Matter distribution and scaling laws in clusters of galaxies

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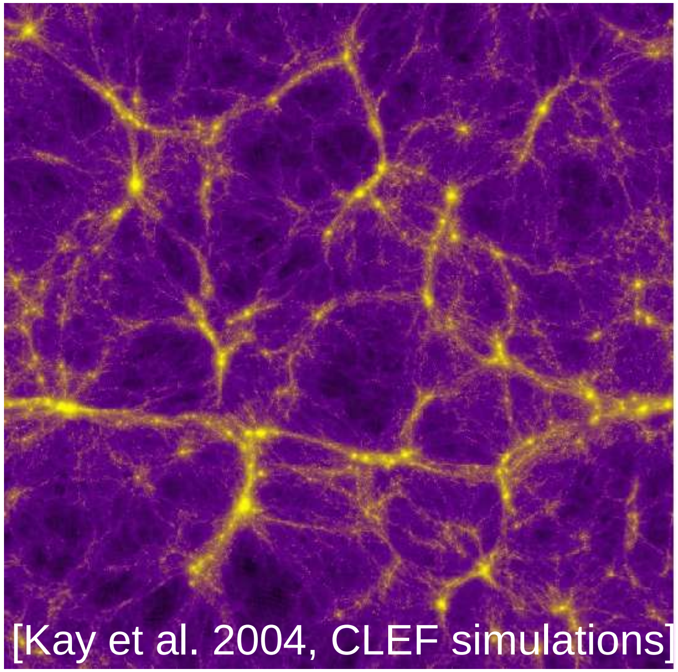
Overview

- Studying galaxy clusters
- Structural properties of clusters
- From X-ray observations to scientific products
- The DM properties
- The ICM properties
- Conclusion & perspectives

Studying clusters of galaxies

- What are clusters of galaxies?
  - → nodes of the cosmic web
    filamentary structures
  - → mass growth by constant
    accretion and mergers events
  - → largest virialized structures



Studying clusters of galaxies

- What are they made of?

M_{tot} ~10^{13} – a few 10^{15} M_{sol}

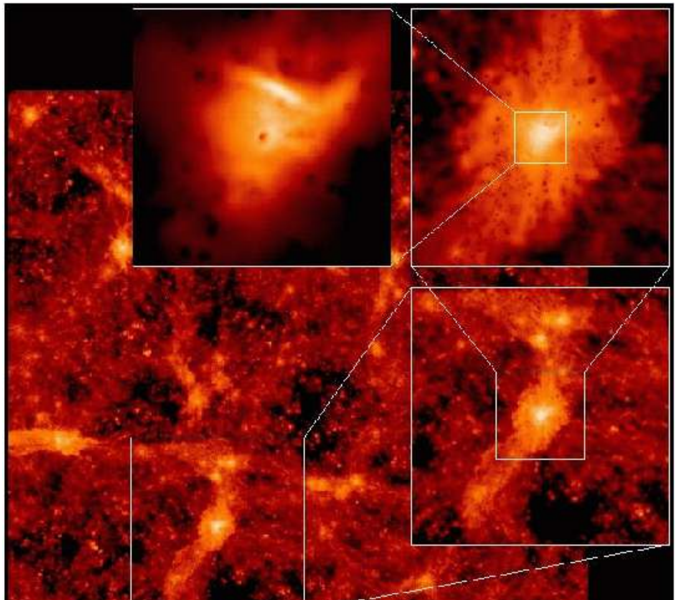
→ DM ~80%

→ galaxies ~5%

→ gas ~15%

$T \sim 10^6$-10^8 K ; $n_e \sim 10^{-4}$-10^{-2} cm^{-3} ; $Z \sim 0.3 Z_\odot$

complex physical processes at play in the ICM


[Kay et al. 2004, CLEF simulations]

Giant laboratories for astrophysical processes

Studying clusters of galaxies

What for ?

- Cosmology

→ cluster counts, mass function N(M,z) → (Ω_m, σ_8, Γ)

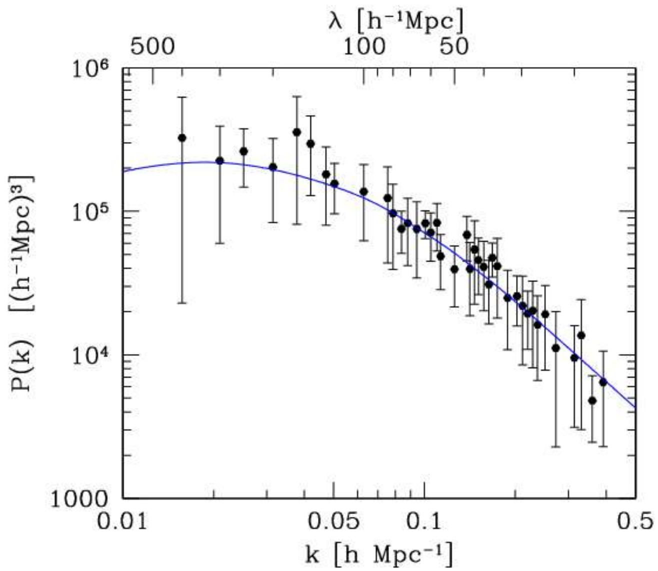
→ gas fraction f_{gas} → Ω_m

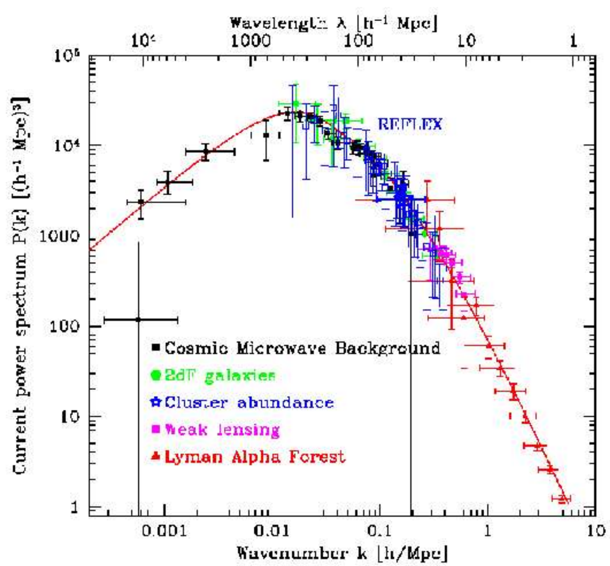
- Physics of structure formation and evolution

→ DM collapse

→ non-gravitational processes , gas physics

Studying clusters of galaxies





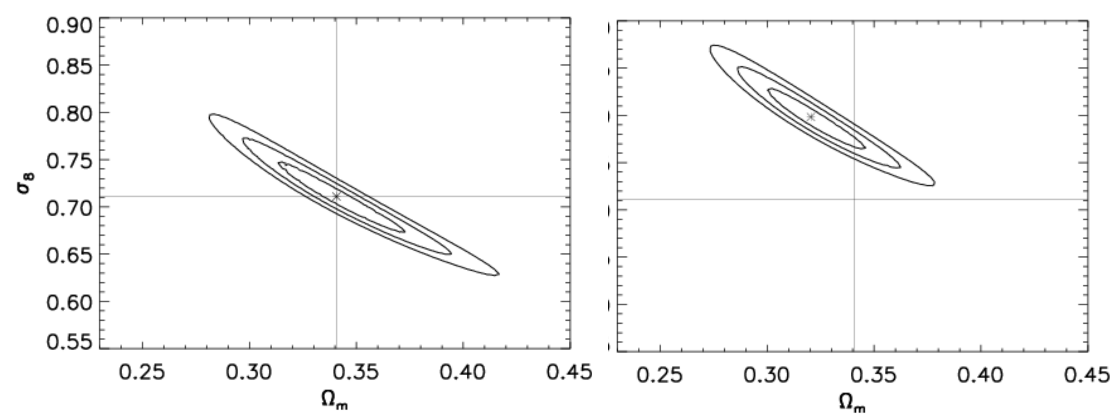
- Cluster counts, clusters abondance
  - → normalization *of P(k)*

    $\sigma_8 = 0.76 \pm 0.10 \quad (\Omega_m = 0.3)$

  - → shape parameter of *P(k)*

    $\Gamma = \Omega_m h = 0.18 \pm 0.03$

[Schuecker 2004]



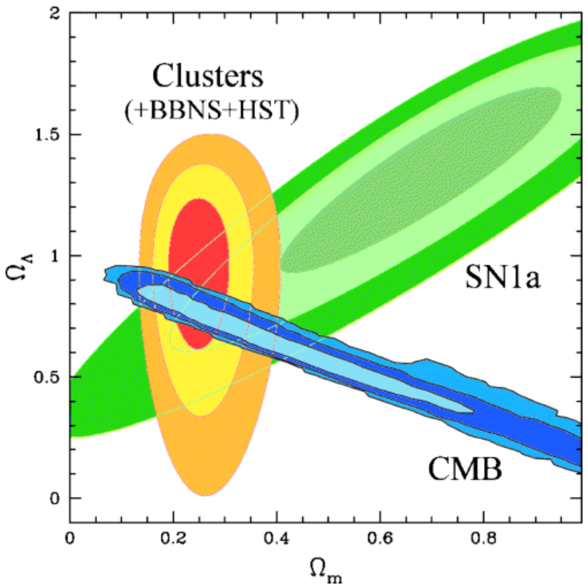
→ uncertainties : L_X-M relation

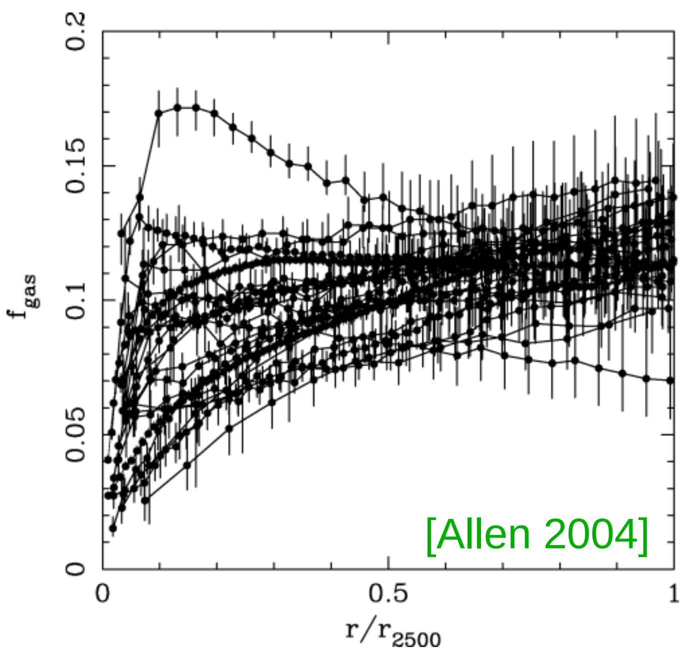
Studying clusters of galaxies

- Gas fraction : $f_g^{amas} \equiv f_b^{Univers}$ (?!?)

  $\rightarrow f_b h^{3/2} = \Omega_b/\Omega_m = (M_{gaz}+M_*)/M_{tot} \approx 0.1$

  avec $\Omega_b = \Omega_{BBN} \rightarrow \Omega_m = 0.3 \pm 0.1$





- f_g + CMB → XCDM :

  $\Omega_m = 0.26 \pm 0.05$

  $\omega_X = -1.26 \pm 0.24$

→ Complementary constraints to the CMB and the SNIa

Studying clusters of galaxies

What for ?

- Cosmology
  - → cluster counts, mass function N(M,z) → $(\Omega_m, \sigma_8, \Gamma)$
  - → gas fraction f_{gas} → Ω_m

- Physics of structure formation and evolution
  - → Physics of the DM collapse
  - → non-gravitational processes , gas physics

Studying clusters of galaxies

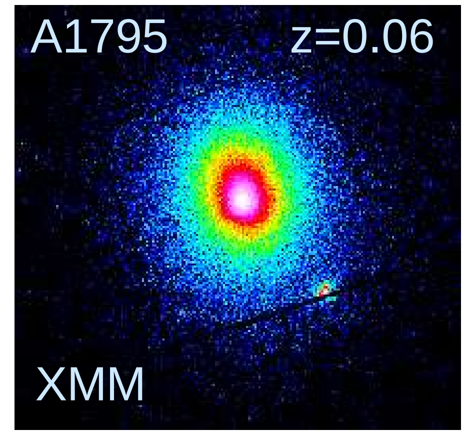
- Statistical properties of clusters

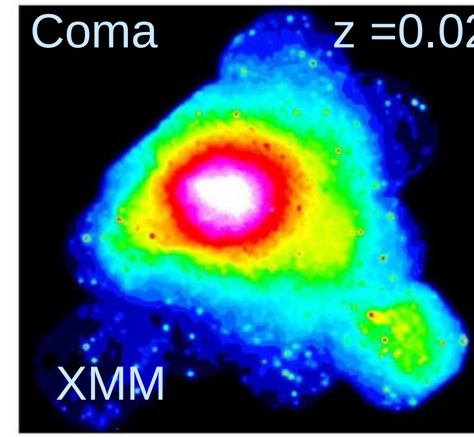
→ Physical parameters

L_{bol} ~10^{41} - a few 10^{46} ergs/s

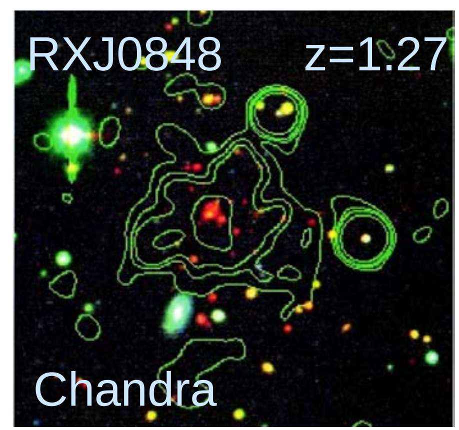
M_{tot} ~10^{13} - a few 10^{15} $M_{\odot}$

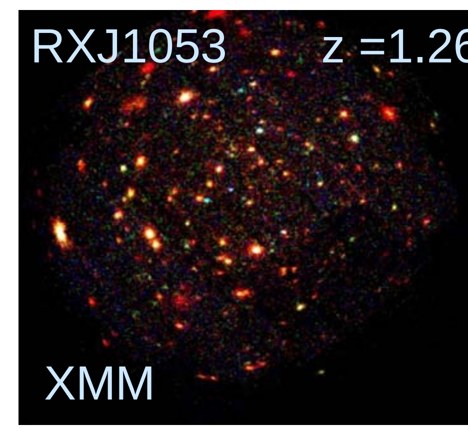
T ~ 0.3 - 15 keV





→ At least up to z ~ 1.5



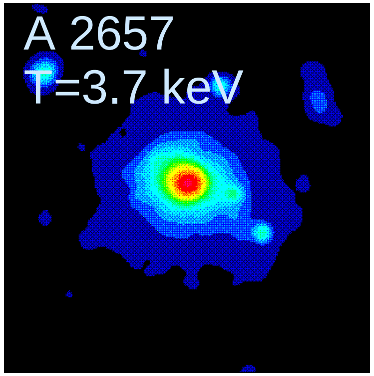


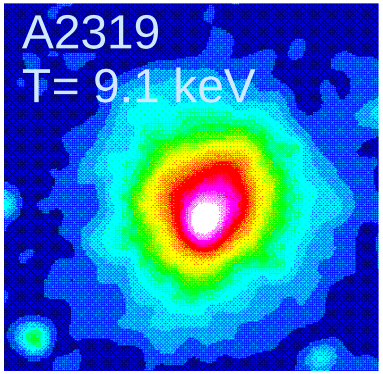
→ Morphology:

regular (~50%)

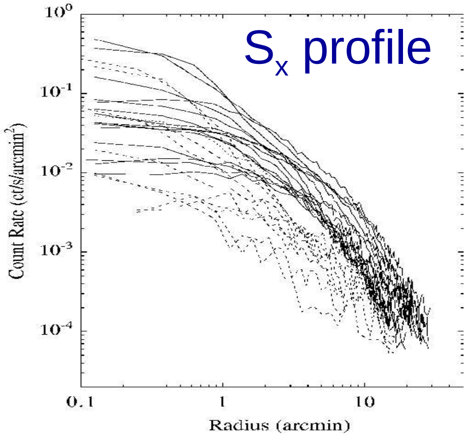
≠ dynamical states at every z

Studying clusters of galaxies

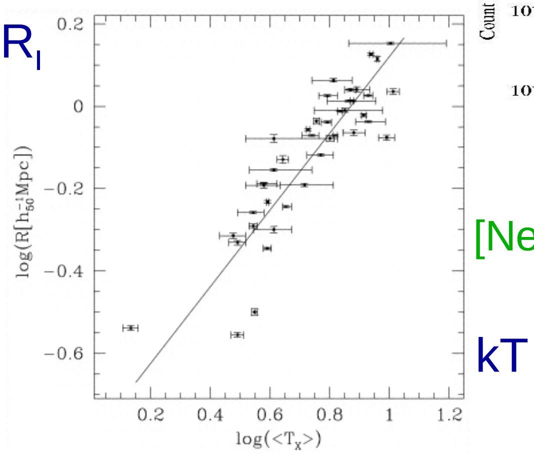




- Signes of similarity
- Correlations
- Formation et evolution of structures
  - → DM collapse
  - → non-gravitational processes
  - → gas physics
  - → DM/baryons coupling
  - → sub-halos abondance
  - → themodynamical evolution
  - → ...



[Neumann & Arnaud 1999]



[Mohr & Evrard 1997]

Structural properties of galaxy clusters

Hierarchical formation of structures

→ semi-analytical spherical collapse; numerical simulations

[Bertschinger 1985, Cavaliere et al. 1999; Evrard & Gioia 2002 (review)]

- Clusters form at a recent epoch (z~2)
- ICM evolving in the *gravitational* well of the DM

→ $f_{gas} = cst$

- The virialized part at z → fixed density contrast $\delta\sim200$

→ $M/R^3 = 4\pi/3\ \delta_c\ \rho_c(z)\ ,\ \delta_c\sim200$ (with $\rho_c(z)=h(z)^2\,(3H_0^2)/(8\pi G)$
$h(z)^2 = \Omega_m(1+z)^3 + \Omega_\Lambda$)

- Are close to virial/hydrostatic equilibrium

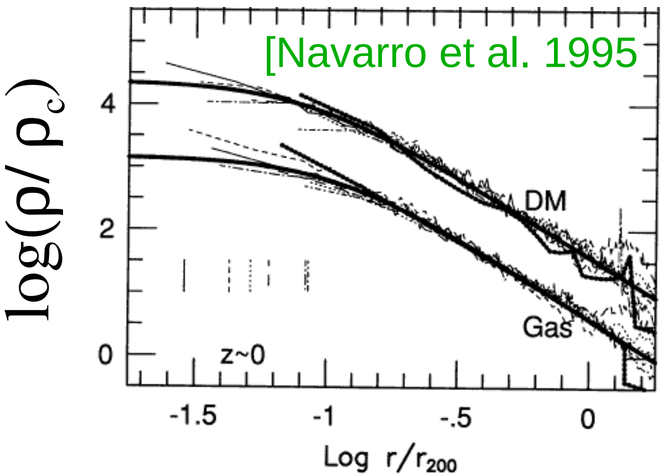
→ $kT \propto GM/R$

Self-similarity is expected from the cluster population

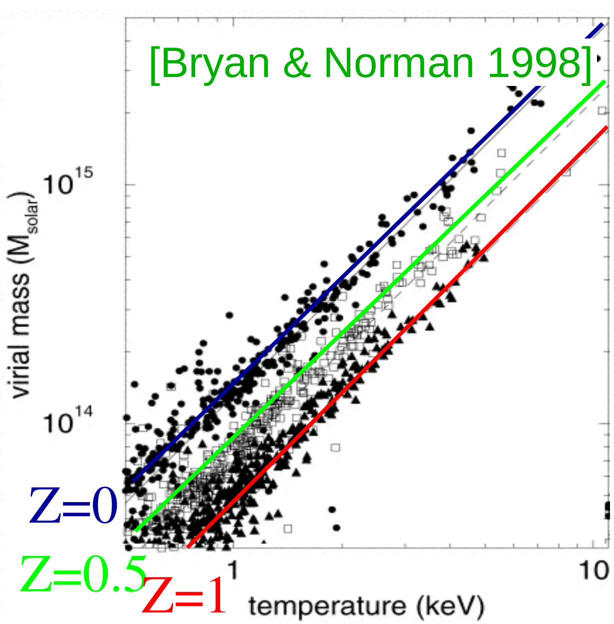
Structural properties of galaxy clusters

Clusters properties of similarity

- Similarity of shape
  - → universal shape of DM halos
  - → same internal DM (and thus gas) structure



- Scaling laws: correlations between physical quantities
  - → *[z, M]:* $Q(z)=A(z)\,M^{\alpha}$
    (or *[z, T]:* $Q(z)=B(z)\,T^{\beta}$)
  - → $M_{tot} \propto T^{3/2}\,h(z)^{-1}$



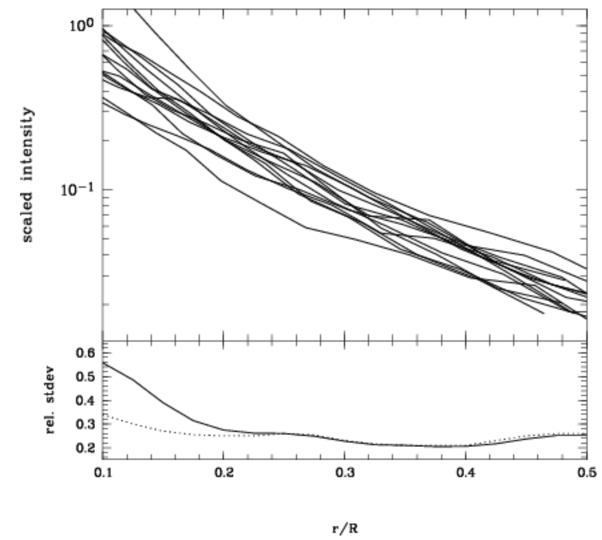
Structural properties of galaxy clusters

On pre-XMM and Chandra era

- Observed structural properties

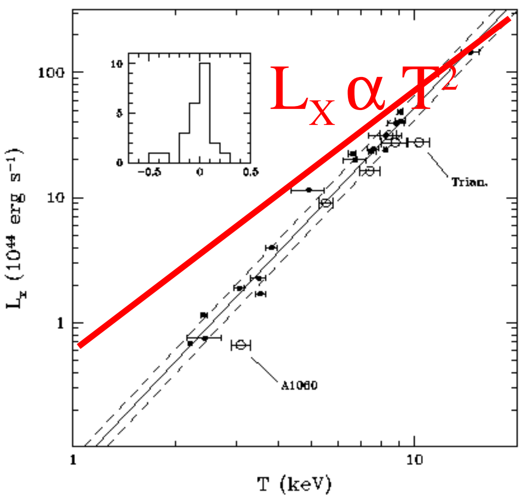
  Signs of self similarity

- Observed scaling laws



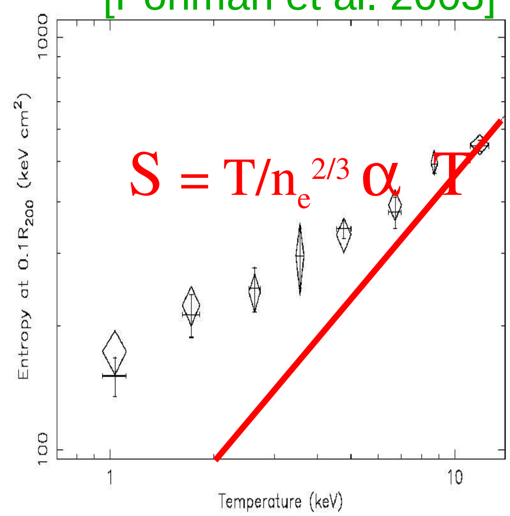
[Neumann & Arnaud 2001]

$L_X \propto T^{\sim 2.8\text{-}3}$



$S \propto T^{\sim 0.65}$

[Ponman et al. 2003]



Departures from the expectations not well understood

Structural properties of galaxy clusters

Theoretical considerations

- Effect of the gas physics on structure formation

  Non-gravitational processes

  → preheating (→ entropy excess)

  [Tozzi & Norman 2001]

  → radiative cooling of the gas

  → feedback from the galaxy formation

  (heating by SN & AGN)

  [Borgani 2004, Kay 2004]

Structural properties of galaxy clusters

Do we understand correctly the DM collapse?

- What is the shape of the gravitational potential in clusters ?

What is the thermodynamical state/history of the gas?

- Do we face a break of similarity?
- Or is it a modified similarity?

Structural properties of galaxy clusters

→ The structural properties of clusters

→ The scaling properties of clusters

are fundamental tools and rich sources of information to

→ Use clusters as cosmological tools

→ Study structure formation and evolution

In such studies the key quantities are:

the **mass** and the **entropy**

Structural properties of galaxy clusters

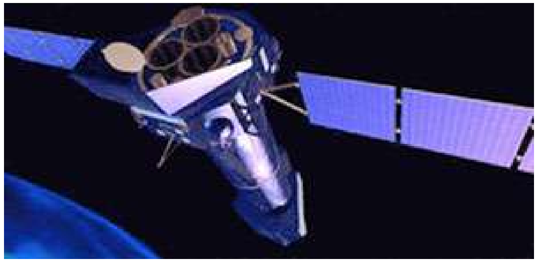
Observational study

- XMM GT time + AO1 time + archives
- The sample :

→ 10 relaxed and nearby clusters ($z<0.15$)

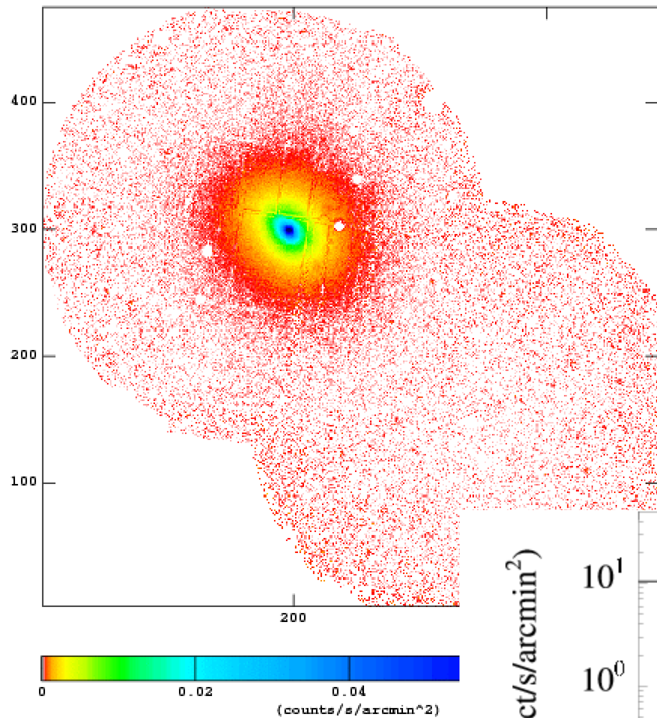
→ Temperature range : [2-9] keV

$kT < 3$ keV	: 4 clusters
$3 < kT < 6$ keV	: 2 clusters
$kT > 6$ keV	: 4 clusters



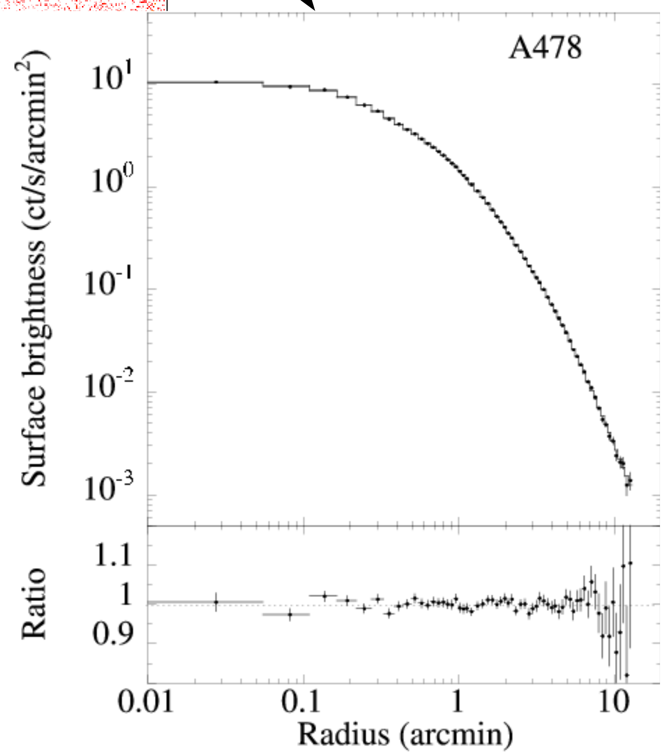
→ ΛCDM ($h=0.7$, $\Omega_m=0.3$, $\Omega_\Lambda=0.7$)

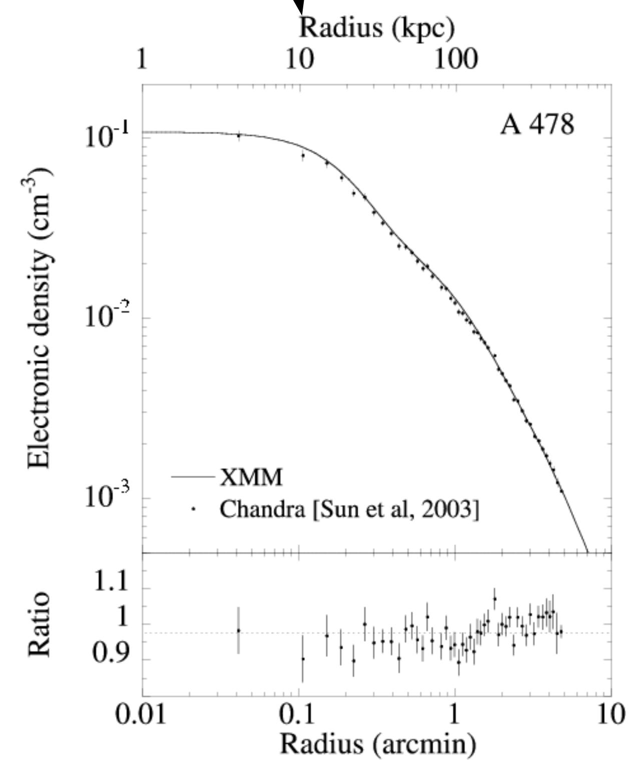
From X-ray observations to scientific products



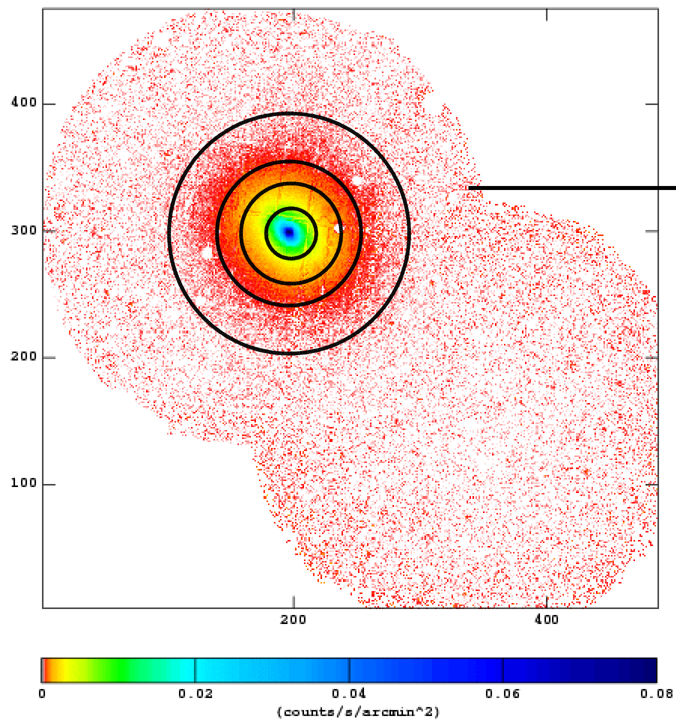
1 - Azimuthaly averaged SB profile

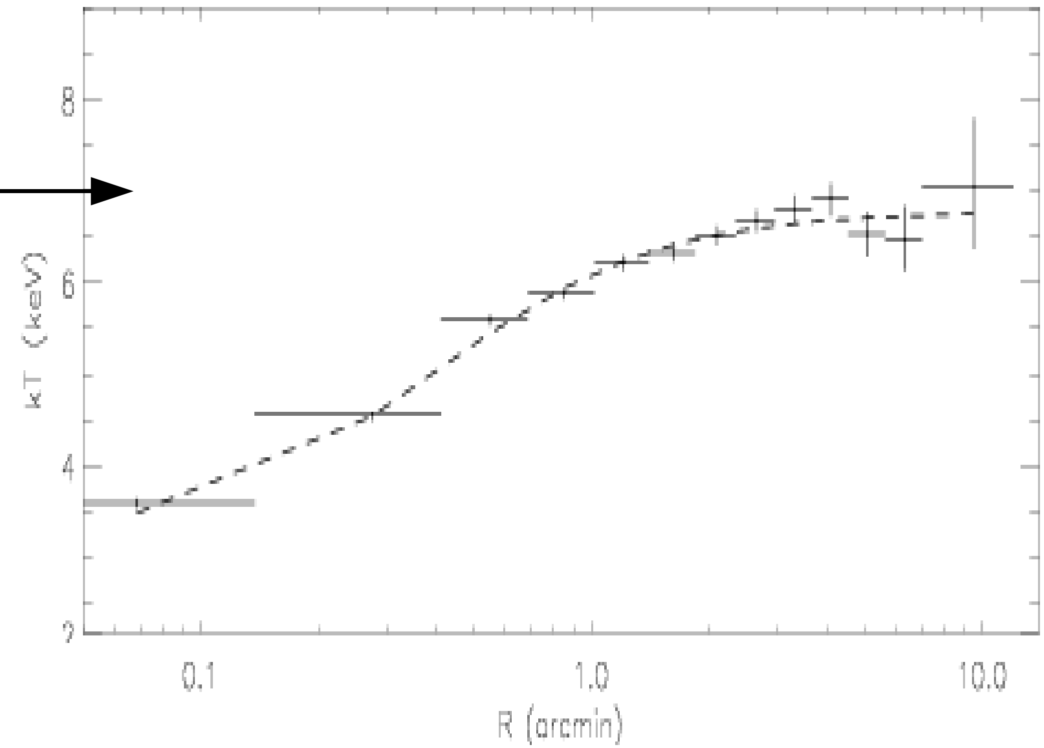
2 - Parametrized density profile





From X-ray observations to scientific products



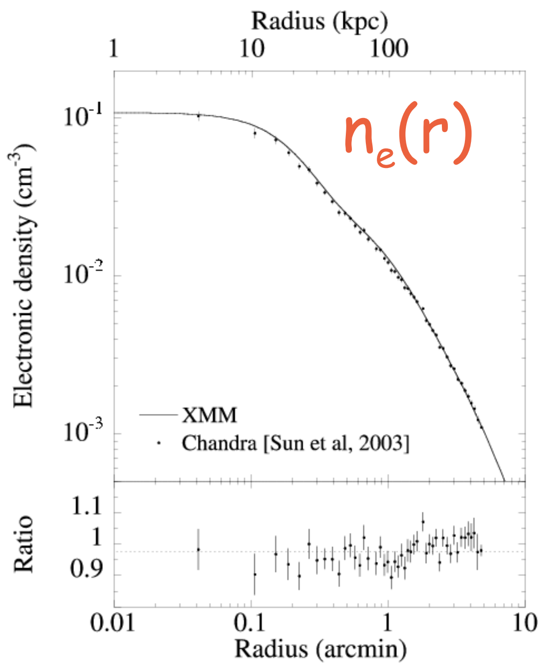


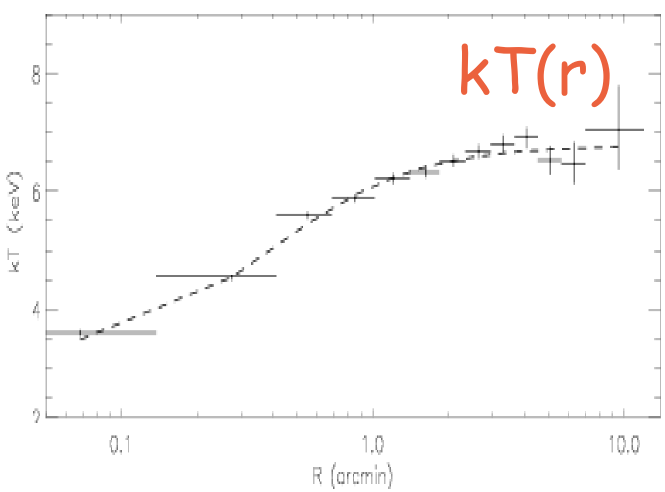
- Spectroscopy

  → kT(r)

- Deprojection & PSF correction (→ kT(r) parametrization)

From X-ray observations to scientific products





- Total mass profile
  - → spherical symmetry
  - → hydrostatic equilibrium

$$M(r) = -\frac{kT}{G\mu m_p}\left[\frac{d\ln n_e}{d\ln r} + \frac{d\ln T}{d\ln r}\right]$$

- Central structure: cold front, ghost cavities, bubbles, bow shocks,…
  - → track departure to HE
  - → cut the central region
- Test DM models

  (e.g. NFW $\rho_{DM} \propto (r/r_S)^{-1}[1+(r/r_S)]^{-2}$)

From X-ray observations to scientific products

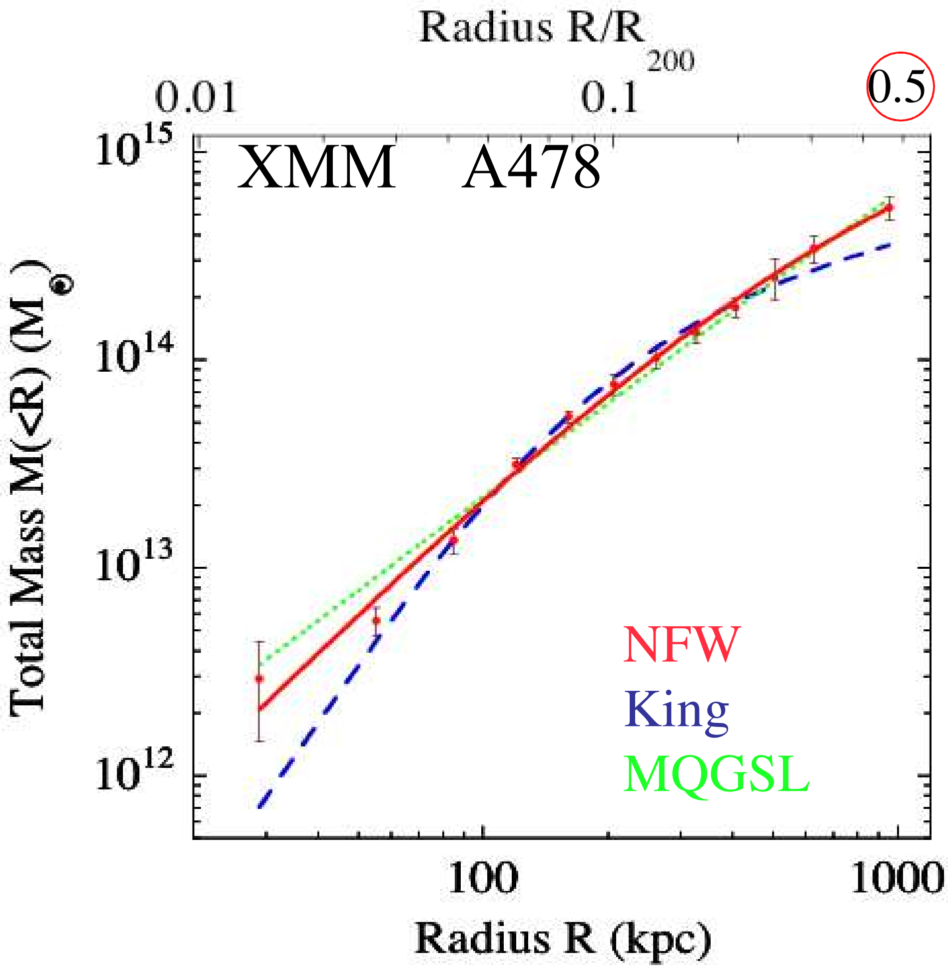
A478

→ M(r) over 0.01-0.5 R_{200}

→ NFW

significantly prefered

[Pointecouteau et al. 2005]



Properties of the DM:

The shape of the mass profile

The M-T relation

Properties of the DM

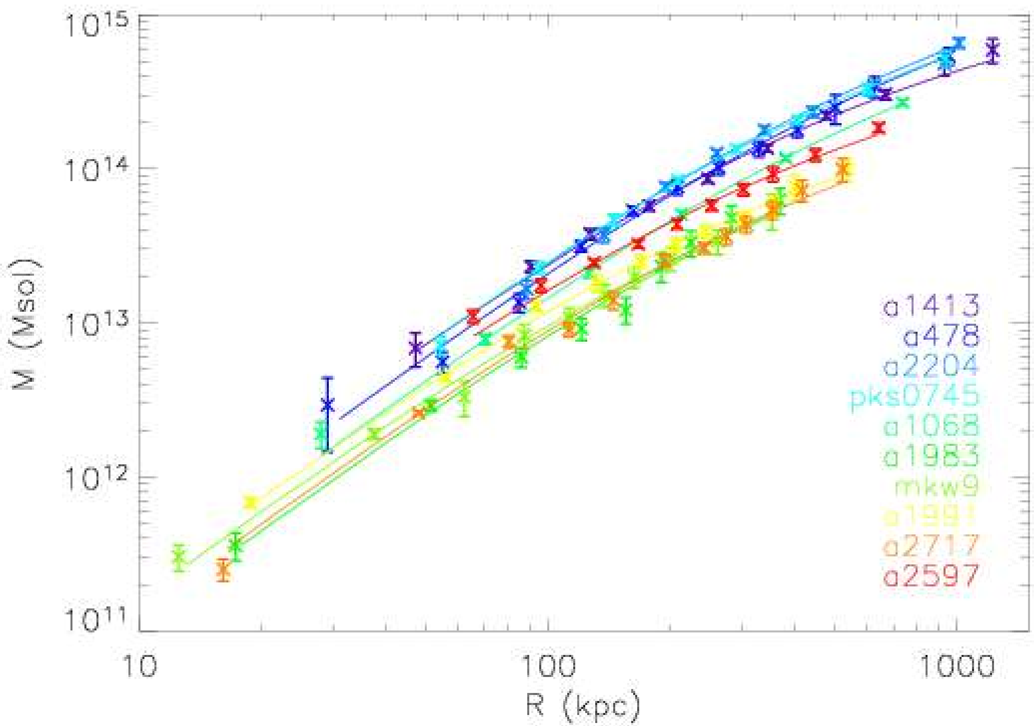
- Best fit results

Name	z	kT (keV)	c	M_{200} ($10^{14}M_{sol}$)	R_{OBS}/R_{200}
A2204	0.152	8.10	4.59	11.80	0.61
PKS0745	0.103	7.61	5.12	10.03	0.57
A478	0.088	6.66	4.22	10.82	0.58
A1413	0.143	6.60	5.82	6.50	0.79
A1068	0.137	4.56	3.69	5.68	0.57
A2597	0.143	3.52	5.86	3.00	0.58
A1983	0.044	2.20	3.83	1.63	0.38
A2717	0.050	2.42	4.21	1.57	0.54
MKW9	0.038	2.44	5.41	1.20	0.41
A1991	0.056	2.62	5.78	1.59	0.60

→ covering *[2-9]* keV and *[1-12]*$\times 10^{14}M_{sol}$

Properties of the DM

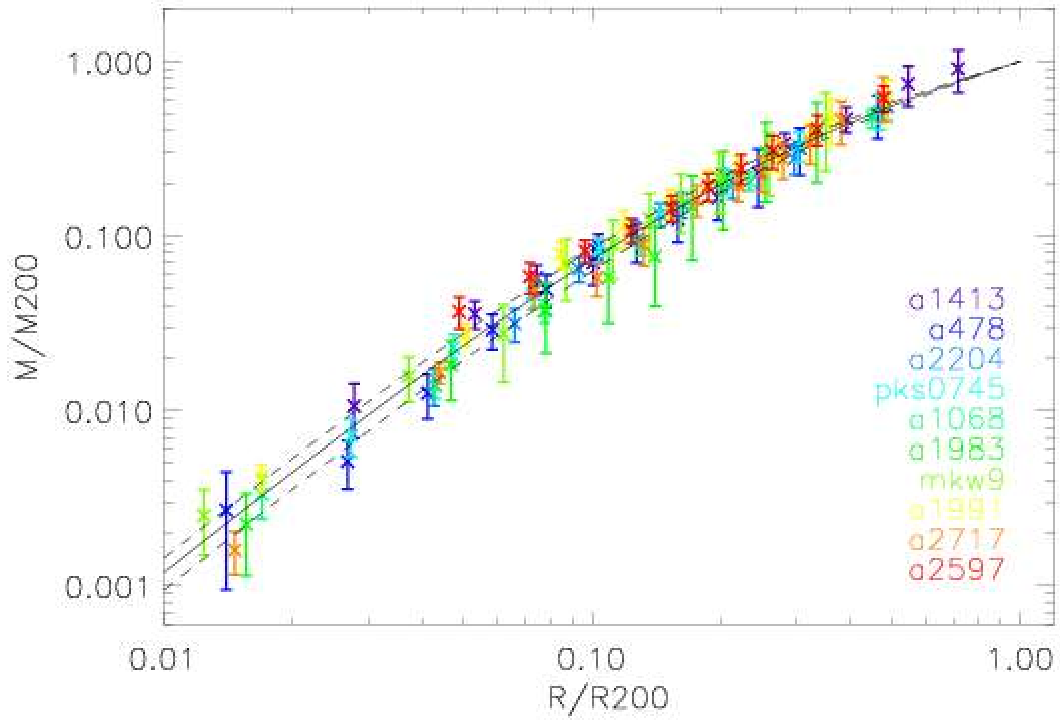
- Raw mass profiles



Properties of the DM

• Scaled mass profiles

→ well described by a NFW profile from 0.01 to 0.5 R_{200}

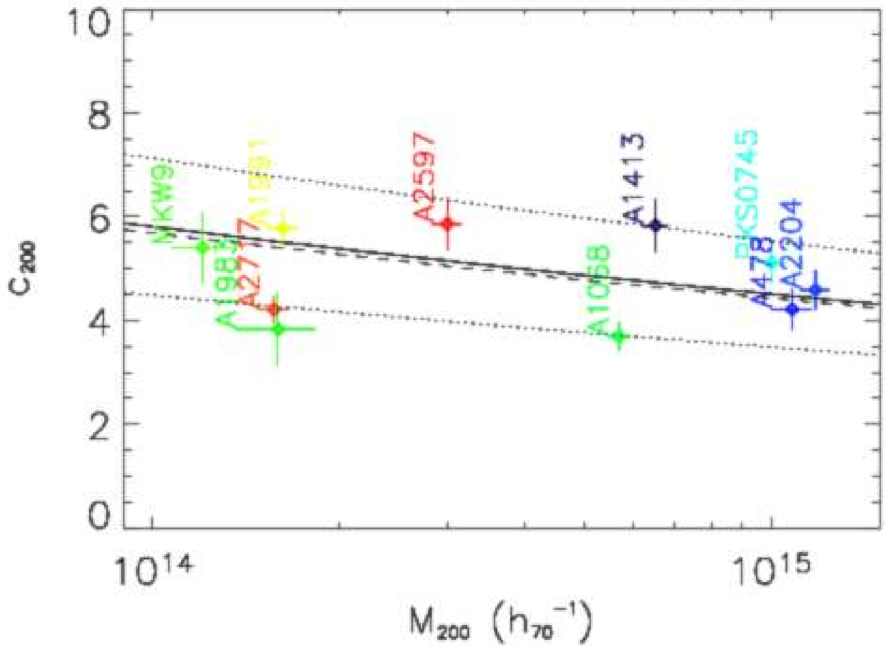


The mass profiles are self-similar.

A universal mass profile is observed.

Properties of the DM

- Mass and concentration parameter
  → predicted dispersion in c(M) [Zhao et al 2003, Dolag et al 2004]
  (scatter in the formation epoch [Wechsler 2002])



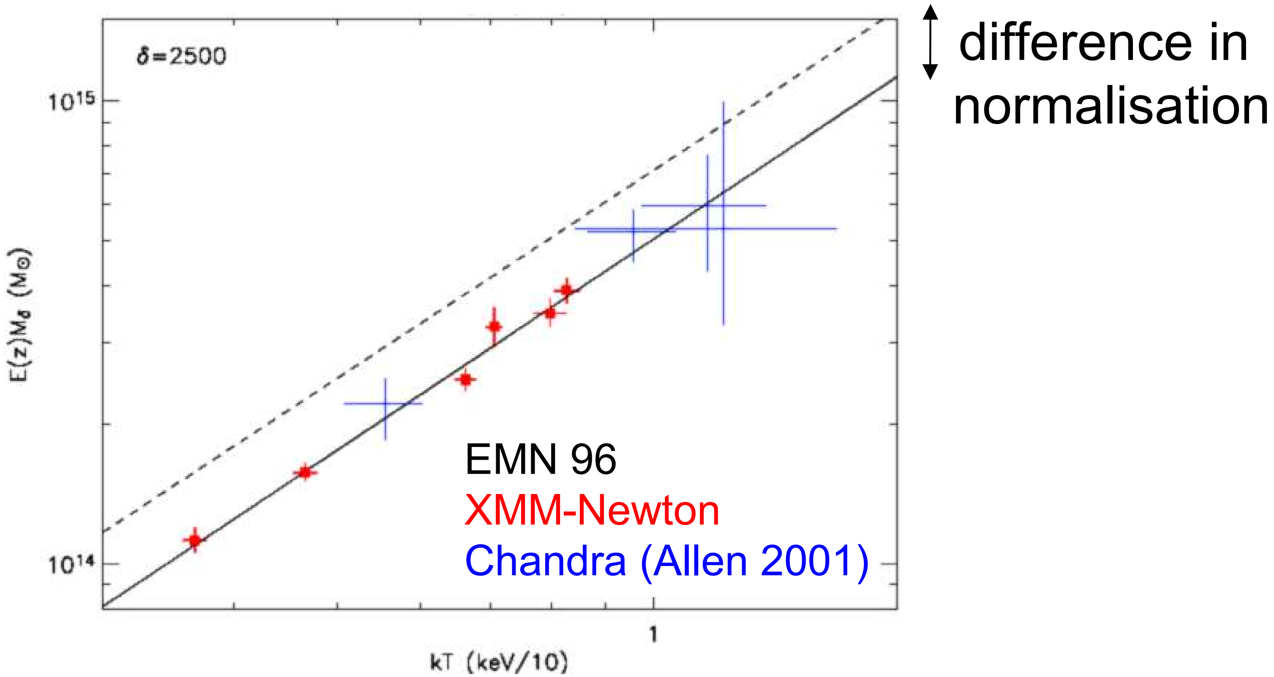
Conforms to the theoretical predictions
Physics of the DM collapse is pretty well understood

Properties of the DM

- Fitting the M-T relation
  - → M_δ directly fitted on the mass profile
  - → kT obtained from direct spectrosopy in [0.1-0.5] R_{200}
  - → Linear regression: $\log M = A + B \ \log kT$
  - → Errors on kT and M_δ taken into account

Properties of the DM

- The M-T relation at δ=2500
  - → hot clusters only (kT>3.5 keV)

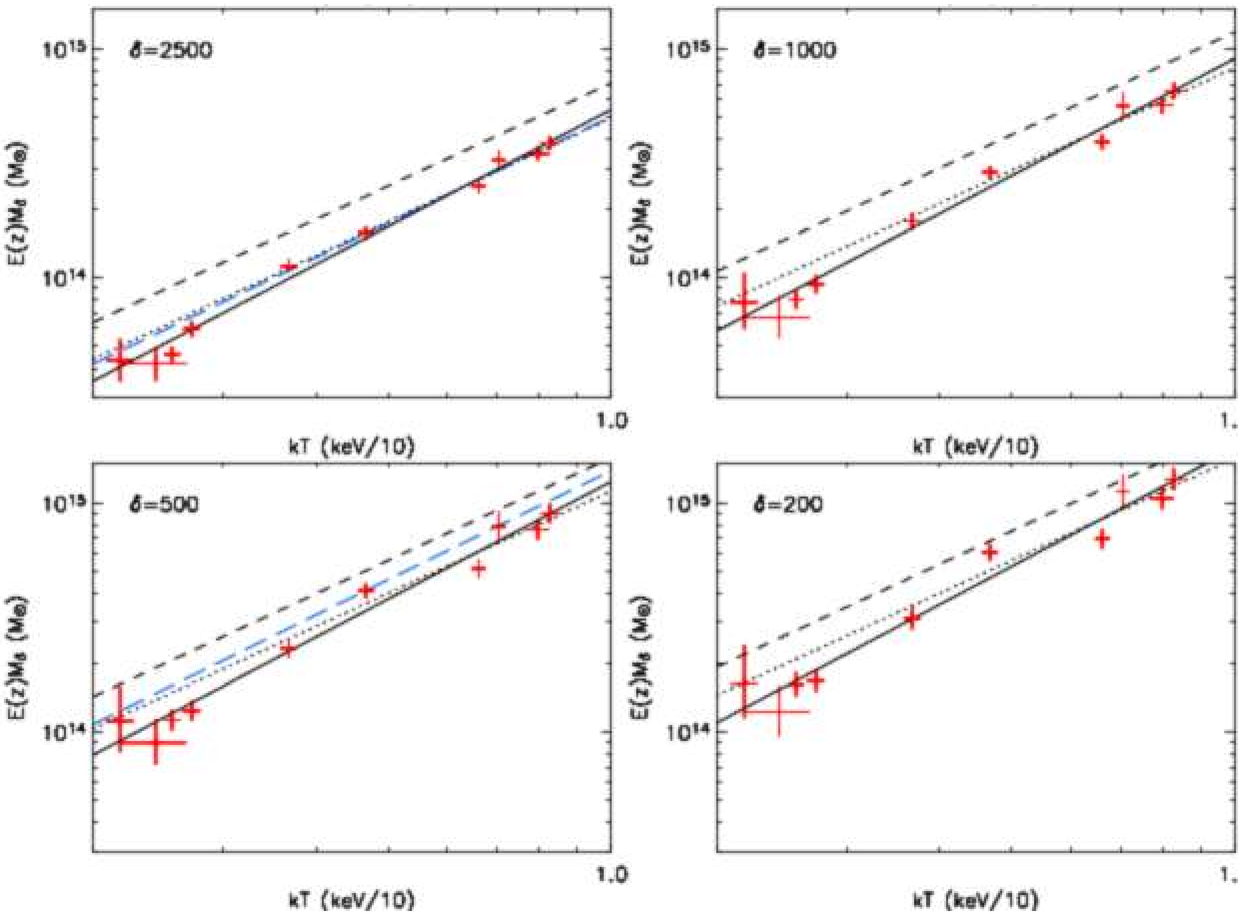


$$M_{2500} = 1.55\times10^{13}\,(kT)^{1.51\pm0.10}\,h_{70}^{-1}\,M_{sol}$$

Slope: conforms to the prediction of 1.5

Properties of the DM

- The M-T relation as seen by XMM-Newton



$\forall\ \delta$

$M_\delta \propto T^{1.7}$

Different slope (~1.7) but not at high masses (~1.5)

Normalization: improving but still differences with simu.

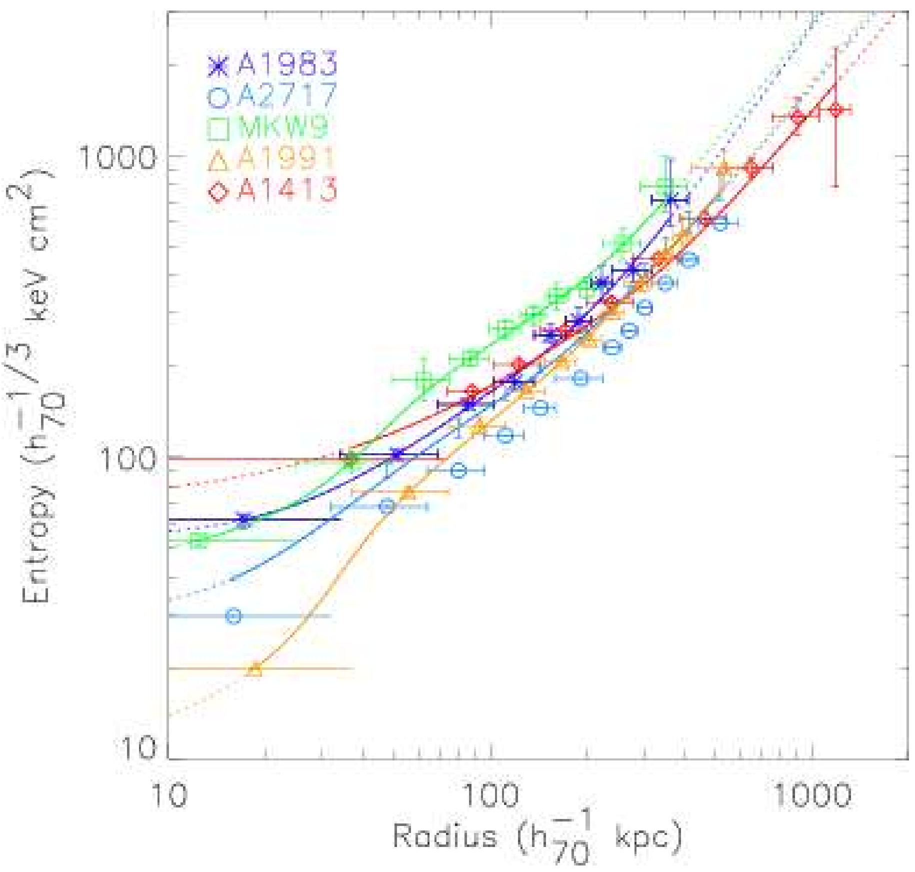
Properties of the ICM:

The entropy profiles and the S-T relation

Thermal state of the gas

Properties of the ICM

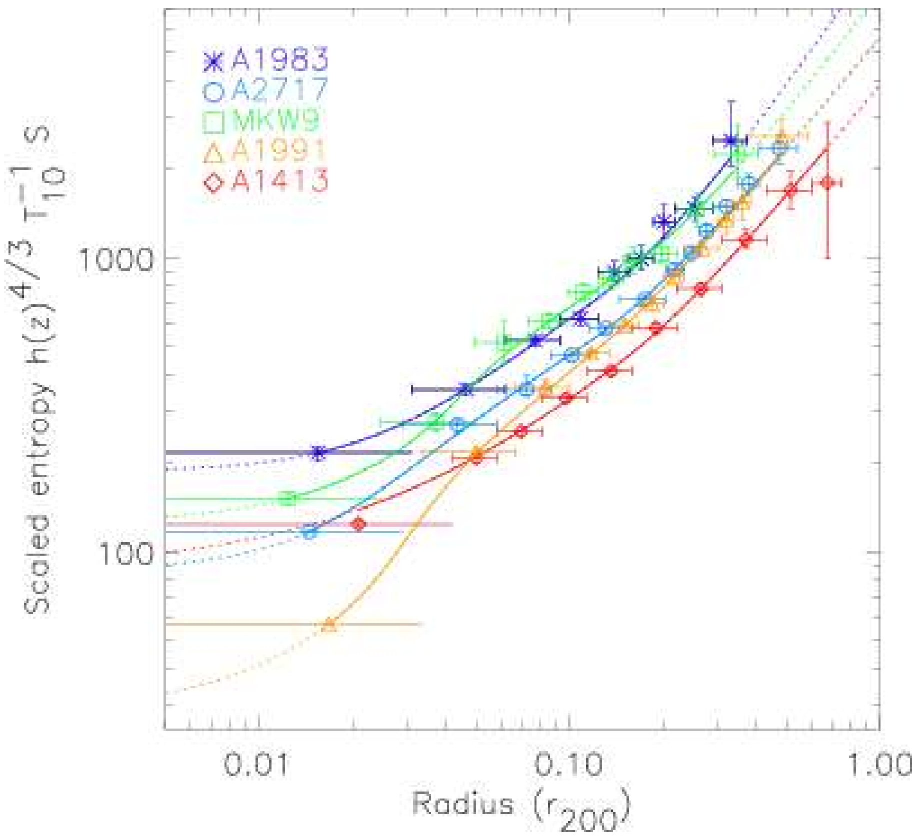
- Raw entropy profiles



[Pratt & Arnaud 2004]

Properties of the ICM

- Scaled entropy profiles: $S \propto T$



[Pratt & Arnaud 2004]

Properties of the ICM

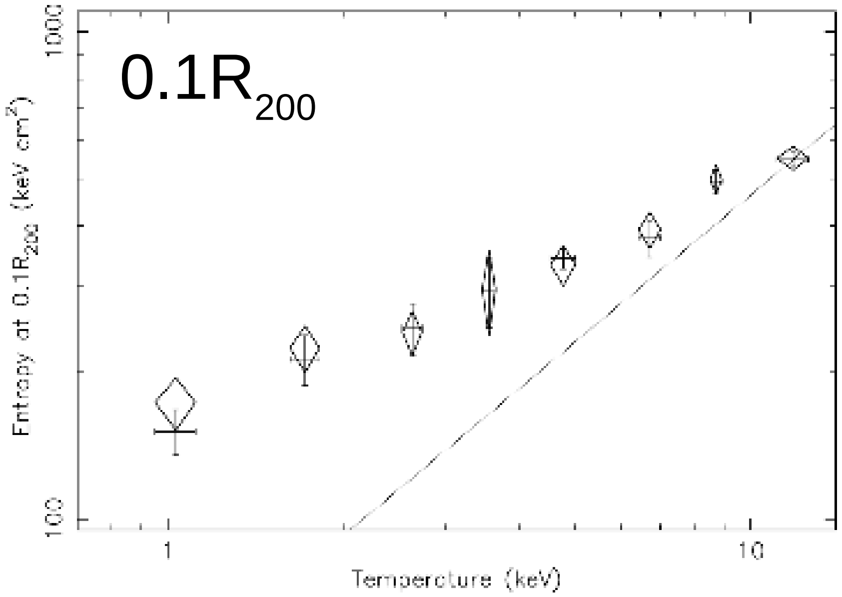
- *S-T relation shallower than expected* [Ponman et al. 2003]

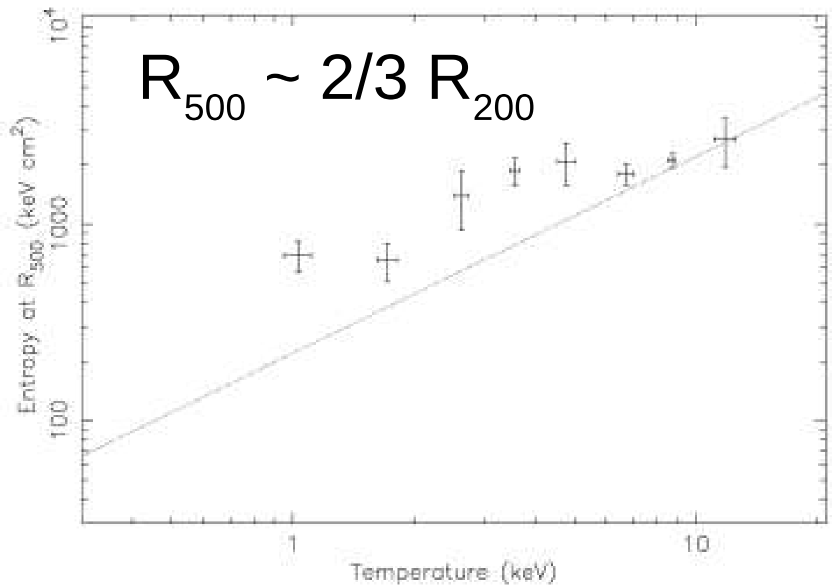
  → *@ 0.1R$_{200}$:* $S \propto T^{0.65}$

- *Entropy excess up to large radii*

  → *from low mass to high mass sytems*

  ⓘ *at R_{500}: extrapolation of the parametric models for ne(r) and kT(r)*



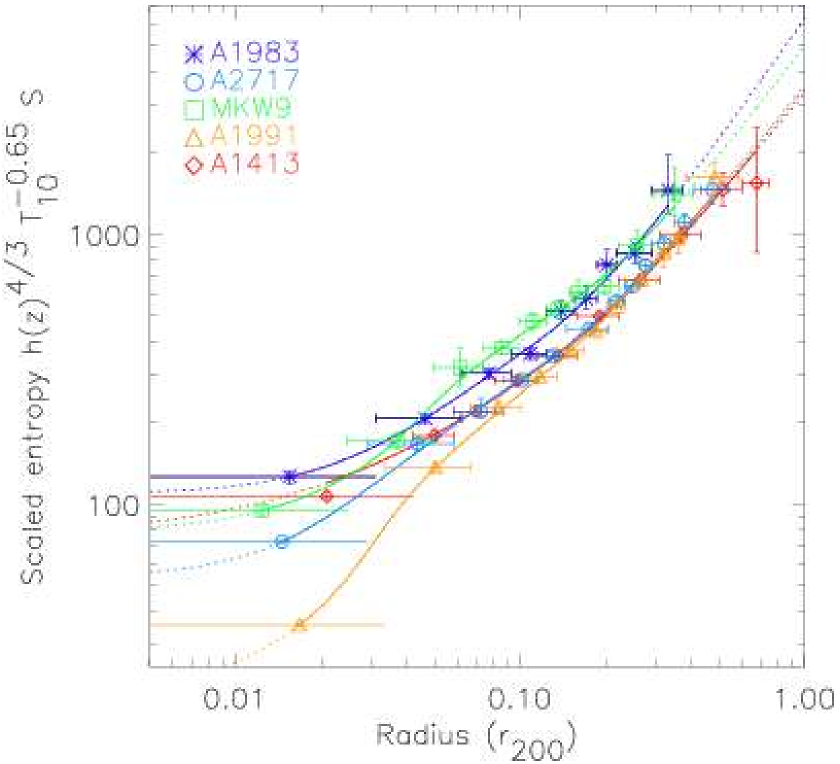


Properties of the ICM

- Scaled entropy profiles

$S \propto T^{0.65}$

[Pratt & Arnaud 2004]



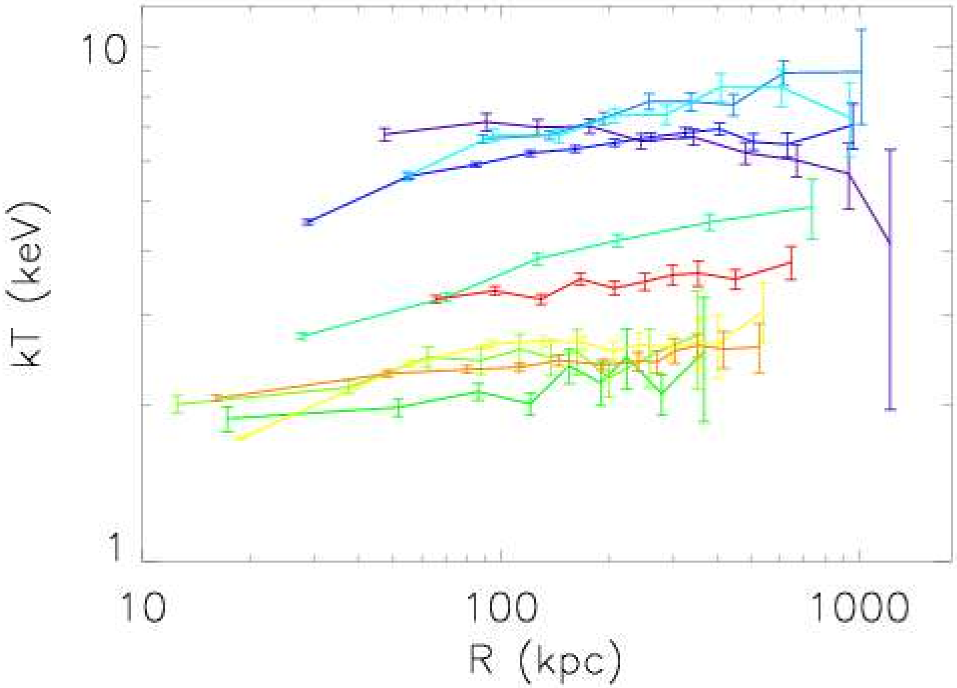
$$S_{2500}(0.1R_{200}) = 470\ T^{0.65}\ (r / 0.1r_{200})^{0.94\pm0.14}\ h^{-4/3}(z)\ \mathrm{keV/cm^2}$$

→ *in* spherical shock accretion models: $r^{1.1}$ [Tozzi & Norman 2001]

Entropy profiles have a similar shape

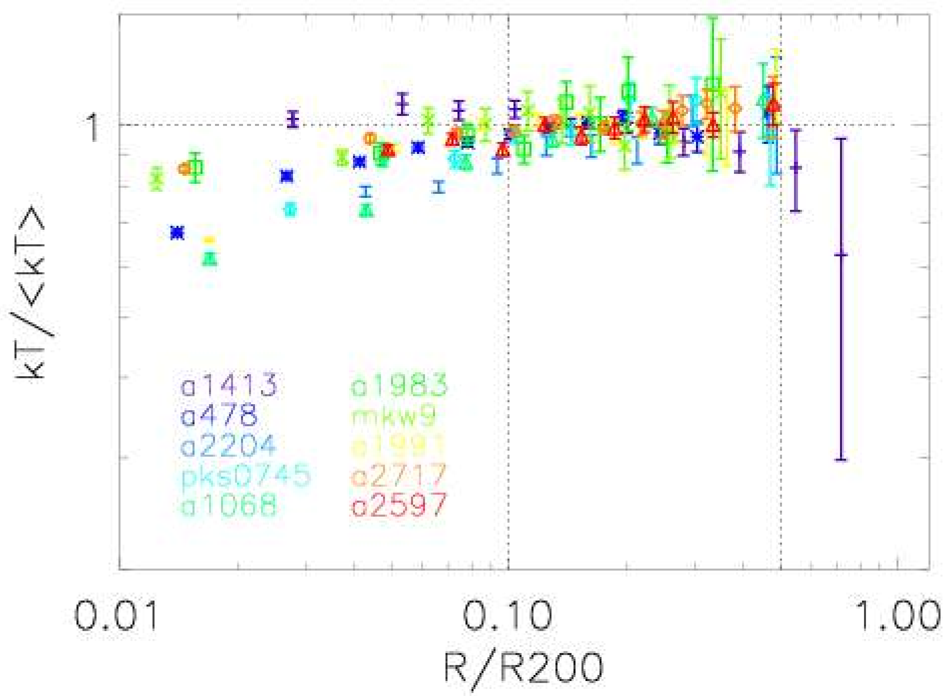
Properties of the ICM

- Raw temperature profiles

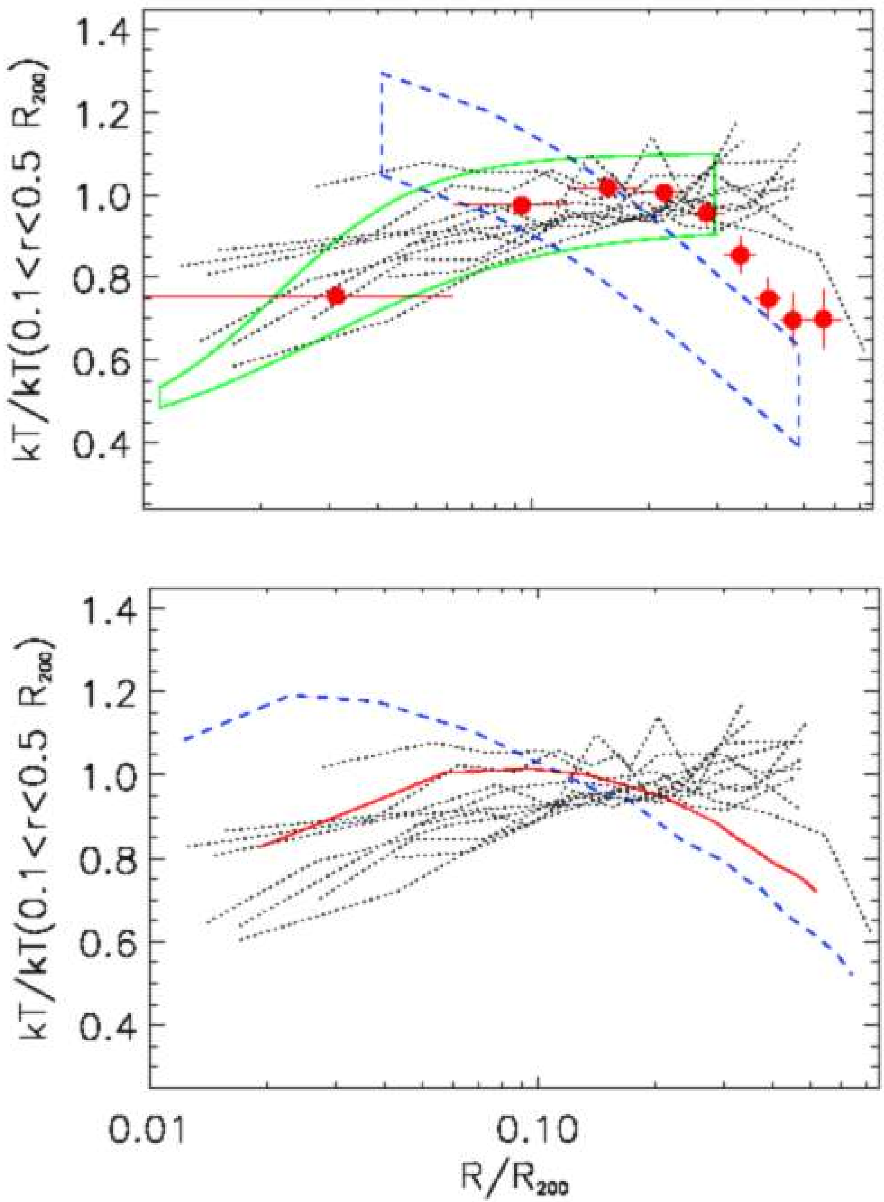


Properties of the ICM

- Scaled temperature profiles
  - → ‹kT› : spectroscopic temperature in [0.1-0.5] R_{200}



Properties of the ICM



- Comparison to previous observations

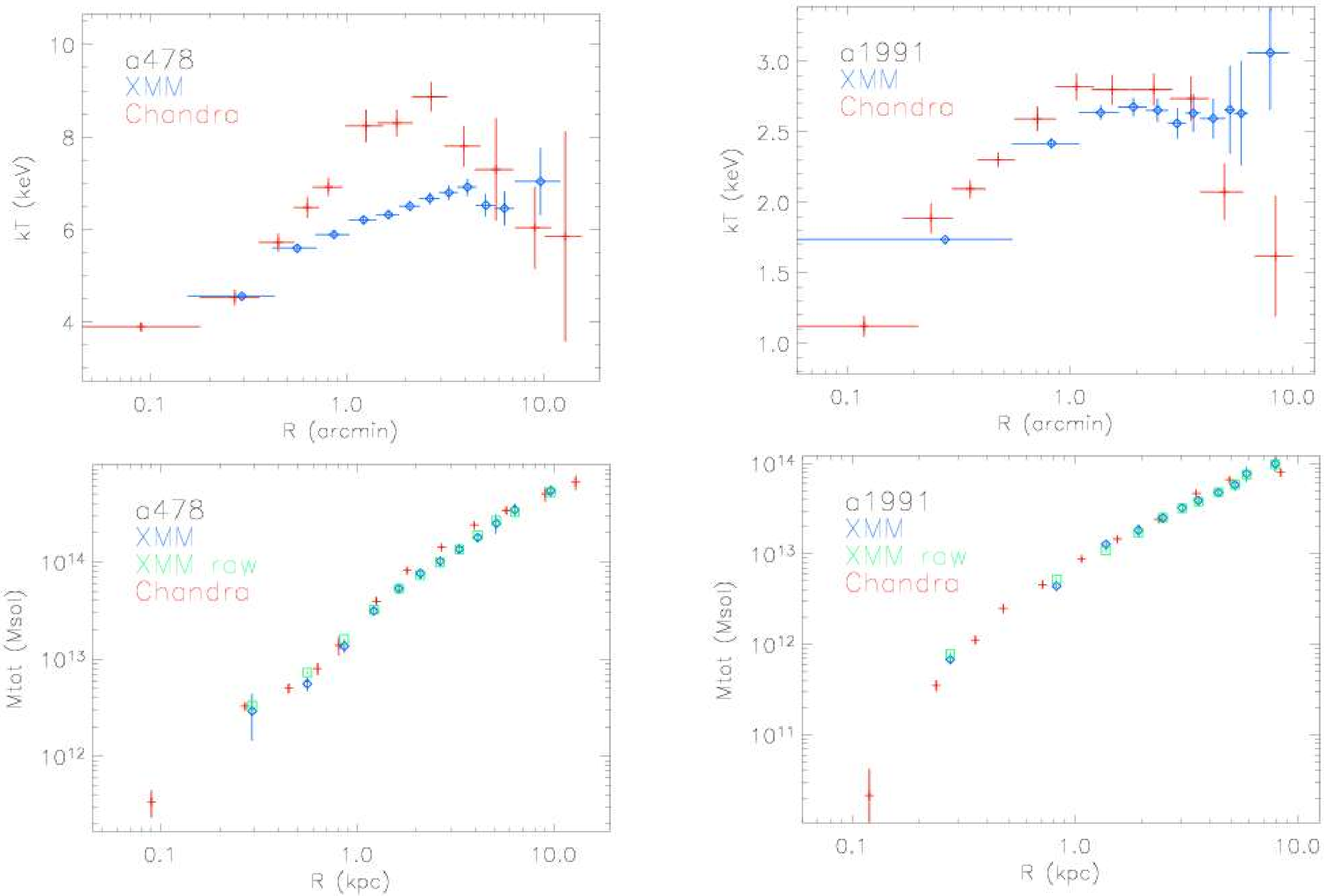
  XMM-Newton (this work)
  ASCA (Markevitch et al. 1998)
  BeppoSAX (De Grandi & Molendi 2002)
  Chandra (Allen at al. 2001)

- Comparison to simulations

  XMM-Newton (this work)
  Borgani et al. 2004
  Kay et al. 2004

Properties of the ICM

- Temperature profiles with XMM et Chandra



Summary

and

Perspectives

Conclusion

- Universality of the DM distribution over 0.01-0.7 R_{200}

  → fairly well described by a NFW whatever kT

  Qualitative and quantitative validation of the DM collapse models

- M-T relation: $M(\delta) \propto T^{1.7}$ whatever δ (obs. → 1000 ; extr. → 200)

  → slightly steeper than expected, normalization problem

  Physics governing the gas is still not well understood

[Pointecouteau, Arnaud & Pratt (astroph/0501635),
Arnaud, Pointecouteau & Pratt (astroph/0502210)]

Conclusion

- The entropy profile up to 0.5 R_{200} has a similar shape

  Ruled out simple preheating models (confirmed)

- Shallow S-T relation confirmed: $S_{2500} \propto T^{0.69}$

  → entropy excess at high radii observed

  The gas thermodynamical evolution is not well understood

  [Pratt, Arnaud & Pointecouteau (en préparation)]

Perspectives for SZ surveys

Coming SZ surveys

- Groundbased SZ surveys coming up:

→ Interferometric instruments: AMI, AMIBA, SZA

→ Single dish: ACT, SPT, OLIMPO, SuZIE-*III*,

ACBAR, MITO, APEX-SZ

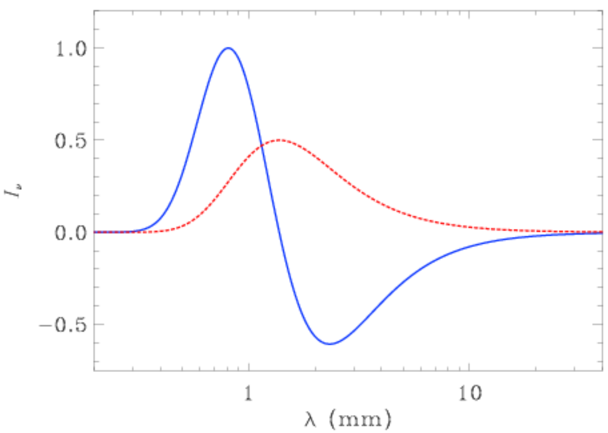
- Spacecraft

→ Planck Surveyor all sky survey

9 photometric bands (350μm-1cm)

~40000 clusters awaited with kT > 4keV (ΛCDM)

Perspectives for SZ surveys



- SZ measurement
  - → $F_{SZ} \propto Y \propto f_{gas}\, T\, M\, d_A^{-2}$
  - → single λ : $F_{SZ} \propto Y$
  - → multiple λ : Y, v_p, kT

  [Pointecouteau et al. 1998, Aghanim et al. 2003, Hansen et al. 2004]

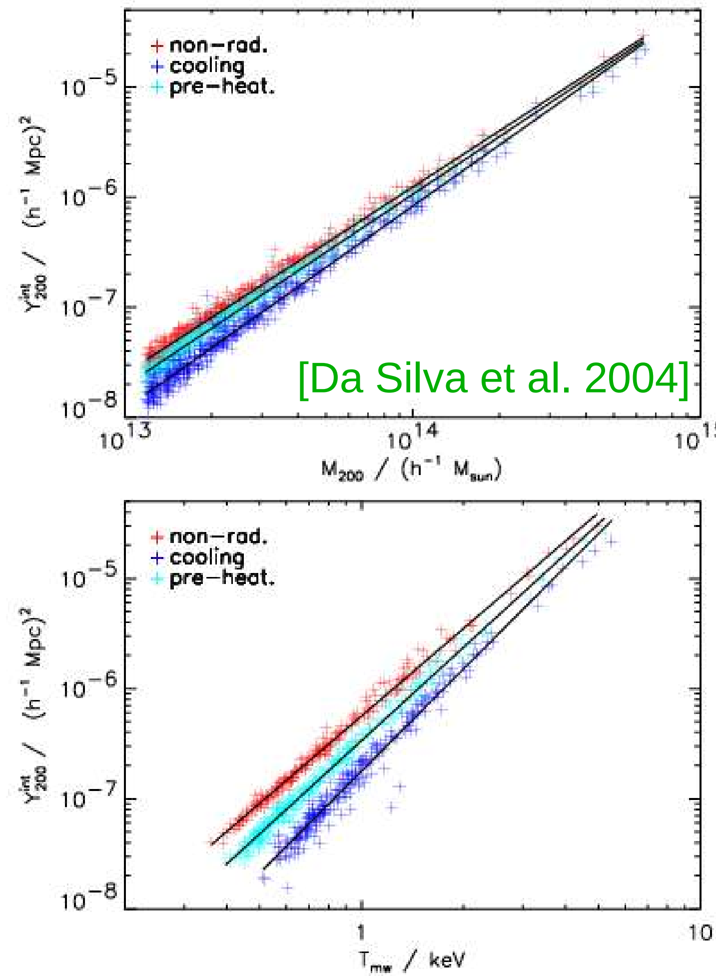
- Combined X/SZ spatial analysis

  [Pointecouteau et al. 2002, Kitayama et al. 2004]
  - → temperature (kT)
  - → X-ray counter part for ~3% of Planck clusters
  - → solution : SZ scaling laws Y-M (Y-T, M-T)

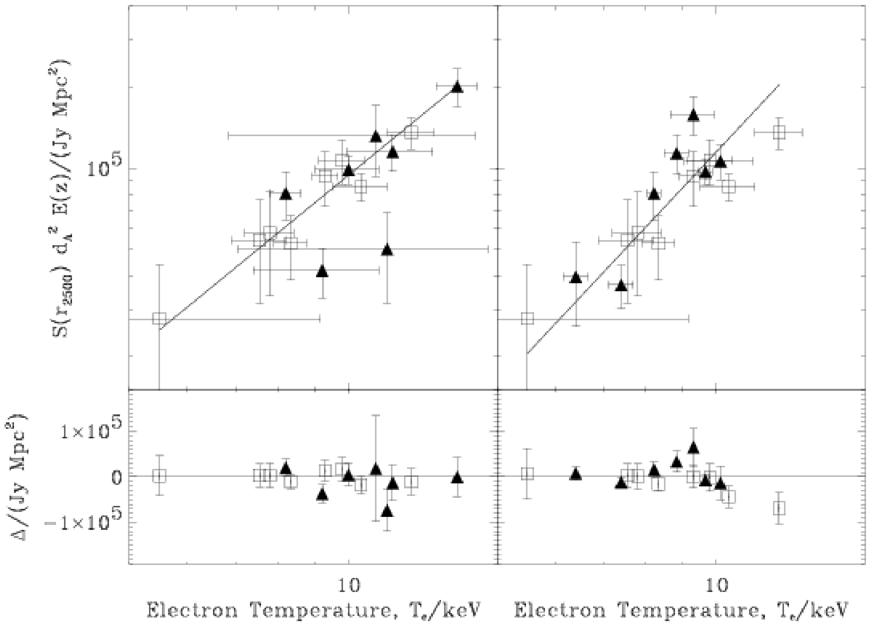
Perspectives for SZ surveys

- *Hydrodynamical simulations*
  - → $Y \propto T^{5/2}$

non radiative	$Y_{200} \propto T_{mw}^{2.63}$
cooling	$Y_{200} \propto T_{mw}^{2.90}$
preheating	$Y_{200} \propto T_{mw}^{3.03}$



[Da Silva et al. 2004]



[Benson et al. 2004]

- Observations (15 SuZIE clusters)

$Y \propto T^{2.21 \pm 0.41}$

Summary and perspectives

- Good results from a test case sample (despite biased)

- Future works with unbiased and complete samples

  local reference [LP AO3 - PI: H. Böhringer]

  evolution [LP AO4 - PI: M. Arnaud]

  → well calibrated scaling laws in [z,M]

  → N(M,z=0), N(M, z=0.5)

- Combination with future SZ data

  → calibration of the SZ scaling laws (Y-M)

  → physics of structure formation

  → cosmological studies with X-ray surveys