Mass profiles of relaxed clusters of galaxies: an X-ray perspective

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Dark matter halos

Cold Dark Matter (CDM) N-body simulations of structure formation produce dark matter halos whose density profiles are well parametrized by a 2 parameter function regardless of their mass or cosmology used.

NFW density profile

(Navarro, Frenk & White 1997)

$$\rho(r) = \frac{\rho_c(z)\,\delta_c}{(r/r_s)(1 + r/r_s)^2}$$

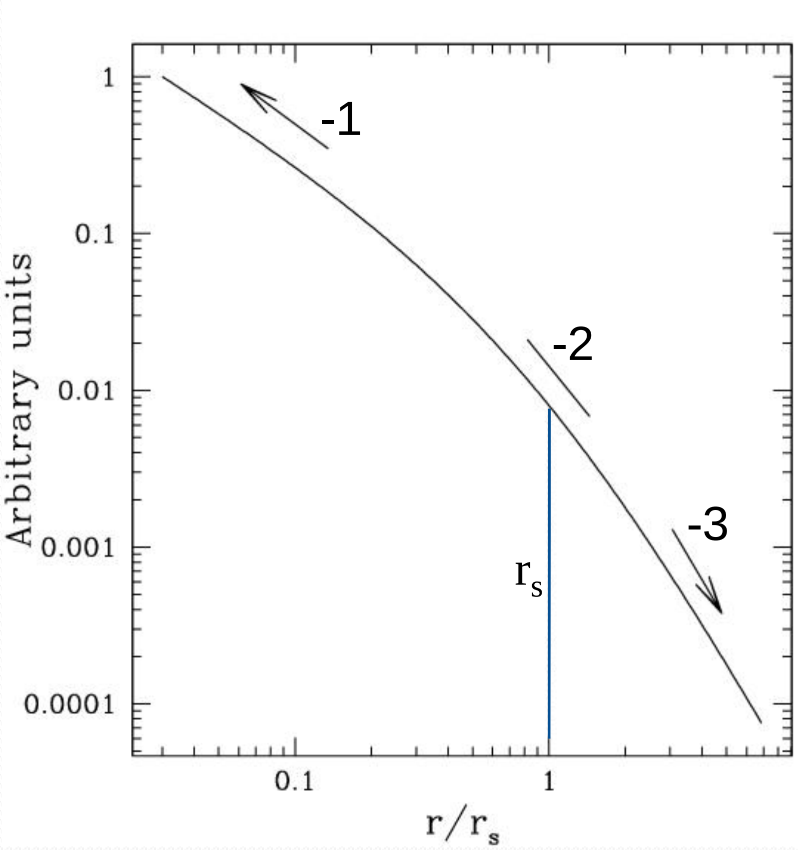
critical density of the universe at redshift z

characteristic dimensionless density

scale radius

NFW density profile

- Inner profile with logarithmic slope -1 giving rise to a cusp
- At large radius the slope reaches a value of -3
- The scale radius (r_s) defines the point in which the slope is -2



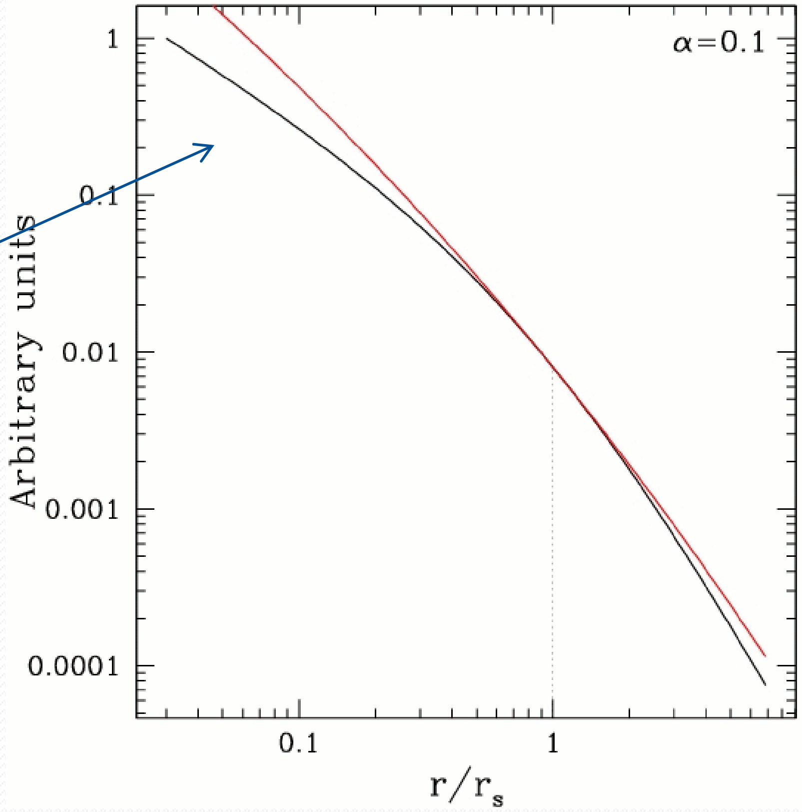
Navarro et al. 2004 profile

Navarro et al. 2004 (N04) with higher resolution simulations found halo inner slopes gradually flattening.

$$\rho(r) = \rho_{-2} \exp\left(\frac{2}{\alpha}\right) \exp\left(-\frac{2}{\alpha} x^{\alpha}\right)$$

$x = r/r_s$

- Same functional form of a Sersic profile
- Flattens gradually producing a constant density core
- $\alpha = 0.172 \pm 0.032$



Profiles modified by adiabatic contraction

From hydrodynamic simulations with gas cooling:

- the condensation of baryons in the cores of dark halos cause the dark matter to adiabatically contract further inward.

Process of Adiabatic Contraction (AC)
(Blumenthal et al. 1986; Gnedin et al. 2004)

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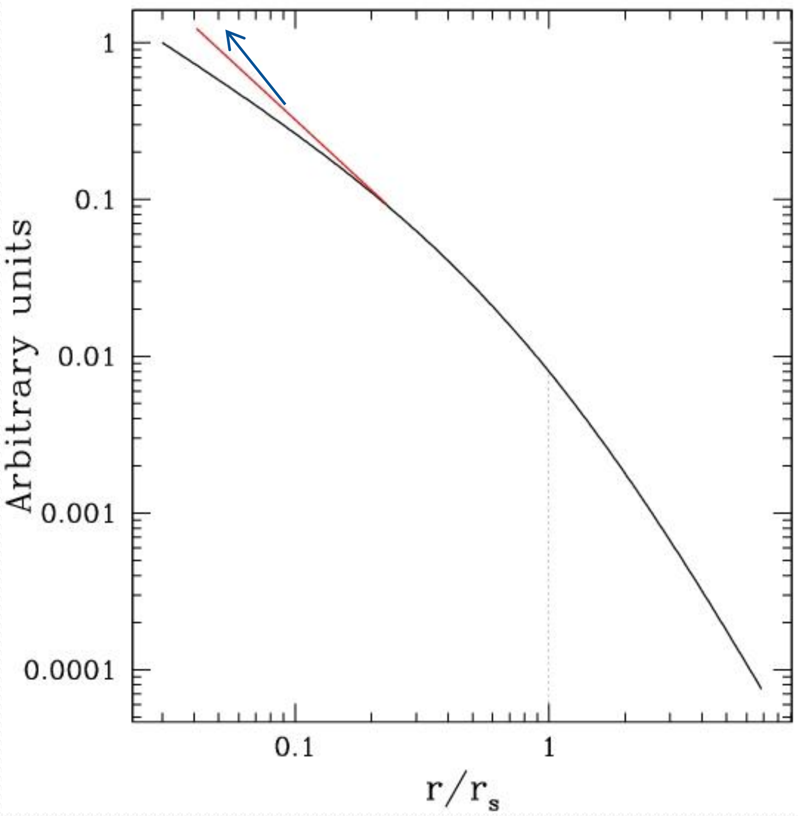
The dark matter density further increases in the center.



Virial quantities and concentration parameter

Each profile can be related to the virial quantities of the halo.

Definitions:

- Virial radius r_{vir} → the radius within which the mean matter density is $\Delta_{vir}\,\rho_c(z)$
- Virial Mass $M_{vir} = 4/3\,\pi\,\Delta_{vir}\rho_c(z)\,r_{vir}^3$ → Mass enclosed in r_{vir}
- r_{-2} is the characteristic radial scale of the profile where the logarithmic slope of the density profile is -2 (*scale radius* for NFW)
- Concentration parameter $c = r_{vir}/r_{-2}$

Mass profiles of clusters of galaxies

Clusters of galaxies are excellent candidates for the study of mass and dark matter profiles

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- dark matter can dominate deep down to $<0.01\ r_{vir}$
  (Lewis et al. 2003)

- Several powerful techniques can be used to recover their mass profiles

Mass profiles: different techniques

- dynamical analysis
- redshift space caustics
- gravitational lensing (strong, weak)
- hydrostatic equilibrium (X-ray)
- and many more...

- Each technique has advantages and disadvantages and are complementary:

  E.g.

  - Caustics and lensing do not require dynamical equilibrium assumptions
  - Lensing probe the projected mass
  - Methods relying on galaxies ➡ good at large radii
  - The X-ray method rely on the ICM ➡ good in central regions

Mass profiles from X-rays

If the X-ray emitting IntraCluster Medium (ICM) is in hydrostatic equilibrium in the cluster potential

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The mass enclosed whitin a radius r can be inferred by the hydrostatic equilibrium equation.

By assuming spherical symmetry and ideal gas law

$$M_{\rm grav}(<r) = \frac{k_{\rm B}}{G\mu m_p} rT\left(-\frac{d\ln\rho}{d\ln r} - \frac{d\ln T}{d\ln r}\right)$$

(Fabricant et al. 1980)

Mass profiles from X-rays

If the X-ray emitting IntraCluster Medium (ICM) is in hydrostatic equilibrium in the cluster potential

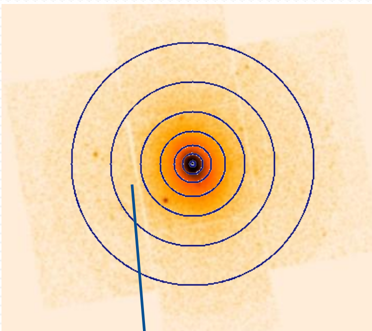
Reliable mass estimates

The hydrostatic equilibrium technique has been validated against other techniques
(Girardi et al. 1998, Allen et al. 2001, Diaferio et al. 2005, Sehgal et al. 2007)

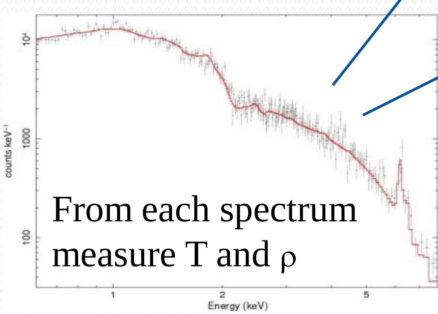
$$M_{\rm grav}(<r) = \frac{k_{\rm B}}{G\mu m_p} rT \left(-\frac{d \ln \rho}{d \ln r} - \frac{d \ln T}{d \ln r} \right)$$

(Fabricant et al. 1980)

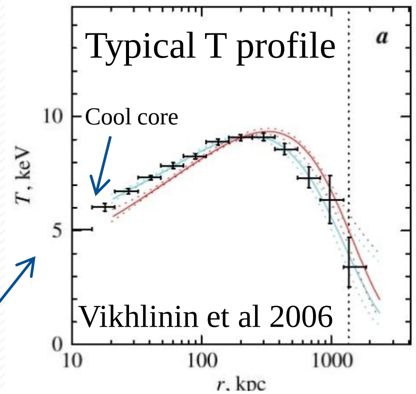
Measuring a mass profile from X-rays: a schematic view

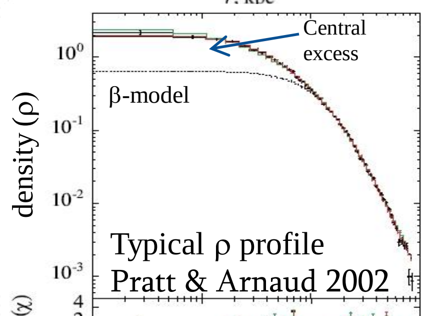


Extract a spectrum from each annulus



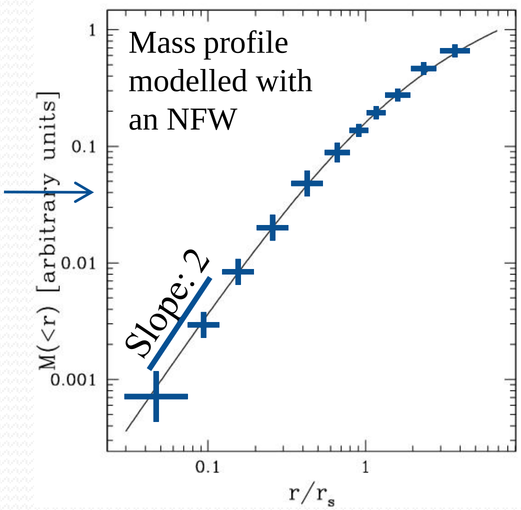
From each spectrum measure T and ρ





Approximate functions

Hydrostatic Equilibrium equation



At this stage is important to account for projection effects since the ICM plasma is optically thin.

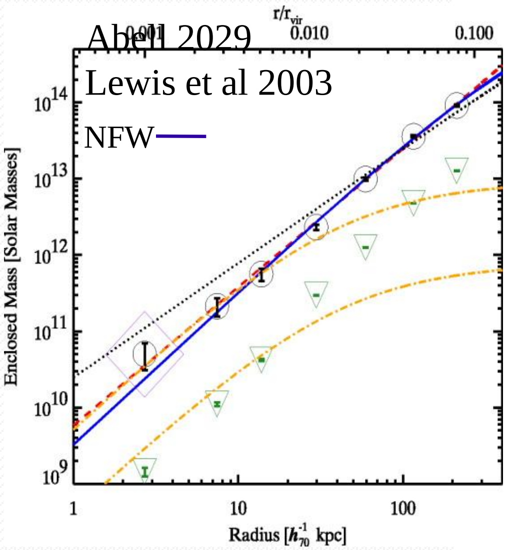
Mass profiles from X-rays: the observer point of view

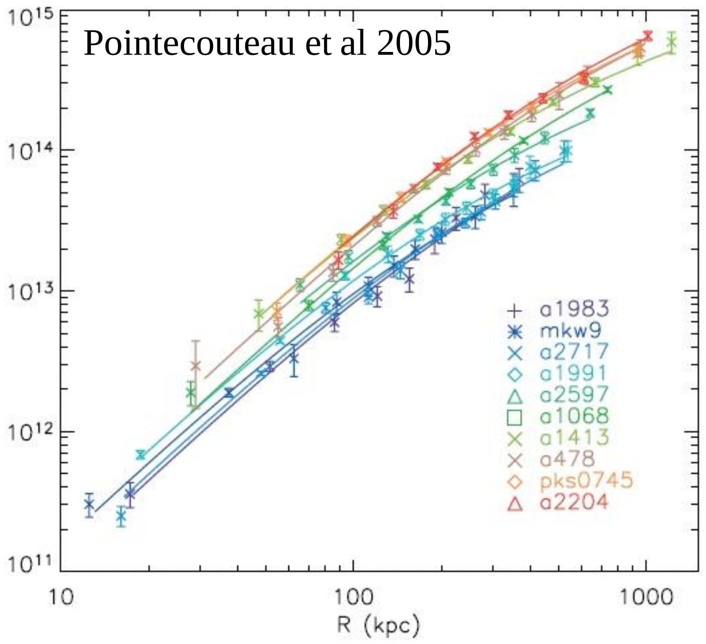
Thanks to XMM and Chandra

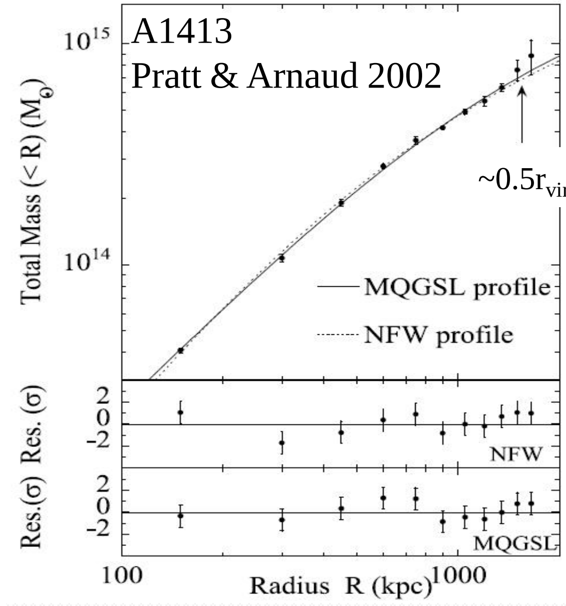
High sentitivity, high spatial and spectral resolution

- Mass profiles of relaxed X-ray clusters of galaxies can be measured in great detail from $<$ **$0.01r_{vir}$** to $\geq$ **$0.5r_{vir}$**
  (Lewis et al 2003, Pratt & Arnaud 2002)
- Generally an NFW provide a good description of the total mass profiles for clusters of galaxies
  (Pointecouteau et al. 2005)

Mass profiles from X-rays: the observer point of view II

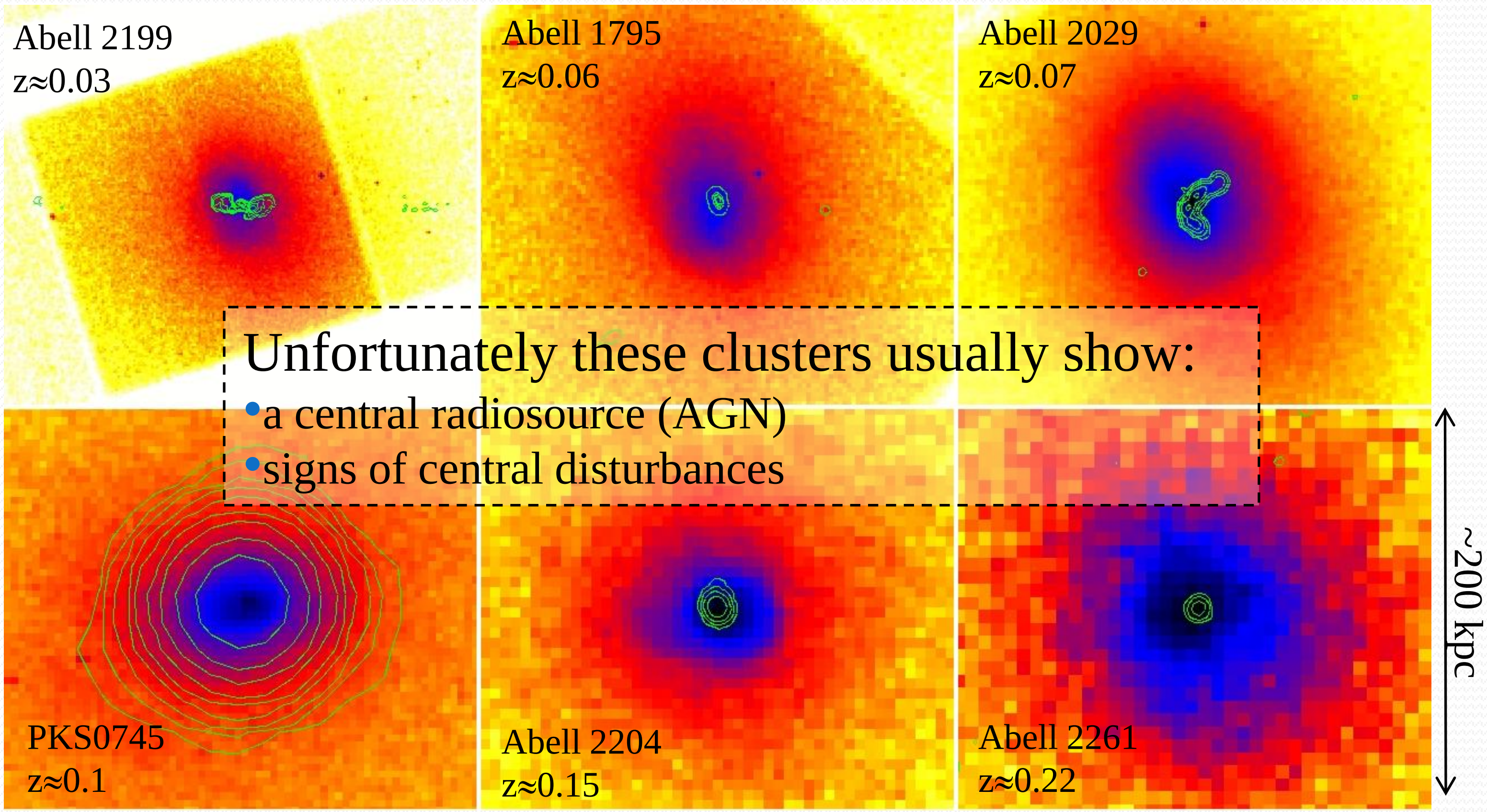






Mass profiles from X-rays: the observer point of view III

Only clusters with regular morphologies indicative of a relaxed dynamical state. To validate the hydrostatic equilibrium assumption.



Unfortunately these clusters usually show:

- a central radiosource (AGN)
- signs of central disturbances

Mass profiles from X-rays: the observer point of view III

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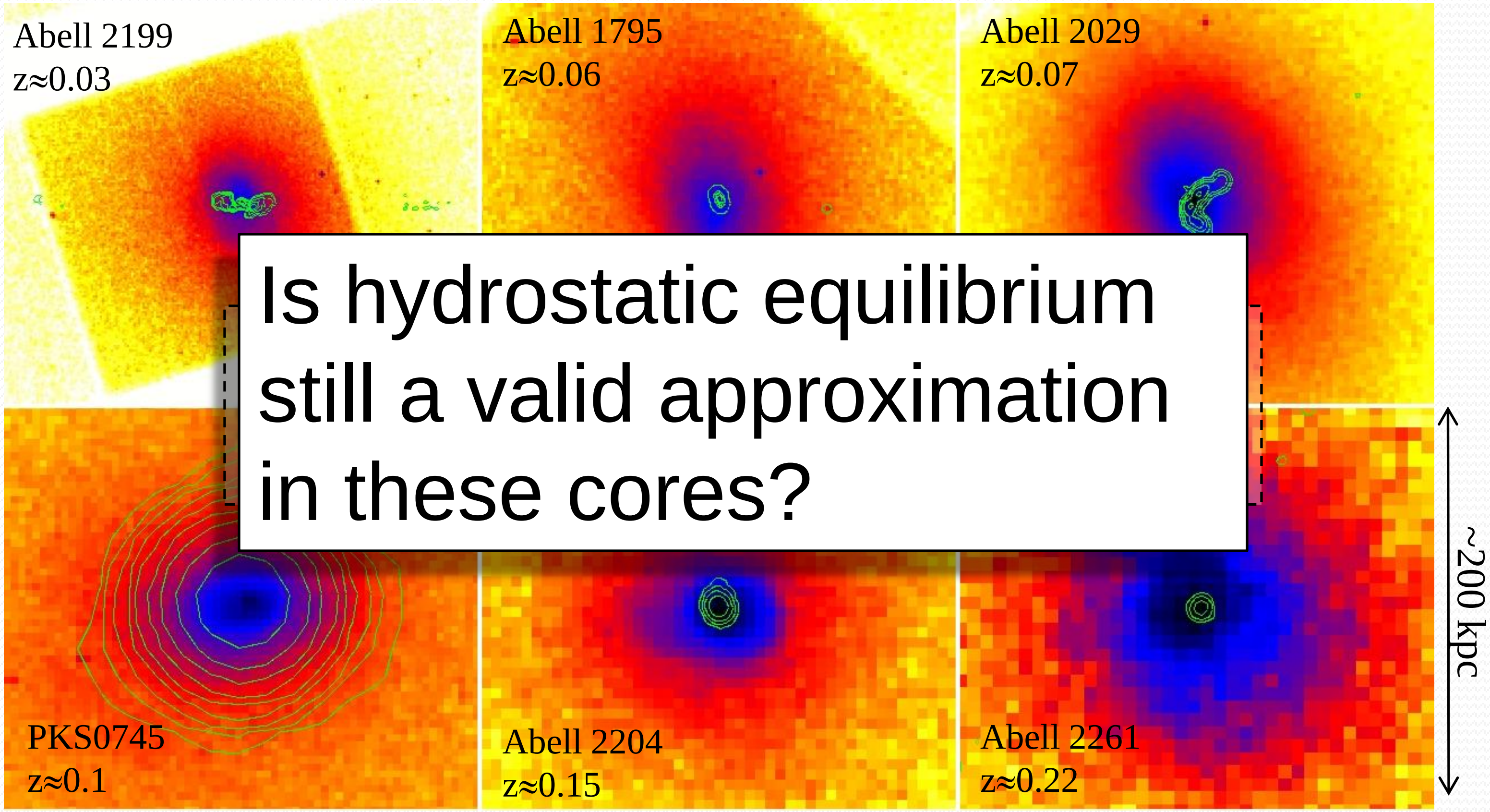


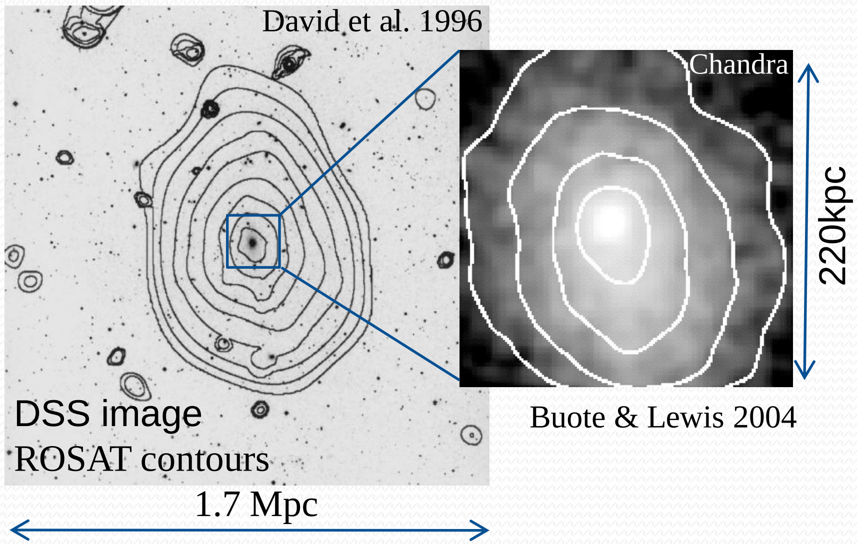
Is hydrostatic equilibrium still a valid approximation in these cores?

The relaxed radio-quiet cluster Abell 2589

One way to examine the mass profiles in cores of clusters is to select and study relaxed radio-quiet clusters

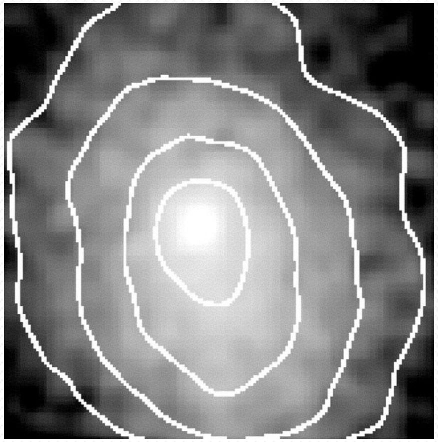
One of the most promising candidates is: **Abell 2589**

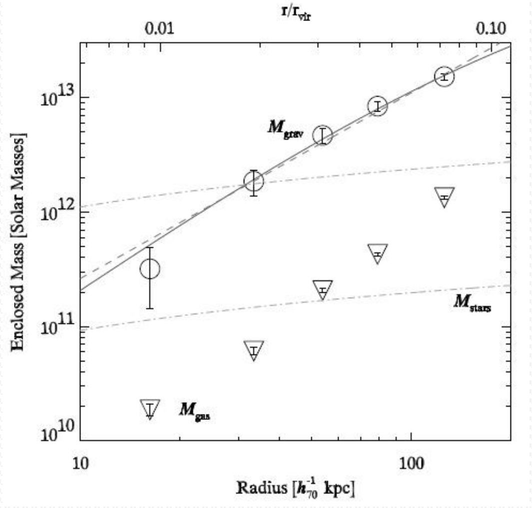
- z=0.0414
- No central radio emission at 1.4 GHz (NVSS maps)
- Relaxed from ~Mpc scales down to kpc scales



Chandra analysis of A2589

- Buote & Lewis 2004 analysed a 14ks mildly flared Chandra observation
- Cluster relaxed in the core apart from a ~12kpc center shift (between the core and the outermost observed region).
- Isothermal temperature profile at ~3.2 keV
- Mass profile: NFW
- r_{vir} ~1 Mpc (for both total mass and dark matter)
- Inner mass and dark matter profile slope: ~1.6±0.2 (measured at ≥ 0.02 r_{vir})





XMM analysis of Abell 2589

(Zappacosta et al. 2006)

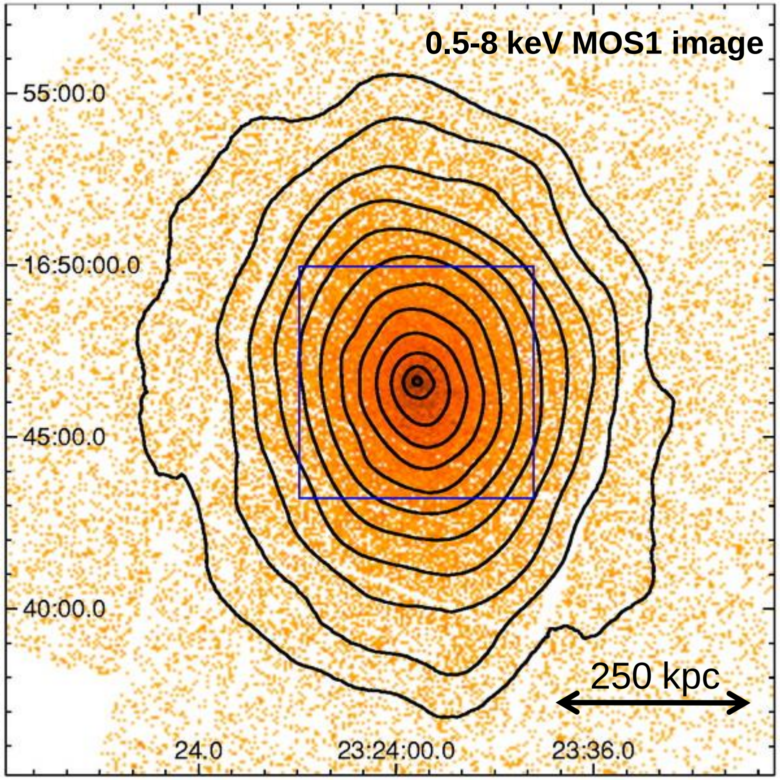
- Abell 2589 was observed with XMM for ~46ks
- only 1/3 of the original exposure per detector could be used for the analysis (because of background flarings)
- Data quality better than the Chandra observation analysed in Buote & Lewis 2004

- Improve the Chandra constraints
- Test the NFW vs N04 profile
- Test the occurrence of AC in the cluster core

Morphological analysis

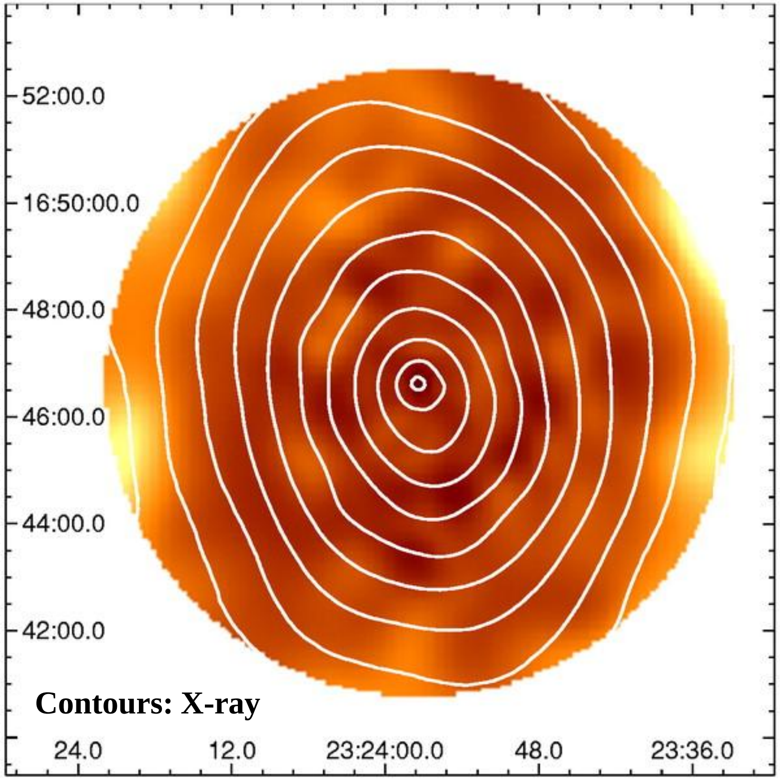
X-ray image

Very relaxed apart from a center shift of 16kpc between the 0-15kpc and 45-60kpc regions



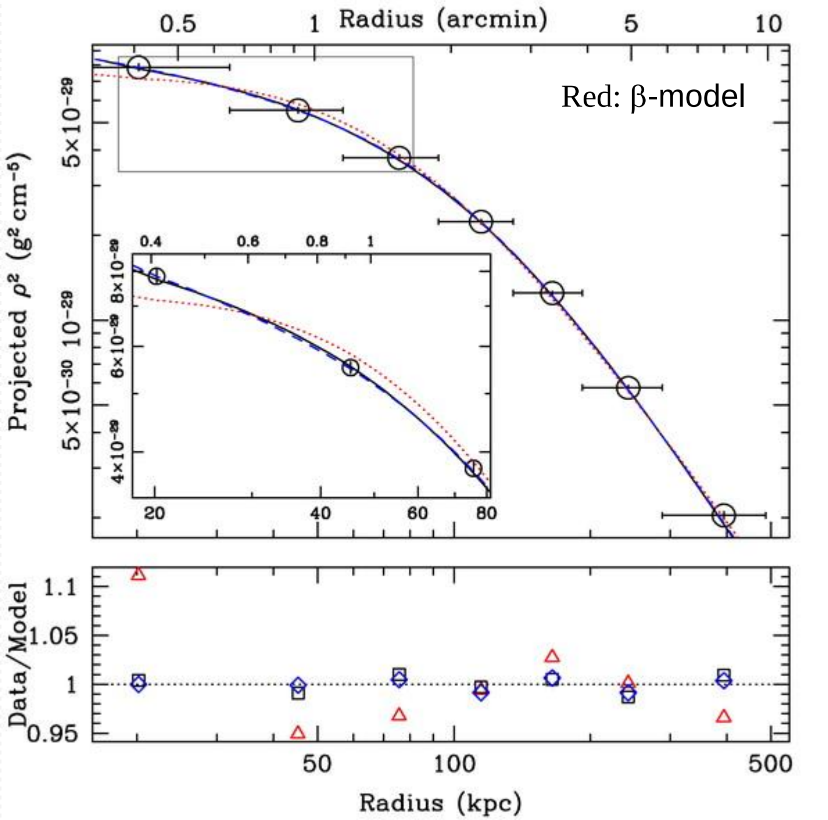
Hardness ratio map

No evidence of significant deviation in the temperature structure

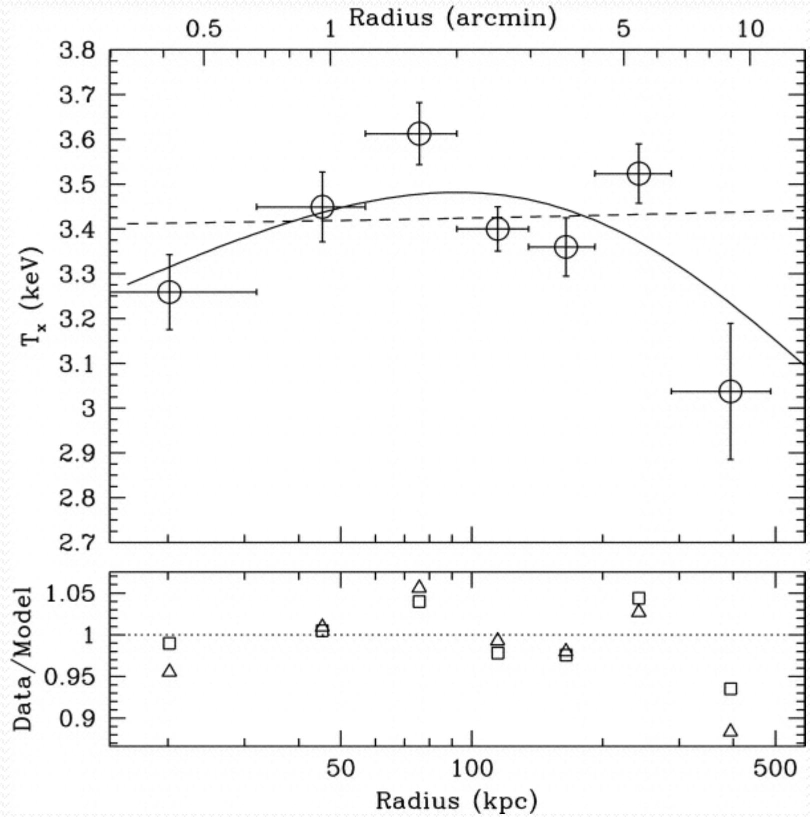


Density and Temperature profiles

Density profile well parametrized by a β-model with central cusp

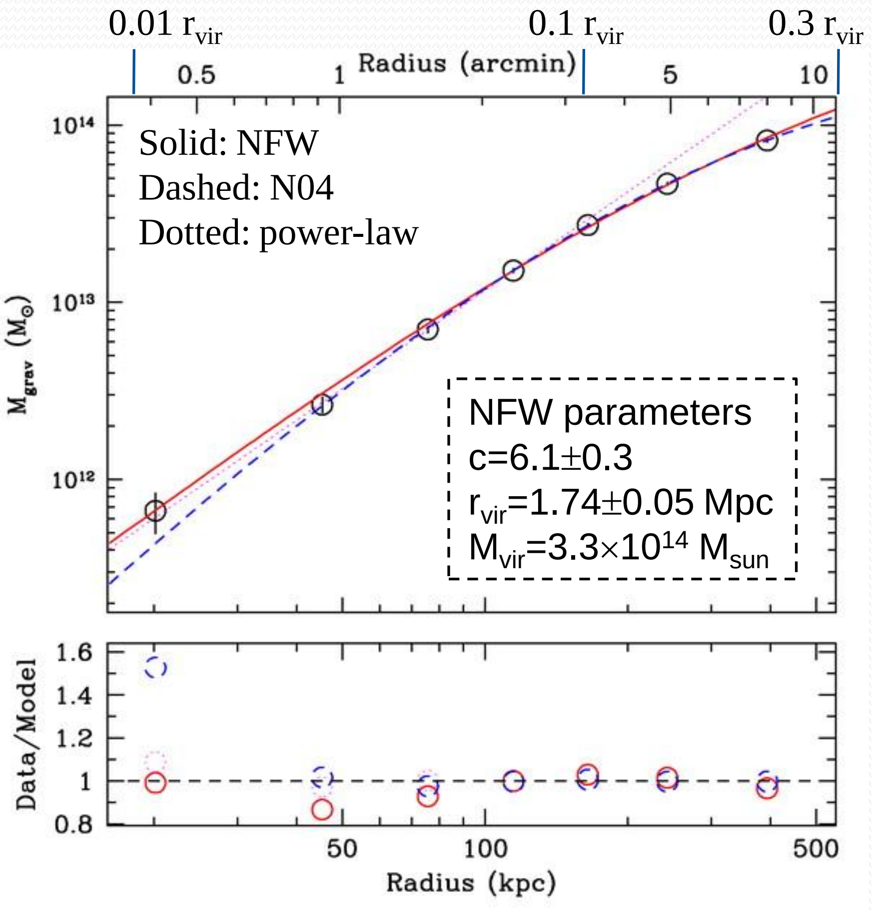


The temperature profiles is nearly isothermal with a hint of cool core



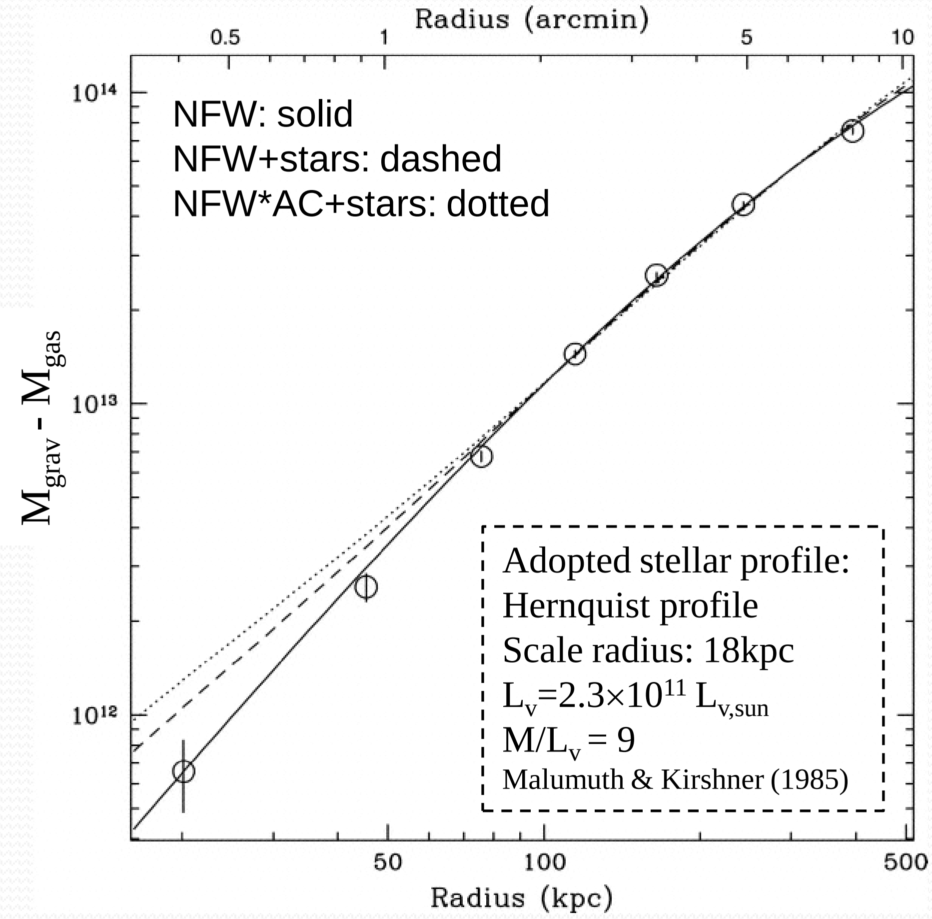
Gravitating mass profile

- The total mass profile is well parametrized by an NFW
- The sersic-like N04 profile underestimate the inner data point
- The N04 index $\alpha=0.4\pm0.05$ is inconsistent with the predicted 0.172 ± 0.032
- The slope computed in the range 0.01-0.05 r_{vir} is 1.84 ± 0.18 (agrees at 1σ with NFW)



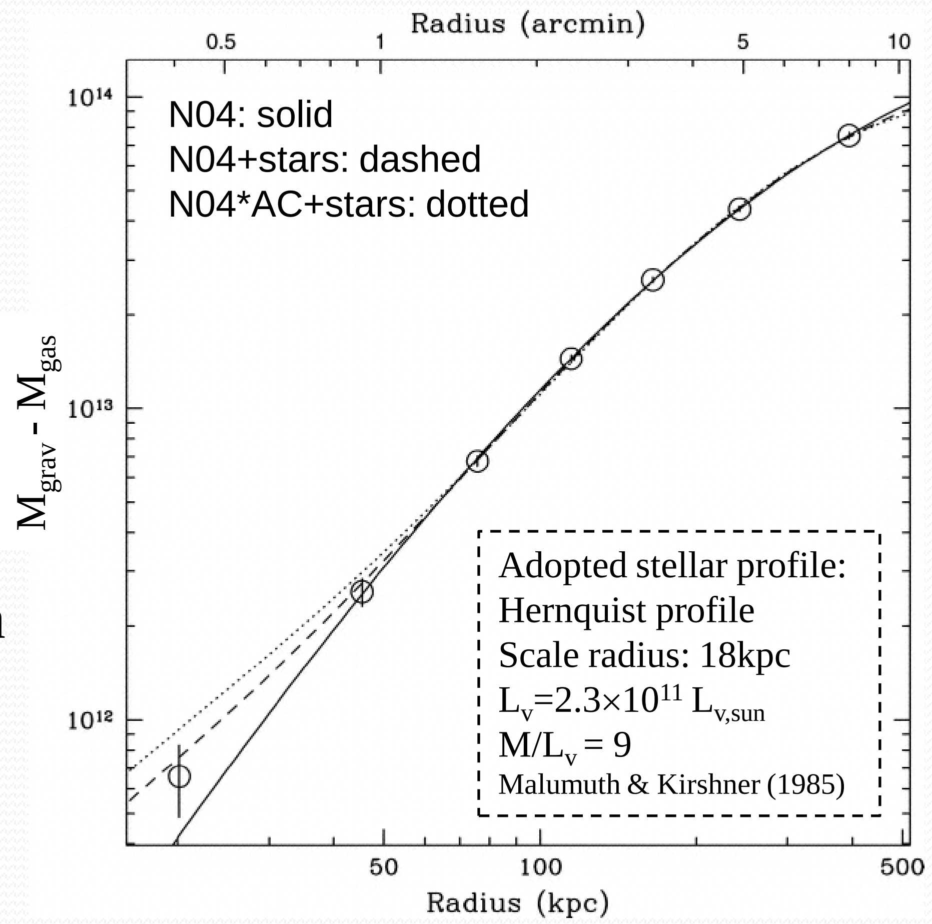
Dark matter profile I

- We fitted dark matter+stellar profiles to M_{grav}-M_{gas}
- A simple NFW still fits very well
- Adding stellar mass does not improve the fit
- Accounting for AC further worsen the fit
- If we let M/L_v to be a free parameter, it assumes unphysically low values (i.e. <0.15)



Dark matter profile II

- A simple N04 still underestimate the inner data point
- Adding stellar mass improves the fit
- Accounting for AC worsen the fit
- An M/L_v free produce values the range 3-5
- These results have to be taken with caution because the N04 index α reaches very high values (>0.6) to accomodate more central stellar mass



Adiabatic contraction in Abell 2589

Apparently AC does not take place in the core of A2589

- Can departures from hydrostatic equilibrium like additional pressure support from non-thermal processes reconcile the mass profile with the AC scenario?

We consider turbulent motions and magnetic field

(how much is needed to bring AC in agreement with the data?)

- Turbulent motions: turbulent velocity of ~1.3c_s much larger then the predicted 0.1-0.3c_s (Nagai et al 2003; Faltenbacher et al. 2005)
- Magnetic field: 56μG (current evidences favor magnetic field values of 1-10μG; Govoni & Feretti 2004)

What did we learn from Abell 2589

- A simple NFW profile is all we need to model A2589 mass and dark matter profile in the range 0.015-0.3r_{vir}
- N04 profile underestimate the central region and gives an index α too large (i.e. core too shallow)
- Adiabatic contraction does not seem have taken place during this cluster formation
- Other processes may counteract the effect of AC in cores
- El-Zant et al. 2004 propose that during halo formation dynamical friction experienced by member galaxies may heat-up the dark matter flattening the central cusp and leading to a total mass profile consistent with NFW

Future prospects

- We need better data for A2589 to better constrain the profile in the very inner core (i.e. $< 0.015r_{vir}$) and place more stringent limits on the degree of adiabatic contraction that could be present in this object

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80ks of Chandra time awarded and already observed in AO7

- We need to carry this study on a sample of objects to draw more general conclusions

⬇

Chandra and XMM archives contain ~15 radio quiet clusters

Predicted concentration-mass relation

CDM N-body simulations find:

- A relation between concentration parameter (c) and the virial mass (M_{vir}) of a halo *at any given fixed epoch*.

c-M_{vir} relation

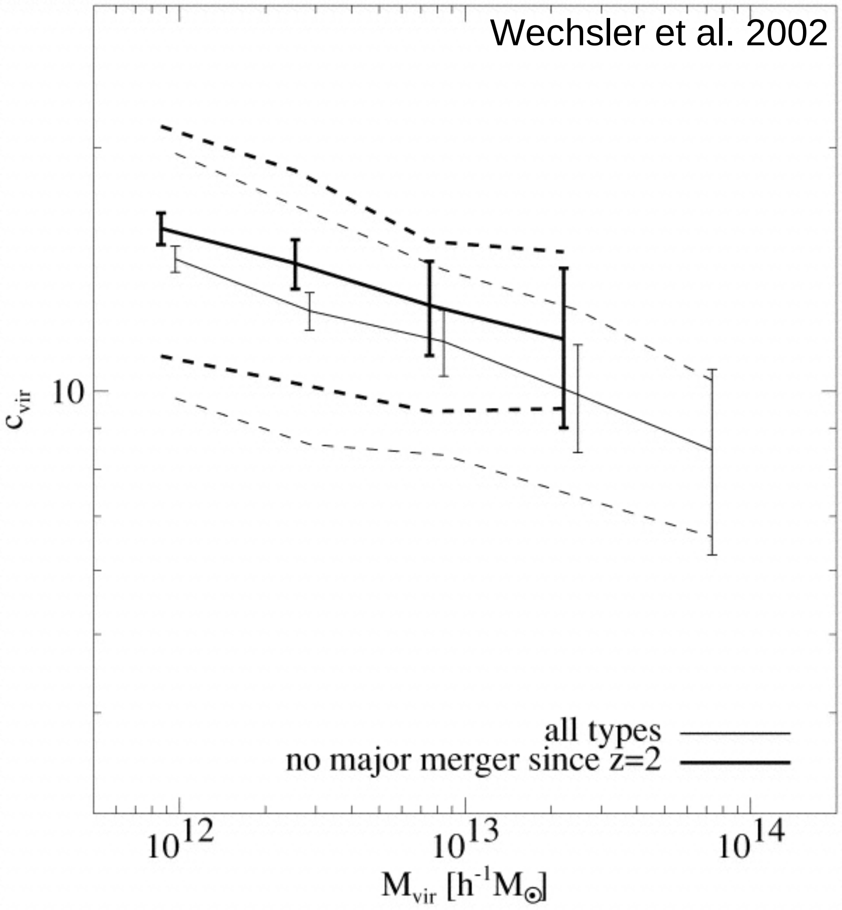
(Navarro et al. 1997, Bullock et al. 2001, Dolag et al. 2004, Kuhlen et al. 2005, Shaw et al. 2006, Neto et al. 2007)

- An intrinsic scatter of the c-M_{vir} relation of 0.14Δlog(c)

(Bullock et al. 2001)

- relaxed halos: c-M_{vir} relation with ~10% higher normalization and ~0.1Δlog(c) of intrinsic scatter.

(Wechsler et al. 2002)



Qualitative explanation of the c-M_{vir} relation

The hierarchical scenario of structure formation

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Less massive halos form at earlier times

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They will reflect the high density of the universe exhibiting higher concentration than late forming halos

The intrinsic scatter can be explained with a scatter in formation times for halos of fixed mass

Modeling the c-M_{vir} relation

- Several semianalytic models have been proposed to explain quantitatively the relation

(Navarro et al. 1997, Bullock et al. 2001, Eke et al. 2001)

- They predict qualitatively the same c-M_{vir} but differ for details on low/high masses

- Dolag et al. 2004 introduced a power-law parametrization to empirically describe the relation on small ranges of mass:

$$c \propto c_0/(1+z)\, M_{vir}^{a}$$

Typical values:
$a \approx -0.1 - -0.14$
$c_0 \approx 6 - 9$

Modeling the c-M_{vir} relation

- Several semianalytic models have been proposed to explain quantitatively the relation

(Navarro et al. 1997, Bullock et al. 2001, Eke et al. 2001)

- They

details

In the following we will compare our results with the Bullock et al. 2001 model and use the Dolag et al. 2004 power-law parametrization

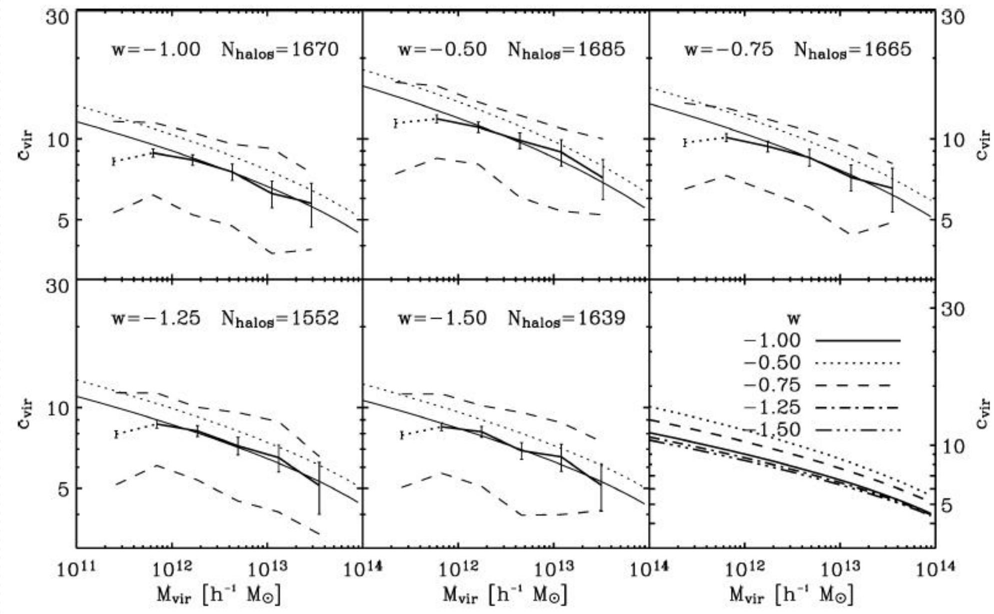
- Dola... to empirically describe the relation on small ranges of mass.

$$c \propto c_0/(1+z)\, M_{vir}^{a}$$

Typical values:
$a \approx -0.1 - -0.14$
$c_0 \approx 6 - 9$

Cosmology with the c-M_{vir} relation

- The normalization of the c-M_{vir} relation is sensitive to the cosmology used.
- In particular it depends on Ω_m, *w* and σ_8

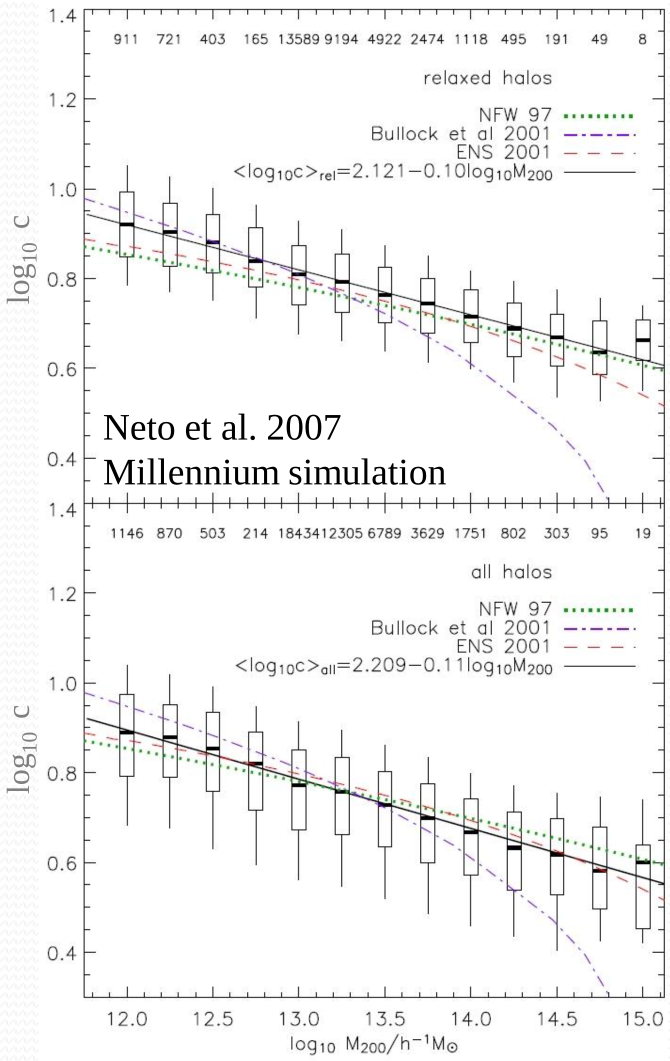


Kuhlen et al. 2005

c-M_{vir} on cluster scales

- c-M_{vir} not well tested on cluster scales
- Difficult to create enough clusters for statistical studies if simulated boxes are not large enough
- Only few studies exploring the cluster scale (i.e. 10^{14}-$10^{15}M_{sun}$)

(Dolag et al. 2004, Shaw et al. 2006, Neto et al. 2007)



Predicted concentration redshift relation

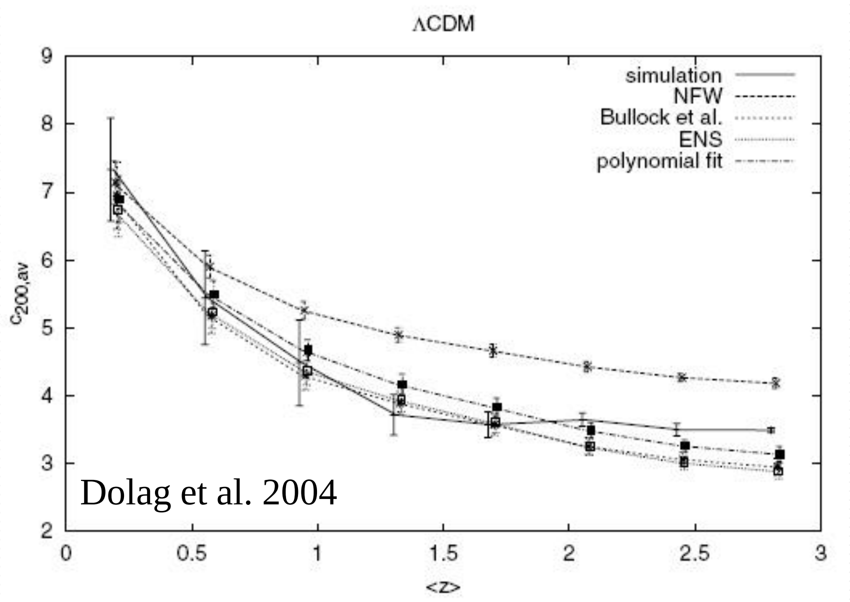
From N-body simulations

- Predicted dependence between c and redshift *at fixed mass*

  c-z relation

  (Bullock et al. 2001)

- $c \propto 1/(1+z)$



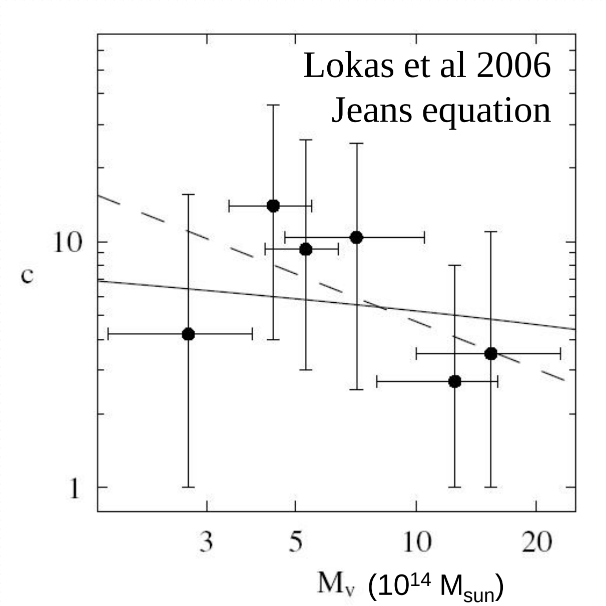
c is roughly related to the halo central density over the varying (with time) background density of the universe

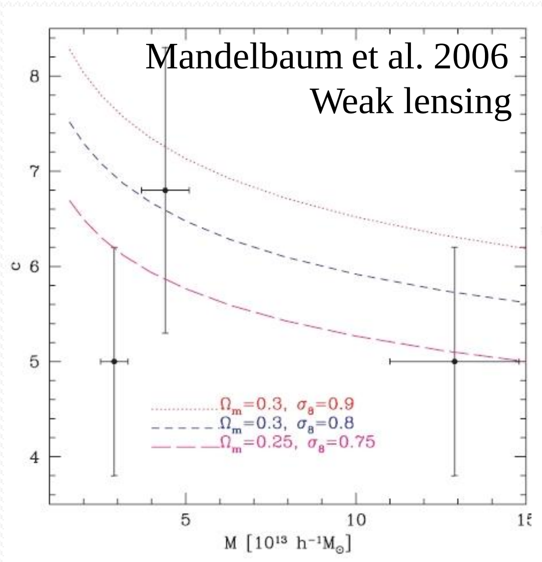
$$c \propto (\rho_{halo}/\rho_{univ}(z))^{1/3} = (1+z_{form})/(1+z)$$

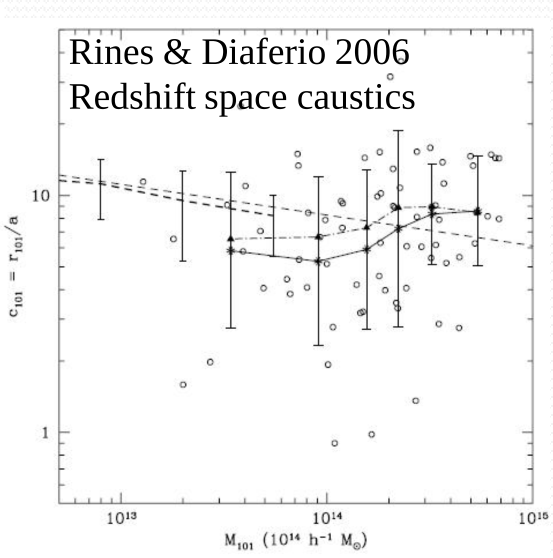
Observational results. I
c-M_{vir} the optical view

- Optical observers using a variety of techniques obtain results consistent with ΛCDM

(Biviano & Salucci 2006, Łokas et al. 2006, Rines & Diaferio 2006, Mandelbaum et al. 2006)



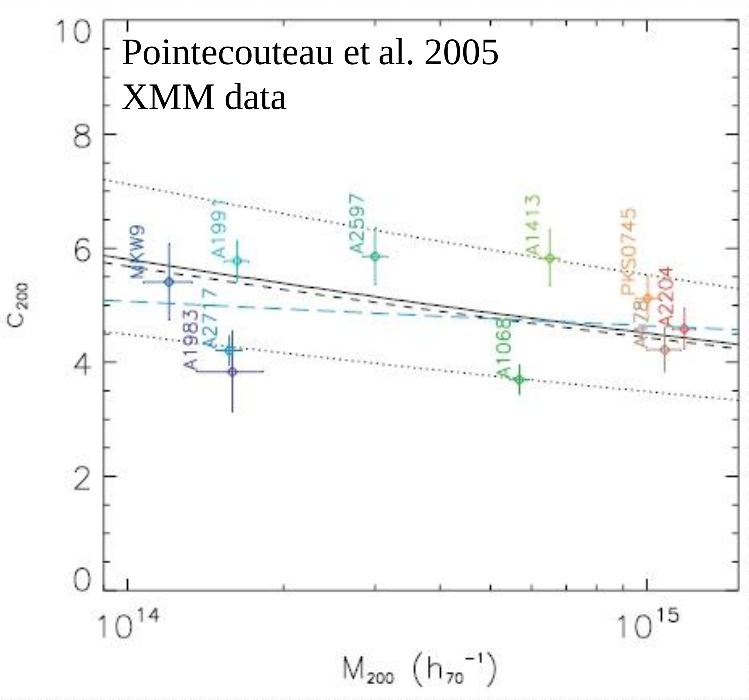


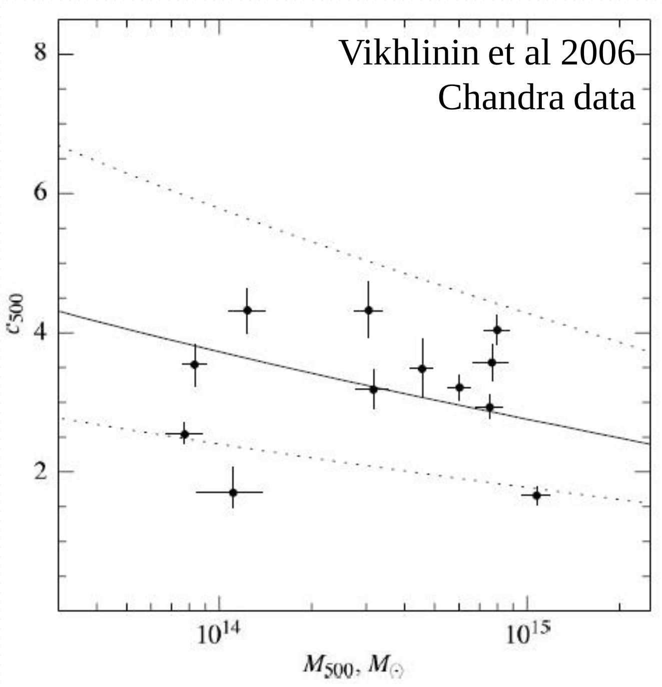


Observational results. II
c-M_{vir} the X-ray view

- Also X-ray observers find consistency with predictions

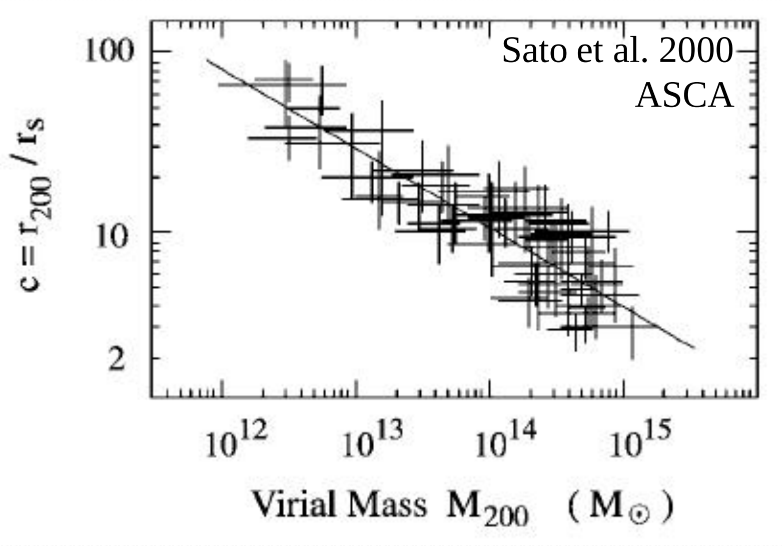
(Pointecouteau et al. 2005 , Vikhlinin et al. 2006)

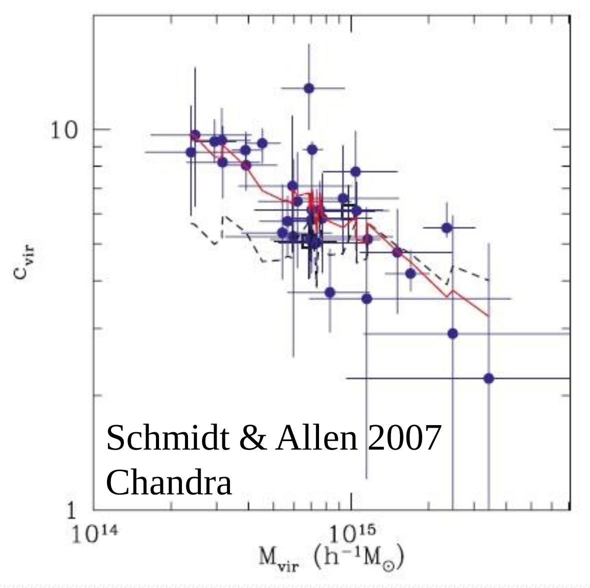




Observational results. III
c-M_{vir} the X-ray view

- ... not always!
- Some author find c-M_{vir} slopes too steep than predicted (Sato et al. 2000, Schmidt & Allen 2007)





Observational results. IV
c-z relation

So far only few studies

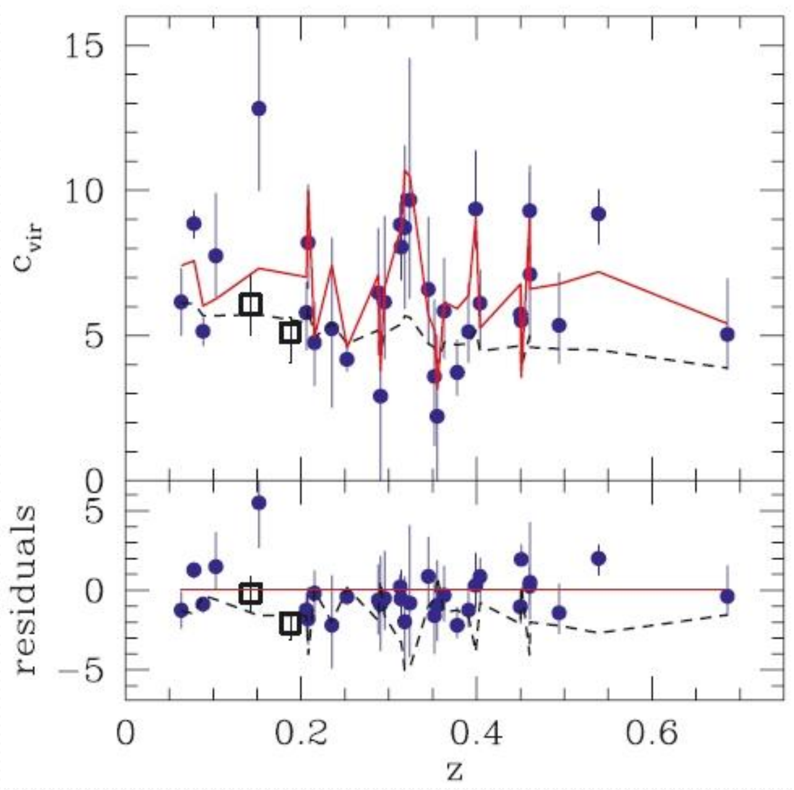
Observational results. IV
c-z relation

X-ray

- Schmidt & Allen (2007; SA07 hereafter) analyzing Chandra observations for 34 clusters of galaxies observed in the redshift range 0.06-0.7.

$$c \propto (1+z)^{-b} {M_{\rm vir}}^{a}$$

  - b=0.71±0.52 (but a=-0.45±0.12)
  - no variation of c-z (b=0.3±0.49) assuming a predicted c-M slope

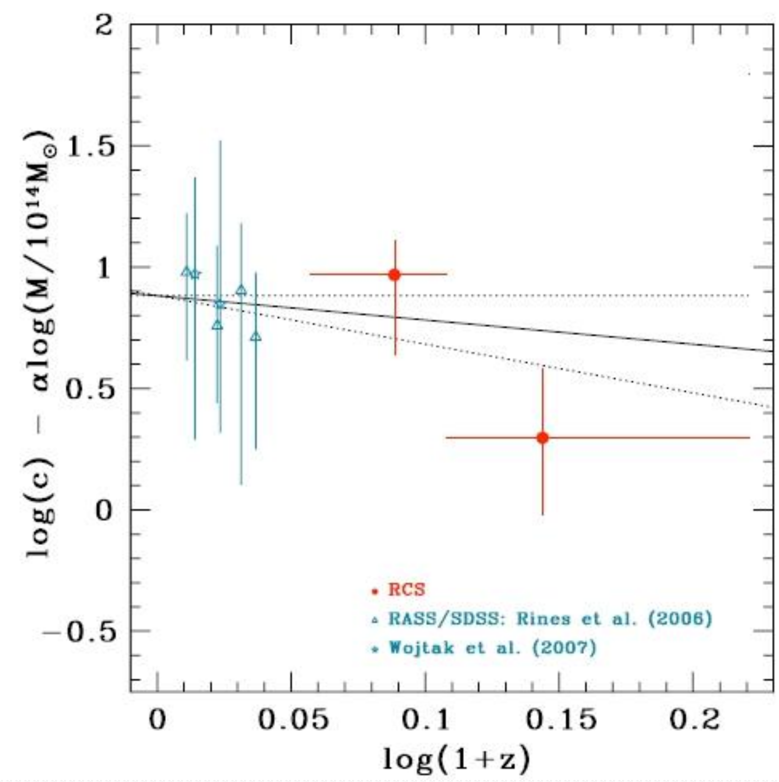


Observational results. IV c-z relation

Optical

- Blindert (2007) using RCS clusters at <z> = 0.33 find a somewhat steeper c-z

$$c \propto (1+z)^{-b} \, {M_{\rm vir}}^{a}$$



Constraining the c-M_{vir} relation (Buote et al. 2007)

- Aim: significantly improve the constraints by enlarging the mass range and employing many more systems

- Sample of 39 relaxed galaxy systems spanning a mass range of (0.06-20) $\times 10^{14}$ M_{sun} (i.e. from ellipticals to clusters)

⇓

- Accurate mass profiles have been obtained by us for 24 low mass systems in the mass range $6 \times 10^{12} \leq M_{vir} \leq 3 \times 10^{14}$ M_{sun}

  (Humphrey et al. 2006, Zappacosta et al. 2006, Gastaldello et al. 2007)
- Data for more massive systems have been taken from the literature

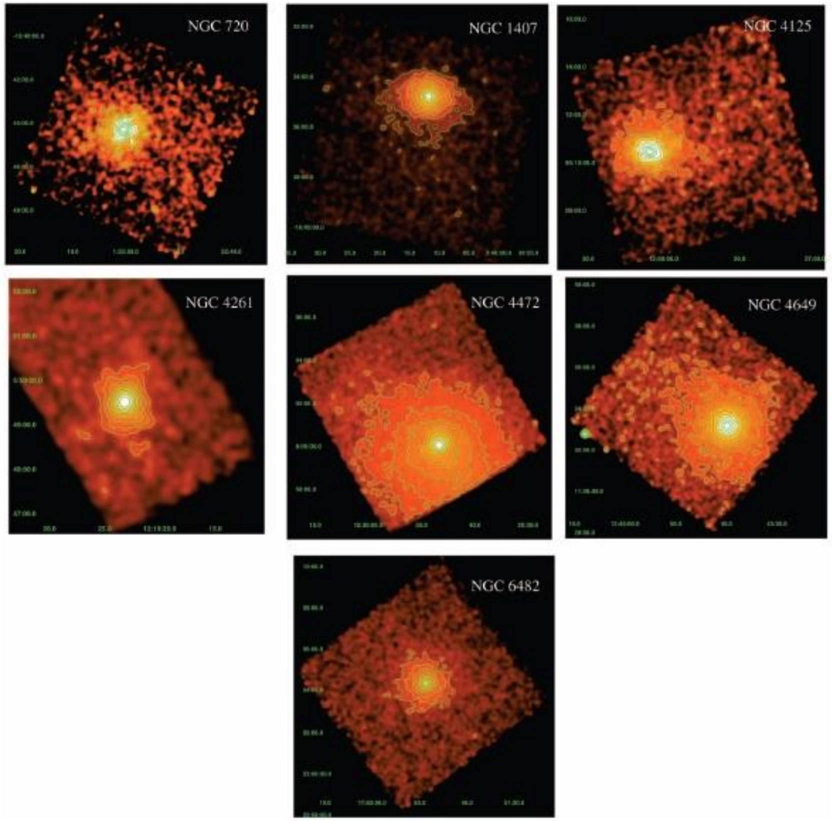
  (Pointecouteau et al 2005, Vikhlinin et al 2006)

Brief highlights on the galaxy scale
(Humphrey et al. 2006)

- Sample of 7 elliptical galaxies observed with Chandra
- Regular X-ray morphologies

<u>MAIN RESULTS</u>

- c-M_{vir} relation agrees with the predictions
- M_{tot}-M_{gas} profiles are parametrized by NFW+stellar component
- AC make M/L discrepant



Brief highlights on the galaxy scale

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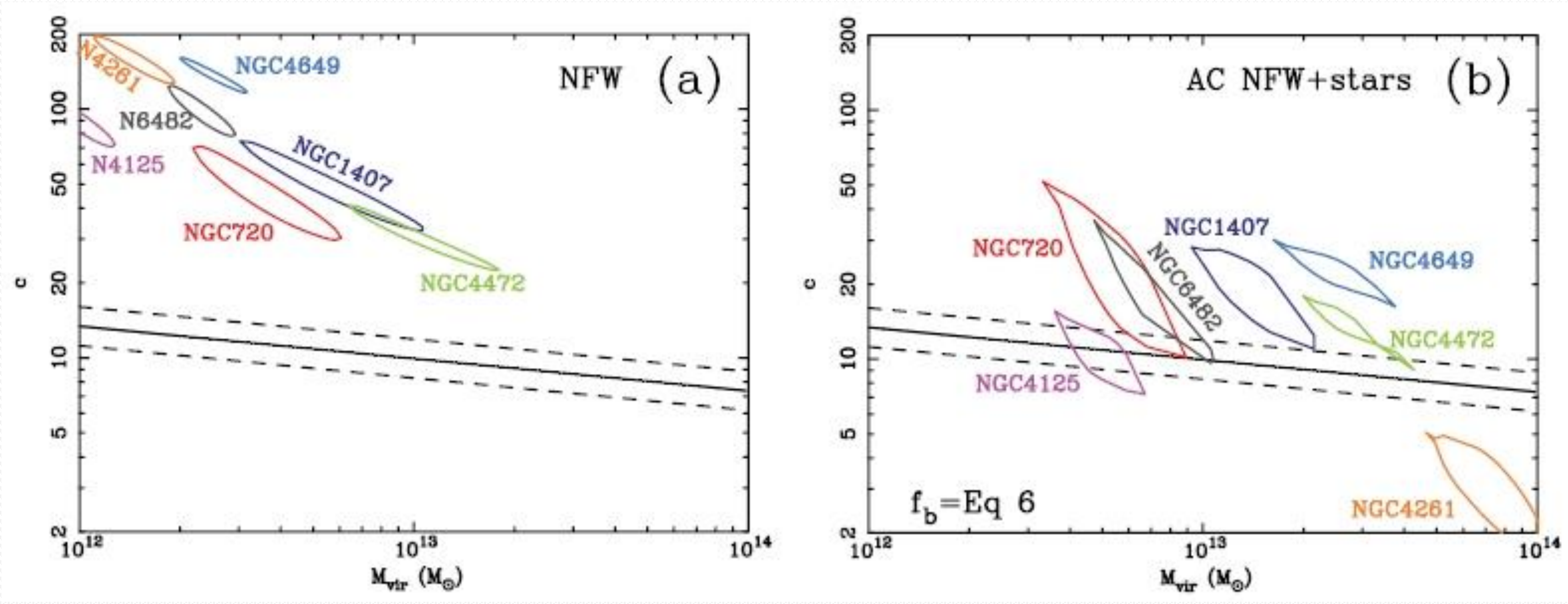
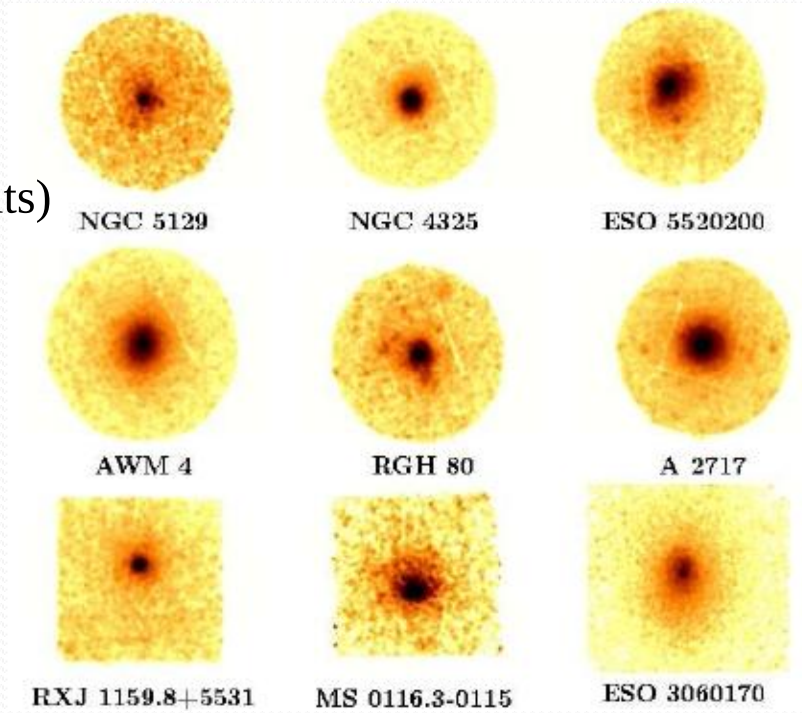


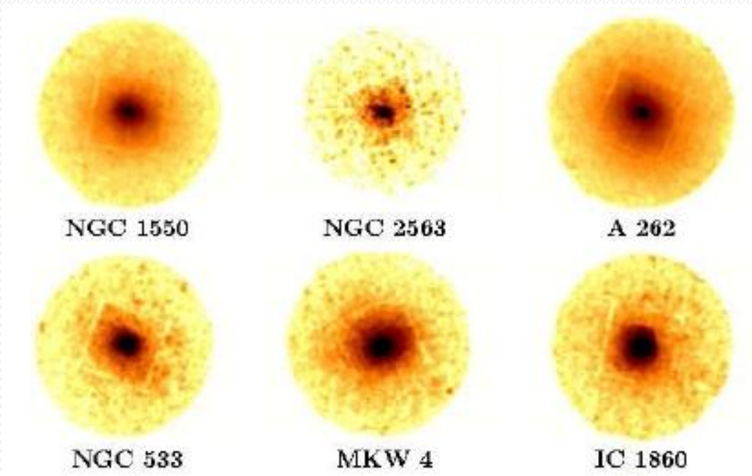
Brief highlights on the group scales
(Gastaldello et al. 2007)

Joint analysis of Chandra and XMM observations of 16 groups/poor clusters

MAIN RESULTS

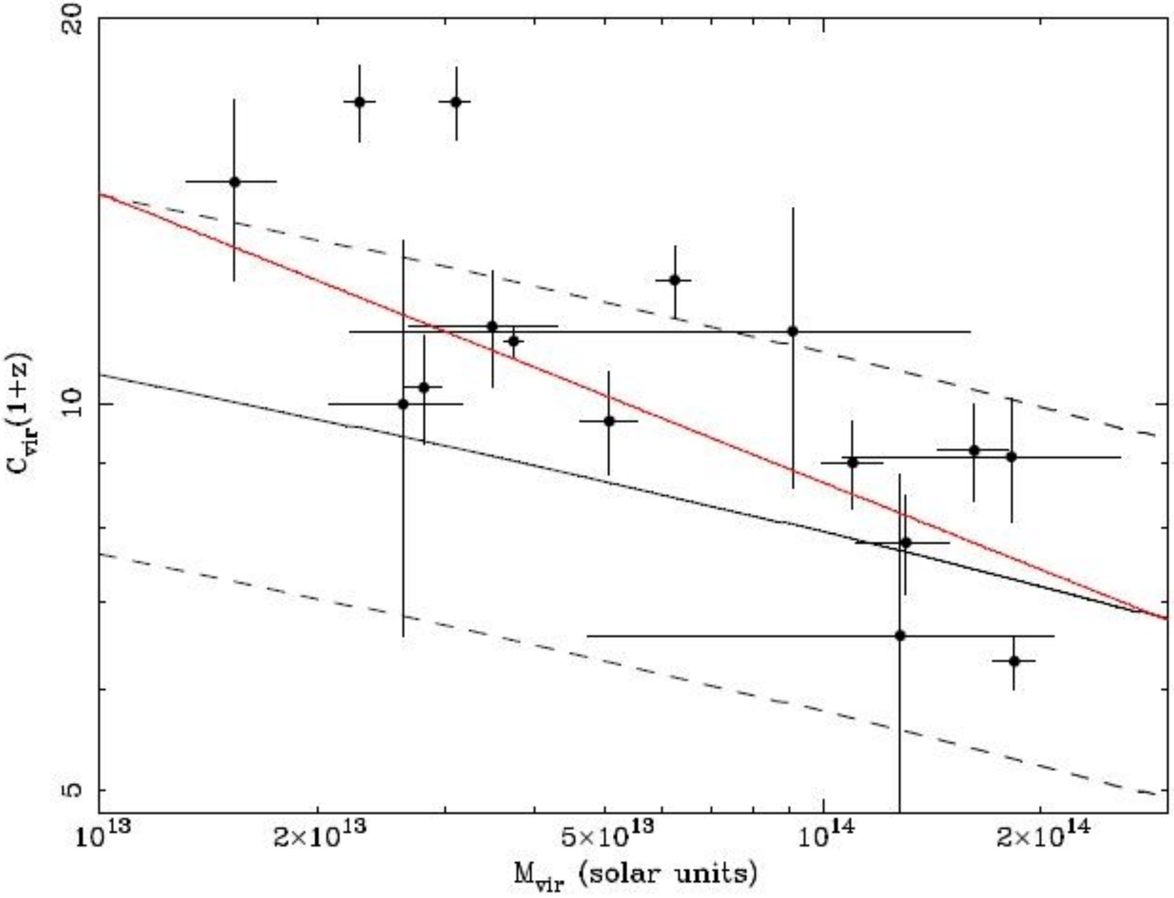
- M_{tot}-M_{gas} profiles are modeled by and NFW+stellar component for 8 systems the others do not require any stellar mass
- c-M_{vir} in agreement with the predictions and inconsistent at 3σ with no variation
- AC is not required (does not improve the fits)





Brief highlights on the group scales

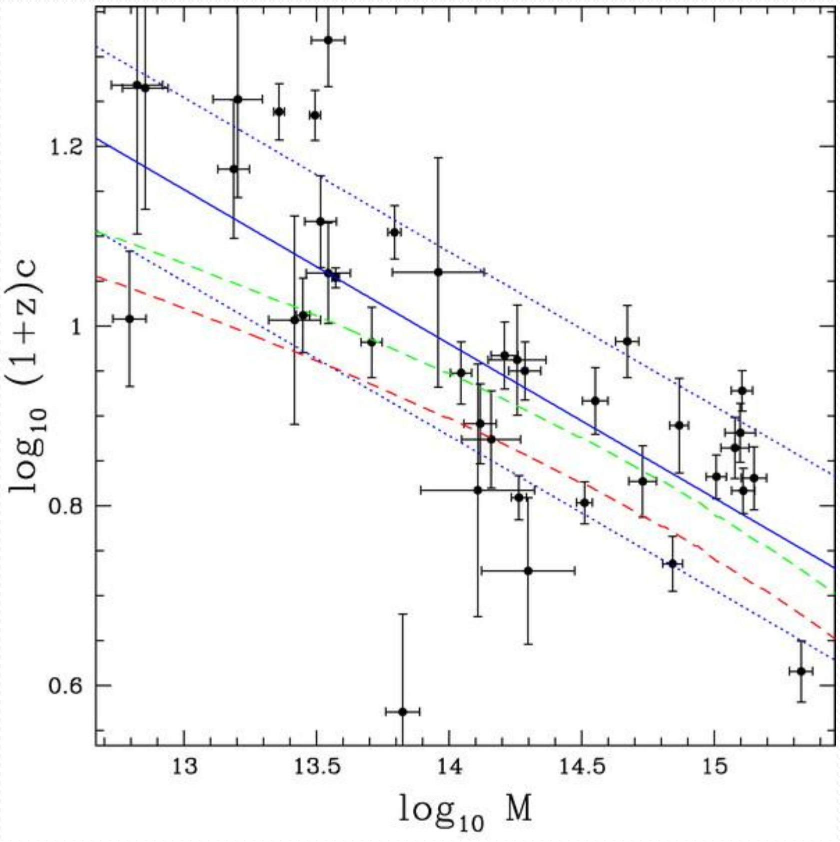
(Gastaldello et al. 2007)



Constraining the c-M_{vir} relation continued... (Buote et al. 2007)

c-M_{vir} relation

- Power-law good approximate description
- c-M_{vir} relation significant at 6.6σ
- Slope a=-0.172±0.026
- Consistency with Bullock et al. 2001 models assuming cosmological parameters form 1[st]yr WMAP results (assuming 10% higher normalization for early forming halos)
- Intrinsic scatter and normalization consistent with early forming halos



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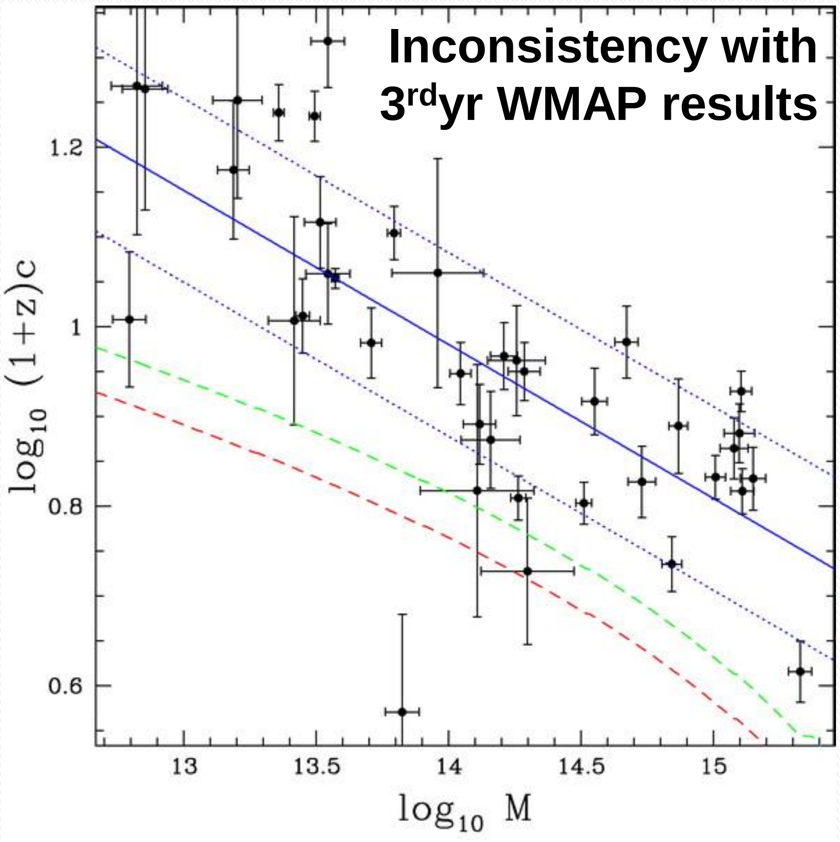
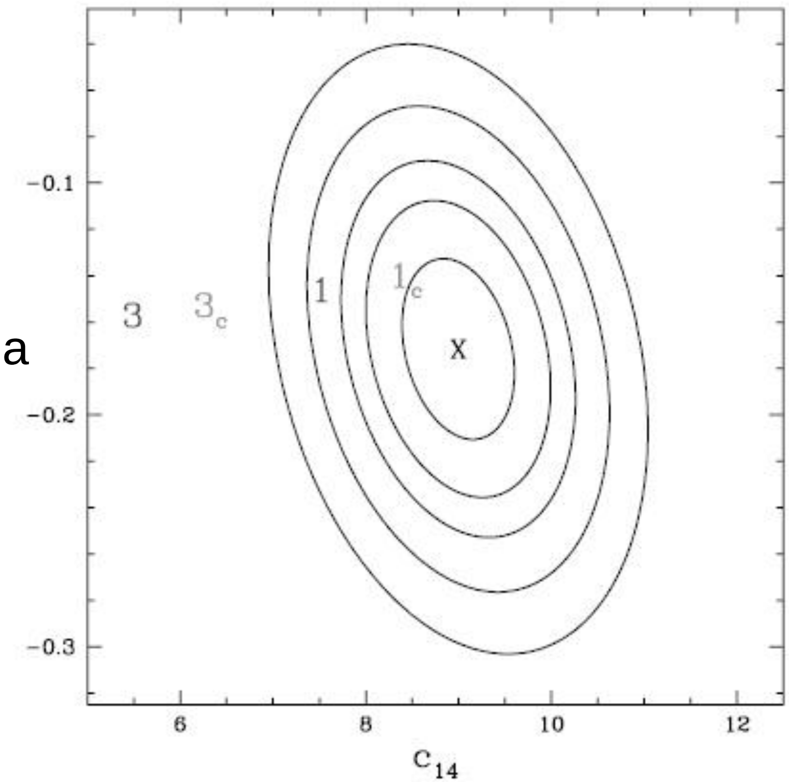


Constraining the c-M_{vir} relation
(Buote et al. 2007)

Disagreement mainly due to the lower value of σ_8=0.76, but also the tilt of the power spectrum and the low value of Ω_m may play a role. Increasing *w* may also help.

a



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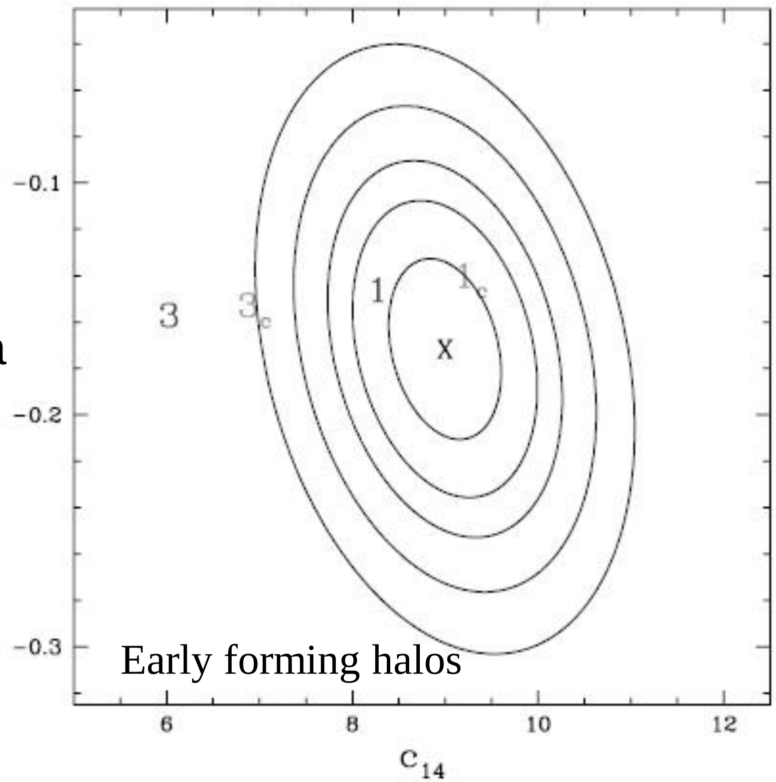


Constraining the c-M_{vir} relation
(Buote et al. 2007)

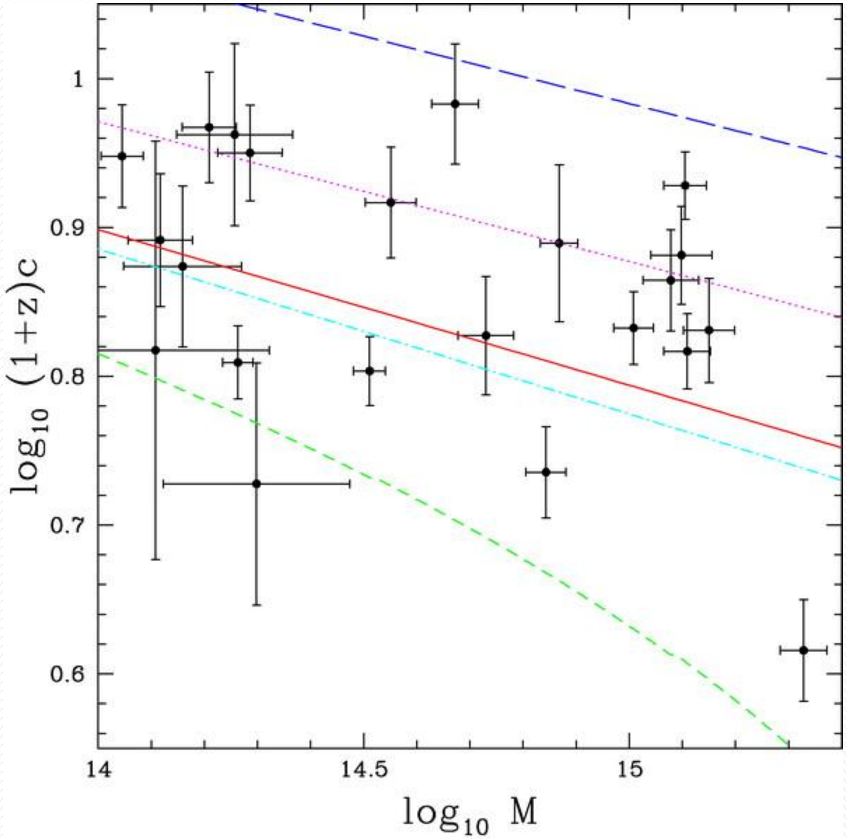
Only clusters

- Slope not constrained and consistent with 0
- Normalization may help in discriminating several different cosmological models

TABLE 2
Cosmological Model Parameters

Name	Ω_m	Ω_Λ	$\Omega_B h^2$	h	σ_8	n_s	$-w$
ΛCDM1	0.30	0.70	0.022	0.7	0.90	1.00	1.0
ΛCDM3	0.24	0.76	0.022	0.73	0.76	0.96	1.0
DECDM	0.30	0.70	0.022	0.7	0.90	1.00	0.6
QCDM	0.30	0.70	0.022	0.7	0.82	1.00	≈0.8
OCDM	0.30	0.00	0.022	0.7	0.90	1.00	...

Notes.—Ω_m is the energy density parameter for matter in the universe; Ω_Λ is the energy density parameter associated with a cosmological constant or, more generally, dark energy; Ω_B is the energy density parameter of baryons; h is $H_0/100$ km s^{-1} Mpc^{-1}; σ_8 is the rms mass fluctuation within spheres of comoving radius 8 h^{-1} Mpc. See § 4.



Constraining the c-M_{vir} relation
(Buote et al. 2007)

From Cluster abundance studies:

$\Omega_m \approx 1 \rightarrow \sigma_8 \approx 0.45$

(e.g . Hoekstra et al. 2002, Van Waerbeke et al. 2005, Rines et al. 2007)

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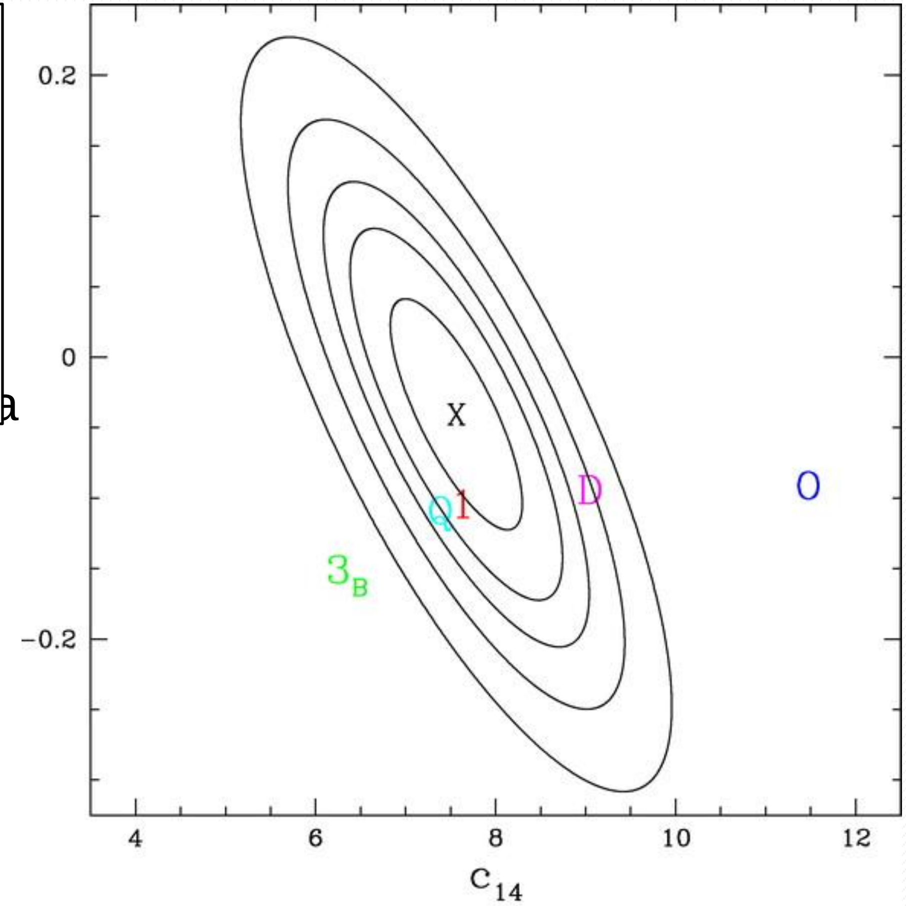


Constraining the c-M_{vir} relation
(Buote et al. 2007)

From Cluster abundance studies:
$\Omega_m \approx 1$ -
(e.g . Hoekstra
et al. 2005, Ri
cosmologi

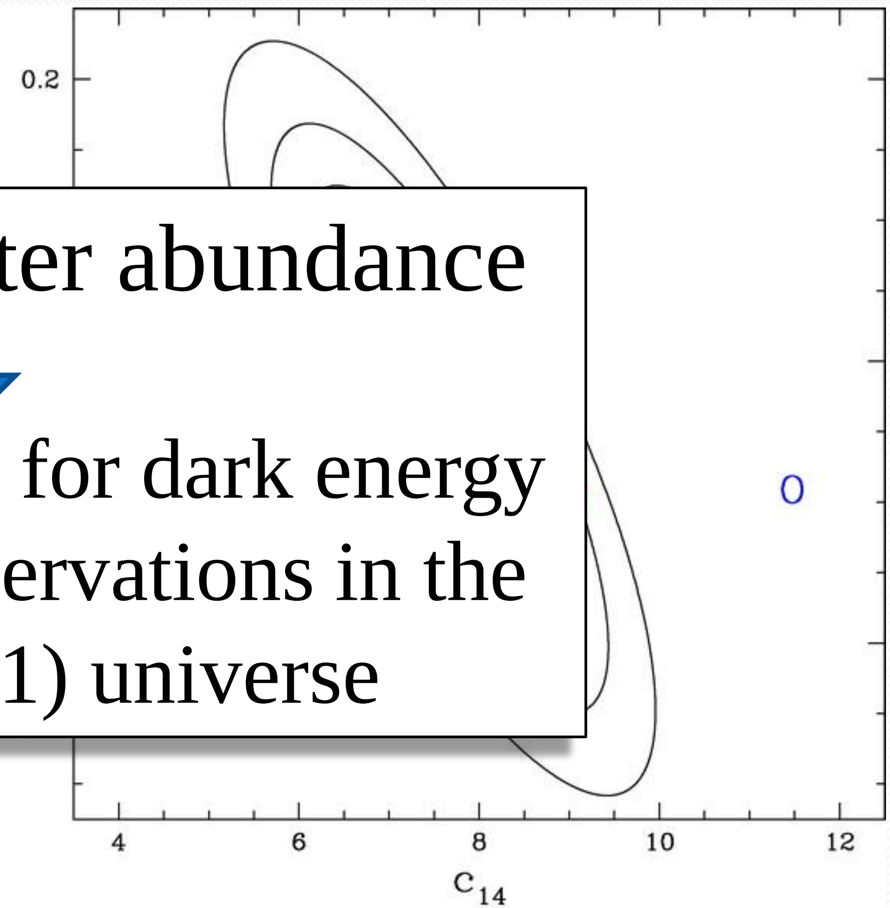
c-M_{vir} + cluster abundance

novel evidence for dark energy using only observations in the local (z<<1) universe

Cos

Name	Ω_m
ΛCDM1	0.30
ΛCDM3	0.24
DECDM	0.30
QCDM	0.30
OCDM	0.30

NOTES.—Ω_m is the energy density parameter for matter in the universe; Ω_Λ is the energy density parameter associated with a cosmological constant or, more generally, dark energy; Ω_B is the energy density parameter of baryons; h is H_0/100 km s^{-1} Mpc^{-1}; σ_8 is the rms mass fluctuation within spheres of comoving radius 8 h^{-1} Mpc. See § 4.



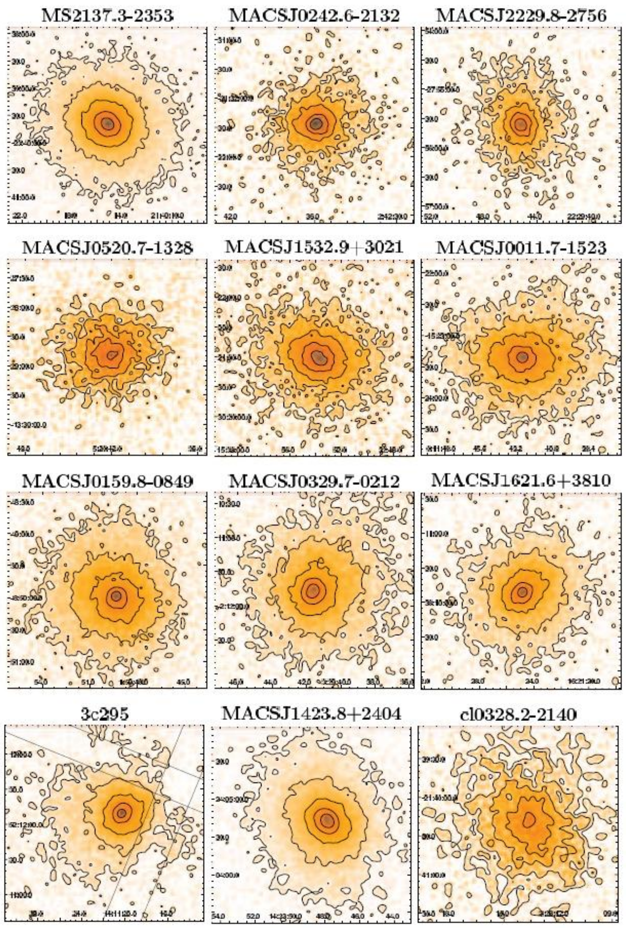
Constraining the c-z relation
(Zappacosta et al. in prep.)

- Aim: Constrain the c-z relation out to the highest redshift possible
- Sample: 19 clusters of galaxies at redshifts $0.3<z<1.1$
- Selection: the most relaxed and with best available Chandra data

Sample heavily biased toward high redshifts:

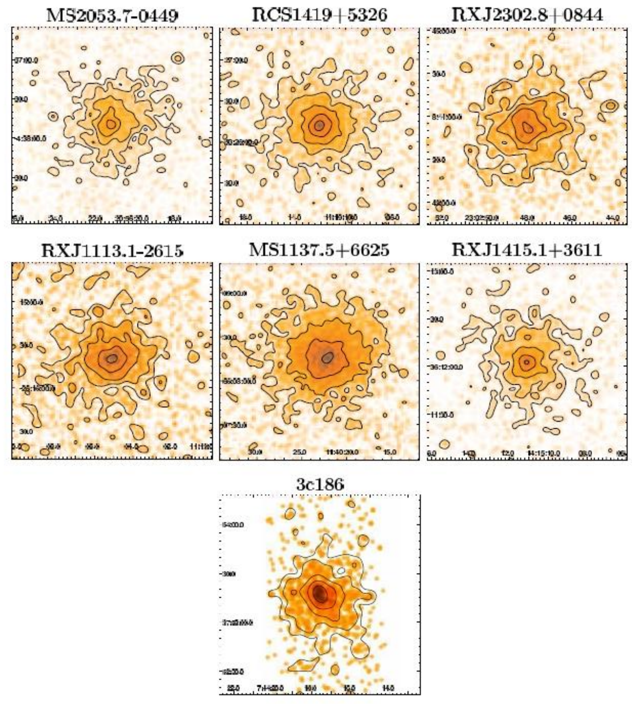
- Highest redshift probed: ~1.1
- 9 clusters at $z>0.5$
- SA07 only probed up to 0.7, with 2 clusters at $z>0.5$ (one of them is manifestly disturbed)

Morphologies



Morphologies have been checked:

1. visual inspection
2. power-ratios technique (Buote & Tsai 1995)



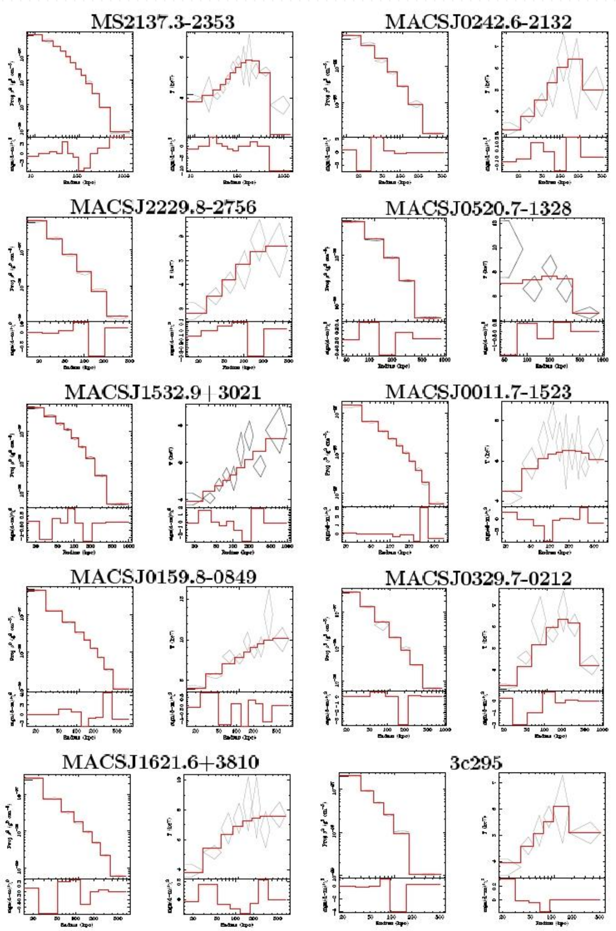
Mass profiles

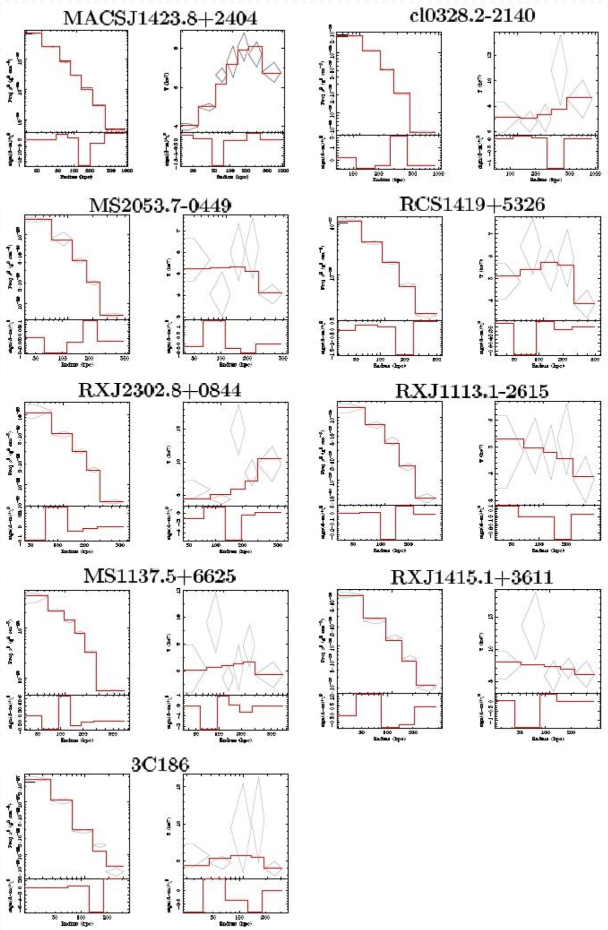
- Computed inverting the equation of hydrostatic equilibrium and solving for the temperature.

$$T_g(r) = T_0 \frac{\rho_{g0}}{\rho_g(r)} - \frac{\mu m_p G}{k_B \rho_g(r)} \int_{r_0}^{r} \frac{\rho_g M \, dr}{r^2}$$

- (cusp/simple) β-model and NFW are assumed for gas density and mass profiles
- The temperature profile is determined by the hydrostatic equilibrium assumption according to the data

Gas density and temperature profiles





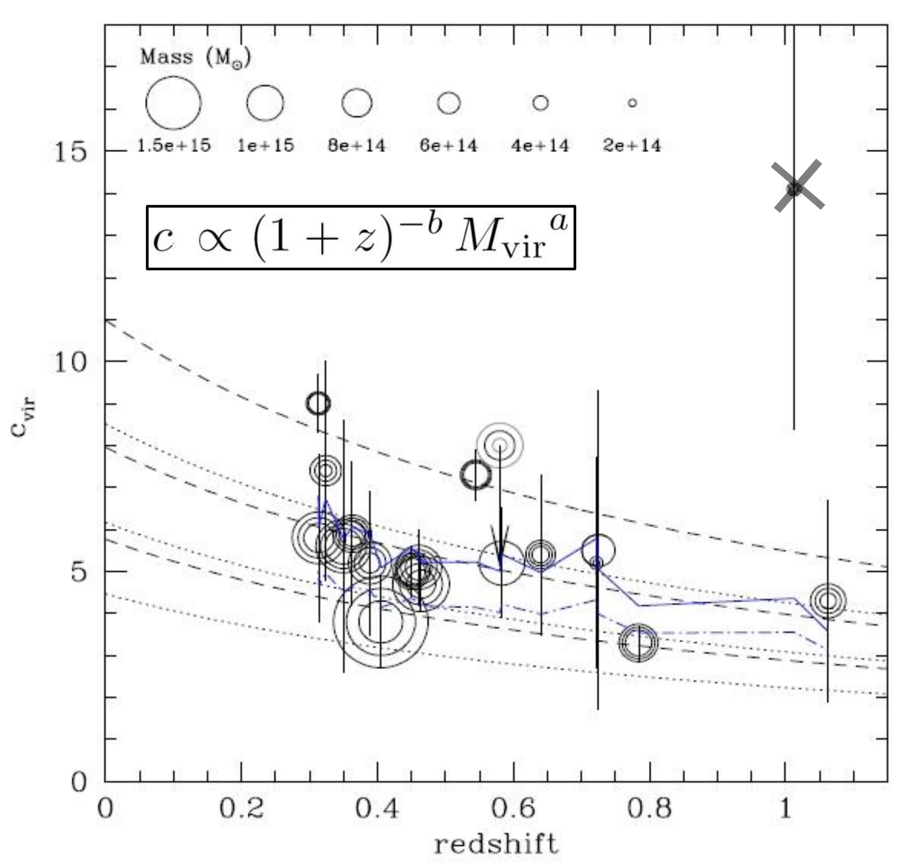
c-z with only high-z clusters

Assumptions:

- c-M_{vir} slope a=-0.172 (Buote et al. 2007)
- Intrinsic scatter 0.1Δlog(c)

Results:

- b ≈1.3±0.4
  - consistent with predictions
  - Inconsistent at 3σ with not variation
- Slightly high normalization

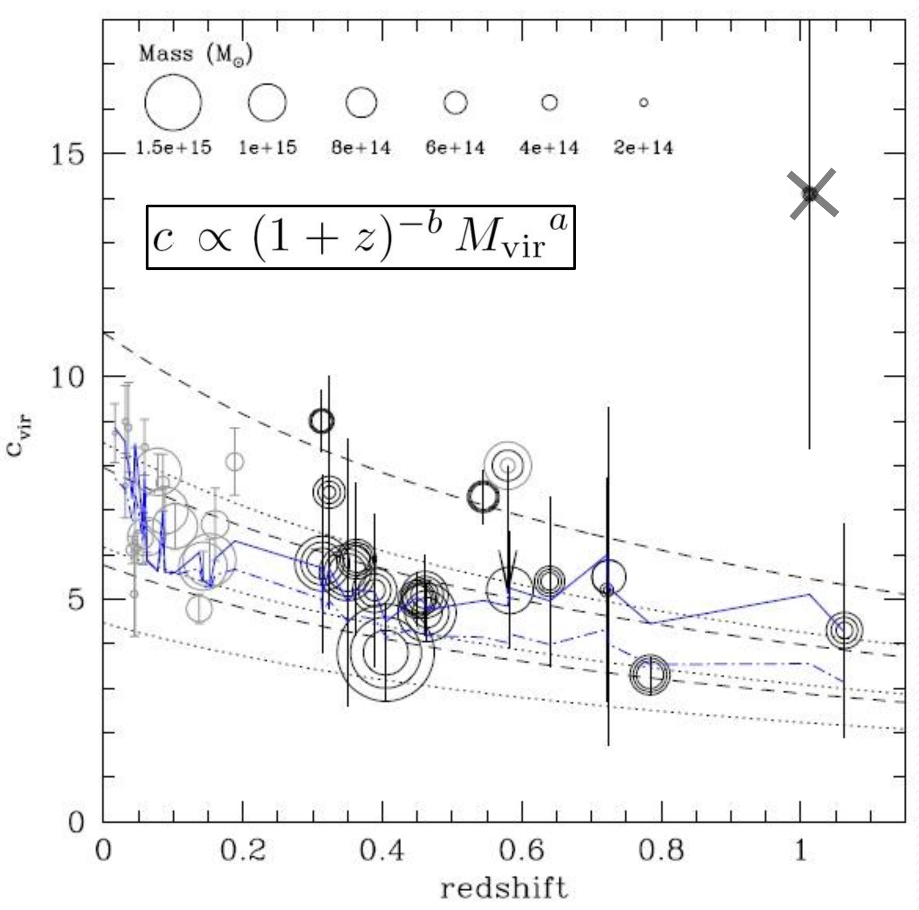


c-z including local clusters

- Inclusion of low-z systems with $M_{vir}>10^{14}\,M_{sun}$ (from Buote et al. 2007)

RESULTS:

- b=0.52 ±0.19
- Inconsistent with no variation at 2.7σ
- Inconsistent at 2.5σ with the predictions
- Normalization: consistency at 1.5σ
- Larger a values predicted by CDM improve the agreement at 2σ level



c-z including local clusters

- Inclusion of low-z systems with $M_{vir} > 10^{14} M_{sun}$ (from Buote et al. 2007)

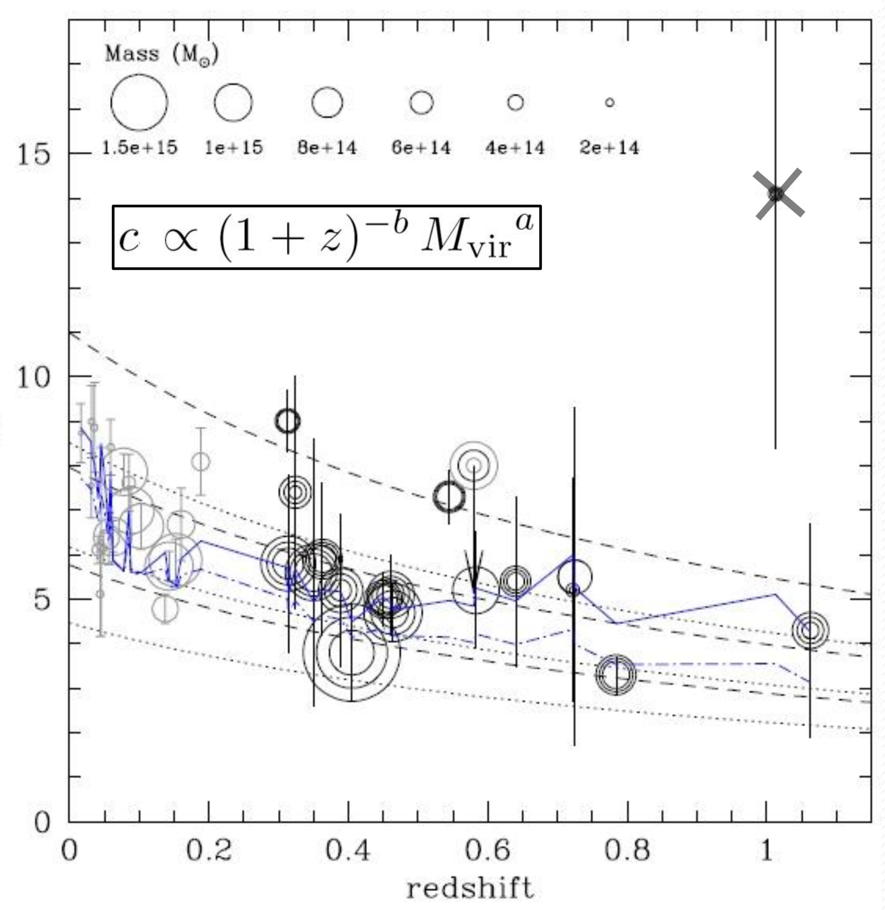
RESULTS:

Assuming a=–0.45 as found by SA07

⬇

b=0.0±0.3
(no c-z relation)

at 2σ level



Future prospects on the c-z relation

- Enlarge the sample (intrinsic scatter)
- Improve our redshift coverage especially at $z > 0.5$

- Doubling the sample at $z>0.3$ ➡ $b \sim 0.7 \pm 0.2$
- Halving also the errors in c and M_{vir} ➡ $b \sim 0.8 \pm 0.16$

  (assuming a c-z relation as predicted)

Conclusions on the c-M_{vir} and c-z relations

- Large sample of local (z<0.2) relaxed galaxy systems from ellipticals to massive clusters
  - significant variation of c with M_{vir}
  - consistency with CDM predictions (slope, scatter and normalization)
  - Clusters only: exclude an open cosmology and provide new evidences for the existence of dark energy *at low redshift* (including cluster abundance studies results)

- Including distant relaxed galaxy clusters (z=0.3-1.1)
  - We detect variation of c with redshift at ~3σ level
  - Marginal consistency with CDM predictions