Clusters of galaxies.
Structure and dynamics in the last 8 Gyr

Andrea Biviano (INAF-OATs - Trieste, Italy)

Main collaborators
(color-coded by redshift):

G. Mamon, A. Cava, B. Poggianti, A. Moretti, D. Bettoni, G. Fasano +WINGS

P. Rosati, B. Sartoris, A. Mercurio, C. Grillo, G. Caminha, M. Nonino +CLASH-VLT

M. Balogh, R. van der Burg, D. Gilbank, A. Muzzin, G. Rudnick, J. Chan + GOGREEN

+ Tania Aguirre Tagliaferro (IATE - Córdoba)

Outline of this talk:

- Introduction on clusters of galaxies
- Weighting clusters *(how to determine cluster mass profiles)*
- Cluster mass profiles: *dark matter and more*
- Summary and perspectives

What are clusters of galaxies?

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

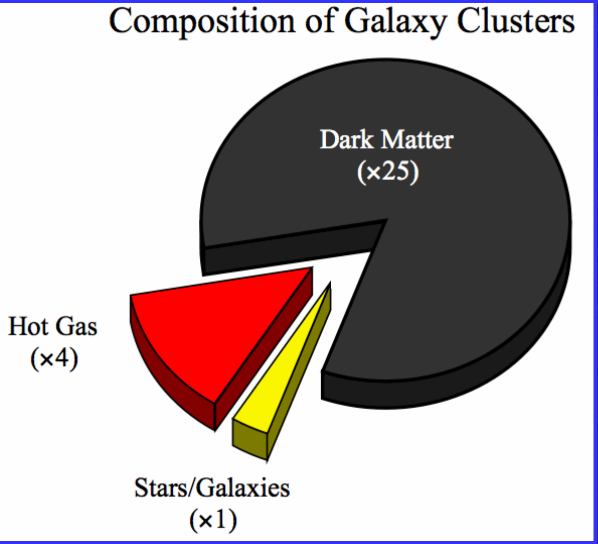
Encyclopedia of Astronomy & Astrophysics

The Coma cluster of galaxies

G.O. Abell

Known since the XVIII century, first classified by Abell in the 50s, re-discovered by their X-ray emission in the 70s (due to the hot diffuse intra-cluster gas)

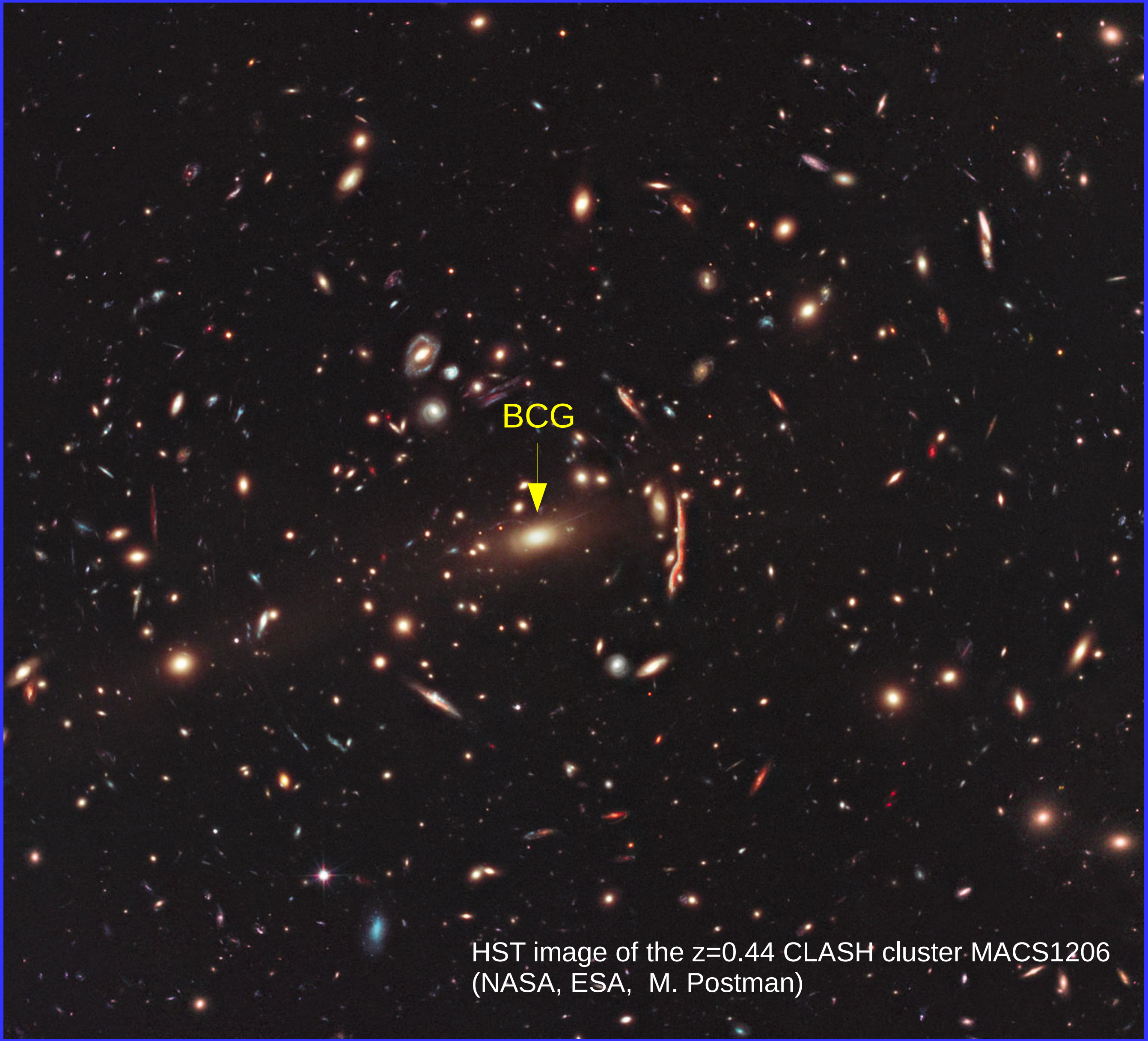
What are clusters of galaxies?



Dark Matter dominates

Baryons are mostly in the form of a diffuse, hot, X-ray emitting gas,

but at the cluster center the stellar component of the Brightest Cluster Galaxy (BCG) dominates (in many clusters)



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

Clusters probe Dark Matter

1933

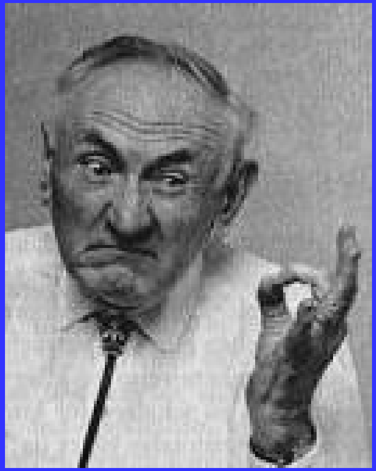
Die Rotverschiebung von extragalaktischen Nebeln
von **F. Zwicky.**
(16. II. 33.)

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

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

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]

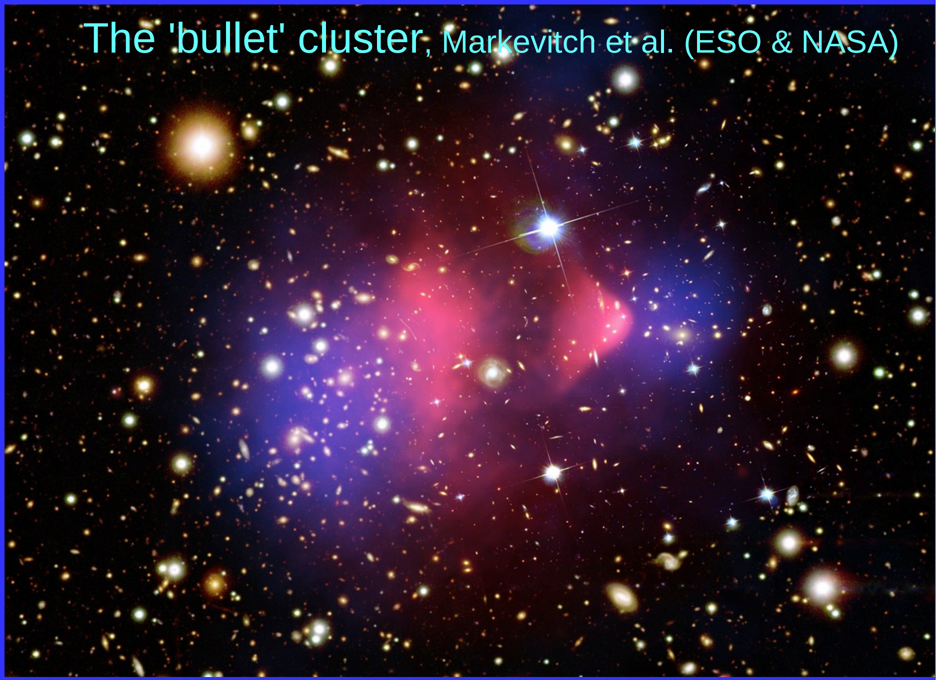
Douglas Clowe[2]
Institut für Astrophysik und Extraterrestrische Forschung der Universität Bonn, Auf dem Hügel 71, 53121 Bonn, Germany; dclowe@as.arizona.edu

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


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

Clusters probe Dark Matter

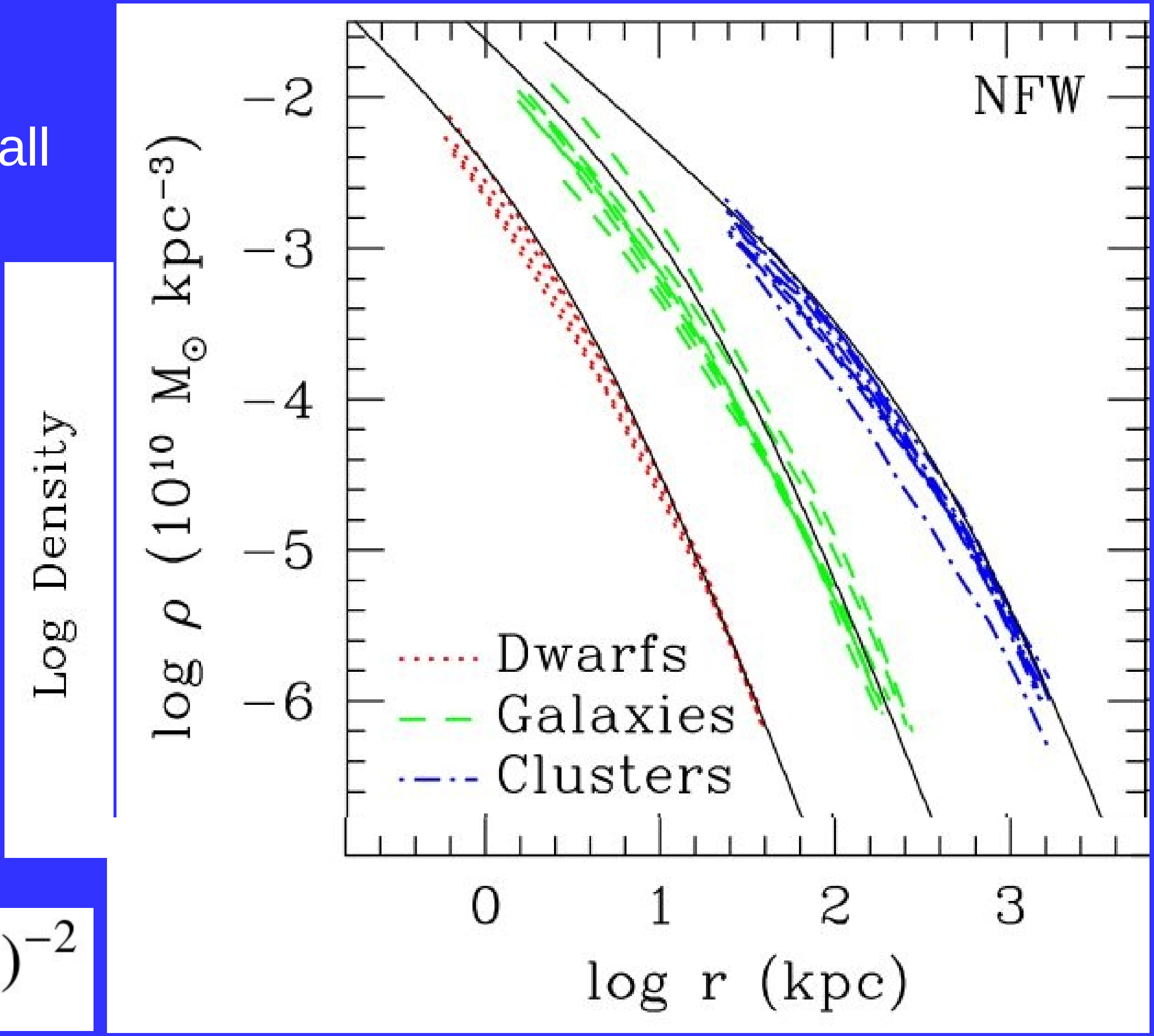
Is there **A UNIVERSAL DENSITY PROFILE** of clusters?

Navarro, Frenk & White 97:

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



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



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

(Navarro+04)

Clusters probe Dark Matter

Since clusters are DM dominated, their mass distribution should be similar to the NFW shape found in collisionless Cold DM cosmological simulations

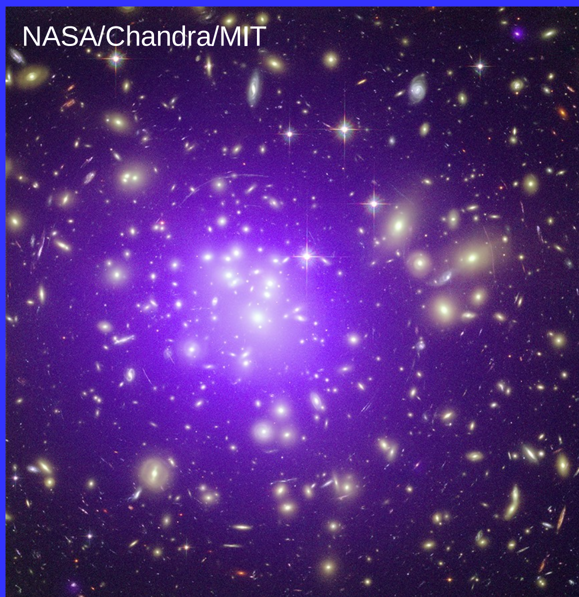
If cluster DM distribution deviates from NFW shape,
DM may not be Cold (Warm DM; *Bode+01*),
or it may be collisional (self-interacting DM; *Spergel+Steinhardt 00*)

However, other cosmological simulations have shown that the DM distribution can deviate from the NFW shape because of physical processes:

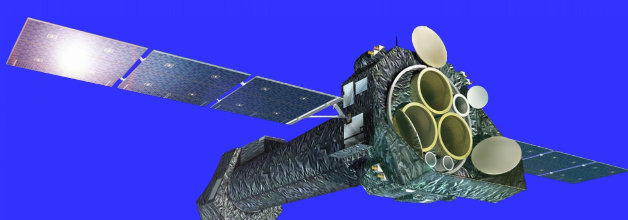
- adiabatic contraction *(Blumenthal+86, Gnedin+04),*
- mass accretion *(Laporte+12, Diemer+Kratsov 14, Schaller+15),*
- dynamical friction *(El-Zant+01, +04),*
- AGN feedback *(Navarro+96, Ragone-Figueroa+12, Peirani+17)*

Since these processes have different impact at different cosmological times, while the DM characteristics are not expected to change with cosmological time, **it is important to study the DM distribution in clusters at different redshifts**

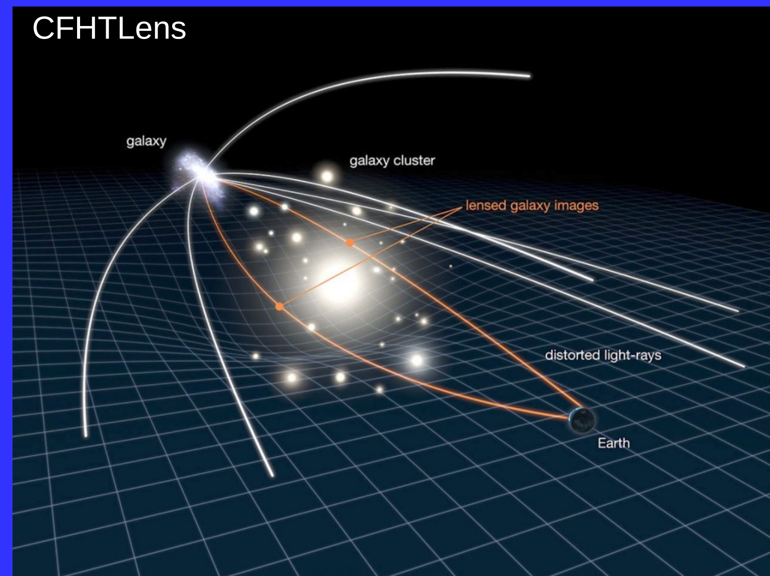
How to determine cluster mass profiles



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

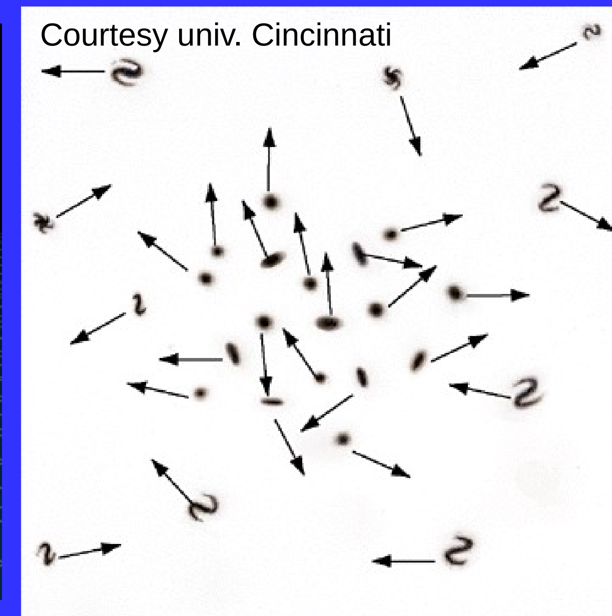


XMM-Newton space telescope



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

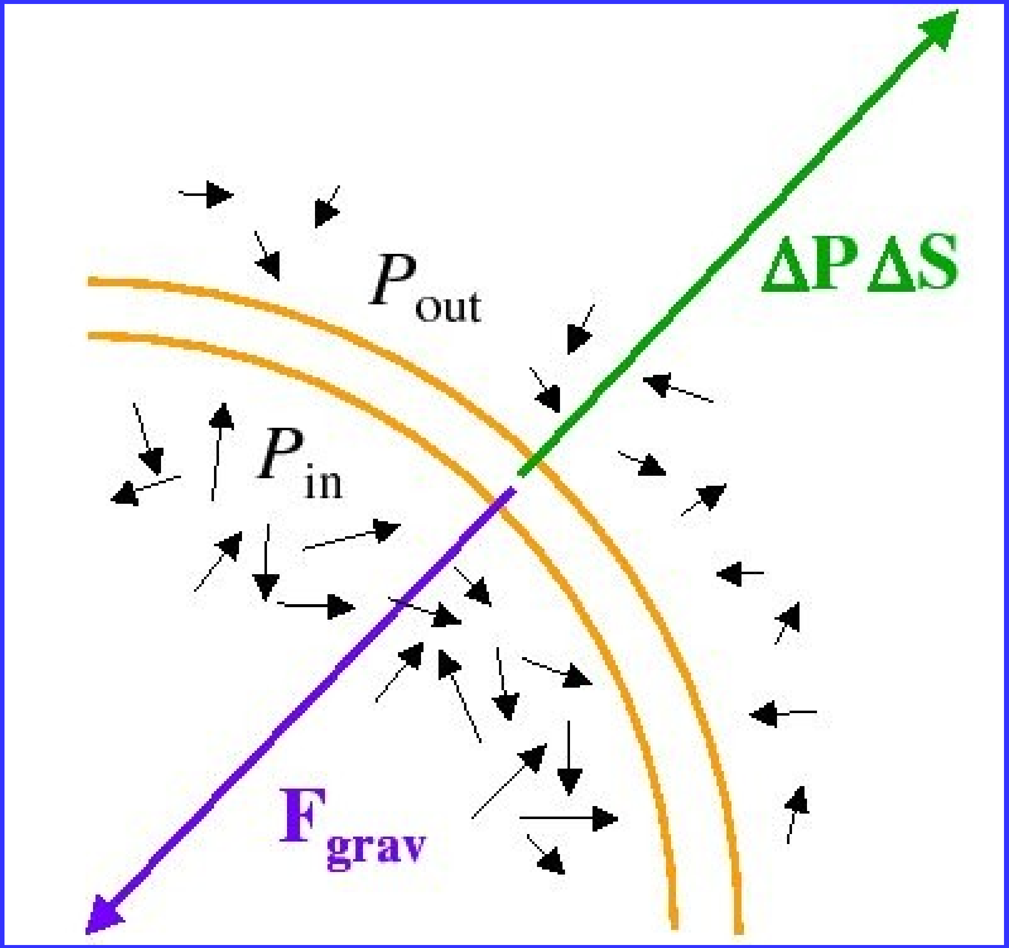
Hubble space telescope



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

Very Large Telescope

How to determine cluster mass profiles

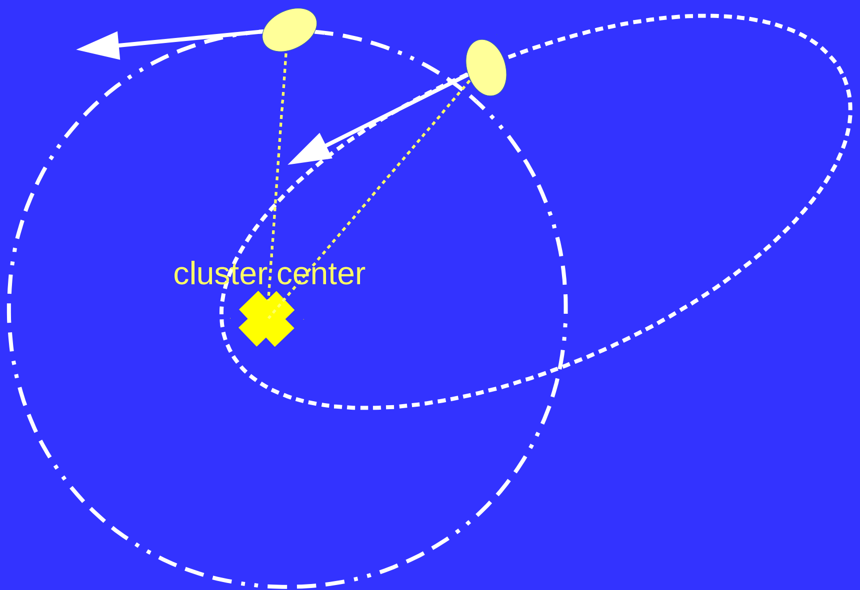


(courtesy of G. Mamon)

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)



How to determine cluster mass profiles

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

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

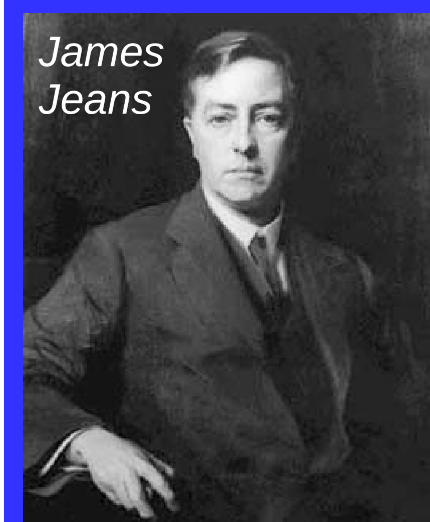
Mass profile

3D number density profile

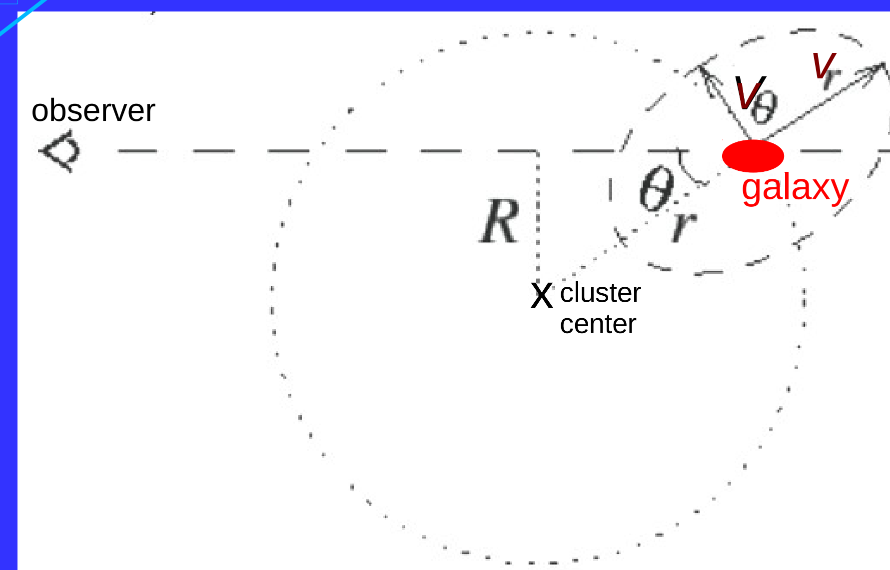
Velocity dispersion profile along the radial direction, r

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):

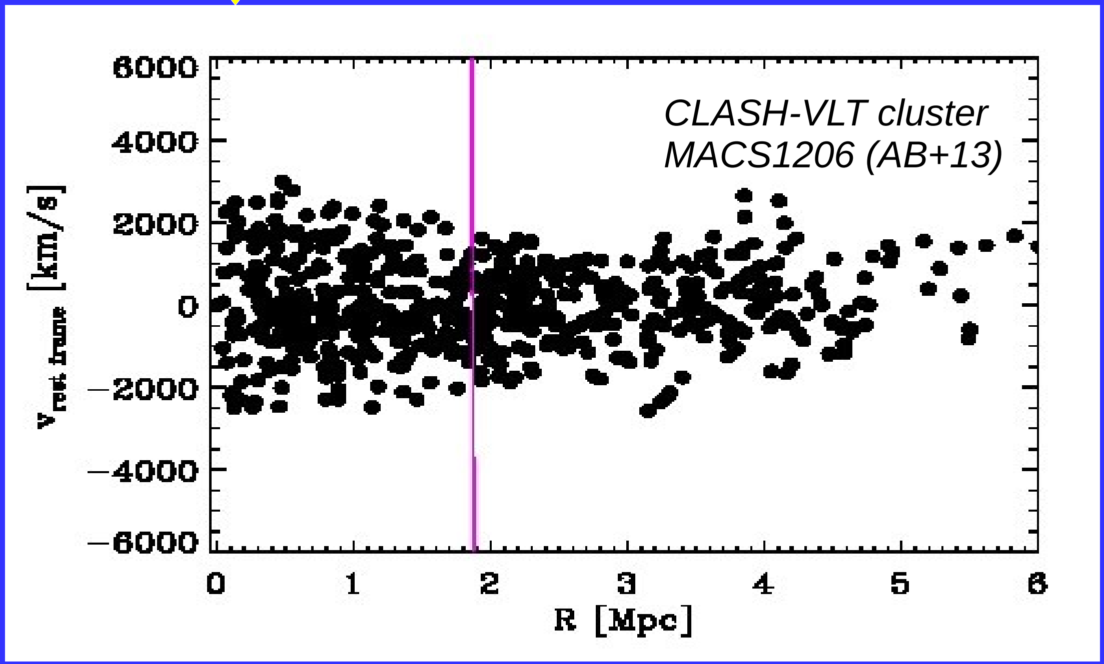
***M**ass-**A**nisotropy **D**egeneracy*
*(aka Jeans' **MAD**ness)*

How to determine cluster mass profiles

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

Modelling
Anisotropy and
Mass
Profiles of
Observed
Spherical
Systems



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

Tested on cosmological numerical simulations – Tania Tagliaferro's talk

How to determine cluster mass profiles

MAMPOSSt constrains parameters of models:

Mass M(<r) models, differing for inner / outer slope, γ_0 / γ_∞ :

(1) ***SIS:*** $\gamma_0 = 0.0$, $\gamma_\infty = 2$ *...softned isothermal, cored central density, slow decrease at large radii*
(2) ***gNFW:*** $\gamma_0 = 0.0$, $\gamma_\infty = 3$ *...generalized NFW, cored central density*
(3) ***gNFW:*** $\gamma_0 = 0.5$, $\gamma_\infty = 3$ *...generalized NFW, central density less cuspy than NFW*
(4) ***NFW:*** $\gamma_0 = 1.0$, $\gamma_\infty = 3$ *...NFW, central density is cuspy*
(5) ***gNFW:*** $\gamma_0 = 1.5$, $\gamma_\infty = 3$ *...generalized NFW, central density cuspier than NFW*
(6) ***Burkert:*** $\gamma_0 = 0.0$, $\gamma_\infty = 3$ *...central density has a core, similar to model (1)*
(7) ***Hernquist:*** $\gamma_0 = 1.0$, $\gamma_\infty = 4$ *...central density like NFW, but steeer decrease at large radii*

gNFW: $\rho = \rho_0 \, (r/r_s)^{-\gamma} \, (1+r/r_s)^{\gamma-3}$ (≡NFW if γ=1)

The spectroscopic data-sets

0.0<z<0.1;
PI: G. Fasano & B. Poggianti
WYFFOS@WHT +
2dF@AAT *(Cava+09)*
+ literature data +
AAOmega@AAT *(Moretti+17)*
⇒ ~ 9000 cluster members with z in 68 clusters

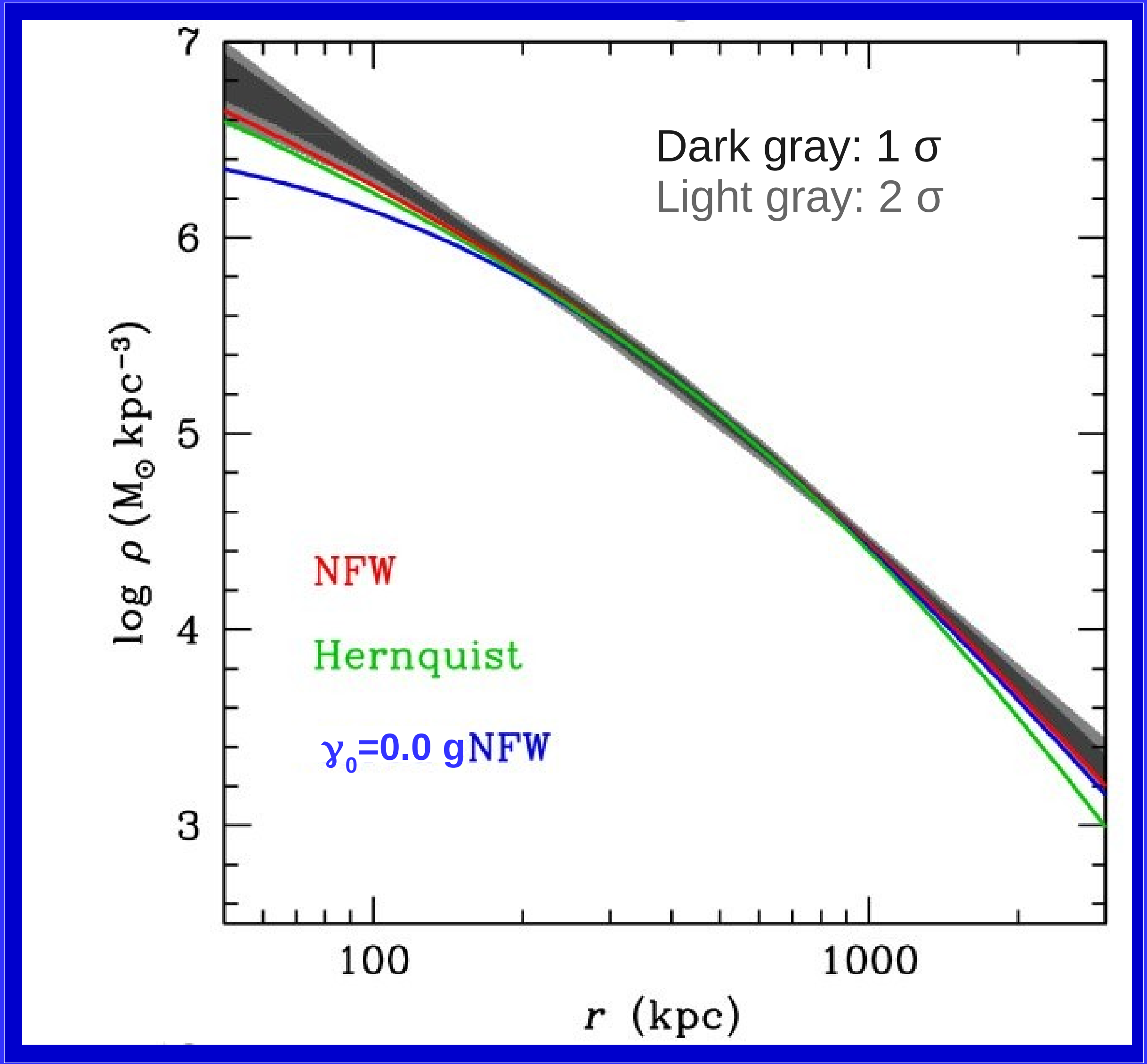
0.2<z<0.5; PI: P. Rosati & M. Nonino
VIMOS@VLT *(Rosati+14)* + MUSE@VLT *(Caminha+17)*
⇒ ~ 8000 cluster members with z in 12 clusters
+ velocity dispersion profiles of 7 Brightest Cluster Galaxies

GOGREEN
Gemini Observations of Galaxies in Rich Early ENvironments

0.9<z<1.5; PI: M. Balogh

GMOS@Gemini N+S *(Balogh+17)*
⇒ ~ 500 cluster members with z in 14 clusters

The cluster *total* mass profile: results

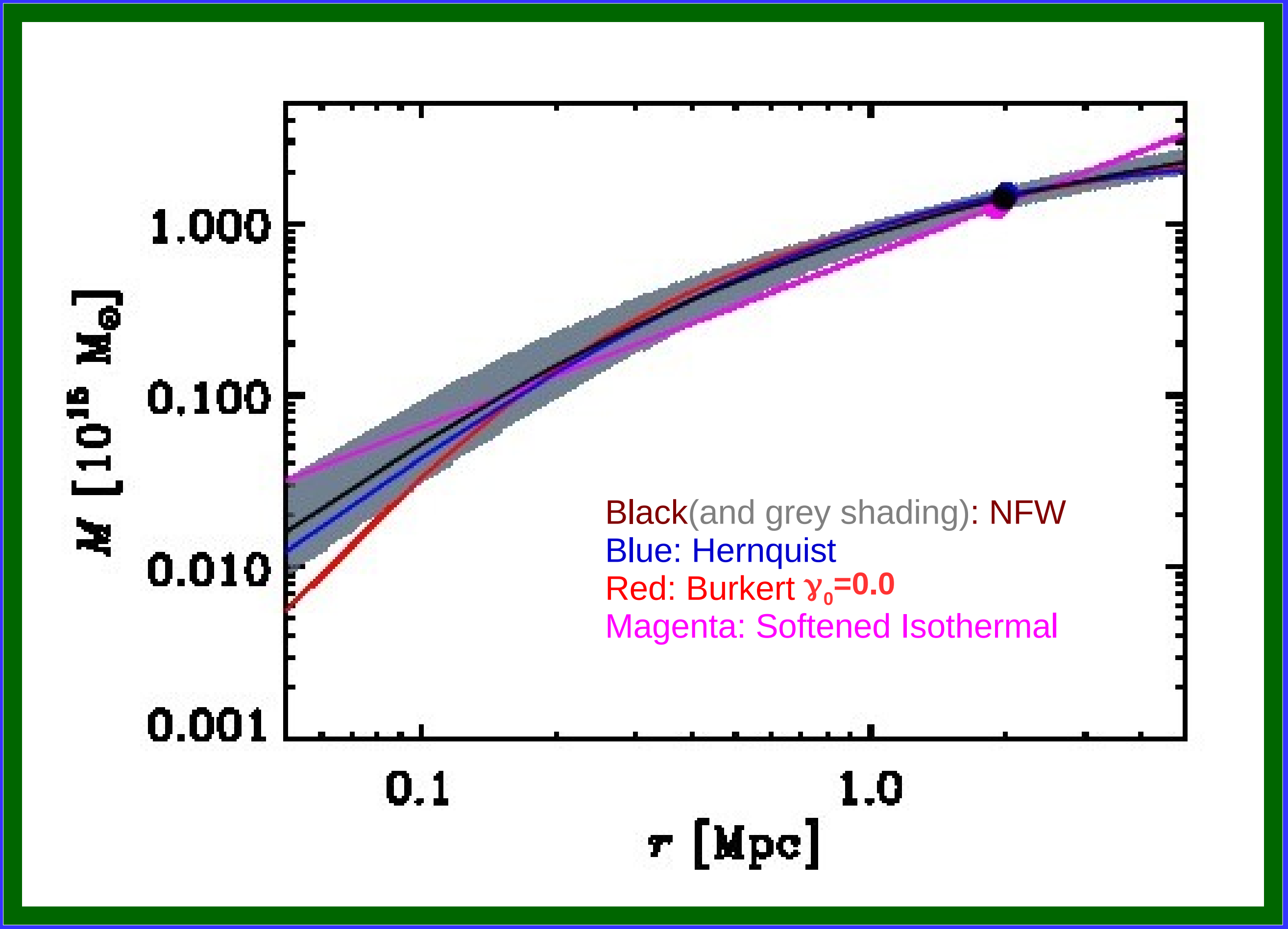


Mamon+19: total mass density profile ρ(r) of low-z clusters (WINGS)

low redshift:

Total ρ(r) inner slope steeper than NFW,
γ_{total} = 1.6 ± 0.4

The cluster *total* mass profile: results

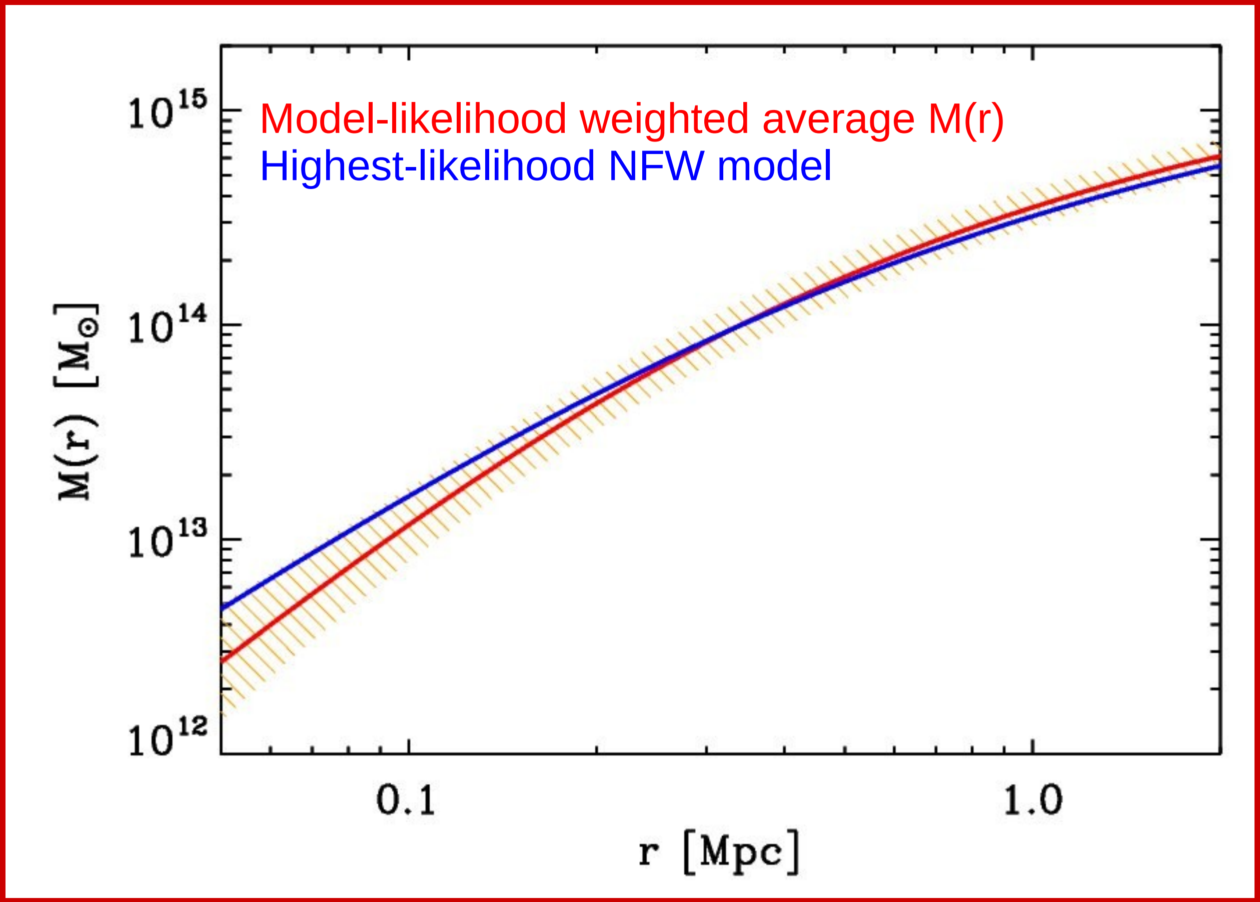


AB+13: total M(r) of a medium-z cluster (CLASH-VLT)

medium redshift:

Total M(r) consistent with NFW,
cored profiles ruled out
$\gamma_{total} \approx 1$

The cluster *total* mass profile: results



high redshift:

Total M(r) has flatter inner slope than NFW

$\gamma_{total} < 1$

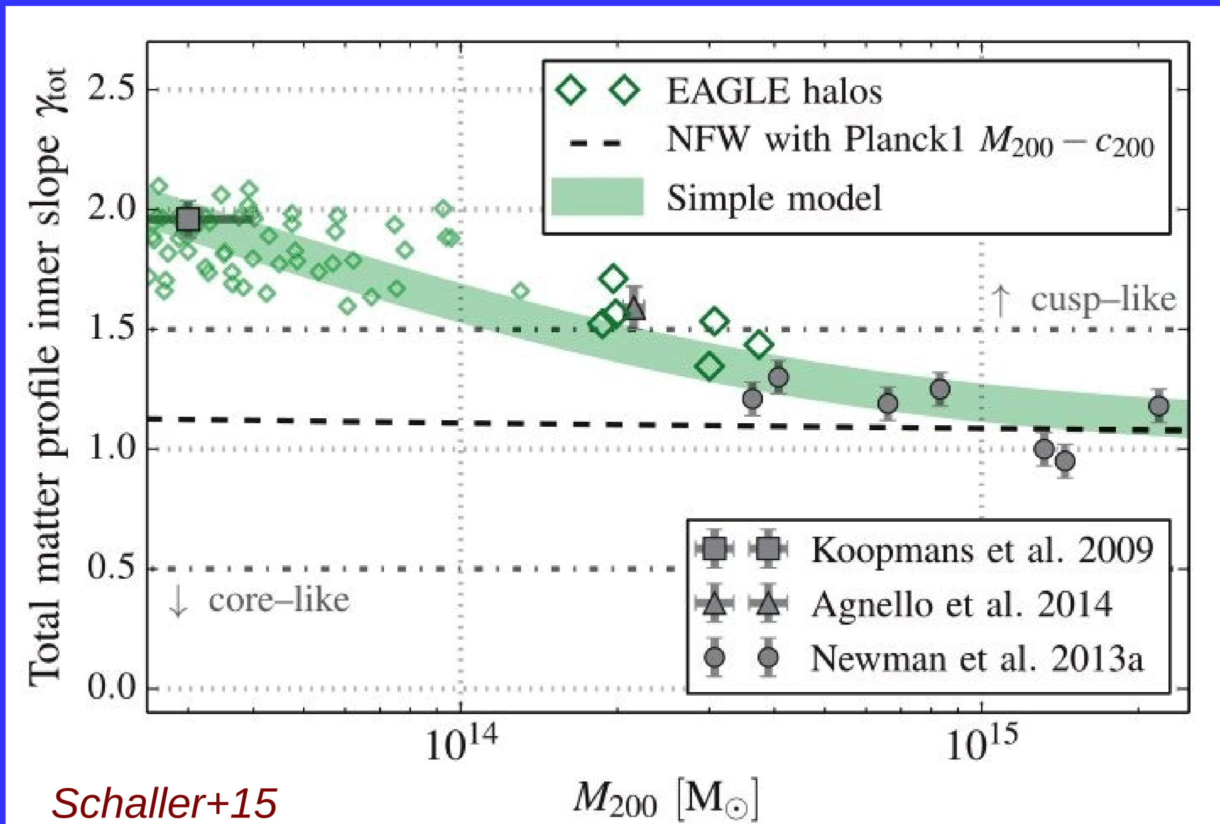
Highest-redshift determination of cluster mass profile (by any methodology)

AB+ in preparation: total M(r) of high-z clusters (GOGREEN)

⇒ *Apparent steepening of total mass density profile at r~0 with time: γ_{total} changes from ~0.5 at z~1 to 1.6 at z~0)*

Clusters probe Dark Matter

total



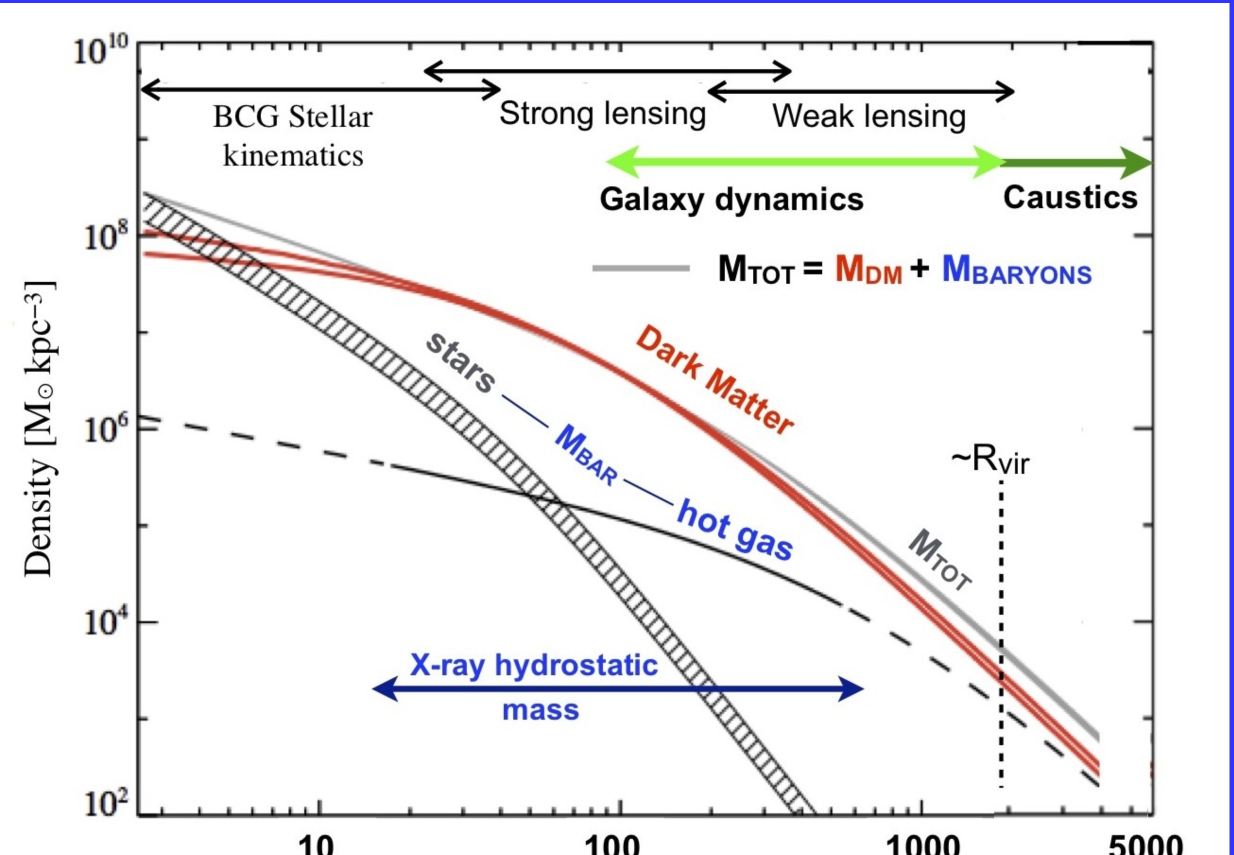
Schaller+15

EAGLE simulations (that include baryons) predict inner total matter slope $\gamma_{total} \geq 1$ (steeper than NFW) at low-/medium-z

Total matter = DM + *baryons* *(Brightest Cluster Galaxy, other galaxies, diffuse Intra-cluster gas)*

⇒ must subtract baryonic contribution from total M(<r) to get DM-only M(<r)

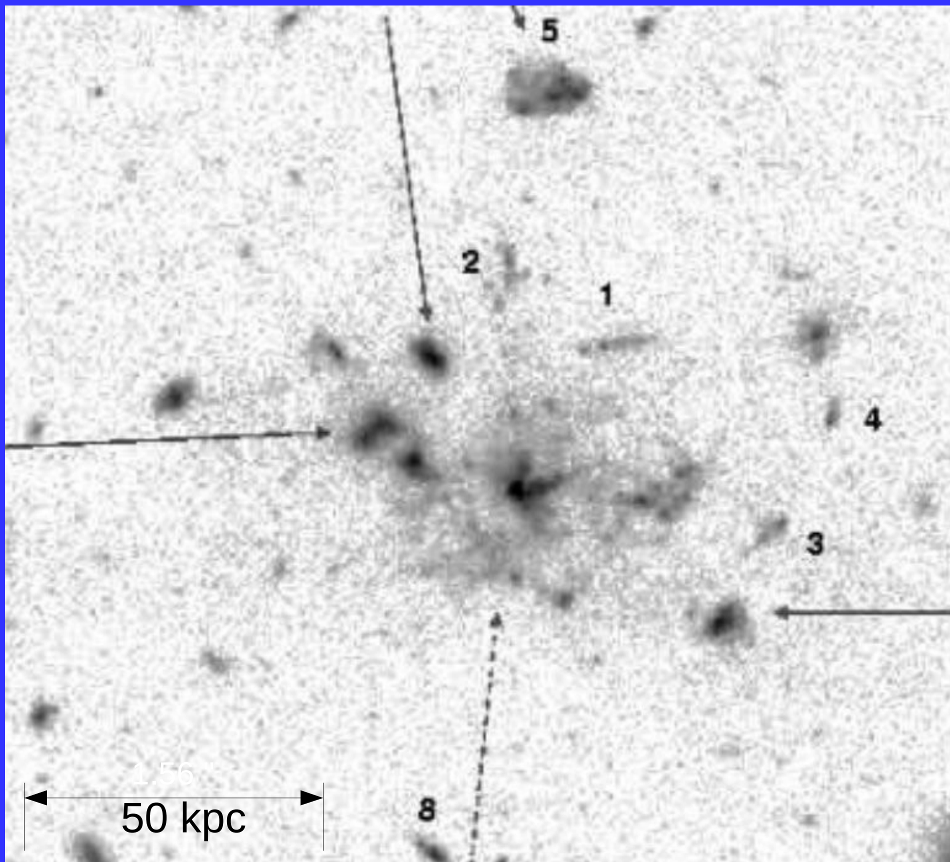
Clusters probe ~~Dark~~ total Matter



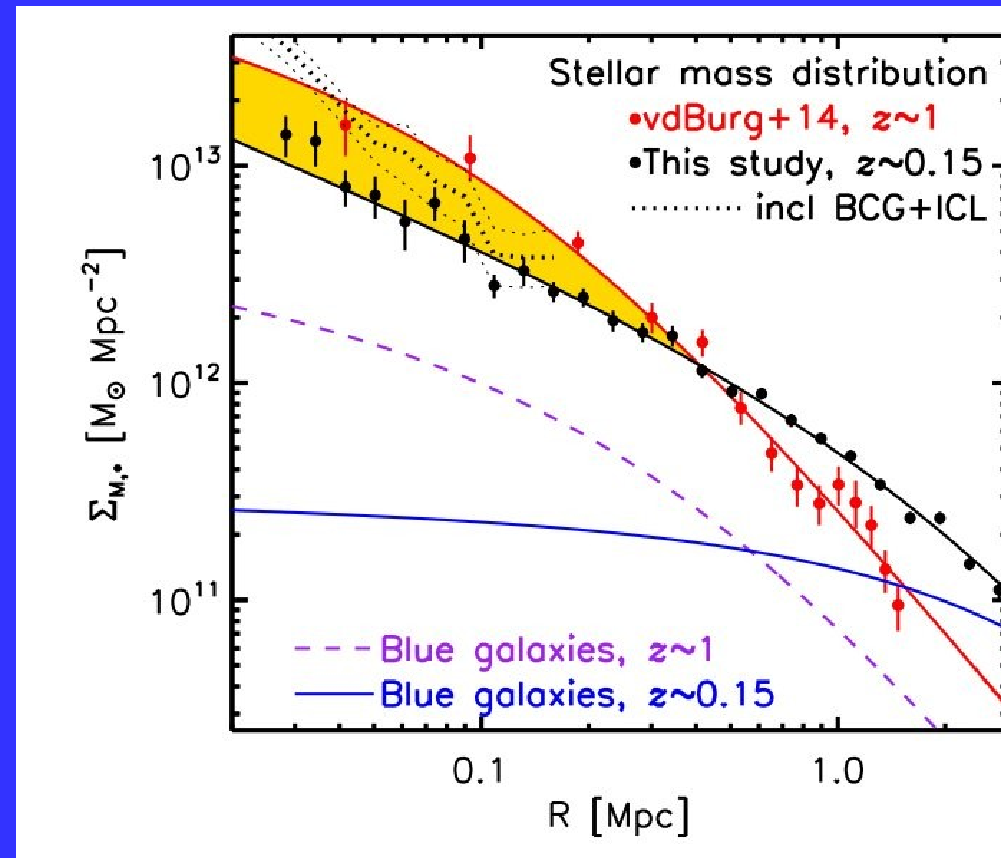
(courtesy P. Rosati)

Near the cluster center M(r) is dominated by the stellar mass of the **B**rightest **C**luster **G**alaxy
→ **must account for the BCG stellar mass to infer γ_{DM}, the inner slope of the DM M(r)**

The BCG assembly at the cluster center



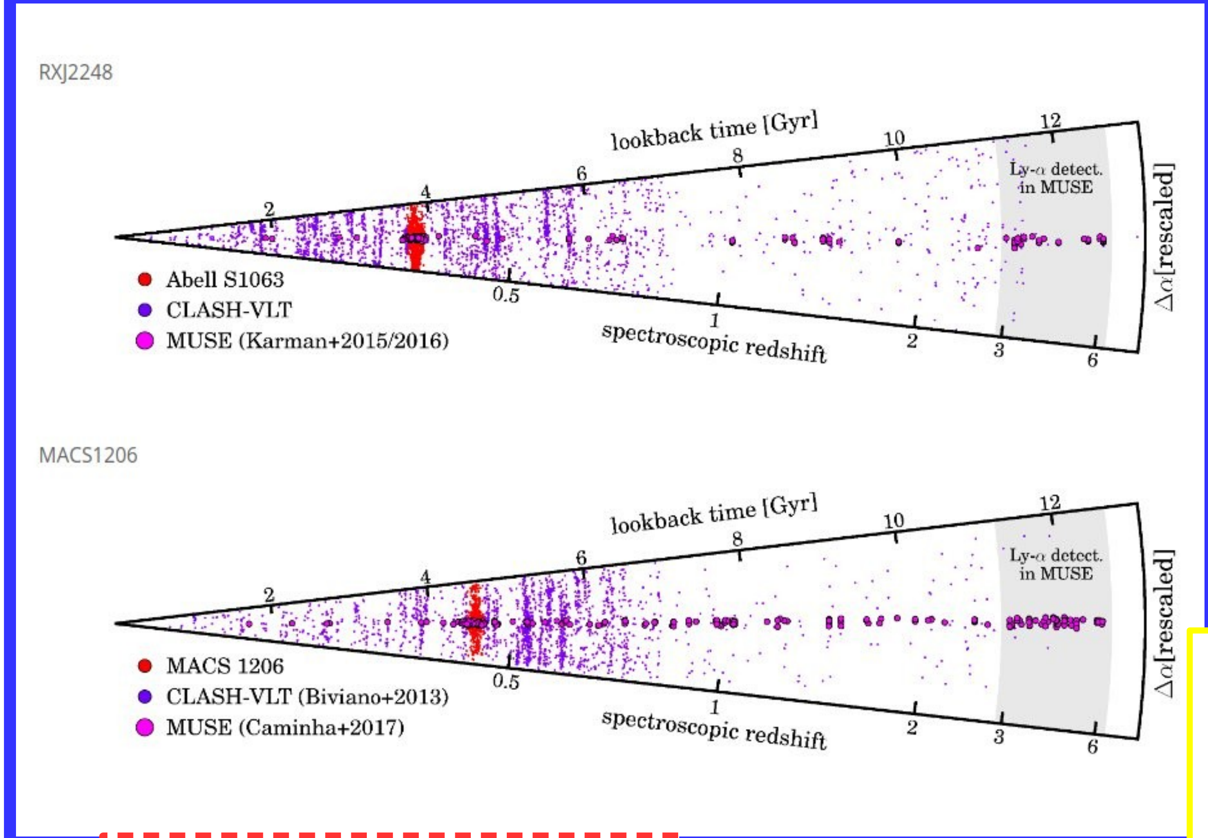
Miley+06: a BCG precursor identified in a proto-cluster environment at z=2.2: velocities of the small galaxies near the proto-cluster center indicate they will merge to form a giant galaxy (the BCG)



van der Burg+15: there is a lack of stellar mass near the cluster center at low-z w.r.t. high-z clusters, when the BCG is *not* accounted for, indicating that z~1 cluster galaxies will merge together to form the z~0 BCG

The increasing value of γ_{total} with time might be reflecting the growth of the BCG stellar mass, that at z~0 ends up dominating the total M(r) at r→0

Using the BCG kinematics to estimate γ_{DM}

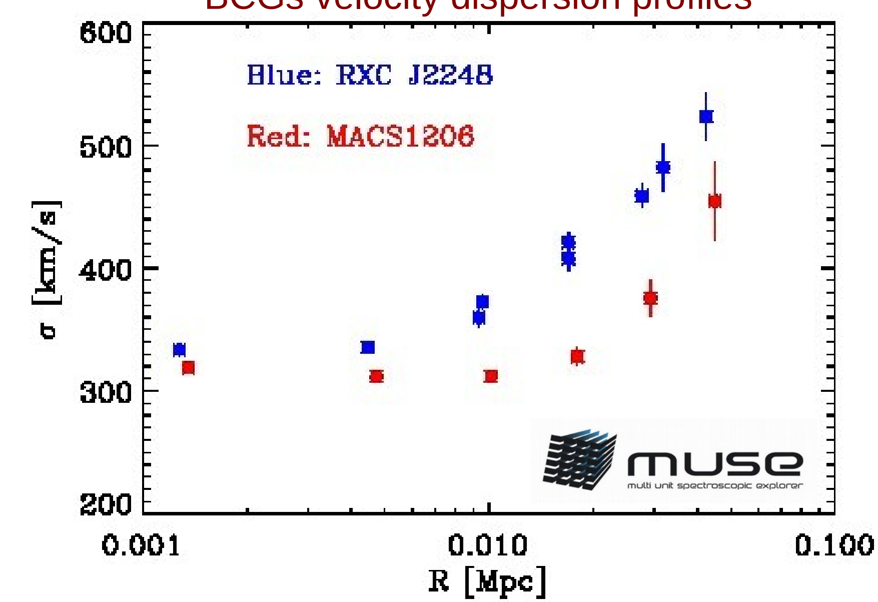


MUSE observations of the central regions of two clusters:

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

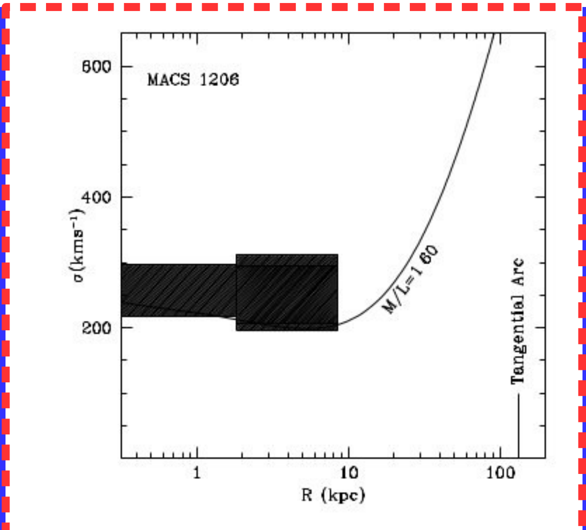
MACS1206.2-0847, <z>=0.440, r_{200}=2.0 Mpc, 600 members with z

BCGs velocity dispersion profiles



Quality of MUSE BCG velocity dispersion profiles is impressive!

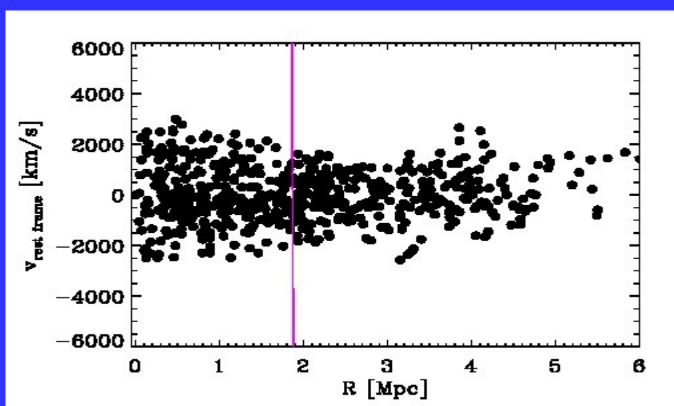
(Cmp to Sand+04 ESI at KeckII profile)



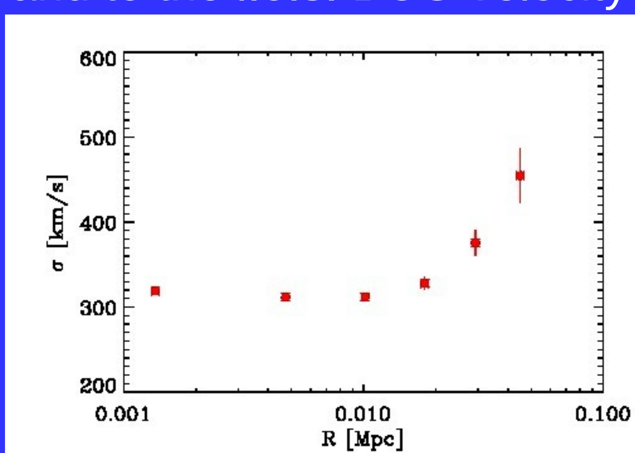
How to determine cluster DM profiles

Extension of MAMPOSSt to take into account simultaneously the constraints from the spatial and velocity distribution of cluster galaxies AND the BCG stars

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

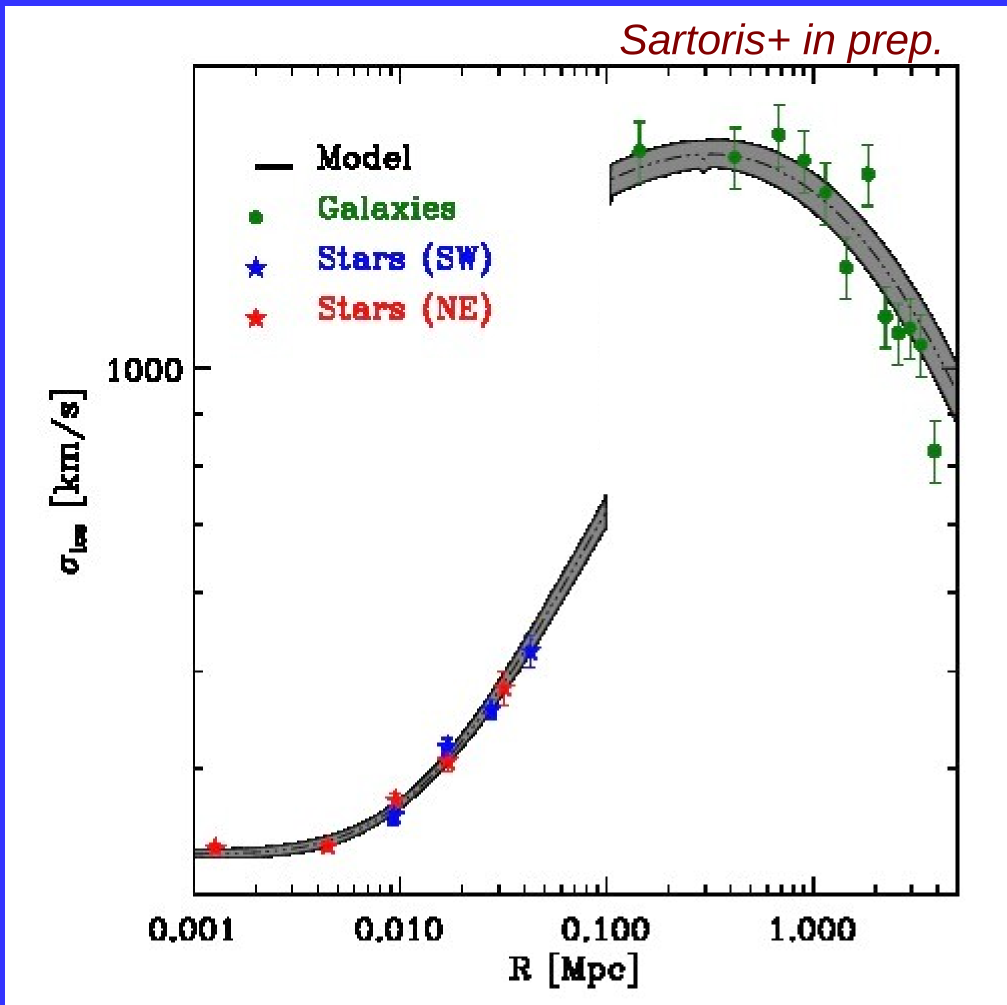
DM

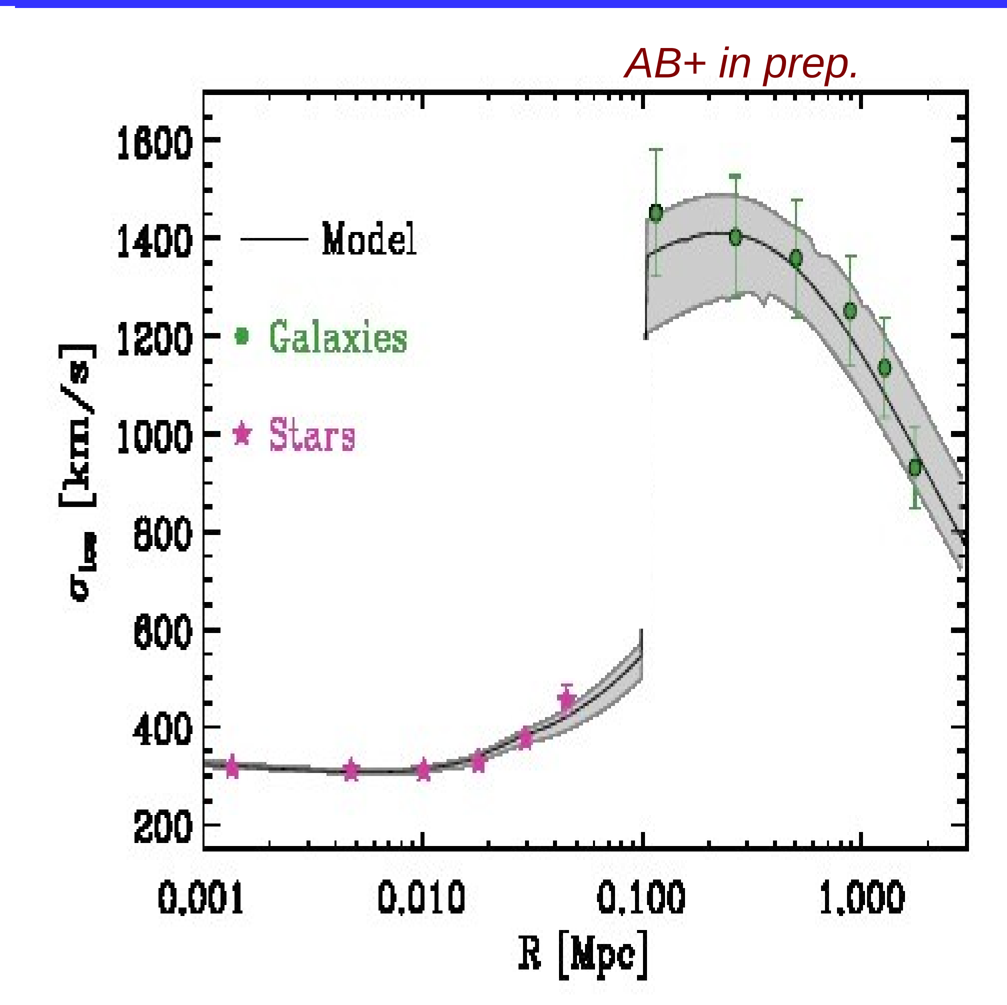
Intra-cluster gas

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

galaxies stellar mass

The cluster *DM* mass profile: results

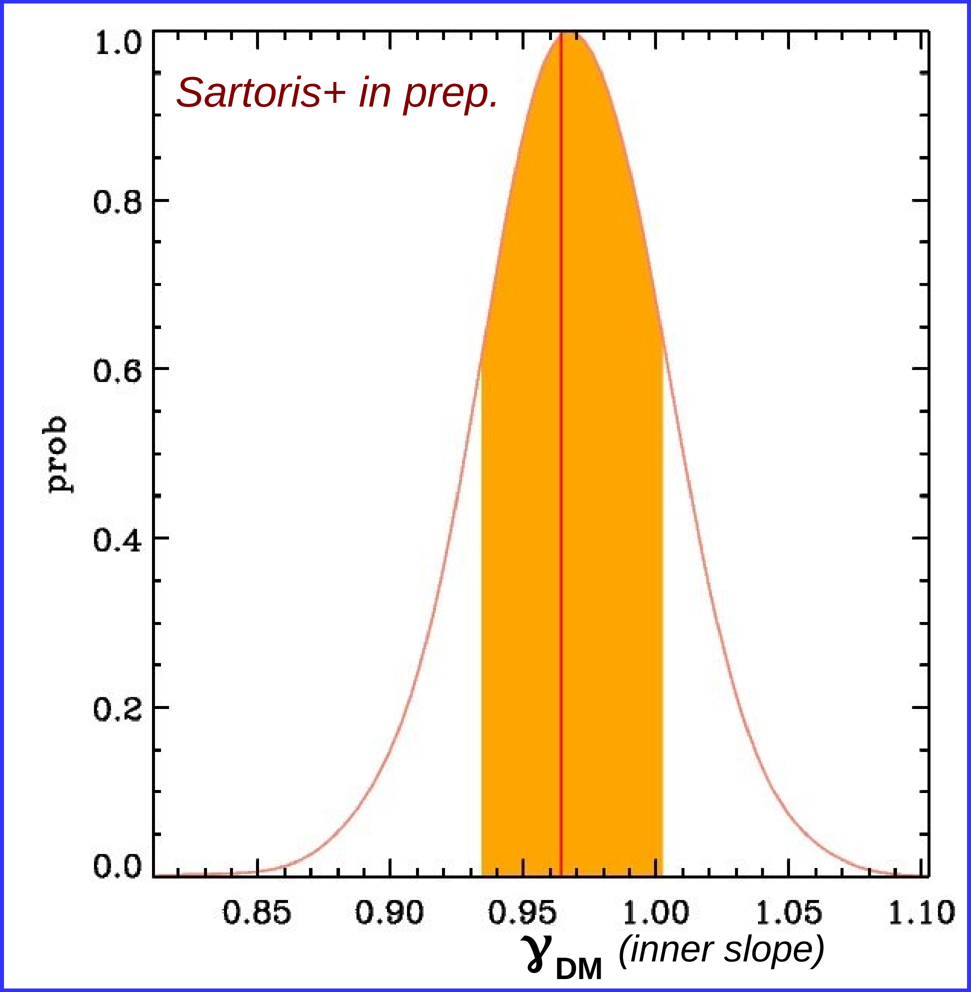


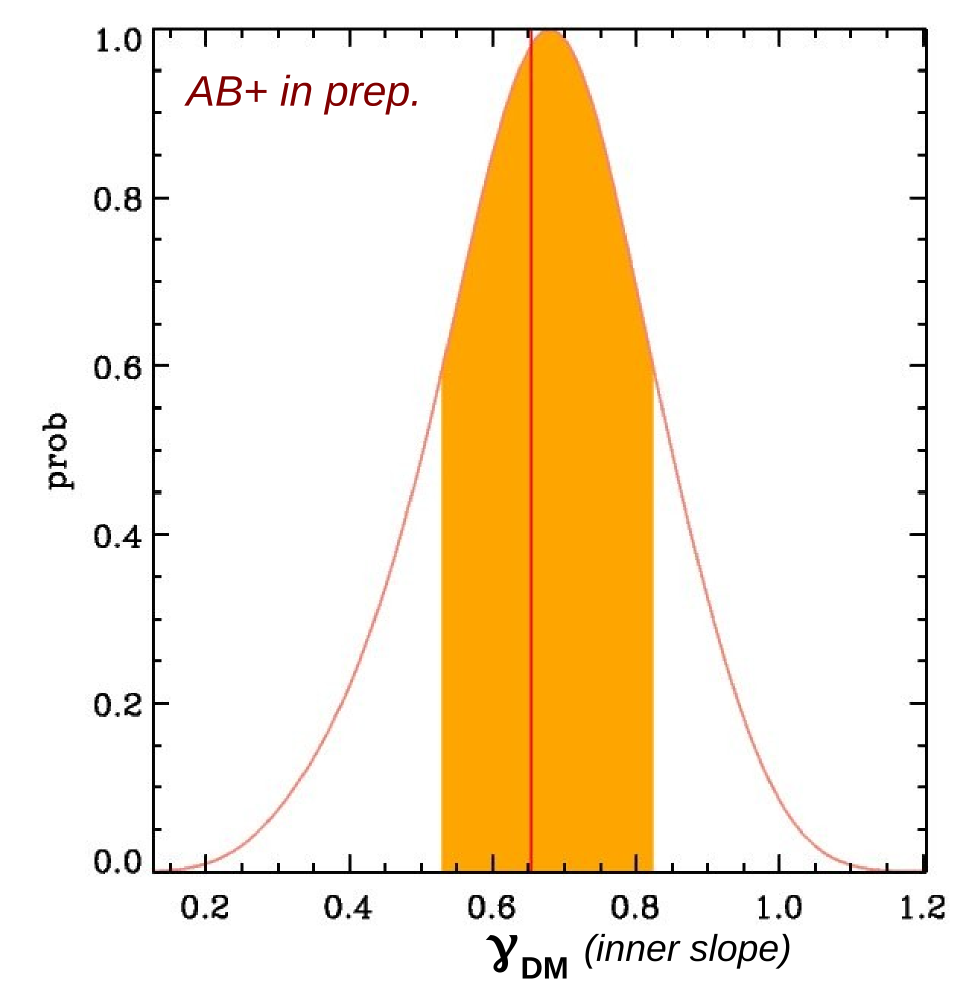


RXC J2248.7-4431, predicted velocity dispersion profile from the best-fit M(r) compared with the observed velocity dispersion profiles of cluster galaxies and the BCG

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

The cluster *DM* mass profile: results





RXC J2248.7-4431
*inner slope of **DM** ρ(r→0):*
γ_{DM} = -d ln ρ/ d ln r = 0.97 ± 0.04

fully consistent with NFW

MACS 1206.2-0847
*inner slope of **DM** ρ(r→0):*
γ_{DM} = -d ln ρ/ d ln r = 0.67 ± 0.15

***in*consistent with NFW at 2 σ**

The cluster *DM* mass profile: discussion

Different values of γ_{DM} of different clusters cannot be caused by different DM properties *(DM must be the same for all clusters)*

⇒ no support for alternative DM models

(such as, e.g., warm DM, Bode+01, or self-interacting DM, Spergel & Steinhardt 00)

Baryonic processes can change γ_{DM}:

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

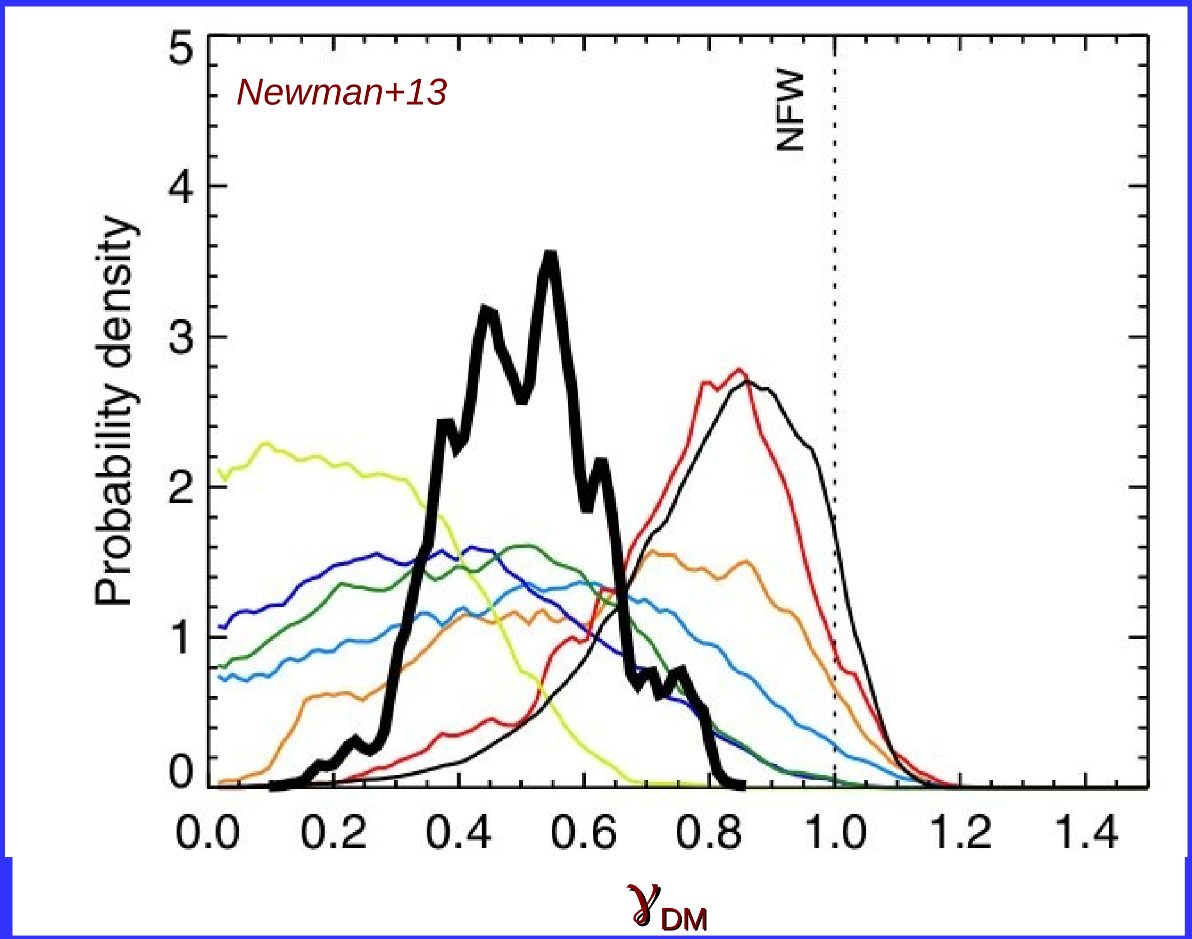
Dynamical friction *(El-Zant+01, +04)*
Collisionless mergers *(Laporte+12)*
AGN feedback *(Navarro+96, Ragone-Figueroa+12, Peirani+17)*
} $\gamma_{DM}<1$

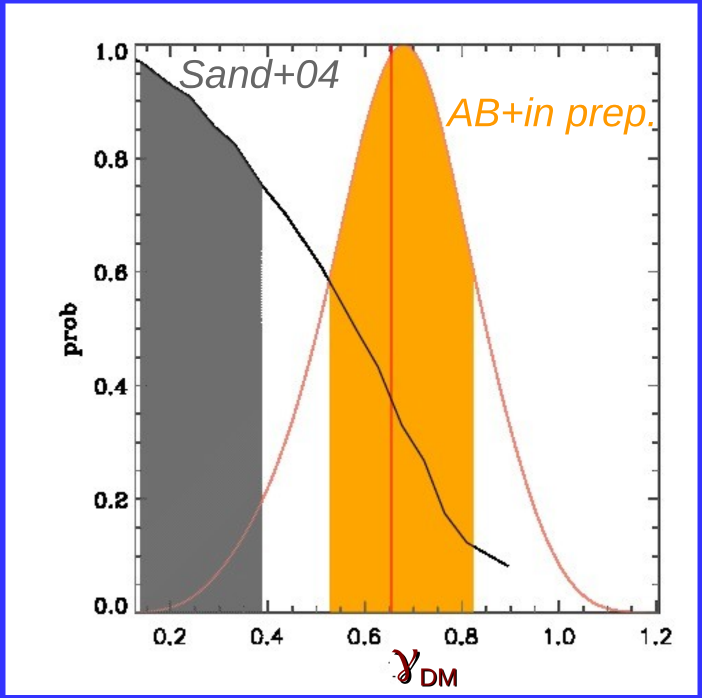
As a cluster goes through different evolutionary stages, γ_{DM} can differ for the same cluster at different times

The cluster *DM* mass profile: discussion

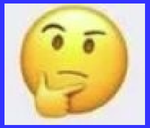
Previous investigations (Sand+04, 08, Newman+13; Annunziatella+17):

~all clusters have $\gamma_{DM}<1$



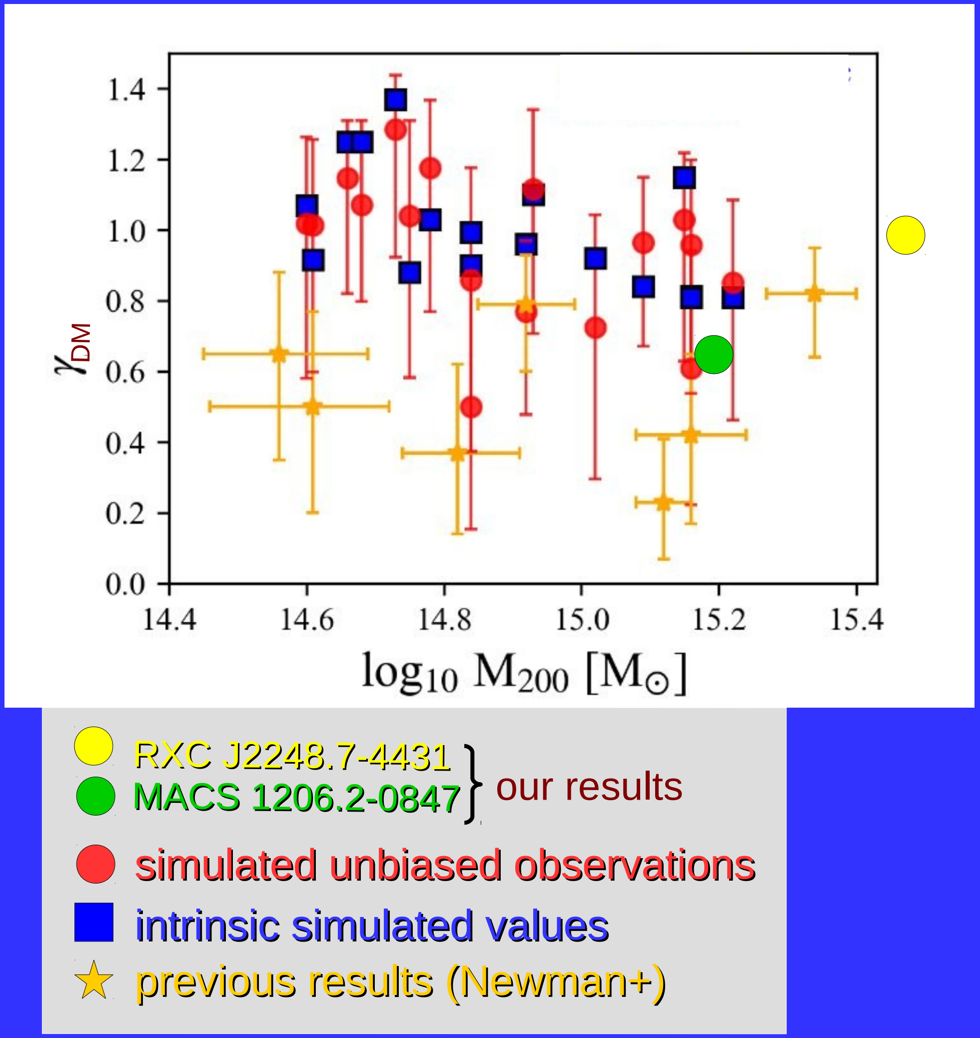


However… for the one cluster we have in common with Sand+ (MACS 1206.2-0847) we find a larger value for γ_{DM}



The cluster *DM* mass profile: discussion

Why do clusters analysed by *Newman+15, Sand+04, +08* all have small values of γ_{DM}?
→Look at the C-EAGLE simulations *(He+19)*



The problem is the covariance between different parameters of M(r) – to get the inner slope parameter γ_{DM} right, one needs to estimate the mass profile scale radius (r_{-2}) right.

MAMPOSSt allows us to estimate r_{-2} but the strong lensing measurements of Newman+ and Sand+ might be in trouble *(because information is needed well beyond the cluster central region)*

Correcting the r_{-2} estimates of Newman+ and Sand+ gives values of γ_{DM} close to the simulated ones (and ours own)

Summary

- Cluster ρ(r) is ~**NFW from z~0 to z~1**; no well-formed cluster is observed at z>2: ⇒ NFW profile must establish in ≤2 Gyr (via violent relaxation?, *Lynden-Bell 1967*)
- Inner slope $\gamma = -d \ln \rho / d \ln r$: must distinguish ***total*** γ_{total} from ***dark*** matter γ_{DM}, **BCG stellar mass is important** at the center
- Cluster **total** ρ(r) seems to get steeper near the center with time, this might be **related to the BCG formation**
- **Different DM γ_{DM}** for different clusters:

  can't be related to the nature of DM,
  must be due to different importance of **baryonic processes** such as:

  - central condensation of cooled gas ⇒ $\gamma_{DM} > 1$
  - dynamical friction, AGN feedback ⇒ $\gamma_{DM} < 1$

  and/or: different dynamical status (ongoing/past major? merger)

But beware of observational systematic errors!

Perspectives

a) Determine DM ρ(r) inner slopes of more clusters

to see if γ changes with cluster and BCG properties

- 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?*

b) 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 and BCG properties

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

¡Muchas gracias!

Cúmulo de galaxias

Cúmulo de lobos marinos