# THE STRUCTURE OF GALAXY CLUSTERS from optical observations

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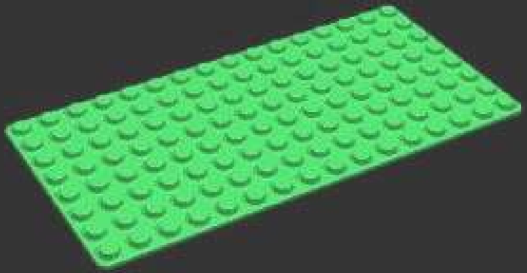
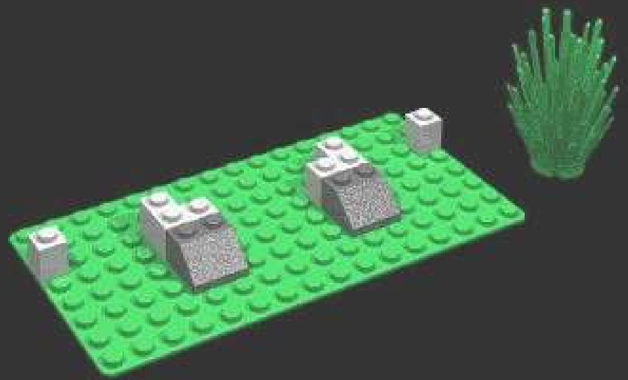


# from optical observations...

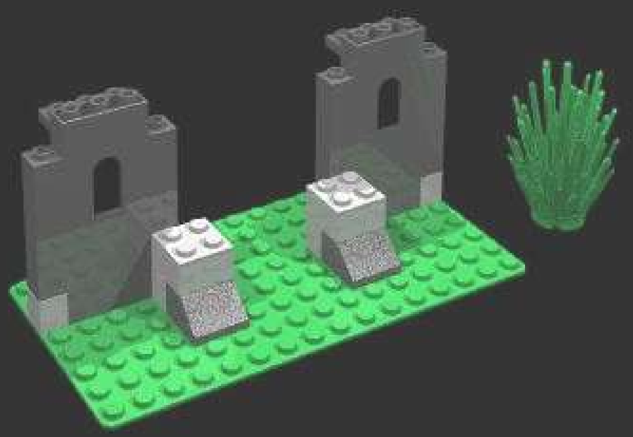
# ...lensing excluded!

*(see talks by Treu, Kneib, Reiprich...)*

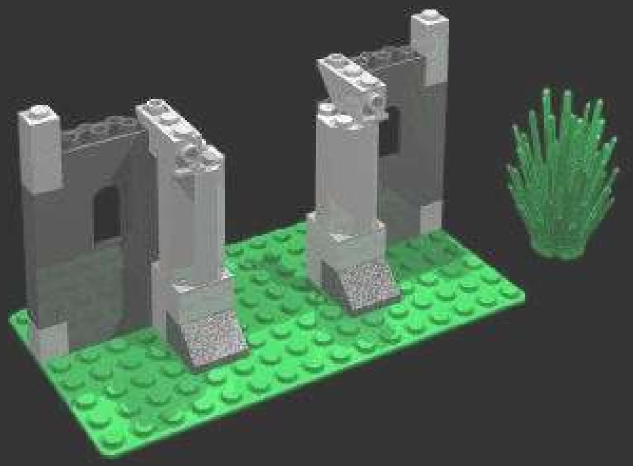


# Plan of the review talk:

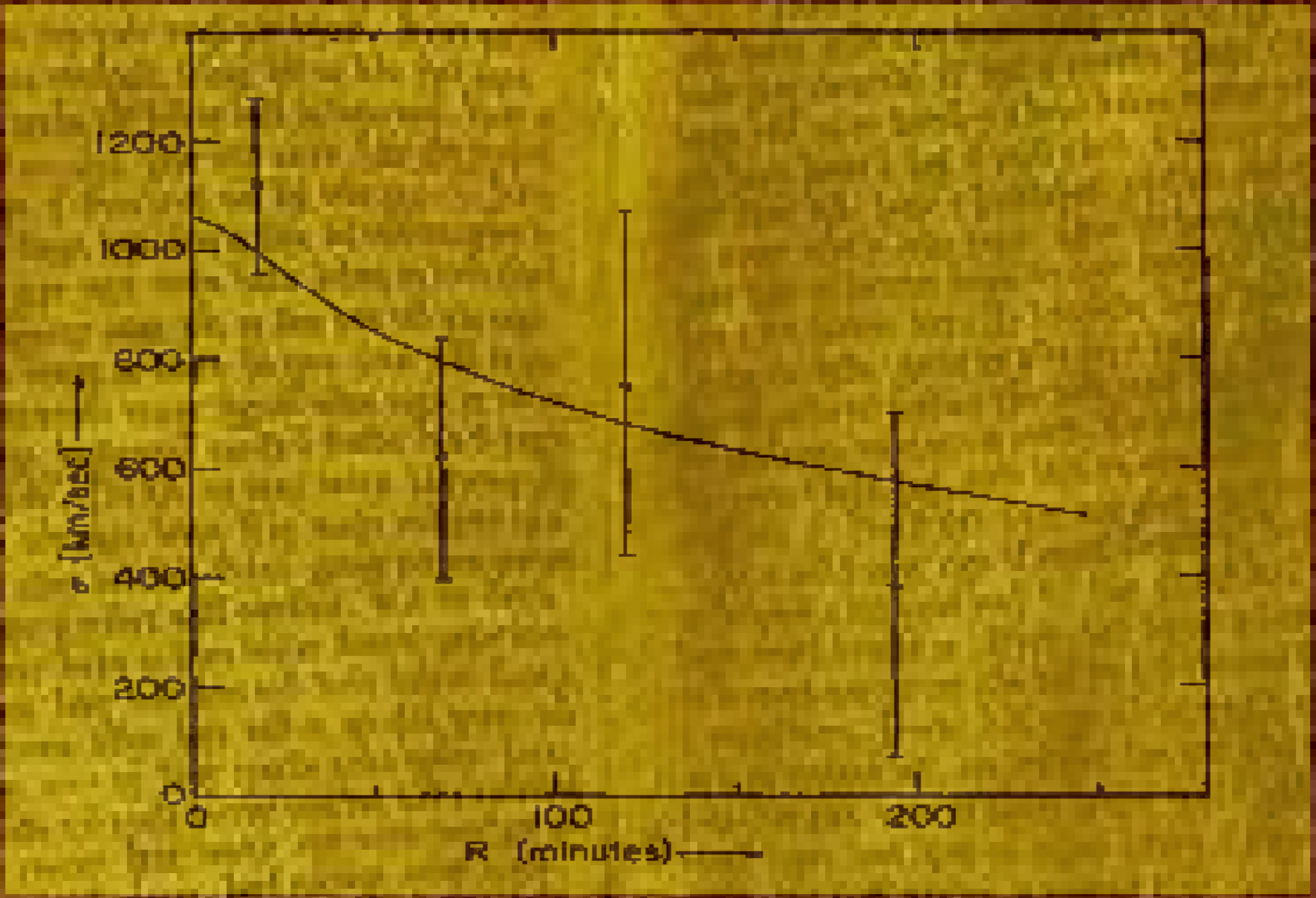
- Mass profile
- Mass-to-light profile,
  i.e. the relative distribution of dark matter and galaxies
- Orbital structure
- Shape
- Substructure
- Scaling relations
  i.e. M/L vs. the halo mass or M vs. $N_{gal}$
  or the fundamental plane of
  galaxy clusters properties



# Mass profile



# Historical




Model fit to Coma velocity dispersion profile from Rood et al. (1972)

# Scientific motivations

- Is the mass profile universal?
- Does it depend on the halo mass?
- How does it evolve?

*...constrains theories of structure formation*

- What is its form?

*...constrains nature of dark matter*

# $M(<r)$ from the Jeans analysis

*(e.g. Binney & Tremaine 1987)*

Assumes dynamical equilibrium of the system

$I(R)$ and $\sigma_v(R) \leftrightarrow \nu(r)$, $\sigma_r(r)$, $M(<r)$, 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)

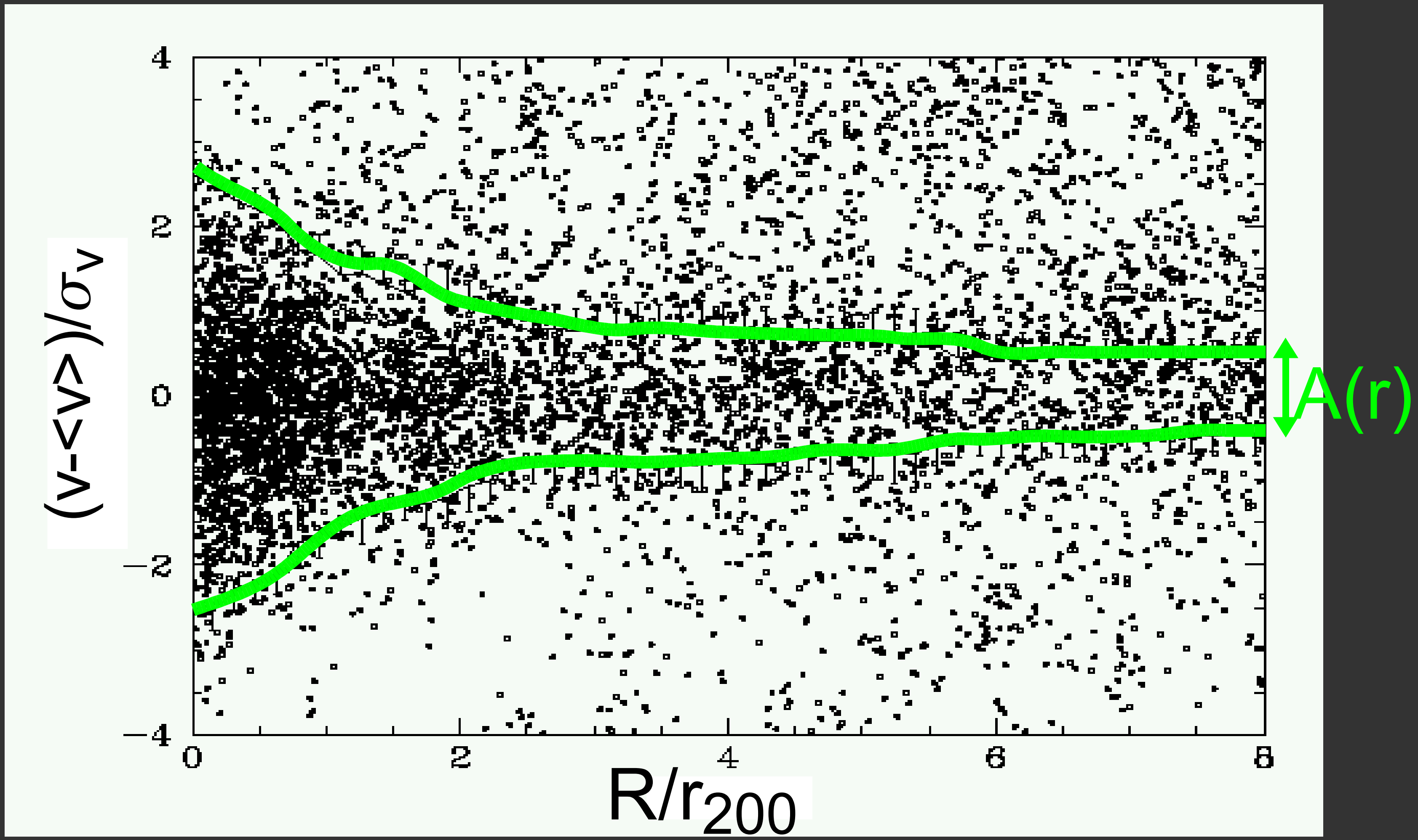
Possible solutions to the problem include:

- analysis of the shape of the velocity distribution
- use of several tracers of the cluster potential

# $M(<r)$ from the caustic method:

*(Diaferio & Geller 1997)* Num.sims. predict cluster dynamics dominates v-field around cluster, i.e. (R,v) caustic amplitude $A(r)$ is a measure of $\Phi(r)$, independently of dynamical state

*(from Rines et al. 2003)*



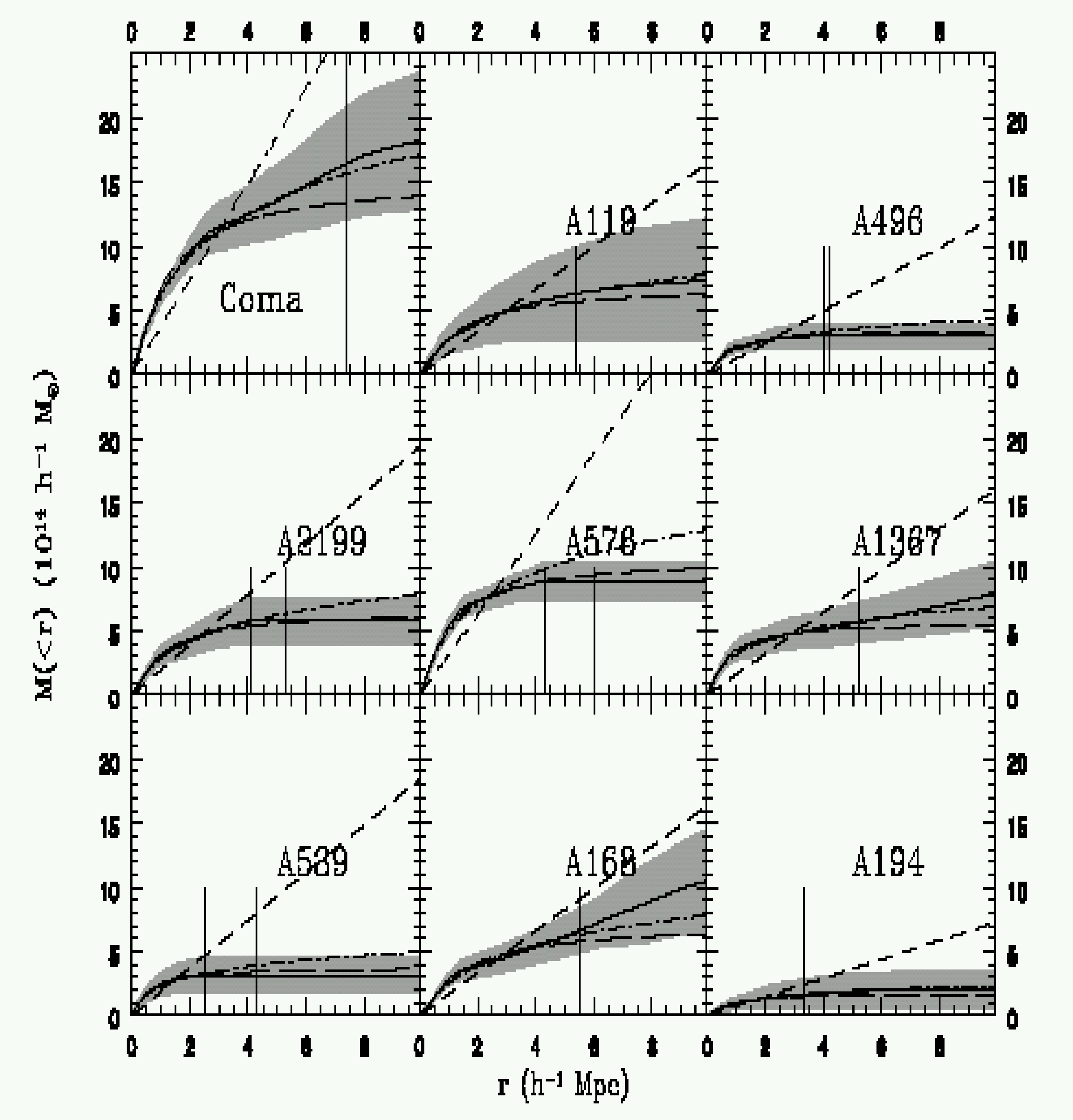

$A(r) \rightarrow \Phi(r)$ through $F(\Phi,\beta,r) \approx$ const ...*only at large radii*

# M(<r) results: CAIRNS & Coma

Rines et al. 00,03,04
9 nearby clusters

Best fit $\rho(r) \sim r^{-1}$ for r~0,
and $r^{-3}$ or $r^{-4}$ for large r
NFW with $5 \leqslant c \leqslant 17$

Other results on Coma:
*(Merritt & Saha 93,*
*Geller et al. 99, Rines et al. 01,*
*?okas & Mamon 04)*
$\rho(r) \sim r^{-1}$ or $r^{-2}$ for r~0,
and $r^{-3}$ or $r^{-4}$ for large r
NFW with $8 \leqslant c \leqslant 10$



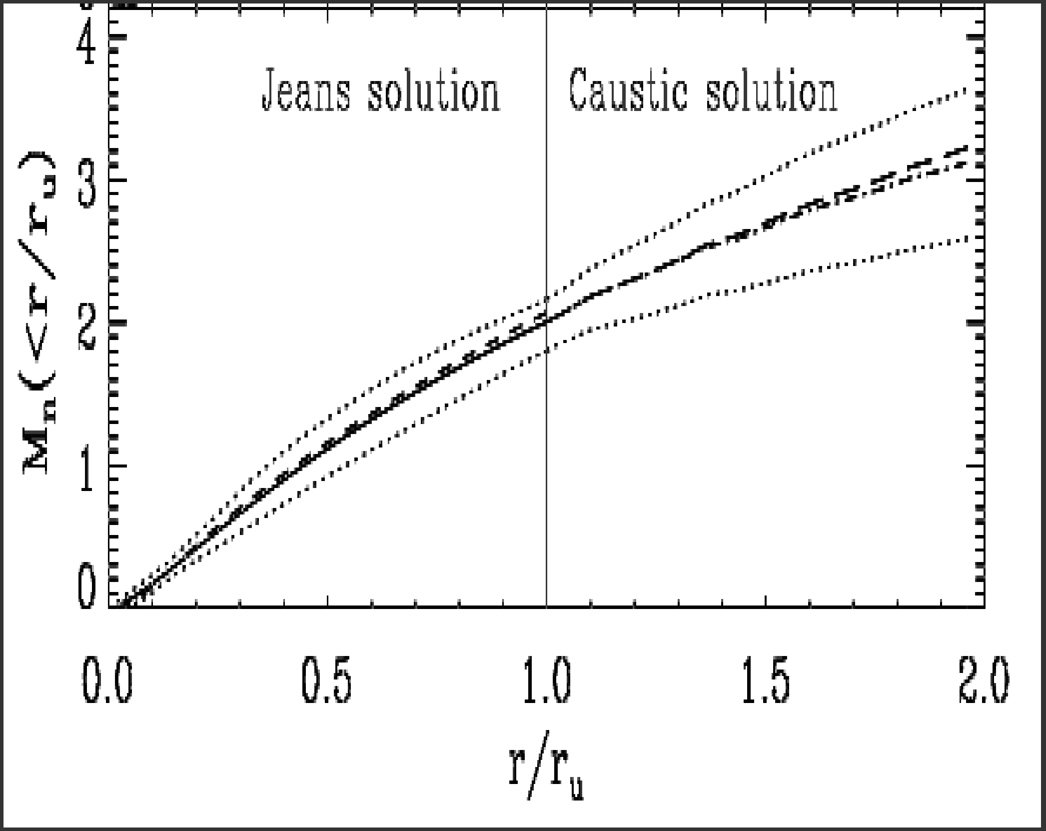

*Short-dashed: isoth., long-dashed: Hernquist, dash-dotted: NFW*

# M(<r) results: 2dFGRS

*(B. & Girardi 03)*: 1345 member gals at $r \leq 2\, r_{200}$
in 43 non-interacting nearby clusters

*Combine the Jeans and the Caustic methods*

$\rho(r) \propto (r/a)^{-\xi}\, (1+r/a)^{\xi-3}$
best-fit $\xi$=1.4
NFW c=5.6 also OK,
cored profiles only OK if
core radius small < $0.1\, r_{200}$
The caustic solution shows
that the Jeans solution
is also valid at large r,
i.e. $\rho(r) \sim r^{-3}$

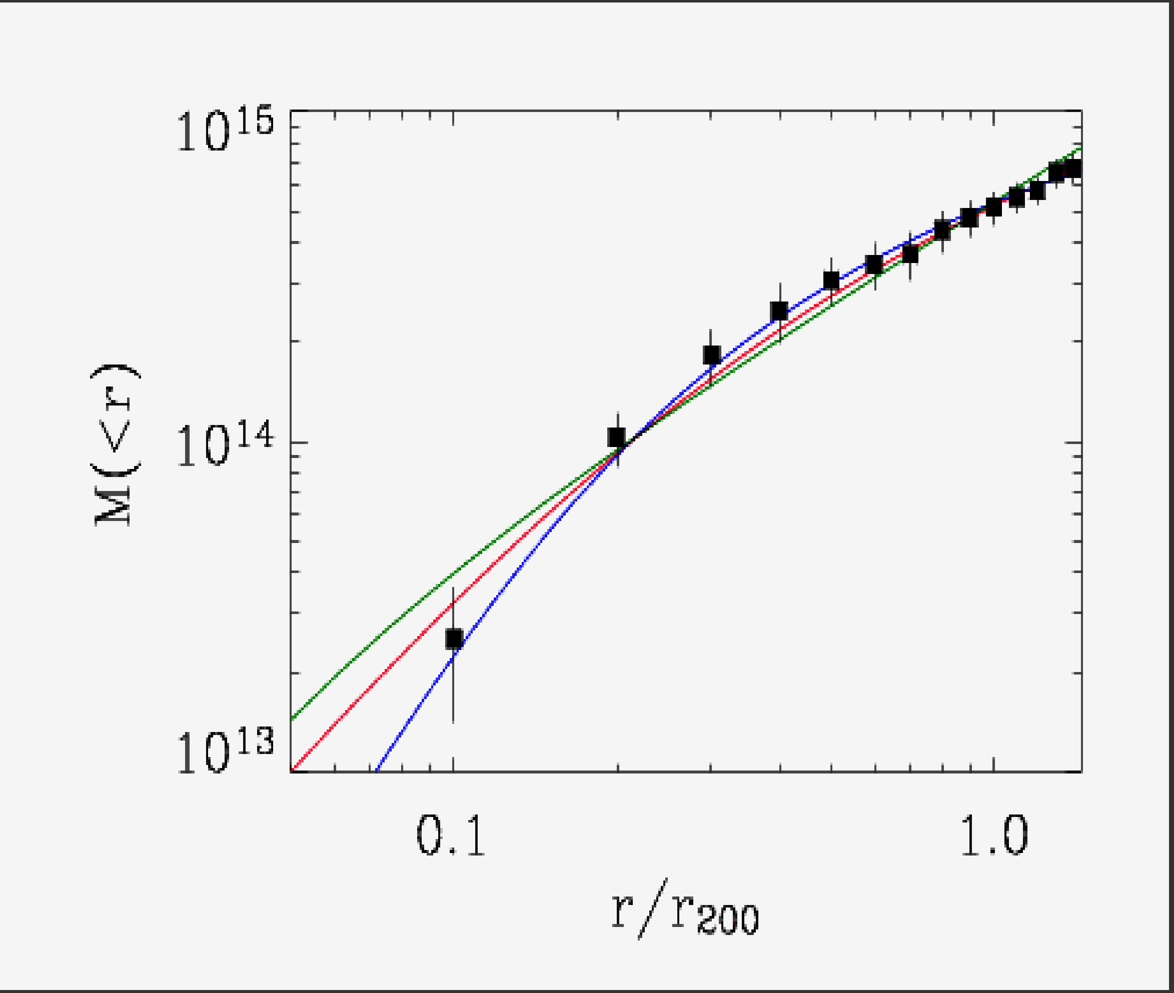


# M(<r) results: ENACS *(Katgert, B. & Mazure 04)*

3056 member gals at $r \leq 1.5\ r_{200}$ in 59 nearby clusters
Jeans method applied on raw smoothed data – no model
*Several tracers of the potential used*

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

Fitting models:
NFW $c=4\pm2$,
Burkert 95 $r_{core}=0.15\ r_{200}$
Isothermal gives poor fit



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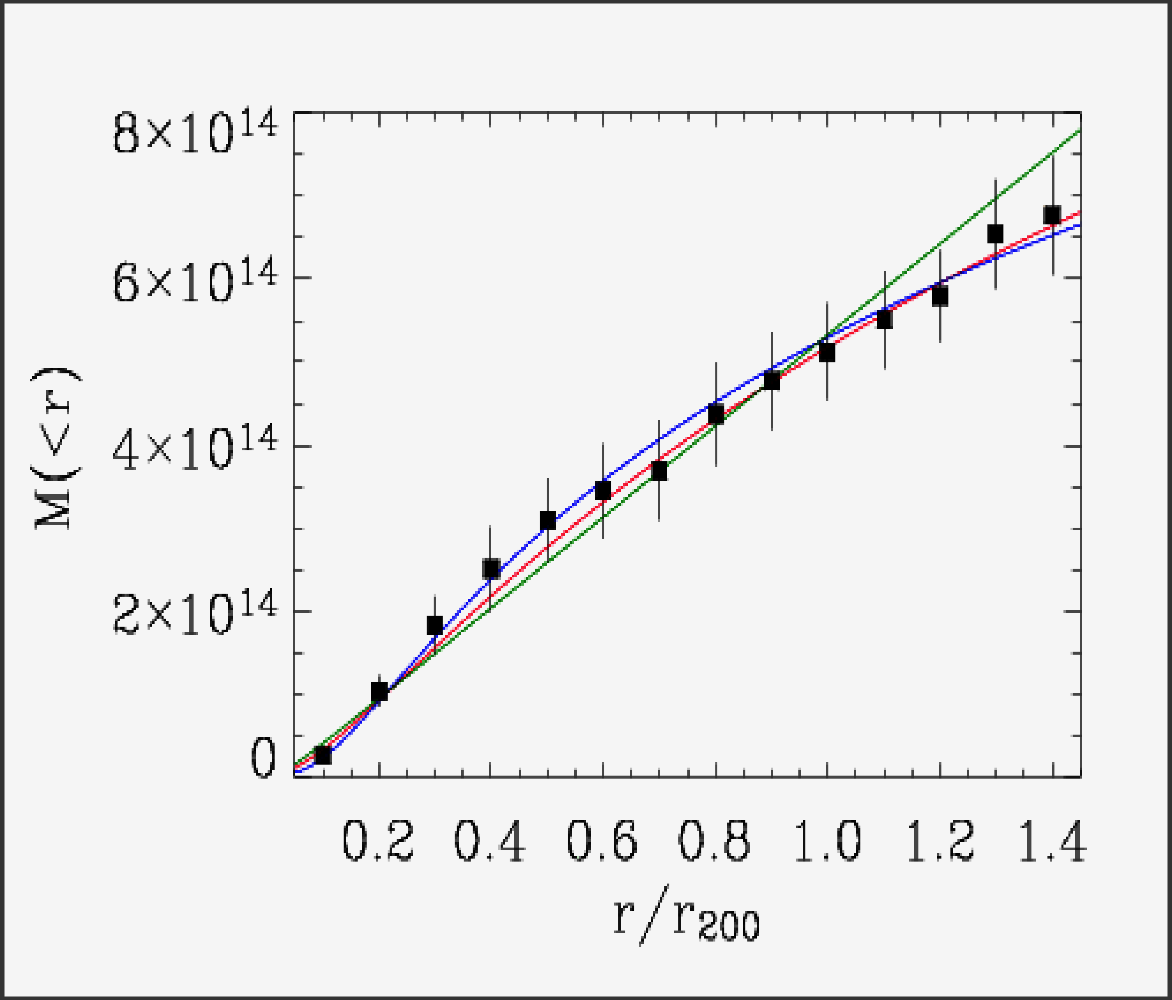


# M(<r) results: Groups

*(Mahdavi et al. 99, 04; Carlberg et al. 01)*

## Conflicting results so far!

Hernquist profile? $\rho(r) \sim r^{-2}$ at all radii? inner core + $\rho(r) \sim r^{-1.75}$?

Result depends on groups sample, not all groups are dynamically virialized structures *(Giuricin et al. 88, Diaferio et al. 93, Mamon 95, Mahdavi et al. 99)*

# M(<r) results: GEMS groups

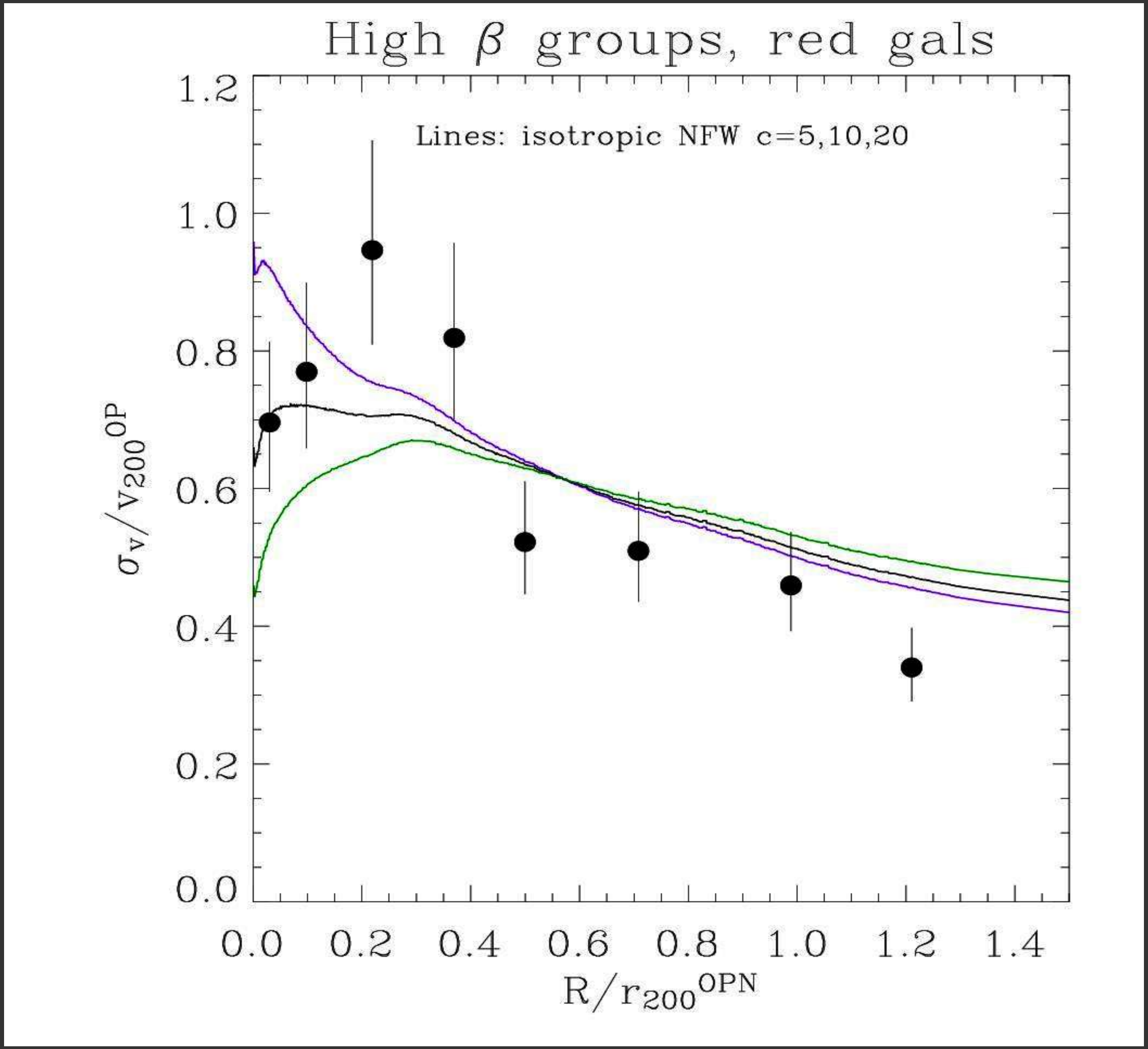
*(B., Mamon, Ponman, et al. in preparation)*

Two classes of groups?

*(see also Mahdavi et al. 99)*

high-$\beta_{spec}$ : virialized!

low-$\beta_{spec}$: projection, collapsing, tidally affected, or ... dynamically evolved?



# M(<r) results: evolution

**CNOC:** *(Carlberg et al. 97, van der Marel et al. 00)*

16 clusters at z=0.17-0.55

Best fit $\rho(r) \sim r^{-\xi}$ : for r~0: $0.7 \leqslant \xi \leqslant 1.2$,

for r large: $3 \leqslant \xi \leqslant 4$

Best-fit NFW: c=4–5

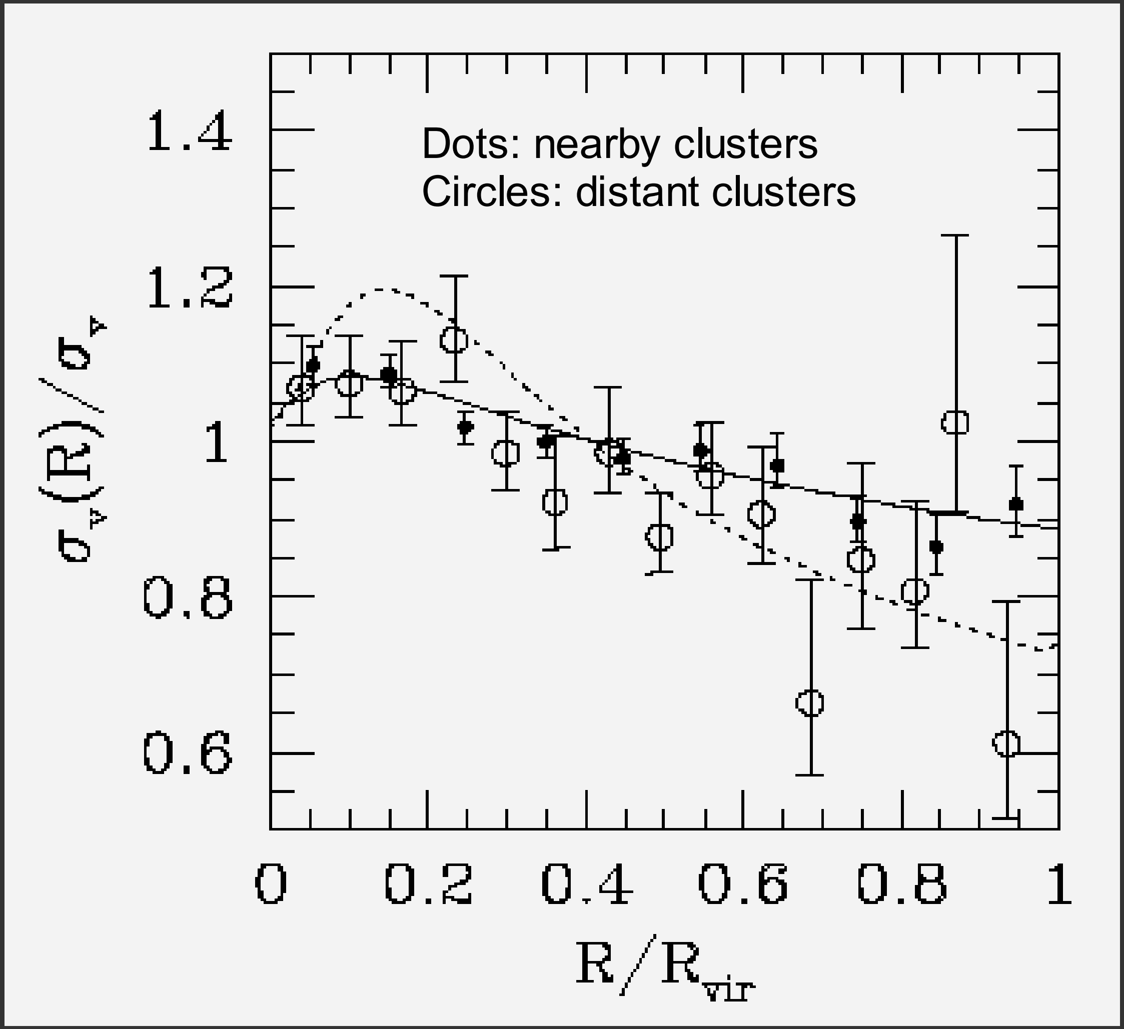
Mass profile is similar to that found in nearby clusters

# M(<r) results: evolution

*(Girardi & Mezzetti 2001; also: Adami et al. 2001)*

No evolution in observed projected galaxy number density & l.o.s. velocity dispersion profiles out to z $\simeq$0.4

$\Rightarrow$ No evolution in M(<r)



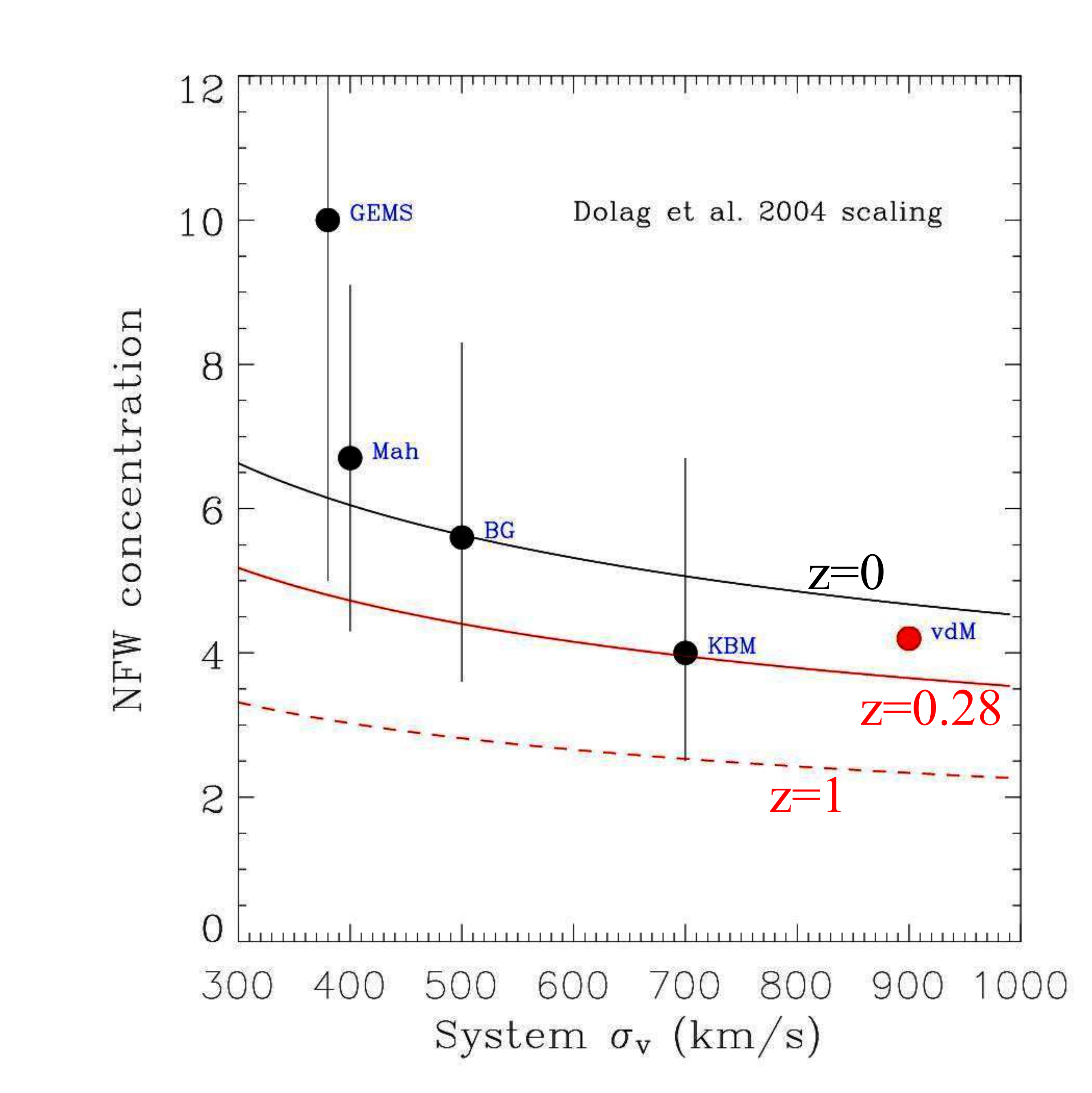

*More galaxies on radial orbits (infalling)?*

# M(<r) results: concentration vs. mass

*(from:*
*Mahdavi et al. 99,*
*B. et al. in prep.,*
*Katgert et al. 04,*
*B. & Girardi 03,*

*van der Marel et al. 00)*

Can we hope to detect evolution of c=c(M) with z?



# M(<r) results summary:

Mass density profile of galaxy clusters $\rho(r) \propto r^{-\xi}$ :

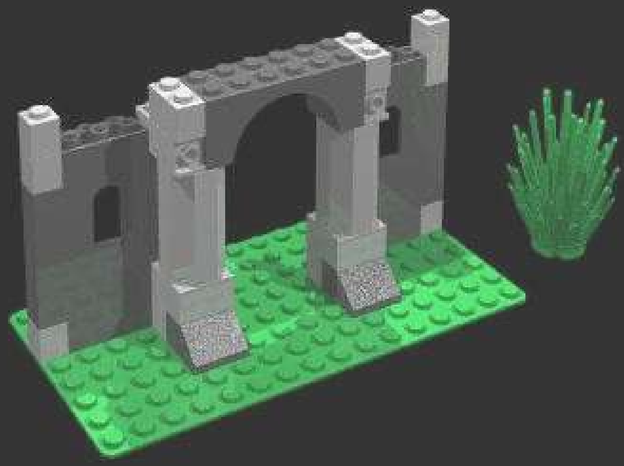
poor constraints near r=0 : $0 \leqslant \xi \leqslant 2$
better constraints at large r: $3 \leqslant \xi \leqslant 4$

→NFW and Hernquist OK, isothermal ruled out
If NFW, c=c(M) has correct trend
If $\xi$=0 near r=0, core radius is small, $r(\rho=\rho_{0/2})<0.1\ r_{200}$

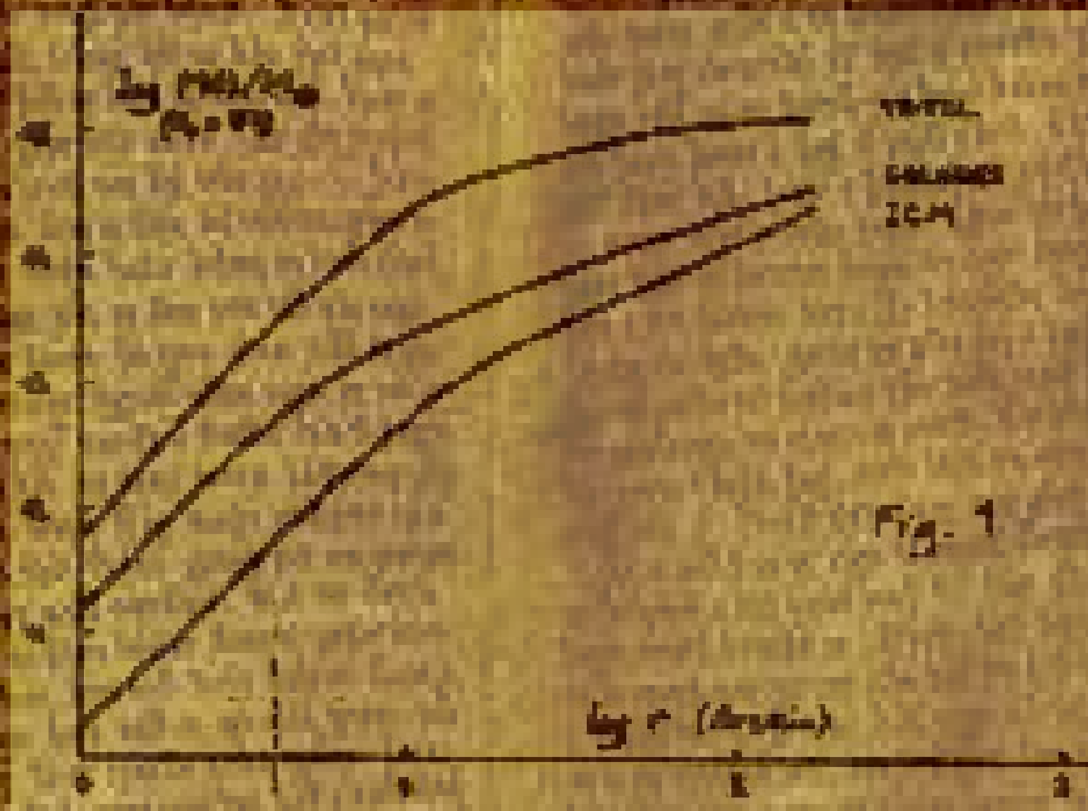
*Progress:*

- mass profile of galaxy groups
- mass profile evolution, check that c(M) ⬇ with z

# Mass-to-light profile



# Historical




Relative distribution of total mass, mass in galaxies and ICM mass in Coma, from Gerbal et al. (1984)

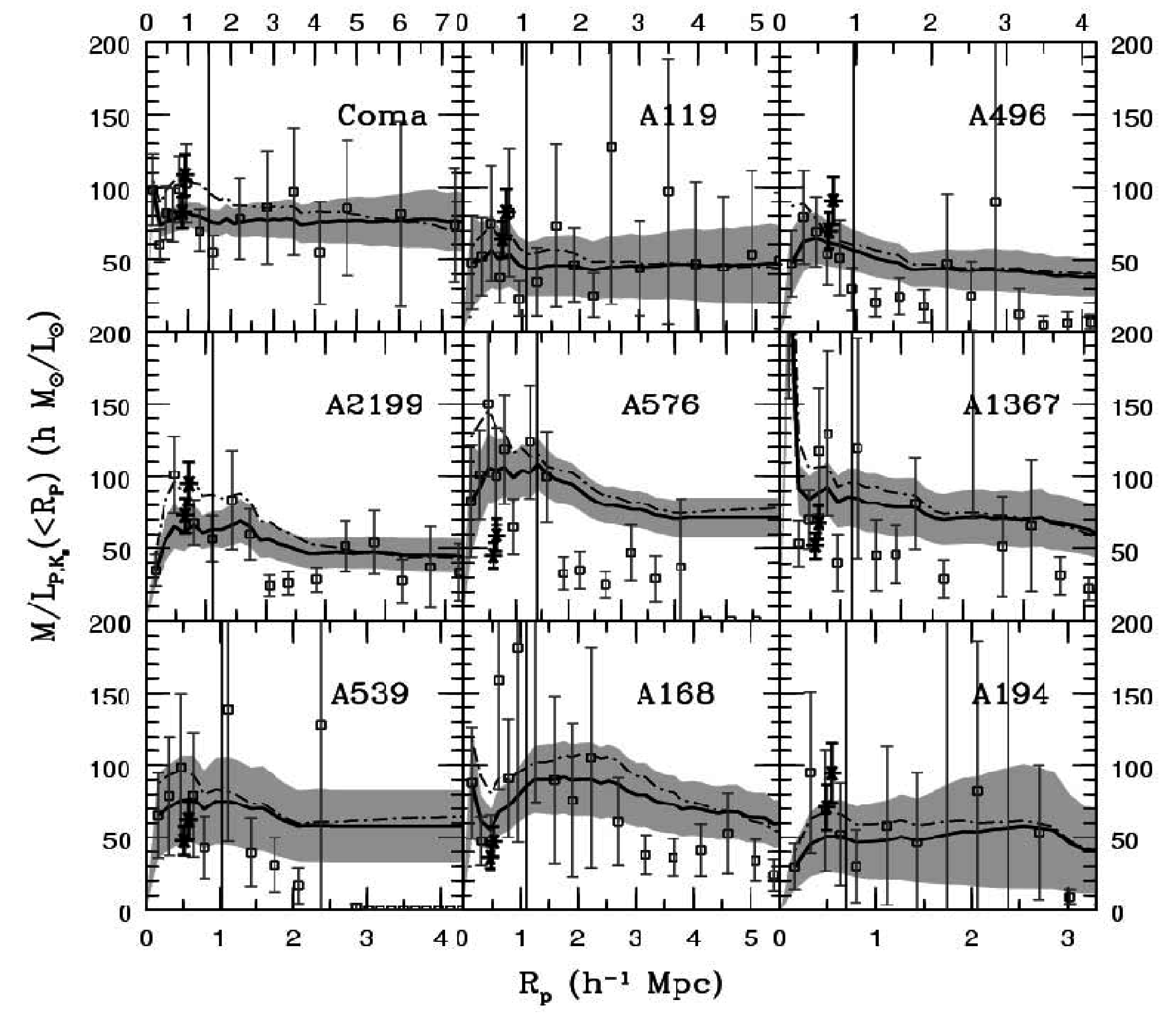
# Scientific motivations

- How do baryons settle in cluster potential?
- Is the galaxy distribution biased relative to dark matter?
- Relative importance of physical mechanisms: *dynamical friction, tidal stripping, merging...*

# M/L results: CAIRNS

*(Rines et al. 04)*

Flat M/L within $r_{200}$, some excess of luminosity near the centre, mild decrease outwards,
*but ≠ clusters have ≠ trends, probably caused by projection effects*

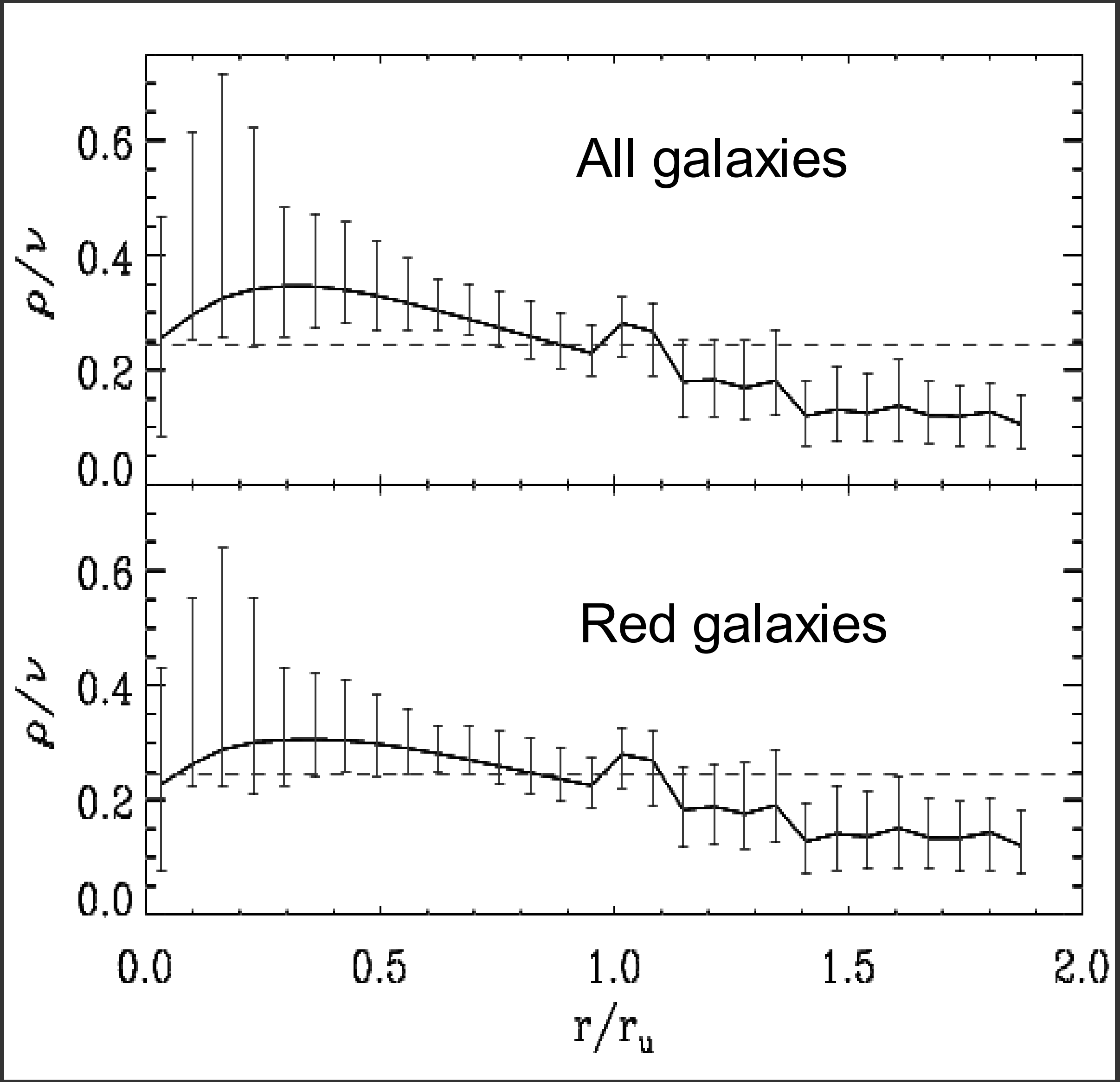


# M/L results: 2dFGRS

Averaging over several clusters allows to beat projection effects

Some central light excess and a slight decrease beyond 0.3 $r_{200}$, mostly due to late-type galaxies

*(B. & Girardi 03)*

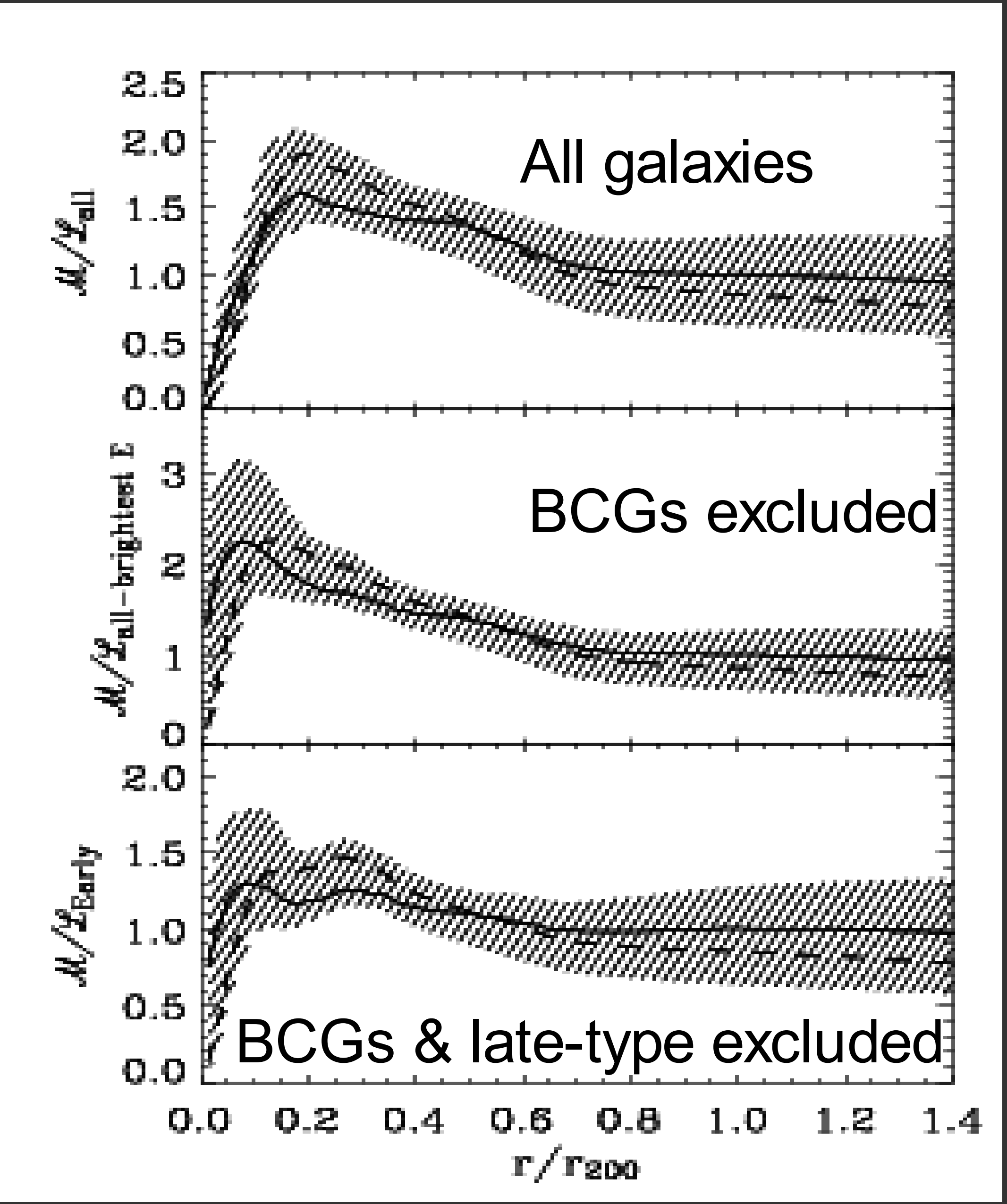


# M/L results: ENACS

Averaging over several clusters allows to beat projection effects

Some central light excess mostly due to BCGs, and a slight decrease beyond 0.3 $r_{200,}$ mostly due to late-type galaxies

*(Katgert, B. & Mazure 04)*



# M/L results: Groups

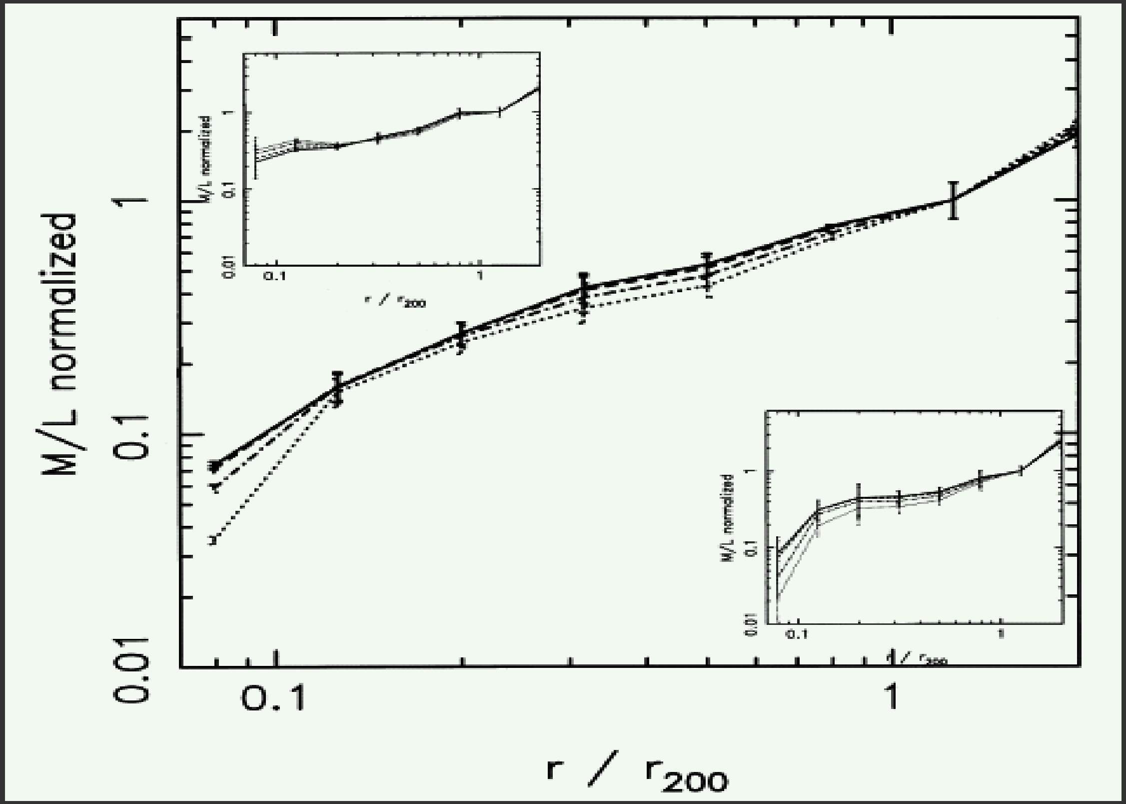
## Conflicting results so far!

**Constant M/L?**
*(Mahdavi et al. 99)*

↓

*...but only for ¼ of all groups, those with declining velocity dispersion profile!*

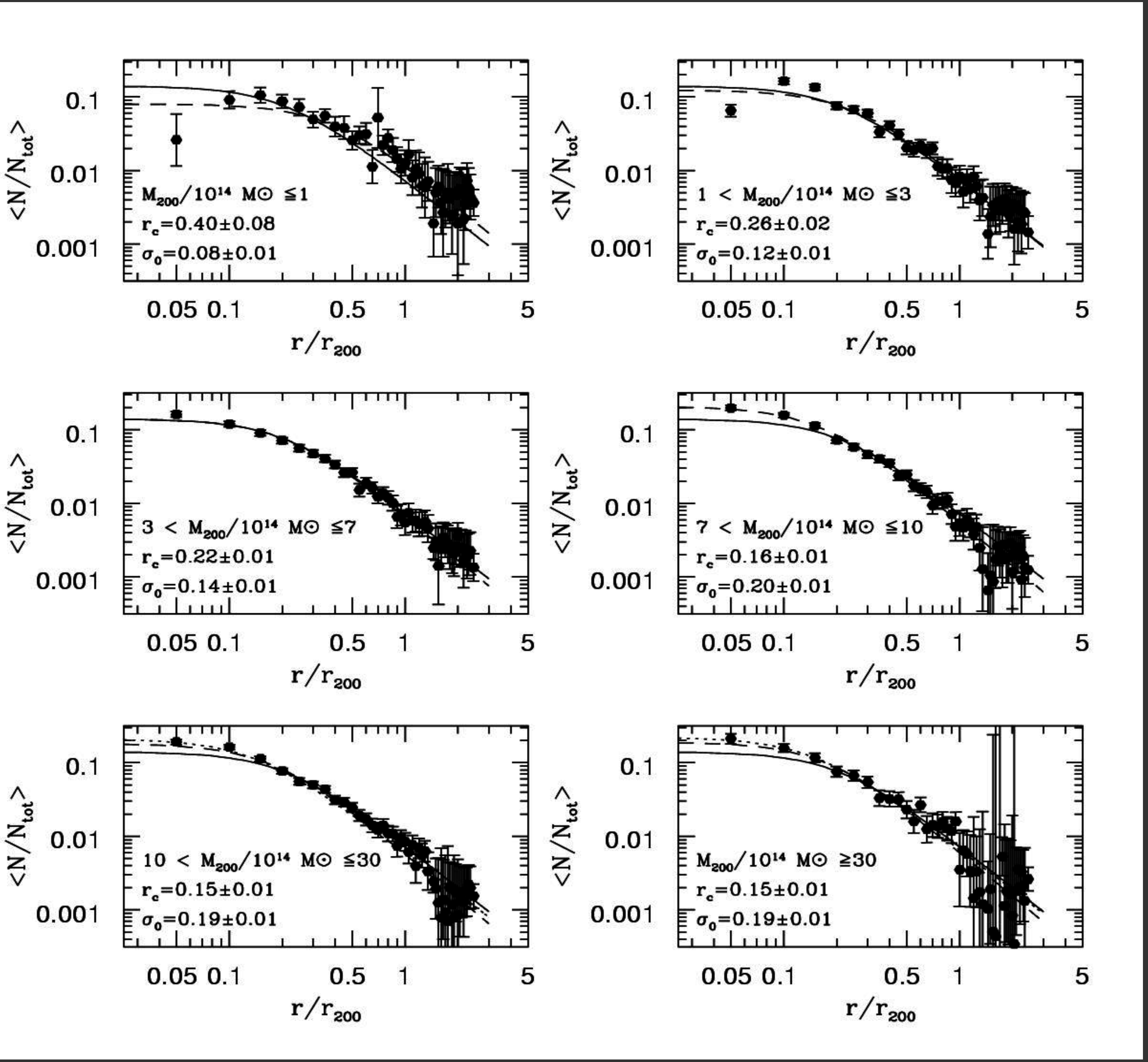
**... or steeply rising M/L?**
*(Carlberg et al. 01)*



# M/L results: groups vs. clusters

Galaxies in groups have less peaked number density profiles than galaxies in clusters
*(Popesso et al. in prep.)*

➞M/L at r→0 is larger in groups than in clusters

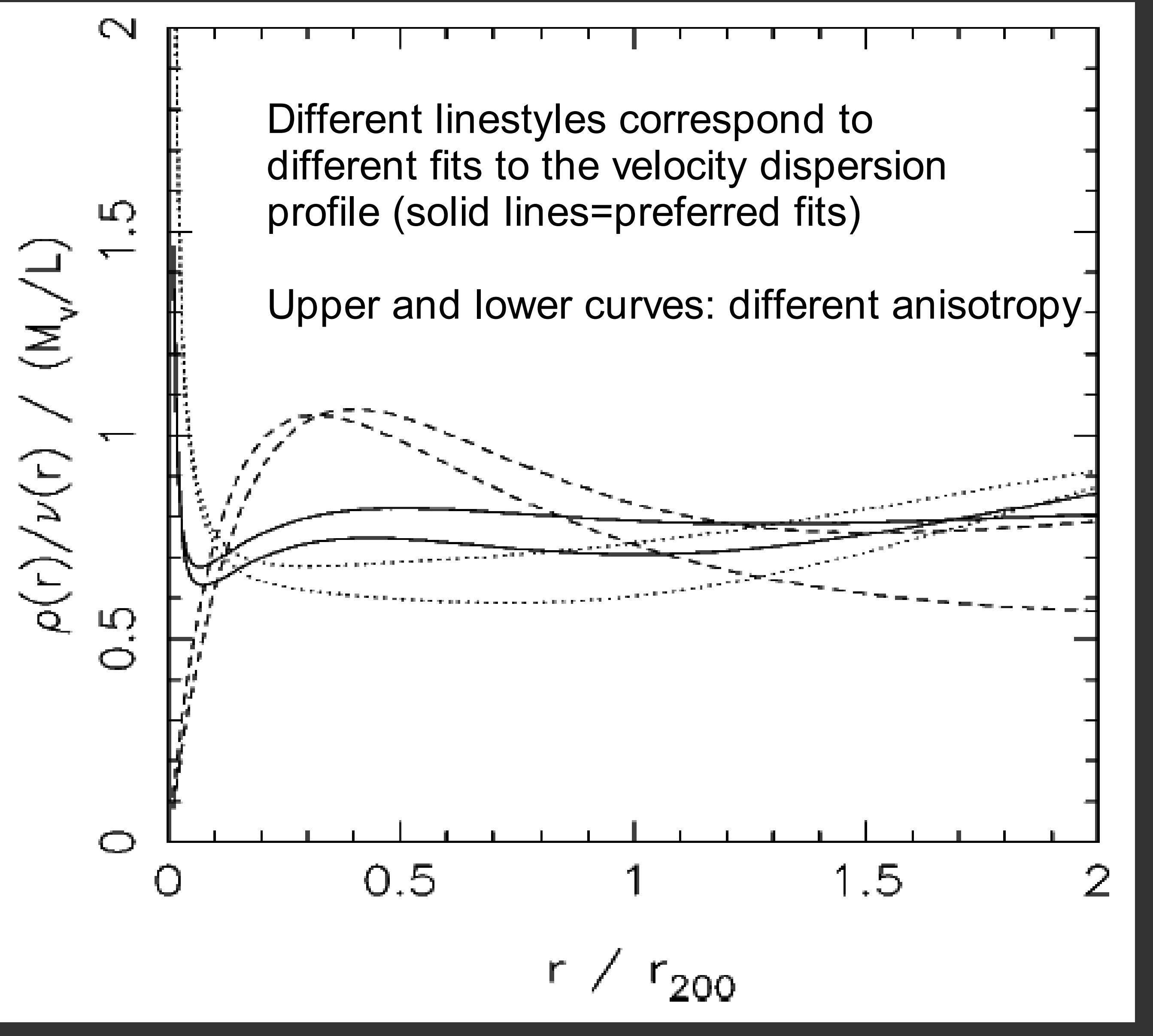


# M/L results: evolution

## CNOC

Flat M/L for <z>=0.3 clusters? Less evidence for central luminosity excess

*(Carlberg et al. 97)*



# M/L results summary:

$z \simeq 0$

Evidence for excess light near the centre
Mild M/L decreasing trend with radius (factor 2 at 2 $r_{200}$)
Early-type galaxies fair tracers of mass within $r_{200}$

$z \simeq 0.4$

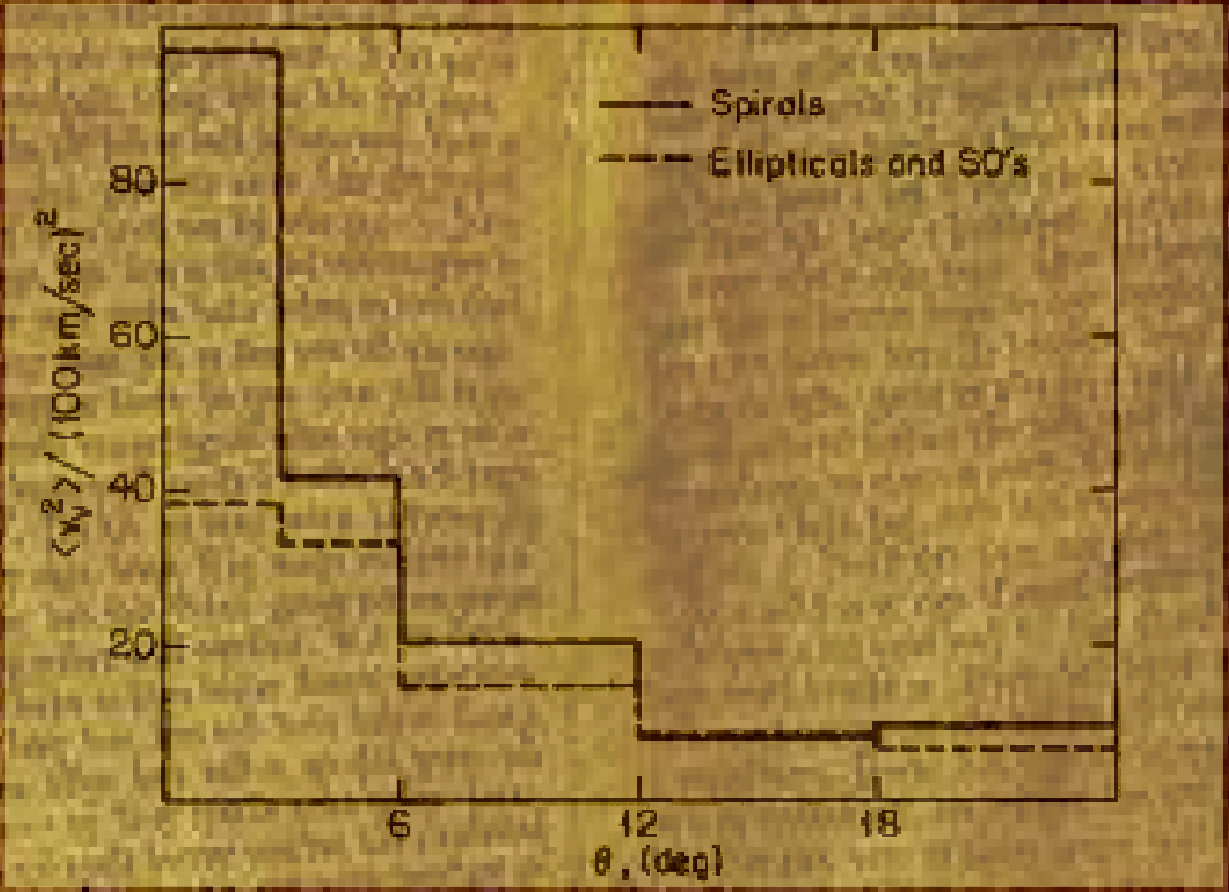
No central light excess (?)
(central assembly of very bright galaxies still ongoing?)
No decreasing M/L with radius (?)
(more field galaxies yet to be captured?)

*Progress:*

- mass-to-light profile of galaxy groups
- mass-to-light profile evolution with z

# Orbital structure

# Historical




Velocity dispersion profiles of early- and late-type galaxies in Virgo from Hoffman et al. (1980)

# Scientific motivations

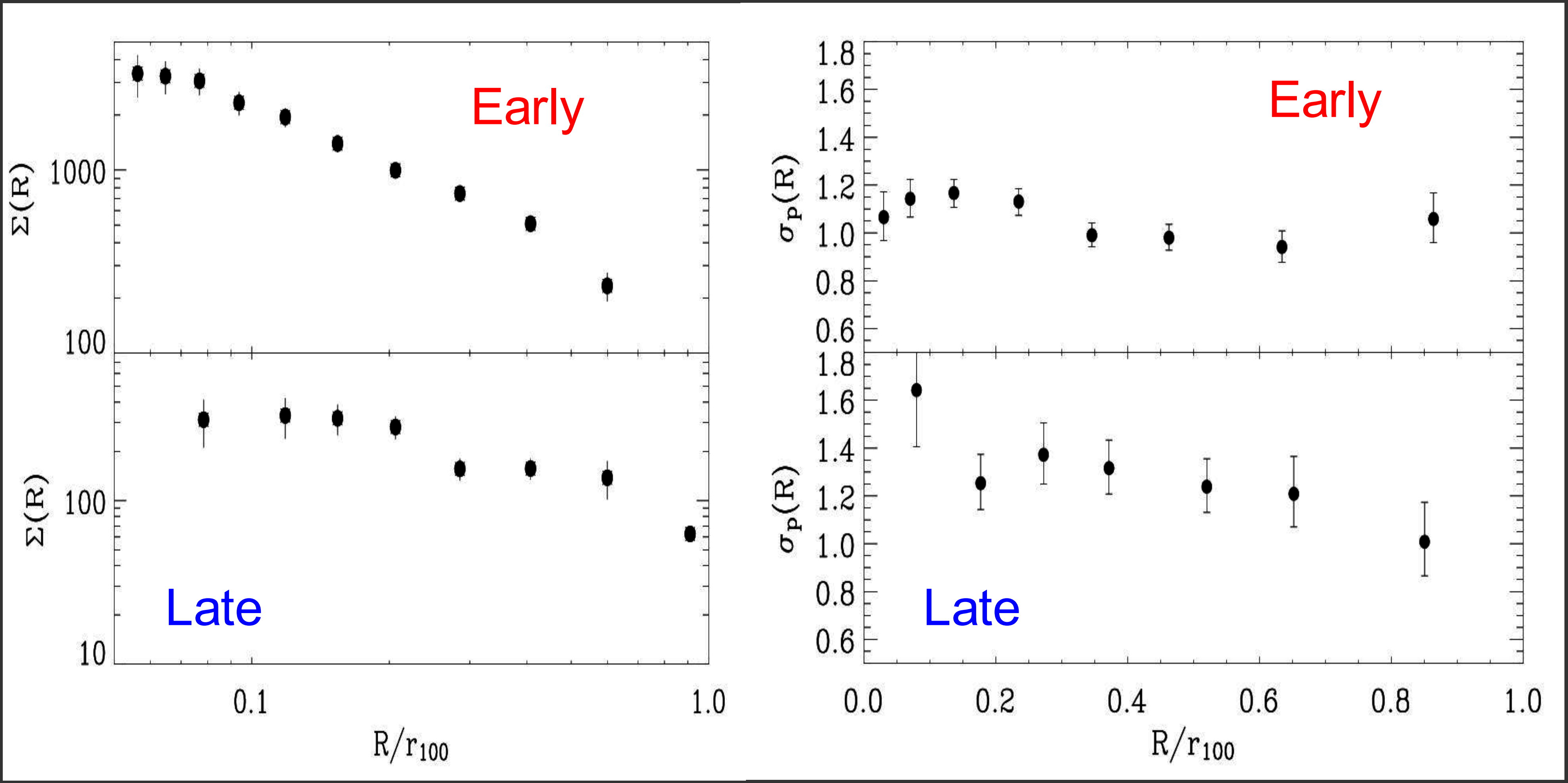
- Test hierarchical accretion models

  *accretion rate of field galaxies vs. redshift*

- Test cluster galaxy evolution models

  *orbits of cluster galaxies evolve as a result of e.g. selective tidal destruction of galaxies on radial orbits (e.g. Faltenbacher et al. 05)*

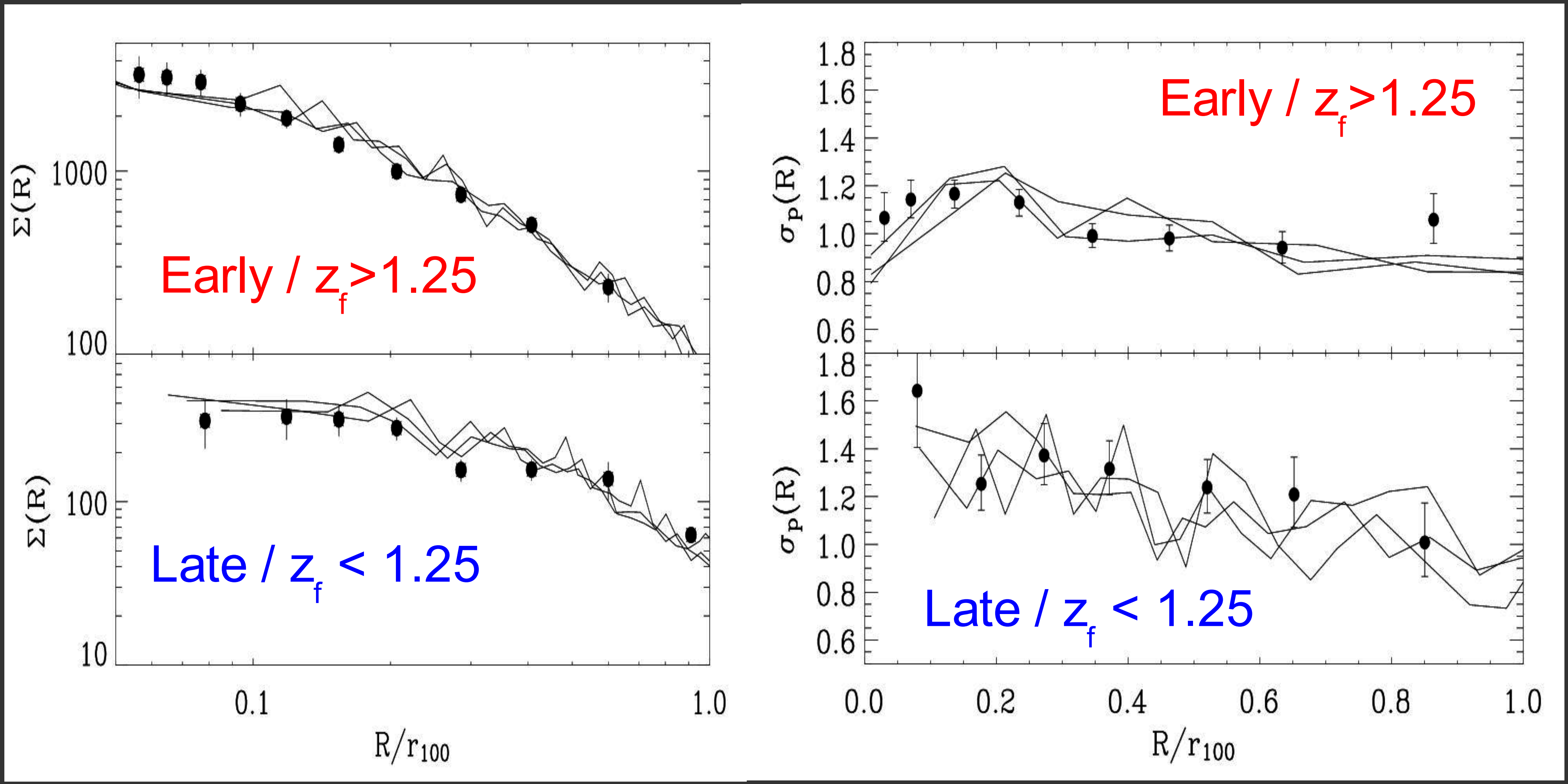
# Orbits results: ENACS *(B. & Katgert 04)*




Early- and late-type cluster galaxies have ≠ number density profiles and ≠ velocity dispersion profiles

→ do they move with different orbits in the cluster potential?

# Orbits results: ENACS vs. SIMULATIONS

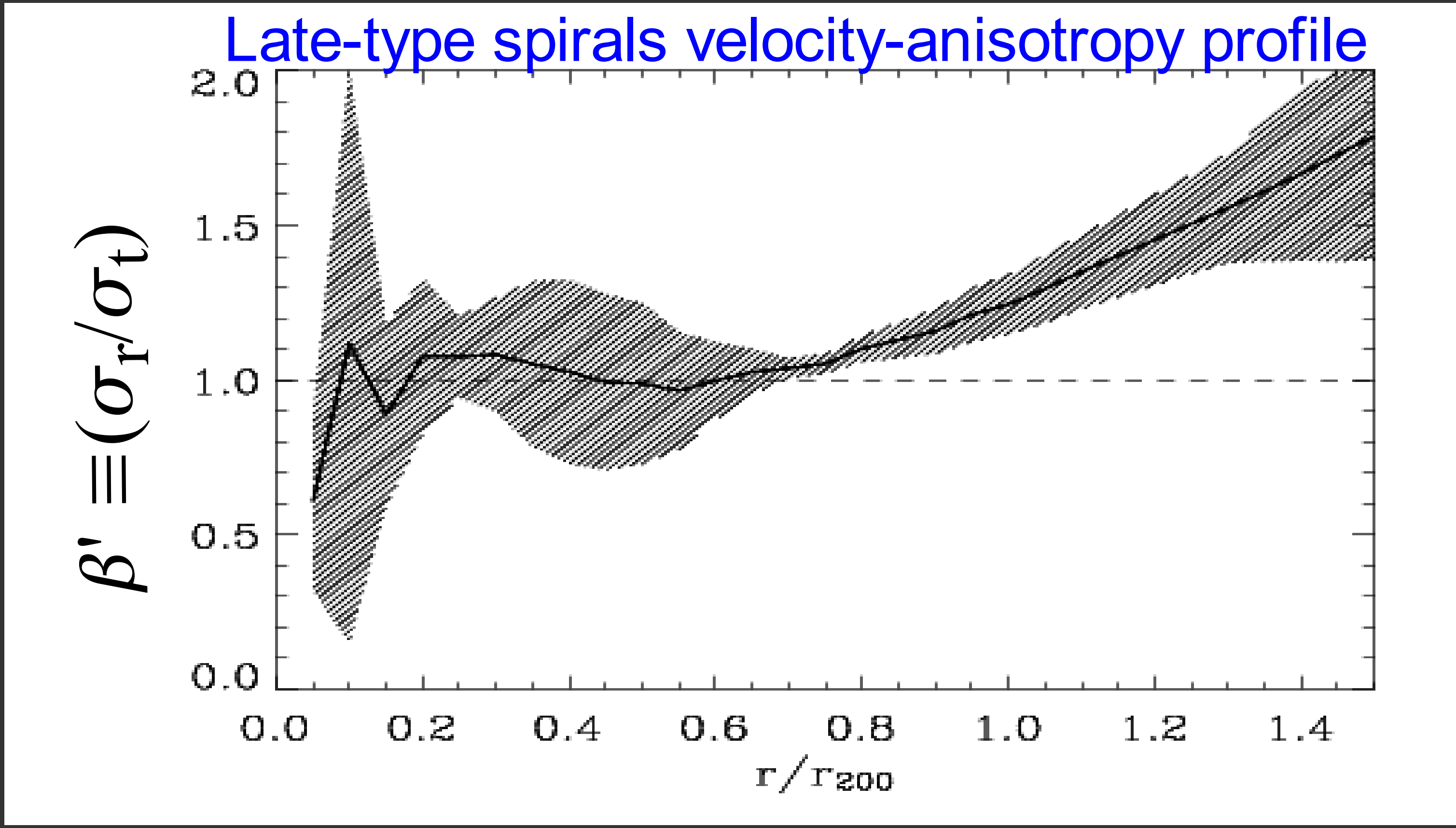



Numerical simulations can reproduce the early- and late-type cluster galaxies number density profiles and velocity dispersion profiles *(B., Murante, Borgani, Dolag et al. in prep.)*

➡ allows better understanding of cluster galaxies evolution

# Orbits results: ENACS *(B. & Katgert 04)*

Early-type galaxies have nearly isotropic orbits, $0.8 \leqslant \beta' \leqslant 1.05$ from the analysis of the velocity distribution

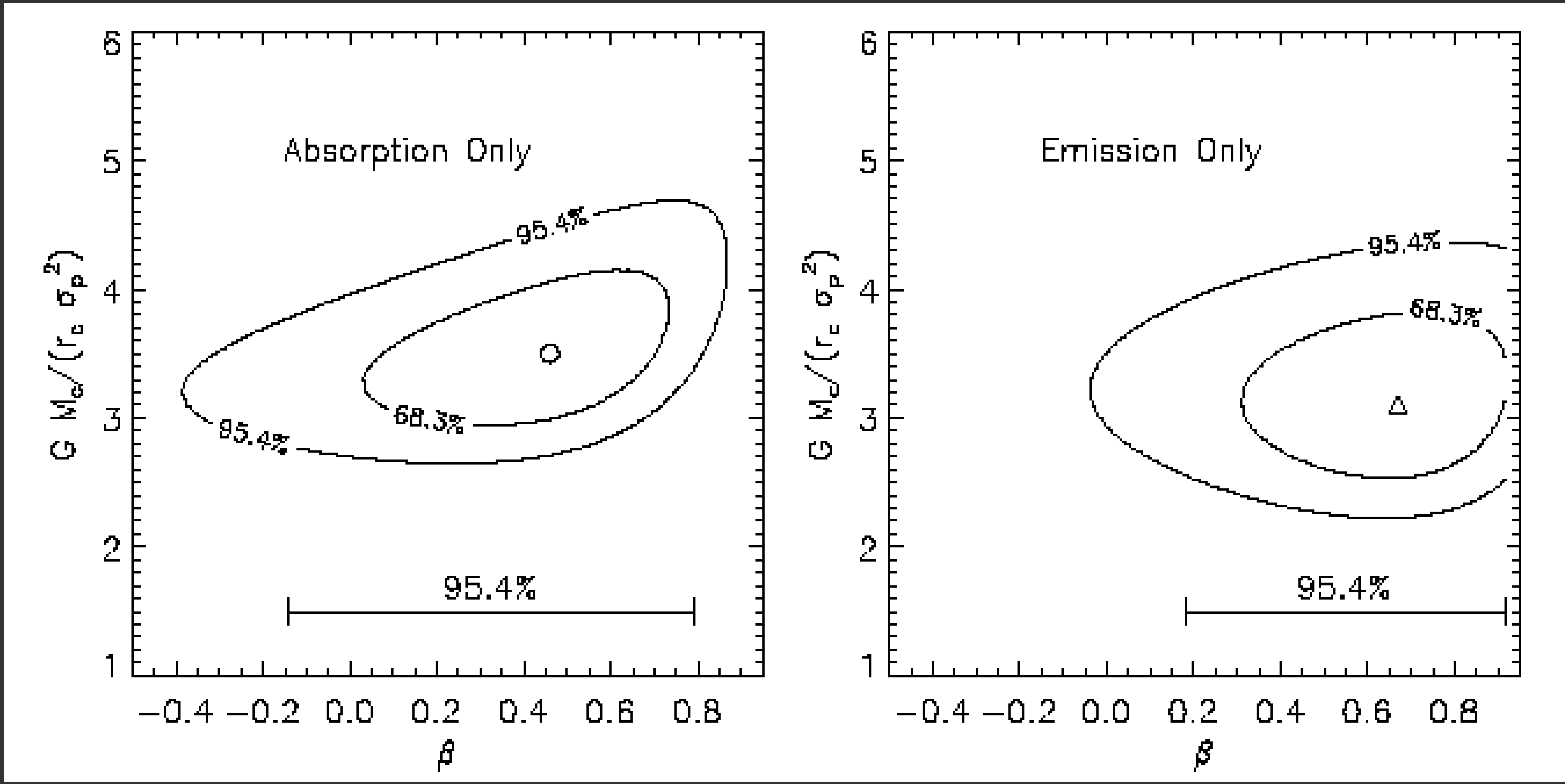



Late-type spirals are on increasingly radial orbits with radius while early-type spirals have nearly isotropic orbits, based on the Jeans-equation inversion

# Orbits results: groups *(Mahdavi et al. 99)*

Early-type galaxies have nearly isotropic orbits,
late-type galaxies have moderate radial velocity anisotropy
(constant anisotropy assumed)

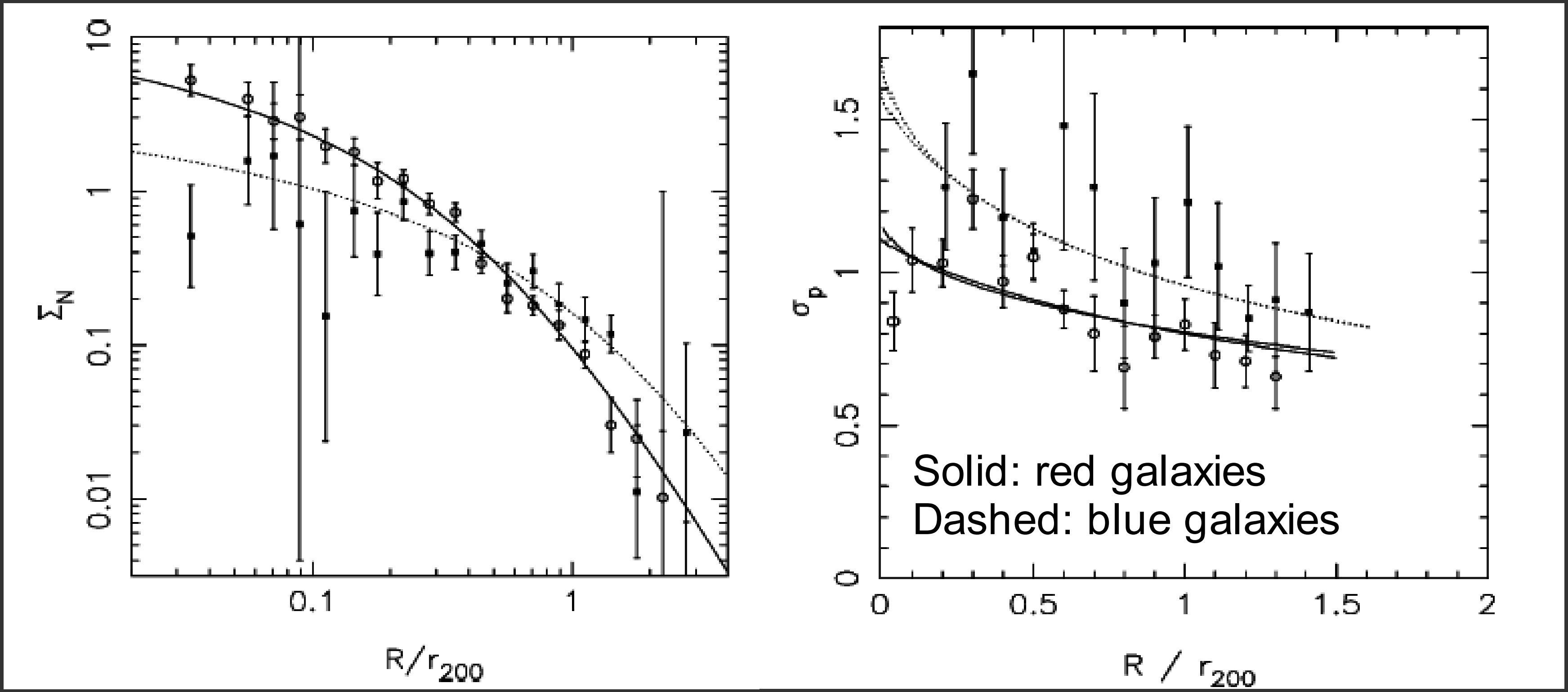
Mass




$$\beta \equiv 1-(\sigma_t/\sigma_r)^2$$

# Orbits results: evolution; CNOC

*(Carlberg et al. 97, van der Marel et al. 00)*




Similar differences between red and blue galaxies distributions as seen in nearby clusters. Red galaxies shown to have $0.74 \leqslant \beta' \leqslant 1.05$, blue galaxies? Perhaps on more radial orbits

# Orbits results summary:

- Nearby clusters:

  Early-type galaxies on isotropic orbits

  (probably also early-type *spirals*)

  Late-type spirals (and Irr) on radial orbits, $\beta(r)$ ↑ with r

- Similar results for nearby (virialized) groups

- Similar results for medium-z clusters

  Higher fraction of late-type galaxies

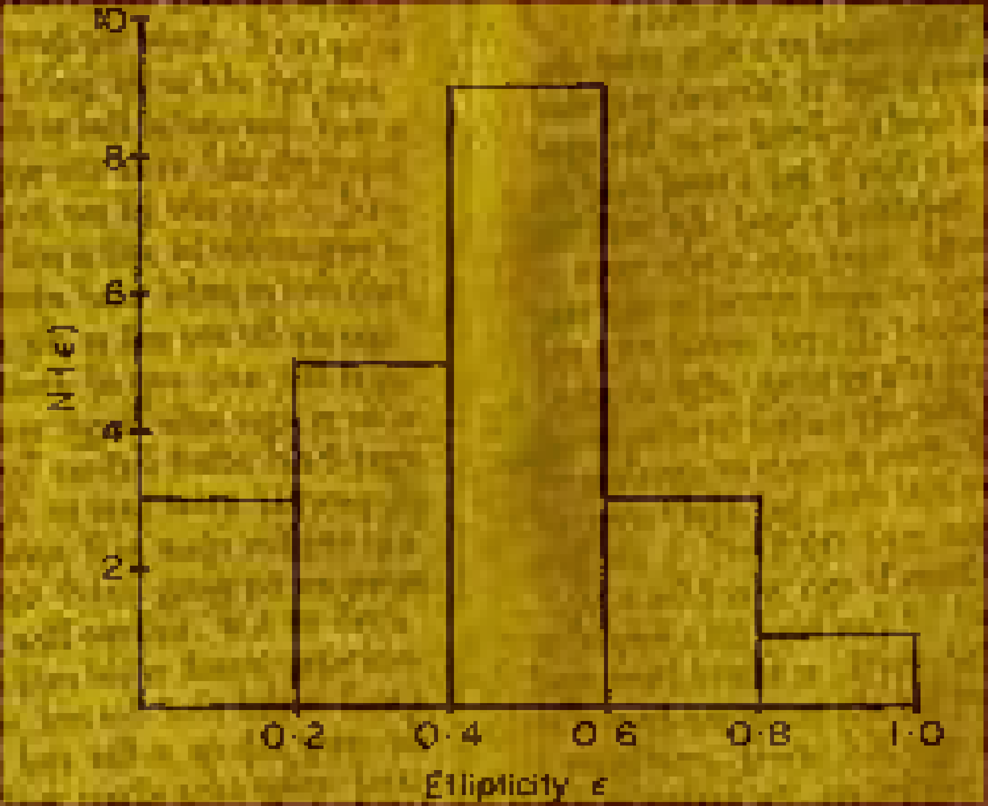
  → more radial anisotropy of the overall cluster population (?)

*Progress:* orbital structure as a f=f(z)

*(constrain galaxy infall from the field and relation with BO effect, see Ellingson et al. 01)*

# Shape

# Historical




The distribution of galaxy clusters ellipticities from Carter & Metcalfe (1980)

# Scientific motivations

- Test hierarchical build-up models

  *mechanisms of matter accretion from filaments*

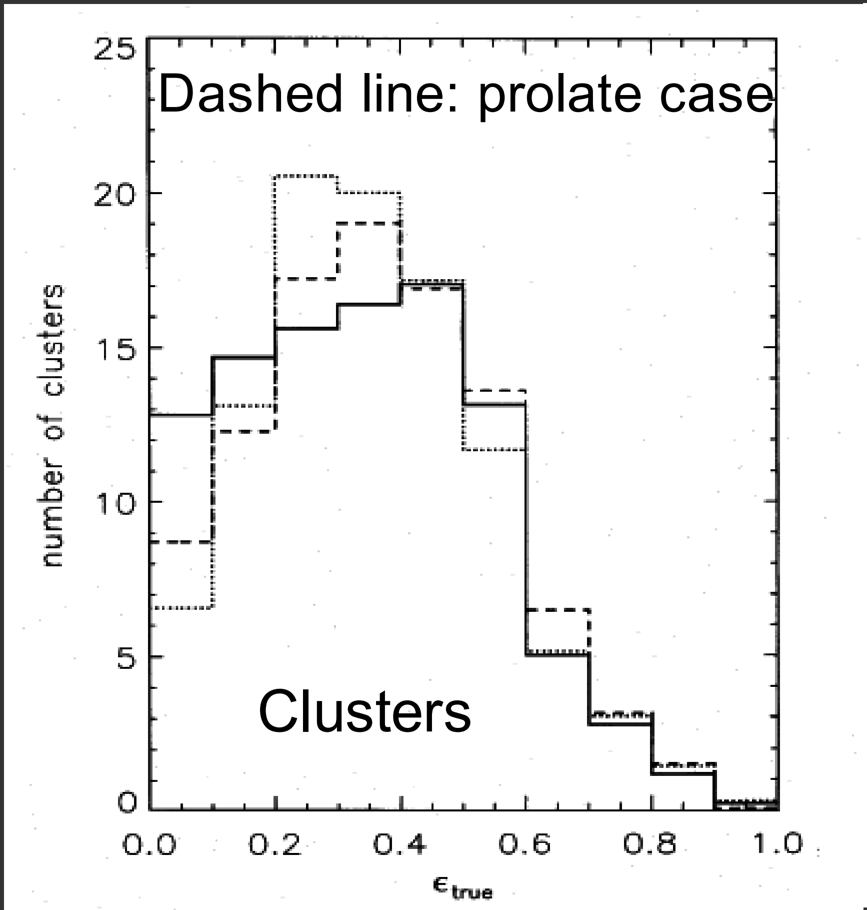
  *Virialized haloes at given mass expected to evolve to more spherical shape as z⬇ and evolution is faster for lower-mass haloes (e.g. Allgood et al. 05, Kasun & Evrard 05)*

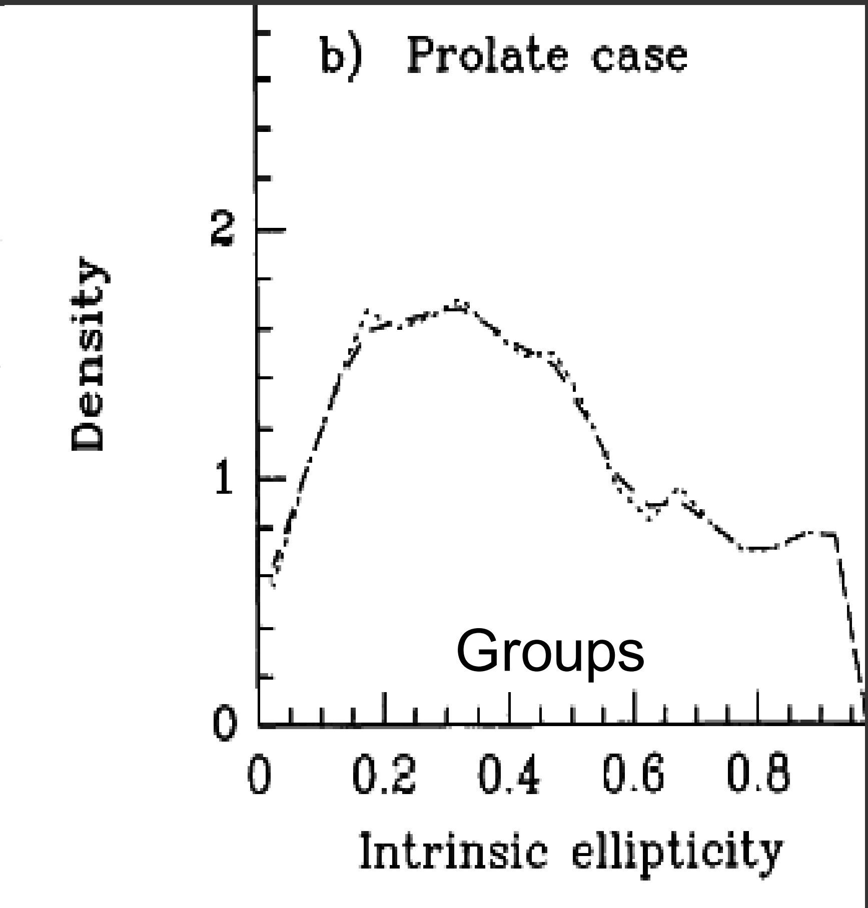
- Cluster mass estimates are affected by deviations from spherical shape

  *(e.g. Piffaretti et al. 03, Gavazzi 05)*

# Shape results

Intrinsic ellipticity $\epsilon \equiv$ 1-(minox axis)/(major axis)



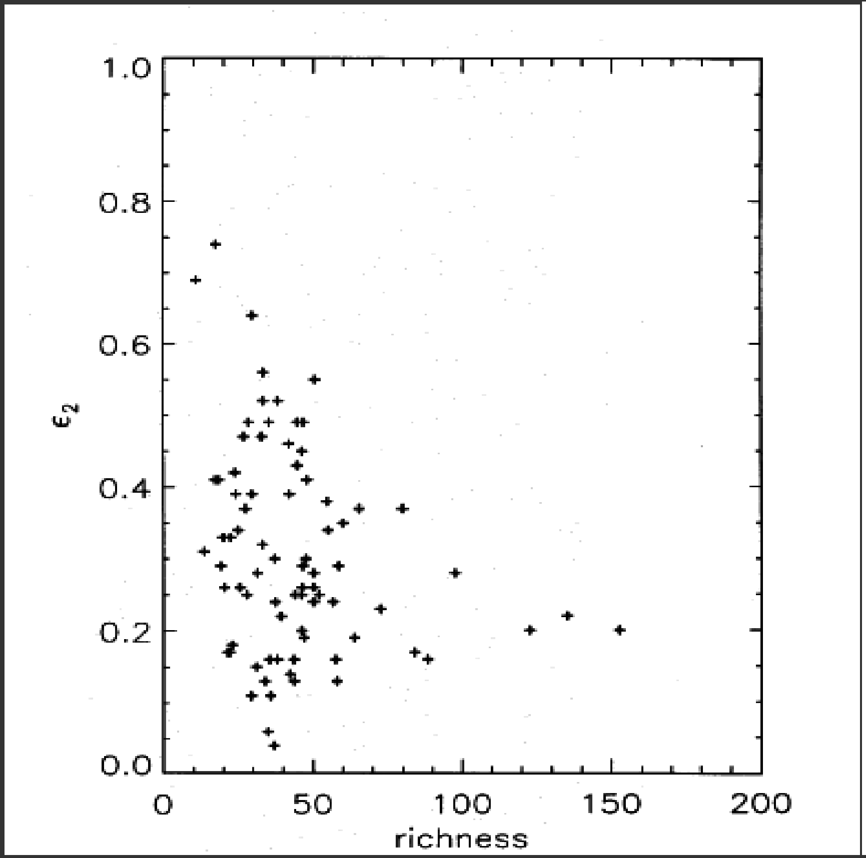



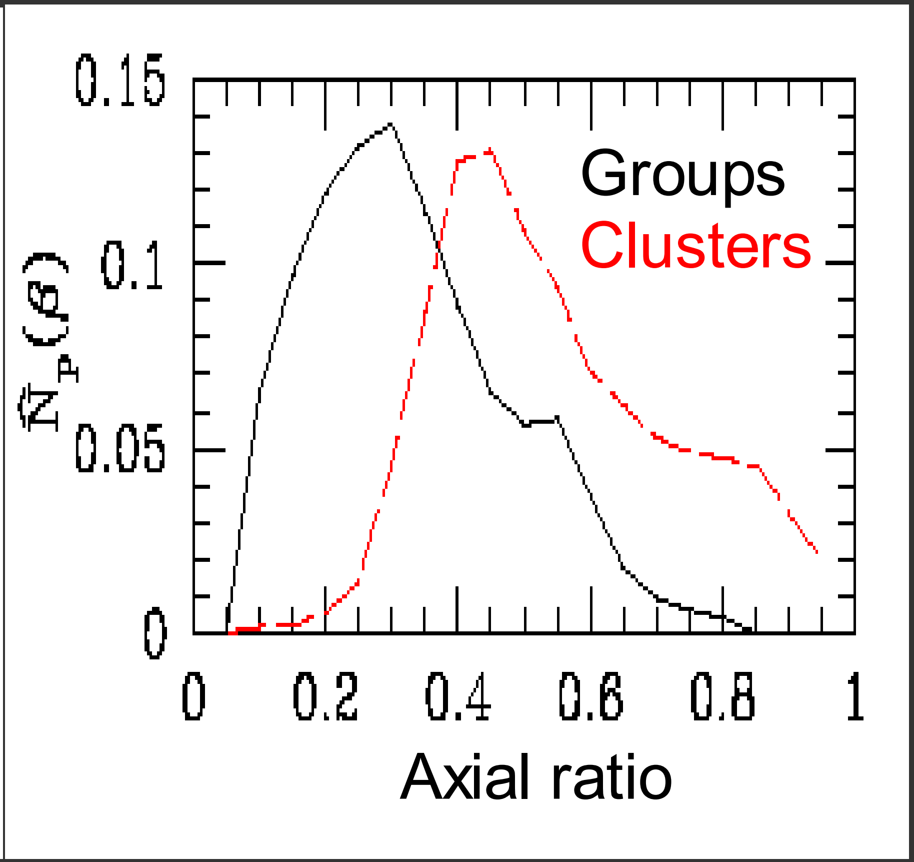

*(de Theije et al. 95, Fasano et al. 93)*

*Fraction of groups with $\epsilon$>0.6*
*twice the corresponding cluster fraction*

# Shape results

Ellipticity



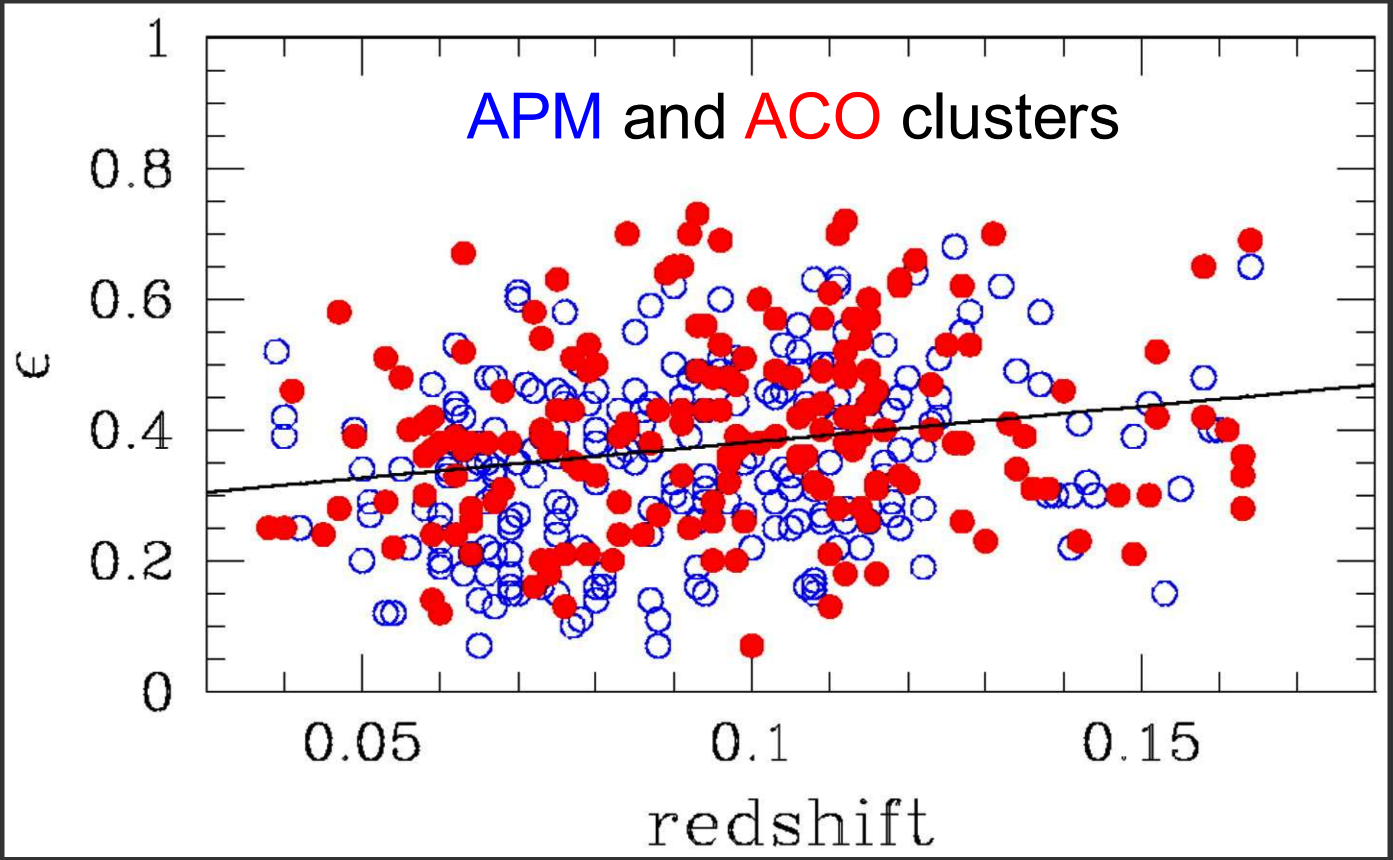




*(de Theije et al. 95, Plionis et al. 04; consistent with Strazzullo et al. 05)*

Lower mass systems are less spherical, contrary to theoretical expectations

*(but are we comparing apples and oranges?)*

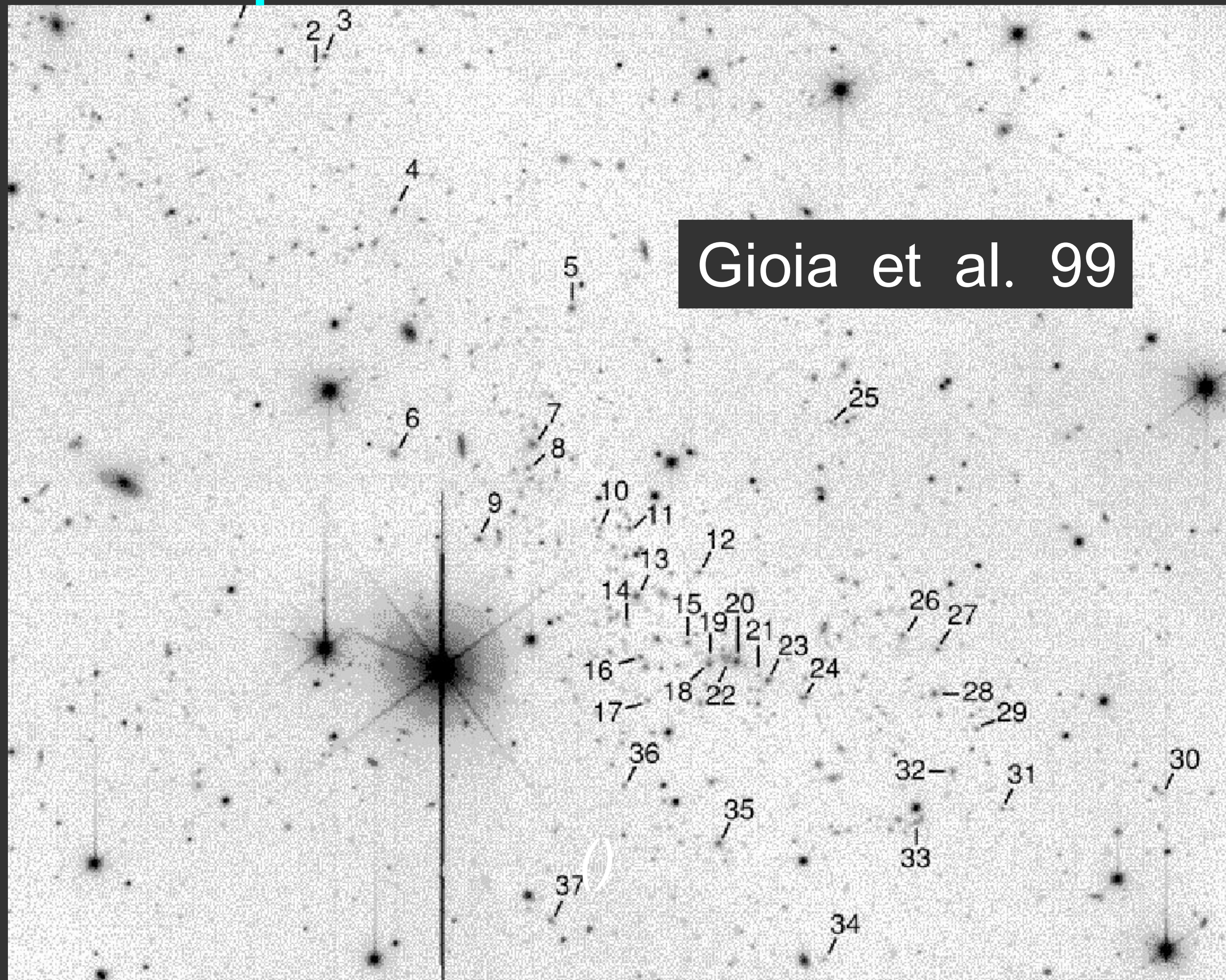
# Shape results: evolution




*(Melott et al. 01, Plionis 02; but see Flin et al. 04)*

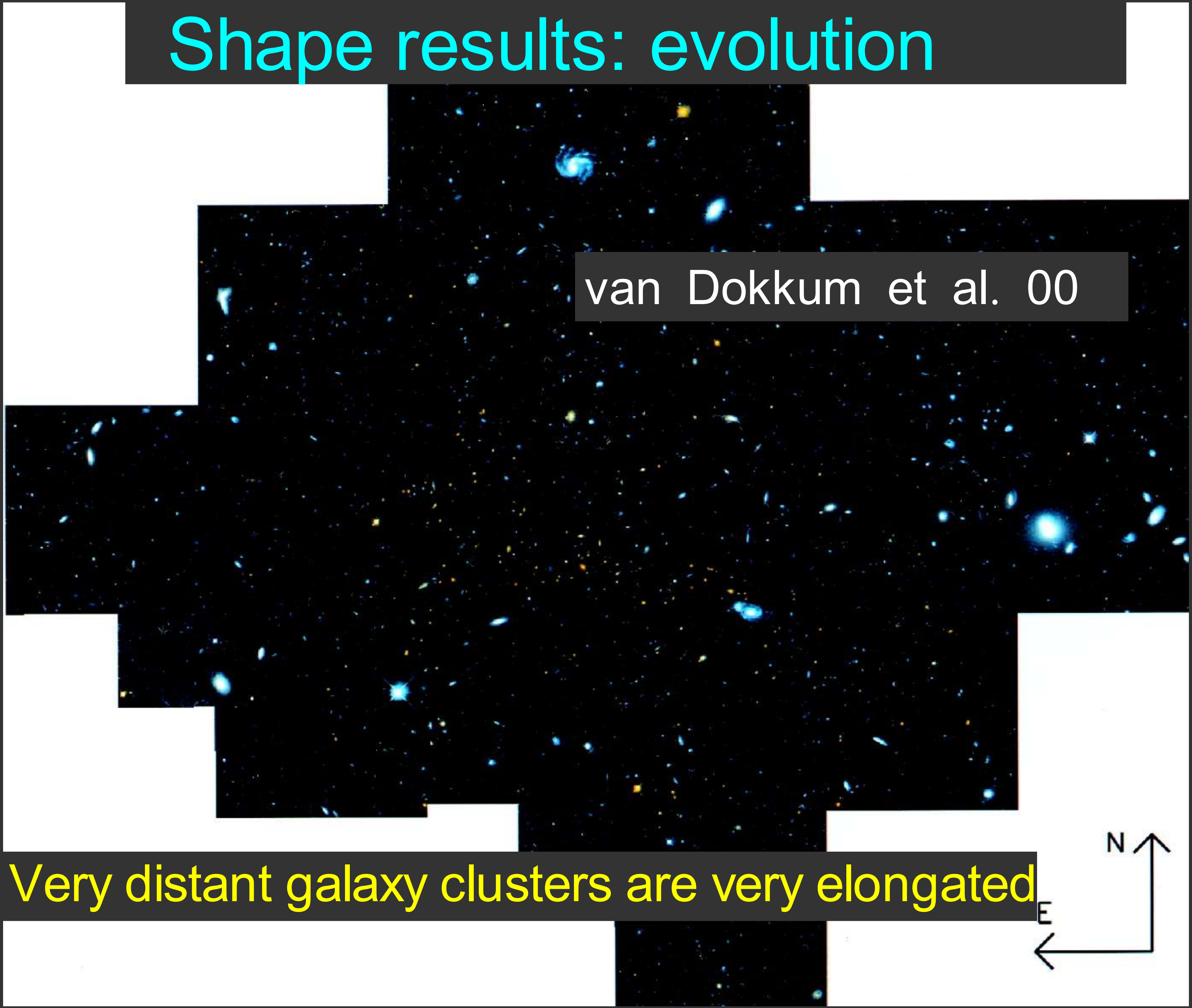
Higher-z galaxy clusters are less spherical; trend in agreement with theoretical expectations *but maybe too strong?* *(Floor et al. 04)*

# Shape results: evolution



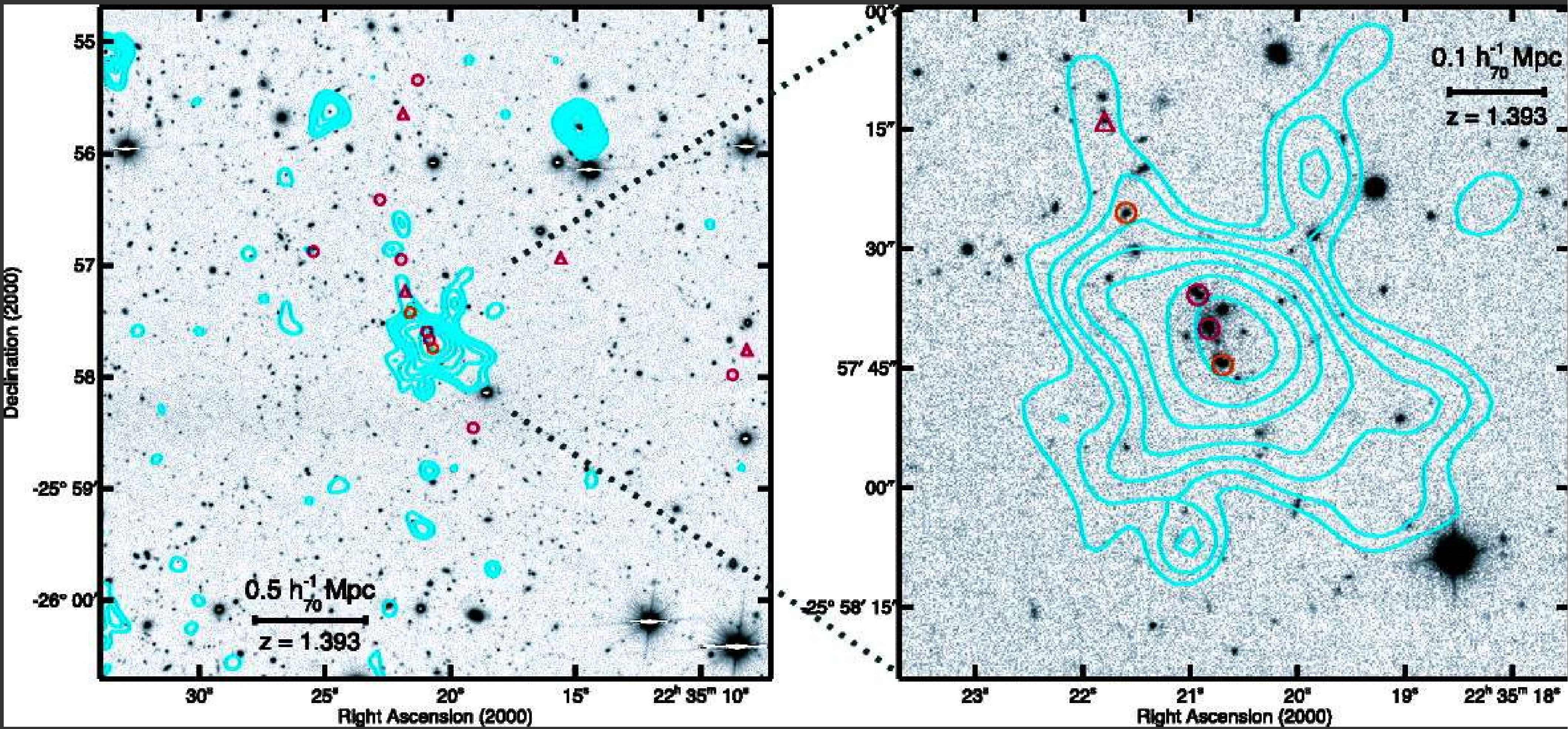

Very distant galaxy clusters are very elongated

# Shape results: evolution




Very distant galaxy clusters are very elongated

# Shape results: evolution




*Mullis et al. 05*

Very distant galaxy clusters are very elongated

# Shape results summary:

- Nearby clusters are less elongated than nearby groups

  Conflict with predictions from num. sims.?

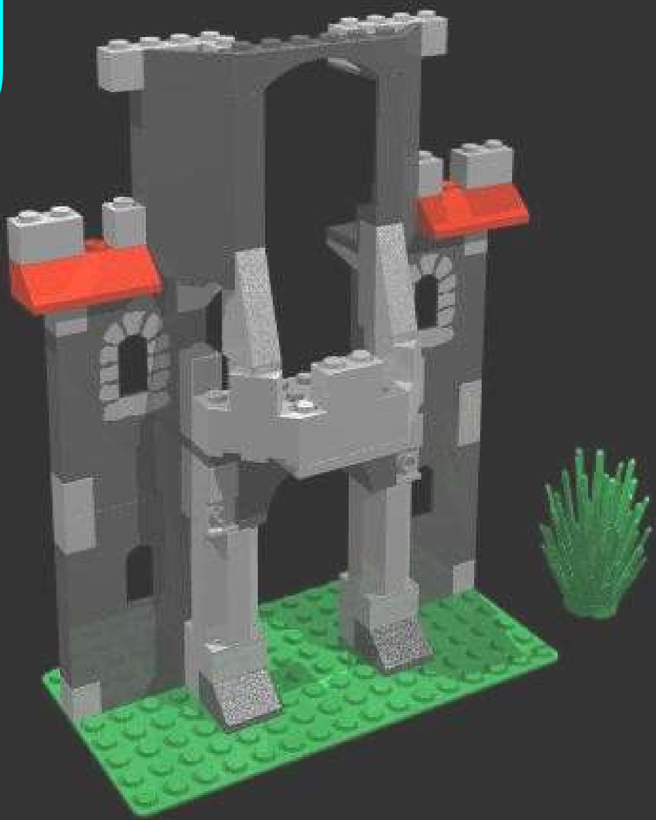
  (but: are observed groups *virialized* low-mass haloes?)

- Distant clusters are more elongated

  Projection effects more severe for mass estimation

*Progress:* clusters shape distribution at high-z

# Subclustering



# Historical


Excess of low-velocity galaxy pairs in Virgo from van den Bergh (1961)

# Scientific motivations

- Constrain cosmological build-up of structures
- Cluster mass estimates are affected by subclustering (collisions & mergers)
- Influence on internal properties of galaxies

# Subclustering results

Frequency of clusters with subclusters: 30–80 %

*(Geller & Beers 82, Dressler & Shectman 88, Salvador-Solé et al. 93, Bird 94, Escalera et al. 94, Girardi et al. 97, Kriessler & Beers 97 ...)*

*But fraction overestimated because of* projection effects (Kolokotronis et al. 01)

Typical size of detected subclusters: 0.4–0.6 Mpc

*(Geller & Beers 82, Salvador-Solé et al. 93, Escalera et al. 94, Girardi et al. 97)*

Their typical mass: 10% Mass of parent cluster

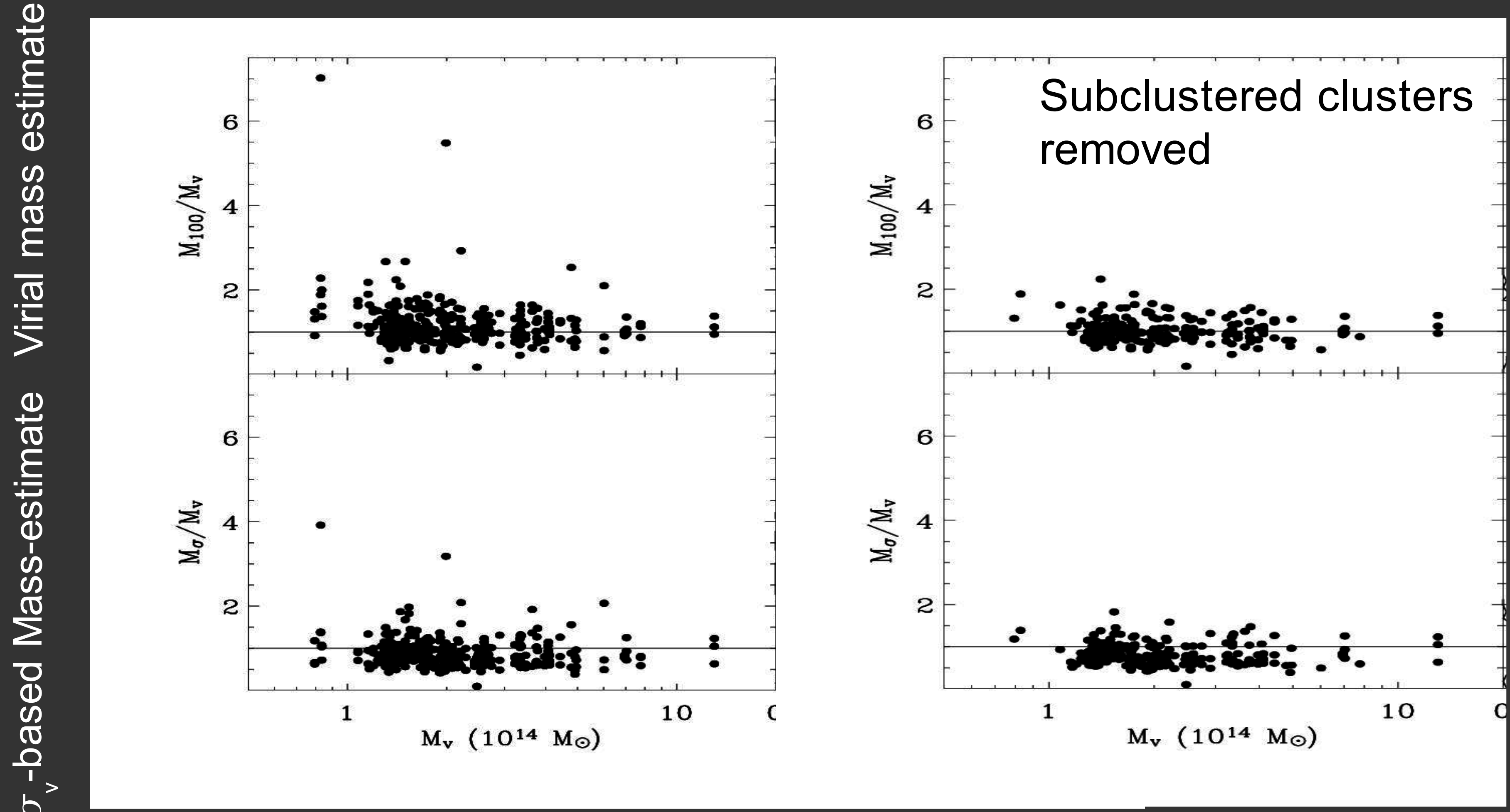
*(Escalera et al. 94, Girardi et al. 97)*

10–20% clusters are bimodal *(Girardi et al. 98)*

*Hence virial mass estimates are little affected on average*

# Subclustering results

Simulations: subclusters are a serious concern for virial mass estimates, when unaccounted for; but subclustered clusters can be identified and removed




*(B., Murante, Borgani, Dolag et al. in prep.)*

# Subclustering results: WINGS

A wide-field, multiwavelength imaging and spectroscopic survey of 78 nearby clusters

*(Fasano et al. 05)*

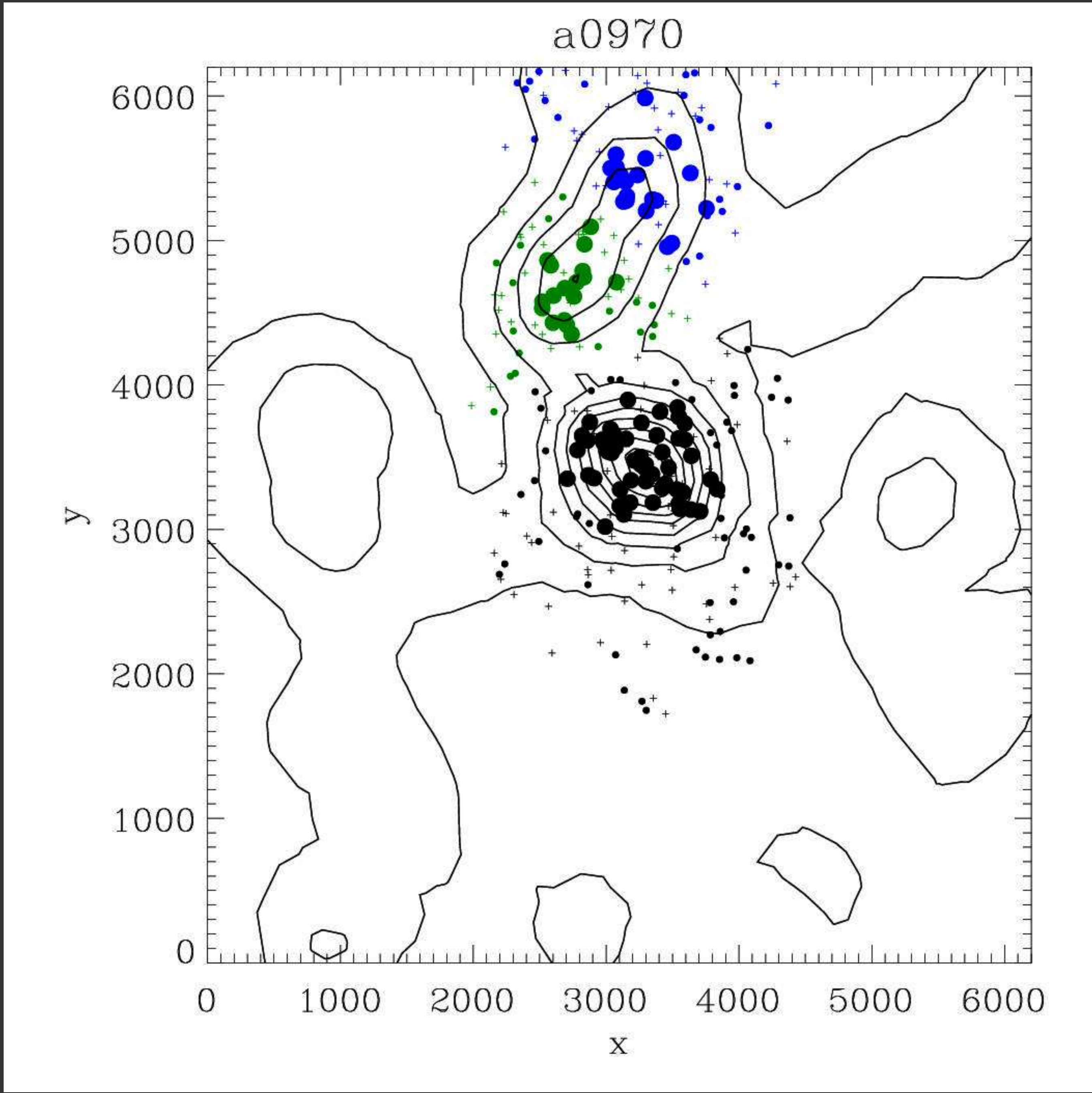
*Work in progress to establish the frequency of* subclusters in WINGS clusters and the properties of subcluster galaxies relative to the whole cluster population.

Current analysis of projected galaxy distribution with the DEDICA algorithm for structure detection

(Pisani 1996; Ramella et al. in prep.)

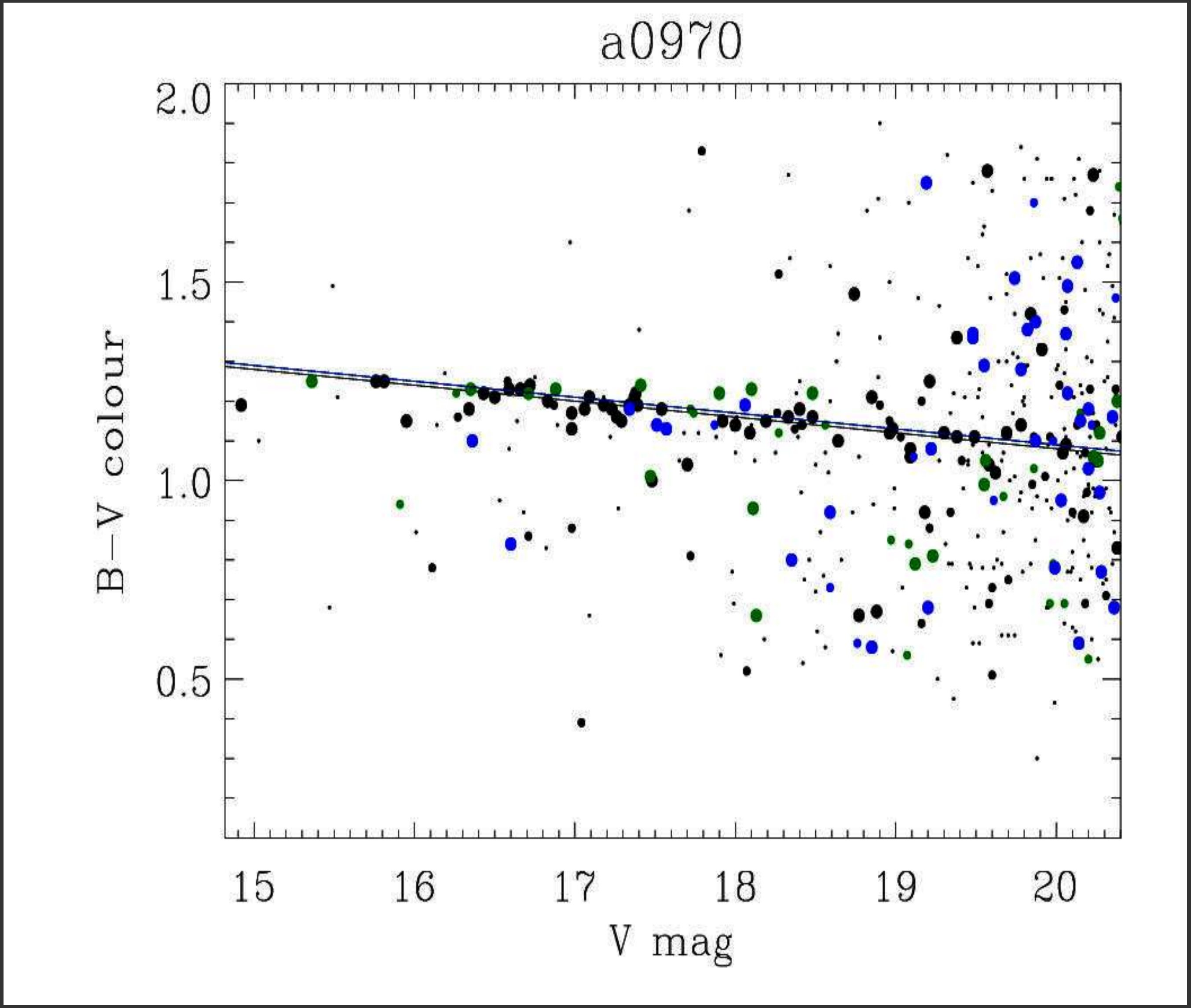
# Subclustering results: WINGS

Three structures detected by DEDICA




0.5 Mpc

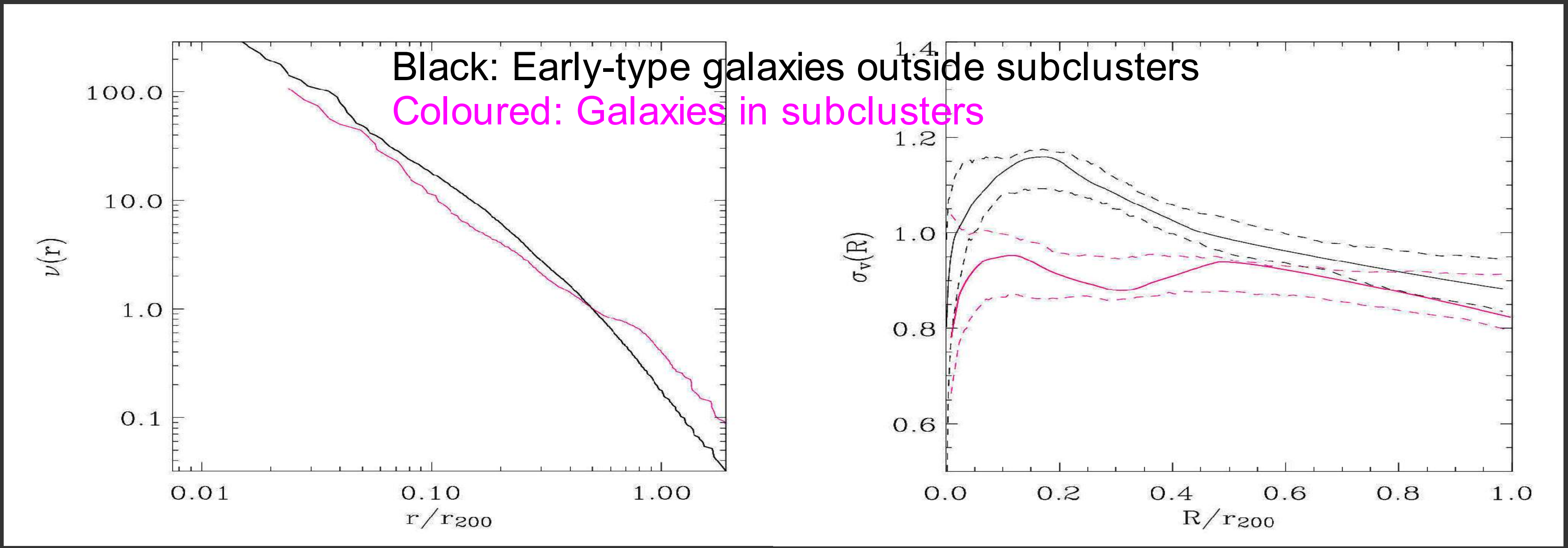
# Subclustering results: WINGS




Use location in colour-magnitude diagram to distinguish real subclusters from projected structures

# Subclustering results: ENACS *(Katgert & B. in prep.)*

Identify individual galaxies in substructures
rather than subclusters as a whole




Preliminary results:

- 31 % cluster galaxies are in subclusters
- Substructure galaxies avoid the central cluster regions and have small velocities → tangential velocity anisotropy
- There are relatively more emission-line galaxies in substructures than in the cluster as a whole (30±6 % vs. 15±3 %)

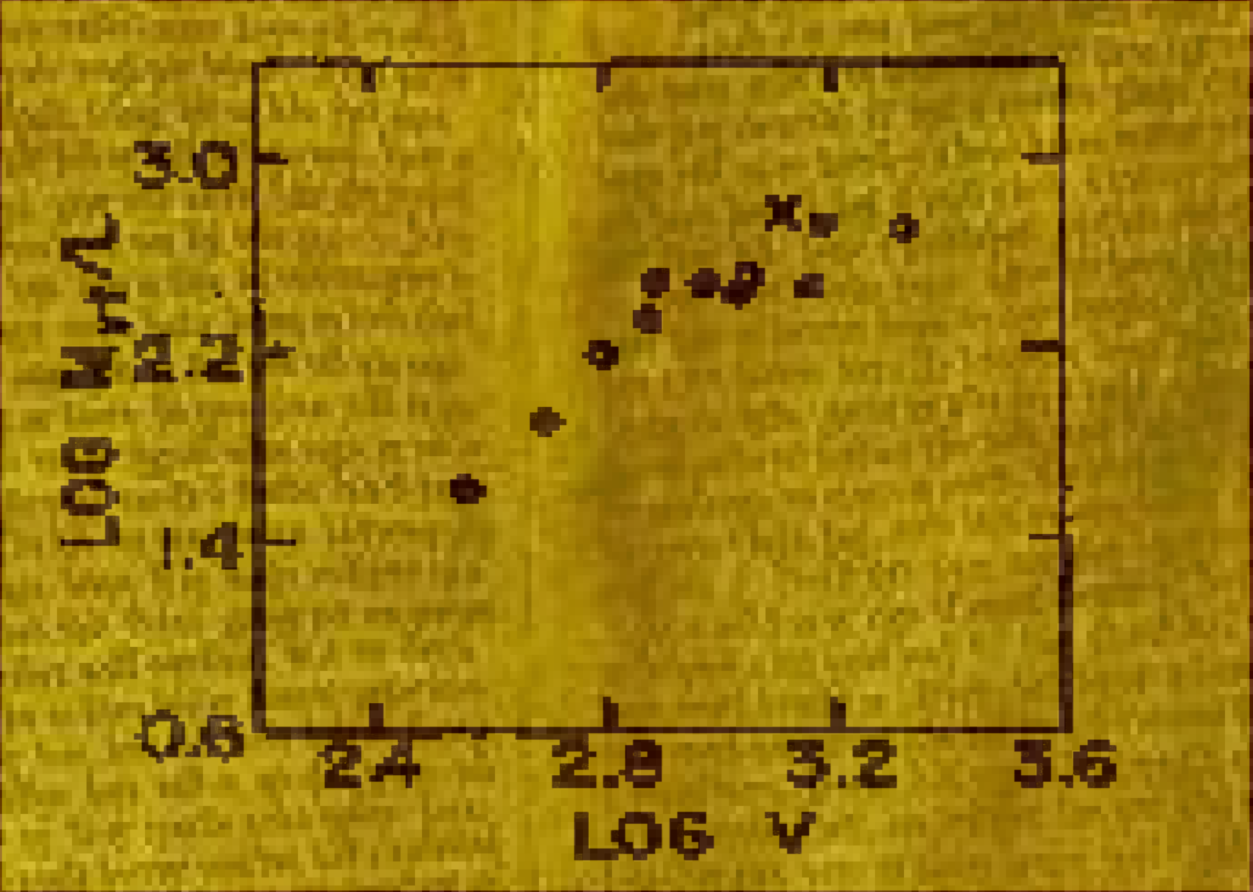
# Subclustering results summary:

- Good identification of subclusters in nearby clusters: allows for a cleaner statistical sample of cluster masses
- Higher fraction of emission-line galaxies in subclusters than in the cluster as a whole
- Galaxies in subclusters follow tangential orbits
- Only sparse results on more distant clusters
  *(e.g. Halliday et al. 04: 10–100 % cls. with subcls.;*
  *Rosati et al. 99, Lubin et al. 00, Pentericci et al. 00*
  *and Haynes et al. 01: merging subcls. at high-z)*

*Progress:* characteristics of subcluster properties and systematic analysis in distant clusters

# Scaling Relations

# Historical




M/L increases with the velocity dispersion of the galaxy system (Rood 1974)

# Scientific motivations

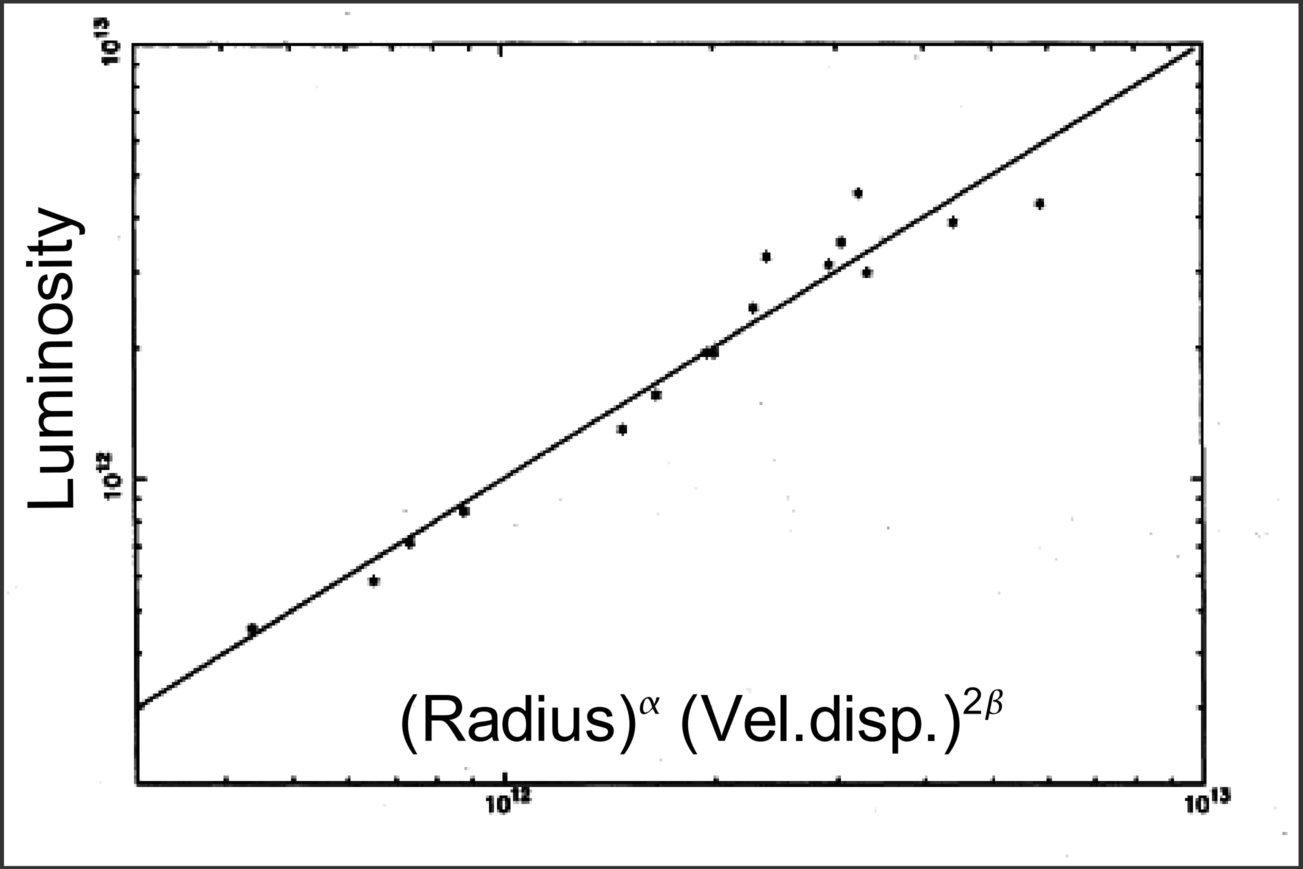
- Understand the efficiency of galaxy formation, and/or the ageing/evolution of galaxies *(e.g. Bahcall et al. 00; Lin, Mohr & Stanford 04)*

- Use optical luminosities as cheap proxies for cluster masses *(e.g. Yee & Ellingson 03)*

# Scaling relations: results

Cluster global quantities lie on a fundamental plane

*(Schaeffer et al. 93, Adami et al. 98, ...)*

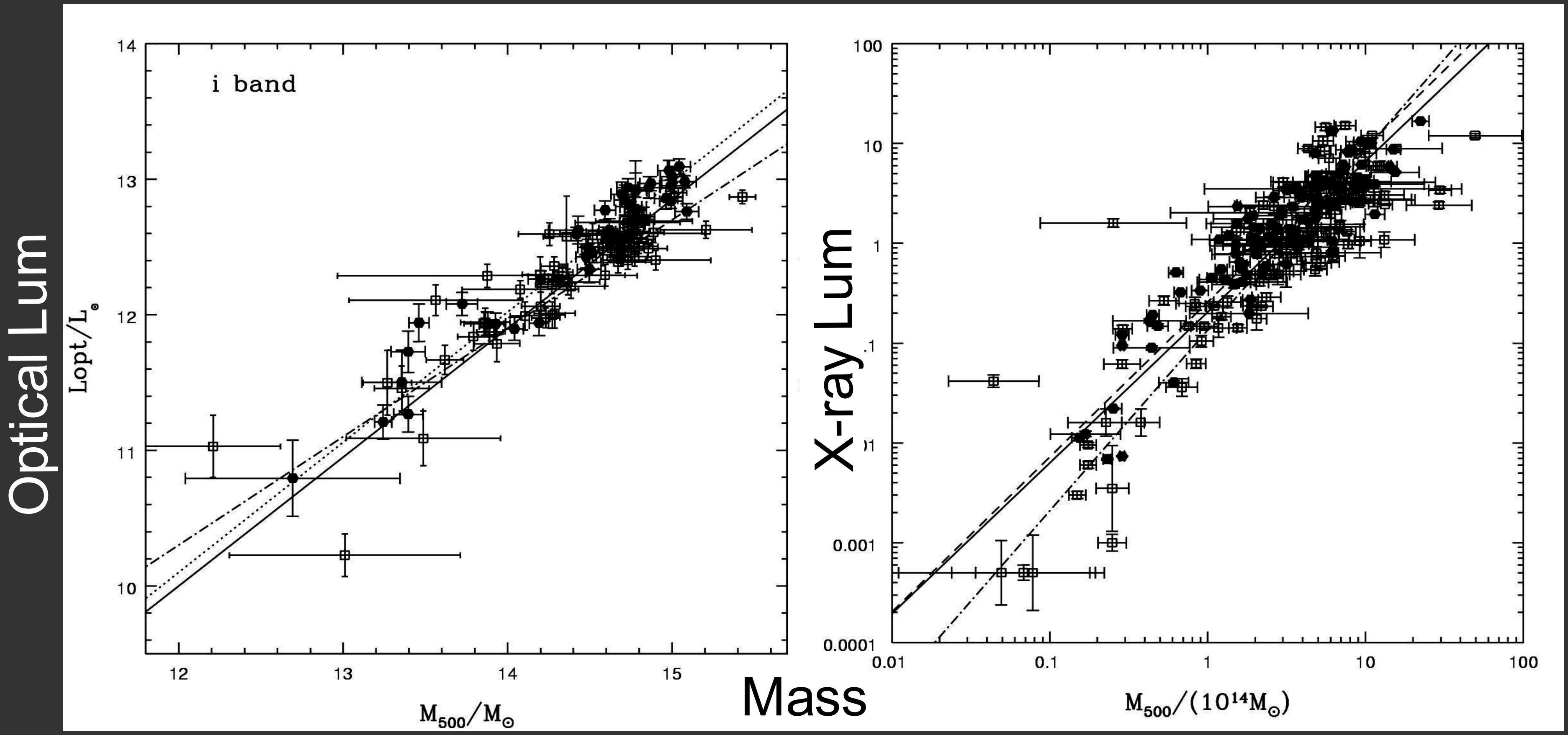



FP $\Rightarrow$ M/L $\propto$ $M^{\gamma}$, $\gamma$=0.4–0.5

# Scaling relations: results

$L_{opt}$ is as good a proxy for M as $L_X$ (or better)

*(Yee & Ellingson 03; RASS+SDSS, Popesso et al. 05)*



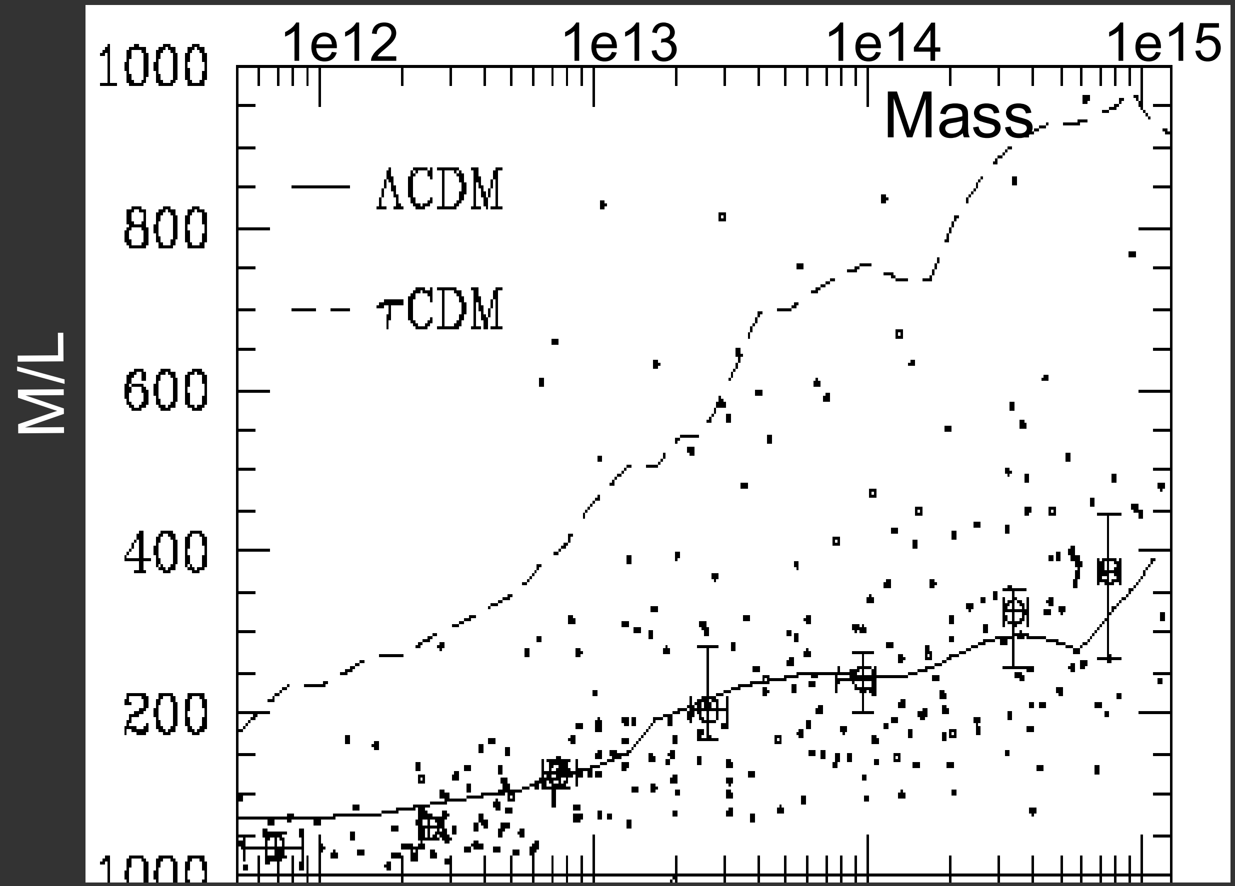

Fitting a power-law: $M/L \propto M^{\gamma}$, $\gamma=0.2$

The slope is the same in the four SDSS bands

# Scaling relations: groups & clusters

## M/L vs. M (or L) is not a power-law

*(NOG groups + rich clusters catalogue, Girardi et al. 02)*



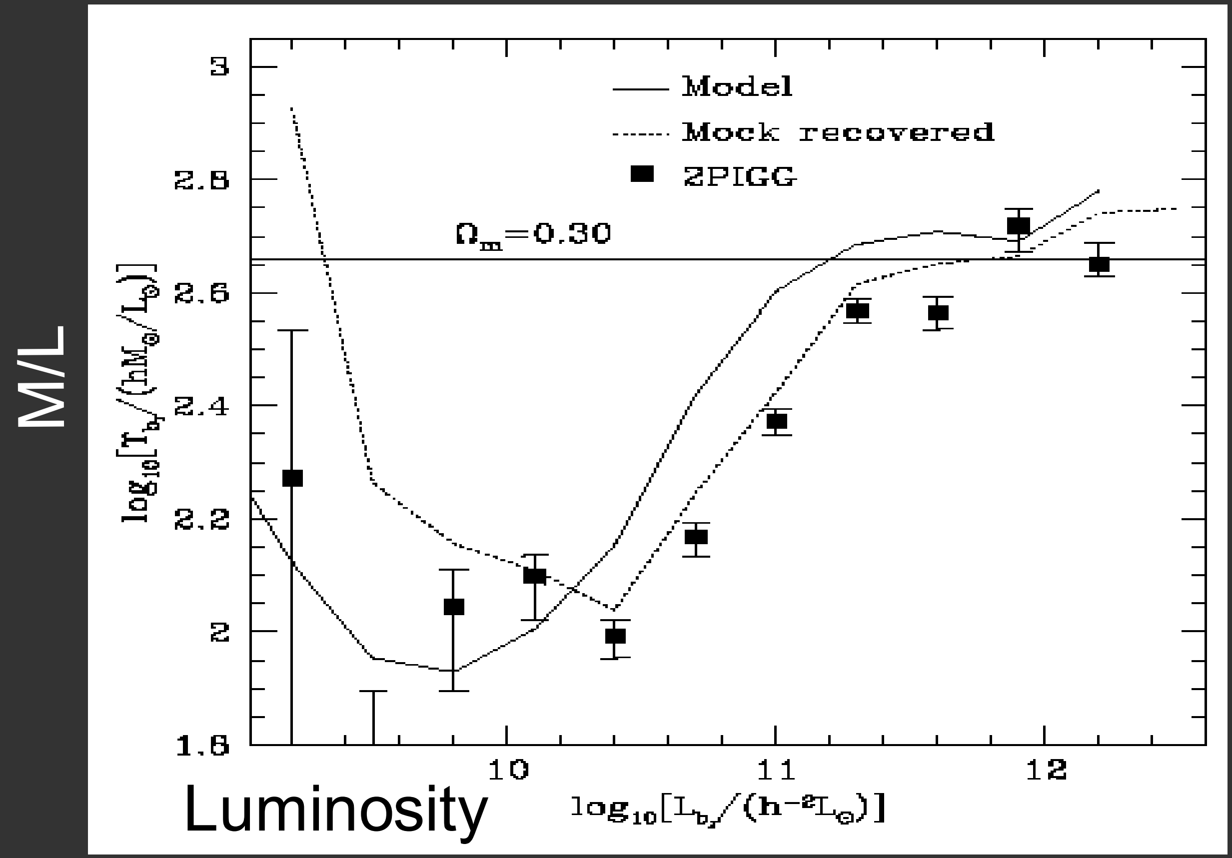

## Agreement with theoretical expectations

*(Kauffmann et al. 1999)*

# Scaling relations: groups

Groups M/L vs. M (or L) is not a power-law

*(2dFGRS groups catalogue, Eke et al. 04)*



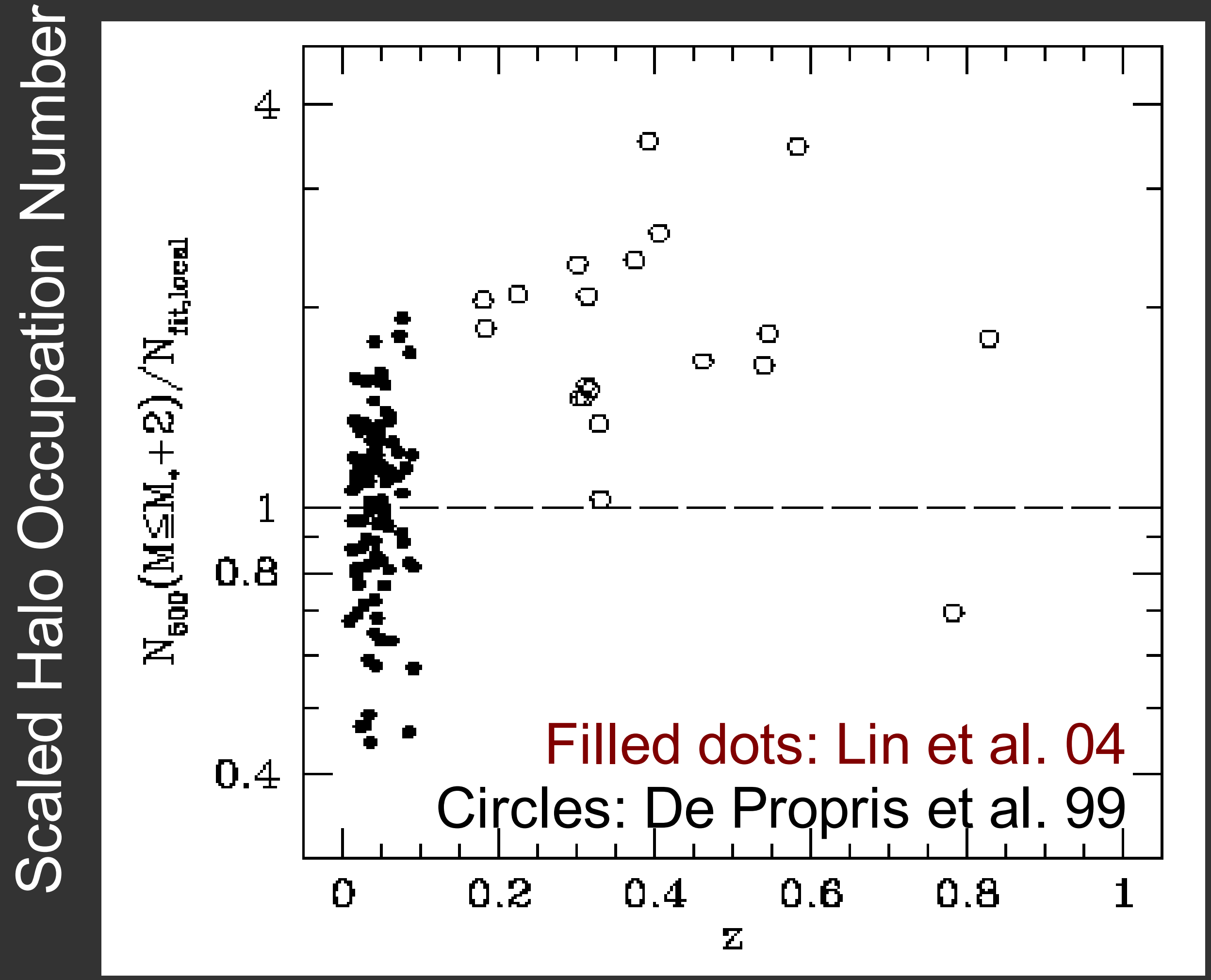

Agreement with theoretical expectations

*(e.g. Benson et al. 2000)*

# Scaling relations: evolution

*(Lin, Mohr, & Stanford 04)*

More distant clusters have a higher mean number of galaxies per given mass




*Galaxy evolution must act as to decrease cluster HON with time (merging, fading, stripping,...)*

# Scaling relations results summary:

- Cluster global properties lie on a FP
- Mass-to-light is higher in higher mass galaxy systems
- M/L vs. M relation does not depend on $\lambda$

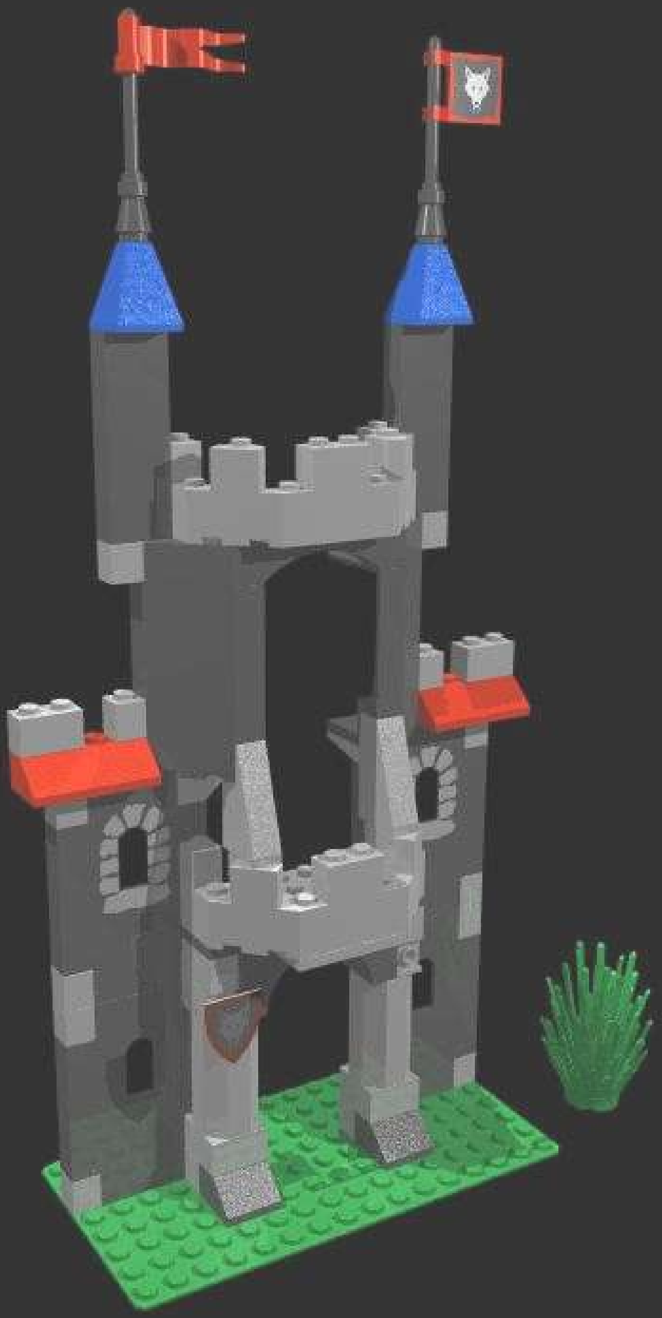
  ➡ $\neq$galaxy formation efficiencies in clusters of $\neq$mass?
  or $\neq$galaxy evolution in clusters of $\neq$mass?

*(simple ageing of galaxy populations cannot explain the scaling)*

- Higher number of galaxies per given system mass at higher z

*Progress:* Scaling relations as a function of cluster properties and redshift

# Summary
# &
# conclusions



- Mass profile: at $r>r_{200}$, slope is -3 or -4, at $r\simeq0$, cusp or small core (galaxy-sized) are allowed; similar M(r) for $z\simeq0$ and $z\simeq0.3$ clusters; trend of concentration with mass as expected

- Mass-to-light profile: red galaxies trace the mass within $r_{200}$, but M/L decreases beyond $r_{200}$ and also at $r\simeq0$; groups have higher M/L near the centre; *$z\simeq0.4$ clusters have flatter M/L*

- Orbits of galaxies: isotropic for E, S0, Sa-b, increasingly radial with radius for Sbc-Irr, *tangential for galaxies in subclusters;* *$z\simeq0.3$ clusters have more galaxies on radial orbits*

- Shape: richer galaxy systems are less elongated, distant clusters are more elongated

- Subclusters: subcluster detection allows correcting wrong cluster mass estimates,
  *1/3 of all cluster galaxies are in subclusters,*
  *subclusters contain relatively more emission-line galaxies,*
  *subclusters have tangential orbits*

- Scaling relations: cluster global properties obey a FP,
  M/L increases with M,
  slope of M/L vs. M relation changes with M, not with $\lambda$,
  *the halo occupation number increases with z*

# Conclusions

*Current constraints on cluster structure from optical observations (lensing excluded):*

- ✔ *M(r) and orbits of red galaxies out to $z \simeq 0.3$,*
- ✔ *cluster shapes out to $z \simeq 0.2$,*
- ✔ *M/L, orbits of blue galaxies, subclusters, and scaling relations only at $z \simeq 0.0$*

*...more to come soon from EdisCS and IMACS!*

Thank you for your attention!

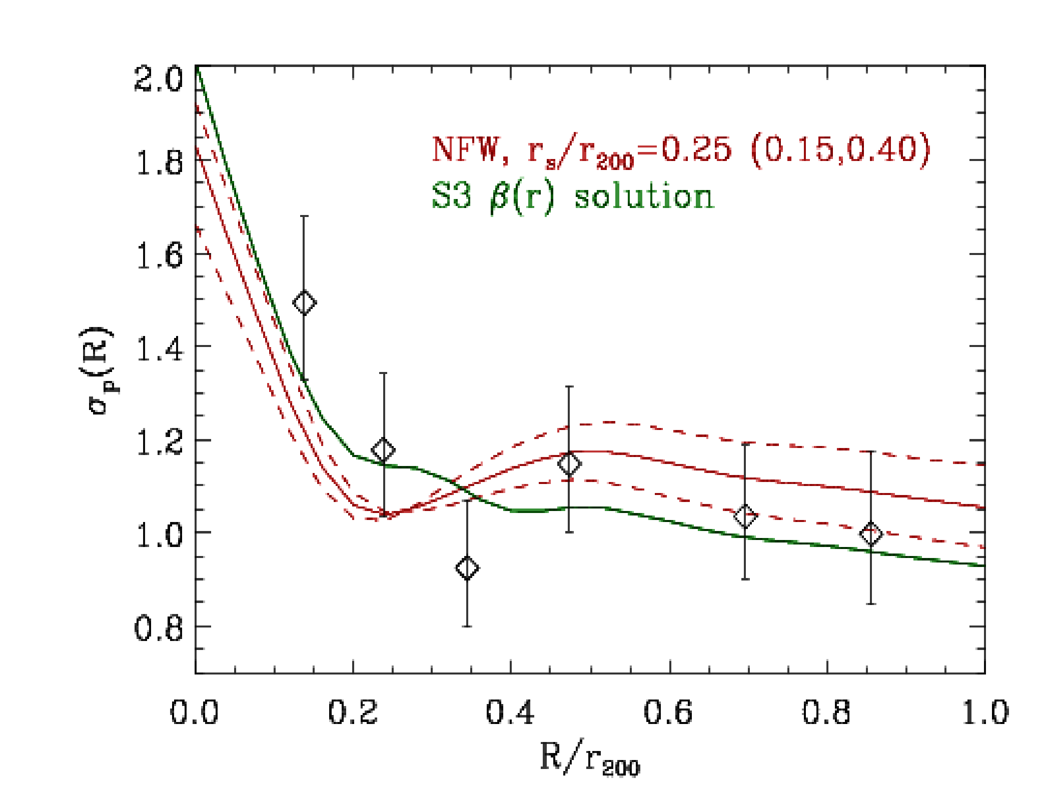
More material (not shown at the worskhop)

# M(<r) for clusters from the ENACS

## E+S0 M(<r) confirmed using other cluster galaxy populations

Given M(<r) solve Jeans eq.s for $\beta(r)$

(see Binney & Mamon 82, Merrifield & Kent 90, Solanes & Salvador-Solé 90, Dejonghe & Merritt 92)



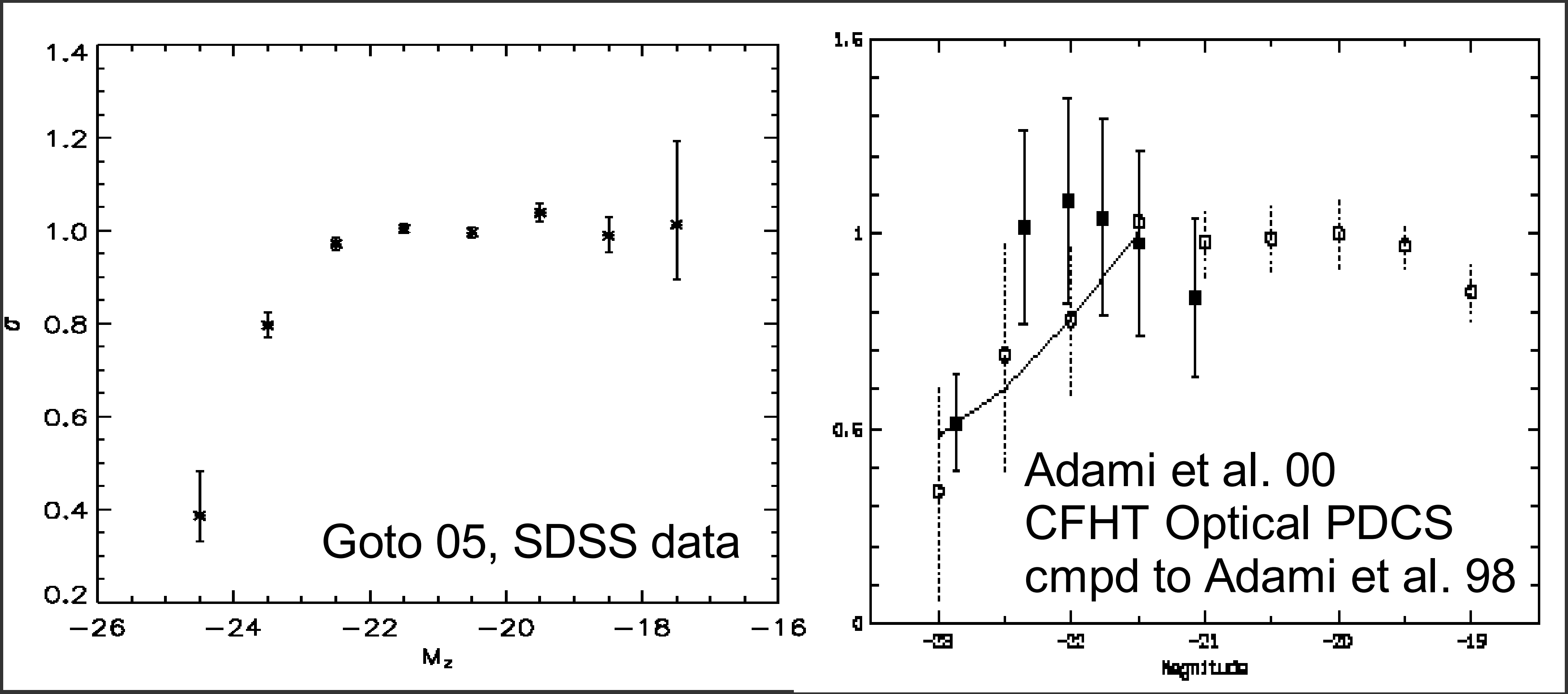

Early spirals in equilibrium within the same grav. potential traced by E+S0, with nearly isotropic orbits

# M/L results: evolution

Brighter galaxies move slower in clusters

*(B. et al. 92, Adami, B. & Mazure 98, Goto 05)*

and perhaps also in groups *(Girardi et al. 03, Lares et al. 04)*




Some evolution of luminosity segregation in clusters at $z \simeq 0.4$?

➞larger M/L at $r \to 0$ in distant clusters

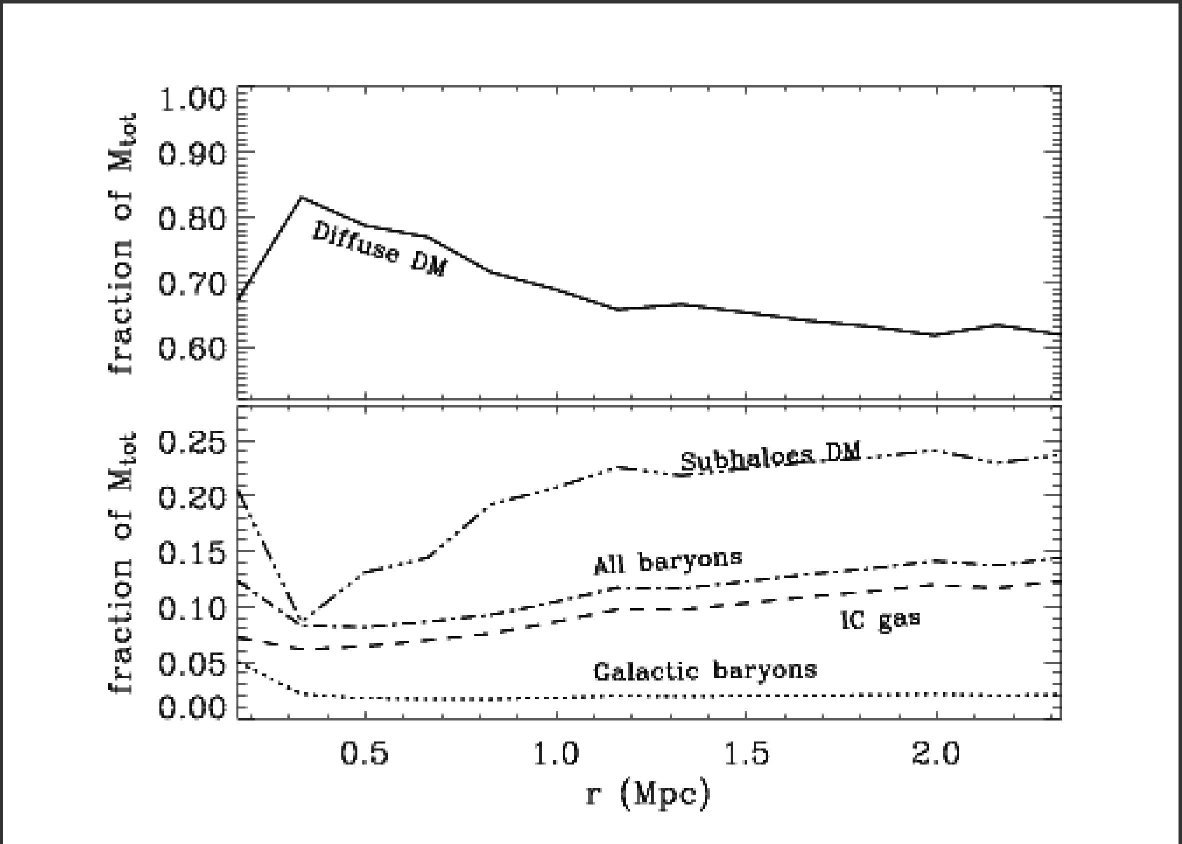
# M(<r) for clusters from the ENACS

Biviano & Salucci 05 (work in progress):
Determine the DARK MATTER,
not the TOTAL MATTER profile

- *Convert galaxies luminosities into baryonic masses (Borriello, Salucci & Danese 03; Persic & Salucci 99)*
- *Estimate the Intra-cluster gas baryonic mass profile using the clusters sample of Reiprich & Boehringer 02*
- *Determine the Dark Matter profile in subhaloes from galaxy luminosities (Shankar, Salucci & Danese 05) by also accounting for halo stripping and overlapping*

# M(<r) for clusters from the ENACS

Fractions of total mass in galactic and gas baryons and in dark matter subhaloes

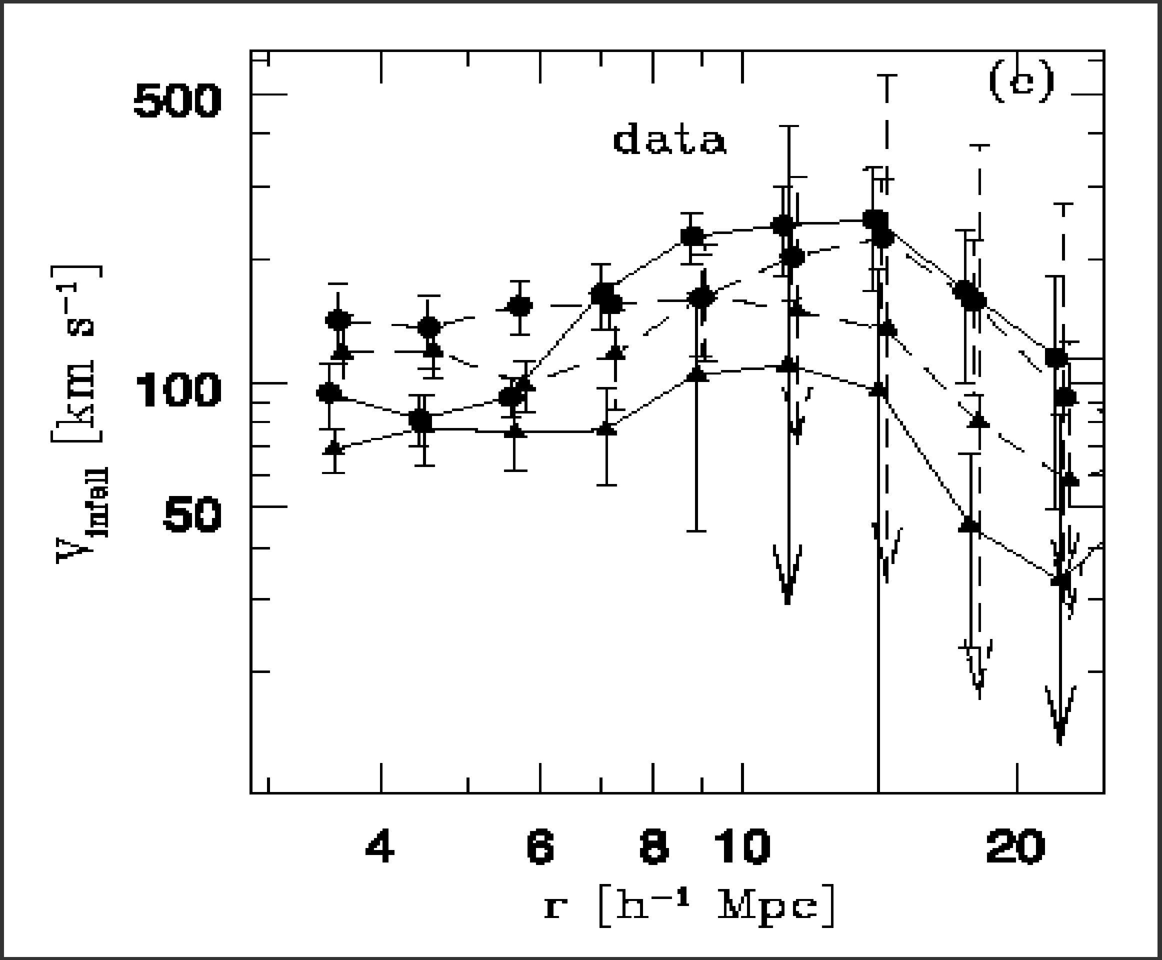



- Subtracting the baryons from the total mass makes M(<r) more concentrated (NFW $c=5\pm2$, Burkert 95 $r_c=0.13\ r_{200}$)
- Subtracting also the Dark Matter subhaloes makes M(<r) even more concentrated (NFW $c=8\pm2$, Burkert 95 $r_c=0.09\ r_{200}$)

Both the NFW and the Burkert 95 models are still acceptable

# Orbits results: infall *(Ceccarelli et al. 05)*

The infall of field galaxies into groups is measured directly by using the Catalog of Peculiar Velocities *(Giovanelli & Haynes 02)*




Dots: high-M or high-L groups

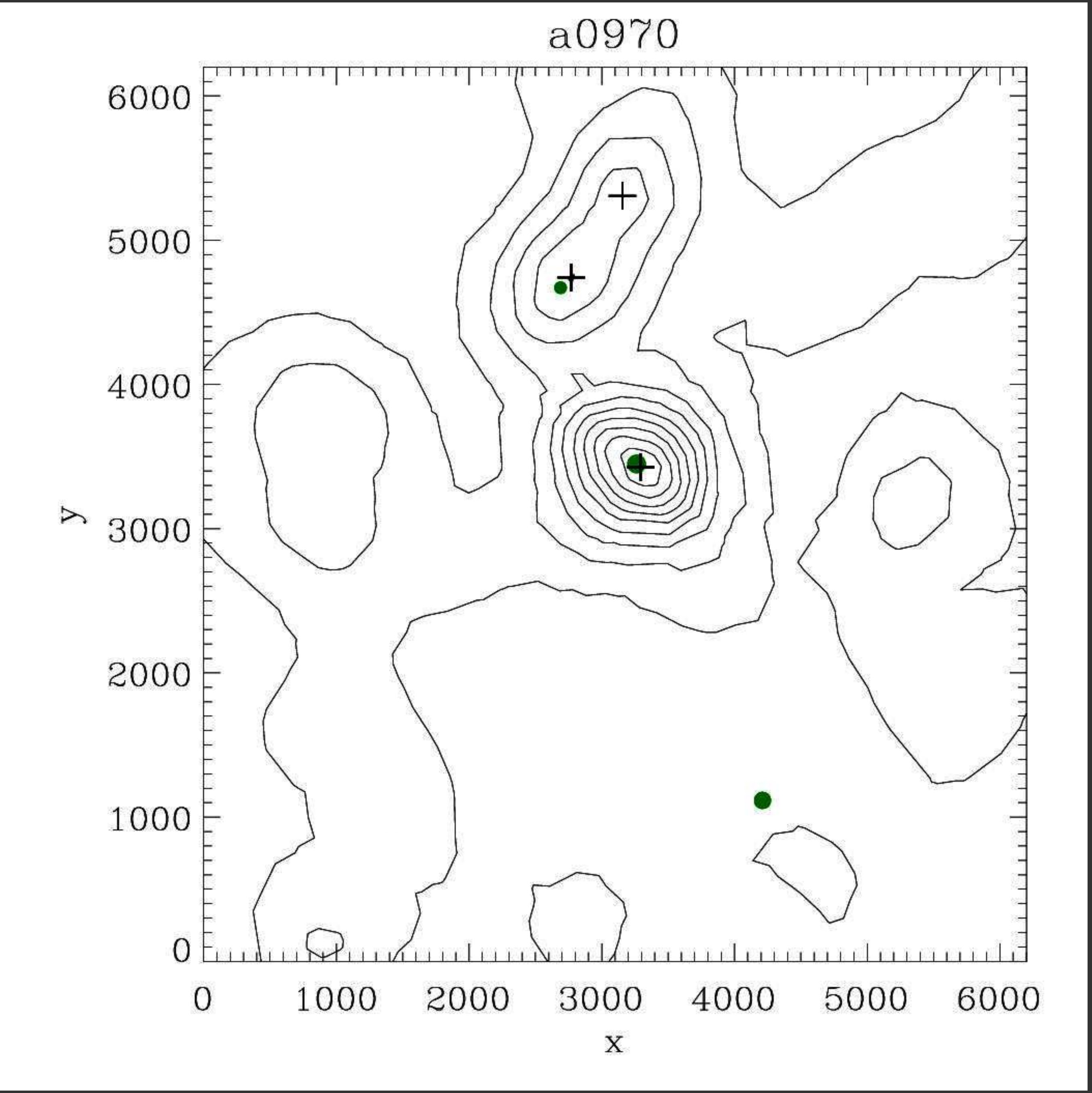
Triangles: low-M or low-L groups

Solid lines: groups divided by Lum

Dashed lines: groups divided by Mass

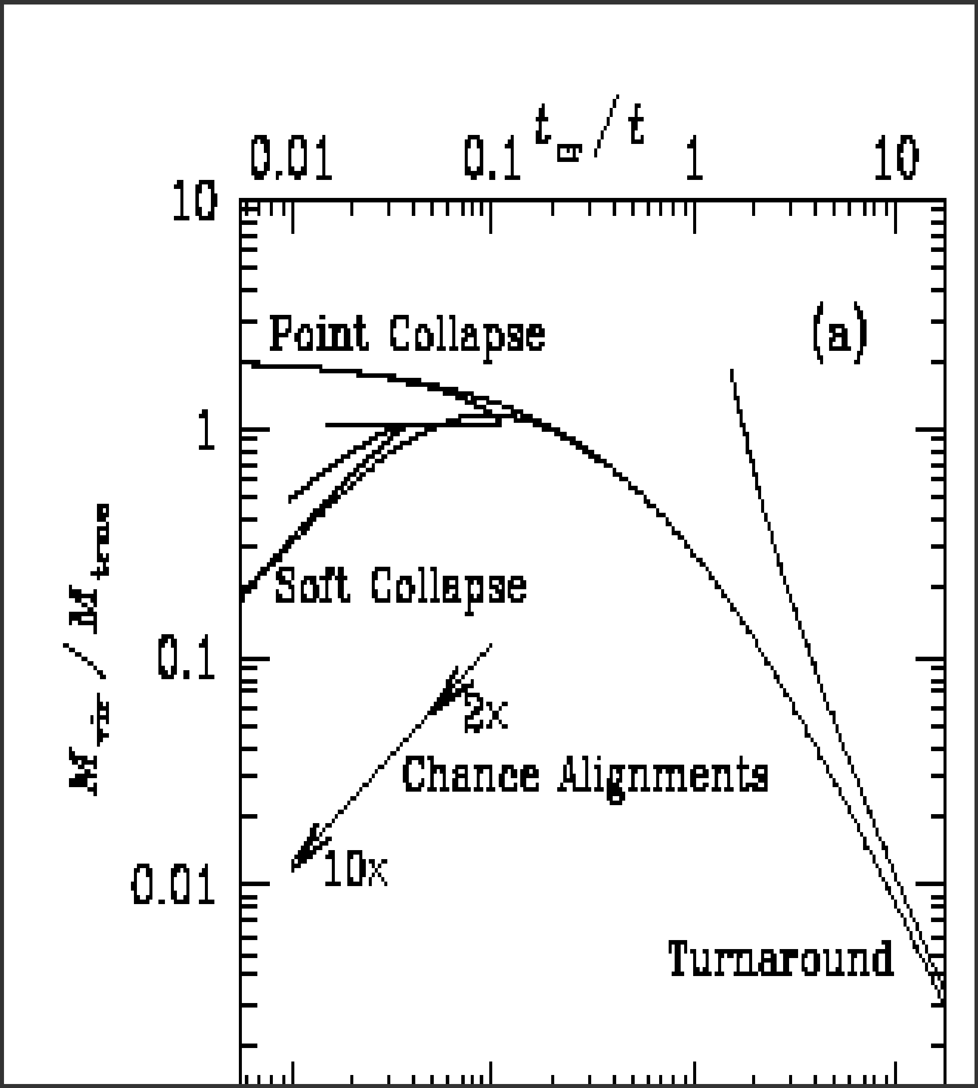
# Subclustering results: WINGS

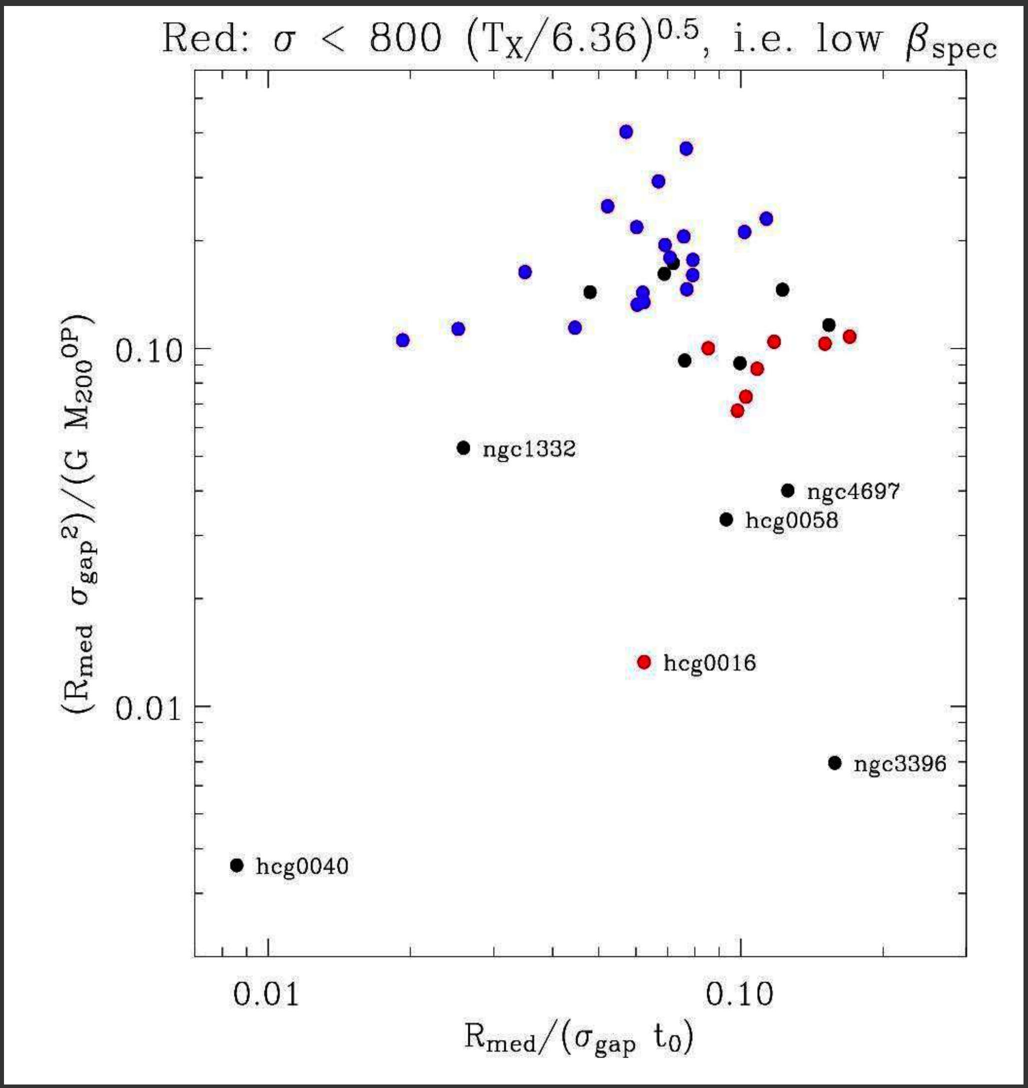
Location of BCGs




0.5 Mpc

# Are groups virialized? GEMS



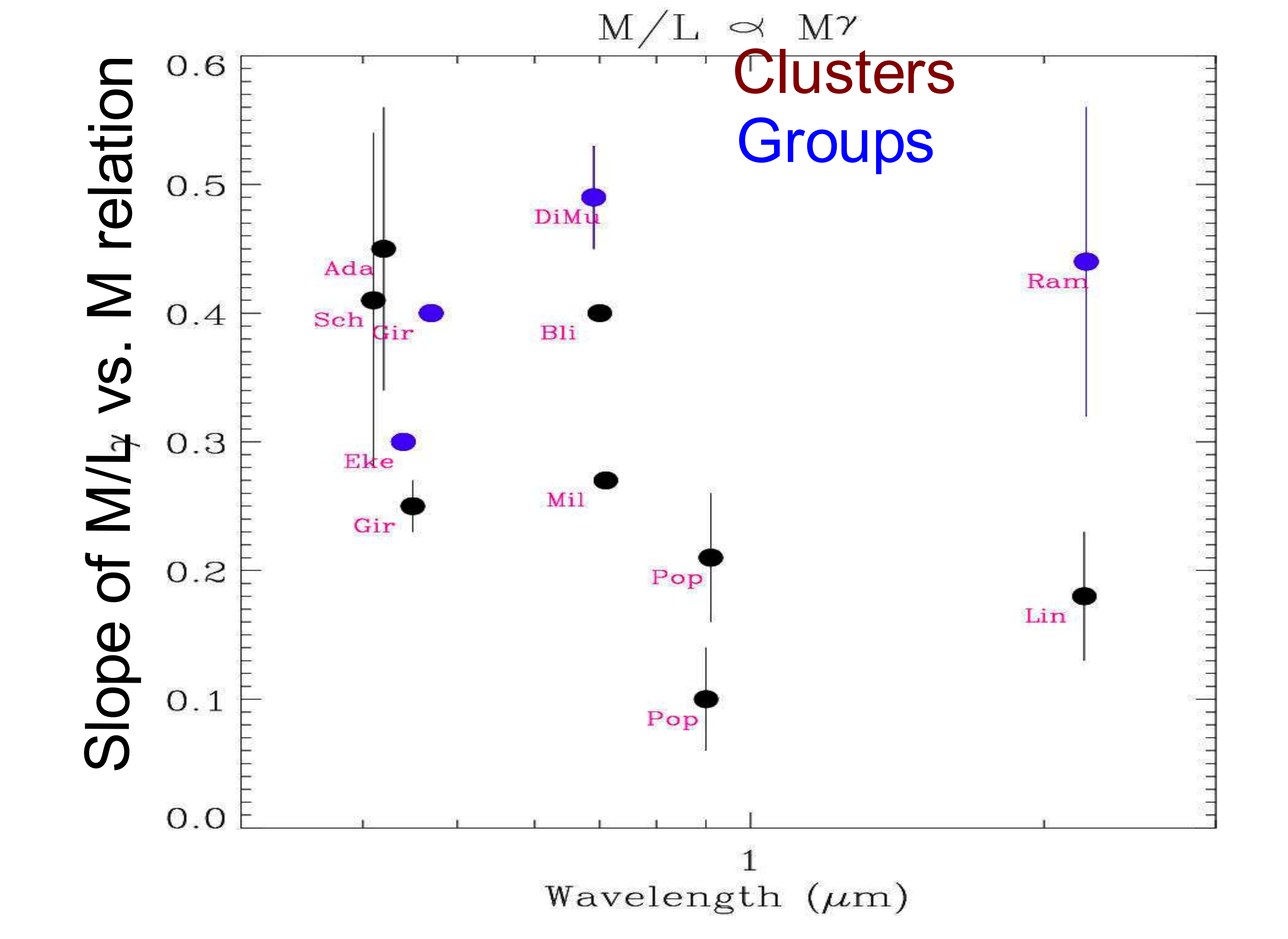




The 'fundamental track' diagram of Mamon 94 (spherical collapse theory)

# Scaling relations: results

## Does the slope $\gamma$ of $M/L \propto M^{\gamma}$ depend on $\lambda$?

*(no evidence in RASS-SDSS sample, Popesso et al. in prep.)*




Implications for interpretation of why $M/L \neq$ const