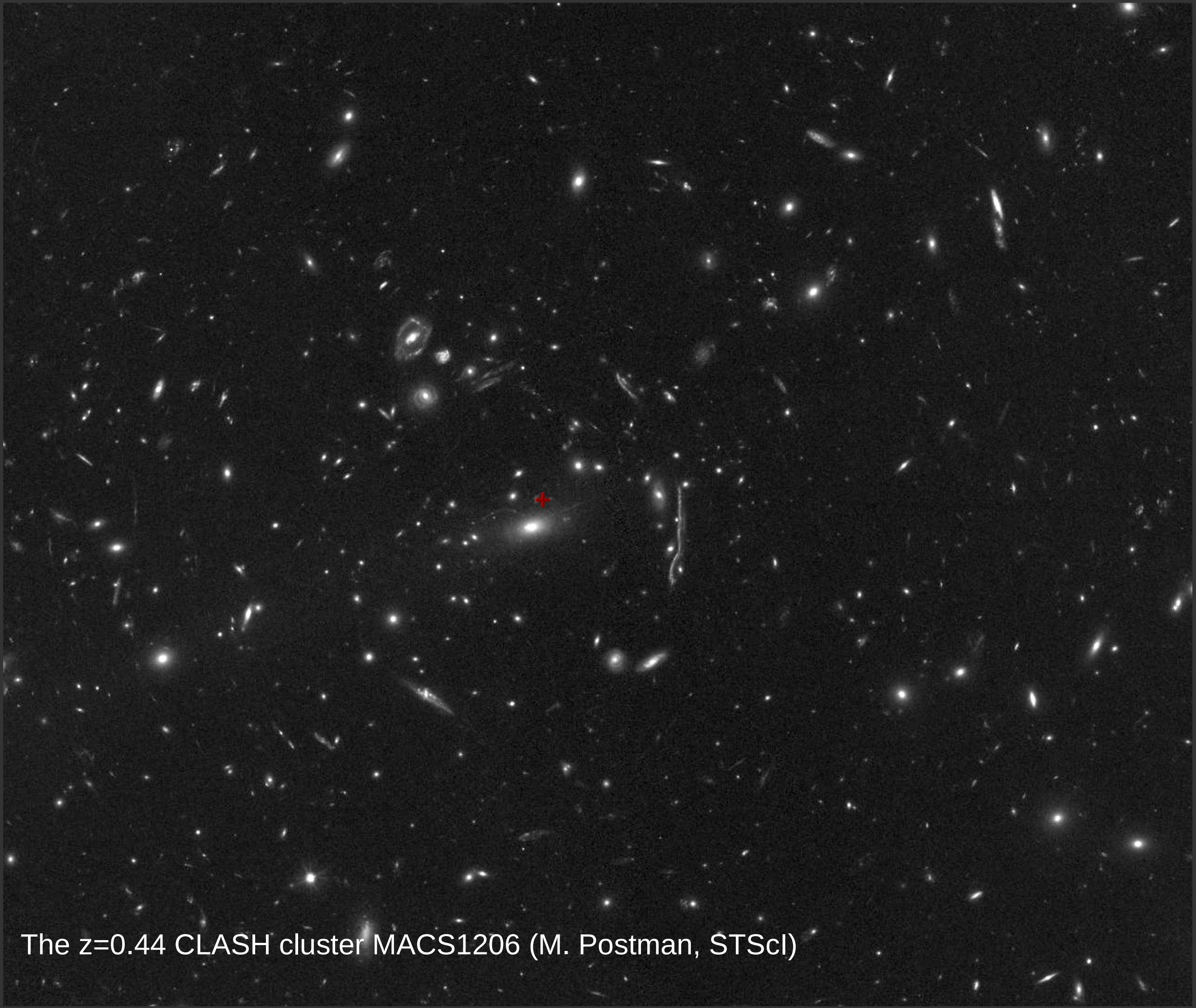
# The inner slope of the cluster mass density profiles*


The z=0.44 CLASH cluster MACS1206 (M. Postman, STScI)


**Andrea Biviano**

**INAF-OATs**
**& IFPU**

**Trieste, Italy**


** Mostly based on:*

- *Sartoris, AB + 2020, A&A, 637, A34*
- *AB + 2023, ApJ, submitted*

# Outline of this talk

- Introduction - *the mass distribution in clusters of galaxies*
- Methods - *how to determine cluster mass profiles*
- Results
  - *the hydrostatic bias of the mass estimate*
  - *the inner slope of the cluster dark matter density profile*
- Discussion - *the inner slope of the cluster dark matter density profile*
- Summary and perspectives

# **Introduction** – Clusters of galaxies probe Dark Matter

1933

**Die Rotverschiebung von extragalaktischen Nebeln**
von **F. Zwicky.**
(16. II. 33.)

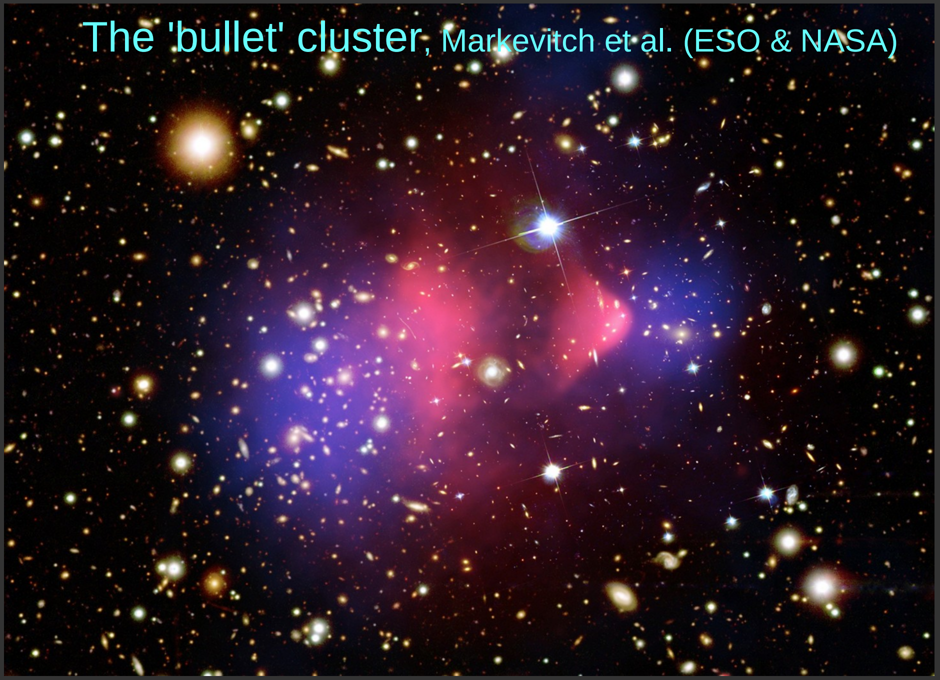
1. Setzt man voraus, dass das Comasystem mechanisch einen stationären Zustand erreicht hat, so folgt aus dem Virialsatz

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

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.

2004




WEAK-LENSING MASS RECONSTRUCTION OF THE INTERACTING CLUSTER 1E 0657−558: DIRECT EVIDENCE FOR THE EXISTENCE OF DARK MATTER[1]

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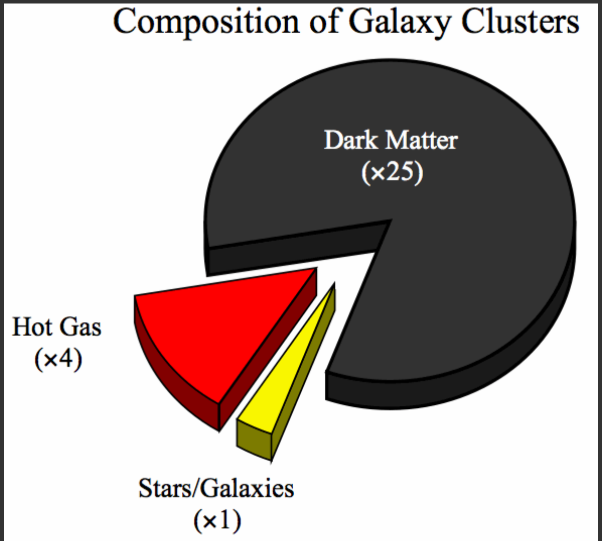
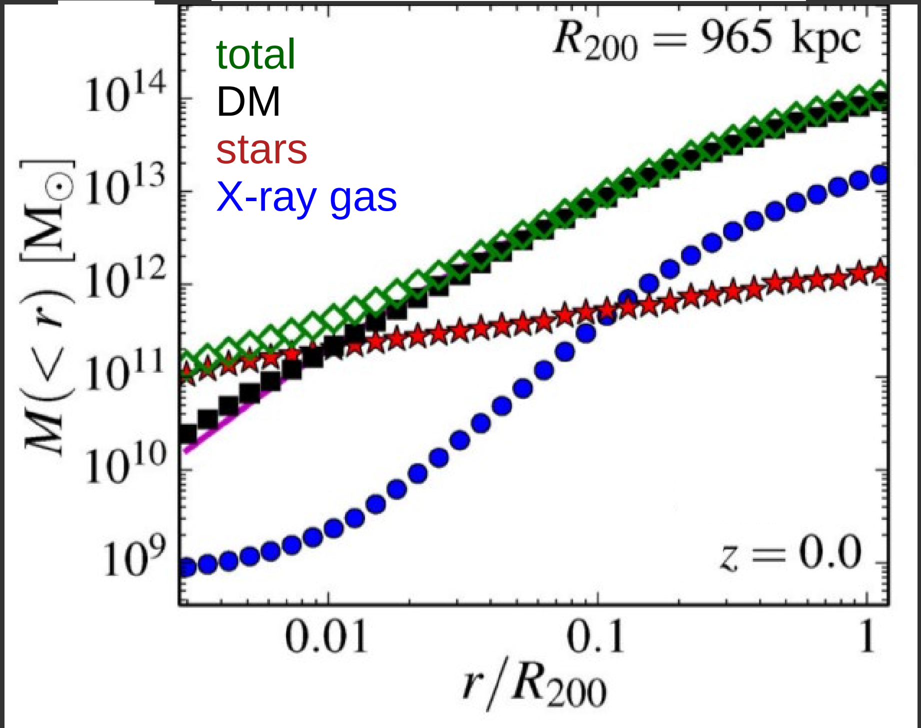
*Received 2003 October 28; accepted 2003 December 11*

of relaxed clusters. The observed offsets of the lensing mass peaks from the peaks of the dominant visible mass component (the X-ray gas) directly demonstrate the presence, and dominance, of dark matter in this cluster. This

# **Introduction** – Mass components distribution in clusters



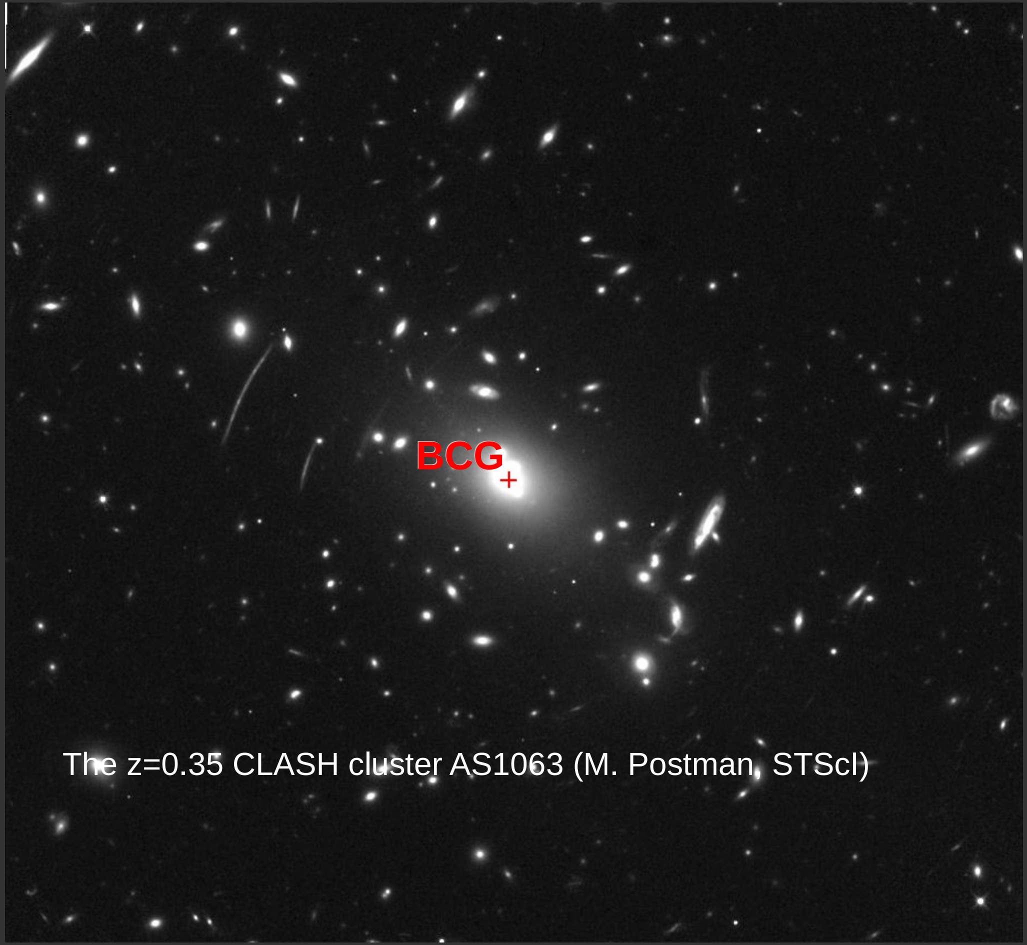




*EAGLE simulations, Schaller+15*

Dark Matter dominates at most radii

Most baryons are in the diffuse, hot, X-ray emitting gas,

At the cluster center the stellar component of the **Brightest Cluster Galaxy (BCG)** becomes dominant




The z=0.35 CLASH cluster AS1063 (M. Postman, STScI)

# **Introduction** – Dark Matter distribution in clusters

Is there A UNIVERSAL DENSITY PROFILE of cosmological halos?

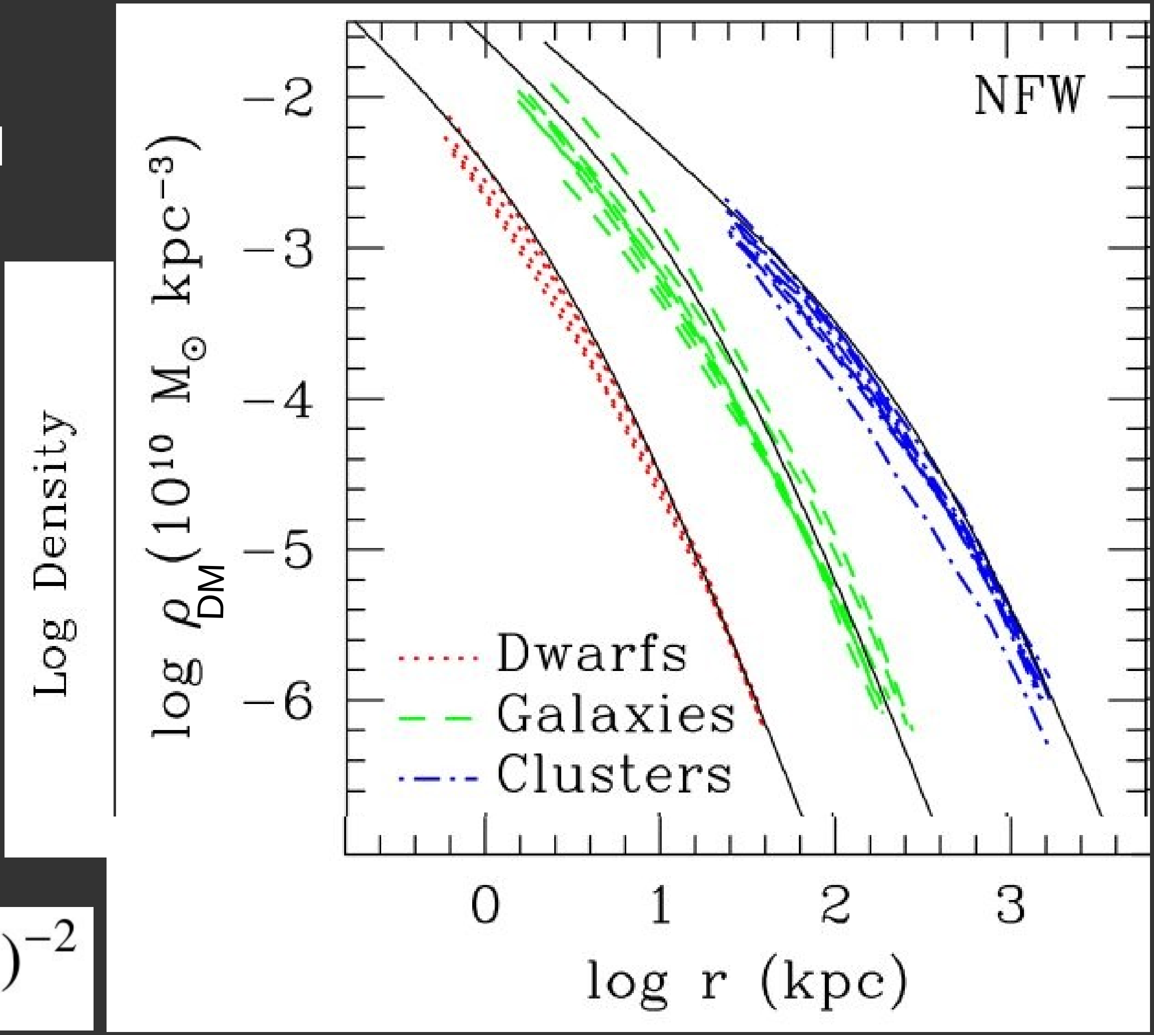
Navarro, Frenk & White 97:

the DM density profile, ρ(r), of all cosmological halos, is **universal**
- based on (collisionless) Cold DM numerical simulations


Julio Navarro

$$\rho_{DM}(r) \propto (r/r_{-2})^{-1} \times (1 + r/r_{-2})^{-2}$$

*Inner logarithmic slope -1, asymptotic slope -3 with a change in slope at a characteristic radius $r_{-2}$*



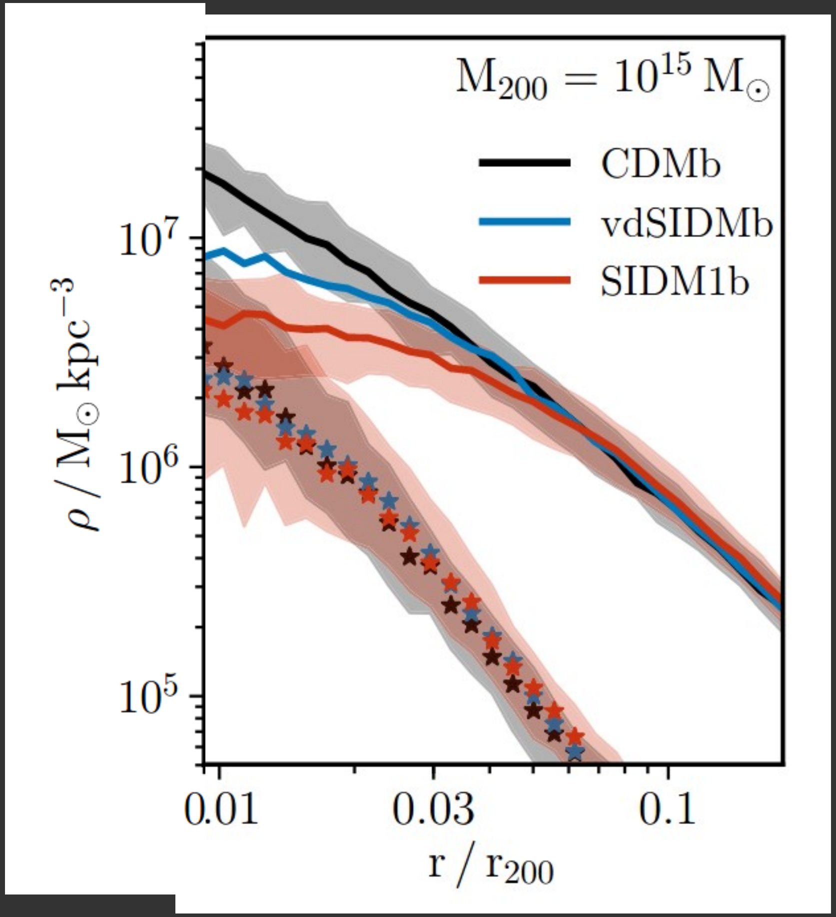

(Navarro+04)

# **Introduction** – Dark Matter distribution in clusters

Clusters are DM dominated ⇨ their mass distribution should be similar to the NFW shape found in collisionless Cold DM cosmological simulations

*If* cluster DM distribution deviates from NFW shape, *then:*

- DM may not be Cold *(e.g. Warm DM; Bode+01)*,
- or it may be collisional *(e.g. Self-Interacting DM; Spergel+Steinhardt 00)*




*The flattening of the mass density profile of simulated clusters in Self-Interacting DM models cmpd to Cold DM (Robertson+21)*

# **Introduction** – Dark Matter distribution in clusters

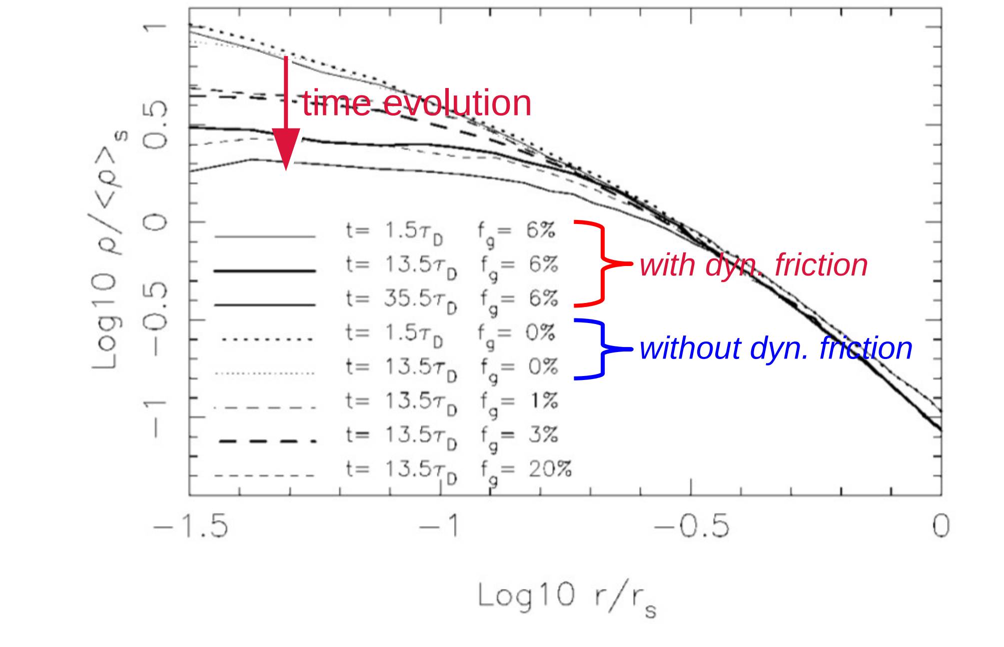
*However*:
the DM distribution can deviate from NFW because of physical processes:

- Adiabatic contraction *(Blumenthal+86, Gnedin+04)*
- Recent accretion of a large subcluster *(Schaller+15)*

} *$\rho_{DM}(r \to 0)$ cuspier*

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

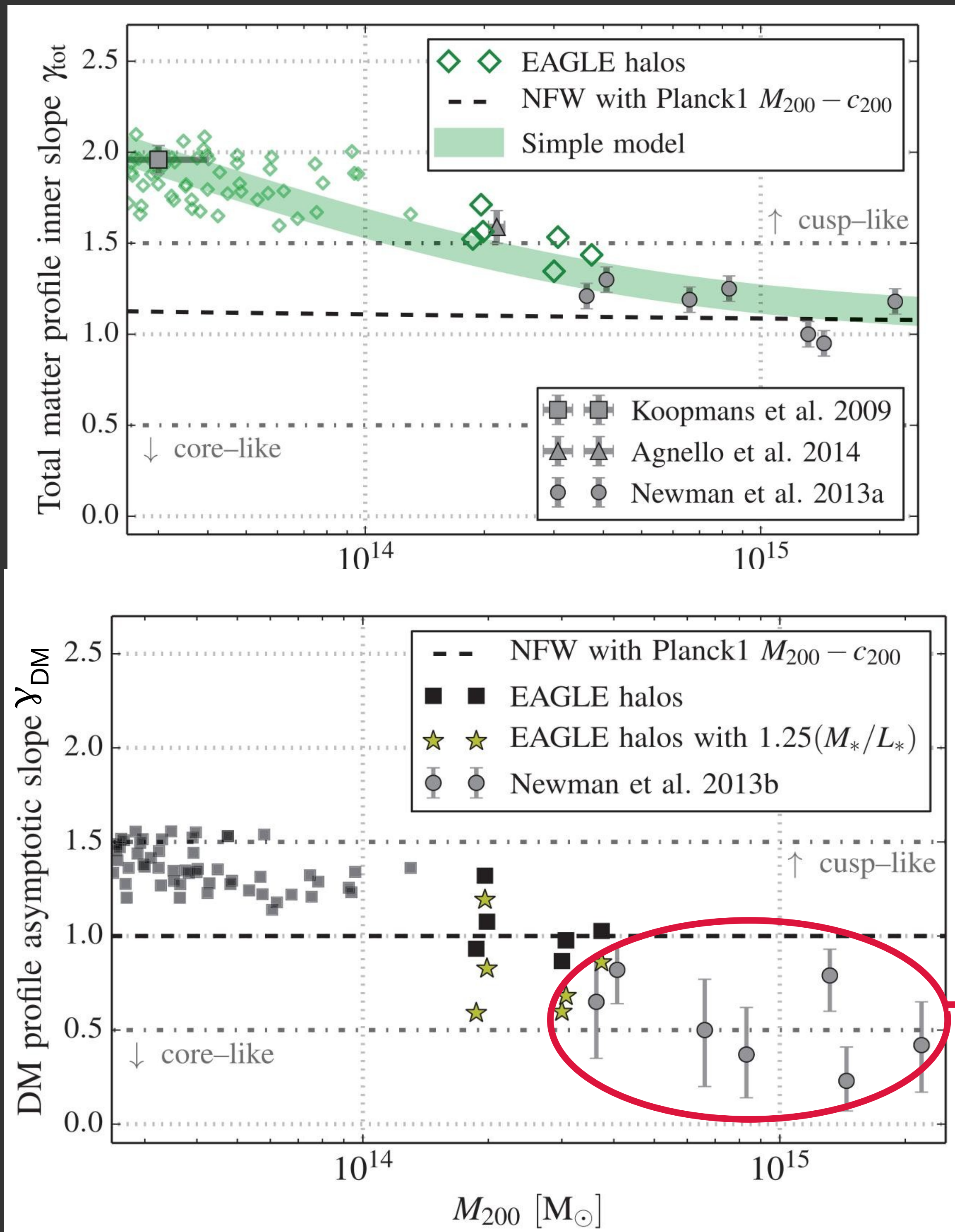
} *$\rho_{DM}(r \to 0)$ flatter*




*Time evolution of the mass density profile of simulated clusters in models w/wo dynamical friction energy transfer from subclumps to main halo (El-Zant+04)*

⇒ Measuring the inner slope of several cluster DM profiles at different redshifts constrains the properties of DM and/or these physical processes

# **Introduction** – Dark Matter distribution in clusters




*Schaller+15:*

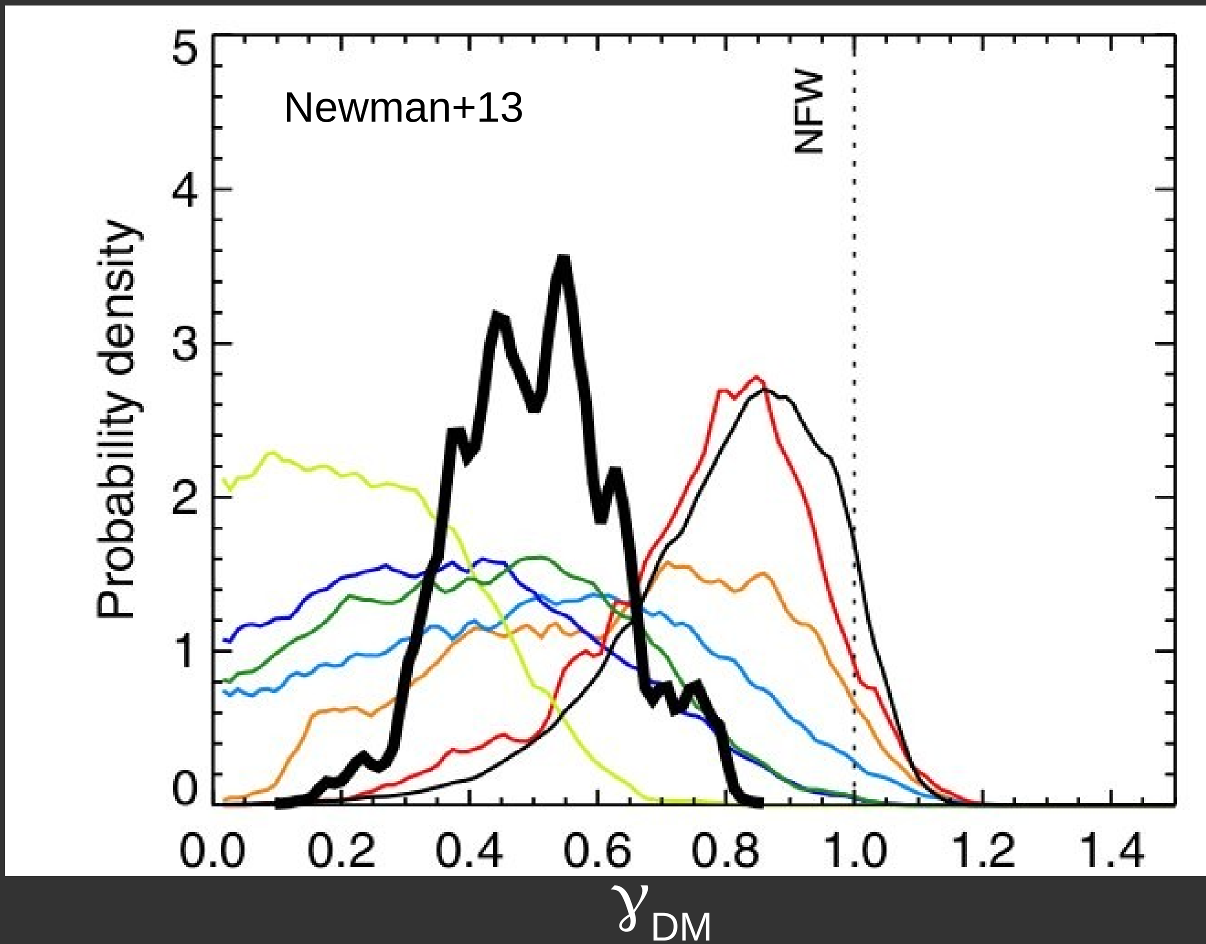
We must distinguish the inner logarithmic slope of the *total* matter profile, $\boldsymbol{\gamma_{tot}}$, from the inner logarithmic slope of the *DM* profile $\boldsymbol{\gamma_{DM}} \equiv d \log \rho_{DM}/d \log r$

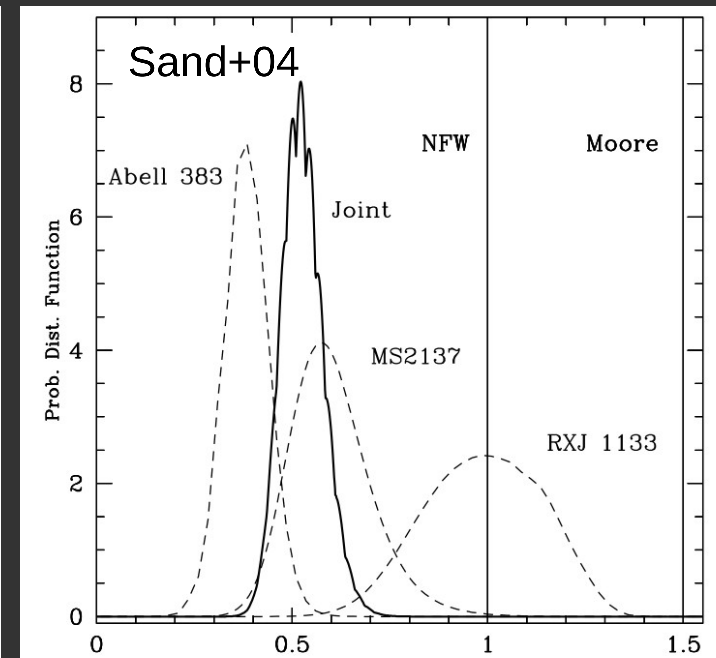
The stellar mass contribution to the total mass makes $\boldsymbol{\gamma_{tot} > \gamma_{DM}}$

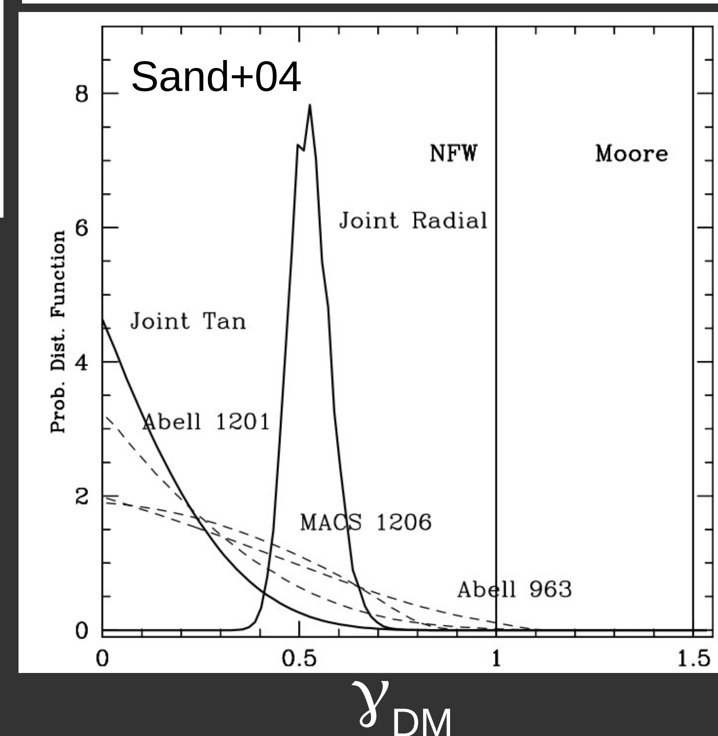
*($\gamma_{tot}$ - $\gamma_{DM} \approx 0.1$ for very massive halos)*

*Newman+13's* determinations of $\gamma_{DM}$ for clusters based on observations of gravitational lensing and kinematics are in disagreement with the results from the EAGLE simulations

# **Introduction** – Dark Matter distribution in clusters



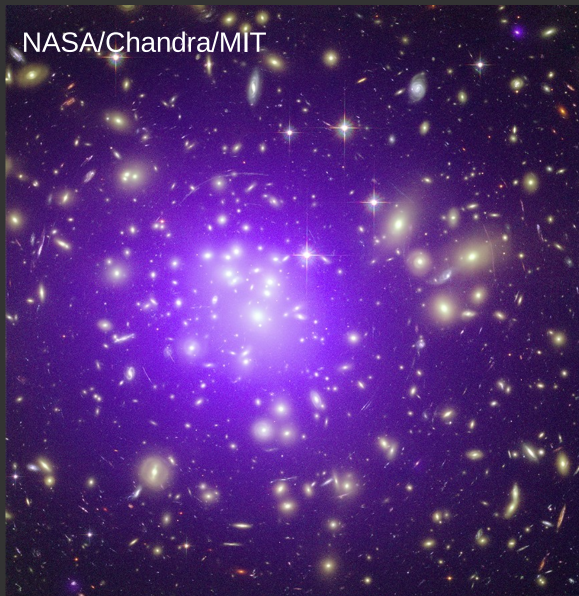




Previous results for 10 clusters based on Strong Lensing + kinematics of BCG *(Sand+04, +08; Newman+13)* find

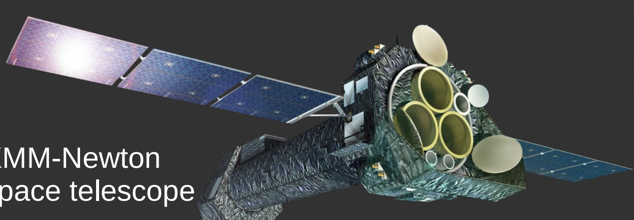
$$\boldsymbol{\gamma_{DM} = 0.5 \pm 0.1}$$

*(<1, flatter than NFW at the center)*

# **Methods** – How to determine the cluster mass distribution

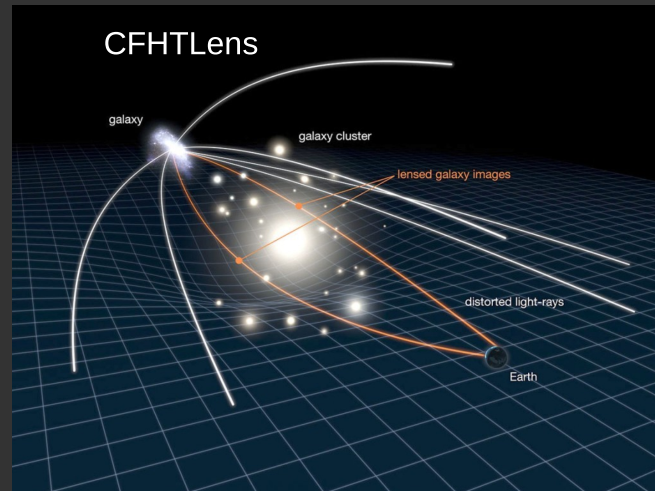



X-ray & radio (Sunyaev-Zeldovich) observations: assuming hydrostatic equilbrium of the intra-cluster gas



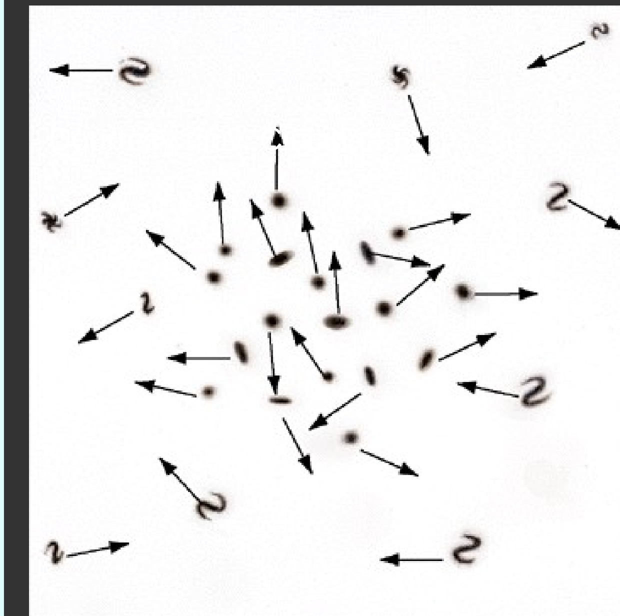
XMM-Newton space telescope

ACT radio telescope




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

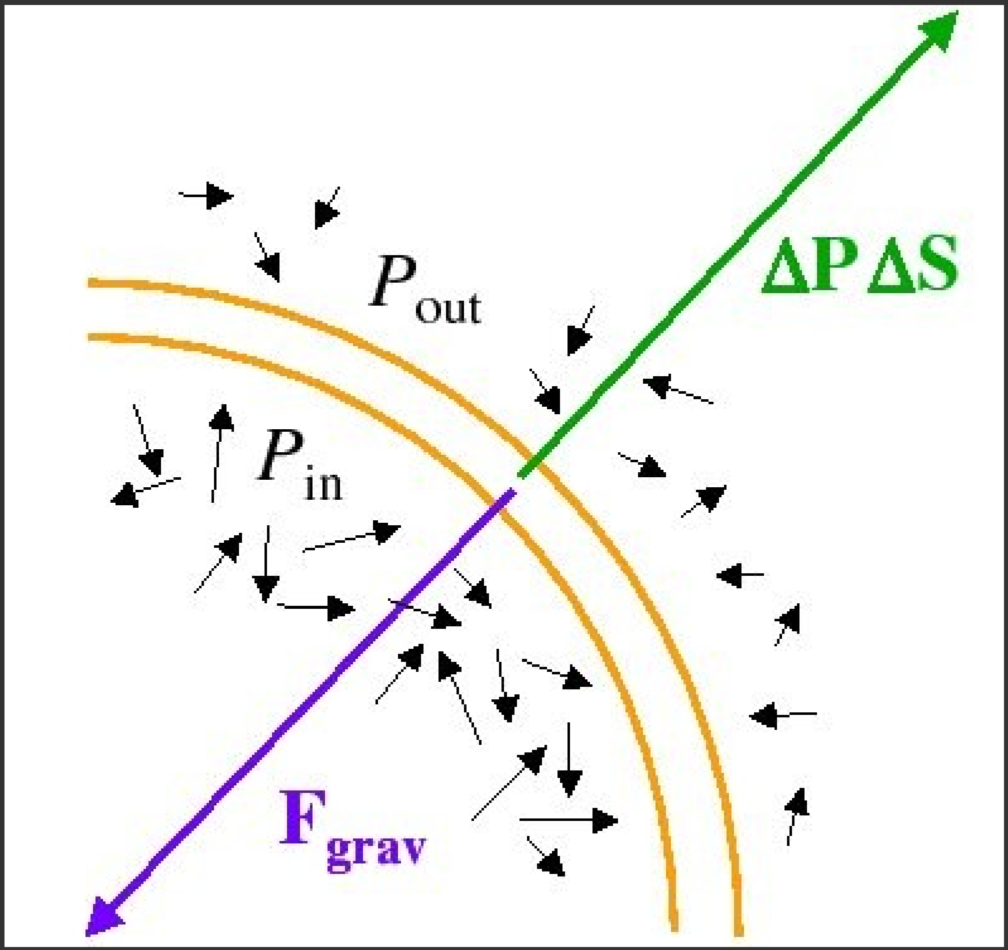
Hubble space telescope



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

Very Large Telescope

# **Methods** – How to determine the cluster mass distribution

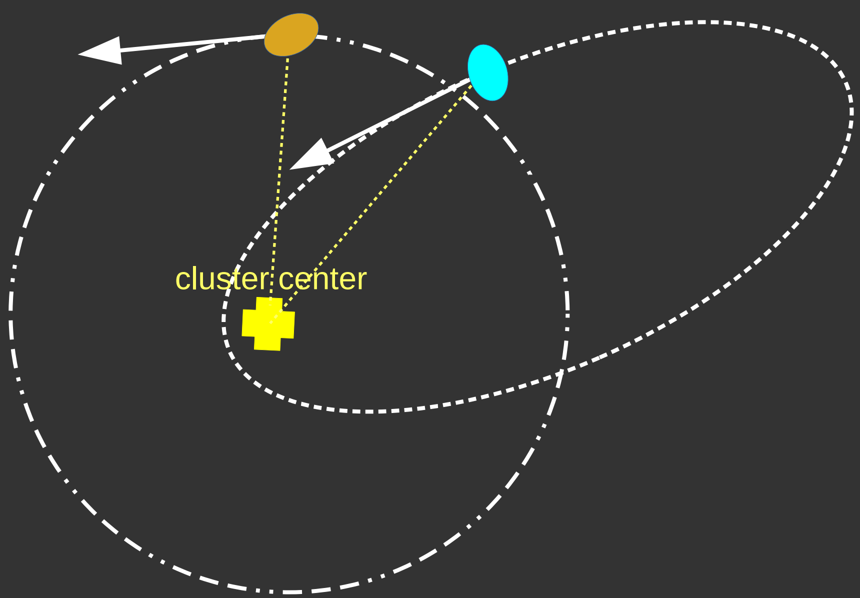



*(courtesy of G. Mamon)*

Cluster mass ⇒ Gravitational pull

Number density +
velocity distribution of galaxies ⇒
Pressure against gravitational pull

Pressure is different if the velocity vector is aligned with or orthogonal to the gravitational pull, i.e. it depends on the galaxy orbital shape (radial vs. tangential)



# **Methods** – How to determine the cluster mass distribution

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

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

Mass profile

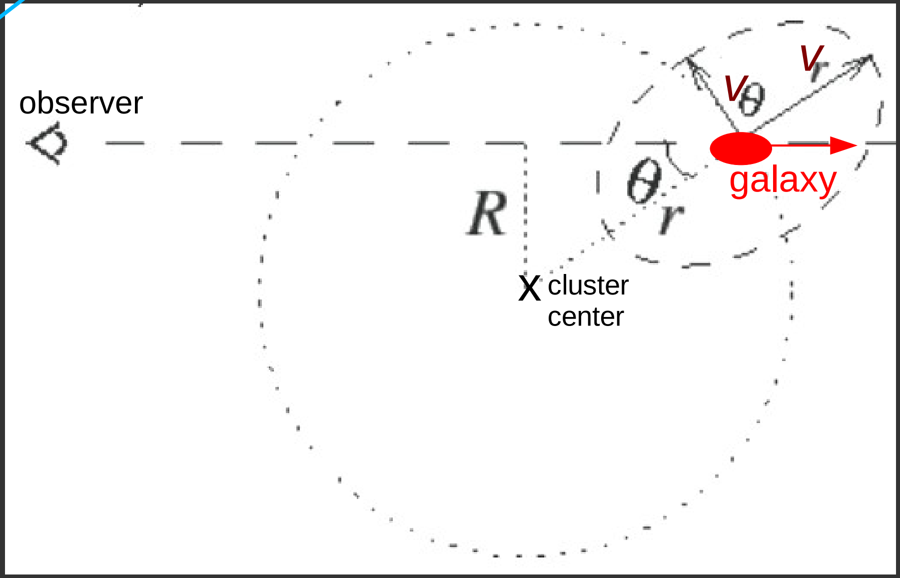
3D number density profile

Velocity dispersion profile along the radial direction, r

Velocity anisotropy profile

Velocity dispersion profile along the tangential direction


β(r) is related to the orbital distribution of cluster galaxies:
β(r)<0 tangentially elongated
β(r)>0 radially elongated




*(courtesy of G. Mamon)*

The solution for the mass profile M(<r) is degenerate with the solution for the velocity anisotropy profile β(r):

***M**ass-**A**nisotropy **D**egeneracy*

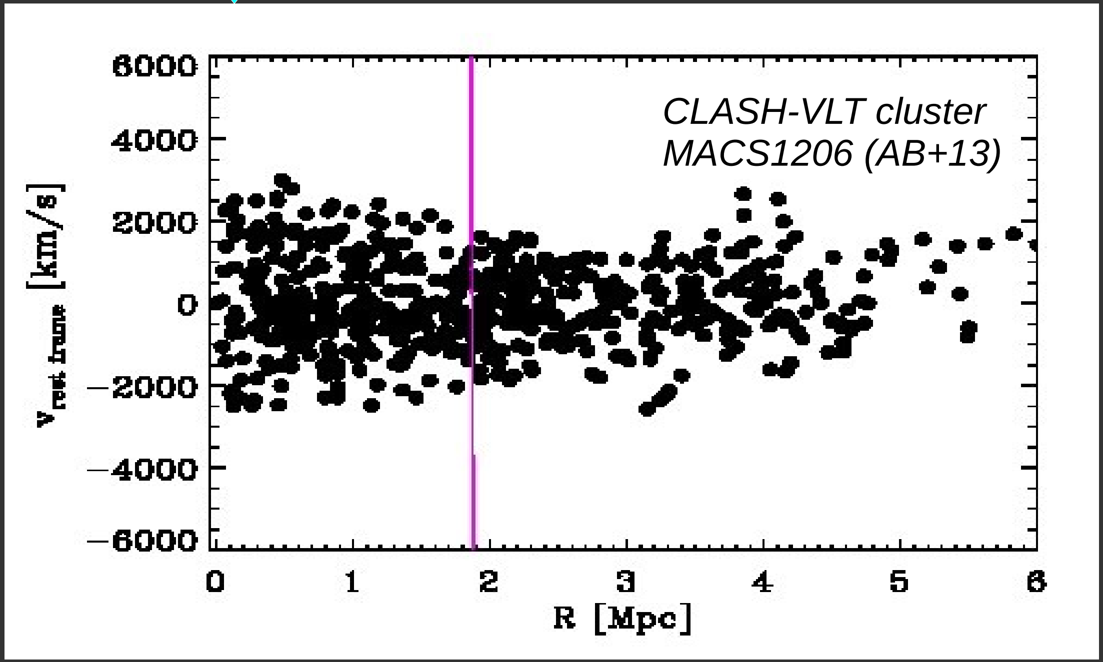
# **Methods** – How to determine the cluster mass distribution

## MAMPOSSt *(Mamon, AB, Boué 13)*

It performs a maximum likelihood fit of model M(<r) and model β(r) to the projected phase-space distribution of cluster galaxies

**M**odelling
**A**nisotropy and
**M**ass
**P**rofiles of
**O**bserved
**S**pherical
**S**ys**t**ems

Traditional approaches cannot solve the Jeans equation without making assumptions on the distribution of the orbital shapes of cluster galaxies



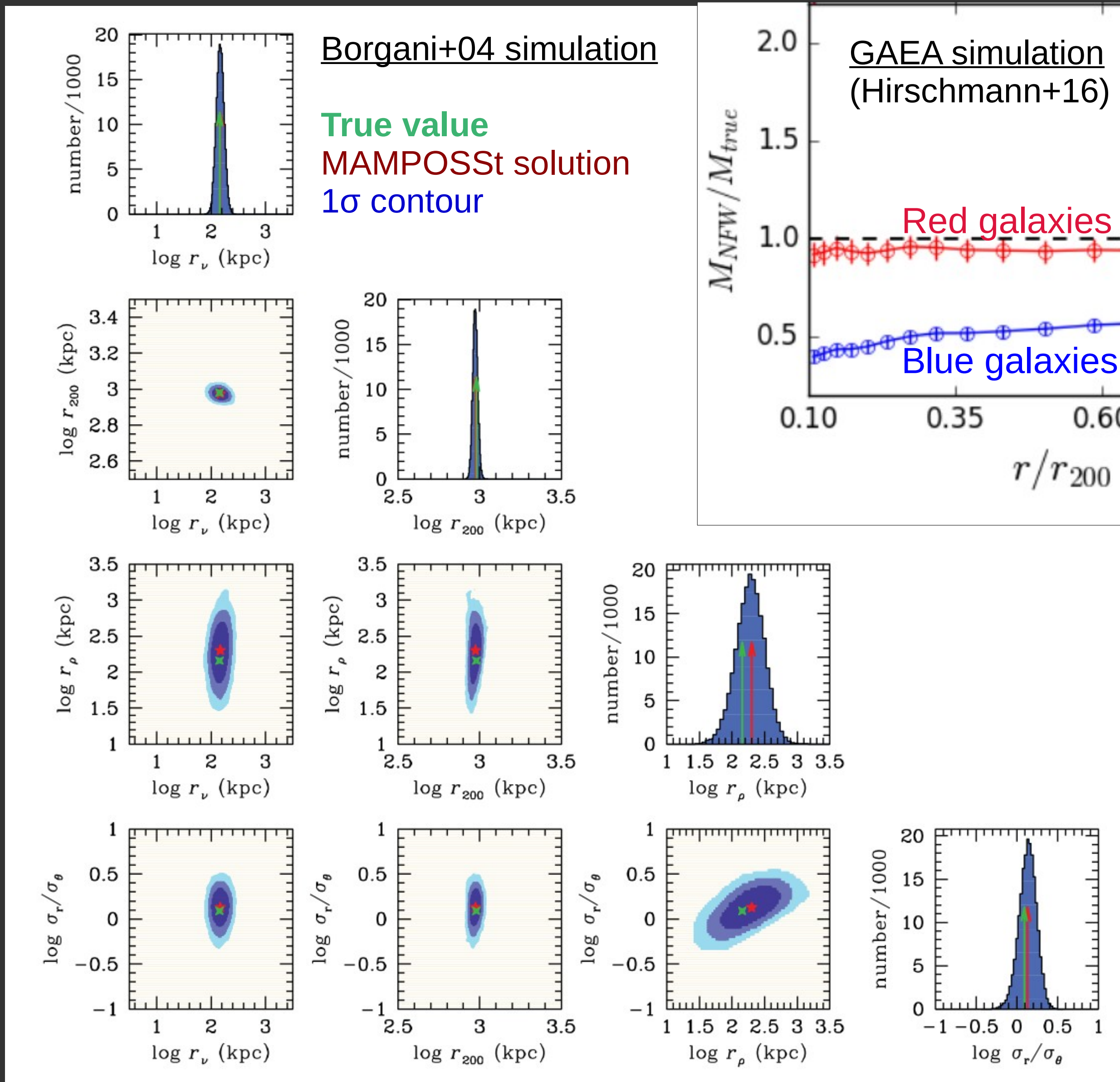

MAMPOSSt breaks the mass-anisotropy degeneracy of the Jeans equation by using the full information available in the spatial and velocity distributions of cluster galaxies

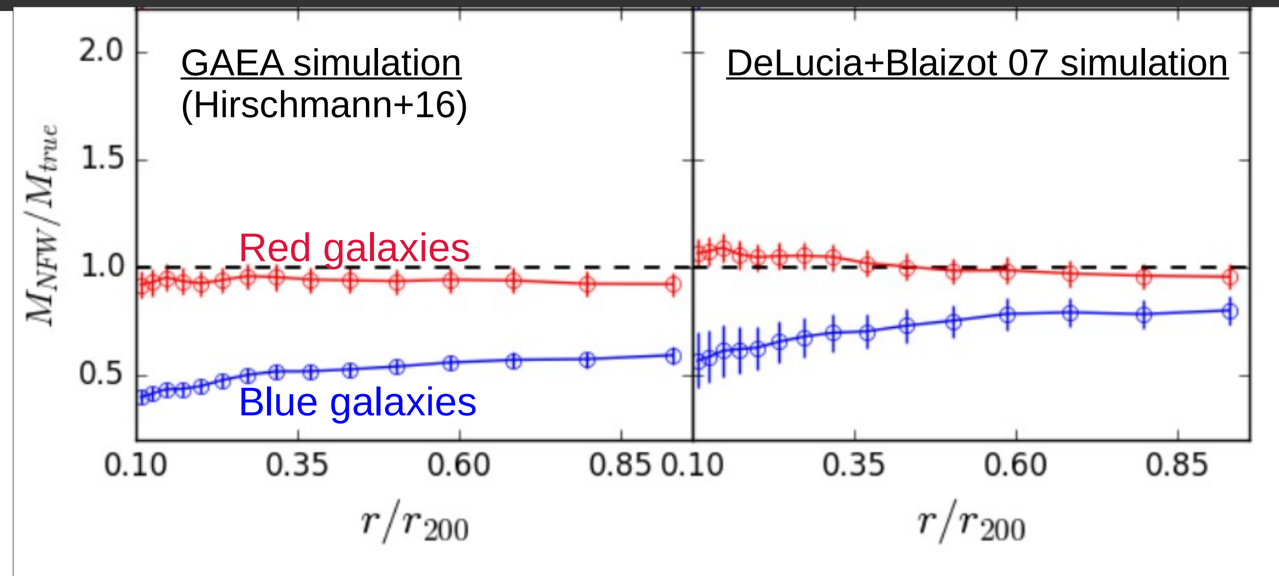
MAMPOSSt constrains M(<r) and β(r) at the same time

*Fortran+python code available on GitHub (Pizzuti+23)*

# **Methods** – How to determine the cluster mass distribution

MAMPOSSt tested on numerical simulations (hydrosim and semi-analytic) that include projection effects (interlopers)



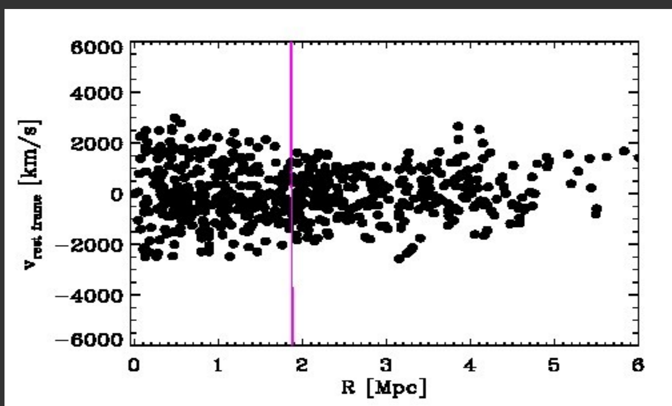

MAMPOSSt M(r) NFW model solution to true M(r) for 100 clusters x 3 projection axes: using red galaxies as tracers allows an accurate M(r) determination
*(Aguirre Tagliaferro, AB + 21)*

500 particle cluster-sized halo, NFW model with 4 free parameters
*(Mamon, AB, Boué 13)*

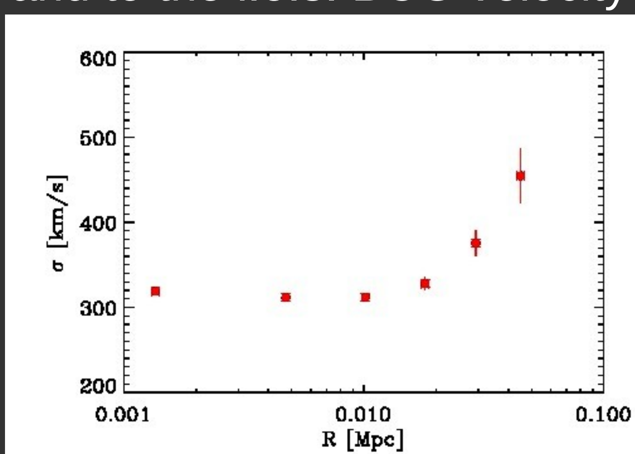
# **Methods** – How to determine the cluster mass distribution

**MAMPOSSt+**: extension of MAMPOSSt to take into account simultaneously the constraints from the spatial and velocity distribution of the cluster galaxies <u>and</u> the BCG stars *(Sartoris, AB+ 20)*

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 a sum of:

DM mass profile
+ BCG stellar mass profile
+ Intra-Cluster gas mass profile
+ stellar mass profile of all other galaxies

BCG stellar mass

DM

Intra-cluster gas

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

galaxies stellar mass

# **Methods** – How to determine the cluster mass distribution

We run MAMPOSSt assuming spherical symmetry, and constrain the best-fit parameters of the different components of the total mass profile

$M_{tot} = M_{DM} + M_{BCG} + M_{ICM} + M_{galaxies}$
(gNFW) (Jaffe)

gNFW: $\rho = \rho_0 \, (r/r_\rho)^{-\gamma_{DM}} \, (1+r/r_\rho)^{\gamma_{DM}-3}$

Jaffe: $M_{BCG} = (M/L) \, L_{BCG} \, r/r_J \, (1+r/r_J)^{-1}$

*4 free parameters for $M_{tot}(r)$:*

- 1 for the $M_{BCG}(r)$: (M/L)
- 3 for the $M_{DM}(r)$: $r_{200}$, $r_\rho$, $\gamma_{DM}$

$L_{BCG}$ and $r_J$ derived from fit to observed BCG surface brightness profile

$M_{ICM}$ and $M_{galaxies}$ derived directly from observations, no free parameters
(they do not contribute much to the cluster mass in the inner region)

*+ 1 (constrained) free parameter for the number density profile of cluster galaxies: $r_\nu$*

*+ ≤ 2 free parameters for the galaxy velocity anisotropy profile:*

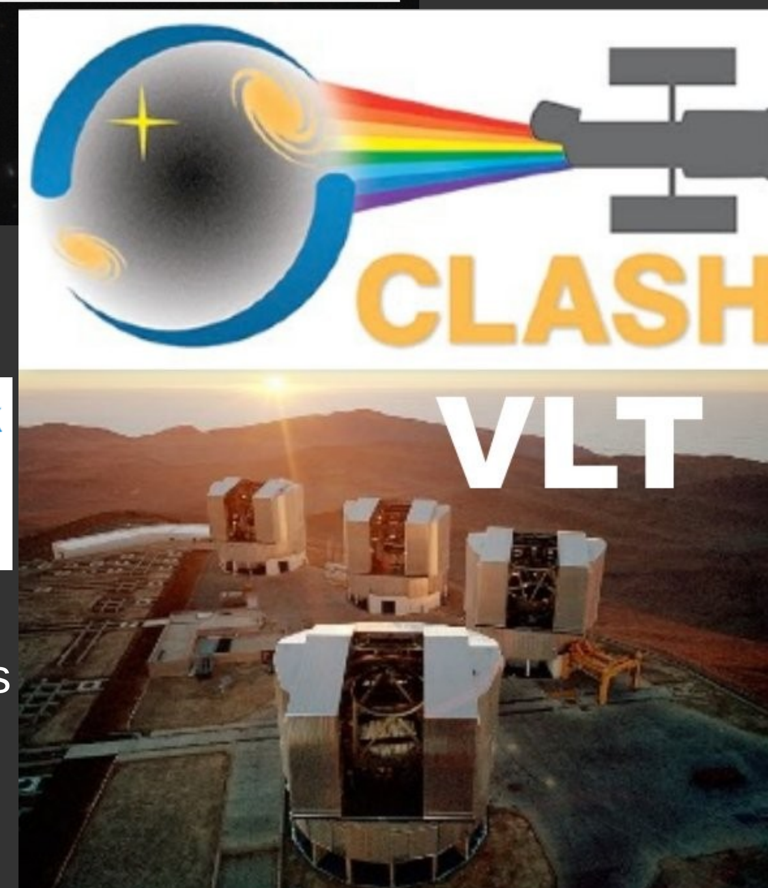
- Tiret model with free outer ($\beta_\infty$) and free or fixed inner ($\beta_0$) anisotopy

*We also consider ≤3 models for the velocity anisotropy profile of the BCG stars:*

a) isotropic, b) moderately radial ($\beta$=0.3), c) increasing with radius (Osipkov-Merritt $r_\beta$=$r_J$)

# **Data sets** – CLASH clusters AS1063 and MACS1206

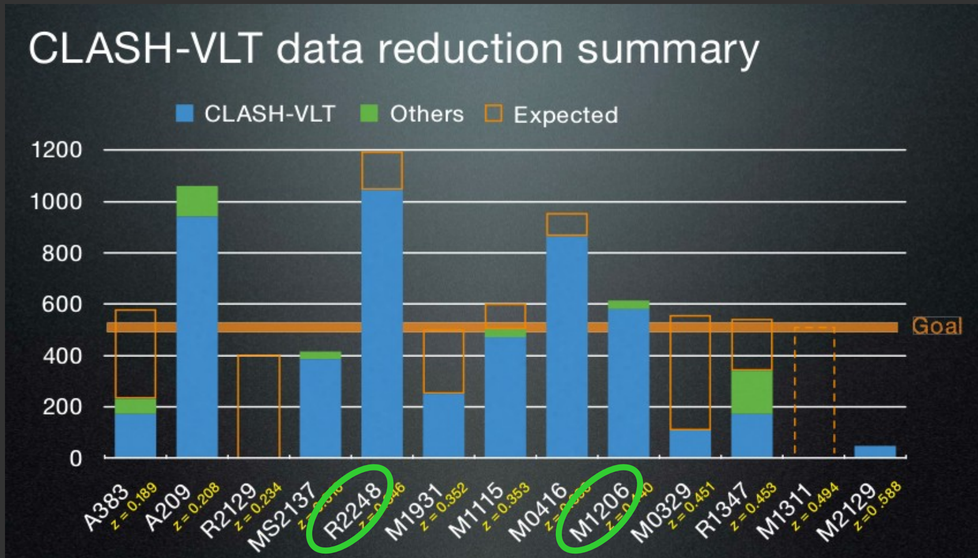

*Postman+12*




CLASH-VLT: A VIMOS Large Programme to Map the Dark Matter Mass Distribution in Galaxy Clusters and Probe Distant Lensed Galaxies *(Rosati+14)*

VIMOS@VLT: ~ 8000 cluster members with z in 12 clusters
+ MUSE@VLT: velocity dispersion profiles of 7 BCGs

# **Data sets** – CLASH clusters AS1063 and MACS1206

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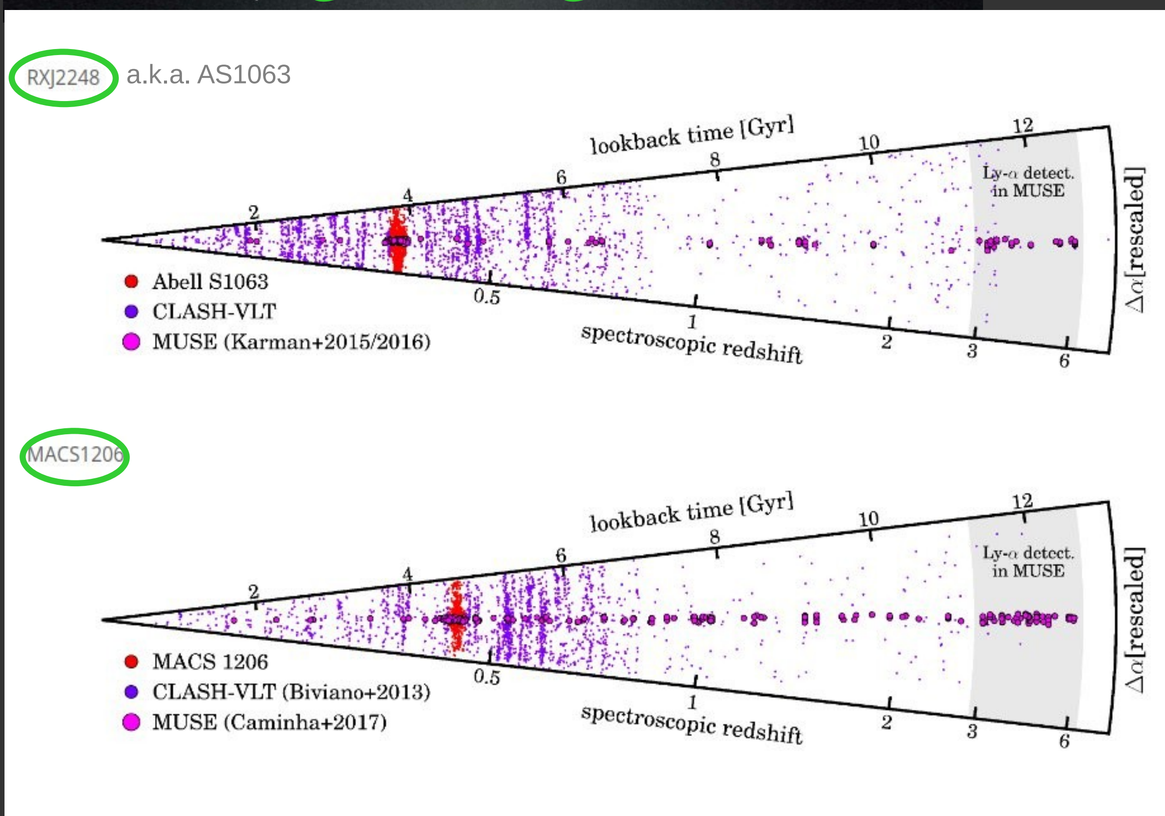


<u>The team:</u>

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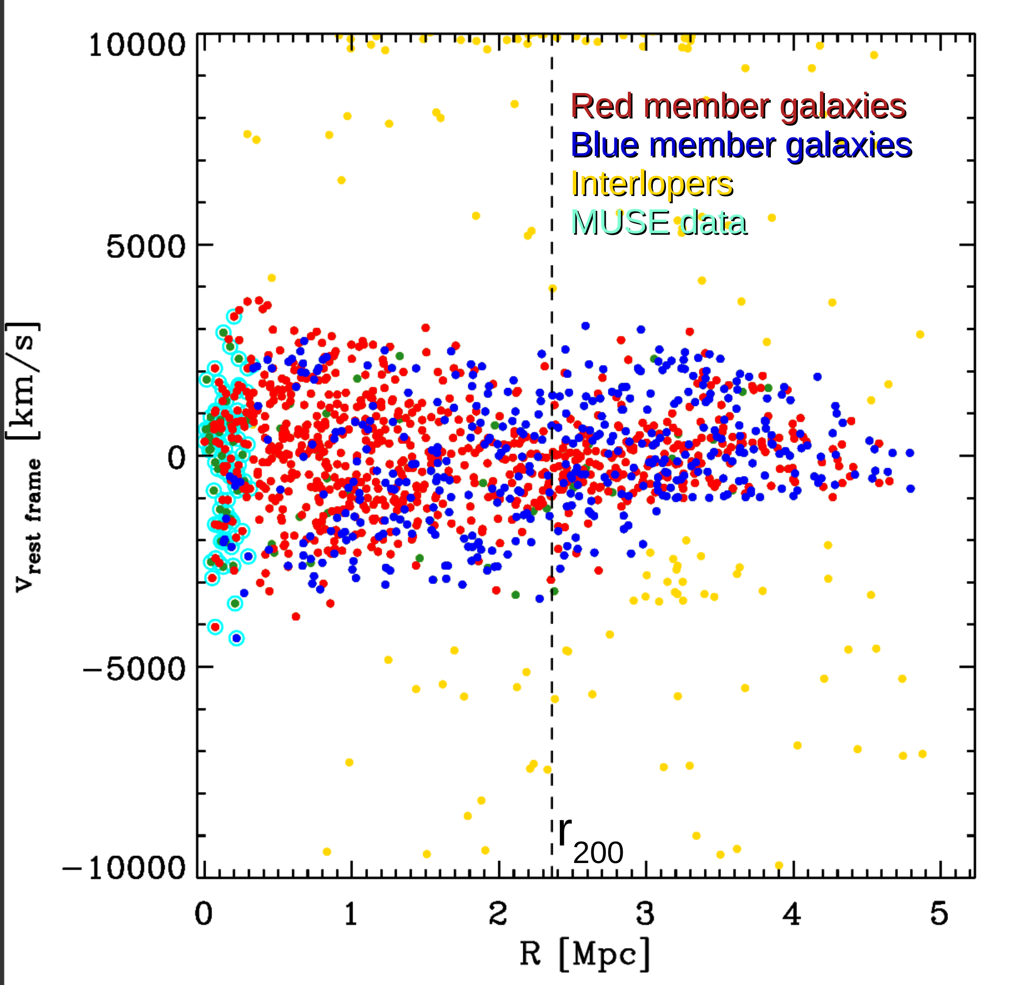
C. Grillo, A. Mercurio, ***M. Nonino***,
B. Sartoris, K. Umetsu, E. Vanzella
+ L. Pizzuti

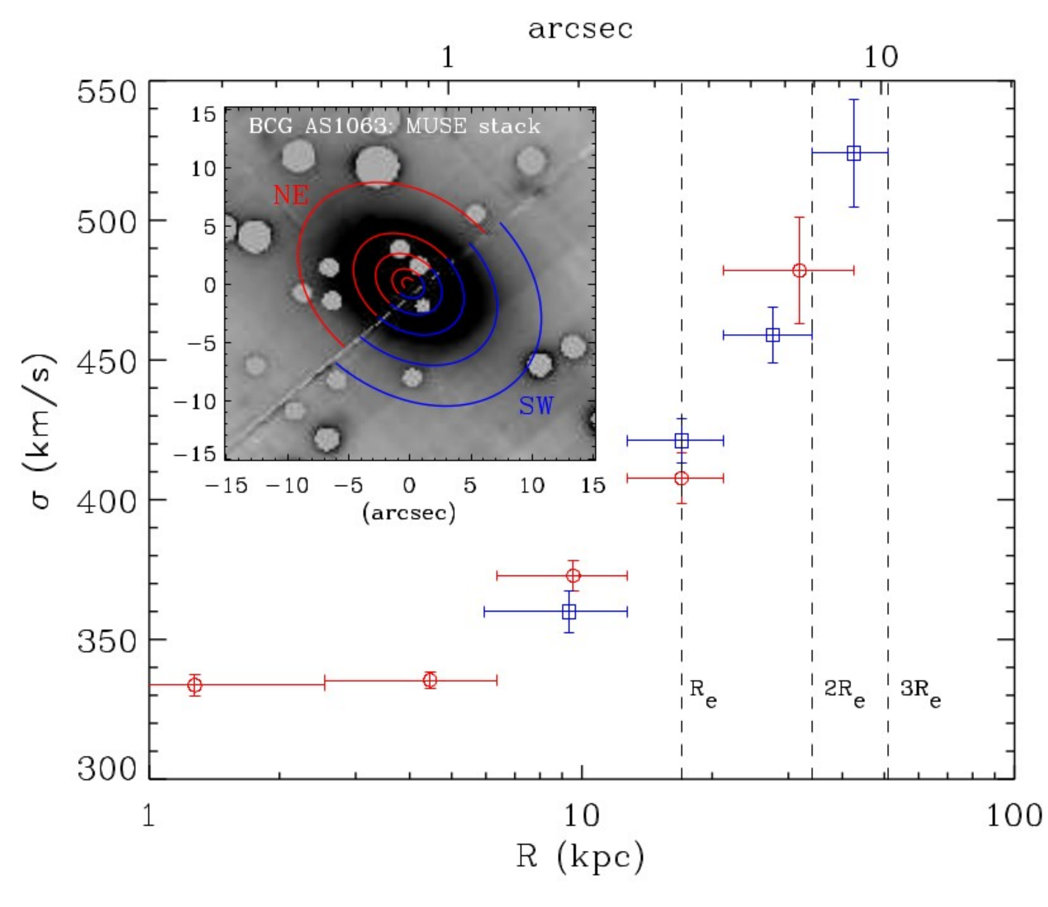
Mario Nonino (1960-2023)

# **Data sets** – CLASH clusters AS1063 and MACS1206

AS1063, z=0.3458, $M_{200}$=2.8 $10^{15}$ $M_\odot$




Projected phase-space distribution of galaxies; 1234 cluster members, of which 792 with R ≤ $r_{200}$ used in our dynamical analysis



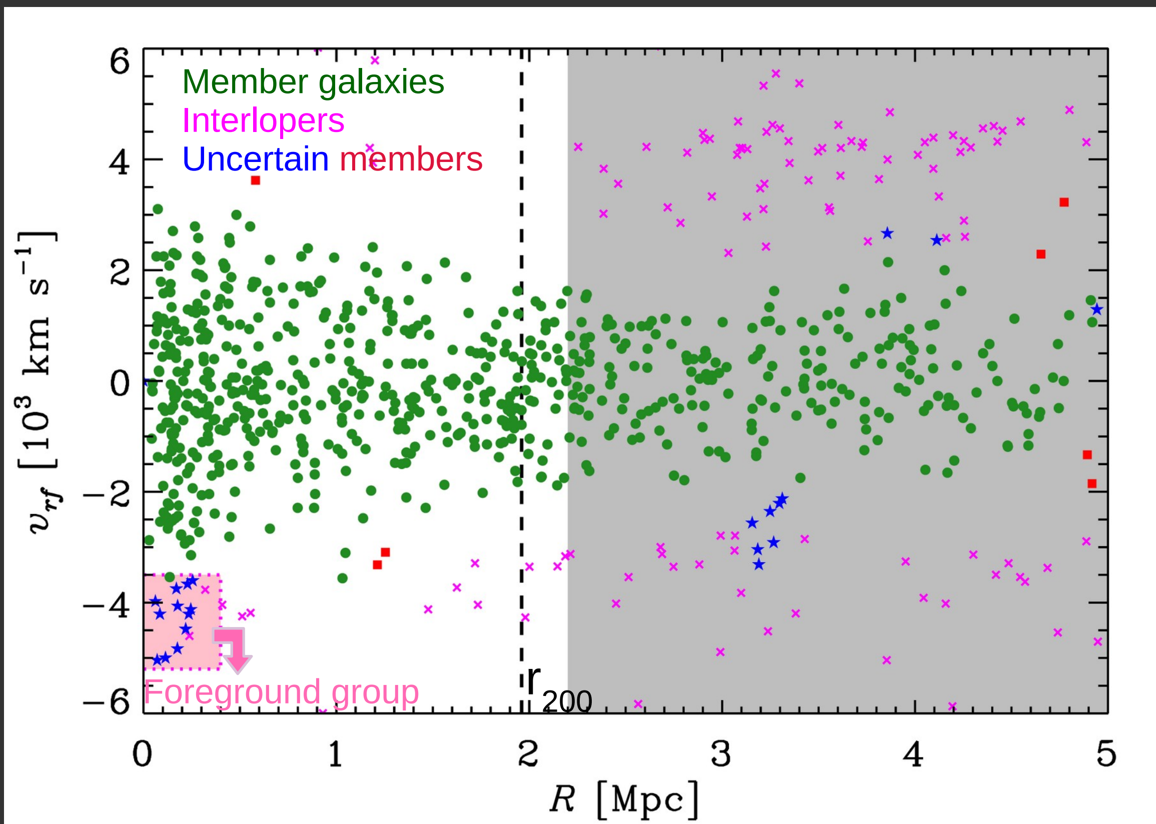

BCG image and velocity dispersion profile

Intra-cluster gas mass profile estimated from Chandra data

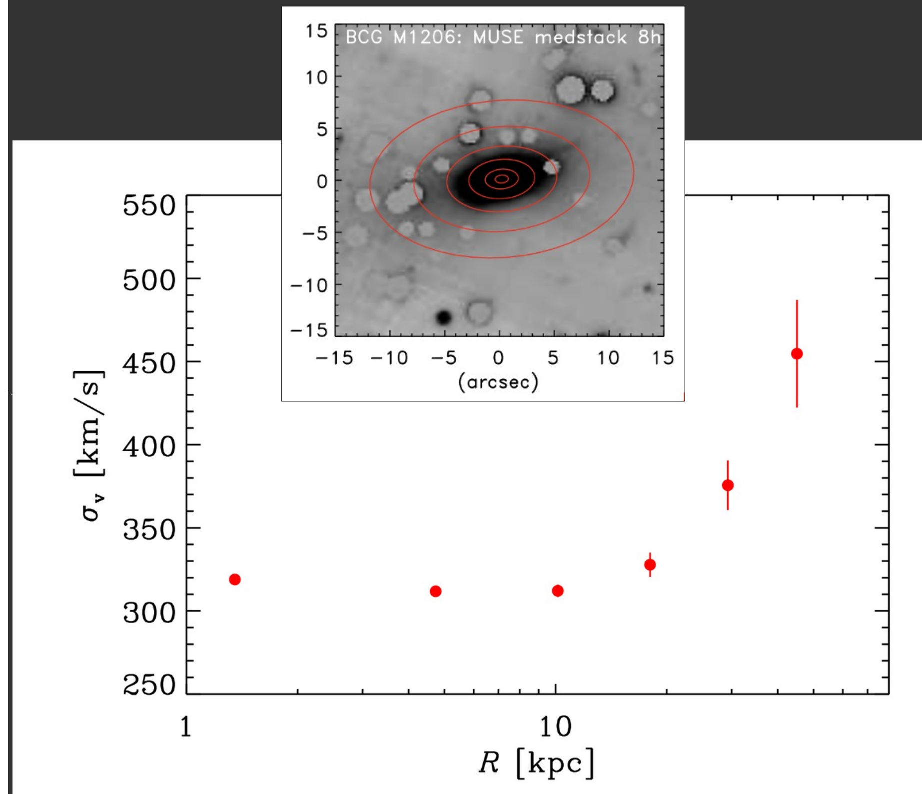
Galaxy stellar masses estimated from SED fitting to 5-band photometry

# **Data sets** – CLASH clusters AS1063 and MACS1206

MACS1206, $z=0.4398$, $M_{200}=1.4\ 10^{15}\ M_{\odot}$




Projected phase-space distribution of galaxies;
680 cluster members, of which
476 with $R \leq 1.2\ r_{200}$ used in our dynamical analysis




BCG image and velocity dispersion profile

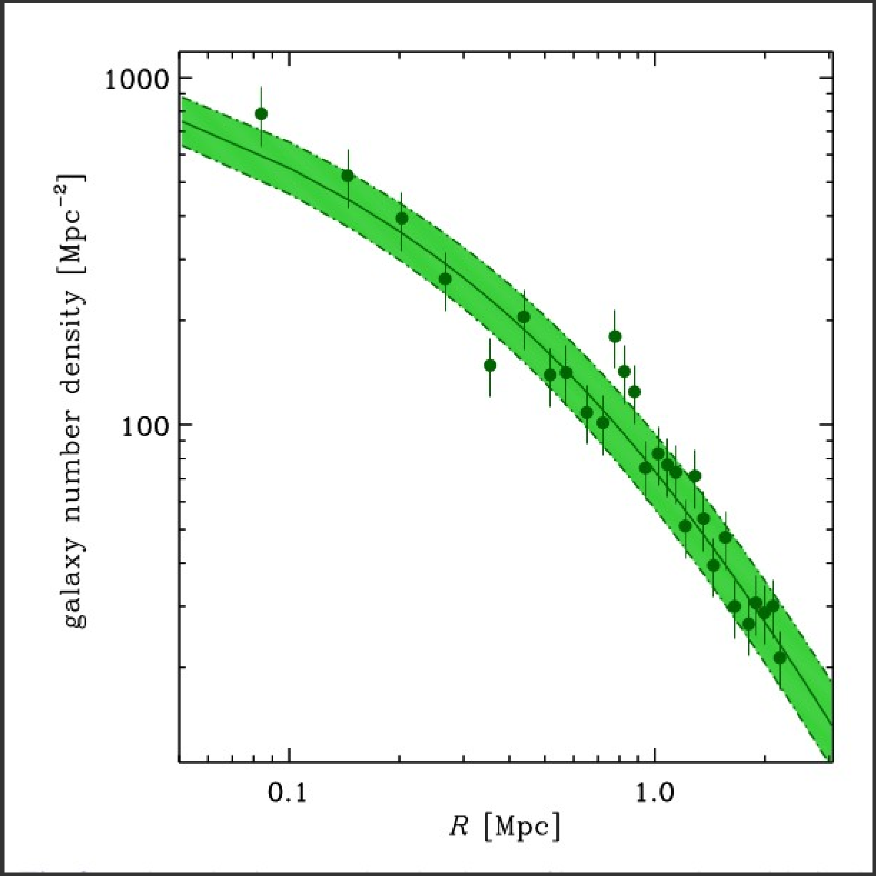
Intra-cluster gas mass profile estimated from Chandra data

Galaxy stellar masses estimated from SED fitting to 6-band photometry

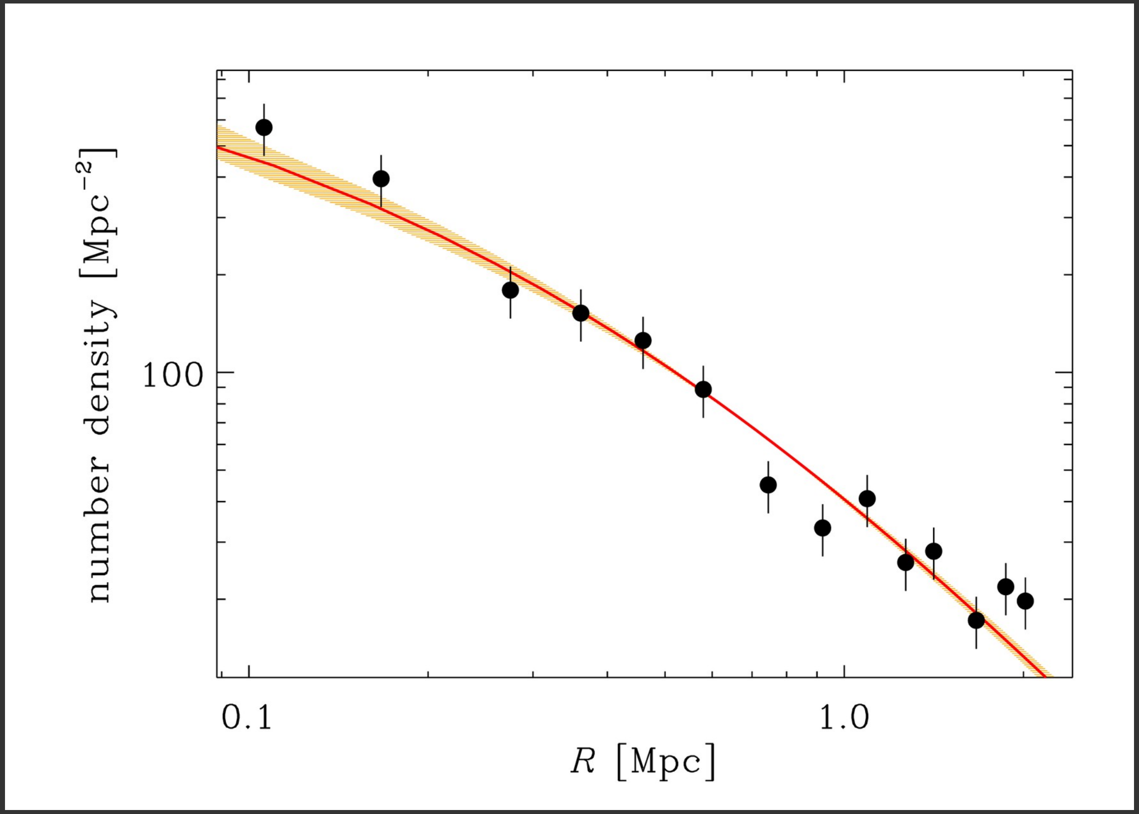
# **Results** – the spatial distribution of cluster galaxies

The galaxy number density profile is a direct observable; it can be fit outside the dynamical analysis of MAMPOSSt.

We use a projected-NFW model, and then de-project it assuming spherical symmetry (Abel inversion) ⇒ scale radius of the galaxy distribution $r_\nu$




AS1063, $r_\nu$= 0.76 ± 0.08 Mpc



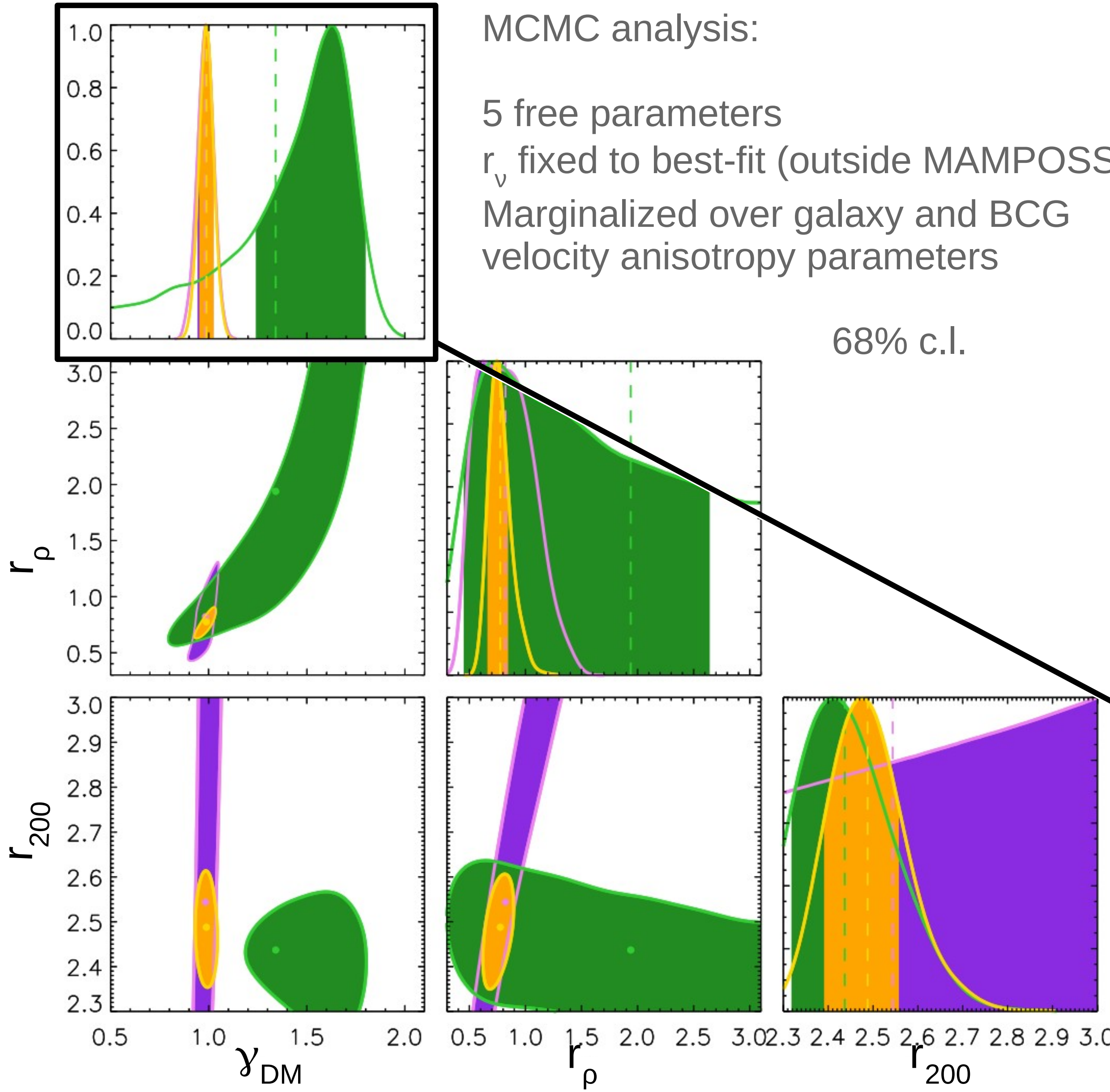

MACS1206, $r_\nu$= 0.46 ± 0.08 Mpc

# **Results -** MAMPOSSt dynamical analysis: AS1063

MCMC analysis:

5 free parameters
$r_\nu$ fixed to best-fit (outside MAMPOSSt)
Marginalized over galaxy and BCG velocity anisotropy parameters

68% c.l.




$r_{200}$ = 2.5 Mpc

$r_\rho$ = 0.8 Mpc

$M_{BCG}$ = 1.2 $10^{12}$ $M_\odot$

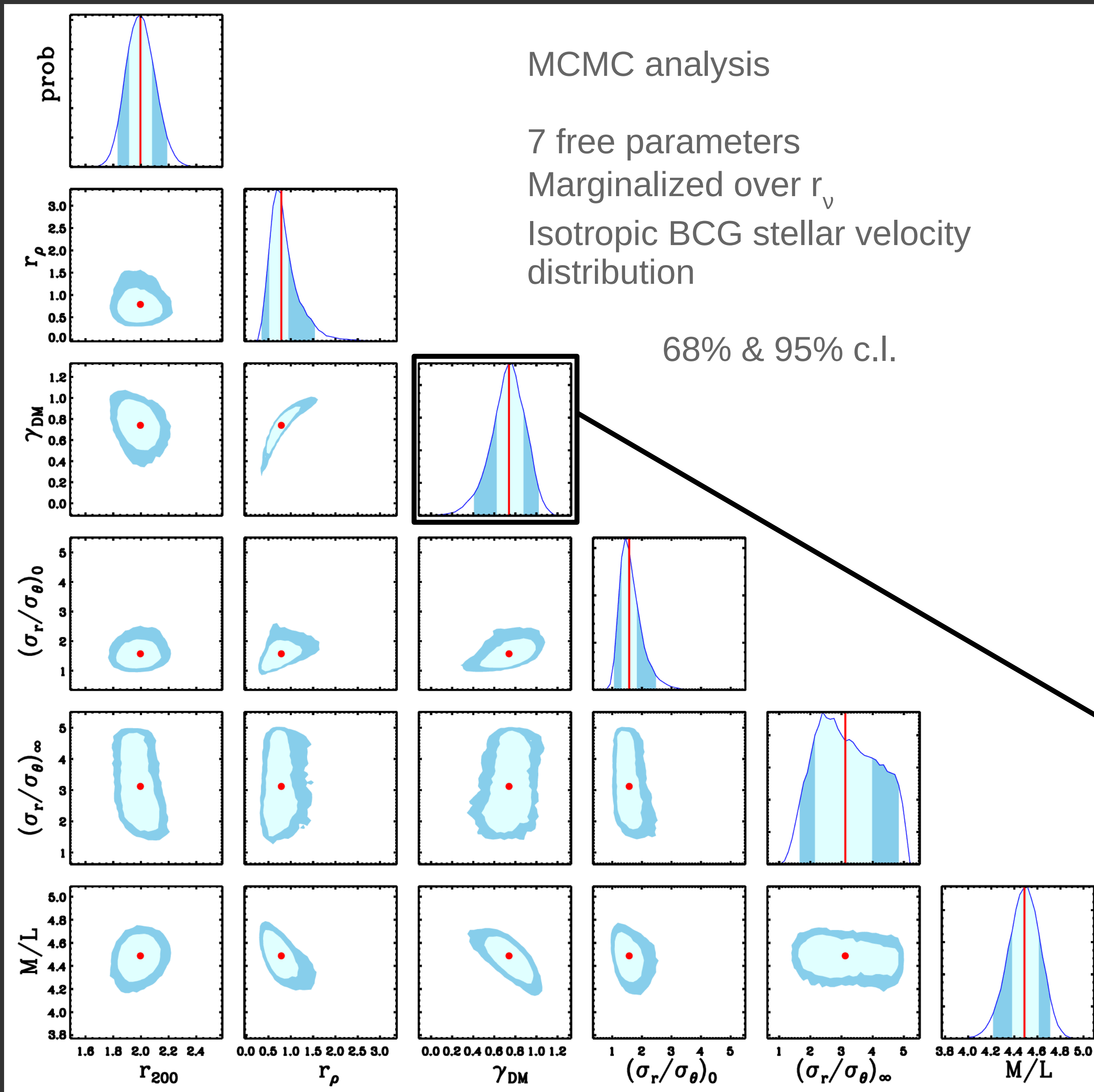
BCG stellar orbits almost isotropic

Galaxy orbits radially elongated, increasingly so at larger radii

$\gamma_{DM} = 0.99_{-0.04}^{+0.04}$ (1 σ)

Constraints from: galaxy velocity distribution, BCG velocity dispersion profile, combined

# **Results** – MAMPOSSt dynamical analysis: MACS1206




MCMC analysis

7 free parameters
Marginalized over $r_\nu$
Isotropic BCG stellar velocity distribution

68% & 95% c.l.

$r_{200}$ = 2.0 Mpc

$r_\rho$ = 0.9 Mpc

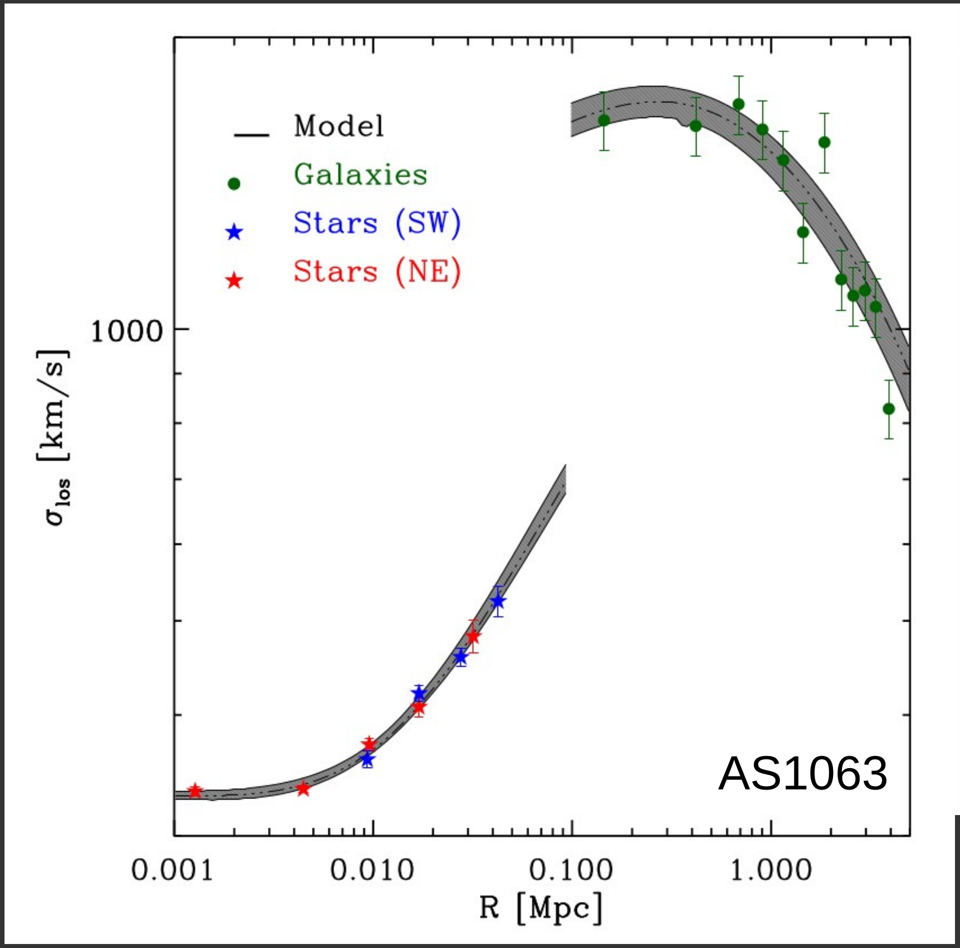
$M_{BCG} = 2.2\ 10^{12}\ M_\odot$

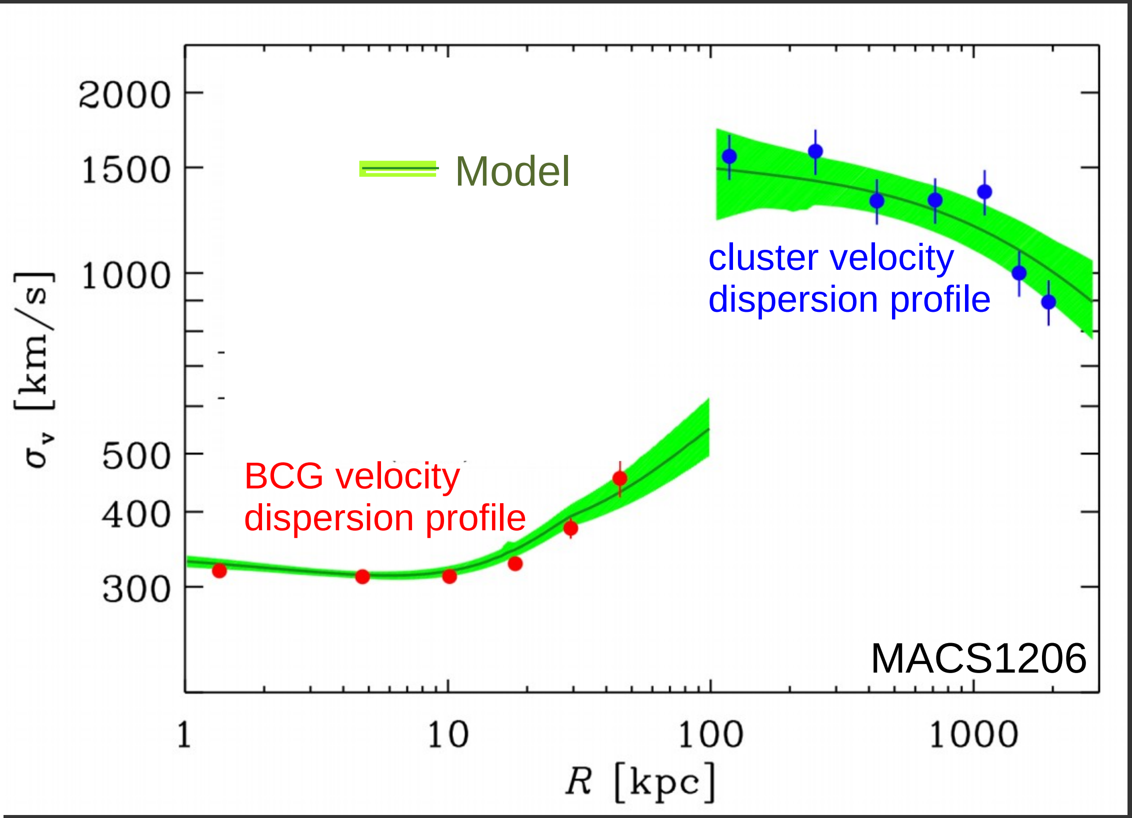
BCG stellar orbits almost isotropic

Galaxy orbits radially elongated, increasingly so at larger radii

$\gamma_{DM} = 0.73_{-0.14}^{+0.18}$ (1 σ)

# **Results** – The velocity dispersion profiles

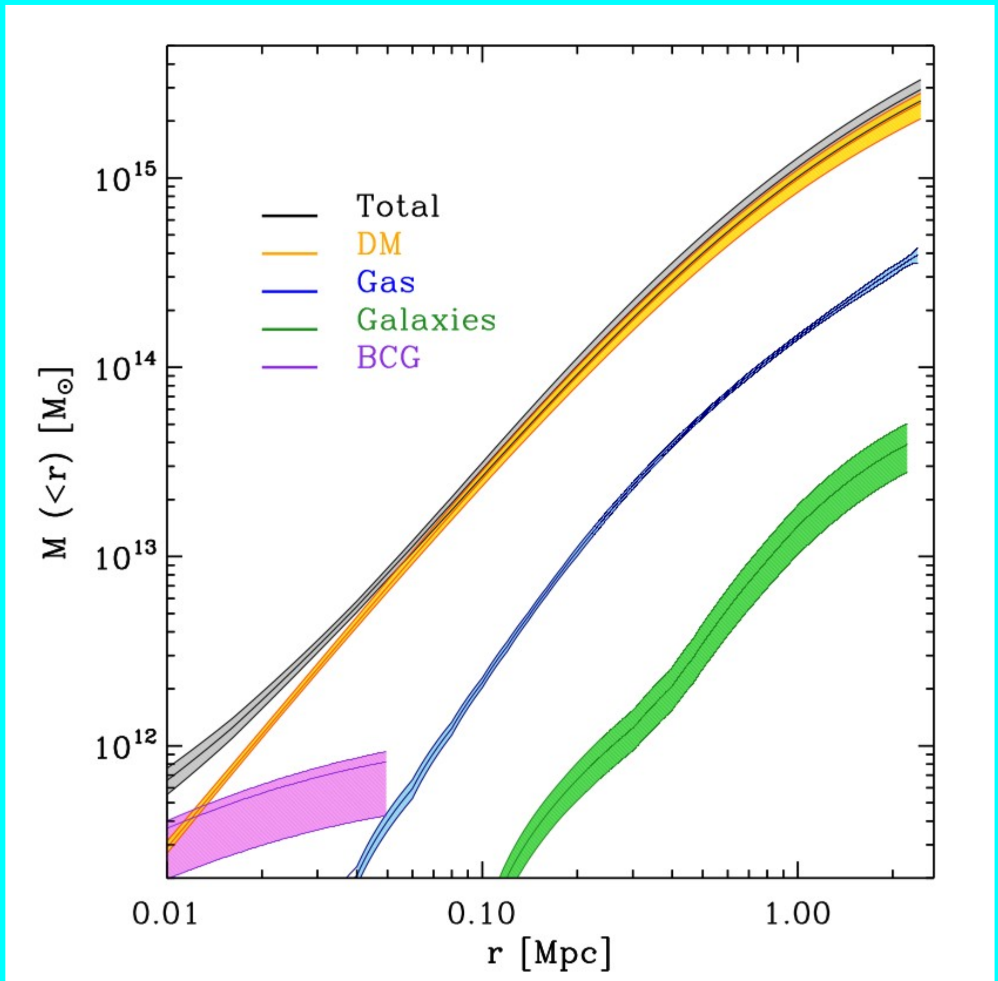


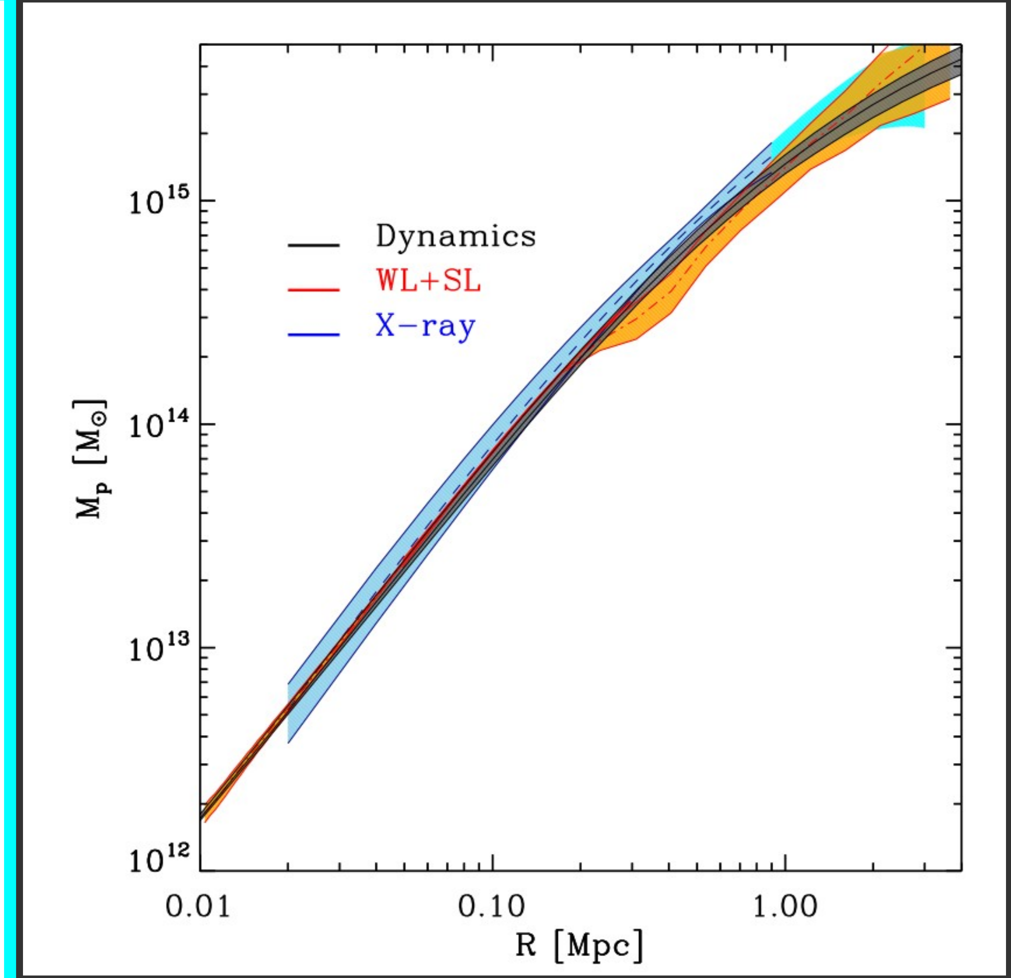

Projecting the best-fit MAMPOSSt solution onto the space of observables:
the velocity dispersion profiles of the BCG and the cluster
⇨ the MAMPOSSt best fit is a good fit

*Note: the BCG and cluster l.o.s. velocity dispersion profiles do not need to be continuous, since the orbits and density distributions of the BCG stars and the cluster galaxies are ≠*

# **Results** – the mass profiles: AS1063

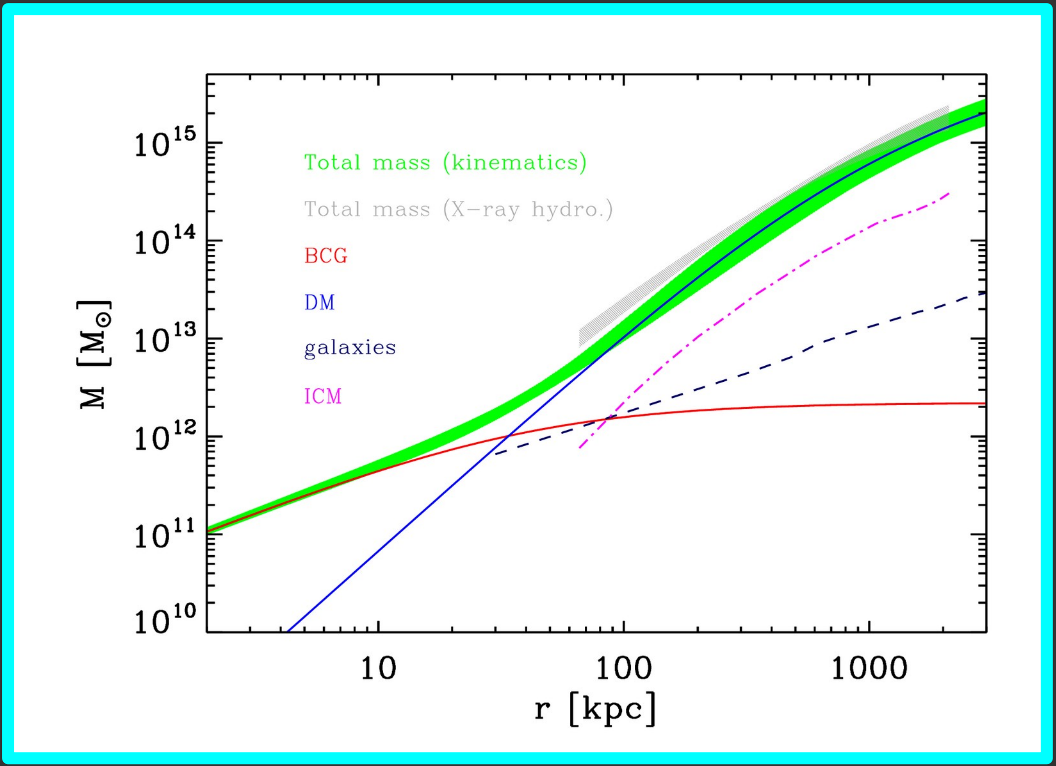


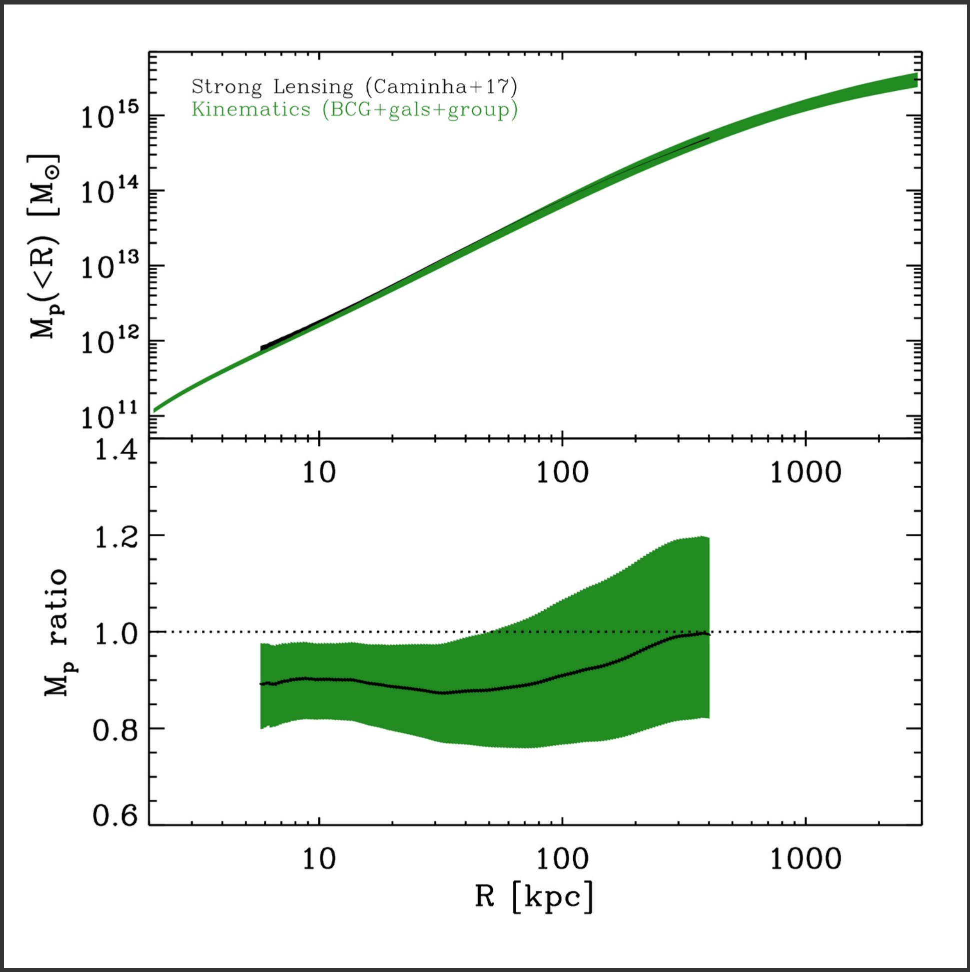

The BCG stellar mass dominates near the center, DM everywhere else




The (projected) total mass profile derived from MAMPOSSt is in good agreement with independent determinations from gravitational lensing and from application of the hydrostatic equilibrium to the intra-cluster plasma

# **Results** – the mass profiles: MACS1206



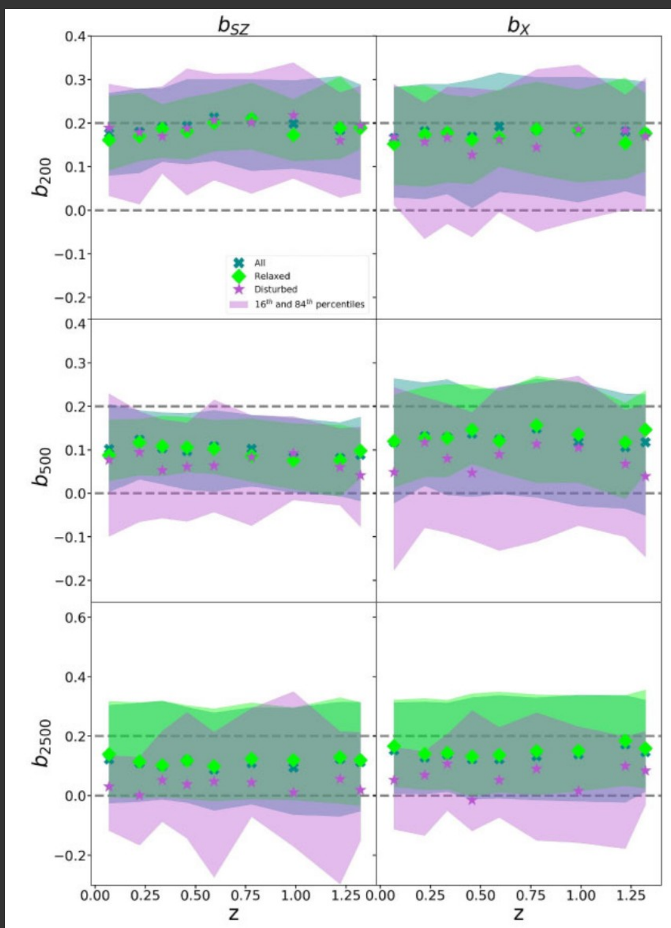

The BCG stellar mass dominates near the center, DM everywhere else

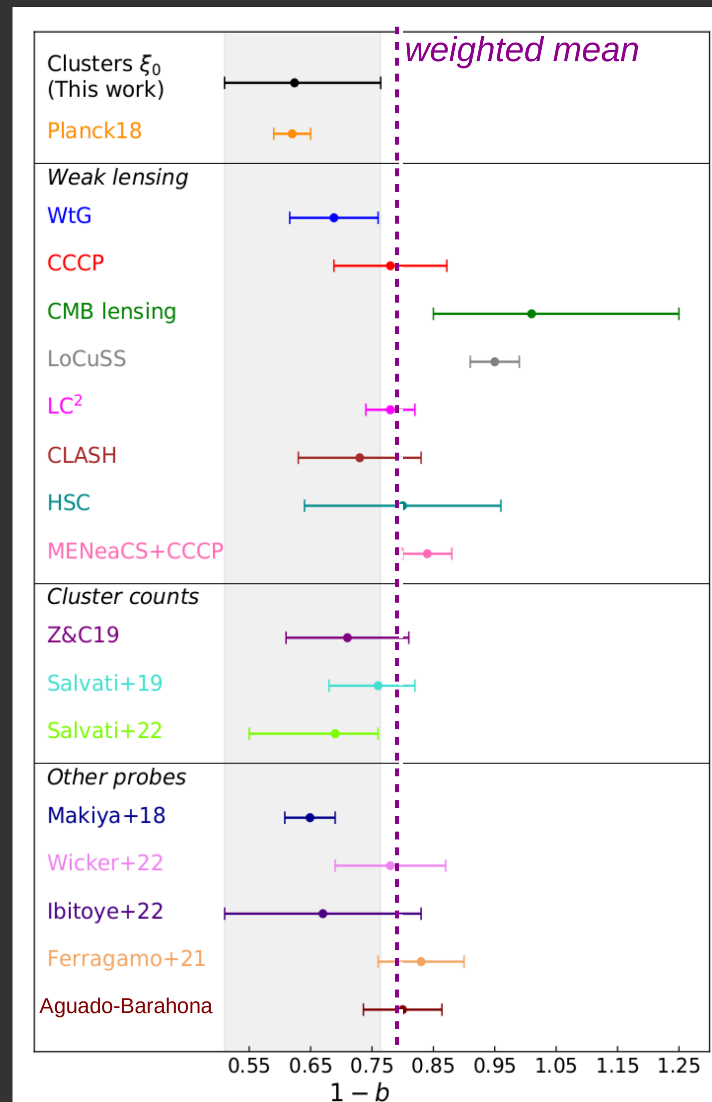
The total mass profile derived from MAMPOSSt is in good agreement with the independent determination from application of the hydrostatic equilibrium to the intra-cluster plasma, and the total (projected) mass profile derived from MAMPOSSt is in good agreement with the independent determination from strong gravitational lensing, once the contribution of a foreground group along the l.o.s. is accounted for

# **Results** – no hydrostatic mass bias?

Inconsistency between Planck base-cosmology and Planck SZ cluster counts cosmology
⇨ cluster masses from X-ray data (assuming hydrostatic equilibrium of Intra-Cluster gas) must be biased low, $\mathbf{b = 1\text{-}M_X/M_{true} = 0.38 \pm 0.03}$ (Planck coll. 2020, VI)

Simulations (the Three Hundred) indicate smaller values b ≈ 0.1-0.2 *(Gianfagna+23)*




Observations indicate <b> = 0.22 ±0.03 *(compilation by Lesci+23)*

AS1063 and MACS1206:

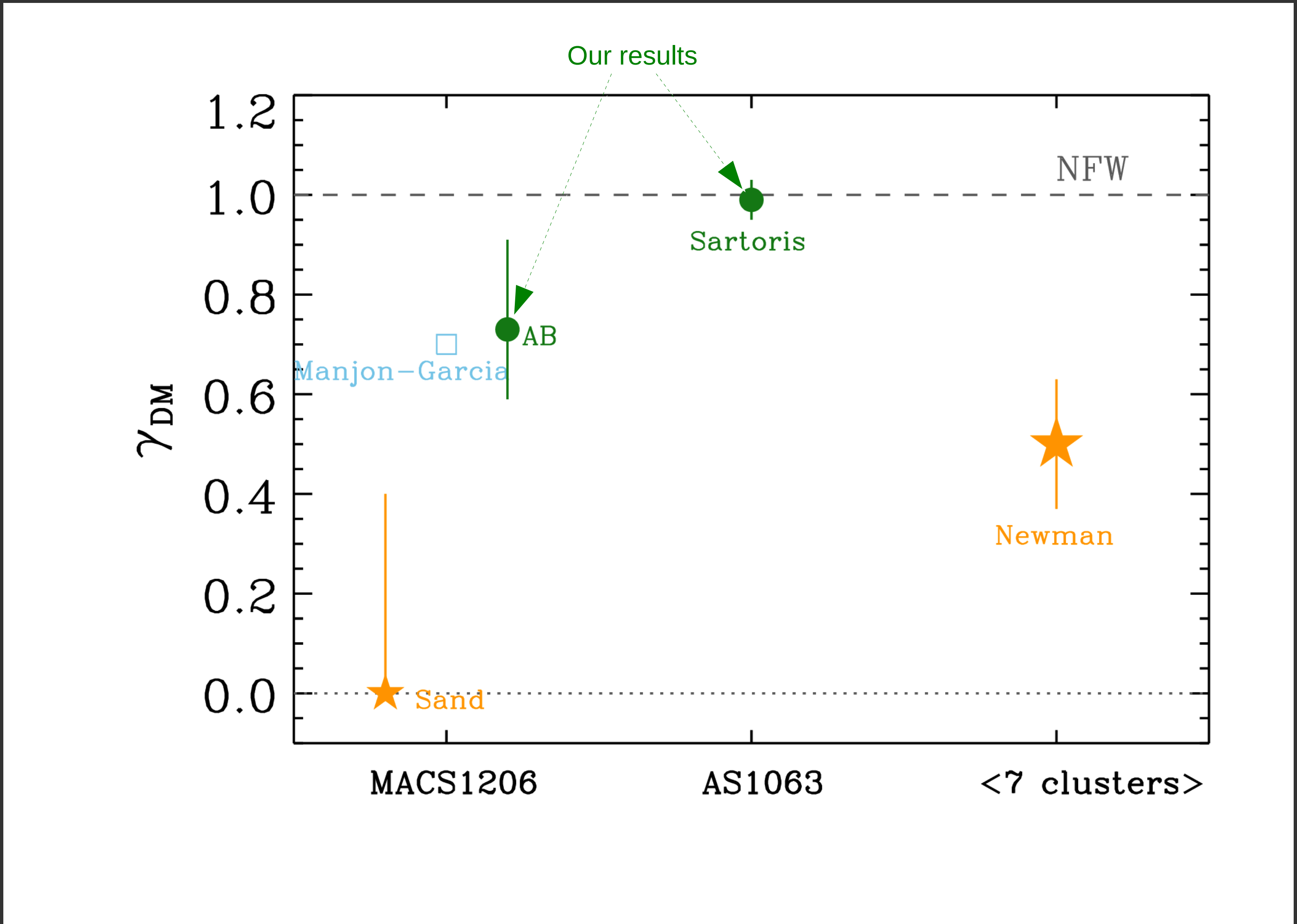
The good agreement between MAMPOSSt M(r) and M(r) from X-ray data (hydrostatic eq. IC gas) **do NOT support b>0**


*(Ongoing analysis of other CLASH-VLT clusters)*

# **Results** – the inner slope of the DM density profile

Previous results, based on cluster strong lensing + (in some cases) BCG kinematics:
Newman+13: $\gamma_{DM}<1$ for 8 clusters; Sand+04: $\gamma_{DM}=0$ for MACS1206 (supported by Limousin+22);
Manjon-Garcia+22: higher $\gamma_{DM}$ value for MACS1206, but no error estimate given
Kelson+02: inner core in the DM distribution of A2199

Our results, *based on BCG and cluster galaxies kinematics*, are closer to NFW prediction, $\boldsymbol{\gamma_{DM} \approx 1}$



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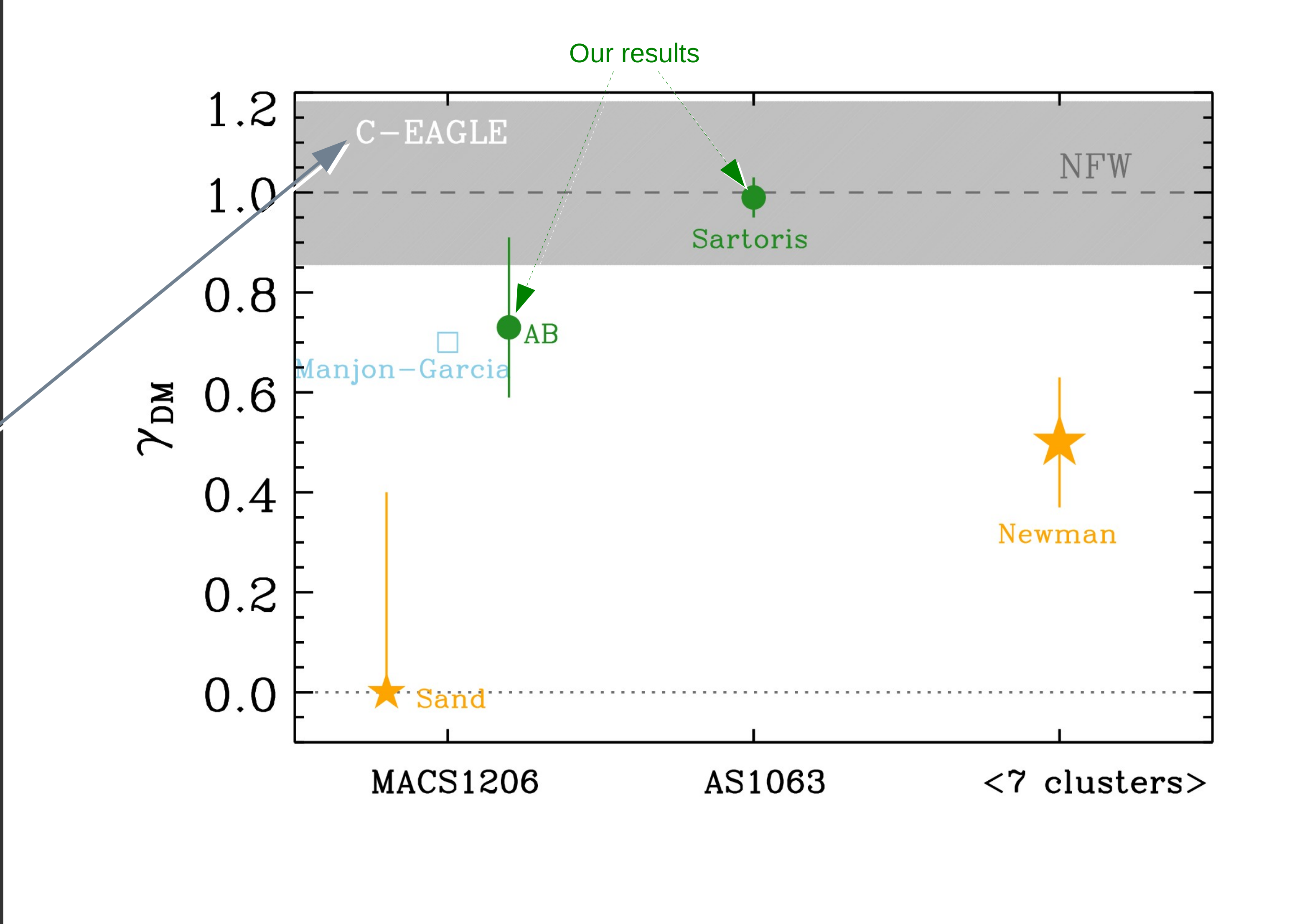
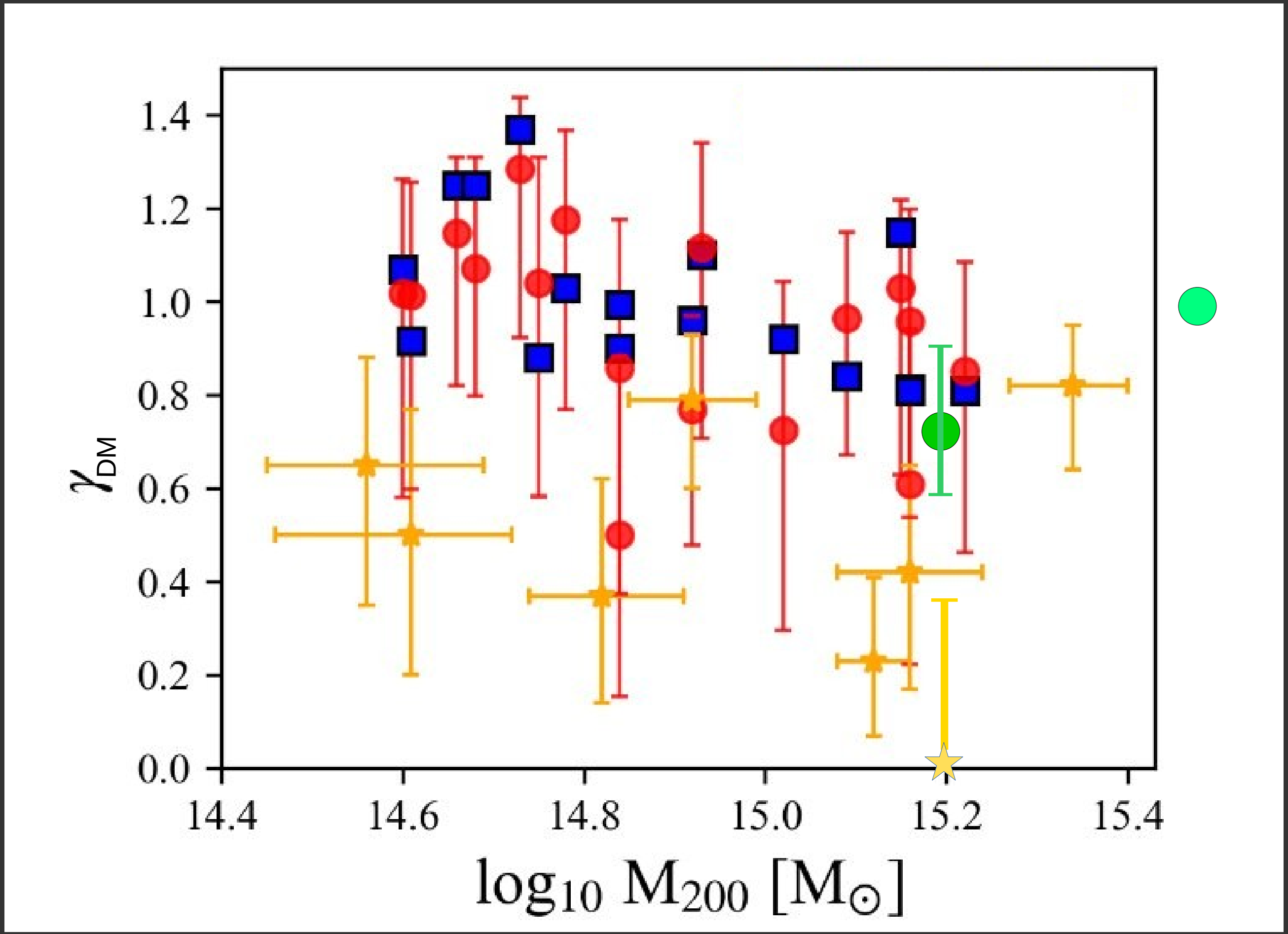
Our results agree with recent predictions from the C-EAGLE hydrodynamical simulations *(He+20)*

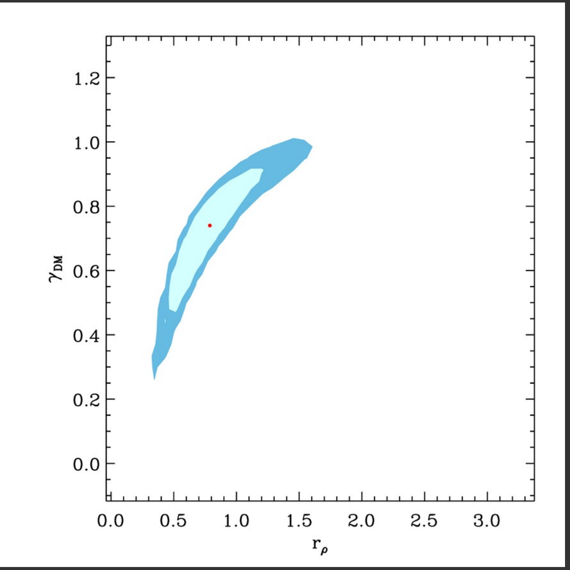


# **Discussion** – the inner slope of the DM density profile




Cmp with C-EAGLE simulations *(He+20)*

A possible problem in SL-based $\gamma_{DM}$ determinations: to estimate $\gamma_{DM}$ correctly, one also need a good estimate of the M(r) scale radius, $r_\rho$. because of covariance:

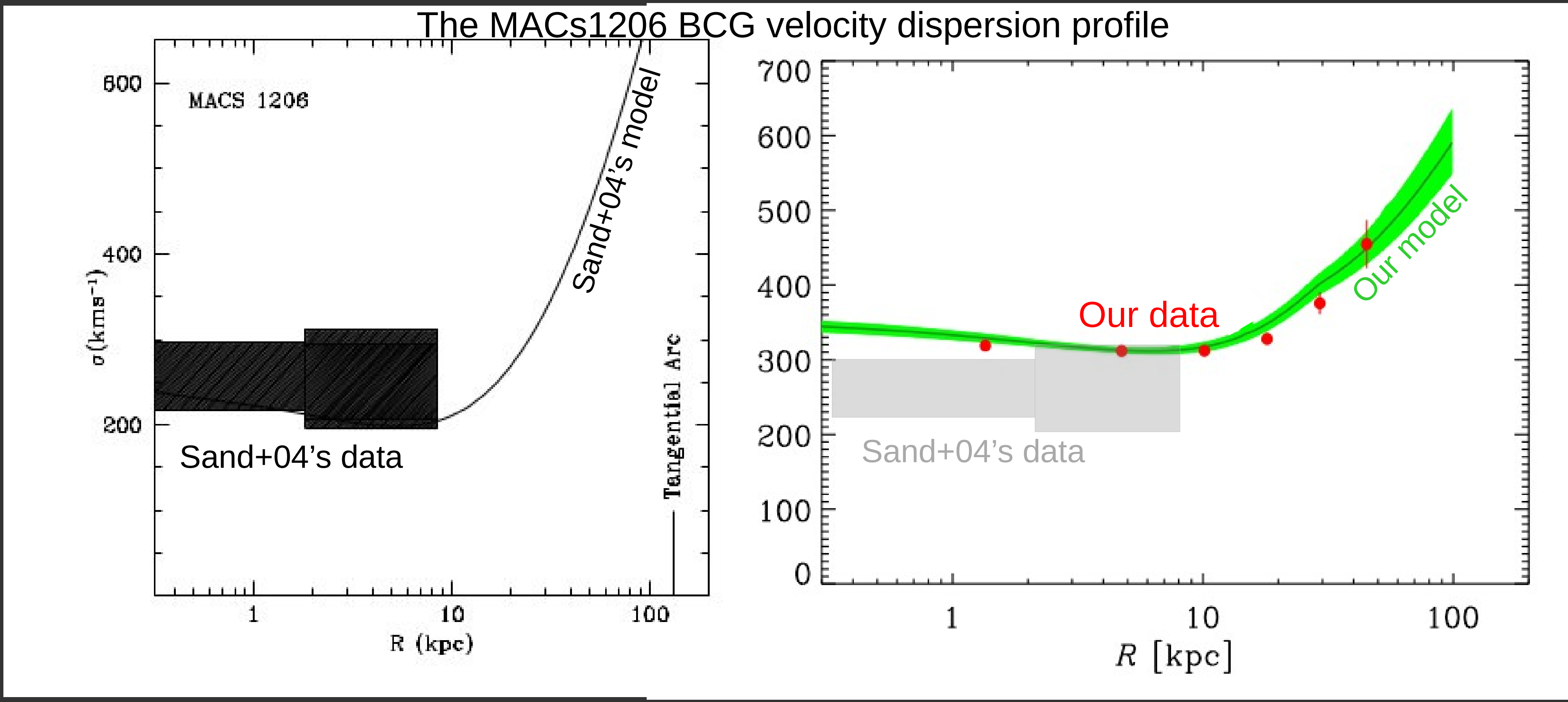



our results {
- AS1063 *(Sartoris, AB + 20)*
- MACS 1206.2-0847 *(AB submitted)*

- simulated unbiased observations
- intrinsic simulated values
- previous results (Newman+13, Sand+04)

Need to sample the cluster potential at radii well beyond $r_\rho$; the kinematic data for cluster galaxies reach well beyond $r_\rho$, but Strong Lensing data do not

# **Discussion** – the inner slope of the DM density profile

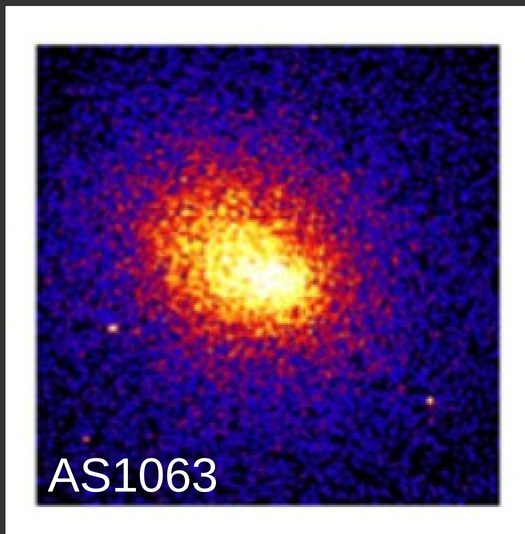


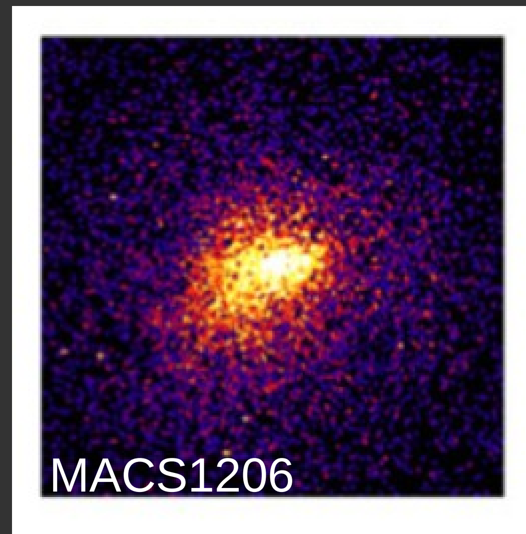

At least part of the reason of the DM difference between Sand+04's result and ours can be ascribed to the different BCG velocity dispersion profile determinations,

better data ⇒ better results

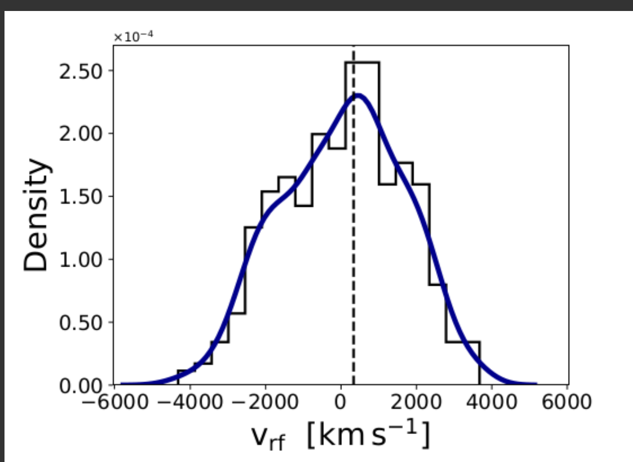
# **Discussion** – systematics

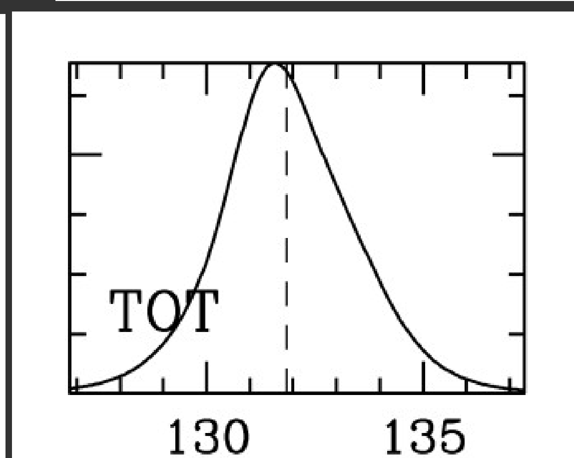
We assume dynamical equilibrium for AS1063 and MACS1206 – is this justified?




CLASH clusters originally selected to look "relaxed" in Chandra X-ray images (Postman+12: well defined central surface brightness peak + nearly concentric isophotes)




AS1063: BCG velocity ≈ cluster mean, **but velocity distribution is not Gaussian** *(Mercurio+21)*

MACS1206: BCG velocity ≈ cluster mean; Gaussian velocity distribution *(Girardi+15)*

Good agreement between masses from kinematics and masses from lensing
(the latter do not make any assumption about dynamical relaxation)

# **Discussion** – systematics

We assume spherical symmetry for AS1063 and MACS1206 – is this justified?

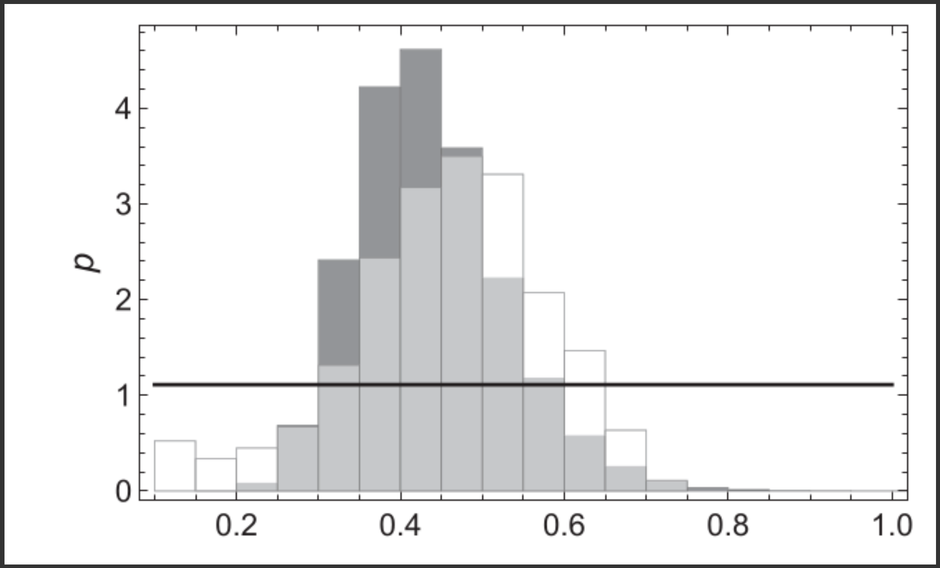
Clusters are not spherical. Triaxiality induces a systematic uncertainty.

Combining X-ray, Sunyaev-Zel'dovich, lensing data or modeling strong+weak lensing data ⇒ constrain elongation and orientation of main halo *(e.g. Limousin+13, Chiu+18)*

AS1063, from strong+lensing modeling has minor/major axis ratio 0.5 ± 0.2 *(Chiu+18)*
MACS1206, from S+L modeling has $0.6_{0.1}^{+0.4}$ *(Chiu+18)*
higher than, but consistent with estimate obtained adding X-ray and SZ data *(Sereno+17)*

These are average values for cluster-size halos, and MAMPOSSt has been tested on random sets of cluster-size halos, irrespective of their sphericity 😃

An over-estimate of $\gamma_{DM}$ could result from an orientation of the cluster major axis along the line-of-sight; but the BCGs and X-ray projected shapes of AS1063 and MACS1206 argue **against** such a geometry 😃




Probability distribution of the MACS1206 minor-to-major axis ratio (Sereno+17)

# Summary and perspectives

- We combine the kinematics of the Brightest Cluster Galaxy stars and of the cluster galaxies for two massive CLASH-VLT clusters at z~0.3-0.4 to determine their DM radial profile

- The total mass profile from kinematics agrees with those inferred from lensing, an indication that the two clusters are in dynamical equilibrium, and with that inferred from applying the hydrostatic equation to the intra-cluster gas, an indication that there is little, if any, "hydrostatic mass bias"

- The DM profiles have inner slopes $\gamma_{DM}$ = 0.7-1.0, consistent with recent results from hydrodynamical ΛCDM simulations (C-EAGLE), rejecting previous claims of significant inconsistence with $\gamma_{DM}$=1 (NFW) on the cluster scale

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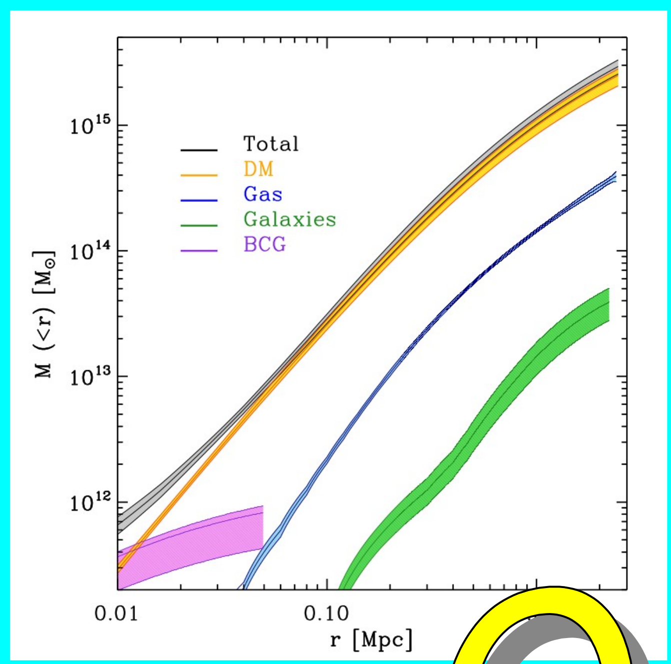
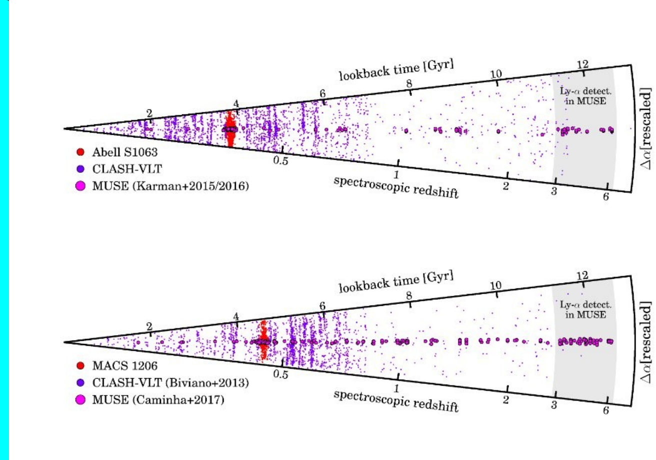
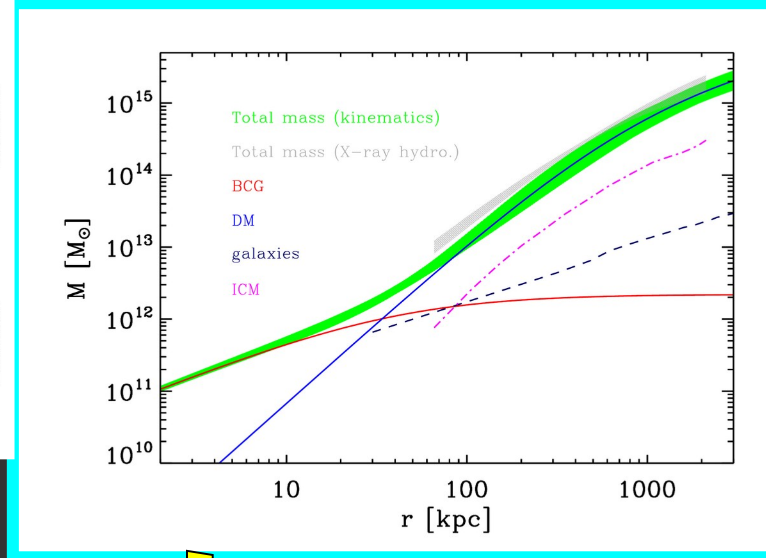
➔ Extend this analysis to another ~5 CLASH-VLT clusters with BCG MUSE data, + data from the literature for more nearby clusters

➔ Analyse all 12 CLASH-VLT clusters for constraining the X-ray mass hydrostatic bias

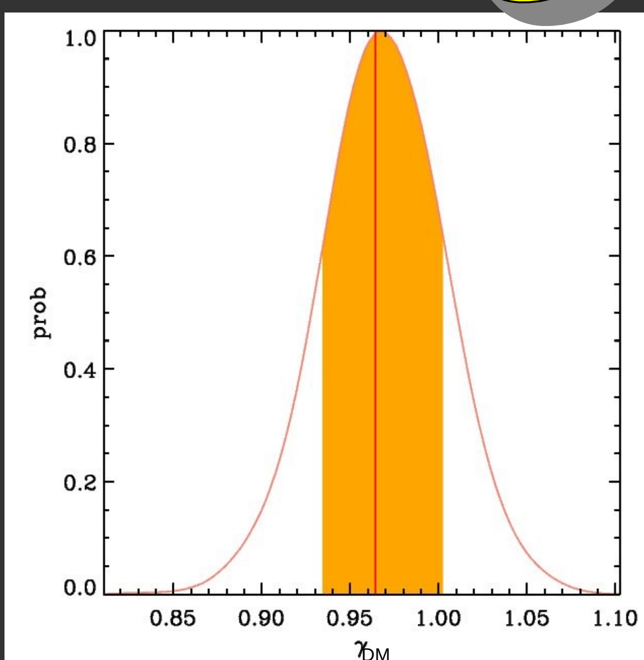
➔ MAMPOSSt constrains M(r) but also the velocity anisotropy β(r) (of cluster galaxies and BCG stars): find the mean velocity anisotropy profile of clusters and its variance and constrain the velocity anisotropy of their BCG stars

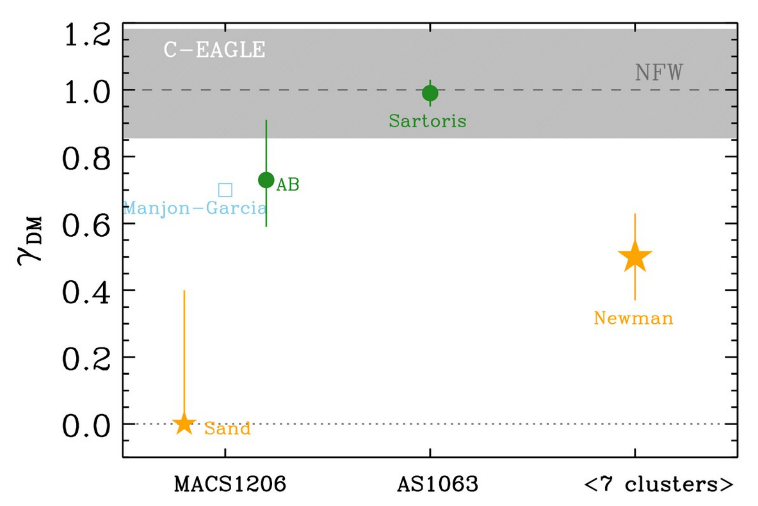

Total
DM
Gas
Galaxies
BCG
M (<r) [M⊙]
r [Mpc]
0.01
0.10

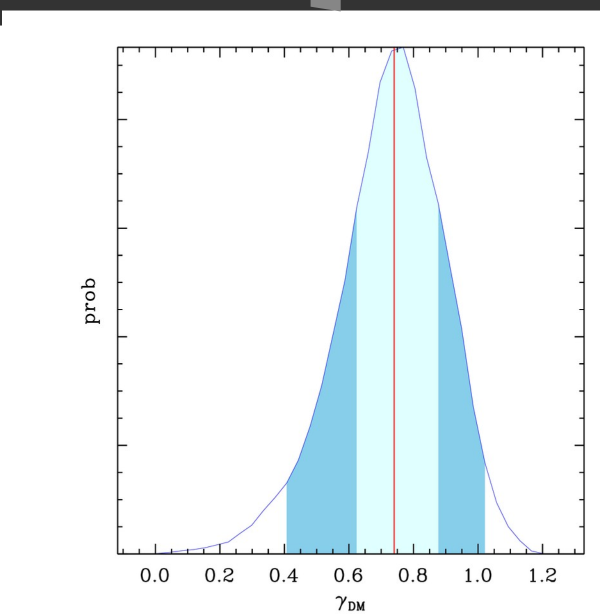

lookback time [Gyr]
spectroscopic redshift
Ly-α detect. in MUSE
Δα [rescaled]
Abell S1063
CLASH-VLT
MUSE (Karman+2015/2016)
MACS 1206
CLASH-VLT (Biviano+2013)
MUSE (Caminha+2017)


Total mass (kinematics)
Total mass (X-ray hydro.)
BCG
DM
galaxies
ICM
M [M⊙]
r [kpc]

# Obrigado!


prob
$\gamma_{DM}$


C-EAGLE
NFW
Sartoris
AB
Manjon-Garcia
Newman
Sand
$\gamma_{DM}$
MACS1206
AS1063
<7 clusters>


prob
$\gamma_{DM}$