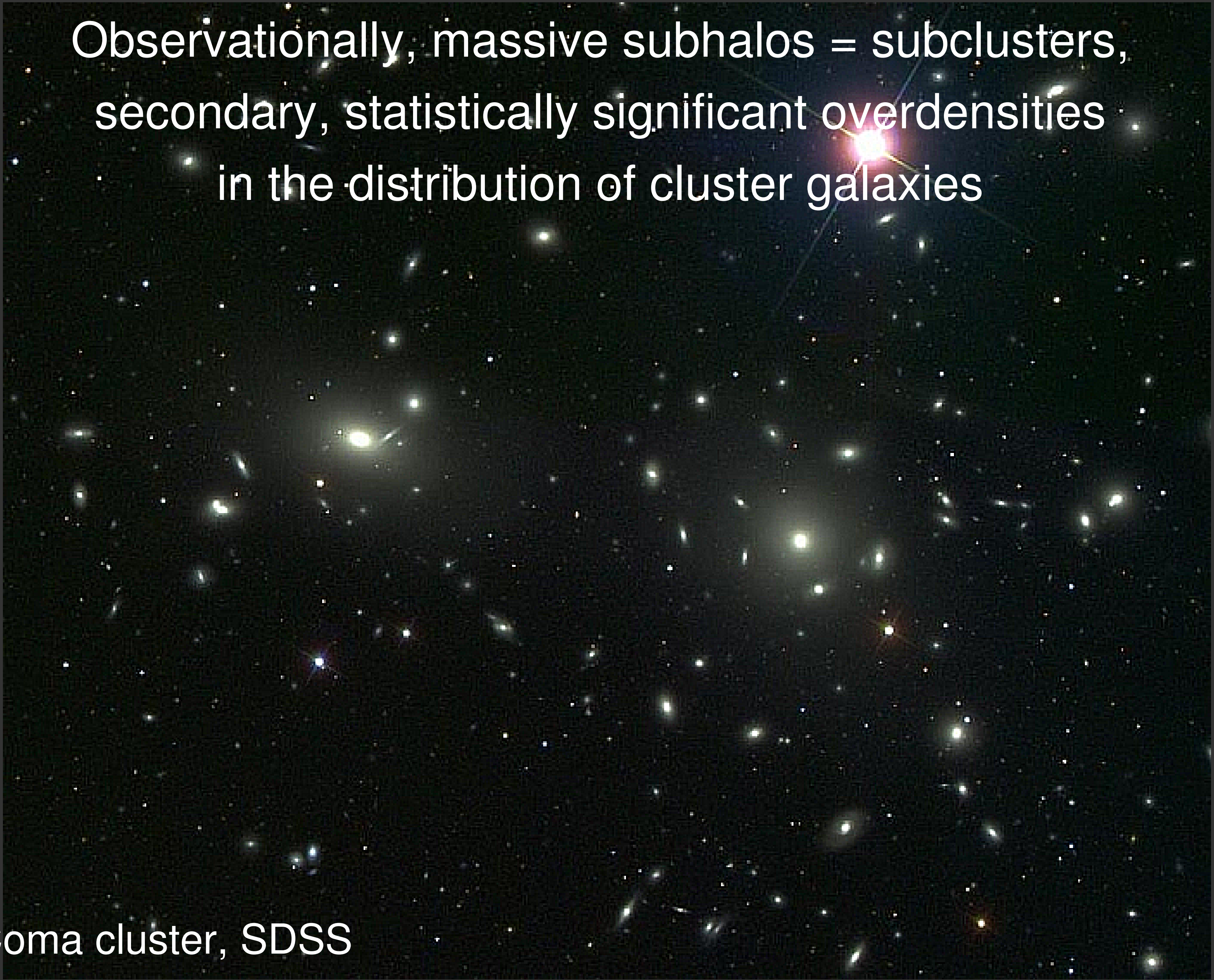
- Subhalo survival = f(orbit,mass)
  regulated by dyn. friction + tidal truncation

- Shape of subhalo f(M) independent of M_{halo}

- Most massive subhalos avoid the halo center

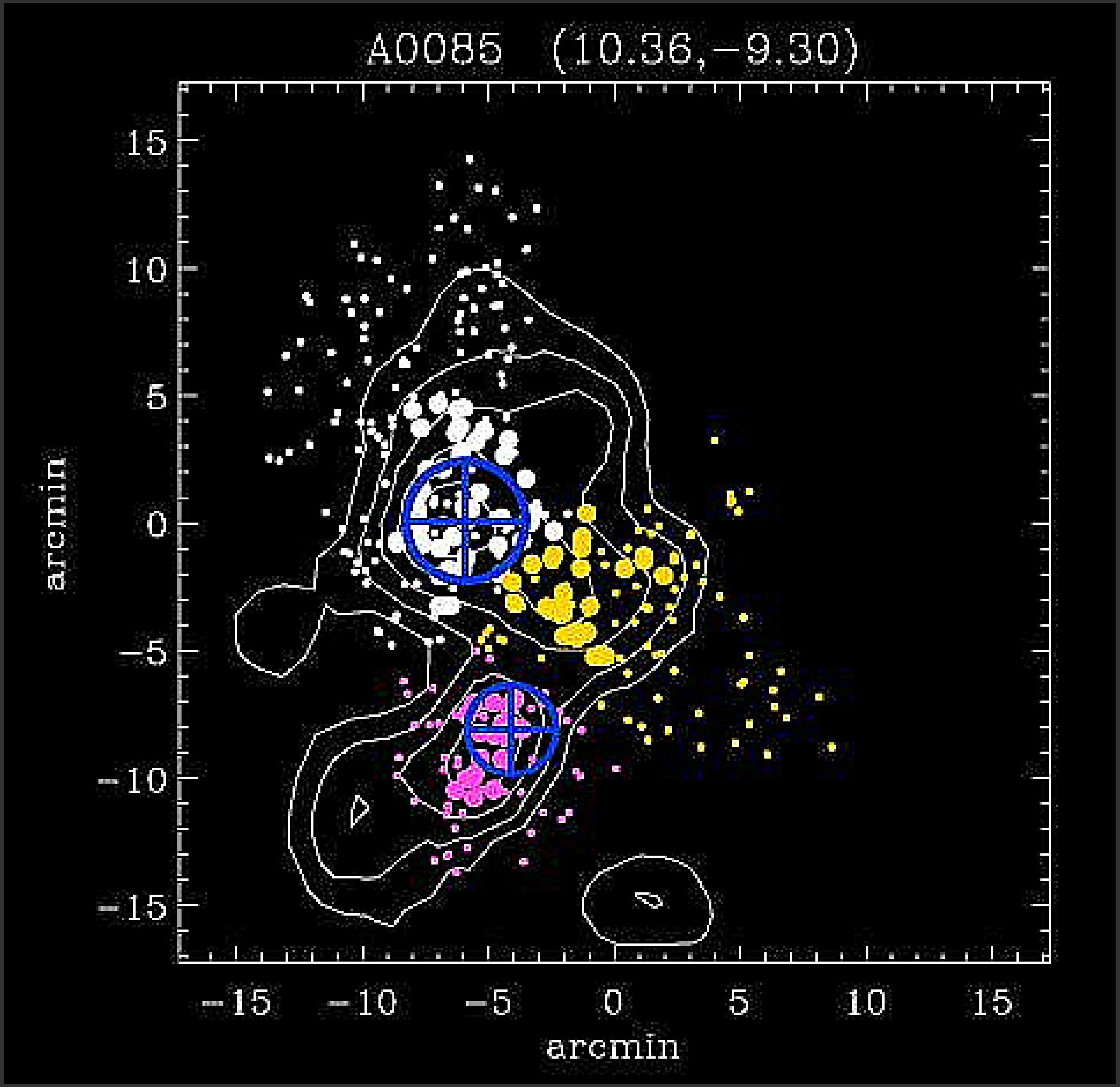
Can we test the expectations?

Observationally, massive subhalos = subclusters, secondary, statistically significant overdensities in the distribution of cluster galaxies



Coma cluster, SDSS

Subcluster identification:



Deviation from symmetry and/or detection of secondary overdensities in the spatial and/or velocity distribution of cluster galaxies

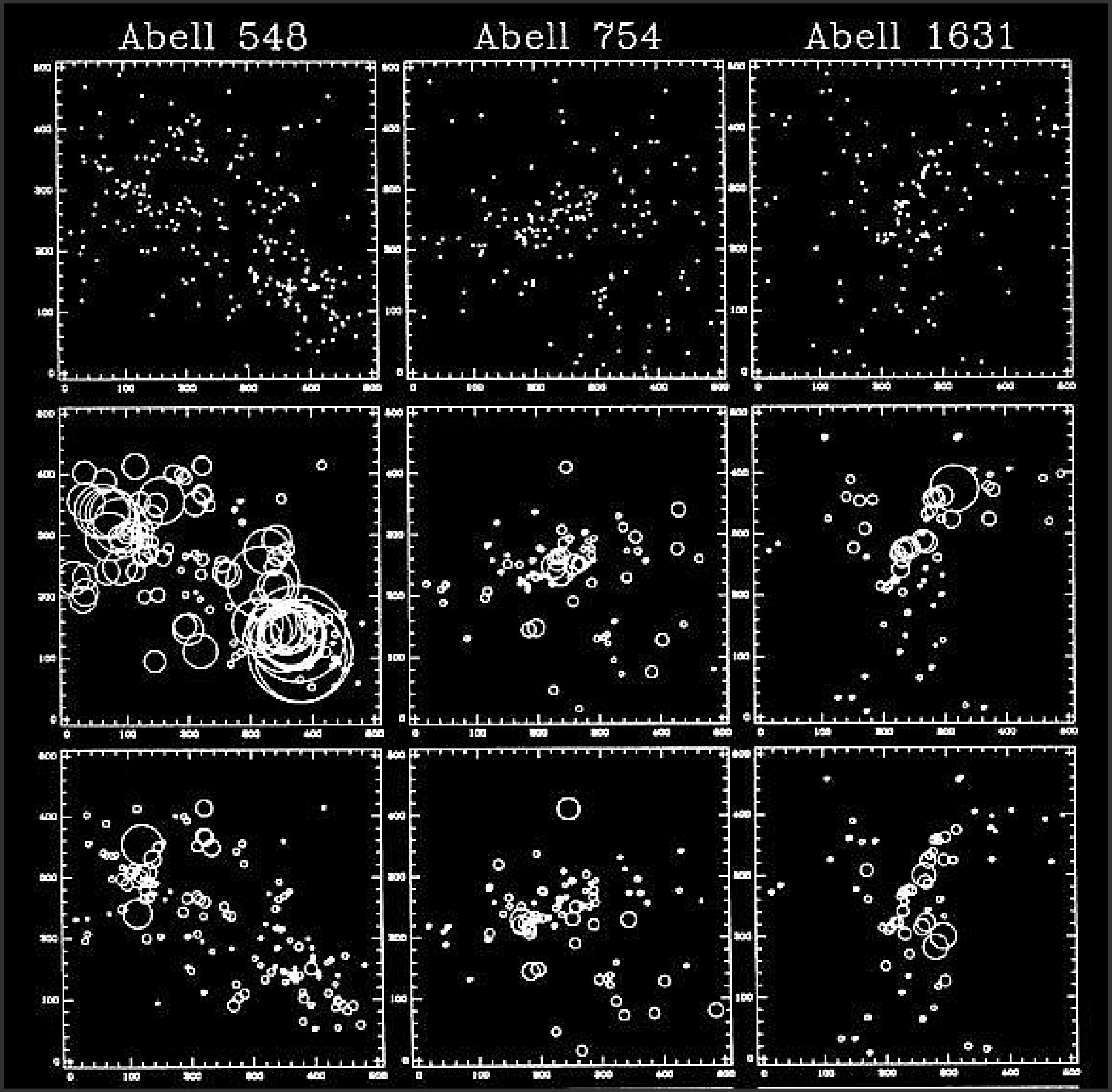
(Ramella+07)

The method of Dressler & Shectman (1988):

$$\Delta = \sum_{i=1}^{N} (11/\sigma_p^2)[(\overline{v}_i - \overline{v})^2 + (\sigma_{p,i} - \sigma_p)^2]$$

Typically, >50 galaxy velocities needed

The method of Dressler & Shectman (1988):



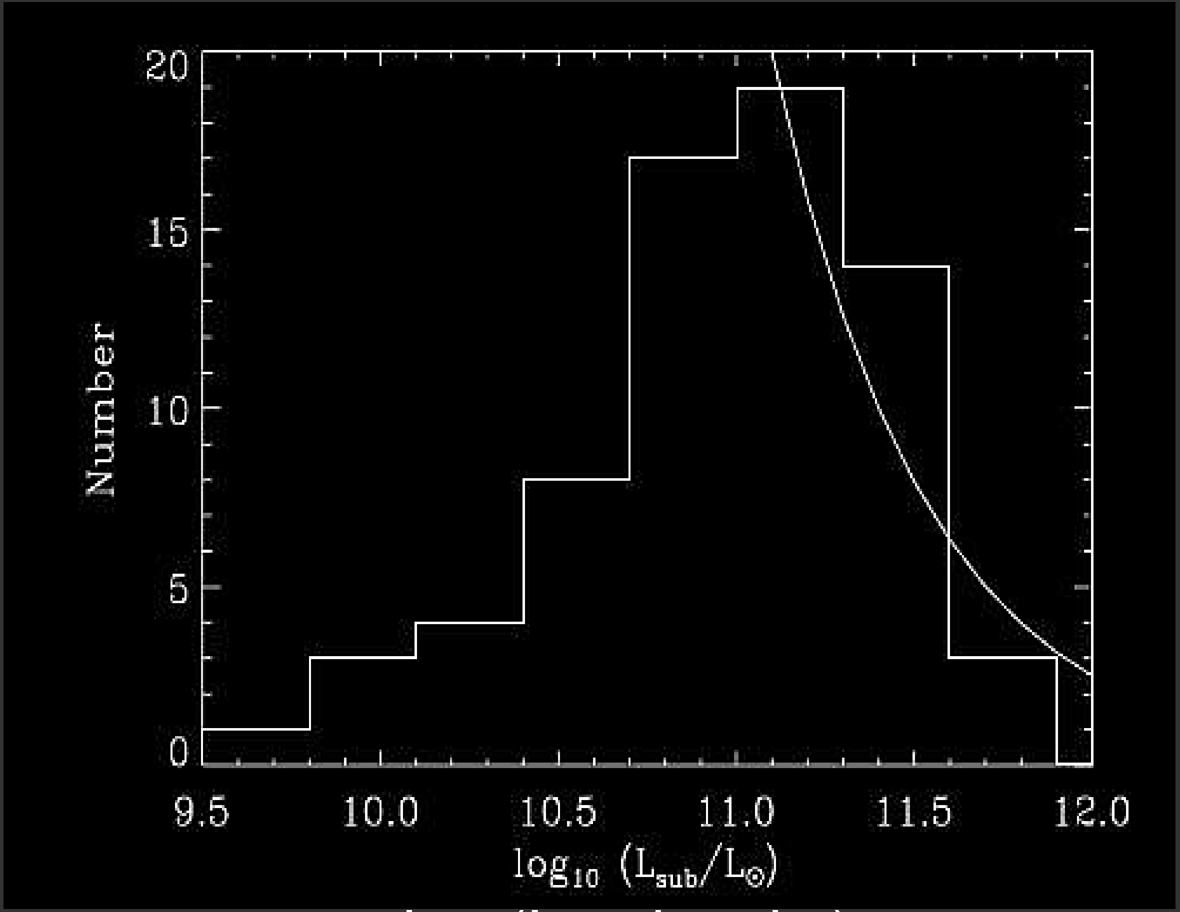
$\simeq$1/3 nearby clusters show subclustering

$\geq$1/3 nearby clusters show subclustering

≥1/3 nearby clusters show subclustering

$f(M_{subcl})$ starts being measured

(Ramella+07)



log (Luminosity)

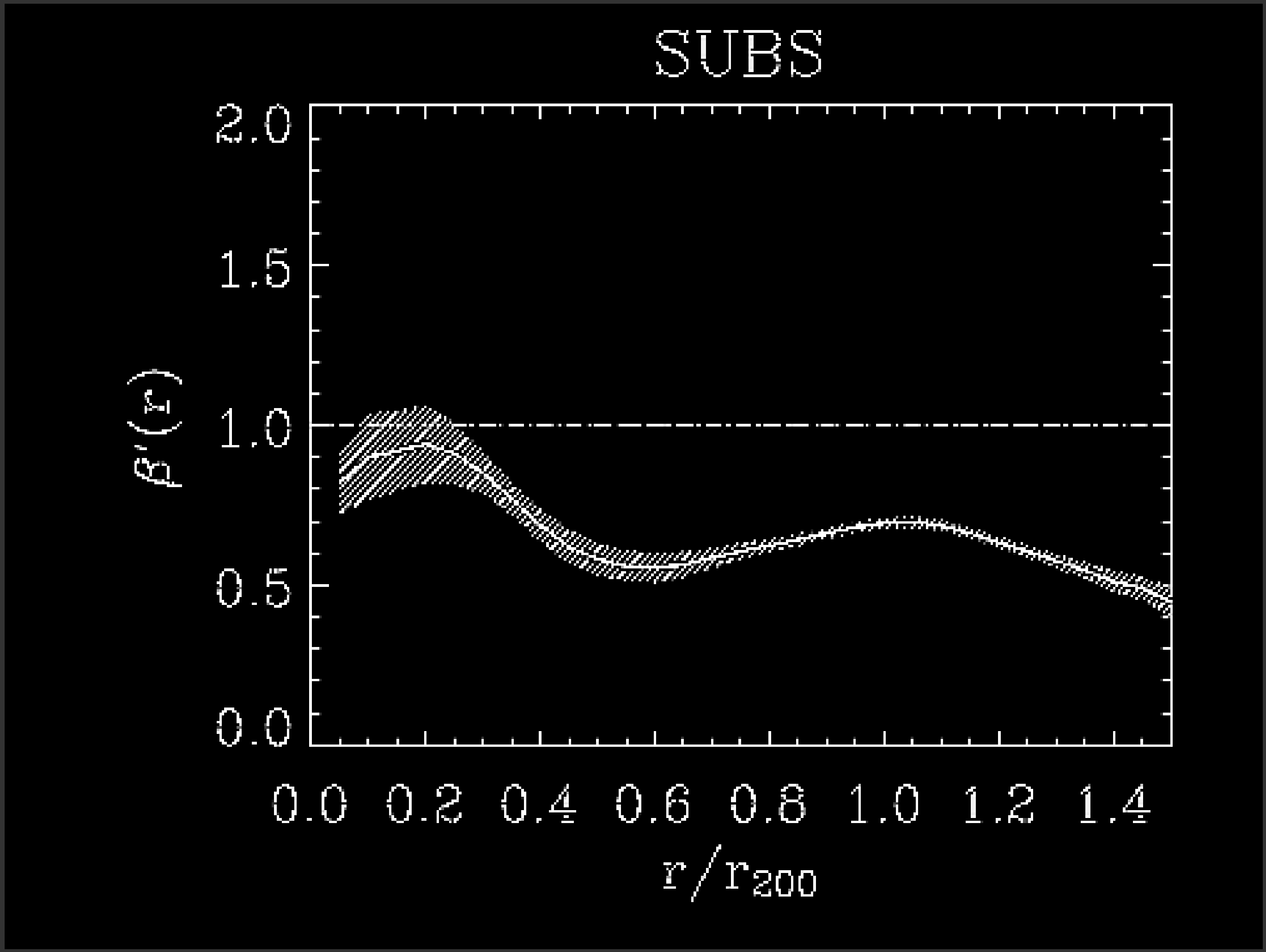
$\geq$1/3 nearby clusters show subclustering

$f(M_{subcl})$ starts being measured

Spatial and velocity distributions

of subclusters suggests tidal disruption

(B. & Katgert 04)



Spatial and velocity distributions
of subclusters suggests tidal disruption
(B. & Katgert 04)

Perspectives

- NFW or Burkert? ◁ 5x larger sample

- NFW or Burkert? ◁ 5x larger sample

- c=c(M) normalization? ◁ larger sample over M range

- NFW or Burkert? ◁ 5x larger sample

- c=c(M) normalization? ◁ larger sample over M range

- c-distribution? ◁ many 500 z's clusters

- NFW or Burkert? ◁ 5x larger sample

- c=c(M) normalization? ◁ larger sample over M range

- c-distribution? ◁ many 500 z's clusters

- M(r) depends on M(t)? ◁ M(r) and M_{subcl}

- galaxy orbits and properties? ◁ larger sample, morphology vs. color

- galaxy orbits and properties? ◁ larger sample,
morphology vs. color

- $M(r) \leftrightarrow \beta(r)$ (Hansen & Moore 06)? ◁ larger sample

- galaxy orbits and properties? ◁ larger sample, morphology vs. color

- M(r) ↔ β(r) (Hansen & Moore 06)? ◁ larger sample

- M(r) & β(r) evolution?
  2-phase assembly of M(r) (Lu+06)?
  ◁ higher-z samples

- galaxy orbits and properties? ◁ larger sample, morphology vs. color

- M(r) ↔ β(r) (Hansen & Moore 06)? ◁ larger sample

- M(r) & β(r) evolution?
  2-phase assembly of M(r) (Lu+06)?
  ◁ higher-z samples

- Mass accretion vs. z? ◁ subclustering at high-z