Galaxy evolution in clusters from the CLASH-VLT survey

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(on behalf of the CLASH-VLT team)

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This talks is *(mostly)* based on:

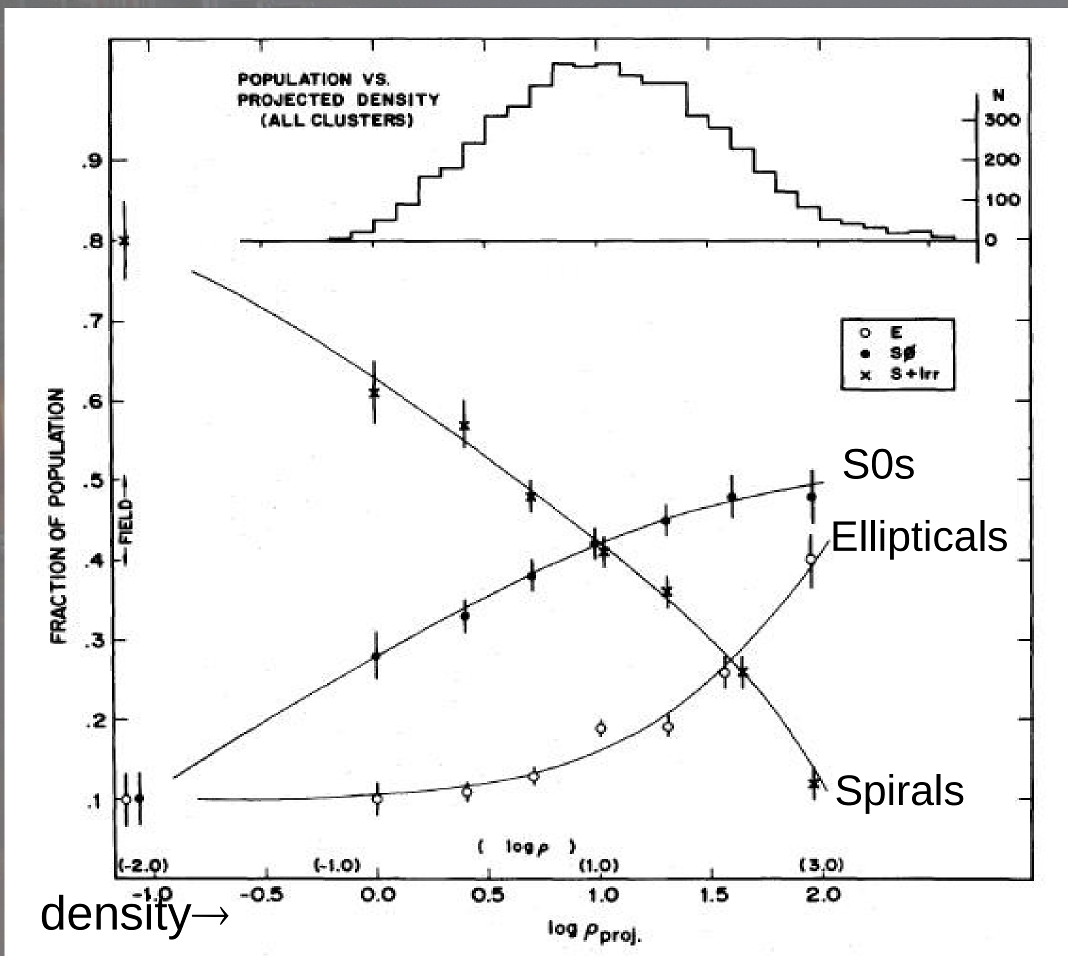
Annunziatella, Biviano, Mercurio et al. 2014, A&A, 571, A80
Annunziatella, Mercurio, Biviano et al. 2015, A&A, in press

Outline:

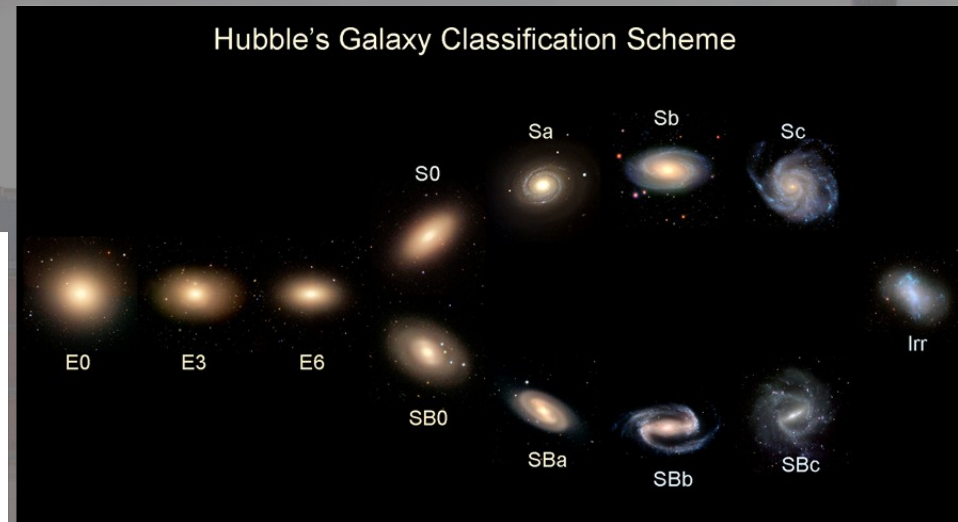
- Introduction: *the properties of cluster galaxies*
- Introduction: *physical processes affecting galaxies in clusters*
- The CLASH-VLT survey & our data-sample
- Results: *the stellar mass functions of cluster galaxies*
- Results: *the intra-cluster light*
- Results: *the stellar mass vs. size relation of cluster galaxies*
- Results: *the orbits of cluster galaxies*
- Results: *the mass and number density profile ratios*
- Summary & conclusions

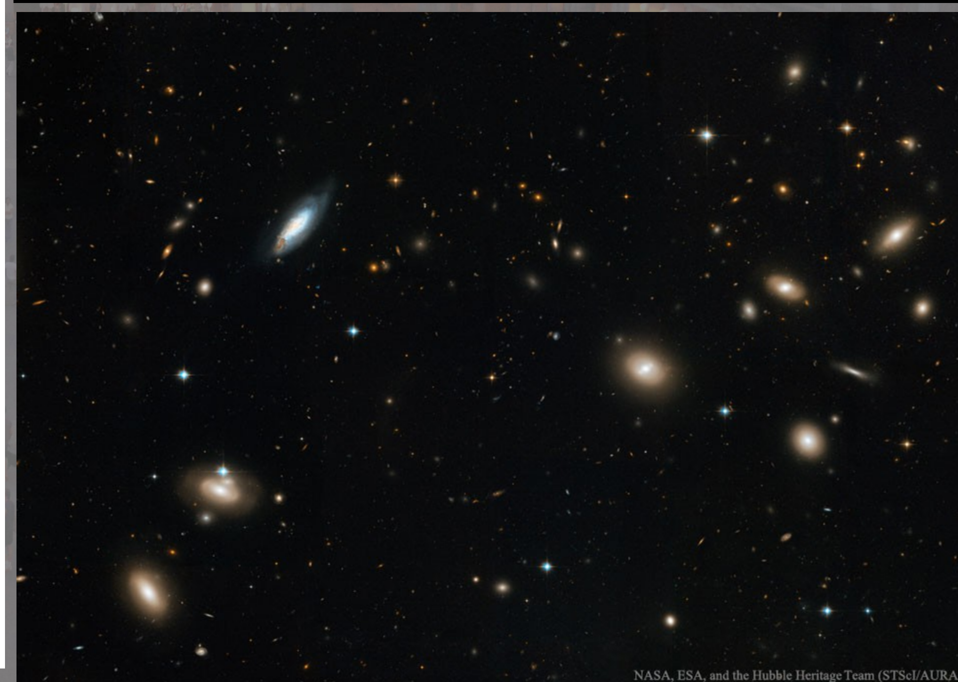
The properties of cluster galaxies

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

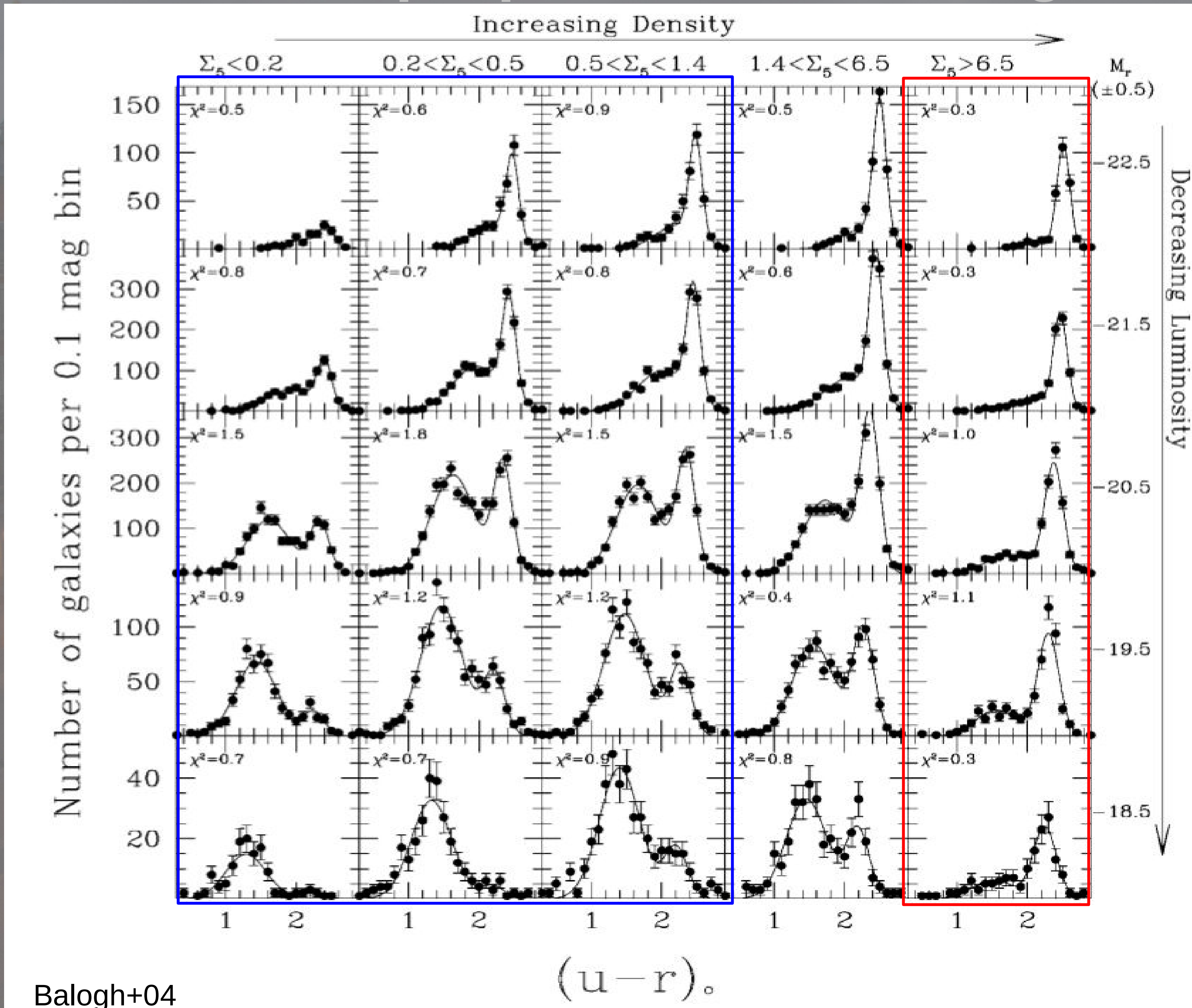


The morpholgy-density relation in clusters of galaxies, A. Dressler (1980)



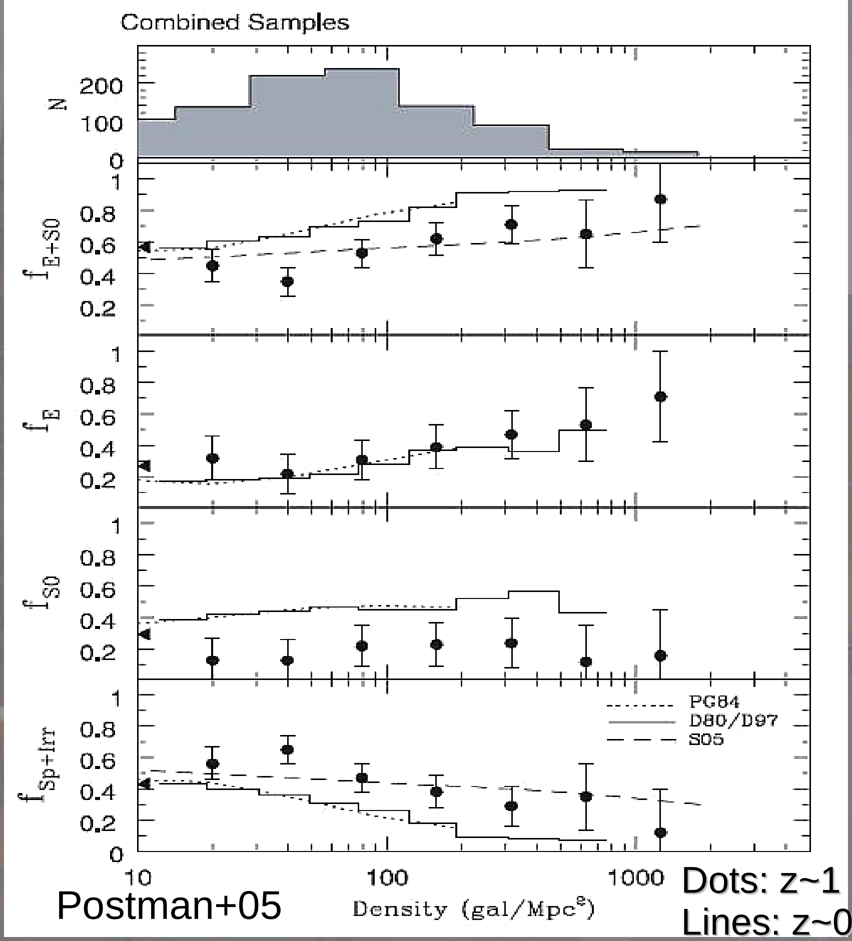


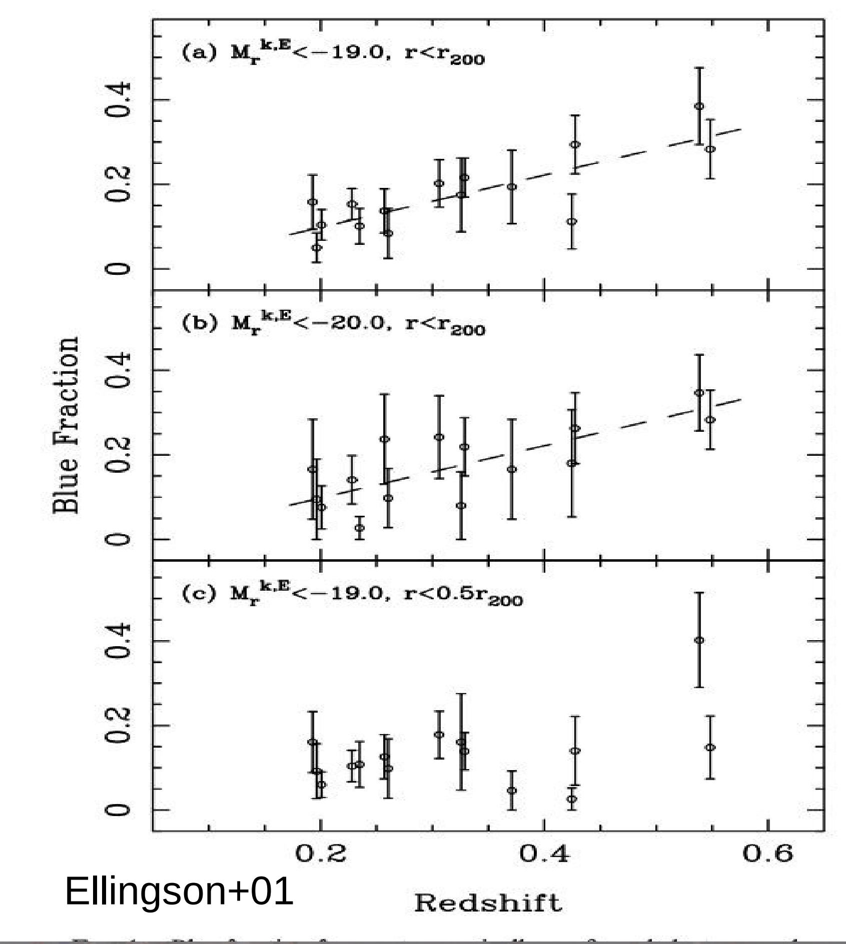
The properties of cluster galaxies



Cluster galaxies are mostly red, field galaxies are mostly blue

The properties of cluster galaxies





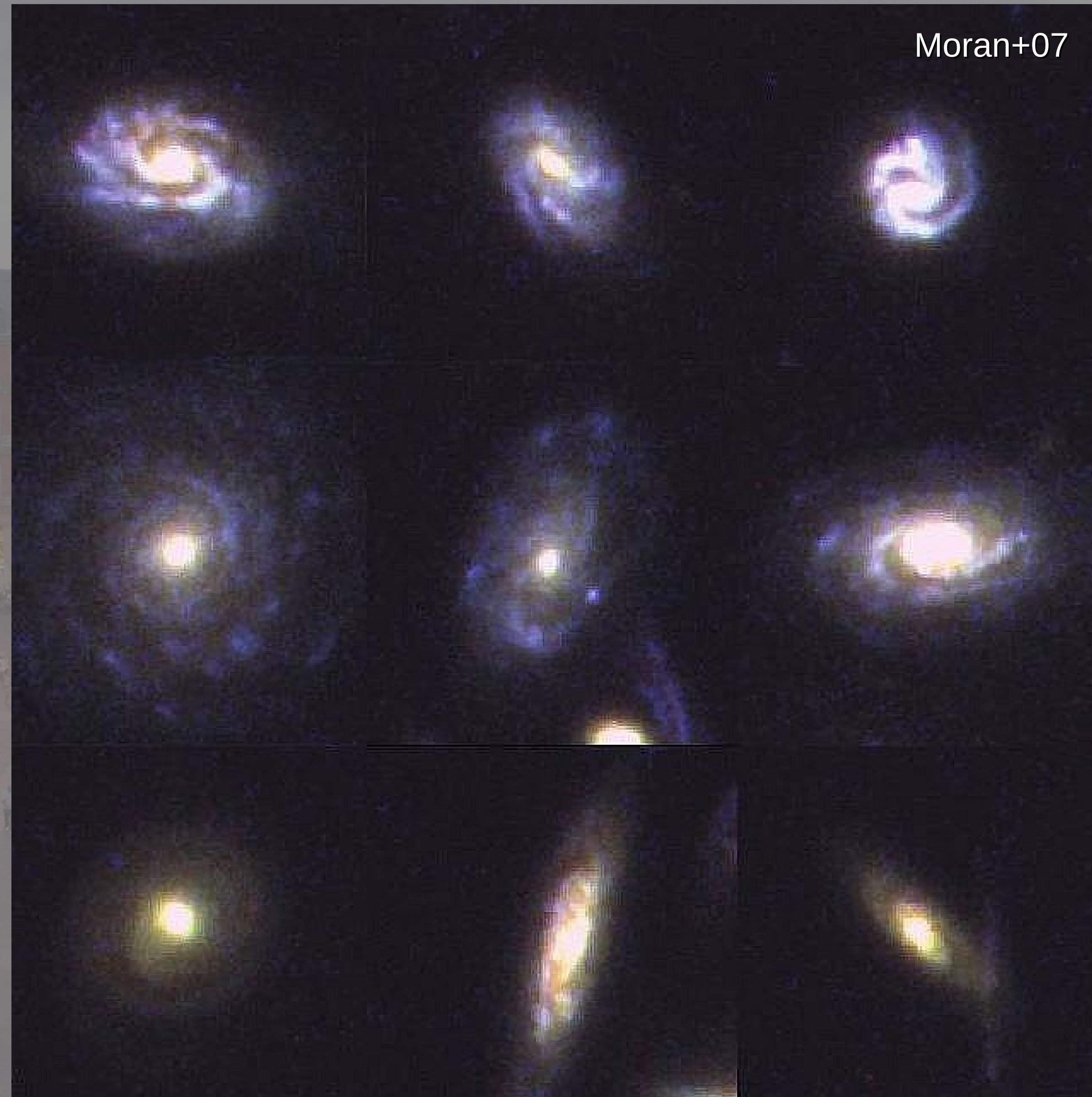
Evolution of the morphological mix of galaxies in clusters with redshift:

⇒ Spirals in clusters evolve into S0s (and/or Ellipticals) with time

The fraction of blue galaxies in clusters increases with redshift (the 'Butcher-Oemler' effect)

⇒ Blue cluster galaxies become red with time

The properties of cluster galaxies



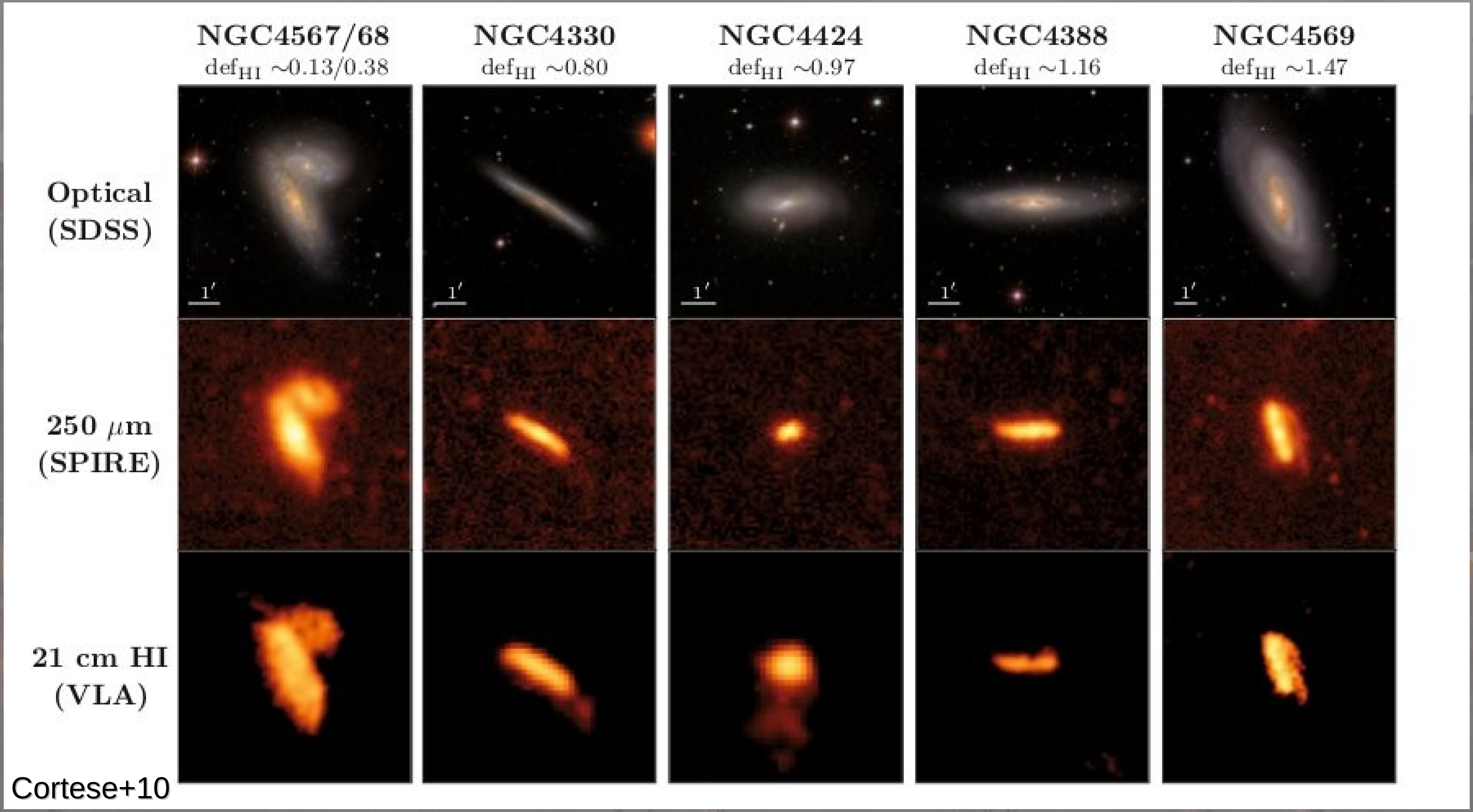
Blue, star-forming spirals

Blue-disk, passive spirals: a transition population of galaxies characteristic of the cluster environment

Red-disk, passive spirals, S0s

⇒ Color and spectral evolution occurs before morphological evolution

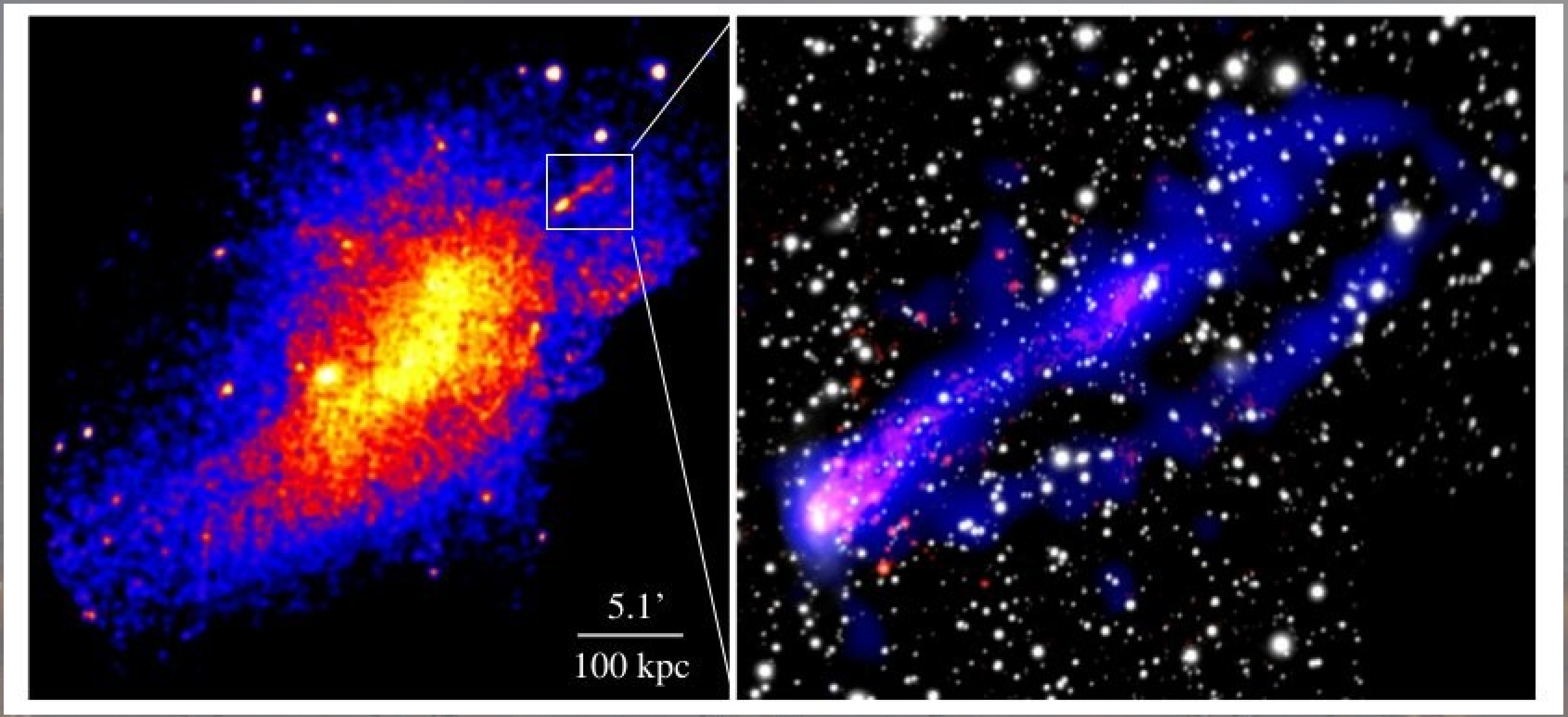
The properties of cluster galaxies



Some galaxies in clusters show truncation of the HI (and dust) disk

⇒ Gas stripping is occurring

The properties of cluster galaxies



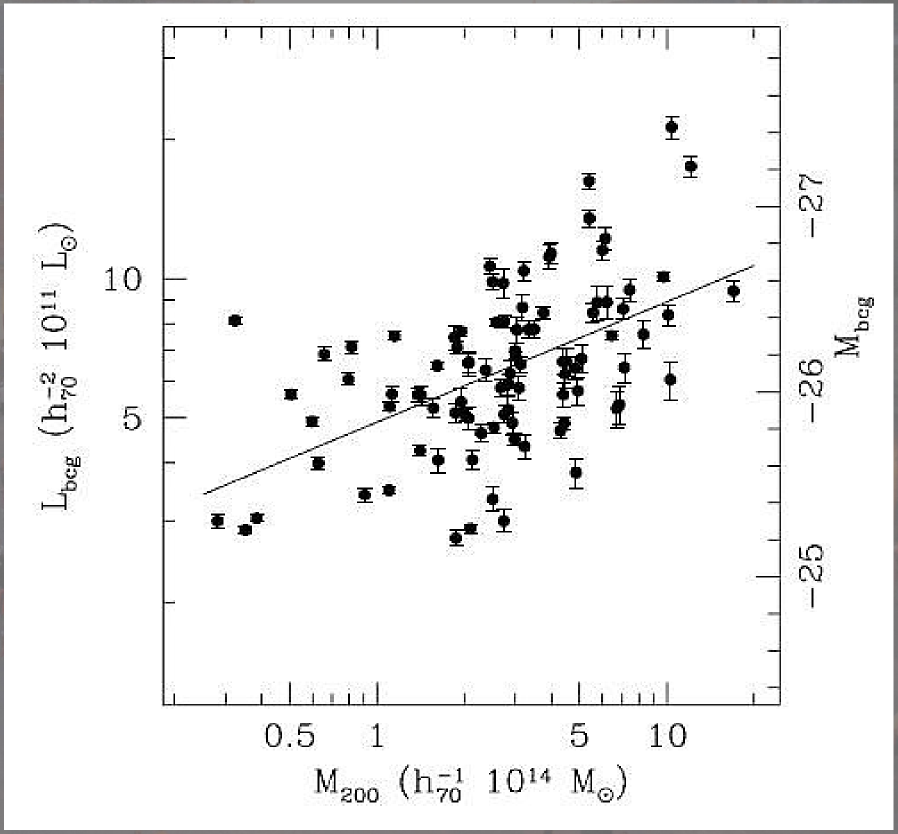
Sun+10: Left, cluster of galaxies in X-ray (XMM-Newton)
Right, zoom on galaxy (Chandra X-ray in blue, Hα in red, optical in white)

Some galaxies in clusters show trails of gas

⇒ Gas stripping is occurring

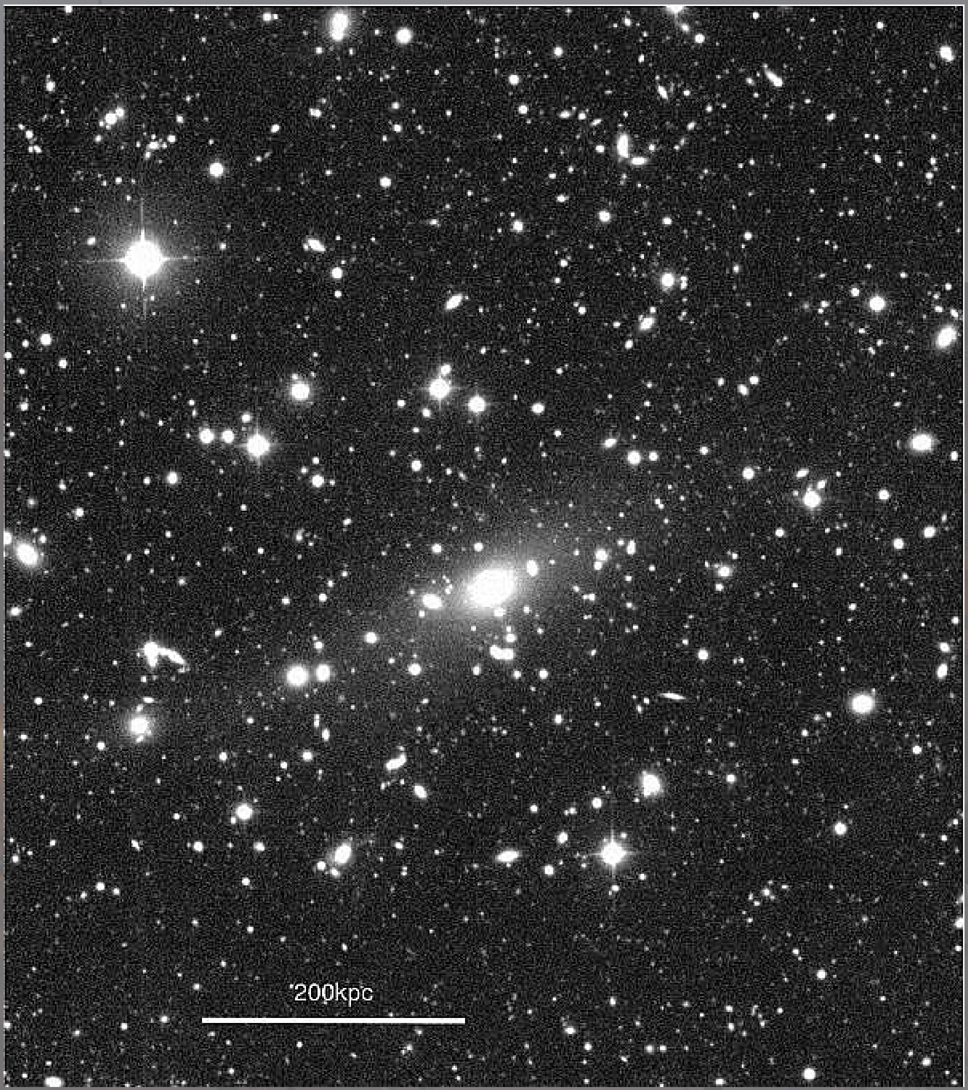
The properties of cluster galaxies

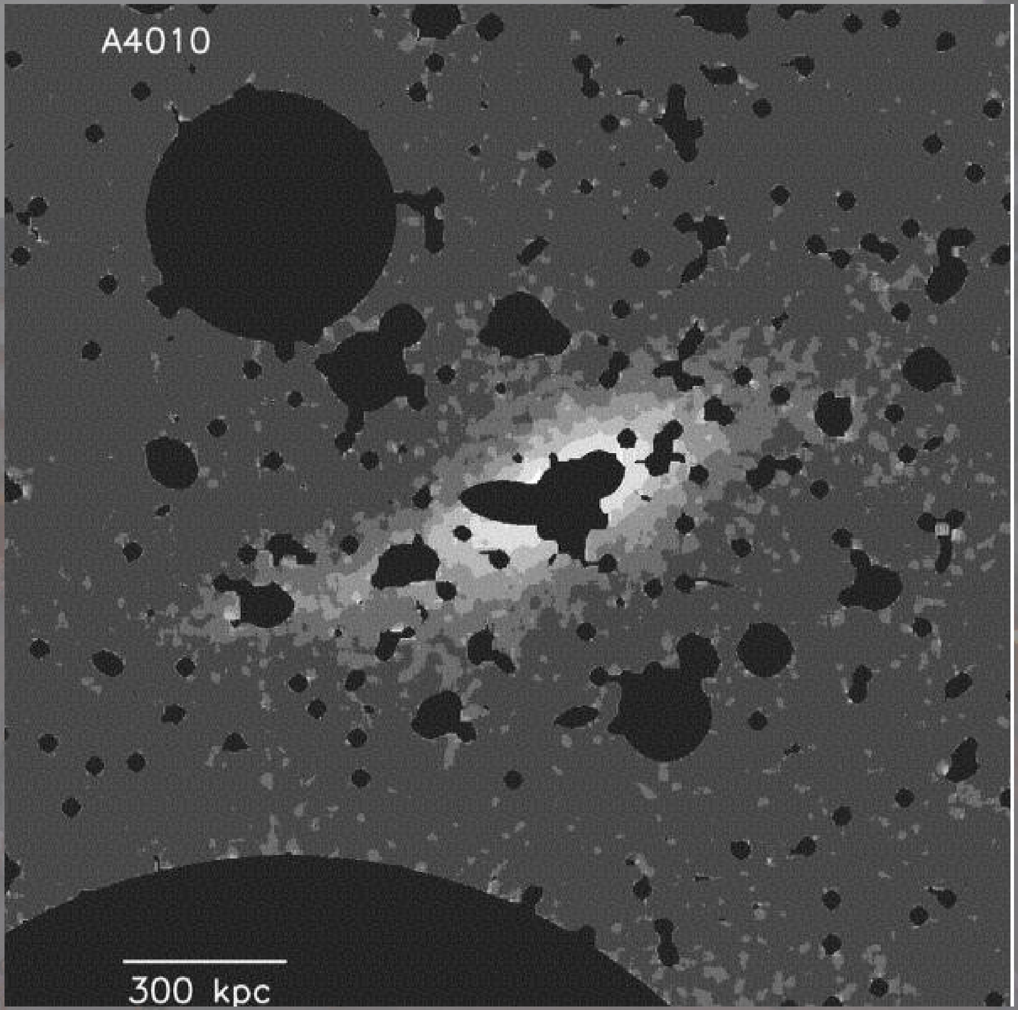
Brightest Cluster Galaxies (cD):
same luminosity but larger sizes than the brightest ellipticals in the field



BCG luminosity scales with the parent cluster dynamical mass (Lin & Mohr 04)

The properties of cluster galaxies





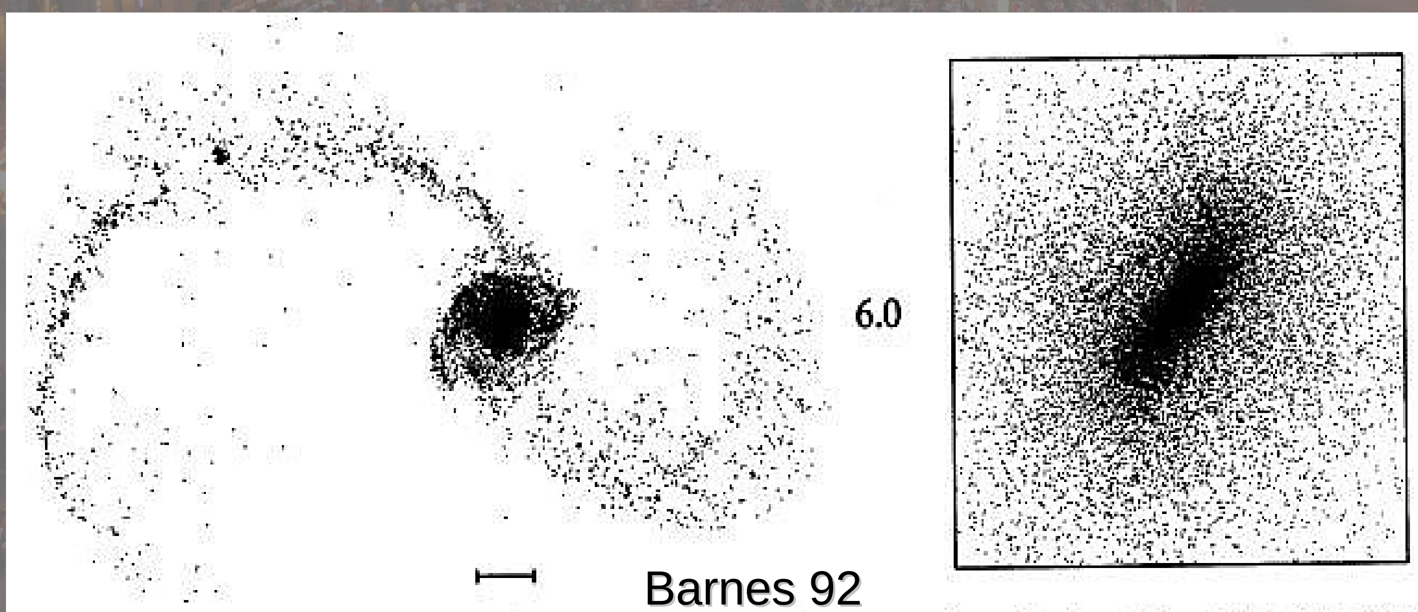
Brightest Cluster Galaxies (cD):
surrounded by a diffuse stellar component, **the Intra-Cluster Light**

Physical properties affecting cluster galaxies

a) Gravitational processes:

a1) Galaxy-galaxy collisions

a1.1) Slow & small impact parameter ⇒ mergers
a1.2) Fast &/or large impact parameter ⇒ tidal stripping
Many fast encounters ≡ "harassment" (Moore+96)



Barnes 92

a1.1:
Simulation of a galaxy-galaxy collision leading to a merger

Physical properties affecting cluster galaxies

a) Gravitational processes:

a1) Galaxy-galaxy collisions

a1.1) Slow & small impact parameter ⇒ mergers
a1.2) Fast &/or large impact parameter ⇒ tidal stripping

Many fast encounters ≡ "harassment" (Moore+96)

Garth Illingworth

a1.2:
Observation of a galaxy-galaxy collision leading to tidal stripping

Physical properties affecting cluster galaxies

a) Gravitational processes:

a1) Galaxy-galaxy collisions

a1.1) Slow & small impact parameter ⇒ mergers
a1.2) Fast &/or large impact parameter ⇒ tidal stripping
Many fast encounters ≡ "harassment" (Moore+96)

a2) Galaxy tidal interaction with cluster gravitational field
Tidal stirring, truncation, disruption can be caused by strong gradients of the cluster gravitational potential experienced by the galaxy along its orbit

Physical properties affecting cluster galaxies

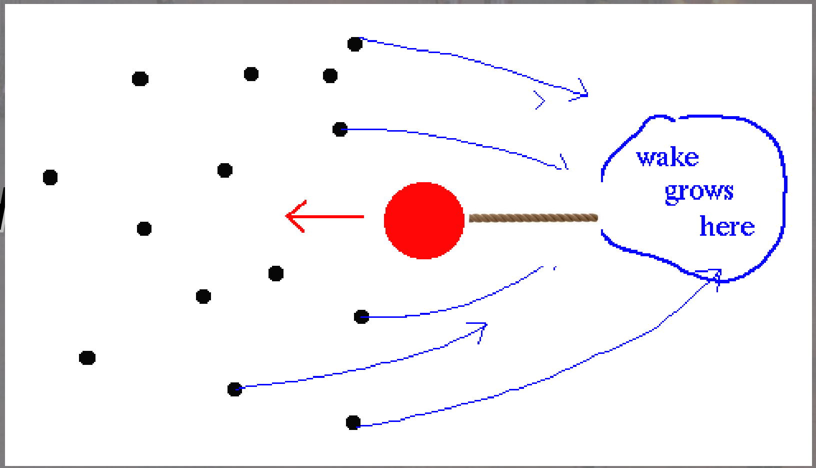
a) Gravitational processes:

a1) Galaxy-galaxy collisions

a1.1) Slow & small impact parameter ⇒ mergers
a1.2) Fast &/or large impact parameter ⇒ tidal stripping
Many fast encounters ≡ "harassment" (Moore+96)

a2) Galaxy tidal interaction with cluster gravitational field

a3) Dynamical friction
Transfer of kinetic energy from massive galaxies to the background medium of DM particles (Chandrasekhar 43)



Can ease mergers by decreasing galaxy velocities

Physical properties affecting cluster galaxies

b) Hydrodynamical processes:

b1) Starvation

Removal of external reservoir of gas by some unspecified process: the galaxy continue to use its disk gas to form stars until it is totally consumed

b2) Ram-pressure stripping

Removal of disk gas by the pressure exerted by the hot intra-cluster plasma onto the cold disk gas

Physical properties affecting cluster galaxies

b) Hydrodynamical processes:

b1) Starvation

Removal of external reservoir of gas by some unspecified process: the galaxy continues to use its disk gas to form stars until it is totally consumed

b2) Ram-pressure stripping

Removal of disk gas by the pressure exerted by the hot intra-cluster plasma onto the cold disk gas

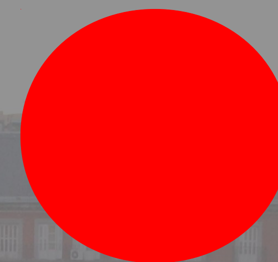
b3) Thermal evaporation

By conducting heat from the hot intra-cluster plasma to the colder galaxy gas, the latter can escape the gravitational potential well of the galaxy

Physical properties affecting cluster galaxies

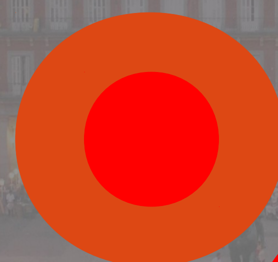
...are effective at different distances from the cluster center:

a1.2) galaxy-galaxy tidal stripping
(harassment)
b1) starvation



Whole cluster

a3) dynamical friction



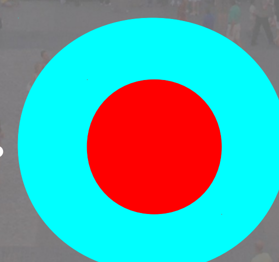
Mostly in the inner regions

a1.1) galaxy-galaxy mergers

In the outskirts; in the center only if dynamical friction is effective

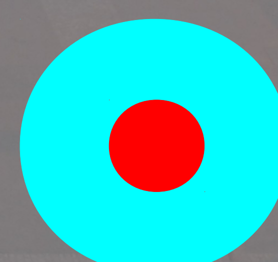
b2) ram-pressure stripping

b3) thermal evaporation



In the inner regions

a2) tidal interaction with cluster grav. field



In the very center

The CLASH-VLT survey

*What causes cluster galaxies
to be different from field galaxies?*

Need dedicated surveys of galaxies in clusters

Previous spectroscopic surveys:

ENACS, 59 z~0 clusters ~4200 spectroscopic members (Katgert+96)
CNOC, 16 z~0.3 clusters, ~1500 spectroscopic members (Carlberg+97)
EDisCS, 18 z~0.5 clusters, ~600 spectroscopic members (White+05)
WINGS, 48 z~0 clusters, ~3600 spectroscopic members (Cava+09)

The CLASH-VLT survey

CLASH: *Cluster Lensing And Supernova survey with Hubble*
P.I. Postman, 25 clusters at 0.18 < z < 0.9, 524 HST orbits
(Postman + 12)

VLT follow-up: ESO Large Programme

"Dark Matter Mass Distributions of Hubble Treasury Clusters and the Foundations of ΛCDM Structure Formation Models"

P.I. ***Rosati****, Univ. Ferrara*
225 hours (almost complete, data-reduction ongoing):

CLASH-VLT, 13 z≈0.4 clusters, *~7000 members expected*

The CLASH-VLT survey

Astronomical Science

CLASH-VLT: A VIMOS Large Programme to Map the Dark Matter Mass Distribution in Galaxy Clusters and Probe Distant Lensed Galaxies

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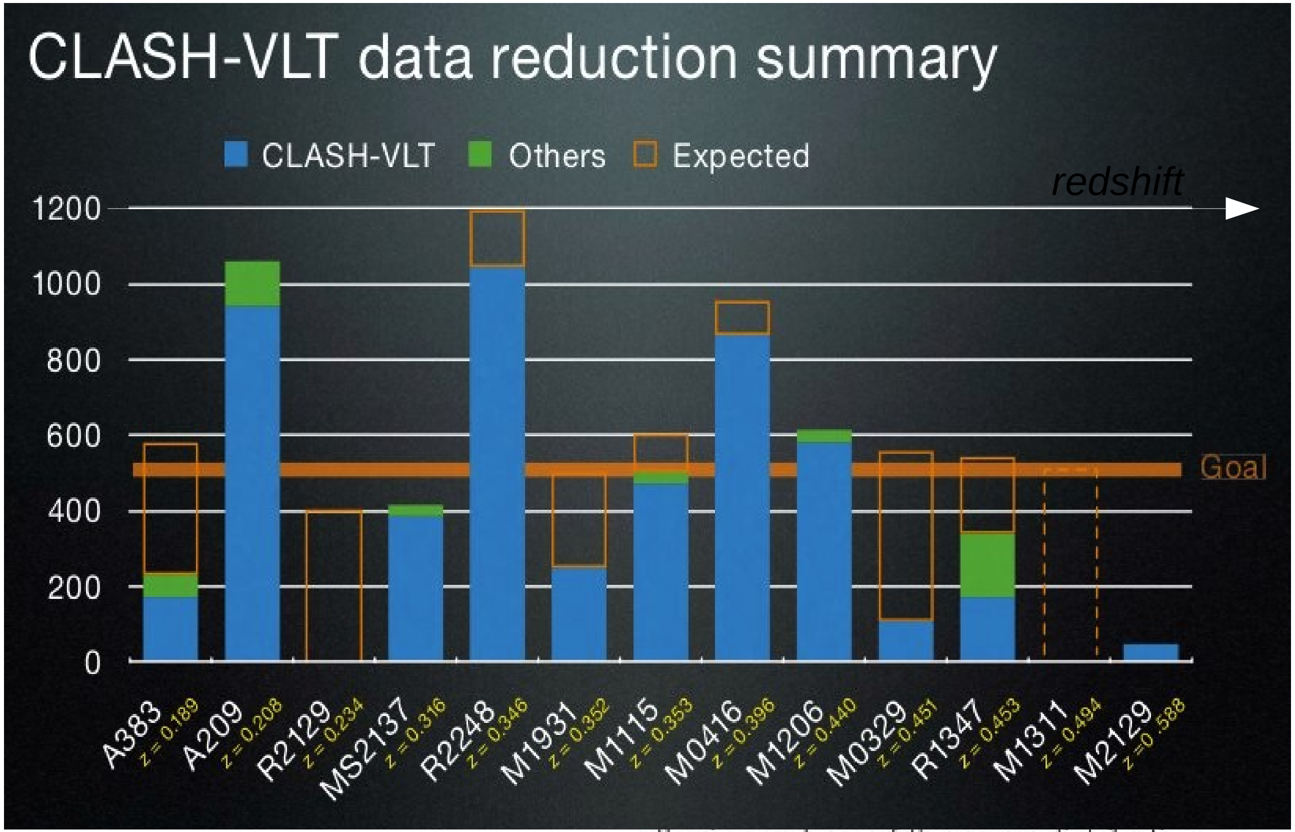

Rosati et al. 2014, The Messenger 158, 48

The CLASH-VLT survey & our data-set

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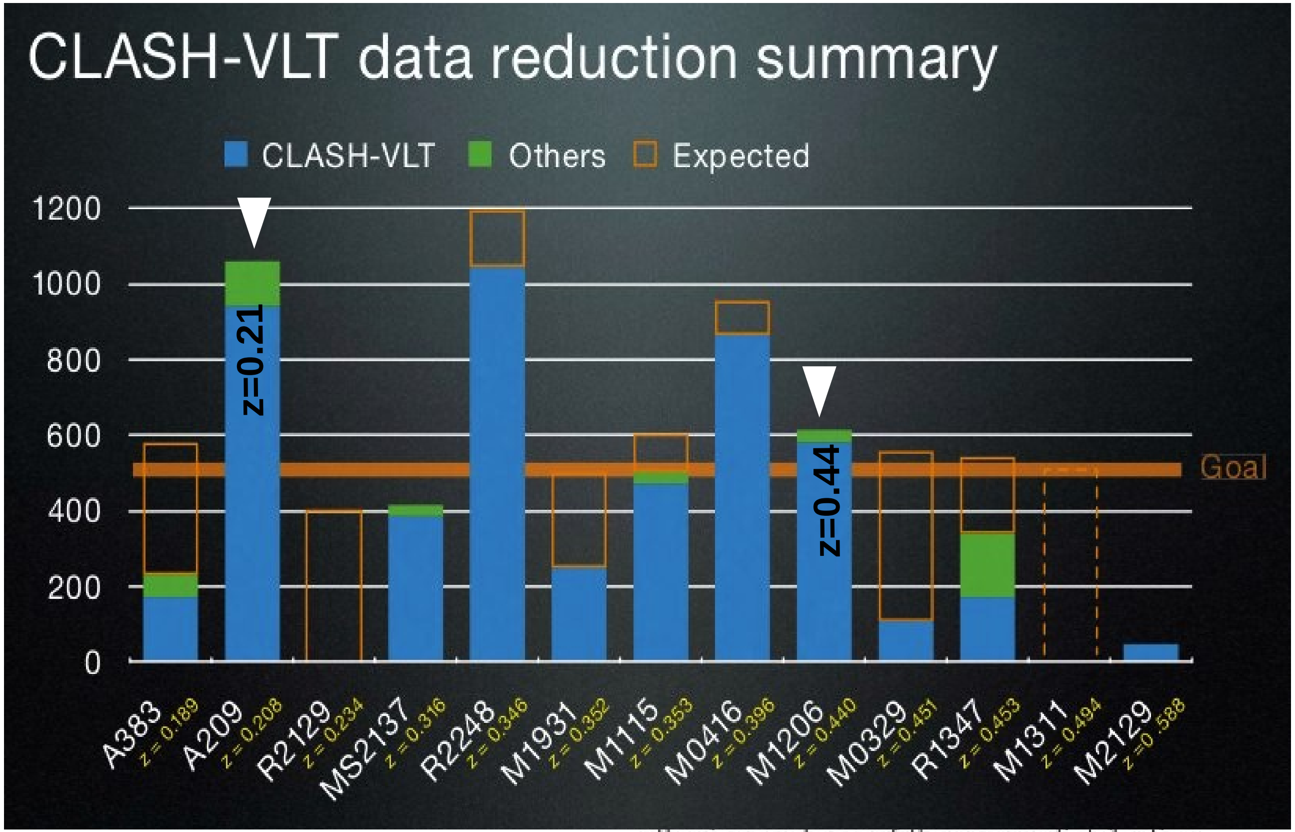

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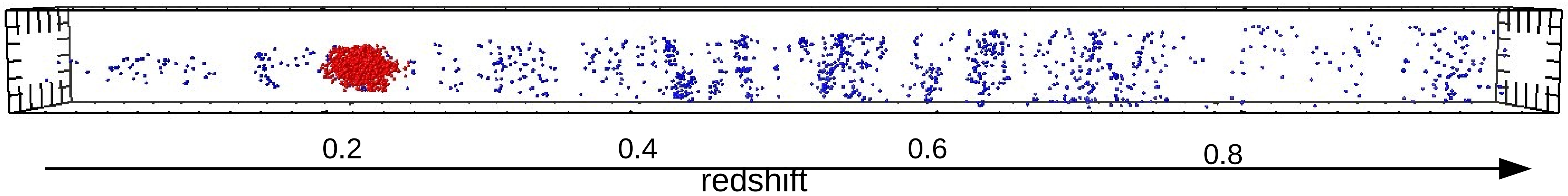
The CLASH-VLT survey & our data-set

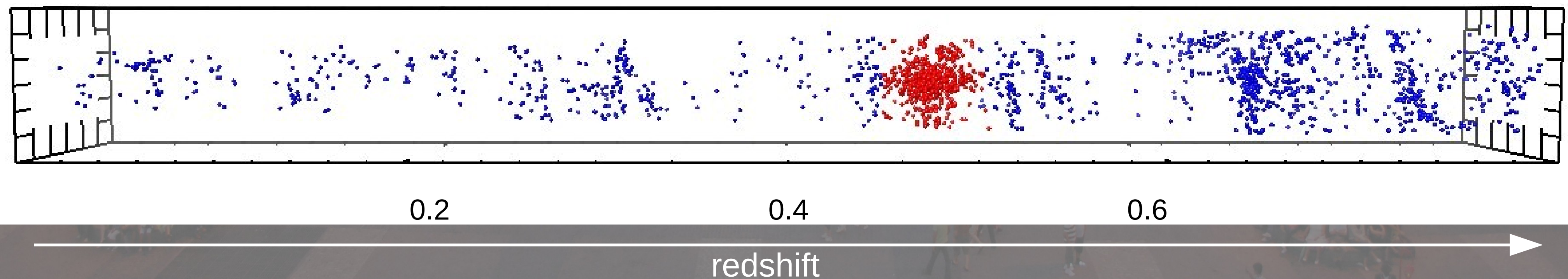
The clusters Abell 209 and MACS 1206 in RA, Dec, redshift

(dots: galaxies with a CLASH-VLT spectroscopic redshift;
red: members, blue: interlopers along the line-of-sight)

A209: ~1100 cluster menbers with z



M1206: ~600 cluster menbers with z

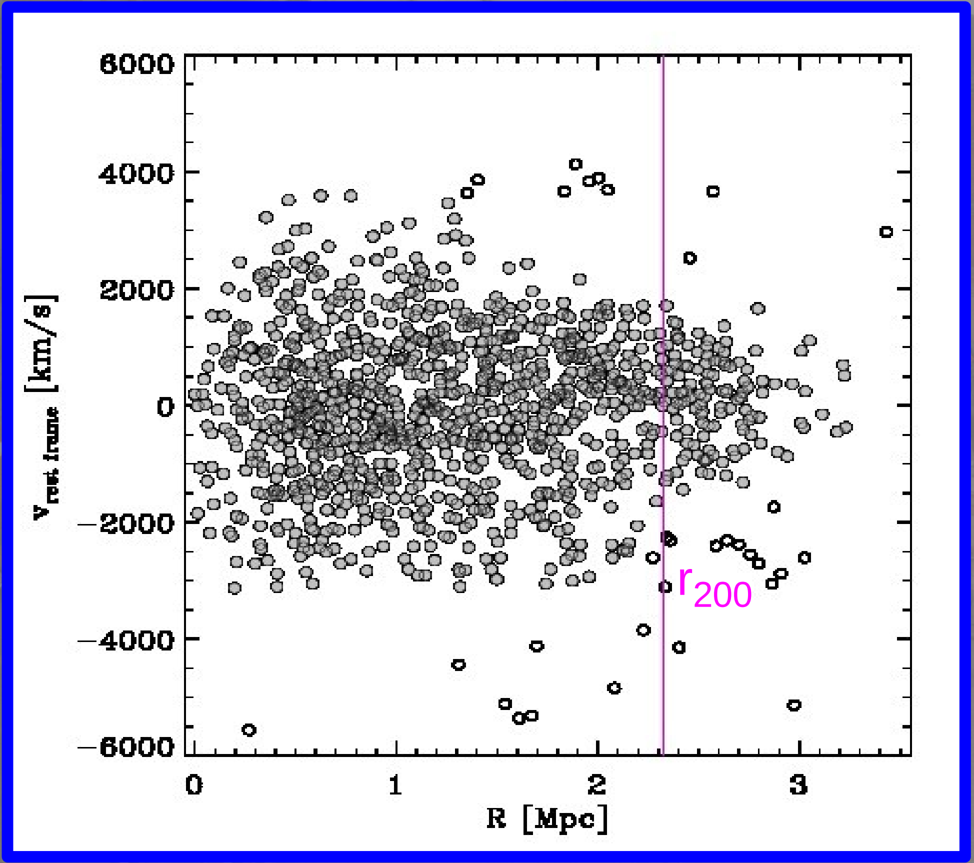


(courtesy Italo Balestra)

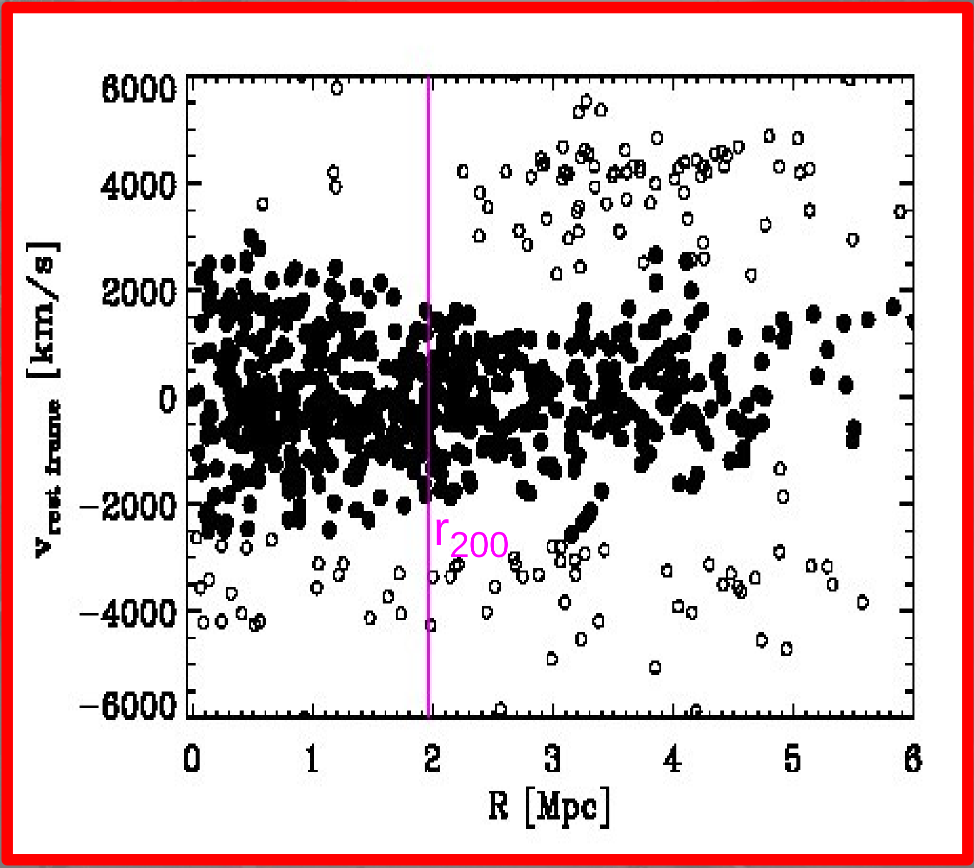
The CLASH-VLT survey & our data-set

The clusters Abell 209 and MACS 1206 in projected phase-space
(rest-frame velocities vs. clustercentric distances)

Filled (grey/black) dots: cluster members; open dots: interlopers



A209, <z> = 0.21
M_{200} = 1.6 10^{15} $M_\odot$ *(h=0.7)*

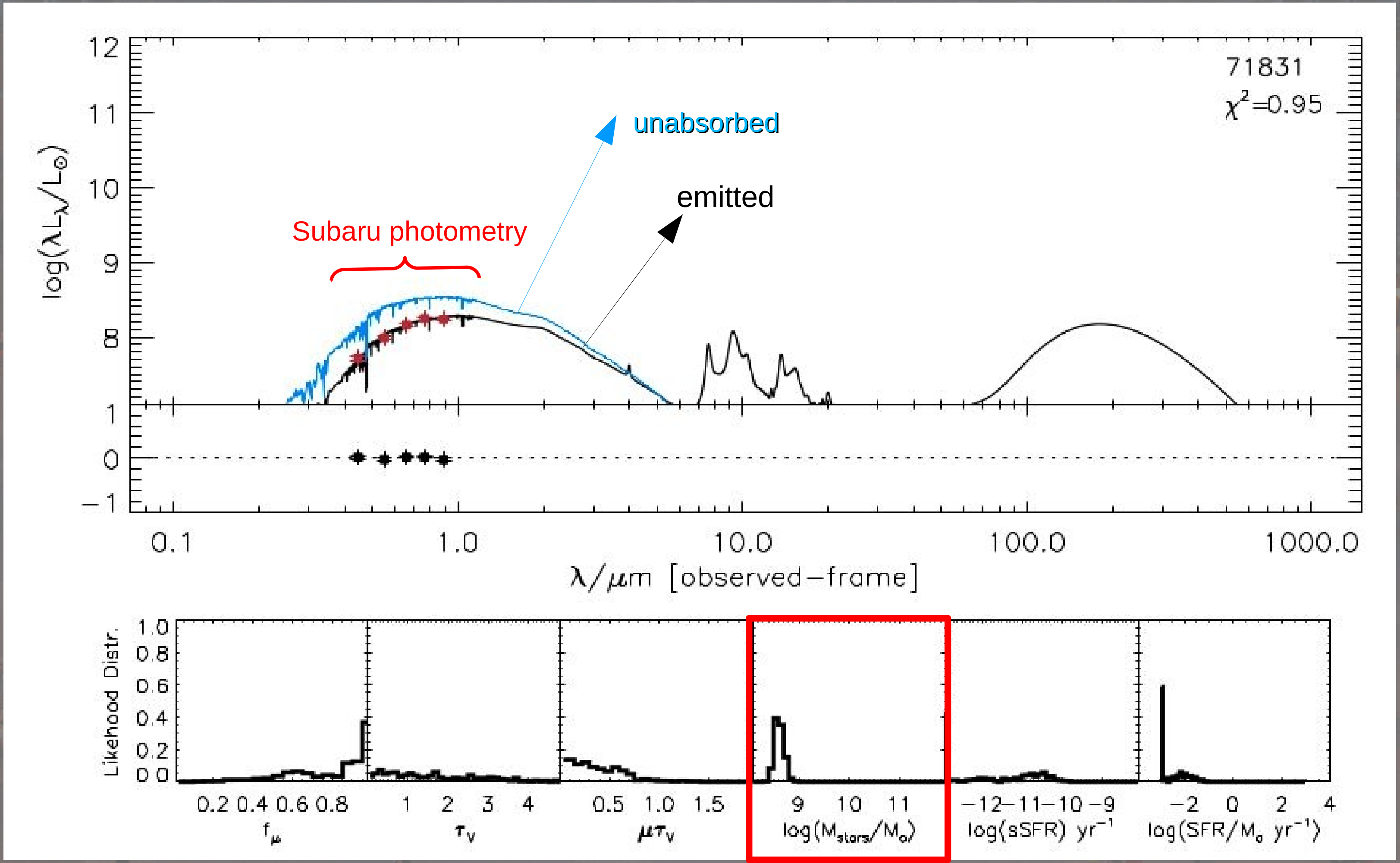


M1206, <z> = 0.44
M_{200} = 1.4 10^{15} $M_\odot$ *(h=0.7)*

The CLASH-VLT survey & our data-set

The data-samples of cluster members

Spectral Energy Distribution fitting (Subaru BVR$_c$I$_c$z' photometry) with MAGPHYS *(Da Cunha et al. 2008)*: → Galaxy stellar masses



The CLASH-VLT survey & our data-set

The data-samples of cluster members

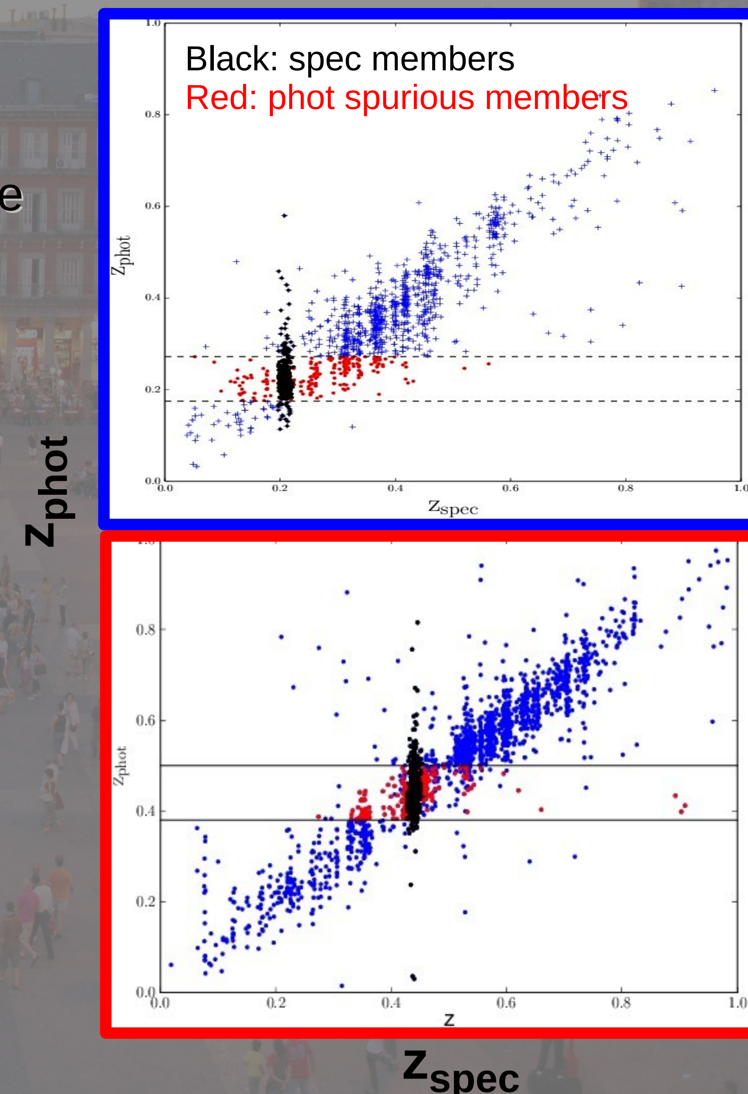
For galaxies without z_{spec} determine z_{phot} using neural network method *(Brescia et al. 2013)*

Correct for:

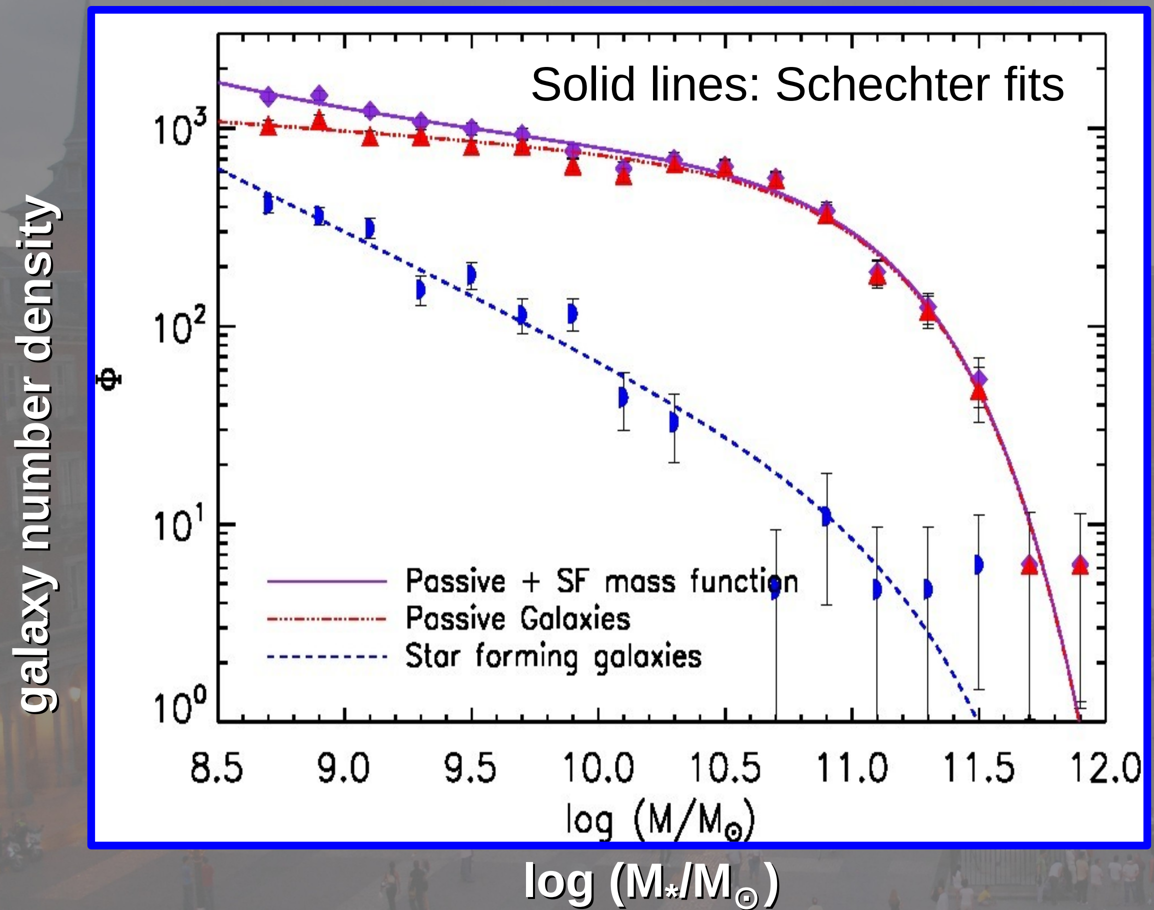
- incompleteness of the photometric sample
- contamination by interlopers in the photometric sample

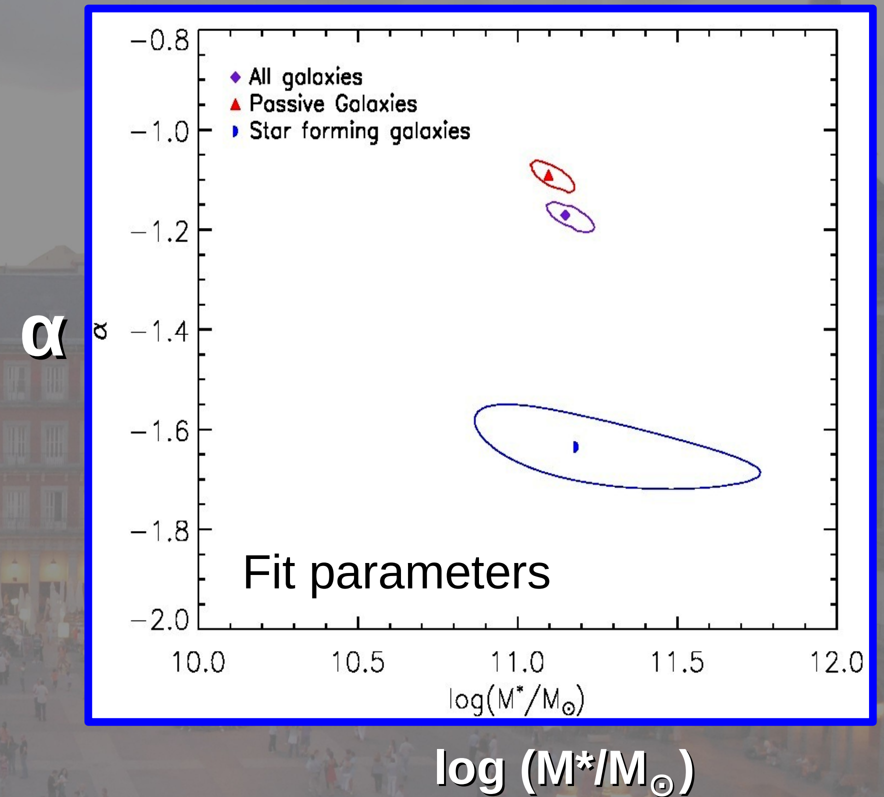
A209: Sample complete down to log $M_* / M_\odot = 8.6$
1916 members (z_{phot} or z_{spec})
1580 passive (814 z_{spec})

M1206: Sample complete down to log $M_* / M_\odot = 9.5$
1363 members (z_{phot} or z_{spec})
846 passive (352 z_{spec})



The Stellar Mass Functions

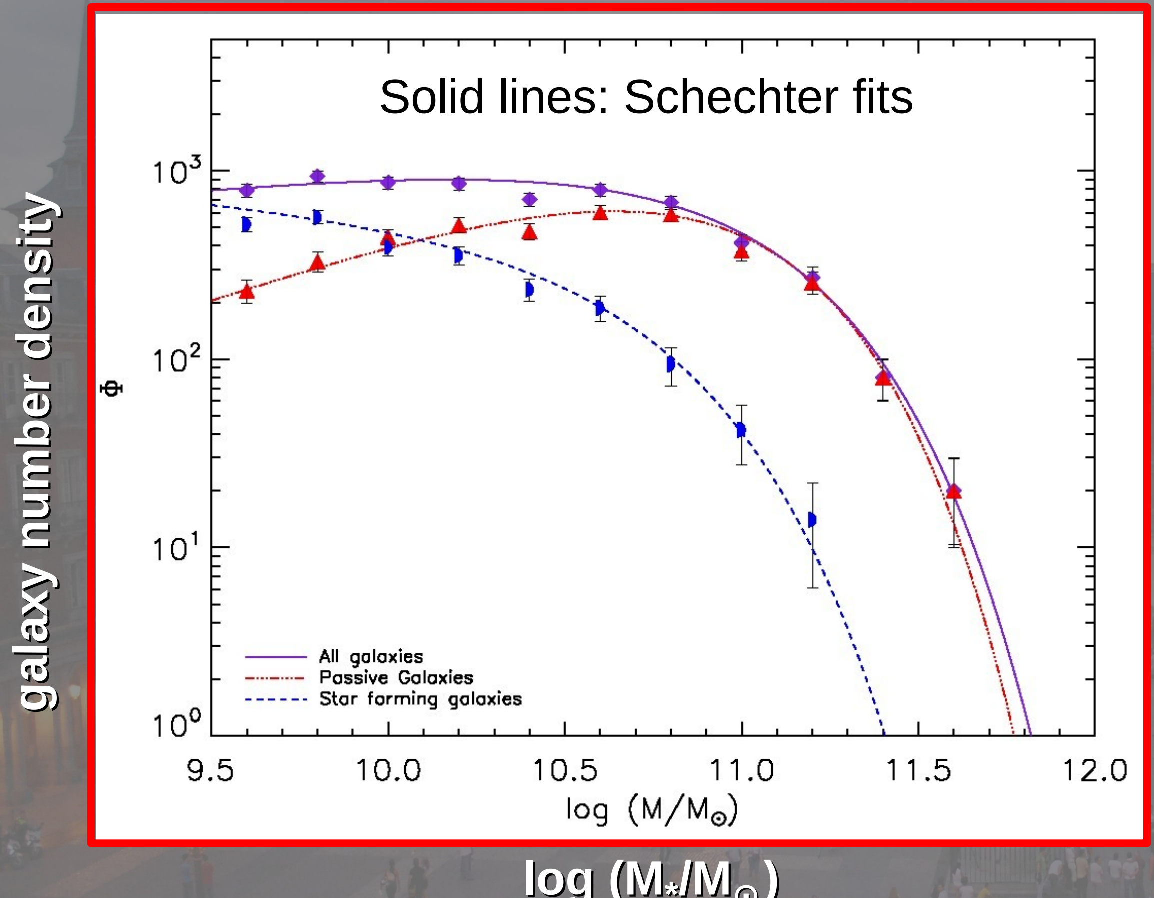


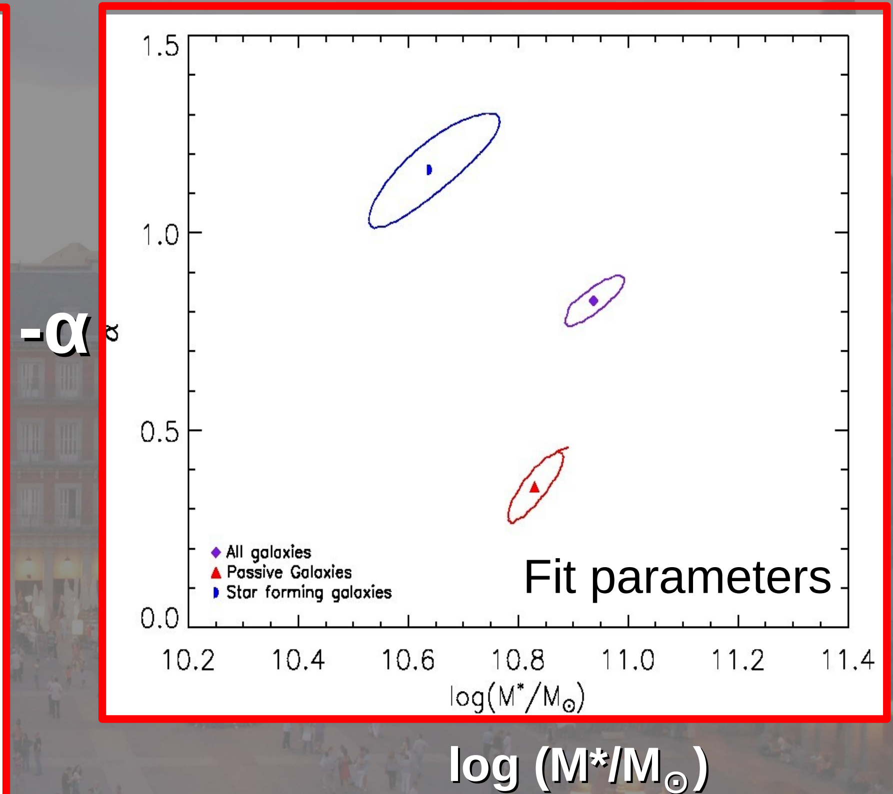


A209: over the whole cluster region (~r_{200}=2.3 Mpc)

- Significant difference between passive and Star-Forming galaxy SMF
- Passive galaxies dominate over SF galaxies at all stellar masses

The Stellar Mass Functions



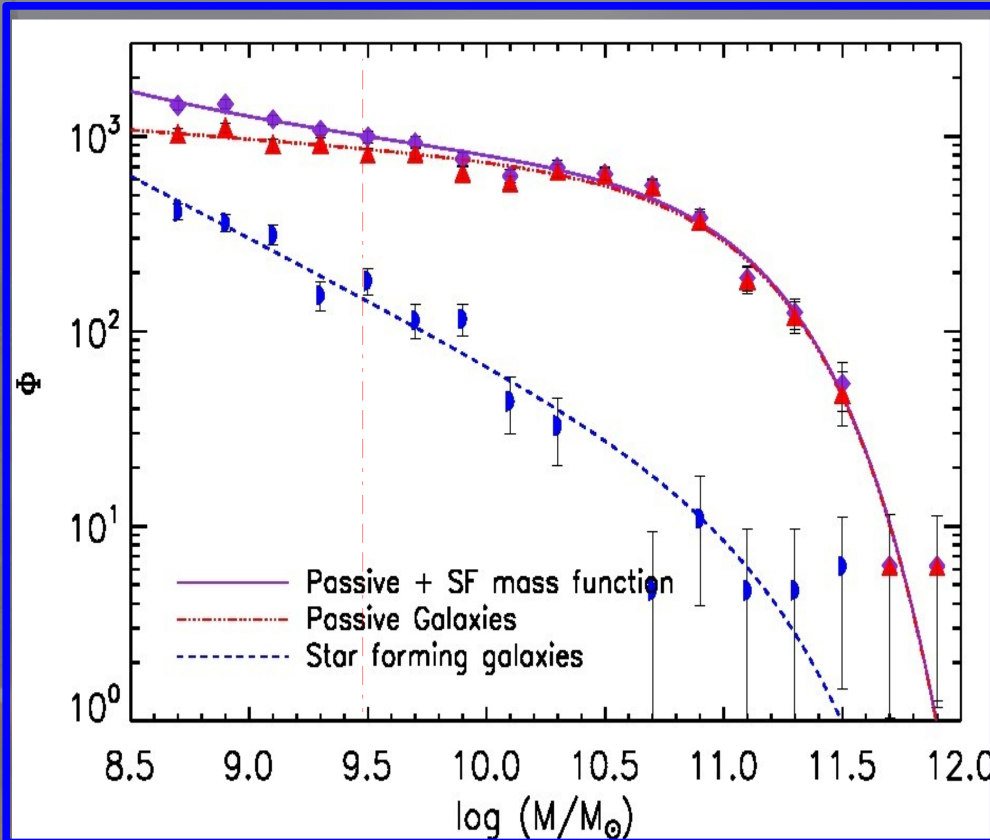


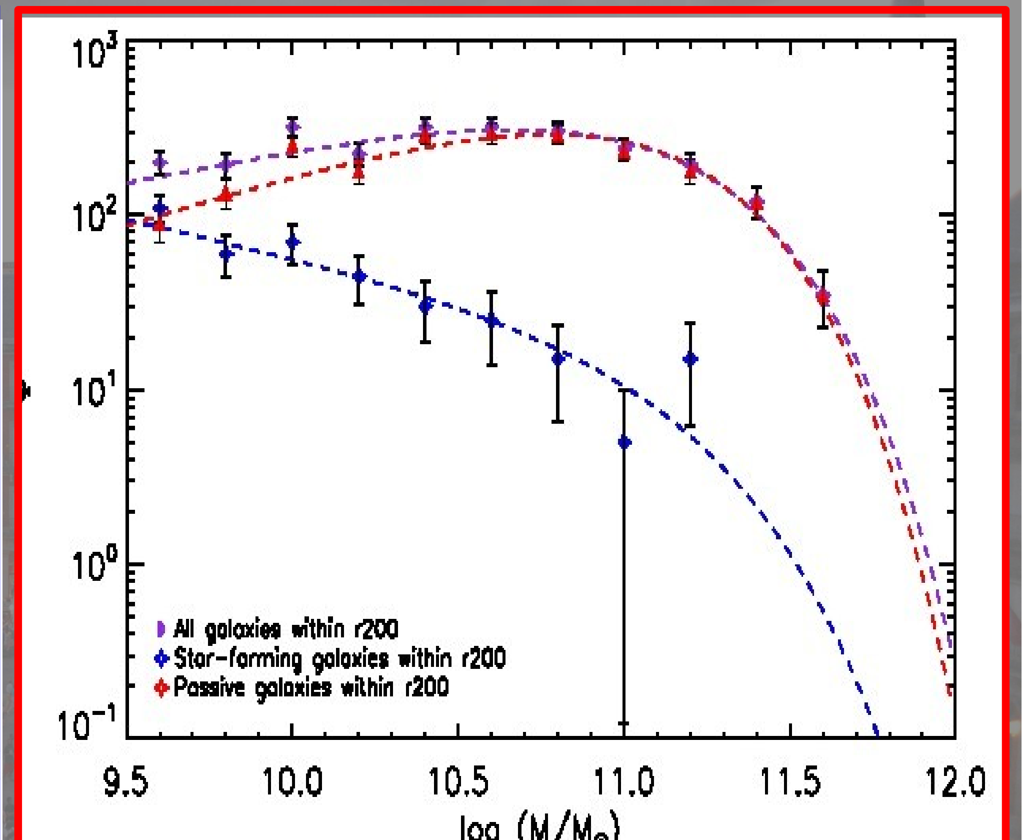
M1206: over the whole cluster region (>2 r_{200}~5 Mpc)

- **Significant difference between passive and Star-Forming galaxy SMF**
- **Passive galaxies dominate over SF galaxies at high stellar masses**

The Stellar Mass Functions

galaxy number density





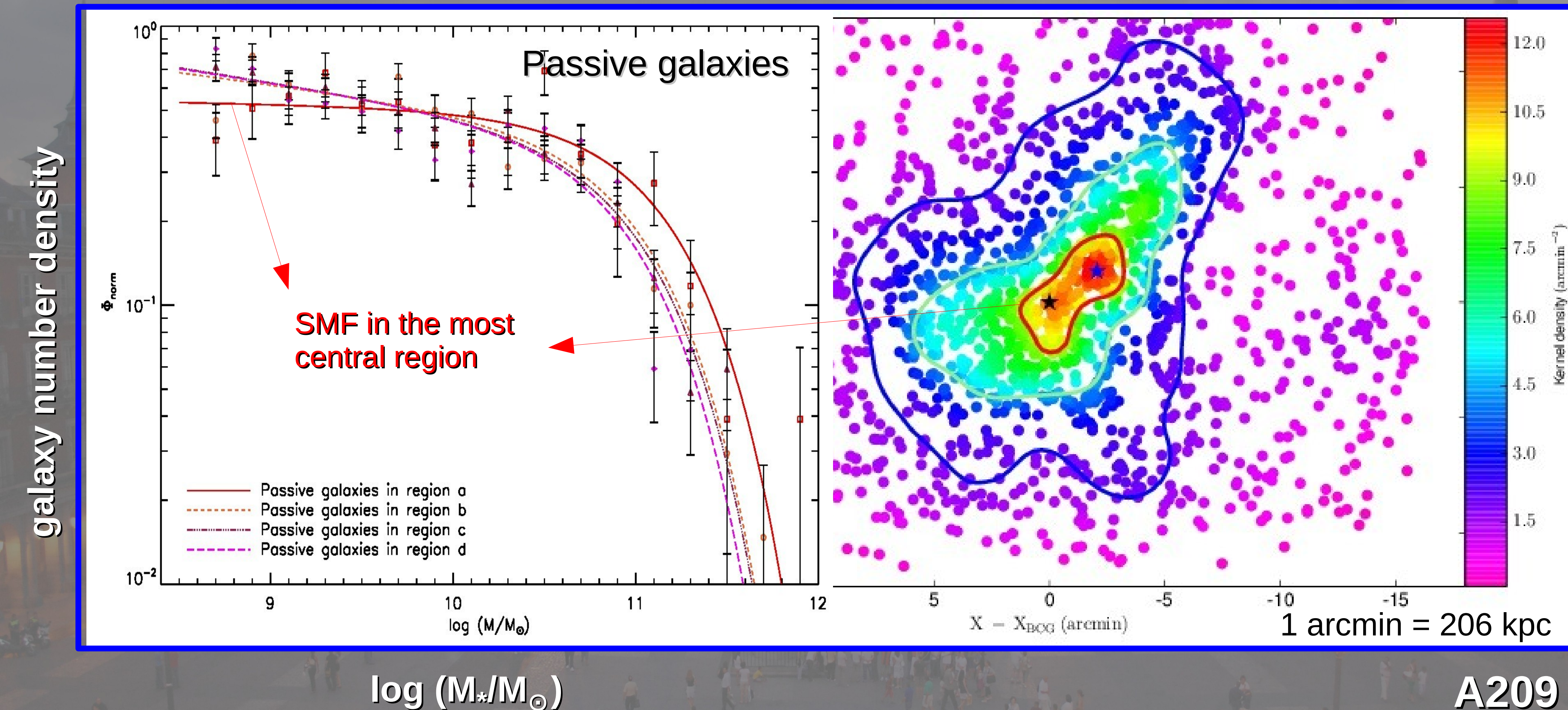
log ($M_*/M_\odot$)

Both cluster SMFs evaluated within r_{200} for comparison

Evolution of faint-end slope of passive SMF from z=0.44 to z=0.21

- **Star-forming galaxies become passive and steepens the SMF low-mass end**
- **Transformation occurs over the whole cluster ⇒ *starvation and/or harassment***

The Stellar Mass Functions

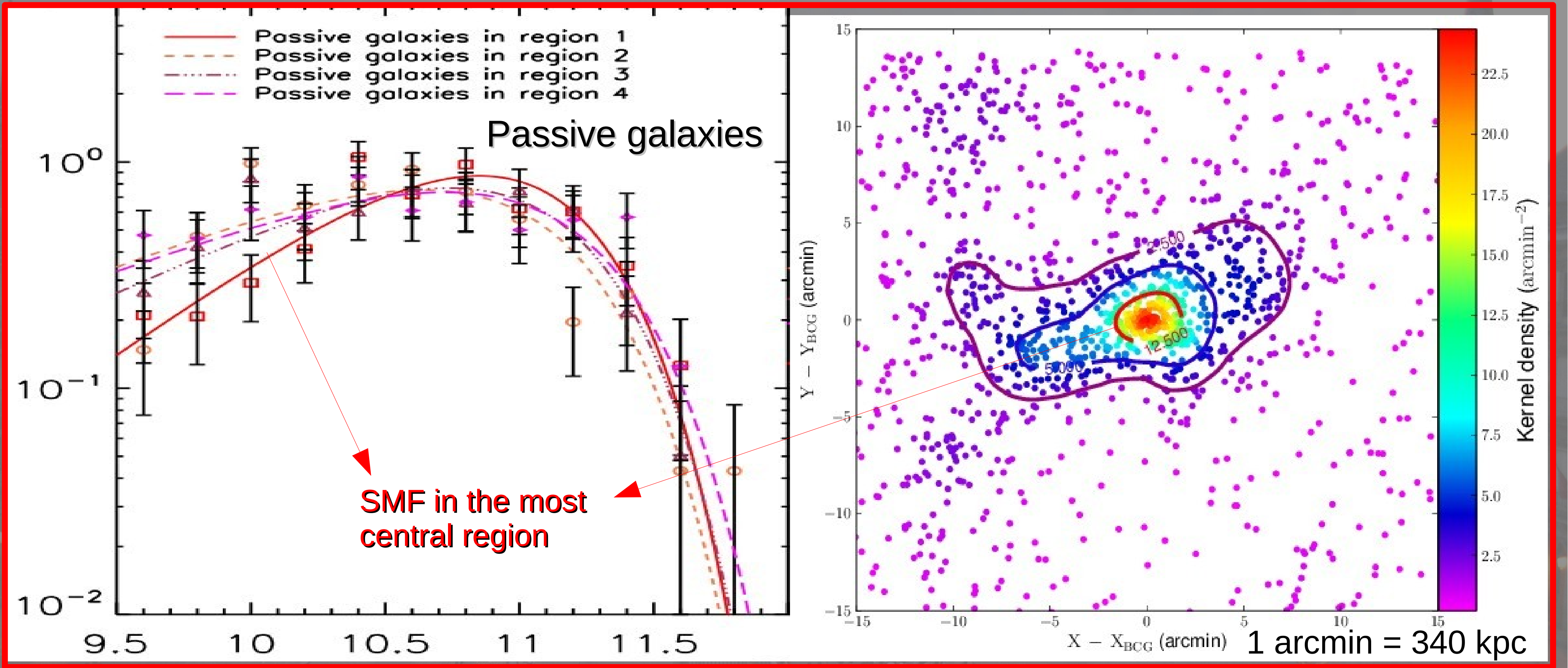


SMF of star-forming galaxies does not depend on local density

- **SMF of passive galaxies is different in the most central region**
- **Lack of low-mass galaxies and excess of high-mass galaxies**
  ⇒ tidal destruction by cluster gravitational field + dynamical friction (and mergers)

The Stellar Mass Functions

galaxy number density



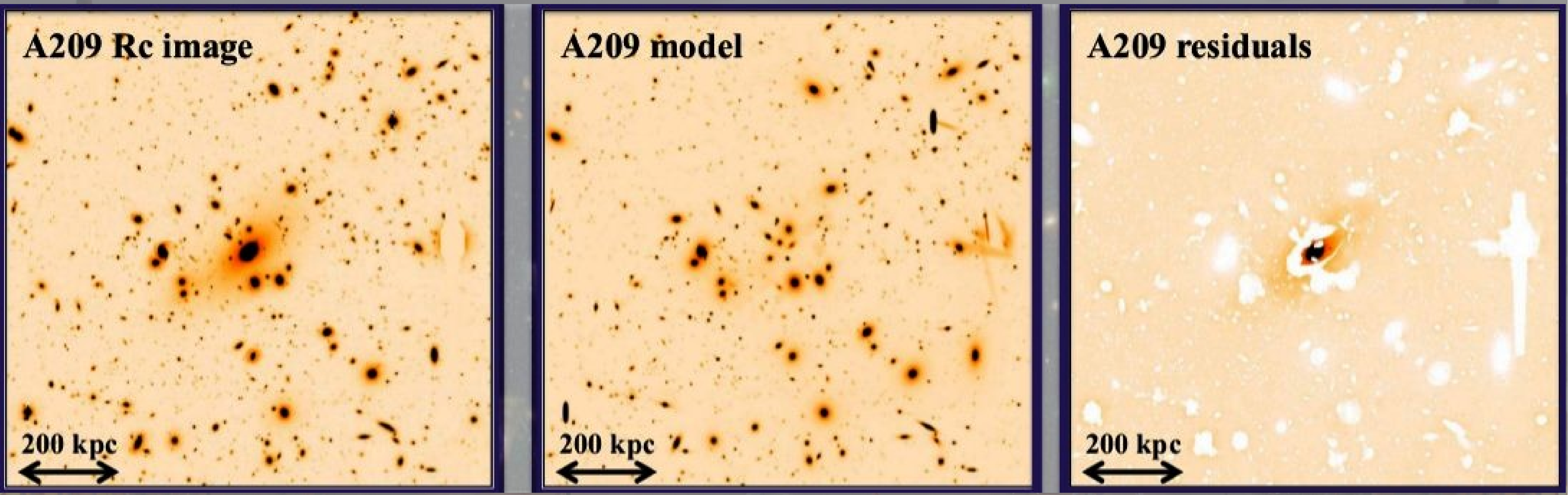
log $(M_*/M_\odot)$

M1206

SMF of star-forming galaxies does not depend on local density

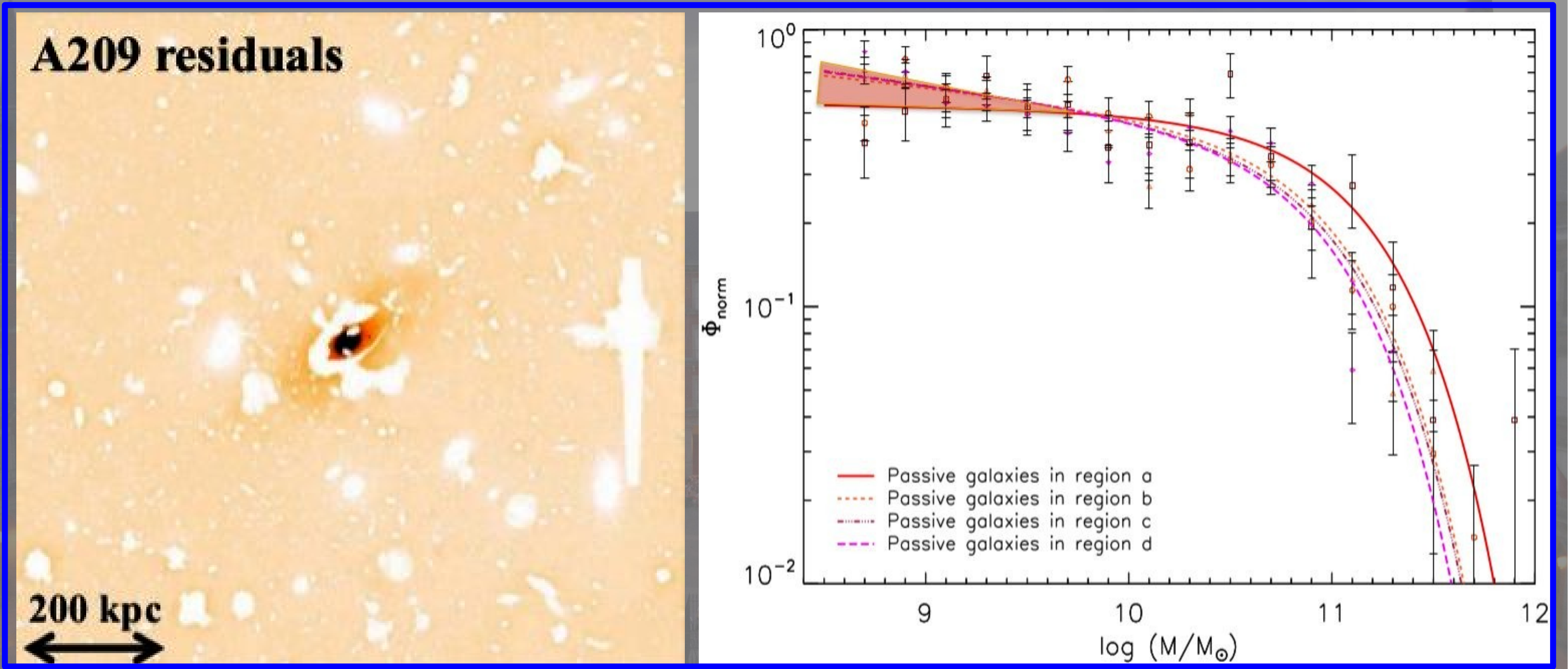
- **SMF of passive galaxies is different in the most central region**
- **Lack of low-mass galaxies**
  ⇒ tidal destruction by cluster gravitational field

The Intra-Cluster Light



SExtractor (Bertin+Arnouts 96) selection of sources in R_c band image
GALAPAGOS (Barden+12) + GALFIT (Peng+10) Sérsic fits to galaxy images
GALtoICL (Presotto+14) extraction of BCG + ICL components
BCG + ICL fitted with three components (2 for the BCG and its halo)
Use the R_c band model for the B band also and determine B-R_c color
Use the stellar mass vs. R_c relation for passive galaxies to infer ICL stellar mass

The Intra-Cluster Light

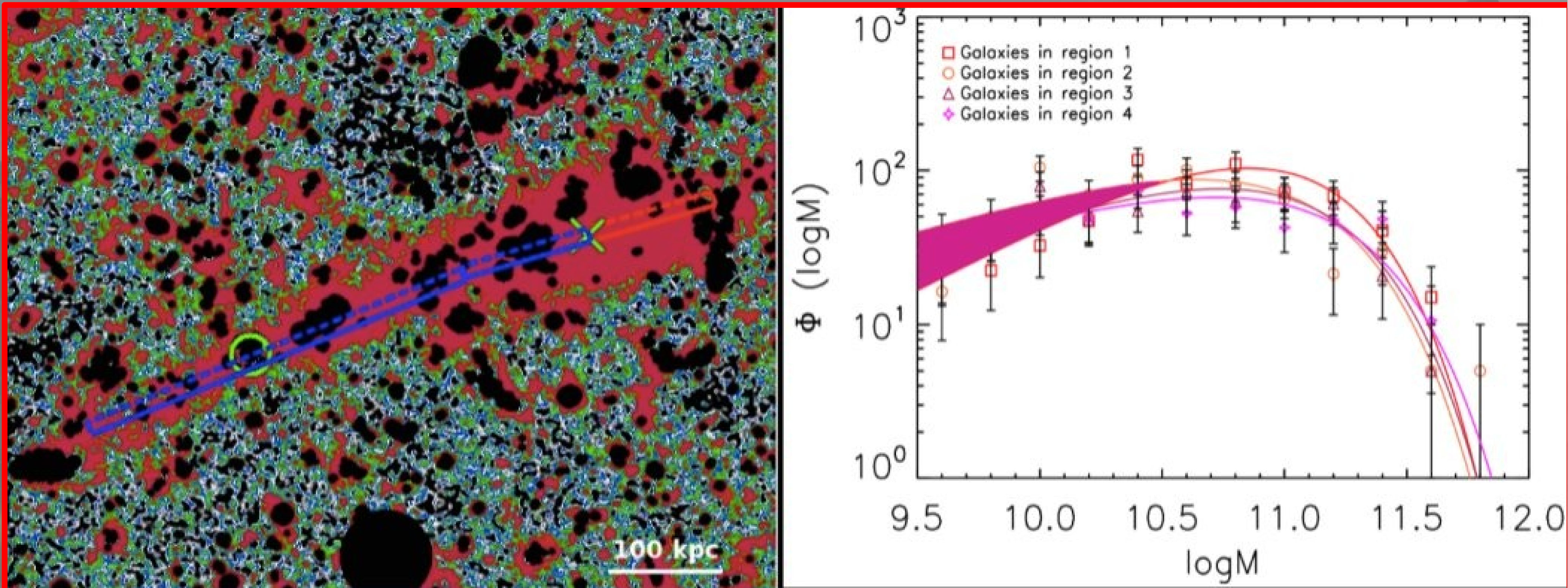


A209

The lacking stellar mass at the low-mass end of the central SMF ($1.4 \pm 0.6\ 10^{11}\ M_\odot$) ≈ stellar mass in the ICL ($2.9 \pm 0.7\ 10^{11}\ M_\odot$), and the ICL color ≈ passive galaxies

- **Lacking low-mass galaxies have been tidally destroyed by the cluster gravitational field and their stripped stars have enriched (formed) the ICL**

The Intra-Cluster Light



M1206

The lacking stellar mass at the low-mass end of the central SMF (6 ± 3 10^{11} $M_\odot$) ≈ stellar mass in the ICL (10 ± 4 10^{11} $M_\odot$)

- **Lacking low-mass galaxies have been tidally destroyed by the cluster gravitational field and their stripped stars have enriched (formed) the ICL**

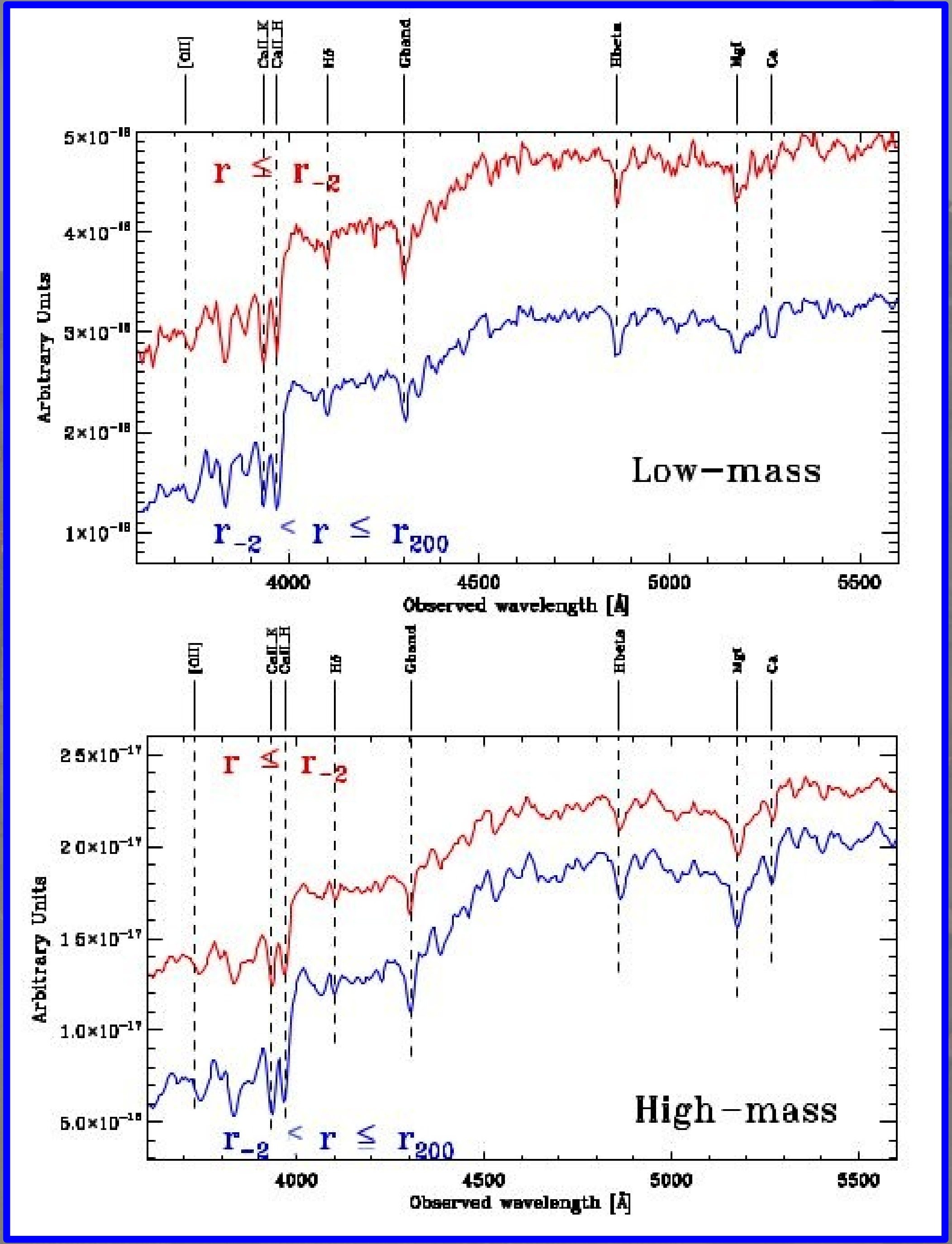
The stellar mass – size relation

Check sizes derived from Subaru image on overlapping HST image ⇒ sizes are reliable for A209 galaxies, not for M1206 galaxies

Consider only passive ($sSFR<10^{-10}$ yr^{-1}) and early-type (Sérsic index>2.5) galaxies

Check passive status of galaxies using spectra for subsample:

Stacked spectra indicate age 8±1 Gyr for passive galaxies
(similar at different radii and masses) and higher metallicity for higher mass galaxies
(pPFX s/w, Cappellari+Emsellem 04)



The stellar mass – size relation

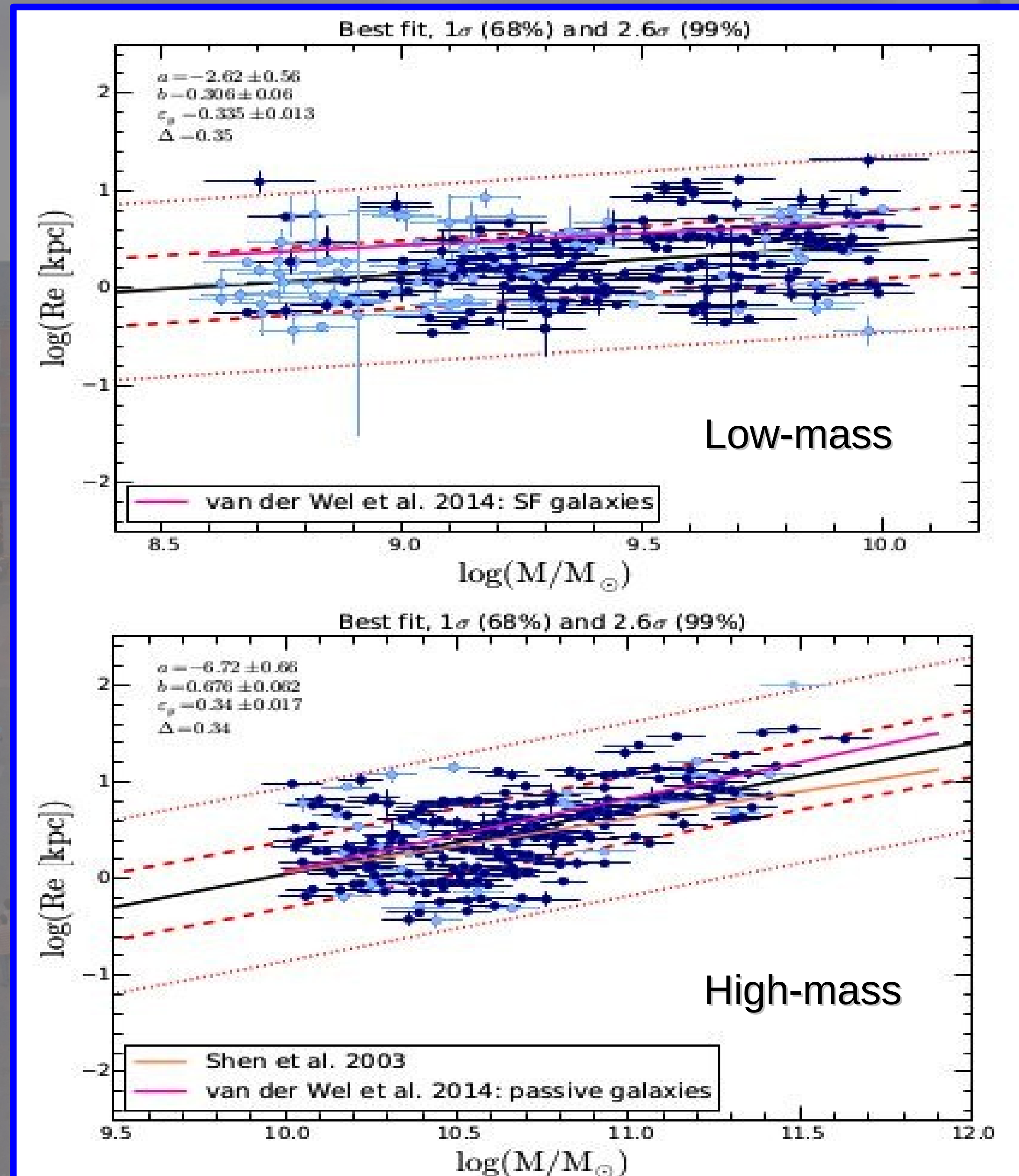
Dark blue: spectroscopic members
Light blue: photometric members

Different relations for low-mass and high-mass passive galaxies

High-mass passive cluster galaxies follow the same relation for field passive galaxies of same mass

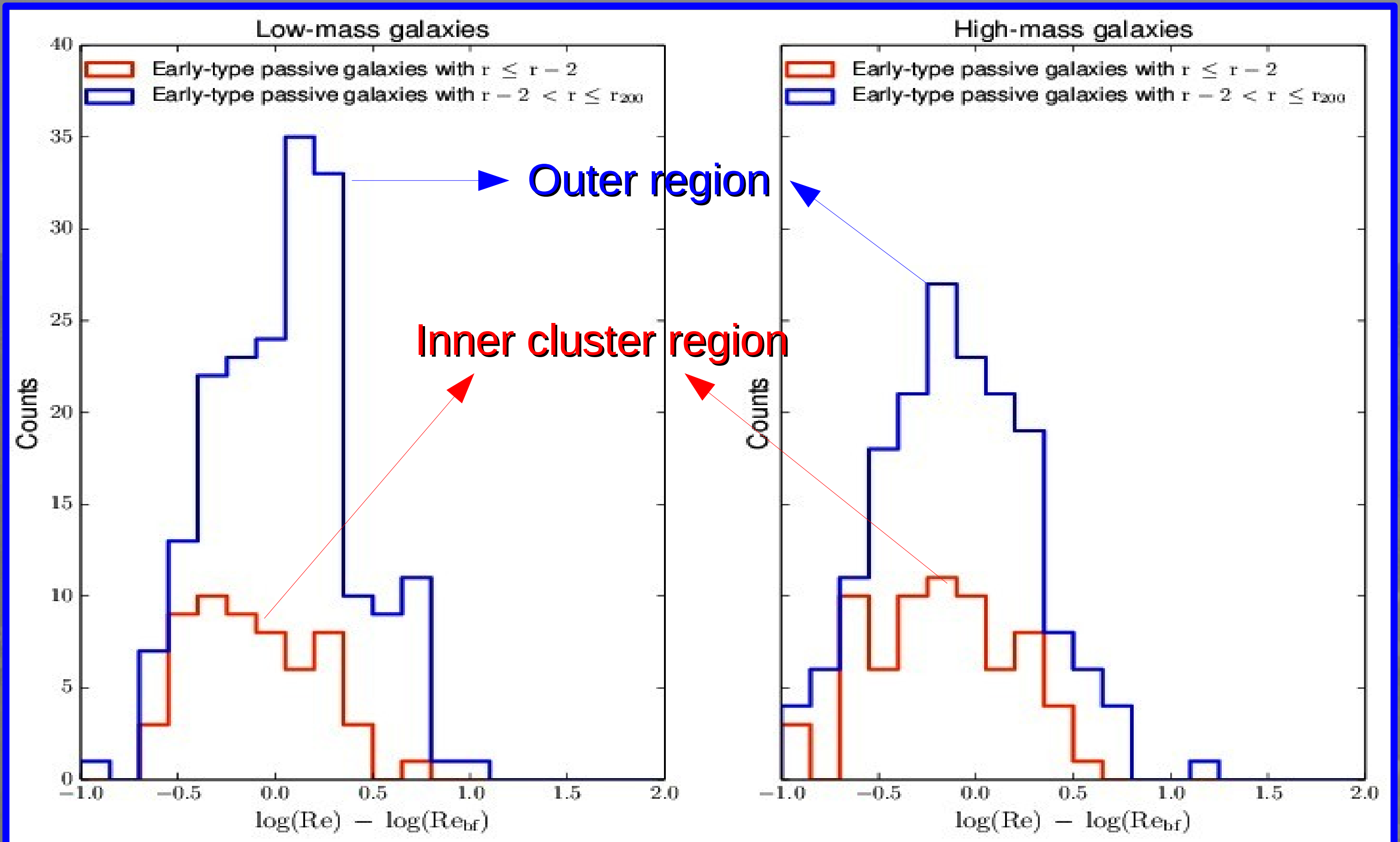
Low-mass passive cluster galaxies obey a relation of similar slope but different normalization as that of star-forming field galaxies

⇒ Transformation of infalling field star-forming galaxies into cluster passive low-mass galaxies by harassment and/or starvation



The stellar mass – size relation

Low-mass



High-mass

Size residuals w.r.t. scaling relation at fixed stellar mass

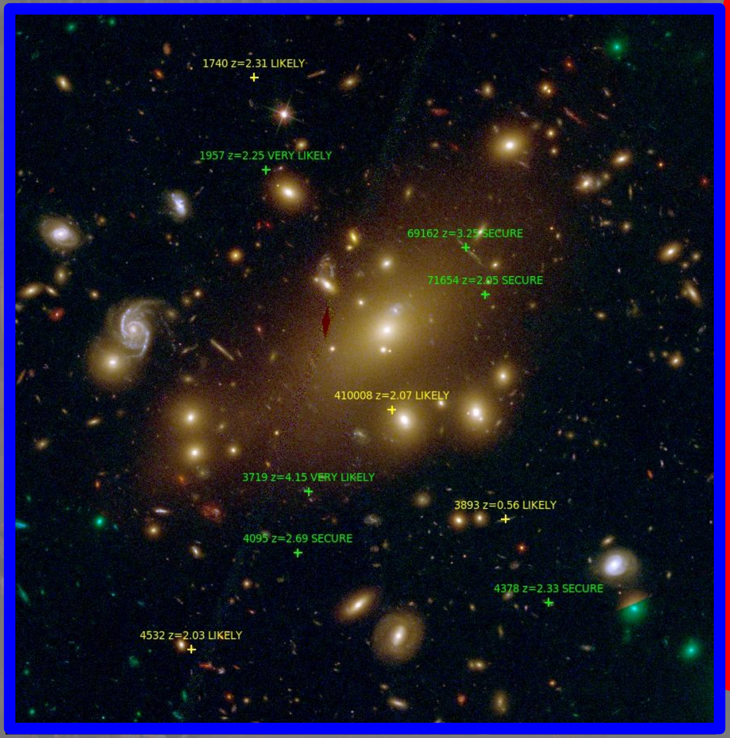
At fixed stellar mass, the sizes of high-mass passive galaxies do not depend on clustercentric distance. The sizes of low-mass passive galaxies are smaller near the cluster center ⇒ Tidal effects by cluster gravitational field

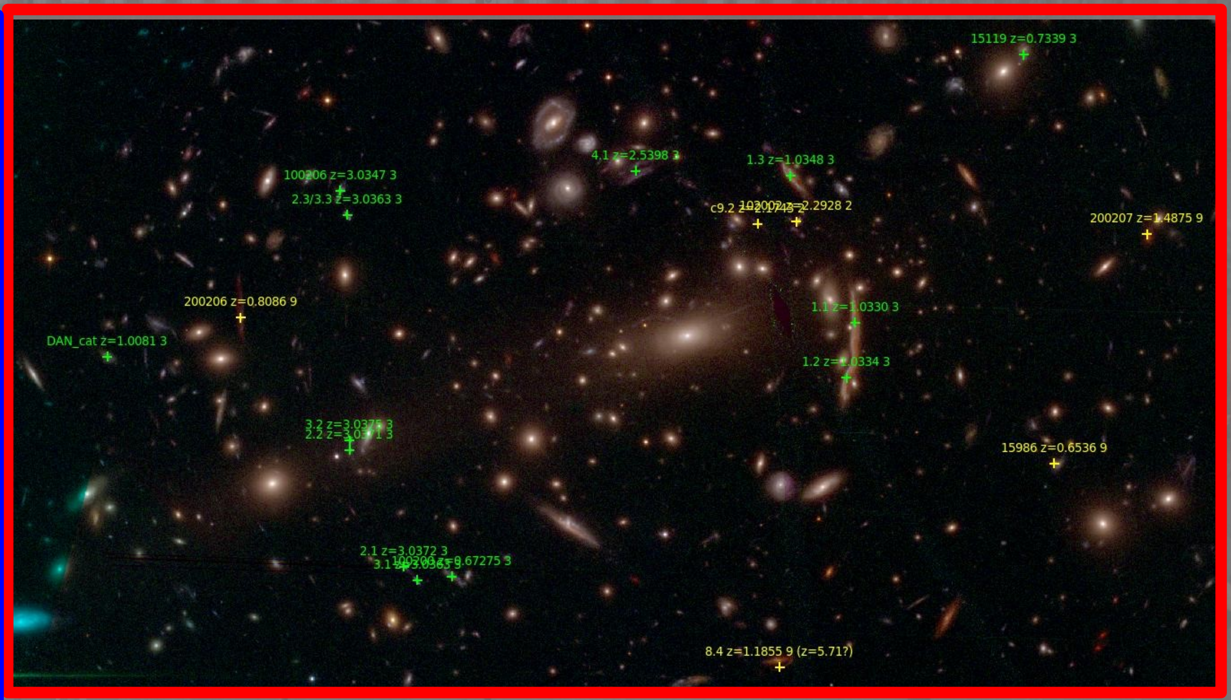
Orbits of passive galaxies

Invert the Jeans equation to obtain the velocity anisotropy profile given:

- the projected number density profile of cluster galaxies *(observable)*
- the line-of-sight velocity dispersion profile of cluster galaxies *(observable)*
- the cluster mass profile *(derived from lensing)*

see Binney & Mamon (1982), Solanes & Salvador-Solé (1990), Dejonghe & Merritt (1992)





Total mass profiles from strong+weak gravitational lensing analysis by the CLASH collaboration *(A209: Merten et al. 2014; M1206: Umetsu et al. 2012)* thanks also to CLASH-VLT spectra for lensed galaxies

Orbits of passive galaxies

Invert the Jeans equation to obtain the velocity anisotropy profile given:

- the projected number density profile of cluster galaxies *(observable)*
- the line-of-sight velocity dispersion profile of cluster galaxies *(observable)*
- the cluster mass profile *(derived from lensing)*

see Binney & Mamon (1982), Solanes & Salvador-Solé (1990), Dejonghe & Merritt (1992)

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

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

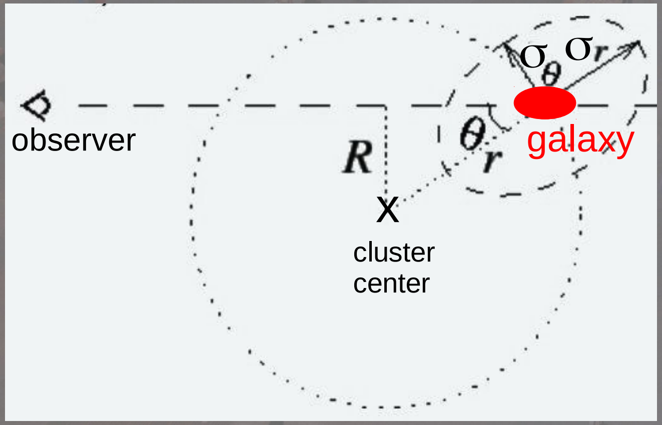
Mass profile

3D number density profile

Velocity dispersion profile along the radial direction, r

Velocity anisotropy profile

Velocity dispersion profile along the tangential direction



The velocity anisotropy profile β(r) is related to the elongation of the velocity ellipsoid and hence to the orbits of cluster galaxies:
β>0: radially elongated, β<0: tangential, β=0: isotropic

Orbits of passive galaxies

$$\Psi(r) = -GM(<r)\nu(r)/r^2 \tag{1}$$

$$H(R) = \frac{1}{2} I(R)\sigma_p^2(R) \tag{2}$$

$$K(r) = 2\int_r^\infty H(x)\frac{x\mathrm{d}x}{\sqrt{x^2-r^2}}. \tag{3}$$

$$[3-2\beta(r)] \times \langle \mathrm{v}_\mathrm{r}^2 \rangle(\mathrm{r}) = \frac{-1}{\nu(r)} \int_r^\infty \Psi(x)\mathrm{d}x - \\ - \frac{2}{\pi r \nu(r)} \frac{\mathrm{d}K(r)}{\mathrm{d}r} \tag{4}$$

$$\beta(r) \langle \mathrm{v}_\mathrm{r}^2 \rangle(\mathrm{r}) = \frac{1}{\nu(r) r^3} \int_0^r x^3 \Psi(x)\mathrm{d}x + \\ + \frac{1}{\pi r \nu(r)} \frac{\mathrm{d}K(r)}{\mathrm{d}r} - \\ - \frac{3K(r)}{\pi r^2 \nu(r)} + \frac{3}{\pi r^3 \nu(r)} \int_0^r K(x)\mathrm{d}x \tag{5}$$

(Solanes & Salvador-Solé 1990)

M(r) +

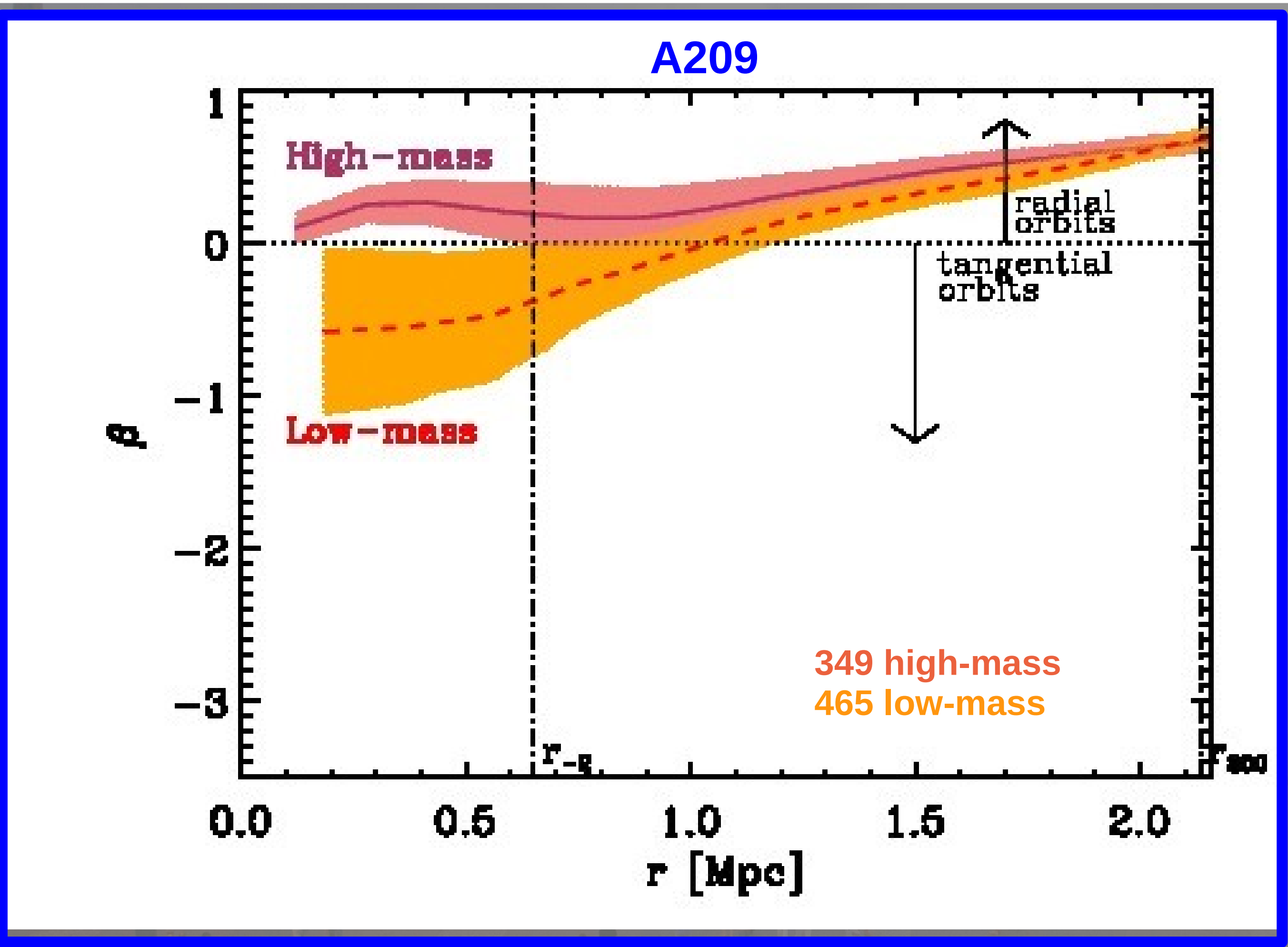
Observables
I(R), σ_p(R)

via a lot of smoothing, differentiation, integration …

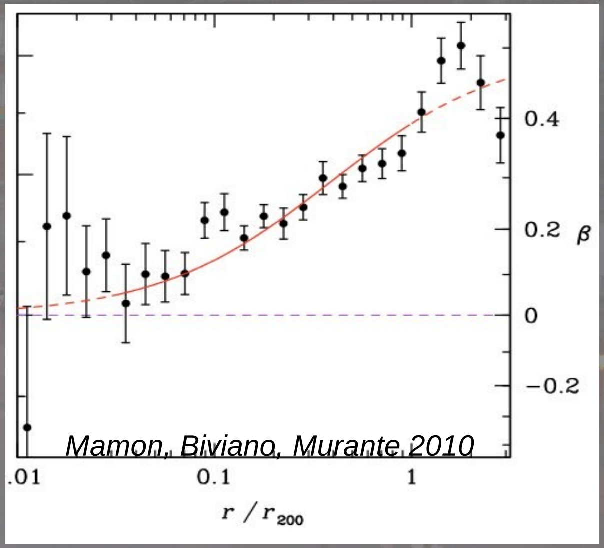
β(r)

Orbits of passive galaxies

Low-mass galaxies: log $M_* / M_\odot < 10.0$ **High-mass galaxies: log $M_* / M_\odot \geq 10.0$**



High-mass galaxies move on mostly radial orbits
(as DM particles in cluster-size halos from cosmo. sims)

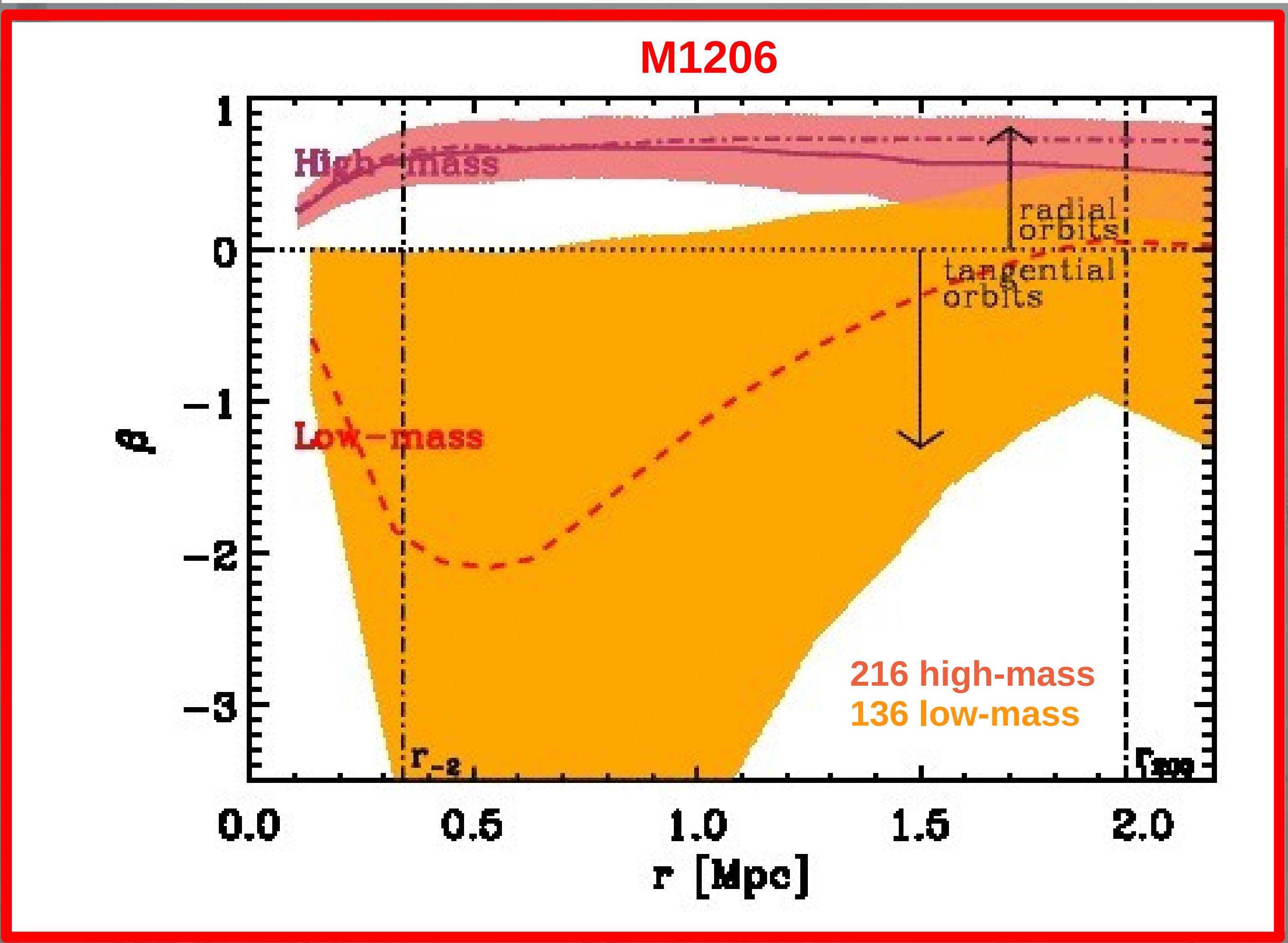


Low-mass galaxies move on tangential orbits near the cluster center

→ Tidal destruction: Low-mass galaxies on radial orbits have small pericenter, so when they pass near the cluster center they are destroyed by the strong tidal effects due to the cluster gravitational potential

Orbits of passive galaxies

Low-mass galaxies: log $M_* / M_\odot < 10.5$ **High-mass galaxies: log $M_* / M_\odot \geq 10.5$**



High-mass galaxies move on radial orbits, more than those in A209:

→ Isotropization of the galaxy orbits with time?

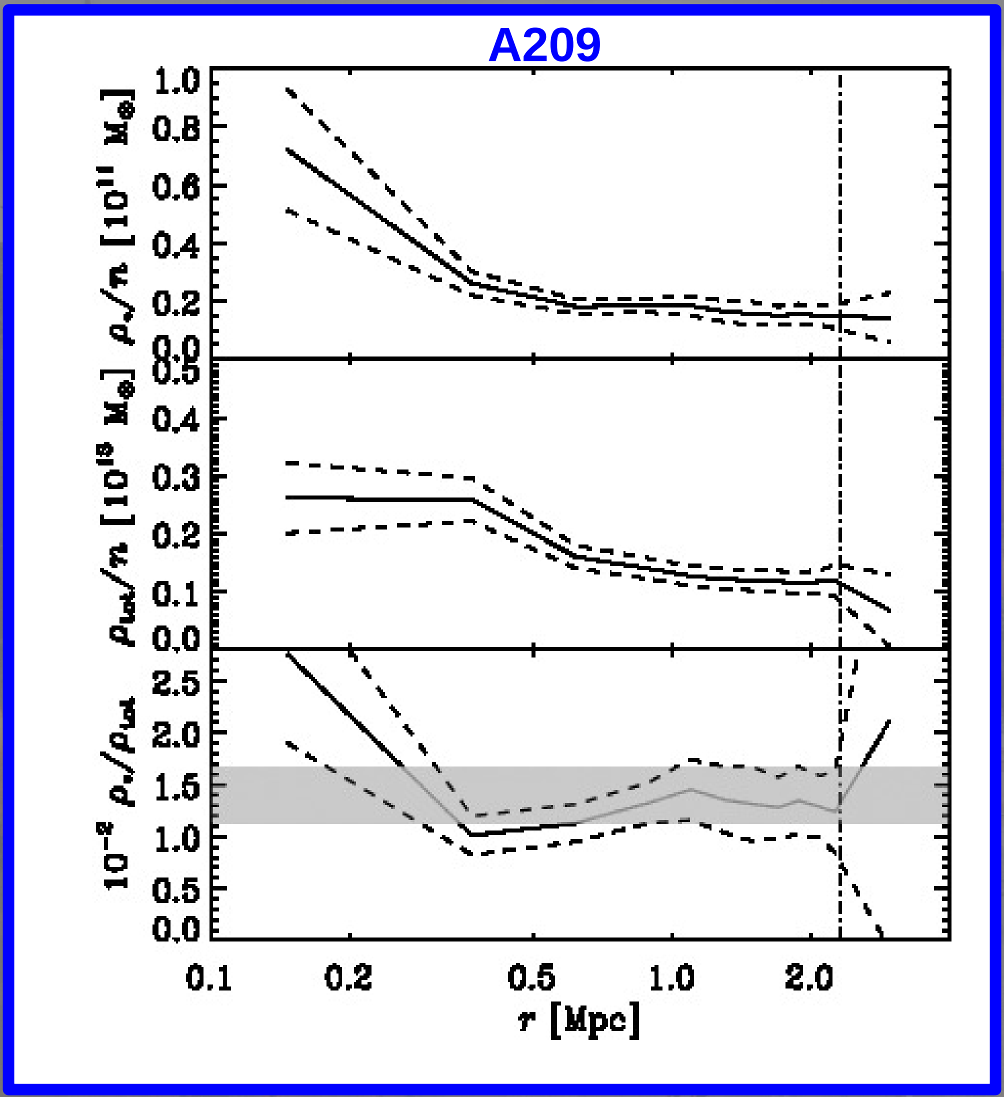
(as suggested by Biviano & Poggianti 2009, based on the ENACS and EDisCS samples)

Possibly caused by dynamical friction of massive galaxies

Low-mass galaxies move on tangential orbits near the cluster center

→ Tidal destruction: Low-mass galaxies on radial orbits have small pericenter, so when they pass near the cluster center they are destroyed by the strong tidal effects due to the cluster gravitational potential

Density profiles



stellar-mass density profile / number density profile

total-mass density profile / number density profile

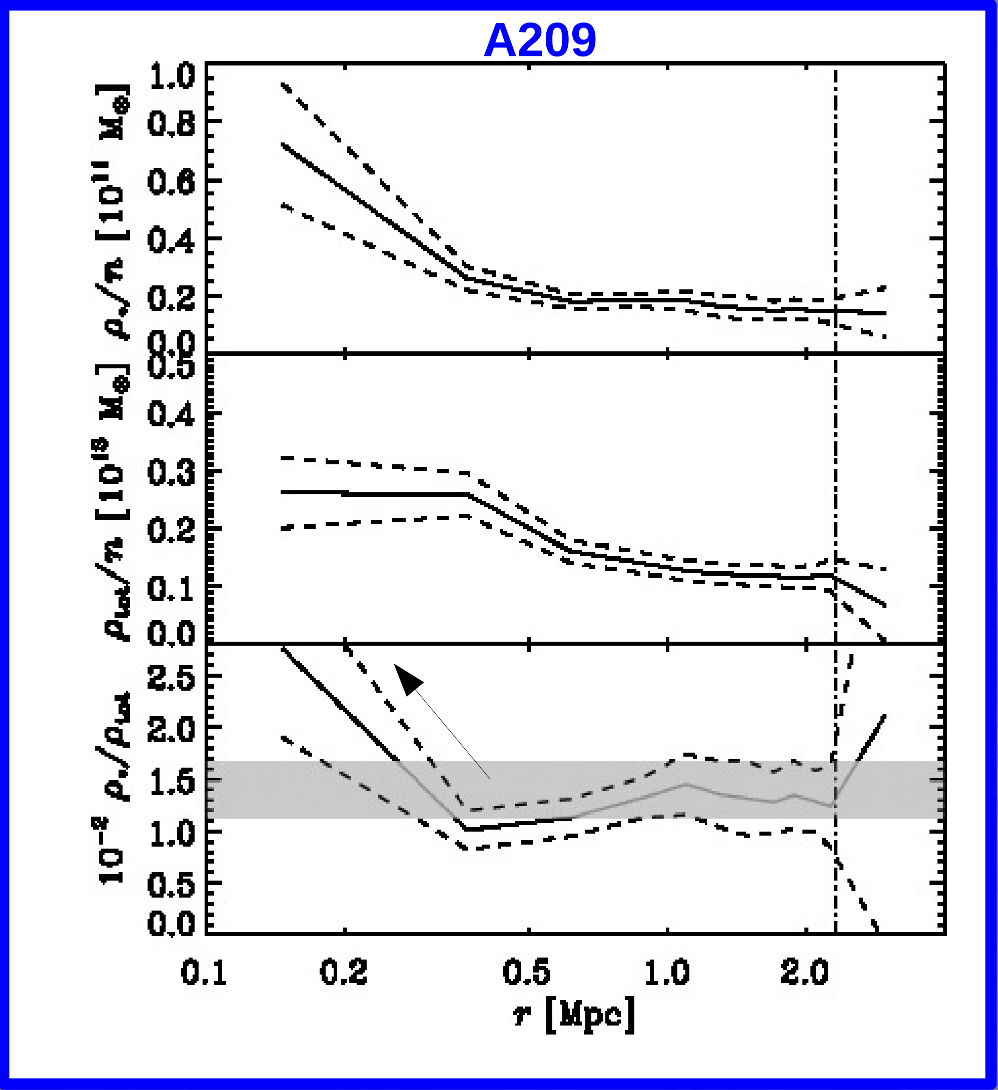
stellar-mass density profile / total-mass density profile

Shading:
cosmic value of the stellar mass fraction at the cluster <z> *(Muzzin+13)*

distance from cluster center (=BCG position)

Consider passive galaxies only
All profiles de-projected assuming spherical symmetry

Density profiles



distance from cluster center (=BCG position)

$$\frac{\text{stellar-mass density profile}}{\text{number density profile}}$$

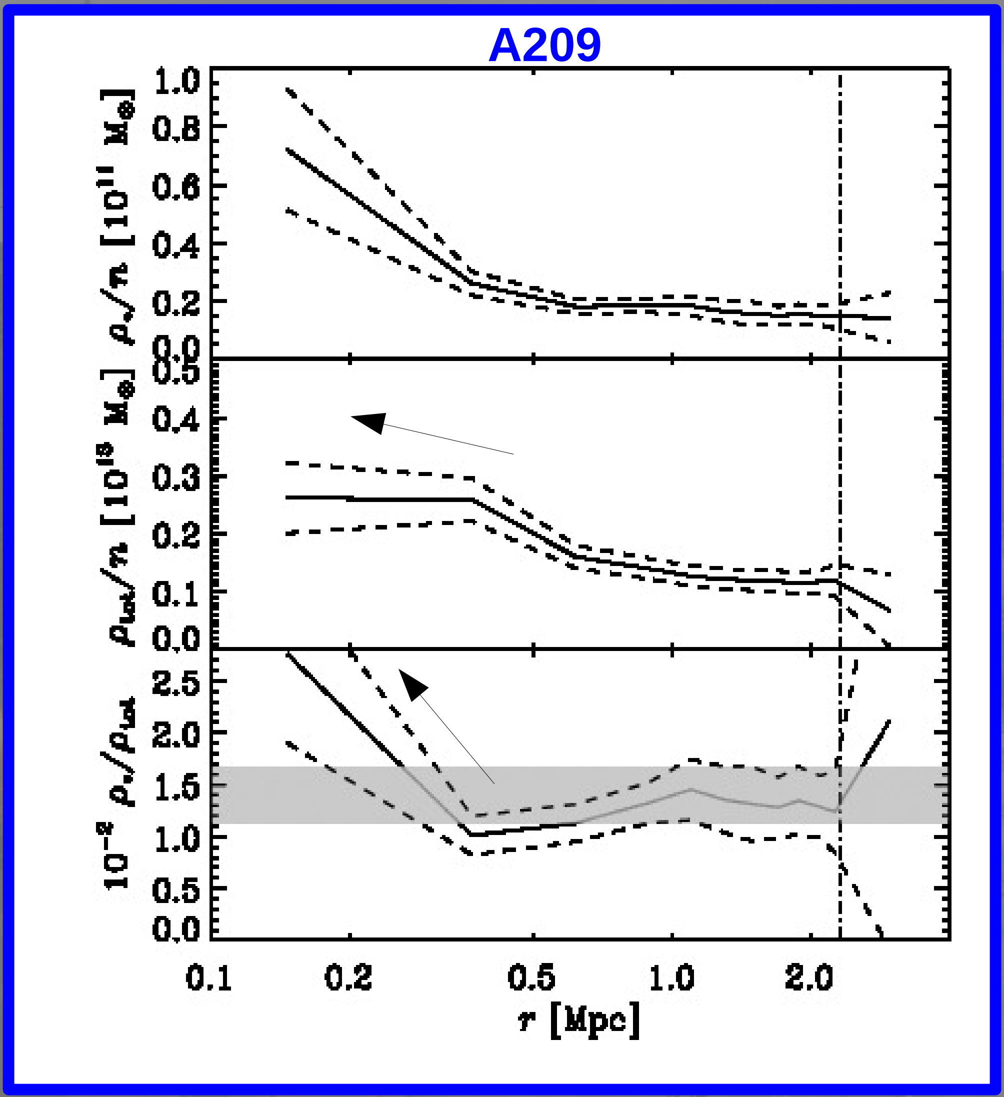
$$\frac{\text{total-mass density profile}}{\text{number density profile}}$$

$$\frac{\text{stellar-mass density profile}}{\text{total-mass density profile}}$$

→ Dynamical friction:

massive galaxies loose kinetic
energy to the diffuse DM particles
and concentrate near the cluster center

Density profiles



distance from cluster center (=BCG position)

stellar-mass density profile / number density profile

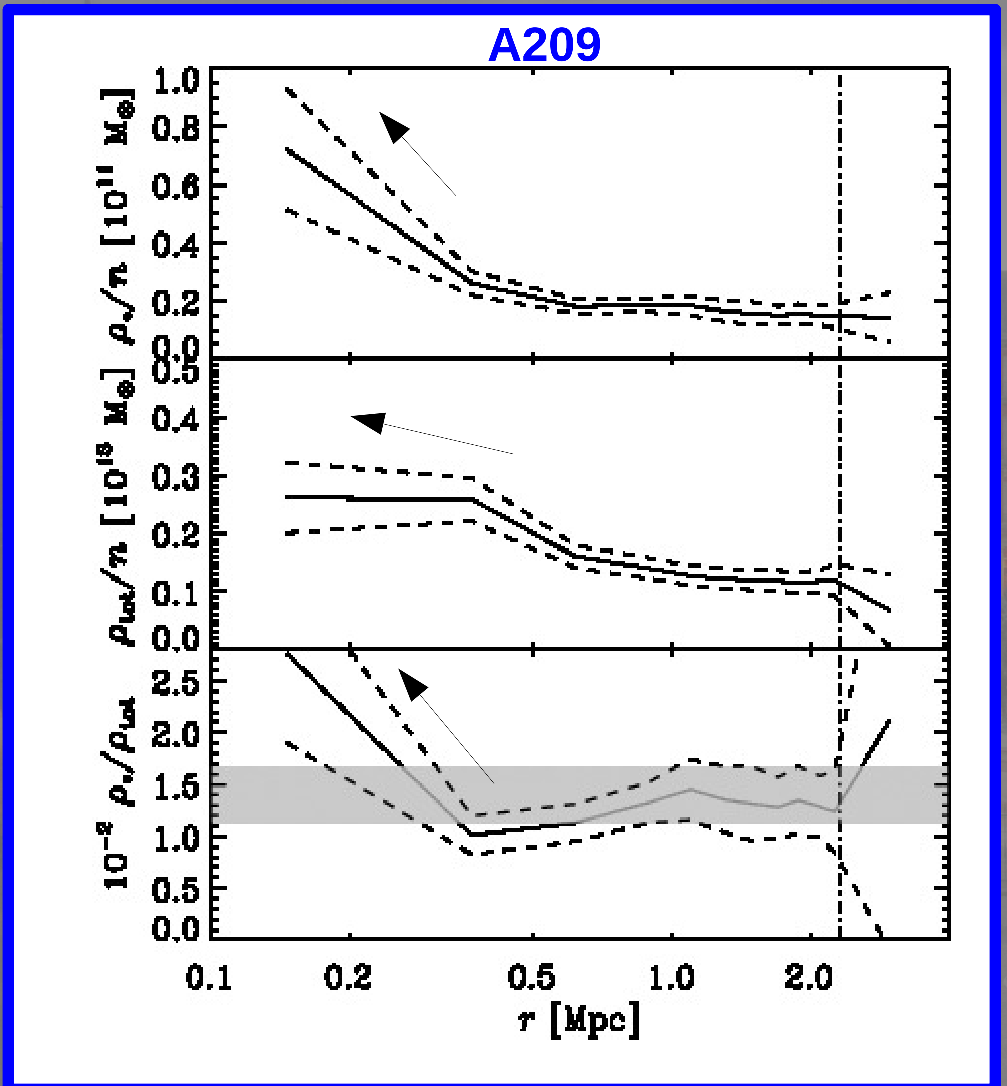
total-mass density profile / number density profile

→ **Tidal destruction:**
galaxies are lacking in the center

stellar-mass density profile / total-mass density profile

→ **Dynamical friction:**
massive galaxies loose kinetic
energy to the diffuse DM particles
and concentrate near the cluster center

Density profiles



distance from cluster center (=BCG position)

$\dfrac{\text{stellar-mass density profile}}{\text{number density profile}}$

→ Dynamical friction+Tidal destruction: galaxies are more massive near the cluster center

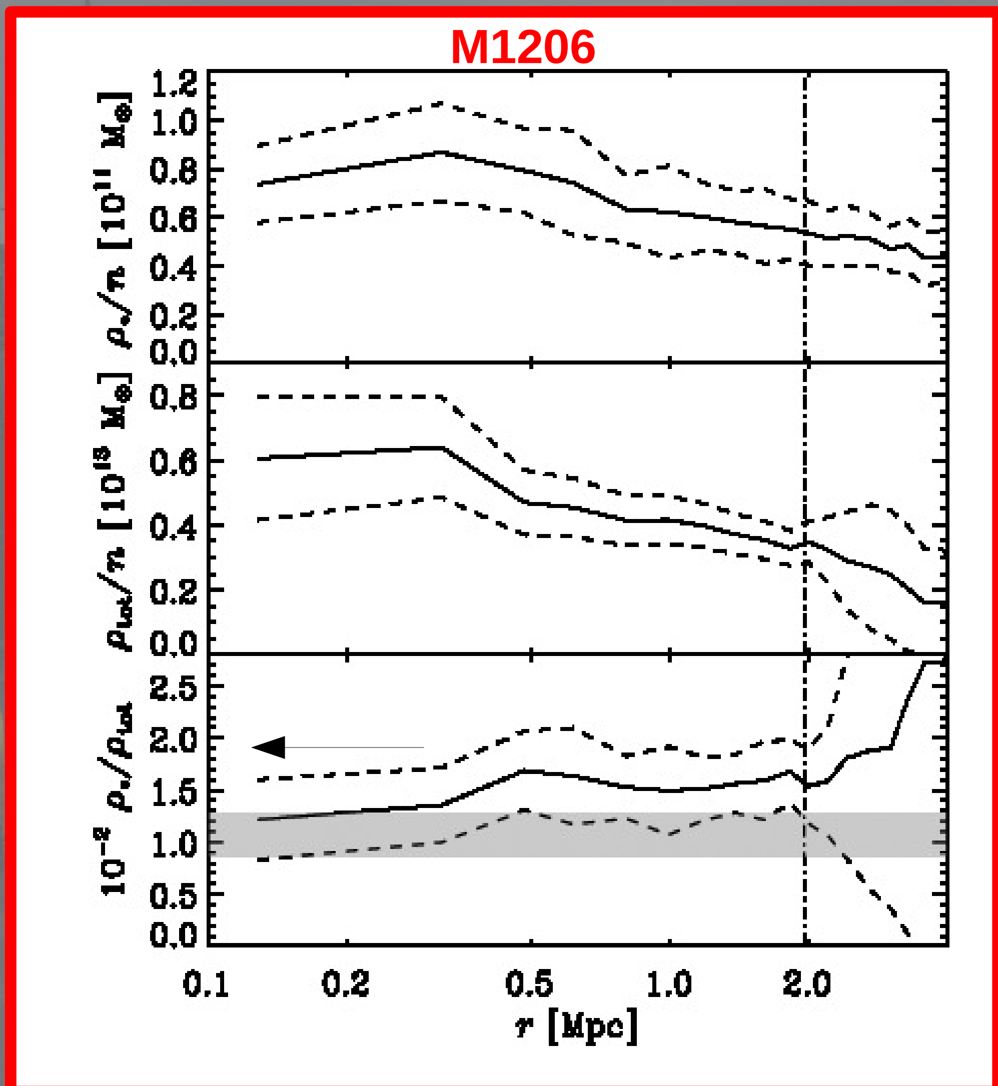
$\dfrac{\text{total-mass density profile}}{\text{number density profile}}$

→ Tidal destruction: galaxies are lacking in the center

$\dfrac{\text{stellar-mass density profile}}{\text{total-mass density profile}}$

→ Dynamical friction: massive galaxies loose kinetic energy to the diffuse DM particles and concentrate near the cluster center

Density profiles



stellar-mass density profile / number density profile

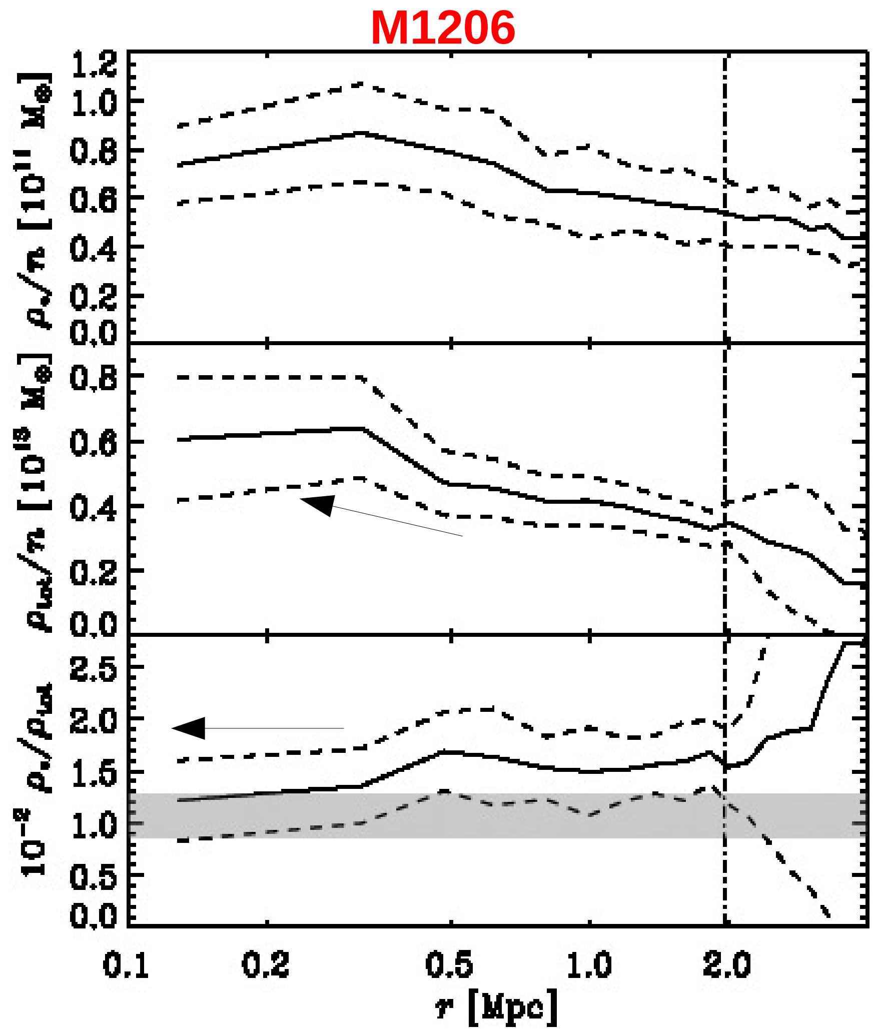
total-mass density profile / number density profile

stellar-mass density profile / total-mass density profile

→ No dynamical friction:
no evidence of massive galaxies segregation at the cluster center

distance from cluster center (=BCG position)

Density profiles



distance from cluster center (=BCG position)

stellar-mass density profile
———
number density profile

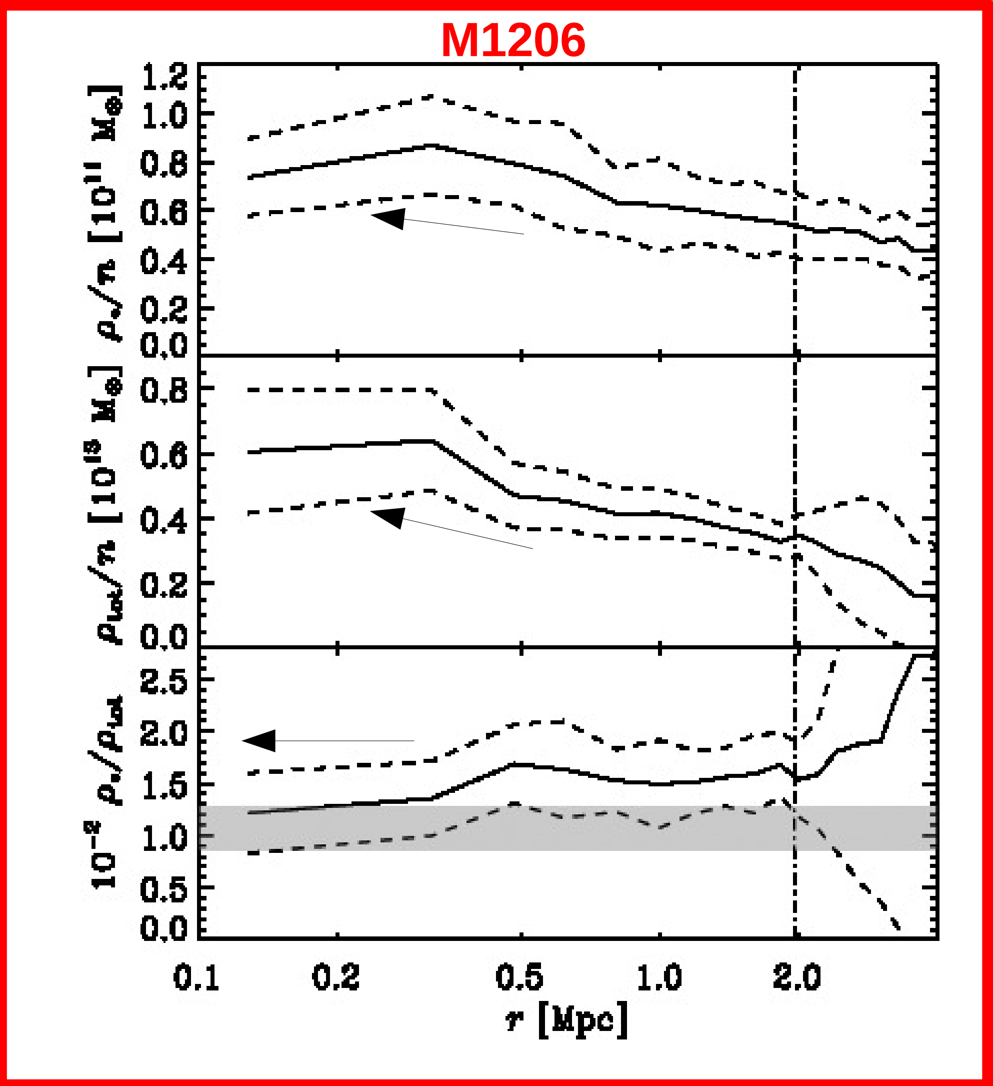
total-mass density profile
———
number density profile

→ Tidal destruction:
galaxies are lacking in the center

stellar-mass density profile
———
total-mass density profile

→ No dynamical friction:
no evidence of massive galaxies segregation at the cluster center

Density profiles



distance from cluster center (=BCG position)

stellar-mass density profile / number density profile

→ Tidal destruction:

low-mass galaxies are destroyed near the cluster center

total-mass density profile / number density profile

→ Tidal destruction:

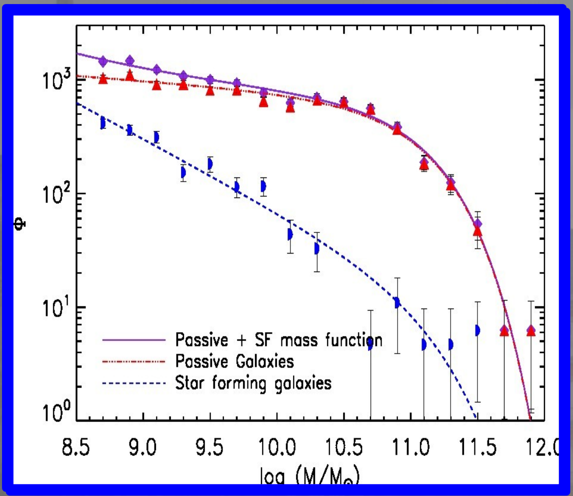
galaxies are lacking in the center

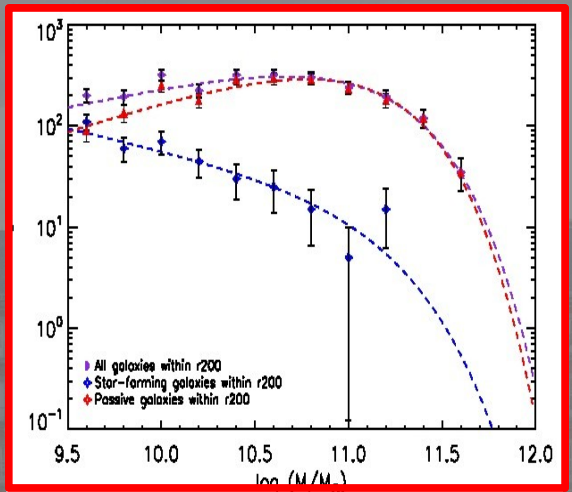
stellar-mass density profile / total-mass density profile

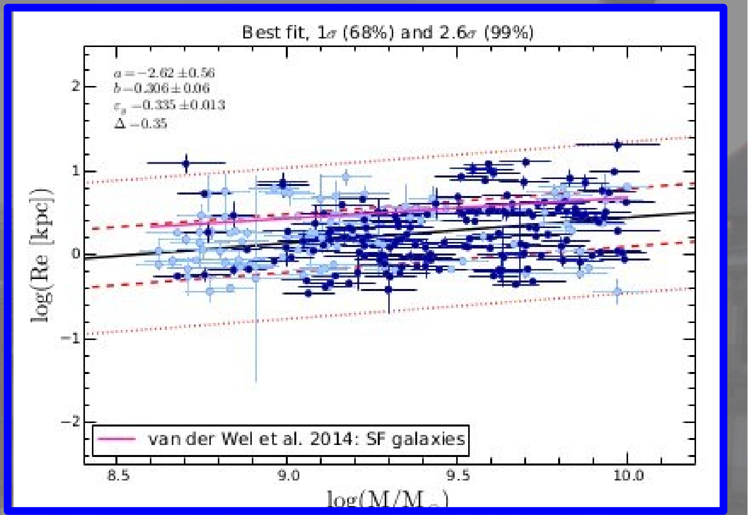
→ No dynamical friction:

no evidence of massive galaxies segregation at the cluster center

Summary & conclusions:
physical processes







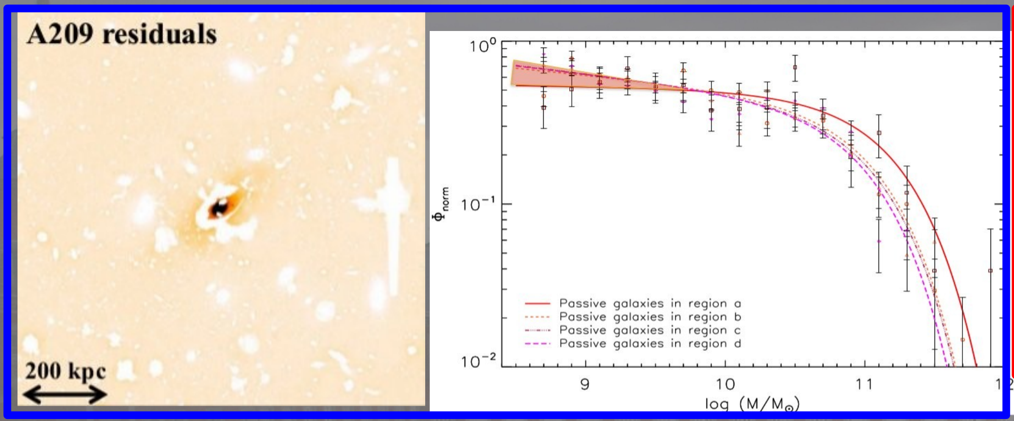
Steepening of low-mass slope of passive galaxy SMF from z=0.44 to z=0.21

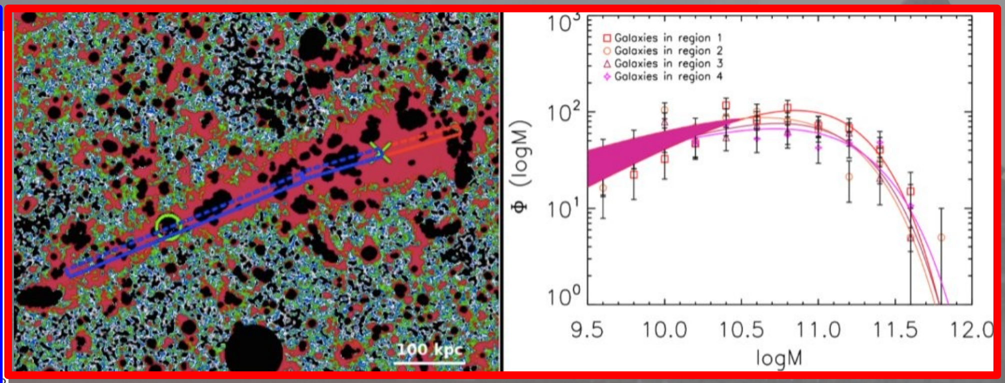
Flat slope of stellar mass – size relation of low-mass passive galaxies (similar to that of field spirals)

Transformation of infalling spirals into passive and early-type galaxies; requires gas removal and internal structural change to occur over wide cluster region:

starvation + harassment
(possibly assisted by ram pressure and thermal evaporation in the central cluster regions)

Summary & conclusions:
physical processes



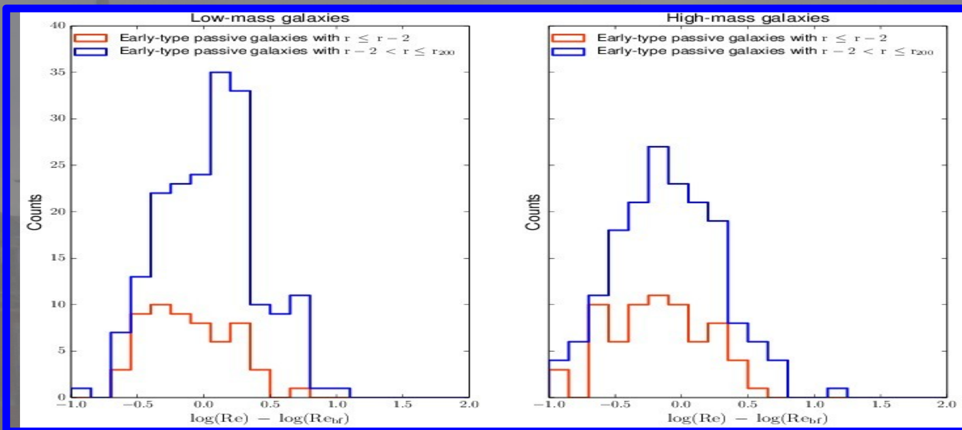


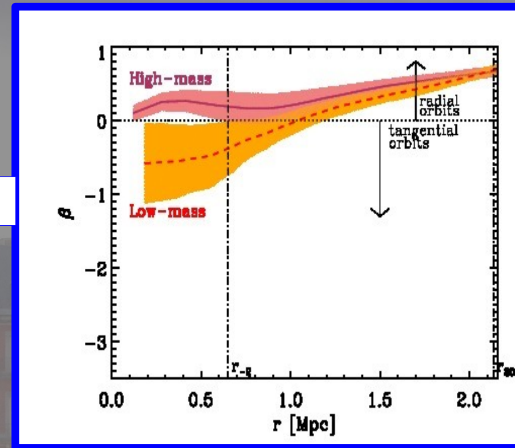
Lack of low-mass passive galaxies near the cluster center and similarity of this lacking mass with the mass in the ICL

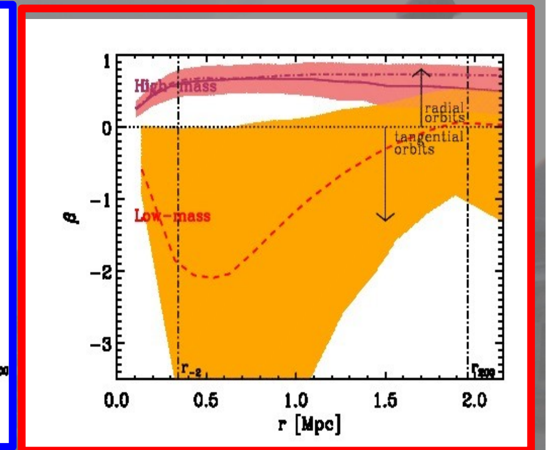
Destruction of low-mass galaxies as they cross the cluster center:

tidal destruction
by the cluster gravitational field

Summary & conclusions:
physical processes







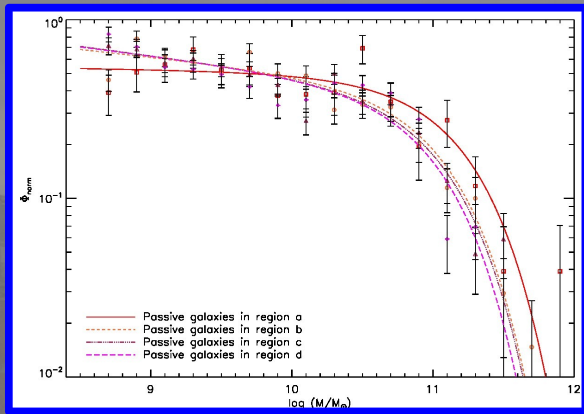
Smaller radii of low-mass passive galaxies near the cluster center

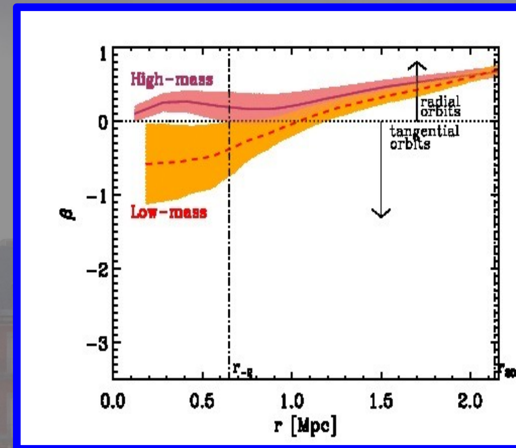
Tangential orbits of low-mass passive galaxies near the cluster center

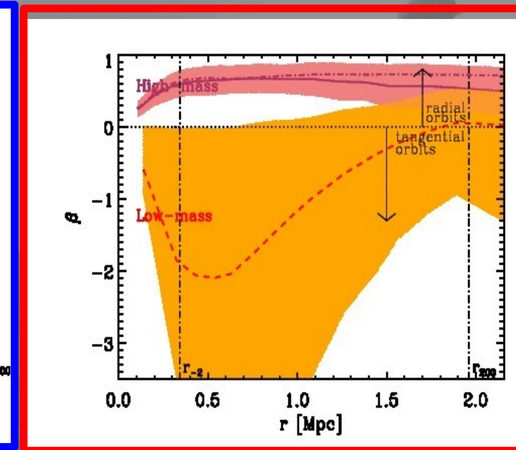
Not all low-mass galaxies are destroyed as they cross the cluster center: those more likely to be destroyed are those on radial orbits and small pericenters. The others may survive on more tangential orbits but do suffer some minor tidal truncation.

tidal stripping
by the cluster gravitational field

Summary & conclusions:
physical processes







Excess of high-mass galaxies in the central cluster region

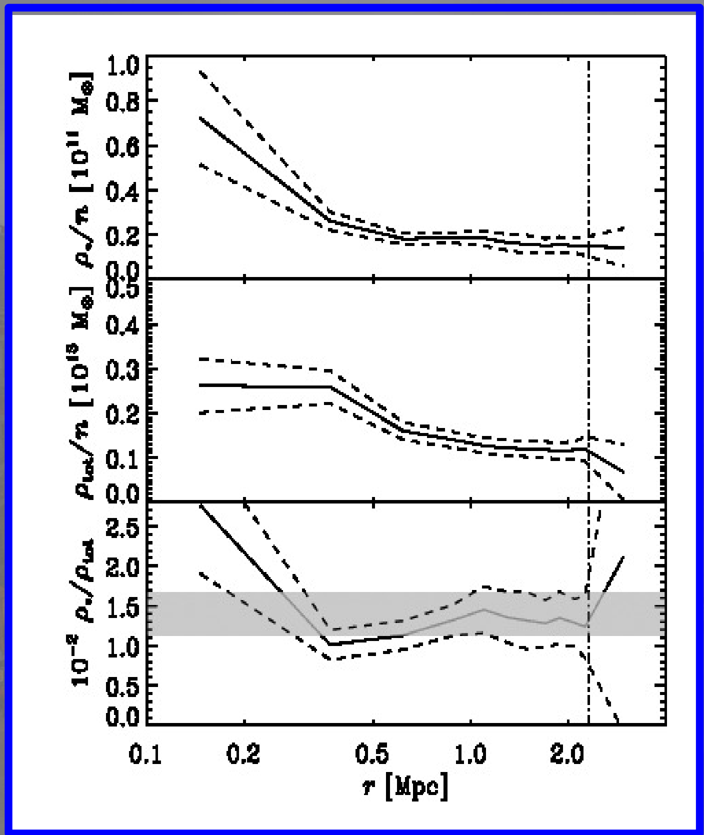
Isotropization of orbits of high-mass galaxies near the cluster center from z=0.44 to z=0.21

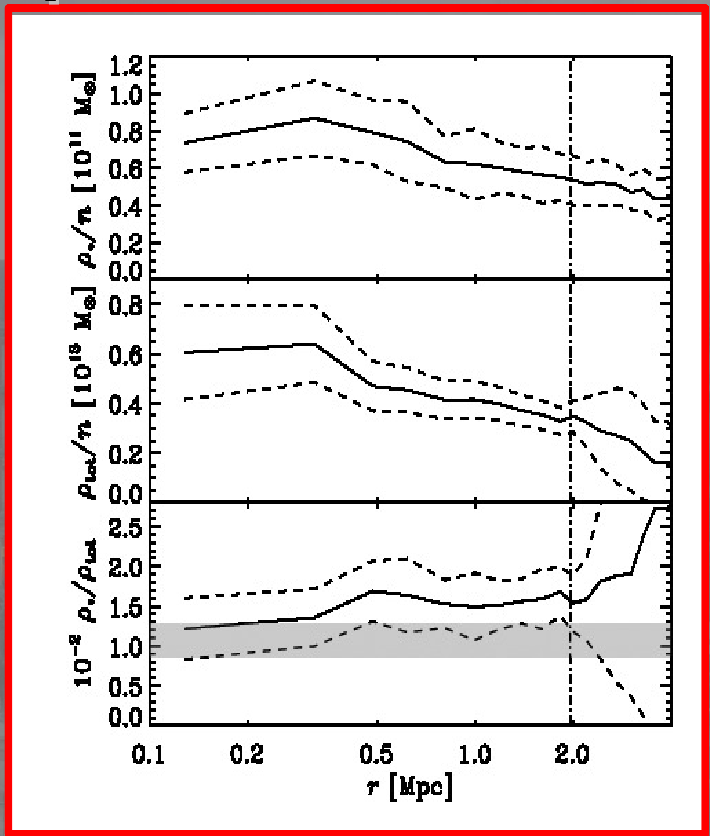
High-mass galaxies concentrate near the cluster center as a consequence of dynamical friction slowing down their motions. Their reduced velocities can favor their mergers in the cluster center. Dynamical friction tends also to isotropize orbits by affecting mostly the velocity component along the main orbital direction

dynamical friction

(and possibly mergers)

Summary & conclusions:
physical processes



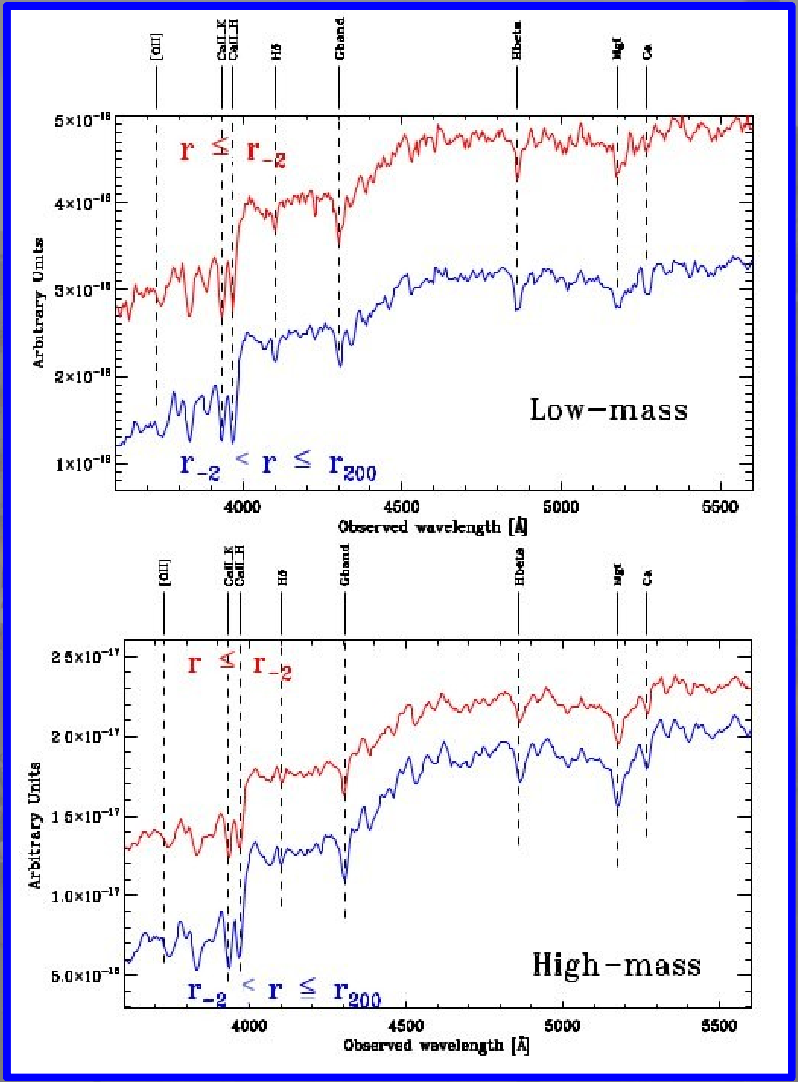


Ratios of number-, stellar-mass-, and total-mass-density profiles show excess of baryonic mass w.r.t. total mass in the central region of the low-z cluster and lack of galaxies near the centers of both clusters

dynamical friction *(and possibly mergers)* **at low-z**
& tidal disruption at both low- and high-z

Summary & conclusions:
timescales

Stacked spectra of passive galaxies indicate same old age (8 ± 1 Gyr) for high-mass, low-mass, central and external galaxies



If low-mass galaxies evolved from infalling field spirals, this evolution cannot be recent,
so we cannot explain the evolution of the low-mass end of the SMF by recent infall and transformation of spirals

If dynamical friction is visible at z=0.21 but not at z=0.44, this suggests that the process timescale must be longer than ~ t_{infall} - 2 Gyr (2 Gyr = cosmic time between z=0.44 and z=0.21) with t_{infall}<8 Gyr

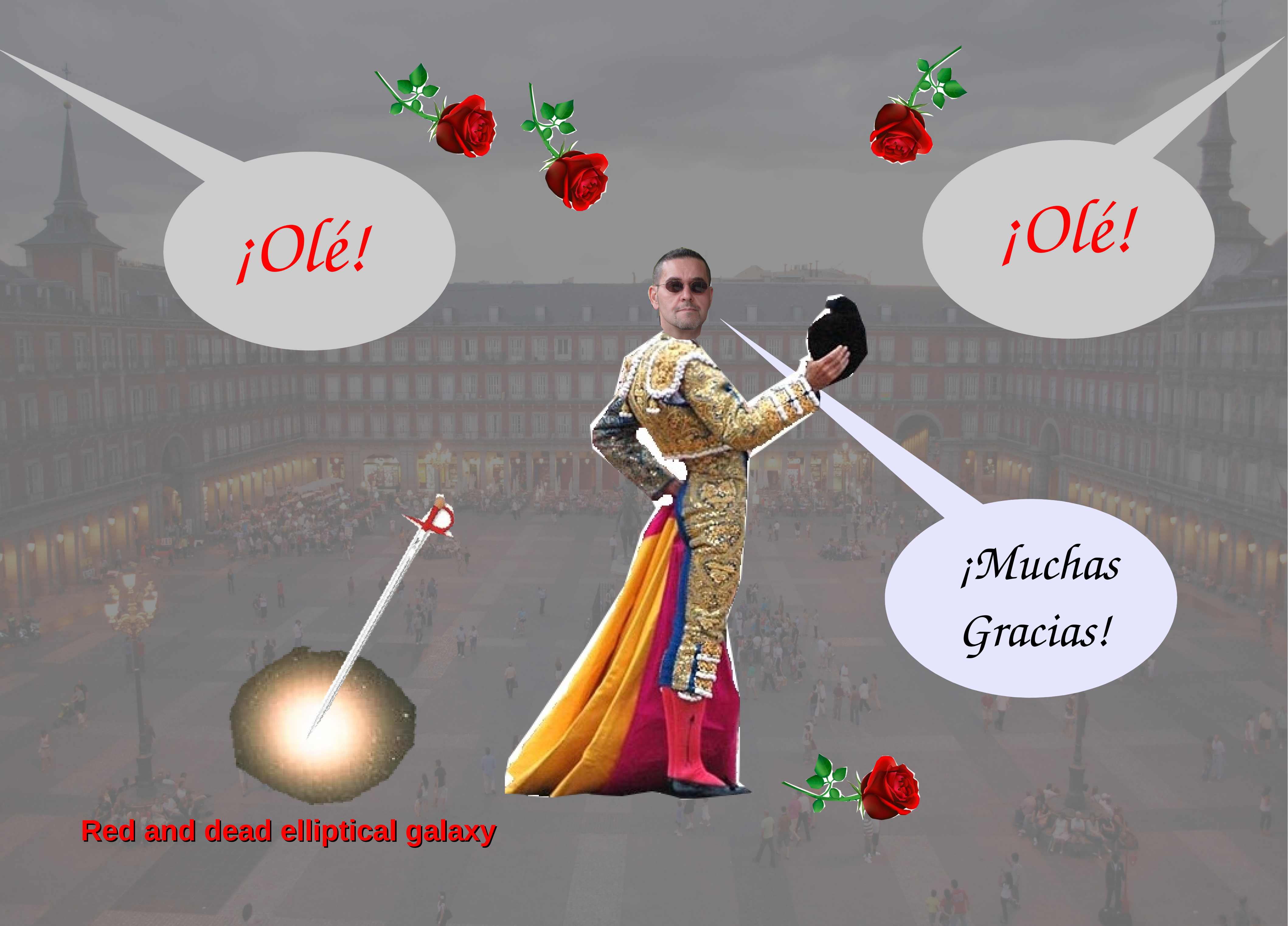
Summary & conclusions

CLASH-VLT survey of 13 medium-z galaxy clusters: unprecedented spectroscopic coverage of cluster members (500-1000 z per cluster)

Two clusters analyzed in full detail so far (both very massive):
A209 at z=0.21, MACS1206 at z=0.44

~9 more well sampled clusters to come
(observations and data-reduction completed by end 2016)

Explore cluster galaxy evolution with several tools as a function
of the cluster redshift and dynamical status
to set the relative importance of physical mechanisms
and determine their timescales
assisted by the comparison to cosmological simulations
(collaboration with S. Borgani, G. De Lucia, P. Monaco, G. Murante in Trieste)


¡Olé!
¡Olé!
¡Muchas Gracias!
Red and dead elliptical galaxy