The structure of clusters from spectroscopic observations

Andrea Biviano, INAF-OATs (Trieste, Italy)

Based on
CLASH-VLT+MUSE data,
in collaboration with:

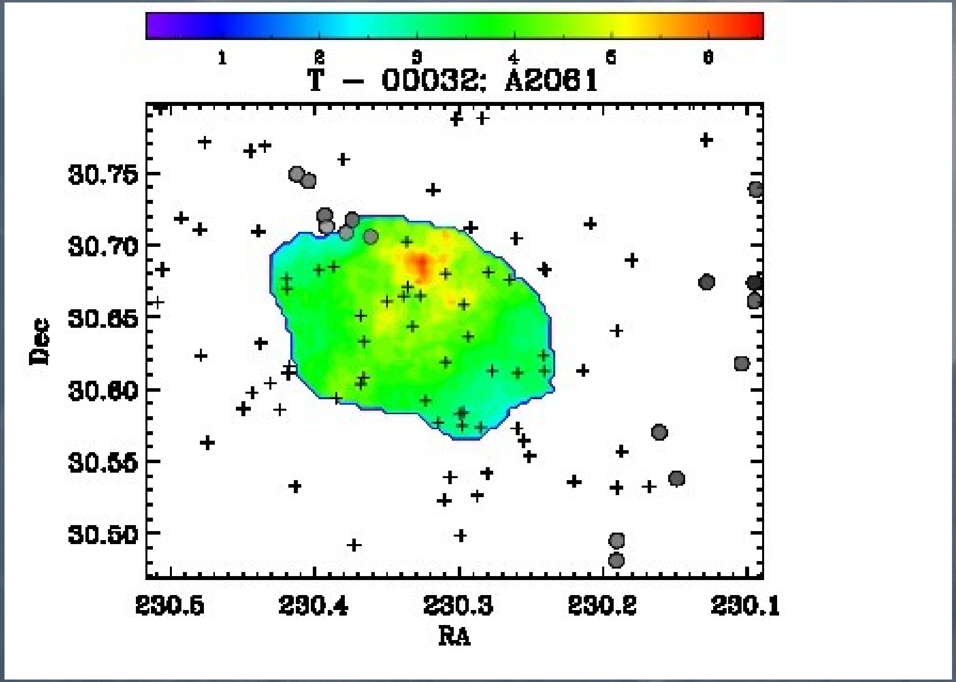
P. Rosati *(p.i.)*
I. Balestra
P. Bergamini
G. Caminha
M. Girardi
C. Grillo
M. Meneghetti
A. Mercurio
M. Nonino
B. Sartoris

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

Using spectroscopic observations to investigate the structure of clusters allows one to:

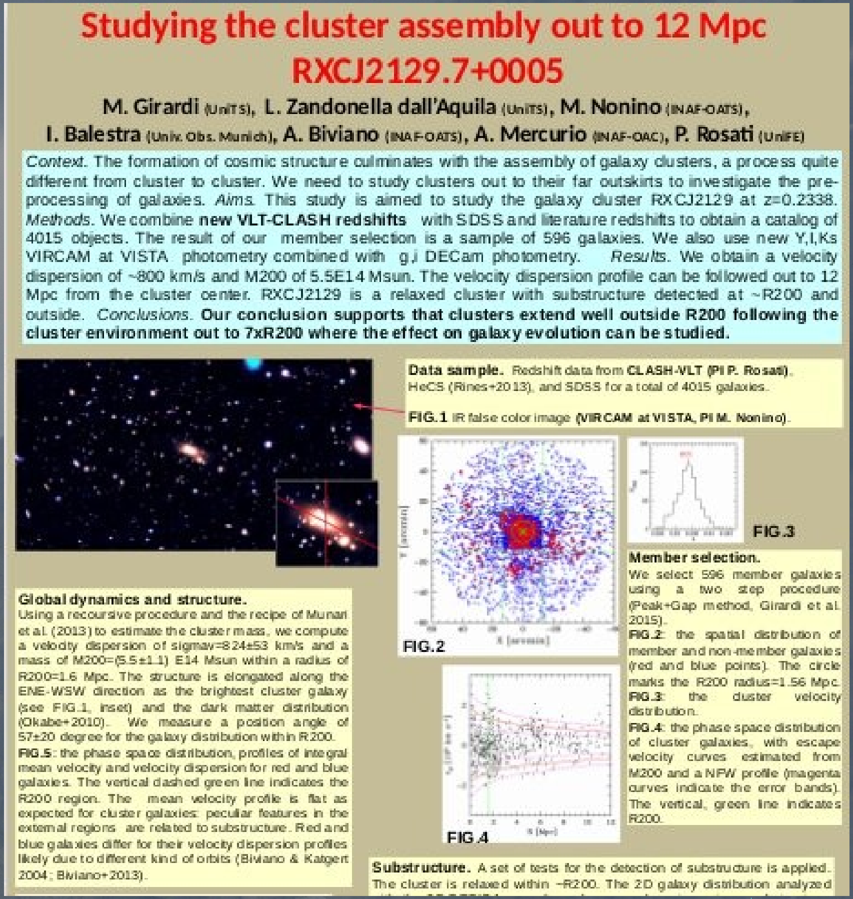
1 - constrain a cluster dynamical status and its accretion history

(by the identification and characterization of subclusters)



T_X map (color), cluster galaxies (crosses), subcluster galaxies (dots)

(AB, Durret, Laganá, in prep.)



Studying the cluster assembly out to 12 Mpc

RXCJ2129.7+0005

M. Girardi (UniTS), L. Zandonella dall'Aquila (UniTS), M. Nonino (INAF-OATS),
I. Balestra (Univ. Obs. Munich), A. Biviano (INAF-OATS), A. Mercurio (INAF-OAC), P. Rosati (UniFE)

Context. The formation of cosmic structure culminates with the assembly of galaxy clusters, a process quite different from cluster to cluster. We need to study clusters out to their far outskirts to investigate the pre-processing of galaxies. *Aims.* This study is aimed to study the galaxy cluster RXCJ2129 at z=0.2338. *Methods.* We combine **new VLT-CLASH redshifts** with SDSS and literature redshifts to obtain a catalog of 4015 objects. The result of our member selection is a sample of 596 galaxies. We also use new Y,I,Ks VIRCAM at VISTA photometry combined with g,i DECam photometry. *Results.* We obtain a velocity dispersion of ~800 km/s and M200 of 5.5E14 Msun. The velocity dispersion profile can be followed out to 12 Mpc from the cluster center. RXCJ2129 is a relaxed cluster with substructure detected at ~R200 and outside. *Conclusions.* **Our conclusion supports that clusters extend well outside R200 following the cluster environment out to 7xR200 where the effect on galaxy evolution can be studied.**

Data sample. Redshift data from **CLASH-VLT (PI P. Rosati)**, HeCS (Rines+2013), and SDSS for a total of 4015 galaxies.

FIG.1 IR false color image **(VIRCAM at VISTA, PI M. Nonino)**.

FIG.2

FIG.3

Member selection.
We select 596 member galaxies using a two step procedure (Peak+Gap method, Girardi et al. 2015).
FIG.2: the spatial distribution of member and non-member galaxies (red and blue points). The circle marks the R200 radius=1.56 Mpc.
FIG.3: the cluster velocity distribution.
FIG.4: the phase space distribution of cluster galaxies, with escape velocity curves estimated from M200 and a NFW profile (magenta curves indicate the error bands). The vertical, green line indicates R200.

FIG.4

Global dynamics and structure.
Using a recoursive procedure and the recipe of Munari et al. (2013) to estimate the cluster mass, we compute a velocity dispersion of sigmav=824±53 km/s and a mass of M200=(5.5±1.1) E14 Msun within a radius of R200=1.6 Mpc. The structure is elongated along the ENE-WSW direction as the brightest cluster galaxy (see FIG.1, inset) and the dark matter distribution (Okabe+2010). We measure a position angle of 57±20 degree for the galaxy distribution within R200.
FIG.5: the phase space distribution, profiles of integral mean velocity and velocity dispersion for red and blue galaxies. The vertical dashed green line indicates the R200 region. The mean velocity profile is flat as expected for cluster galaxies: peculiar features in the external regions are related to substructure. Red and blue galaxies differ for their velocity dispersion profiles likely due to different kind of orbits (Biviano & Katgert 2004; Biviano+2013).

Substructure. A set of tests for the detection of substructure is applied. The cluster is relaxed within ~R200. The 2D galaxy distribution analyzed

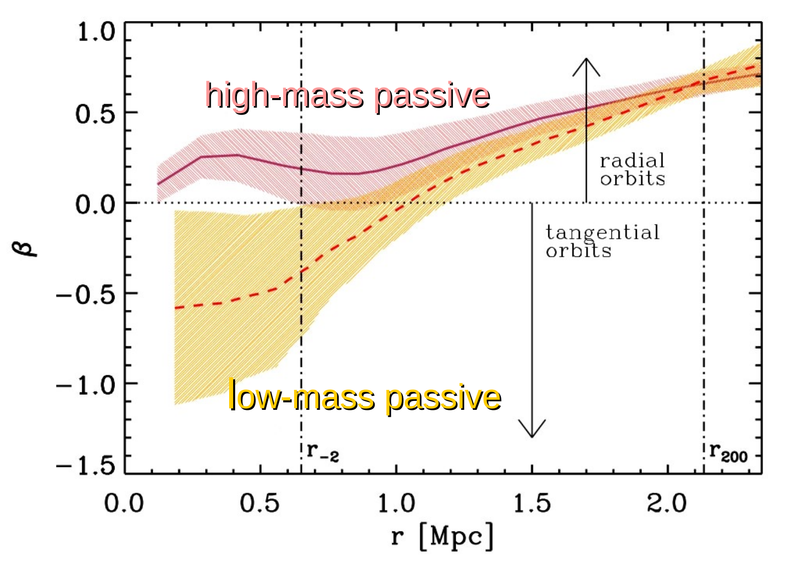
See poster by M. Girardi!

Using spectroscopic observations to investigate the structure of clusters allows one to:

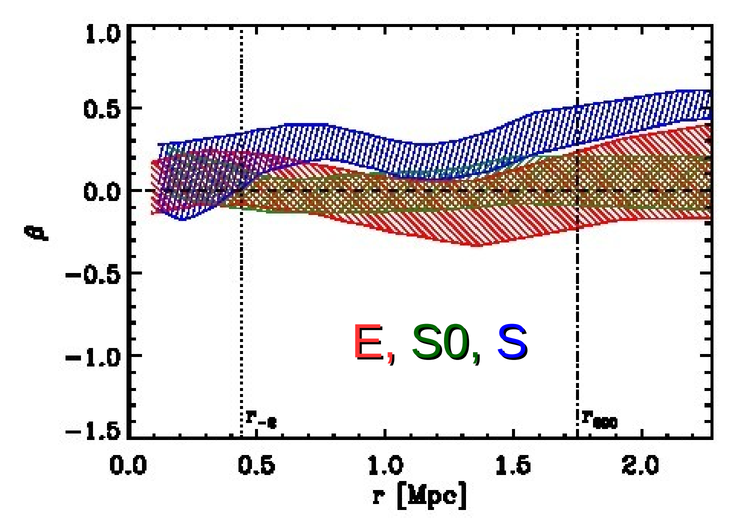
2 – determine the orbits of cluster galaxies

(by the Jeans equations of dynamical equilibrium)

A209
z=0.21

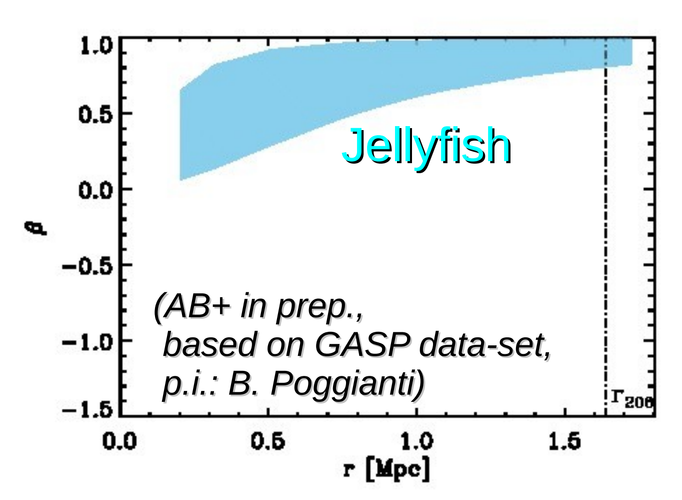


(Annunziatella+16, based on CLASH-VLT, p.i.: P. Rosati)



Stack of
59 z~0.06
clusters

(Mamon+ subm., WINGS data, p.i.: G. Fasano & B. Poggianti)



(AB+ in prep., based on GASP data-set, p.i.: B. Poggianti)

Stack of
50 z~0.06
clusters

Passive galaxies: radial orbits at z>0.2,
isotropic at z~0

Spiral/blue galaxies: mildly radial orbits at all z

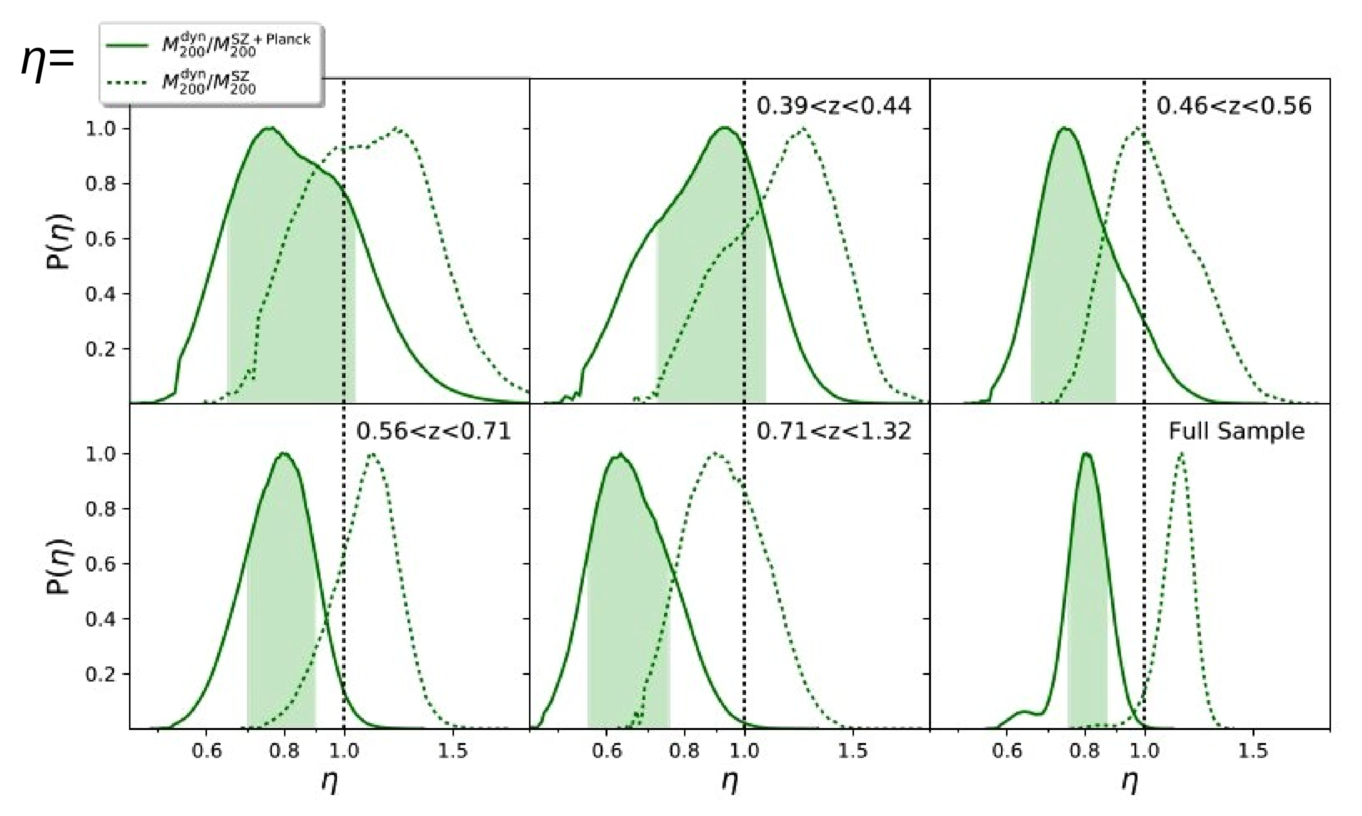
Jellyfish galaxies: extremely radial orbits

Using spectroscopic observations to investigate the structure of clusters allows one to:

3 – determine the mass and mass profile of clusters

(over a wide radial range: from a few kpc to several Mpc)

3a – use cluster masses to constrain cosmology



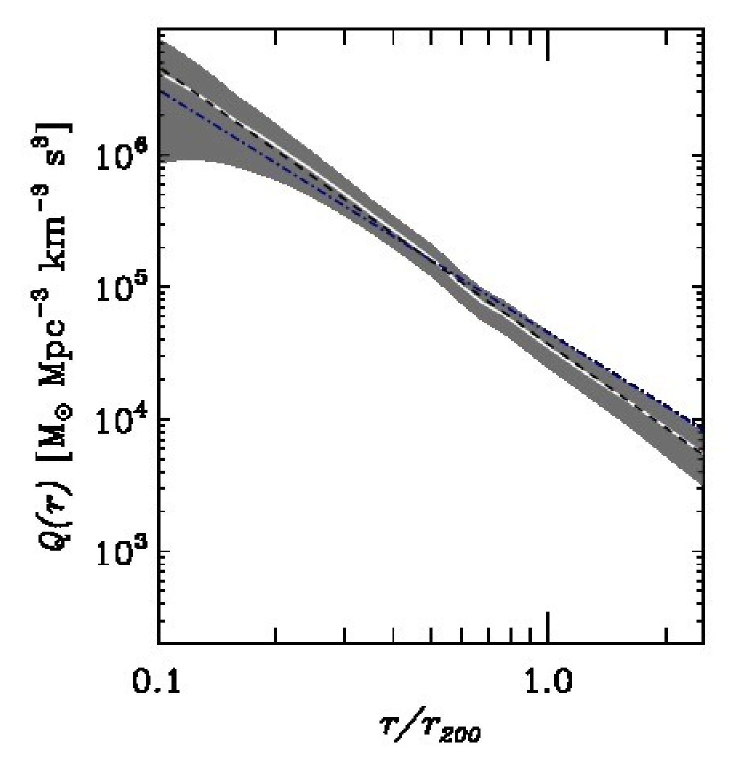
(Capasso+19, based on spectroscopic survey of SPT-SZ clusters, Bocquet+15)

Using spectroscopic observations to investigate the structure of clusters allows one to:

3 – determine the mass and mass profile of clusters

(over a wide radial range: from a few kpc to several Mpc)

3b – constrain the dynamical evolution history of clusters



(AB+16, based on the GCLASS spectroscopic survey of z~1 clusters. p.i. G. Wilson)

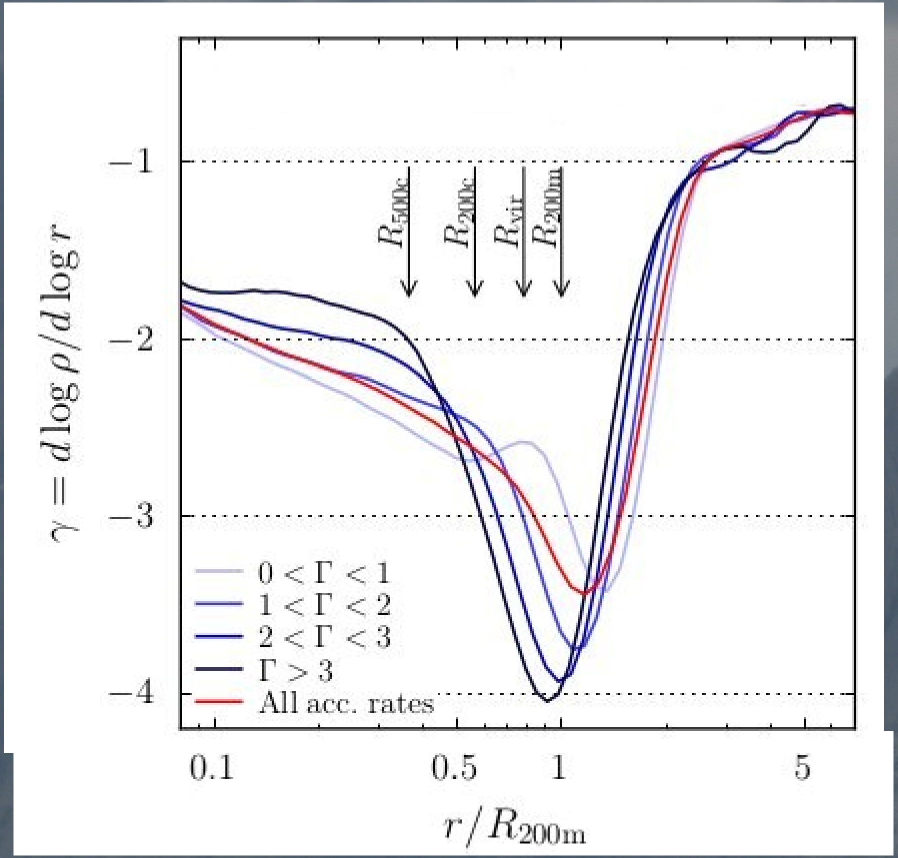
The pseudo-phase-space density profile $Q \equiv \rho/\sigma^3$ *(Taylor+Navarro 01)* for clusters is a power-law, from z~0 to z~1, as predicted by theory *(Lapi+Cavaliere 09)* and numerical simulations *(Dehnen+McLaughlin 05)*

Using spectroscopic observations to investigate the structure of clusters allows one to:

3 – determine the mass and mass profile of clusters

(over a wide radial range: from a few kpc to several Mpc)

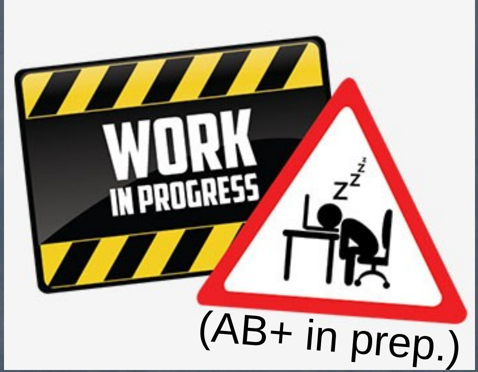
3c – constrain the cluster mass accretion rate



(Diemer+Kravtsov 14, numerical simulations;
Γ is the mass accretion rate)

The external slope of the mass density profile is a measure of the halo mass accretion rate *(Diemer+Kravtsov 14)*

$M(r>>r_{200})$ can be measured from the kinematics of cluster galaxies



(AB+ in prep.)

Using spectroscopic observations to investigate the structure of clusters allows one to:

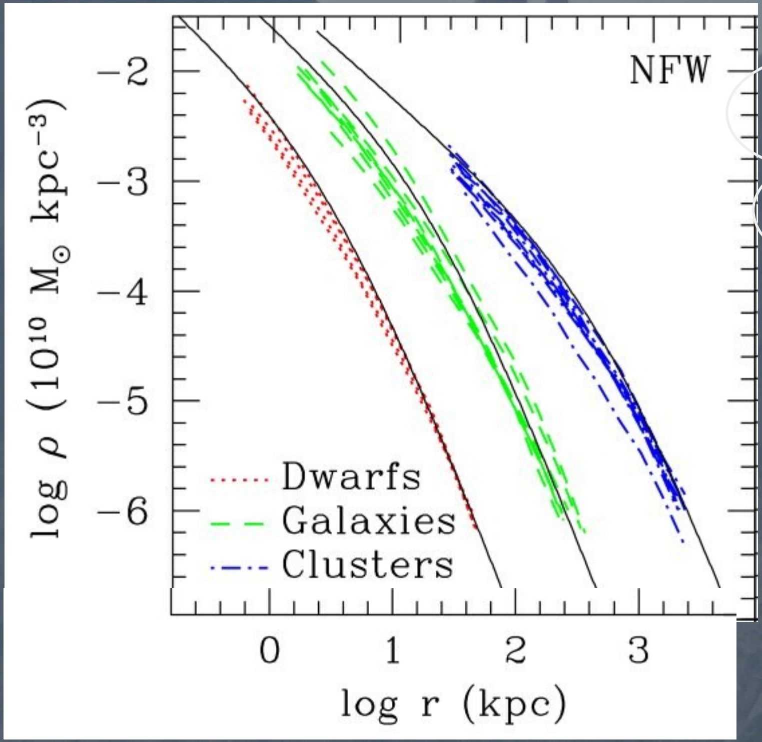
3 – determine the mass and mass profile of clusters

(over a wide radial range: from a few kpc to several Mpc)

3d – constrain the properties of Dark Matter and/or its dynamical interaction with baryons

(AGN feedback, dynamical friction, adiabatic contraction)

(Navarro+04)



Do observations confirm the theoretical predictions *(Navarro, Frenk & White 96, 97)* of a steep inner slope, γ=1, of the cluster DM density profile?

The inner slope of clusters DM density profile

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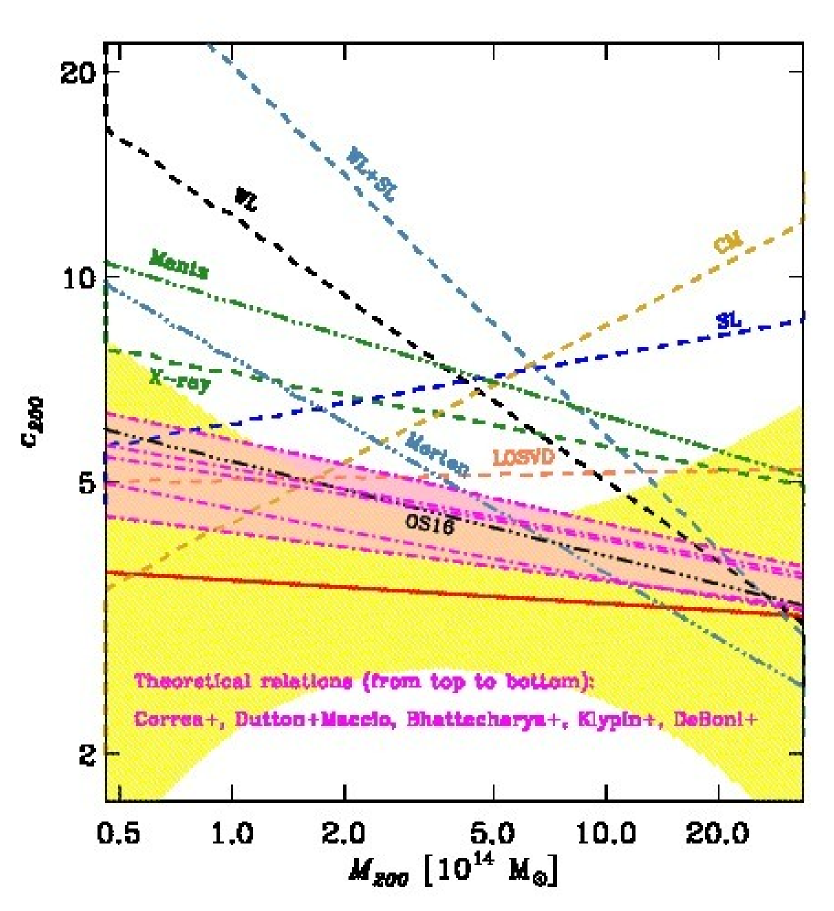
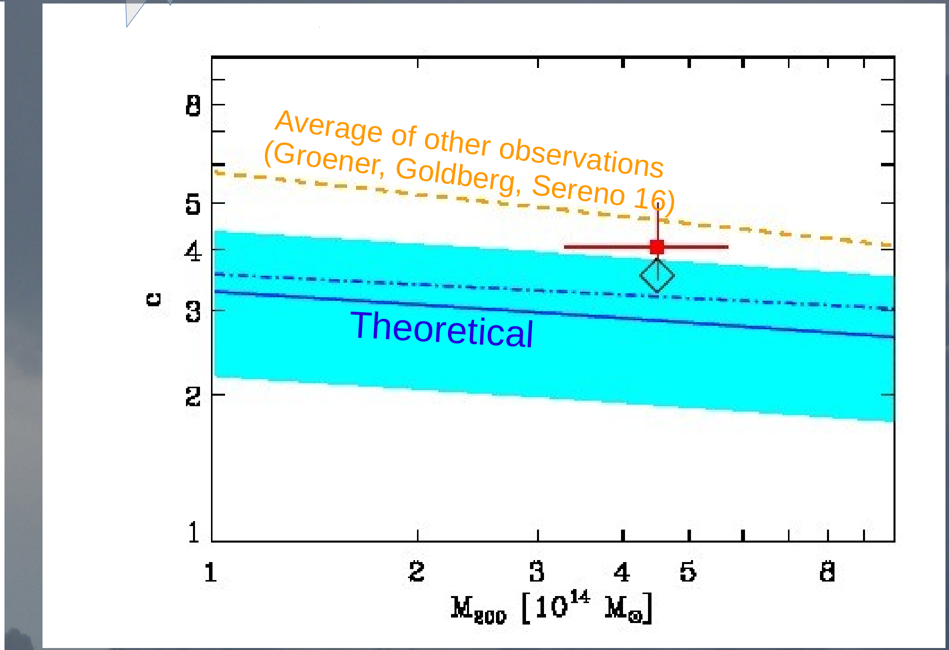
HST image of the z=0.44 CLASH cluster MACS1206
(NASA, ESA, M. Postman)

The inner slope of clusters DM density profile

total





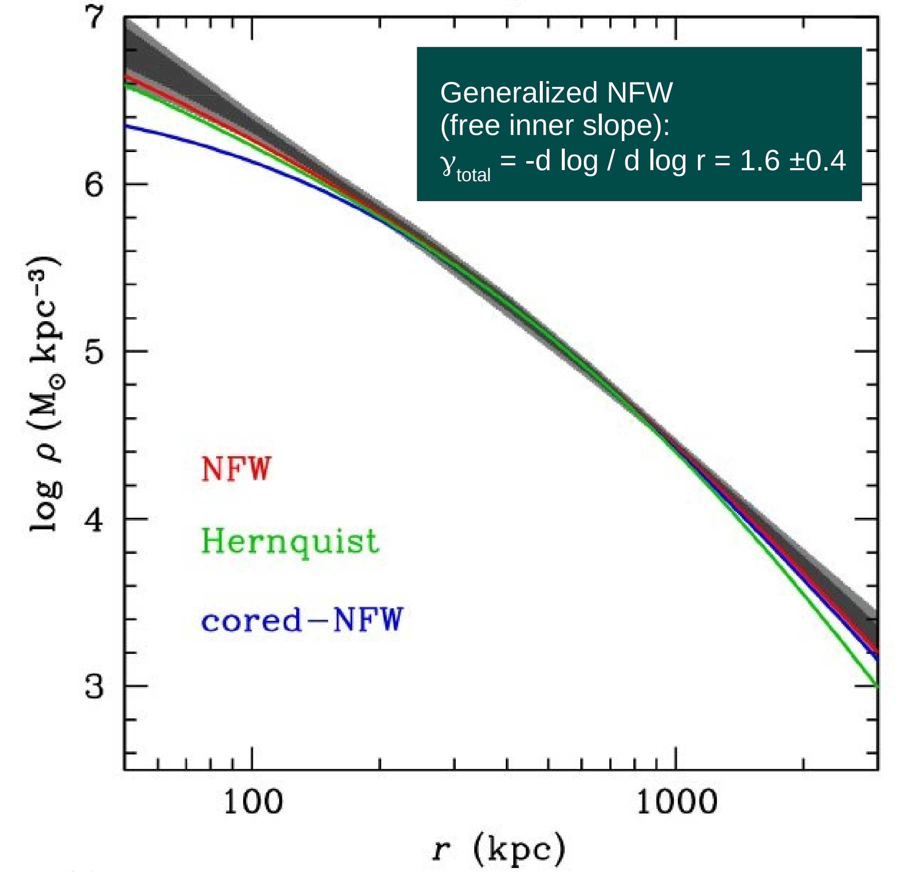
AB+16: cross and diamond:
mean concentration of z~1
GCLASS clusters *(p.i.: G. Wilson)*

AB+17: red line and yellow region:
concentration-mass relation
of z~0 ΩWINGS clusters
(p.i.: B. Poggianti)

Concentration-mass relation as expected for NFW-like clusters from z~0 to z~1

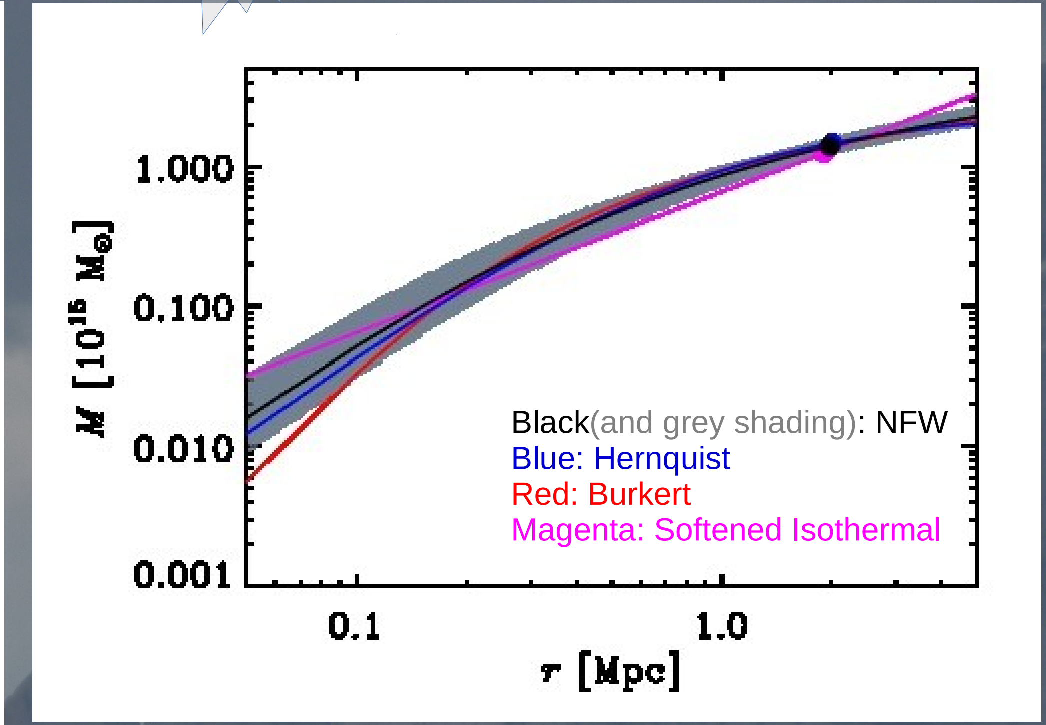
The inner slope of clusters DM density profile

total



Generalized NFW
(free inner slope):
γ_{total} = -d log / d log r = 1.6 ±0.4

Mamon+19: total M(r) of z~0 WINGS clusters *(p.i.: G. Fasano & B. Poggianti)* is steeper than NFW



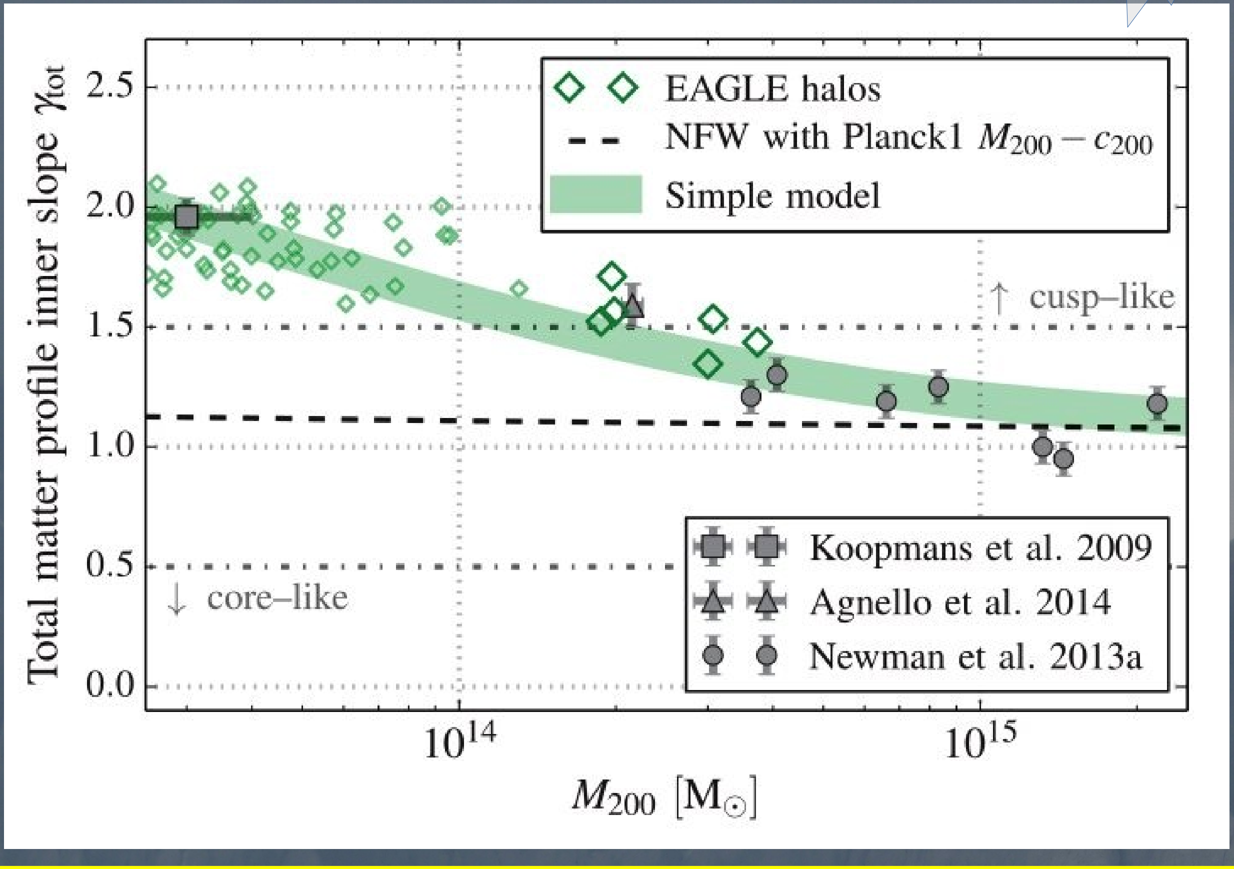
Black(and grey shading): NFW
Blue: Hernquist
Red: Burkert
Magenta: Softened Isothermal

AB+13: total M(r) of a z=0.4 massive cluster is compatible with NFW, Burkert (cored) profile excluded *(based on CLASH-VLT data, p.i.: P. Rosati)*

Total M(r) inner slope steeper than, or compatible with, NFW, $\gamma_{total} \geq 1$

The inner slope of clusters DM density profile

total



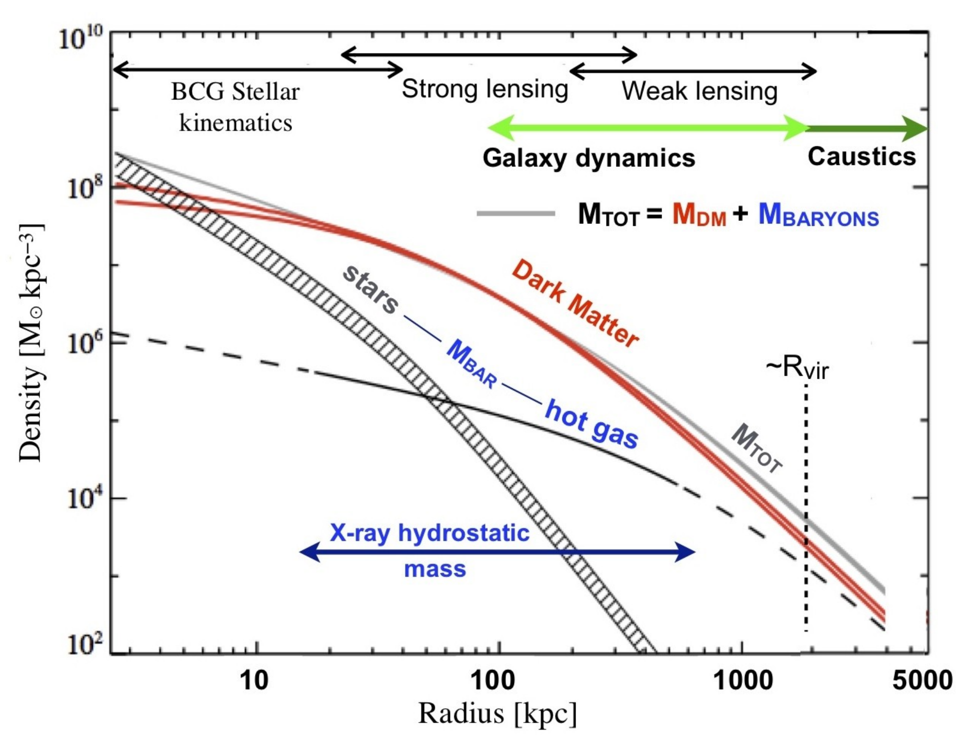
EAGLE simulations (that include baryons; *Schaller+15*) do predict $\gamma_{total} \geq 1$,

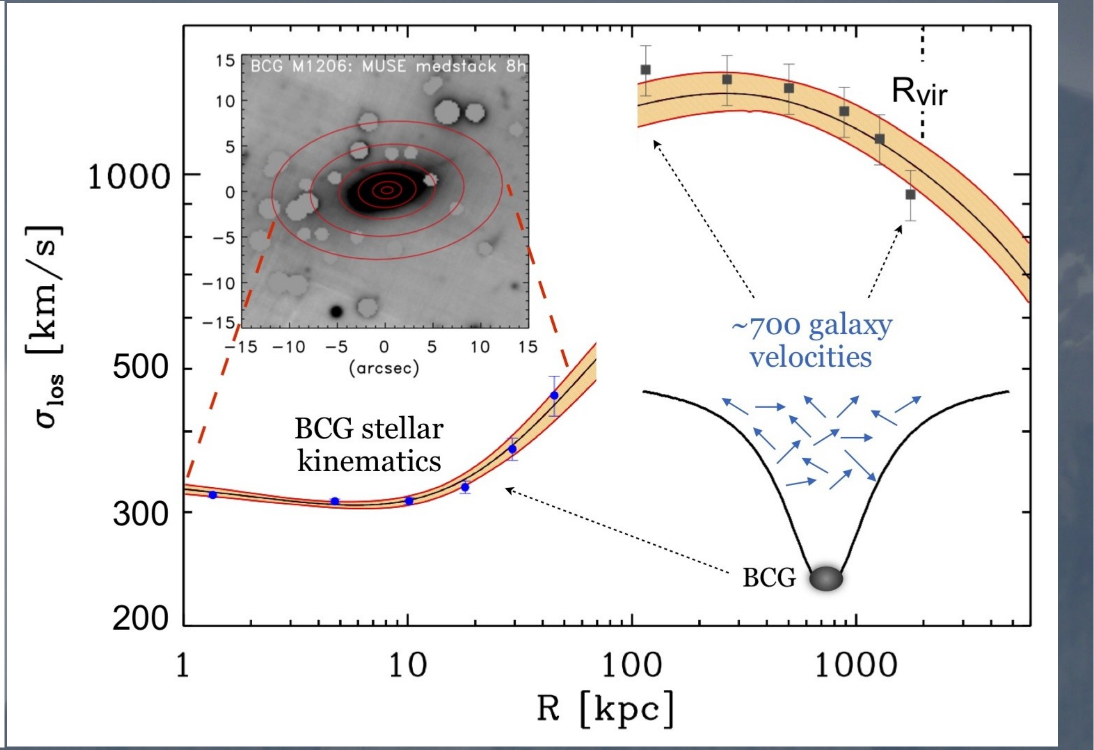
in agreement with *Newman+13* observational data based on Strong+Weak Lensing + BCG stellar kinematics

Total matter = DM + baryons
⇒ must consider ICM + galaxies + BCG contributions to total matter to get DM

BCGs dominate the cluster centers;
⇒ use of BCG stellar kinematics is fundamental to constrain M(r) at r → 0

The inner slope of clusters DM density profile





Use **muse** multi unit spectroscopic explorer, the Multi Unit Spectroscopic Explorer at VLT to determine the BCG stellar velocity dispersion profile *(p.i.: P. Rosati)*

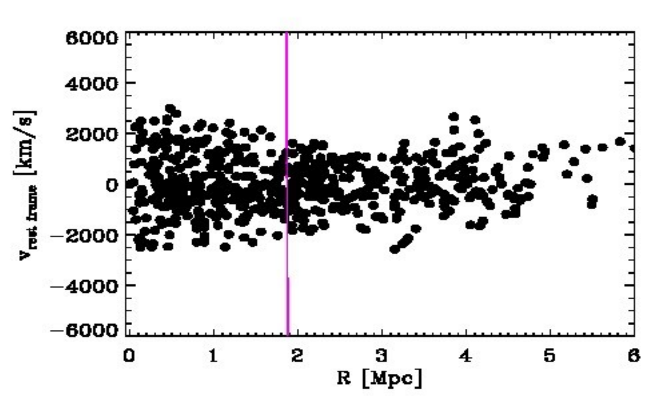
Constrain the cluster mass profile over 3 orders of magnitudes in length by **simultaneous** fitting of the projected phase-space distribution of cluster galaxies and the velocity-dispersion profile of the BCG **(combined likelihhods)**

The inner slope of clusters DM density profile

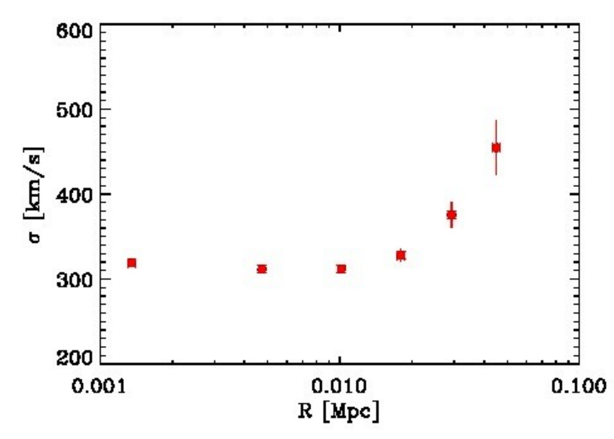
Method of analysis: MAMPOSSt *(Mamon, AB, Boué 13)*

Modelling Anisotropy and Mass Profiles of Observed Spherical Systems

Joint Maximum Likelihood fit to the projected phase-space distribution of cluster members:



and to the l.o.s. BCG velocity dispersion profile:



Constrain the best-fit parameters of the cluster mass profile M(r) parameterized as:

$$M(r) = M_{\rm gNFW} + M_{\rm Jaffe} + M_{\rm ICM} + M_{\rm gal}$$

$$M_{\rm Jaffe} = M_\infty r/r_J \, (1 + r/r_J)^{-1}$$

BCG stellar mass

$$M_{\rm gNFW} = M_{200} \frac{{}_2F_1(3-\gamma, 3-\gamma, 4-\gamma, -r/r_s)}{{}_2F_1(3-\gamma, 3-\gamma, 4-\gamma, -r_{200}/r_s)}$$

$$\rho = \rho_0 \, (r/r_s)^\gamma \, (1 + r/r_s)^{3-\gamma}$$

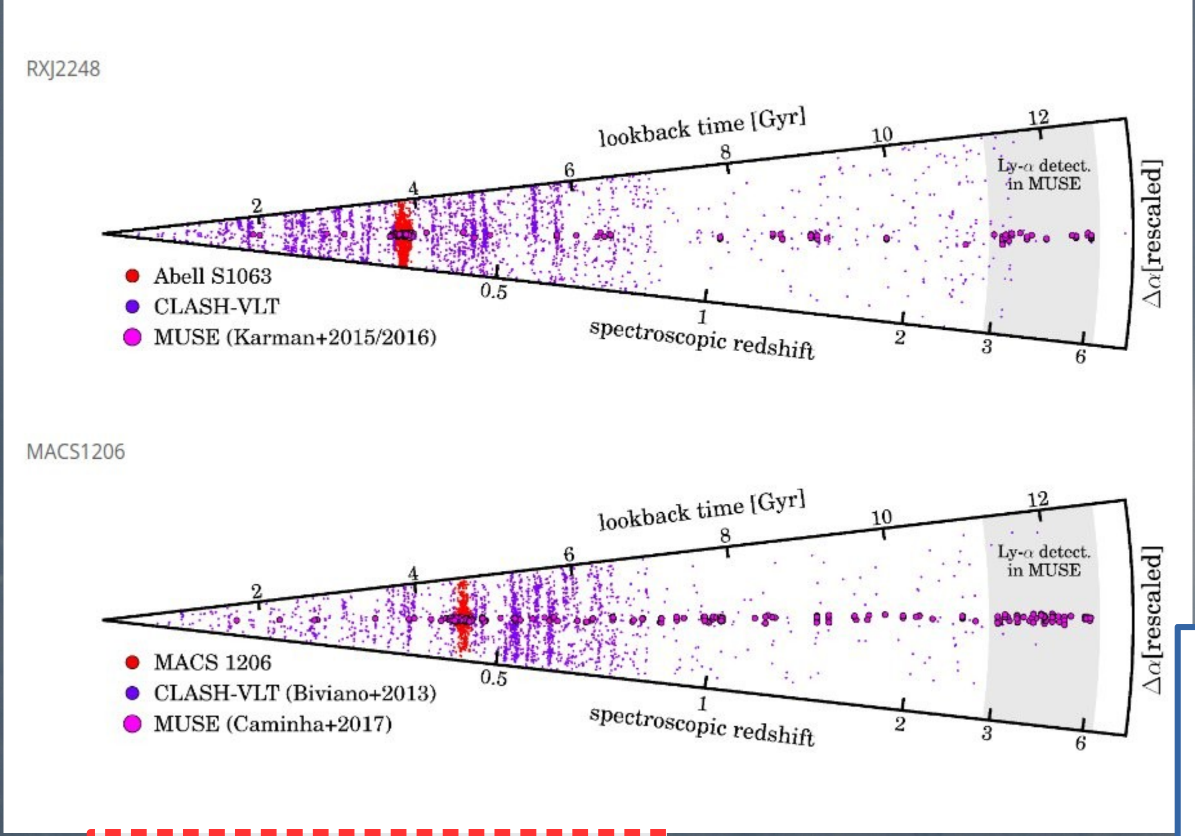
DM

With free parameters: r_{200}, r_s, γ.

Additional parameters that can be left free:

$\beta_{\rm galaxies}(r)$, $\beta_{\rm BCG\ stars}(r)$, $M_{*,\rm BCG}$

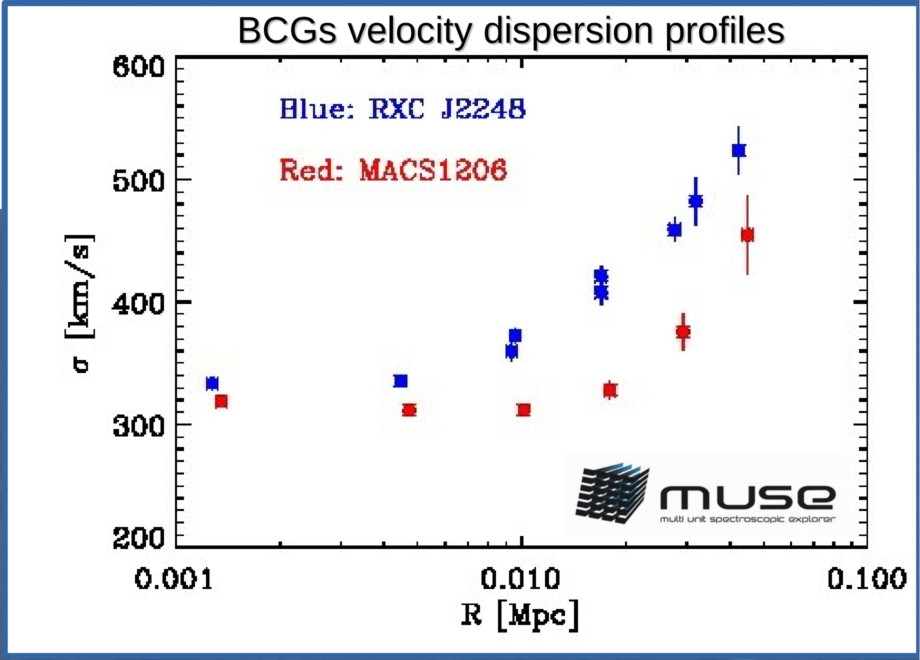
The inner slope of clusters DM density profile



Choose two CLASH-VLT clusters, dynamically relaxed and centered on their BCGs:

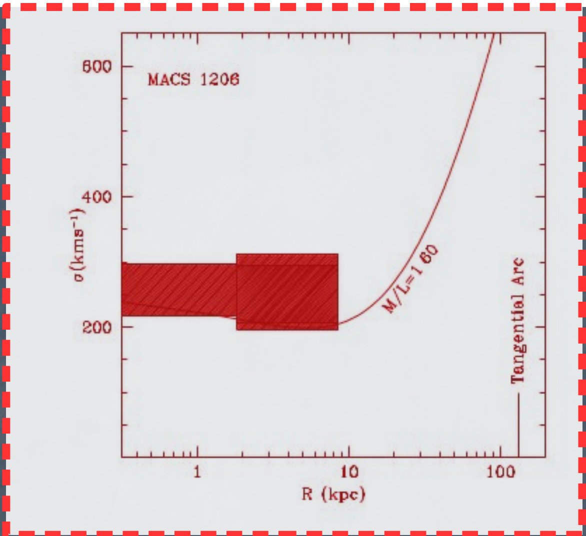
RXJ2248-7-4431, <z>=0.348, r_{200}=2.6 Mpc, 1100 members with z

MACS1206.2-0847, <z>=0.440, r_{200}=2.0 Mpc, 600 members with z



Quality of MUSE BCG velocity dispersion profiles is impressive!

(Cmp to Sand+04 ESI at KeckII profile)



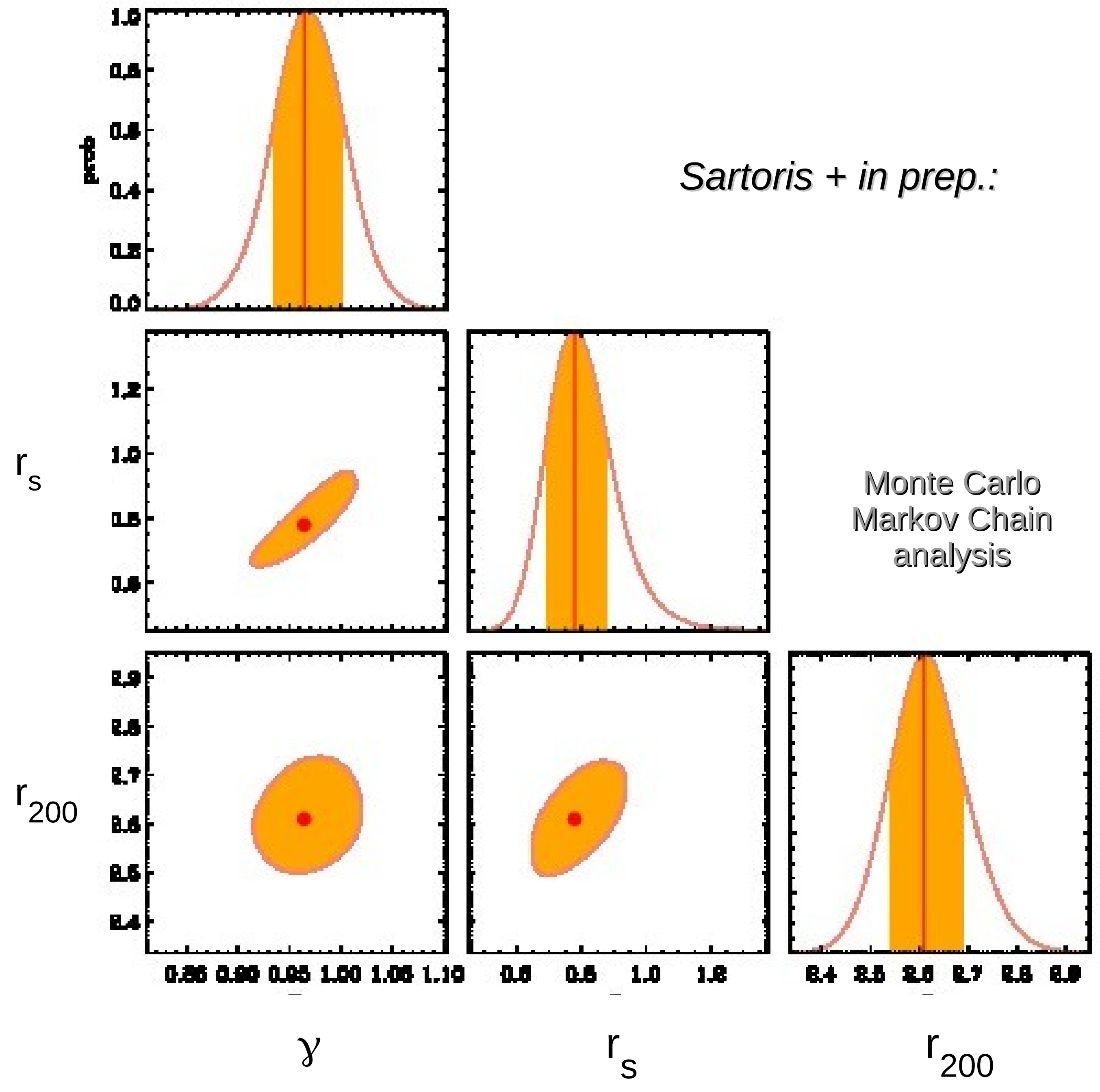
The inner slope of clusters DM density profile

RXC J2248.7-4431
(CLASH-VLT + MUSE):

inner slope of ***DM***
ρ(r→0):

$\gamma = -d \ln \rho / d \ln r$
$= 0.97 \pm 0.04$

fully consistent
with NFW

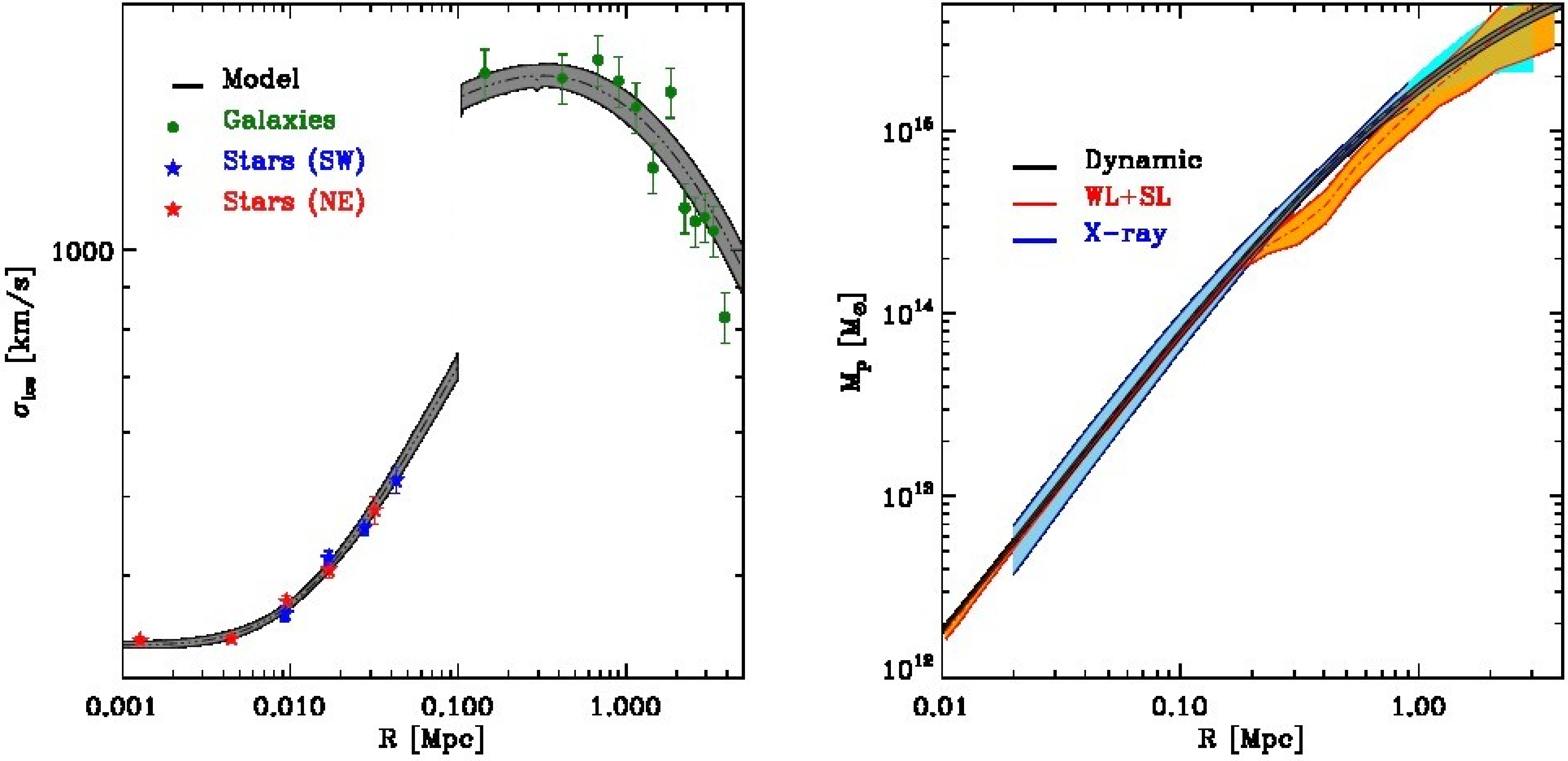


Sartoris + in prep.:

Monte Carlo
Markov Chain
analysis

The inner slope of clusters DM density profile

Sartoris + in prep.:



RXC J2248.7-4431, predicted velocity dispersion profile from the best-fit M(r) compared with the observed velocity dispersion profiles of cluster galaxies and the BCG

RXC J2248.7-4431, projection of best-fit kinematic determination of M(r) along the l.o.s. and comparison with other mass profile determinations *(Strong Lensing: Caminha+16, Weak Lensing: Umetsu+16, X-ray: Chandra)*

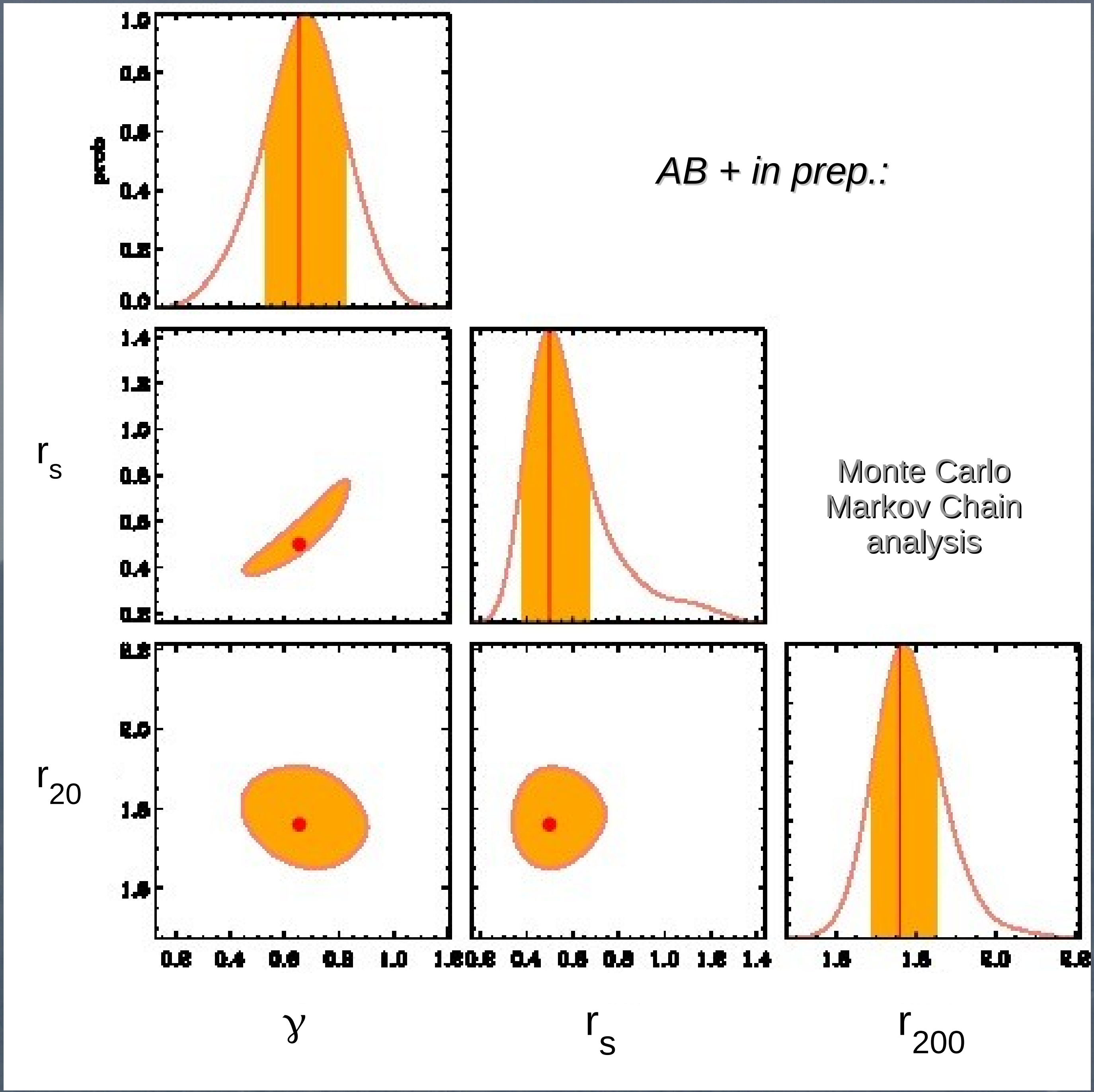
The inner slope of clusters DM density profile

MACS 1206.2-0847
(CLASH-VLT + MUSE):

inner slope of ***DM***
ρ(r→0):

$\gamma = -d \ln \rho / d \ln r$
$= 0.67 \pm 0.15$

*in*consistent
with NFW at 2 σ

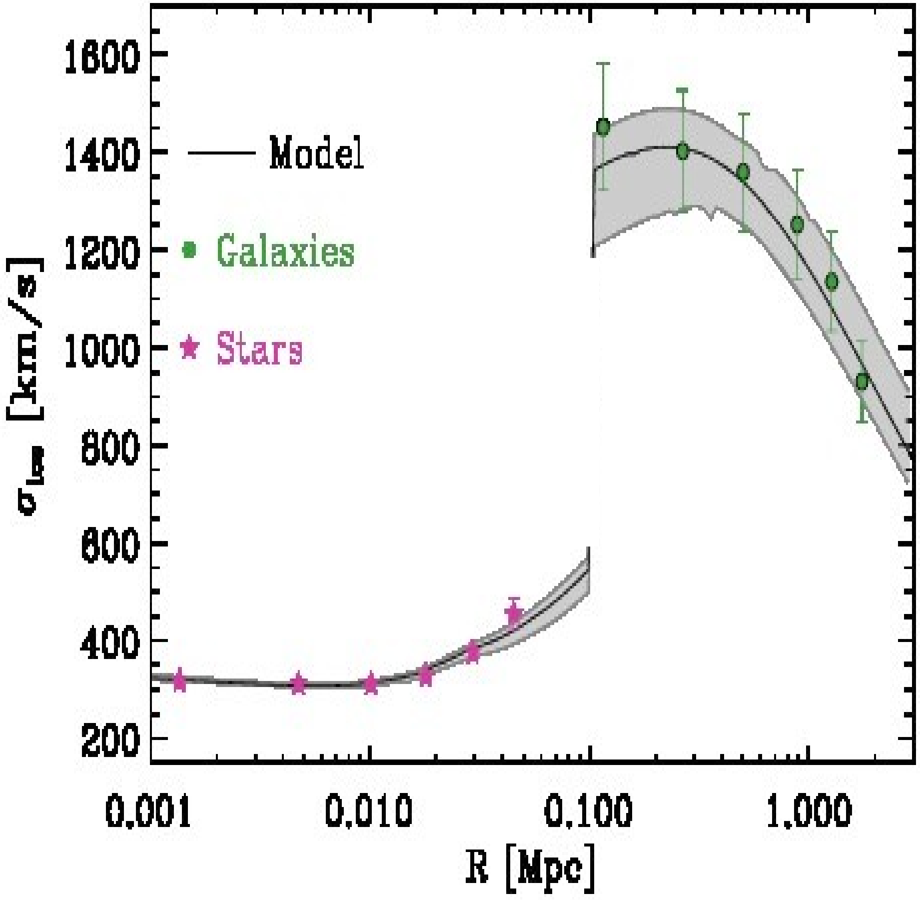


AB + in prep.:

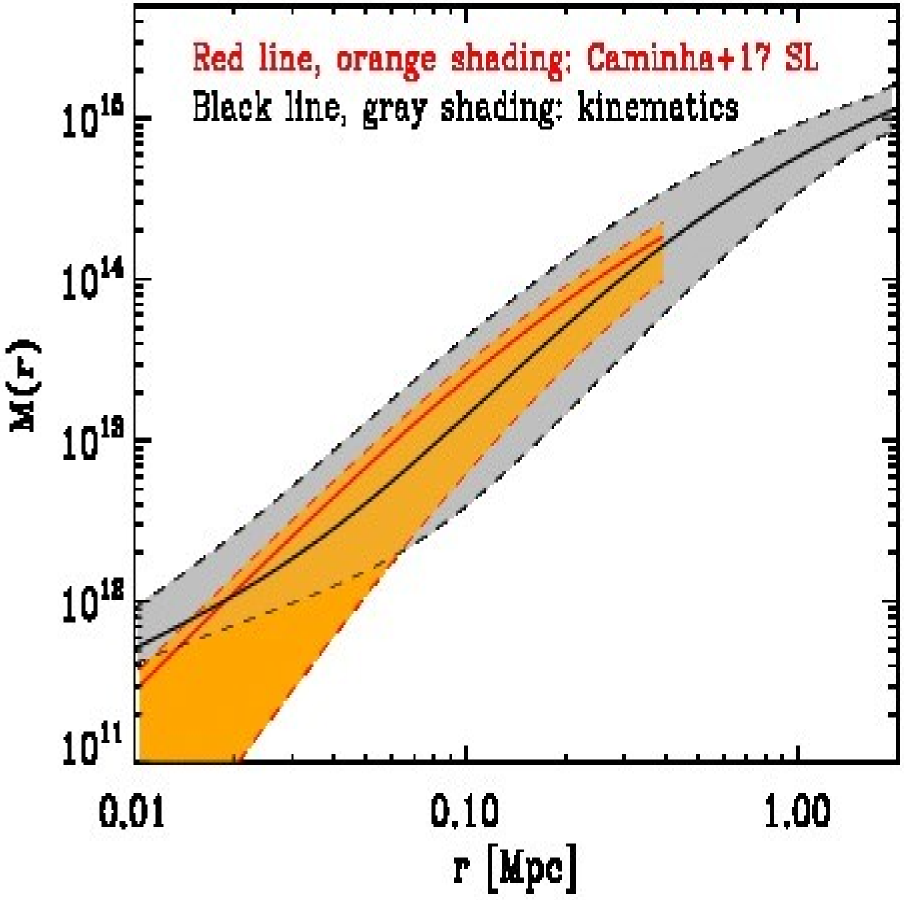
Monte Carlo
Markov Chain
analysis

The inner slope of clusters DM density profile

AB + in prep.:



MACS 1206.2-0847, predicted velocity dispersion profile from the best-fit M(r) compared with the observed velocity dispersion profiles of cluster galaxies and the BCG



MACS 1206.2-0847, comparison with strong lensing determination of 3d M(r) by *Caminha+17*

The inner slope of clusters DM density profile

Variance in values of different clusters cannot depend on DM properties *(DM must be the same for all clusters)* ⇒ *no motivation for alternative DM models (e.g. self-interacting DM, Spergel & Steinhardt 00)*

Baryonic processes can change γ:

Adiabatic contraction *(Blumenthal+86, Gnedin+04)*
Recent accretion of a large subcluster *(Schaller+15)*
} $\gamma > 1$

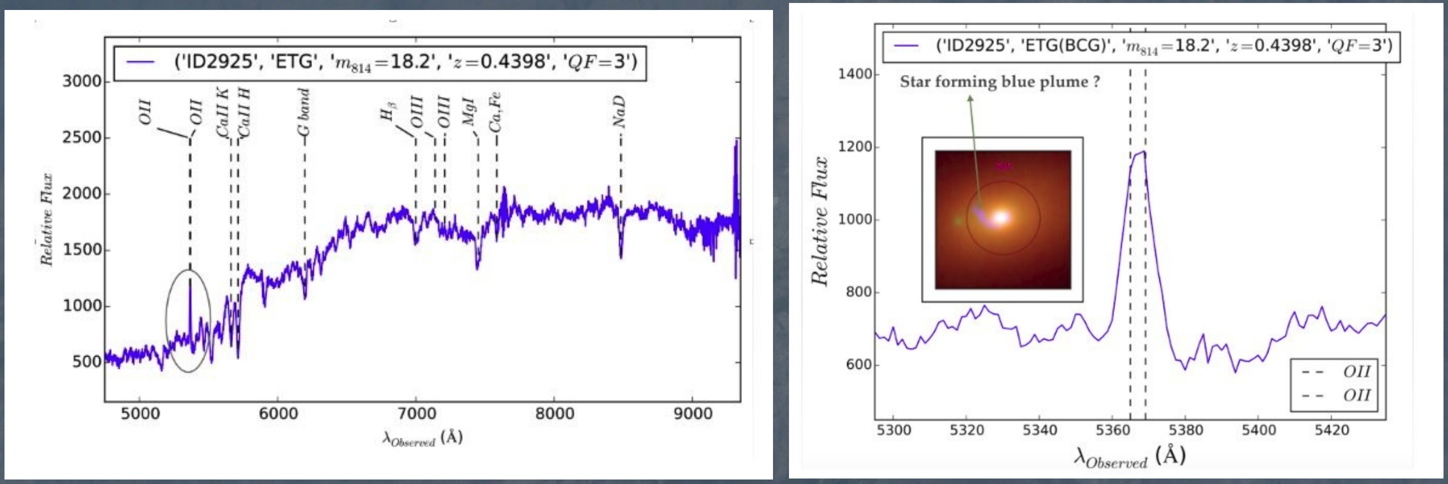
Dynamical friction *(El-Zant+01, +04)*
Collisionless mergers *(Laporte+12)*
AGN feedback *(Navarro+96, Ragone-Figueroa+12, Peirani+17)*
} $\gamma < 1$

As a cluster goes through different evolutionary stages, γ can differ for the same cluster at different times

The inner slope of clusters DM density profile

Which of our cluster properties can explain their γ difference?

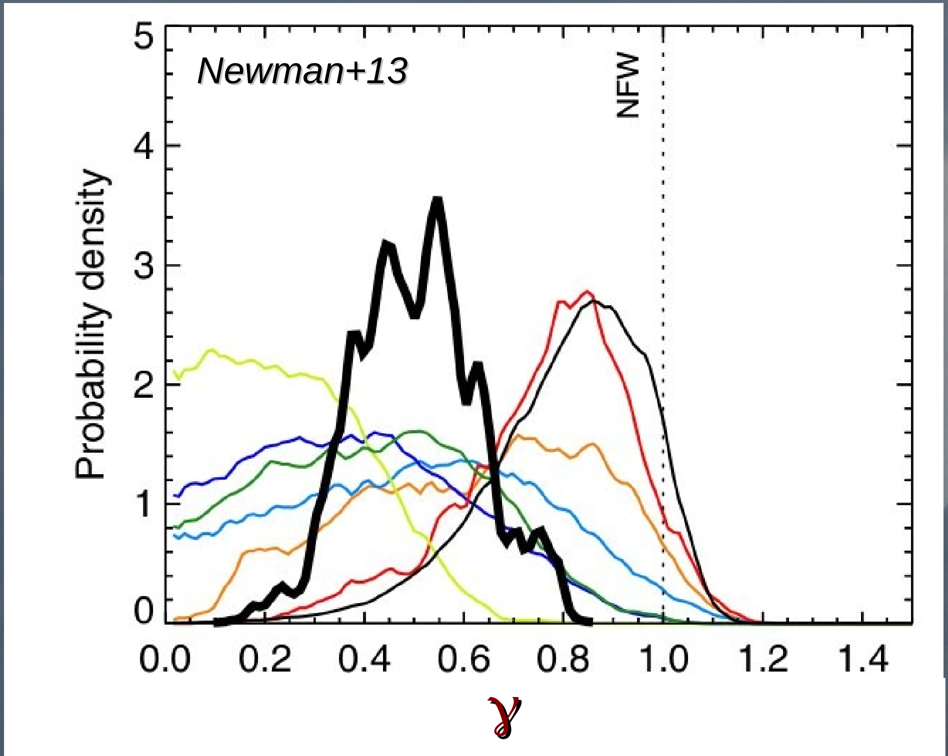
- No evidence for dynamical friction in MACS 1206.2-0847 *(Annunziatella+14)* 😕
- No evidence for recent mergers in the inner regions of any of the two clusters *(Girardi+15, Mercurio+ in prep.)* 😕
- The two BCGs have the same stellar mass, 1.2 $\times 10^{12}$ $M_{\odot}$, but RXC J2248.7-4431 is twice as massive as MACS 1206.2-0847 (2.9 vs 1.4 $\times 10^{15}$ $M_{\odot}$) 🤔
- BCG of MACS 1206.2-0847 is more active than BCG of RXC J2248.7-4431 🙂



The inner slope of clusters DM density profile

Previous investigations (Sand+04, 08, Newman+13; Annunziatella+17):

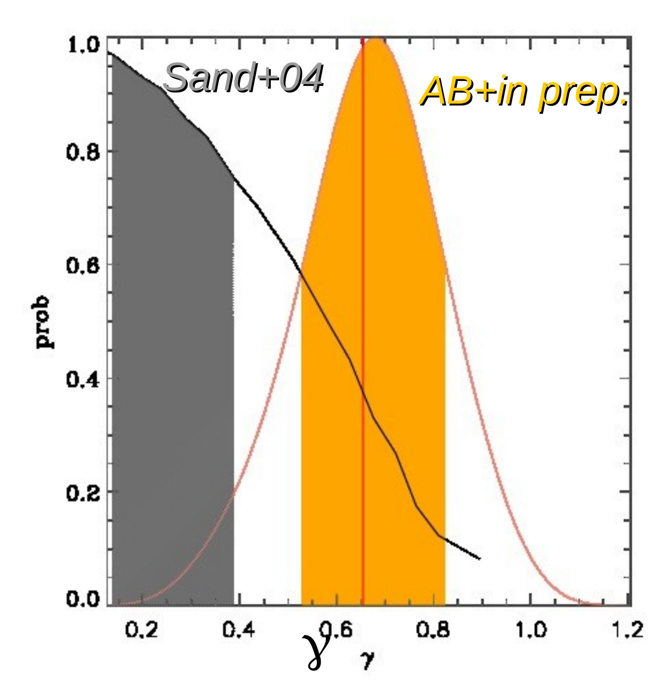
~all clusters have γ<1



Schaller+15: Newman+13 took the wrong isotropic assumption for BCG stellar orbits

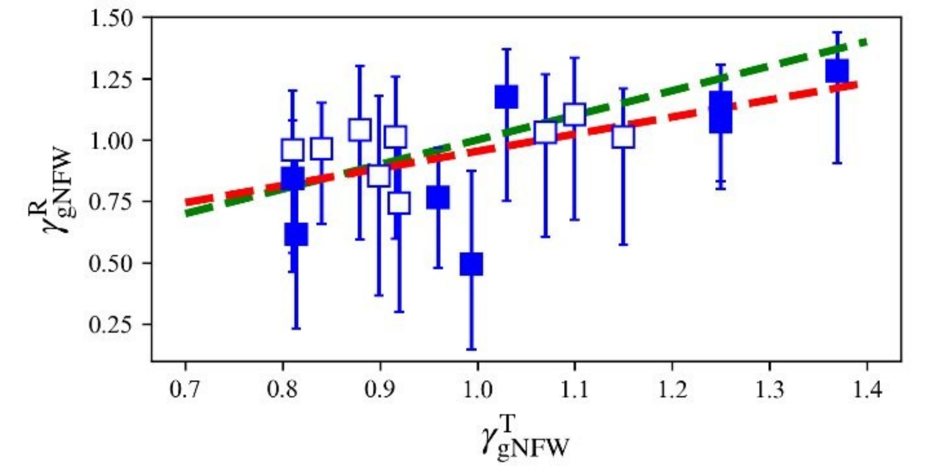
This can't be the explanation: in our analysis we find $\beta_{\text{BCG stars}}(r) \approx 0$ (isotropic) and yet one of our cluster has γ=1

However… for the one cluster we have in common with Sand's (MACS 1206.2-0847) we find a larger value for γ : 🤔



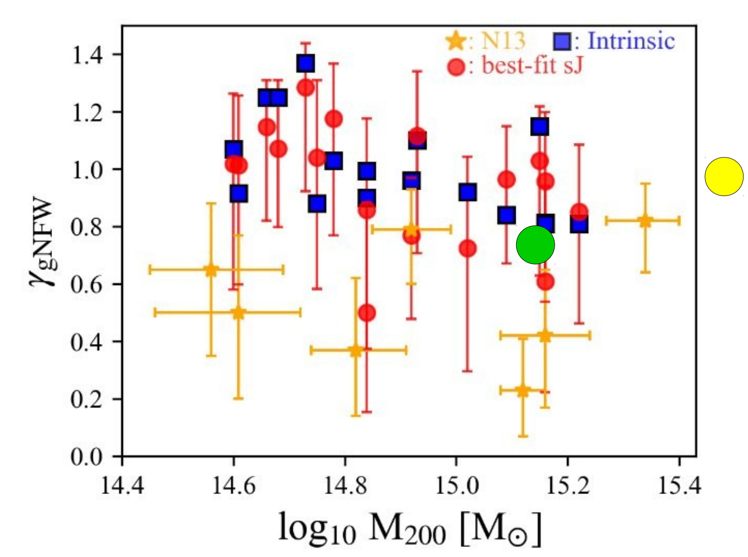
The inner slope of clusters DM density profile

Why do *Newman+15, Sand+04, +08* clusters have low γ?



He+19: C-EAGLE simulations *(less than a week ago!)*:

Validate the procedure of Sand+04, 08, and Newman+13 *(similar to ours, but they use lensing to constrain M(r) at large r, instead of kinematics)*



The procedure seems OK, yet the γ values of C-EAGLE clusters are significantly larger (and closer to NFW) than those of Newman+13 *(but in good agreement with our results!)*

Can Newman+13's values be biased low because of:

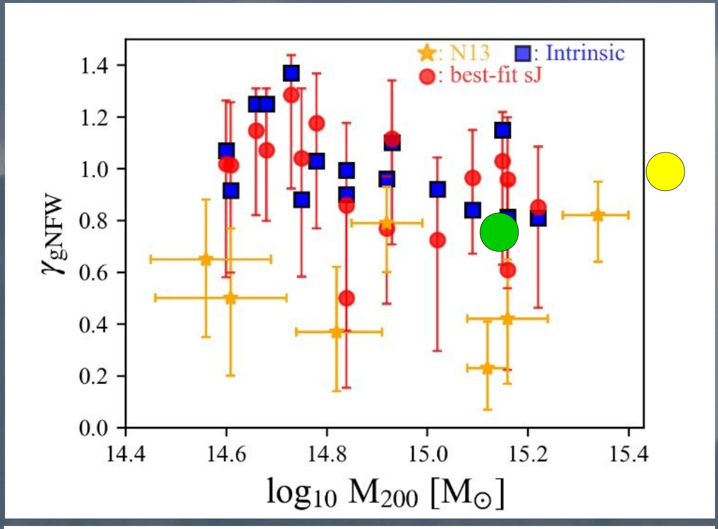
- triaxiality? no!
- M$_*$/L variation with radius? no!
- stellar velocity anisotropy? no!

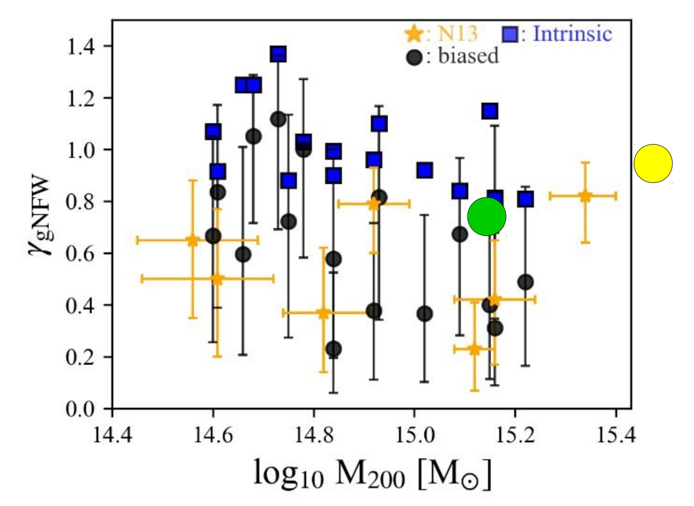
● RXC J2248.7-4431
● MACS 1206.2-0847

The inner slope of clusters DM density profile

Why do *Newman+15, Sand+04, +08* clusters have low γ?

He+19: C-EAGLE simulations



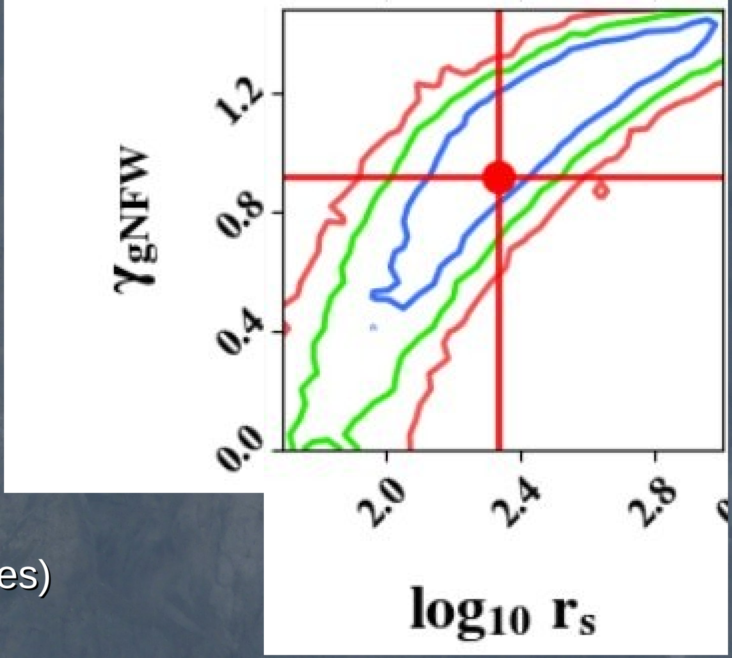


● RXC J2248.7-4431

● MACS 1206.2-0847

The problem may lie in the covariance between r_s and γ *(also present in our analysis)*, + a biased (low) value of r_s in Newman+13 *(in Sand+04 they assume the same r_s value for all clusters for lack of constraints)*

Simulated γ values would agree with Newman+13 if they are obtained by adopting biased values of r_s (½ true values)



The inner slope of clusters DM density profile

What next?

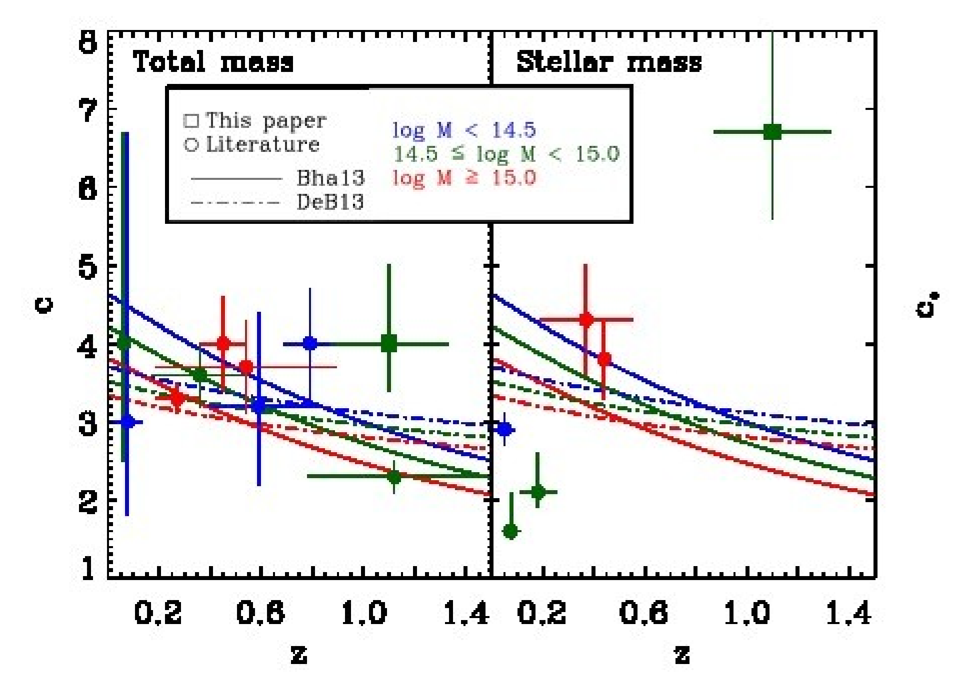
Determine DM ρ(r) inner slopes of more clusters
to see if γ changes with mass, dynamical status, BCG activity:

- 14 z~0.05-0.3 clusters with literature data (HeCS, *Rines+13,* ~200 spec. members/cluster; *Loubser+18,* BCGs velocity dispersion profiles with Gemini N&S)
- 7 z~0.4 clusters with CLASH-VLT data (>500 spec. members/cluster) and MUSE data for the BCGs velocity dispersion profiles
- *can we go to z~1?*

The concentrations of total mass and stellar mass in clusters of galaxies evolve with z in a markedly different way *(AB+16)*

⇩

How do γ_{total} and γ_{DM} evolve with z?



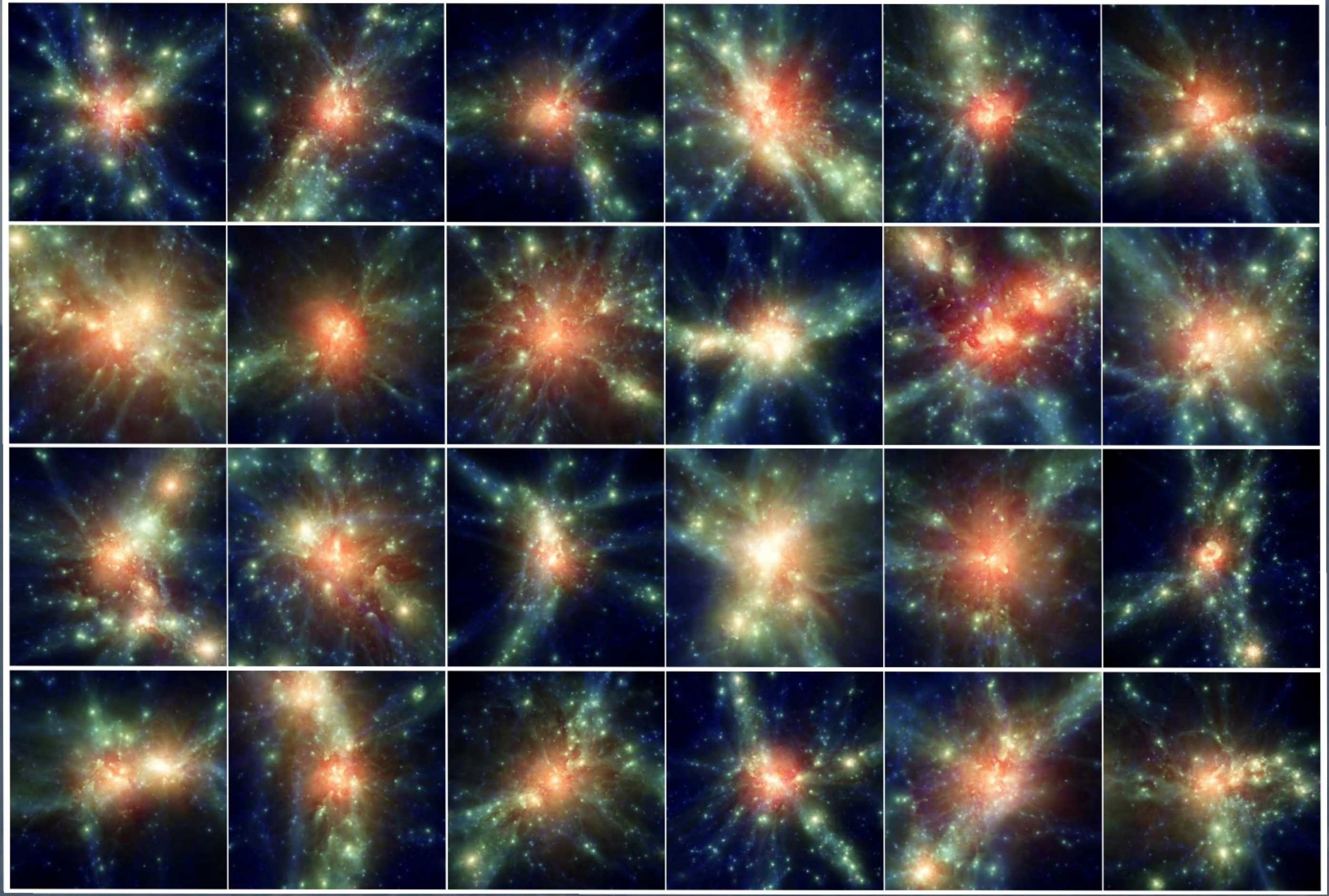
The inner slope of clusters DM density profile

What next?

Determine DM ρ(r) inner slopes of simulated clusters
to see if our procedure to observationally determine γ is correct and unbiased
and to explore how γ changes with cluster dynamical status and BCG AGN activity

- DIANOGA:

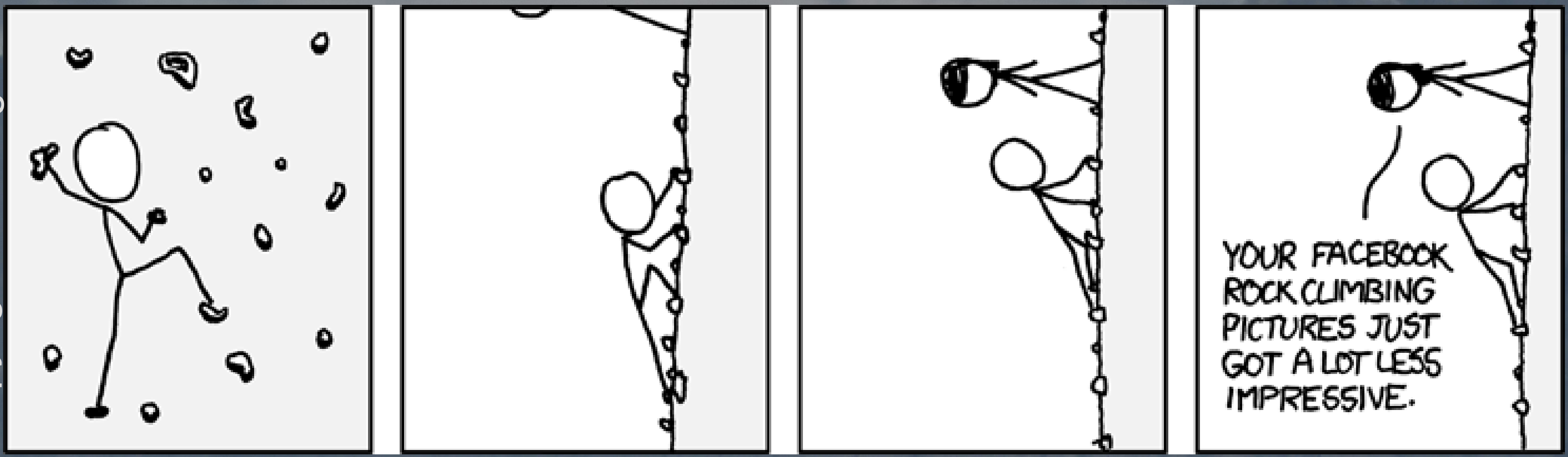
  24 re-simulated clusters extracted from cosmological simulations
  (Rasia+15, Biffi+16, Ragone-Figueroa+18)



The inner slope of clusters DM density profile

In conclusion...

Perhaps clusters do have a flat inner DM density profile slope, after all…
...but beware of how you read your data!



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Steep slope?

Flat slope?

Thanks!