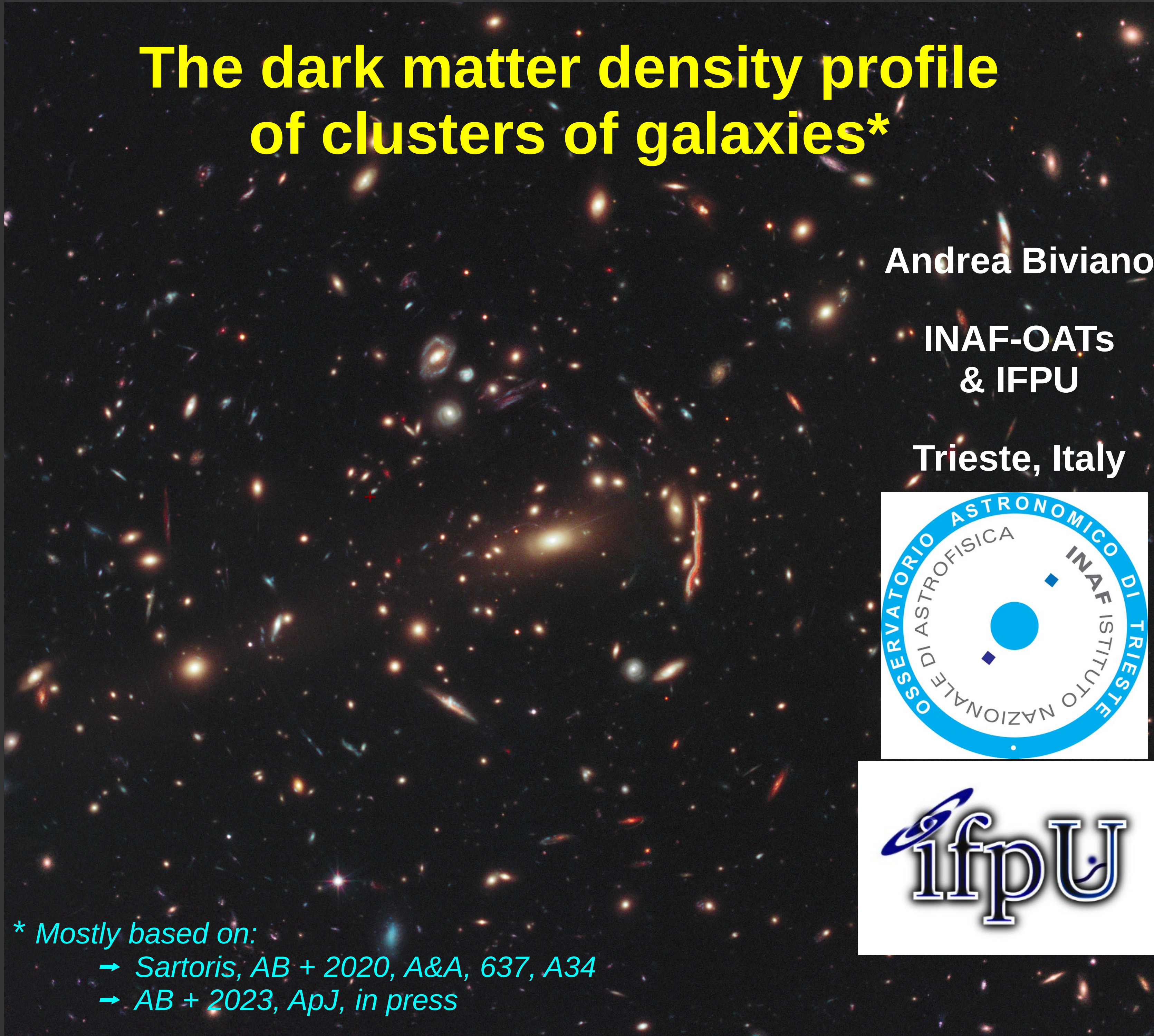
The dark matter density profile of clusters of galaxies*

Andrea Biviano

INAF-OATs & IFPU

Trieste, Italy



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

** Mostly based on:*

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

Outline of this talk

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

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.

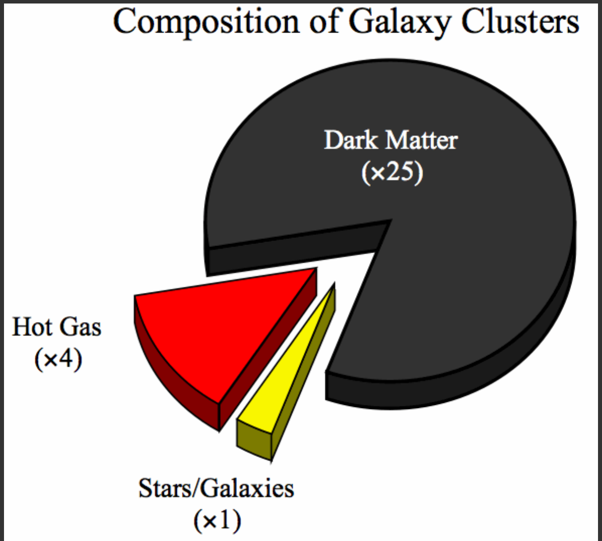
2004

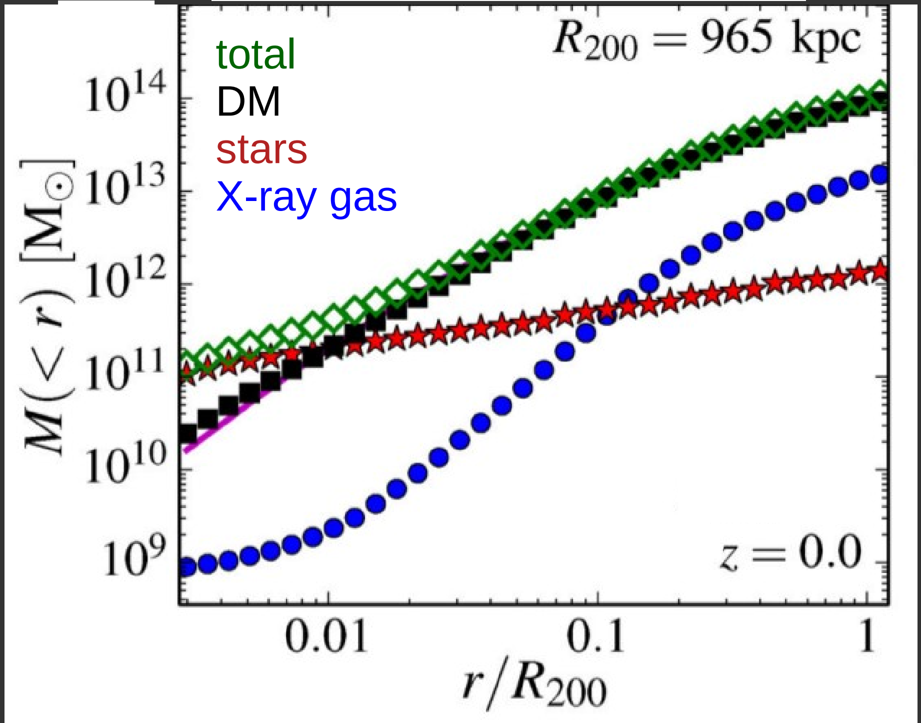
WEAK-LENSING MASS RECONSTRUCTION OF THE INTERACTING CLUSTER 1E 0657−558: DIRECT EVIDENCE FOR THE EXISTENCE OF DARK MATTER[1]

Douglas Clowe[2]
Institut für Astrophysik und Extraterrestrische Forschung der Universität Bonn, Auf dem Hügel 71, 53121 Bonn, Germany; dclowe@as.arizona.edu
Anthony Gonzalez
Department of Astronomy, University of Florida, 211 Bryant Space Science Center, Gainesville, FL 32611-2055
and
Maxim Markevitch
Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138
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



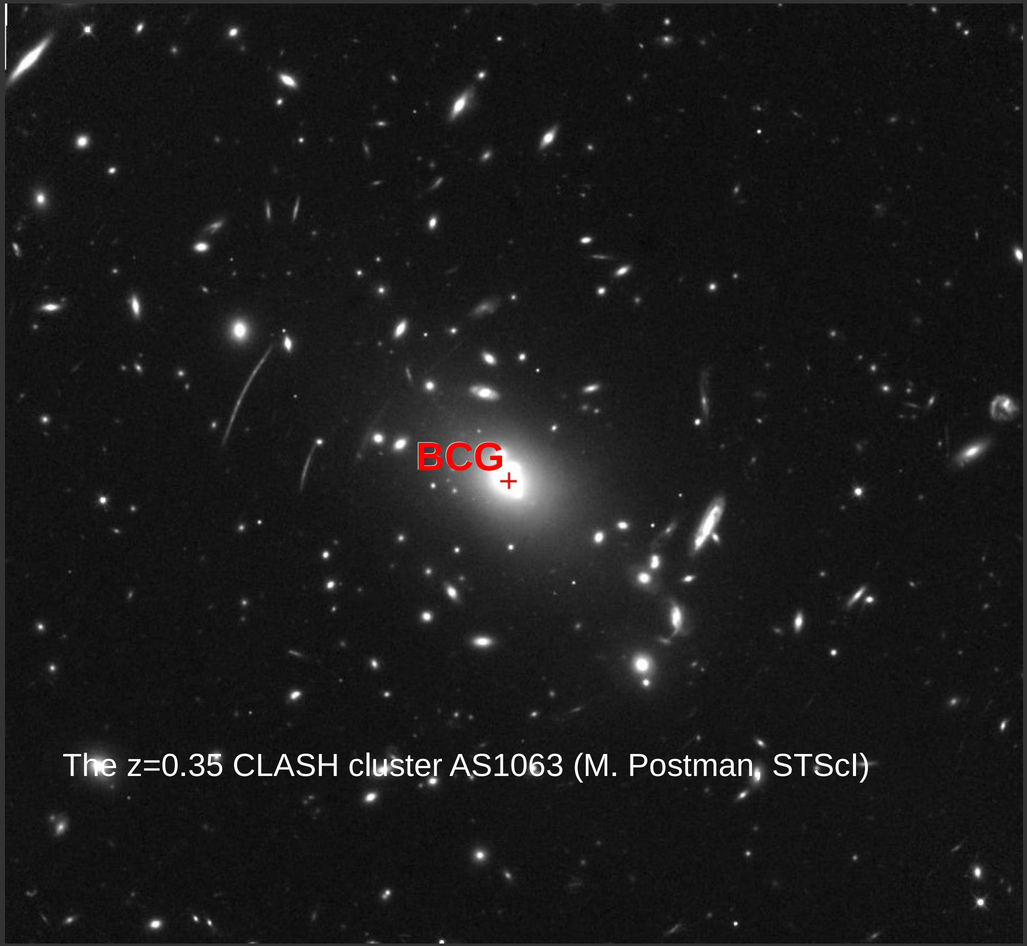


EAGLE simulations, Schaller+15

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



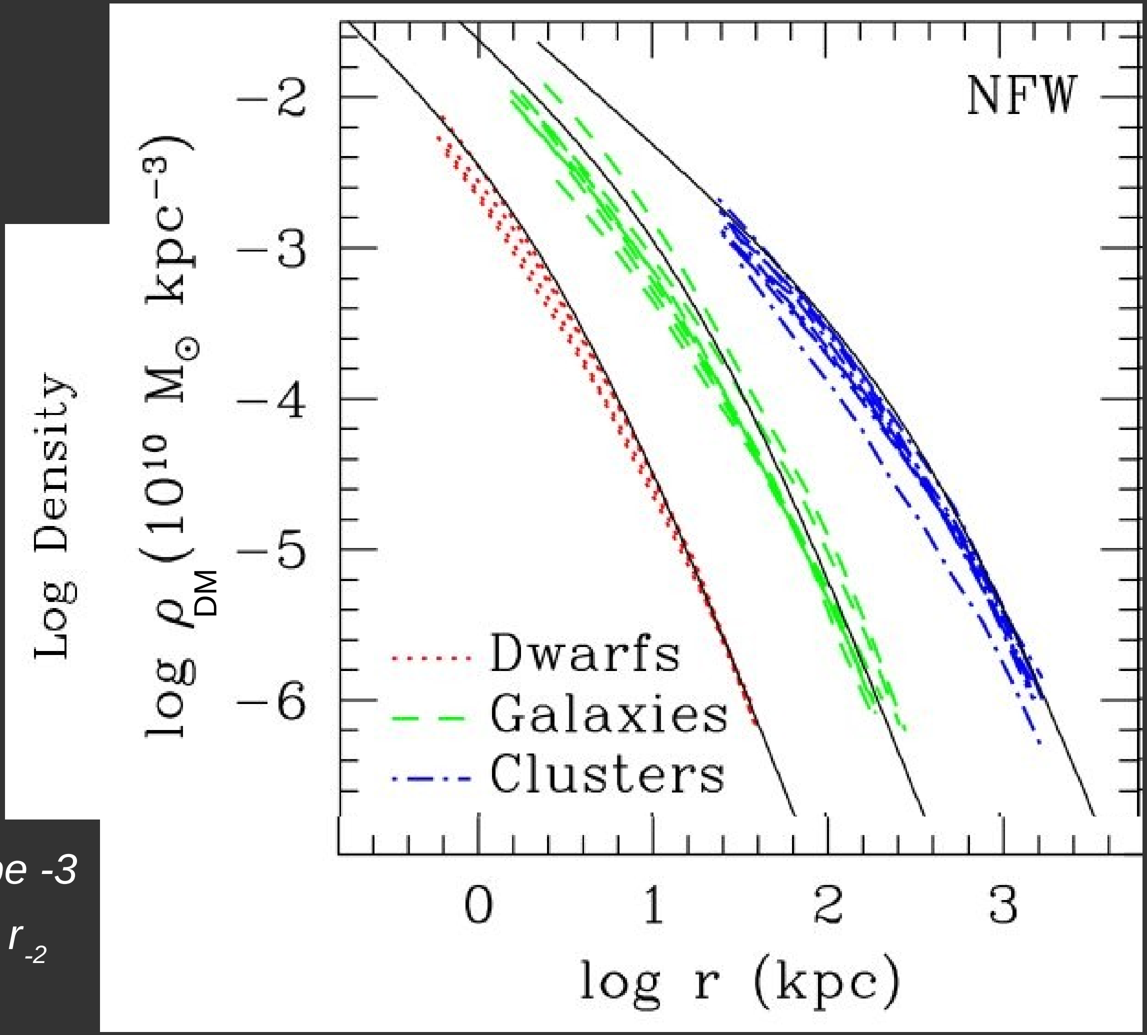
The z=0.35 CLASH cluster AS1063 (M. Postman, STScI)

Introduction – Dark Matter distribution in clusters

Is there A UNIVERSAL DENSITY PROFILE of cosmological halos?

Navarro, Frenk & White 97:
the DM density profile, $\rho_{DM}(r)$, of all cosmological halos, is **universal**
- based on (collisionless) Cold DM numerical simulations

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



Inner logarithmic slope -γ_{DM}=-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:*

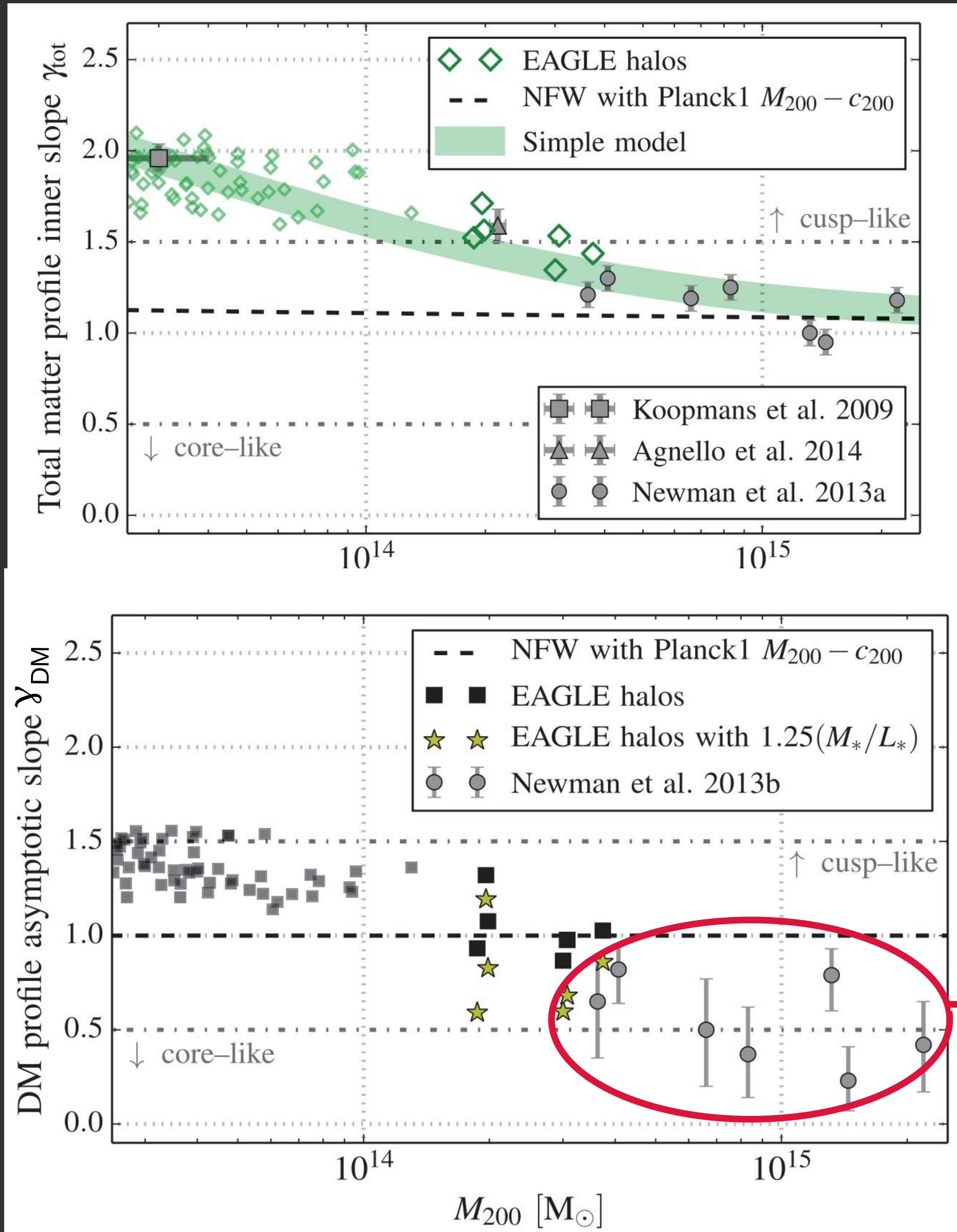
- DM may not be Cold *(e.g. Warm DM; Bode+01)*,
- or it may be collisional *(e.g. Self-Interacting DM; Spergel+Steinhardt 00)*

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

⇒ 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



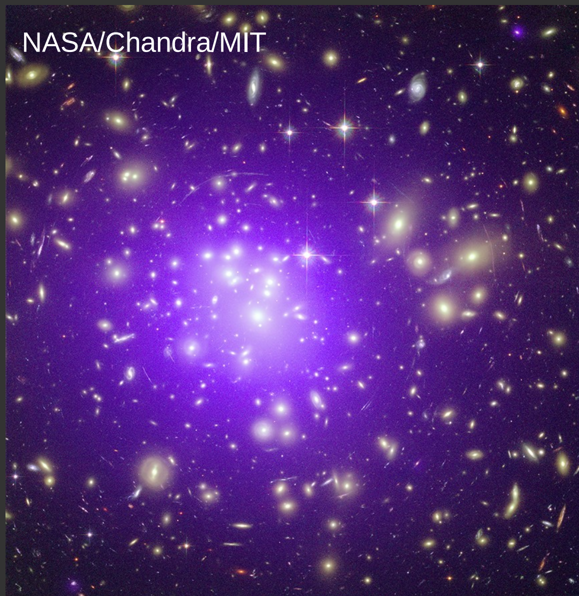
Schaller+15:

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

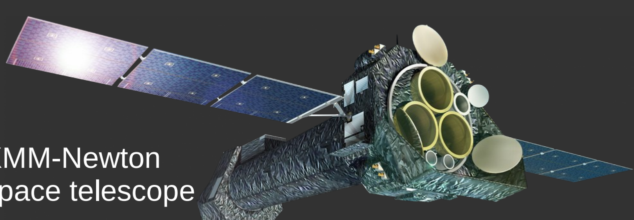
The stellar mass contribution to the total mass makes $\gamma_{tot} > \gamma_{DM}$ *($\gamma_{tot} - \gamma_{DM} \approx 0.1$ for very massive halos)*

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

Methods – How to determine the cluster mass distribution

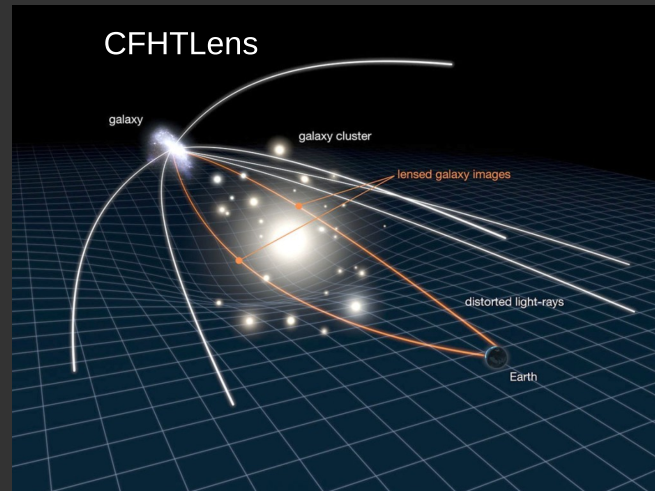


X-ray & radio (Sunyaev-Zeldovich) observations: assuming hydrostatic equilbrium of the intra-cluster gas



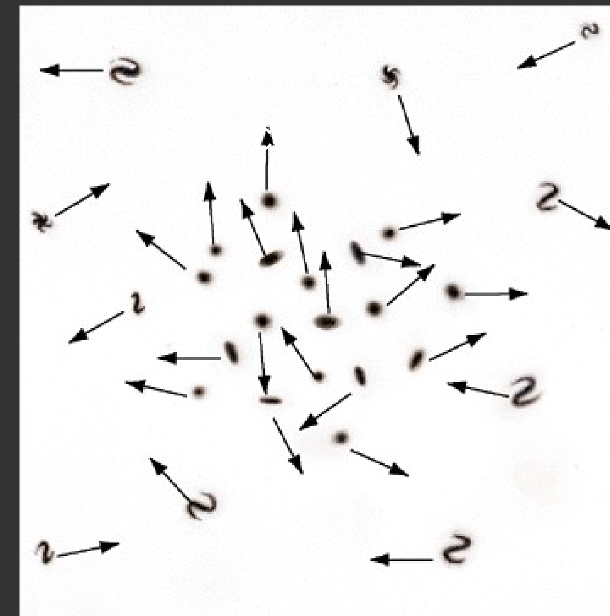
XMM-Newton space telescope

ACT radio telescope



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

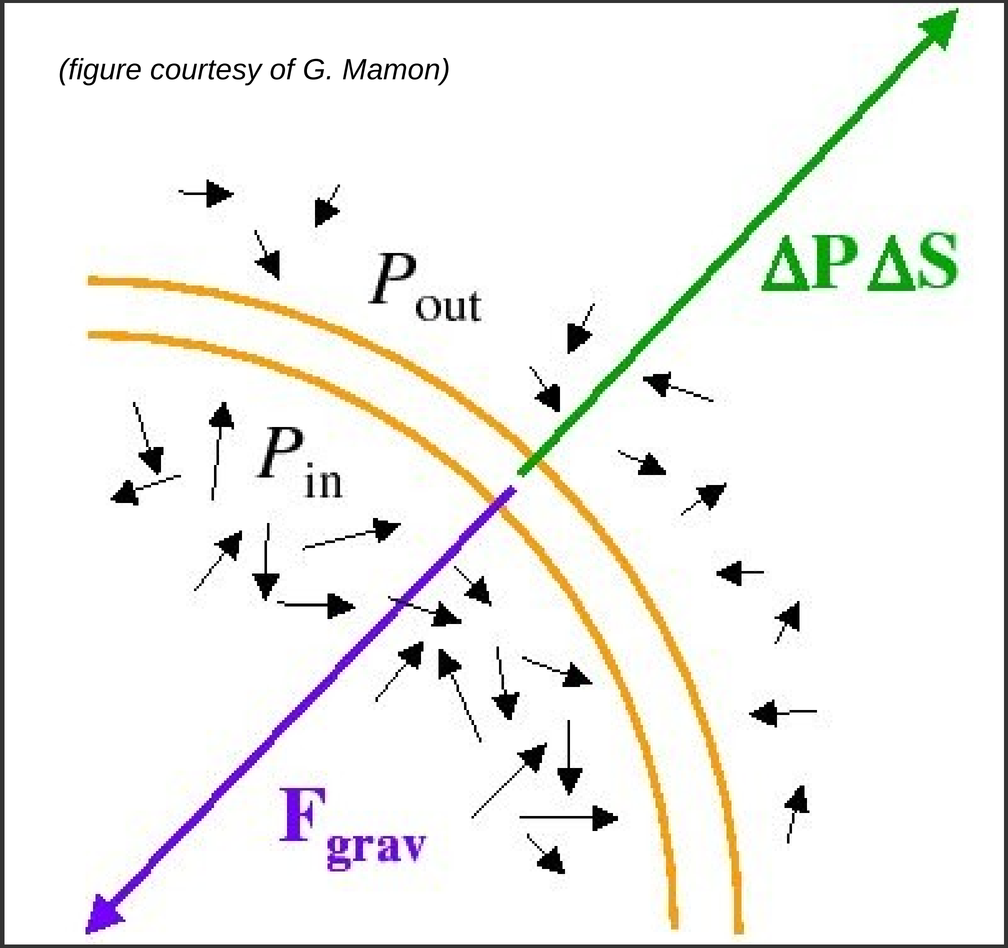
Hubble space telescope



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

Very Large Telescope

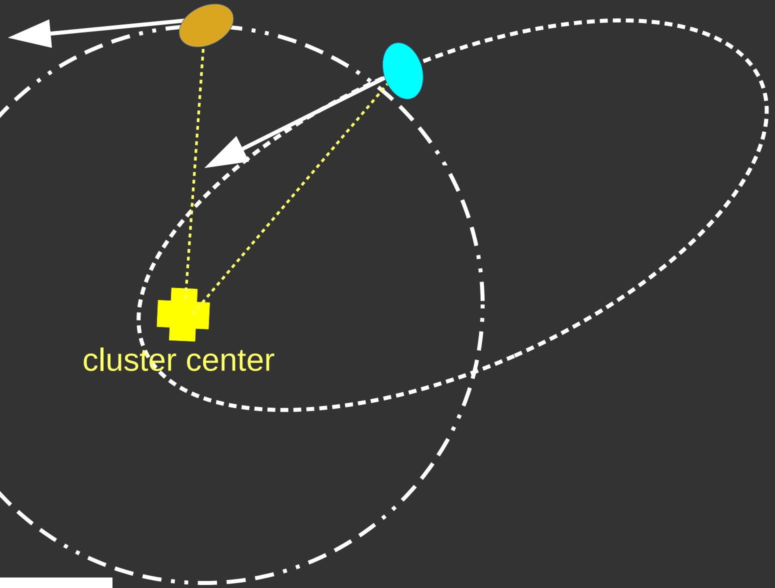
Methods – How to determine the cluster mass distribution



Cluster mass ⇒ **Gravitational pull**

Number density +
velocity distribution of stars/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)



Solve the Jeans equation, assuming
spherical symmetry and **dynamical equilibrium**

$$M(<r) = -\frac{r\sigma_r^2}{G}\left(\frac{d\ln\nu}{d\ln r} + \frac{d\ln\sigma_r^2}{d\ln r} + 2\beta\right) \qquad \beta(r) = 1 - \frac{\sigma_\theta^2(r)}{\sigma_r^2(r)}$$

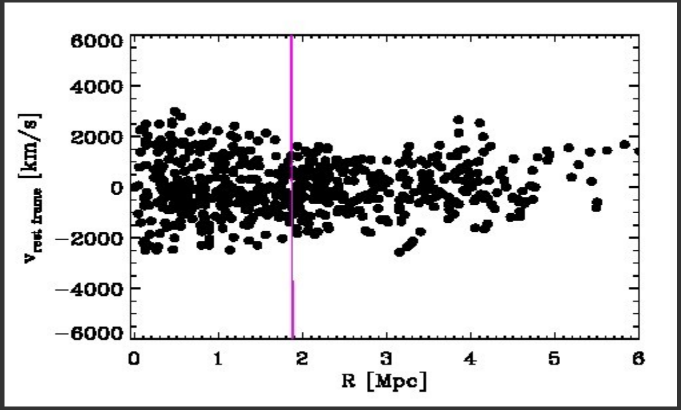
relating mass, $M(<r)$, to the spatial, $\nu(r)$, and velocity, $\sigma_r(r)$ and $\sigma_\theta(r)$, distributions of the tracer (cluster galaxies or BCG stars)

Methods – How to determine the cluster mass distribution

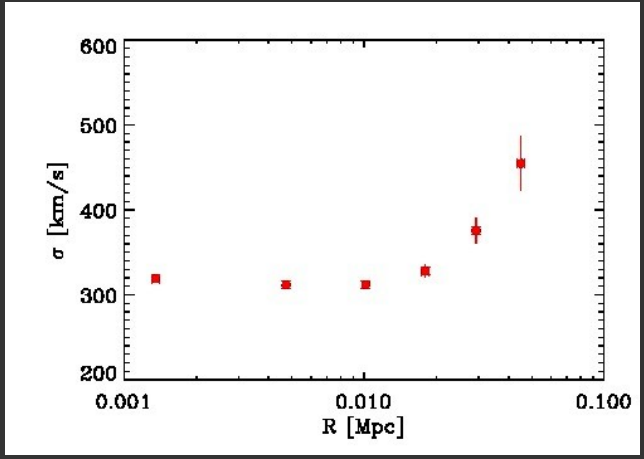
MAMPOSSt+: constrains a cluster mass density profile ρ(r) by a joint maximum likelihood fit to the projected phase-space (spatial and velocity) distribution of cluster galaxies and the velocity dispersion profile of the BCG stars

(Mamon, AB, Boué 13; Sartoris, AB+ 20; Pizzuti+23)

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



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



Constrains the best-fit parameters of the **total** 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

$$M_{tot} = M_{DM} + M_{BCG} + M_{ICM} + M_{galaxies}$$

(gNFW) (Jaffe)

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

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

M_{DM} free parameters: r_{200}, r_ρ, γ_{DM}

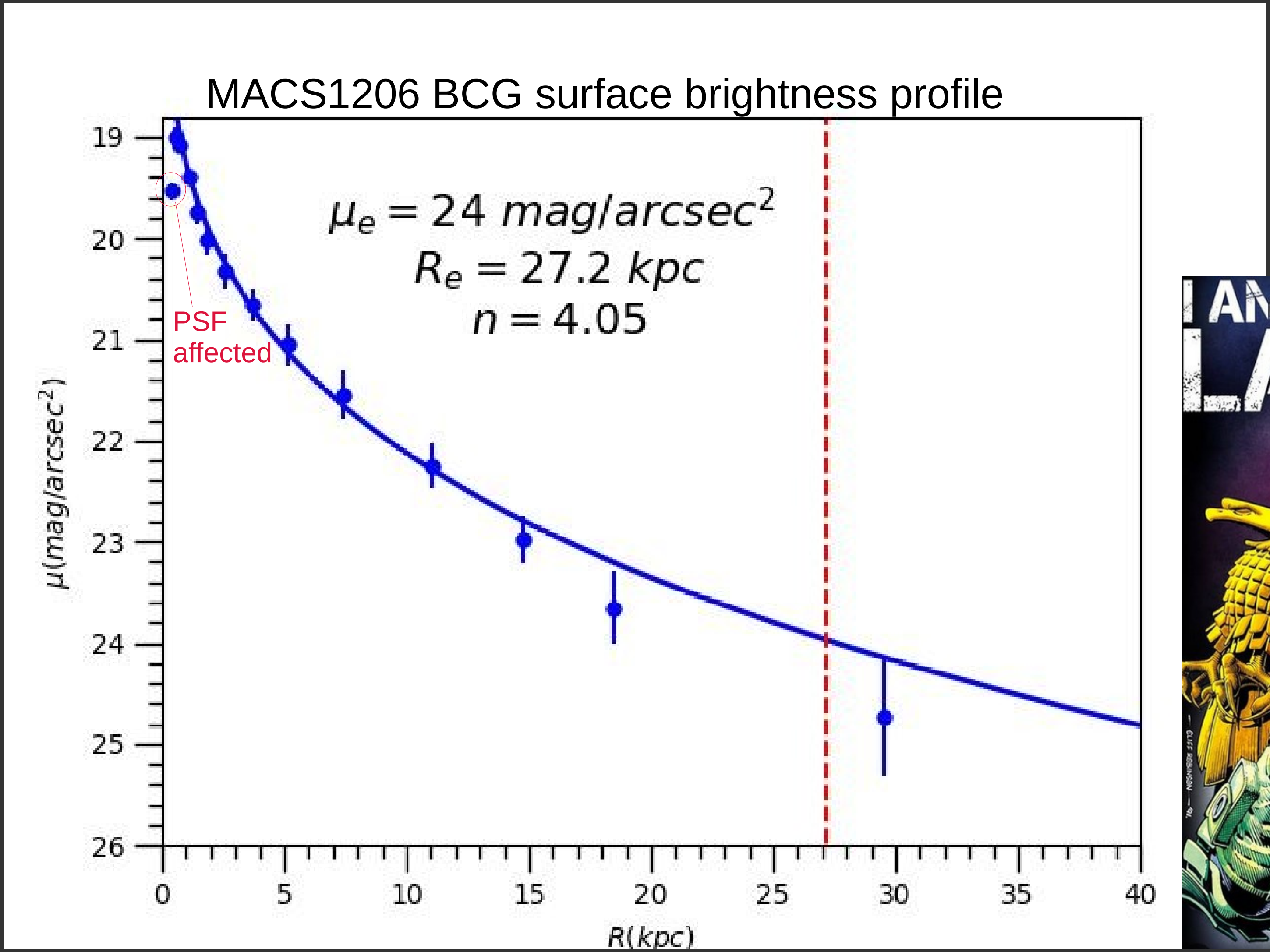
M_{BCG} free parameter: M/L

M_{ICM} and $M_{galaxies}$ directly from observations

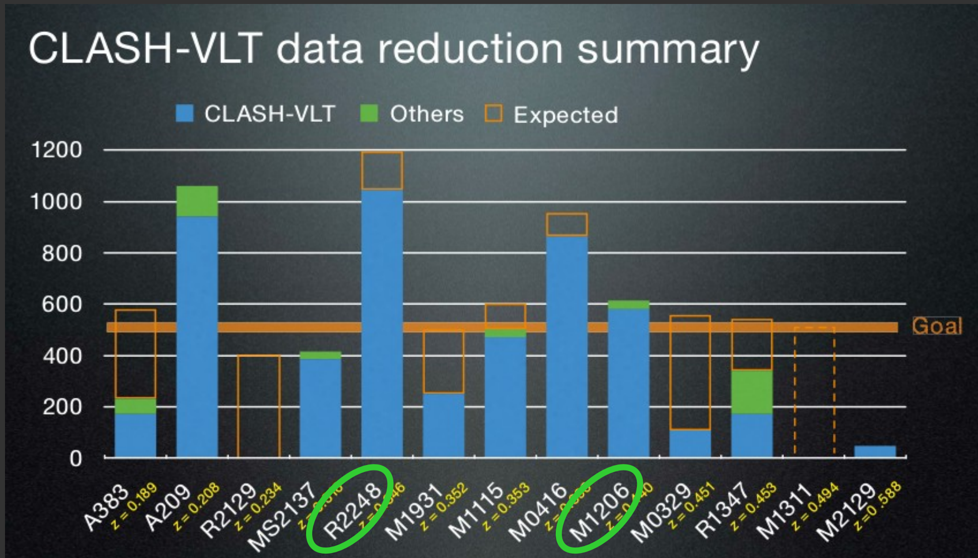
+ up to 3 free parameters to describe the orbits of BCG stars and cluster galaxies

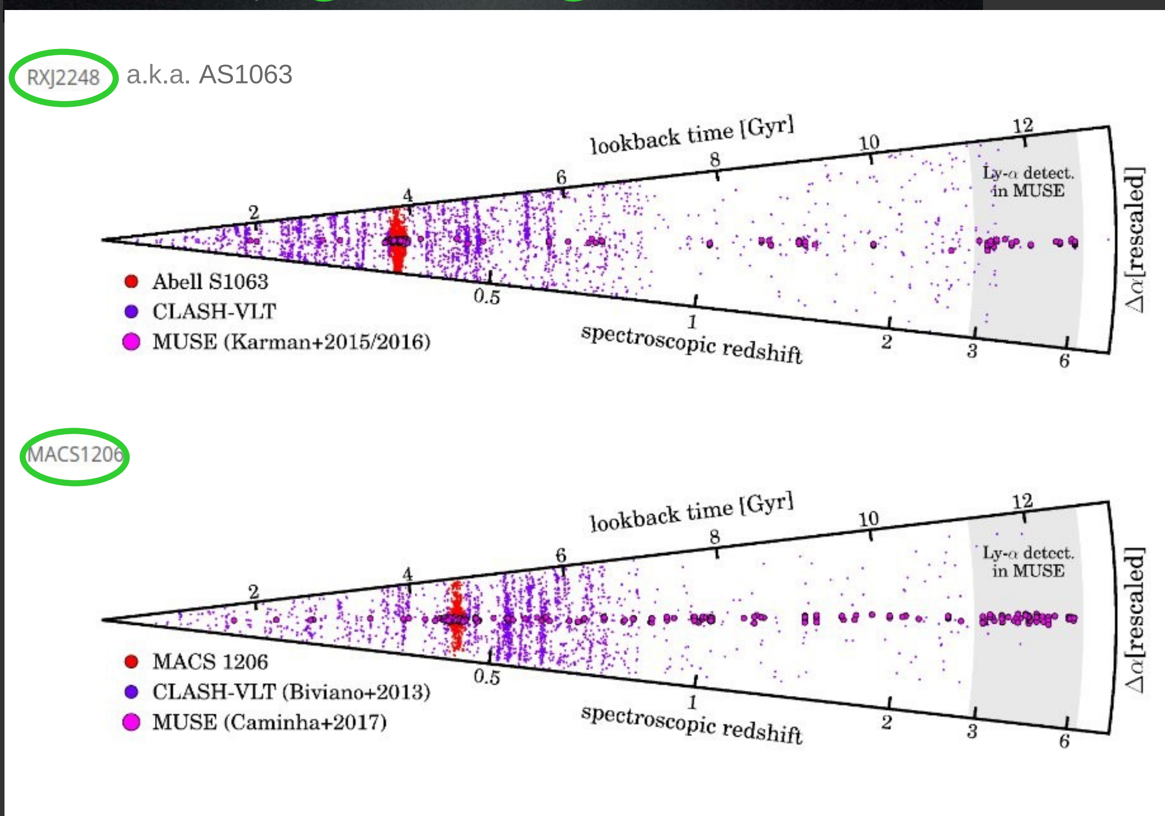
Methods – How to determine the cluster mass distribution

The Jaffe (1983) profile is characterized by a radius $r_J=r_e/0.763$, and r_e is obtained by a Sérsic law fit to the BCG surface brightness profile



Data sets – CLASH clusters AS1063 and MACS1206





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

Spectroscopic follow-up of a subset of the CLASH clusters *(Postman+12)*:

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

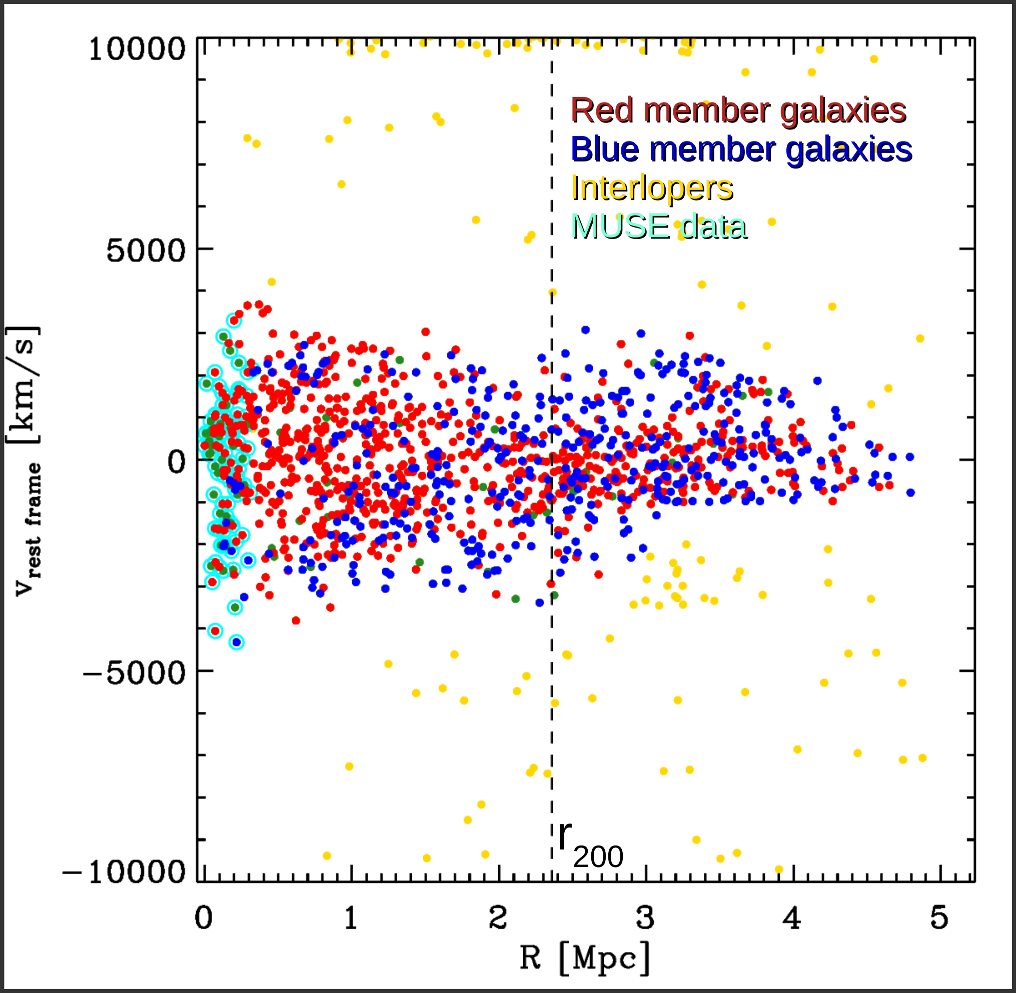
The team:

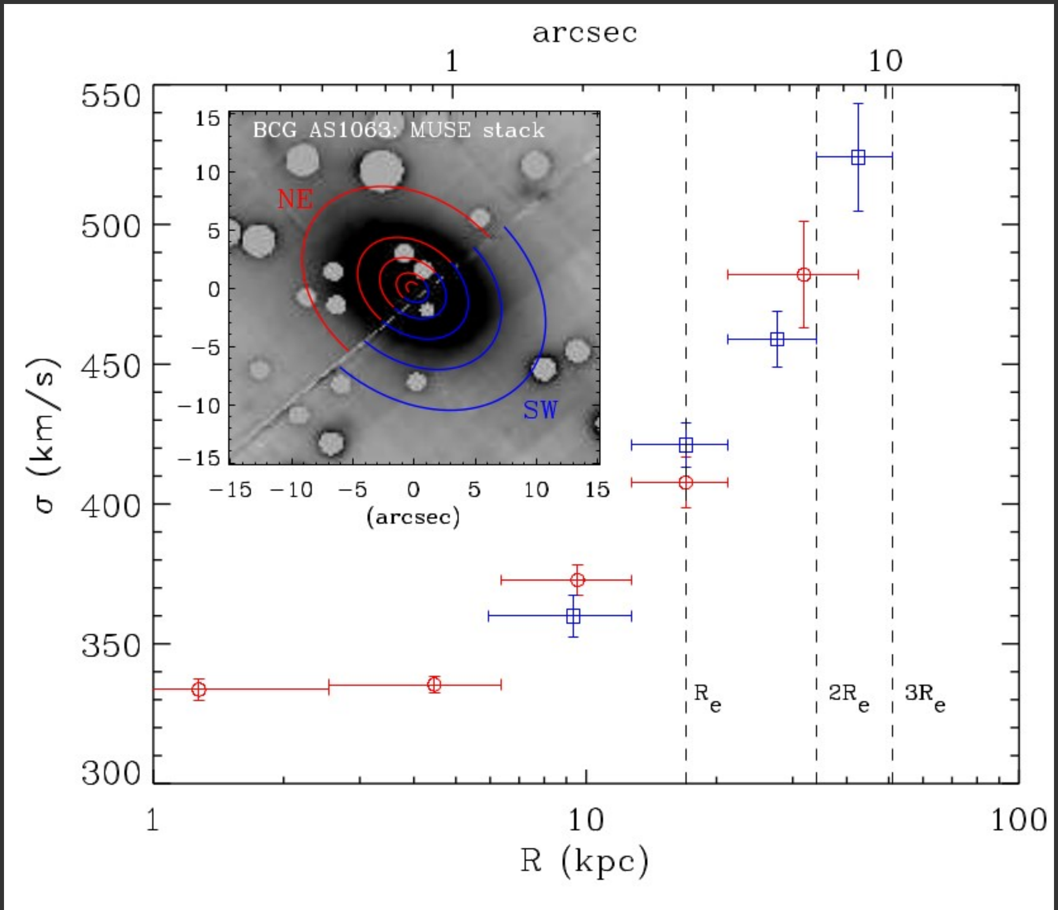
P. Rosati (PI),
I. Balestra, P. Bergamini, **AB**,
G. Caminha, S. Ettori, M. Girardi,
C. Grillo, A. Mercurio, ***M. Nonino***,
B. Sartoris, K. Umetsu, E. Vanzella
+ L. Pizzuti

Mario Nonino (1960-2023)

Data sets – CLASH clusters AS1063 and MACS1206

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





BCG image and velocity dispersion profile

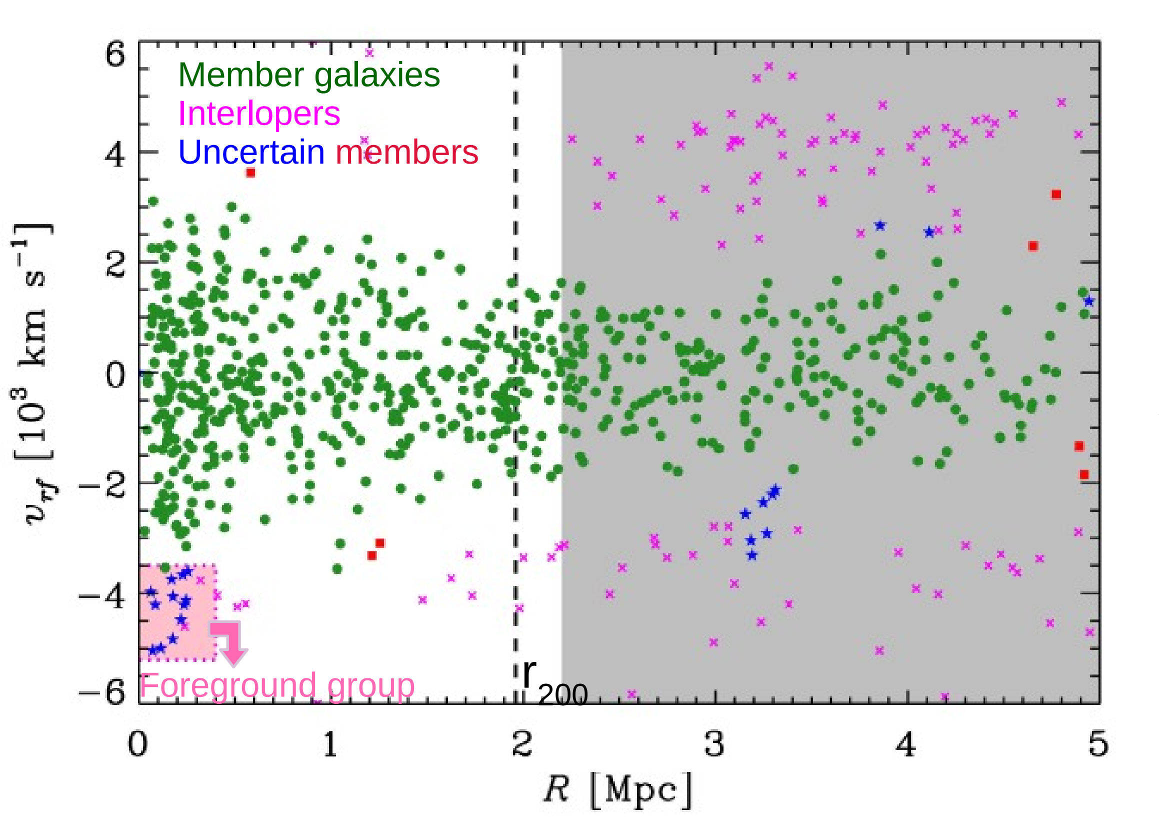
Projected phase-space distribution of galaxies; 1234 cluster members, of which 792 with $R \leq r_{200}$ used in our dynamical analysis

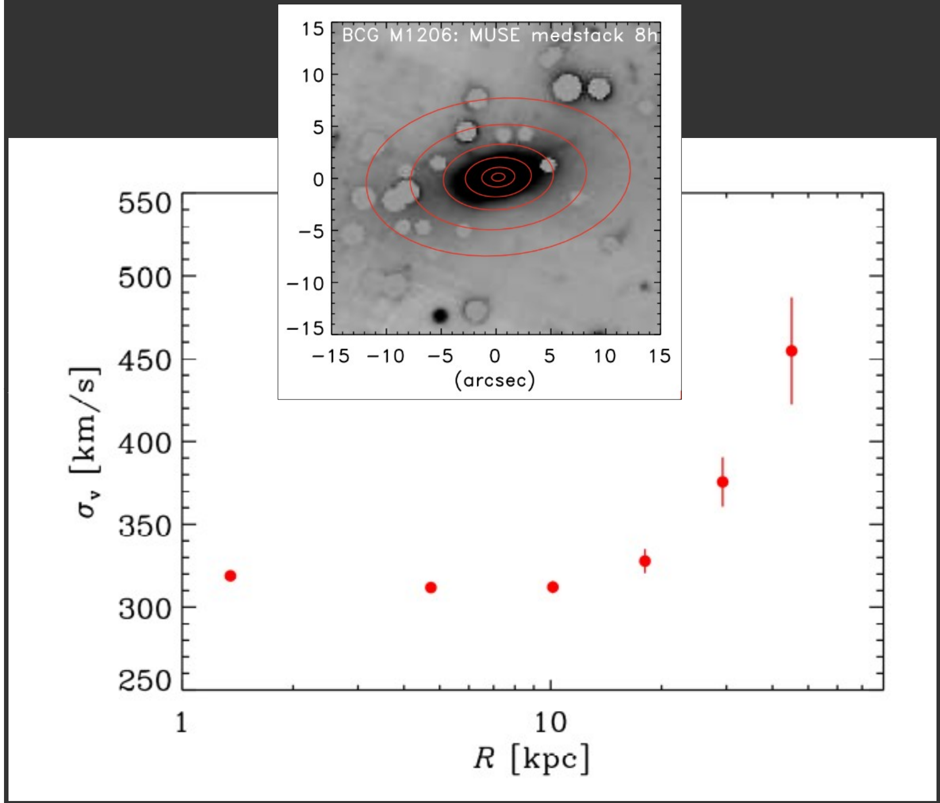
Intra-cluster gas mass profile estimated from Chandra data

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 ≤ 1.2 r_{200} used in our dynamical analysis

BCG image and velocity dispersion profile

Intra-cluster gas mass profile estimated from Chandra data

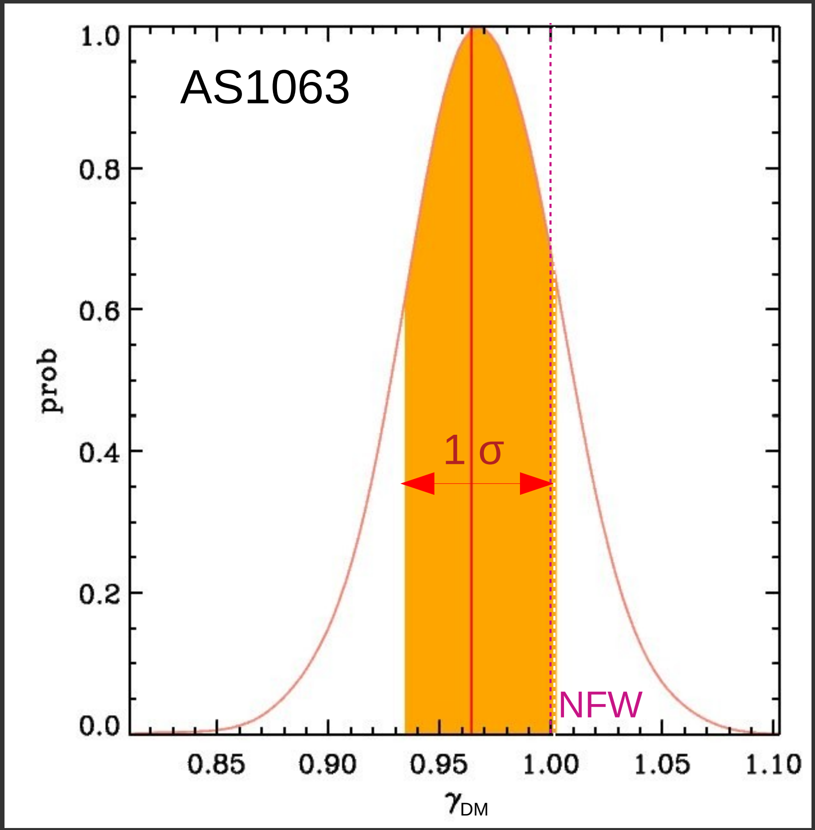
Galaxy stellar masses estimated from SED fitting to 6-band photometry

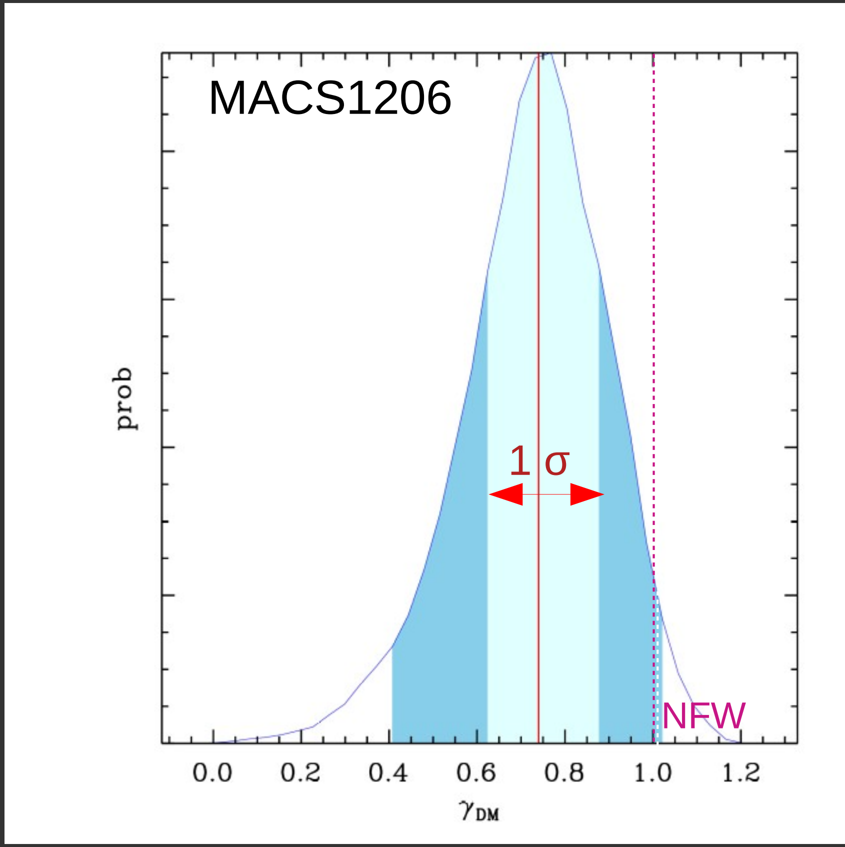
Results - MAMPOSSt dynamical analysis

MCMC analysis: results for the inner slope of the DM density profile, γ_{DM}, marginalized over the other free parameters

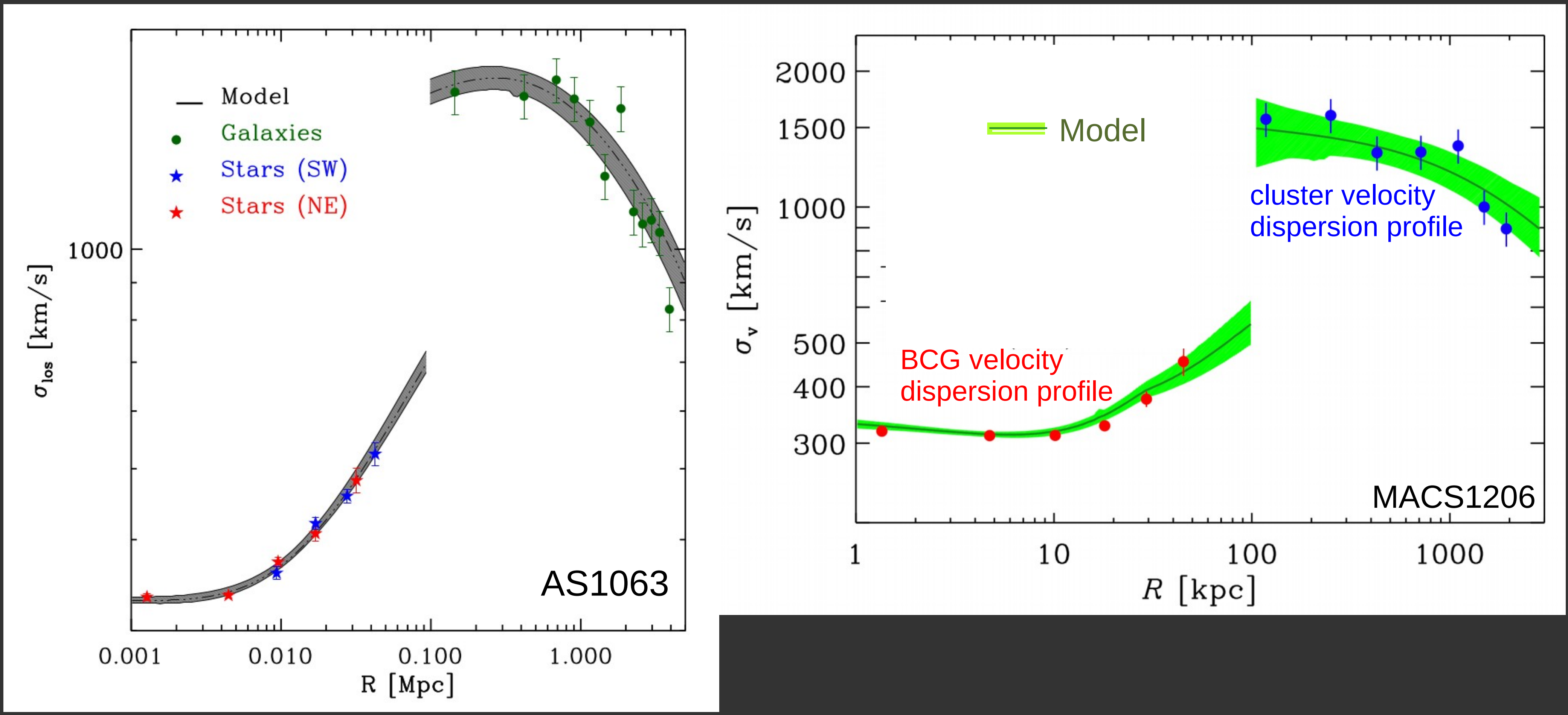
$\gamma_{DM} = 0.96_{-0.04}^{+0.04}$ (1 σ)

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





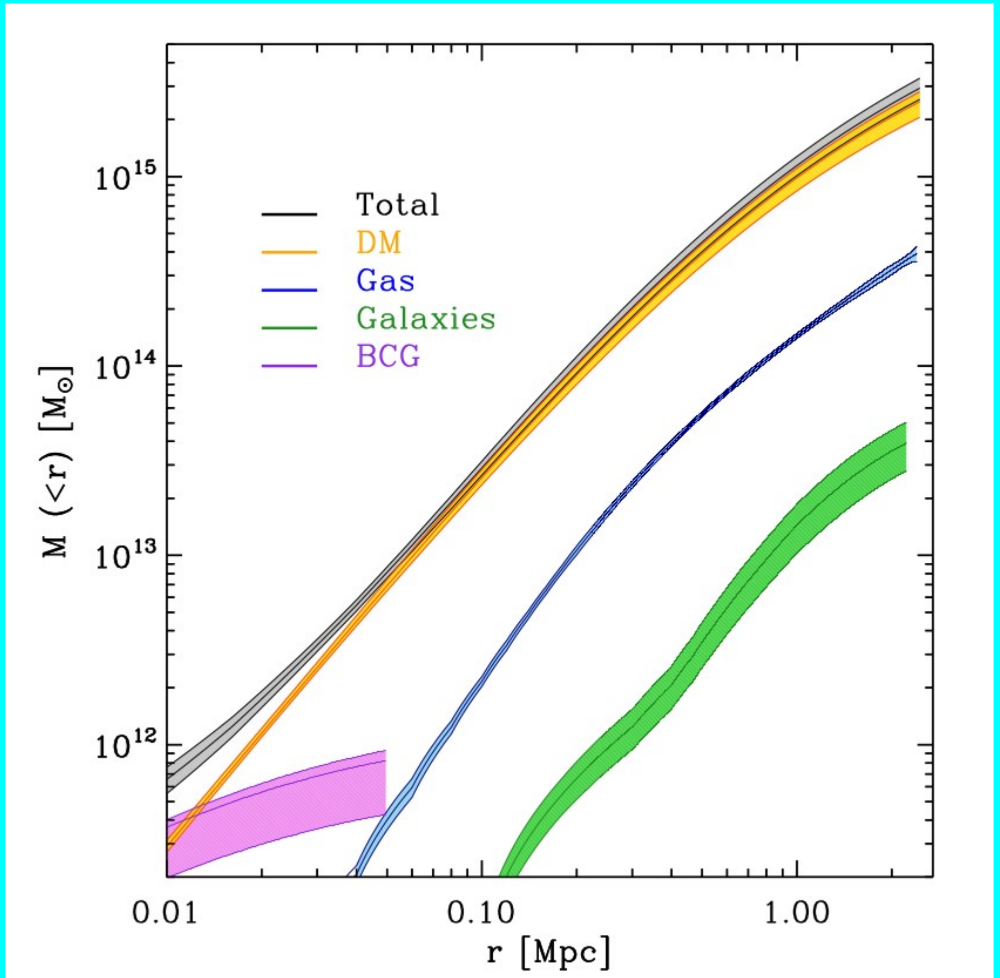
Results – The velocity dispersion profiles

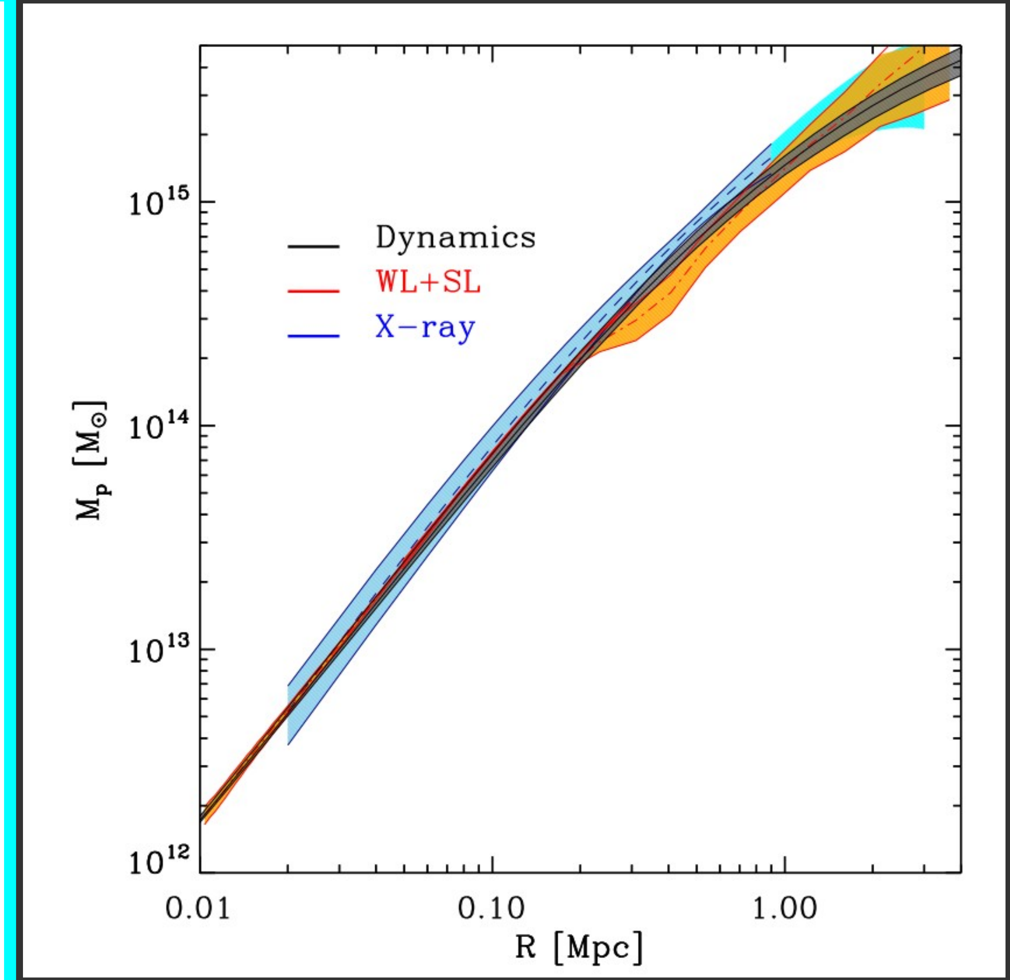


Projecting the best-fit MAMPOSSt solution onto the space of observables:
the velocity dispersion profiles of the BCG and the cluster
⇨ the MAMPOSSt best fit is a good fit

(*Note: the BCG and cluster line-of-sight 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

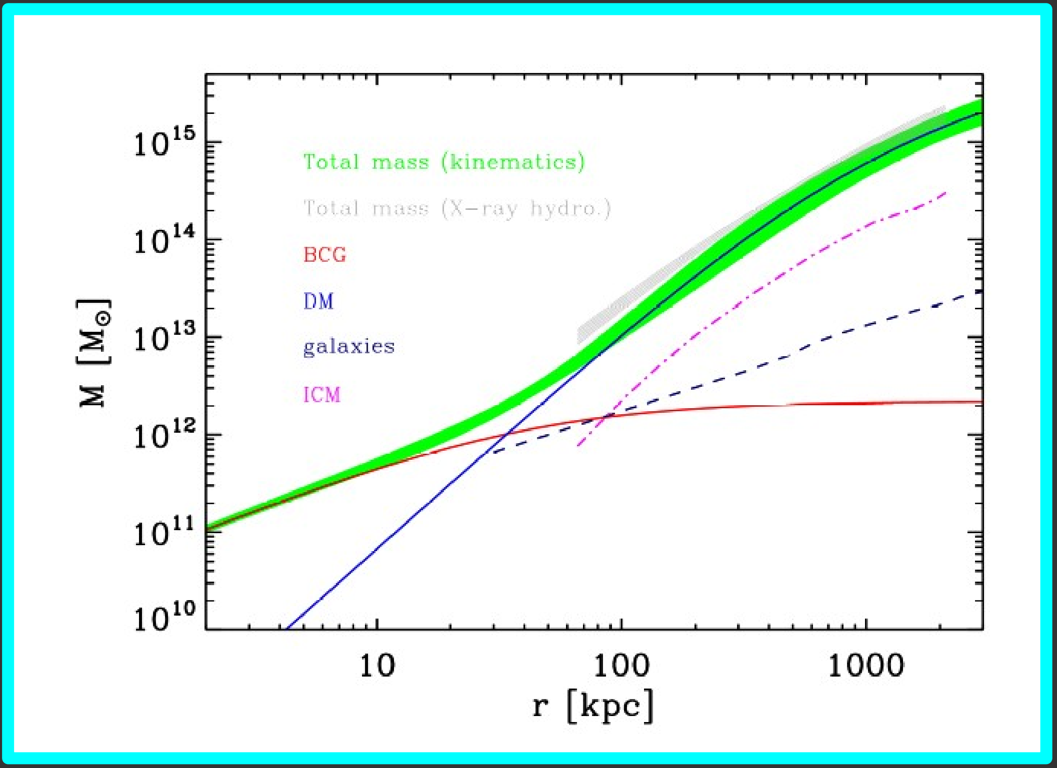


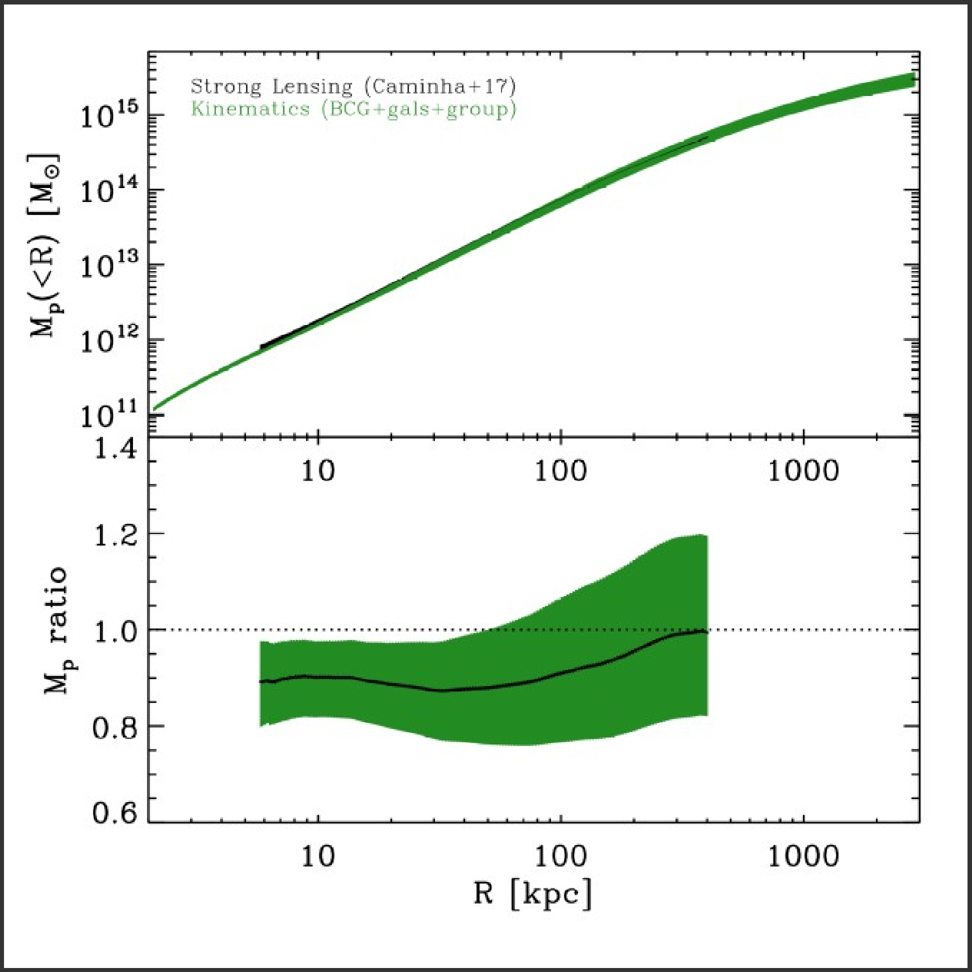


The BCG stellar mass dominates near the center, DM everywhere else

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

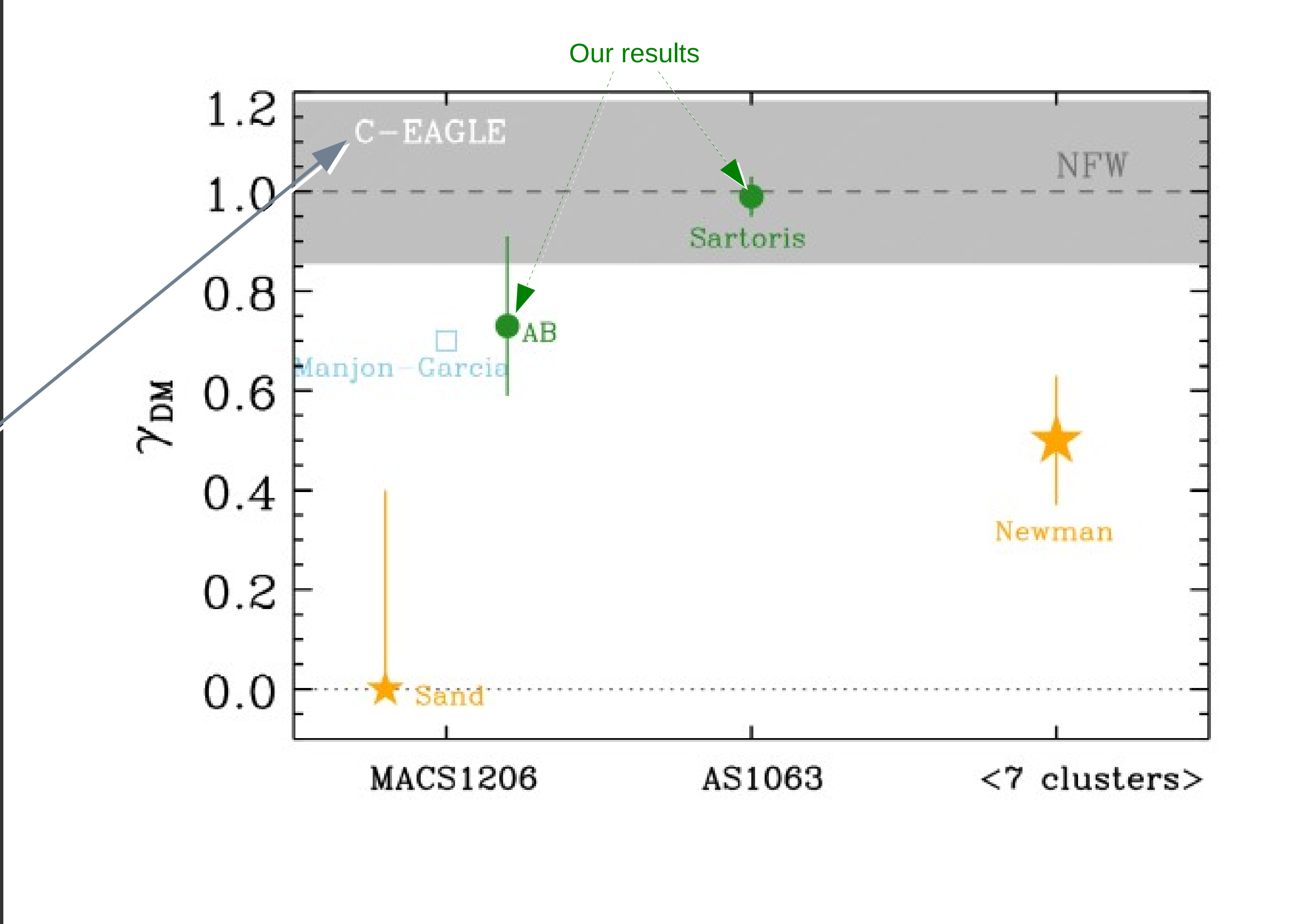
The total mass profile derived from MAMPOSSt is in good agreement with the independent determination from application of the hydrostatic equilibrium to the intra-cluster plasma, and the total (projected) mass profile derived from MAMPOSSt is in good agreement with the independent determination from strong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

Results – the inner slope of the DM density profile

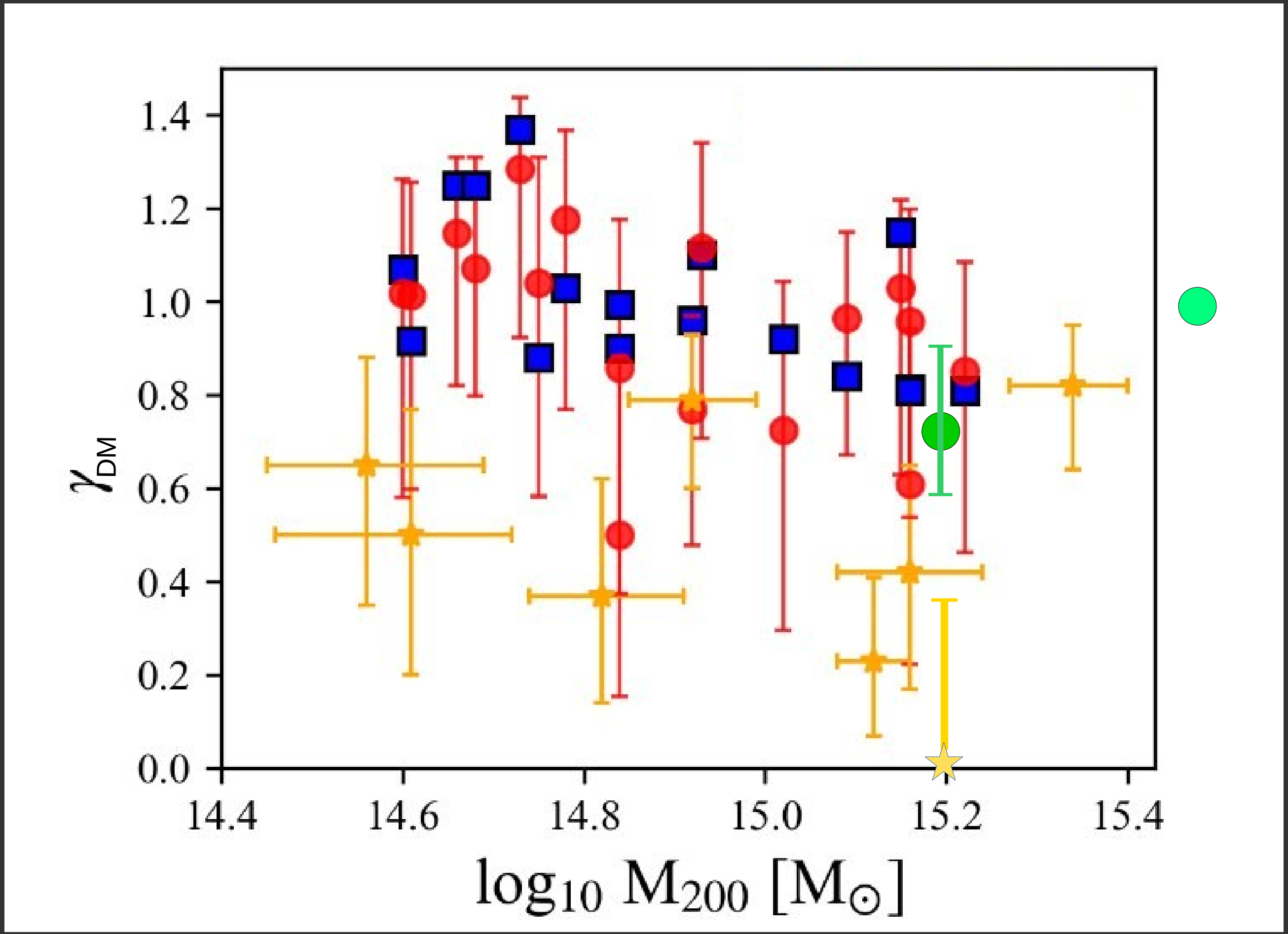
Previous results, based on cluster strong lensing + (in some cases) BCG kinematics:
Newman+13: γ_{DM}<1 for 8 clusters; Sand+04: γ_{DM}=0 for MACS1206 (supported by Limousin+22);
Manjon-Garcia+22: higher γ_{DM} value for MACS1206, but no error estimate given
Kelson+02: inner core in the DM distribution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

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

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

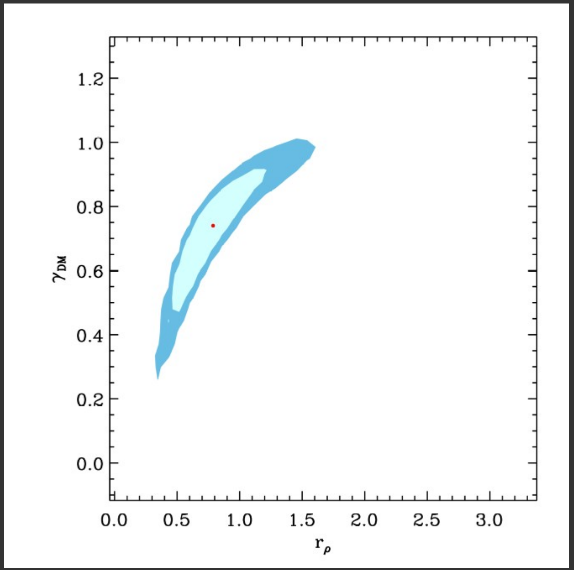


Discussion – the inner slope of the DM density profile



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

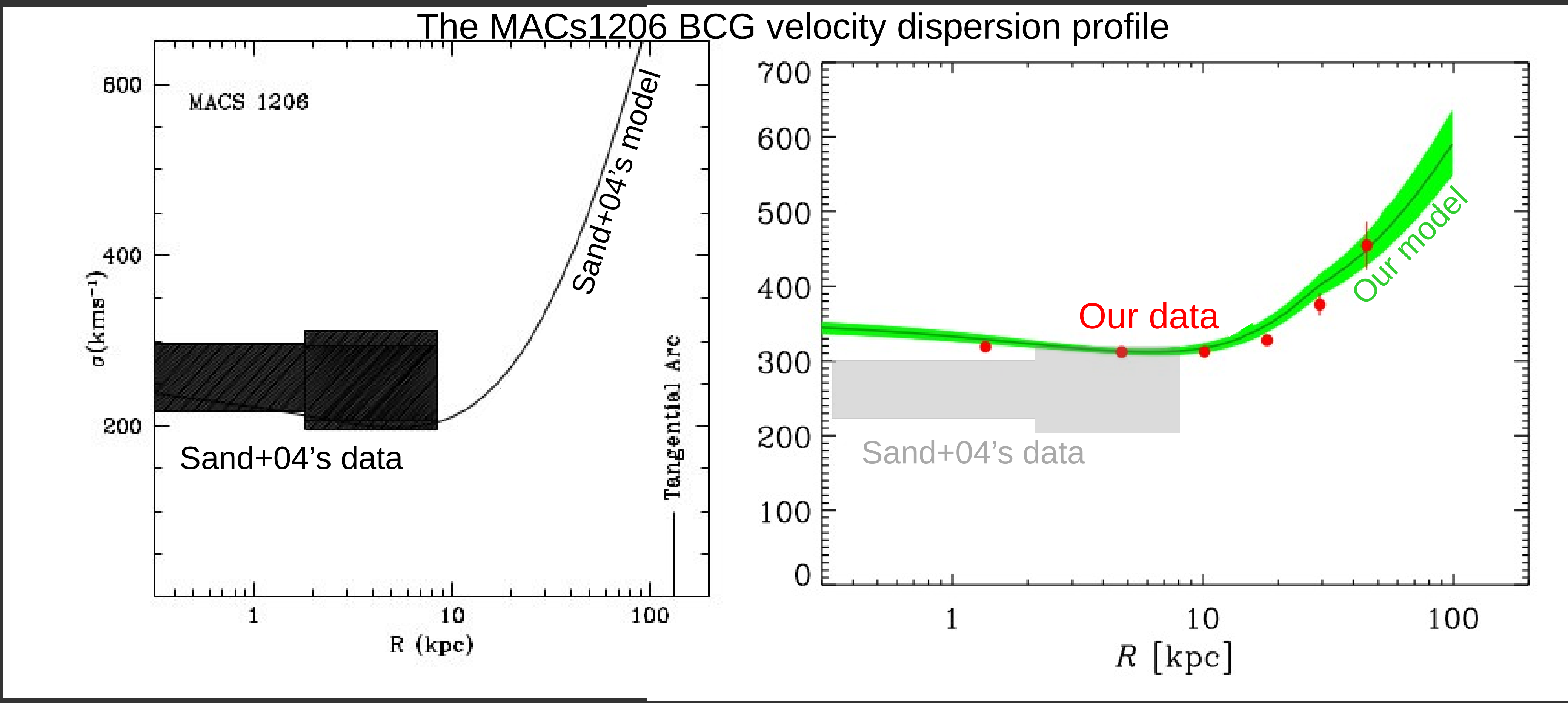
A possible problem in SL-based γ_{DM} determinations: to estimate γ_{DM} correctly, one also need a good estimate of the M(r) scale radius, r_ρ. because of covariance:



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_ρ; the kinematic data for cluster galaxies reach well beyond r_ρ, 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

Summary and perspectives

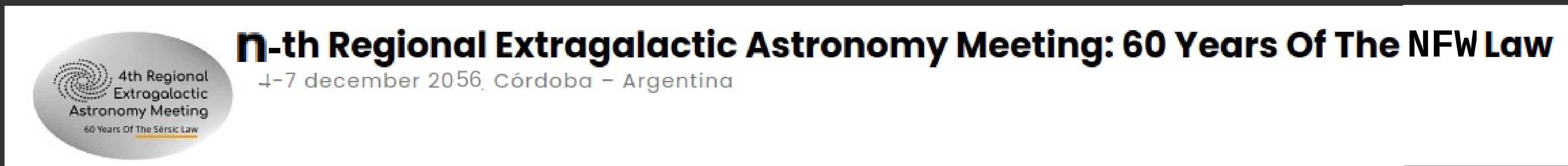
- We combine the kinematics of the Brightest Cluster Galaxy stars and of the cluster galaxies for two massive CLASH-VLT clusters at z~0.3-0.4 to determine their DM radial profile
- The total mass profile from kinematics agrees with those inferred from lensing and with that inferred from applying the hydrostatic equation to the intra-cluster gas, an indication that the two clusters are in dynamical equilibrium
- The DM profiles have inner slopes γ_{DM} = 0.7-1.0, consistent with recent results from hydrodynamical ΛCDM simulations (C-EAGLE), rejecting previous claims of significant inconsistence with γ_{DM}=1 (NFW) on the cluster scale

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

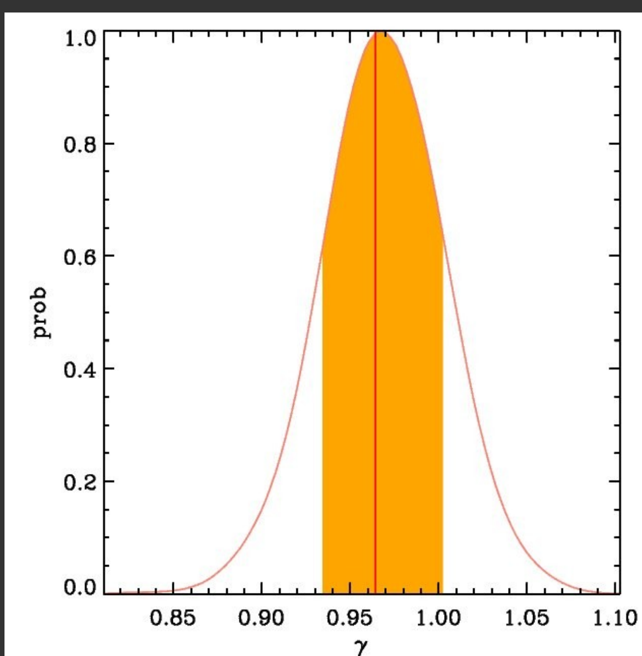
➔ MAMPOSSt constrains M(r) but also the velocity anisotropy β(r) (of cluster galaxies and BCG stars): find the mean velocity anisotropy profile of clusters and its variance and constrain the velocity anisotropy of their BCG stars

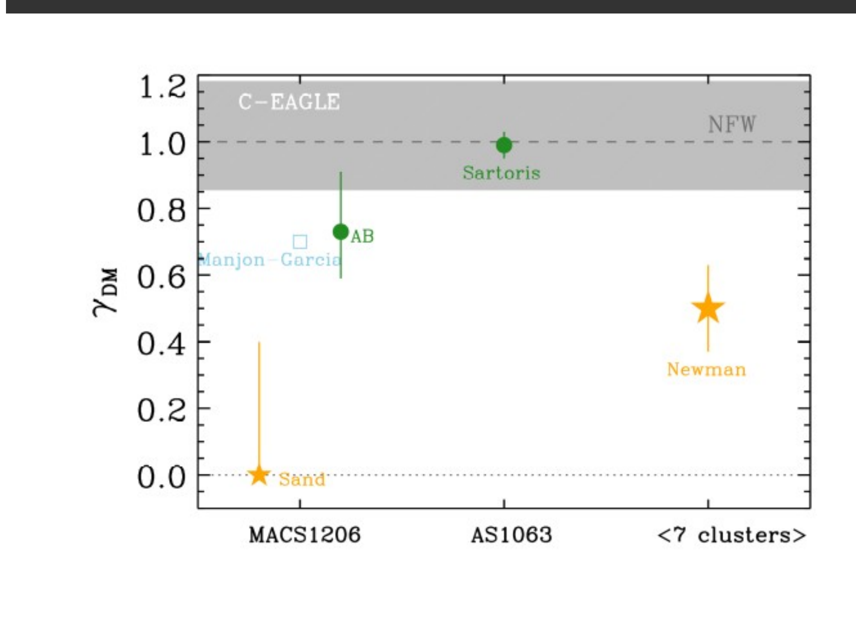
A proposal:

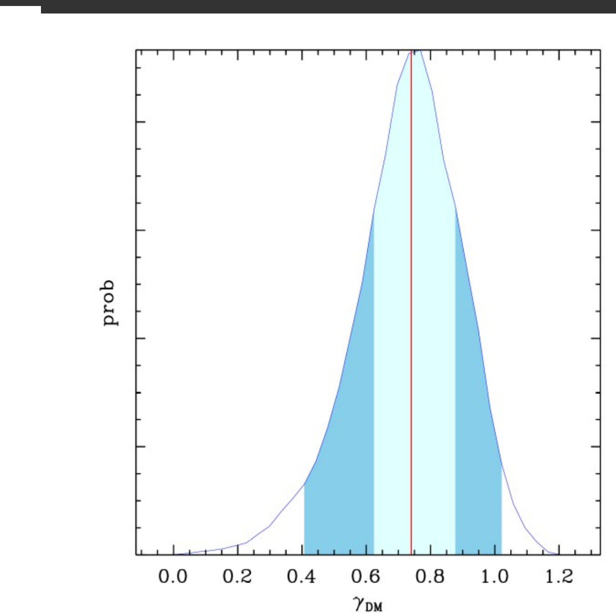
Let's meet again in 2056!



¡Gracias!



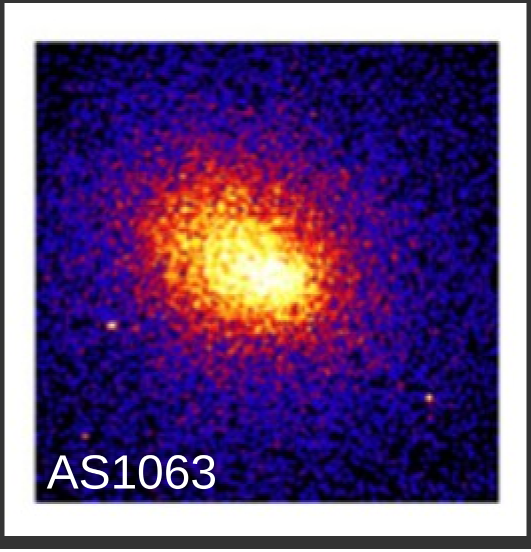


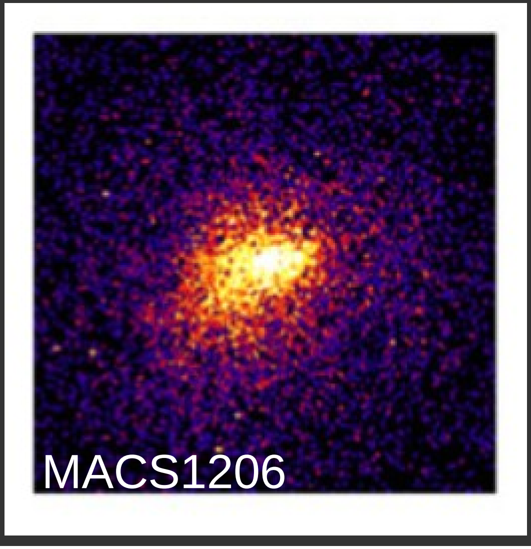


Additional slides

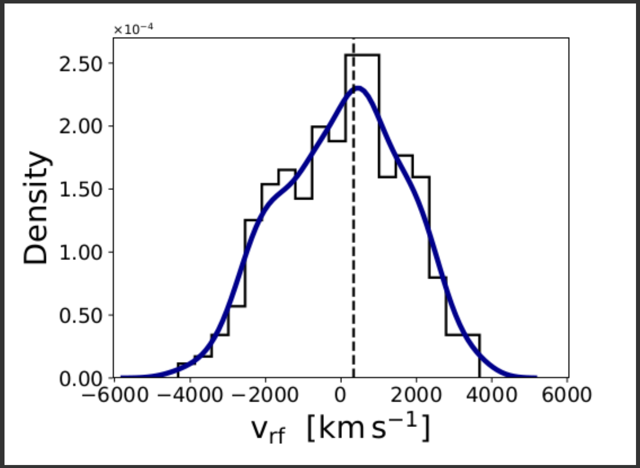
Discussion – systematics

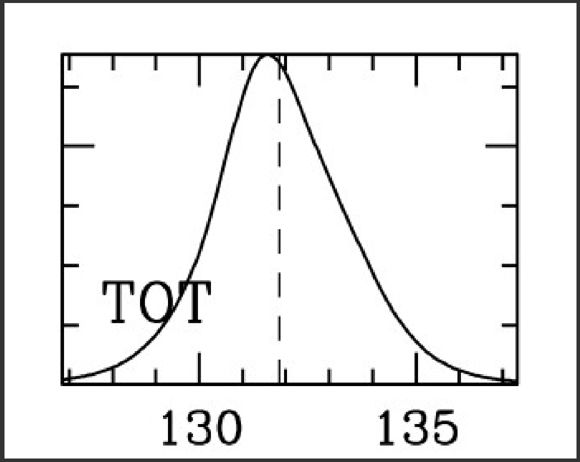
We assume dynamical equilibrium for AS1063 and MACS1206 – is this justified?





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?

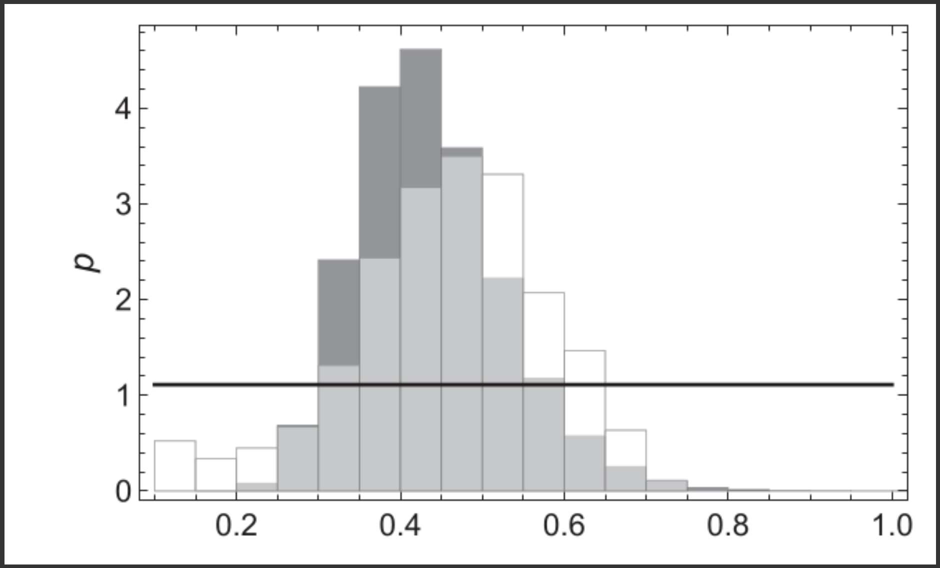
Clusters are not spherical. Triaxiality induces a systematic uncertainty.

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 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)

The surface density of observed objects in projected phase space is:

MAMPOSSt:

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

(Mamon, AB, Boué 13)

$$g(R, v_z) = \Sigma(R)\ \langle h(v_z|R, r)\rangle_{\rm LOS}$$
$$= 2\int_R^\infty \frac{r\,\nu(r)}{\sqrt{r^2-R^2}}\, h(v_z|R,r)\,{\rm d}r\ , \qquad (4)$$
$$= 2\int_R^\infty \frac{r\,{\rm d}r}{\sqrt{r^2-R^2}} \int_{-\infty}^{+\infty} {\rm d}v_\perp \int_{-\infty}^{+\infty} f(r, v_z, v_\perp, v_\phi)\,{\rm d}v_\phi, \qquad (5)$$

Hence, the probability density of observing an object at position (R,v_z) is:

$$q(R, v_z) = \frac{2\pi\, R\, g(R, v_z)}{\Delta N_{\rm p}}$$
$$= \frac{4\pi\, R}{\Delta N_{\rm p}} \int_R^\infty \frac{r\,\nu(r)}{\sqrt{r^2-R^2}}\, h(v_z|R,r)\,{\rm d}r$$

Can be solved by assuming a distribution for 3D galaxy velocities (e.g. Gaussian):

$$h(v_z|R,r) = \frac{1}{\sqrt{2\pi\sigma_z^2(R,r)}} \exp\left[-\frac{v_z^2}{2\,\sigma_z^2(R,r)}\right]$$

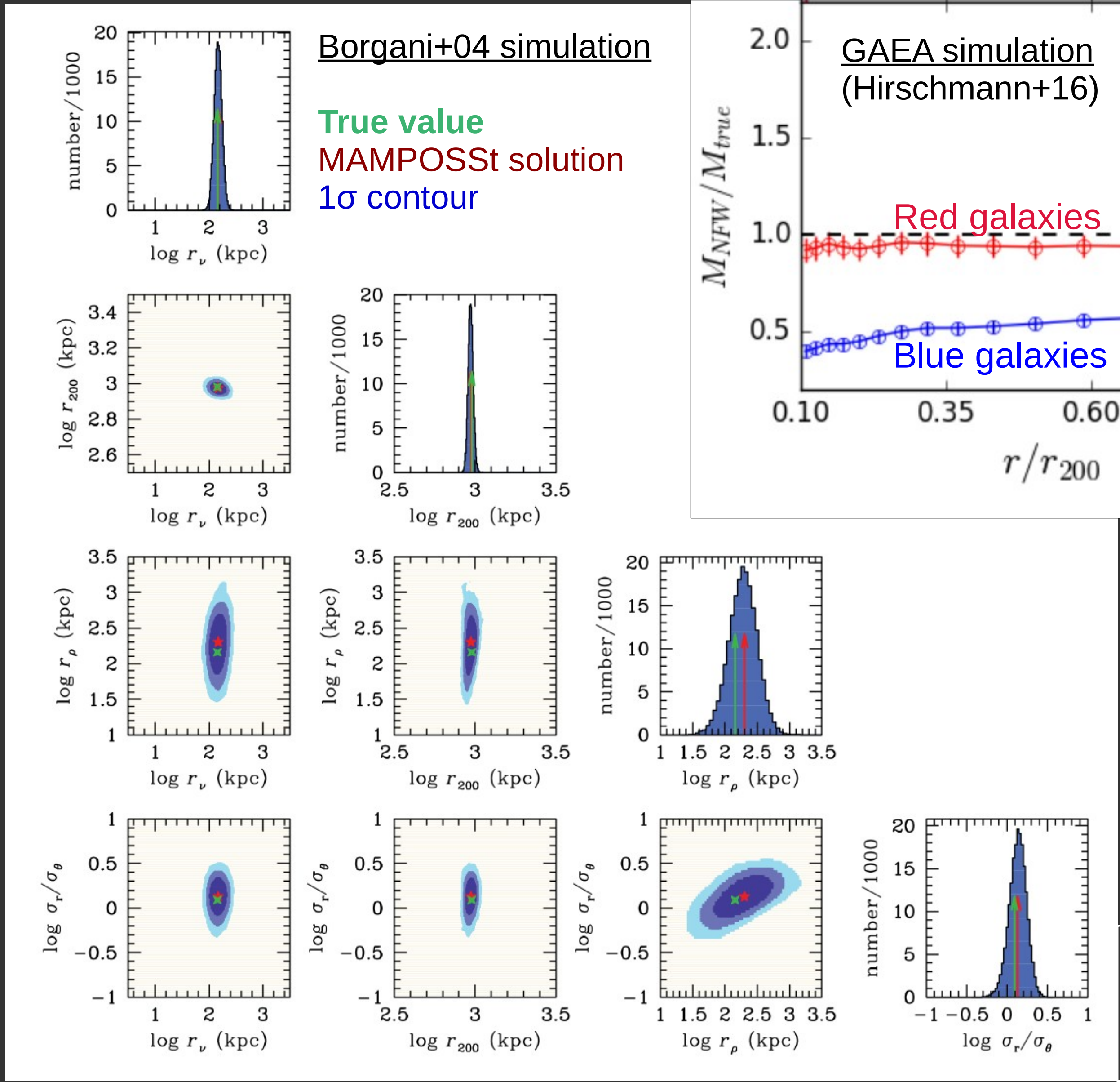
$$\sigma_z^2(R,r) = \left[1-\beta(r)\left(\frac{R}{r}\right)^2\right]\sigma_r^2(r).$$

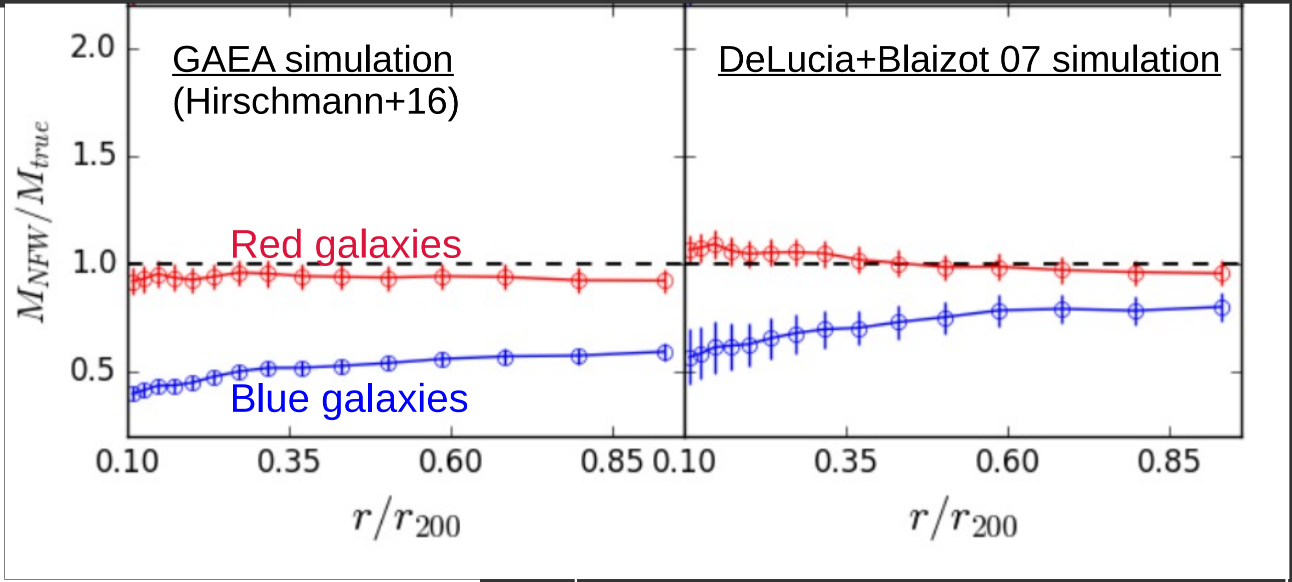
where $\sigma_r^2(r)$ is obtained from the Jeans equation, given $M(r)$ and $\beta(r)$

$$\sigma_r^2(r) = \frac{1}{\nu(r)} \int_r^\infty \exp\left[2\int_r^s \beta(t)\frac{{\rm d}t}{t}\right] \nu(s)\frac{G\,M(s)}{s^2}\,{\rm d}s$$

Methods – How to determine the cluster mass distribution

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





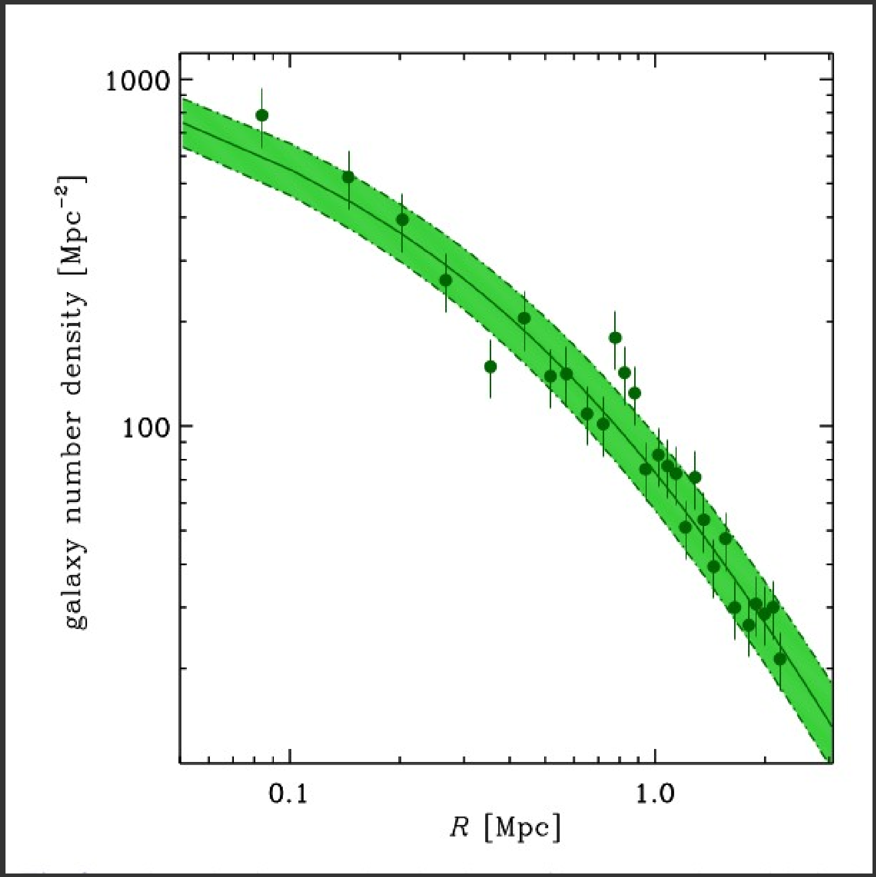
MAMPOSSt M(r) NFW model solution to true M(r) for 100 clusters x 3 projection axes: using red galaxies as tracers allows an accurate M(r) determination
(Aguirre Tagliaferro, AB + 21)

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

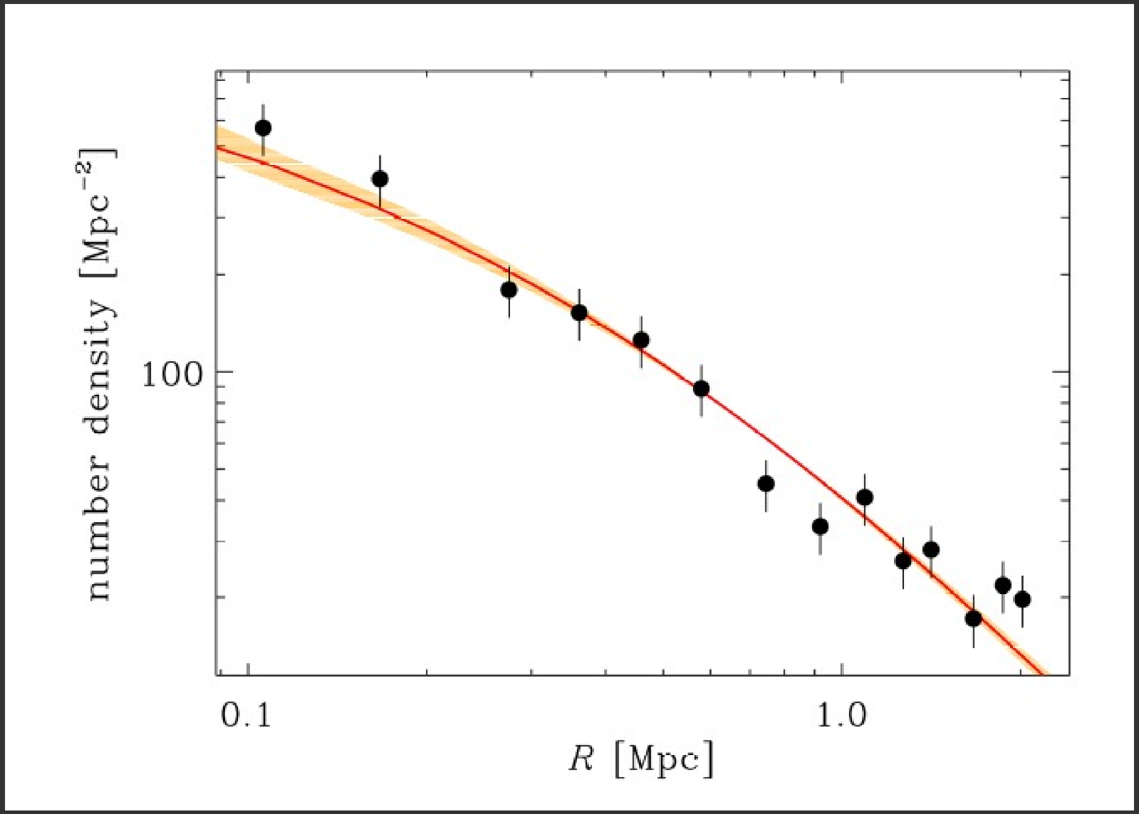
Results – the spatial distribution of cluster galaxies

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_ν

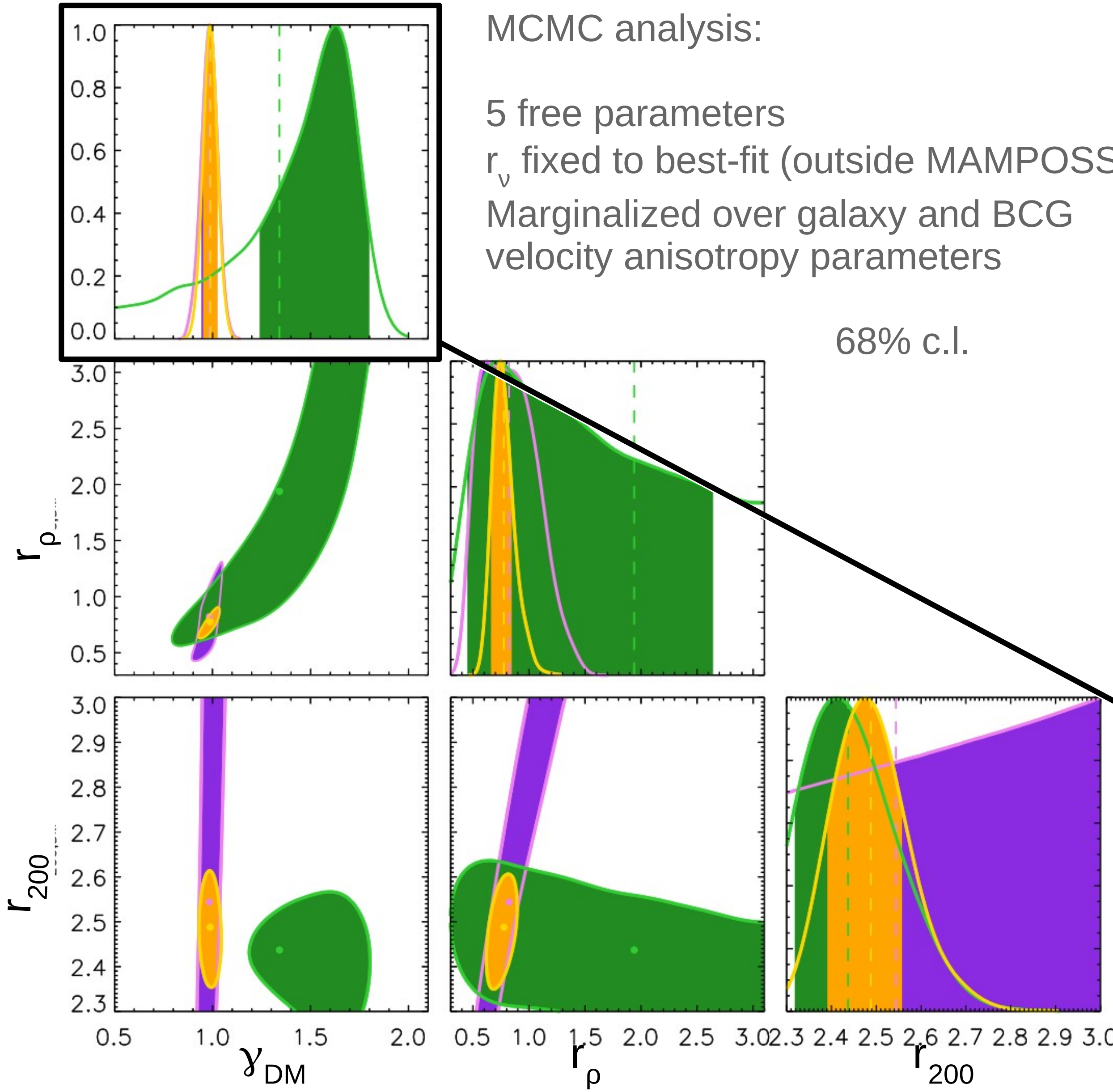


AS1063, r_ν = 0.76 ± 0.08 Mpc



MACS1206, r_ν = 0.46 ± 0.08 Mpc

Results - MAMPOSSt dynamical analysis: AS1063



MCMC analysis:

5 free parameters

r_ν fixed to best-fit (outside MAMPOSSt)

Marginalized over galaxy and BCG velocity anisotropy parameters

68% c.l.

r_{200} = 2.5 Mpc

r_ρ = 0.8 Mpc

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

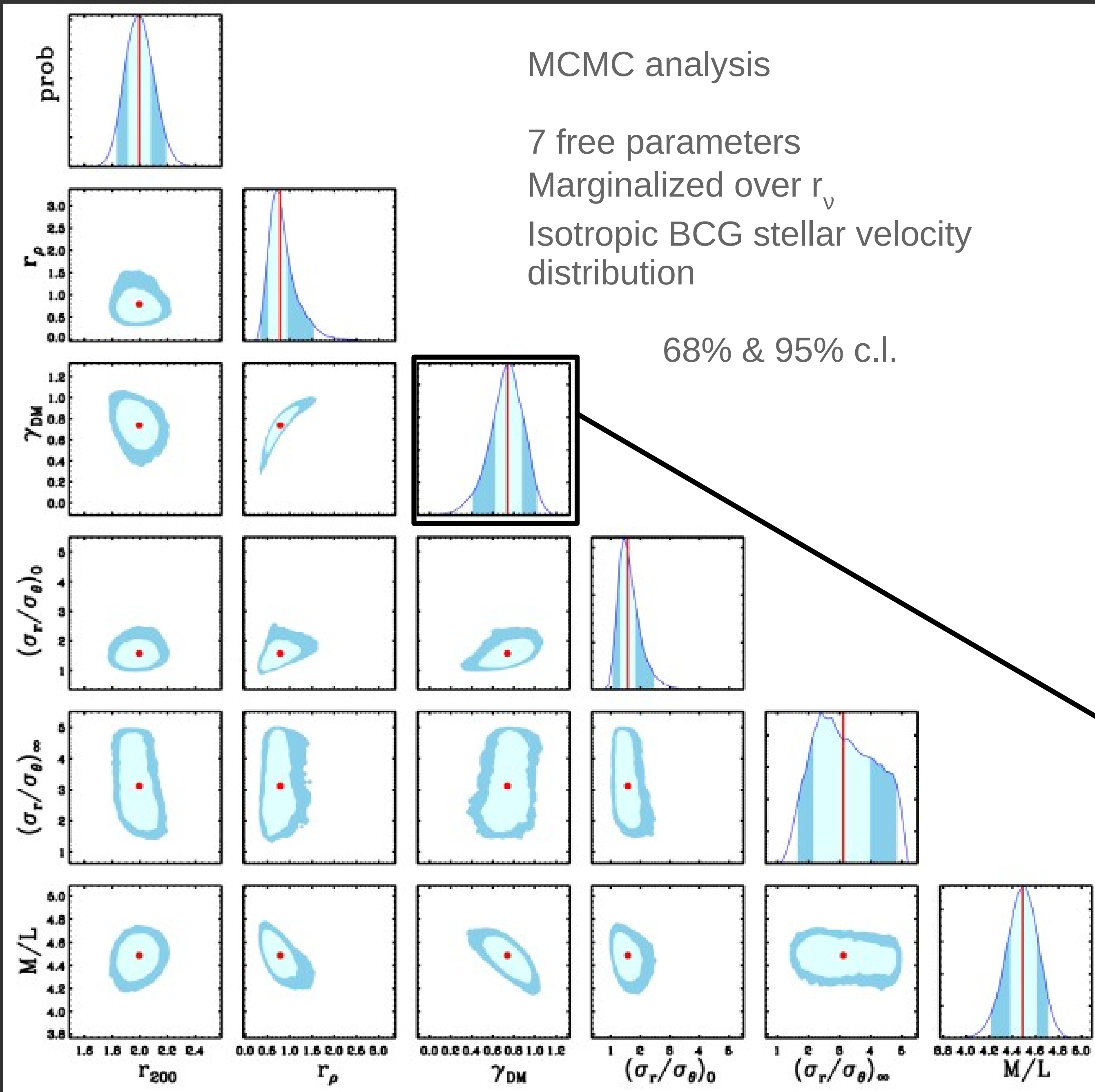
BCG stellar orbits almost isotropic

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_ν
Isotropic BCG stellar velocity distribution

68% & 95% c.l.

r_{200} = 2.0 Mpc

r_ρ = 0.9 Mpc

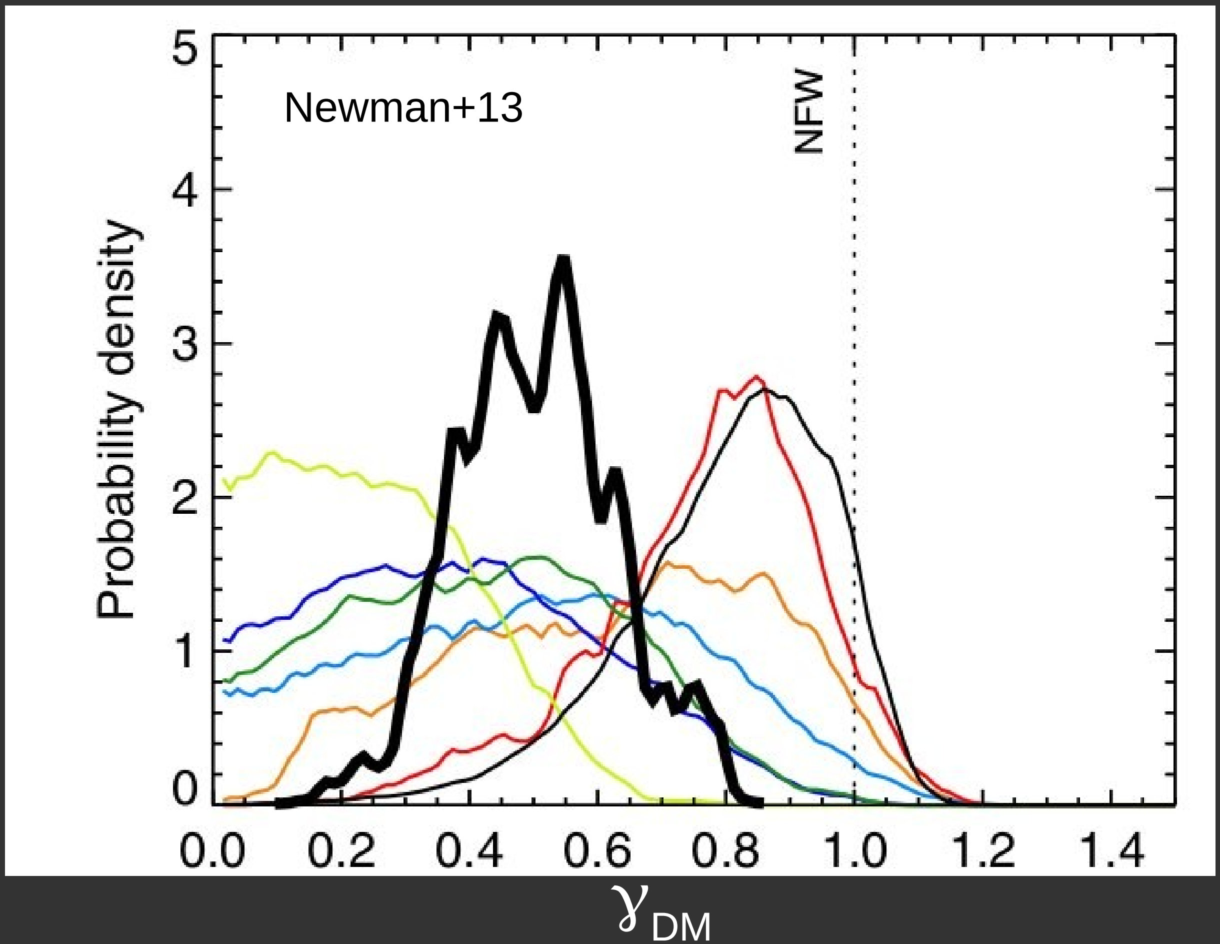
M_{BCG} = 2.2 10^{12} $M_\odot$

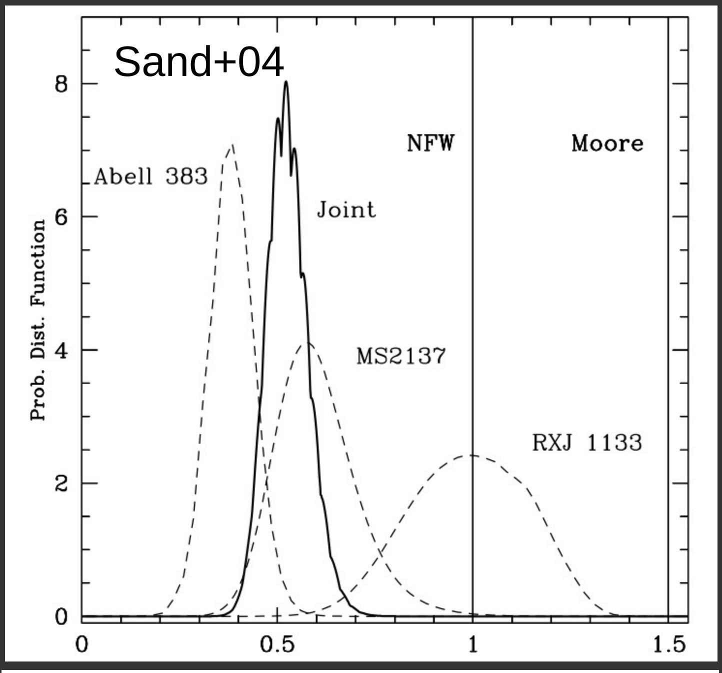
BCG stellar orbits almost isotropic

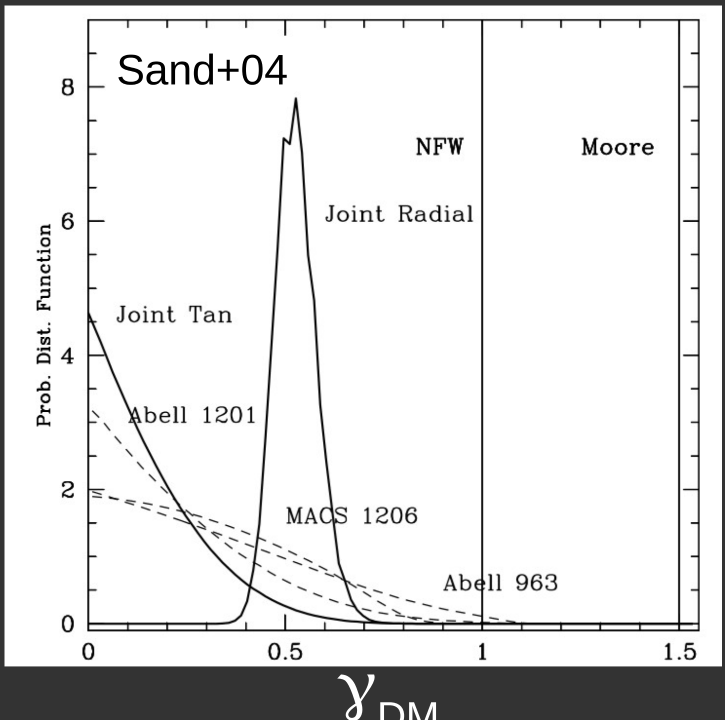
Galaxy orbits radially elongated, increasingly so at larger radii

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

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)