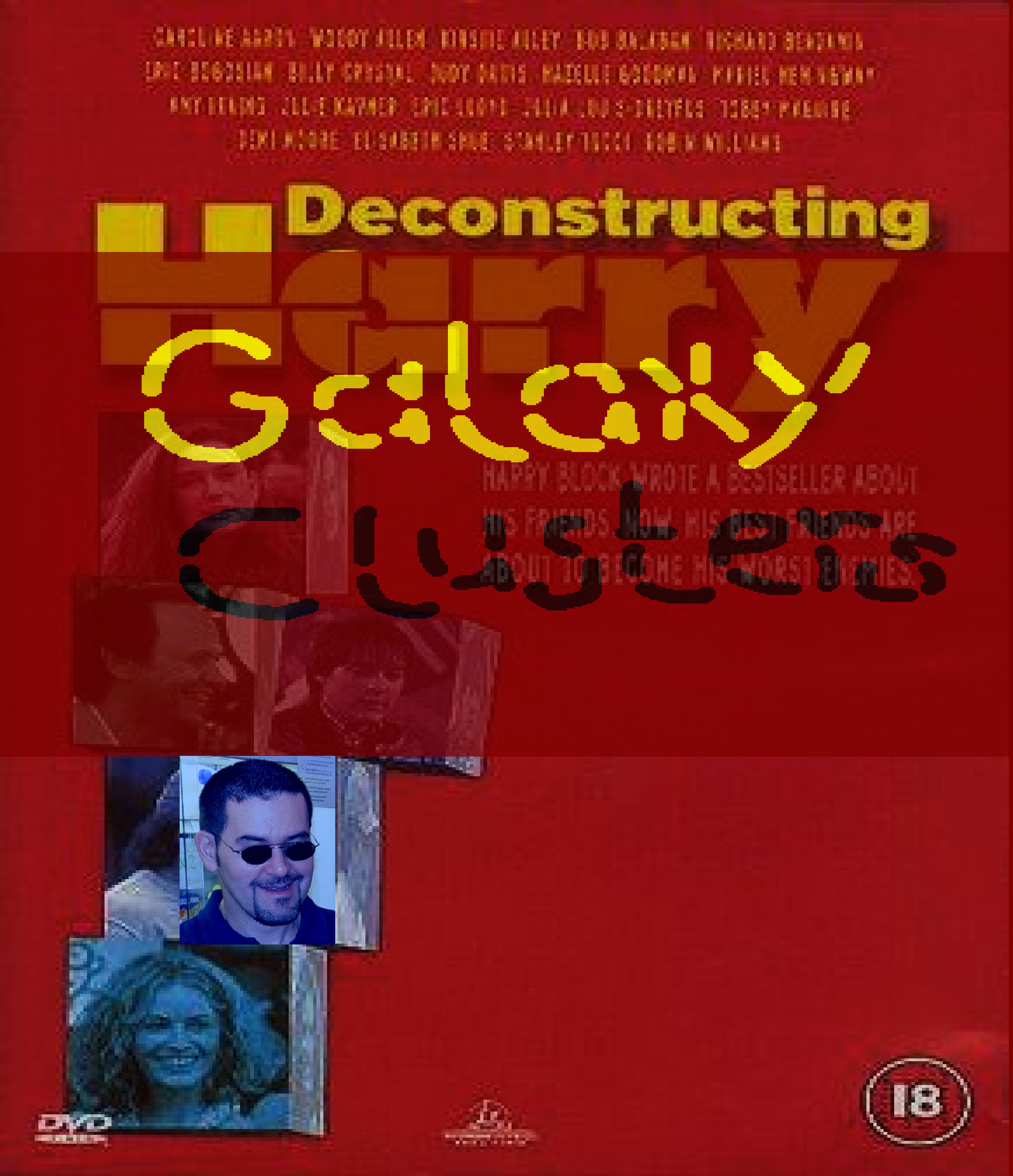

Andrea Biviano
INAF/
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In collaboration with:

Peter Katgert (NL)
Paolo Salucci (I)
Marisa Girardi (I)
Alain Mazure (F)

Talk outline:

- Historical review
- Motivations
- Methods
- Results:

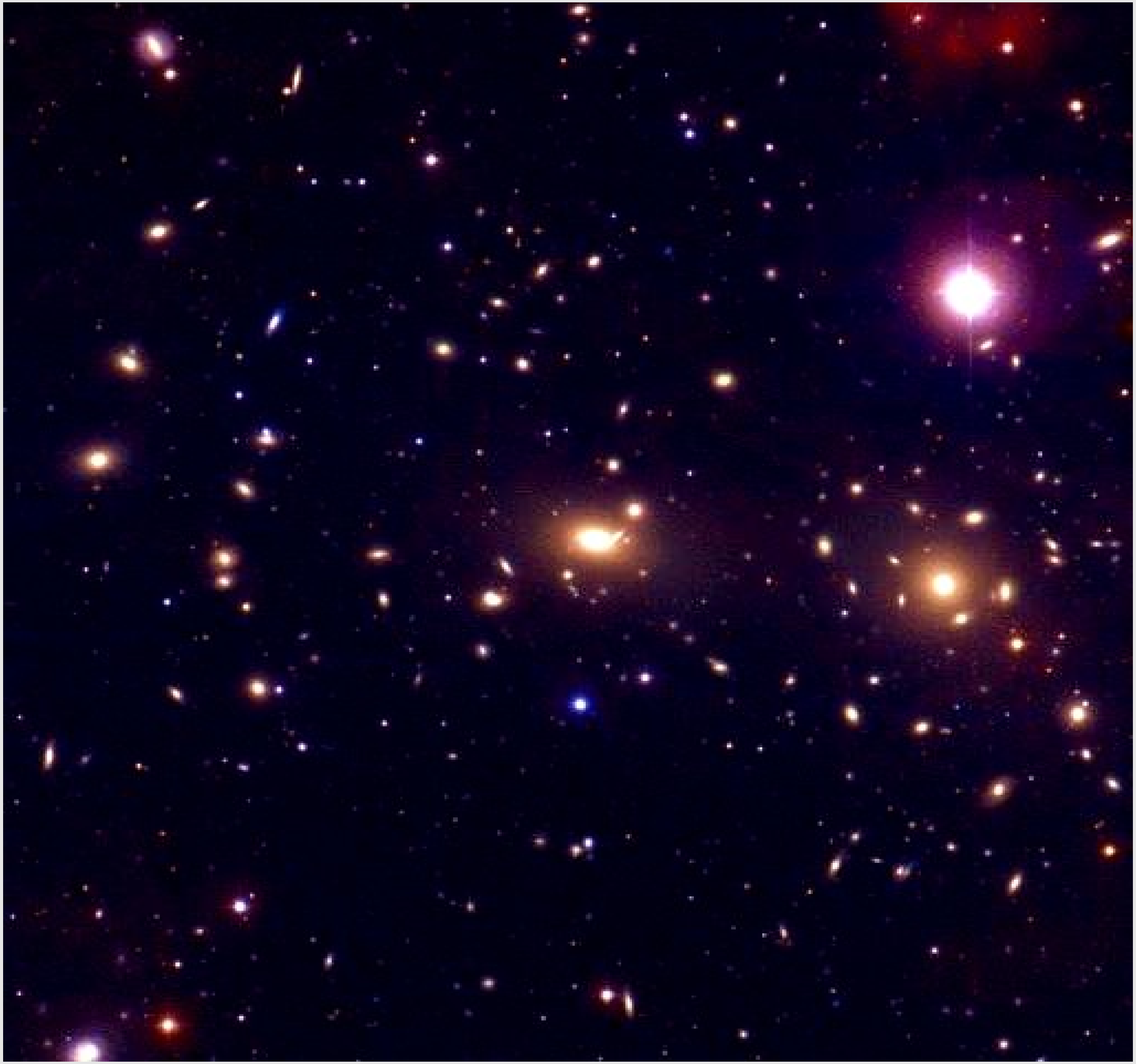
➔ the mass profiles of the different cluster components

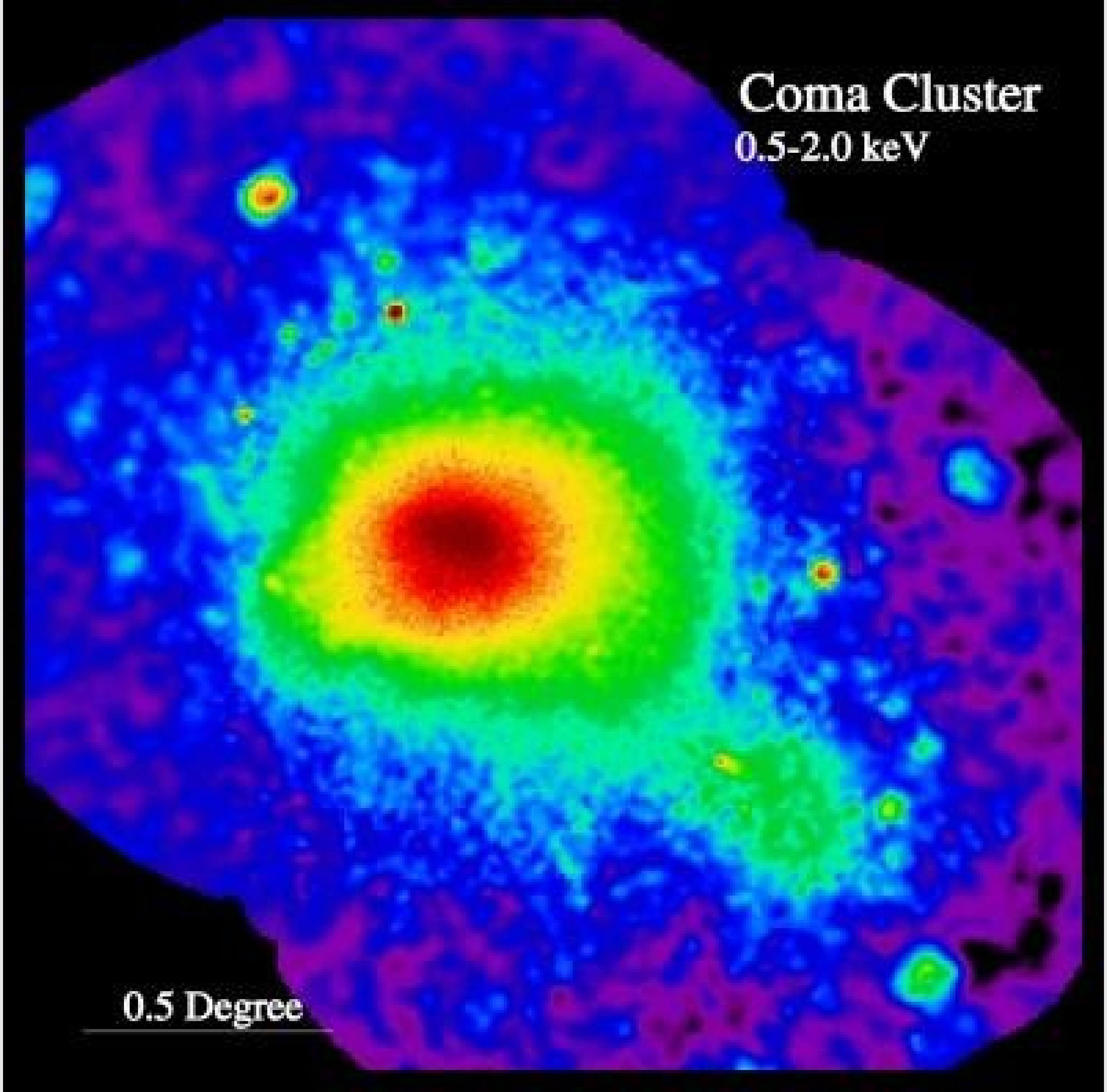
➔ the orbits of galaxies in clusters

- Perspectives

What are galaxy clusters made of?

- Galaxies
- Intra-cluster (IC) gas
- Dark matter




Coma Cluster
0.5-2.0 keV
0.5 Degree


2 Mpc/h

Historical review

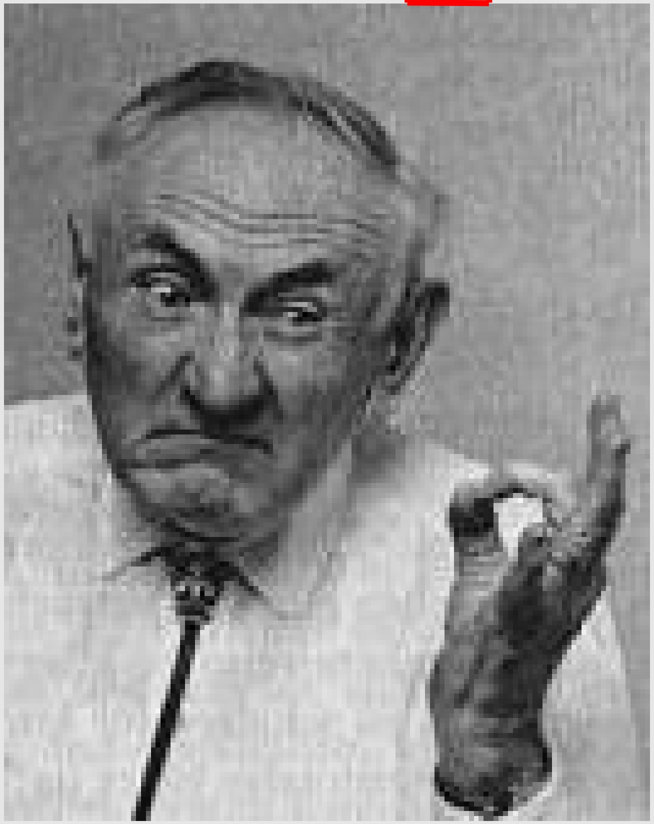
Clusters of galaxies known since 1784 (Messier's objects in Virgo) and catalogued by Herschel since 1785: Coma, Leo, UMa, Hydra, etc.

The discovery of dark matter

Die Rotverschiebung von extragalaktischen Nebeln

von **F. Zwicky.**

(16. II. 33.)



The discovery of dark matter

Die Rotverschiebung von extragalaktischen Nebeln

von **F. Zwicky.**

(16. II. 33.)

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

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

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

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.

The discovery of the intracluster gas

Limber (1959) +
Felten et al. (1967) +
Cavaliere et al. (1971):

predict galaxy clusters contain hot, diffuse gas, detectable in X-ray through its bremsstrahlung thermal emission

The discovery of the intracluster gas

Gursky et al. (1971) & Meekins et al. (1971) detect extended X-ray emission from the Coma cluster

A STRONG X-RAY SOURCE IN THE COMA CLUSTER OBSERVED BY *UHURU*

H. Gursky, E. Kellogg, S. Murray, C. Leong, H. Tananbaum, and R. Giacconi
American Science and Engineering, Inc., Cambridge, Massachusetts 02142
Received 1971 May 17; revised 1971 June 1

ABSTRACT

X-rays have been observed from a source in the Coma cluster of galaxies. The source is extended, with a size of about 45′. Its X-ray luminosity is 2.6×10^{44} ergs s^{-1}, and its spectrum is consistent with thermal bremsstrahlung at 7.3×10^7 °K or a power law. If the source is hot gas, its mass is 3×10^{13} $M_\odot$, which is about 1 percent of the mass required to stabilize the cluster.

Zwicky's discovery of dark matter is not secure because of many assumptions

Using intracluster gas rather than galaxies as tracers of the potential confirms the dark matter problem

Best confirmation comes from the discovery of *gravitational lenses* in galaxy clusters!

Gravitational lensing: predicted by Zwicky (1937)

IV. NEBULAE AS GRAVITATIONAL LENSES

As I have shown previously,[6] the probability of the overlapping of images of nebulae is considerable. The gravitational fields of a number of "foreground" nebulae may therefore be expected to deflect the light coming to us from certain background nebulae. The observation of such gravitational lens effects promises to furnish us with the simplest and most accurate determination of nebular masses. No thorough search for these effects has as yet been undertaken. It

Astron. Astrophys. 172, L14–L16 (1987)

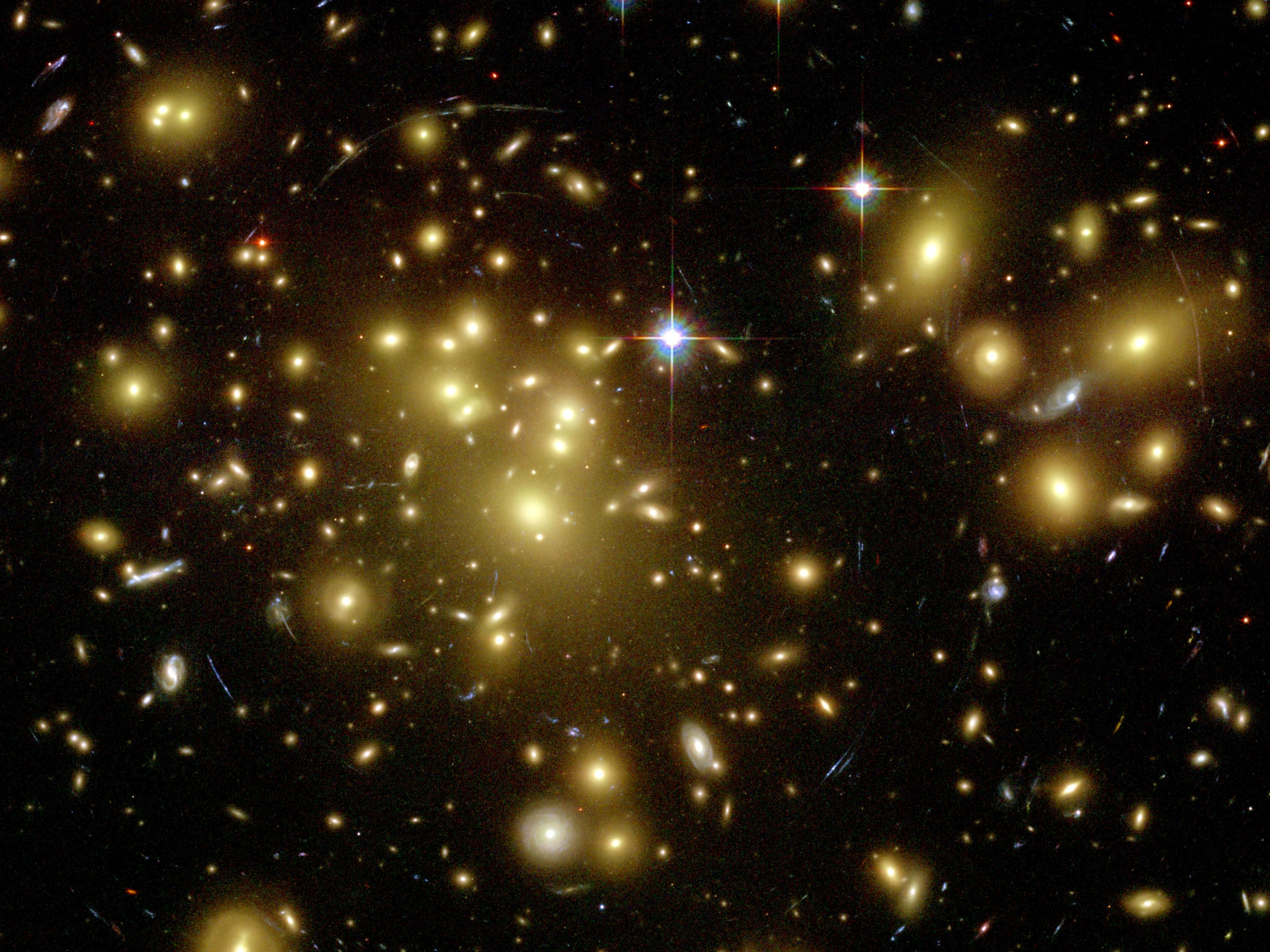
Letter to the Editor

A blue ring-like structure in the center of the A 370 cluster of galaxies

G. Soucail, B. Fort, Y. Mellier, and J. P. Picat
Observatoire de Toulouse, 14 Avenue E. Belin, F-31000 Toulouse, France

Received April 24, accepted August 15, 1986

…and found by Soucail et al., 50 years later!



Motivations

Deconstructing galaxy clusters in their 3 main components

Why is it important?

- Test nature of DM
- Test cosmological models of structure formation and learn about galaxy evolution

Nature of dark matter: 'classical' CDM or self-interacting?

Cosmological numerical simulations of structure formation with Cold Dark Matter predict a 'universal' density profile of DM halos (Navarro, Frenk & White 1996, 1997):

A UNIVERSAL DENSITY PROFILE FROM HIERARCHICAL CLUSTERING

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Received 1996 November 13; accepted 1997 July 15

ABSTRACT

We use high-resolution N-body simulations to study the equilibrium density profiles of dark matter halos in hierarchically clustering universes. We find that all such profiles have the same shape, independent of the halo mass, the initial density fluctuation spectrum, and the values of the cosmological parameters. Spherically averaged equilibrium profiles are well fitted over two decades in radius by a simple

Nature of dark matter: cold or self-interacting?

CDM ‘universal’ density profile of DM halos
is cuspy at the halo center:

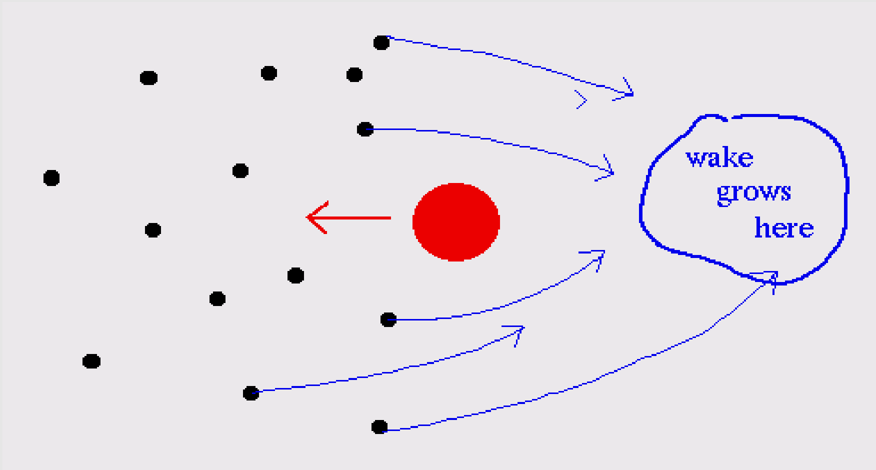
$$\rho_{NFW}(r) = \frac{\rho_0}{(r/r_s)(1 + r/r_s)^2}$$

Does not fit *observed* density profiles of galaxies
(de Blok & Bosma 2002, Gentile et al. 2004, Borriello et al. 2003)

→ alternative to CDM proposed (Spergel & Steinhardt 2000):
Self-Interacting DM could fit galaxy density profiles
by ***reducing*** *the halo central density concentration*
(if SIDM cross-section is large enough)

Models of structure formation: energy transfer from galaxies to DM?

Galaxies are subject to dynamical friction:

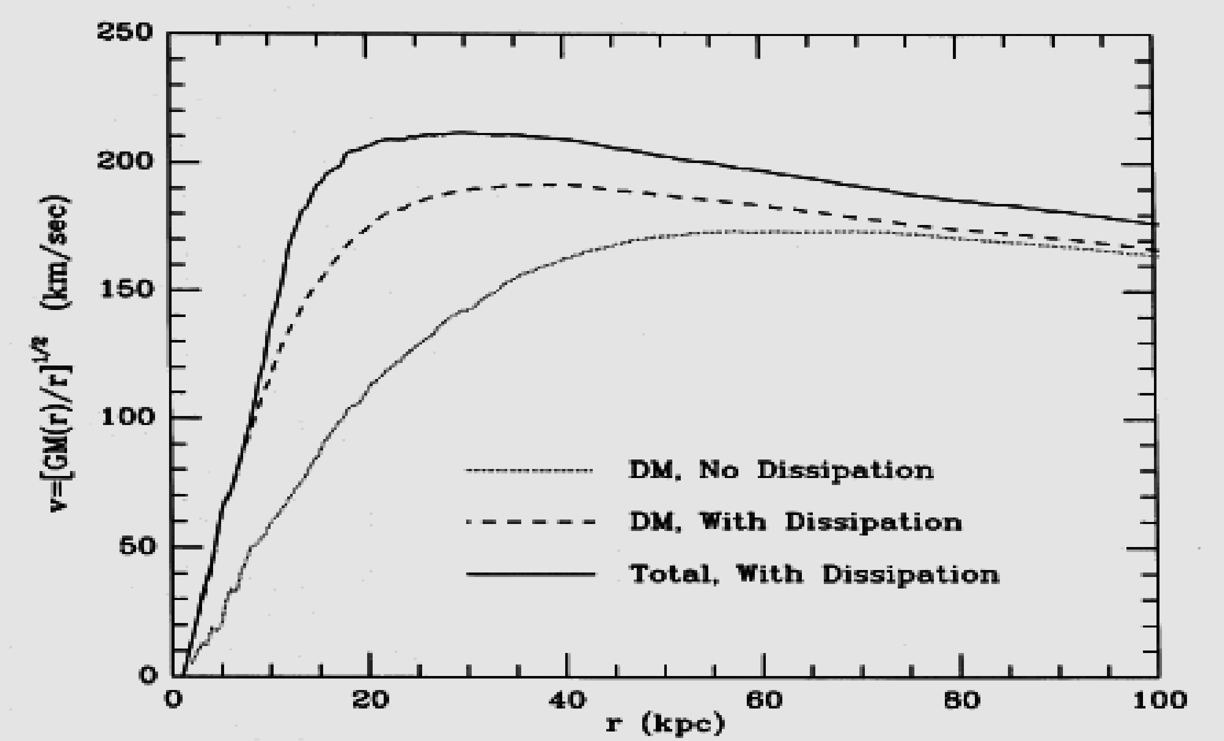


Galaxies tranfer part of their orbital energy to the DM, thus heating up the originally formed cusp.

→ The DM distribution becomes core-like, while the total mass distribution remains cuspy (El Zant et al. 2001)

Models of structure formation: DM adiabatic contraction?

Baryons sink dissipatively (cooling flows)
→ Such infall perturbs the DM distribution, pulling it inward, making the DM profile cuspier



(Blumenthal et al. 1986)

Learn about galaxy evolution

Must determine galaxies orbits
to solve the Jeans equation

Learning how galaxies move in clusters
as a $f=f(M_{cl},z_{cl},\text{type})$ constrains:

- **the hierarchical accretion scenario**
(do we see evidence for infall?)
and
- **the evolution mechanism of galaxy types**
(do the orbits of galaxies affect their properties?
e.g. via tidal stripping if pericenter is small, etc…)

Methods

The relative distribution of the different cluster components

Baryonic component: galaxies + IC gas

Need:

- magnitudes and colours (spectra) of galaxies in the cluster field
- X-ray surface brightness profile of diffuse intracluster gas

Dark Matter component:

invisible, determine it via the gravitational signal of the ***total matter***, then subtract the baryonic matter. To determine the cluster gravitational signal, use:

- cluster galaxies (need spectra)

  or

- diffuse IC gas (need its X-ray spectrum)

  as tracers of the potential,

  or use:

- lensing effect (need high-res imaging)

Mass estimate using galaxies

Use the Jeans equation for the dynamical equilibrium of a spherically symmetric system:

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

r, clustercentric radial distance

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

ν, number density of cluster galaxies

β, velocity anisotropy:

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

Mass estimate using galaxies:

only projected quantities are available:

R, projected clustercentric distance
I(R), projected galaxy number density
$\sigma_p^2(R)$, l.o.s. velocity dispersion profile

Using Abel inversion (Mamon & Boué 2006)

$$I(R) \ \& \ \sigma_p^2(R) \rightarrow \nu(r) \ \& \ \langle v_r^2 \rangle(r) \rightarrow M(r)$$

….if the velocity anisotropy β is known!

Mass estimate using X-rays:

Use the Jeans equation for the dynamical equilibrium of a spherically symmetric system:

$$M(r) = -\frac{rT}{G\mu m_p}\left(\frac{d\ln\nu_{gas}}{d\ln r} + \frac{d\ln T}{d\ln r}\right)$$

r, clustercentric radial distance
T, temperature of diffuse intracluster gas
ν_{gas}, *gas density*

Lensing mass estimate:

Very direct:

determine the distorsion pattern of the images of background galaxies

and/or model the potential to reproduce the shapes and positions of multiple images of the same sources

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

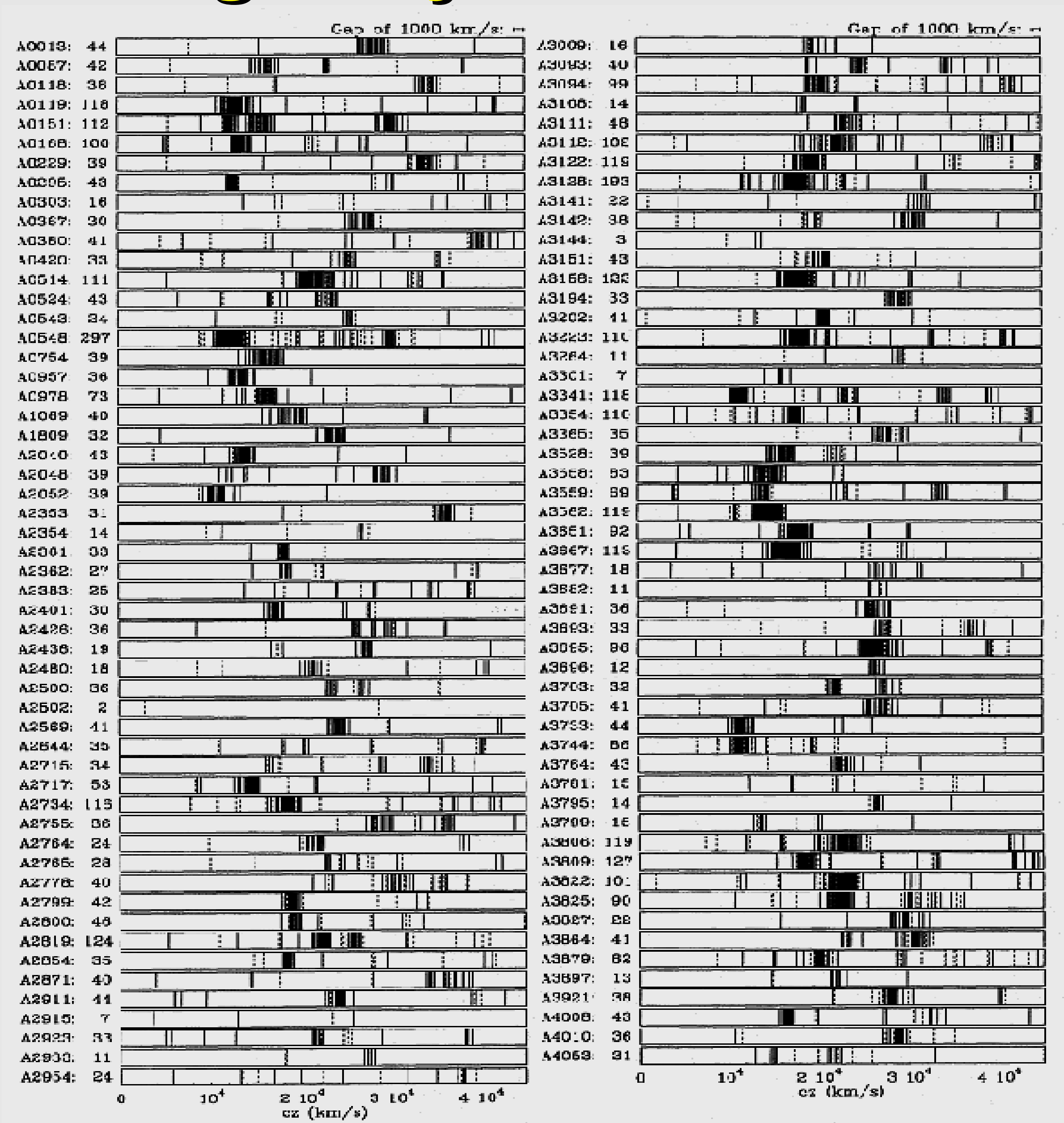
- less direct than lensing and X-ray ↓
- sample mass profile to larger radii ↑
- IC gas not fully thermalized (?) ↑
  (Rasia et al. 2004, Faltenbacher et al. 2005)
- lensing inefficient for nearby clusters ↑
  (Natarajan & Kneib 1997)

…and in any case, 3 is better than 1!

Results:

The mass profiles of
the different cluster components

Our galaxy data-set: subset of ENACS +



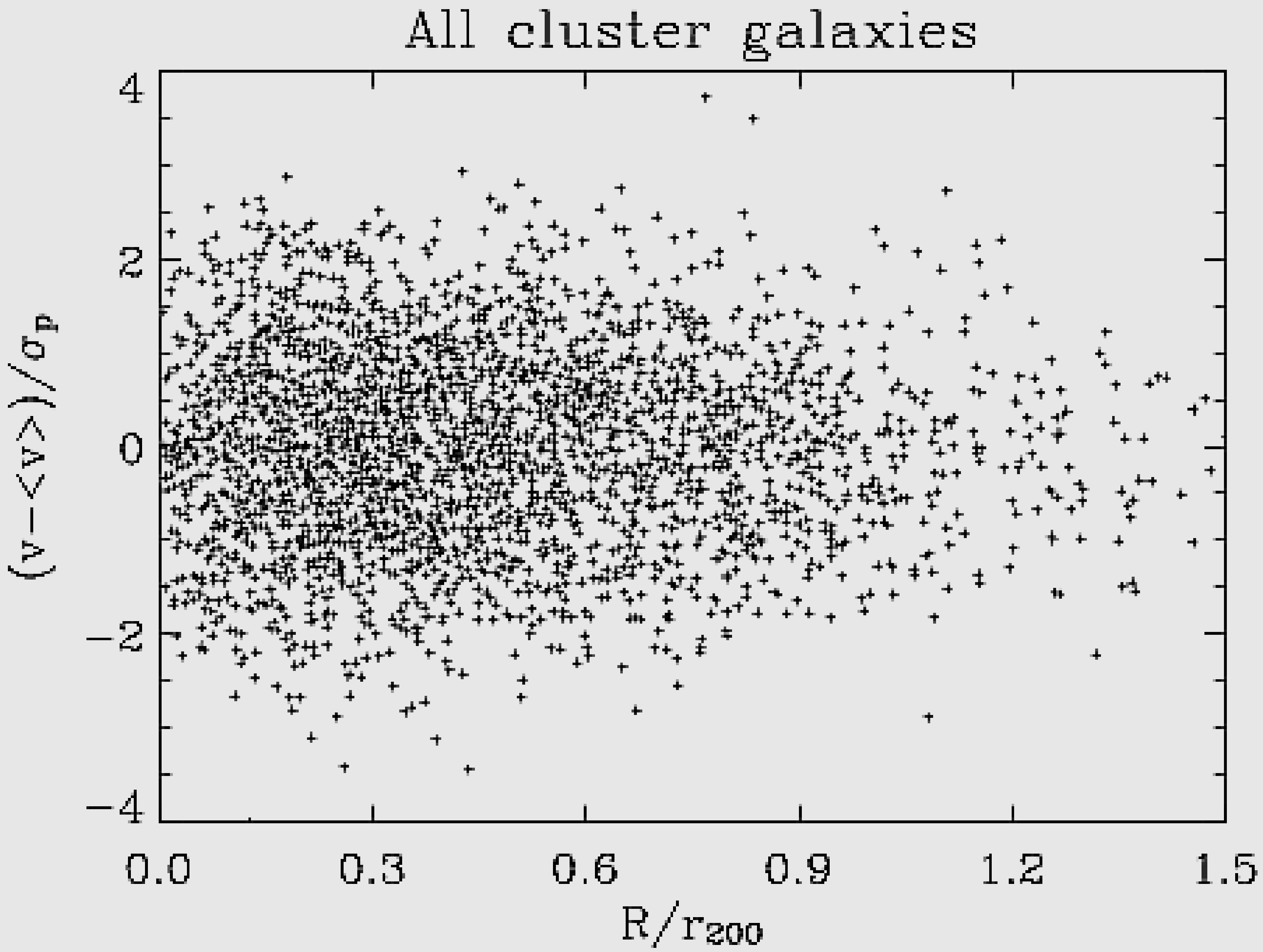
2900 galaxies *identified as members* of 59 clusters with redshifts, positions, magnitudes, types

Stack the 59 clusters together to build an ‘ensemble’ cluster → better statistics

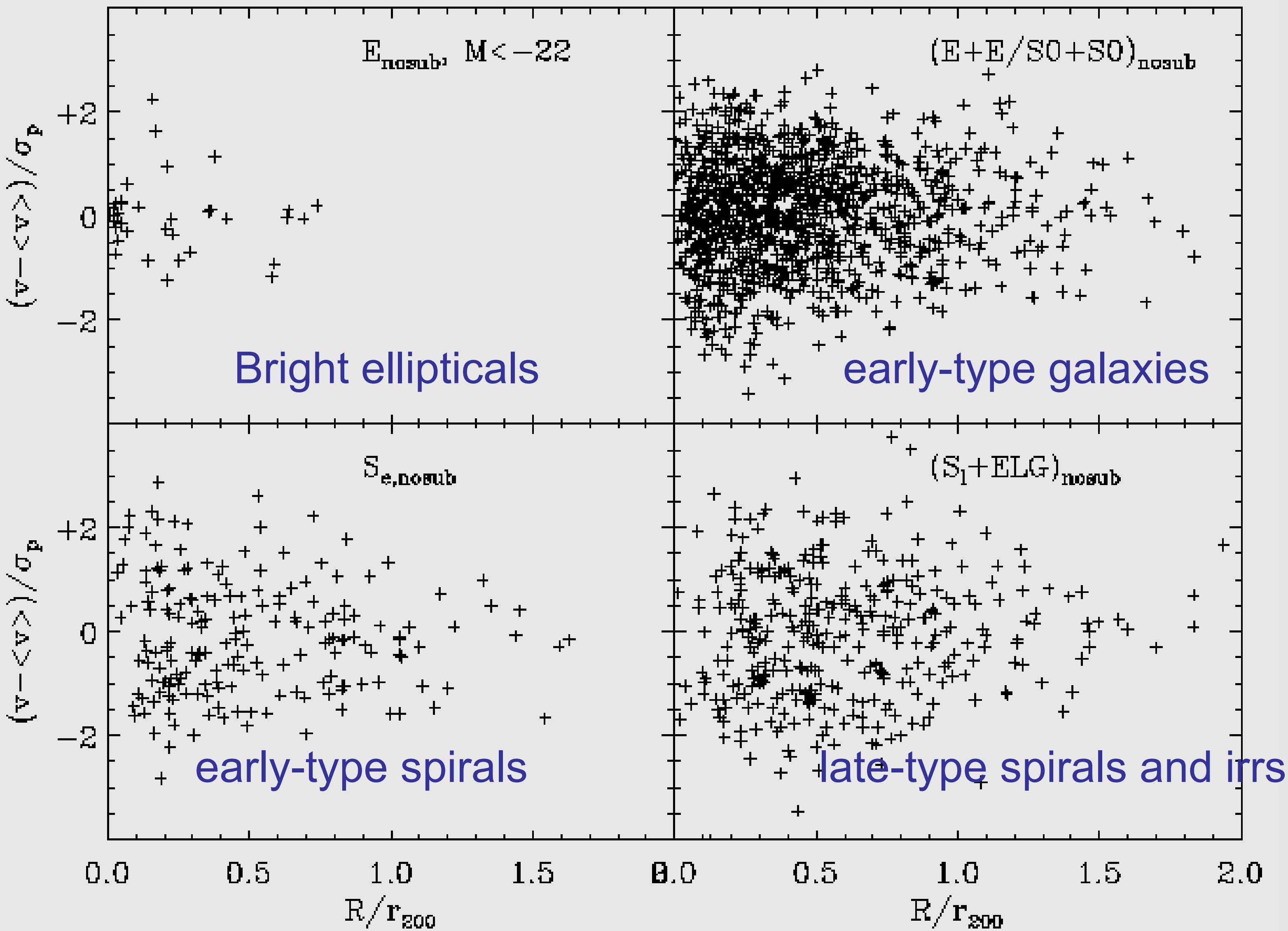
For stacking, scale clustercentric distances, R, with the cluster virial radii, r_{200}, and galaxy velocities, $v-\langle v_{cluster}\rangle$, with the cluster velocity dispersion, σ_p.

- Both r_{200} and σ_p are reliable quantities
  (B. et al. 2006, test on num. simulations)
- Non-sphericity of clusters is not important
- The ensemble cl. is representative of cl.s on average
  (van der Marel et al. 2000, test on models)

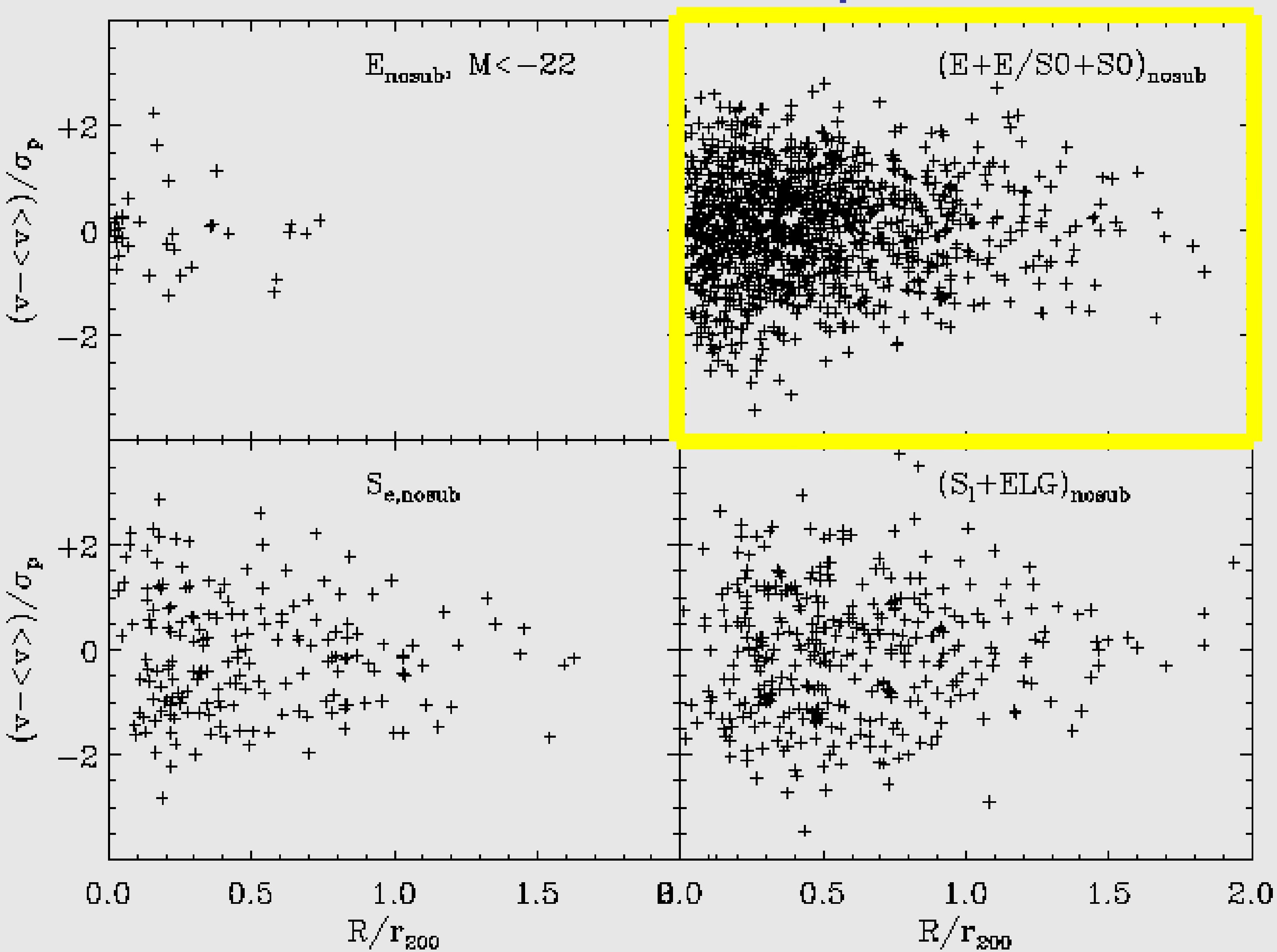
The ensemble cluster in projected phase-space



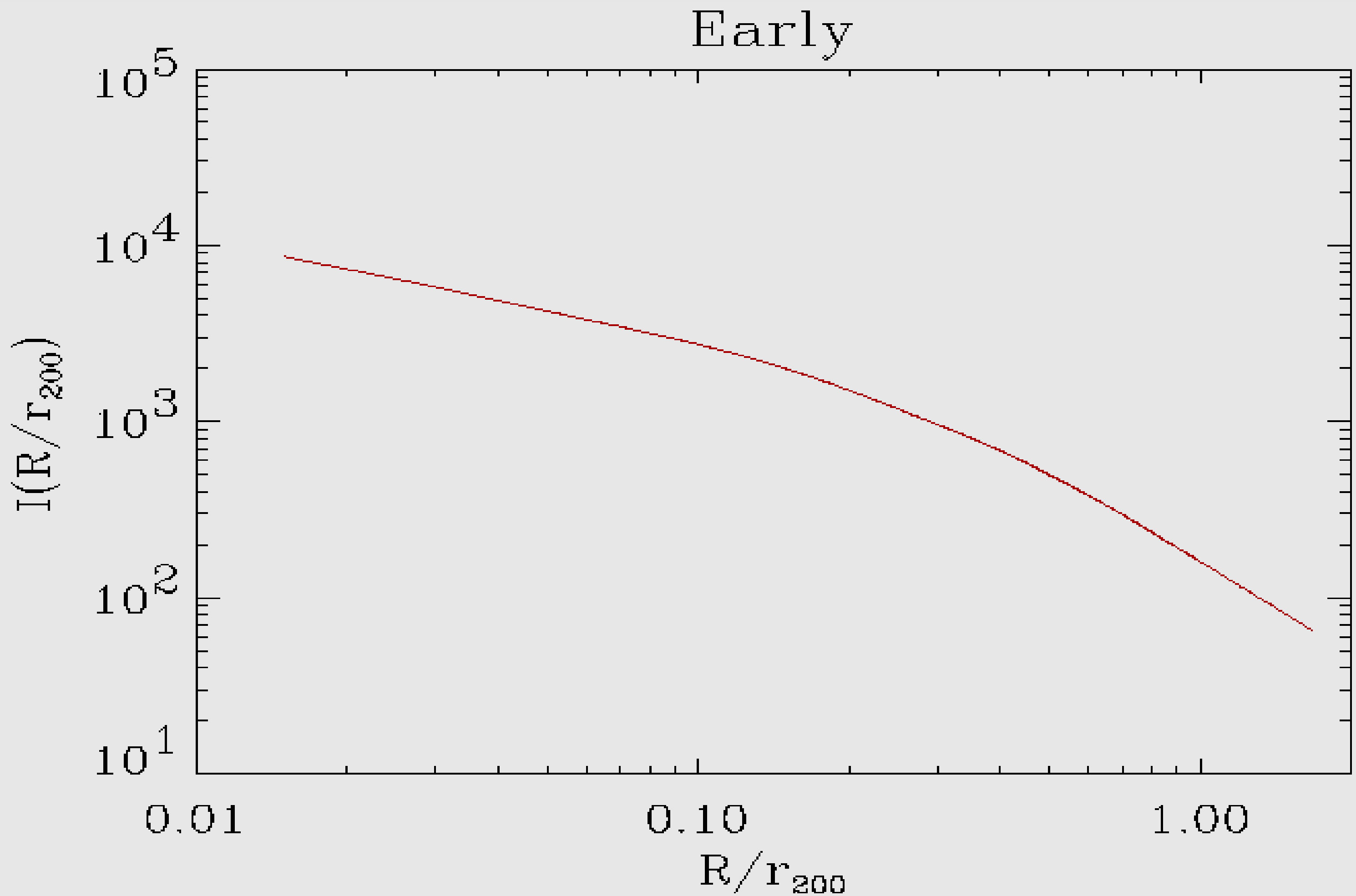
4 subsamples need to be distinguished:



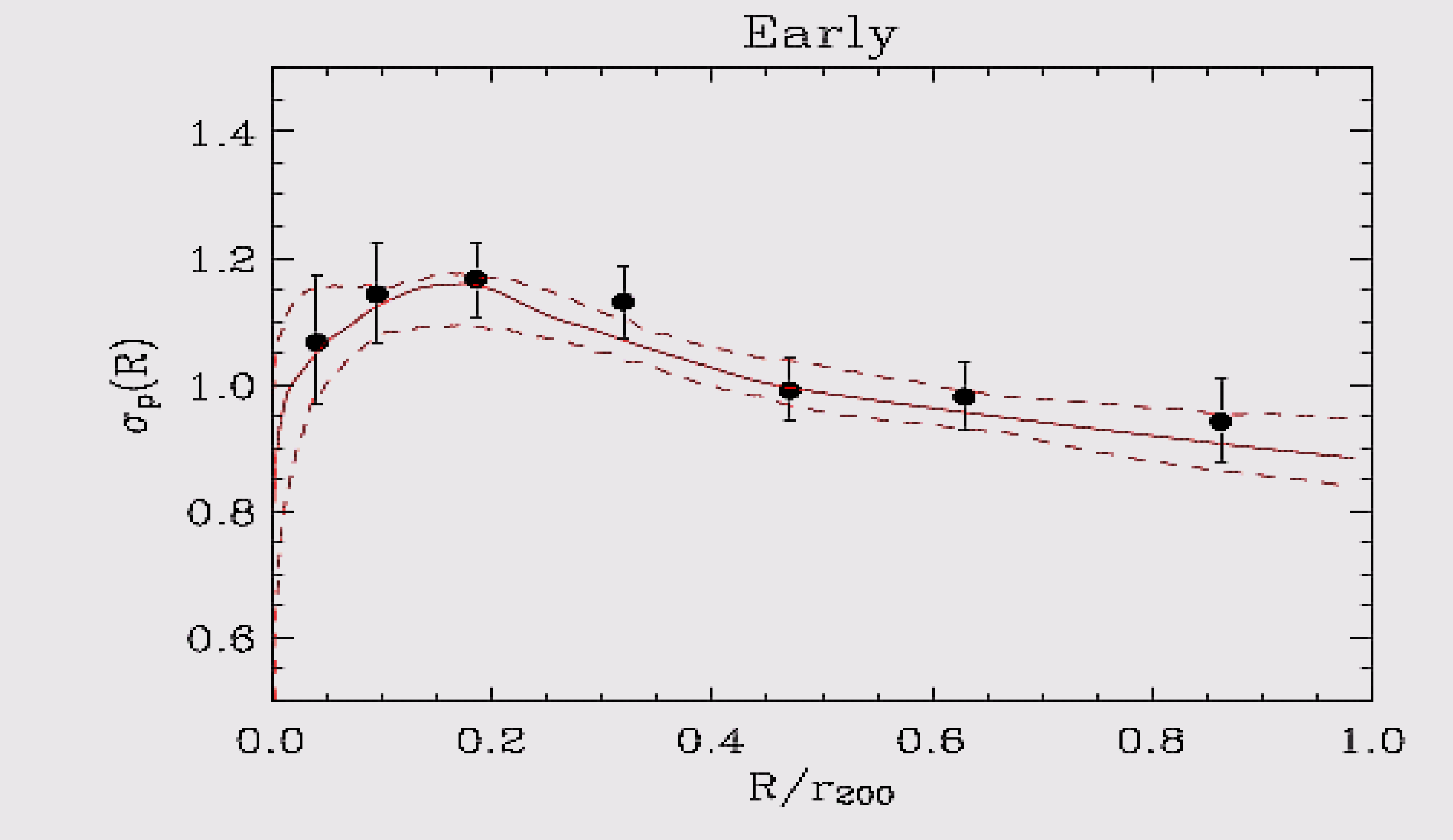
Select early-type galaxies as our fiducial tracers of the cluster potential:



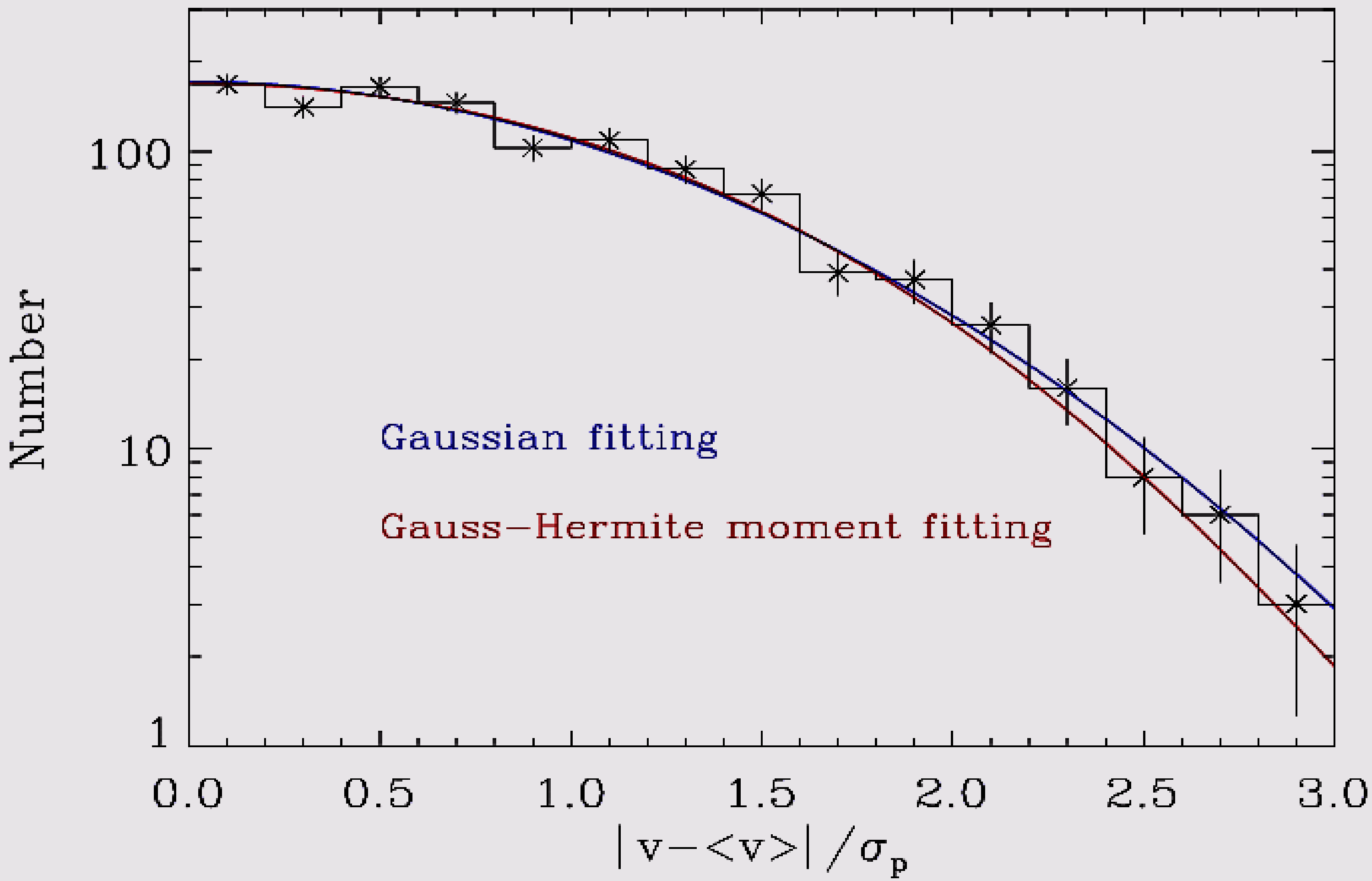
Determine **galaxy number density profile, I(R)**, and l.o.s. velocity dispersion profile $\sigma_p(R)$ for the selected population of tracers:



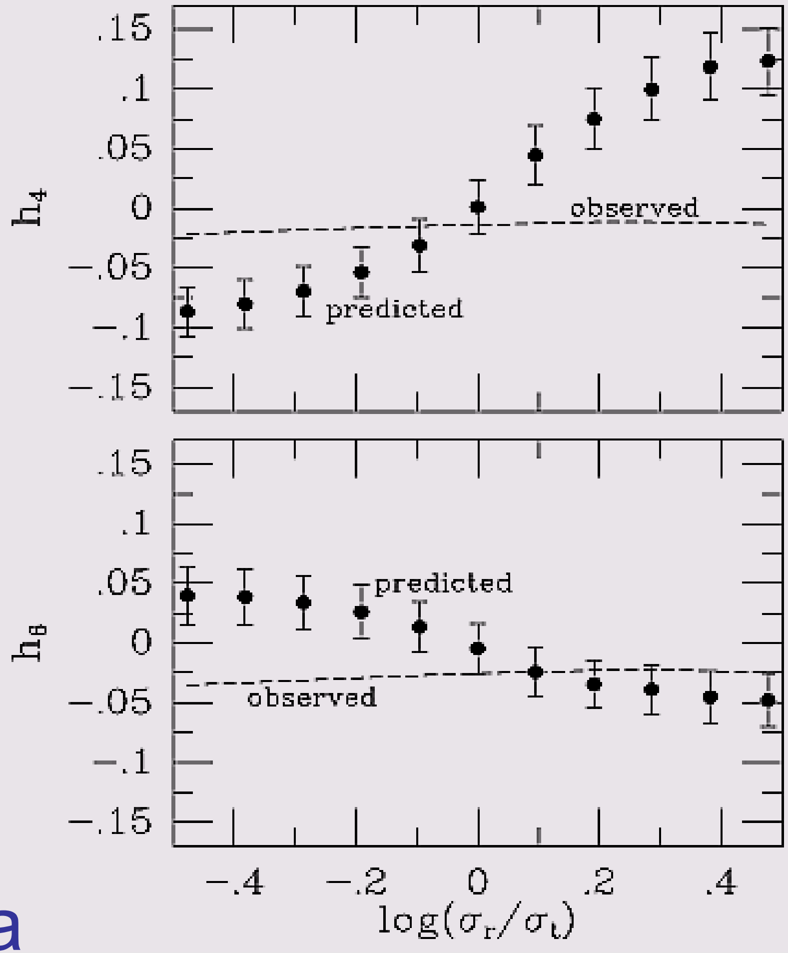
Determine galaxy number density profile, I(R), and l.o.s. velocity dispersion profile $\sigma_p(R)$ for the selected population of tracers:



The shape of the tracer velocity distribution → constrains the tracer velocity anisotropy β (e.g. Merritt 1987, van der Marel et al. 2000)



Compare moments of the Gauss-Hermite polynomial fit to the obsd velocity distribution with those predicted for distribution function models with constant velocity anisotropy (van der Marel et al. 2000):

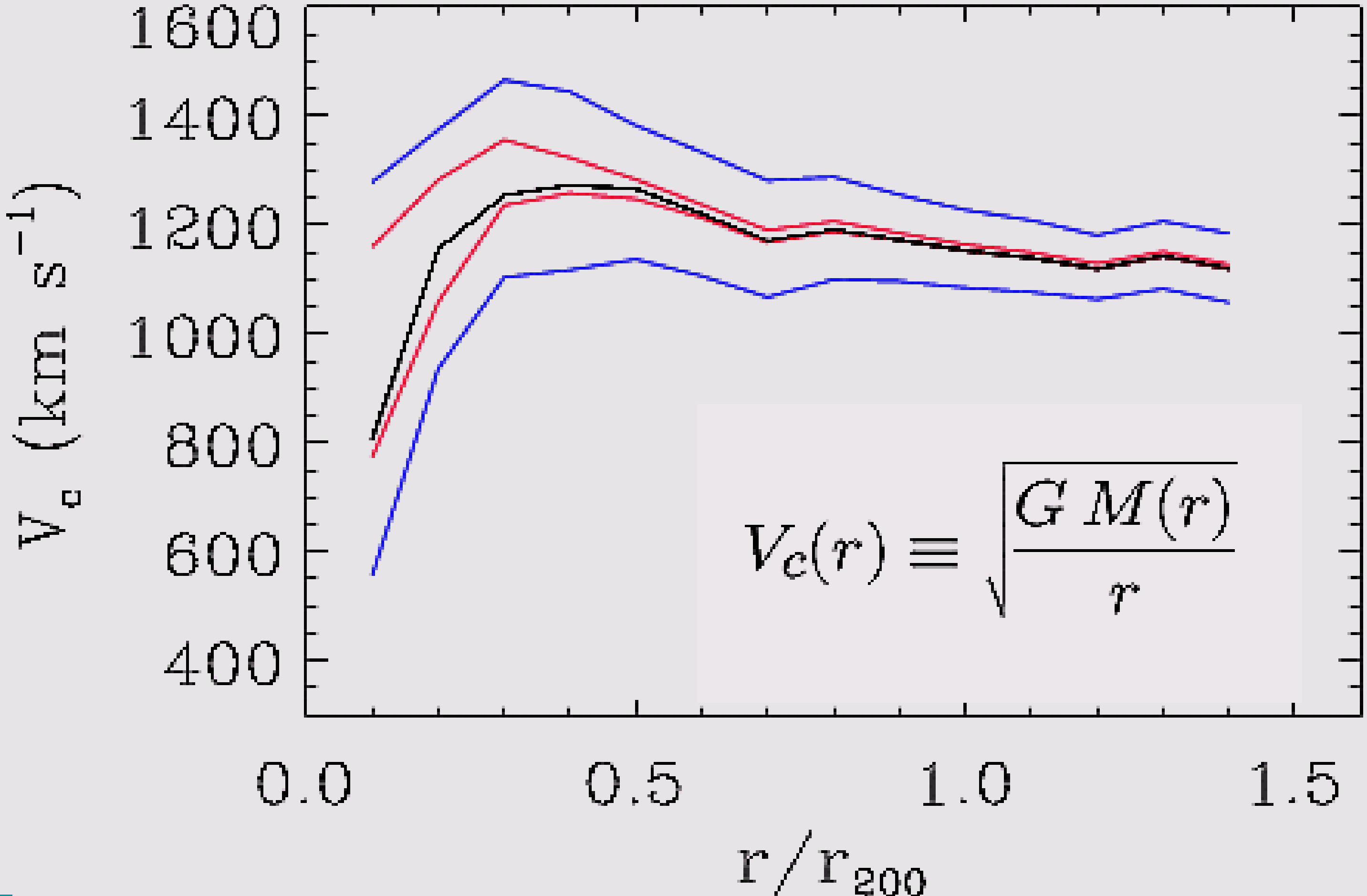


→ Early-type galaxies have a **quasi-isotropic** velocity distribution:

$$\left(<v_r^2>/<v_t^2>\right)^{1/2} \simeq 1.0^{+0.05}_{-0.2}$$

$I(R)$ & $\sigma_p^2(R)$ & $\beta \rightarrow v(r)$ & $\langle v_r^2 \rangle(r) \rightarrow M(r)$

observables & anisotropy *3d quantities* *mass profile*



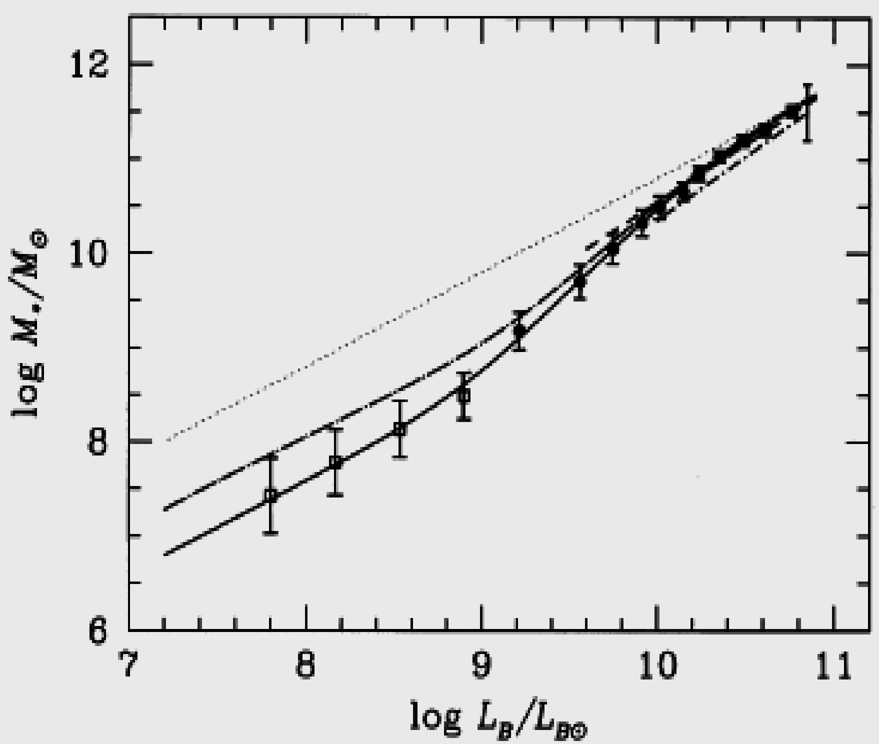
Total mass

Baryonic mass: the galaxies

- Determine the luminosity density profiles, separately for early- and late-type galaxies
- Convert luminosities into baryonic masses, using the relations of Borriello et al. (2003) and of Persic & Salucci (1999)
- Correct for unseen galaxies, beyond m_R=16.5 apparent magnitude limit of ENACS sample using the Schechter luminosity function of Lugger (1986) *[25% correction]*
- Correct for incompleteness of ENACS sample *[33% correction]*

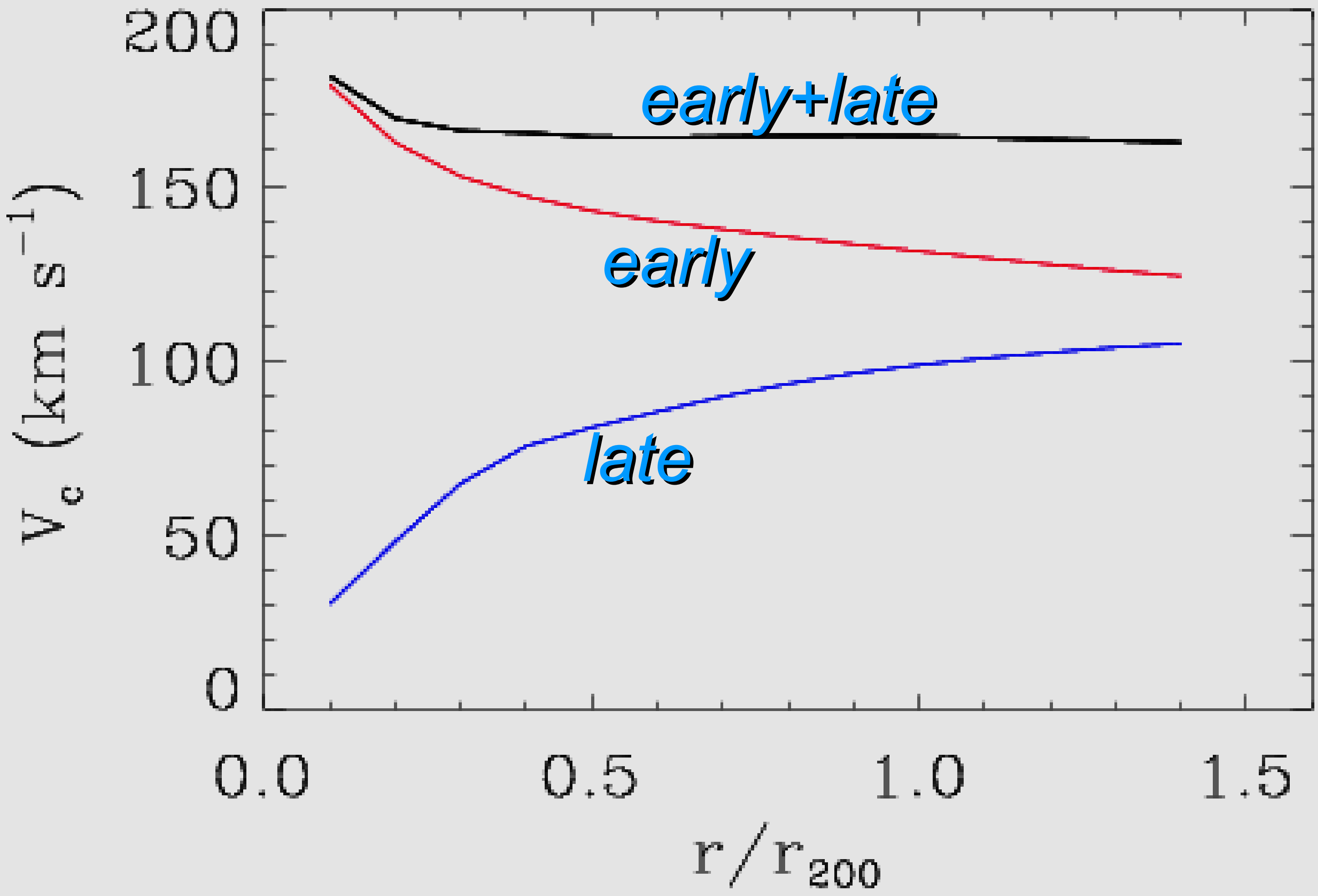
Relation between luminosity and baryonic mass for early-type galaxies derived from modelling the fundamental plane of ellipticals:

$$(M/L)_r = 5.3(L_r/L^{*})^{0.21}$$



Analogous relation for late-type galaxies derived from: models of spiral rotation curves, stellar pop.s templates, and HI measurements

Baryonic mass: the galaxies



Baryonic mass: the IC gas

- IC gas density profiles unavailable for all clusters of our sample, → use another cluster sample
- Reiprich & Böhringer's (2002) sample: based on the *Rosat All Sky Survey,* 106 clusters with measured X-ray surface brightness profiles
- Model fits to the measured s.b. profiles:

$$S_X(R) = S_0\left(1 + \frac{R^2}{r_c^2}\right)^{-3\beta+1/2} + B$$

That deproject into:

$$\rho_{\rm gas}(r) = \rho_0\left(1 + \frac{r^2}{r_c^2}\right)^{-(3/2)\beta}$$

(note: here β is not the velocity anisotropy!)

Baryonic mass: the IC gas

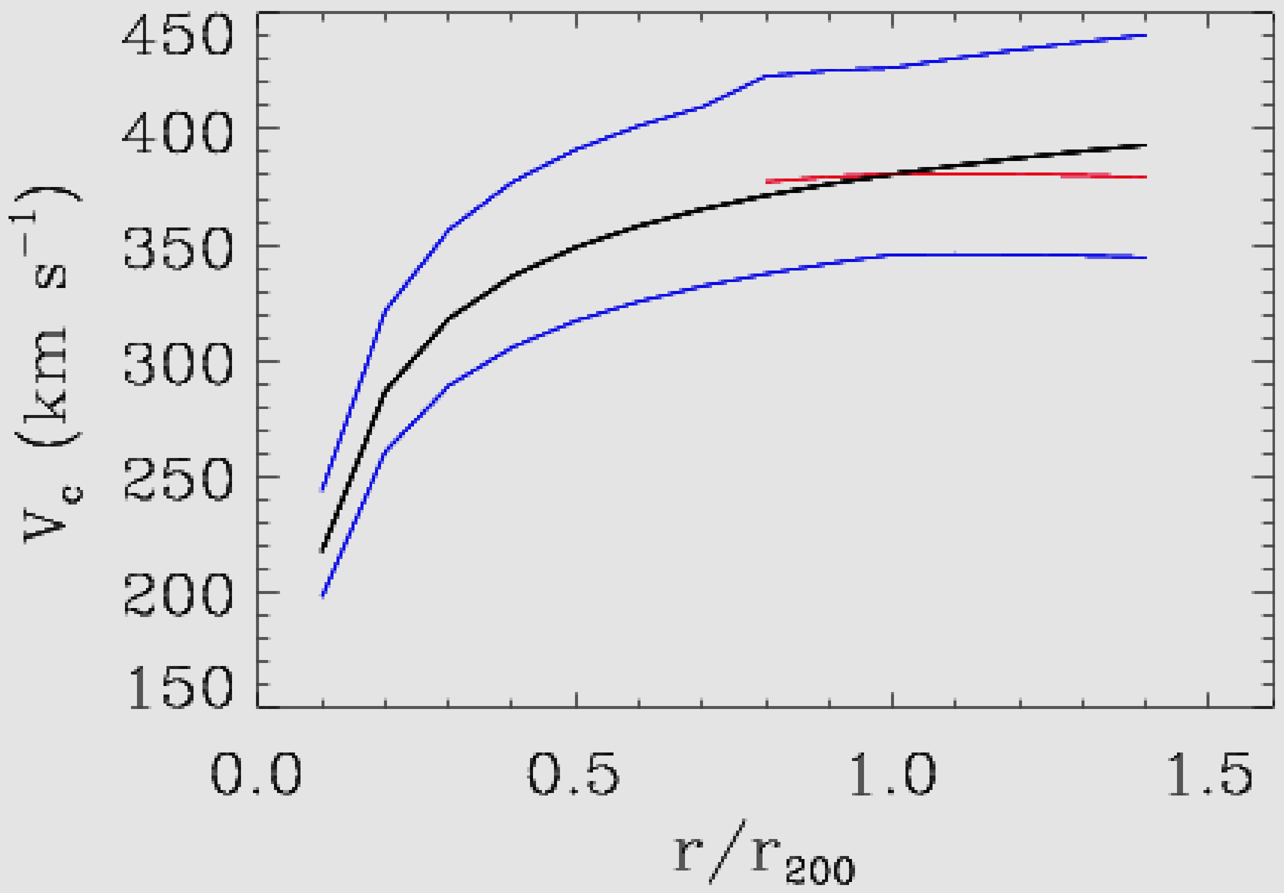
- Bootstrap extraction of a *subset* of 59 clusters with a mass distribution similar to that of our sample

- Take the *average* values of the fitting parameters for the gas density profile

- Integrate the *average* gas density profile to determine the IC gas mass profile, apart from a *constant*

- Fix the *constant* from the ratio M_{gas}/M_{total} $(r=r_{200})$ determined by Ettori (2003) from BeppoSAX observations, $= 0.11 \pm 0.03$

Baryonic mass: the IC gas



Red line: accounting for the uncertain extrapolation of the gas density profile at large radii (Neumann 2005)

Baryonic mass = galaxies + IC gas
Dark mass = Total mass – baryonic mass

...but dark matter can be diffuse or clumped,
i.e. linked to individual galaxies (*subhaloes*)

→ need to estimate *DM in subhaloes*

Definition: DM (sub)halo of the central galaxy
identified with cluster diffuse DM
(e.g. Lin & Mohr 2004, Murante et al. 2004, Zaritsky et al. 2006)

DM in subhaloes

Previously determined luminosity density profiles of early- and late-type galaxies +

+ scaling relations between a galaxy luminosity and its halo mass (Shankar et al. 2006)

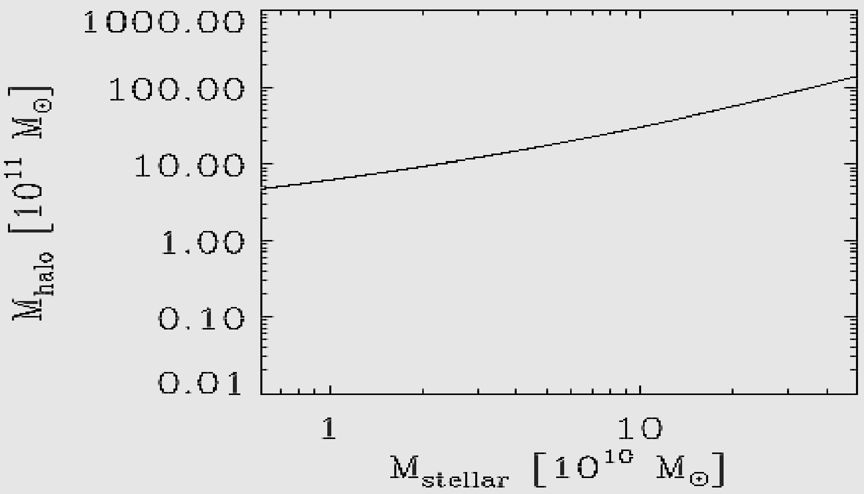
Taking into account that:

Galaxy haloes cannot survive very near the cluster center (tidal stripping and overlap arguments)

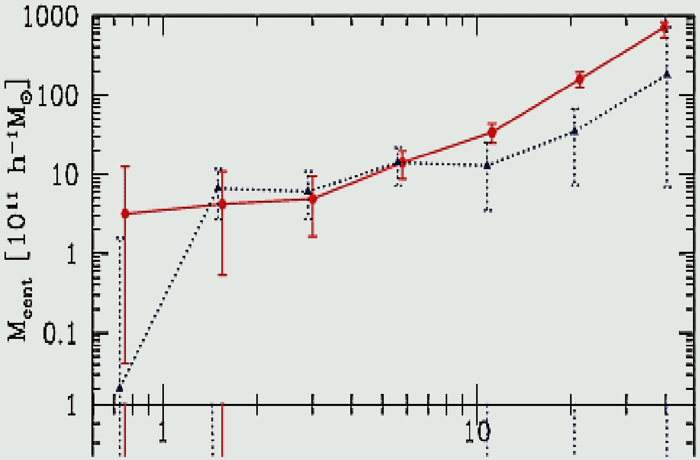
[also: grav. lensing, Natarajan et al. 2002, Gavazzi et al. 2004]

DM in subhaloes

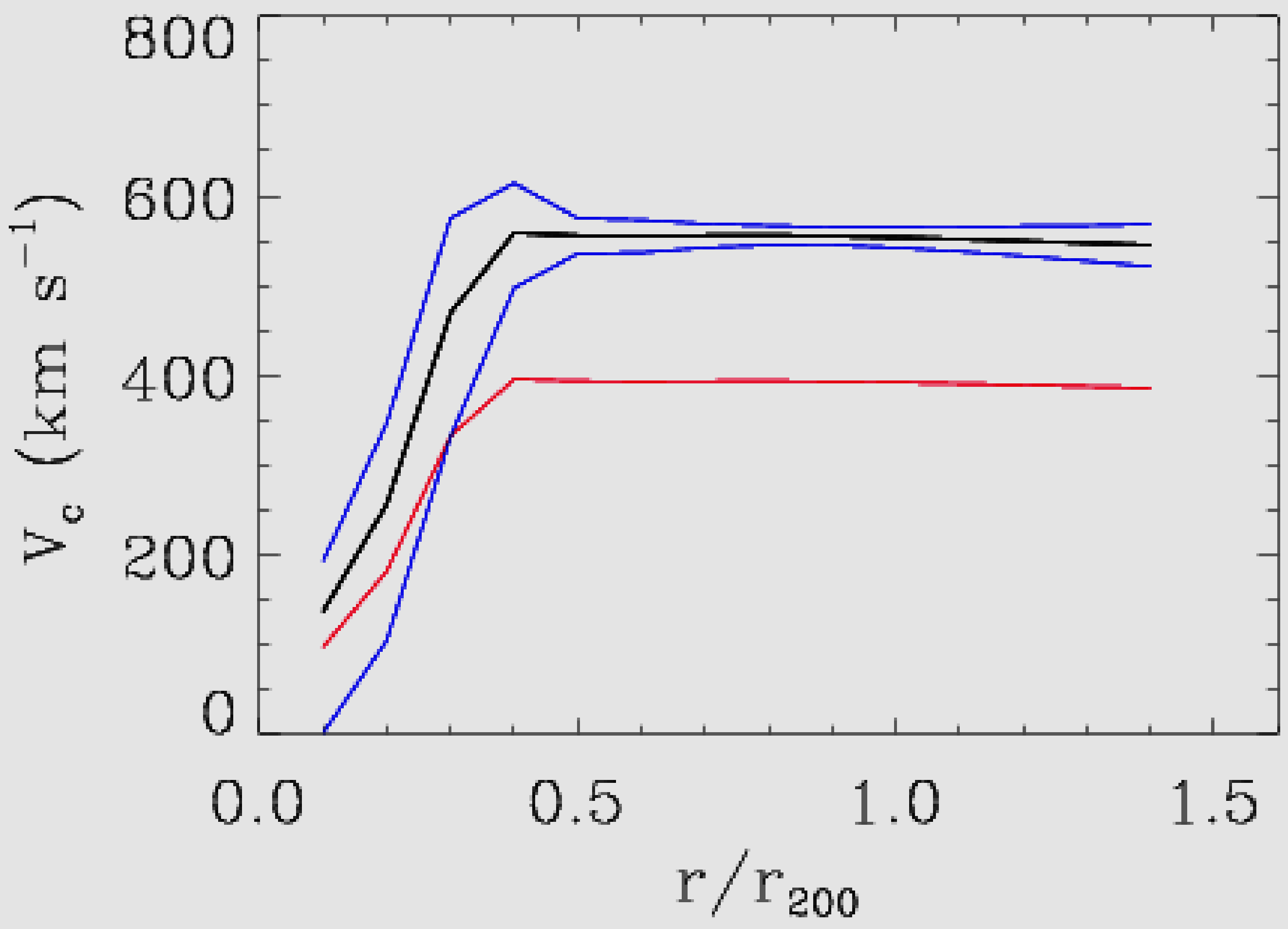
Shankar et al.’s relation determined from *theoretical* mass function of subhaloes and *observed* galaxy stellar mass function …



… compares very well with observationally determined mass function of subhaloes (Mandelbaum et al. 2006,
galaxy-galaxy grav. lensing
signal, SDSS data)



DM in subhaloes

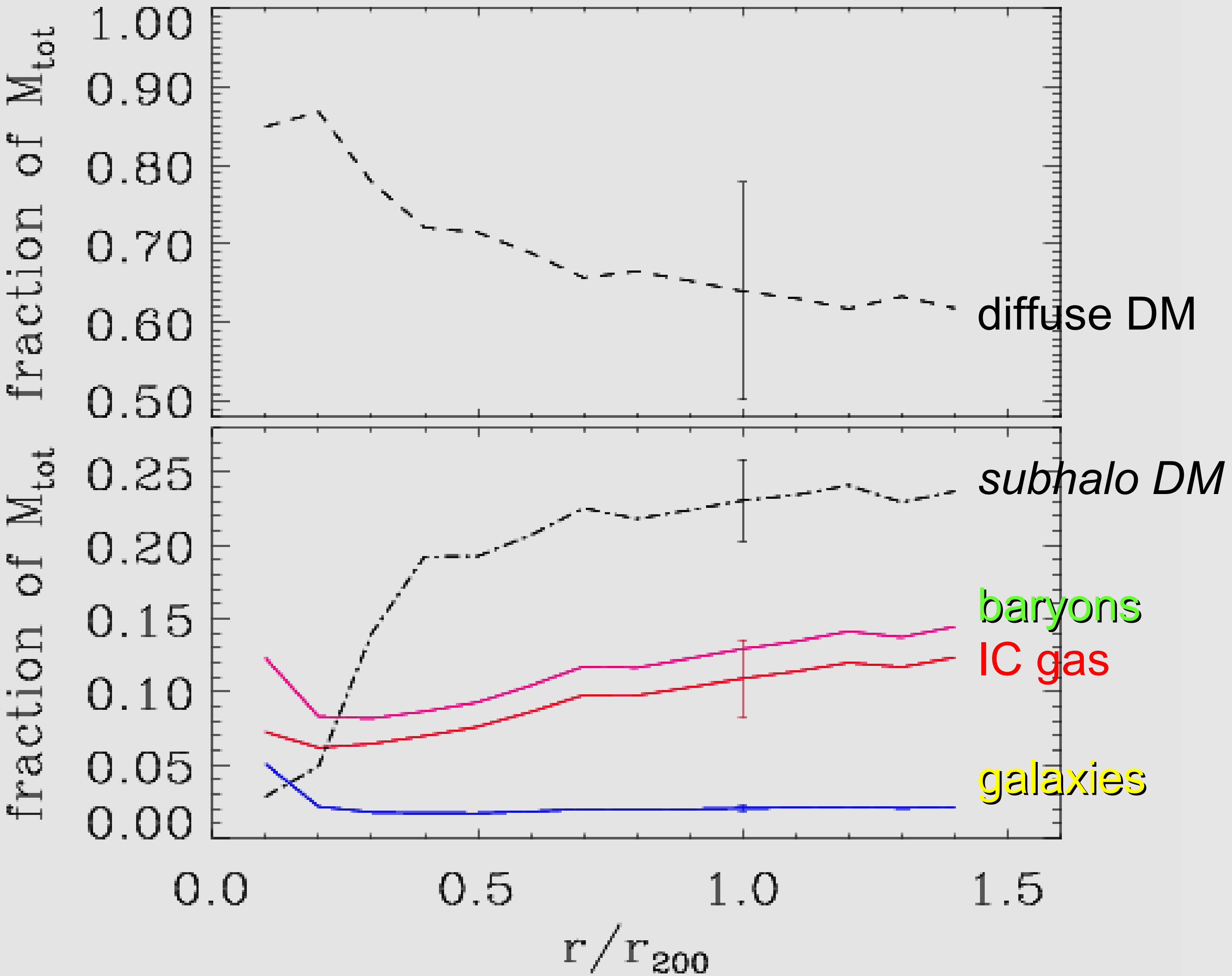


Red line: ‘strong stripping’ scenario, 50% total mass in subhaloes lost at any radii (num. sims., Gao et al. 2004)

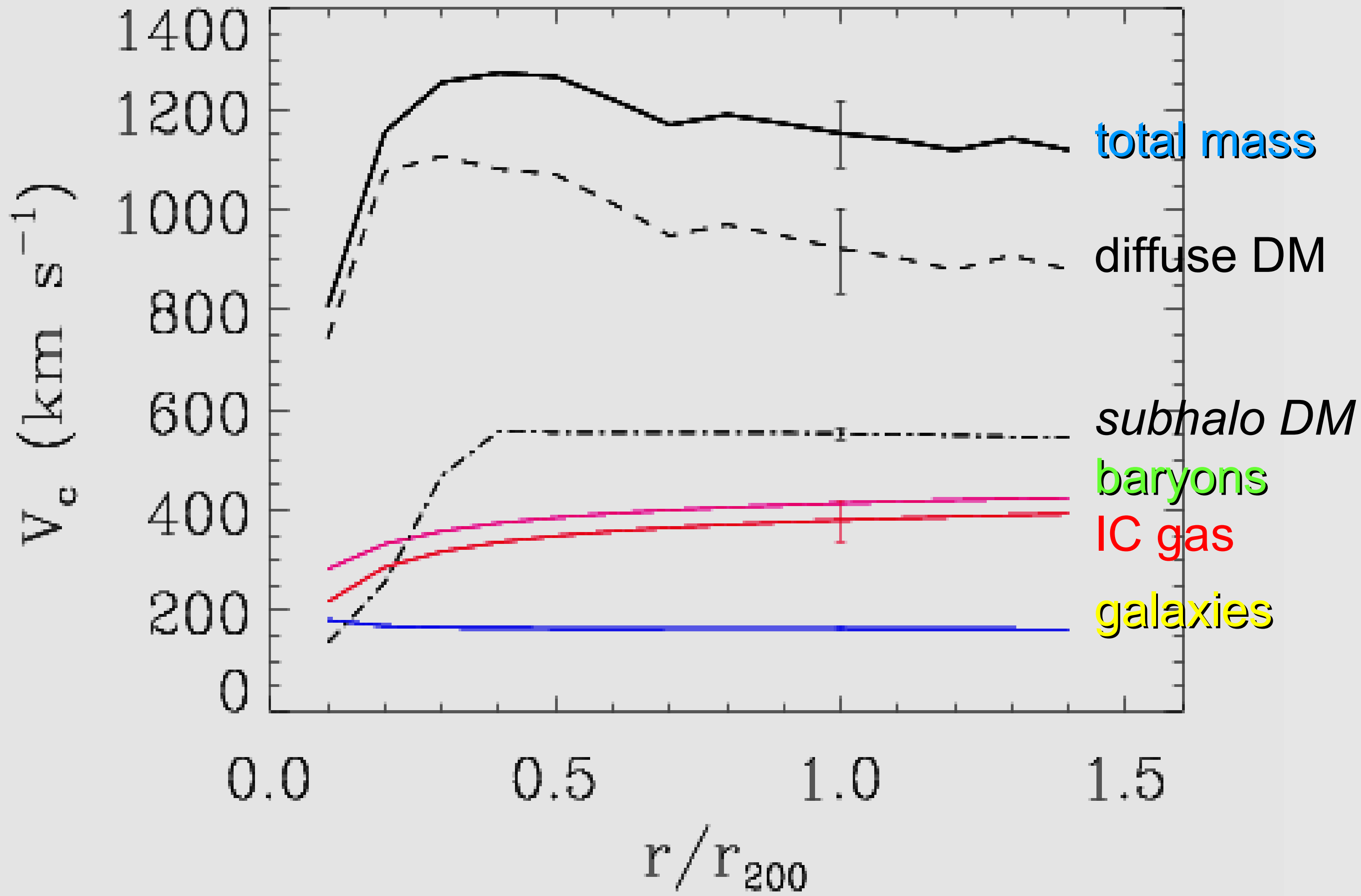
Galaxies +
IC gas =
Baryonic mass

Total mass –
baryonic mass –
subhalo DM =
diffuse DM

Mass fractions of the different cluster components as a function of radius



The circular velocity profiles of the different cluster components



Fitting models to the $V_c(r)$ profiles

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

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

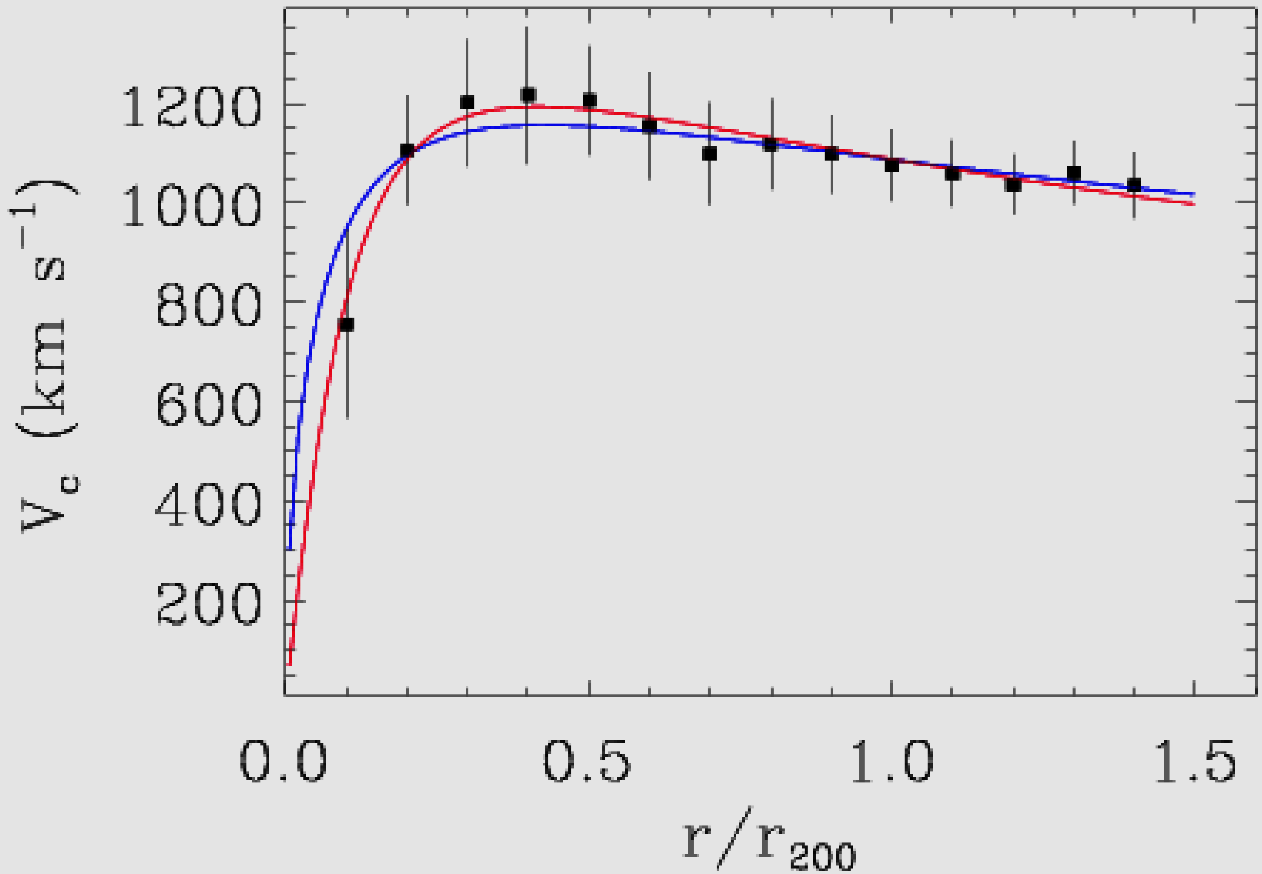
…vs. the cored model of Burkert (1995), motivated by the problems of NFW on galactic scales (e.g., de Blok et al. 2003, Gentile et al. 2004):

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

Fitting models to the Vc(r) profiles

Dark matter

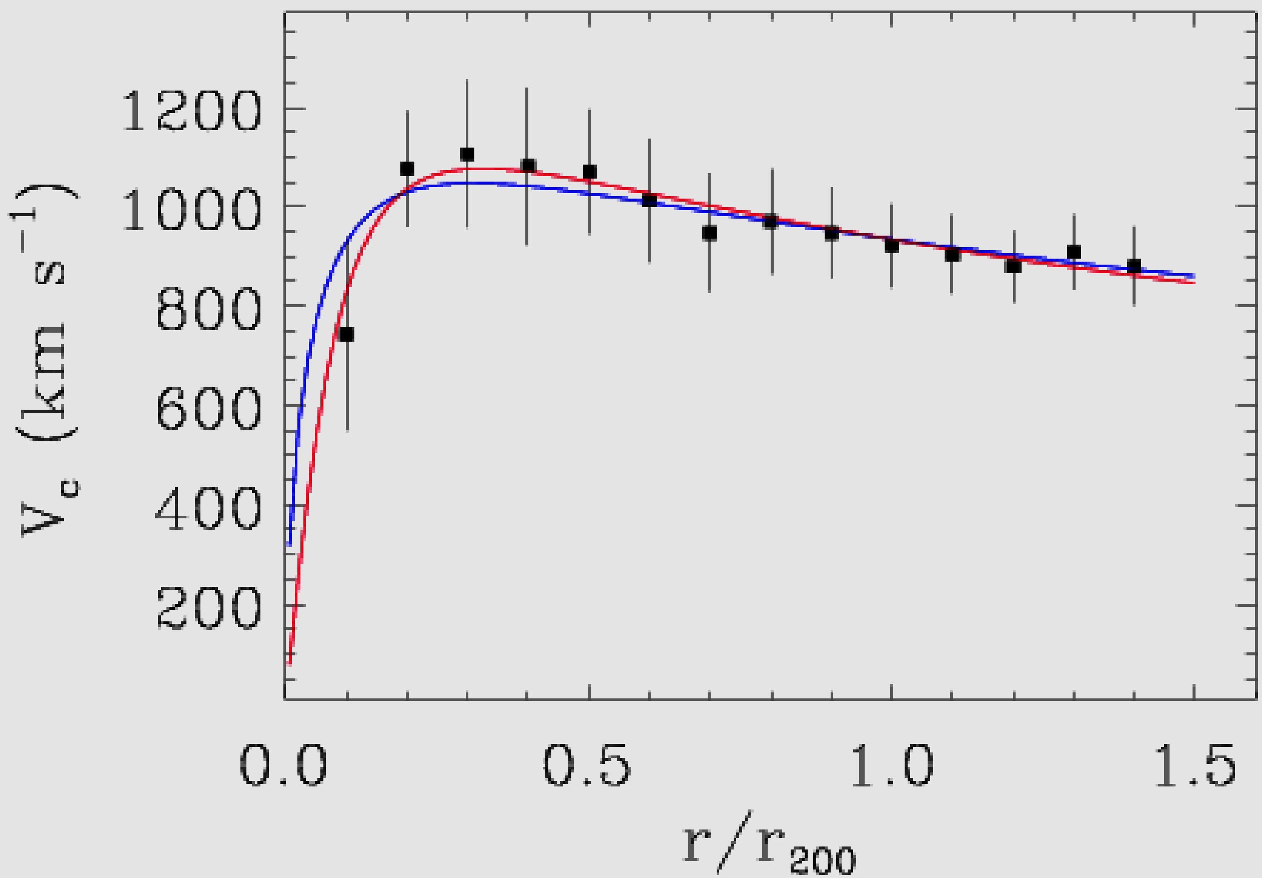
NFW vs. Burkert



Fitting models to the Vc(r) profiles

Diffuse dark matter

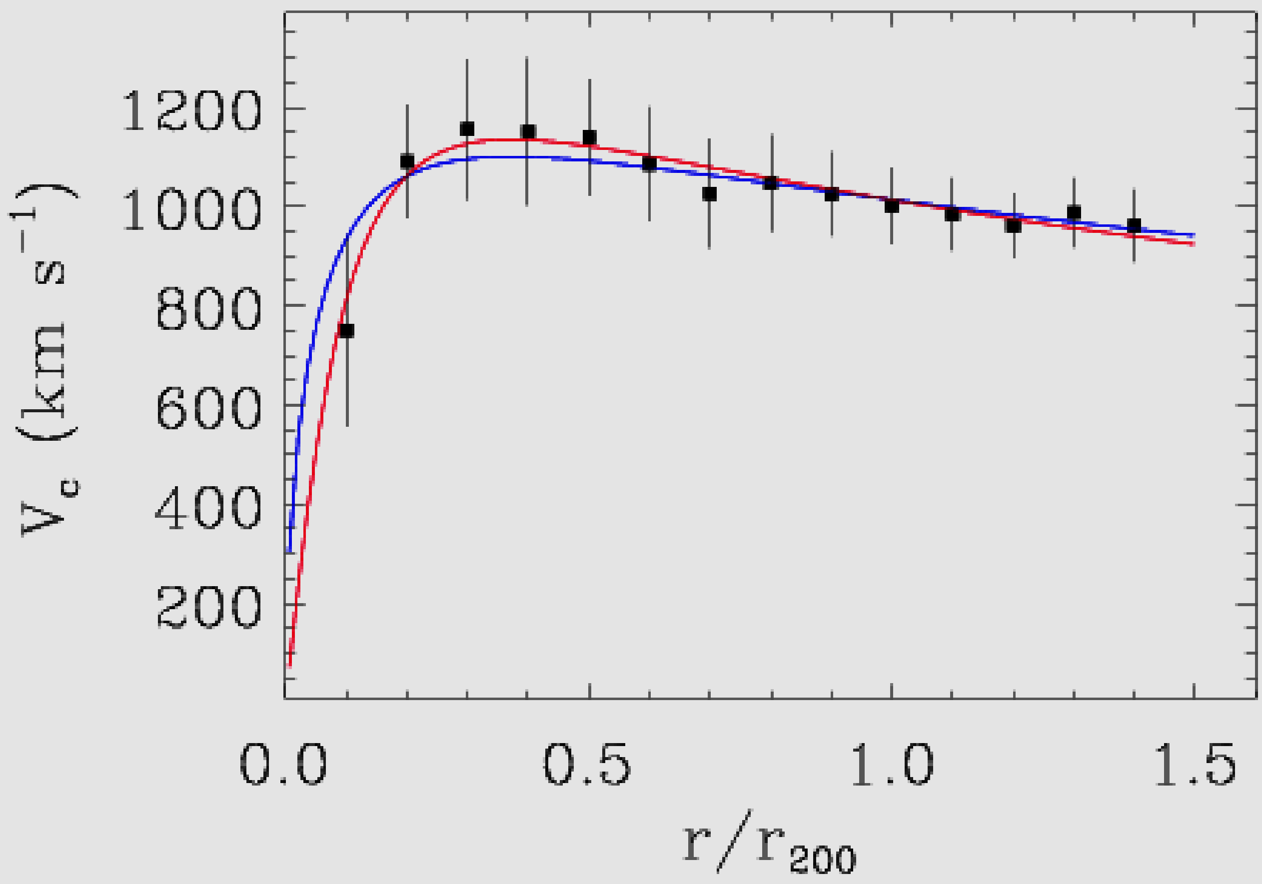
NFW vs. Burkert



Fitting models to the Vc(r) profiles

Diffuse DM, strong stripping scenario

NFW vs. Burkert



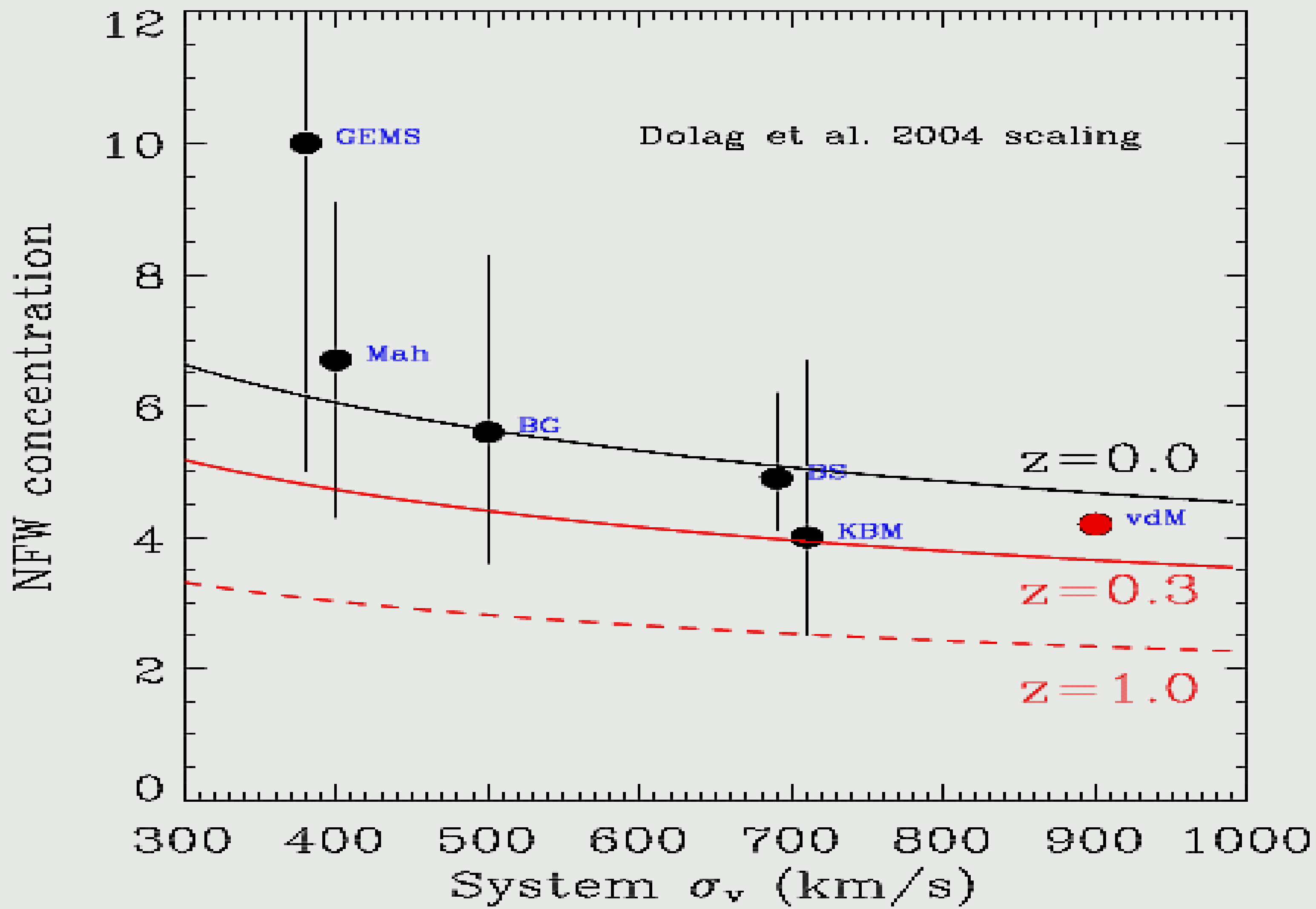
Summary of results (a)

- Diffuse DM dominates total mass at all radii
- Subhaloes account for ≤23% mass within r_{200}
- Baryons account for ≈14% mass within r_{200}
- Baryon fraction changes with r, by ±30%
- IC gas dominate baryons, except at r~0
- Baryons in Es more concentrated than DM
- Baryons in Ss less concentrated than DM
- IC gas mass fraction increases as $r^{0.4}$

Summary of results (b)

- DM, whether in its diffuse form,
  or also accounting for subhalo DM,
  almost equally well fit by cuspy and
  core density models
- The best fitting NFW parameter
  $c = r_{200}/r_s = 5\pm1\ (7\pm2)$,
  is as predicted by cosmo. num. sims.

Observed vs.predicted concentration parameter of NFW profile for systems of different mass



Summary of results (c)

- The best fitting Burkert core-radius is small,
  $0.1\ r_{200} \sim$ size of central cD
  $\rightarrow$ DM scattering cross section $<2\ cm^2\ g^{-1}$
  (By comparison with simulation res. of Meneghetti et al. 2001)

  Much smaller than the 5 $cm^2 g^{-1}$ 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)

Results:

The orbits of galaxies in clusters

The orbits of cluster galaxies

Total mass profile was determined using the **early-type** galaxy population, shown to move on **nearly-isotropic** orbits

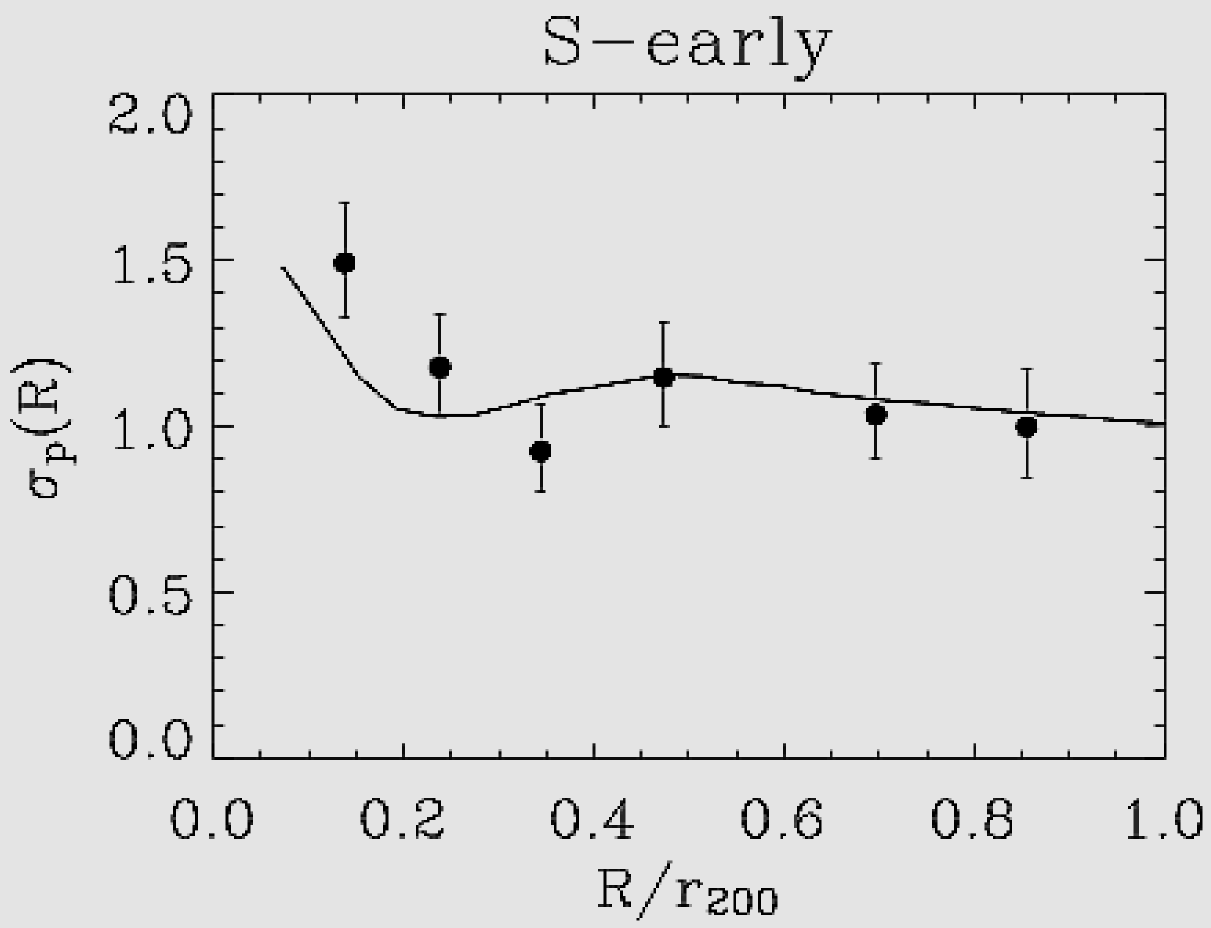
What about the late-type galaxy population?

Invert the Jeans equation:

$$M(r) \;\&\; I(R) \;\&\; \sigma_p(R) \rightarrow \beta(r)$$

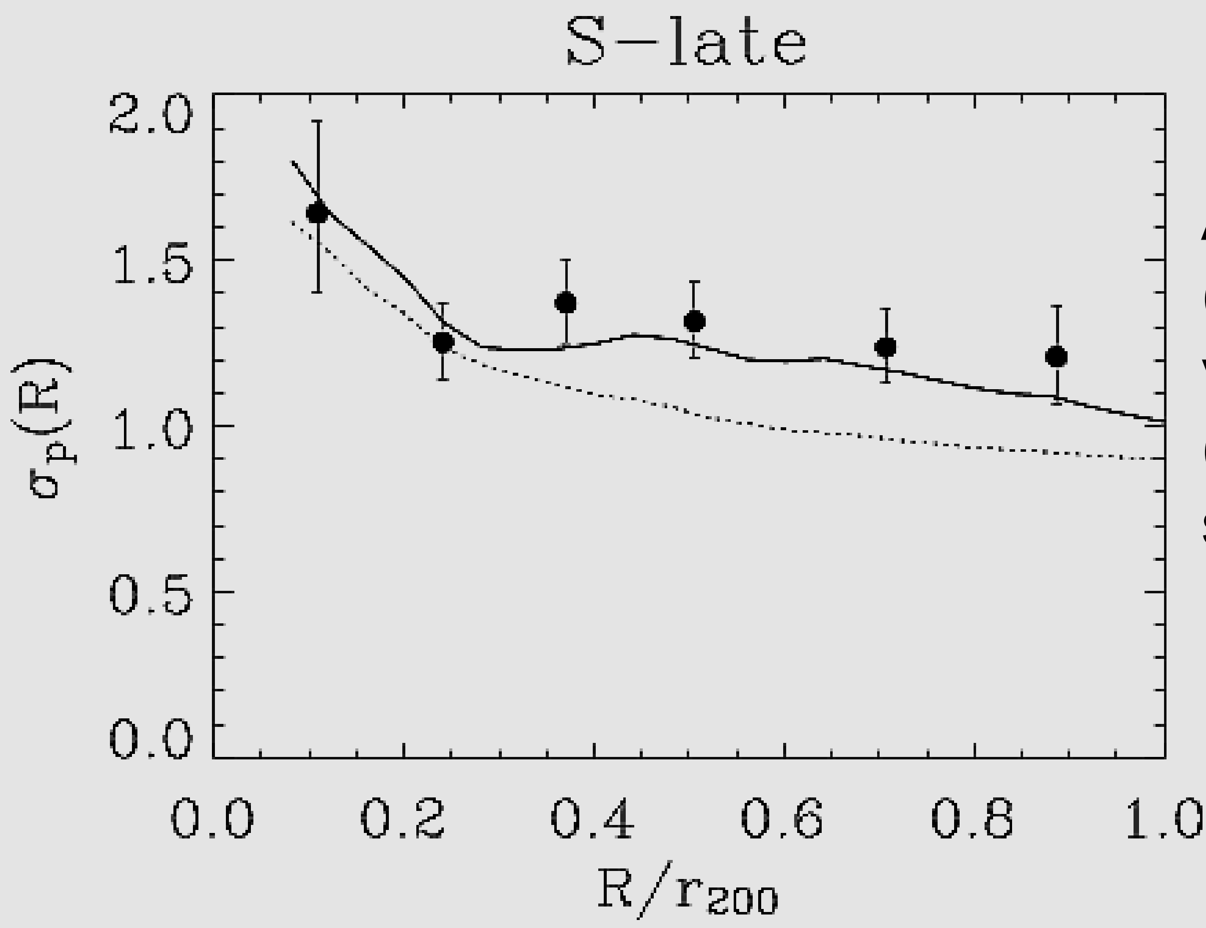
(Binney & Mamon 1982, Solanes & Salvador-Solé 1990, …)

The early Spirals are in dynamical equilibrium with the cluster potential and move on nearly isotropic orbits, just as the early-type galaxies



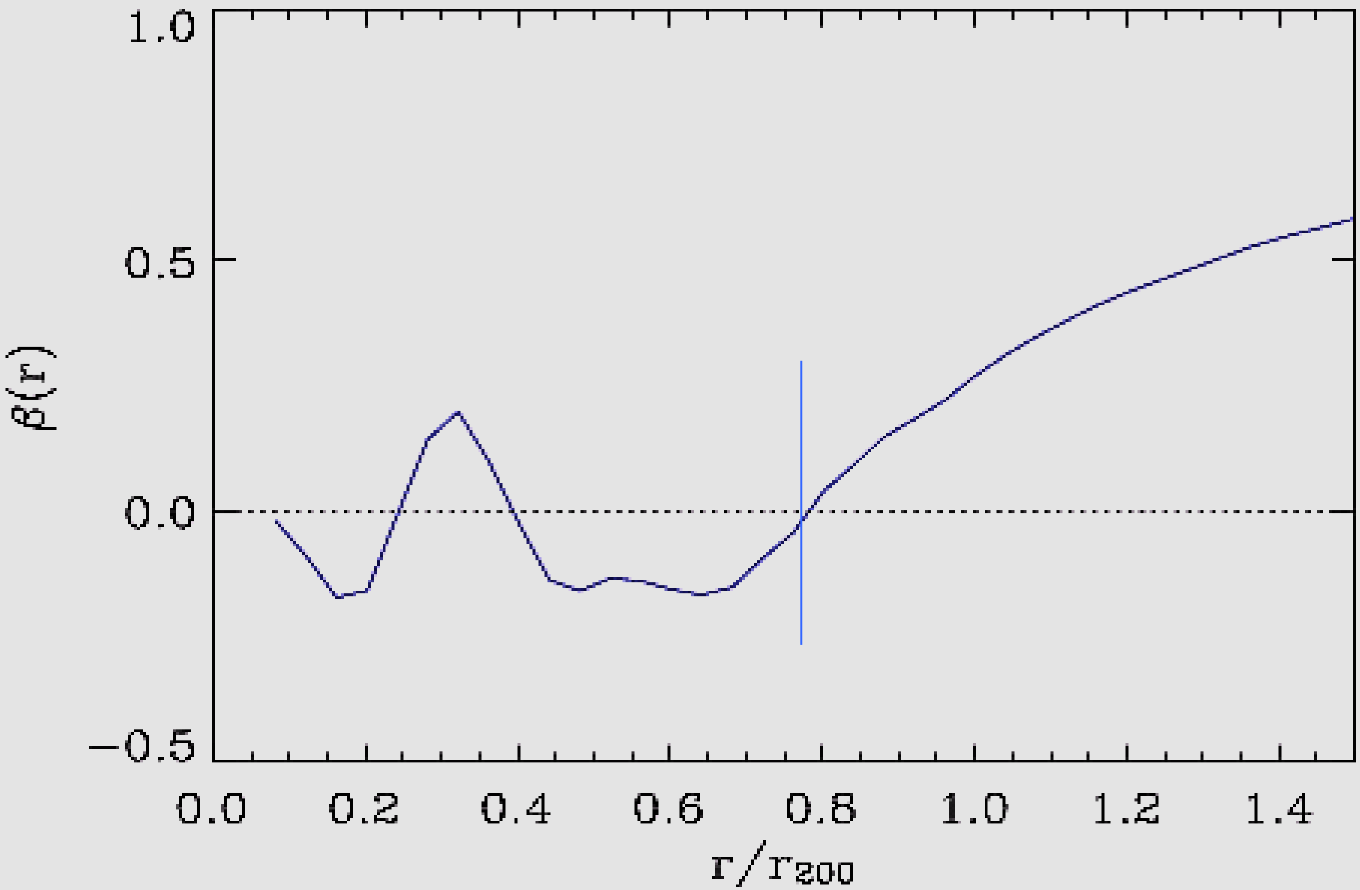
Isotropic solution of the inverse Jeans eq.

The *late* Spirals are in dynamical equilibrium with the cluster potential *but* move on increasingly *radial* orbits with increasing radius



Anisotropic (solid line) vs. isotropic (dashed line) solution

The *late* Spirals are in dynamical equilibrium with the cluster potential *but* move on increasingly *radial* orbits with increasing radius



The orbits of cluster galaxies:

- Ellipticals, S0s, early-Spirals (Sa-Sb) move on isotropic orbits

- Late-Spirals (Sbc...) and Irr move on mildly radial orbits

Suggesting the former are a dynamically old cluster population, the latter retain memory of their recent infall from the field

Studying orbits of cluster galaxies as a $f(M_{cl}, z)$ provides infos on cluster hierarchical growth & galaxy transformation processes

The orbits of cluster galaxies:

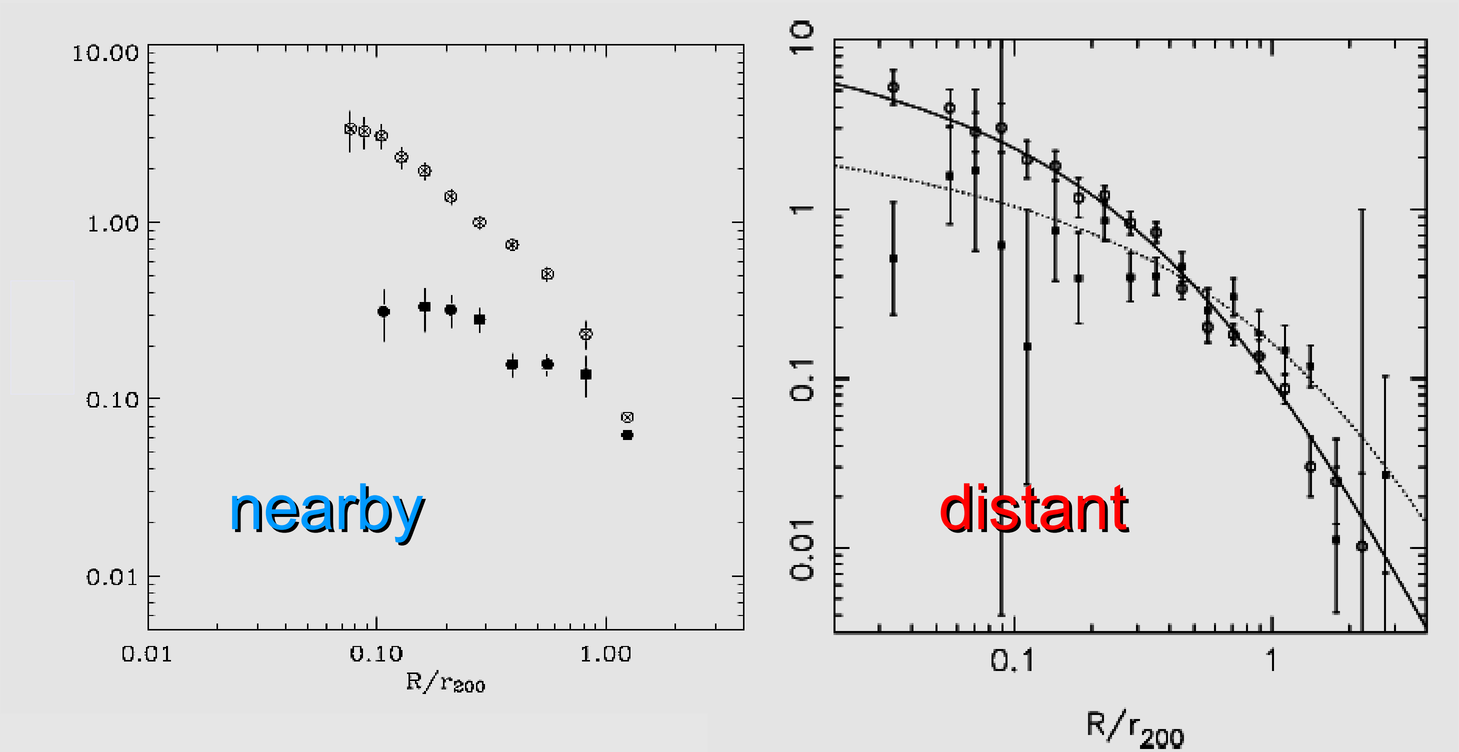
At higher z (≈0.3): CNOC cluster sample

Early-type galaxies have ~isotropic orbits
Late-type galaxies orbits not analysed
(van der Marel et al. 2000)

However:

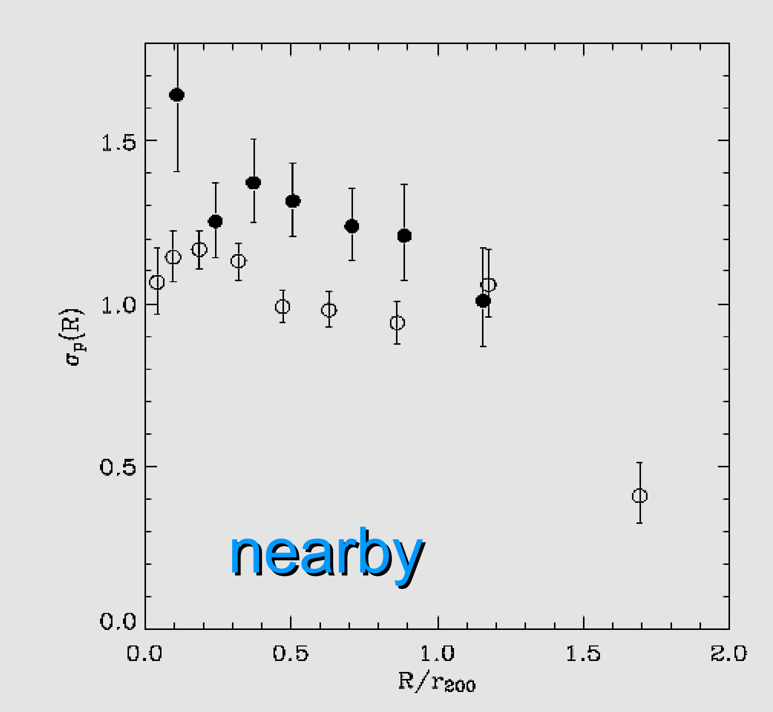
- Early-type galaxies have similar I(R) and σ_p(R) at z≈0 and at z≈0.3
- Also late-type galaxies have similar I(R) and σ_p(R) at z≈0 and z≈0.3

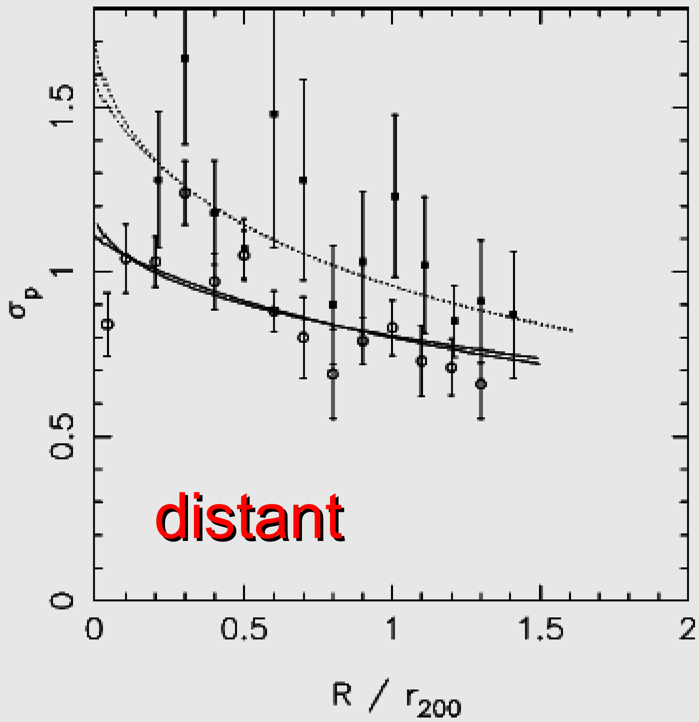
The projected phase-space distributions of nearby and distant cluster galaxies of early- and late-type



I(R) profiles for early- (empty symbols) and late- (filled symbols) cluster galaxies

The projected phase-space distributions of nearby and distant cluster galaxies of early- and late-type





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

The orbits of cluster galaxies:

At higher z (≈0.3): CNOC cluster sample

- Early-type galaxies have ~isotropic orbits, Late-type gal.s not analysed (van der Marel et al. 2000)
- Early-type galaxies have similar I(R) and $\sigma_p(R)$ at z≈0 and at z≈0.3
- Also late-type galaxies have similar I(R) and $\sigma_p(R)$ at z≈0 and z≈0.3

→ Late-type galaxies at z≈0.3 on mildly radial orbits like their nearby counterparts

But the fraction of late-type galaxies ↓ as z→0:
as the orbit of a galaxy isotropizes, its type changes!

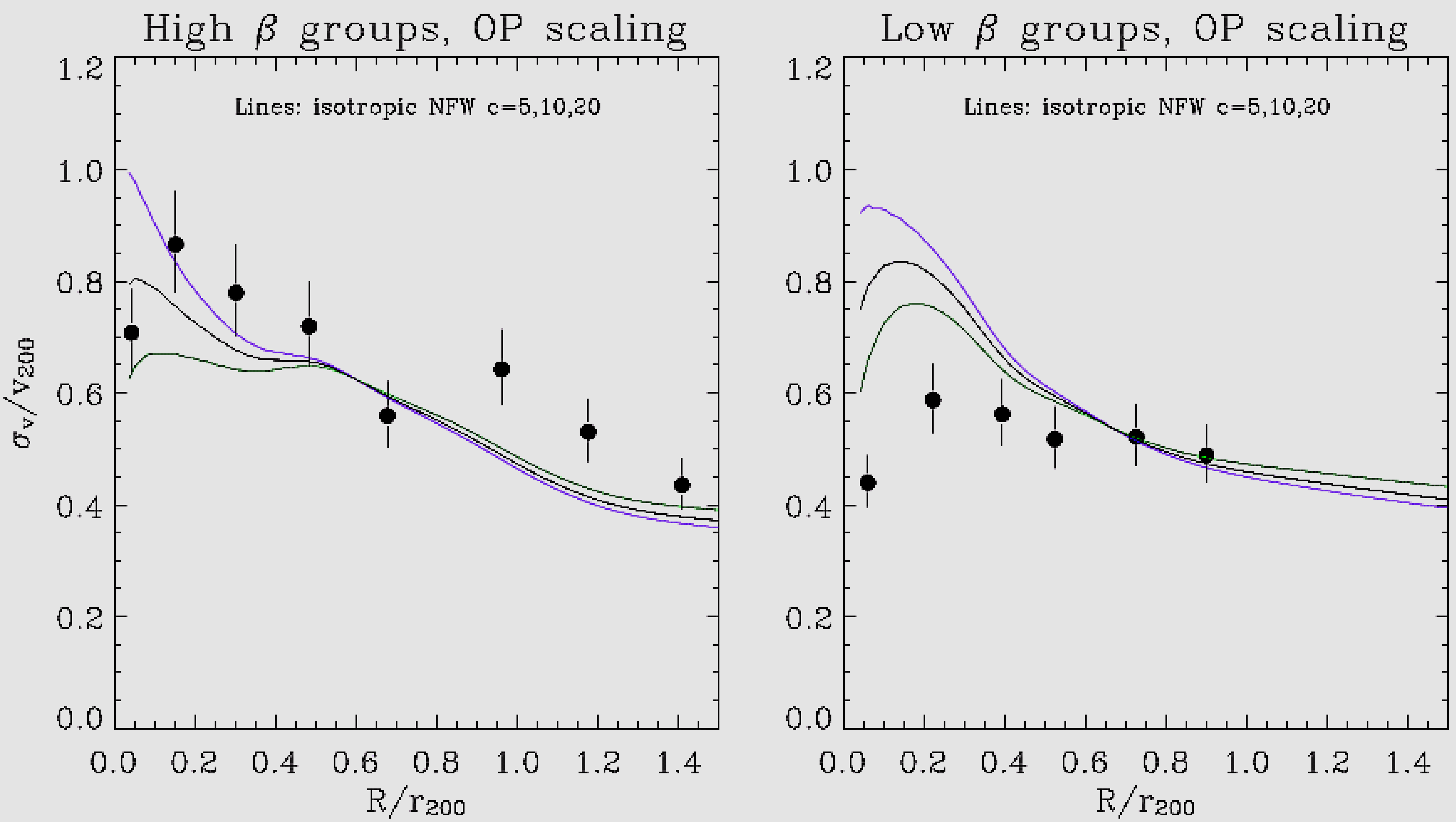
Work in progress and future work

- Investigate physical mechanisms leading to the orbital evolution of galaxies using num. sims. (with Borgani, Murante & co.)

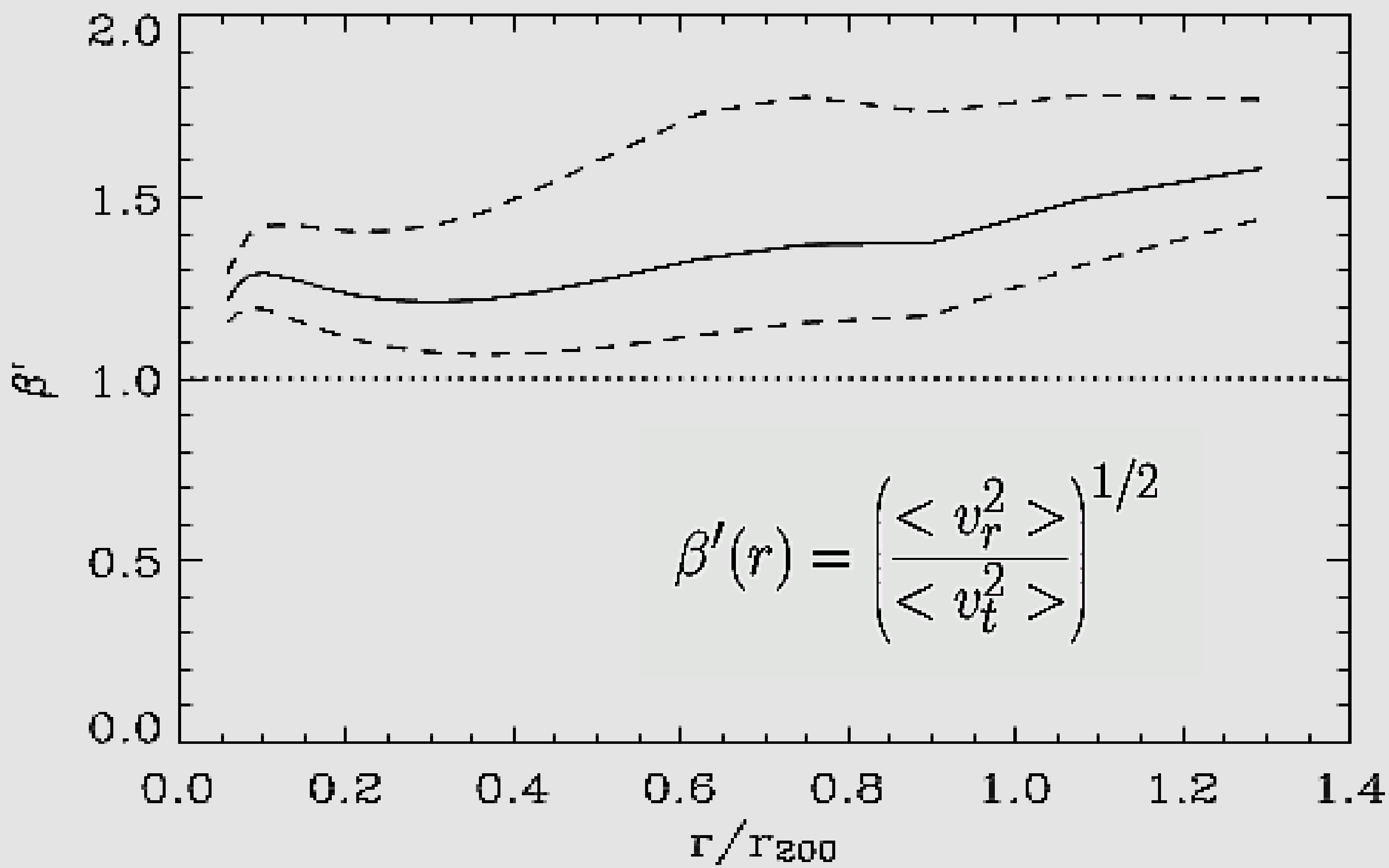
- CDM-predicted profiles work on cluster scales, but not on galactic scales… analyse intermediate scale, galaxy groups (with Mamon & Ponman)

- Improve the current constraints on M(r) – and orbits using larger data-bases:
  SDSS (with Böhringer & Popesso)
  WINGS (with Fasano & co.)

- Extend the analysis to higher-z
  (e.g. EDisCS, White et al. 2005, IMACS, Dressler et al.)



Two classes of galaxy groups (cuspy and cored)?



SDSS data for cluster galaxies confirm late-type (blue) galaxies have midly radial orbits