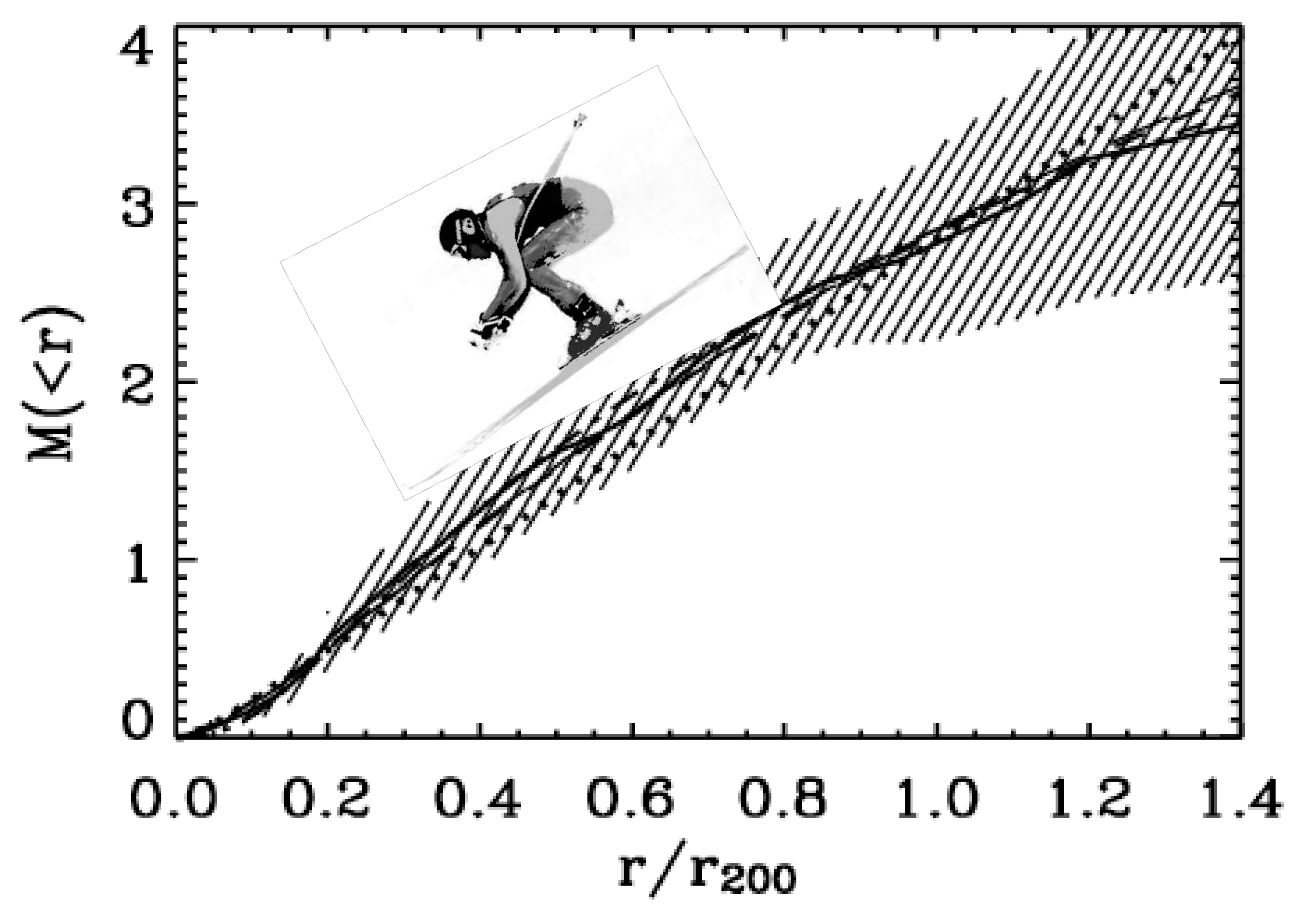
MASS PROFILES OF GALAXY CLUSTERS from dynamics



Andrea Biviano
INAF - Trieste

MASS PROFILES OF GALAXY CLUSTERS from dynamics

Meaning:
from the study of the projected phase-space distribution of cluster galaxies

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Layout of the talk:

1. Scientific motivations

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2. Historical introduction

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3. Methods of mass (profile) determination

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   Mass-to-light profile

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3. Methods of mass (profile) determination
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5. Reliability of the methods
6. Results:
   Mass profile
   Mass accretion
   Mass-to-light profile
7. Conclusions

Motivations

Scientific motivations

Why using galaxies for M(<r) determination?

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- M(<r) determined out to large radii

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- Orbits of galaxies in clusters

  (mass accretion, evolution of galaxies)

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Why using galaxies for M(<r) determination?

- M(<r) determined out to large radii
- Orbits of galaxies in clusters

  (mass accretion, evolution of galaxies)
- Three is better than one

  (gas and galaxies respond differently to the effects of collisions, dynamical and lensing mass estimates are affected by projection in different ways)

Historical introduction

Die Rotverschiebung von extragalaktischen Nebeln

von **F. Zwicky.**

(16. II. 33.)

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1. Setzt man voraus, dass das Comasystem mechanisch einen stationären Zustand erreicht hat, so folgt aus dem Virialsatz

$$\bar{\varepsilon}_k = -\frac{1}{2}\bar{\varepsilon}_p\,, \tag{4}$$

wobei $\bar{\varepsilon}_k$ und $\bar{\varepsilon}_p$ mittlere kinetische und potentielle Energien, z. B. der Masseneinheit im System bedeuten. Zum Zwecke der Ab-

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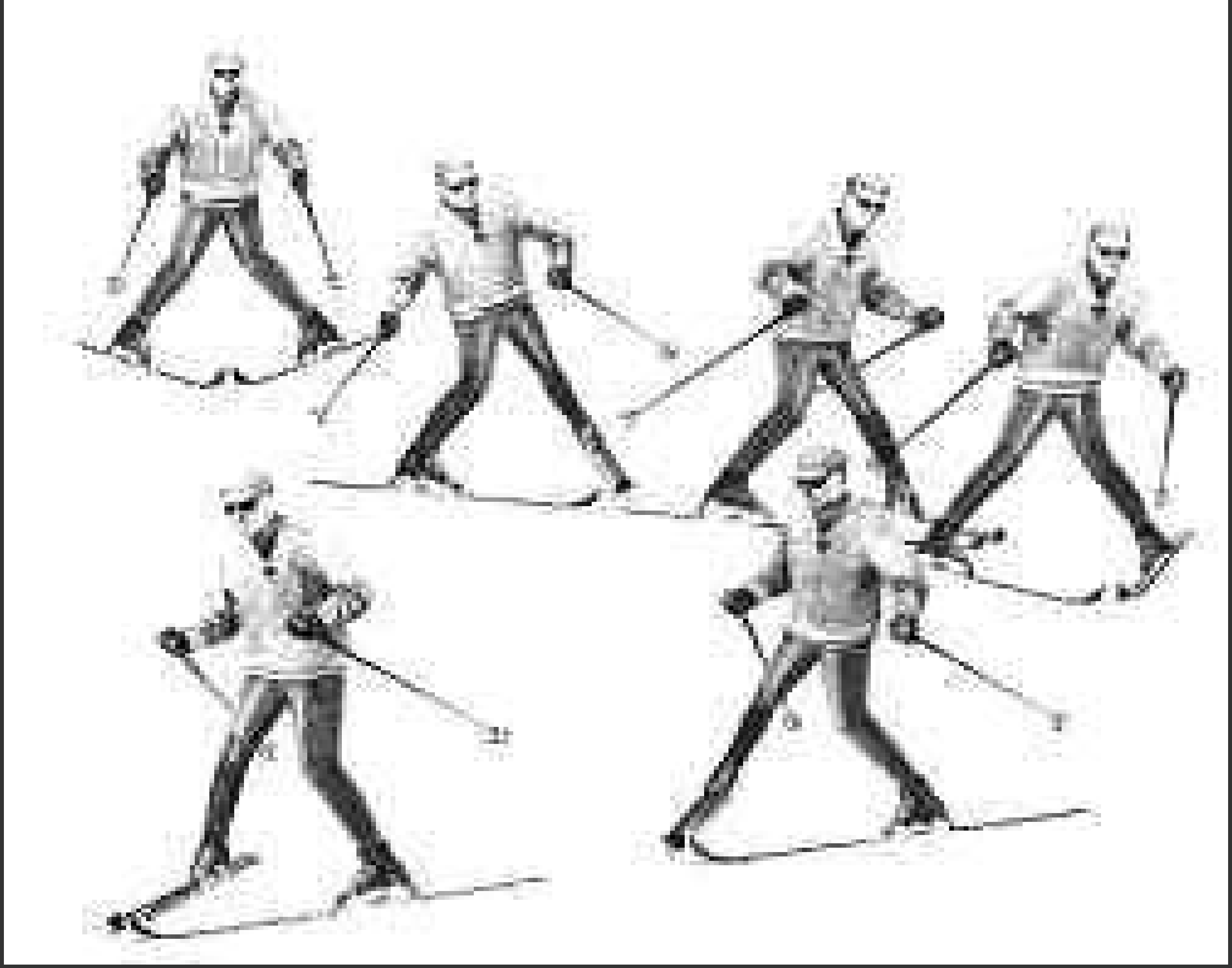
von Beobachtungen an leuchtender Materie abgeleitete[1]). Falls sich dies bewahrheiten sollte, würde sich also das überraschende Resultat ergeben, dass dunkle Materie in sehr viel grösserer Dichte vorhanden ist als leuchtende Materie.

Fritz Zwicky (1933, 1937)
Sinclair Smith (1936)

Virial theorem:
Virgo and Coma masses...
...about right!

But only because
galaxies are distributed like the DM
(e.g. The & White 1986, Merritt 1987)

Methods



Methods of mass determination

With los velocities and projected positions:

- Virial mass

  (and variants: projected-M, isothermal-M, M_σ)

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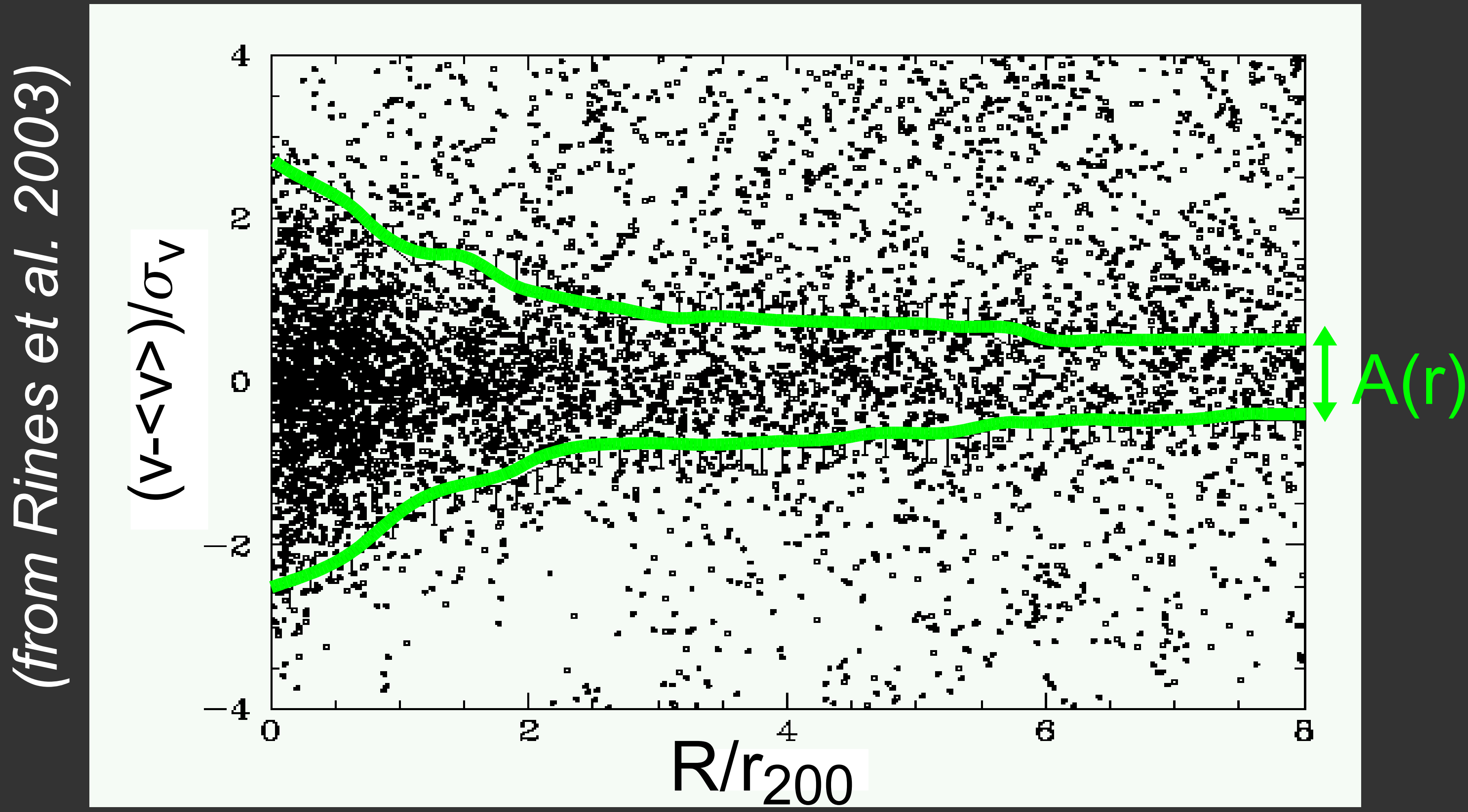
- Caustic method *(Diaferio & Geller 1997)*

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 Φ(r), independently of dynamical state



A(r) → Φ(r) through F(Φ,β,r)≈const ...*outside the center*

Methods of mass determination

With los velocities and projected positions:

- Virial mass

  (and variants: projected-M, isothermal-M, M_σ)

- Jeans analysis *(e.g. Binney & Tremaine 1987)*

- Caustic method *(Diaferio & Geller 1997)*

If galaxy distances also available:

- Least-action method

  (Peebles 1989, and variants: see Mohayee & Tully 2005)

Problems

Problem n.1: The mass-orbits degeneracy

Solutions:

- Use several tracers independently
  (B. & Katgert 2004)

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- Use higher moments of velocity distribution
  (Merritt 1987; van der Marel et al. 2000, Łokas & Mamon 2003, Katgert et al. 2004)

- Full dynamical modelling, $f(E,L^2)$
  (Merritt & Saha 1993, van der Marel 2000, Mahdavi & Geller 2004)

Other problems:

Interlopers - Use robust estimators *(Beers et al. 1990)*

Calibrate bias with num sims

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No dynamical eq. - Identify/remove substructures
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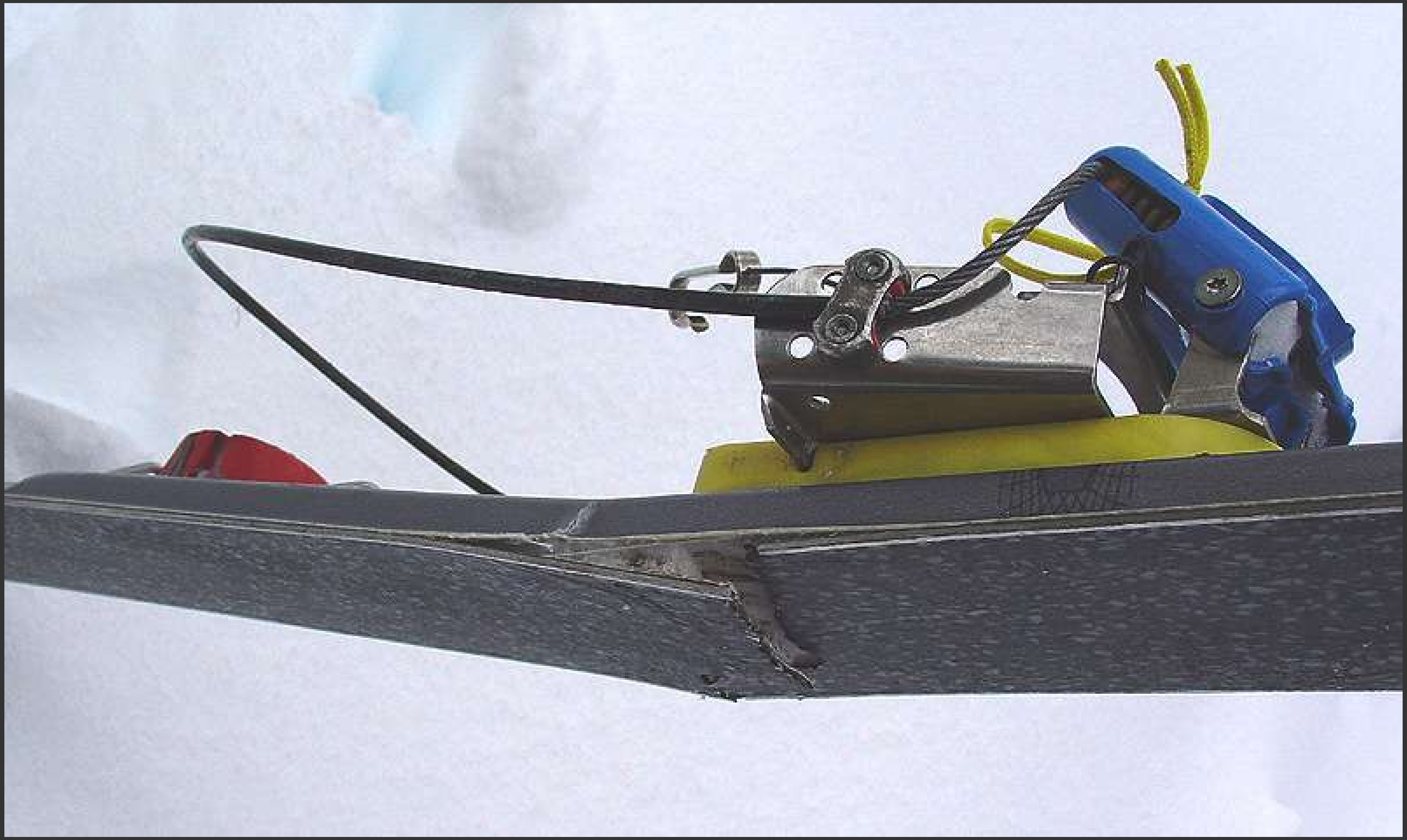
Few galaxies – Stack clusters *(e.g. Carlberg et al. 1997)*
Enforces circularity, statistically reduces projection effects,
should be meaningful because of homology (FP for clusters,
Schaeffer et al. 1993, Adami et al. 1998, etc....)

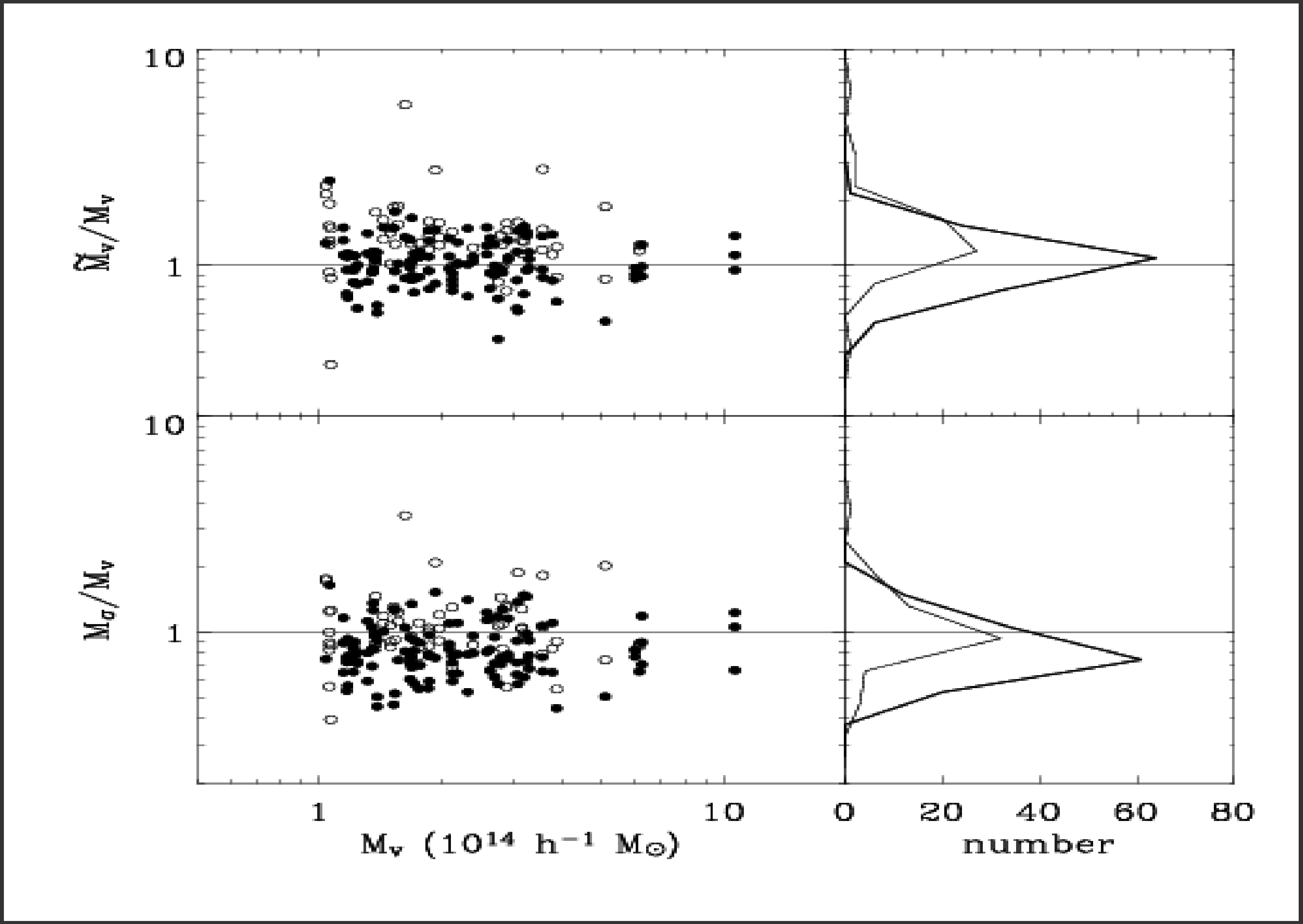
Reliability



Numerical simulations:

mass estimators from galaxies distribution are reliable

Numerical simulations *(B. et al. 2006)*

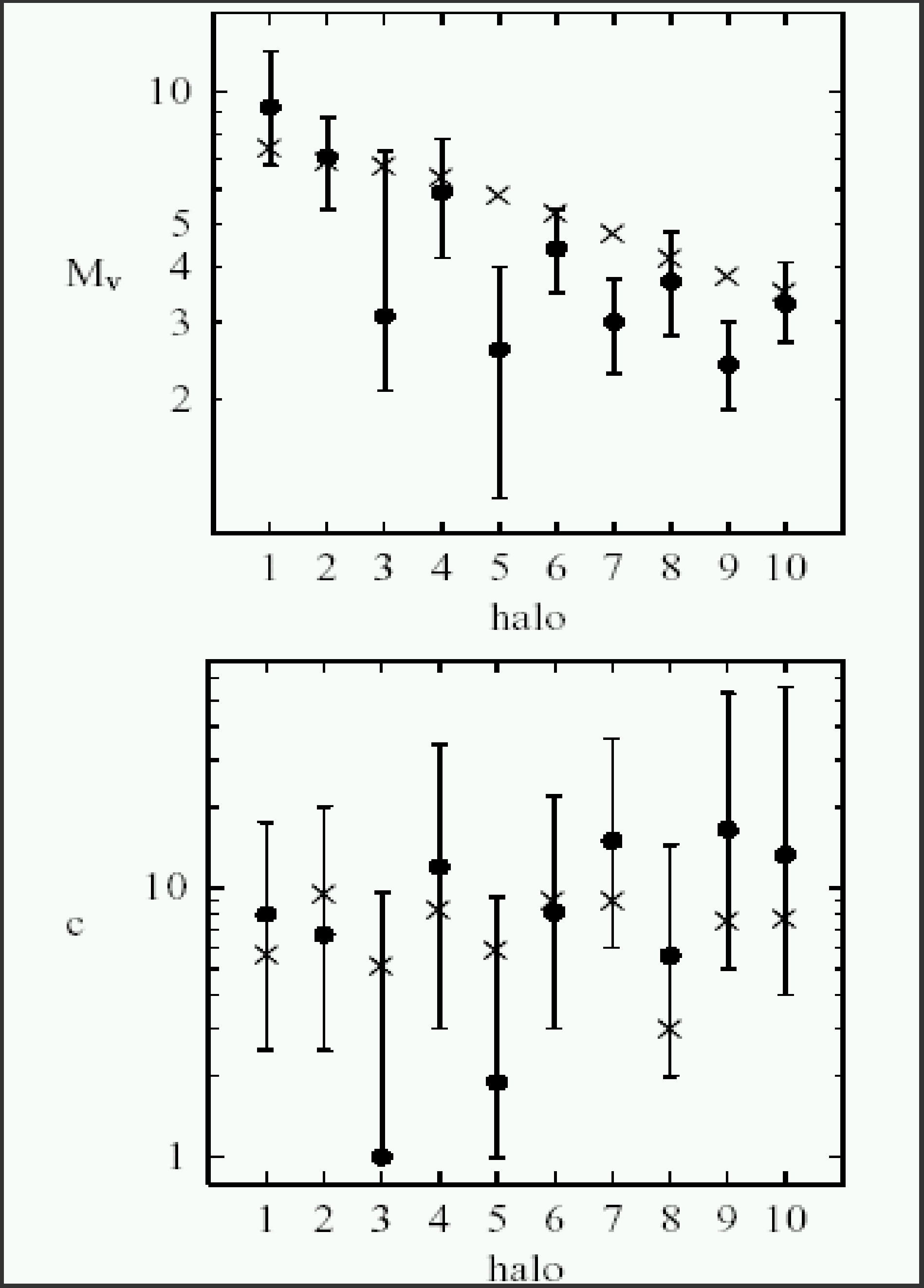


Identify and remove subclusters

Virial mass estimator is 10% biased high

Scatter is ≈30 (40) % with 400 (60) cluster members

Numerical simulations *(Sanchis et al. 2004, Łokas et al. 2006)*



Jeans analysis and 300 cluster members

Estimates of total mass, and concentration

Numerical simulations:

mass estimators from galaxies distribution are reliable

Comparison of mass (profile) estimators:

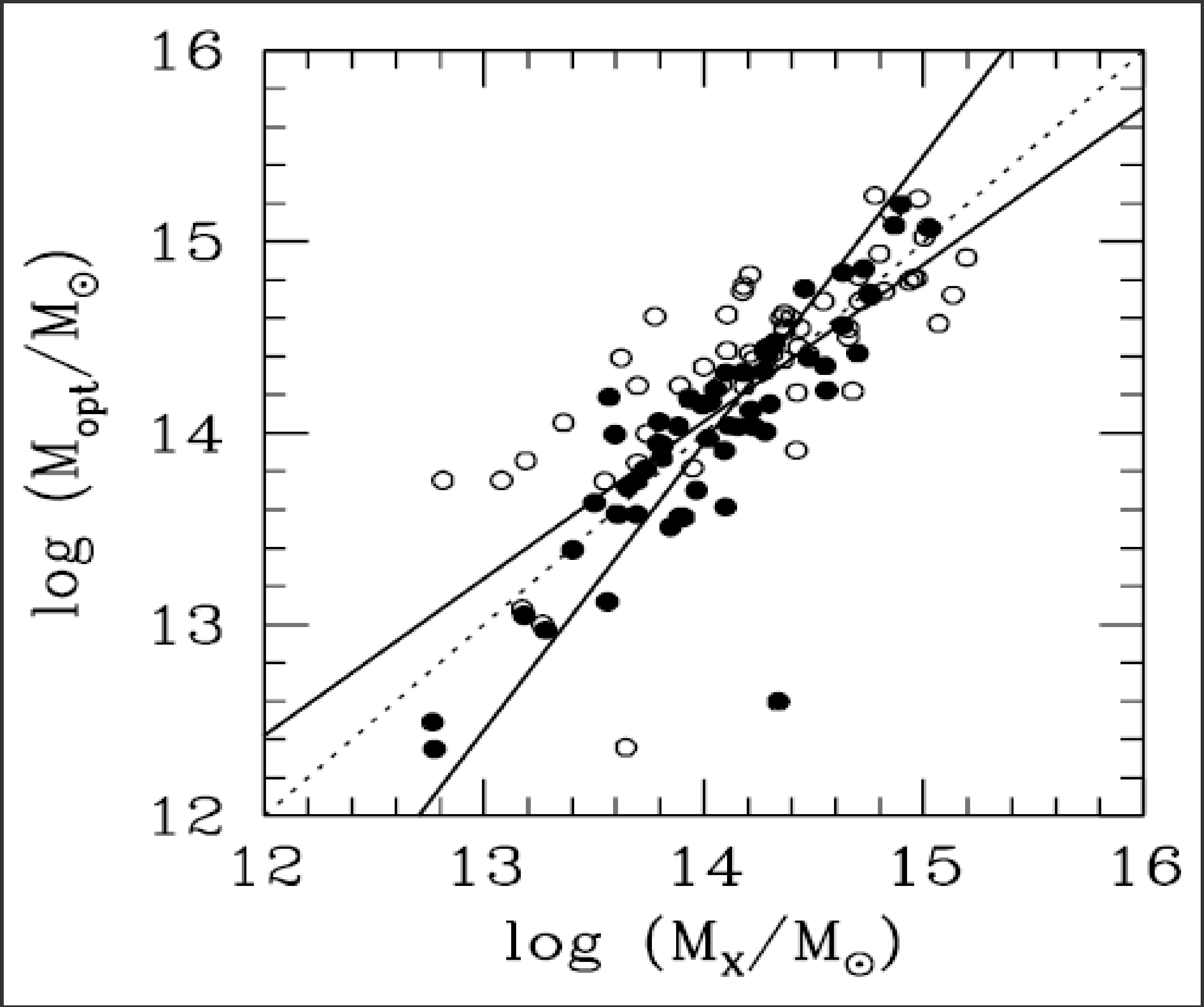
$M(<r)$ from X-ray, strong and weak lensing vs. $M(<r)$ from galaxies distribution (using virial, Jeans, caustic)

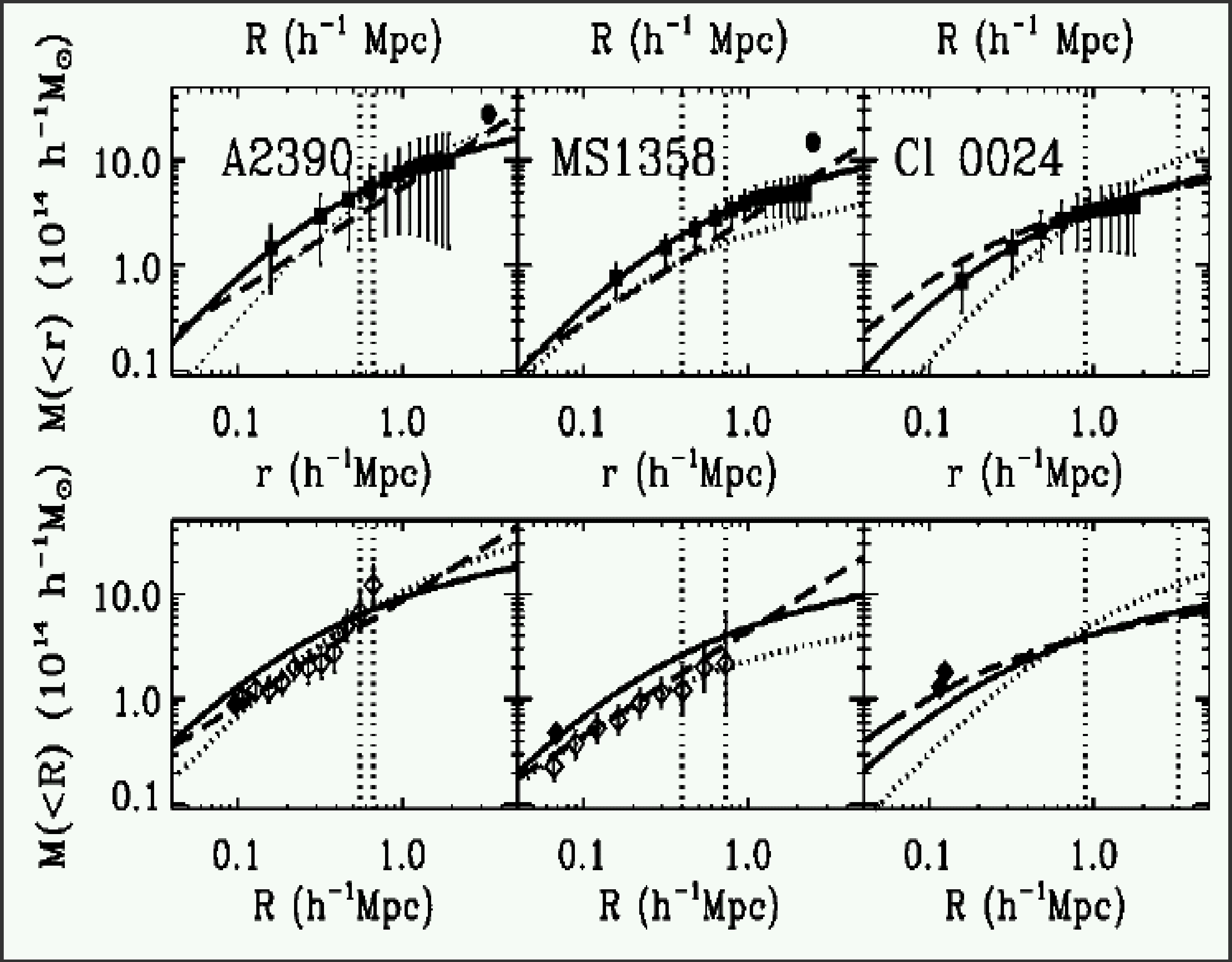
&

Virial and Jeans vs. caustic, least-action:

general agreement with some discrepancies

X-ray masses vs. virial masses
(Girardi et al. 1998)





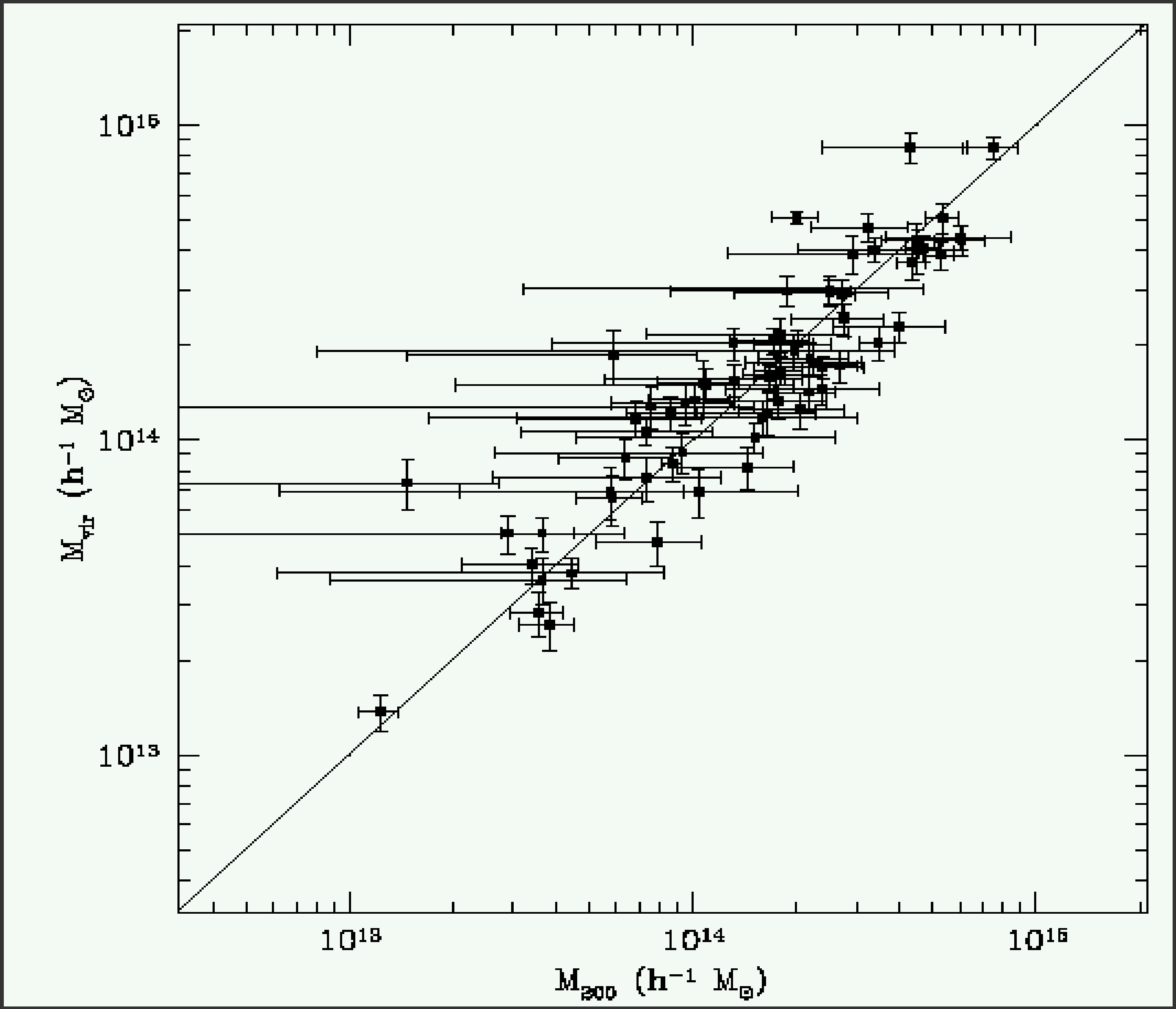
X-ray and lensing $M(<r)$ vs. M_{vir} and caustic $M(<r)$

Solid lines & points with error bars: caustic mass estimates
Dotted lines: mass estimates from X-ray
Dashed lines & diamonds: estimates from lensing
Dots: virial mass estimates

(Diaferio et al. 2005)

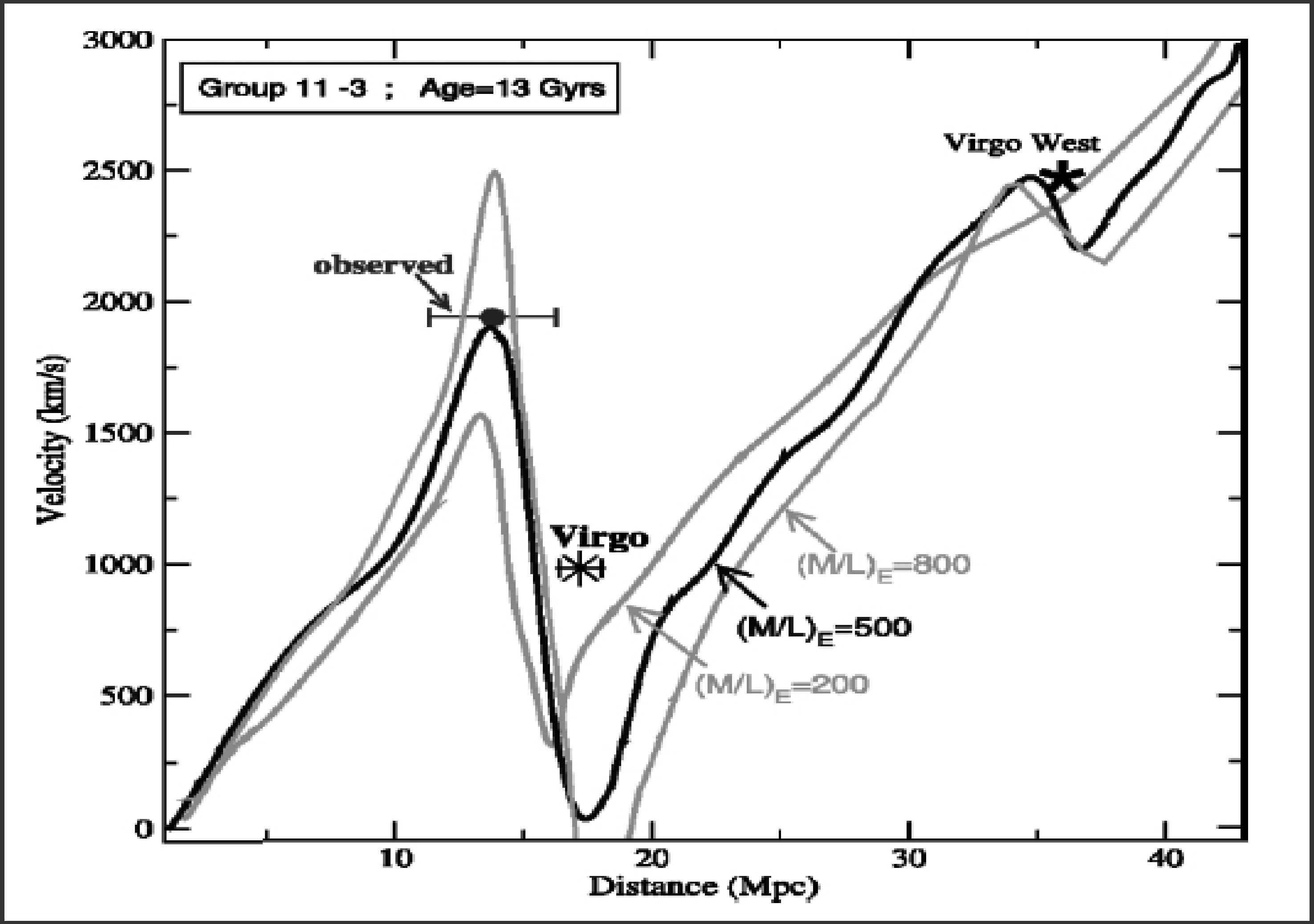
Virial masses vs. caustic masses

(CIRS, Rines & Diaferio 2006)



Virial mass vs. mass from Least-action method

(Mohayee & Tully 2005)

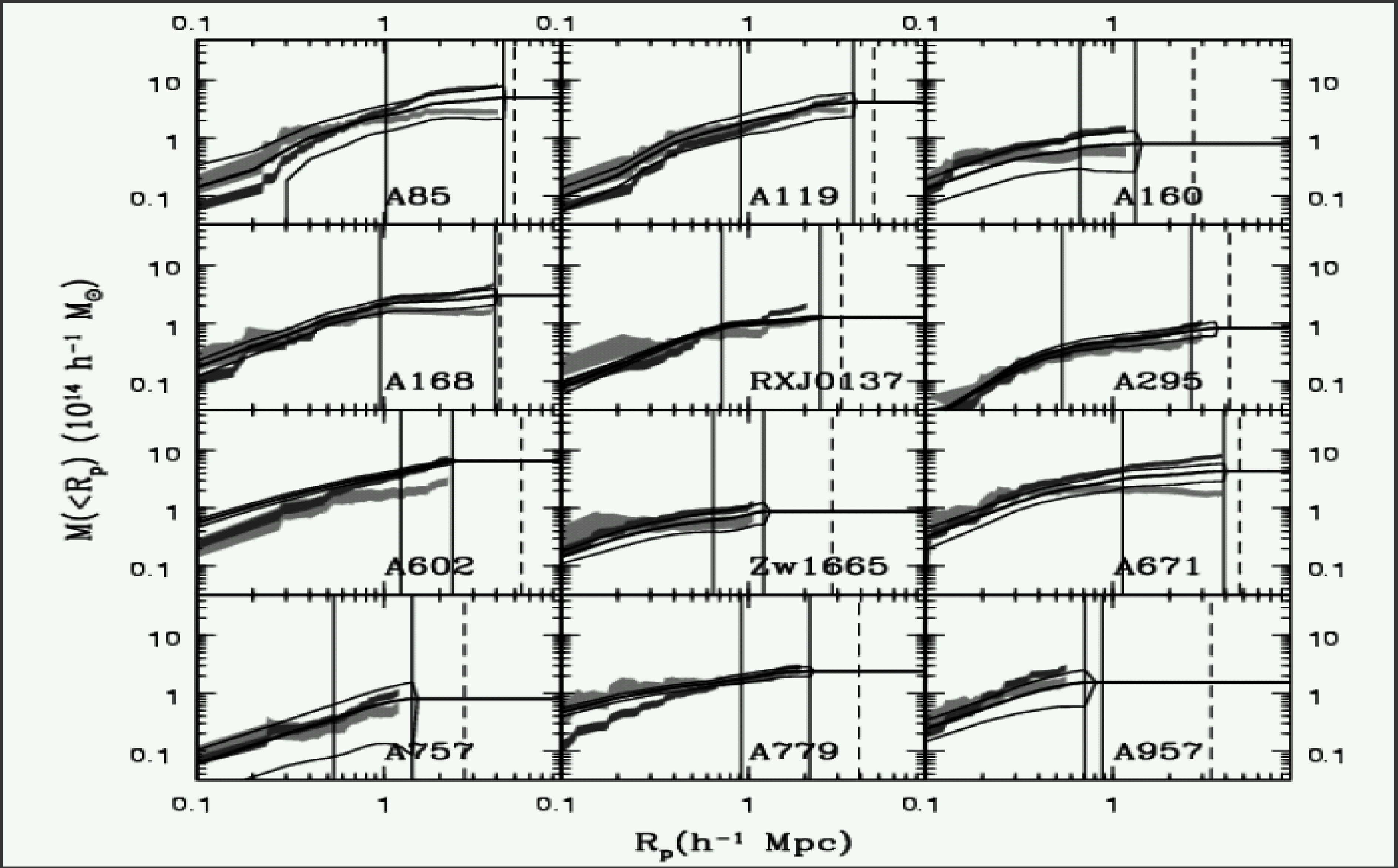


Group infall into Virgo cluster →9 •10^{14} solar masses

close to virial mass estimate: 6.7 •10^{14} solar masses (<2.25 Mpc)

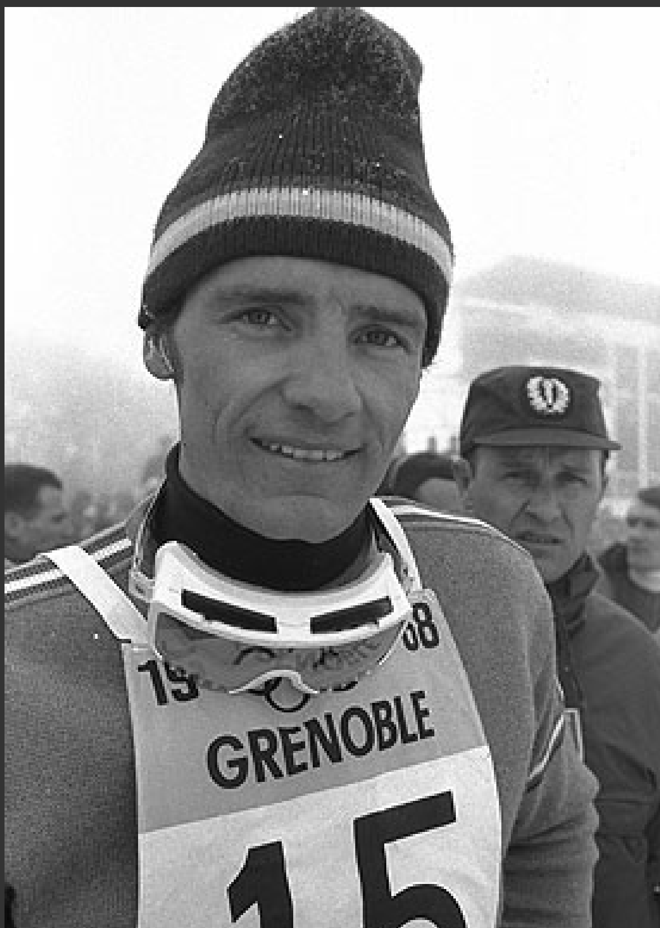
Virial vs. caustic mass profiles

(Rines & Diaferio 2006)



Solid lines: caustic / Dark grey: virial / Light grey: projected-mass

Results: Mass profiles




Jean-Claude Killy, Tony Sailer, & Katja Seizinger
winners of 3 olympic gold medals each in alpine ski

$M(<r)$ 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: $3 \leqslant \xi \leqslant 4$

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→NFW and Hernquist OK, isothermal ruled out

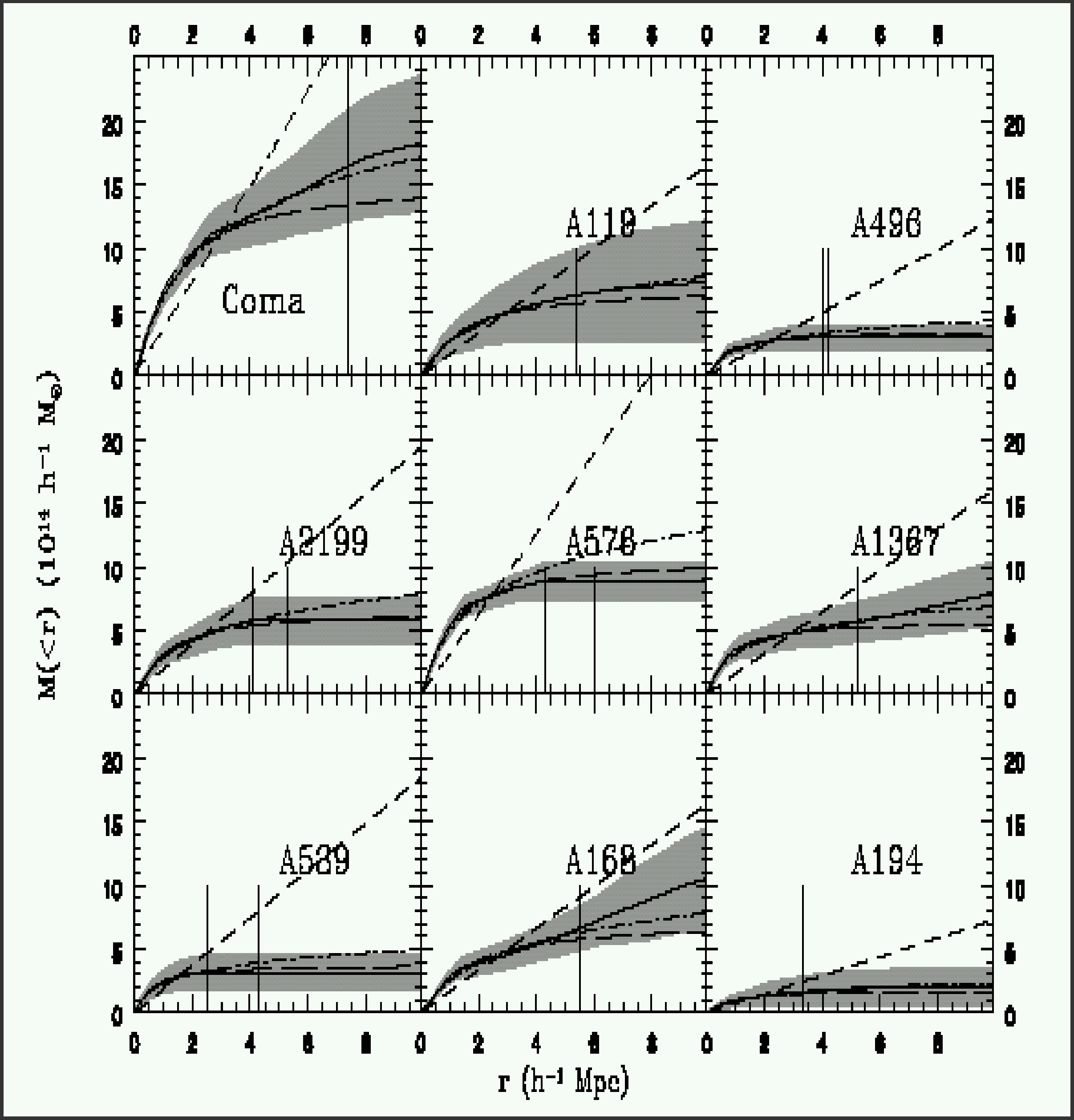
If NFW, c=c(M) has correct trend

If ξ=0 near r=0, core radius is small, $r(\rho=\rho_{0/2})<0.1\ r_{200}$

M(<r) results: CAIRNS & CIRS

Rines et al. 00,03,04
few nearby clusters analysed with Caustic method

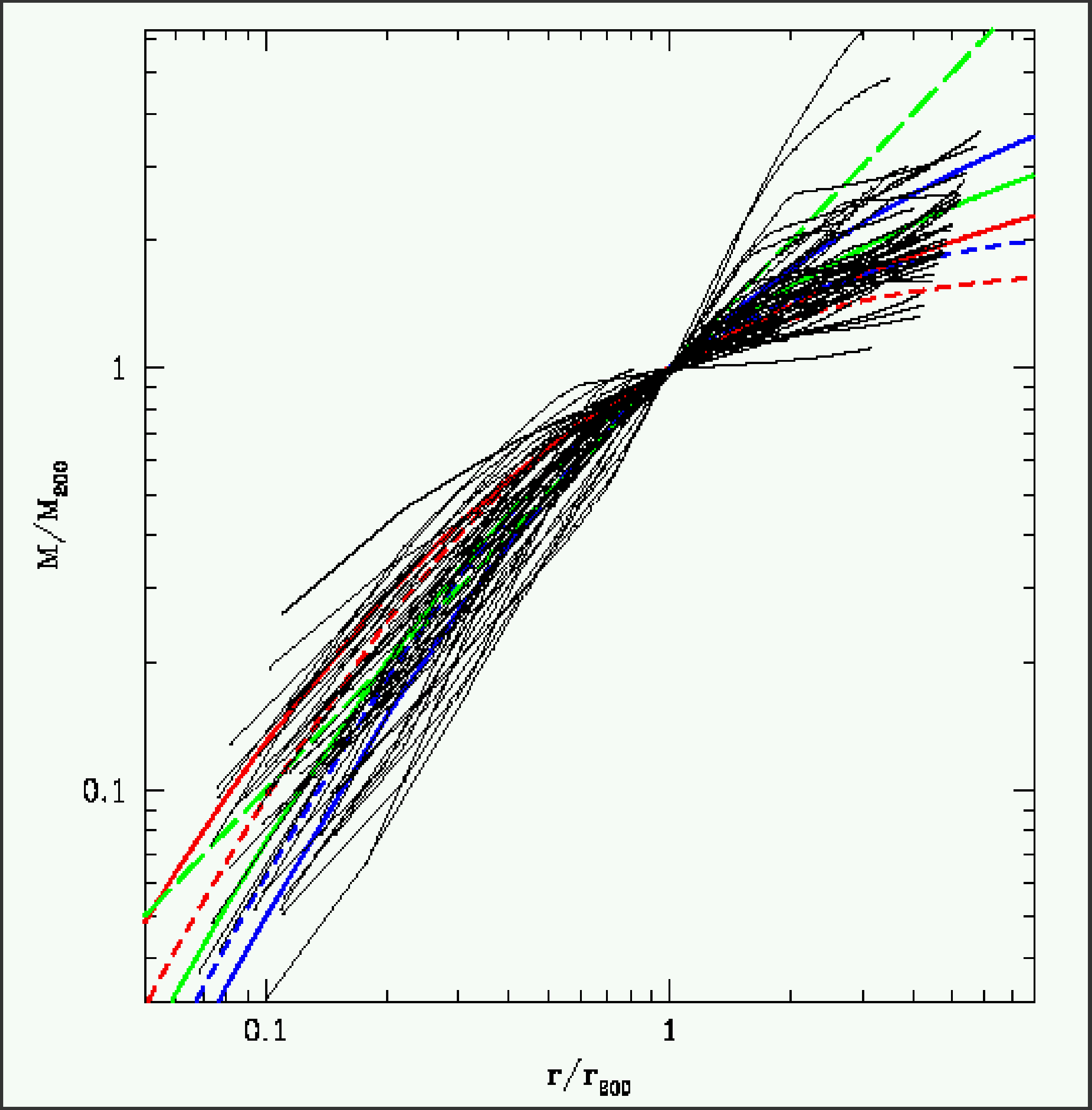
Best fit $\rho(r) \sim r^{-1}$ for r~0, and r^{-3} or r^{-4} for large r
NFW with $5 \leqslant c \leqslant 17$



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

M(<r) results: CAIRNS & CIRS

Rines & Diaferio 2006
72 nearby SDSS clusters analysed with Caustic method



Best fit $\rho(r) \sim r^{-1}$ for r~0,
and r^{-3} or r^{-4} for large r
NFW with <c>=7
and range $2 \leqslant c \leqslant 60$

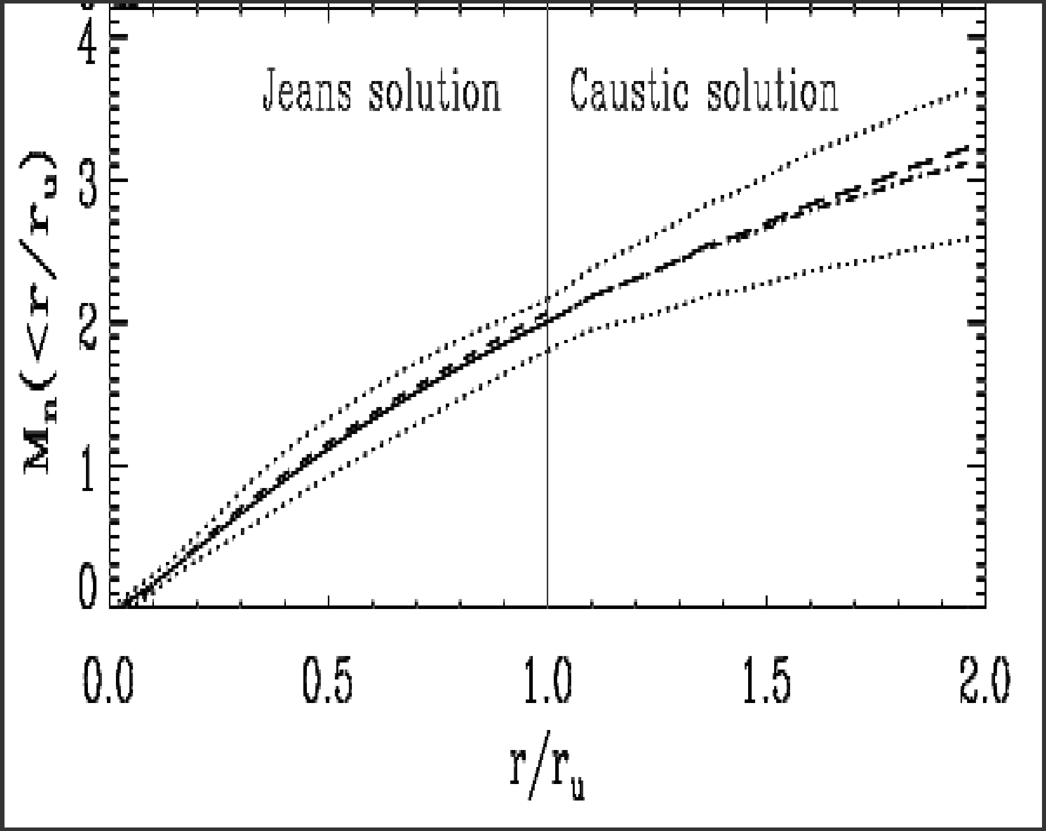
Long-*dashed: isoth., short-dashed: Hernquist, solid: NFW*

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 ξ=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. $\rho(r) \sim r^{-3}$

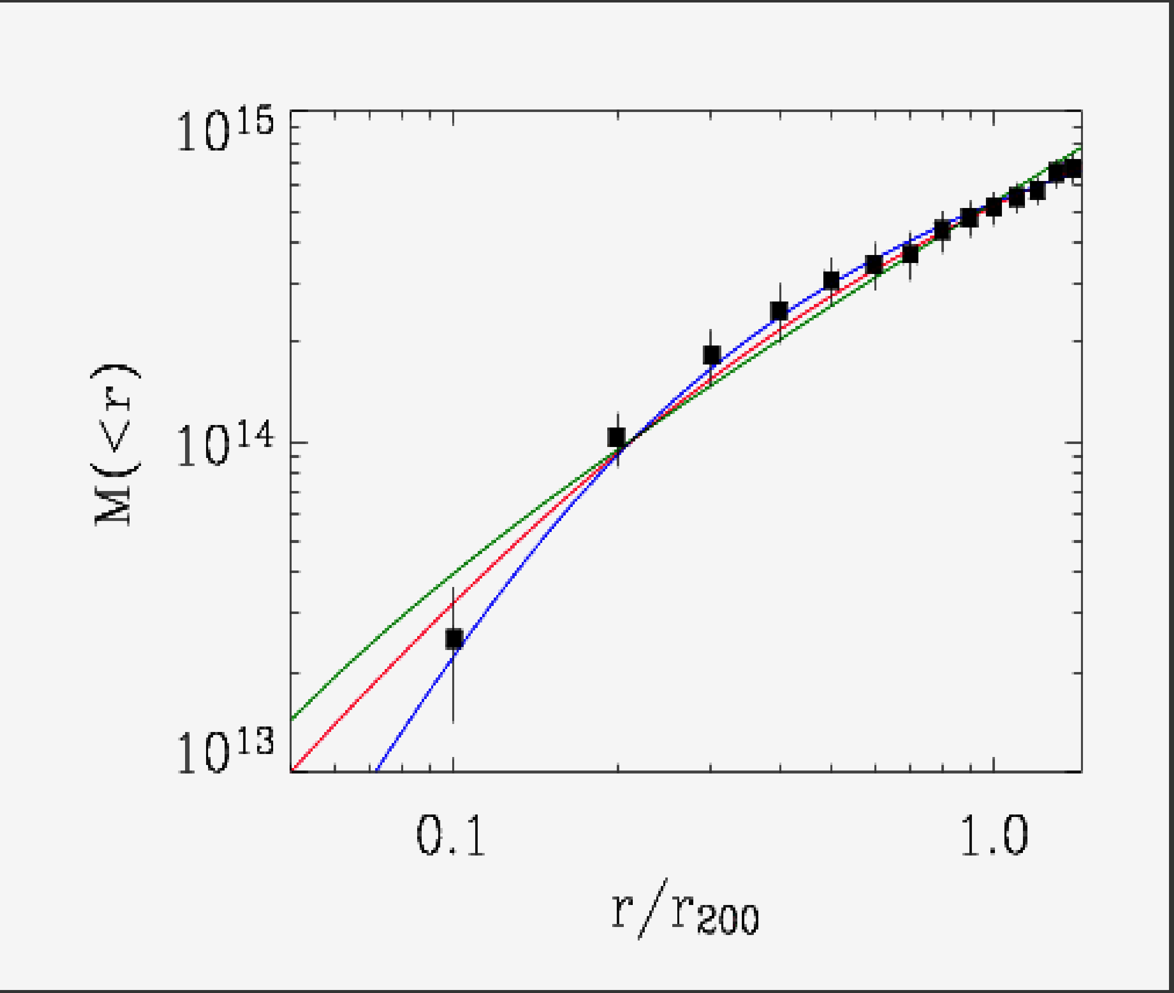


M(<r) results: ENACS *(Katgert, B. & Mazure 04)*

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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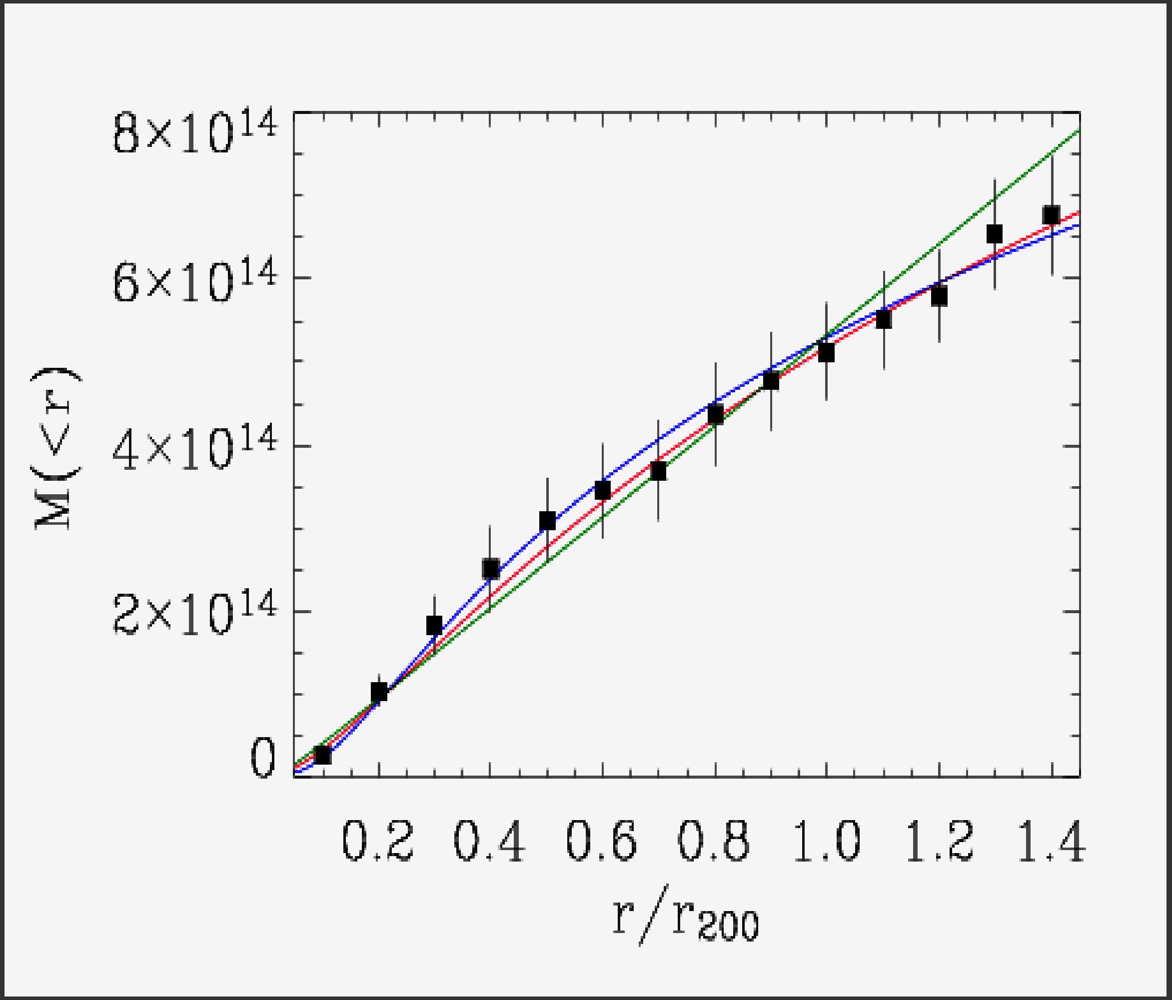
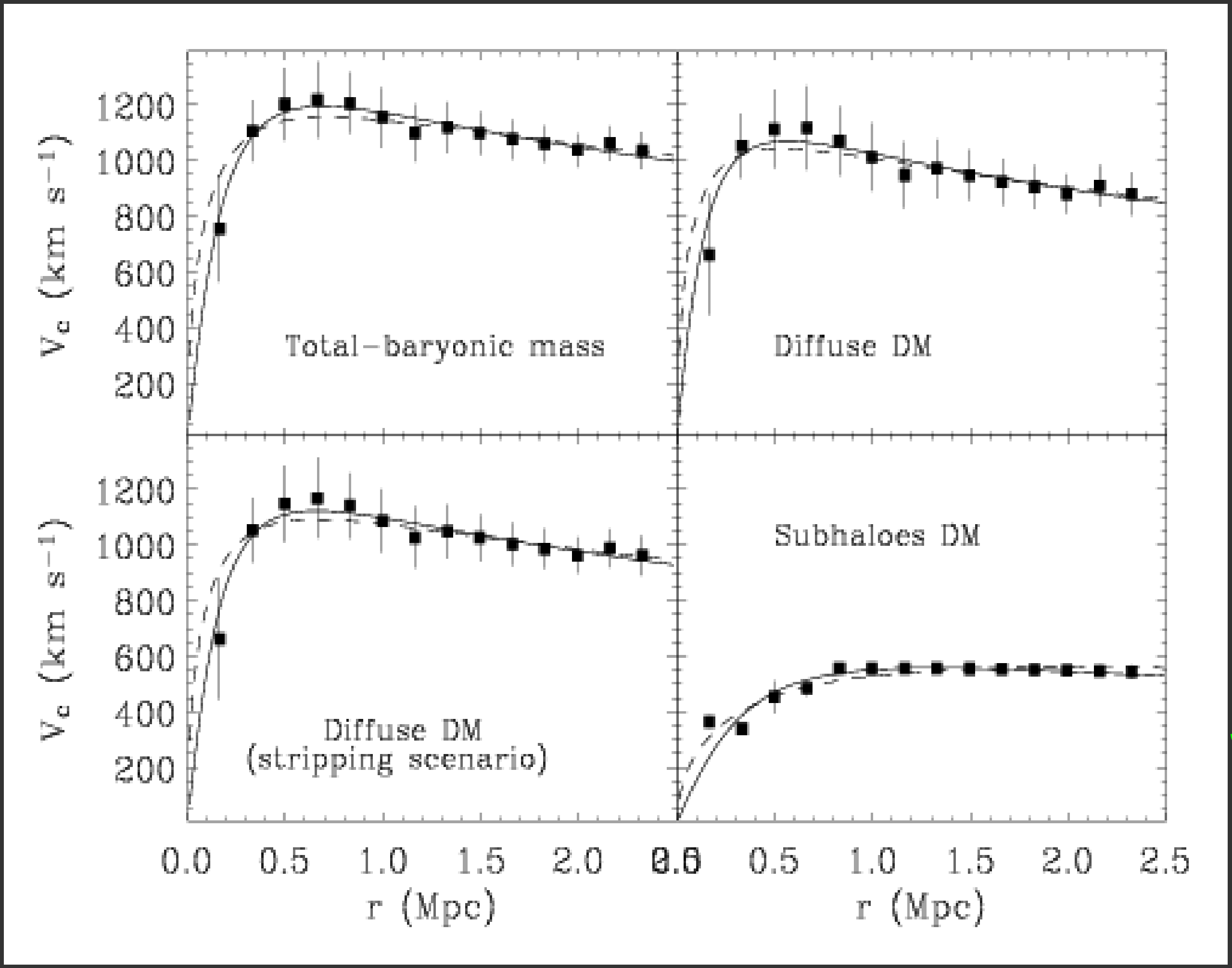


M(<r) results: different mass components

(Łokas & Mamon 03,
B. & Salucci 06)



baryons in galaxies,
baryons in IC gas,
DM in subhaloes,
diffuse DM

Dashed: NFW
Solid: Burkert 95

Both NFW and Burkert 95 good fits to diffuse DM M(<r)
but with slightly higher concentration
and smaller core-radius than
for the fits to the total mass profile

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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

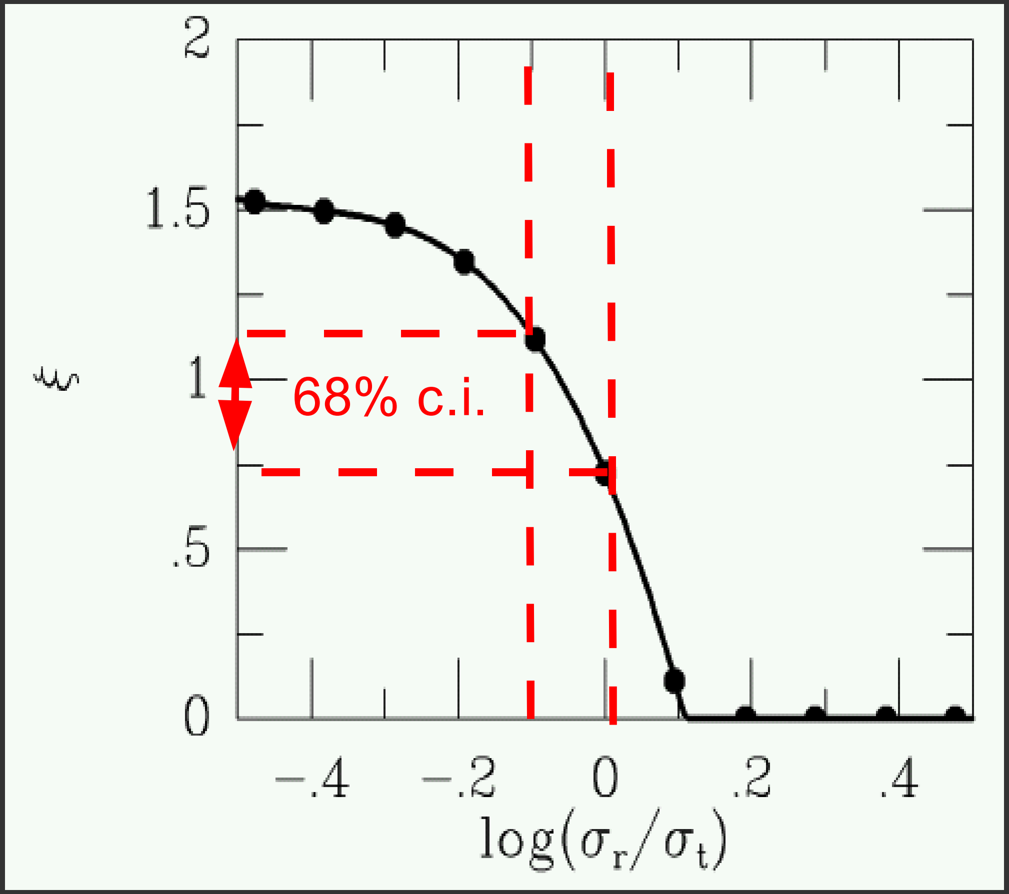
If $\xi=0$ near $r=0$, core radius is small, $r(\rho=\rho_{0/2})<0.1\ r_{200}$

No evolution of $M(<r)$ from $z=0$ to $z=0.3$

M(<r) results: higher-z

CNOC: 16 clusters at z=0.17-0.55

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



Best fit $\rho(r) \sim r^{-\xi}$:

near r~0: $0.7 \leqslant \xi \leqslant 1.2$,

at large radii: $3 \leqslant \xi \leqslant 4$

Best-fit NFW: c=4–5

Mass profile is similar to that found in nearby clusters

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Progress:

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

M(<r) results: lower masses (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 group

(Mamon, B., & Ponman, in preparation)

Use T_x (several T-M relations), σ_v, and L_k
as r_{200} and v_{200} estimators in order to scale velocities
and radii of group galaxies

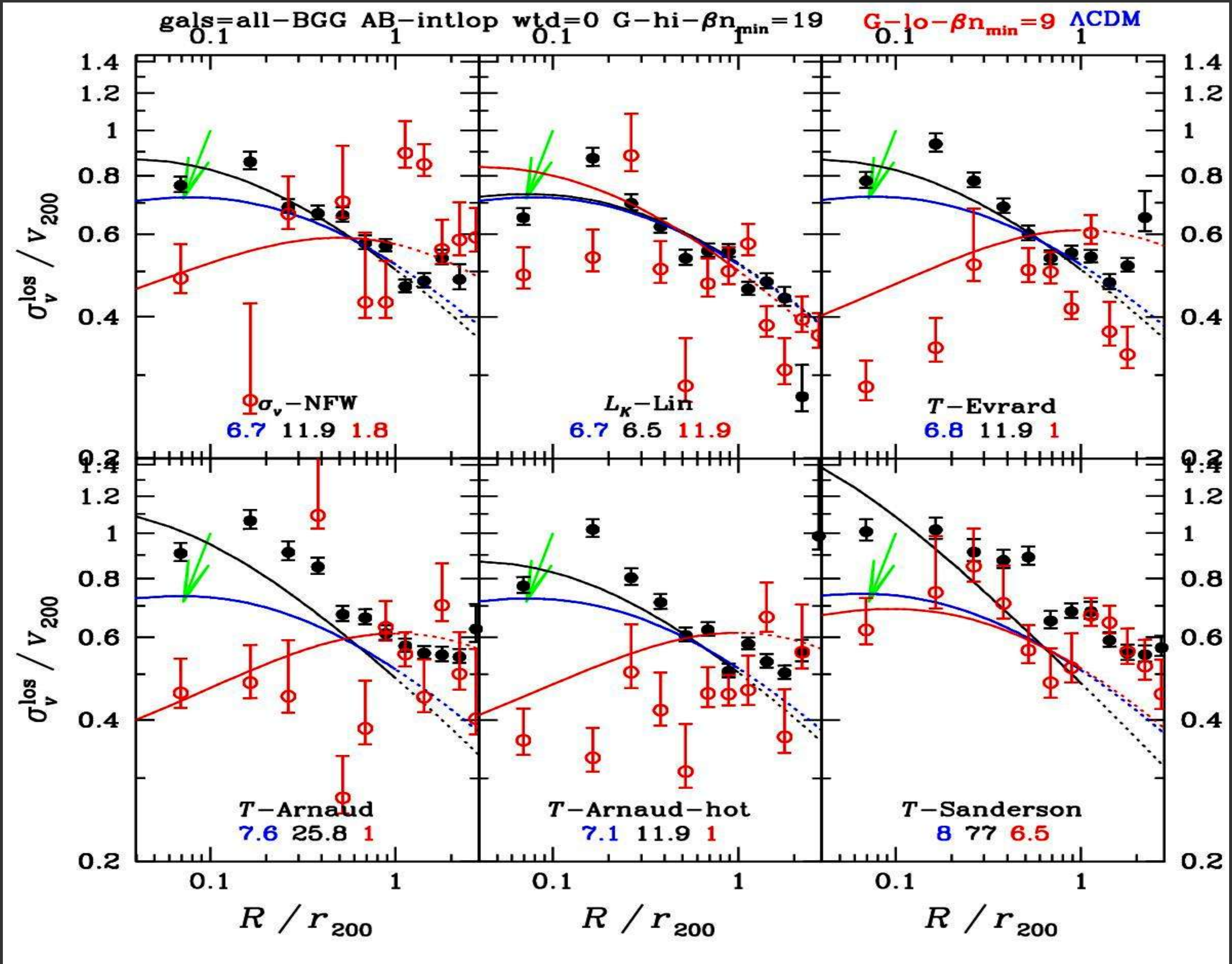
Two classes of groups? (see also Mahdavi et al. 99)

high-$\beta_{\mathbf{spec}}$ (same energy content in galaxies and IC gas):
good fit to M(<r) with NFW, virialized groups!

low-$\beta_{\mathbf{spec}}$: affected by projection, still in collapse phase,
tidally affected by nearby clusters, or ...
...dynamically evolved (dynamical friction + merging)?

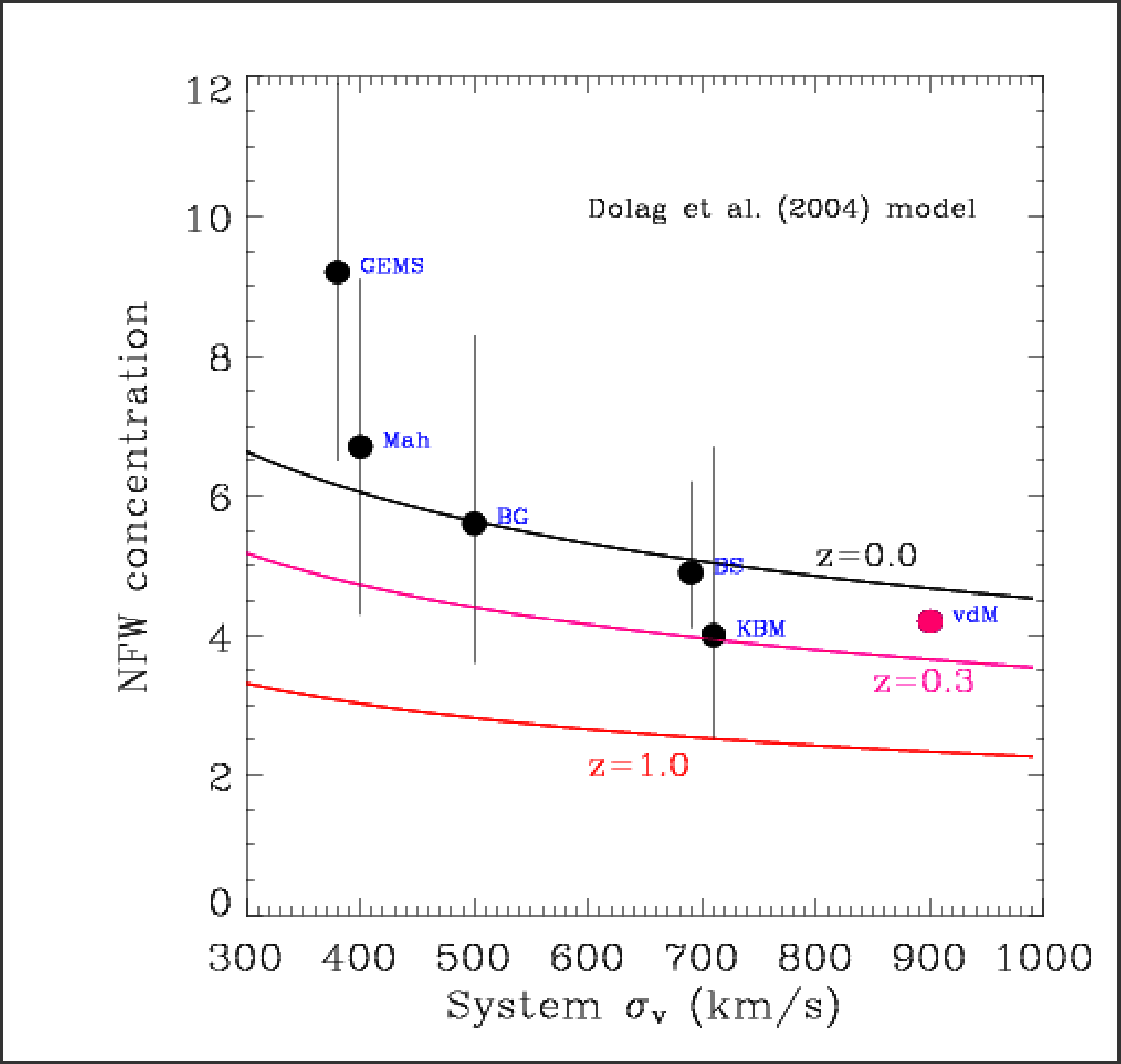
M(<r) results: GEMS group

(Mamon, B., & Ponman, in preparation)



M(<r) results: concentration vs. mass

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



(Mahdavi et al. 99,
van der Marel et al. 00,
B. & Girardi 03,
Katgert et al. 04,
B. & Salucci 06,
Mamon, B. & Ponman in preparation)

Results: Mass accretion

Deborah Compagnoni, Janica Kostelic, & Vreni Schneider
winners of ≥3 olympic gold medals each in alpine ski

Mass accretion results summary:

$M(<r_{tidal}) \approx 2\ M_{200} \rightarrow$ accretion still ongoing at $z \approx 0$

(Rines & Diaferio 06)

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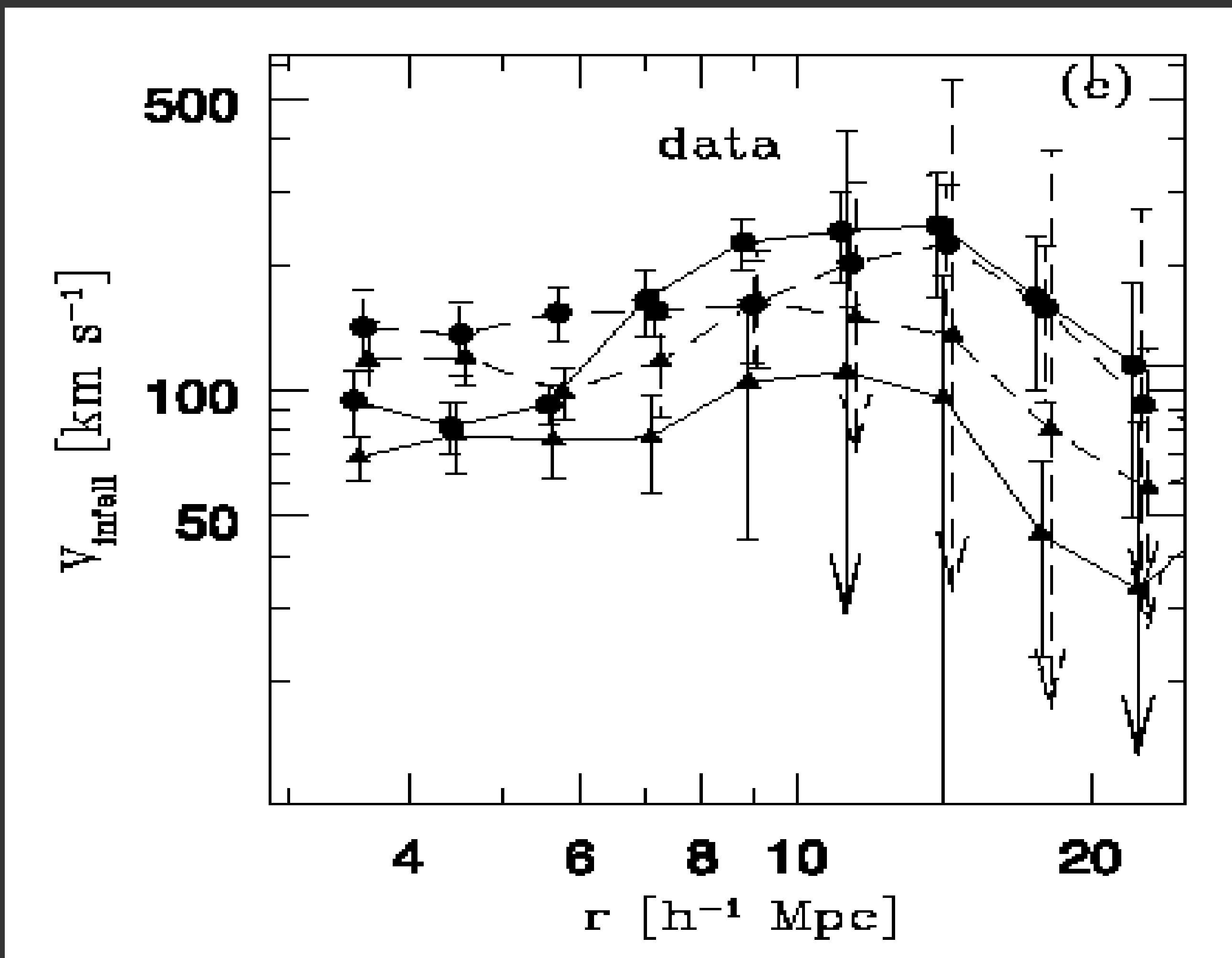
Direct evidence for infall from peculiar velocities of galaxies around nearby groups *(Ceccarelli et al. 2005)*

Mass accretion results: direct evidence for infall



Infall detected around groups of SSRS2 from galaxy peculiar velocities

Infall velocities higher around more massive groups

(Ceccarelli et al. 2005)

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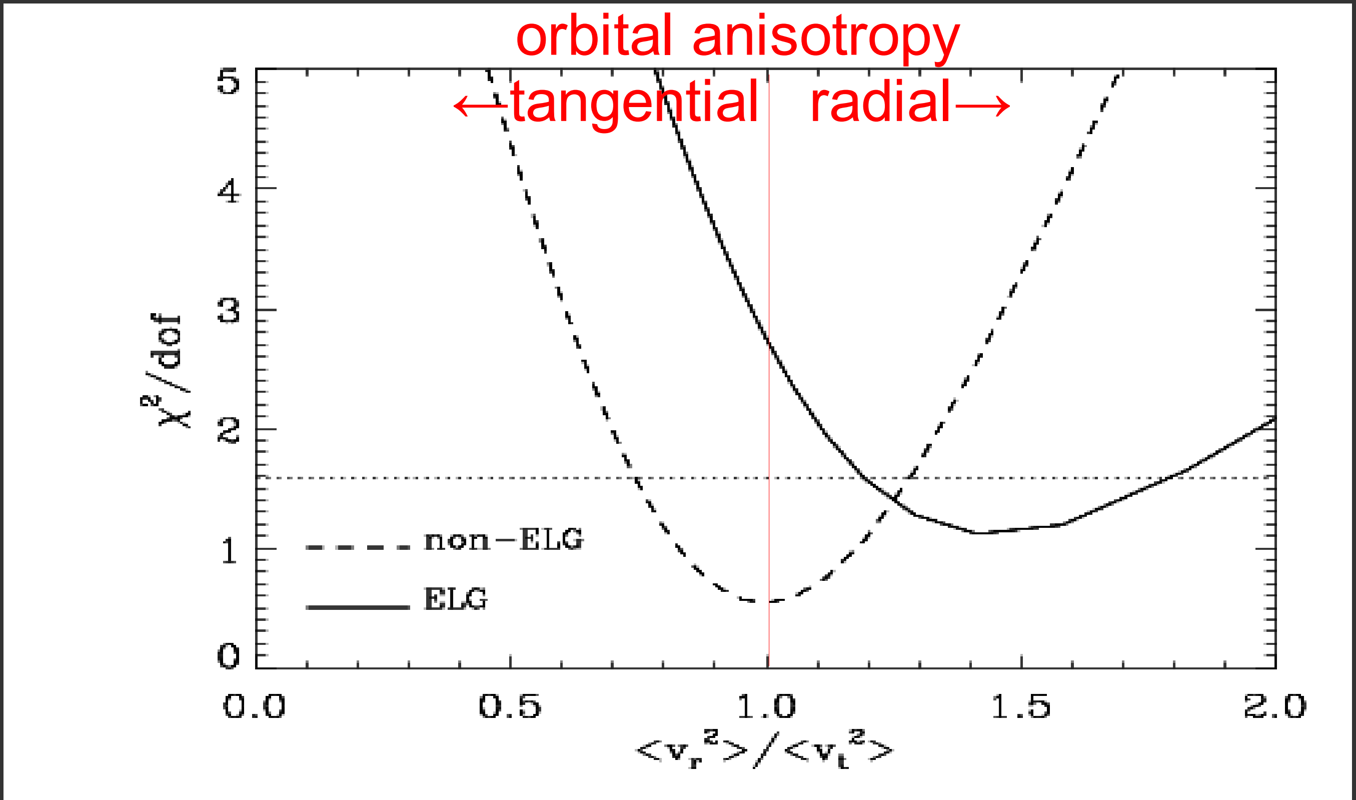
Direct evidence for infall from peculiar velocities of galaxies around nearby groups *(Ceccarelli et al. 2005)*

Orbits of late-type galaxies in clusters & groups: memory of infalling motions, late accretion

(B. et al. 97, Mahdavi et al. 99, B. & Katgert 04)

Mass accretion results: orbital motions of galaxies



Dashed line: Early

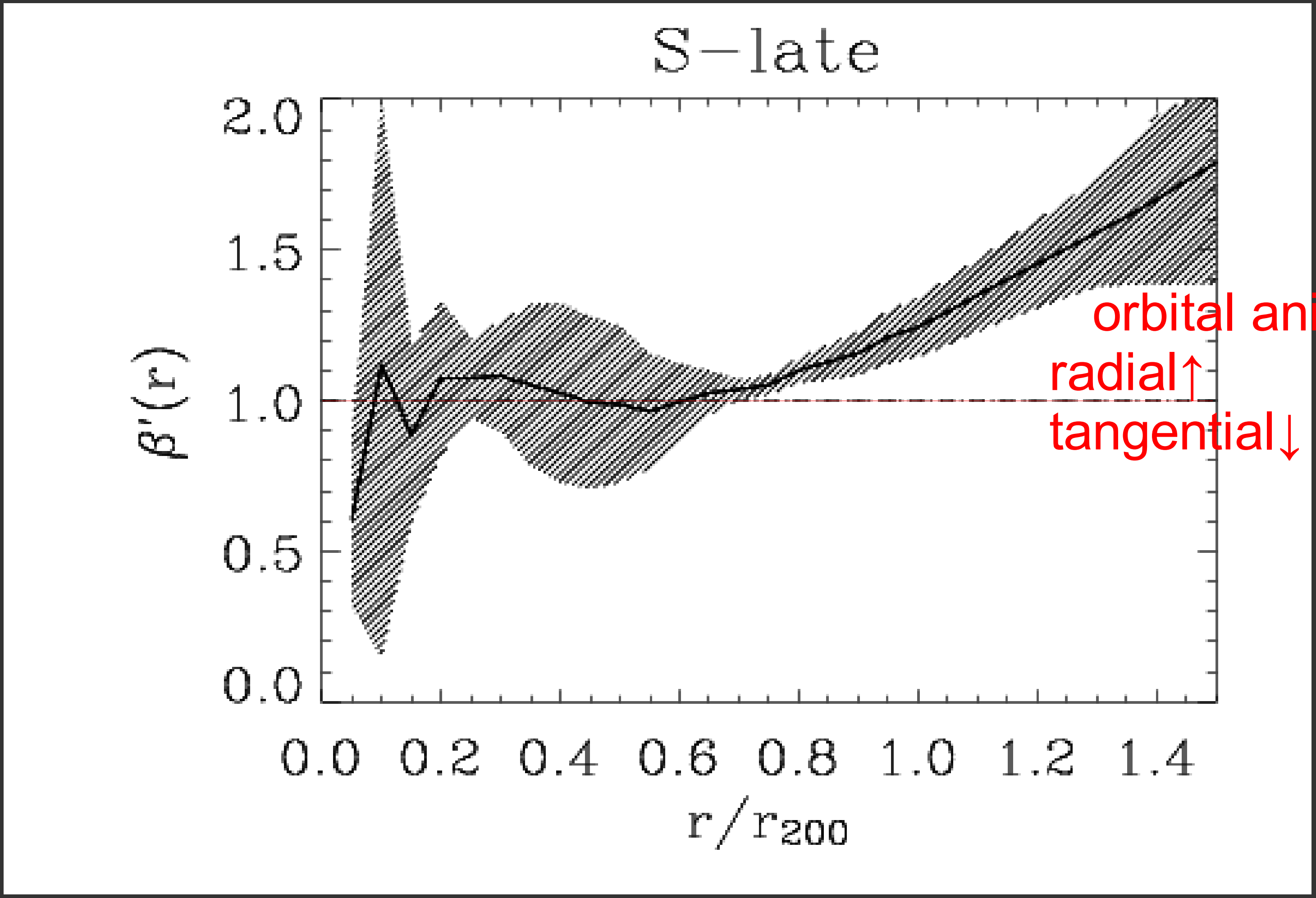
Solid line: Late

Early-type galaxies: isotropic orbits

Late-type galaxies: mildly radially anisotropic orbits

(ENACS clusters: B. 2001)

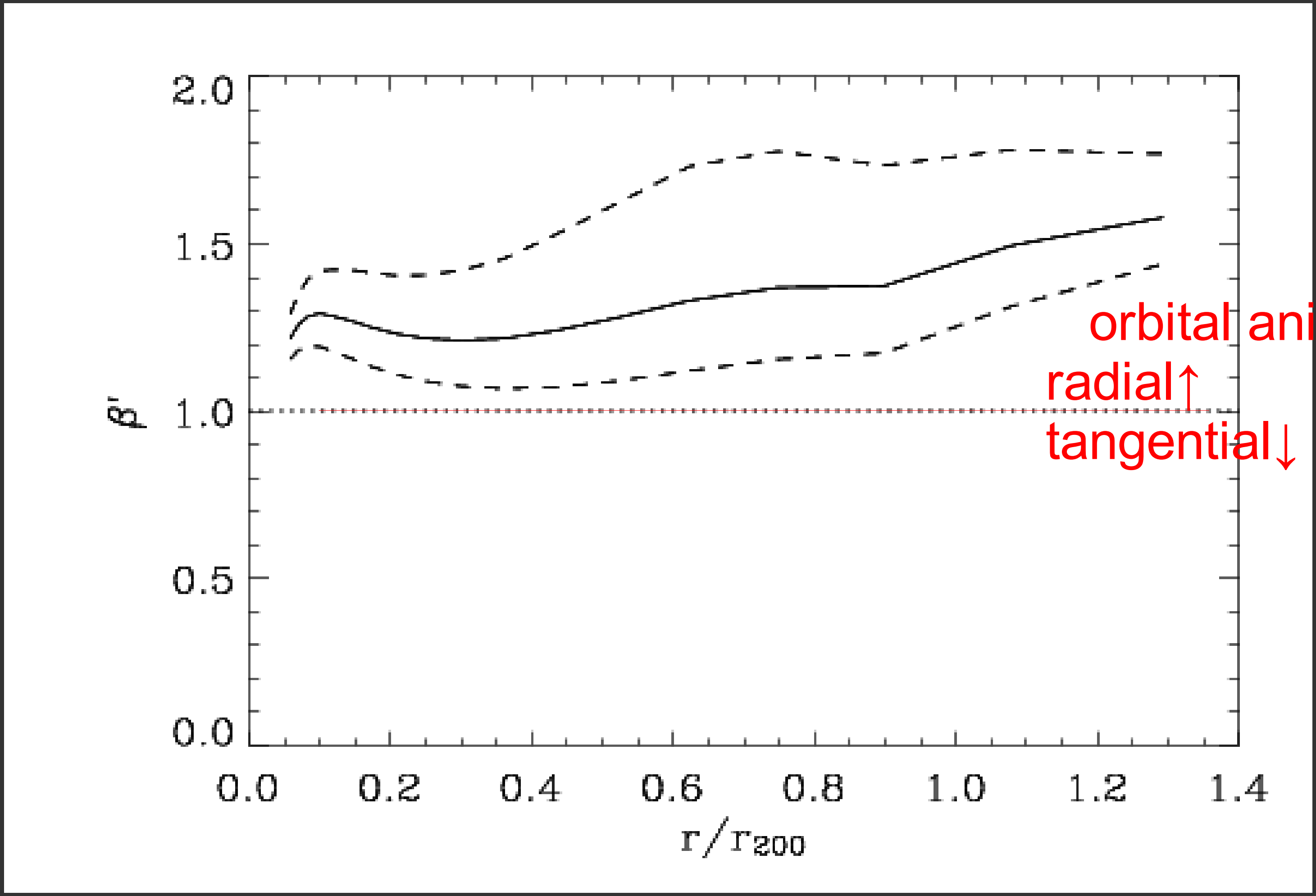
Mass accretion results: orbital motions of galaxies



Late-type galaxies: radial anisotropy increases with radius

(ENACS clusters: B. & Katgert 2004)

Mass accretion results: orbital motions of galaxies



Blue galaxies: radial anisotropy increases with radius

(SDSS clusters: B. et al. in preparation)

Mass accretion results summary:

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Direct evidence for infall from peculiar velocities of galaxies around nearby groups *(Ceccarelli et al. 2005)*

Orbits of late-type galaxies in clusters & groups: memory of infalling motions, late accretion

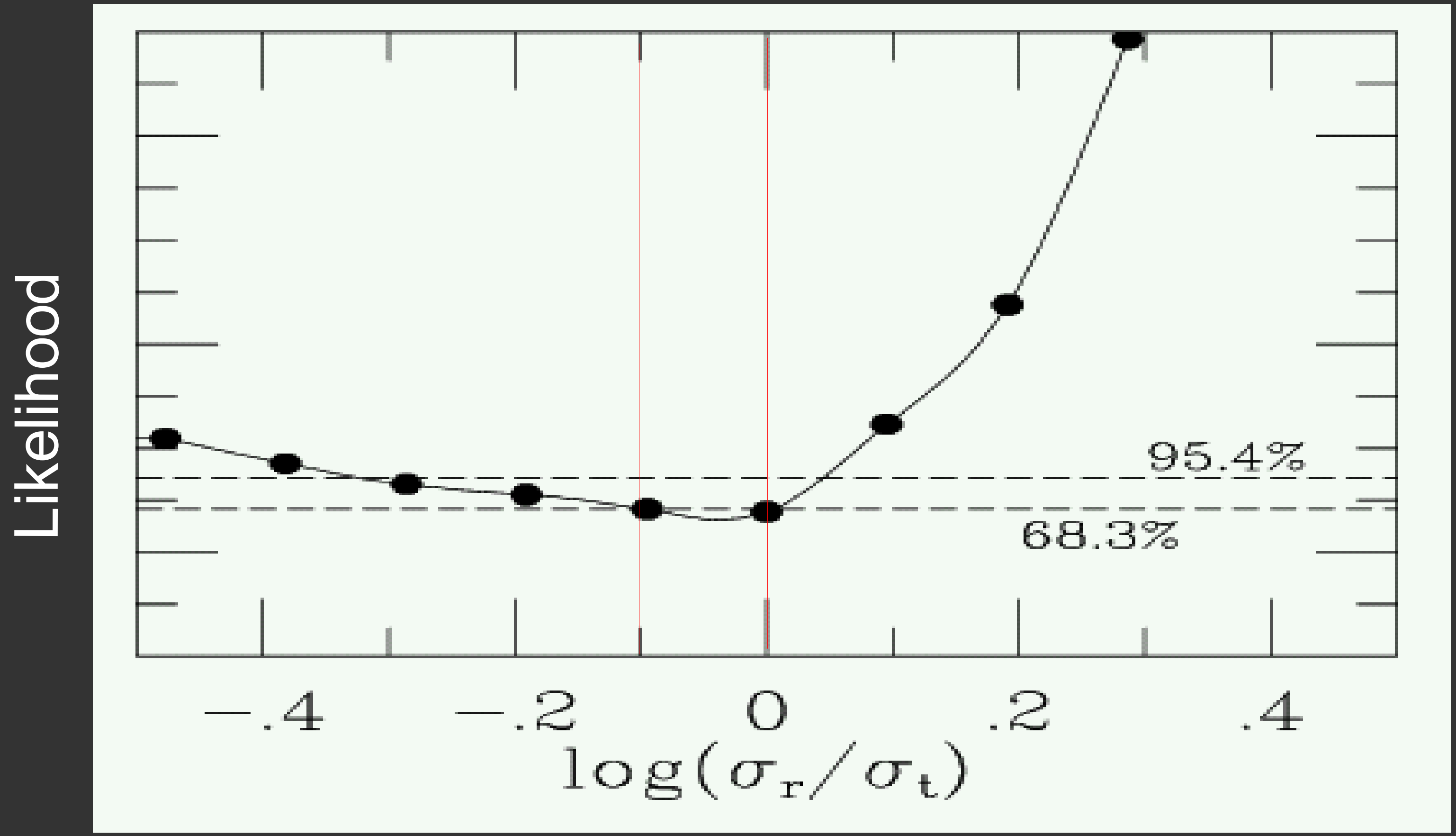
(B. et al. 97, Mahdavi et al. 99, B. & Katgert 04)

- *Progress:* tracing accretion with z

Mass accretion results: higher z (CNOC)

Early-type galaxies at z≈0.3: isotropic orbits

(van der Marel et al. 2000)



Mass accretion results: higher z (CNOC)

Early-type galaxies at z≈0.3: isotropic orbits

(van der Marel et al. 2000)

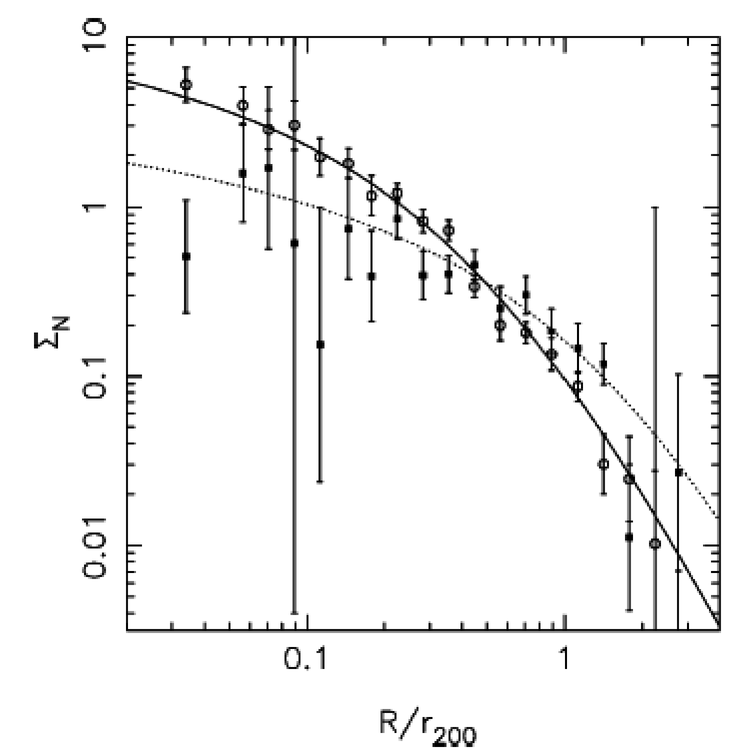
No evolution of phase-space distributions
of early- and late-type galaxies from z=0 to z=0.3

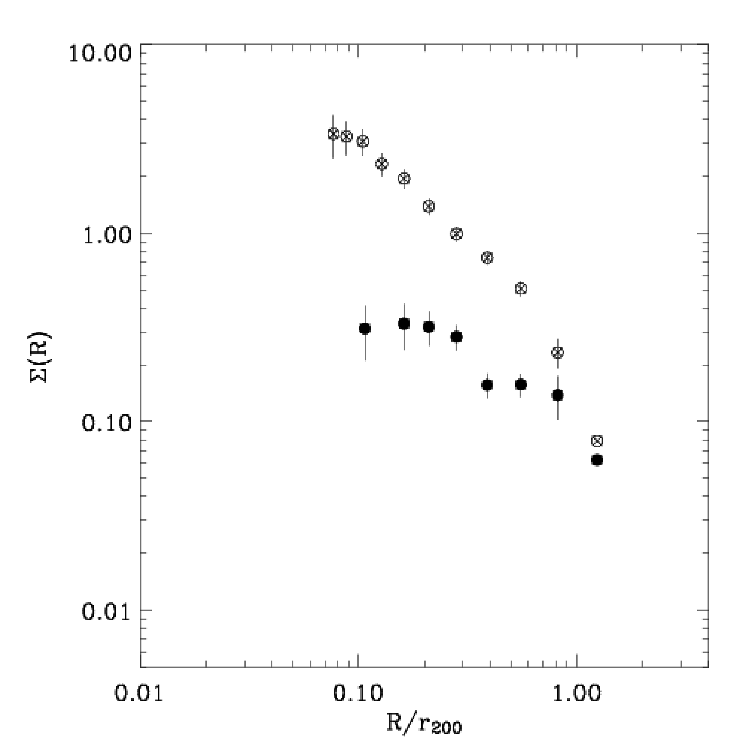
(Carlberg et al. 97 vs. B. & Katgert 04)

Mass accretion results: higher z

Early-type and late-type galaxies at z≈0.3 have similar projected phase-space distributions to those of early- and late-type gals at z≈0

Carlberg et al. (1997)





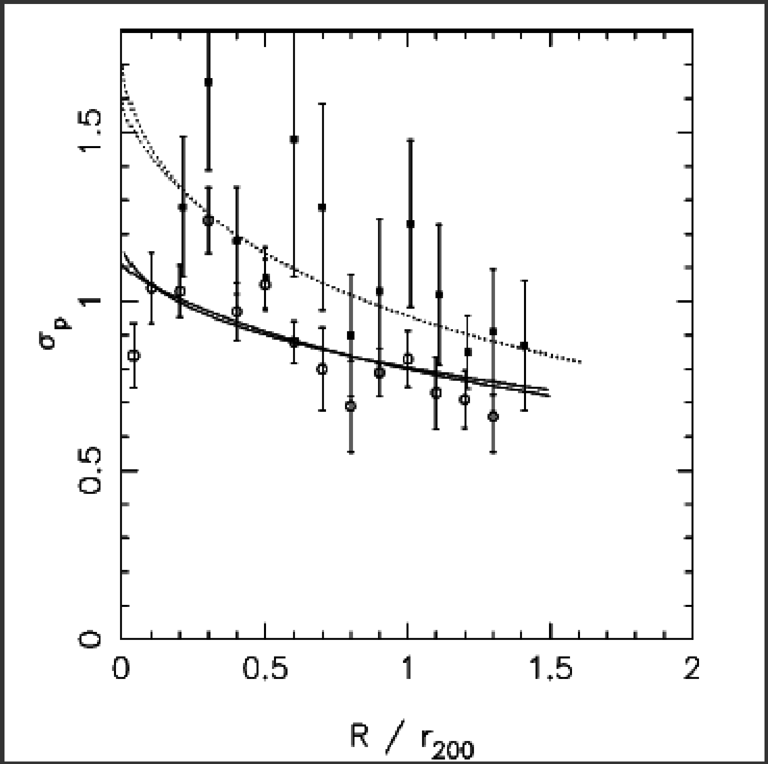
B. e& Katgert (2004)

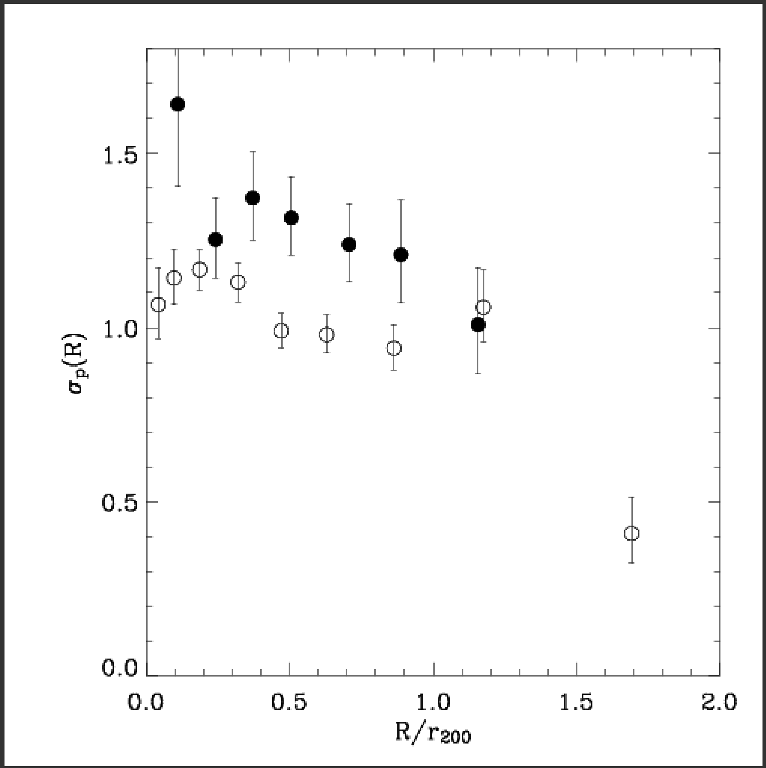
CNOC and ENACS number density profiles of early (open symbols) and late (filled symbols) galaxies

Mass accretion results: higher z

Early-type and late-type galaxies at z≈0.3 have similar projected phase-space distributions to those of early- and late-type gals at z≈0

Carlberg et al. (1997)





B. e& Katgert (2004)

CNOC and ENACS velocity dispersion profiles of early (open symbols) and late (filled symbols) galaxies

Mass accretion results: higher z (CNOC)

Early-type galaxies at z≈0.3: isotropic orbits

(van der Marel et al. 2000)

No evolution of phase-space 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 are an infalling population
like late-type galaxies at z=0.0

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→ late-type galaxies at z=0.3 are an infalling population
like late-type galaxies at z=0.0

Since the late-type -galaxy fraction increases with z
→ the infall rate increases with z
(Ellingson et al. 2001)

Results: M/L profile

Ingemar Stenmark,
Alberto Tomba & Kietjl Aamodt
winners of ≥3 olympic gold medals each in alpine ski

M/L results summary:

- 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}

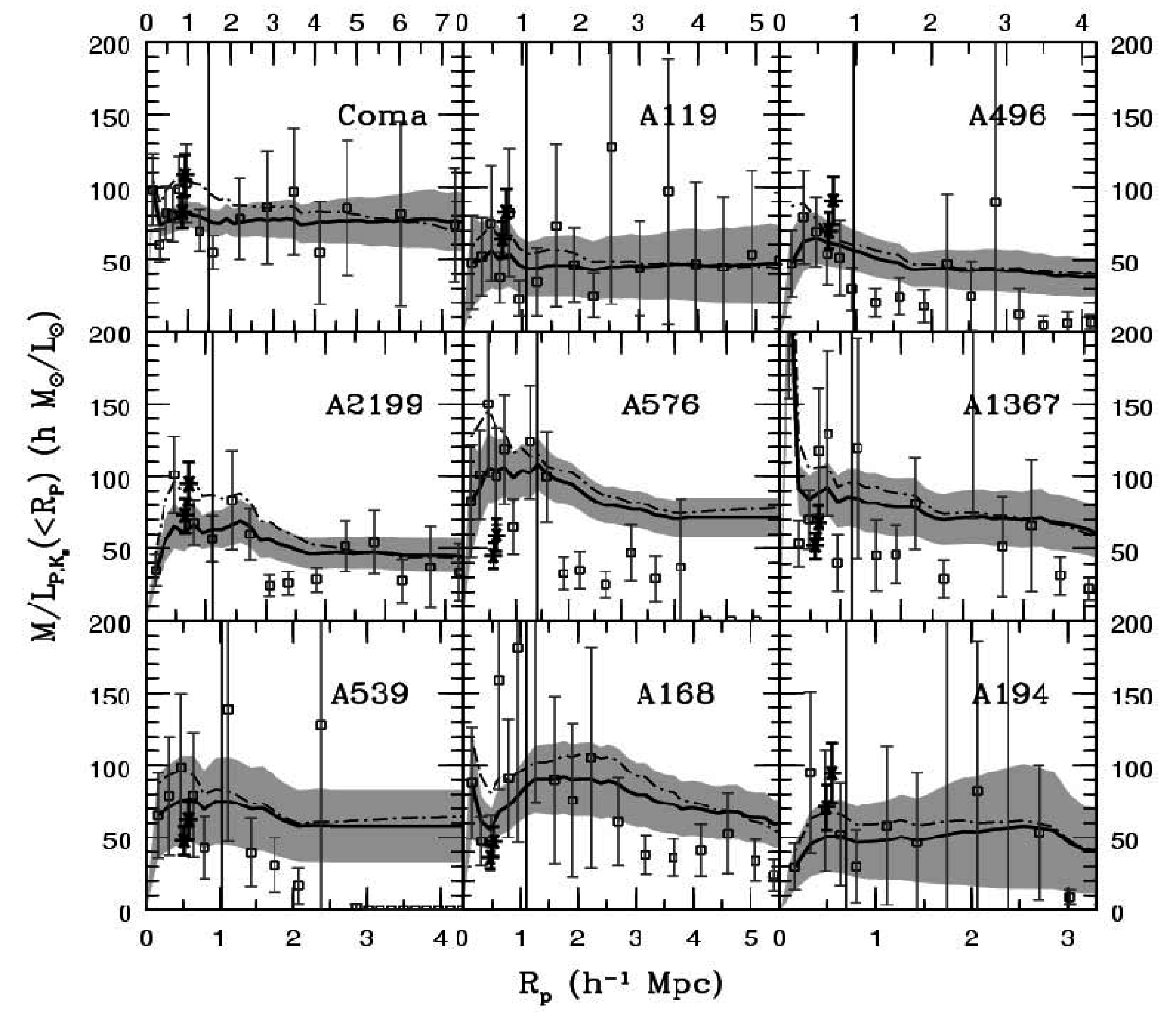
[which explains why virial masses are ok!]

(Rines et al., B. & Girardi 03, Katgert et al. 04)

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*

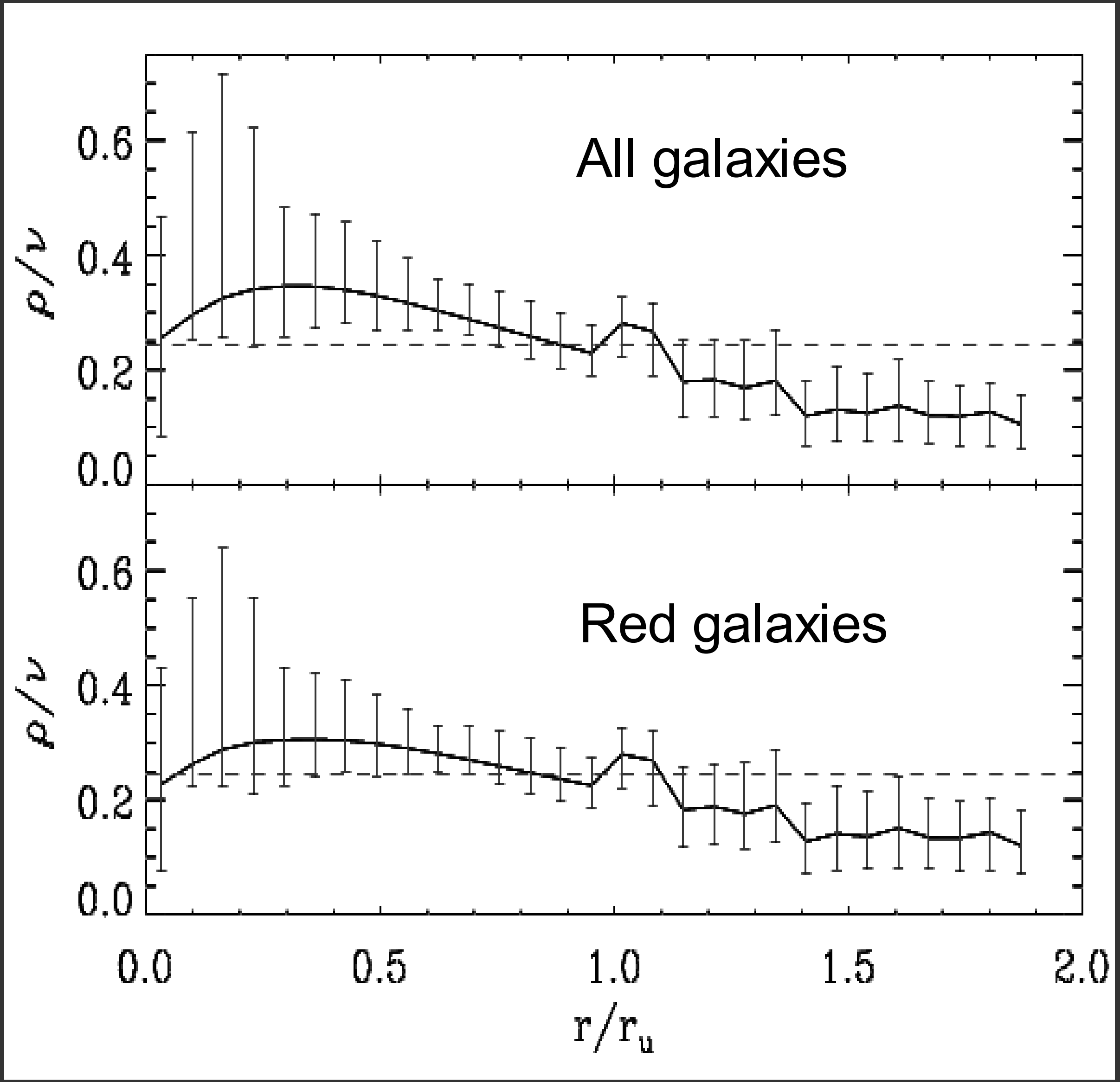


M/L results: 2dFGRS

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)

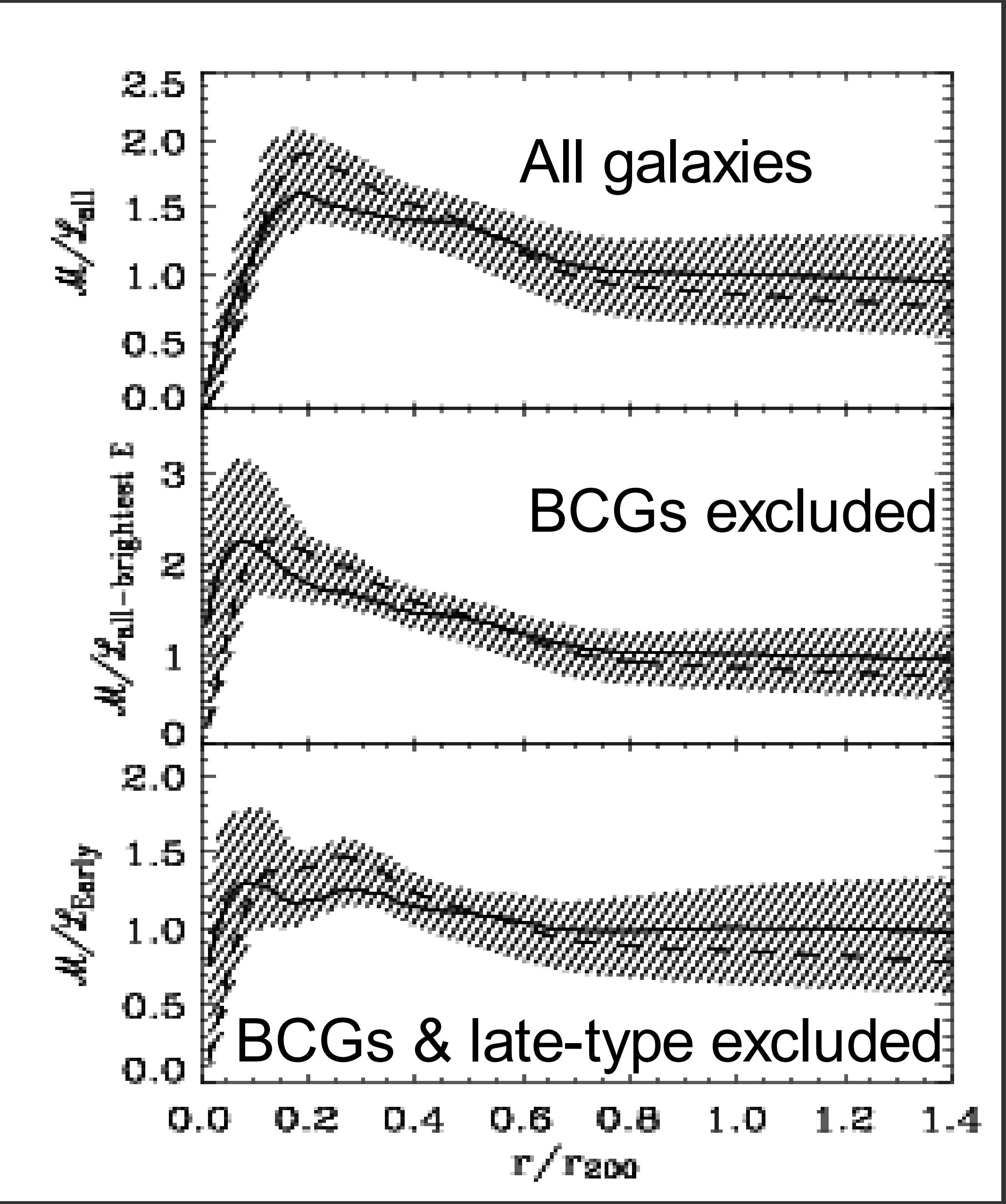


M/L results: ENACS

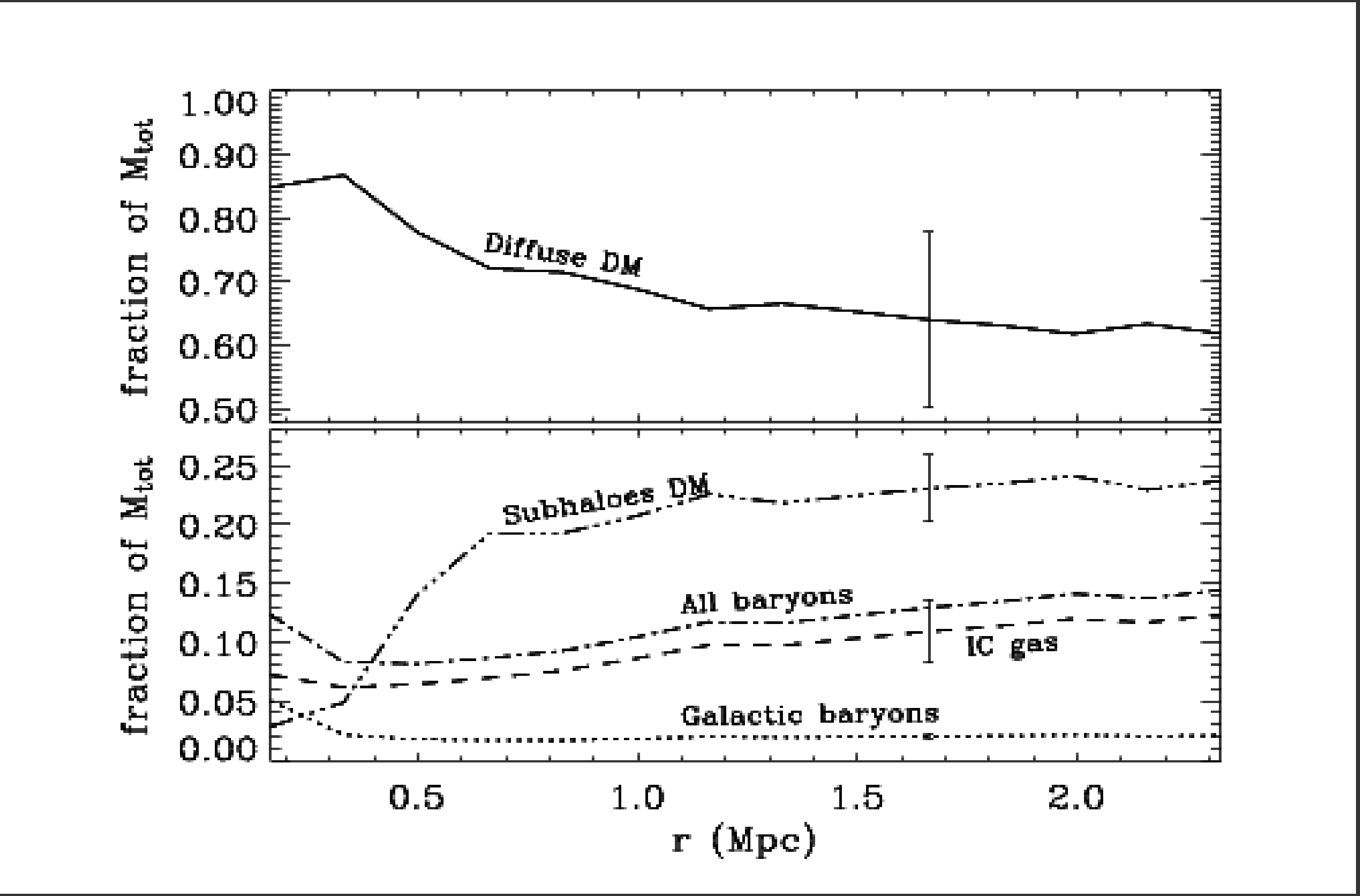
Averaging over several clusters allows to beat projection effects

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: different dark and luminous components



Fractions of total mass in galactic and gas baryons and in dark matter subhaloes (B. & Salucci 2006)

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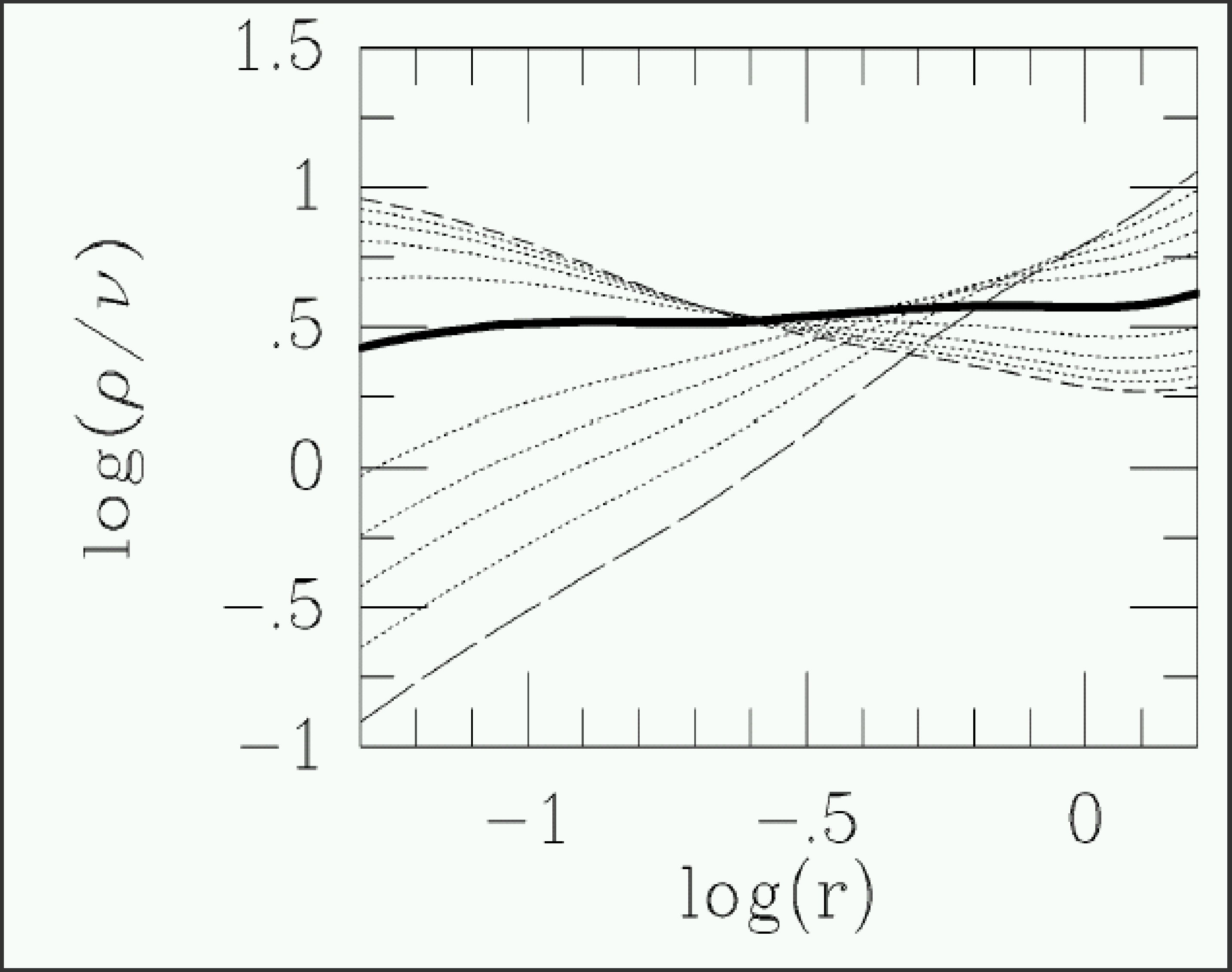
Similar results at $z \approx 0.3$ (van der Marel et al. 00)

M/L results: evolution (CNOC)



M/L ≈ constant, for <z>=0.3 clusters *(van der Marel et al. 00)*

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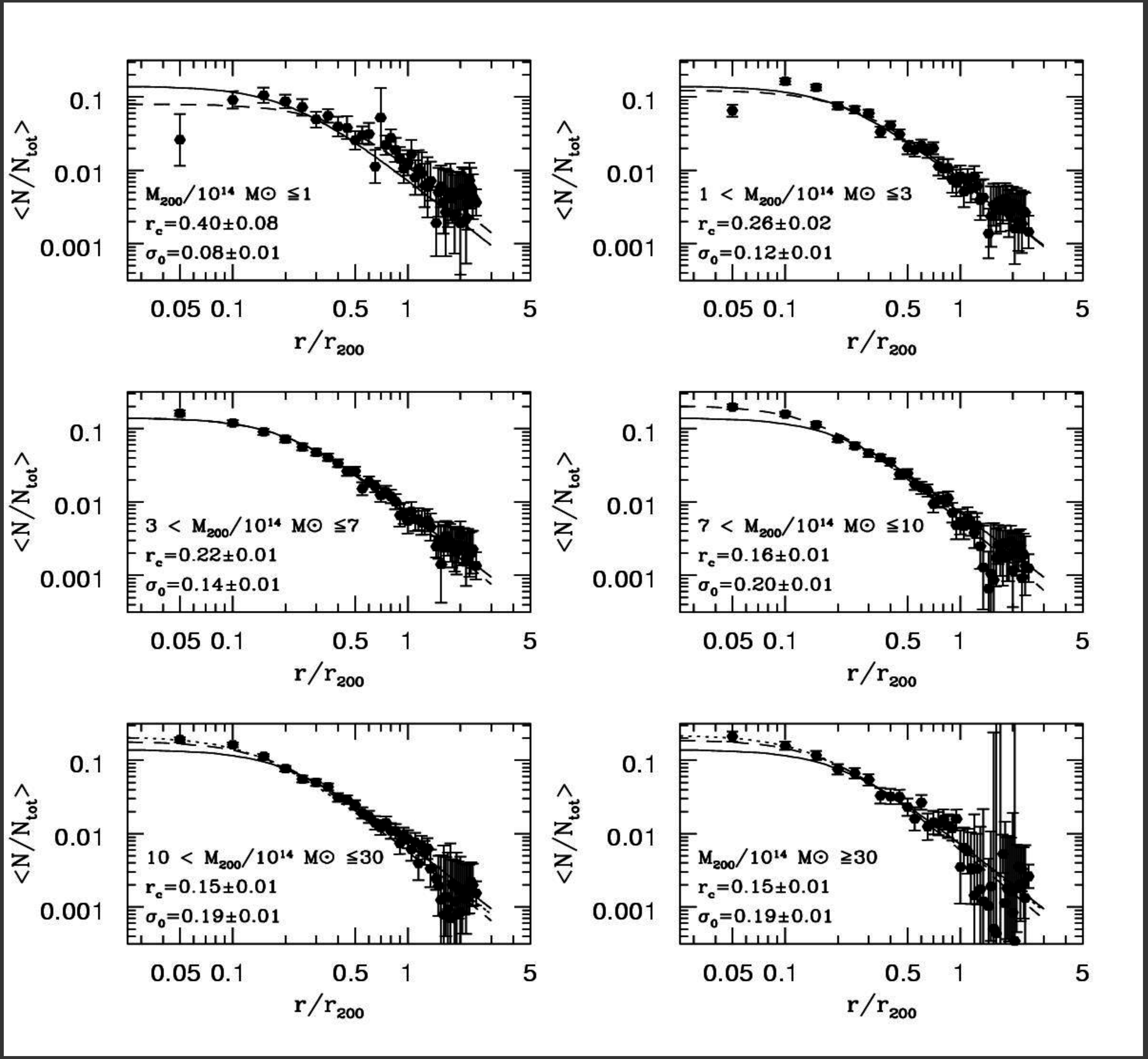
Similar results at $z \approx 0.3$ (van der Marel et al. 00)

Groups: steeper M/L at $r \approx 0$? (Popesso et al. 06)

M/L results: groups vs. clusters

Galaxies in groups have less peaked number density profiles than galaxies in clusters *(Popesso et al. 06)*

If M(<r) more concentrated, ➡M/L at r→0 is larger in groups than in clusters



M/L results: lower mass (groups)

Conflicting results so far!

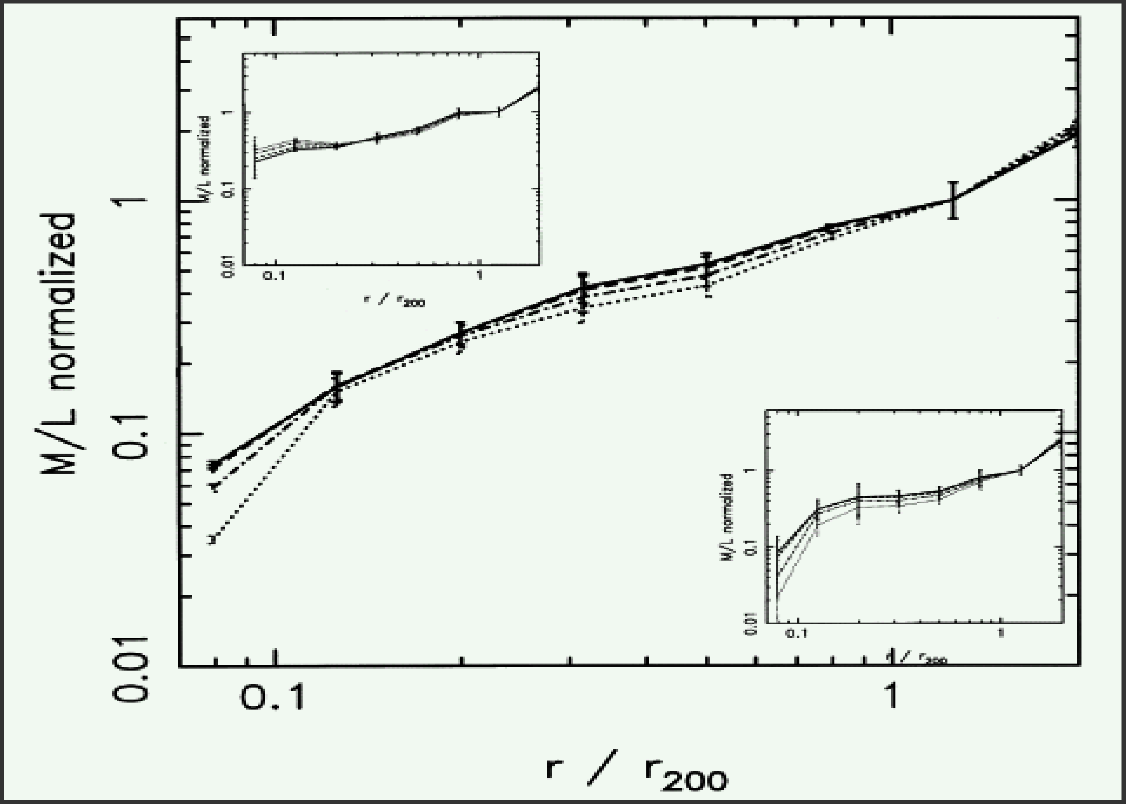
Constant M/L?

(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)



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Progress:

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

Conclusions

Conclusions: M(<r)

- DM dominated
- $r>r_{200}$: $\rho(r)$ slope between -3 and -4
- $r\simeq 0$: $\rho(r)$ cuspy or with galaxy-sized core
- $z\simeq 0$ and $z\simeq 0.3$ clusters have similar M(<r)
- trend c=c(M) as expected

Conclusions: mass accretion

- $M(<r_{200}) \approx M(r_{200}\text{-}r_{tidal})$
  $\rightarrow$ ongoing accretion at $z \approx 0$
- direct evidence of infall from peculiar velocities of galaxies in cluster outskirts
- radial vel. anisotropy of late-type cl. galaxies
  $\rightarrow$ memory of infalling motions
- $z \simeq 0.3$ clusters: more galaxies on radial orbits (higher infall rate)

Conclusions: M/L profile

- M/L decreases beyond r_{200} and also towards $r \simeq 0$
- red galaxies trace the mass within r_{200}
- blue galaxies and IC gas more extended than DM
- *groups have higher M/L near the centre*

Conclusions: prospects

- *Lower-mass systems dynamics: T_X needed*

  (e.g. the GEMS sample, Osmond & Ponman 2004)

- *Larger samples: SDSS*

  (e.g. the CIRS sample, Rines & Diaferio 2006)

  WINGS (see Fasano et al. 2006)

- *Higher-z: more z>0.5 with >100 z's each*

  (e.g. RXJ0152.7-1357 with FORS2@VLT, Girardi et al. 2005)

  EDisCS (see White et al. 2005)

Thank you for your attention!