XXXII Canary Islands Winter School of Astrophysics

Galaxy clusters in the local Universe

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Lecture 2:

Internal structure

Internal structure

“Clusters of galaxies are the largest virialized objects in the Universe”

How do we know?

Internal structure

*"Clusters of galaxies are the **largest virialized** objects in the Universe"*

What about Superclusters?

Ann. Rev. Astron. Astrophys. 1983. 21 : 373–428

SUPERCLUSTERS

J. H. Oort

Sterrewacht Leiden, Leiden, The Netherlands

Astron. & Astrophys. 32, 197—202 (1974)

The Nature of the Distribution of Galaxies*

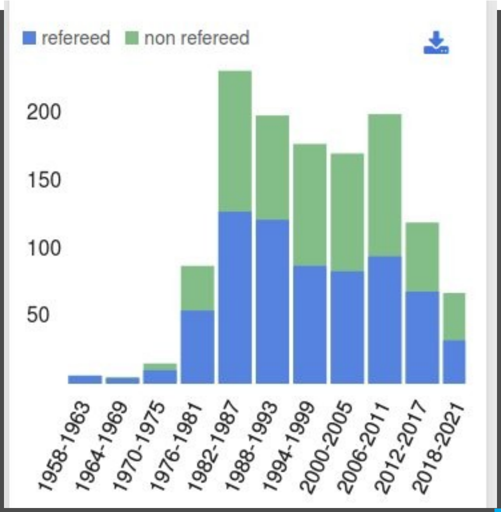
P. J. E. Peebles
University of California, Berkeley, and Joseph Henry Laboratories, Princeton University

Received January 29, 1974

Summary. A striking result has emerged from estimates of the covariance function for the distribution of galaxies. Within the limits of random and systematic errors, there is no evidence of anti-correlation of galaxy positions on any observed scale – there are not holes around clusters. Rather, the covariance function varies as a simple power law over a large range of the argument. To the accuracy we can estimate it, this statistic gives no evidence of a natural division between groups and clusters of galaxies, or between clusters and superclusters.

Key words: galaxies – clusters of

Publications with the word 'supercluster' in their title



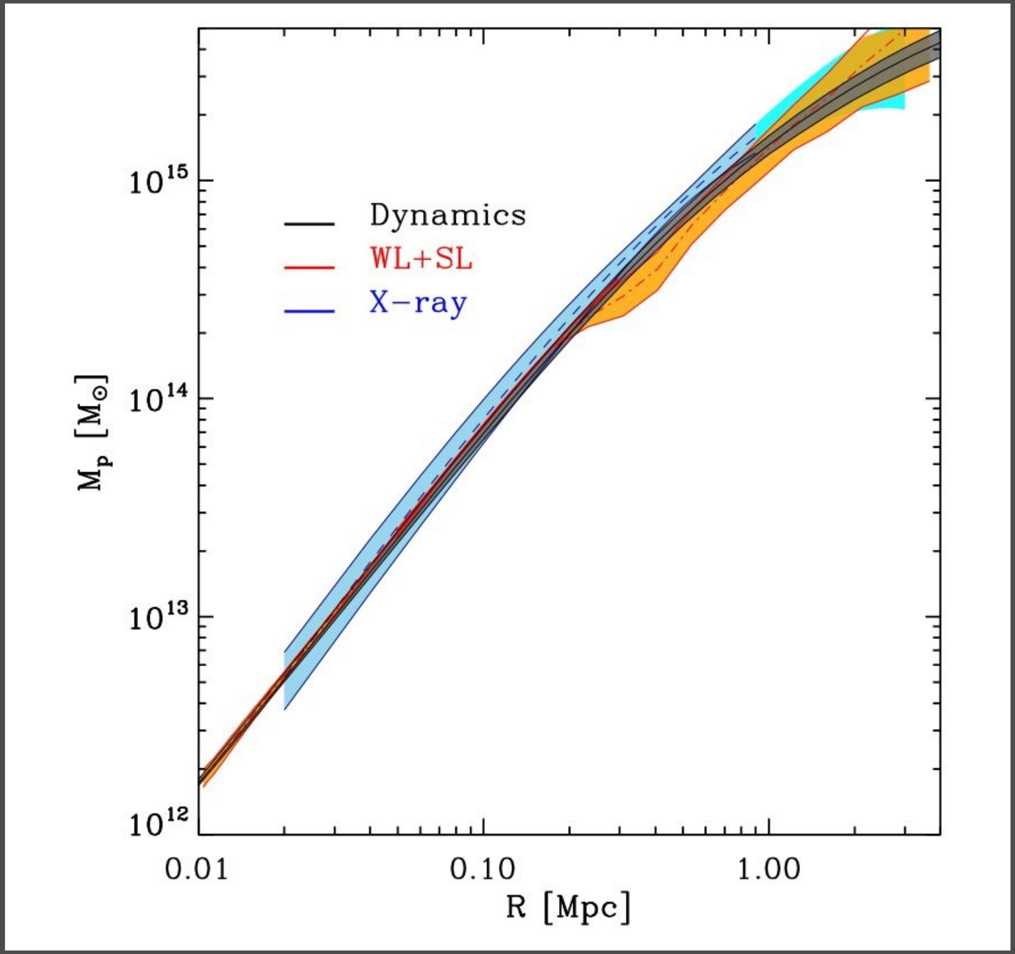
Einasto et al. (2021):

The largest systems in the cosmic web that may eventually become gravitationally bound are galaxy superclusters

Internal structure

*“Clusters of galaxies are the largest **virialized** objects in the Universe”*

Superclusters are not virialized; what about clusters?



Sartoris, AB, et al. (2020)

Comparison of mass profiles for clusters with good spectroscopic and imaging data (**CLASH-VLT**, *Rosati et al. 2014*) shows that mass profile estimates based on gravitational lensing (that do not require dynamical equilibrium) agree with mass profile estimates that are based on the hypothesis of dynamical equilibrium.

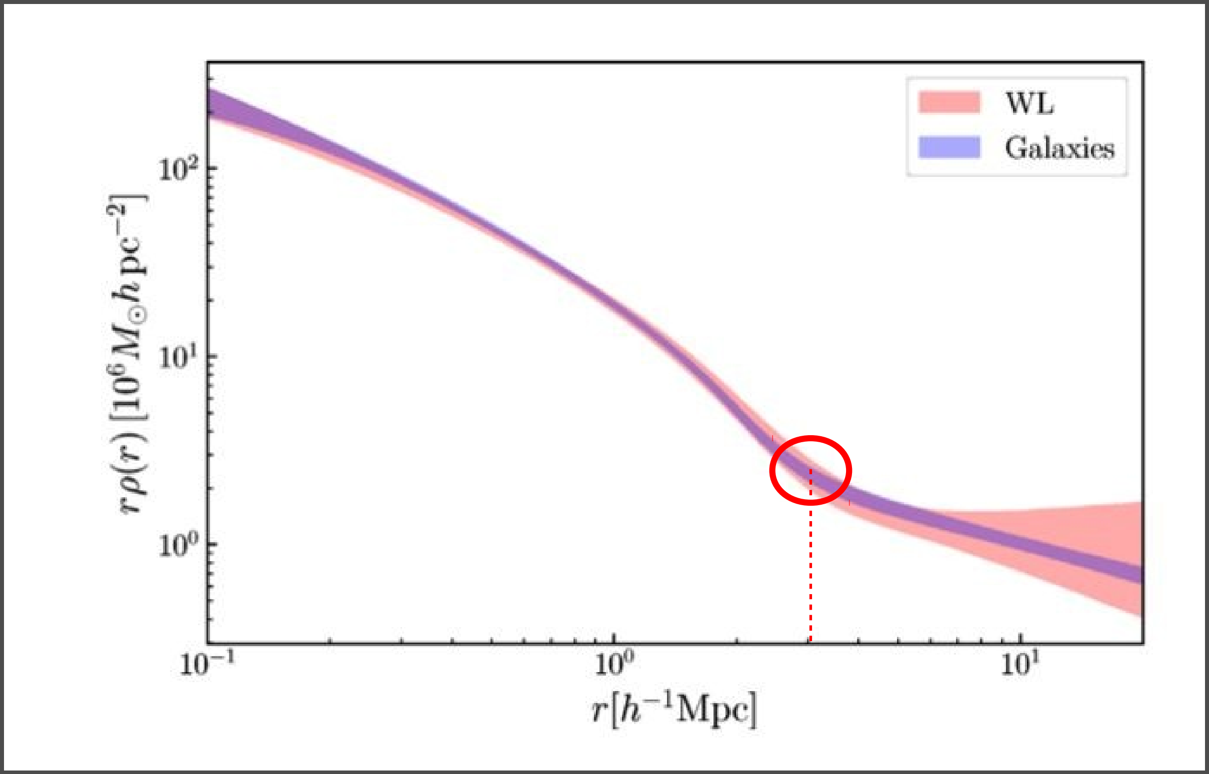
Internal structure

*“Clusters of galaxies are the **largest** virialized objects in the Universe”*

So, clusters are virialized; but how large are they?

Outer boundary: **the splashback radius r_{sp}** *(Diemer & Kravtsov 2014)*, a sharp drop in the density profile near the fapocenters of infalling matter (galaxies)

Shin et al. (2021):
r_{sp} detection using
Dark Energy Survey data
around SZ-selected clusters



Internal structure

Other characteristic radii of clusters of galaxies

$\mathbf{r_\Delta}$: the radius of a sphere with an average over-density $\Delta\rho_c$ or $\Delta\rho_m$ (e.g.: r_{200c}, r_{200m}), often referred to as "**the virial radius**",
from the solution to the collapse of a spherical top-hat perturbation under the assumption that the cluster has just virialized *(Peebles 1980)* with:
$\Delta = 18\,\pi^2 - 82/x - 39/x^2$, $x = 1+\Omega_0/\Omega_\Lambda(1+z)^3$ *(Bryan & Norman 1998)*

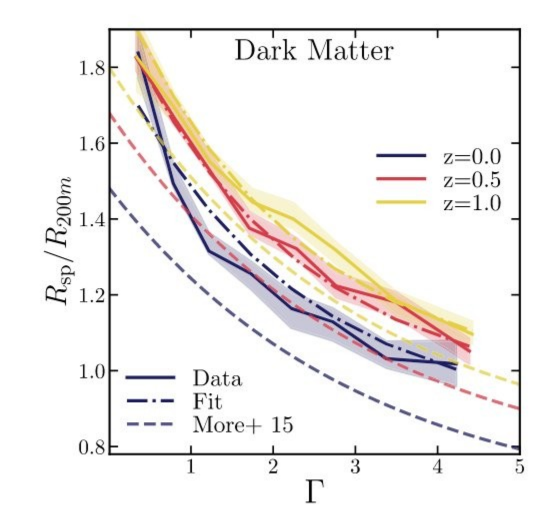
$\mathbf{r_{-2}}$: the radius where the logarithmic derivative of the cluster density profile $d \log \rho / d \log r = -2$

$\mathbf{r_{sh}}$: accretion shock radius, where the low-density pristine gas in the void regions infall on to the cluster potential and is shock heated.
Predicted by theory and numerical simulations, not observed yet.

Internal structure

Characteristic radii of clusters of galaxies

r_{sp}: an indicator of the mass accretion rate Γ of clusters of galaxies *(Diemer & Kravtsov 2004)*

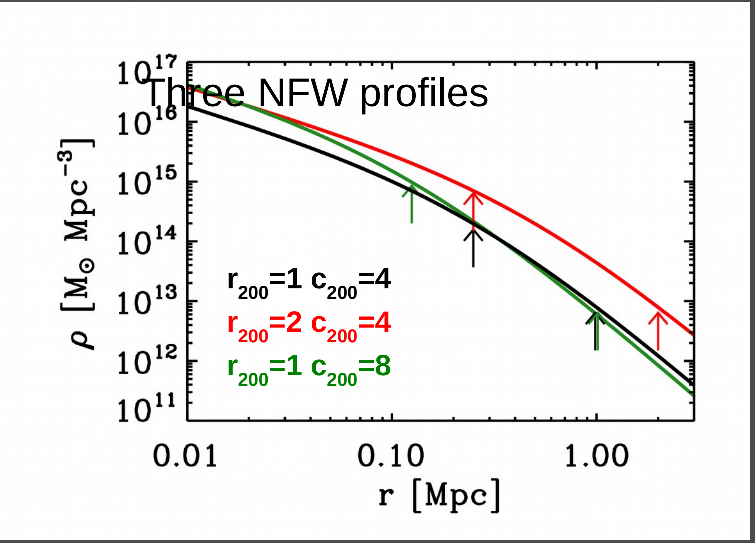


O'Neil et al. 2021
IllustrisTNG sims

r_Δ: directly related to the mass of the cluster via: $M_\Delta \equiv H_z^2\, r_\Delta^3 / (2\, G)$

r_{-2}: measures the shape of the mass density profile ρ(r), in combination with r_Δ via the concentration parameter:

$$c_\Delta \equiv r_\Delta / r_{-2}$$



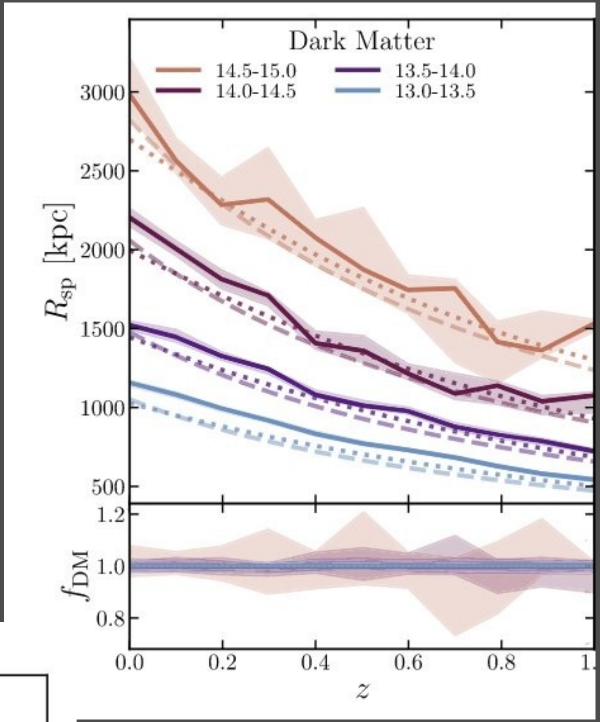
r_{sh}: predicted by theory to be ≡ r_{sp} *(Bertschinger 1985)* but found to be ≫ r_{sp} in num. sim. *(Aung et al. 2021)*

Internal structure

Characteristic radii of clusters of galaxies

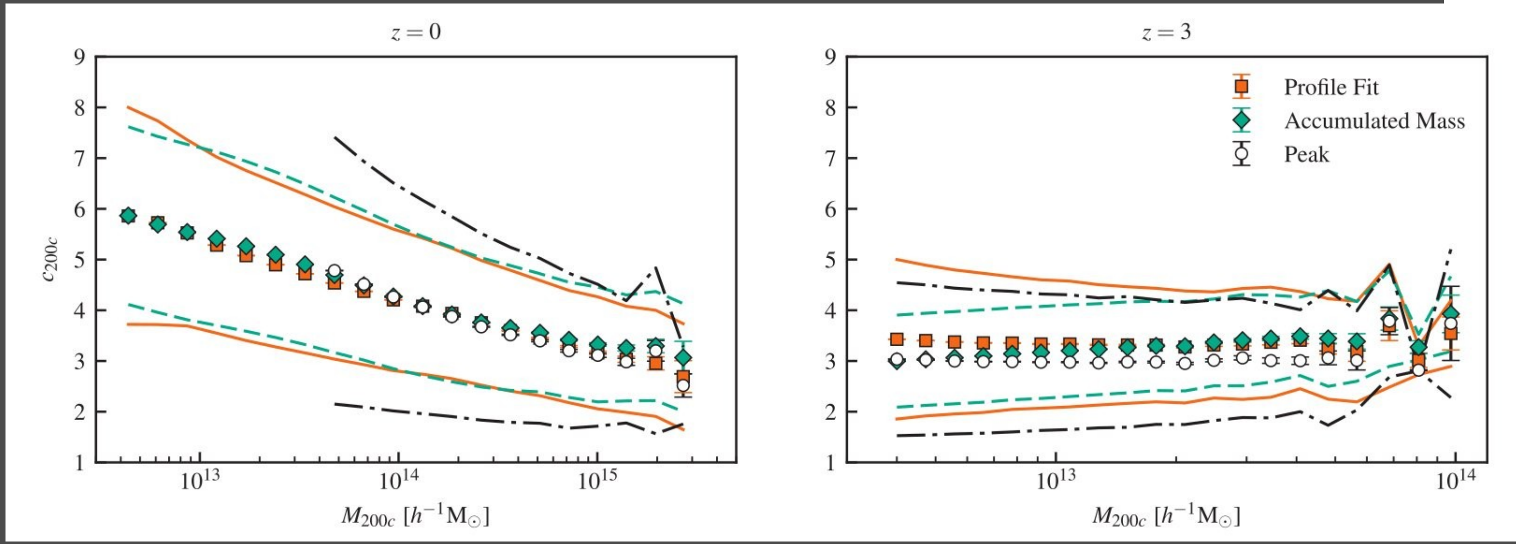
r_{sp} is related to the cluster mass, hence to r_Δ

r_{-2} is related to r_Δ via the concentration-mass relation



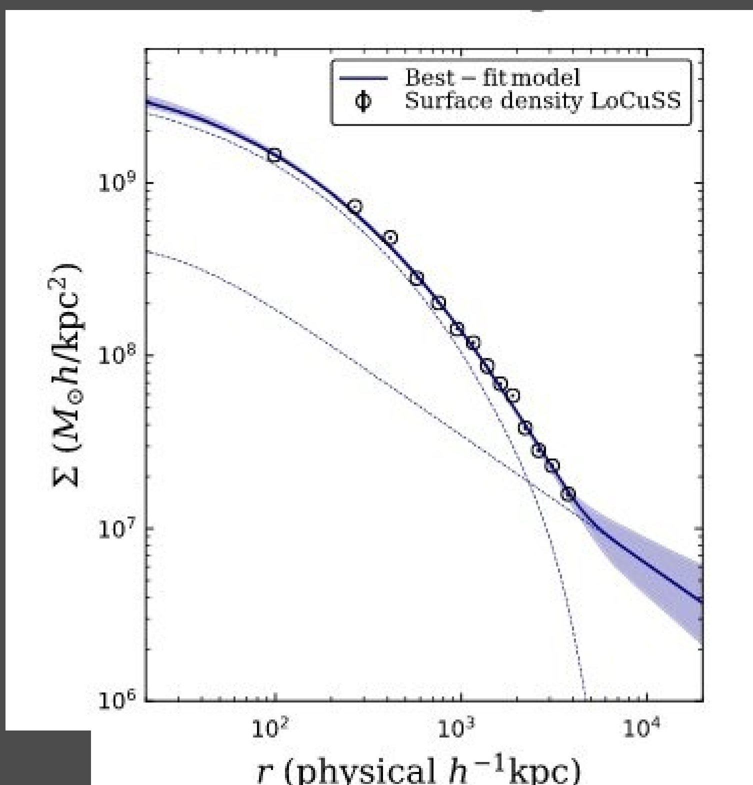
O'Neil et al. (2021): r_{sp} dependence on cluster mass and redshift, IllustrisTNG sims

Child et al. (2018): c_{200} vs M_{200} at z=0 and z=3 for halos extracted from numerical simulations



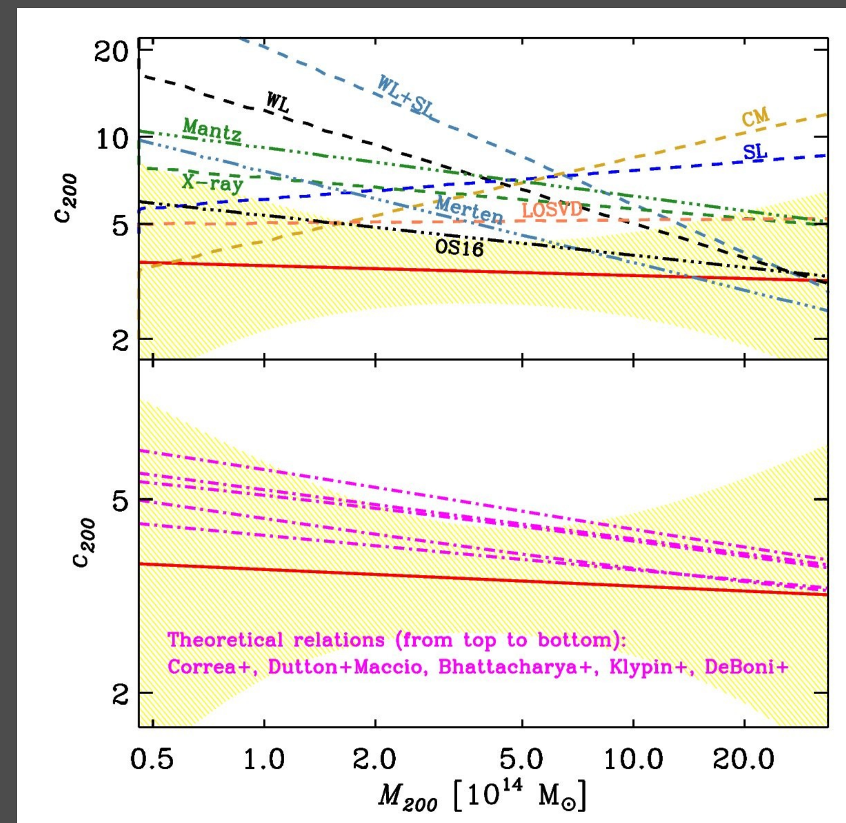
Internal structure

r_{sp} is difficult to measure observationally, because the cluster density contrast is low at large cluster-centric distances. Detected in the galaxy number and luminosity density profiles *(More et al. 2016; Baxter et al. 2017; Bianconi et al. 2021; Murata et al. 2021)*, and in the stacked mass density via gravitational lensing *(Contigiani et al. 2019; Umetsu & Diemer 2018; Shin et al. 2021)*



Bianconi et al. (2021)

r_{-2} and r_Δ (hence also c_Δ and M_Δ) estimated for the mass density profiles of many clusters through dynamical analyses (using galaxies and/or the intra-cluster gas as tracers), and via gravitational lensing



AB et al. (2017)

Internal structure

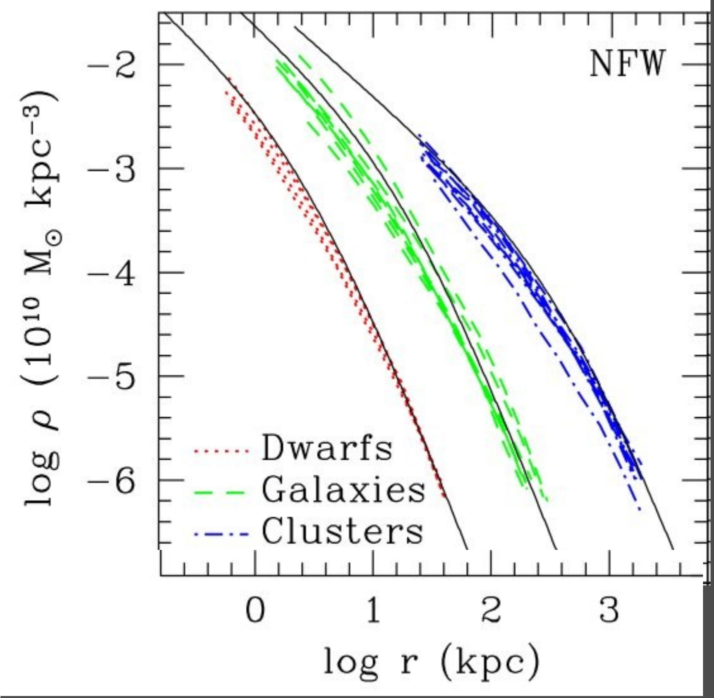
The mass density profile of clusters of galaxies

Navarro, Frenk & White (1996, 1997):
a universal ρ(r) for cosmological halos

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

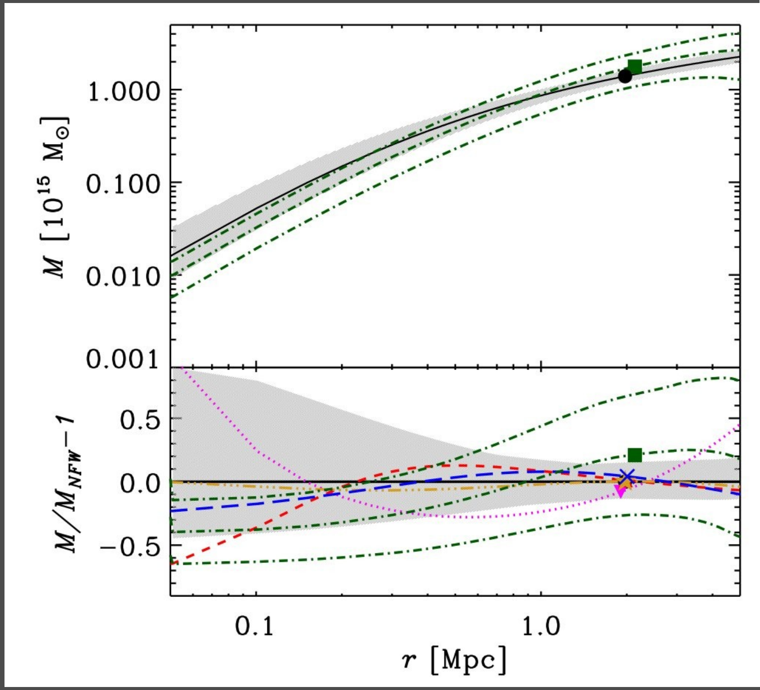
$$M(r) = M_{200} \frac{\ln(1 + r/r_{-2}) - r/r_{-2}\,(1 + r/r_{-2})^{-1}}{\ln(1 + c_{200}) - c_{200}/(1 + c_{200})}$$

2-parameter model



Navarro et al. (2004)

Derived in cosmological simulations, confirmed observationally, in particular on cluster scales:



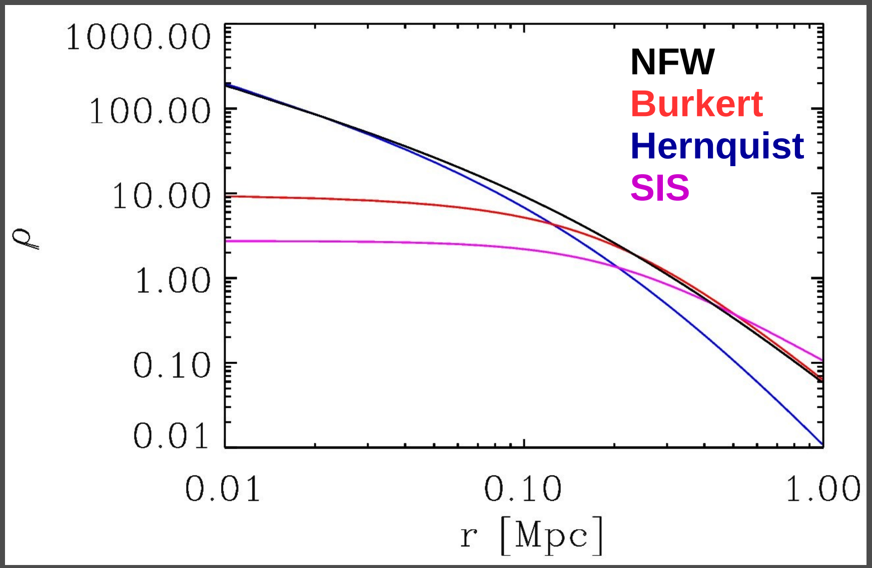
AB et al. (2013)

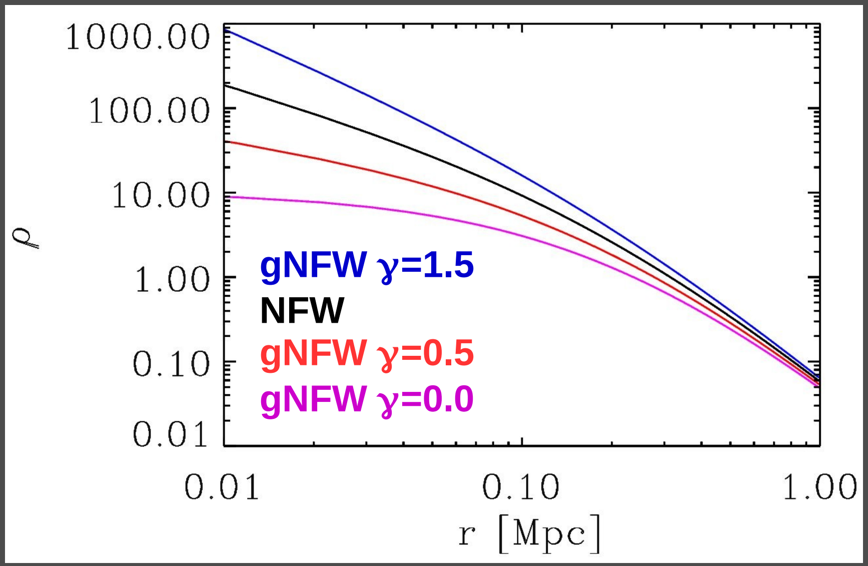
Internal structure

The mass density profile of clusters of galaxies

Other models for ρ(r):

- Burkert, Hernquist: 2-parameter models differing from NFW for the inner, resp. outer slope
- Softened Isothermal Sphere: 2-parameter model with flatter inner slope and slower decrease at large radii than NFW
- Einasto: 3-parameter model with varying inner slope
- generalized NFW: the inner slope γ is a free parameter

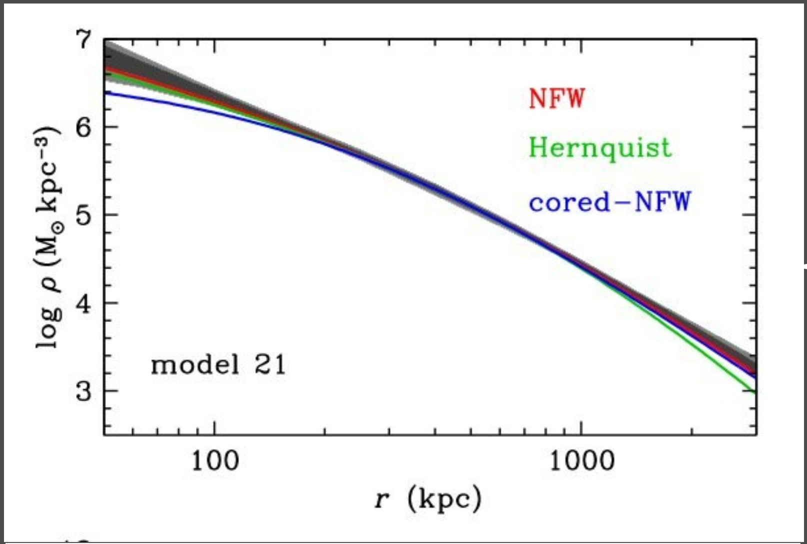




Internal structure

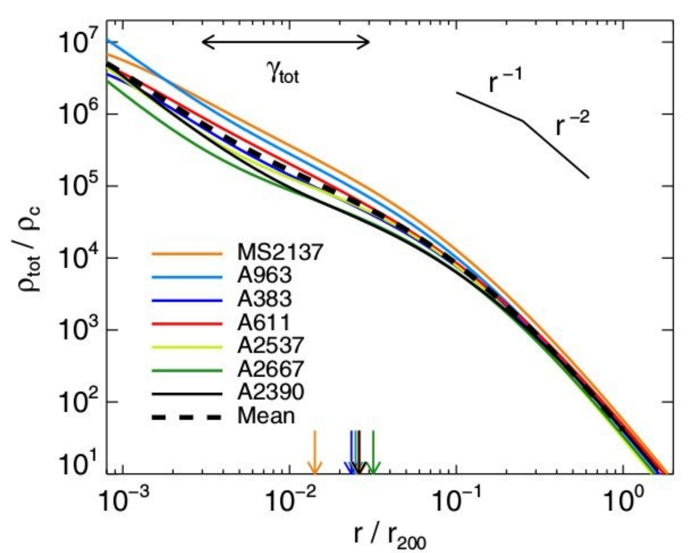
The mass density profile of clusters of galaxies

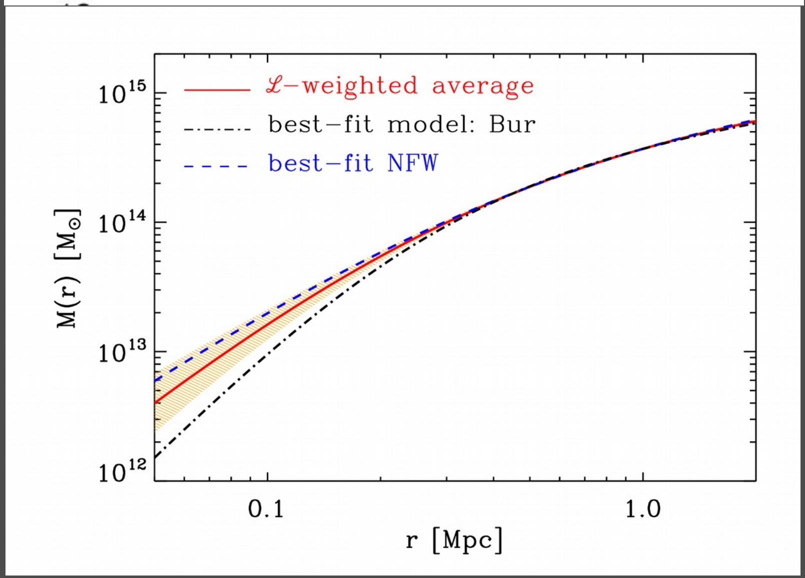
Other models might work better than NFW on the ***total*** mass density profile of galaxy clusters



Low-z clusters prefer ρ(r) with steeper inner slopes than NFW

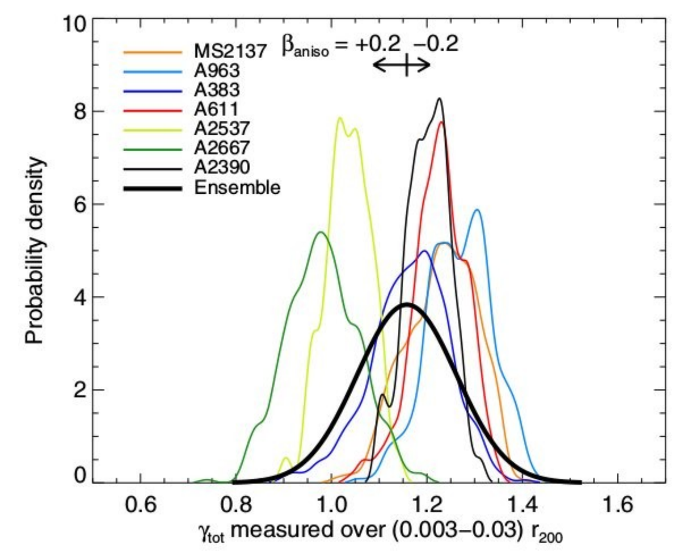
(Mamon et al. 2019; Newman et al. 2013)





High-z (z~1) clusters prefer ρ(r) with shallower inner slopes than NFW

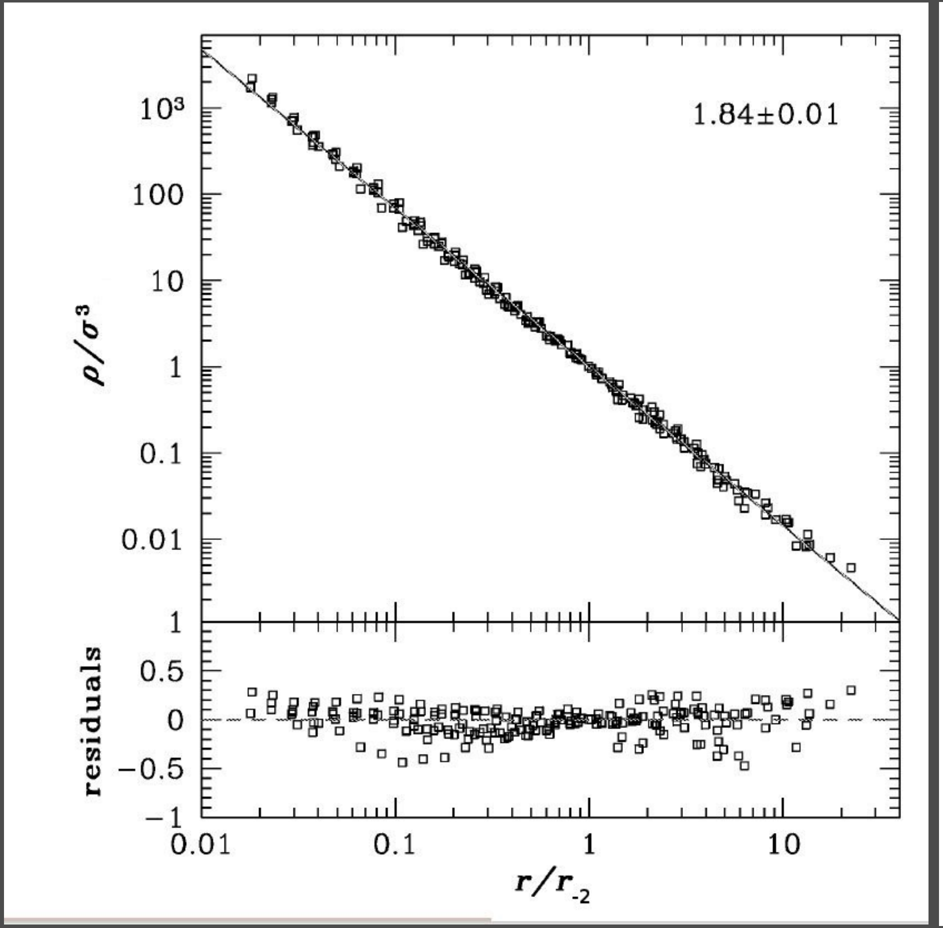
(AB et al. 2021)

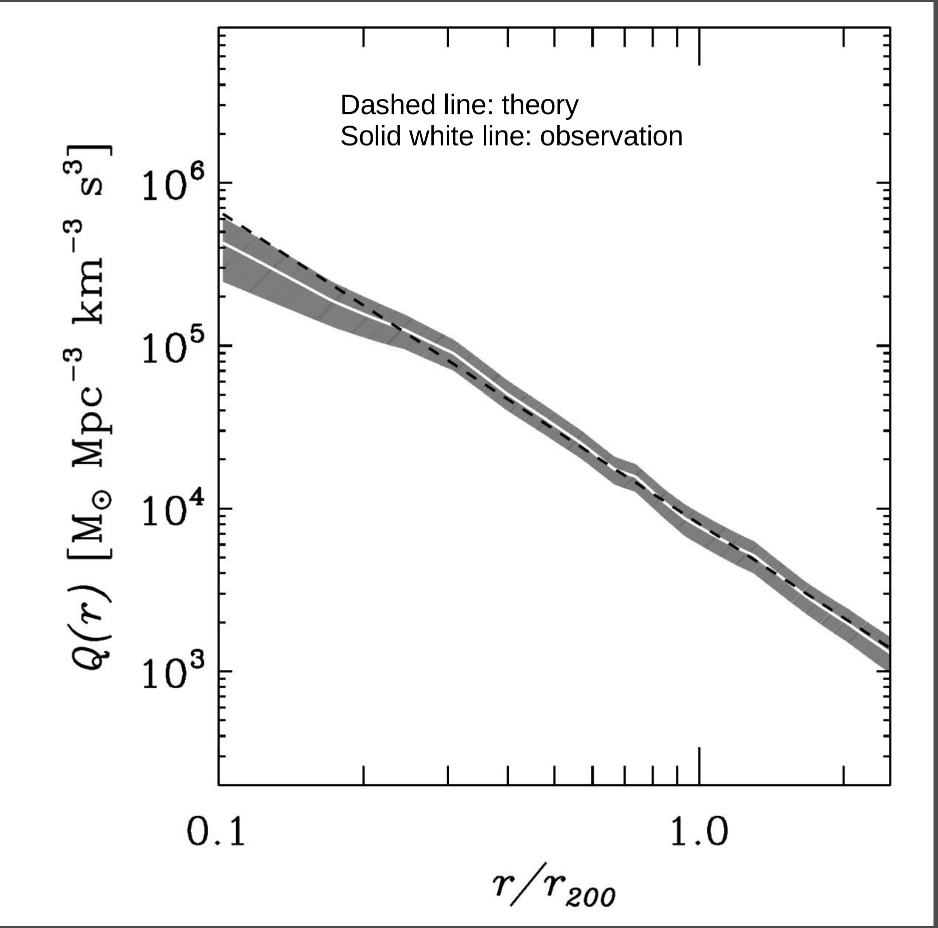


Internal structure

The pseudo phase-space density profile of clusters of galaxies

Perhaps a more universal profile of cosmological halos than ρ(r) is $Q(r) \equiv \rho(r)/\sigma(r)^3$, a power-law in radius, presumably established very early on in cluster history *(Taylor & Navarro 2001; Colombi 2021)*





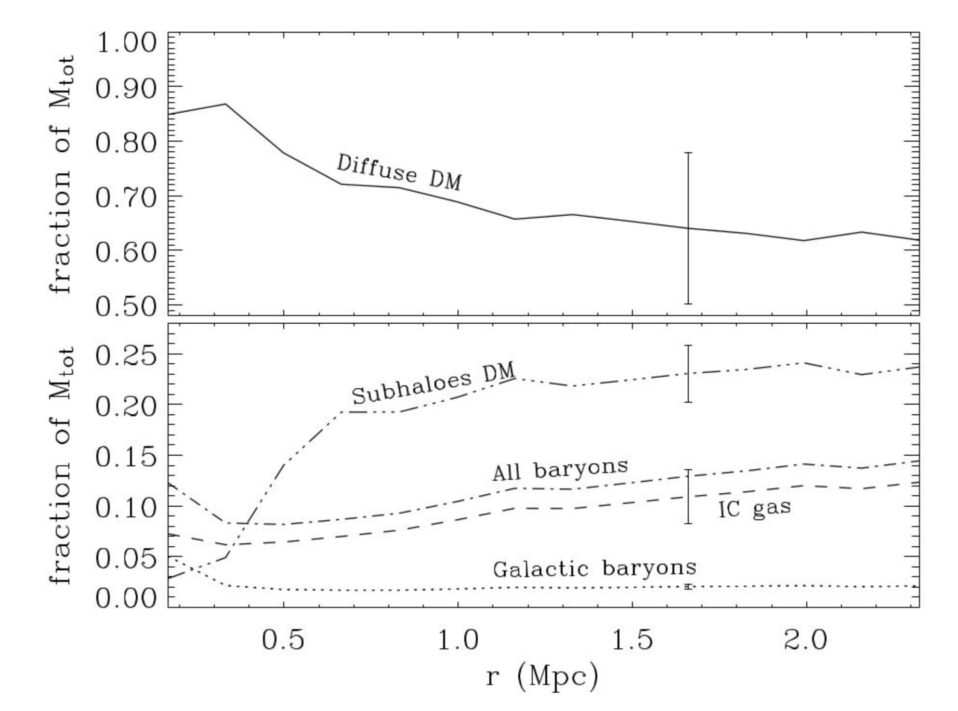
Dehnen & McLaughlin (2005): numerical simulations; *AB et al. (2013):* first observational determination of a cluster Q(r)

Internal structure

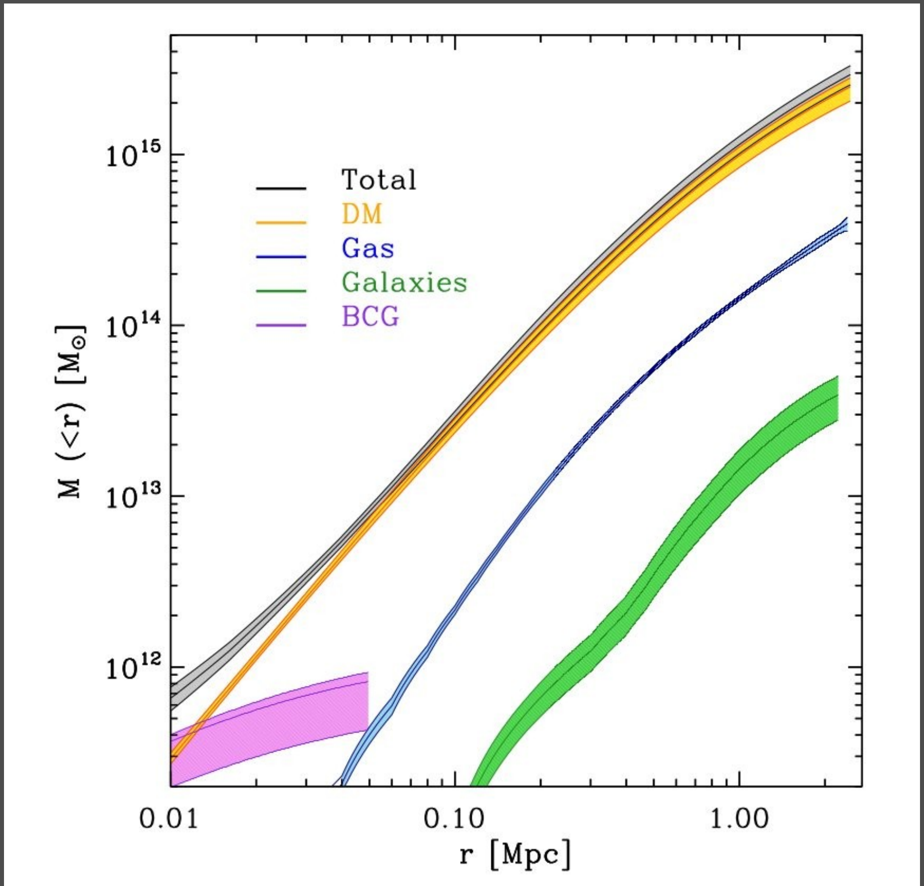
The (mass, number, gas) density profile of clusters of galaxies

The total mass density profile is the sum of many components:
Dark Matter, baryons = galaxies (cD and others) + intra-cluster light + intra-cluster gas

The density profile of each of these components might be better represented by a different model



AB & Salucci (2006)

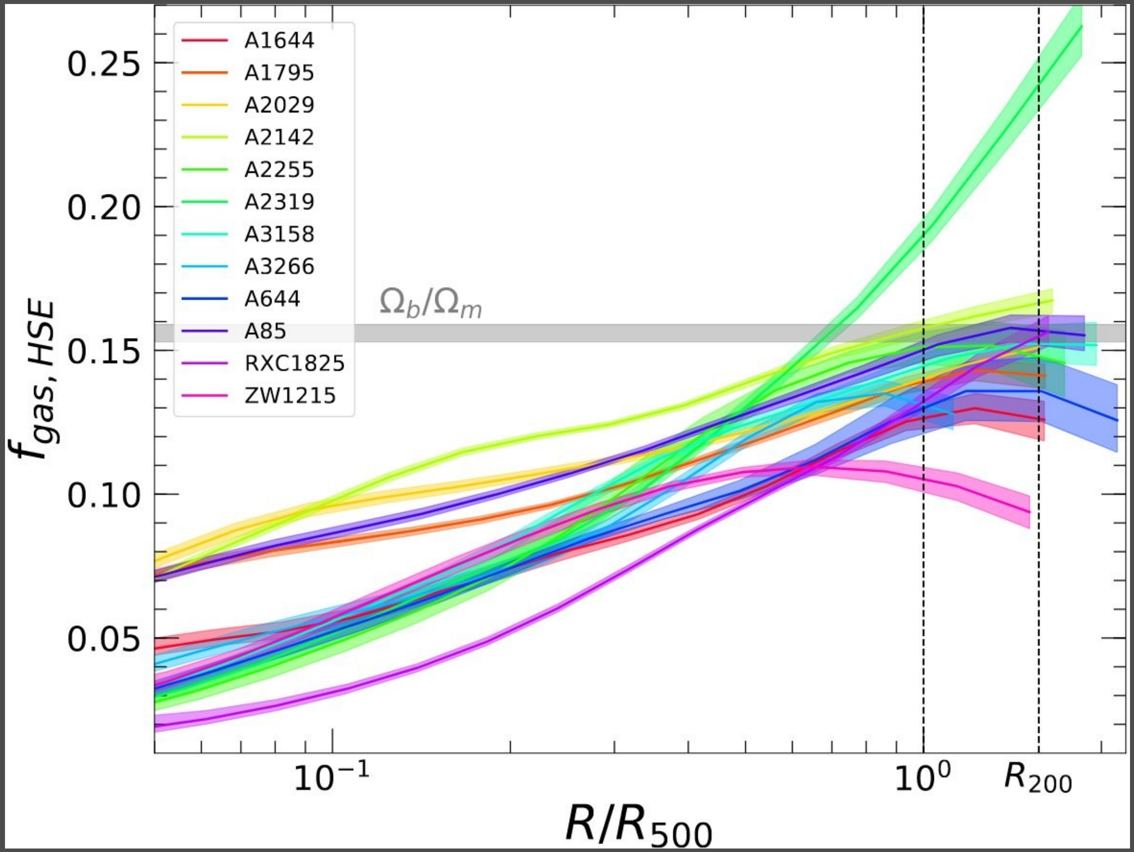


Sartoris, AB et al. (2020)

Internal structure

The gas density profile of clusters of galaxies

The intra-cluster gas spatial distribution is more extended than the mass and dominate the baryon fraction outside the central ~50 kpc



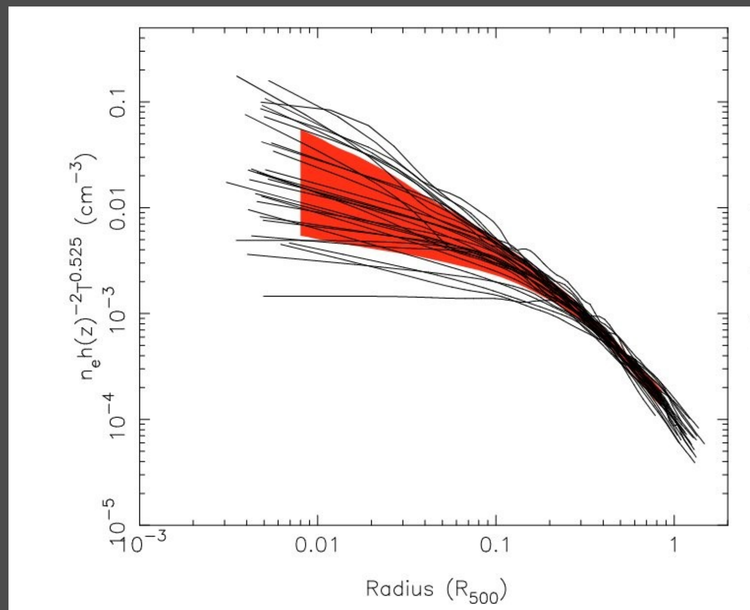
Eckert et al. (2019)

The cluster gas fraction can be used as a cosmological probe *(White et al. 1993)*

Internal structure

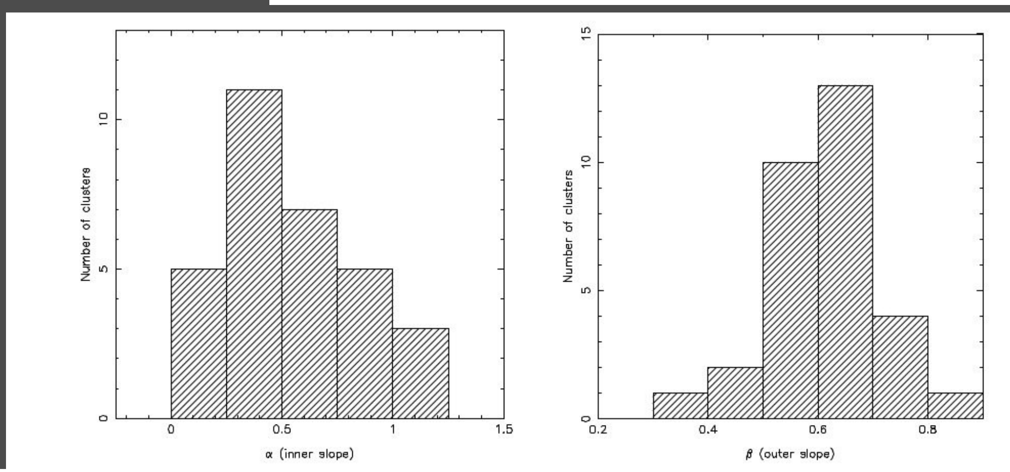
The gas density profile of clusters of galaxies

Croston et al. (2008),
REXCESS sample



The intra-cluster gas spatial distribution is not NFW-like.
A widely used model is the β model of *Cavaliere & Fusco-Femiano (1978):*

$$SB(r) = SB_0 \left(1 + \left(\frac{r}{r_c}\right)^2\right)^{-3\beta+0.5}$$



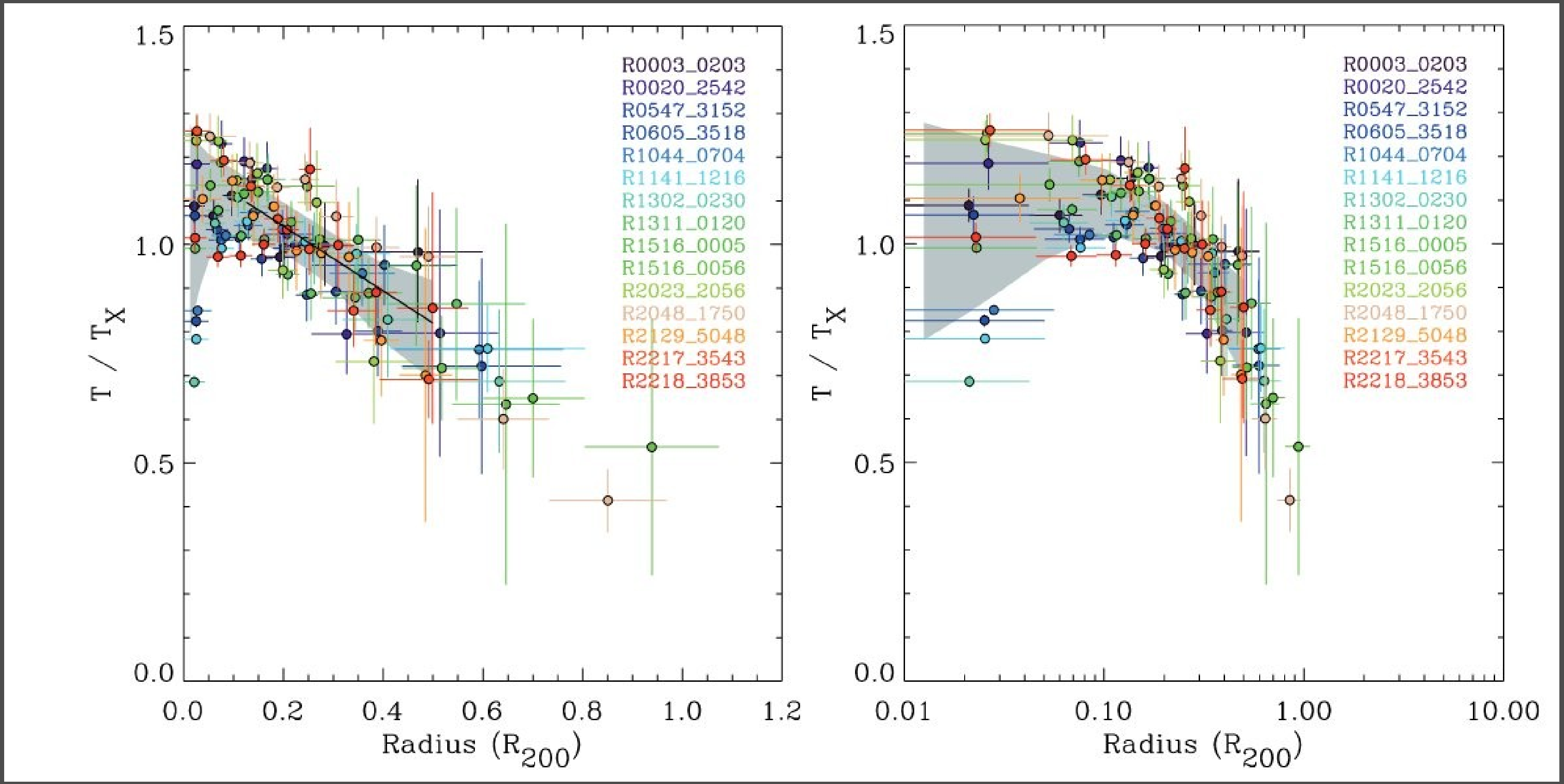
Inner slope   Outer slope β

that provides a good description of the X-ray surface brightness outside the central cluster region, a region that may ("cool core") or may not ("no cool core") be characterized by a central cusp

Internal structure

The gas temperature profile of clusters of galaxies

Cool-core clusters reveal themselves in the X-ray temperature profile, that appear to be universal outside the central cluster region



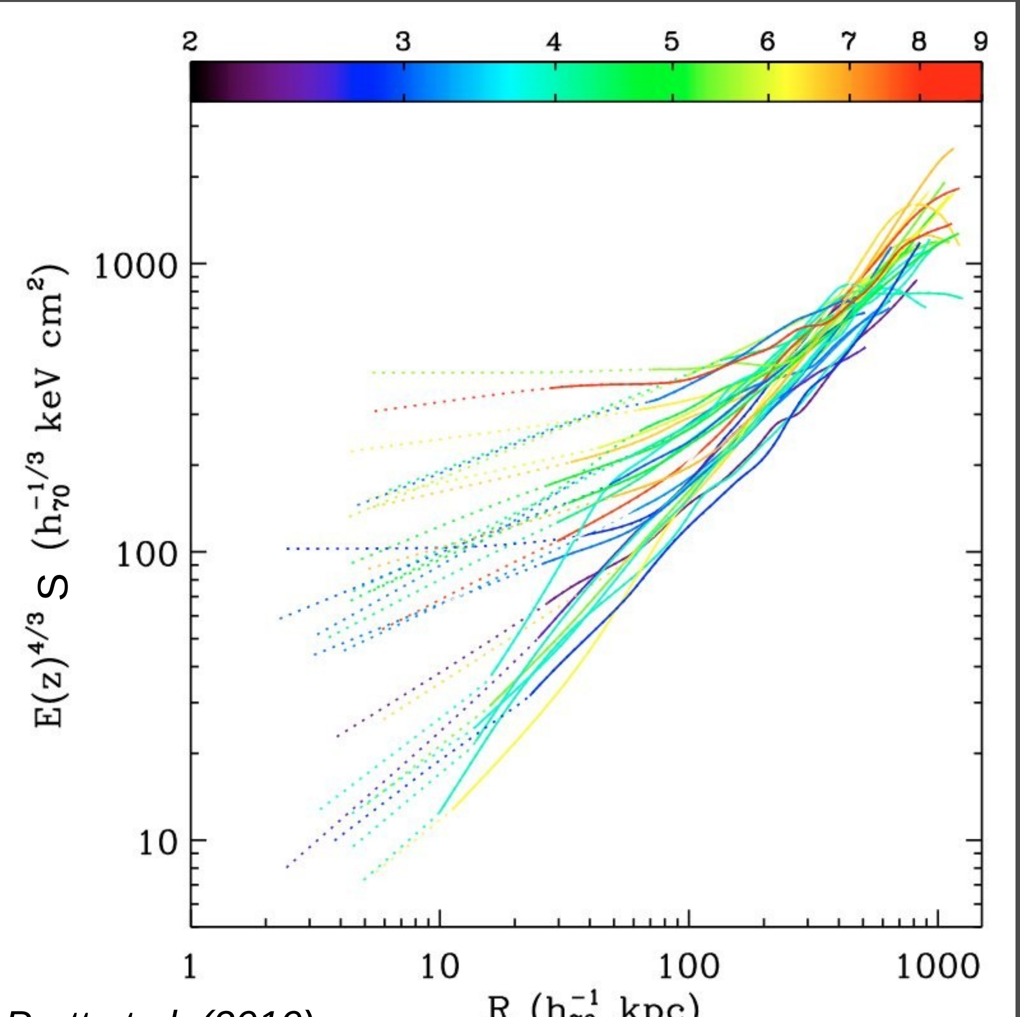
Model fit: **$T/T_X = 1.19 - 0.74\ r/r_{200}$** at $0.125 < r/r_{200} < 0.5$

where T_X = mean spectroscopic temperature *(Pratt et al. 2007)*

Internal structure

The gas entropy profile of clusters of galaxies

Combining the gas density and temperature profile: $S \equiv kT / n_e^{2/3}$



Pratt et al. (2010)

A power-law in radius outside the central regions.

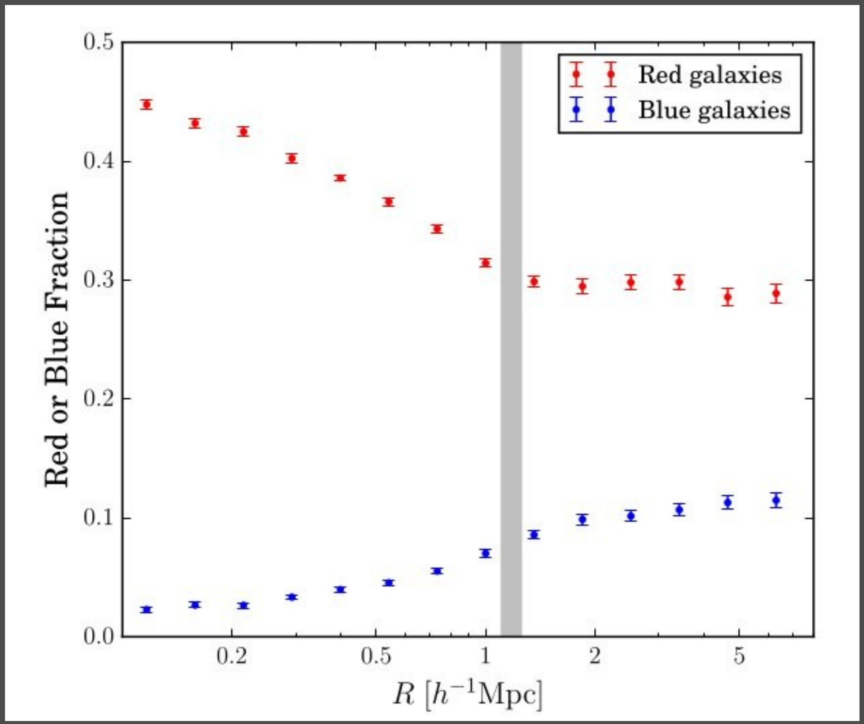
It can be compared to the pseudo phase-space density profile $Q(r) \equiv \rho/\sigma^3$ since one can define a "kinematical" entropy $S_{kin} \equiv \sigma^2/\rho^{2/3} = Q^{-2/3}$

The fact that S_{kin} is a power-law while S deviates at small radii is an indication of baryonic processes (AGN feedback?) affecting the gas but not (or only mildly so) the DM

Internal structure

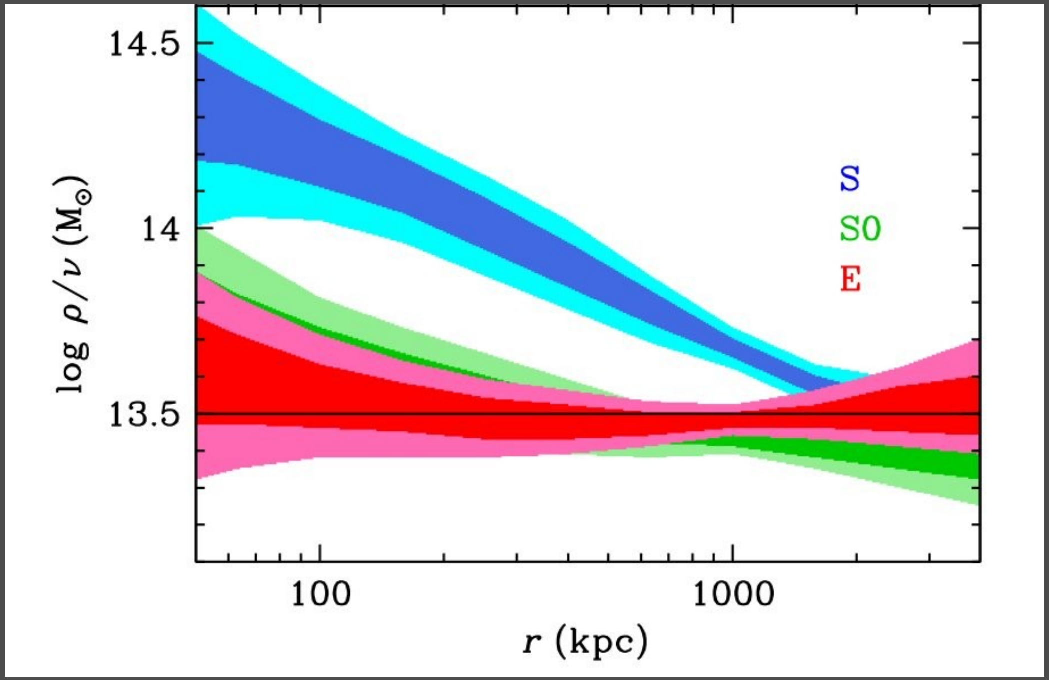
<u>The galaxy number density profile of clusters of galaxies</u>

Red (early-type, quiescent) galaxies have
different spatial distribution from
blue (late-type, star-forming) galaxies



Baxter et al. (2017),
redMaPPer clusters in SDSS

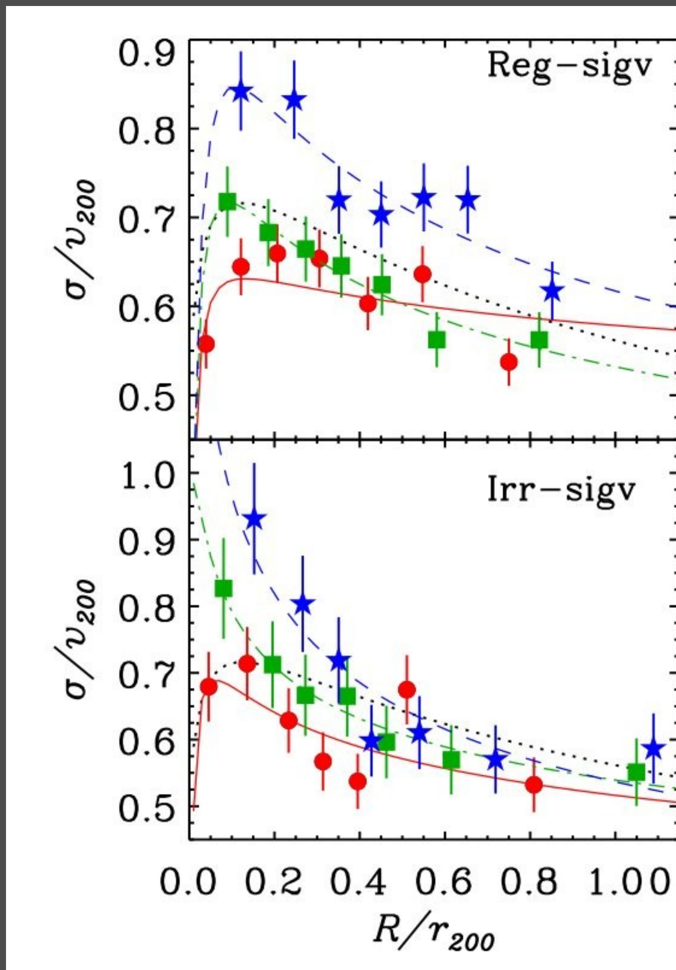
Mamon et al. (2019), WINGS clusters



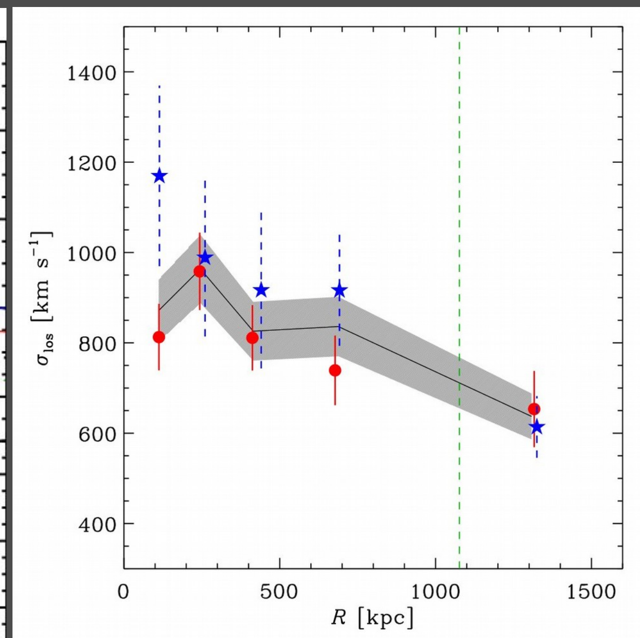
The number density profile ν of early-type galaxies
is similar to the cluster mass density profile ρ

Internal structure

The galaxy velocity dispersion profile of clusters of galaxies



Cava, AB et al. (2017),
low-z clusters from WINGS



AB et al. (2016),
high-z clusters from
GCLASS

$$\frac{\sigma_{\rm los}}{v_{200}} = s_0\,\frac{X}{a_\sigma}\left(1+\frac{X}{a_\sigma}\right)^{-\eta}$$

where: $X=R/r_{200}$

Red (early-type, quiescent) galaxies have different velocity dispersion profiles from blue (late-type, star-forming) galaxies.

This difference is less pronounced for less dynamically evolved clusters and for high-z (z~1) clusters.

Internal structure

The (mass, number) density profile of clusters of galaxies

What's wrong in everything I told you
in the last 14 slides?

Internal structure

The (mass, number) density profile of clusters of galaxies

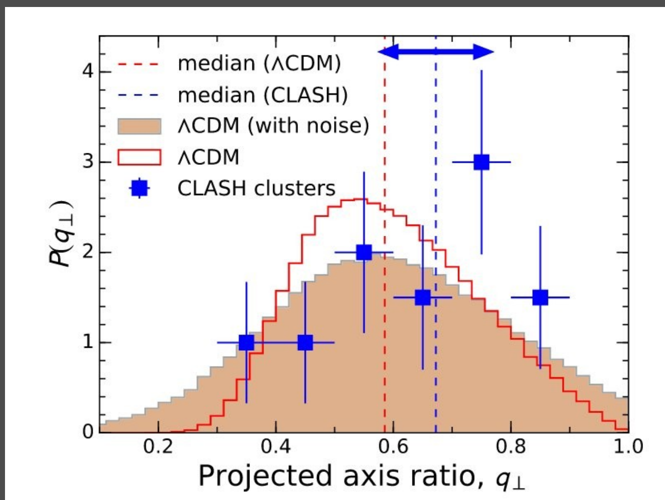
What's wrong in everything I told you
in the last 14 slides:

These density profiles assume spherical symmetry.

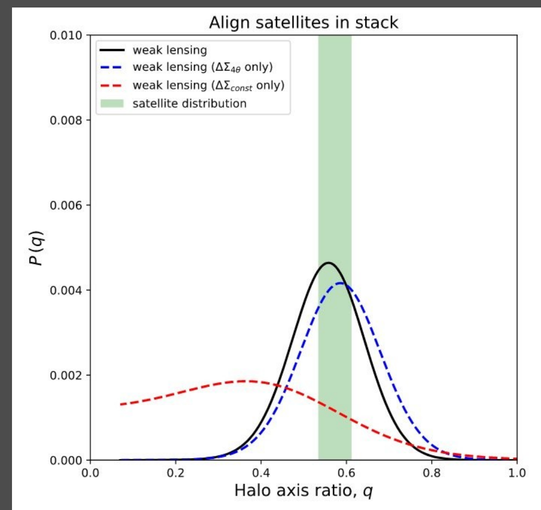
But clusters are not spherical!

Internal structure

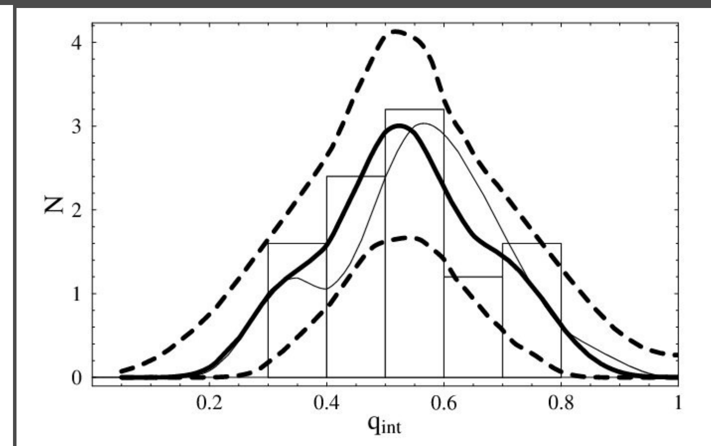
Clusters ellipticity



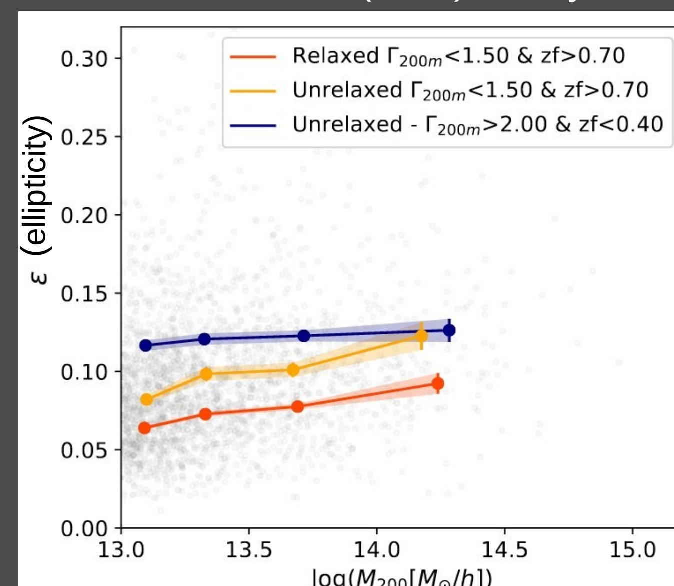
Umetsu et al. (2018): weak lensing



Shi et al. (2021): weak lensing and galaxies



Sereno et al. (2006): X-ray and SZ



Numerical simulations predict dynamically unrelaxed and later forming clusters to be more elliptical *(Gouin et al. 2021)*

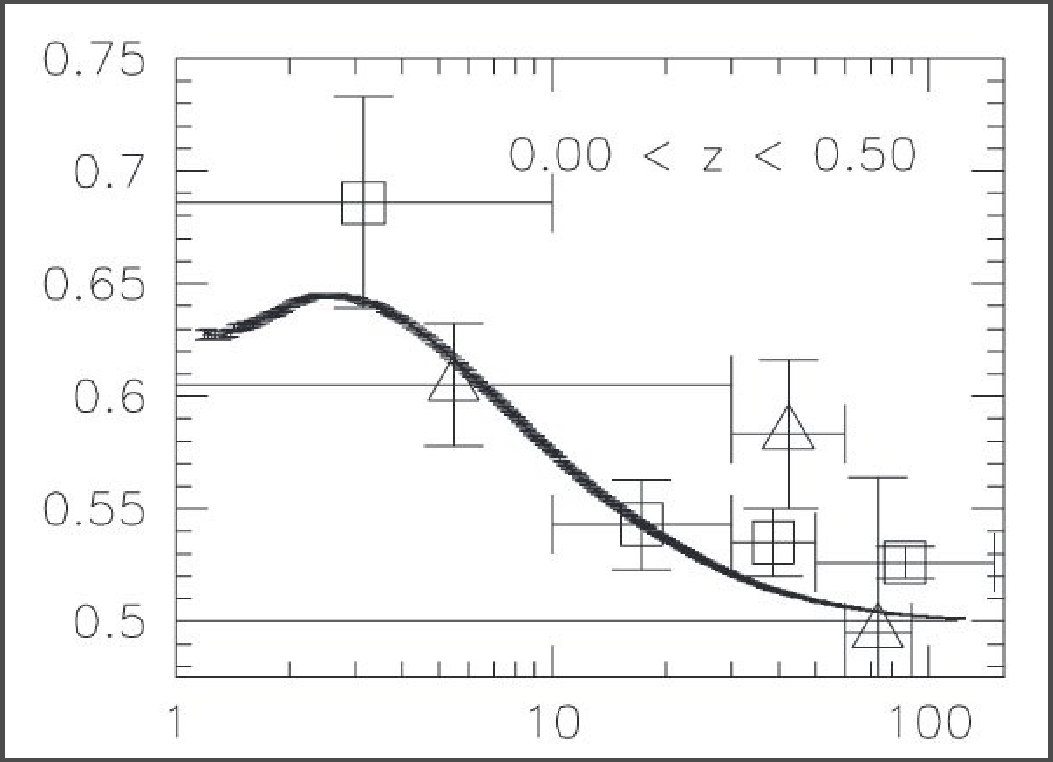
Internal structure

<u>Is cluster ellipticity caused by cluster rotation?</u>

Not according to numerical simulations, clusters are elongated because of their formation process from hierarchical accretion from the large scale structure.

This scenario is supported by observations of a consistent orientation angle over a wide range of scales from the central galaxy to the large scale structure *(West 1989; Plionis 1994)*

$<\cos^2\theta>$

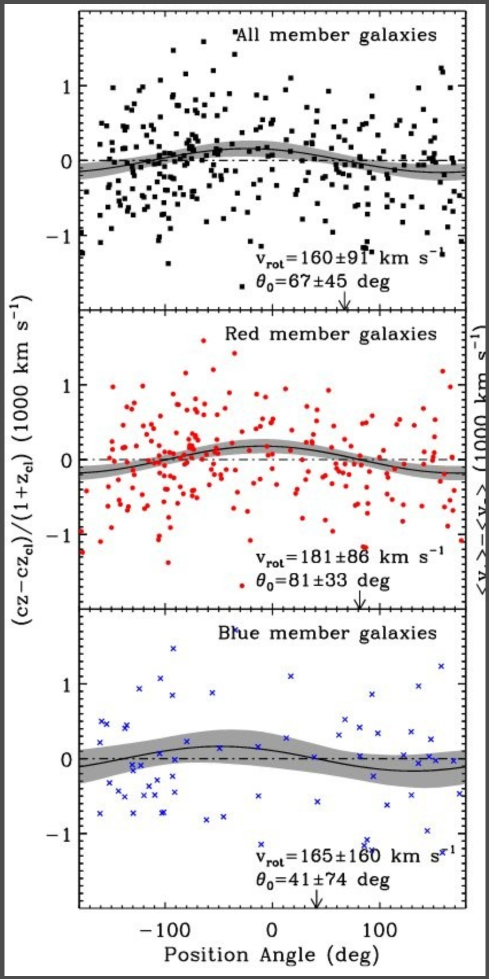


cluster-to-cluster distance

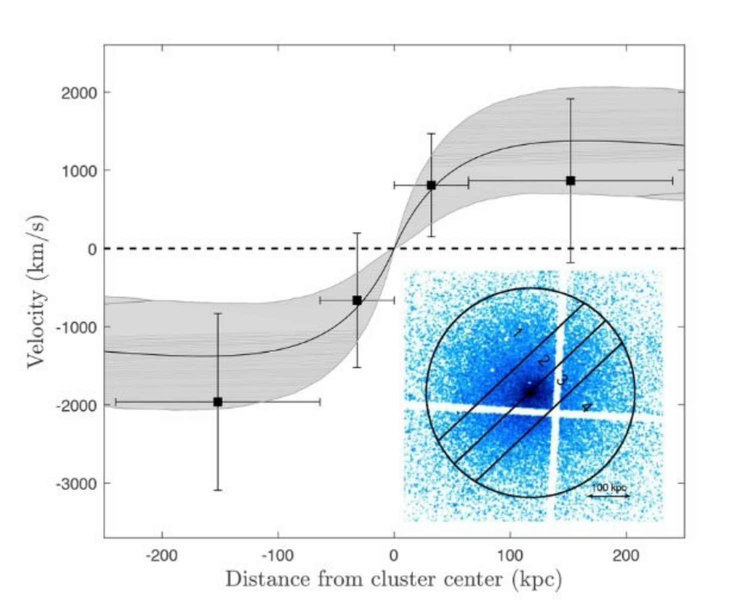
Hopkins et al. (2005):
N-body simulation cmpd to observational data:
(*West 1989*, triangles;
Plionis 1994, squares).
θ is the angular difference between cluster orientations

Internal structure

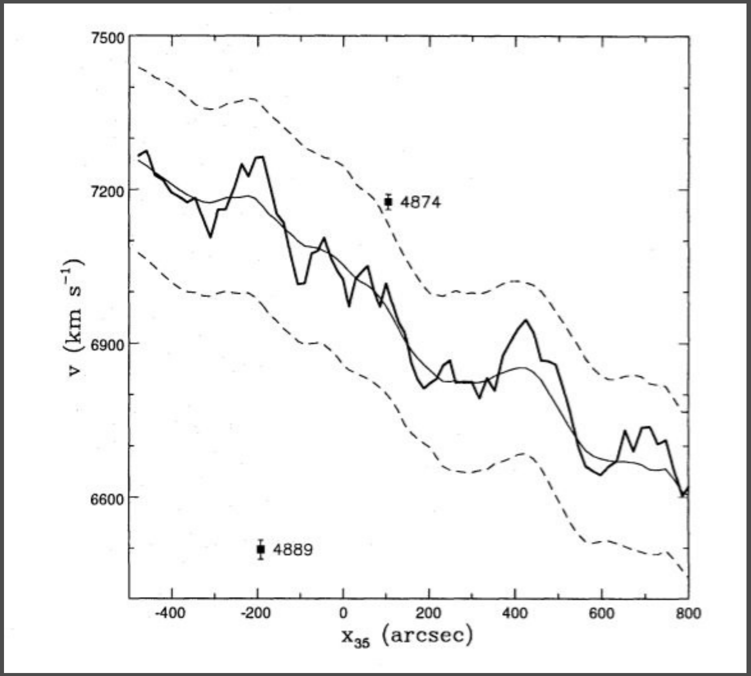
Are cluster rotating?



Song et al. (2018): cluster A2107, galaxy spectroscopy



Liu & Tozzi (2019): cluster A2107, X-ray spectroscopy of the intra-cluster gas

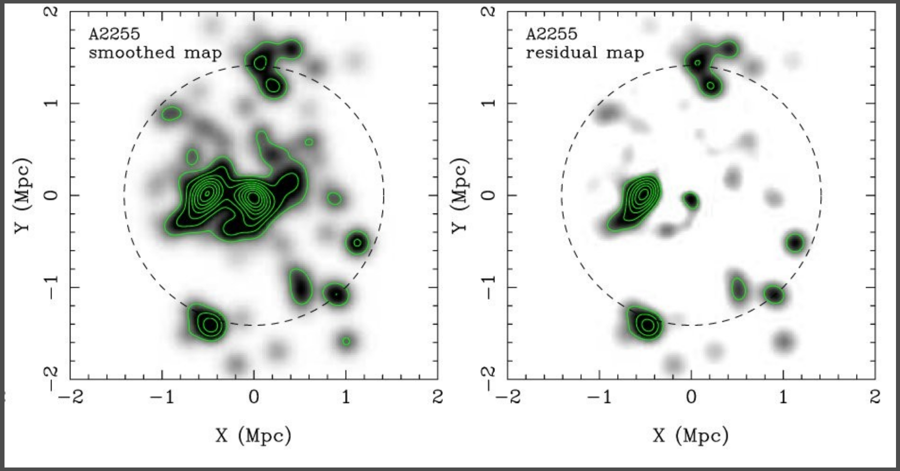


AB et al. (1996): cluster A1656, galaxy spectroscopy

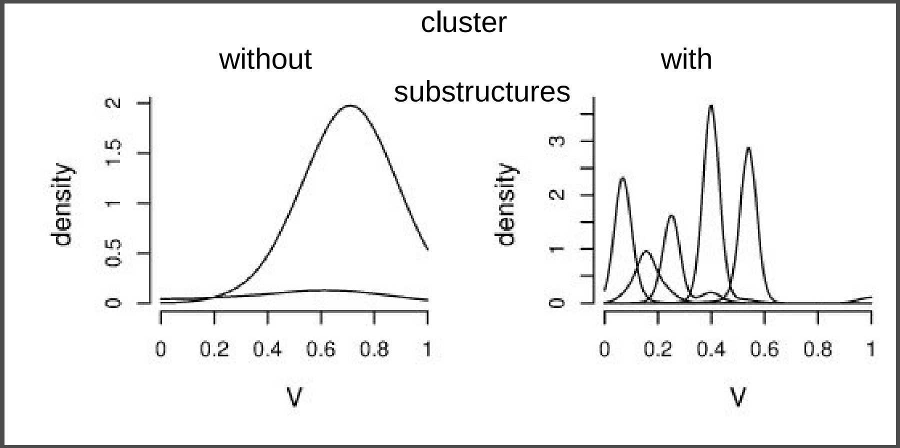
Spectroscopic studies of galaxies and the intra-cluster medium find evidence for angular velocity gradients in a few (or up to 23%? see *Manolopoulou & Plionis 2017*) clusters but is it rotation or... ...**substructure**?

Internal *sub*-structure

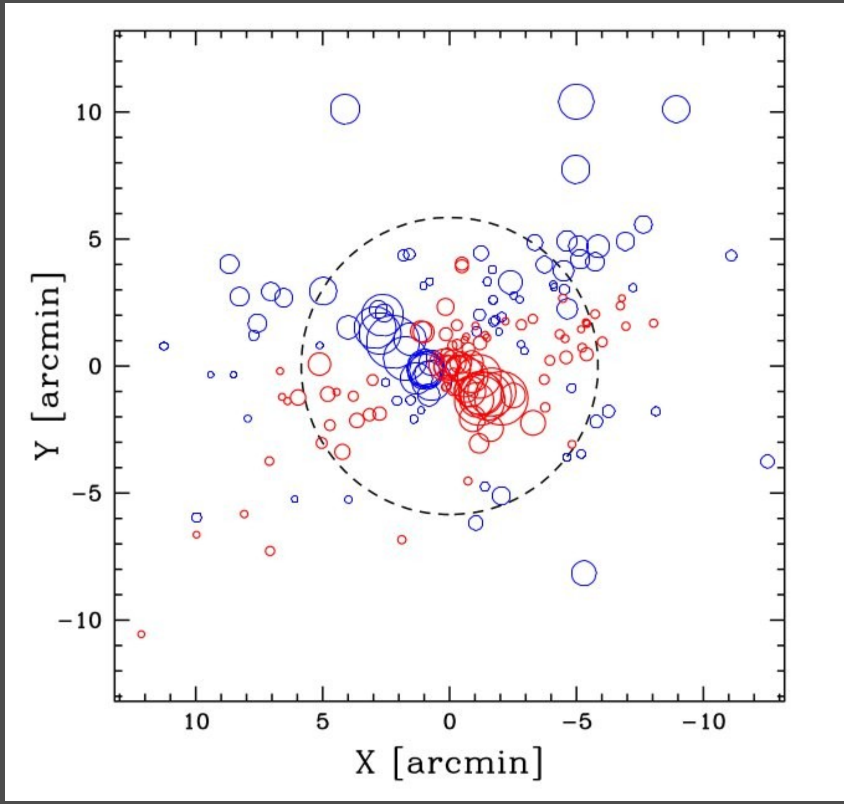
"Substructures" in galaxy clusters are identified in the **spatial and velocity distribution of galaxies**, in the X-ray surface brightness and temperature, in weak lensing, in the radio, as local over-densities, thought to be groups that are being accreted by the clusters.



Wen & Han (2013)



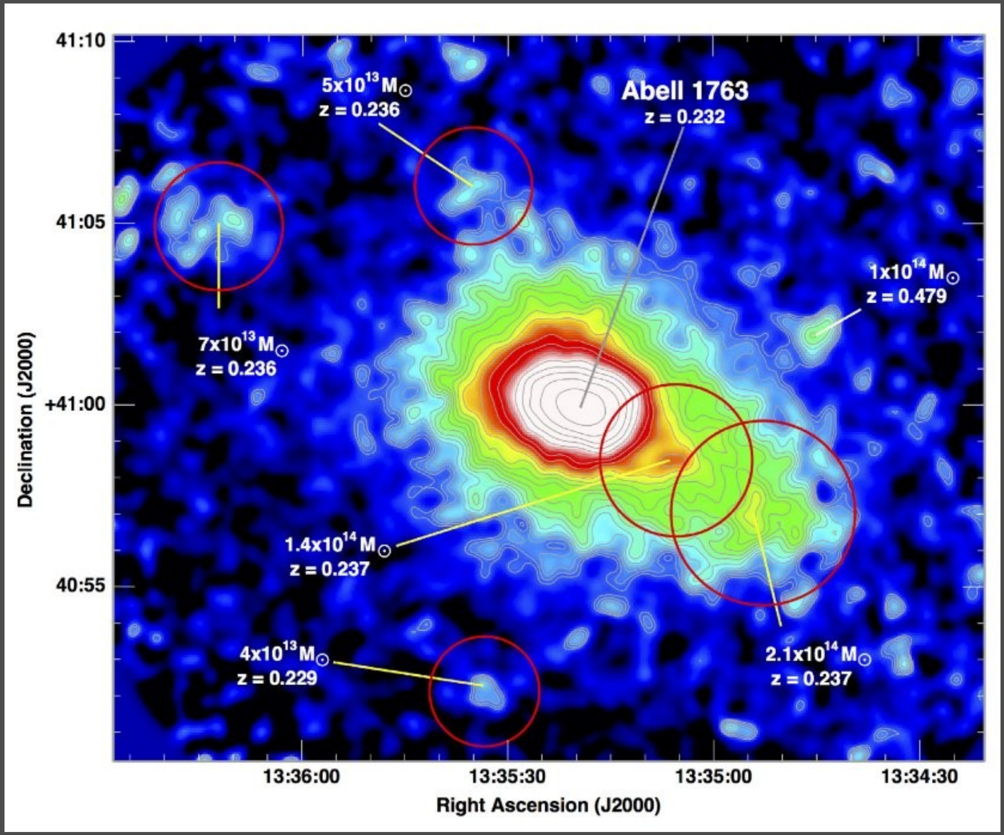
Ribeiro et al. (2011)



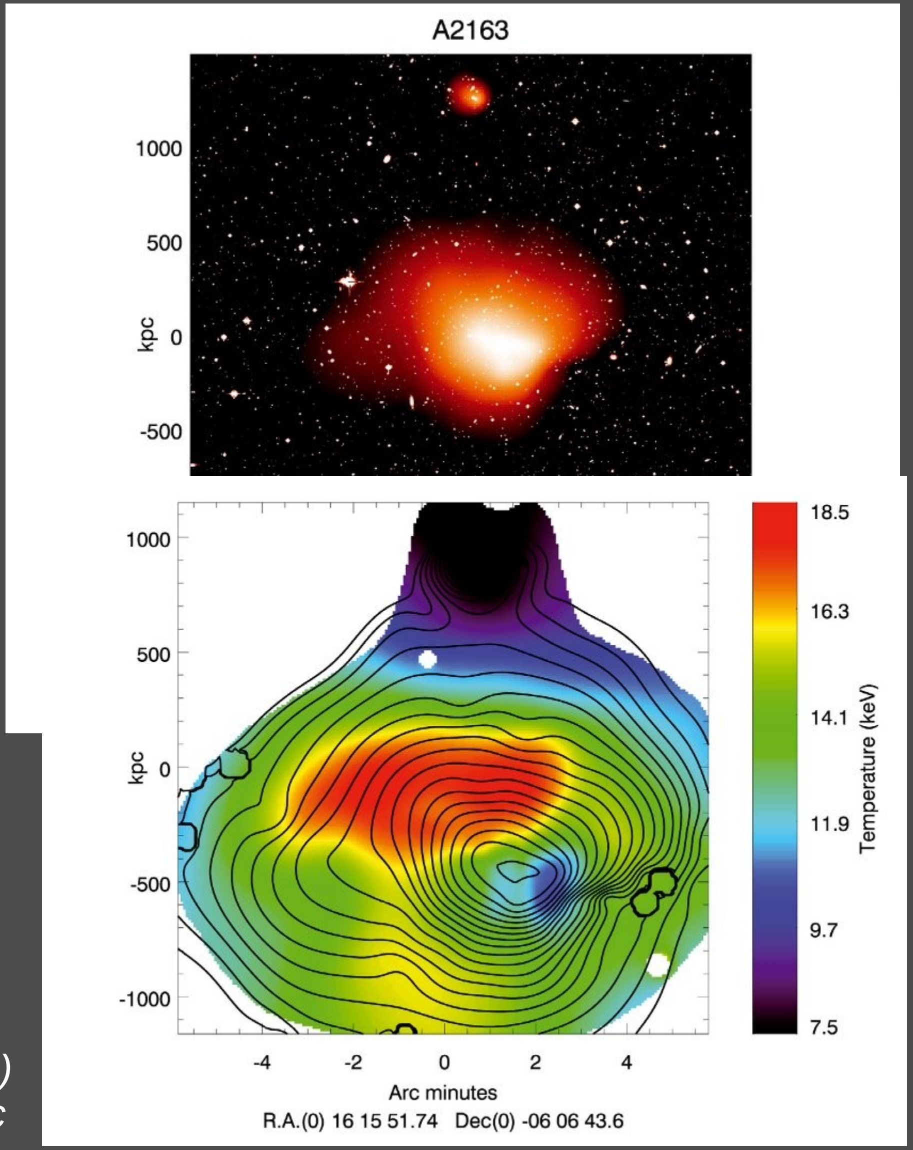
Girardi et al. (2015), MACS J1206.2-0847
1 arcmin ↔ 344 kpc

Internal *sub*-structure

"Substructures" in galaxy clusters are identified in the spatial and velocity distribution of galaxies, in the **X-ray surface brightness and temperature**, in weak lensing, in the radio, as local over-densities, thought to be groups that are being accreted by the clusters.



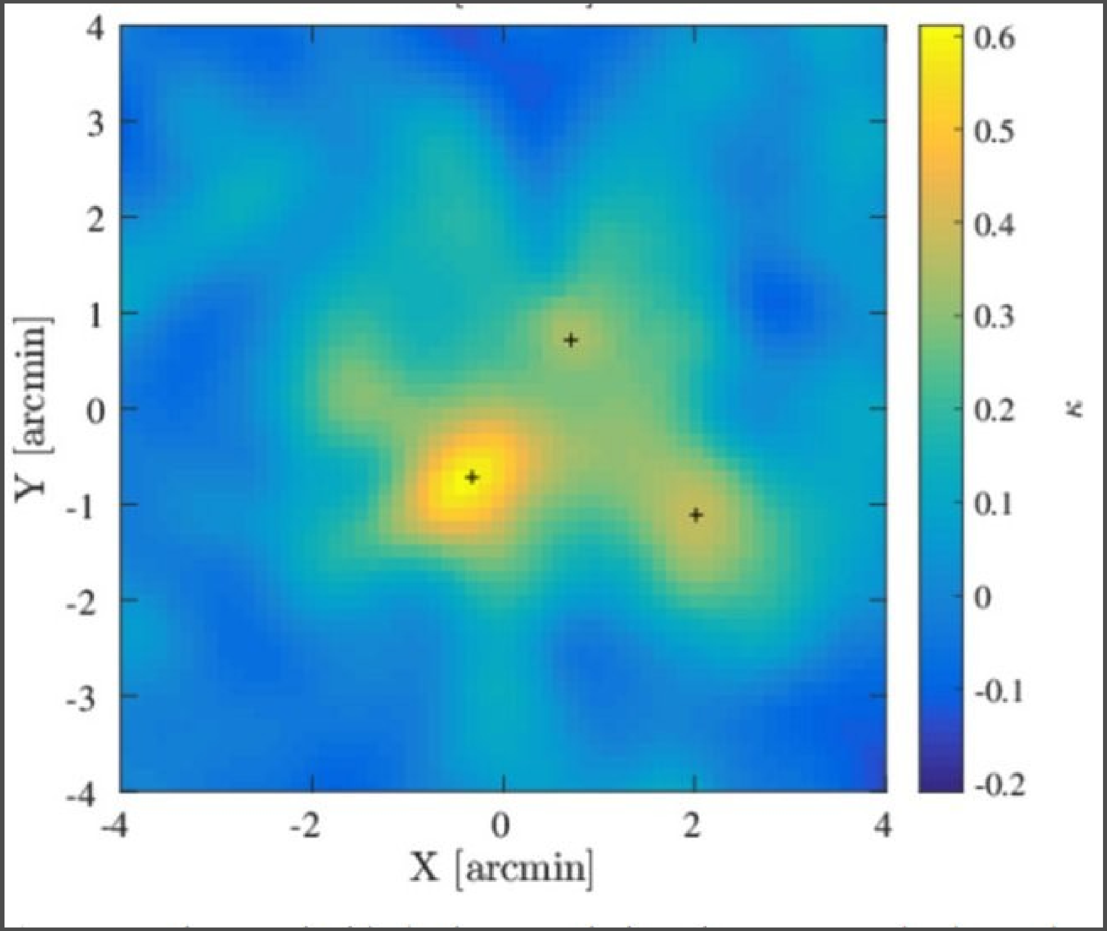
Haines et al. (2018), 1 arcmin ↔ 222 kpc



Bourdin et al. (2011)
1 arcmin ↔ 200 kpc

Internal *sub*-structure

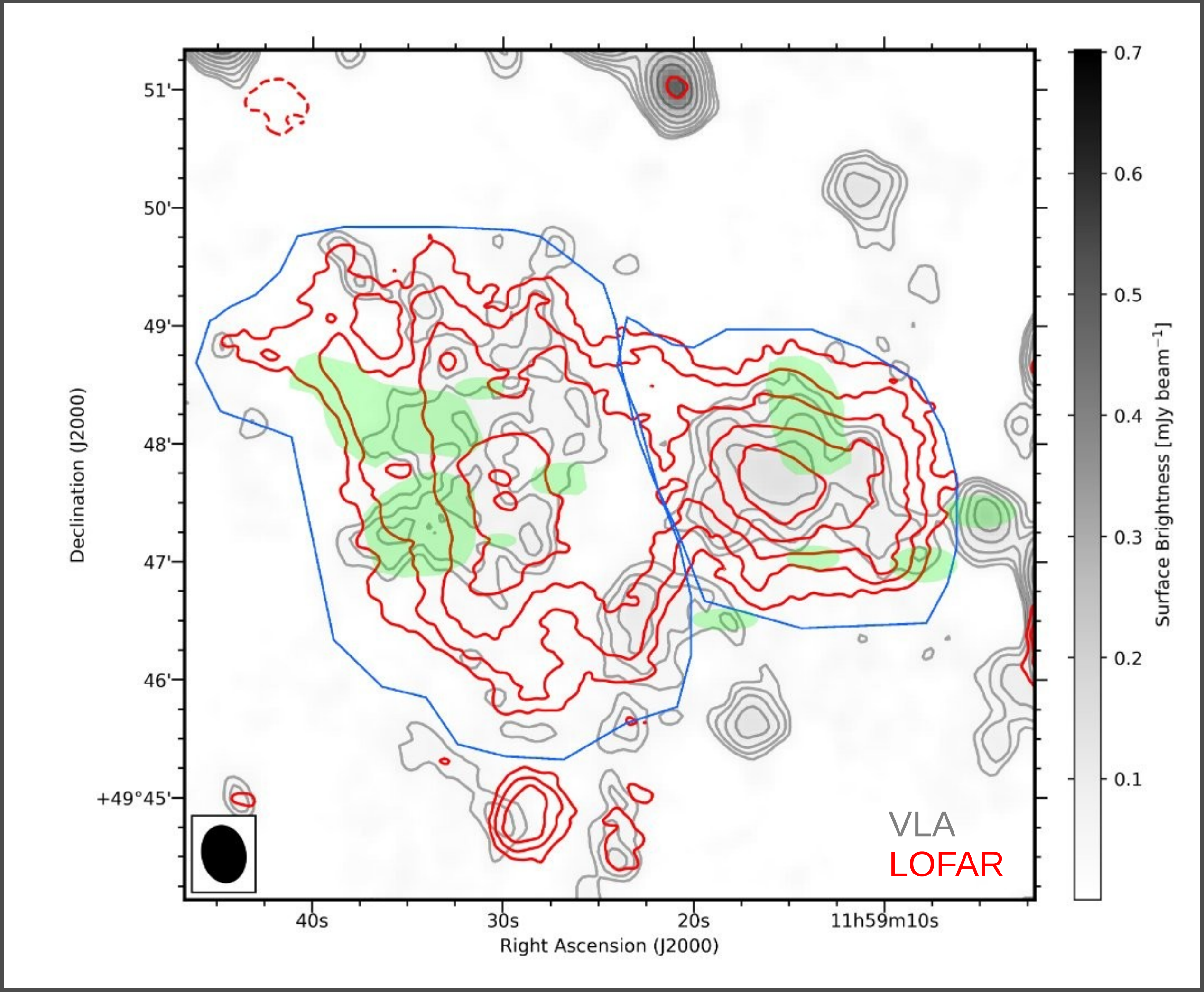
“Substructures” in galaxy clusters are identified in the spatial and velocity distribution of galaxies, in the X-ray surface brightness and temperature, in **weak lensing**, in the radio, as local over-densities, thought to be groups that are being accreted by the clusters.



Medezinski et al.(2016):
weak lensing convergence (surface mass density) map of Abell 2744 (1 arcmin ↔ 272 kpc)

Internal *sub*-structure

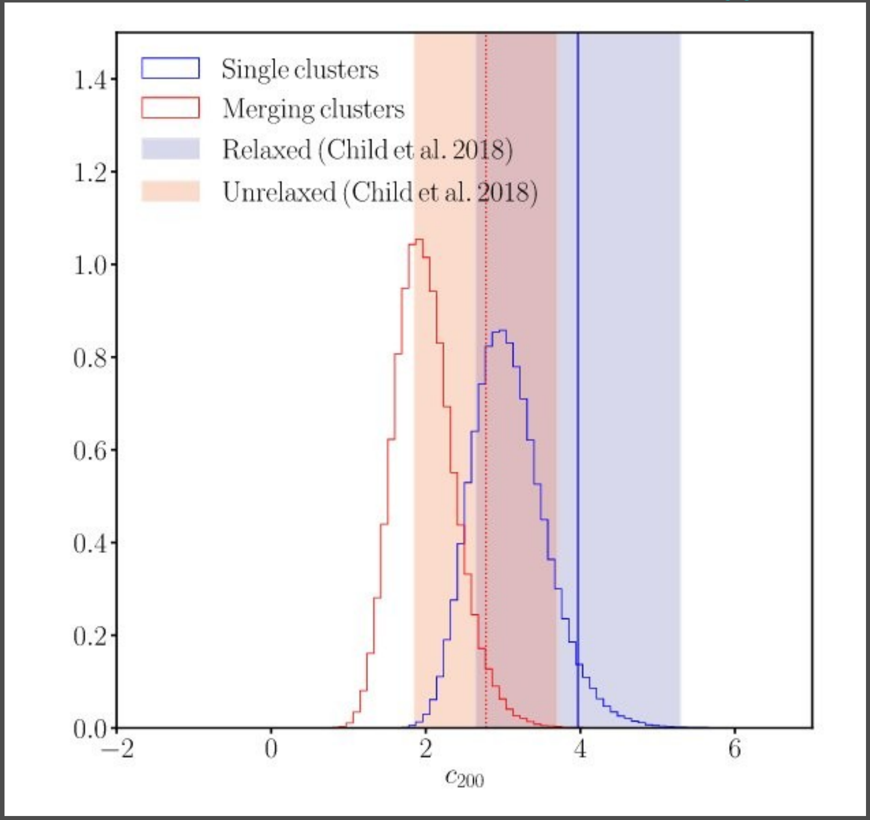
"Substructures" in galaxy clusters are identified in the spatial and velocity distribution of galaxies, in the X-ray surface brightness and temperature, in weak lensing, in the **radio**, as local over-densities, thought to be groups that are being accreted by the clusters.



Hoeft et al.(2021): VLA and LOFAR radio image of Abell 1430 (1 arcmin ↔ 300 kpc)

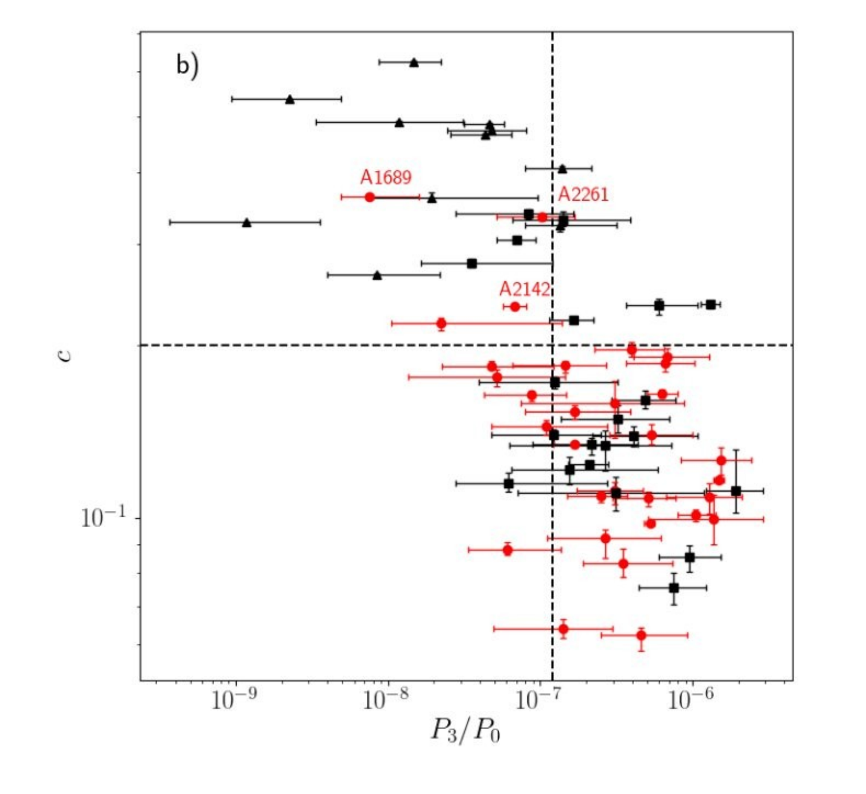
Internal *sub*-structure

Clusters with internal substructure have lower mass concentrations c_{200}:



Okabe et al. (2019), weak lensing analysis
cmpd to predictions from numerical simulations

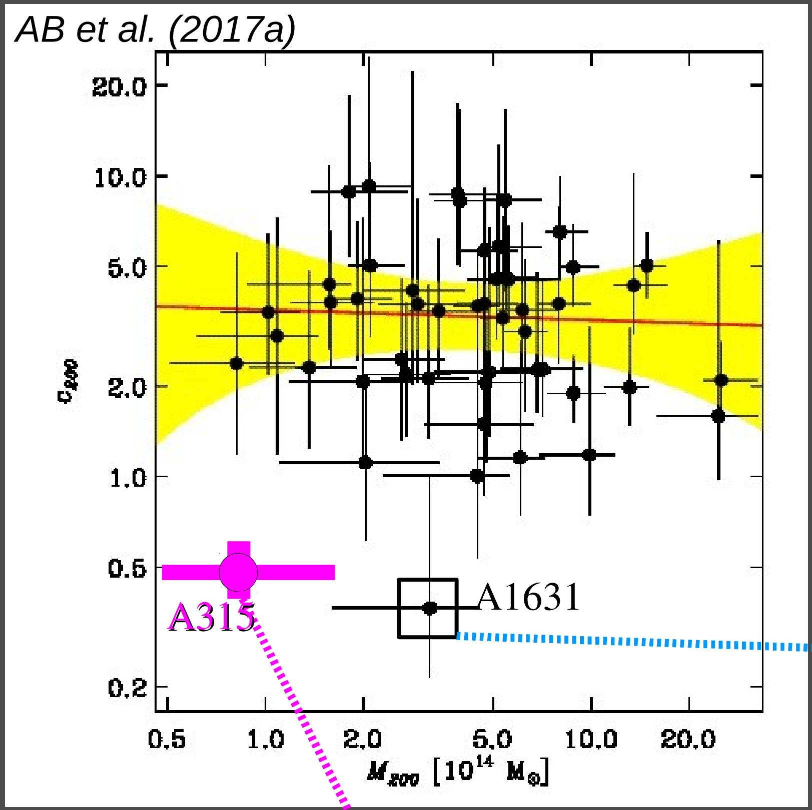
Clusters with radio-halos have lower mass concentrations c_{200}:



Cuciti et al. (2021):
concentration vs. substructure indicator from the X-ray analysis of *Lovisari et al. (2017)*;
red symbols are clusters with radio halos

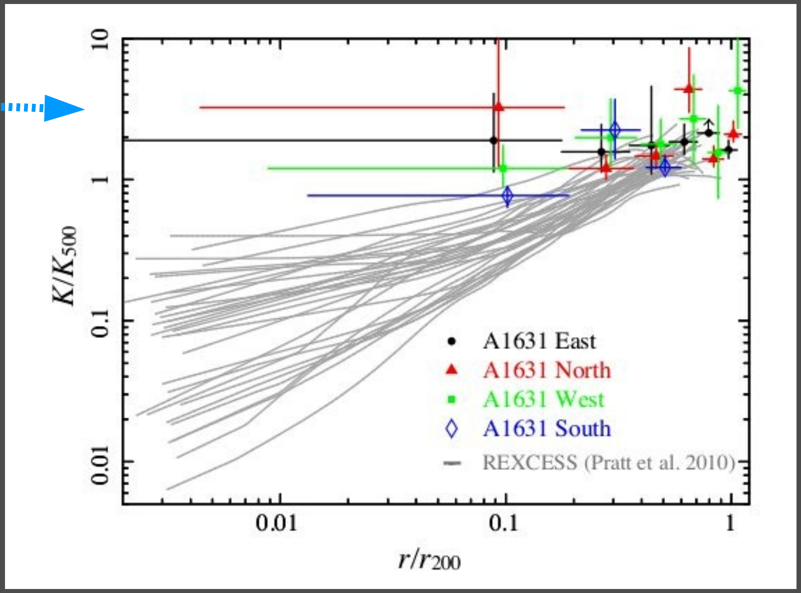
Radio halos originate from relativistic electrons injected from AGN, re-accelerated by turbulence, generated by the collisions of infalling groups and the cluster *(Cassano & Brunetti 2005)*

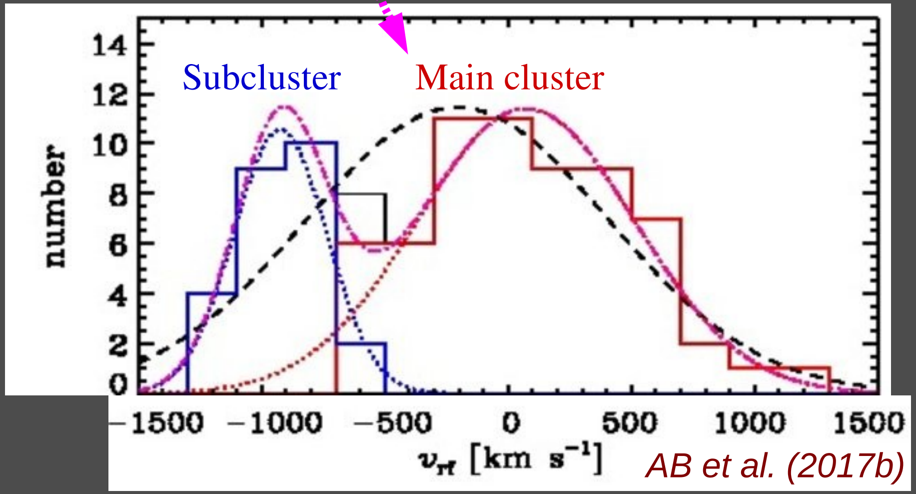
Internal *sub*-structure



Clusters with low concentration have substructures, but also a decreased central intra-cluster gas density.

Decreased central intra-cluster gas density lowers X-ray luminosity, and potentially affects completeness of X-ray-selected cluster catalogs

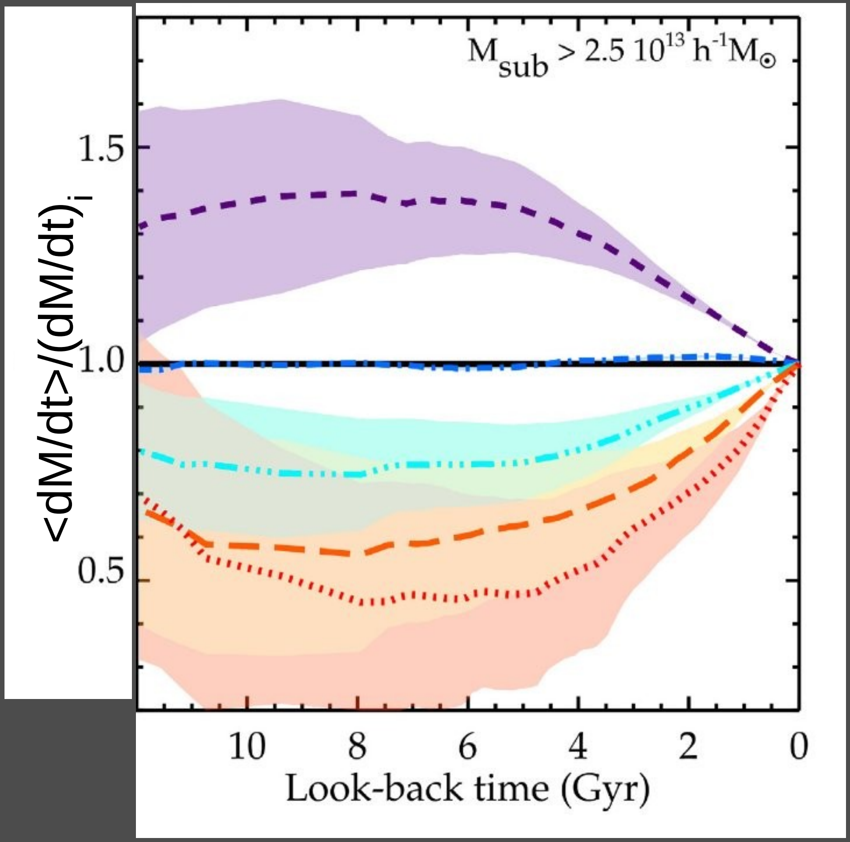




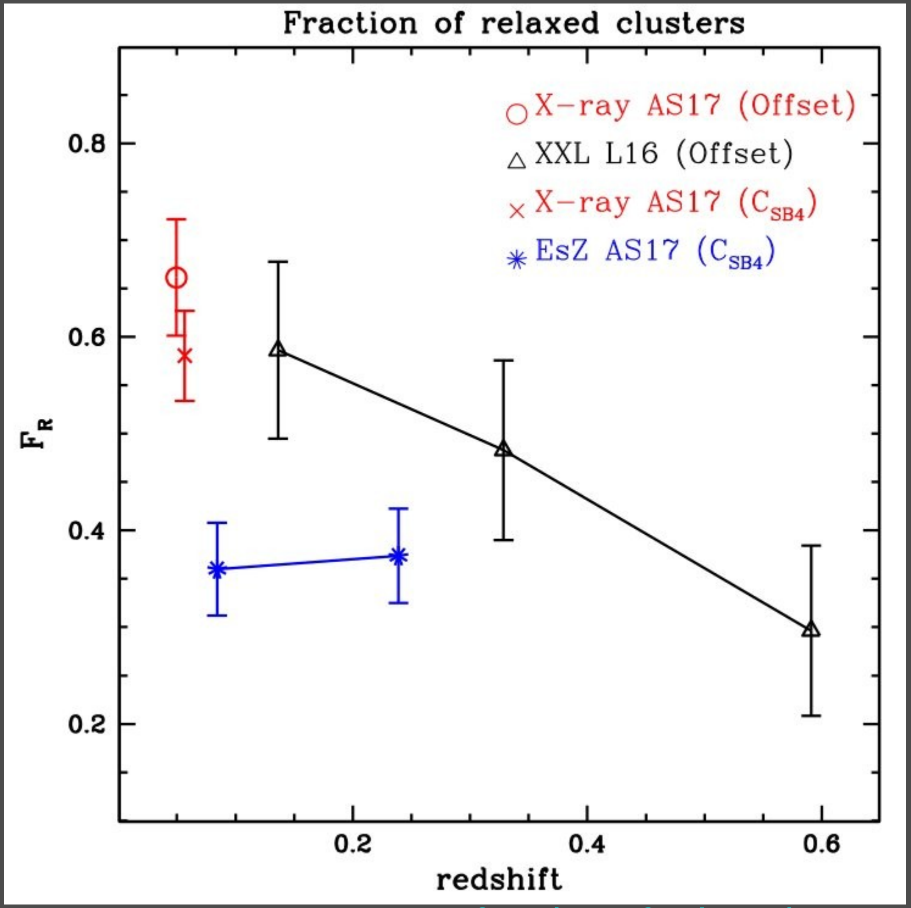
Central intra-cluster medium entropy is high, corresponding to a low central gas density *(Babazaki et al. 2018)*

Internal *sub*-structure

"Substructures" in galaxy clusters can be used as an indicator of their dynamical state



Sorce et al. (2020): MultiDark simulations; colors indicate the amount of substructures (increasing from violet to green to red)



Lopes et al. (2018): fraction of relaxed clusters (less substructures) ↓ with z↑

Detecting substructures informs on dM/dt,
studying substructures as a f(z) constrains cluster evolution (and cosmology)

Internal *sub*-structure

What is the best observational evidence
for the existence of Dark Matter?

Internal *sub*-structure

What is the best observational evidence for Dark Matter:

The “Bullet” cluster!

“Substructures” in galaxy clusters can be used to constrain **the properties of Dark Matter**

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

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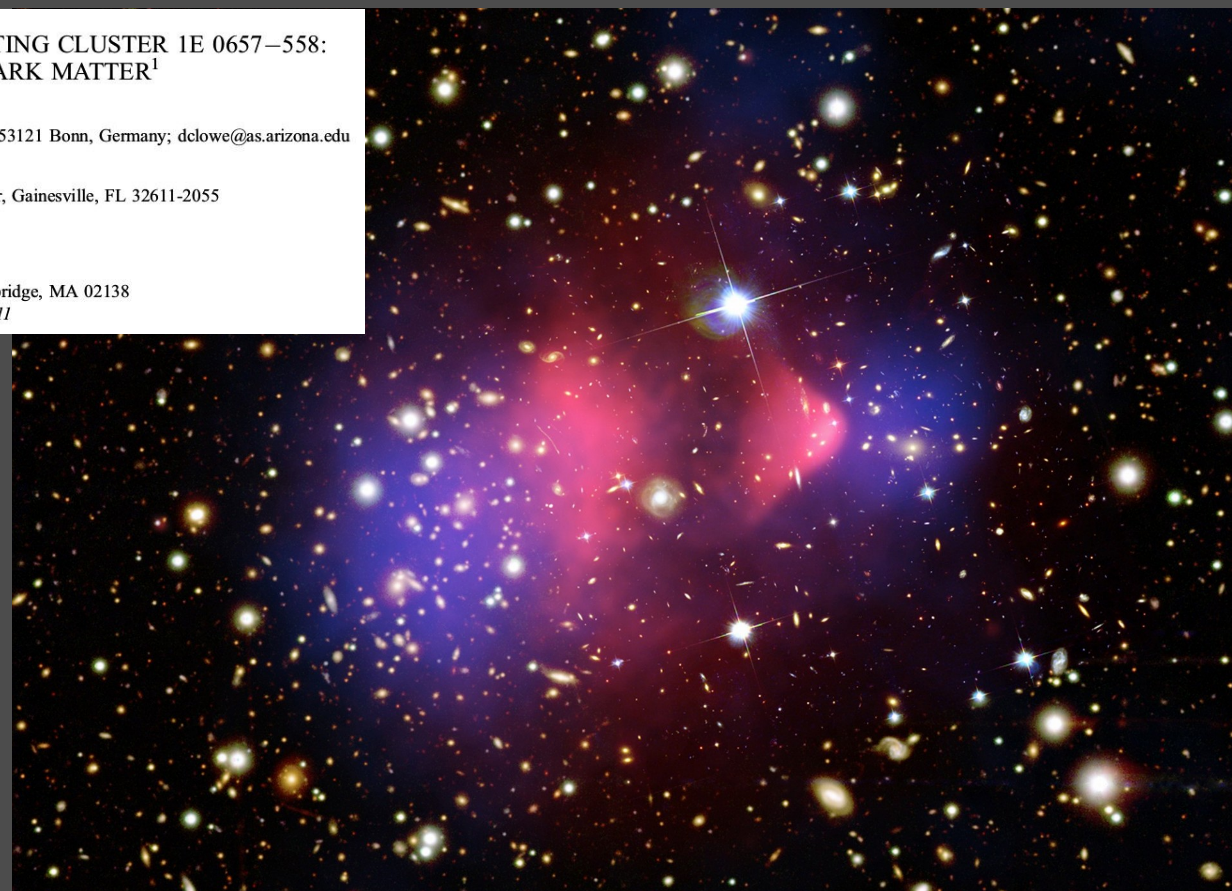


The weak lensing map (blue) directly indicates where the cluster mass is located.

Most of the cluster baryonic mass is in the intra-cluster gas (red) that is displaced from the weak lensing signal.

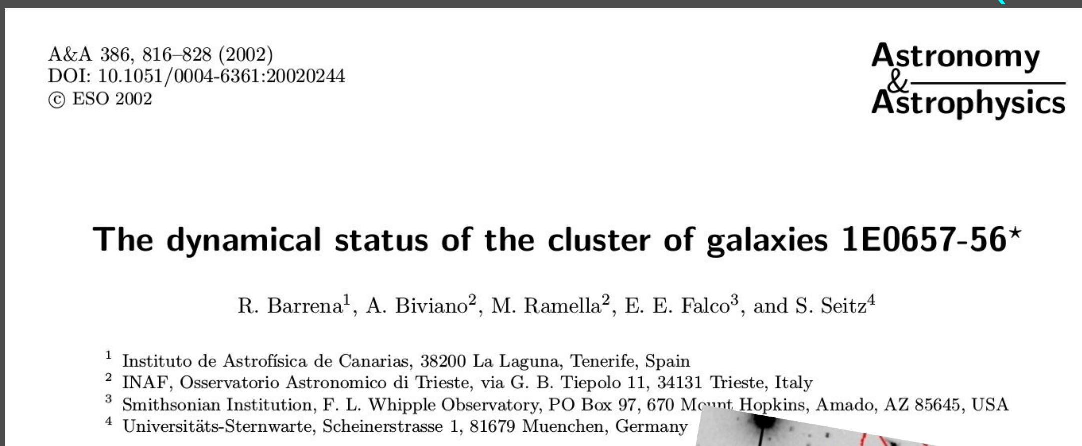
⇒ **Cluster mass cannot be predominantly baryonic**

Markevitch et al.; Clowe et al.

Internal *sub*-structure

The Bullet cluster

...A curiosity: the first dynamical analysis of the Bullet cluster was based on observations done at the TNG in La Palma (before the cluster got its nickname)


A&A 386, 816–828 (2002)
DOI: 10.1051/0004-6361:20020244
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Astronomy & Astrophysics

The dynamical status of the cluster of galaxies 1E0657-56*

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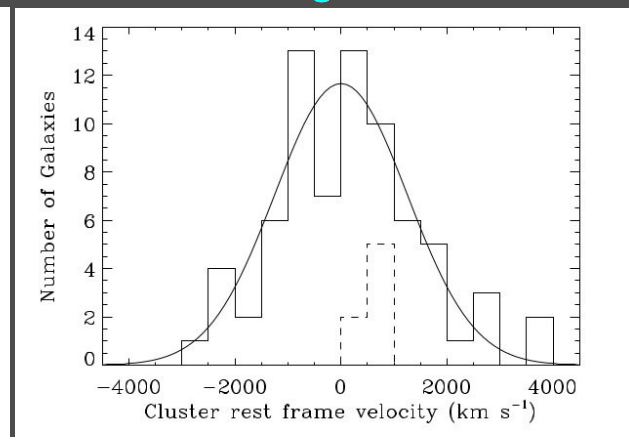

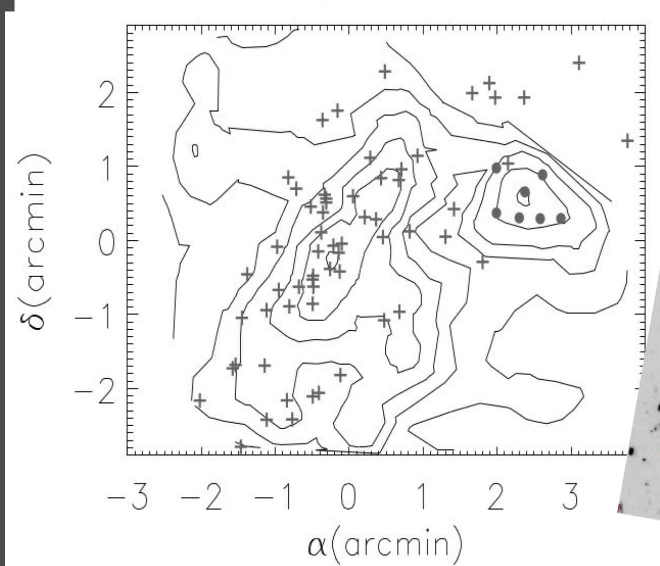

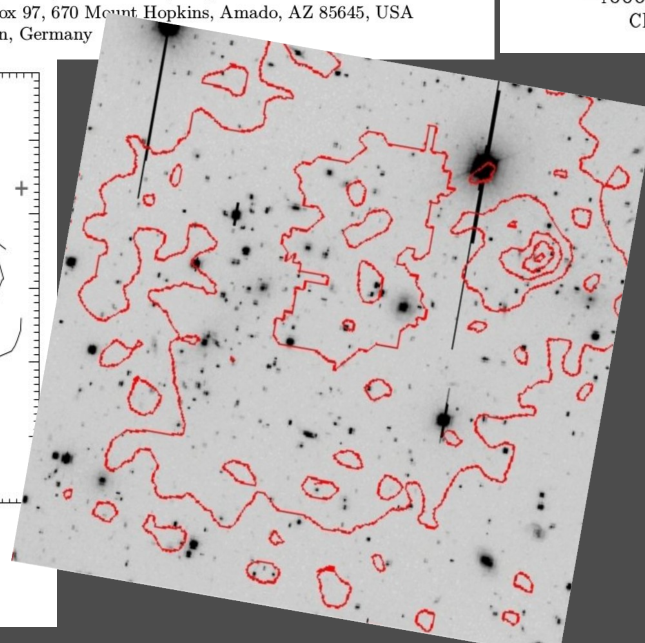

...but we lacked the weak lensing analysis that led to Clowe et al.'s discovery