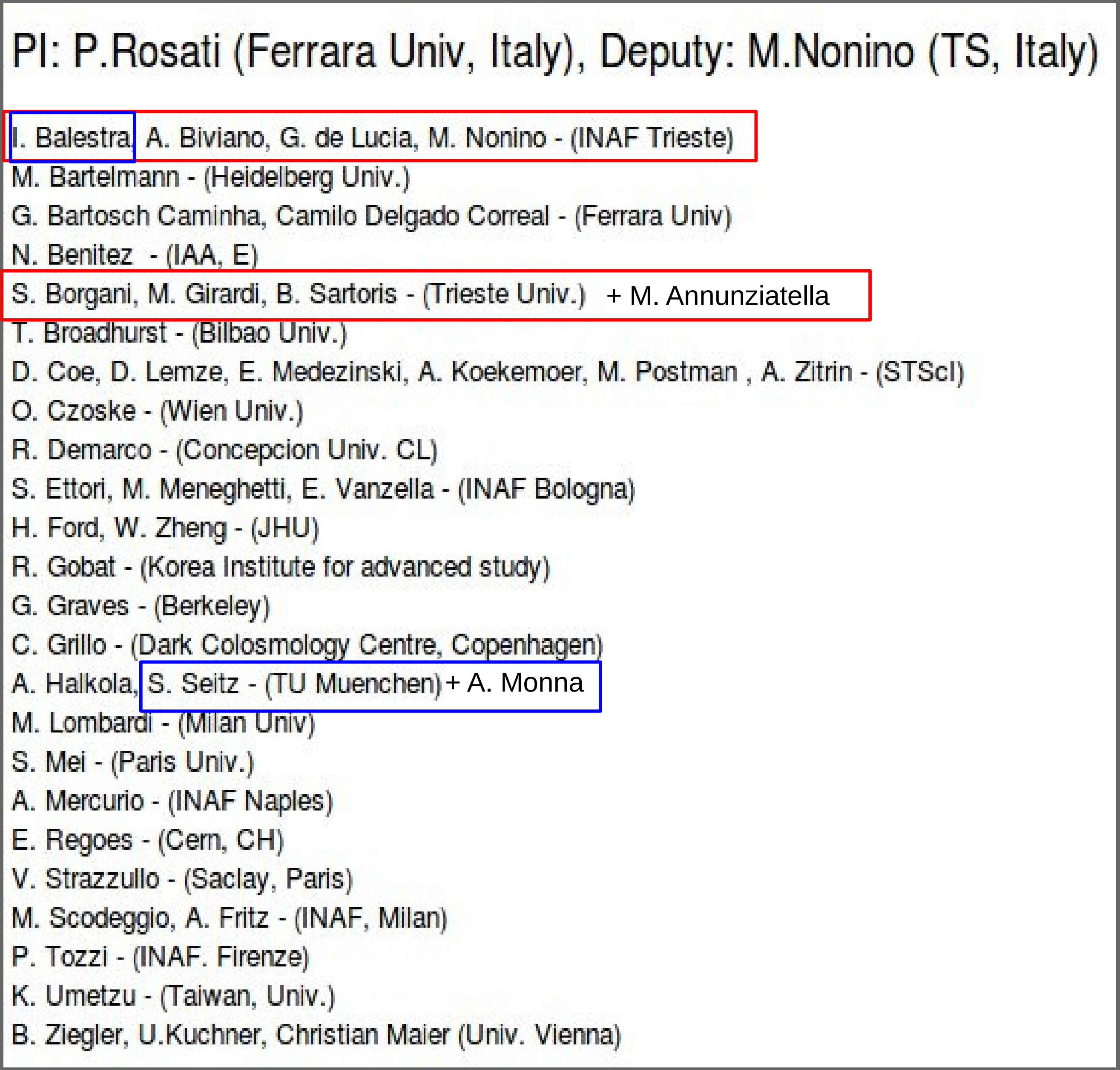
CLASH-VLT: the dynamics of clusters of galaxies

HST image of the z=0.44 CLASH cluster MACS1206
(NASA, ESA, M. Postman)

Andrea Biviano
INAF/Osservatorio Astronomico di Trieste (Italy)

The CLASH-VLT team:



PI: P.Rosati (Ferrara Univ, Italy), Deputy: M.Nonino (TS, Italy)

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G. Graves - (Berkeley)
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M. Lombardi - (Milan Univ)
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A. Mercurio - (INAF Naples)
E. Regoes - (Cern, CH)
V. Strazzullo - (Saclay, Paris)
M. Scodeggio, A. Fritz - (INAF, Milan)
P. Tozzi - (INAF. Firenze)
K. Umetzu - (Taiwan, Univ.)
B. Ziegler, U.Kuchner, Christian Maier (Univ. Vienna)

...and, in particular,

Barbara Sartoris (Univ. Trieste)

Marianna Annunziatella
(Univ.Trieste)

Outline of this talk:

- General introduction on clusters of galaxies
- How to measure cluster masses (and mass profiles)
- CLASH-VLT: the survey
- The internal dynamics of CLASH-VLT clusters:

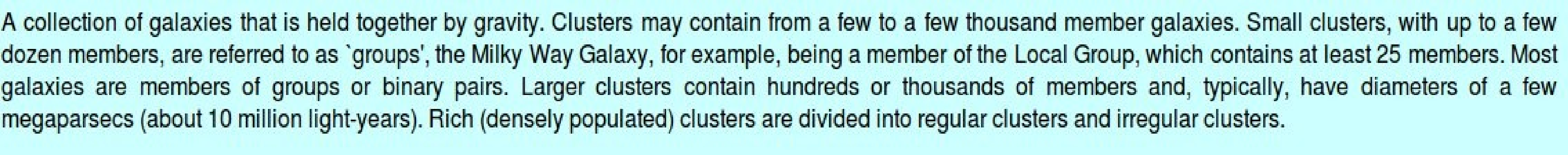
  ➔Mass profiles M(r)
  ➔Dark Matter equation of state
  ➔The pseudo-phase-space density profile Q(r)
  ➔Stellar-to-total mass profile ratio
  ➔Orbits of galaxies in clusters β(r)

- Summary and perspectives

General introduction on clusters of galaxies

(I use the Maibaum to set the timing of this talk)

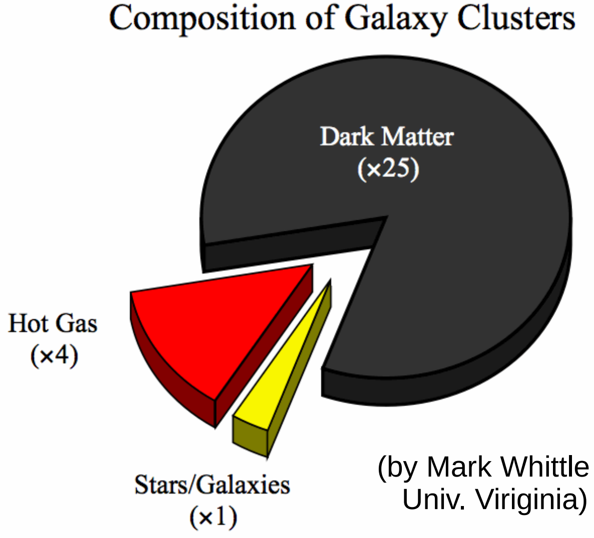
What are clusters of galaxies?



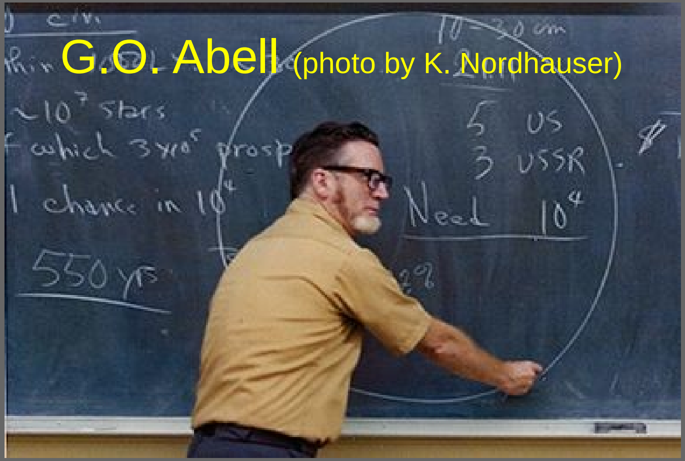
A collection of galaxies that is held together by gravity. Clusters may contain from a few to a few thousand member galaxies. Small clusters, with up to a few dozen members, are referred to as `groups', the Milky Way Galaxy, for example, being a member of the Local Group, which contains at least 25 members. Most galaxies are members of groups or binary pairs. Larger clusters contain hundreds or thousands of members and, typically, have diameters of a few megaparsecs (about 10 million light-years). Rich (densely populated) clusters are divided into regular clusters and irregular clusters.

Encyclopedia of Astronomy & Astrophysics

The Coma cluster of galaxies, by Lopez-Cruz et al.



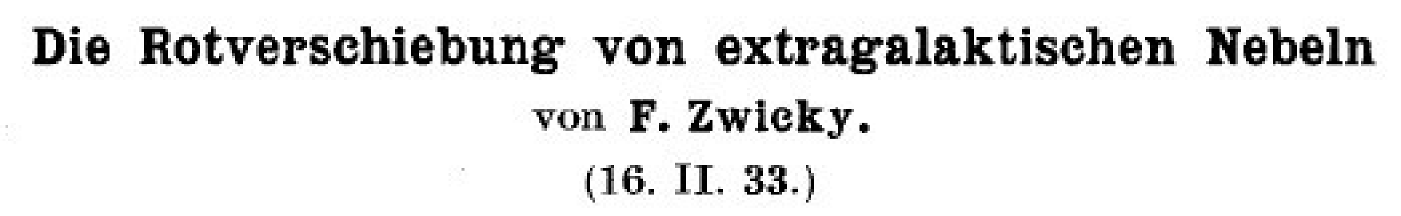
(by Mark Whittle
Univ. Viriginia)



G.O. Abell (photo by K. Nordhauser)

Why are they important?

Dark Matter:

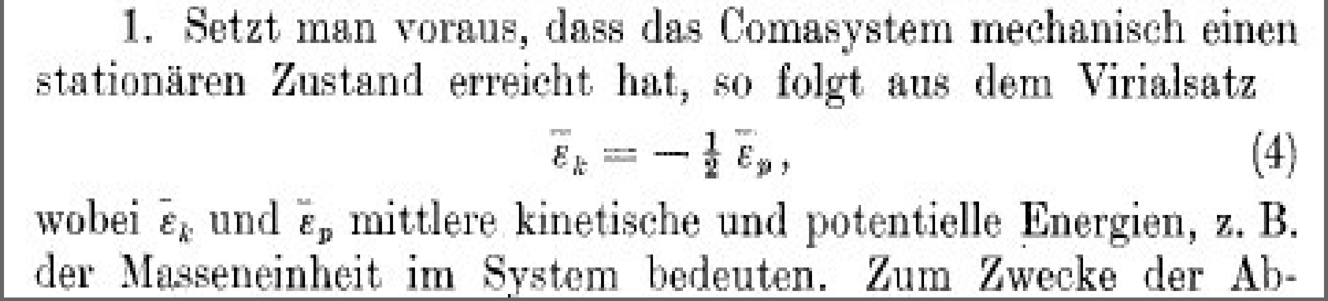


Die Rotverschiebung von extragalaktischen Nebeln

von **F. Zwicky.**

(16. II. 33.)

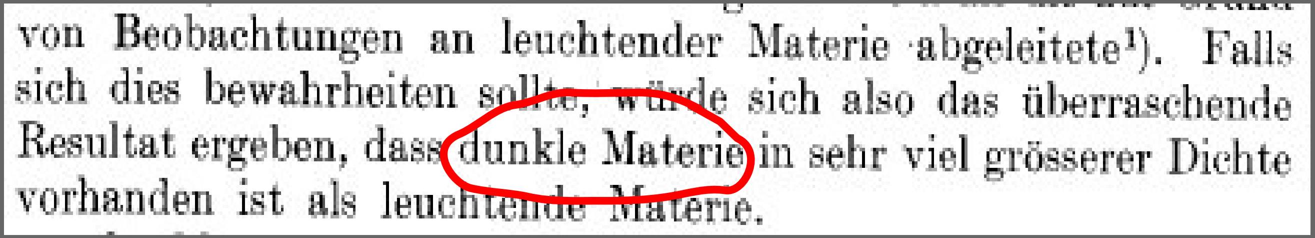
Virial theorem



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

$$\bar{\varepsilon}_k = -\frac{1}{2}\bar{\varepsilon}_p, \qquad (4)$$

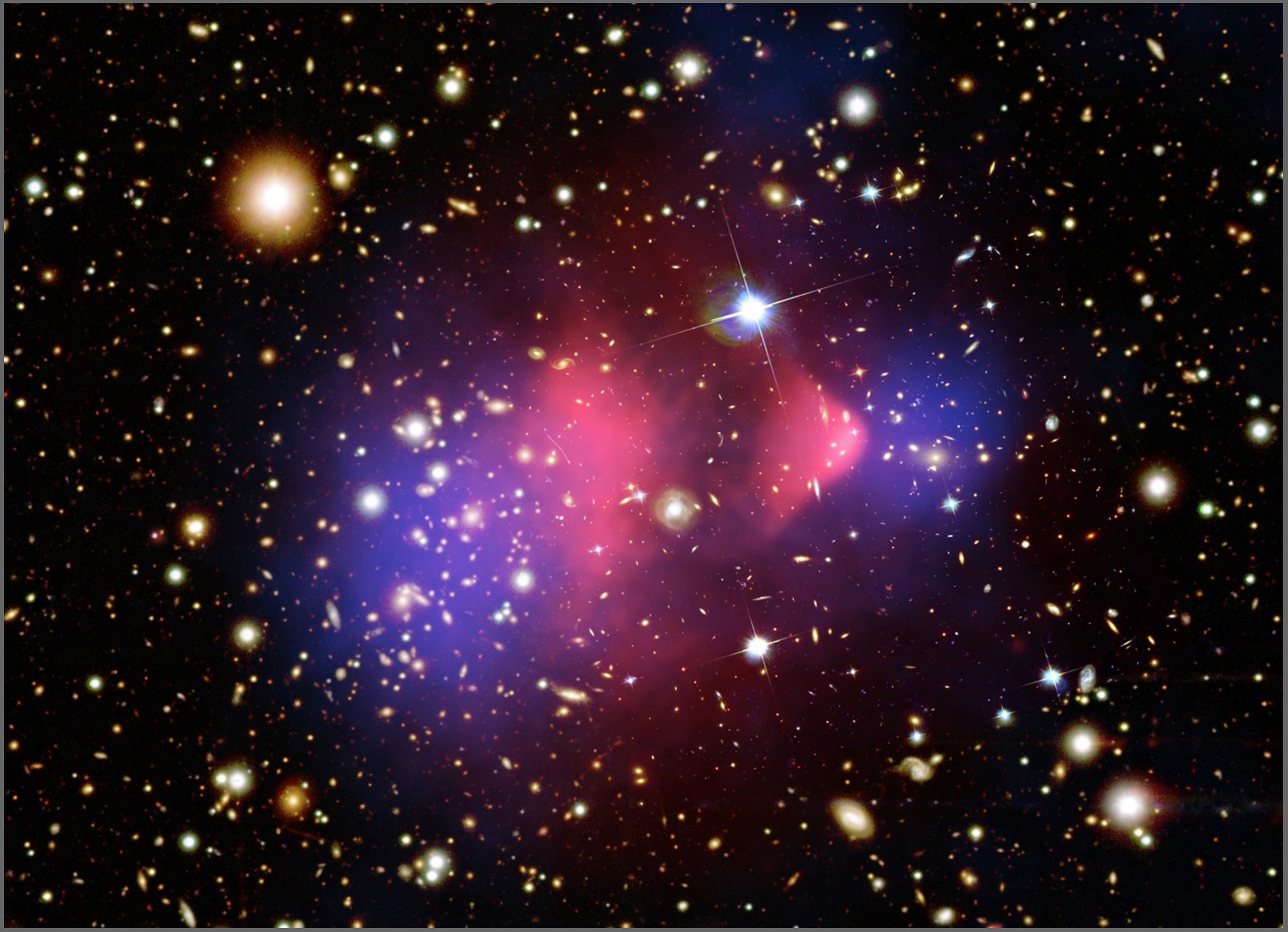
wobei $\bar{\varepsilon}_k$ und $\bar{\varepsilon}_p$ mittlere kinetische und potentielle Energien, z. B. der Masseneinheit im System bedeuten. Zum Zwecke der Ab-



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.

Why are they important?

Dark Matter:



The 'bullet' cluster, Markevitch et al. (NASA & ESO)

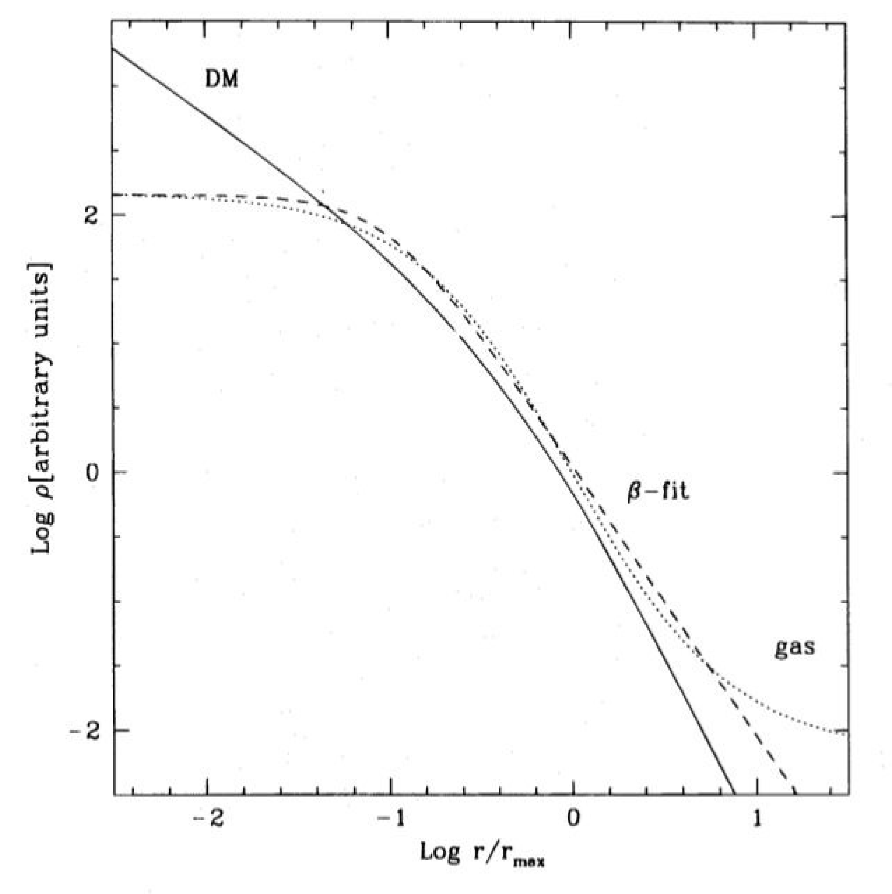
Why are they important?

Dark Matter:

Mapping the distribution of mass inside clusters of galaxies help us understand:

- the nature of dark matter
- the way halos formed

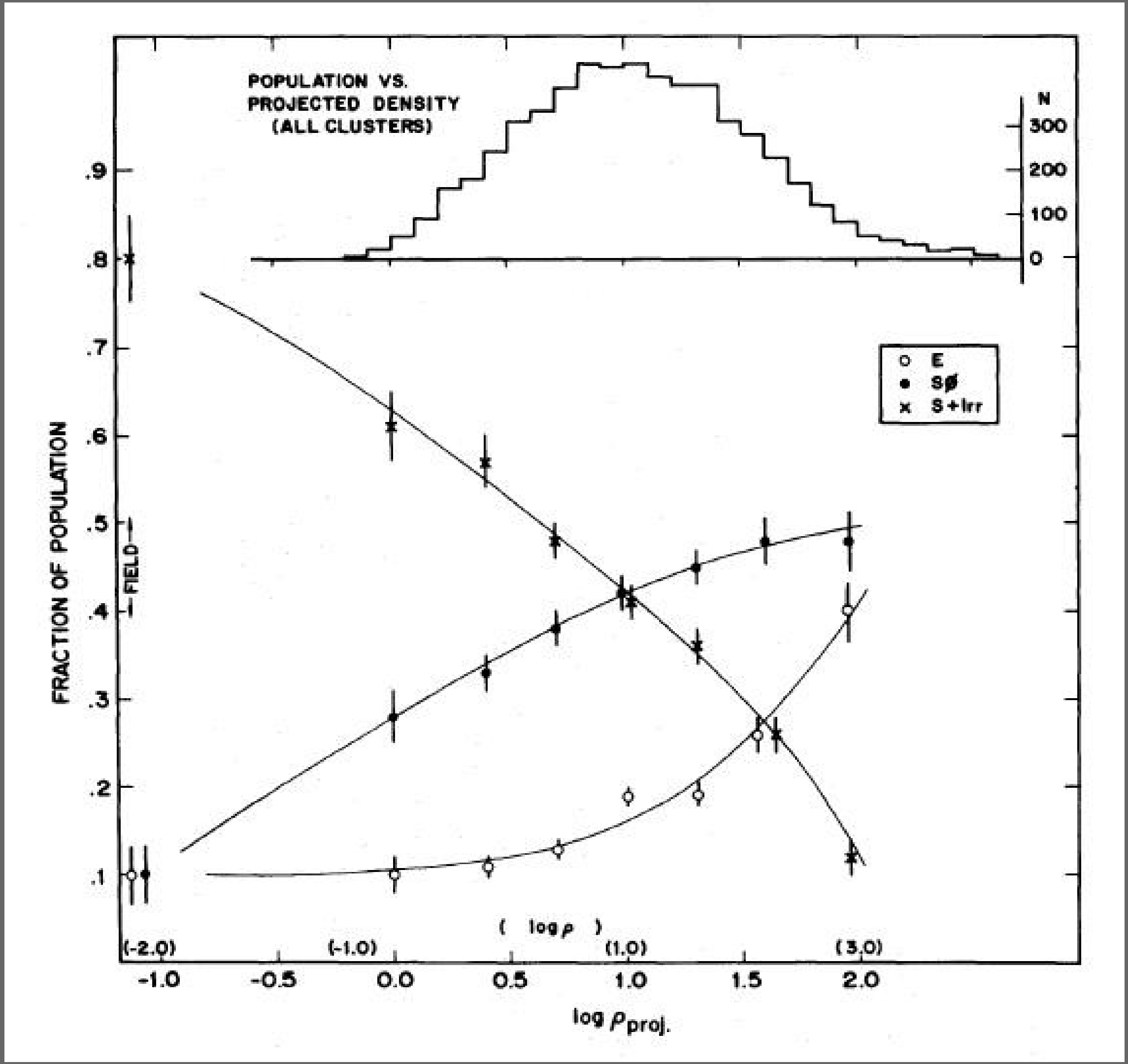
Measuring cluster masses is also important because clusters can be used as cosmological probes (the density of clusters above a given mass as a function of redshift)



Simulation of a cluster mass profile
[Navarro, Frenk & White 1996]

Why are they important?

Evolution of galaxies:



The morpholgy-density relation in clusters of galaxies, A. Dressler (1980)

> *"The predominance of early types is a conspicuous feature of clusters in general"*
> *Hubble & Humason 1931, ApJ, 74, 43*

A. Dressler

Why are they important?

Evolution of galaxies:

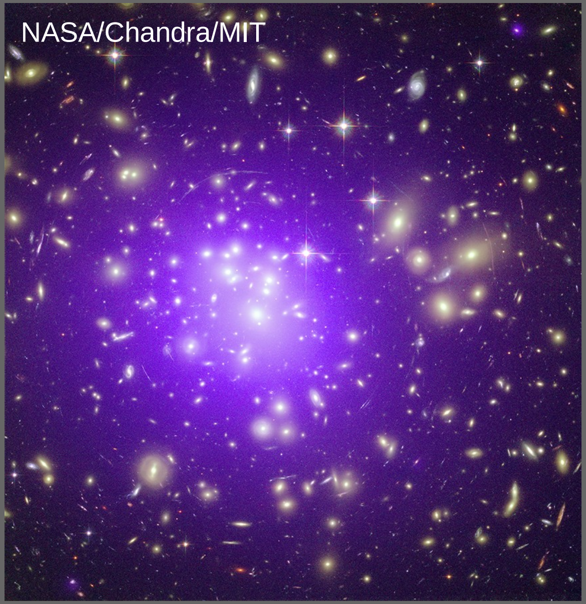
Interaction of galaxies and stripping of gas (Moss et al. 2007, MNRAS)

Ram-pressure stripping of gas from moving galaxy (ESA, NASA)

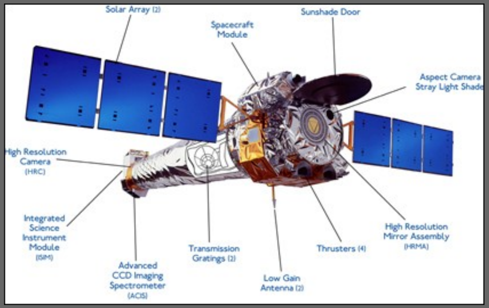
The prevalence of red, early-type, passively-evolving galaxies in clusters inform us about the physical processes that speed up galaxy evolution by removing their gas and changing their internal structure

How to measure cluster masses

How do we measure cluster masses?

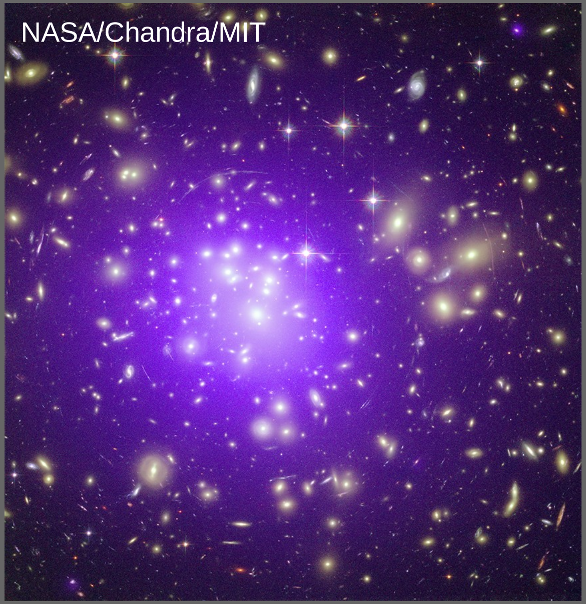


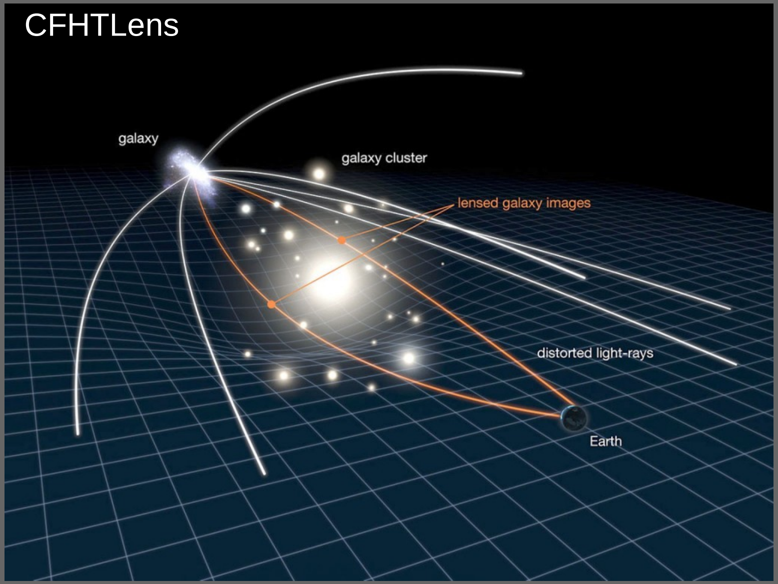
X-ray observations:
assuming the intra-cluster,
X-ray emitting gas is in
hydrostatic equilibrium



Chandra space telescope

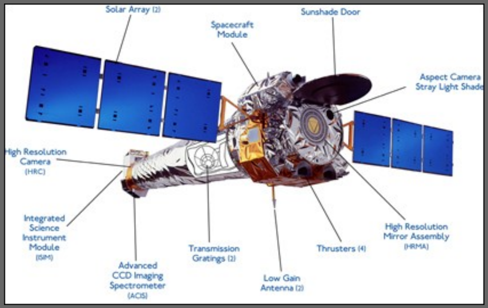
How do we measure cluster masses?


NASA/Chandra/MIT


CFHTLens

X-ray observations: assuming the intra-cluster, X-ray emitting gas is in hydrostatic equilibrium

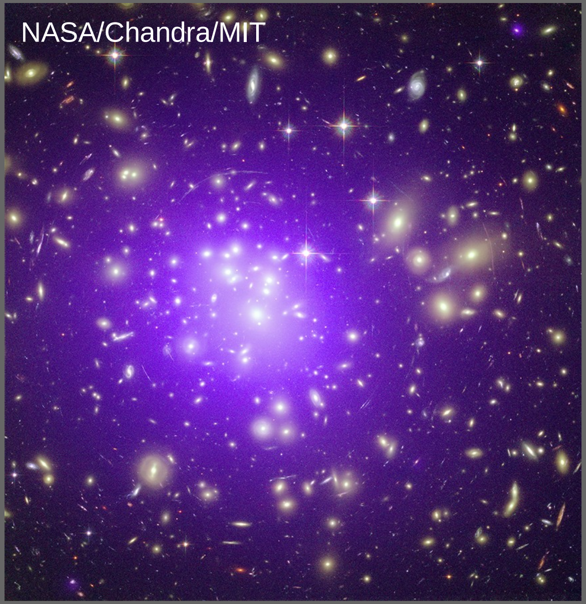
Optical observations: using the deflected and amplified light from background galaxies due to the gravitational lensing effect



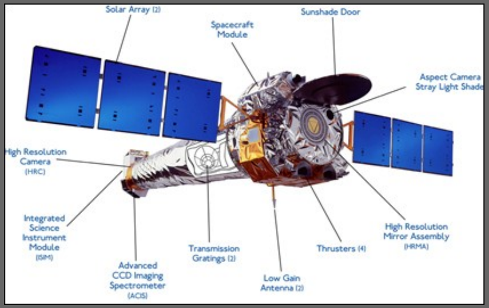
Chandra space telescope

Hubble space telescope

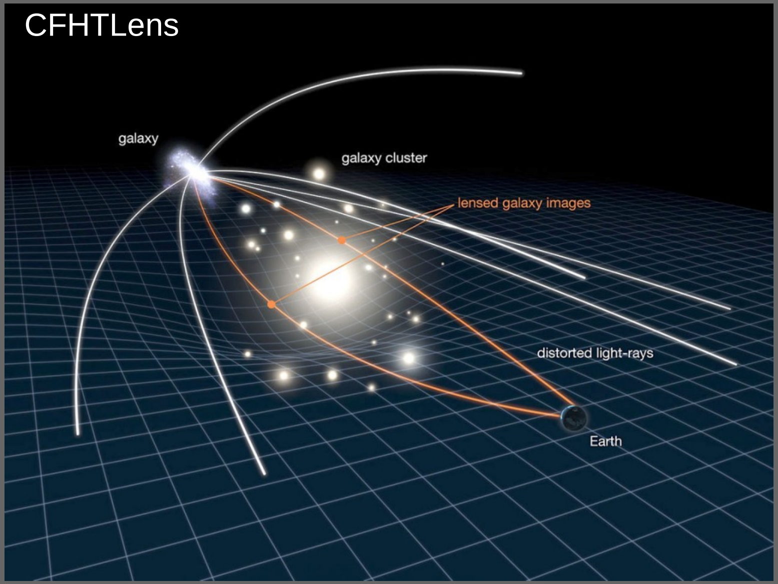
How do we measure cluster masses?



X-ray observations: assuming the intra-cluster, X-ray emitting gas is in hydrostatic equilibrium



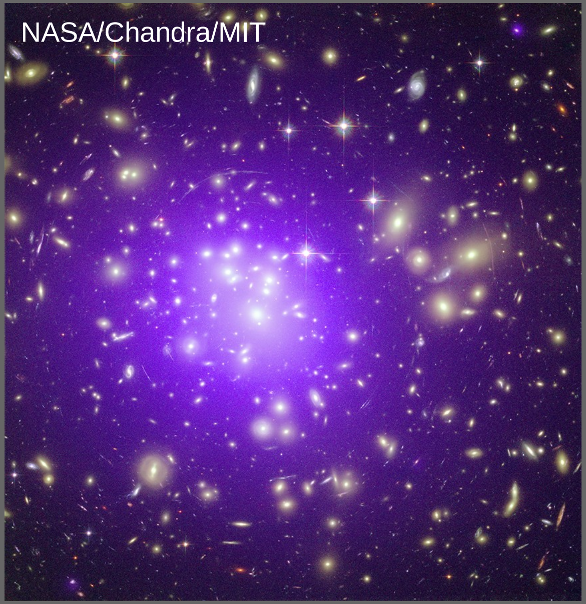
Chandra space telescope



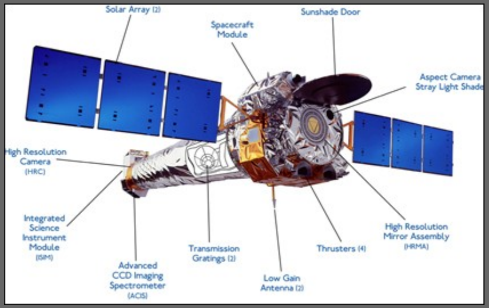
Optical observations: using the deflected and amplified light from background galaxies due to the gravitational lensing effect

Wendelstein telescope

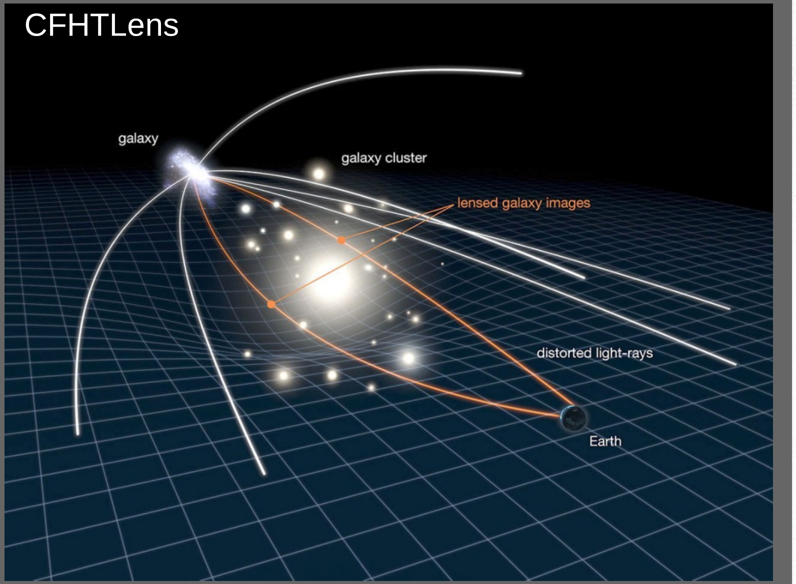
How do we measure cluster masses?


NASA/Chandra/MIT

X-ray observations: assuming the intra-cluster, X-ray emitting gas is in hydrostatic equilibrium



Chandra space telescope


CFHTLens

Optical observations: using the deflected and amplified light from background galaxies due to the gravitational lensing effect

Wendelstein telescope


Univ. Cincinnati

Optical observations: using the spatial and velocity distributions of cluster galaxies


Very Large Telescope

Galaxies as tracers of the gravitational potential

Sir James Jeans' equations:

M = total mass profile
σ_r = velocity dispersion profile along the radial direction
ν = number density profile of the tracer (galaxies)
β = velocity anisotropy profile of the tracer

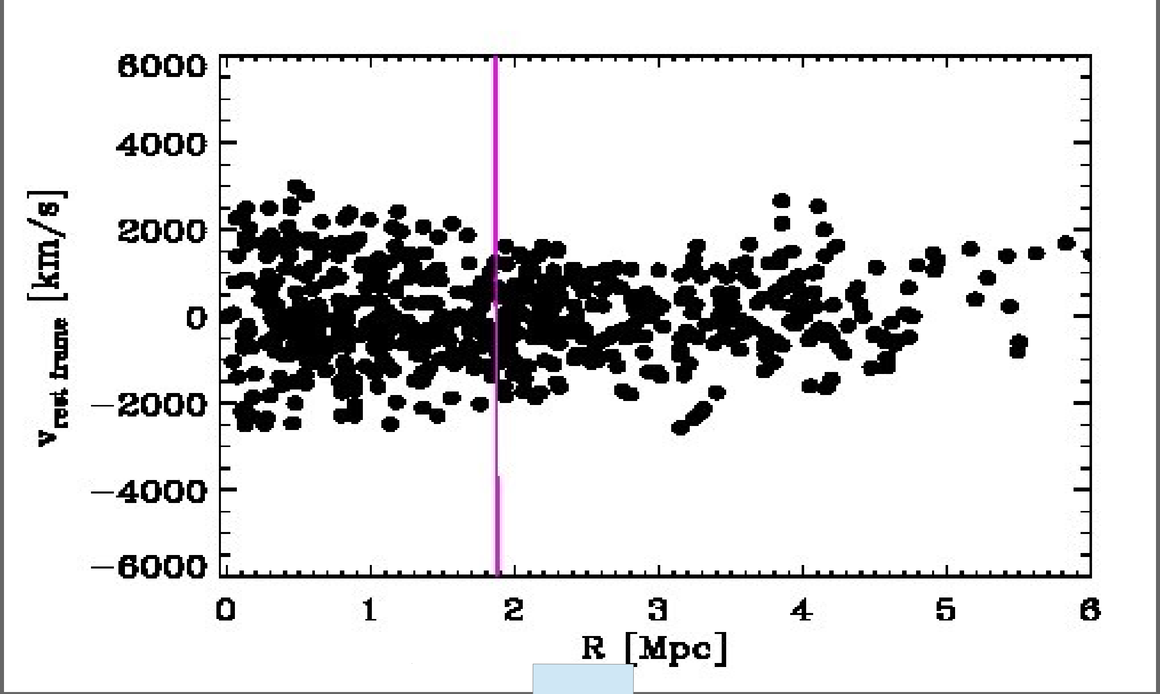
$$M(<r) = -\frac{r\sigma_r^2}{G}\left(\frac{d\ln\nu}{d\ln r} + \frac{d\ln\sigma_r^2}{d\ln r} + 2\beta\right)$$

$$\beta(r) = 1 - \frac{\sigma_\theta^2(r)}{\sigma_\mathrm{r}^2(r)}$$

But how do we get $\nu(r)$, $\sigma_r(r)$, $\beta(r)$ from the observables?

Measuring masses

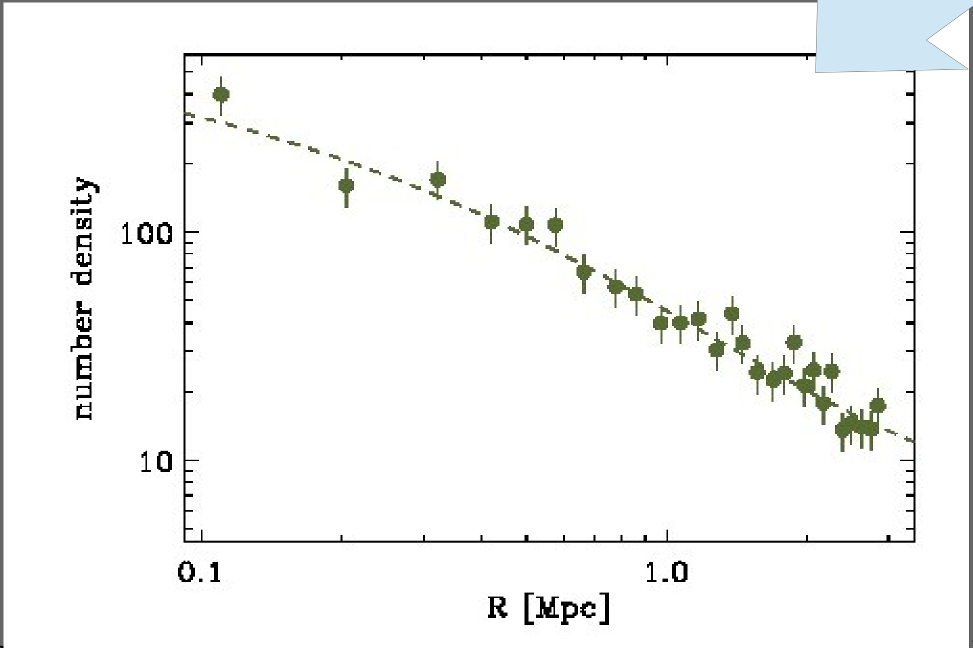
Phase-space
distribution
of cluster
member
galaxies
in projection

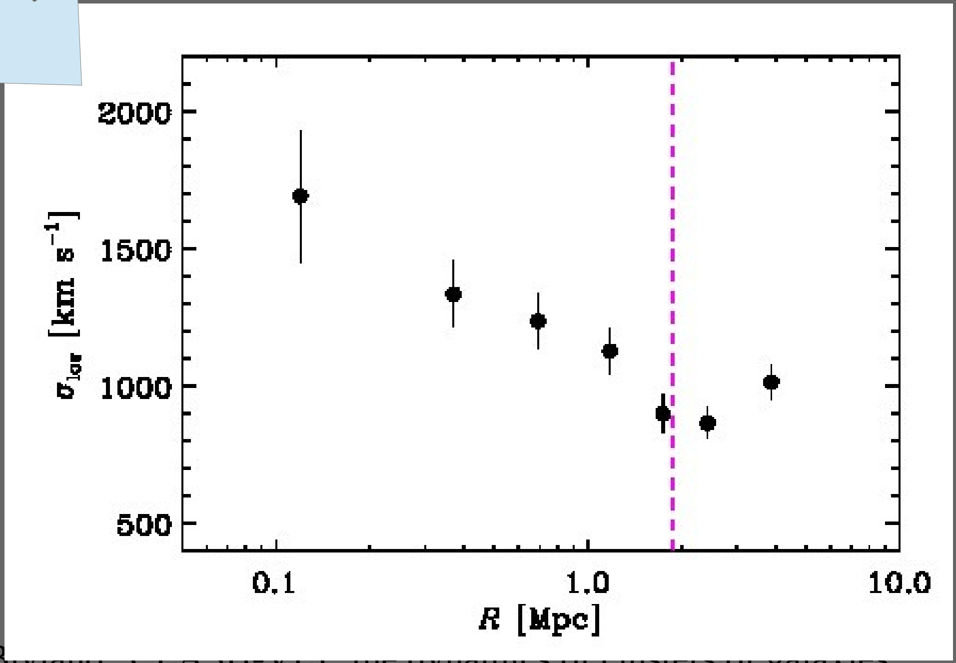


CLASH-VLT
cluster
MACS1206

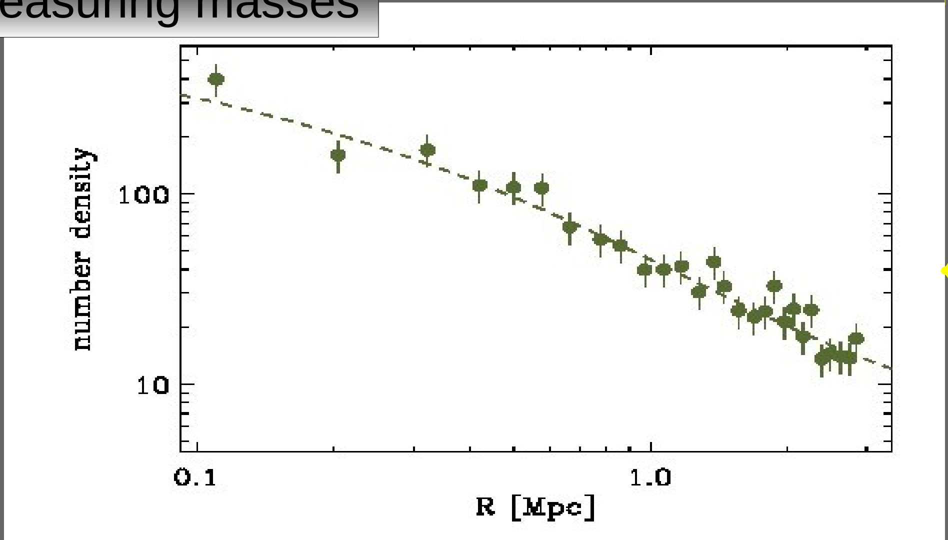
projected number density profile N(R)

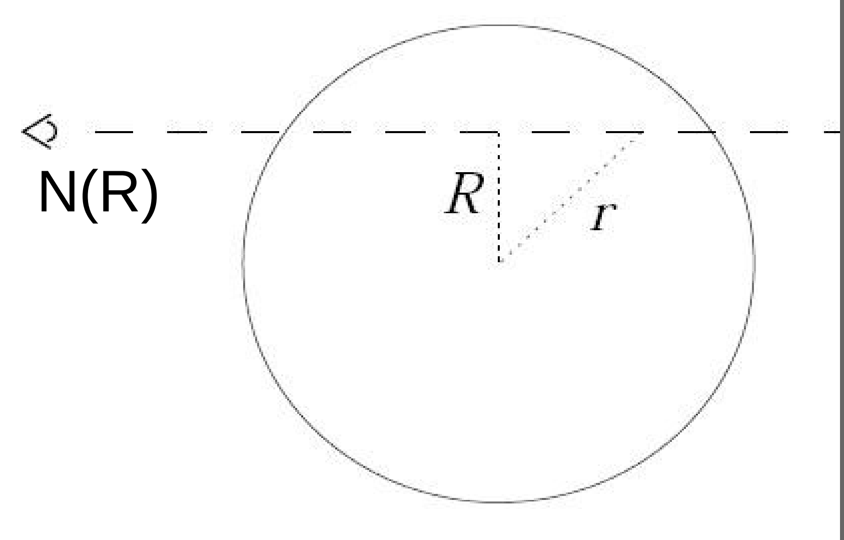
l.o.s. velocity dispersion profile $\sigma_{los}(R)$





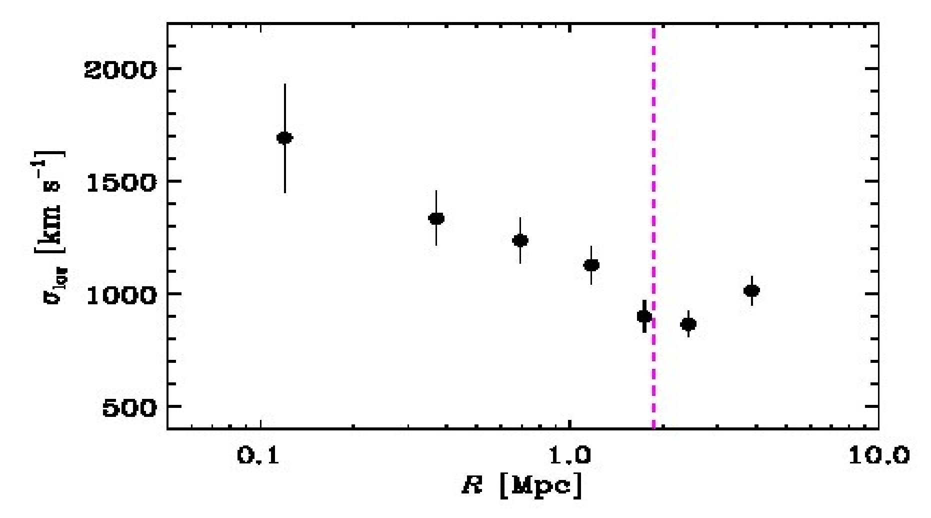
Measuring masses

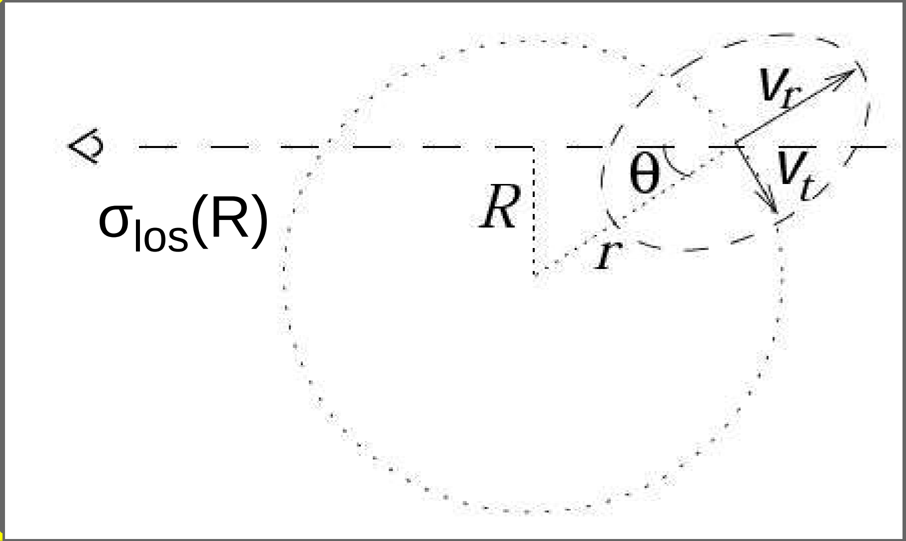




N(R)

$\nu(r)$





$\sigma_{los}(R)$

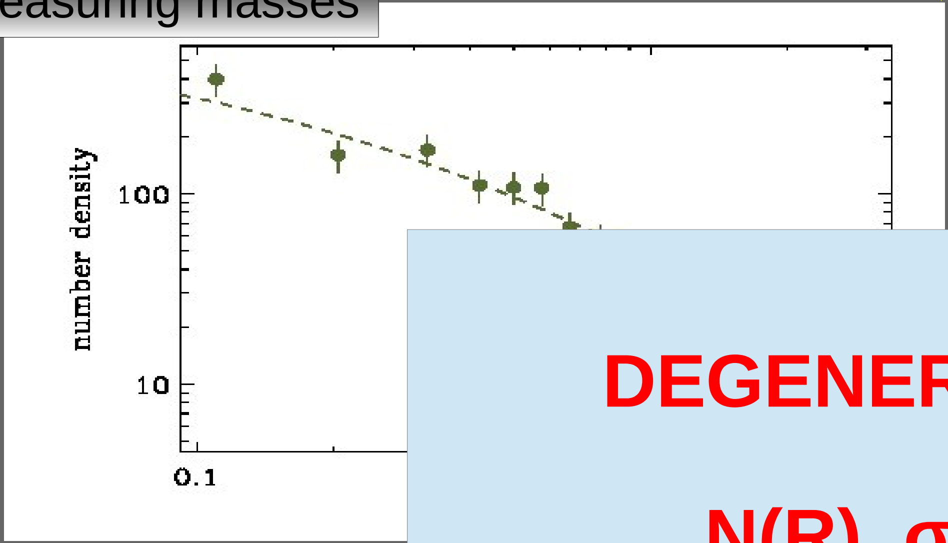
$\sigma_r(r)$

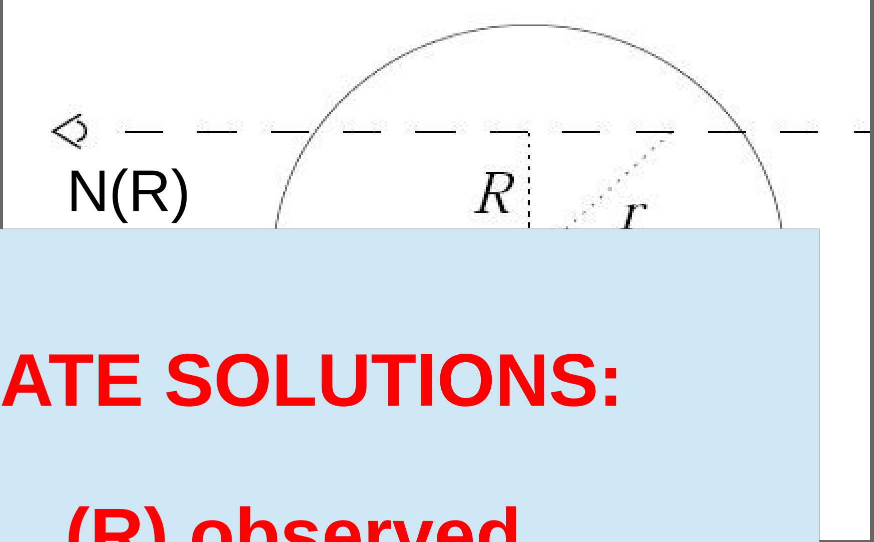
$\sigma_\theta(r)$

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

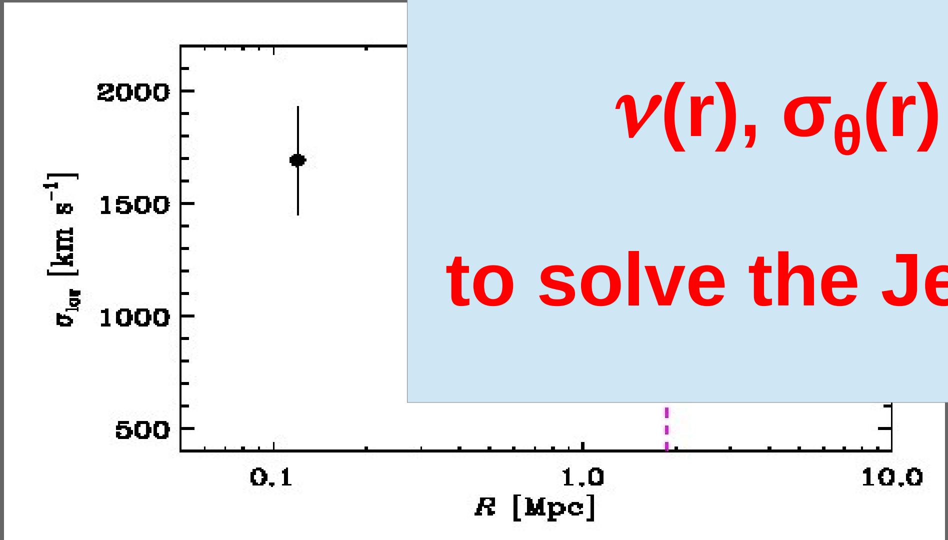
$$\beta(r) = 1 - \frac{\sigma_\theta^2(r)}{\sigma_r^2(r)}$$

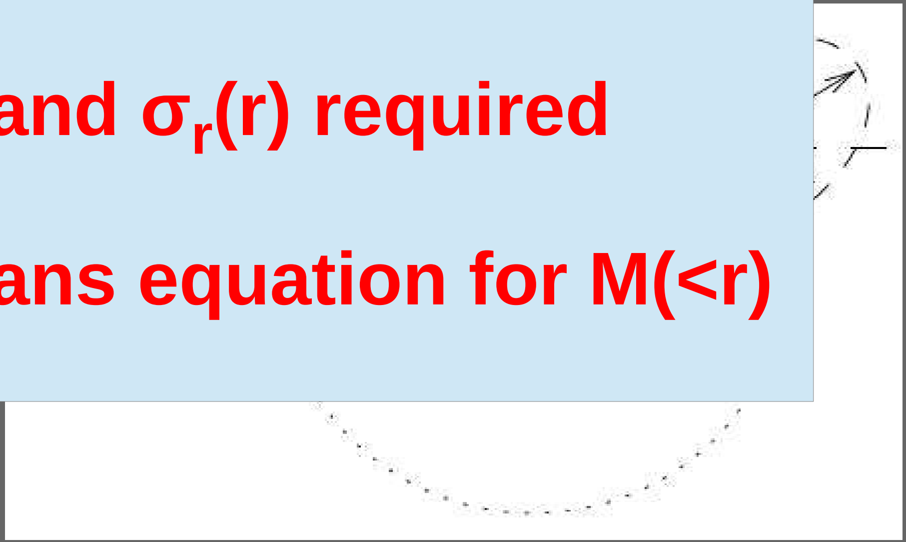
Measuring masses





ν(r)





$\sigma_r(r)$
$\sigma_\theta(r)$

DEGENERATE SOLUTIONS:

N(R), σ_{los}(R) observed

ν(r), σ_θ(r) and σ_r(r) required

to solve the Jeans equation for M(<r)

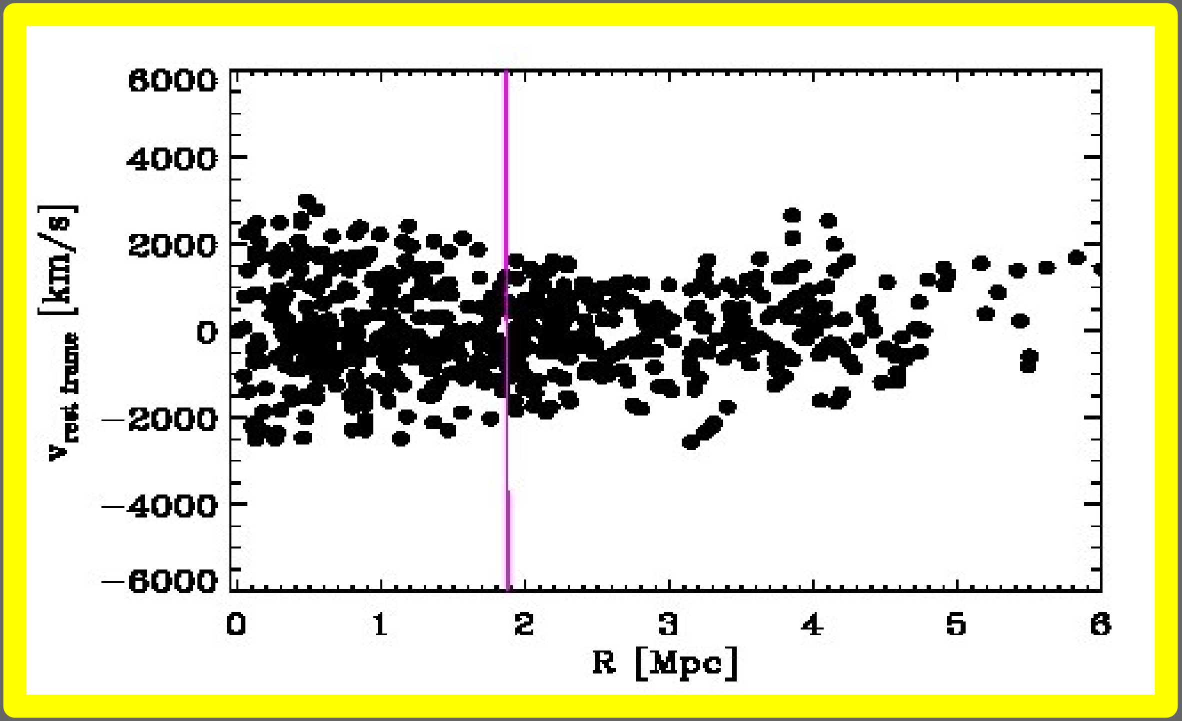
$$M(<r) = -\frac{r\sigma_r^2}{G}\left(\frac{d\ln\nu}{d\ln r} + \frac{d\ln\sigma_r^2}{d\ln r} + 2\beta\right)$$

$$\beta(r) = 1 - \frac{\sigma_\theta^2(r)}{\sigma_r^2(r)}$$

Measuring masses

MAMPOSSt

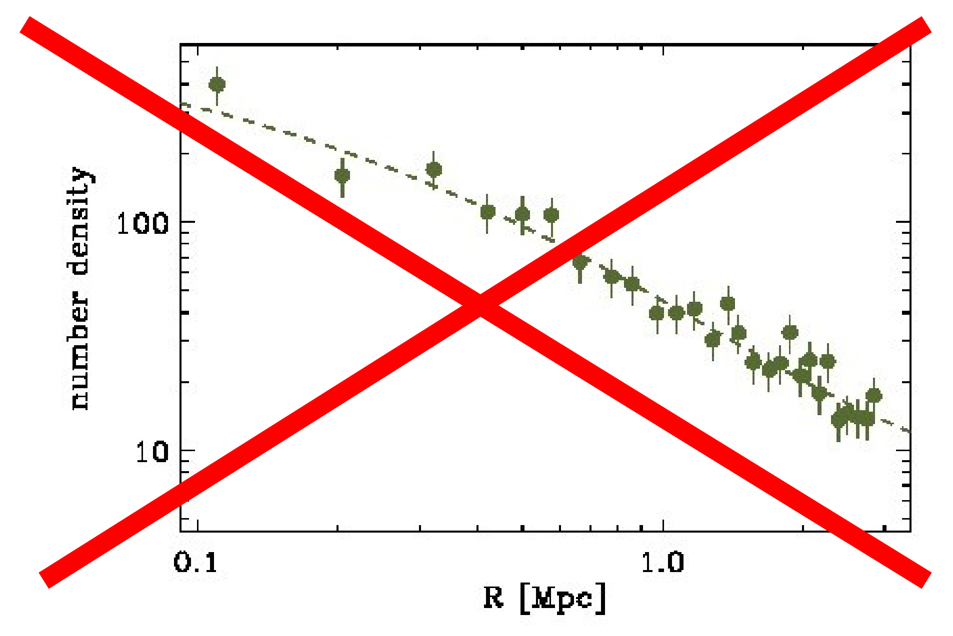
direct
maximum
likelihood
fit to the
phase-space
distribution
of cluster
galaxies
in projection



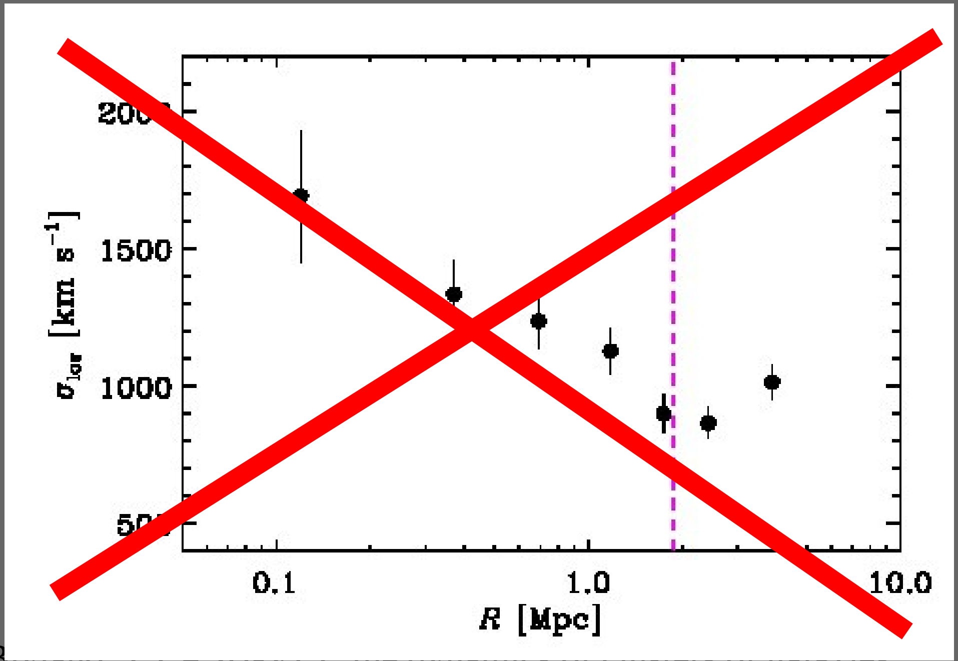
Modelling
Anisotropy and
Mass
Profiles of
Observed
Spherical
Systems

[Mamon, AB, Boué 2013]

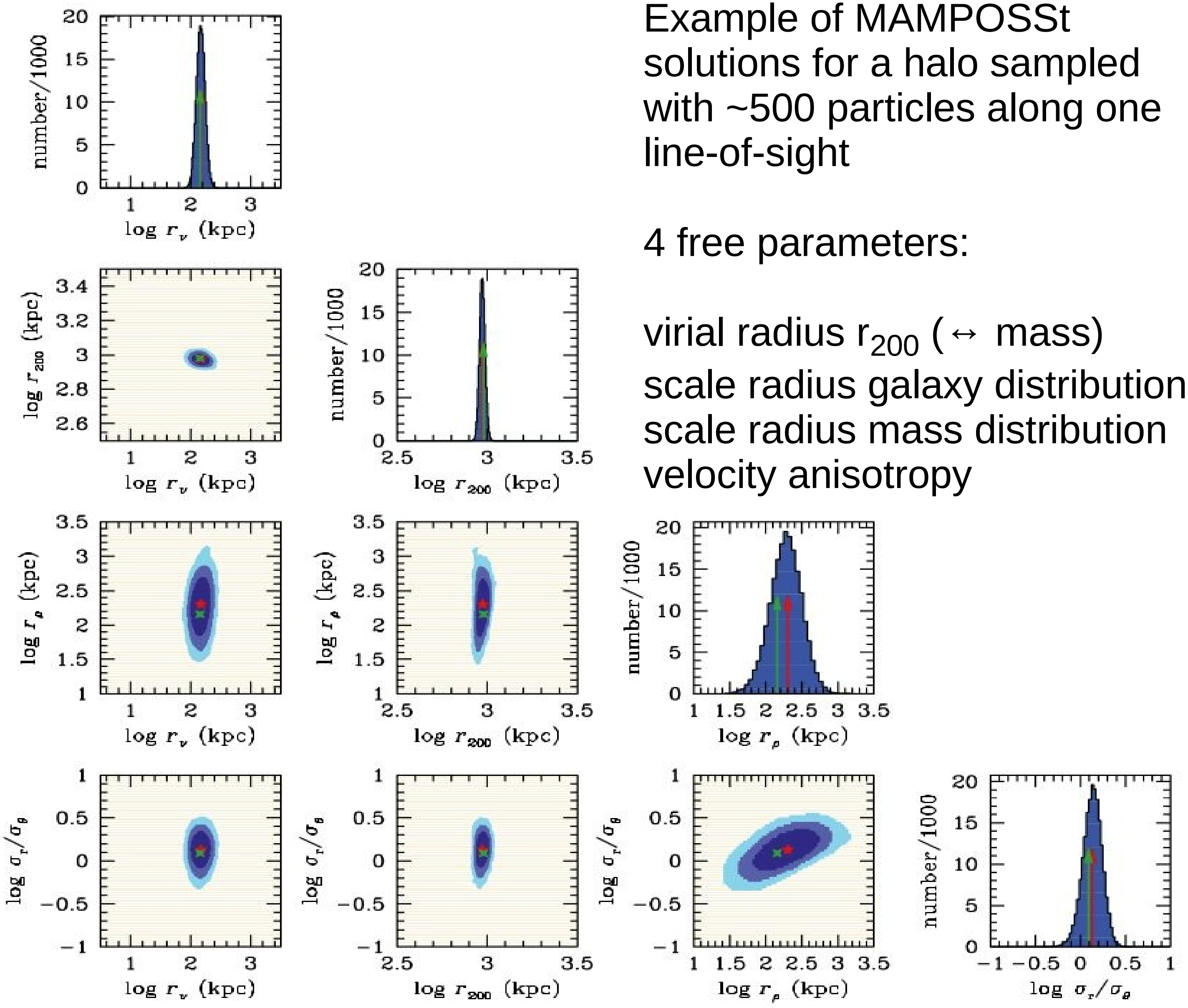
projected number density profile N(R)



l.o.s. velocity dispersion profile σ_{los}(R)



MAMPOSSt: tested on cluster-size halos from cosmological simulations



Example of MAMPOSSt solutions for a halo sampled with ~500 particles along one line-of-sight

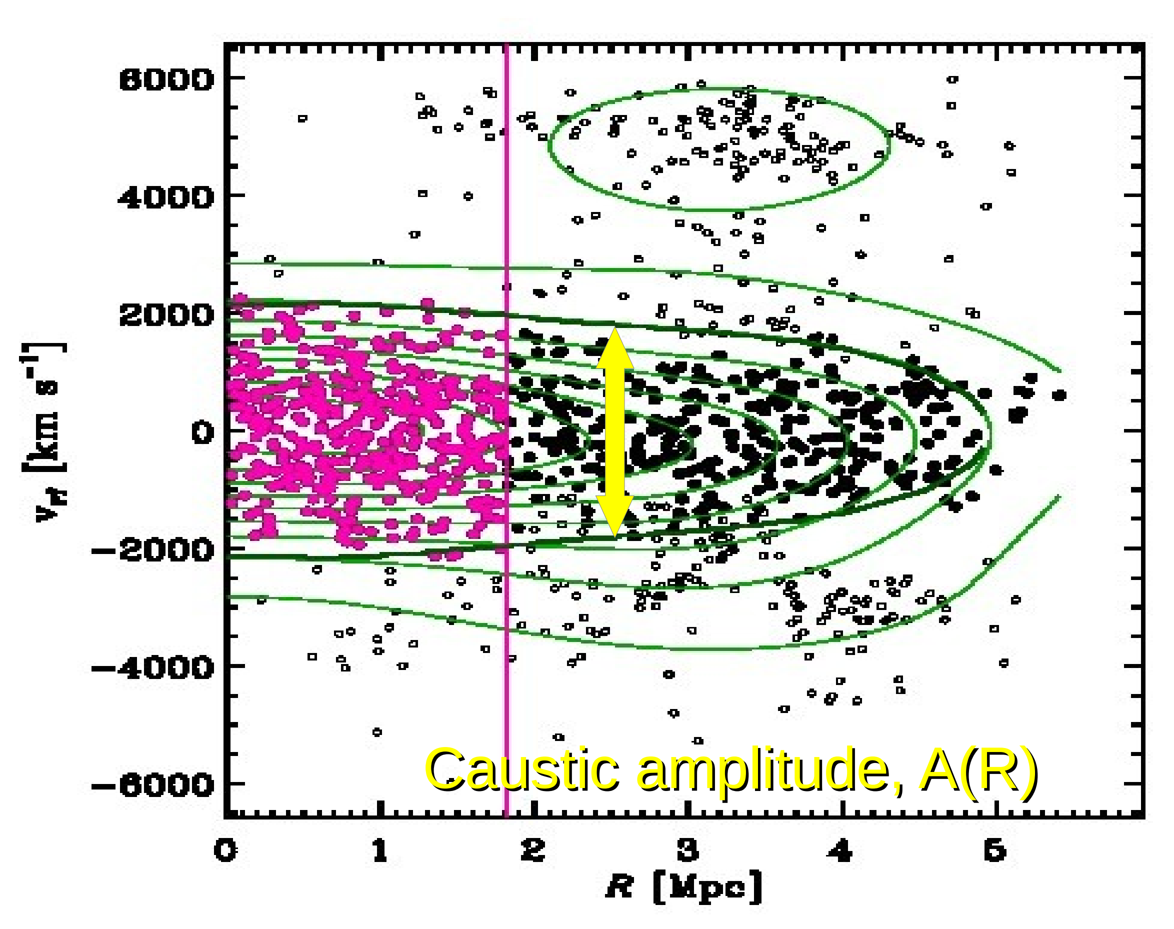
4 free parameters:

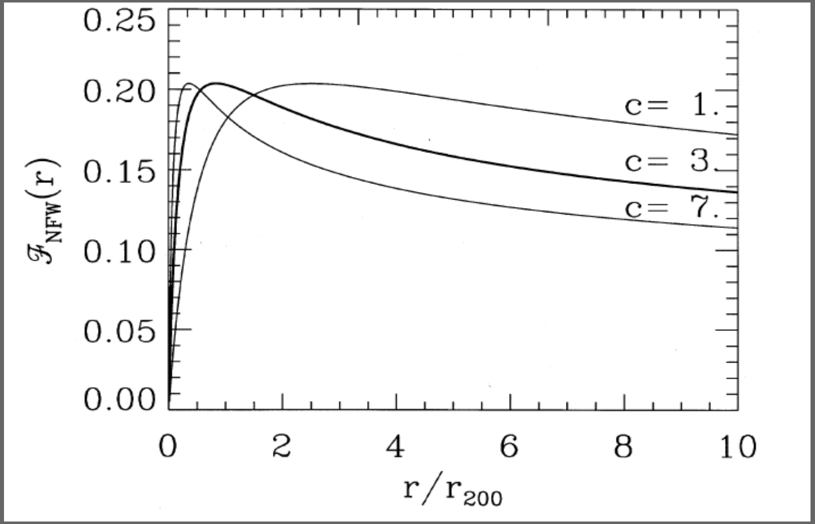
virial radius r_{200} (↔ mass)
scale radius galaxy distribution
scale radius mass distribution
velocity anisotropy

The Caustic technique

[Diaferio & Geller 97; Diaferio 99]

$$GM(<r) - GM(<r_0) = \int_{r_0}^{r} \mathcal{A}^2(x)\mathcal{F}_\beta(x)\,\mathrm{d}x$$





$\mathcal{F}(r)$ depends on M(<r) itself within the virial region but it is ≈ constant outside → can solve the integral

Use the Jeans equation *(MAMPOSSt)* in the virial region and the Caustic technique outside

[AB+Girardi 2003]

CLASH-VLT: the survey

CLASH & CLASH-VLT

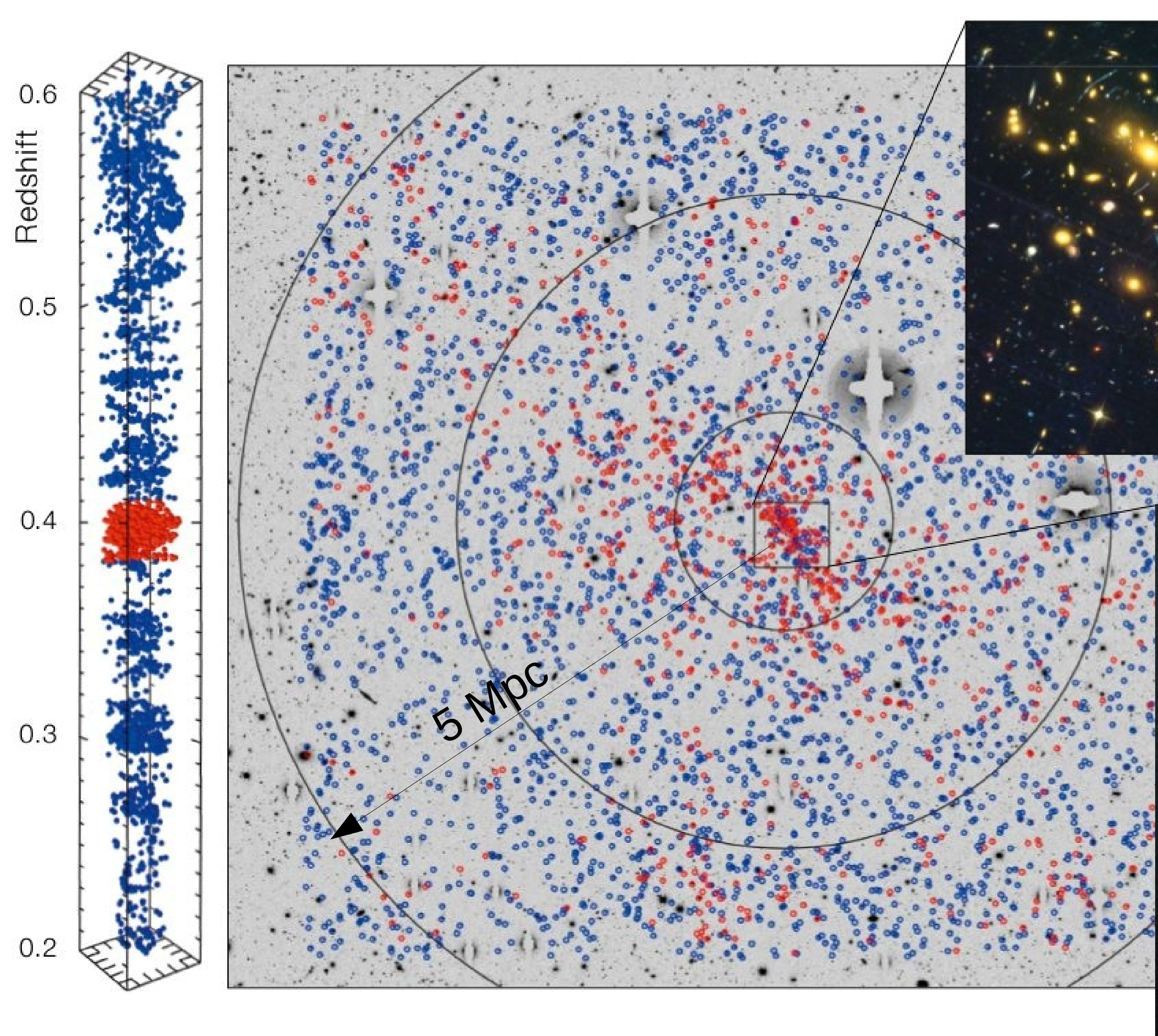
CLASH, *Cluster Lensing And Supernova survey with Hubble,*
PI: M. Postman, (Postman et al. 2012)

524 HST orbits to observe 25 gravitationally lensing clusters of galaxies at $0.18<z<0.90$,
+ Suprime-CAM Subaru follow-up for weak lensing

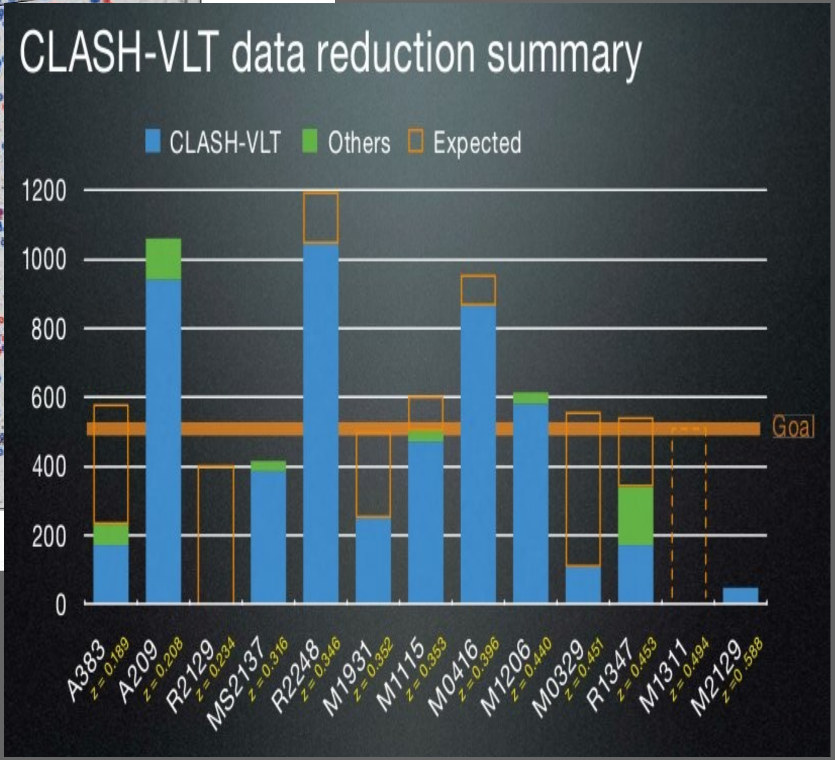
CLASH-VLT, VLT-VIMOS follow-up
from the ESO Large Programme
“Dark Matter Mass Distributions of Hubble Treasury Clusters and the Foundations of ΛCDM Structure Formation Models”, PI: P. Rosati,
(Rosati et al. 2014)

225 hours to observe the 14 southern CLASH clusters and obtain redshifts for ≃500 members in each cluster,
and ~100 lensed images of $z\leq7$ galaxies

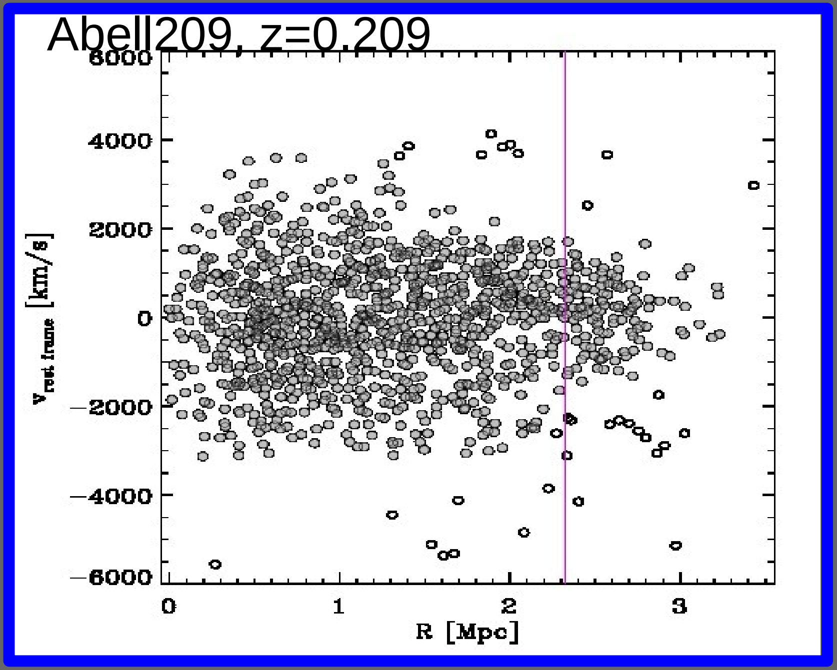
CLASH & CLASH-VLT

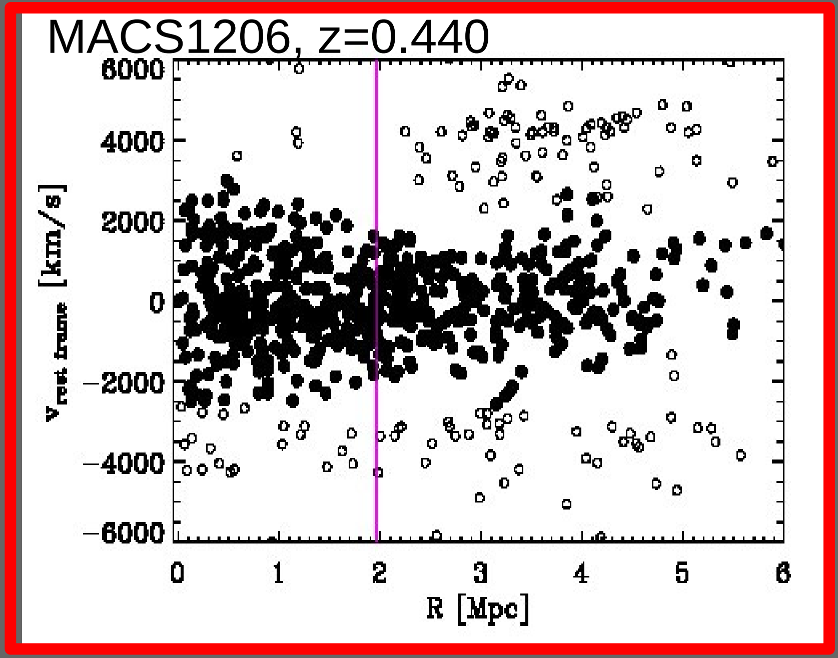


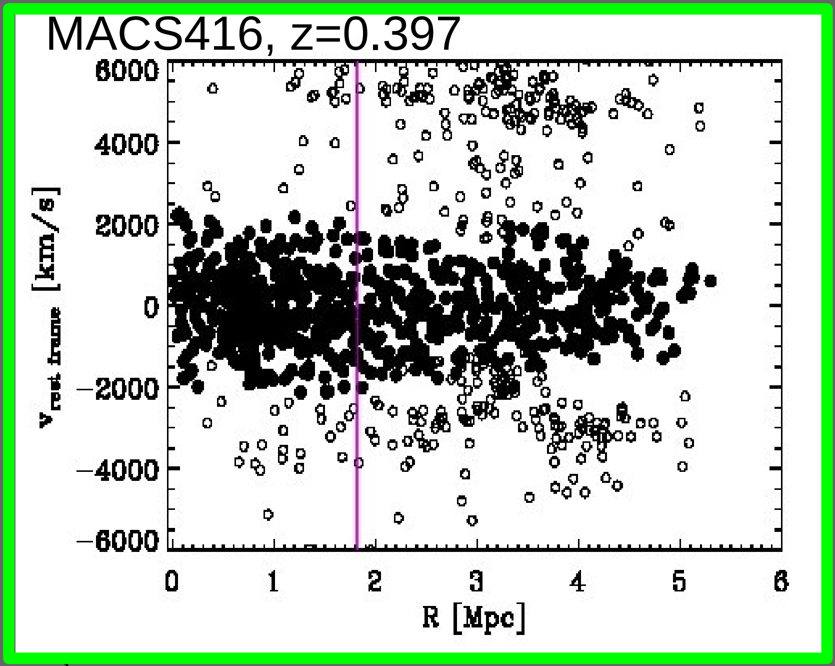
An example: MACS 416 *[from Rosati et al. 2014]*


CLASH-VLT data reduction summary

CLASH & CLASH-VLT


Abell209, z=0.209


MACS1206, z=0.440


MACS416, z=0.397

~ 1000, 900, 600 spectroscopic members out to radii of ~ 3, 5, 5 Mpc, in Abell 209, MACS 416, MACS1206, resp.

+ Subaru 5-band photometry allowing the determination of the galaxy stellar masses via SED fitting *(MAGPHYS, da Cunha et al. 2008)* (only 3 bands for MACS416)

The internal dynamics of CLASH-VLT clusters:
mass profiles M(r)

Run MAMPOSSt : must choose models for M(r) and β(r)

Say: $\gamma \equiv d \ln \rho / d \ln r$, the slope of the mass density profile

5 M(r) models, 2 free parameters, r_{200} and scale radius r_{-2} or r_{core}

1) **NFW,** characterized by $\gamma(0) = -1$ and $\gamma(\infty) = -3$
2) **Einasto,** characterized by $\gamma(0) = -2\ (r/r_{-2}\ )^{1/m}$ (we adopt m=5)
3) **Hernquist,** $\gamma(0) = -1$ and $\gamma(\infty) = -4$
4) **Burkert,** $\gamma(0\ ) = 0$ and $\gamma(\infty) = -3$
5) **Softened Isothermal Sphere,** $\gamma(0\ ) = 0$ and $\gamma(\infty) = -2$

5 Velocity anisotropy models, ,1 free parameter

$$\beta(r) = 1 - \frac{\sigma_\theta^2(r)}{\sigma_r^2(r)}$$

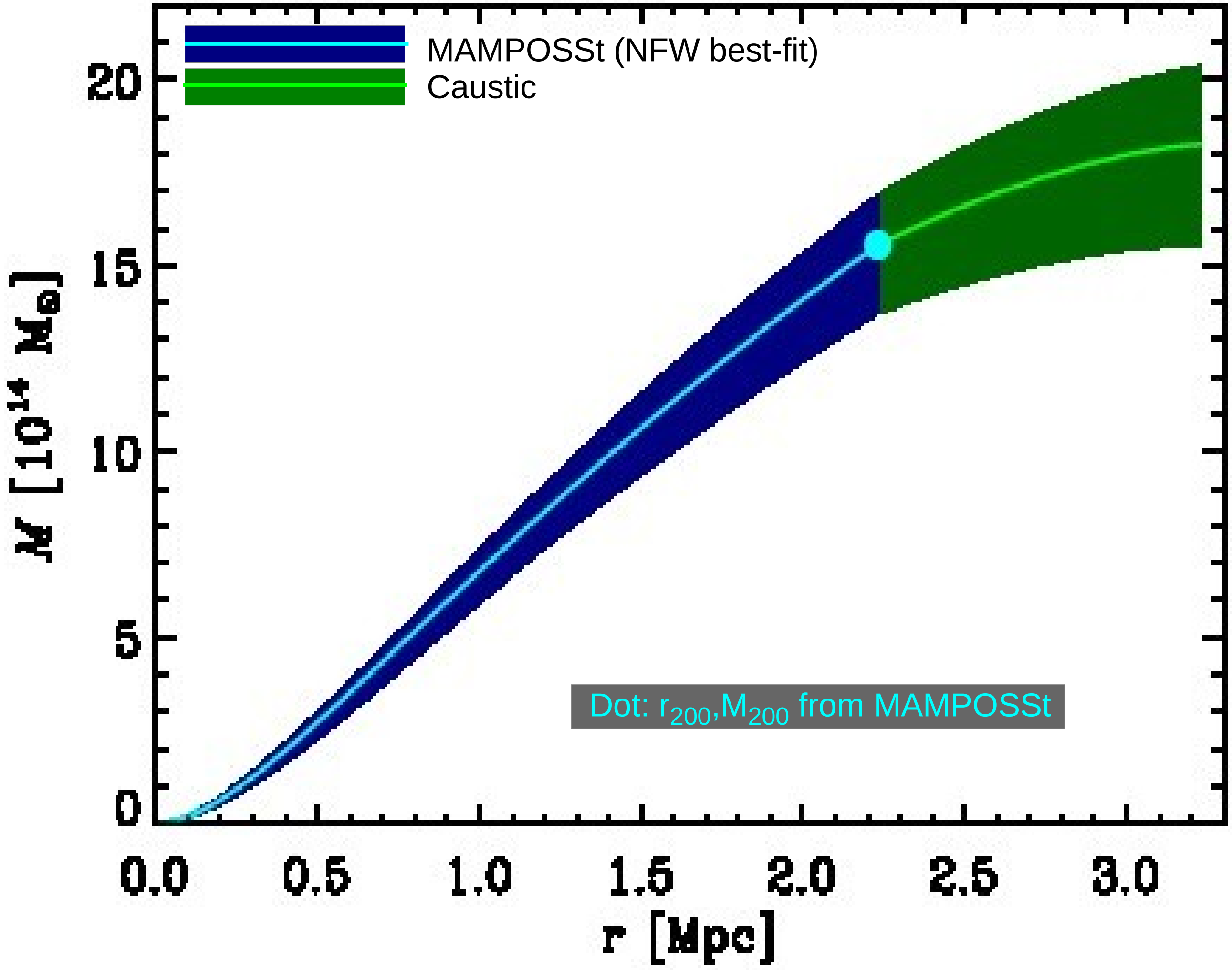
1) **Constant β** at all radii
2, 3, 4) **trhee models** always radial, increasingly so with increasing radius
5) $\beta = \beta_\infty (r - r_{-2})/(r + r_{-2})$, changing anisotropy sign with radius

The mass profiles

Abell 209 *[Sartoris, AB et al. in prep.]*

Best-fit
M(r)
model
is
NFW

M_{200}=15.5 10^{14} $M_\odot$ *(h=0.7)*

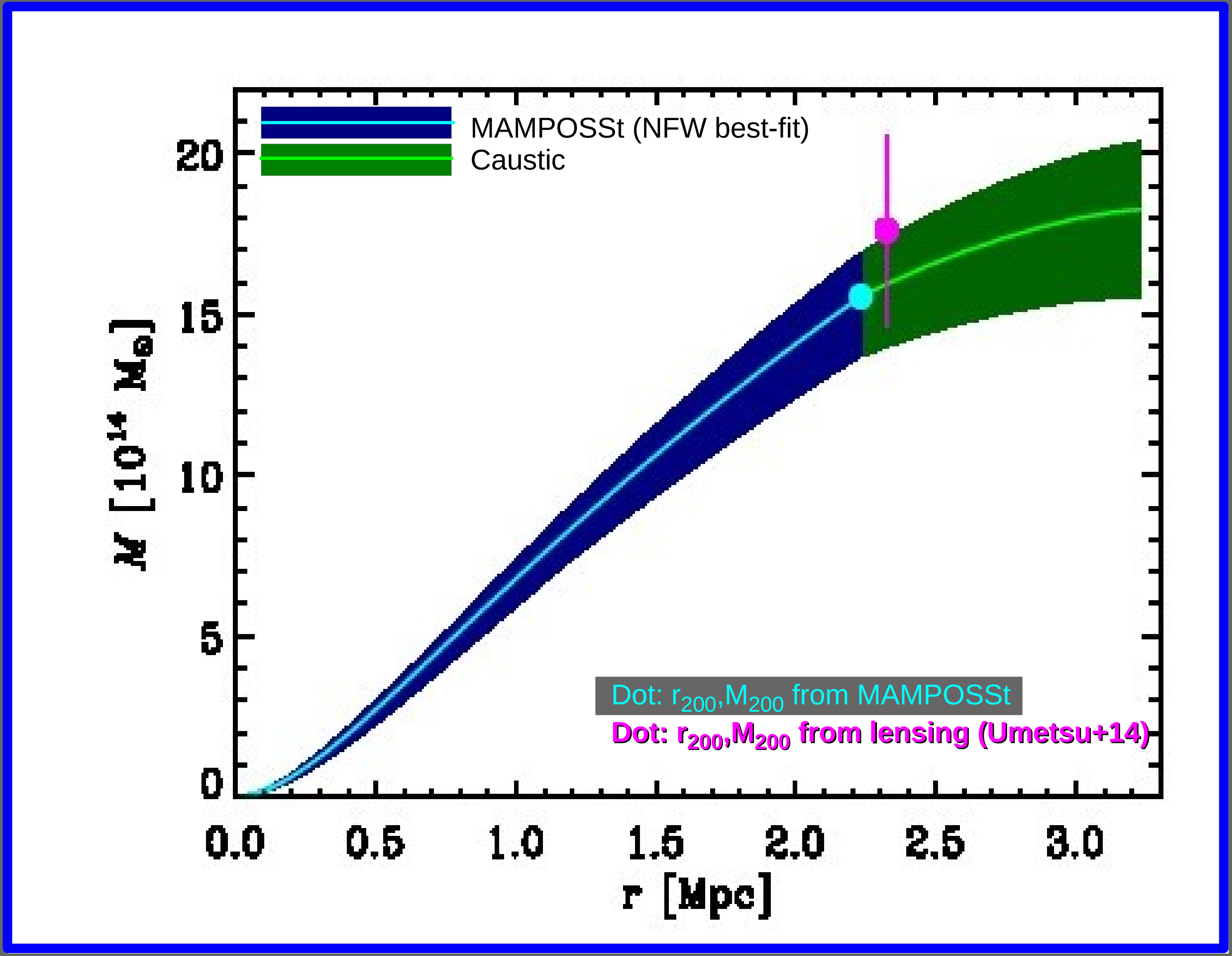


Dot: r_{200},M_{200} from MAMPOSSt

The mass profiles

Abell 209 *[Sartoris, AB et al. in prep.]*

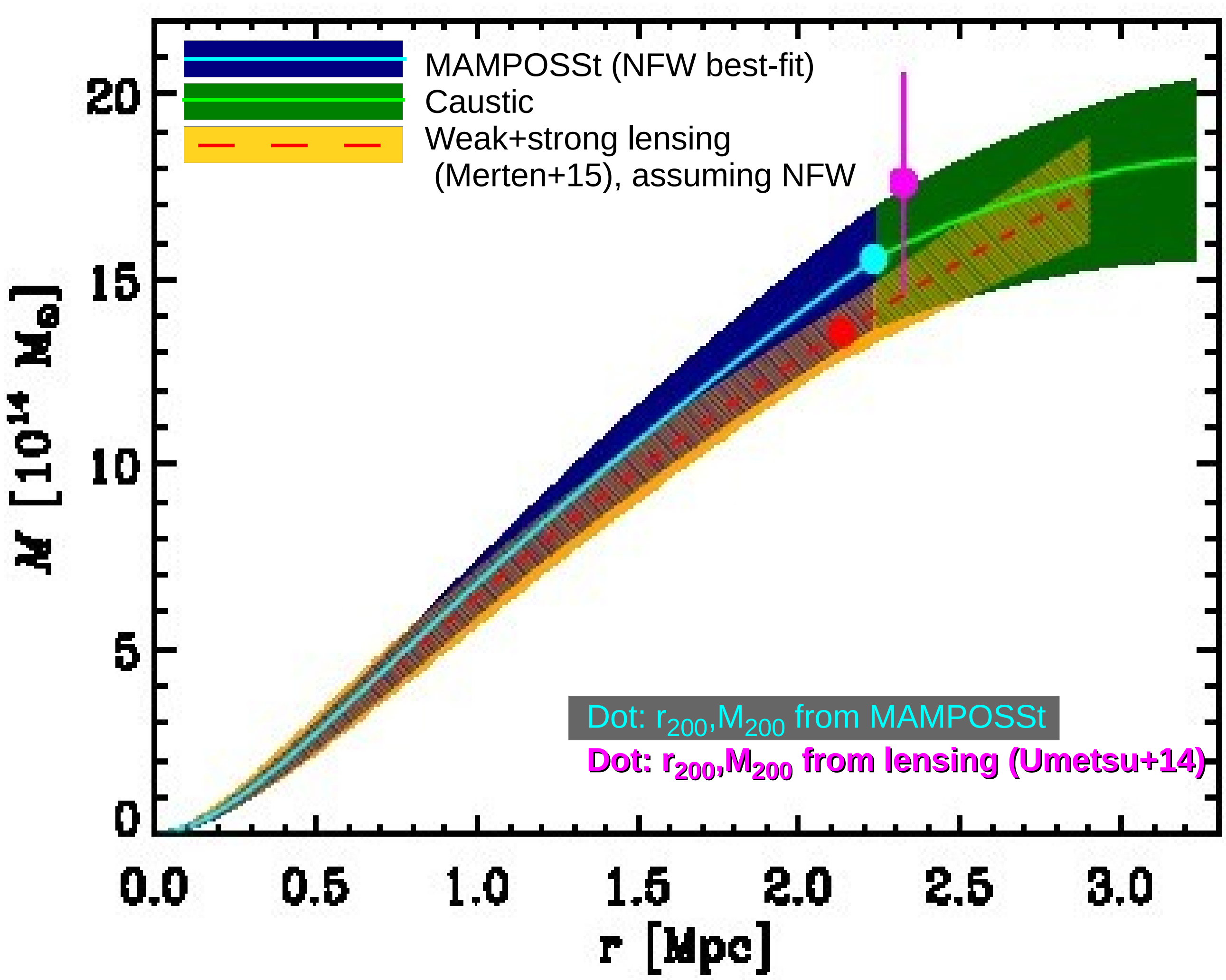
Best-fit M(r) model is NFW



The mass profiles

Abell 209 *[Sartoris, AB et al. in prep.]*

Best-fit M(r) model is NFW



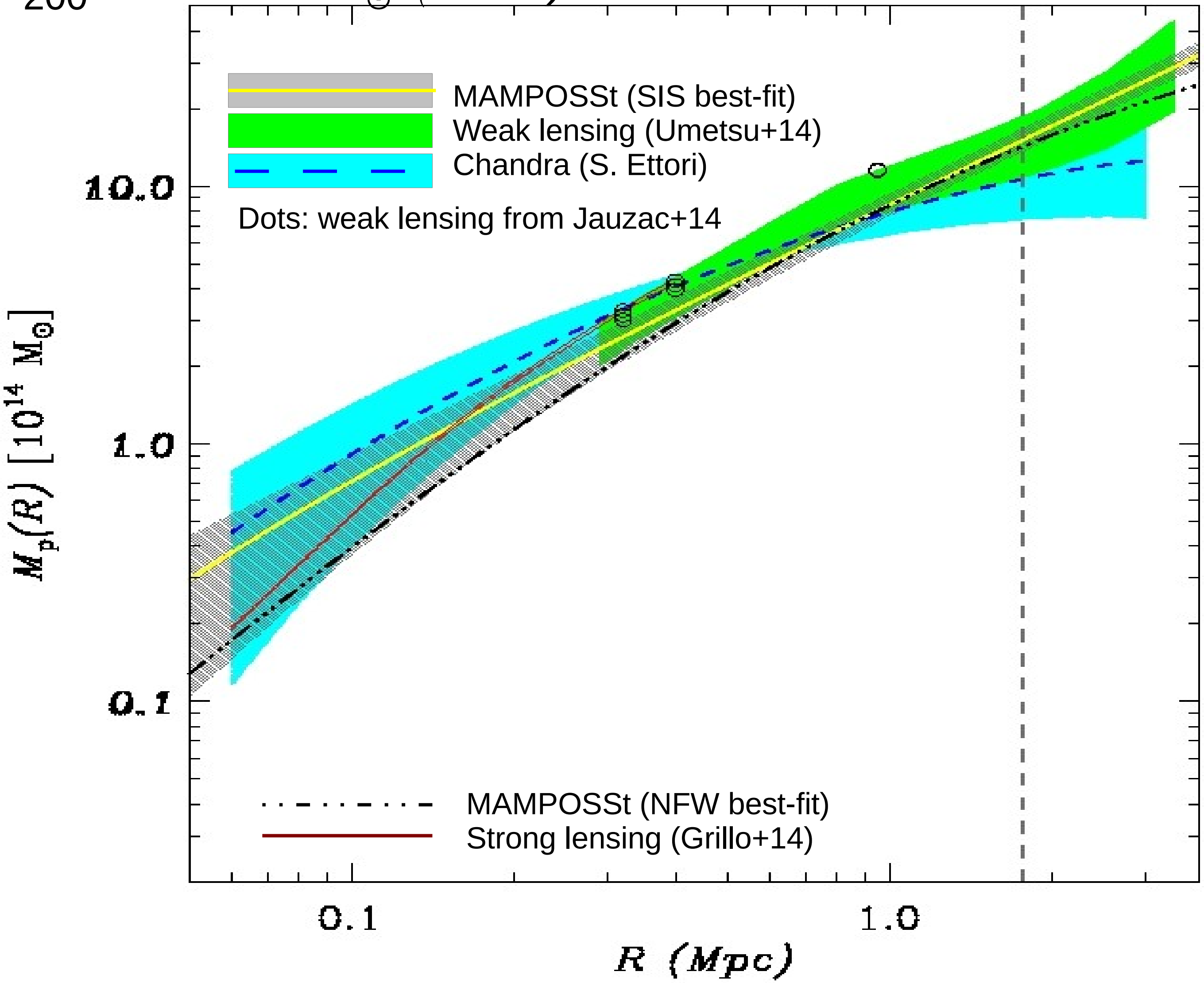
Good agreement between M(r) derived using galaxies as tracers of the gravitational potential and M(r) derived from lensing

MAMPOSSt + Caustic recovers the 3D mass profile M(r).
We compare to the deprojected lensing determination.

The mass profiles

MACS0416 (Balestra et al. in prep.)

M_{200}=9.3 10^{14} $M_\odot$ (*h*=0.7)



Best-fit M(r) model is not NFW but SIS

Good agreement between M(r) derived using galaxies as tracers of the gravitational potential and M(r) derived from lensing (less good with M(r) from X-ray)

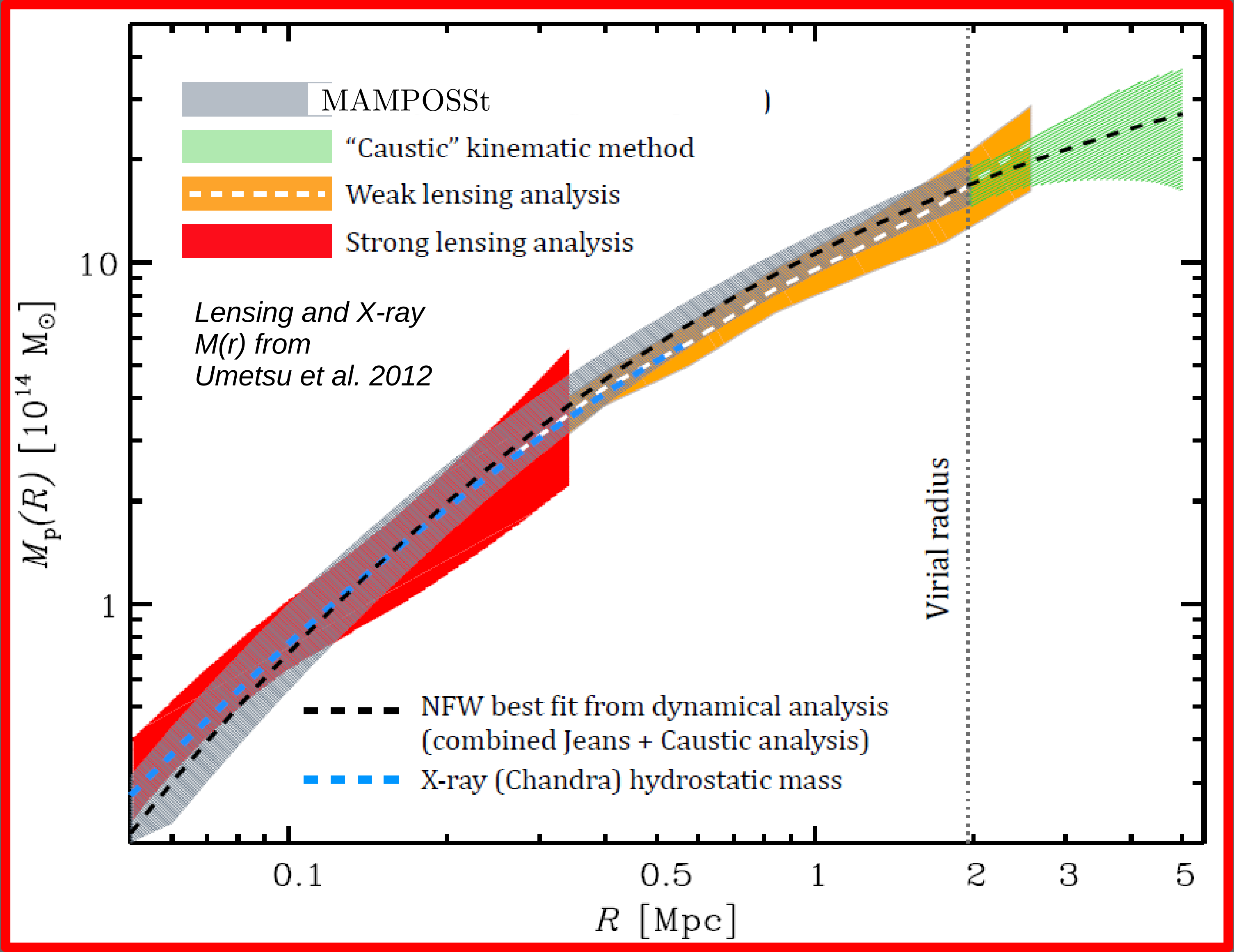
MAMPOSSt + Caustic recovers the 3D mass profile M(r).
We project it along the l.o.s. to allow comparison with the lensing determination.

The mass profiles

M_{200}=13.7 10^{14} $M_\odot$ *(h=0.7)*

MACS1206 *(AB et al. 2013)*

Best-fit M(r) model is NFW



Good agreement between M(r) derived using galaxies as tracers of the gravitational potential and M(r) derived from lensing and from X-ray

MAMPOSSt + Caustic recovers the 3D mass profile M(r).
We project it along the l.o.s. to allow comparison with the lensing determination.

The internal dynamics of CLASH-VLT clusters:

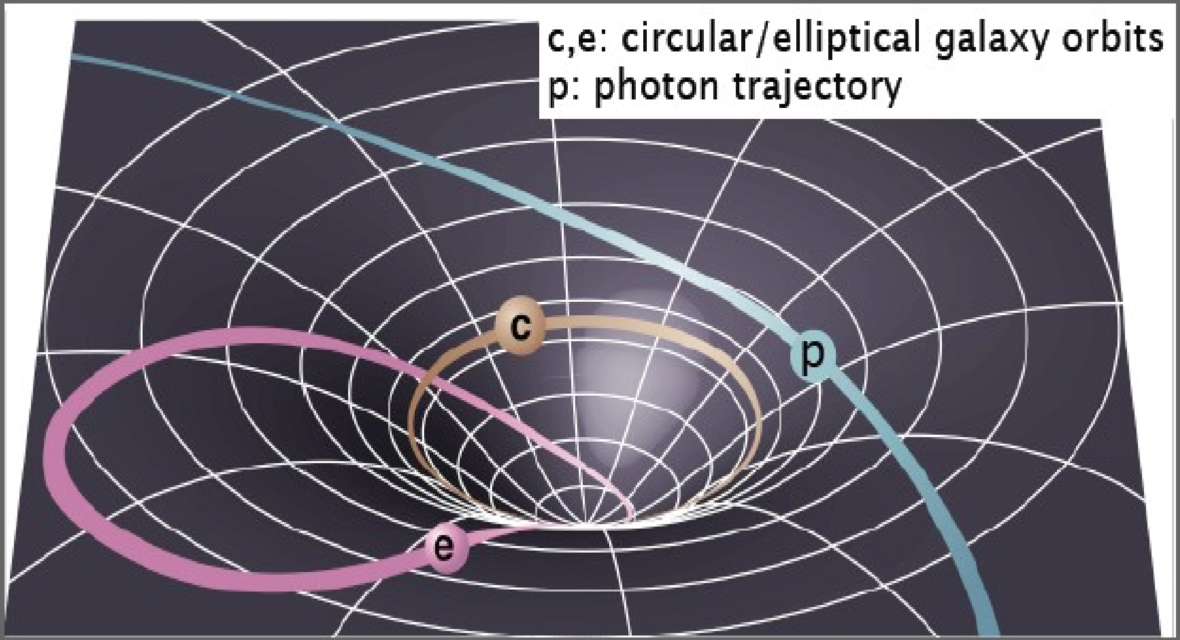
Dark Matter

equation of state

Comparing the M(r) traced by galaxies and by lightrays (lensing)

(Sartoris et al. 2014)

In GR, the cluster potential well ϕ is shaped by the whole mass-energy content of the clusters: density and pressure separately


c,e: circular/elliptical galaxy orbits
p: photon trajectory

Galaxies are non relativistic,
their velocity distribution depends only on ϕ'(r)

$$\Phi'(r) = \frac{Gm_k}{r^2};$$

Light trajectories respond to both ϕ'(r)
and a relativistic term depending on m(r)

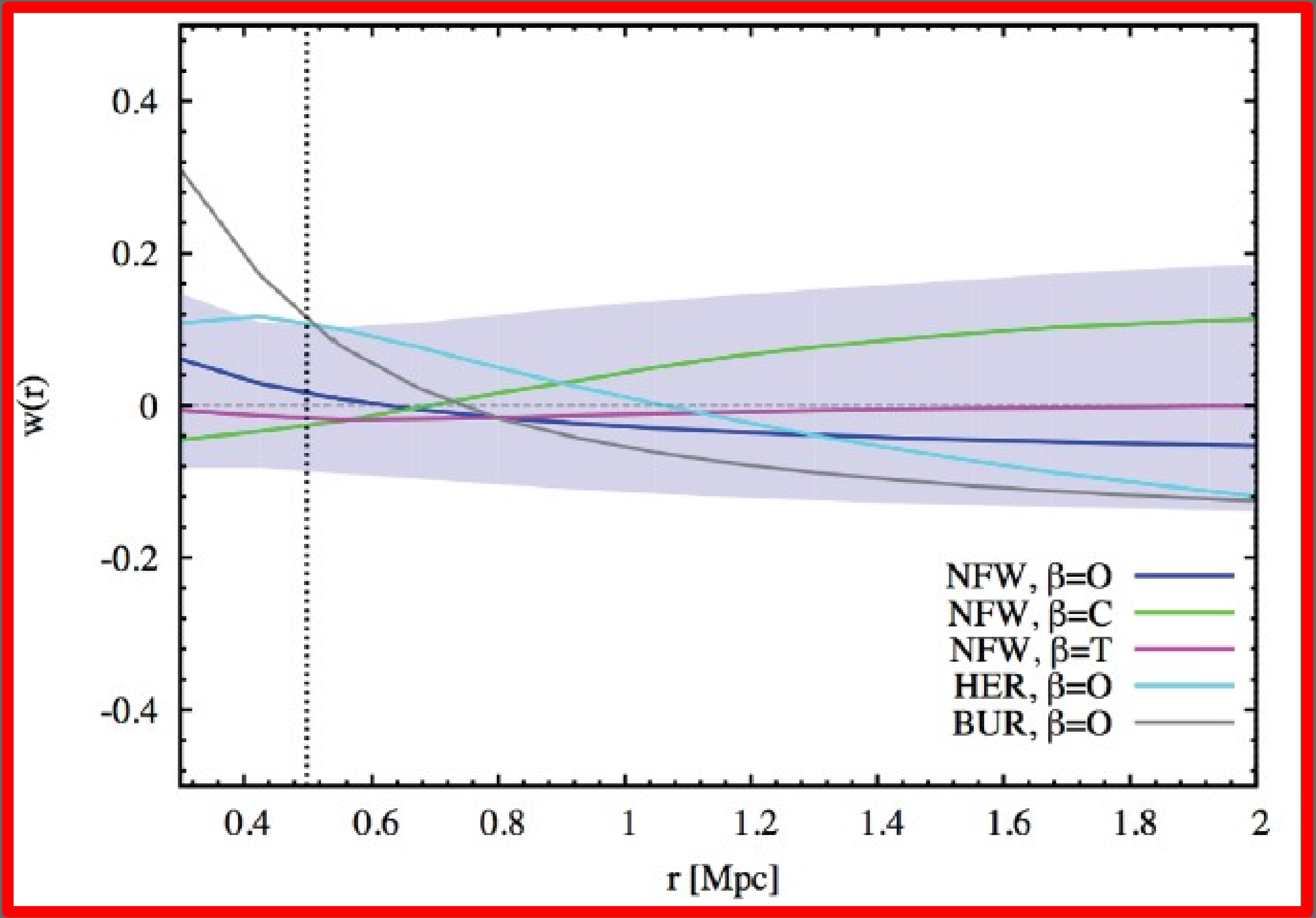
$$m(r) = 2m_{lens}(r) - m_k$$

$$2\,\Phi_{\rm lens}(r) = \Phi(r) + \int \frac{m(r)}{r^2}\,{\rm d}r$$

The Dark Matter equation of state

$$w(r) = \frac{p_r(r) + 2p_t(r)}{3\rho(r)} \approx \frac{2}{3}\,\frac{m'_{\rm K}(r) - m'_{\rm lens}(r)}{2\,m'_{\rm lens}(r) - m'_{\rm K}(r)}$$

Averaging over all radii
w = -0.00 ± 0.15 (stat) ± 0.8 (syst)



(Sartoris et al. 2014; based on a single cluster CLASH-VLT so far)

The internal dynamics of CLASH-VLT clusters:
The pseudo-phase-space density profile Q(r)

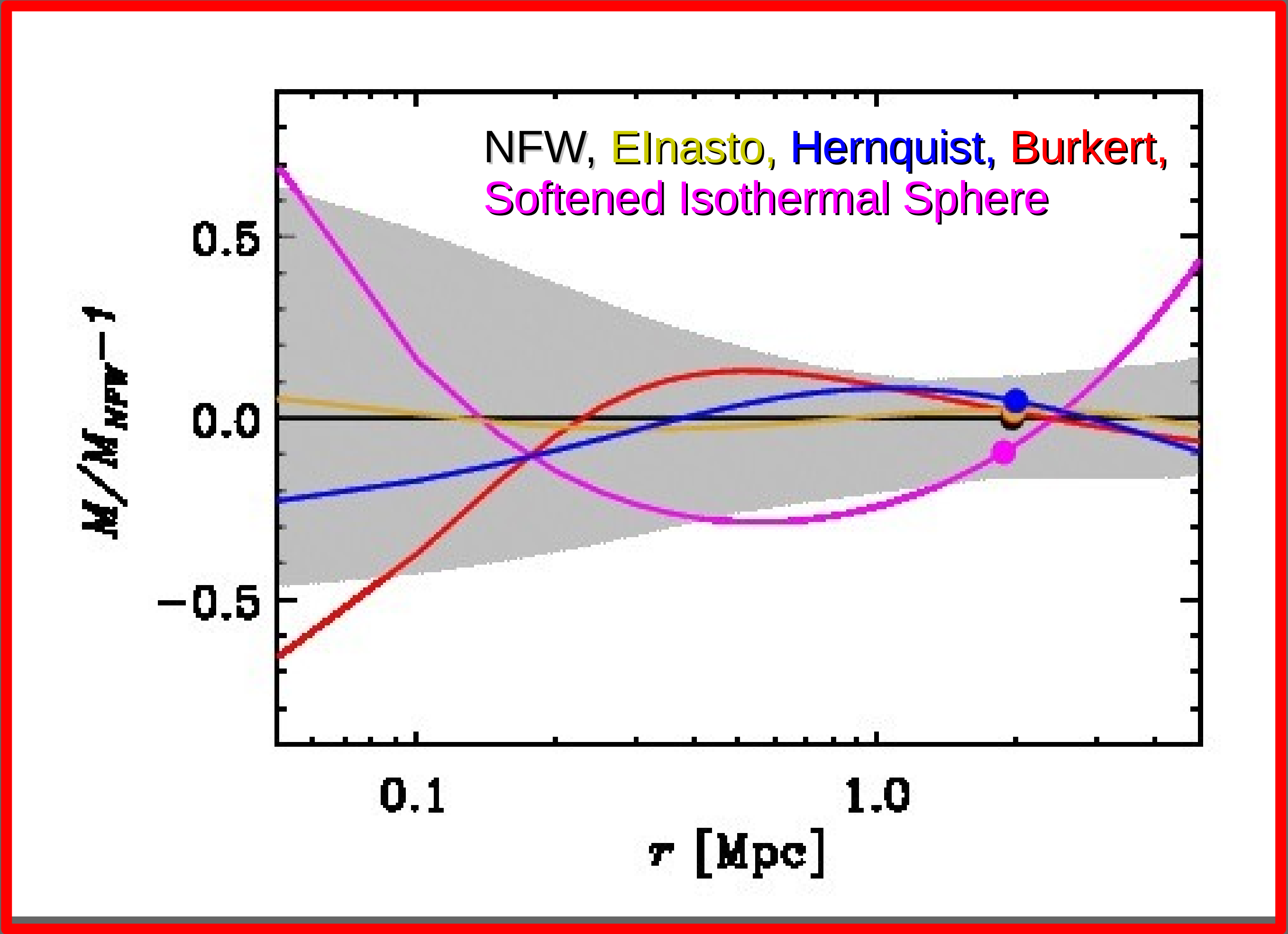
Q(r)

The pseudo-phase-space density profiles of cosmological halos

MACS1206 and Abell 209 are best fitted by the NFW mass profile.

MACS416 is best fitted by the SIS mass profile.

Is there a more fundamental physical quantity that is common to the three clusters?



MACS1206: Ratio of different mass profile best-fitting models

The pseudo-phase-space density profiles of cosmological halos

Taylor & Navarro 2001:
the shape of the PPS density profile of cosmological halos,

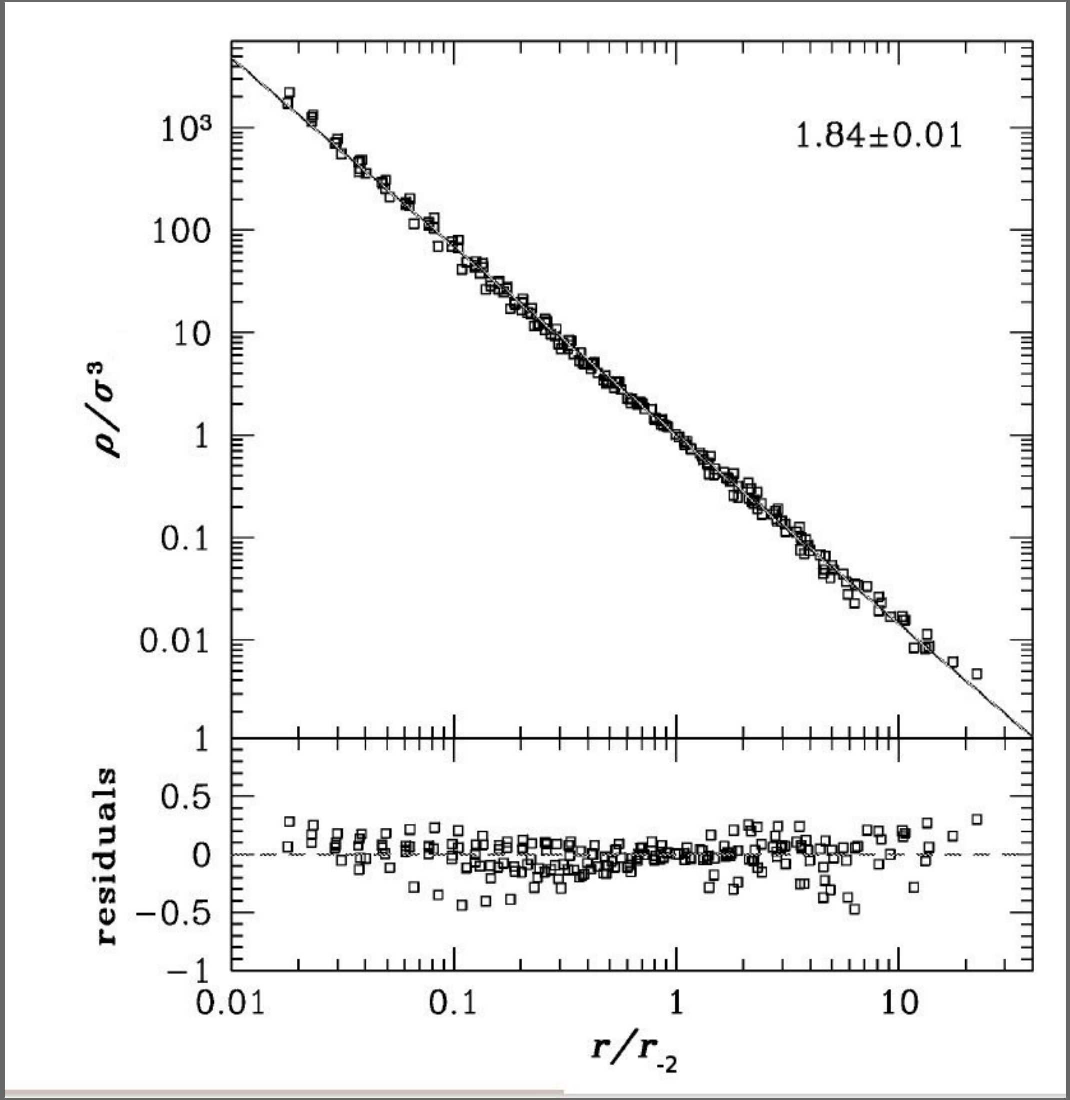
Q(r) = ρ/σ^3

ρ *mass density profile,*
σ *velocity dispersion profile*

is a **universal power-law**

Why?

A scale-invariant profile may result from violent relaxation, subsequently dynamical equilibrium sets the exponent value *(Dehnen & McLaughlin 2005)*



The pseudo-phase-space density profiles of cosmological halos

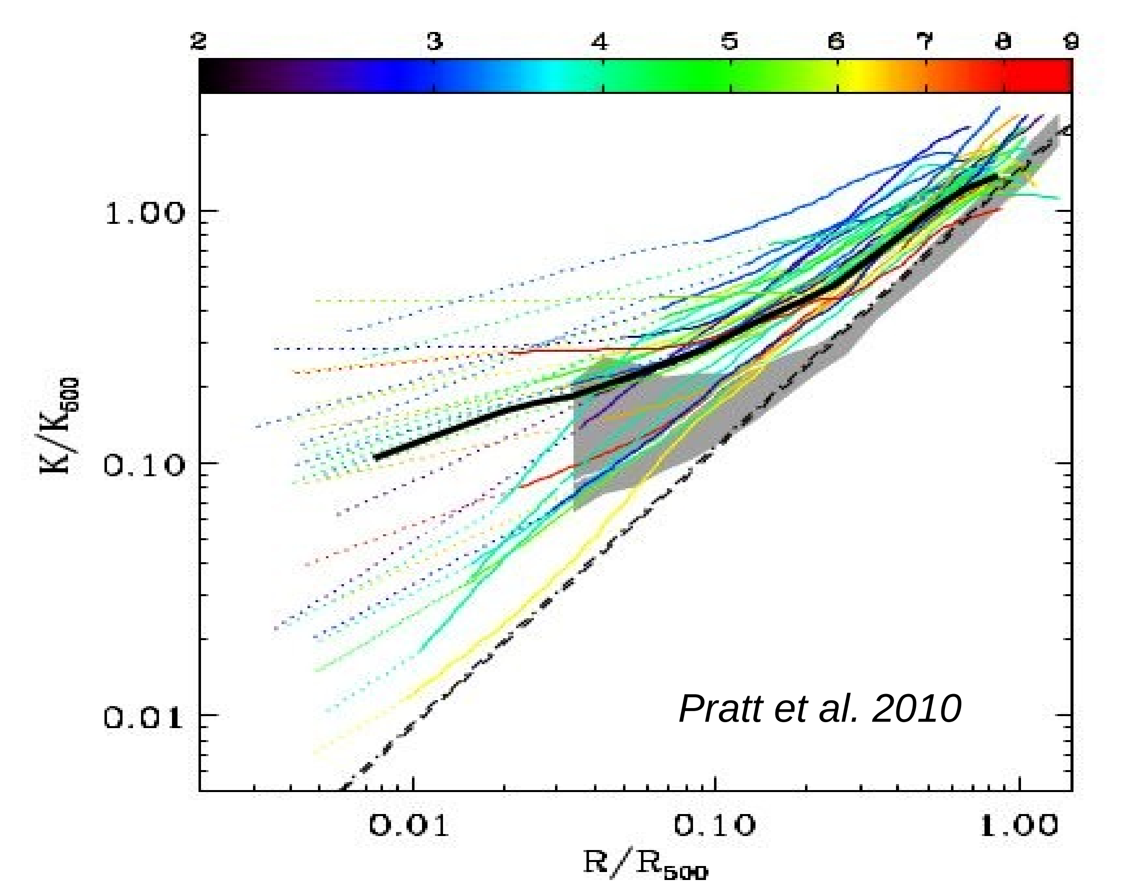
The physical meaning of Q(r): related to the entropy of the system

X-ray observers define the intra-cluster gas 'entropy' $K \equiv kT / n_e^{2/3}$

Taking $kT \sim \sigma_v^2$, $n_e \sim \rho$
→ $Q \sim K^{-3/2}$

K(r) is not a simple power-law for galaxy clusters, suggesting non-gravitational processes shape K(r) of the gas

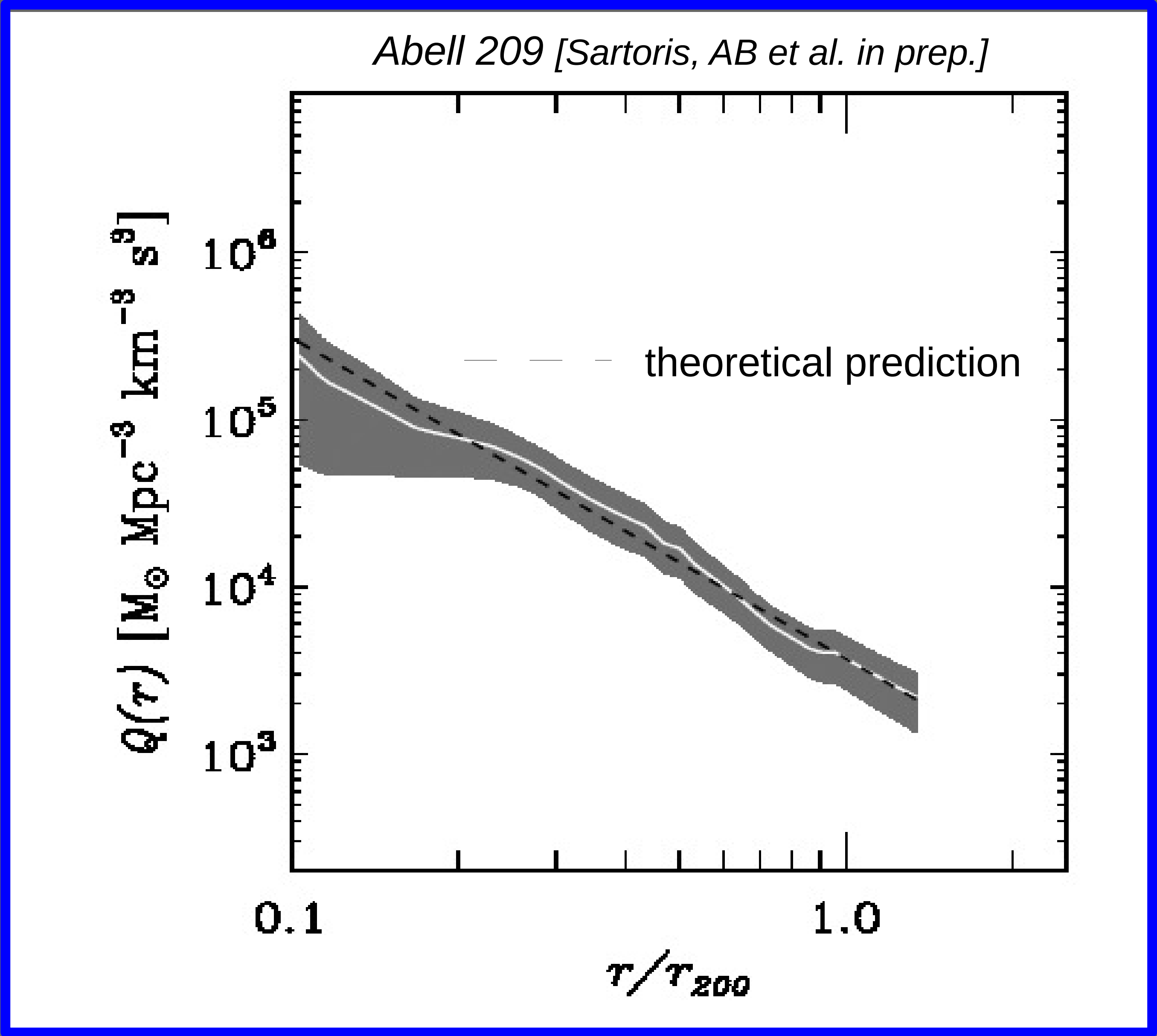
What about (presumed) non-collisional matter (DM, galaxies)?



Q(r)

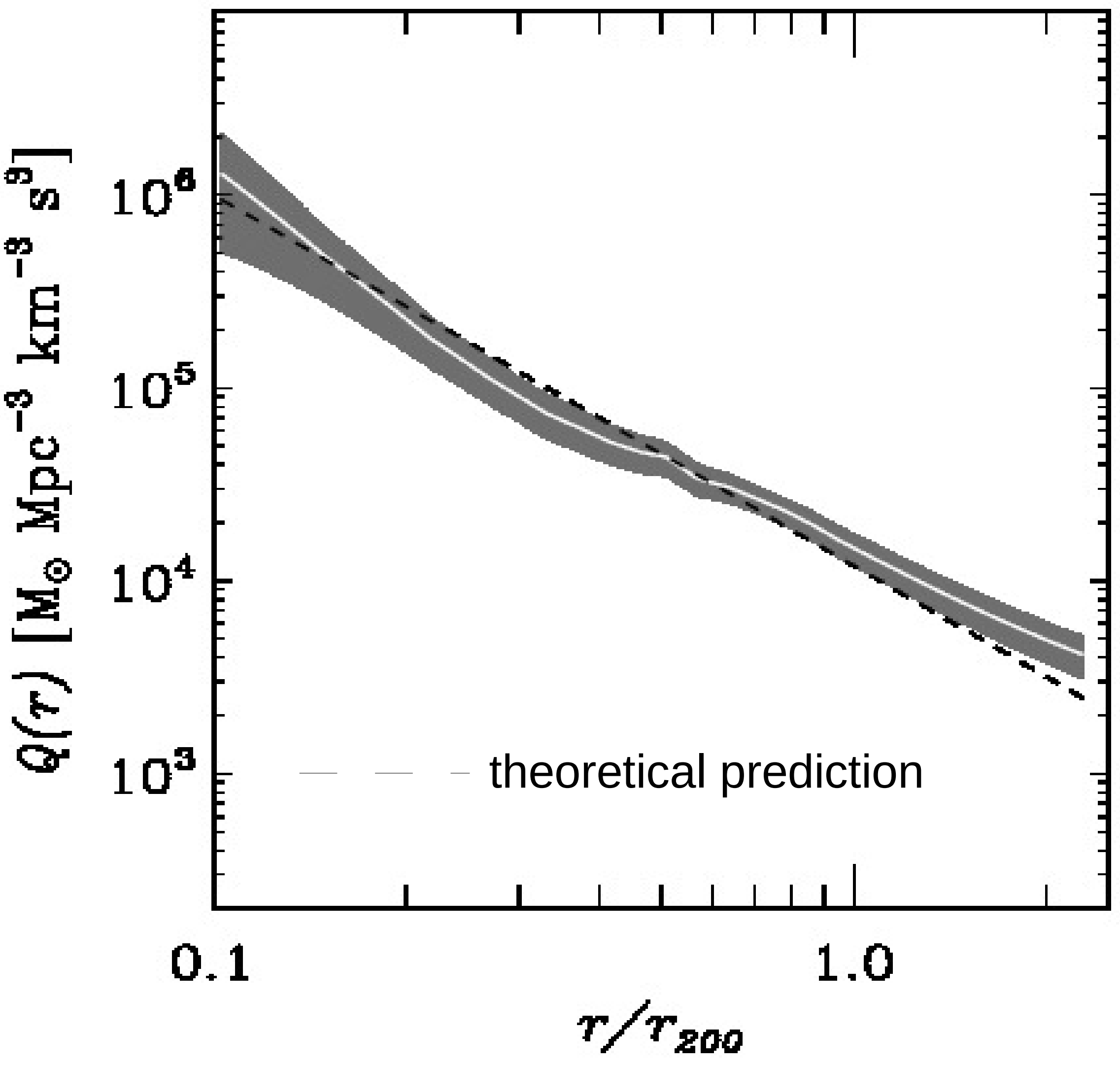
We have ρ (from mass profiles) and σ (from l.o.s. velocity dispersion profiles deprojection), so we can determine Q(r) observationally

Good agreement between observed and theoretically/ numerically expected Q(r) profile


Abell 209 *[Sartoris, AB et al. in prep.]*

Good agreement between observed and theoretically/ numerically expected Q(r) profile

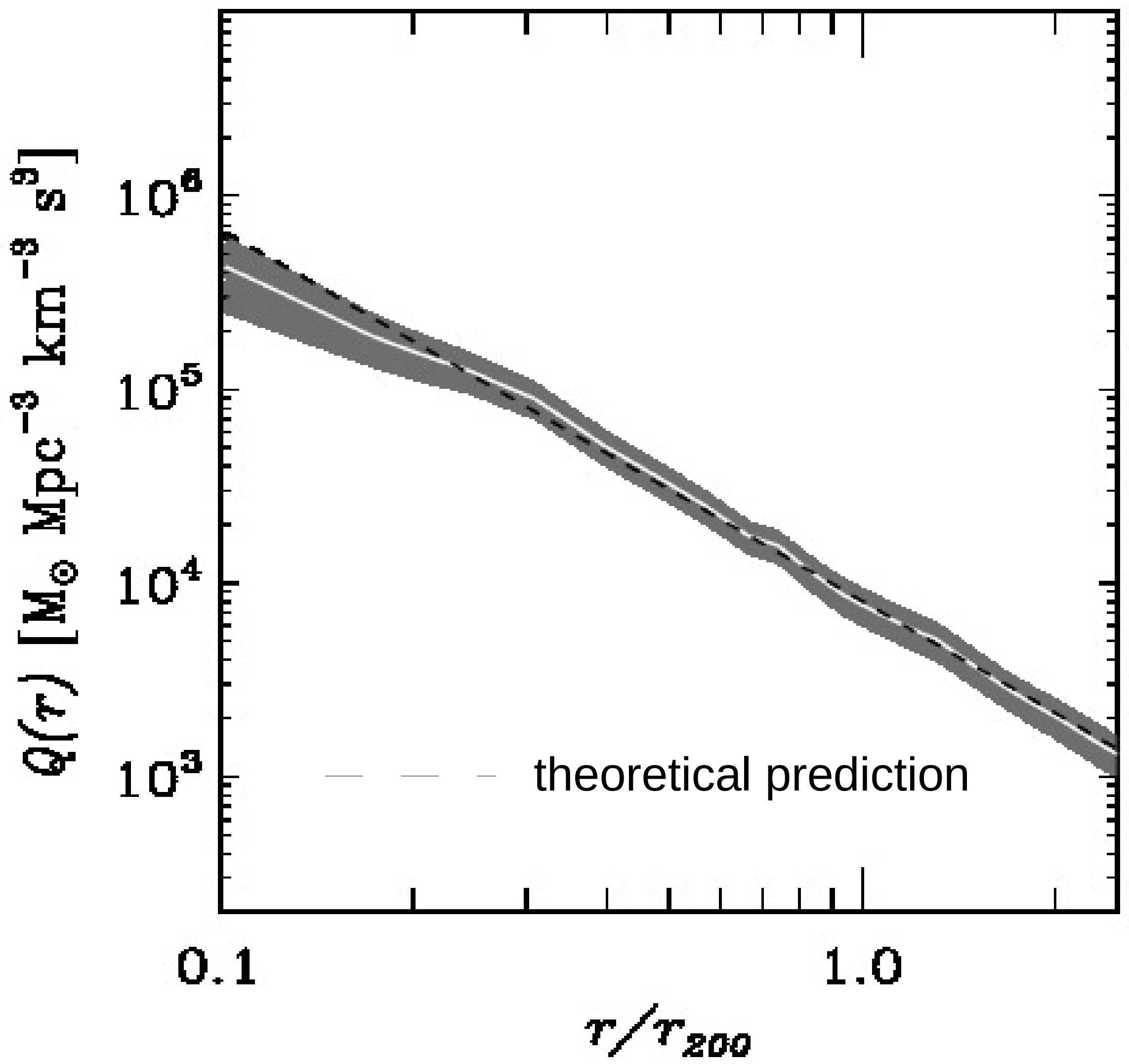
MACS0416 *[Sartoris, AB et al. in prep.]*



Q(r)

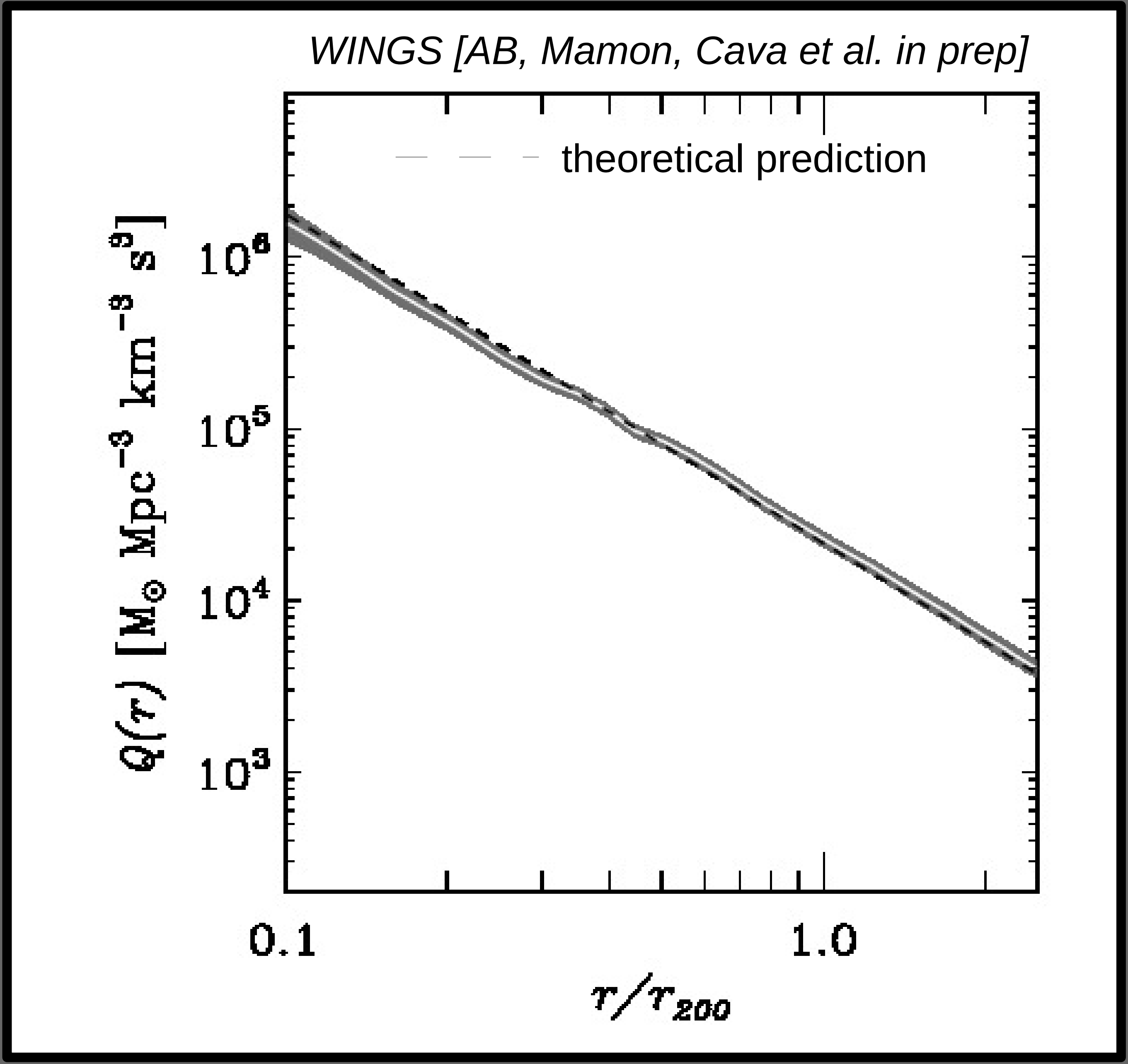
Good agreement between observed and theoretically/ numerically expected Q(r) profile

MACS1206 *[AB et al. 2013]*



What about Q(r) evolution?

The same relation also holds at **low** redshift ($\langle z\rangle=0.05$)

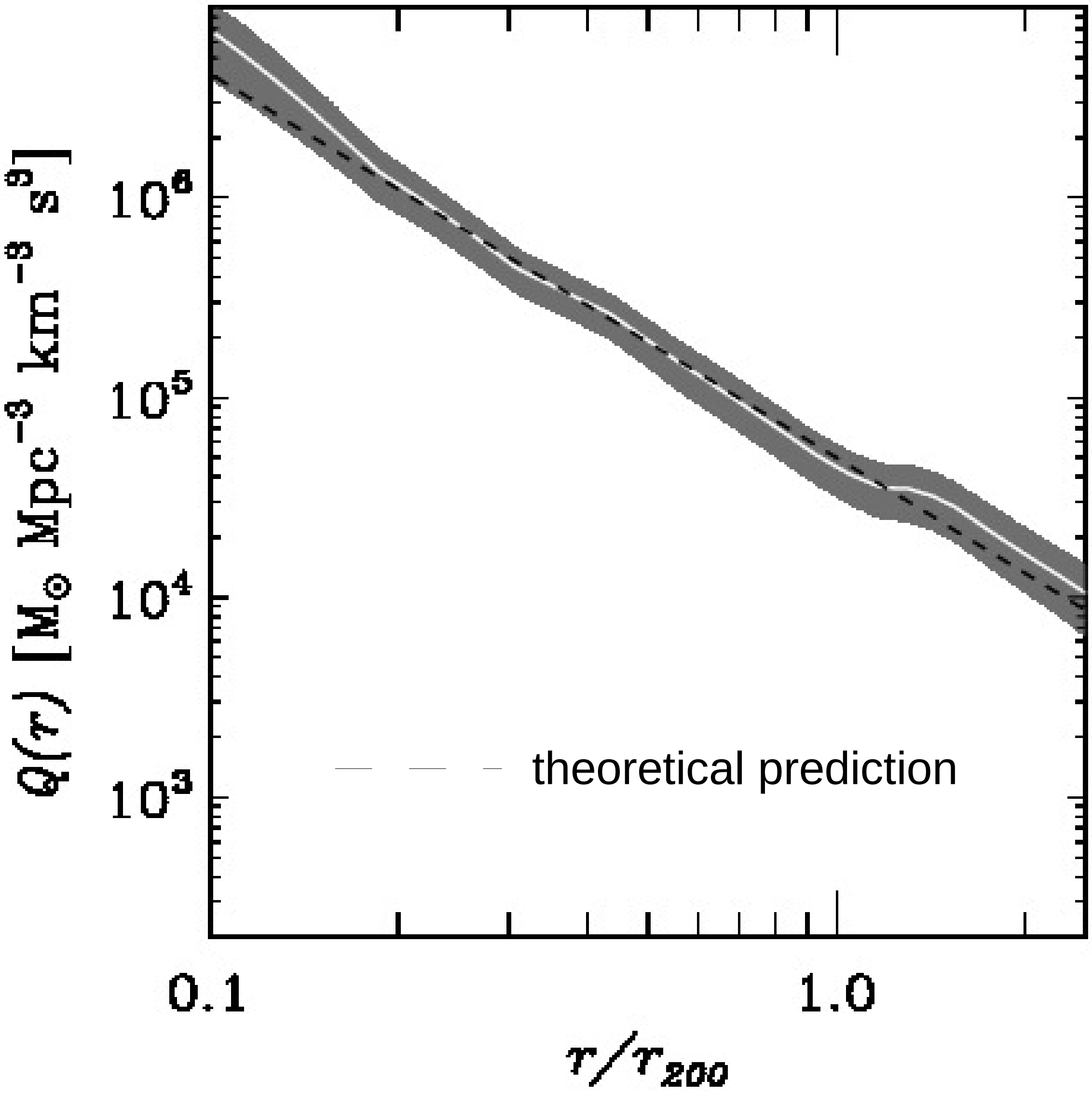


Stack of 40 relaxed clusters from the WINGS sample, ≈ 4900 cluster members

What about Q(r) evolution?

The same relation also holds at **high** redshift ($\langle z \rangle=1.02$)

GCLASS [AB, van den Burg, Muzzin et al. in prep]



Stack of 10 clusters from the GCLASS sample, ≈ 400 cluster members

The internal dynamics of CLASH-VLT clusters:

Stellar-to-mass profile ratio

Learning about galaxy evolution in clusters

Abell 209 and MACS 1206: similar *total* mass profiles

But what about their *stellar* mass profiles?

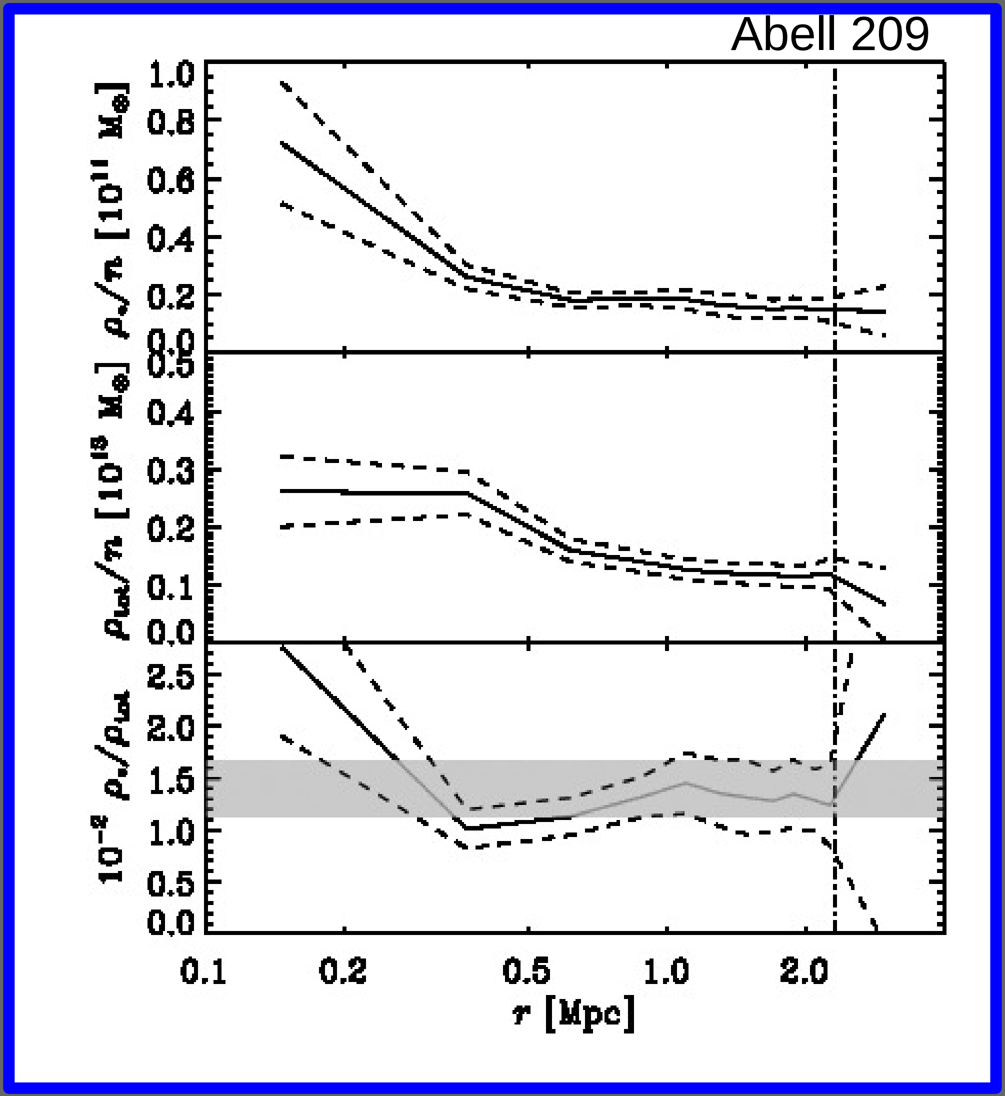
They may inform us on processes affecting galaxy evolution in the clusters environment.

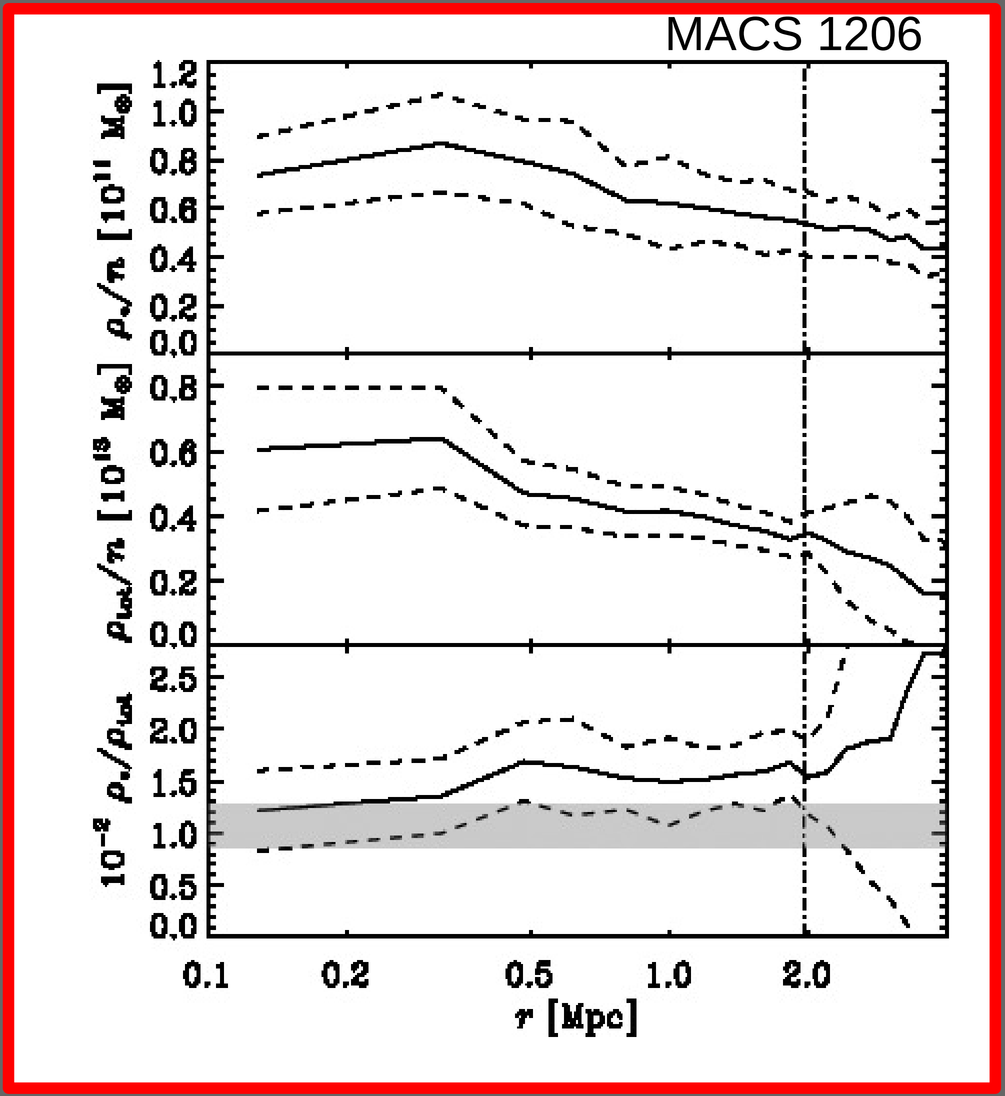
Combine the spectroscopic sample with a photometric sample selected in z_{phot} to achieve 100% completeness.

Fit galaxy spectral energy distributions with MAGPHYS *(da Cunha et al. 2008)* to get the galaxy stellar masses, M_*

Total vs. stellar mass density profiles

[Annunziatella, AB, et al. 2014; Annunziatella, Mercurio, AB et al. in prep.]



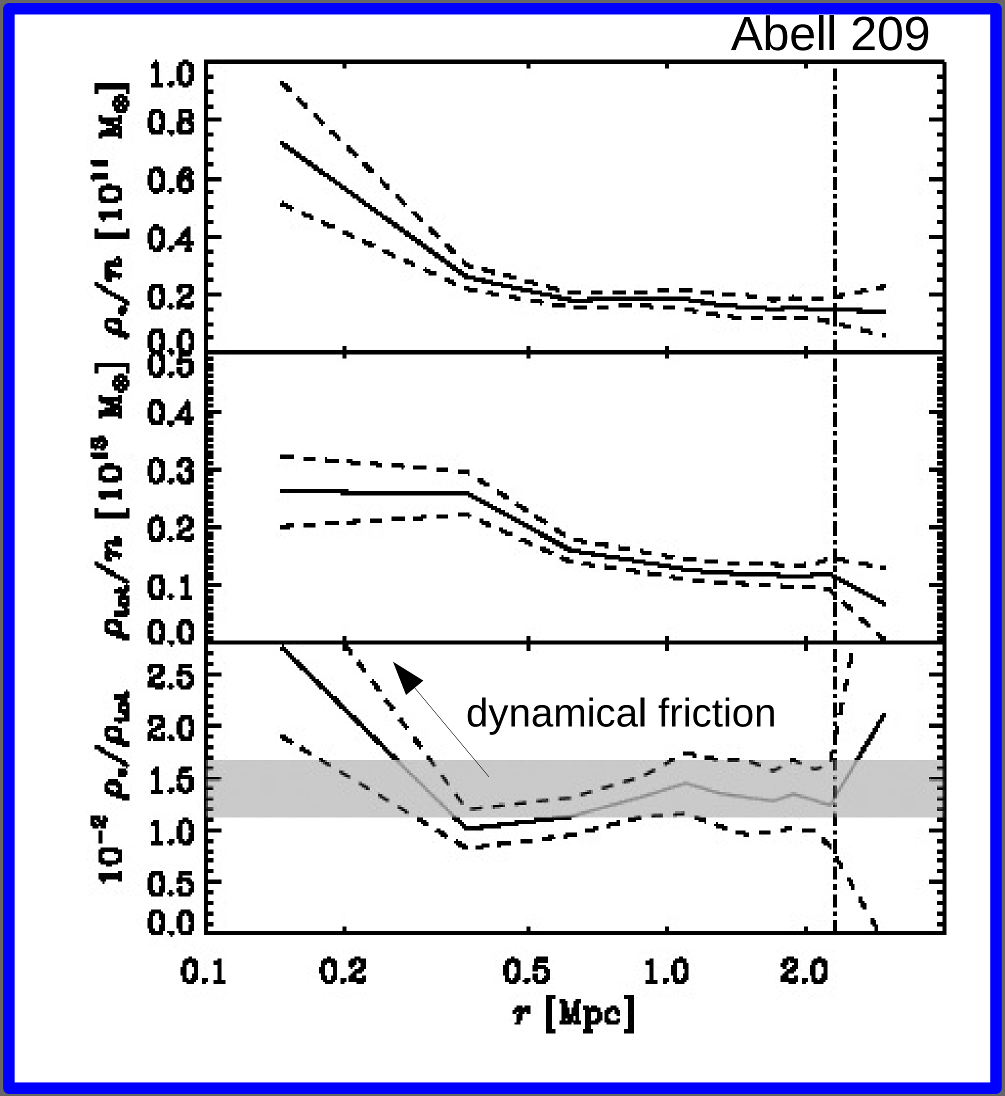


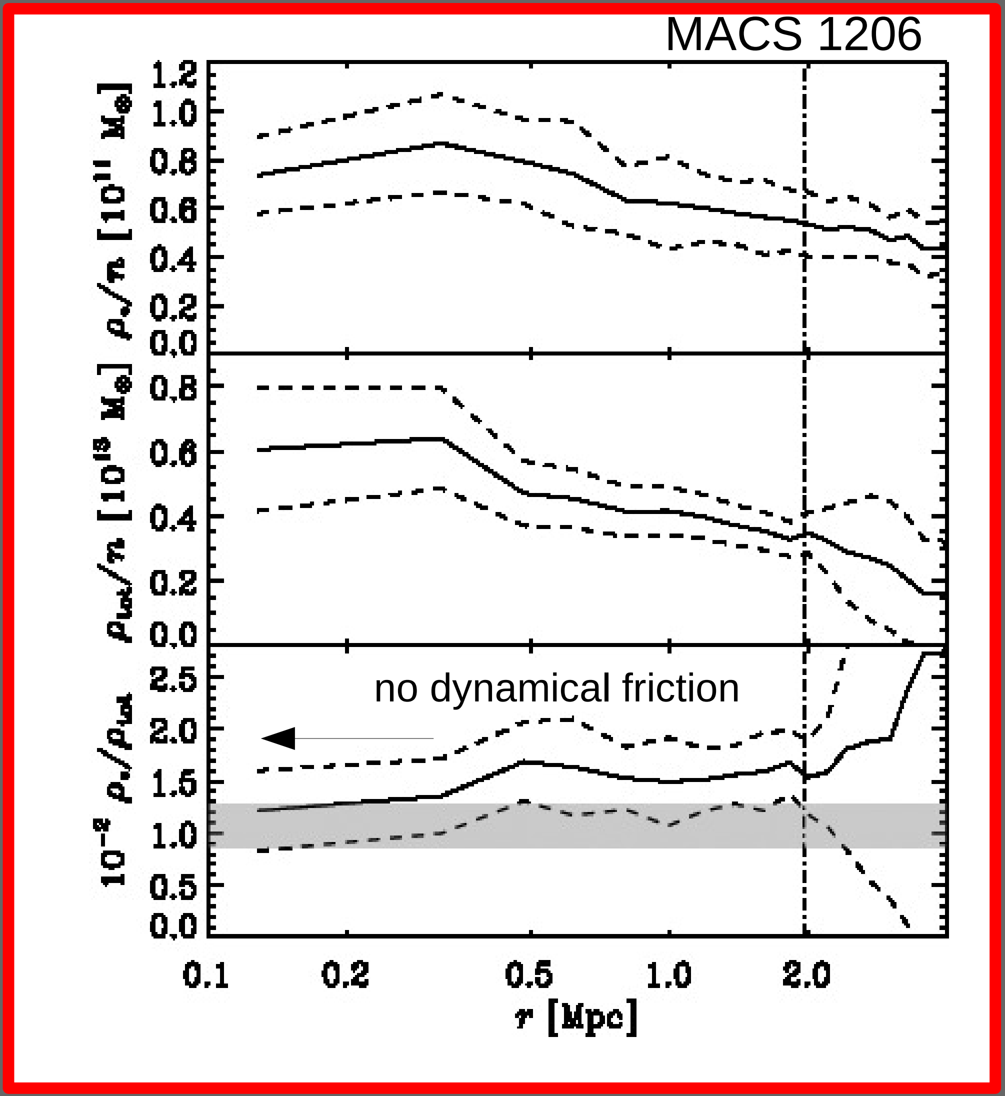
stellar mass density profile, $\rho_*(r)$
galaxy number density profile, $n(r)$
total mass density profile, $\rho_{tot}(r)$

▨ Shading: cosmic value of stellar mass fraction at the cluster <z>

Total vs. stellar mass density profiles

[Annunziatella, AB, et al. 2014; Annunziatella, Mercurio, AB et al. in prep.]





stellar mass density profile, $\rho_*(r)$
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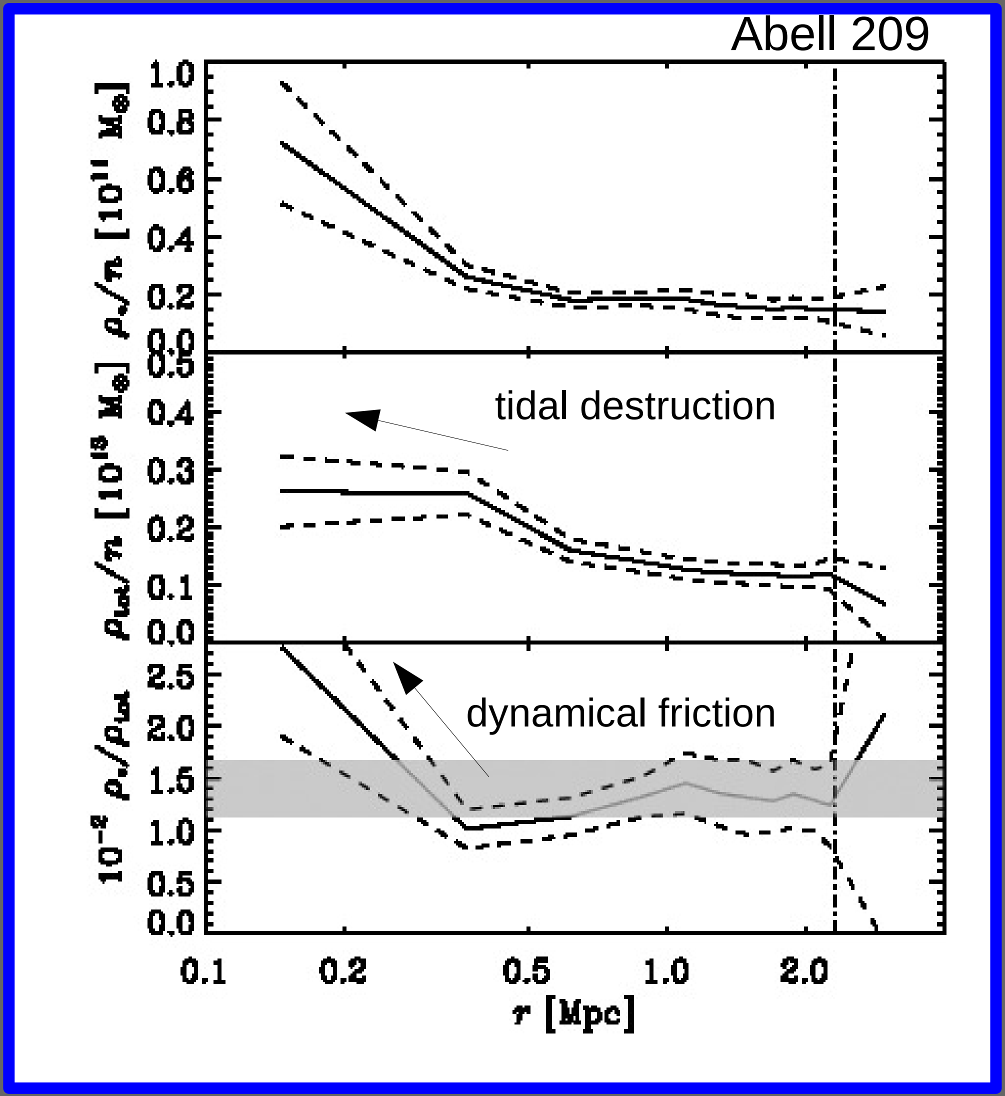

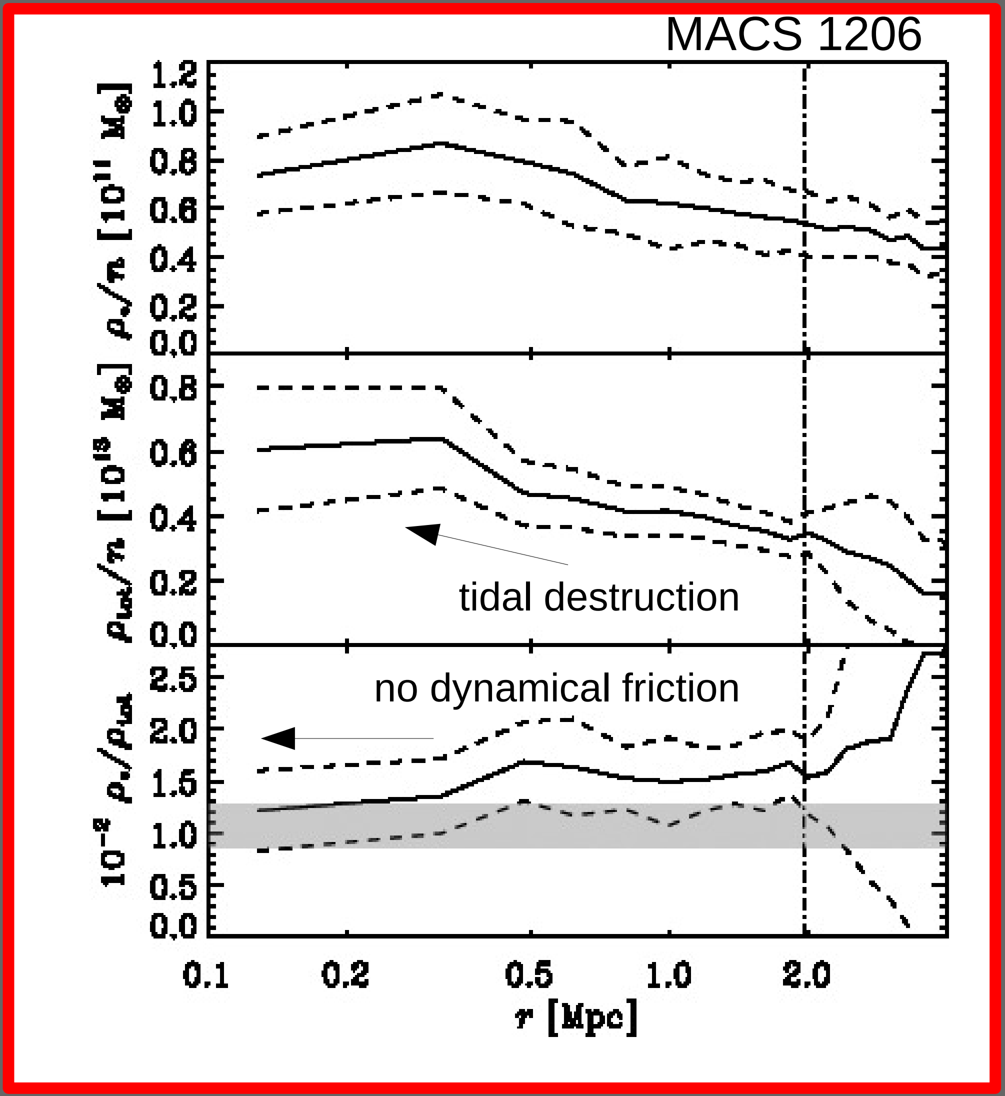

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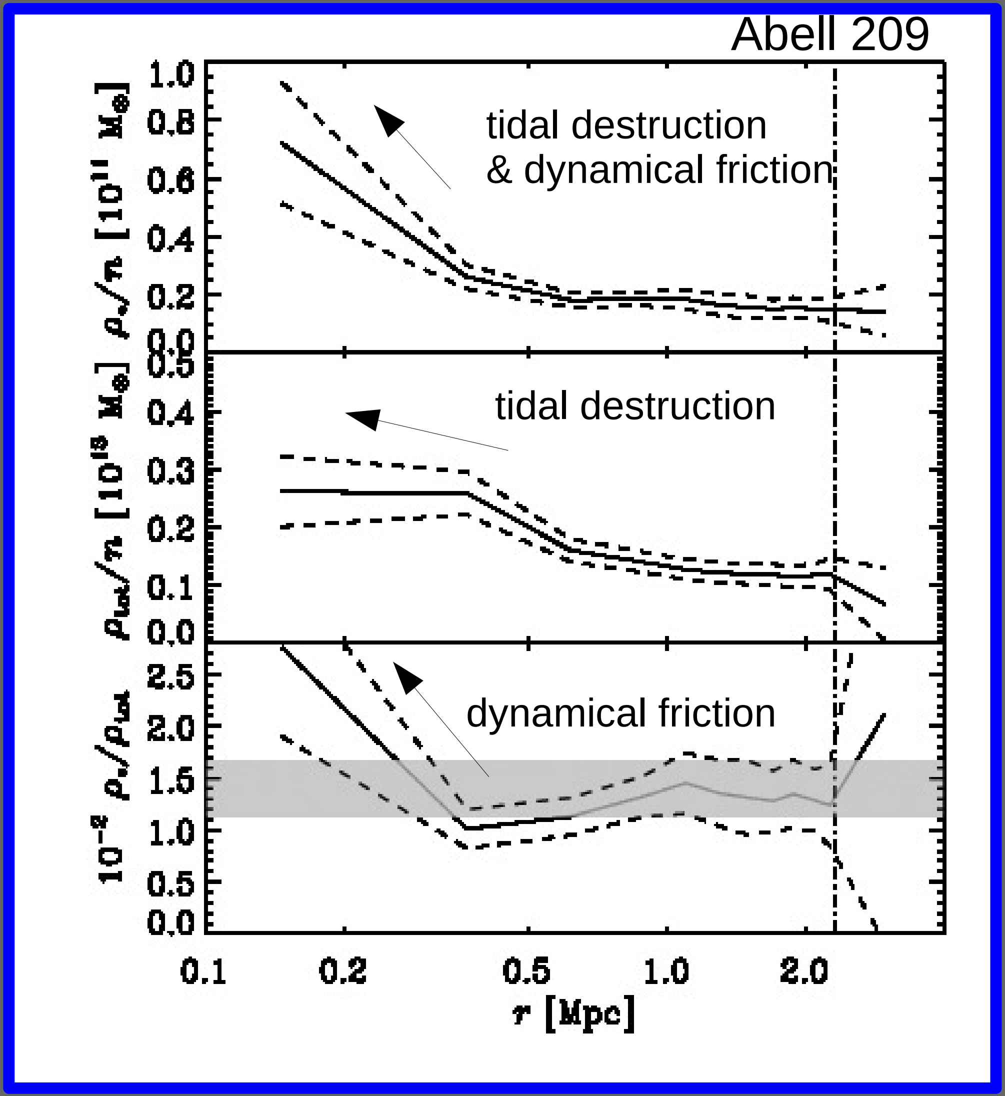
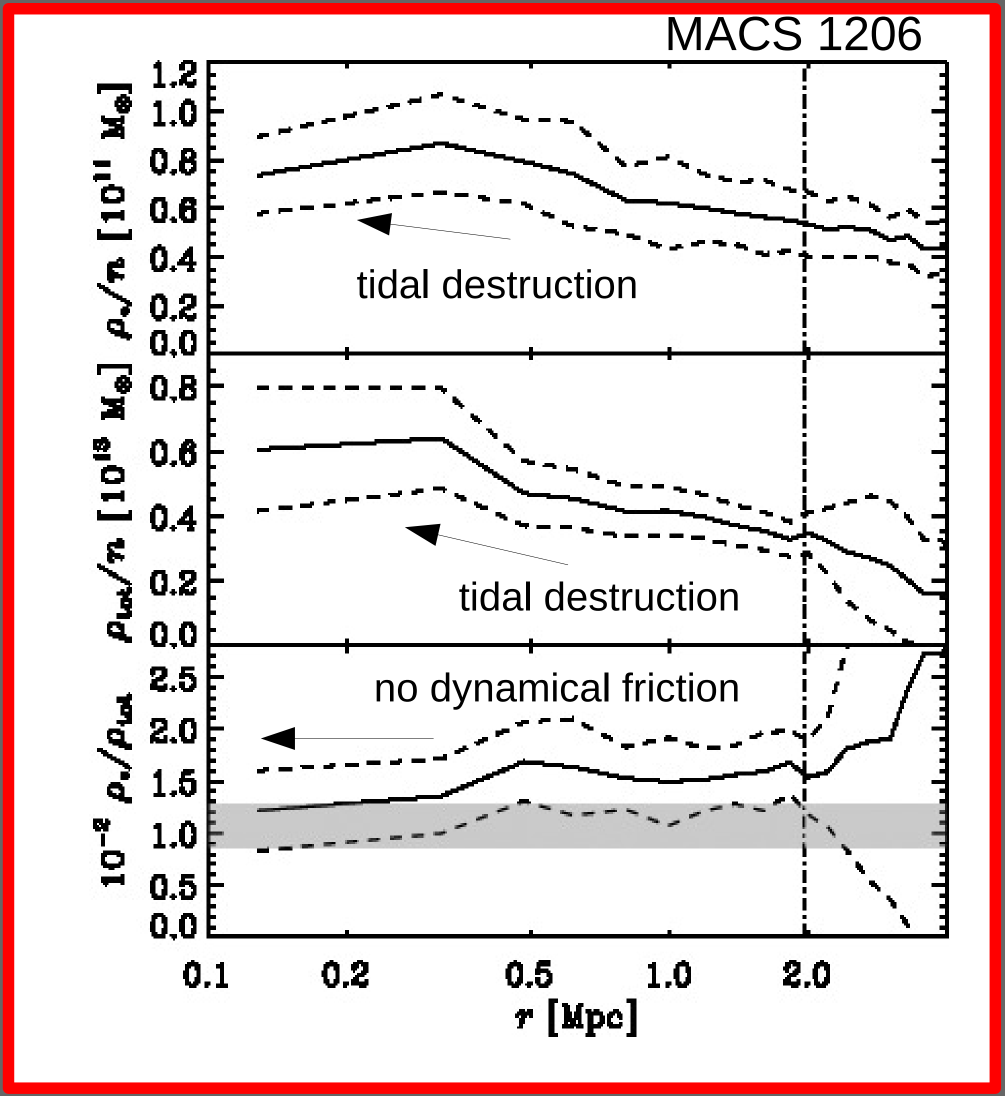




stellar mass density profile, $\rho_*(r)$
galaxy number density profile, $n(r)$
total mass density profile, $\rho_{tot}(r)$

▨ Shading: cosmic value of stellar mass fraction at the cluster <z>

The internal dynamics of CLASH-VLT clusters:

Orbits of galaxies in clusters β(r)

(Got the big brezel in the end!)

Inverting the Jeans equation

Define a fiducial mass profile from the combination of MAMPOSSt, Caustic and lensing M(r) and get a direct, non-parametric estimate of β(r) from the inversion of the Jeans equation
[Binney & Mamon 82, Solanes & Salvador-Solé 90]

Compare with MAMPOSSt parametric solutions (cross-check)

Observables
N(R), σ_{los}(R)

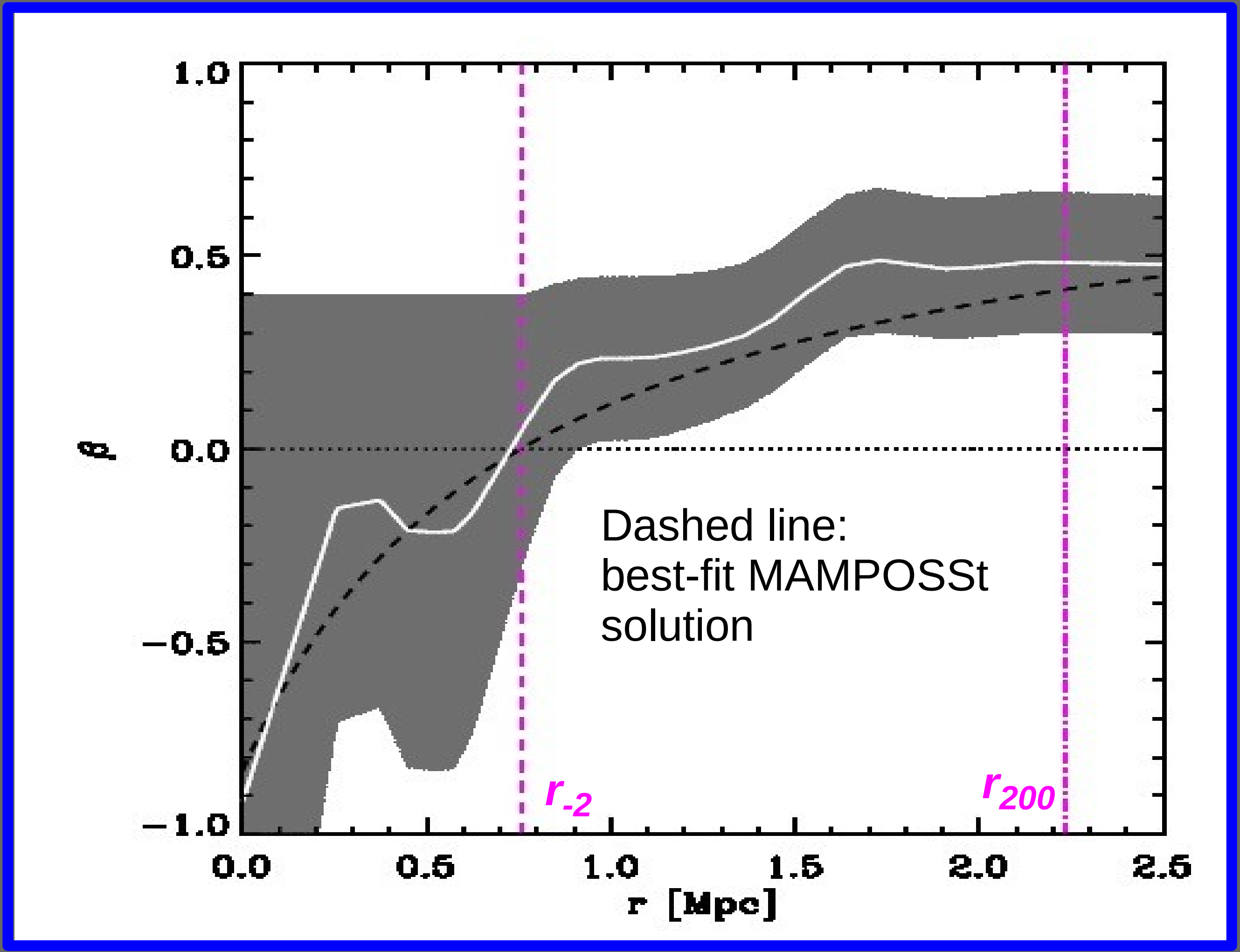
+M(r) →

→ β(r)

number density profile &
l.o.s. velocity dispersion
profile of cluster members

Galaxy orbits

A0209, *[Sartoris, AB et al. in prep.]*



Dashed line:
best-fit MAMPOSSt solution

radial orbits

tangential orbits

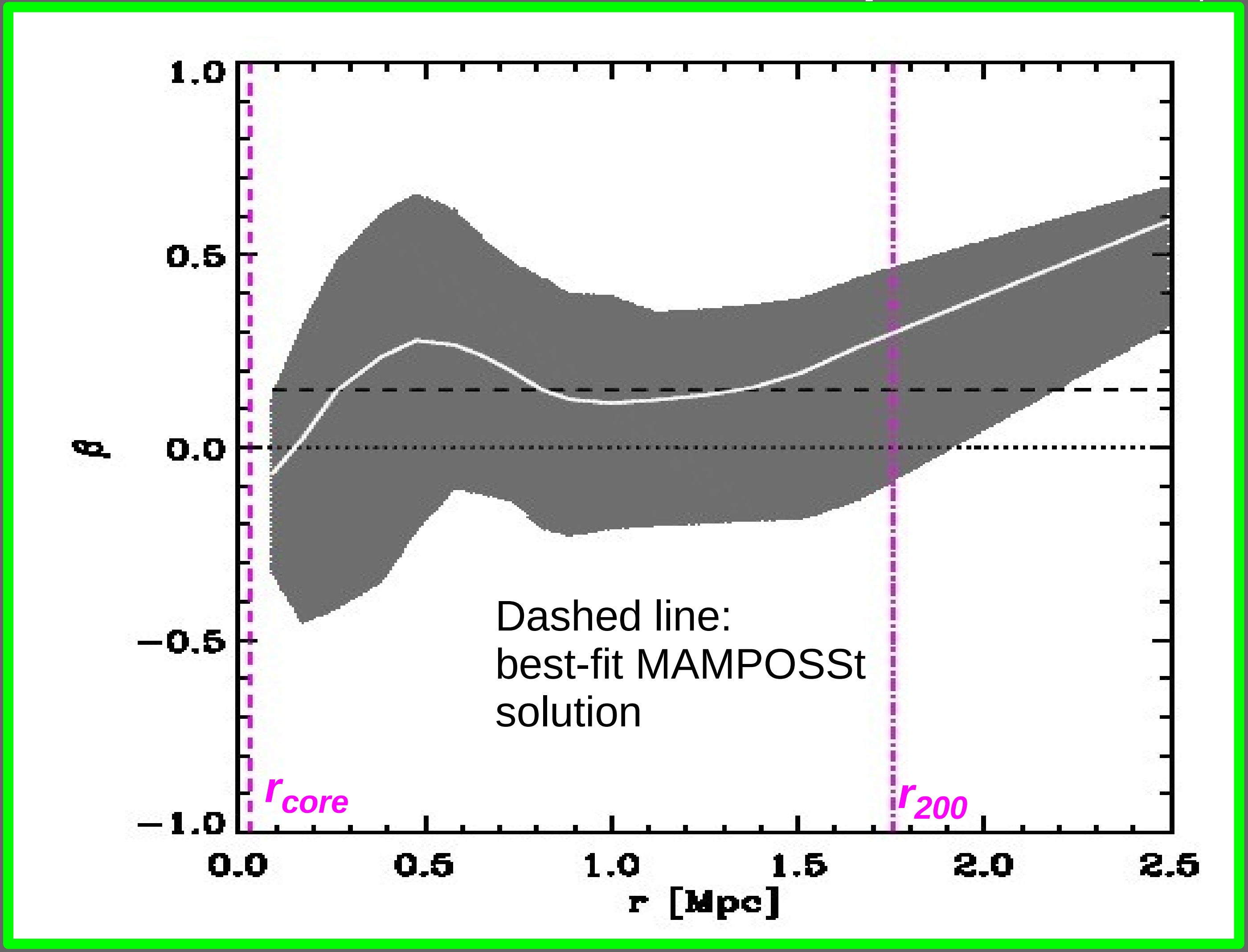
$$\beta(r) = 1 - \frac{\sigma_\theta^2(r)}{\sigma_r^2(r)}$$

→ tangential component of velocity dispersion

→ radial component of velocity dispersion

Galaxy orbits

MACS416, *[Sartoris, AB et al. in prep.]*



Dashed line:
best-fit MAMPOSSt
solution

radial orbits

tangential orbits

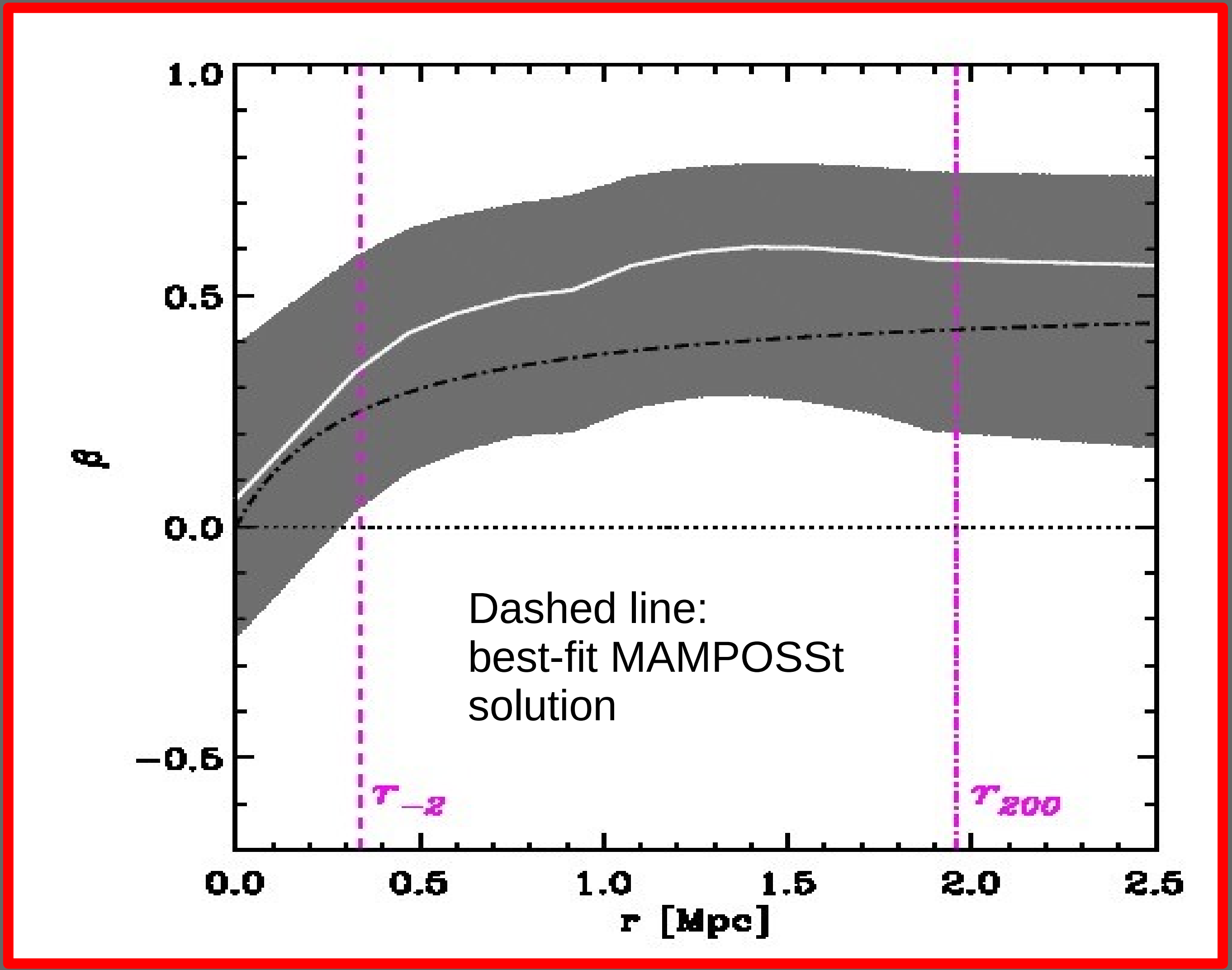
$$\beta(r) = 1 - \frac{\sigma_\theta^2(r)}{\sigma_r^2(r)}$$

→ tangential component of velocity dispersion

→ radial component of velocity dispersion

Galaxy orbits

MACS1206, *[AB et al. 2013]*



Dashed line:
best-fit MAMPOSSt
solution

radial orbits

tangential orbits

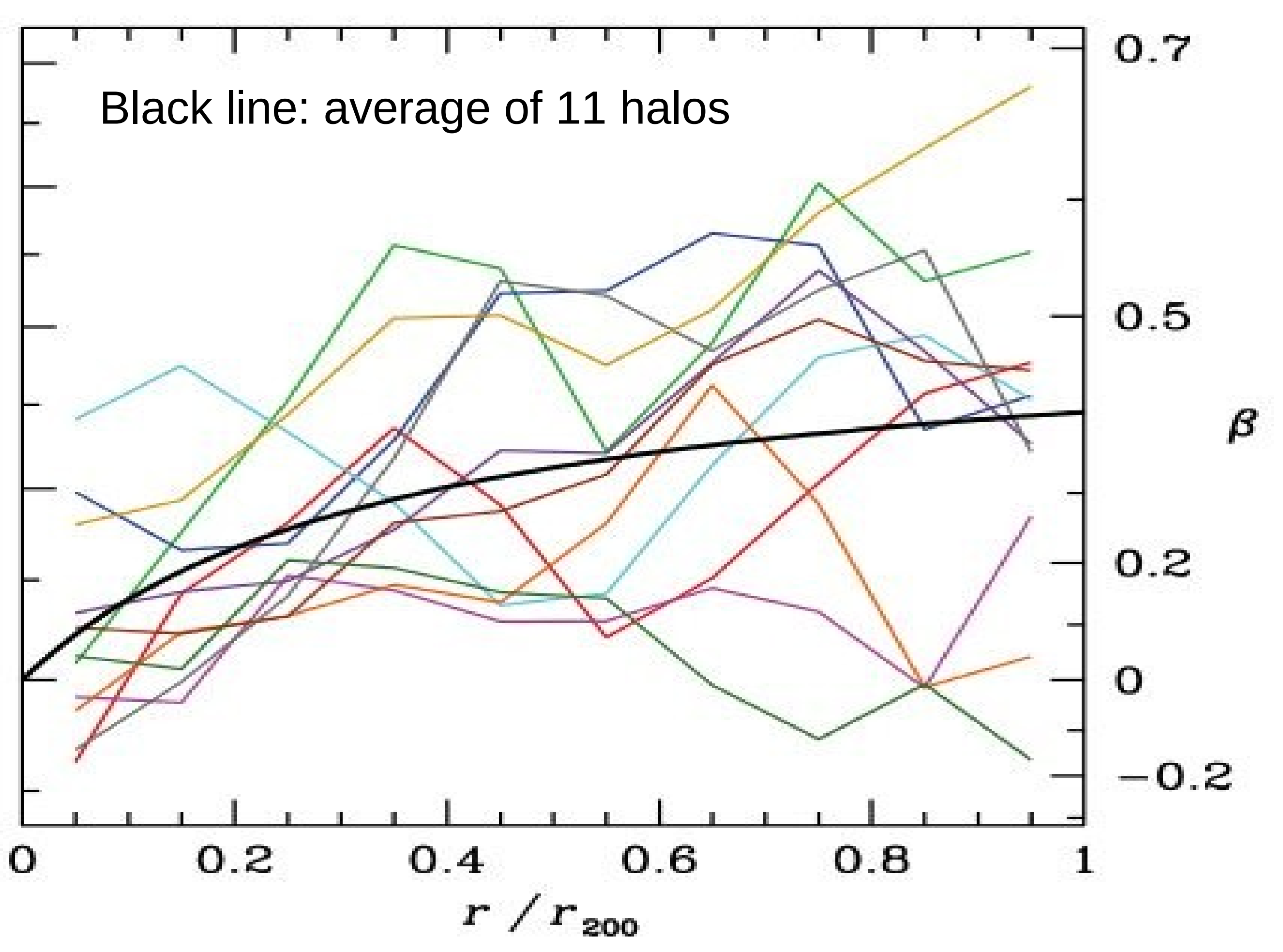
$$\beta(r) = 1 - \frac{\sigma_\theta^2(r)}{\sigma_r^2(r)}$$

→tangential component of velocity dispersion

→radial component of velocity dispersion

The β(r) of cluster-size halos in cosmological simulations

11 simulated halos, *[Mamon, AB , Boué 2013]*



Black line: average of 11 halos

radial orbits

tangential orbits

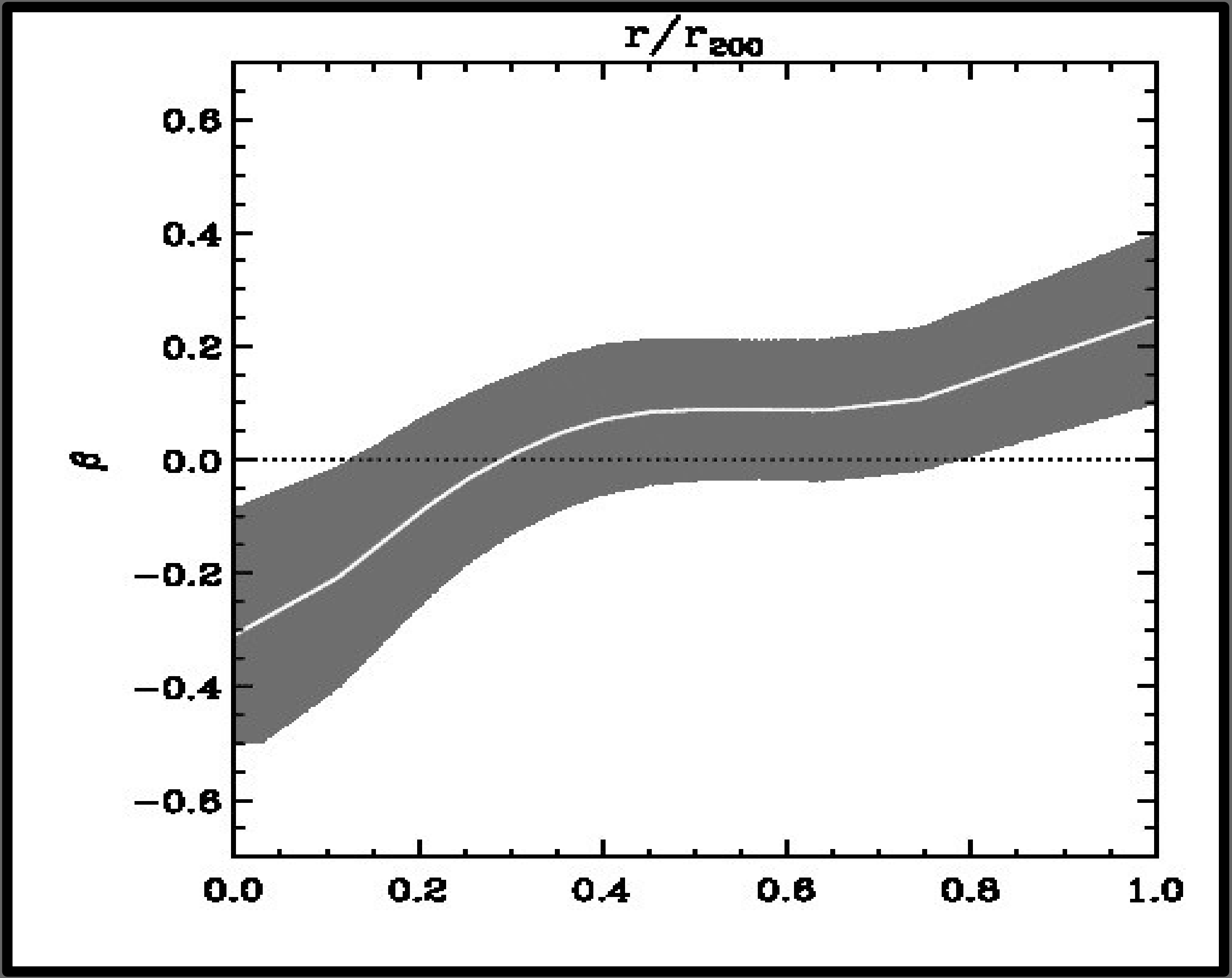
$$\beta(r) = 1 - \frac{\sigma_\theta^2(r)}{\sigma_r^2(r)}$$

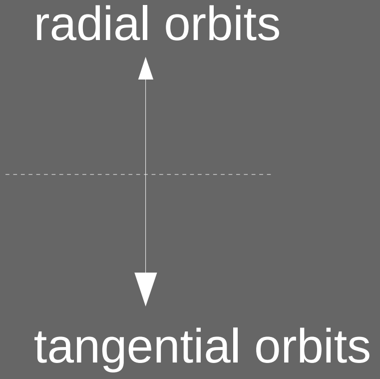
→tangential component of velocity dispersion

→radial component of velocity dispersion

What about β(r) evolution?

WINGS, stack of 42 relaxed <z>=0.05 clusters [Cava, AB , Mamon et al. in prep.]





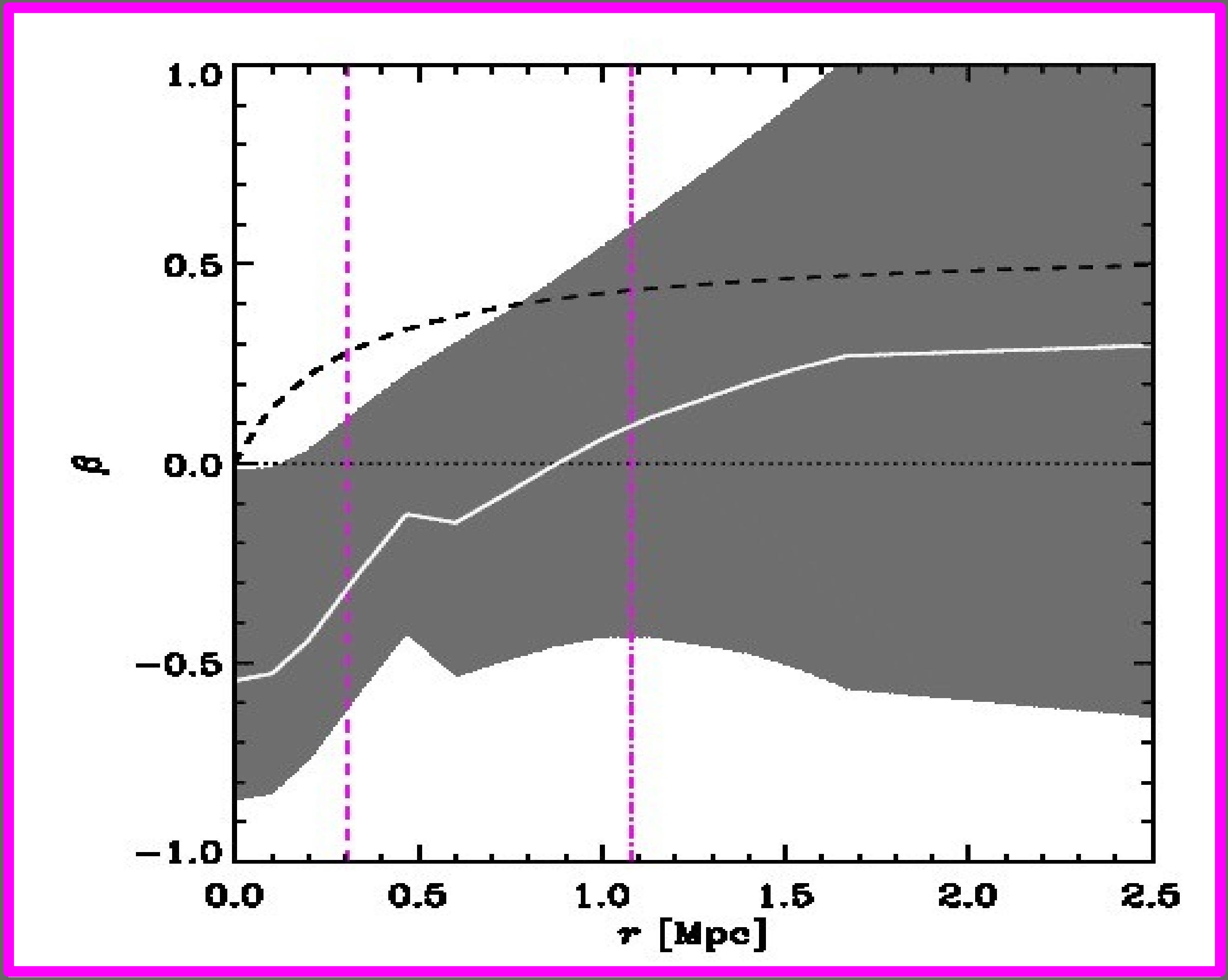
$$\beta(r) = 1 - \frac{\sigma_\theta^2(r)}{\sigma_\mathrm{r}^2(r)}$$

→tangential component of velocity dispersion

→radial component of velocity dispersion

Galaxy orbits

GCLASS, stack of 10 z≈1 clusters [AB ,van der Burg, Muzzin et al. in prep.]



radial orbits

↑

↓

tangential orbits

$$\beta(r) = 1 - \frac{\sigma_\theta^2(r)}{\sigma_r^2(r)}$$

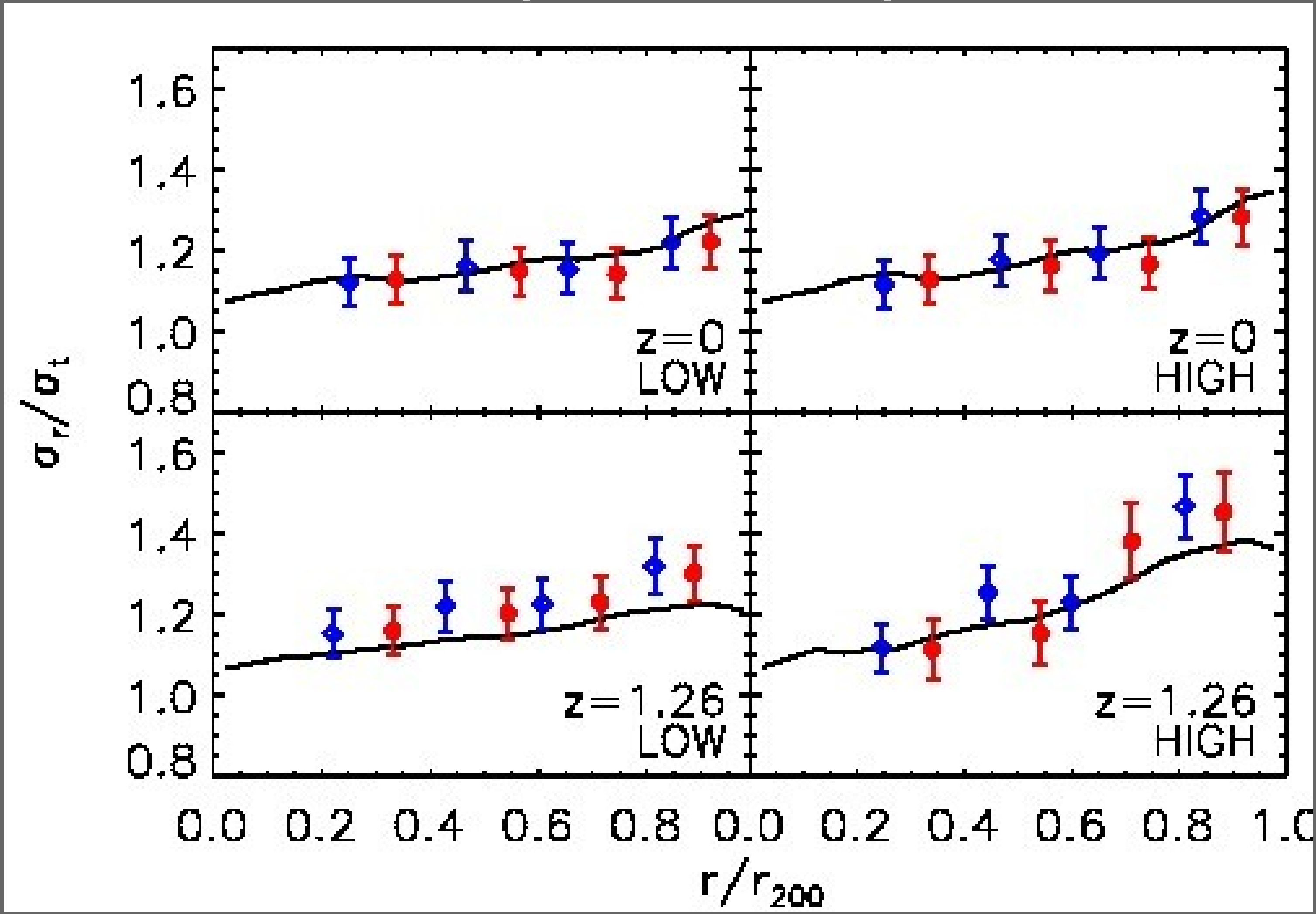
→tangential component of velocity dispersion

→radial component of velocity dispersion

Galaxy orbits

Evolution of β(r) of cluster-size halos in simulations

*[**Munari**, AB et al. 2013]*



radial orbits

tangential orbits

radial orbits

tangential orbits

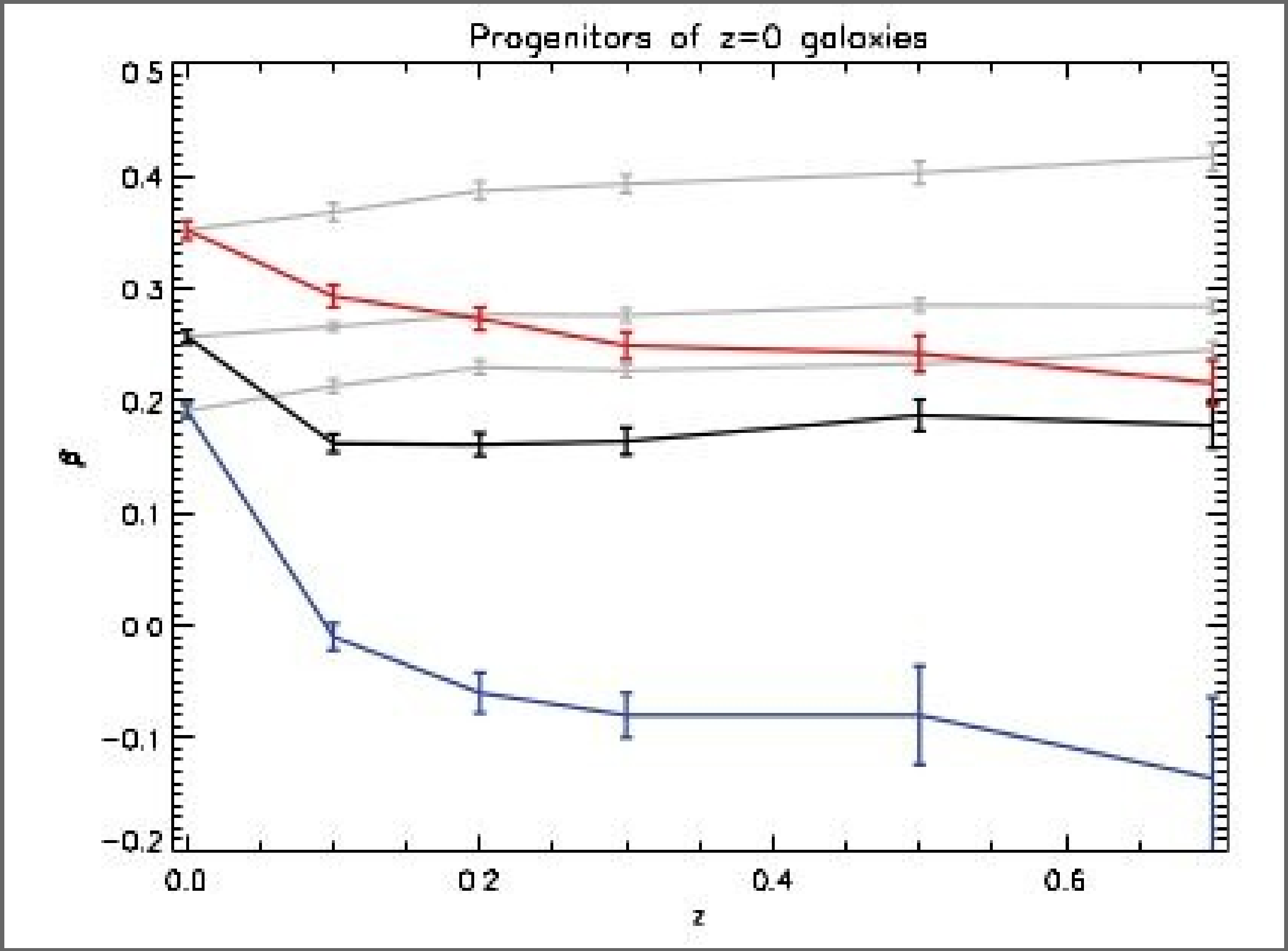
$$\beta(r) = 1 - \frac{\sigma_\theta^2(r)}{\sigma_r^2(r)}$$

→ tangential component of velocity dispersion

→ radial component of velocity dispersion

Evolution of β(r) of cluster-size halos in simulations

[Iannuzzi & Dolag 2012]



radial orbits

tangential orbits

$$\beta(r) = 1 - \frac{\sigma_\theta^2(r)}{\sigma_r^2(r)}$$

→ tangential component of velocity dispersion

→ radial component of velocity dispersion

Summary and perspectives


(C)Rainer Kleinedowe

(Summary of our findings for lazy - or tired - listeners)

Summary (1/2)

- Using 3 (out of 12) clusters from the CLASH-VLT survey with 600-1000 cluster members each
- M(r) traced by cluster galaxies in agreement (and of comparable precision) with M(r) from lensing
- Cmp the two determination of M(r) to constrain DM EoS
- M(r) best-fit model is NFW (2 clusters), SIS (1 cluster)

Summary (2/2)

- Q(r) is remarkably similar and close to the predicted power-law in different clusters and at different redshifts
  → *rapid dynamical relaxation of the collisionless component*

- Two clusters of similar total mass density profiles have different stellar mass density profiles
  → *different relevance of different physical processes affecting galaxy evolution (dyn. friction, tidal disruption)*

- Orbits of galaxies are isotropic near the center, increasingly radial outside; variance among clusters. *No evolution?*

Perspectives

- Enlarge the sample by factor 4 in next ~12 months *(most observations completed, data-reduction ongoing, thanks Italo Balestra and Amata Mercurio!)*

Perspectives

- Enlarge the sample by factor 4 in next ~12 months
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- What makes M(r) different in different clusters?
  Are these profiles universal for dynamically relaxed clusters?

Perspectives

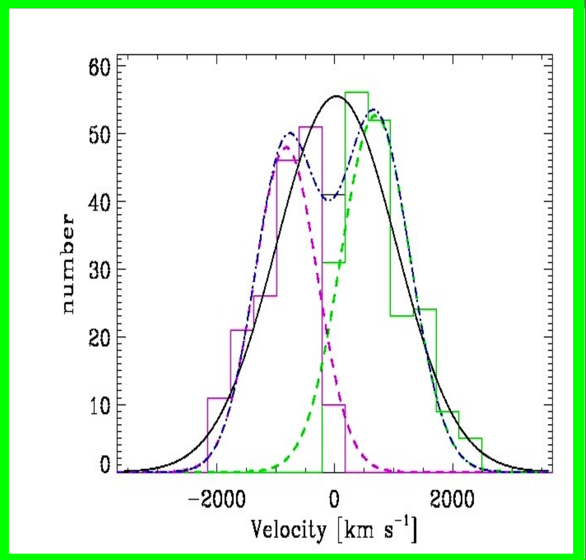
- Enlarge the sample by factor 4 in next ~12 months *(most observations completed, data-reduction ongoing, thanks Italo Balestra and Amata Mercurio!)*
- What makes M(r) different in different clusters?
  Are these profiles universal for dynamically relaxed clusters?
  Can we improve M(r) determination for unrelaxed clusters?
  (ongoing: Sartoris + AB)

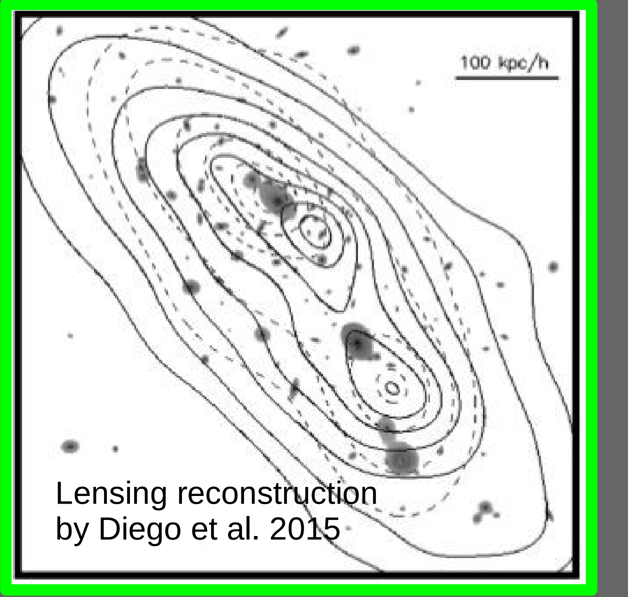
MACS0416, one of the three CLASH-VLT clusters analyzed so far, the one with a non-NFW M(r), shows clear evidence of an ongoing merger between two subclusters *(Balestra et al. in prep.)*

Improving M(r) for bimodal clusters

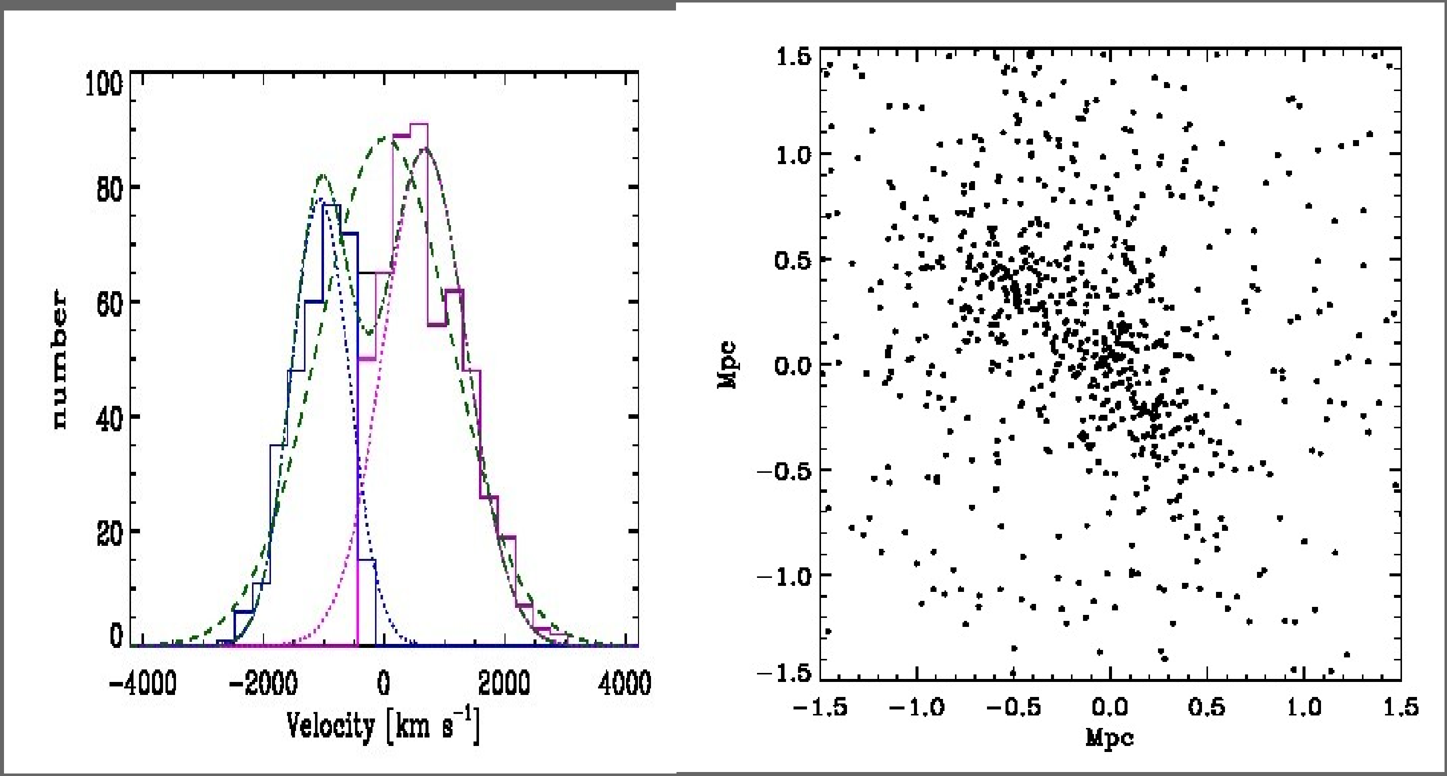
MACS0416: bimodal velocity distribution
elongated spatial distribution

Choose a similar halo from cosmological numerical simulations – M(r) being known for this halo we try to devise a new method to estimate it correctly

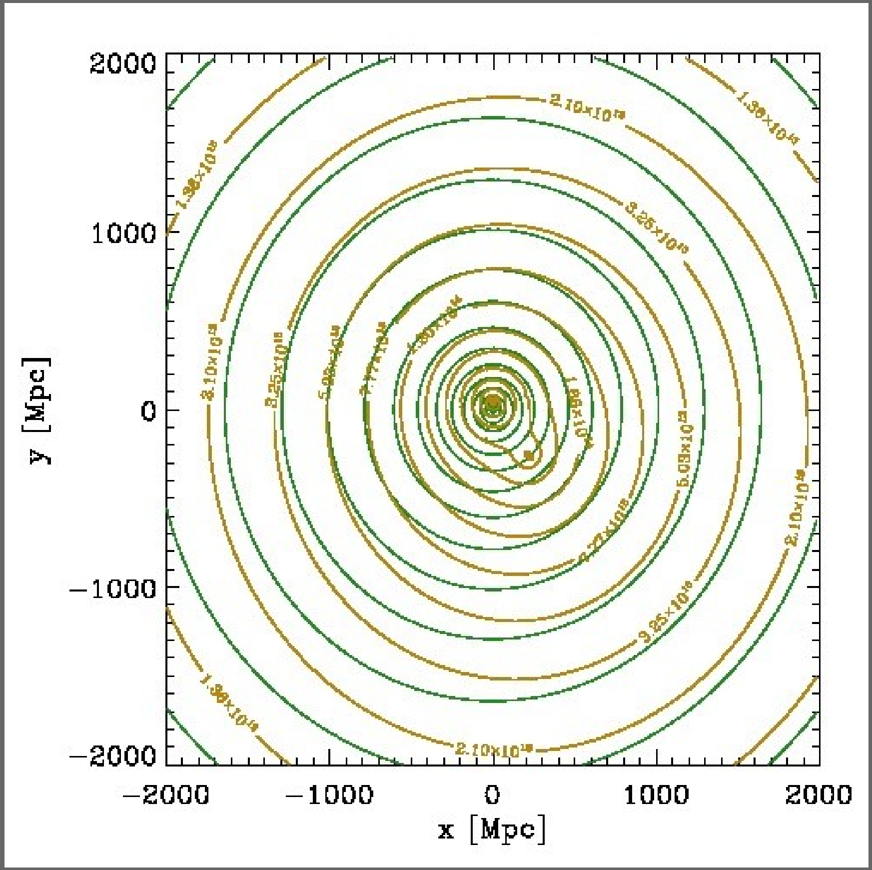




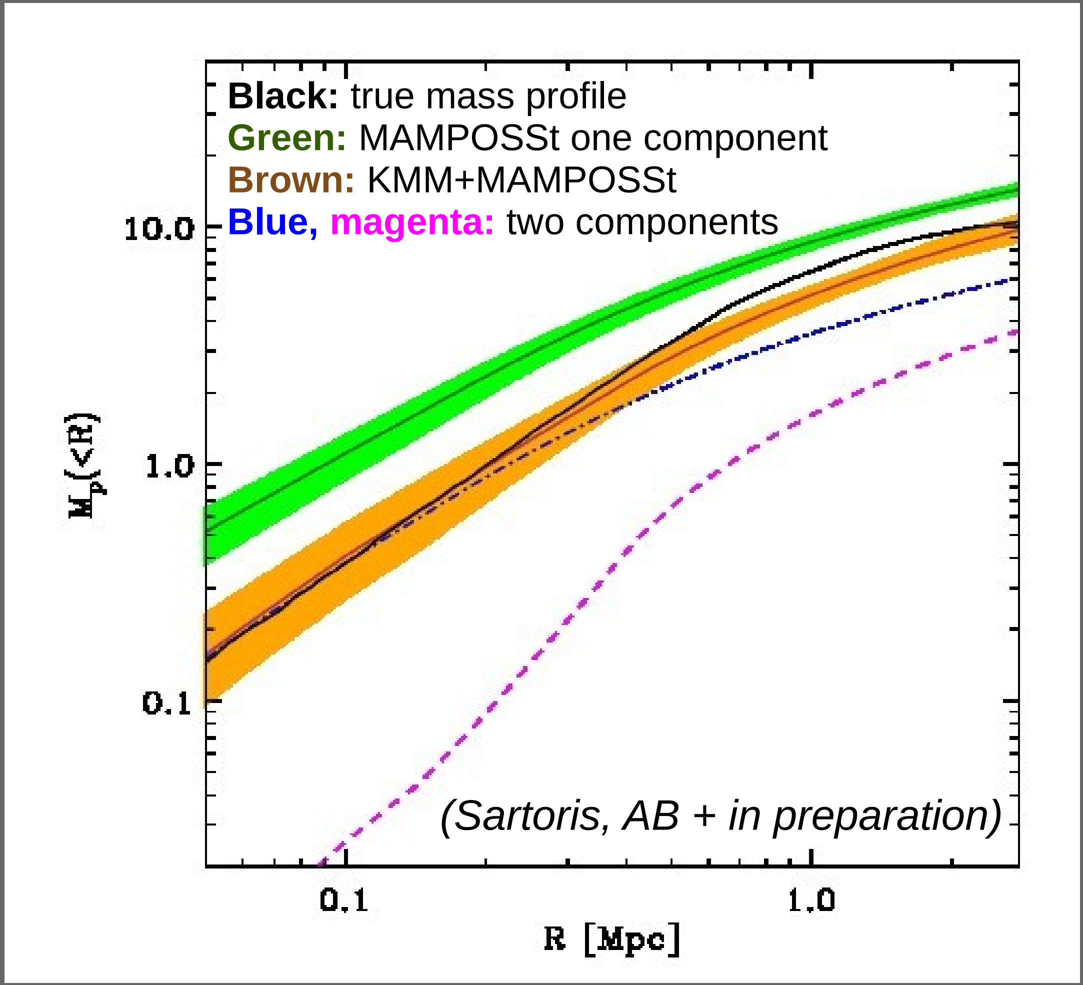
Lensing reconstruction by Diego et al. 2015



Improving M(r) for bimodal clusters



Use KMM algorithm (McLachlan & Basford) to fit two Gaussians to the l.o.s. velocity distribution and separate the two merging components. Then run MAMPOSSt separately on the two components.



(Sartoris, AB + in preparation)

The total projected mass profile relative to a given center is reconstructed from the sum of two surface mass-density components *(this is analog to the procedure adopted in gravitational lensing mass reconstruction)*

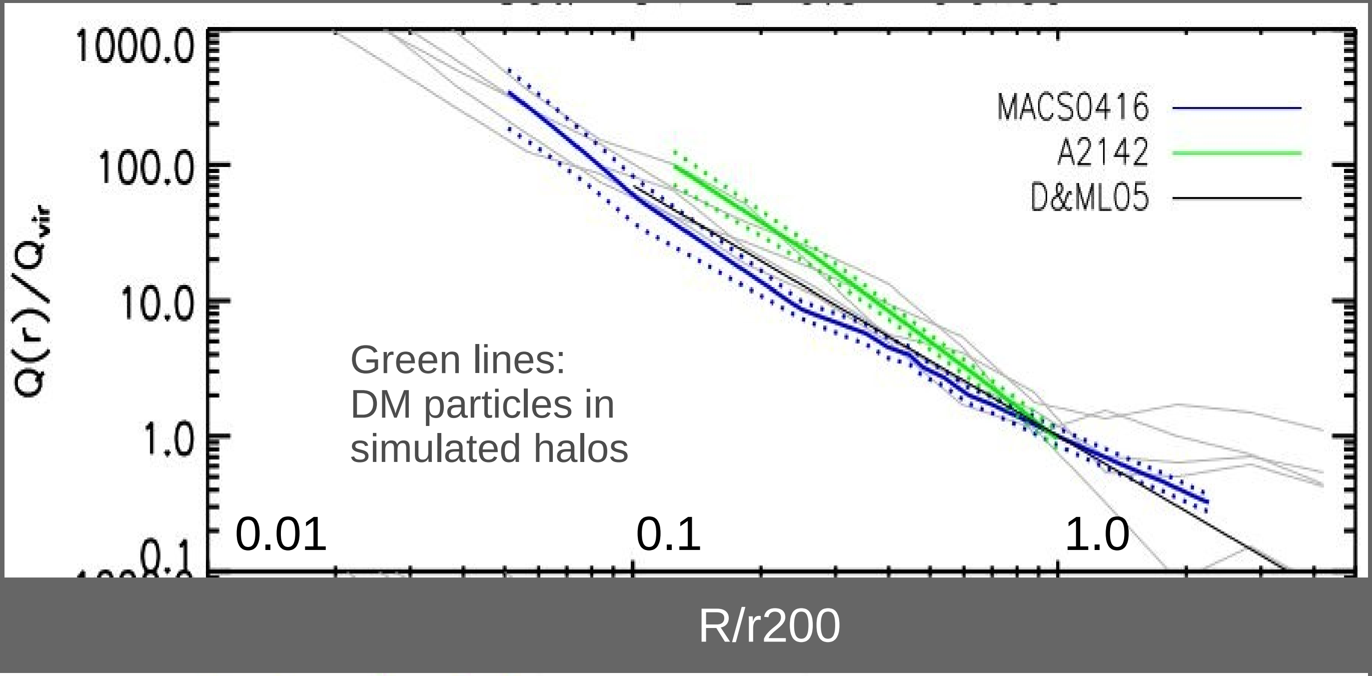
Perspectives

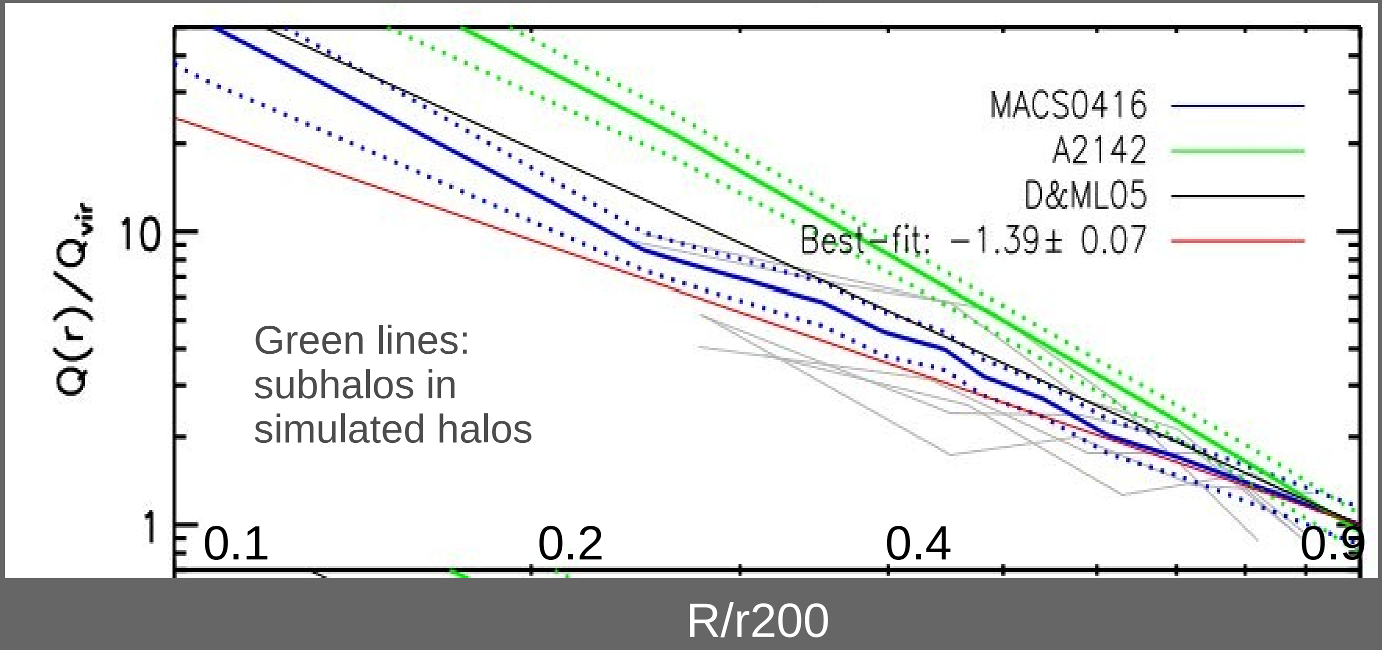
- Enlarge the sample by factor 4 in next ~12 months
  (most observations completed, data-reduction ongoing, thanks Italo Balestra and Amata Mercurio!)

- What makes M(r) different in different clusters?
  Are these profiles universal for dynamically relaxed clusters?
  Can we improve M(r) determination for unrelaxed clusters?
  (ongoing: Sartoris + AB)

- What makes Q(r) so invariant? Cmp. to num. simulations
  (ongoing: Sartoris + Munari + Planelles + AB)

What makes Q(r) so invariant?





Comparison of Q(r)
of observed clusters
(from CLASH-VLT and
Munari, AB, Mamon 2014)
obtained using
galaxies
as tracers of the
velocity field

with Q(r) of halos from
cosmological num.
simulations, using
either DM particles
or subhalos
as tracers of the
velocity field.

Different slope found
when using subhalos

Perspectives

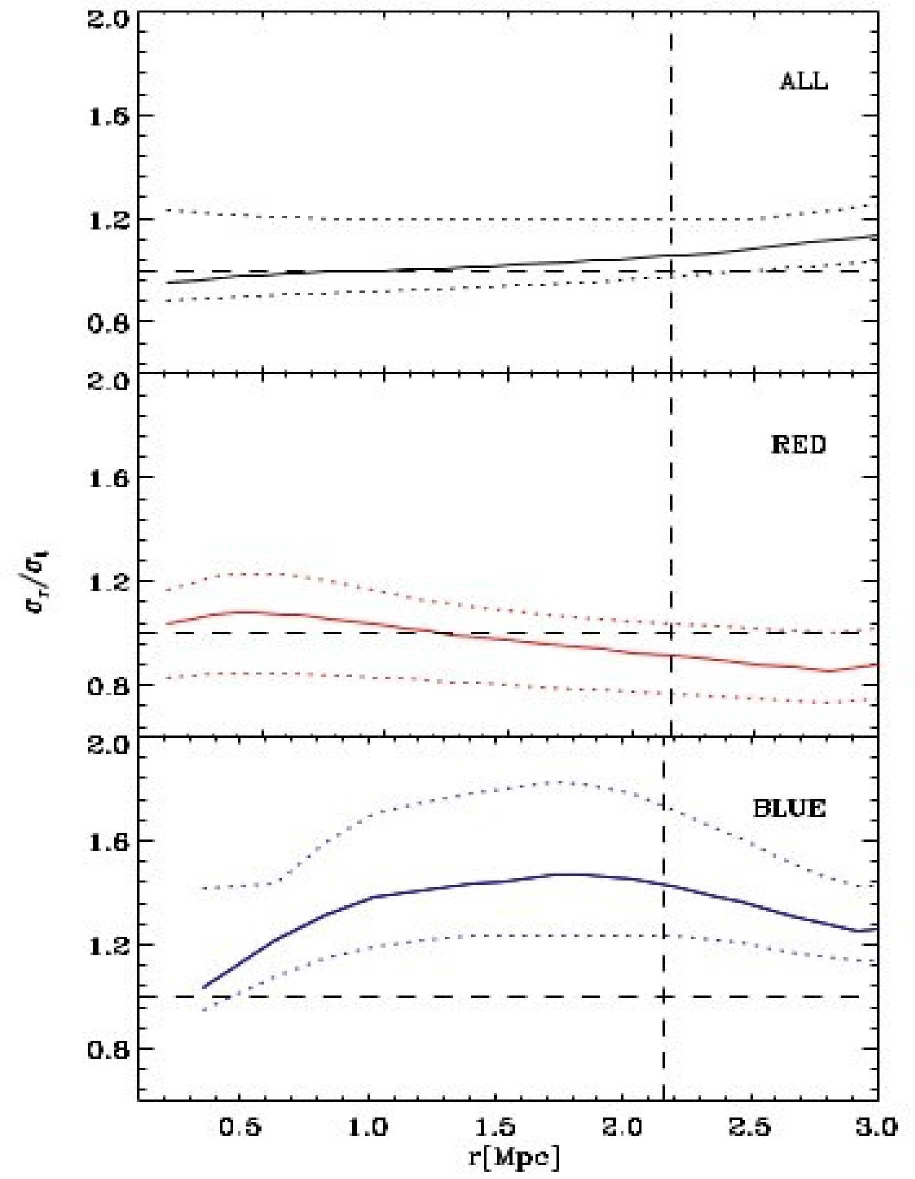
- Enlarge the sample by factor 4 in next ~12 months
  (most observations completed, data-reduction ongoing, thanks Italo Balestra and Amata Mercurio!)

- What makes M(r) different in different clusters?
  Are these profiles universal for dynamically relaxed clusters?
  Can we improve M(r) determination for unrelaxed clusters?
  (ongoing: Sartoris + AB)

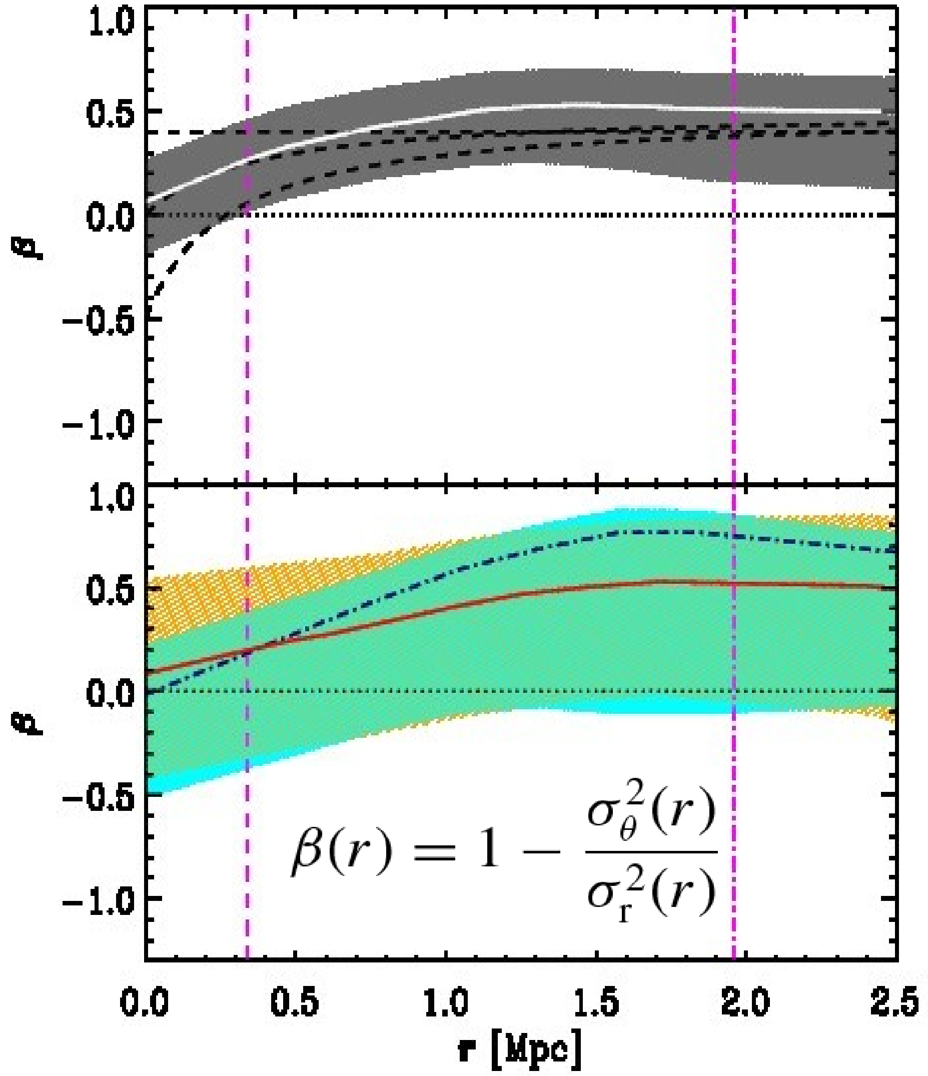
- What makes Q(r) so invariant? Cmp. to num. simulations
  (ongoing: Sartoris + Munari + Planelles + AB)

- Determine β(r) for different cluster galaxy populations
  (orbits might be related to galaxy evolution in clusters)

Determine β(r) for different galaxy populations



Low-z cluster (Munari, AB, Mamon 2014)



$$\beta(r) = 1 - \frac{\sigma_\theta^2(r)}{\sigma_r^2(r)}$$

z=0.44 cluster (AB + 2013)

Perspectives

- Enlarge the sample by factor 4 in next ~12 months
  (most observations completed, data-reduction ongoing, thanks Italo Balestra and Amata Mercurio!)

- What makes M(r) different in different clusters?
  Are these profiles universal for dynamically relaxed clusters?
  Can we improve M(r) determination for unrelaxed clusters?
  (ongoing: Sartoris + AB)

- What makes Q(r) so invariant? Cmp. to num. simulations
  (ongoing: Sartoris + Munari + Planelles + AB)

- Determine β(r) for different cluster galaxy populations
  (orbits might be related to galaxy evolution in clusters)

- The dynamics of the SPT-SZ clusters *(with Raffaella, Alex, Joe, Sebastian, Veronica ...)*

...and if you just came in, here is

The very short summary

*(no need to climb it, get the Maibaum **and** the brezel at once)*