# X-ray observations of Galaxy Clusters

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See also review Arnaud, 2005, astro-ph/0508159

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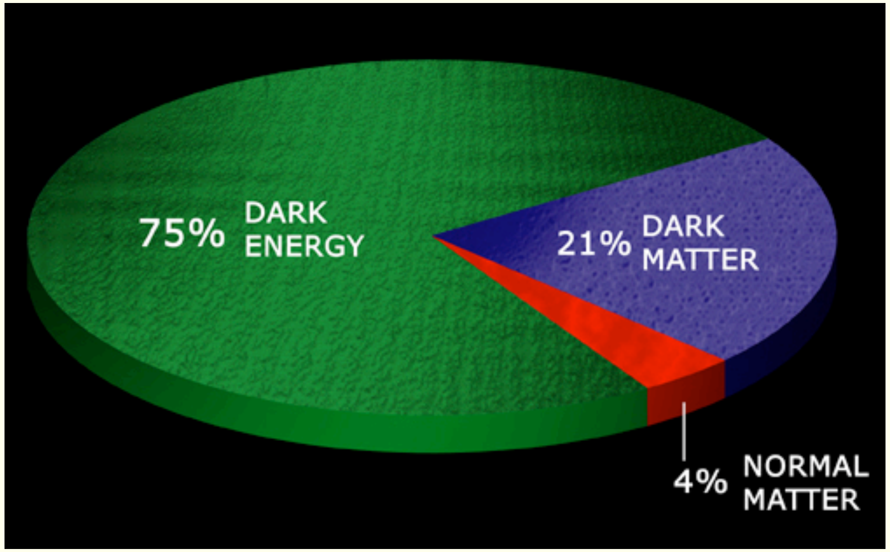
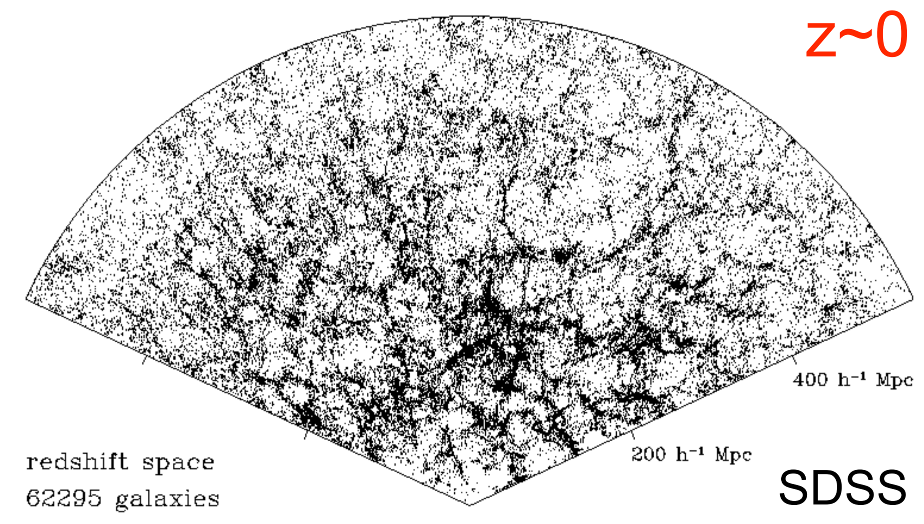
Ed. F.Melchiorri & Y. Rephaeli, IOS Press, 2005

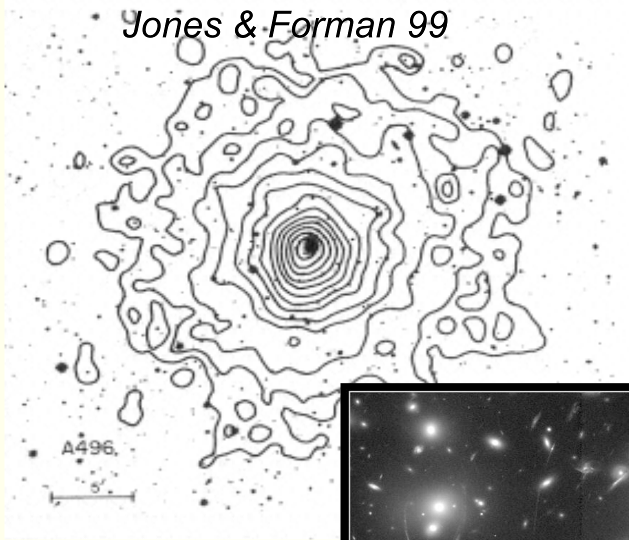
# The Universe : the ‘favored’ cosmological model

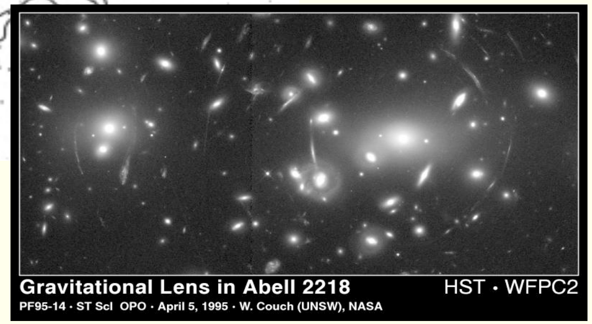



- Geometry: Flat $\Omega_{tot} \sim 1.$
- Dynamics: Present expansion rate: $H_o \sim 73$ km/s/Mpc
  Accelerating
- Content: Dark matter and dark energy dominated
  $\Omega_m \sim 0.25$ , $\Omega_\Lambda \sim 0.75$

# Structures and clusters in the Universe




<u>A highly structured Universe</u>
(stars, galaxies, clusters, filaments, voids..)

<u>Clusters:</u>
the largest collapsed structures
at the crossing of filaments

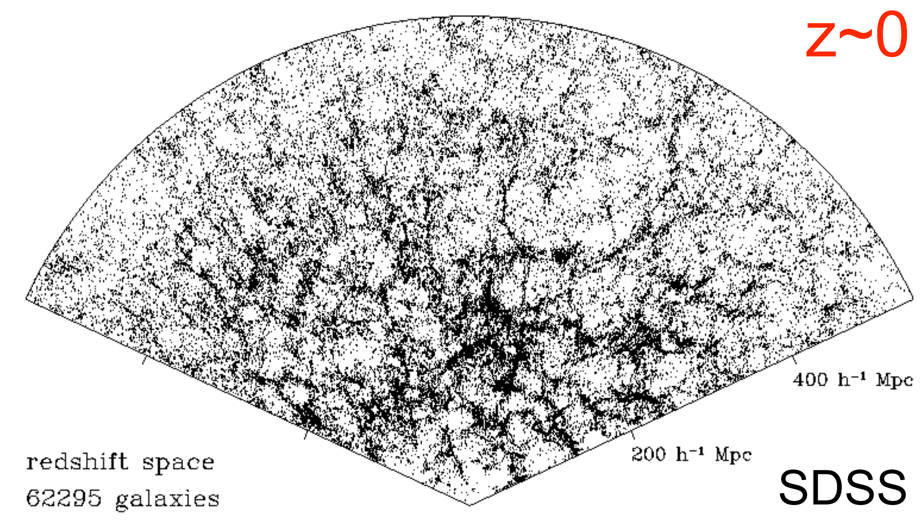
$M_{tot}$ ~$10^{13}$ - a few $10^{15}$ $M_o$

<u>Clusters components:</u>

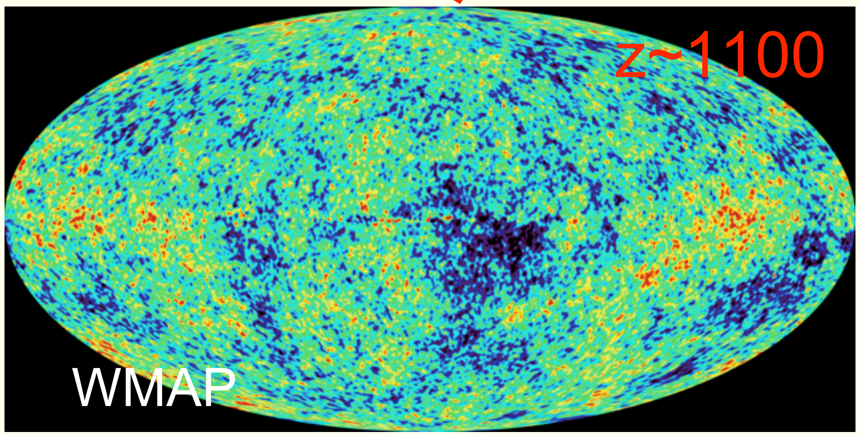
⇒ Dark Matter mostly (~85% as the Universe)
⇒ Galaxies (~2%)
⇒ Diffuse X-ray emitting gas
(13% main baryonic component)

kT ~ 0.3 - 15 keV [kT ~ GM/R]
$n_e$ ~ $10^{-2}$ $cm^{-3}$ [in centre]

# Structures formation in the Universe



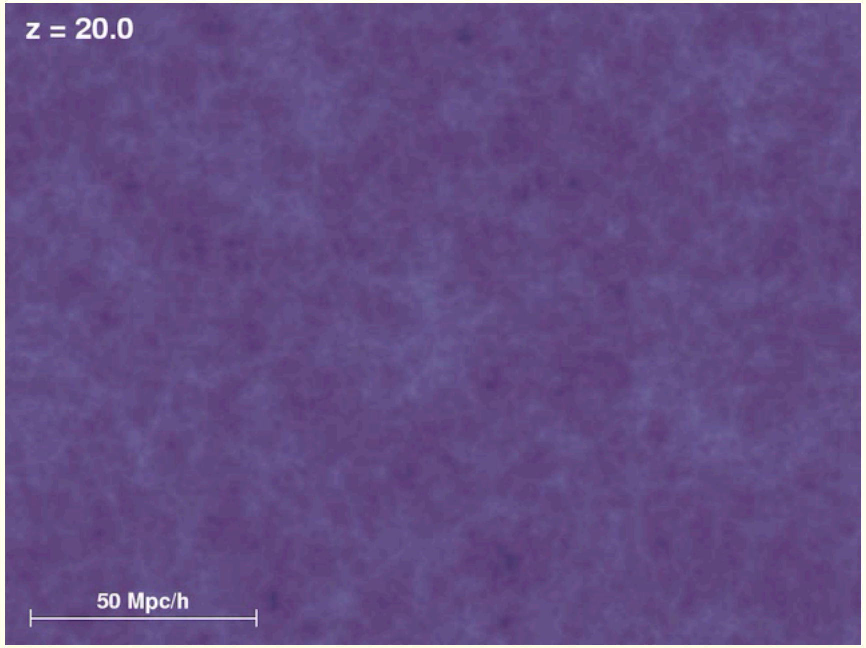

?



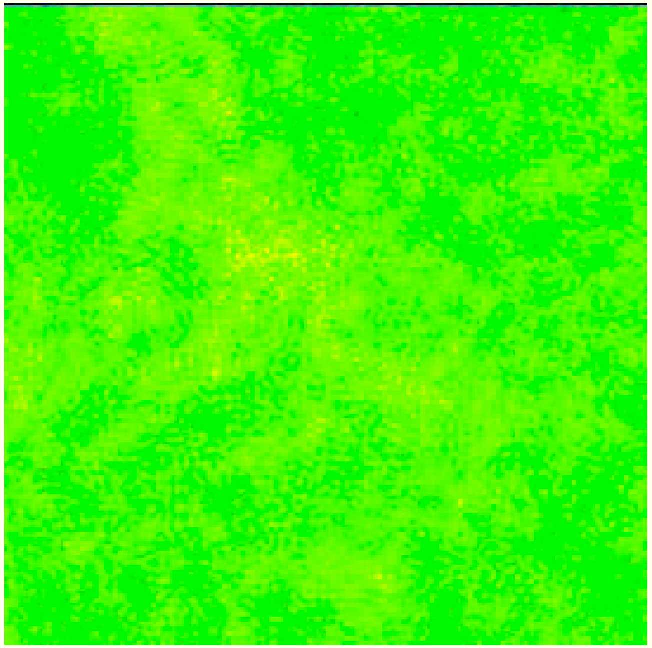

How did structures form and evolve ?

from initial density fluctuations (~ known)
in the 'given' $\Lambda$CDM cosmology.

# Structure and cluster formation




*Credit: Volker Springel*



*Credit: Joerg Colberg*

- Primordial fluctuations (DM) that growth under the influence of gravity

- Hierarchical clustering:
  ⇒ clusters are forming/growing since z~2 *till now* by merger/accretion along LS filaments

- The cluster population is an evolving population
  ⇒ provide powerful test of structure formation *(Dark Matter and Gas)*
  ⇒ can be used to constrain the cosmological parameters

# Outline of the course:

I: The X-ray information on clusters

II: The continuous hierarchical cluster formation

substructures, mergers

III: Clusters form a regular population:

the self-similar collapse of the DM and the gas additional physics

IV: X-ray clusters surveys

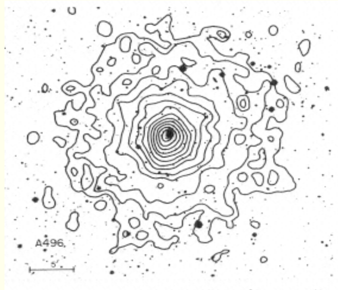
V: Constraining cosmological parameters with X-ray clusters

NB: a few (illustrative) references only
for more complete bibliography see Arnaud, 05, astro-ph/0508159

# The X-ray information

# The ICM X-ray thermal emission

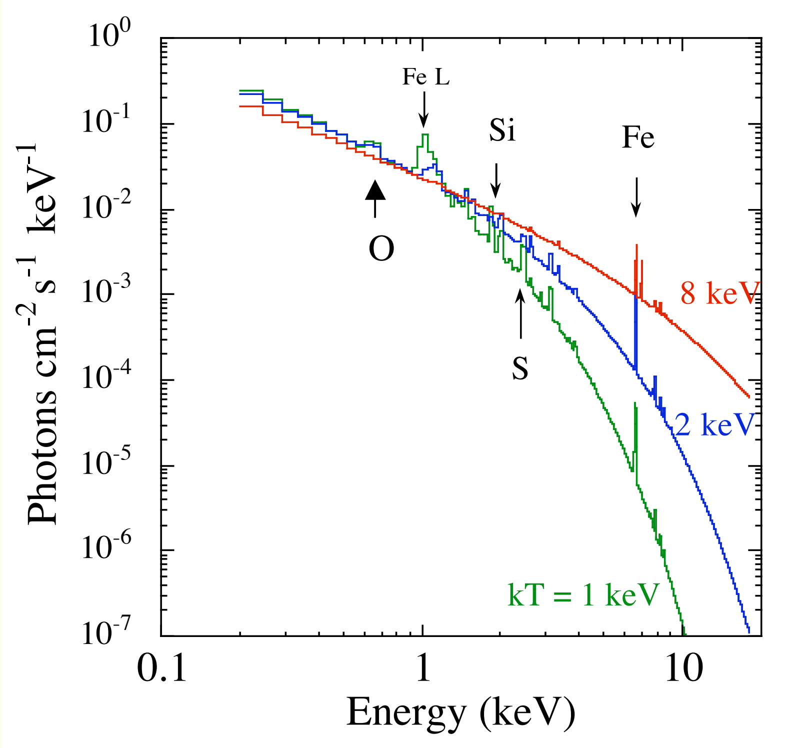
- The Intra Cluster Medium
  - Fully ionised H+He plasma
  - Highly ionised heavy elements




- Emission
  - Mostly bremstrahlung emission
  - Emission lines

$$dN(E)/dE \sim n_e^2\, V\, [g(E,T)\, T^{-1/2} \exp(-E/kT) + \text{lines}]$$

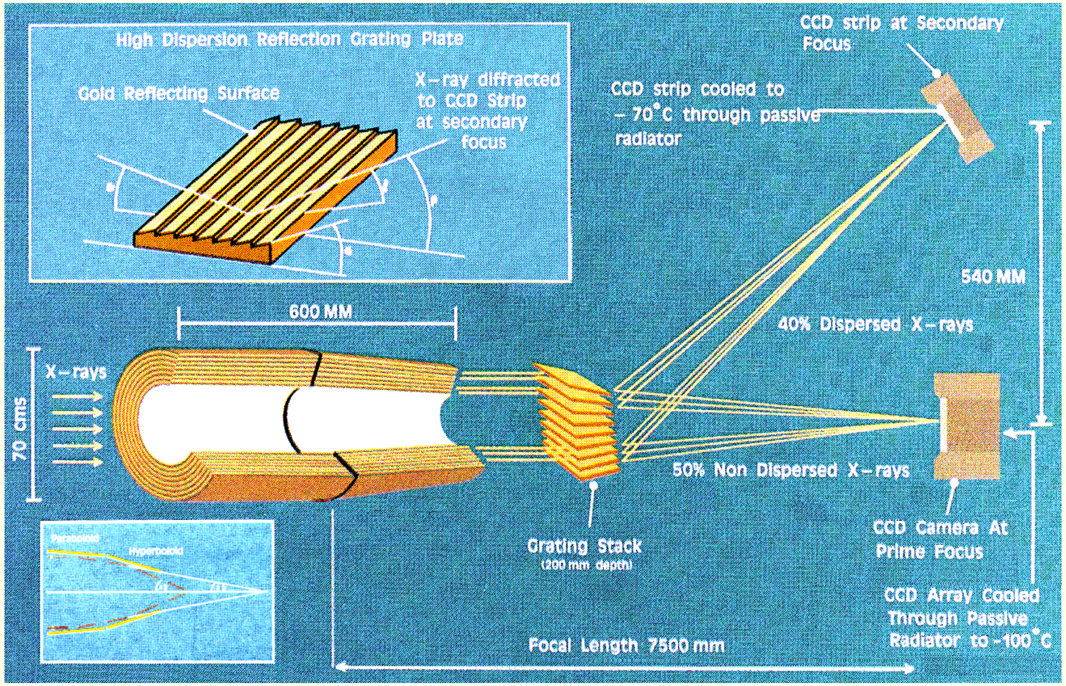
- Normalisation: $EM = \int n_e^2\, dl$
  - Imagery (at low energy)
  - ⇒ gas density distribution




- Spectral Shape: kT, abundance [Z/H]
  - Spectroscopy
  - ⇒ <kT>, kT maps

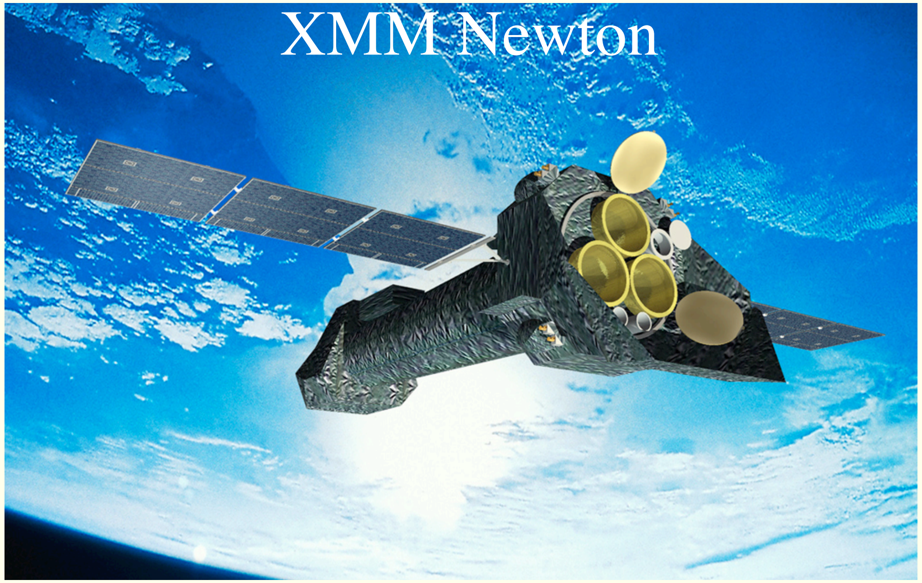
Need sensitivity up to ~ 10 keV

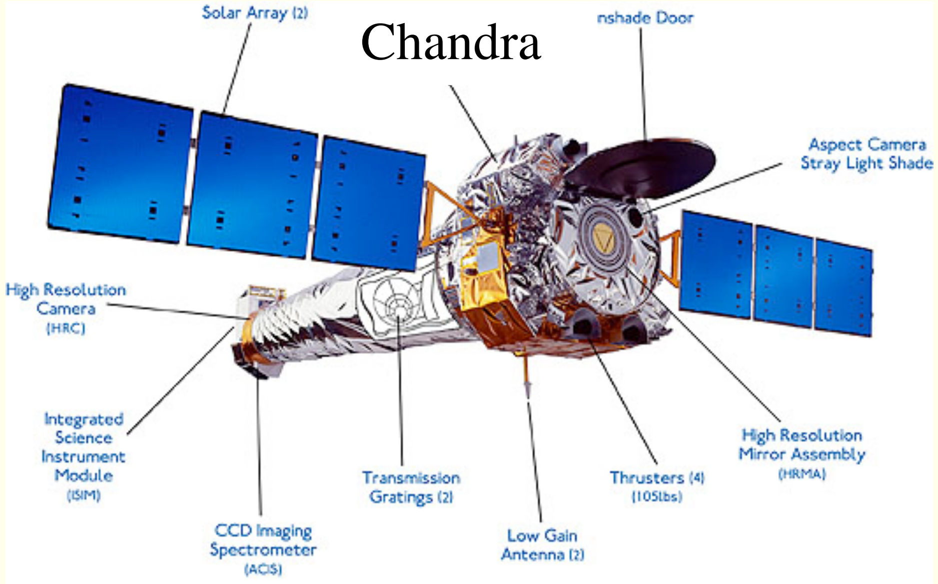
# Principle of modern X-ray detection




- Mirrors: Focus X-ray (small grazing angles required)
- CCD (XMM/EPIC) : detect X-ray photon 1 by one; measure position, E
  - ⇒ spatially resolved spectroscopy with ΔE/E=2-6%
- Gratings (XMM/RGS) = dispersed spectrum ‘ read ’ by CCD
  - ⇒ spectroscopy of central < ~2’ source with ΔE/E=0.1-0.3% in 0.3-2 keV

# XMM and Chandra observatories




3 high throughput X-ray telescopes
FOV = 30’ FWHM < 10”

One X-ray telescope
FOV = 17’X17’ FWHM < 0.5”

Spatially resolved spectroscopy: 0.2< E < 10 keV

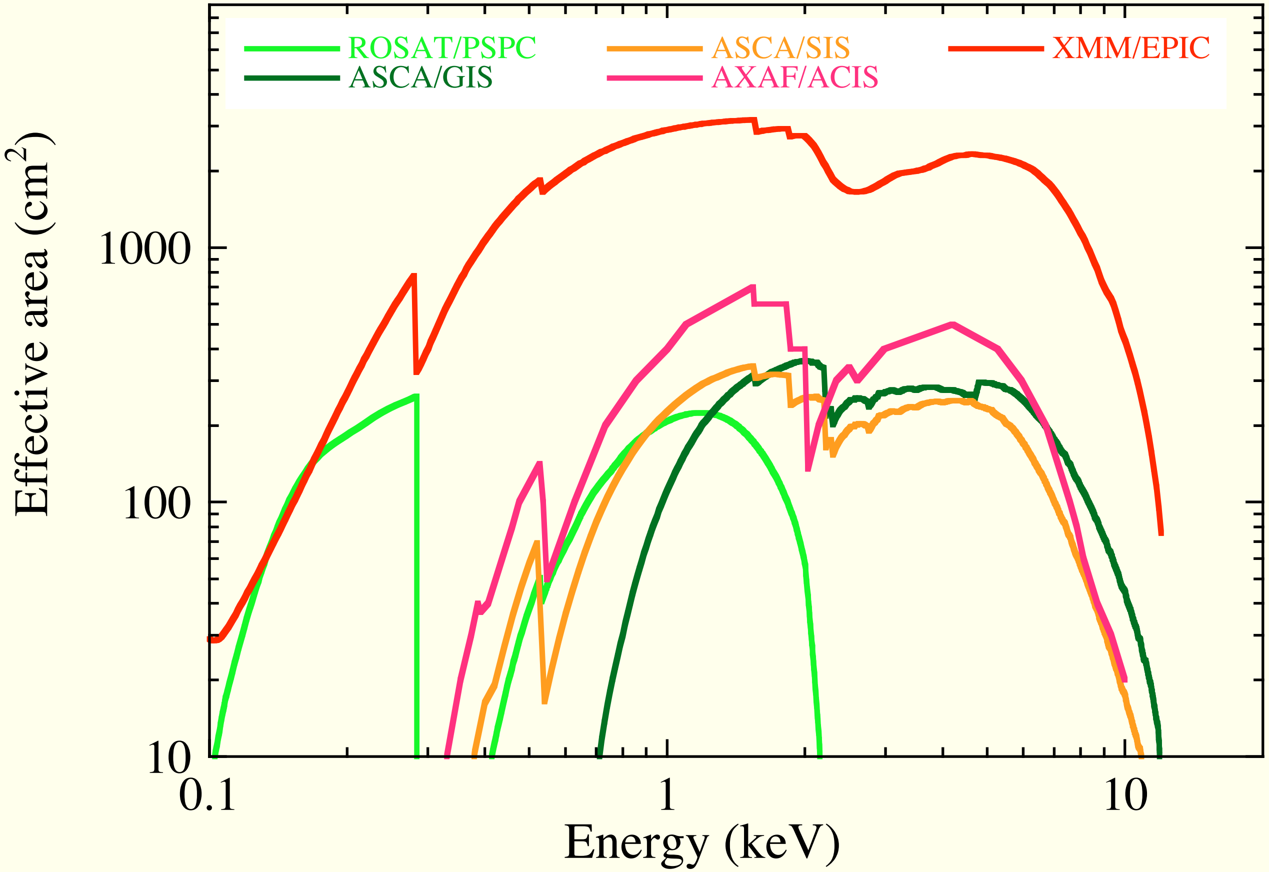
High resolution dispersive spectroscopy:

[and] 0.2< E < 2.5 keV

[or] 0.2< E < 10 keV

and RXTE (hard X-ray) and recently SUZAKU

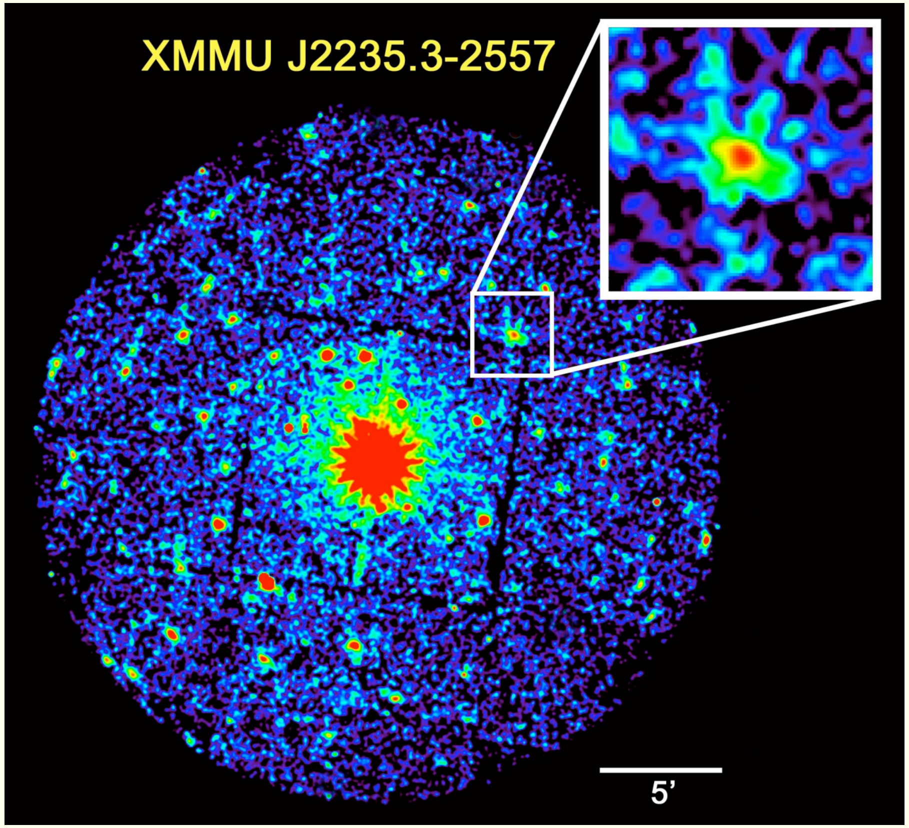
# Comparison with (some) previous satellites

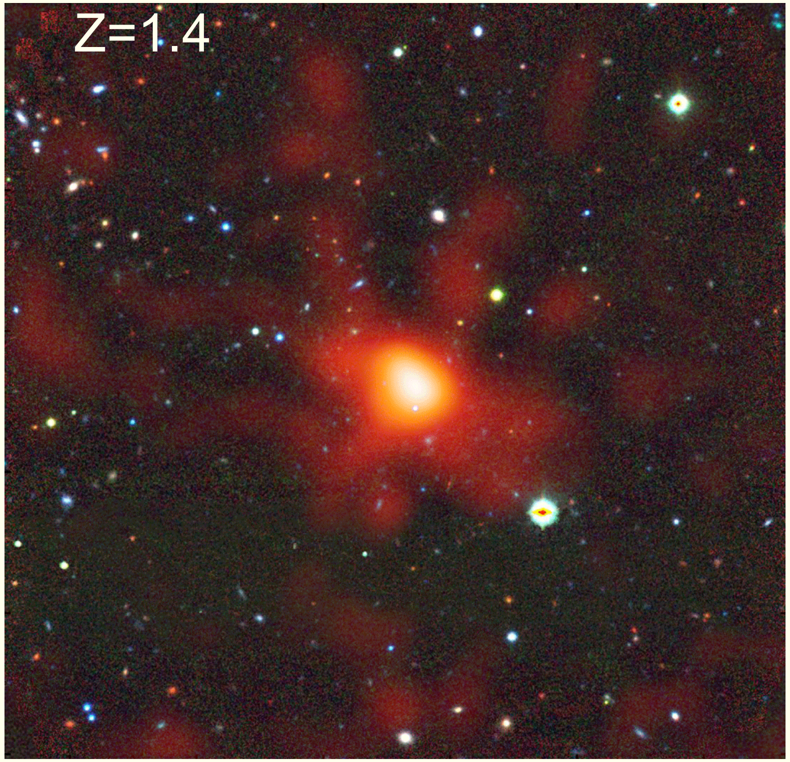



ROSAT: imagery, spectro (kT) for low mass clusters only
ASCA: first satellite with spectro-imagery capability, poor $\Delta\theta$
Beppo-SAX: better $\Delta\theta$ ; hard X-ray capabilities (also RXTE)

# The X-ray information: we can

## detect (new) clusters



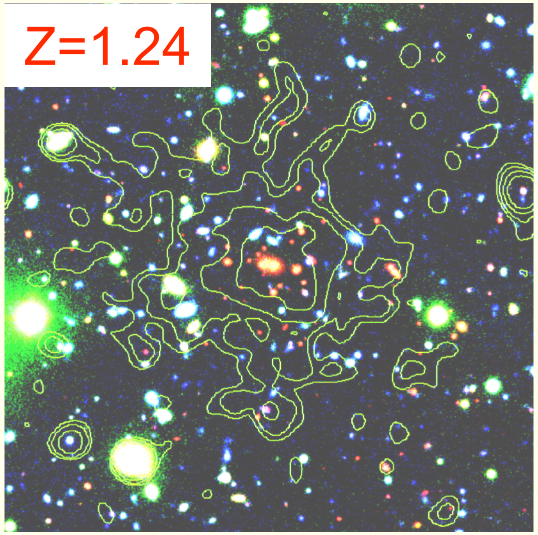



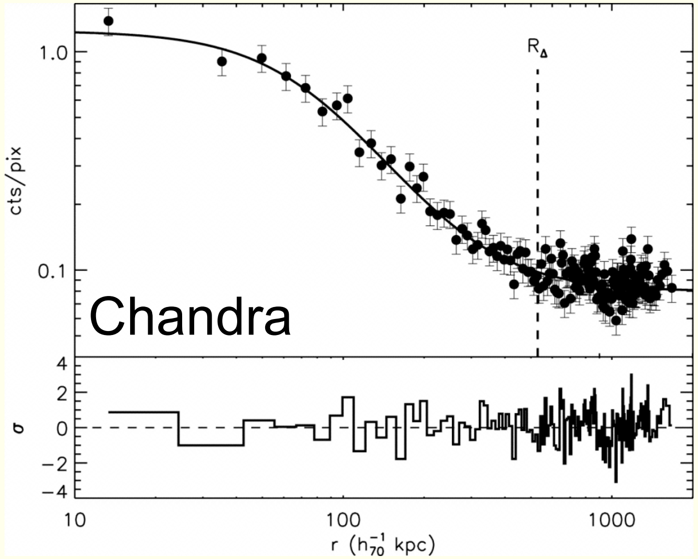

*Mullis et al, 05, ApJ*

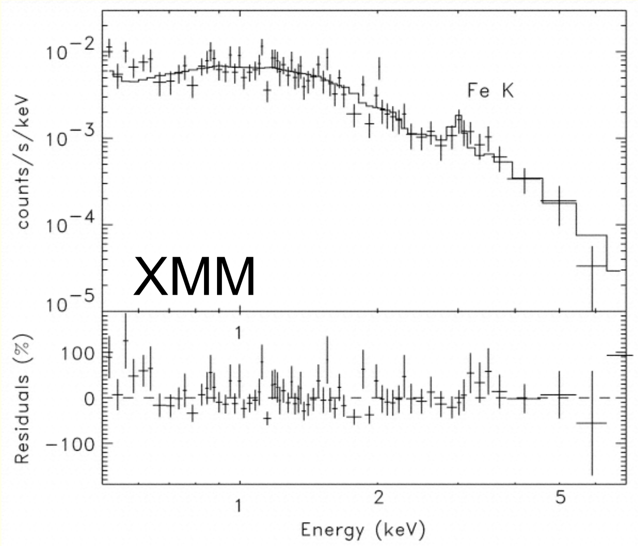
⇒ Luminosity $L_X$

# Measure cluster basic properties up to high z

*Rosati et al., AJ, 04*




## Image

Regular
morphology

## Surface brightness profile

$$S_X = \left[1 + (\theta/\theta_c)^2\right]^{-3\beta+1/2}$$

$$n_e = \left[1 + (r/r_c)^2\right]^{-3\beta/2}$$

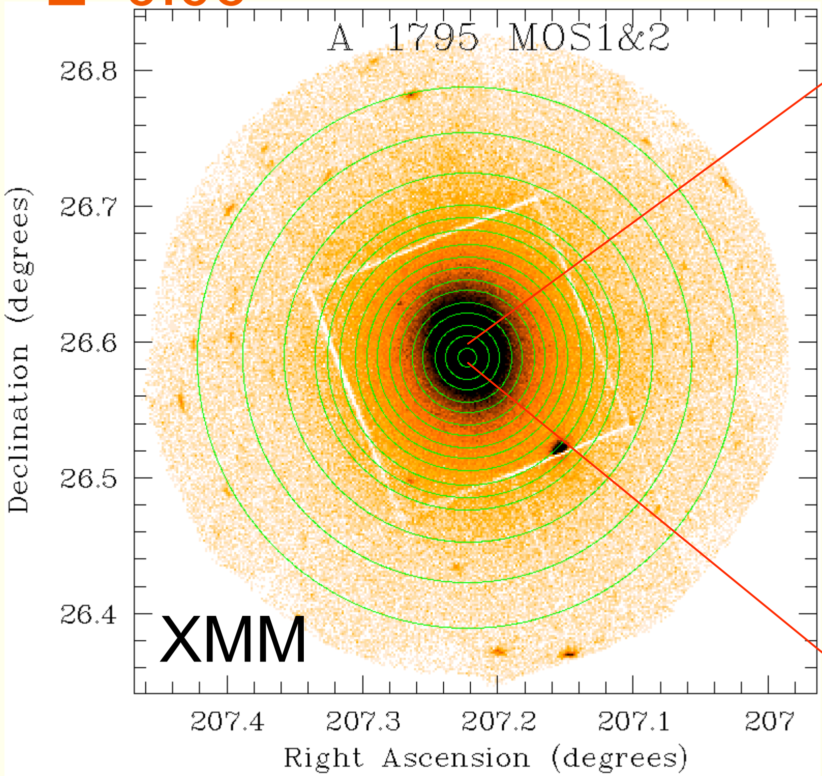
## Global spectrum

kT = 6.0[-0.5,+0.7] keV
Z = 0.36 ±0.11 $Z_0$

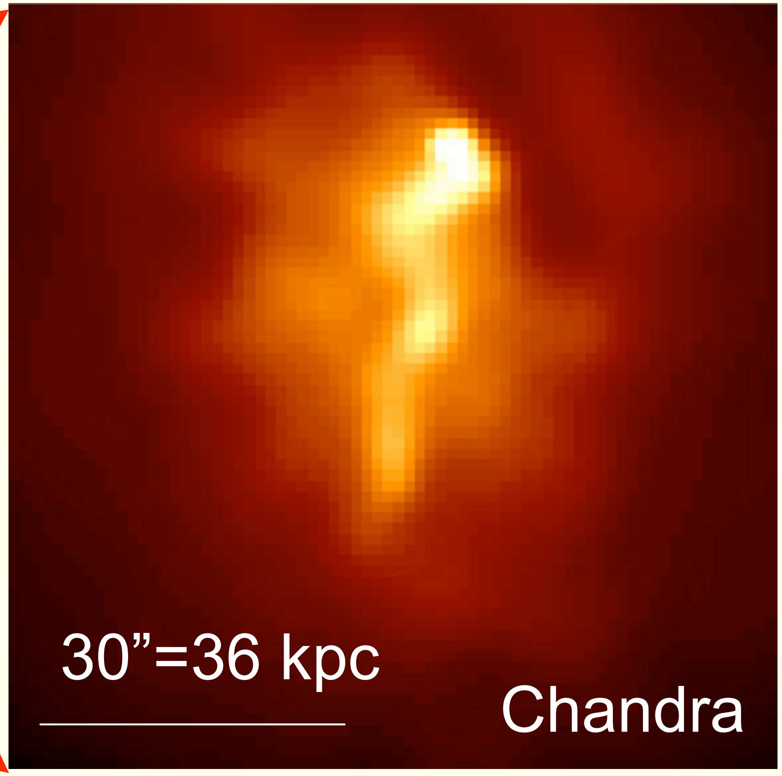
⇒ $L_X$, $M_{gas}$, $M_{tot}$ *down to flux at ROSAT detection limit*

# At low z: map gas distribution

Z=0.06




*Arnaud et al, 01, A&A*




*Fabian et al, 01, MNRAS*

At large scale

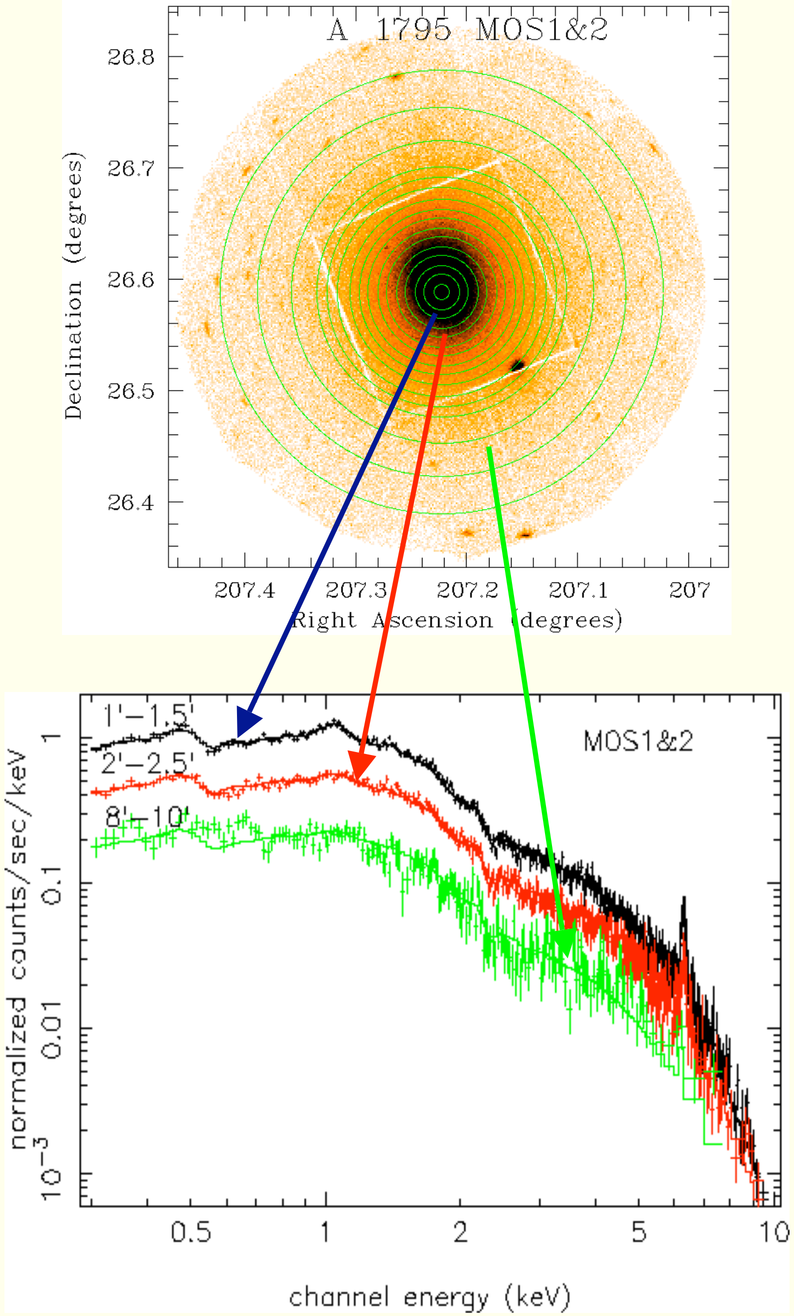
up to close $R_v$ ~ 1-2 Mpc

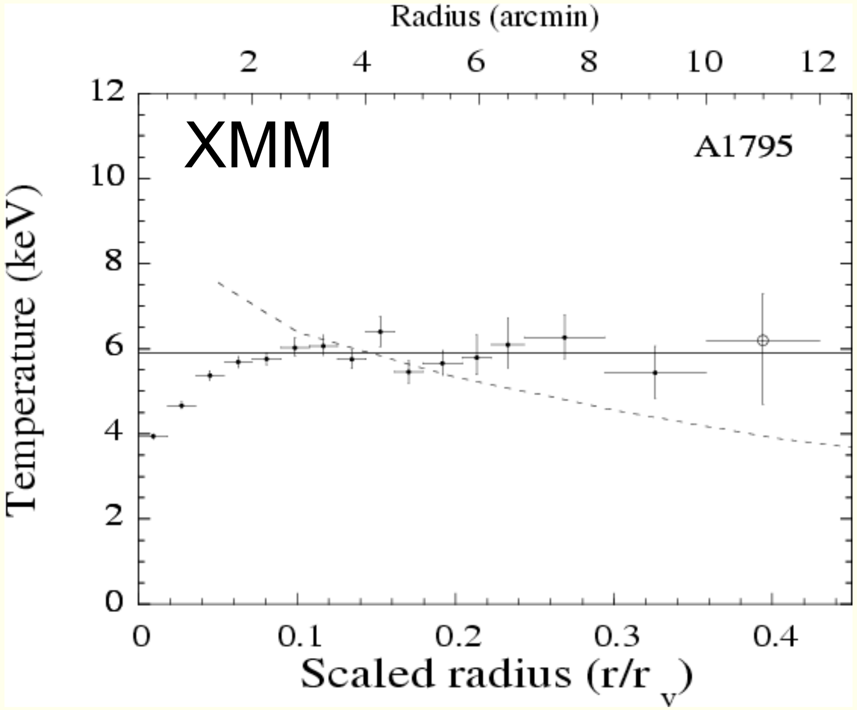
and

deep in the core

at a few kpc scale

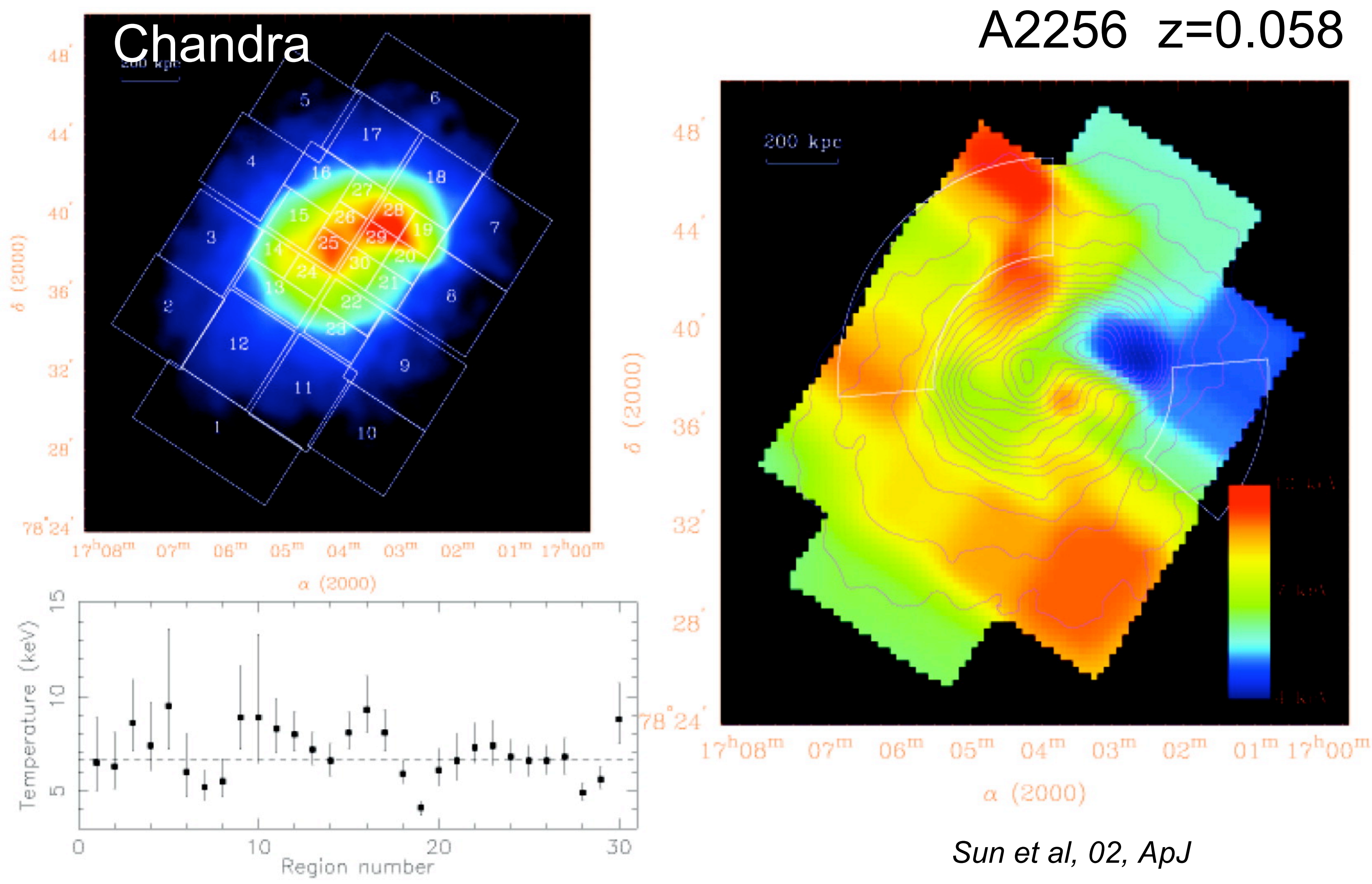
# Measure temperature profiles




*Arnaud et al, 01, A&A*

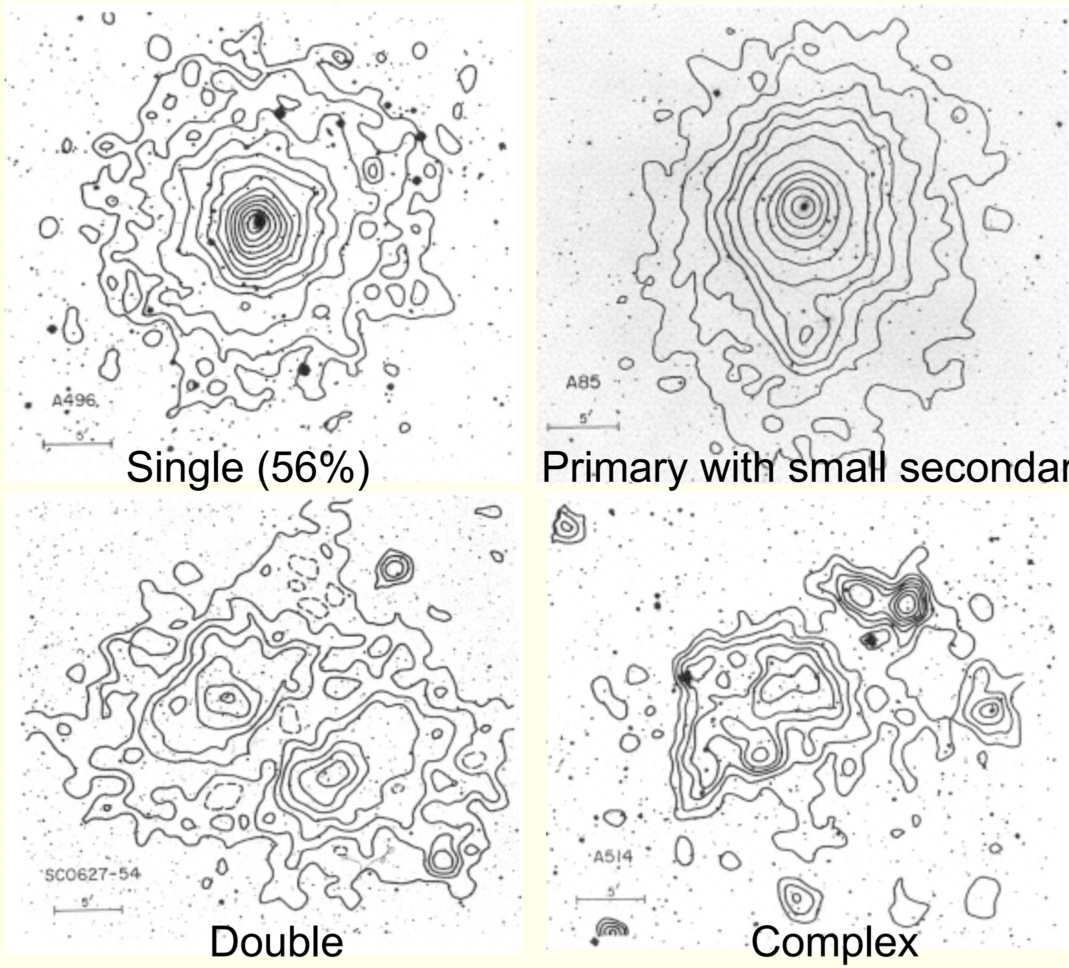
# Map temperature distribution



# Hierarchical Cluster Formation

- Is that true?
- Physics of merger events
- LSS Environment effects
- Evolution

# Variety of morphology: different dynamical states




Single (56%)

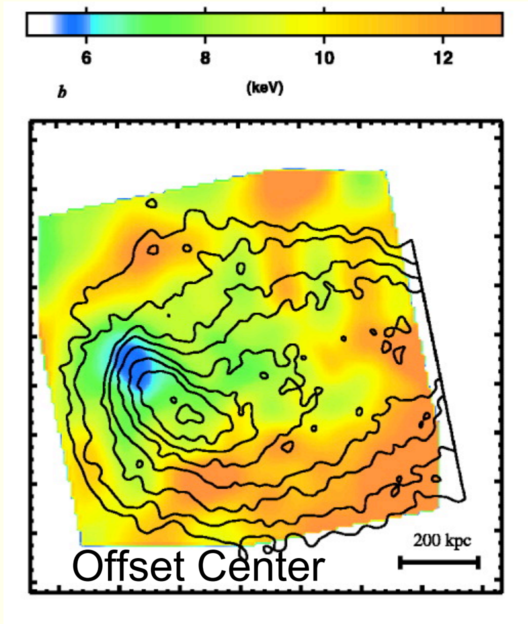
Primary with small secondary

Double

Complex

Einstein images

*Jones & Forman,99*



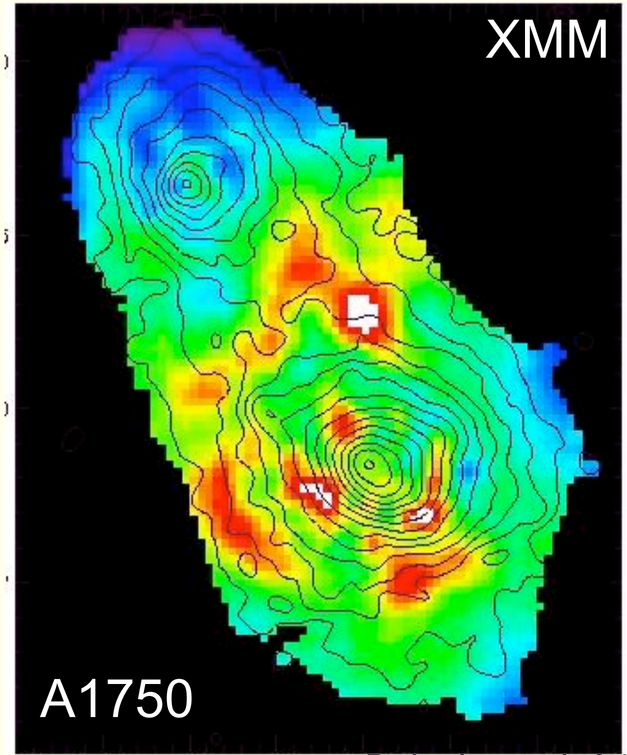

Offset Center

*Govoni et al, 04*

Chandra kT map

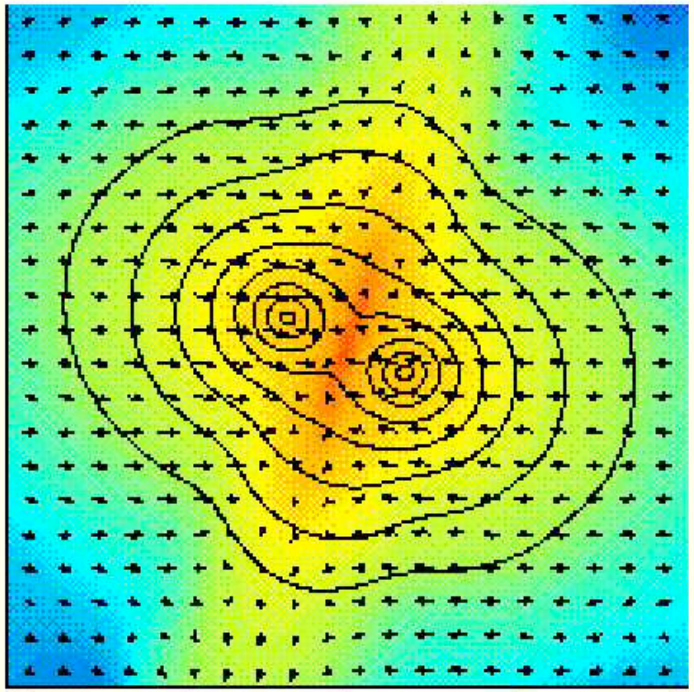
Expected:
clusters still forming today

# Clusters forming via mergers




*Belsole et al, 04*

Simulation

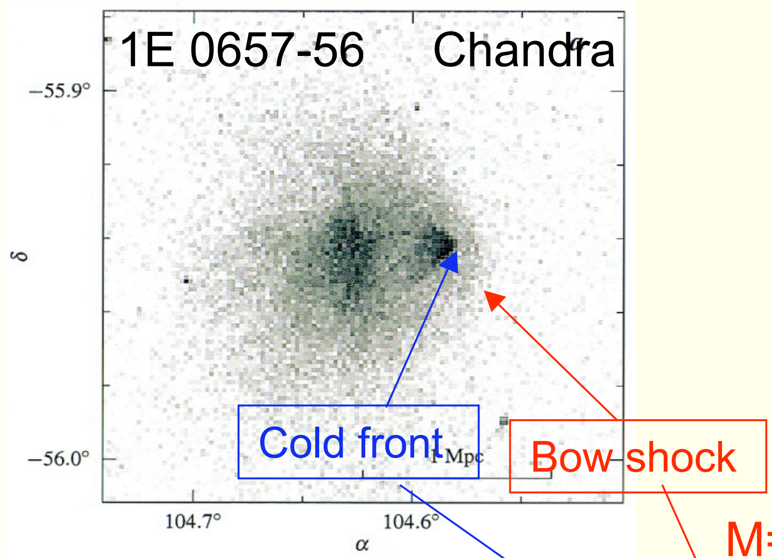


*Ritchie & Thomas, 02*

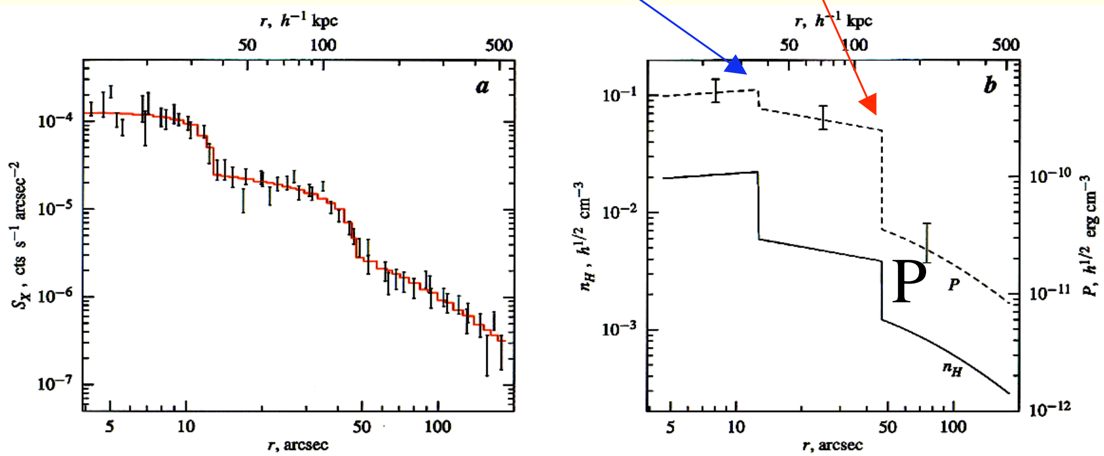
Shocks: major ICM heating source

Turbulence *[Schuecker et al, 04]*

# The complex merger physics




M=2-3




*Markevitch et al, 02*

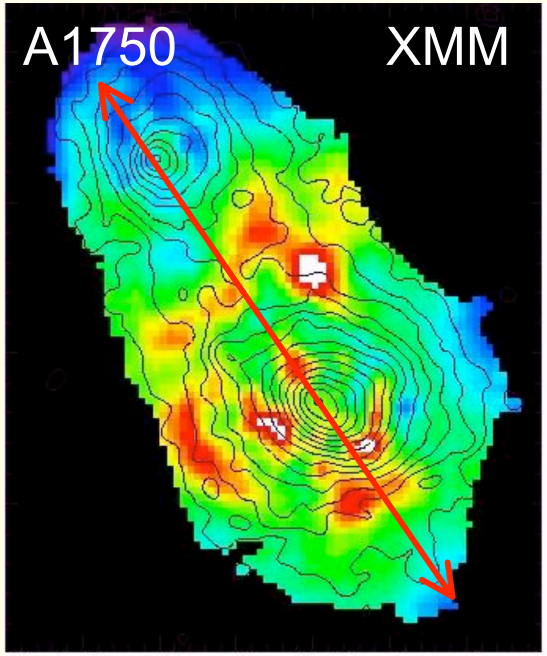
Cool core can survive core passage

also: cool trails *Reiprich et al, 04*

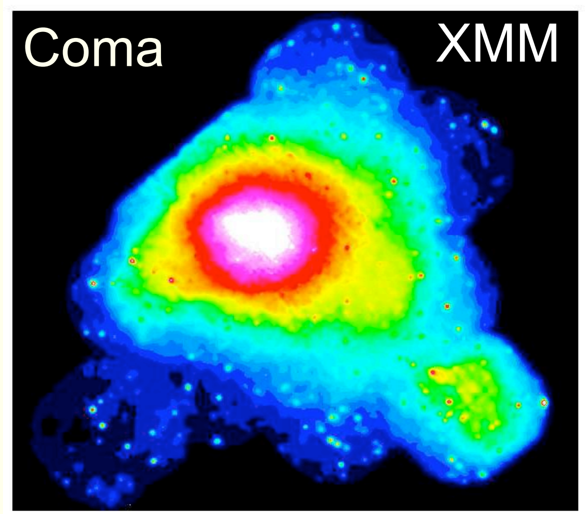
Implications for:
- thermal conduction
- devt of KH instability

*Vikhlinin et al, 01*
*Mazzotta et al, 02*

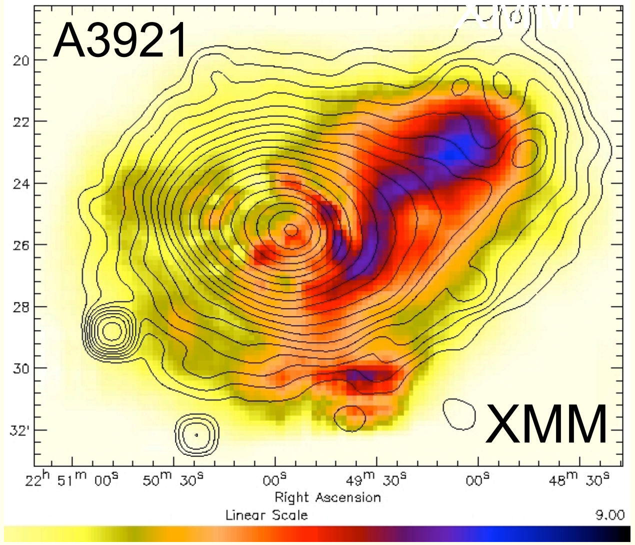
# The effect of LSS environment



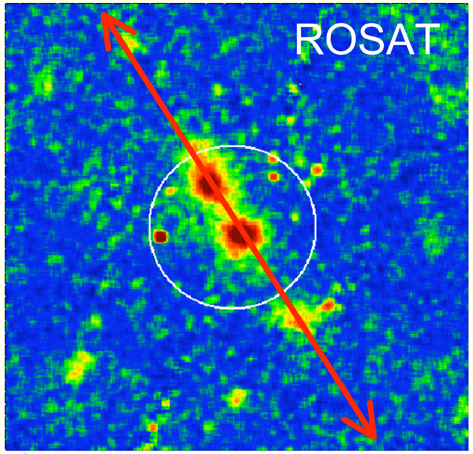

*Belsole et al, 04*




*Briel et al, 01;Neumann et al, 03*




*Belsole et al, 05*




Accretion along filament
Multiple on going mergers
$\tau_{relaxation} > \Delta t_{merger}$

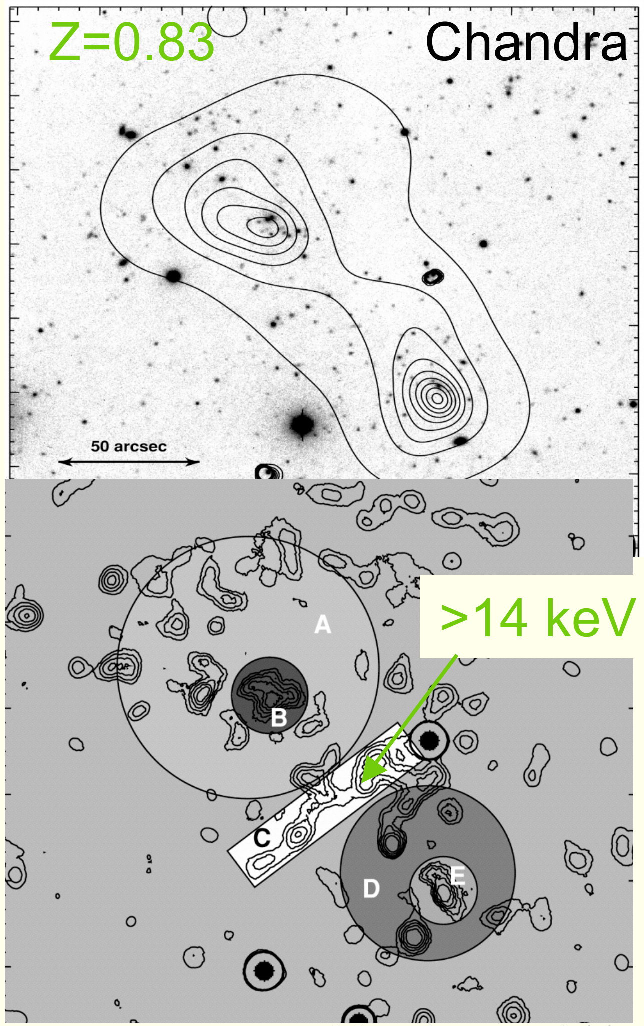
Off-axis merger
=> Tidal torques

Substructure Occurance Rate =52 ± 7 %

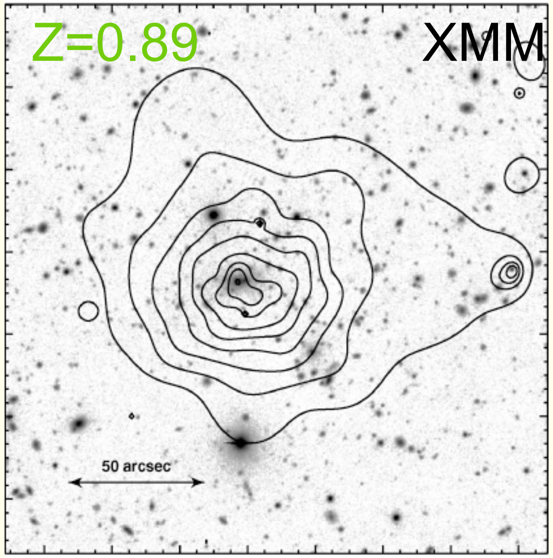
Higher in denser environment

*(from RASS: Schuecker et al,01)*

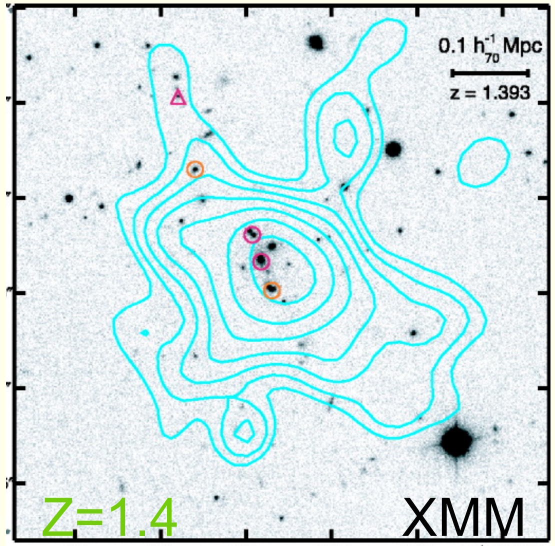
# Formation history



*Maughan et al 03*



*Maughan et al 04*



*Mullis et al 05*

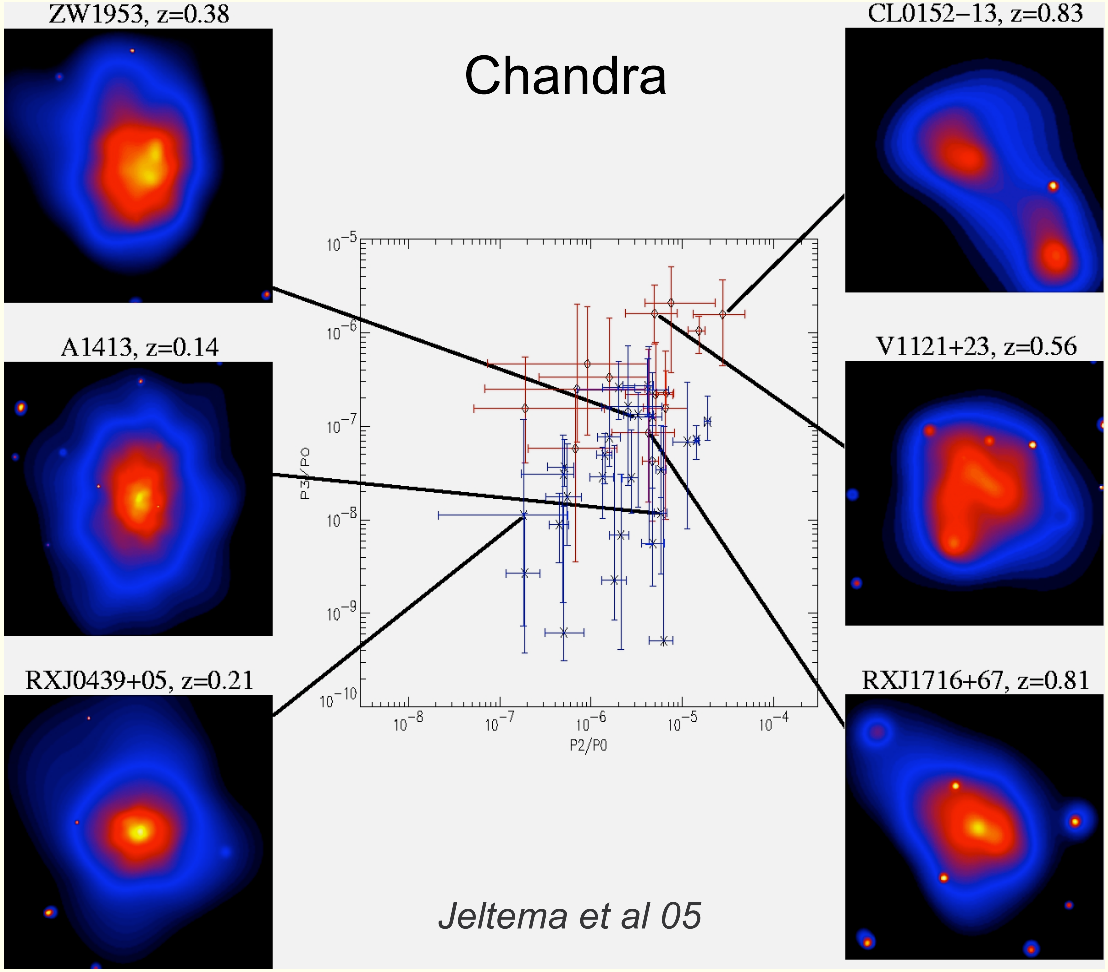
kT=11± 1 keV

massive relaxed cluster

clusters up to z=1.4

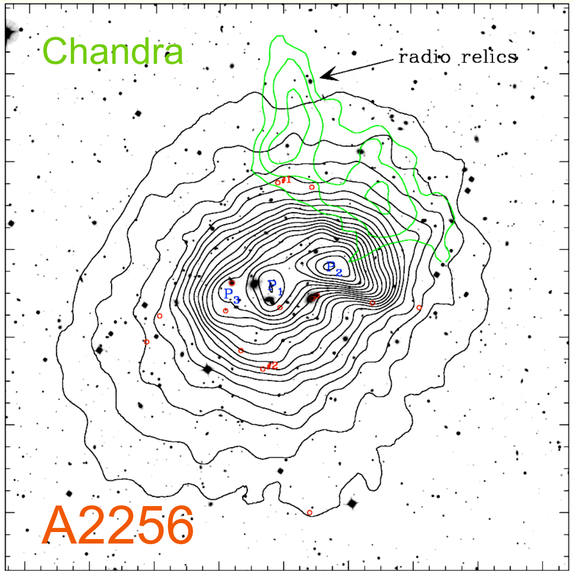
∃: mergers

# High z clusters:  more substructures and dynamically younger

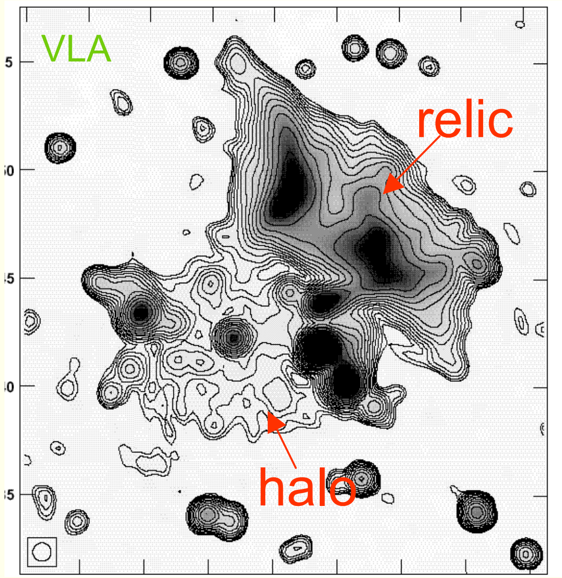



As expected in hierarchical scenario

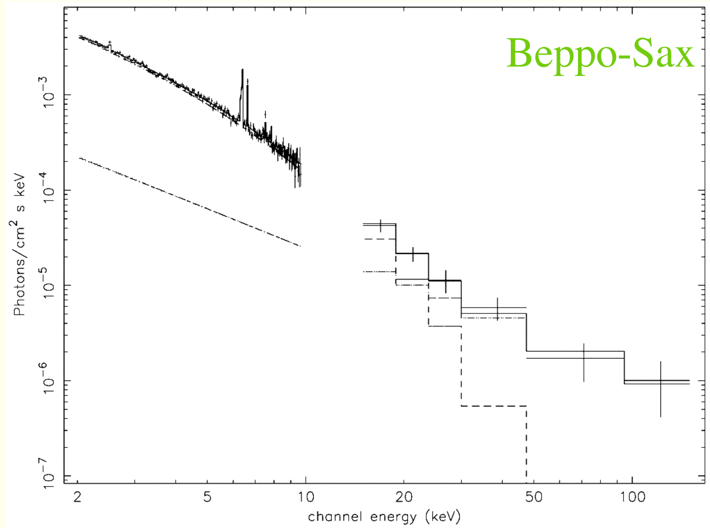
# Mergers and non-thermal emission




*Sun et al, 02*




*Clarke & Ensslin, 01*




*Fusco-Femiano et al, 00*
*See also RXTE Rephaeli & Gruber 03*

Radio synchrotron - diffuse emission

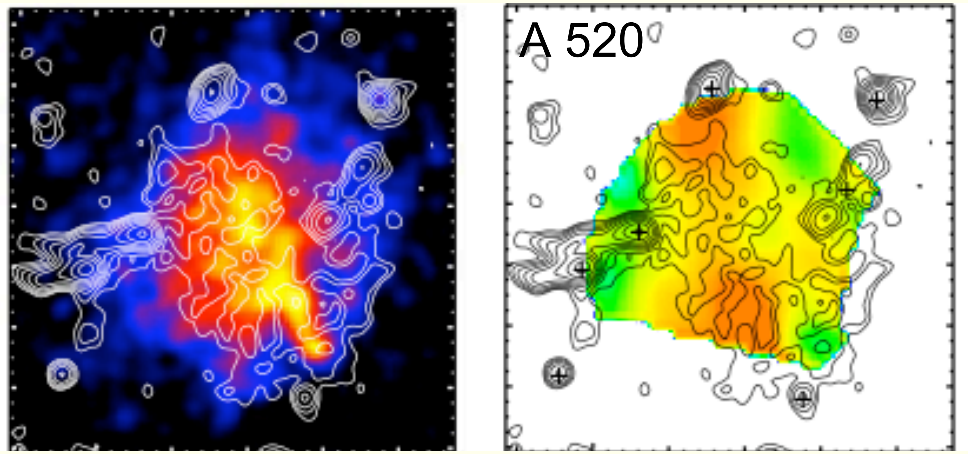
⇒ Relativistic electrons (~1-100 Gev)
⇒ Magnetic Field (0.1 - 1μG)

in unrelaxed (merger) clusters only
e- (re)accelerated by shocks, turbulence..

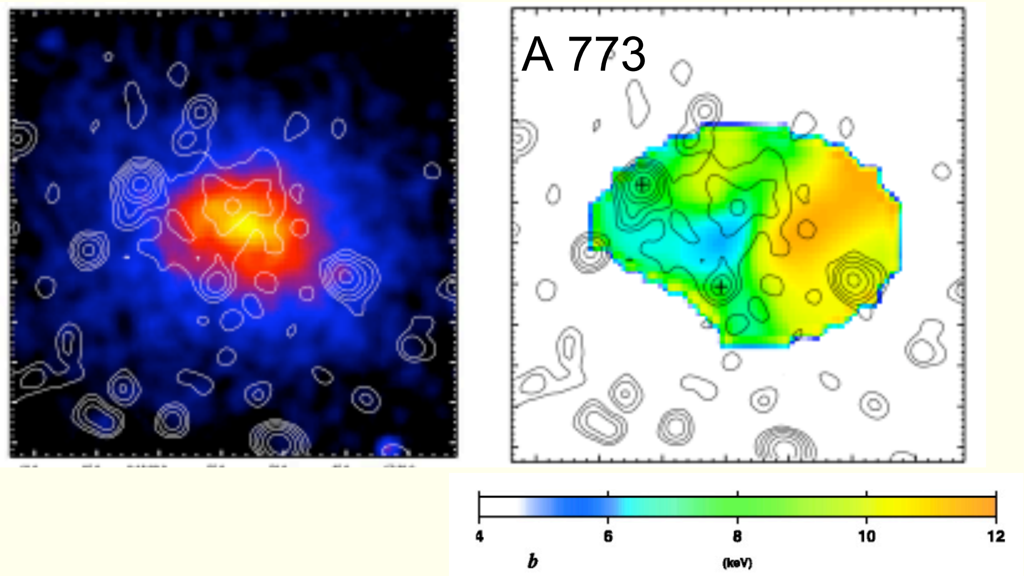
Inverse Compton of e- on CMB
⇒ Non Thermal X-ray (power law)

Detection: S/N low, still ambiguous

## Comparison Radio - thermal X-ray maps




*Govoni et al, 2004*




Probably:
mostly (re)acceleration by turbulence

# Conclusions I

- Clusters still forming today (and at high z) by accreting matter/subclusters

  as expected in the hierarchical scenario for structure formation

  ⇒ variety of dynamical states.

- Merger of two clusters is a highly complex dynamical event

  shocks, discovery of cold front, particle acceleration, relaxation…

- The cluster LSS environment is important

  ⇒ preferential accretion of sub clusters along LS filaments

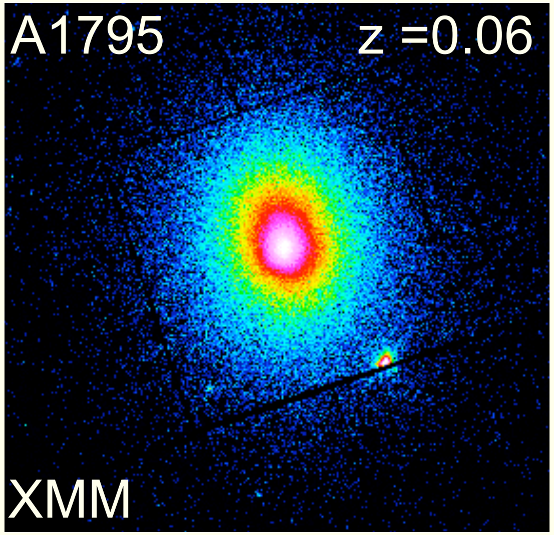
  ⇒ evidence of off-axis mergers

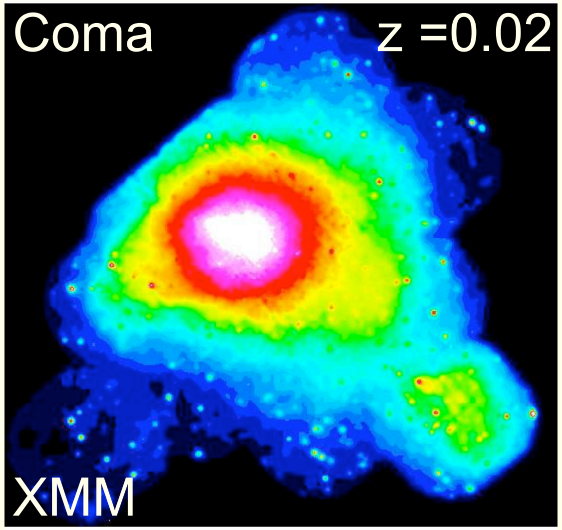
  ⇒ interval between mergers can be shorter than relaxation time

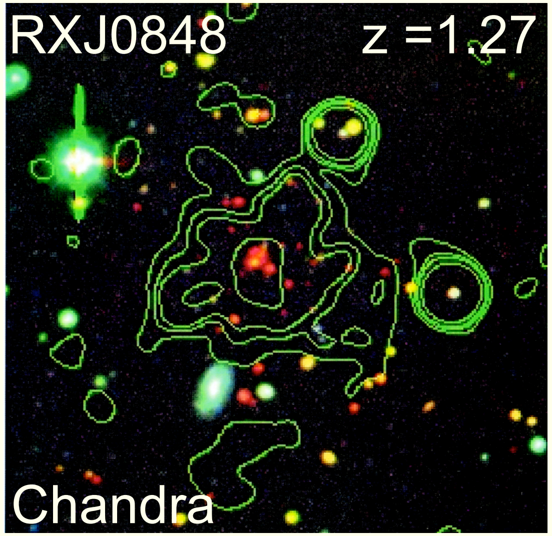
# Statistical properties of the cluster population (structural and scaling properties)

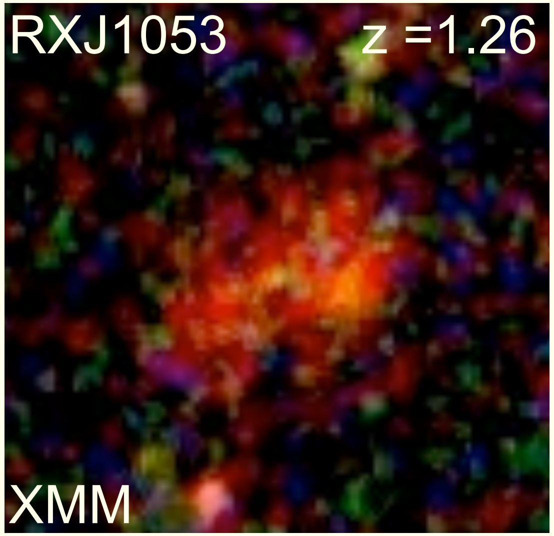
- The dark matter: is the collapse understood ?
- The baryons: purely driven by gravity
  or additional physics ?

# The cluster population




## A large variety of objects

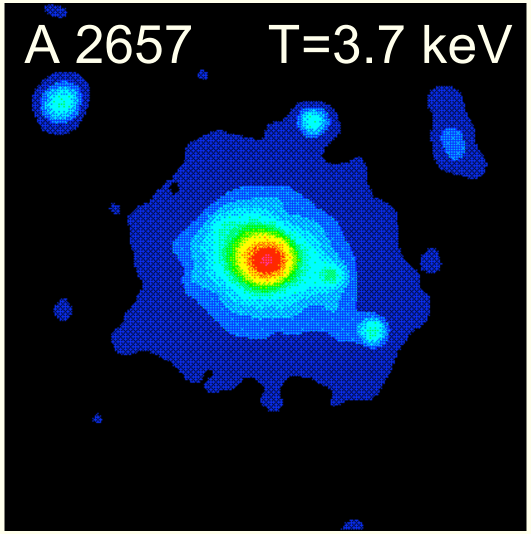
Present at least since z ~ 1.5

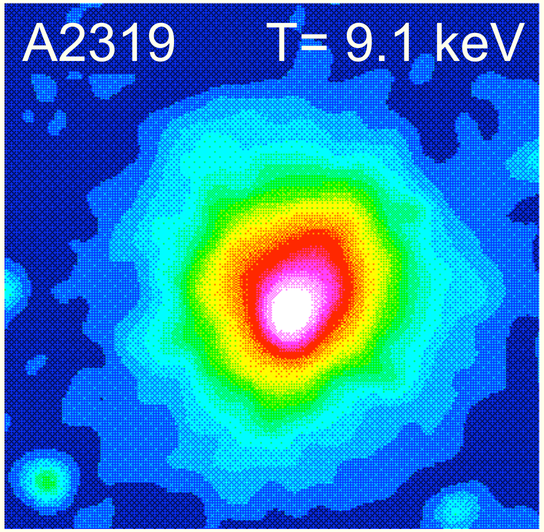
<u>Physical parameters</u>

$L_{bol}$ ~ $10^{41}$ - a few $10^{46}$ ergs/s
$M_{tot}$ ~$10^{13}$ - a few $10^{15}$ $M_o$
T ~ 0.3 - 15 keV

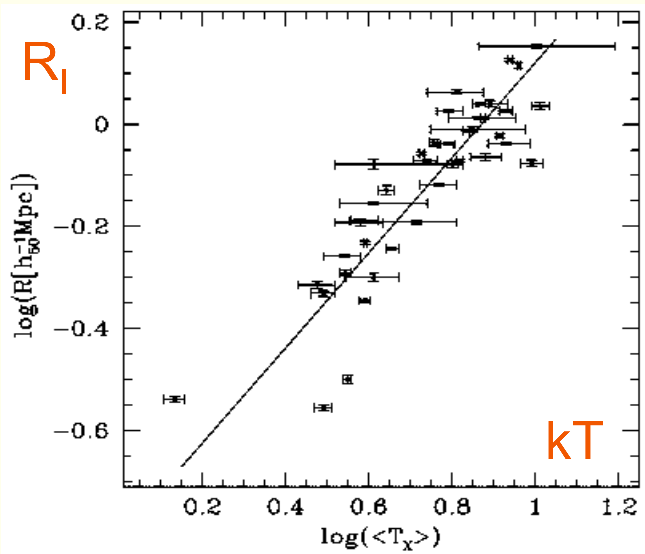
<u>Morphology</u>

regular (~50%) or not
≠ dynamical states at all z



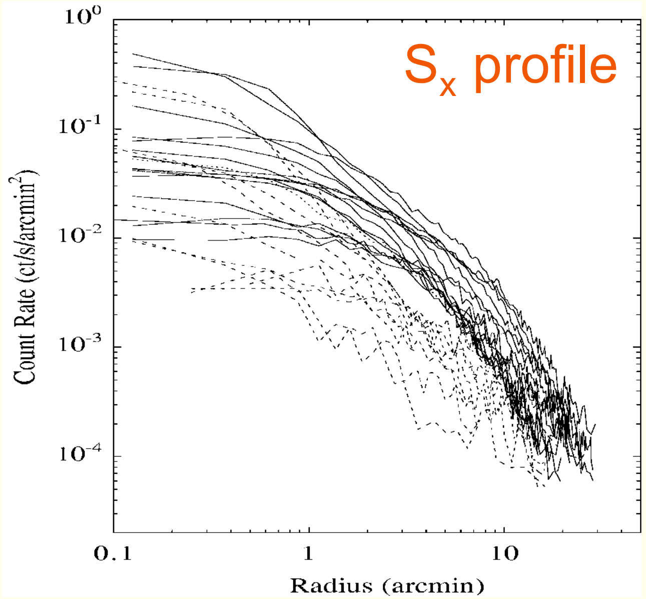




Correlations




*Mohr & Evrard 97*

Some regularity in shape



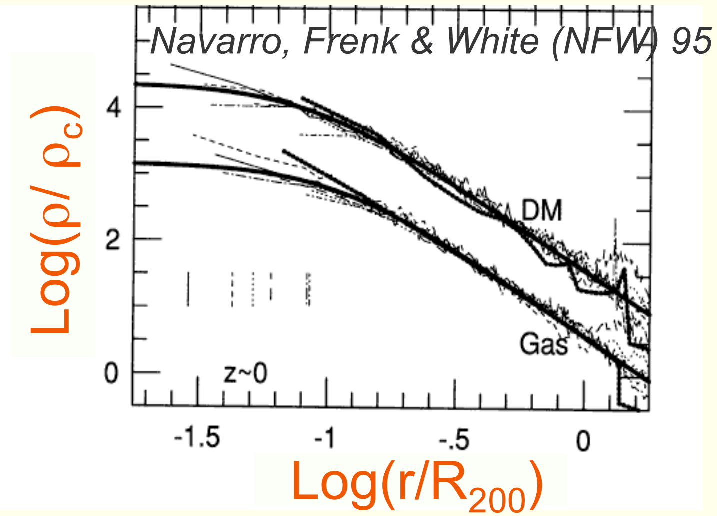

*Neumann & Arnaud 99*

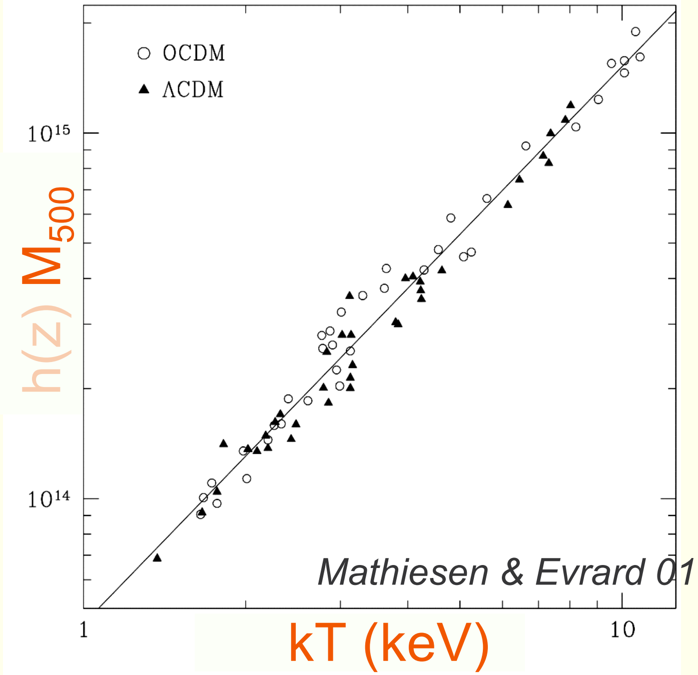
But

all possible clusters do NOT exist

*Why ???*

# Canonical model of cluster formation




Dark matter

⇒ virialized' M( z) : fixed density contrast

$3\,M/\,4\pi\,R^3 = \Delta\,\rho_c\,(z) \qquad \Delta \sim 200$

⇒ universal profile

Gas

evolving in the DM gravitational potential

⇒ universal profile

⇒ $f_{gas}$ = cst

⇒ close to HE (major mergers rare)

$kT = \beta\,GM/R$

Self Similarity of the cluster population

⇒ universal profiles

⇒ simple scaling laws: $Q = A(z)T^{\alpha}$

⇒ evolution via $\rho_c(z)\ \alpha\ h^2(z)$

e.g: $M\ \alpha\ h^{-1}(z)\ T^{3/2}$ ; $L_X\ \alpha\ h(z)\ T^2$

*Comparison with observations*

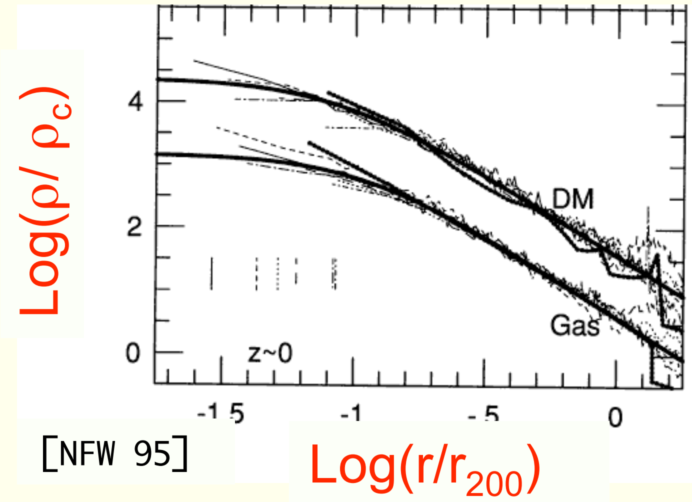
*⇒ test of formation physics*

# The local cluster population

# The dark matter: which test ?

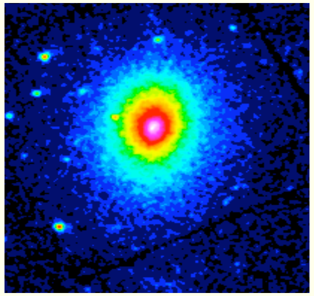
Compare observations with *theoretical predictions*:

• Universal profiles with a cusp in the center:




e.g. $\rho_{DM} \propto (r/r_S)^{-1}[1+ (r/r_S)]^{-2}$
$c= r_{200}/r_S$ weakly depending on $M_{200}$

$M(r) \sim M_{DM}(r) = M_{200}\ m(c\ r/r_{200})/m(c)$



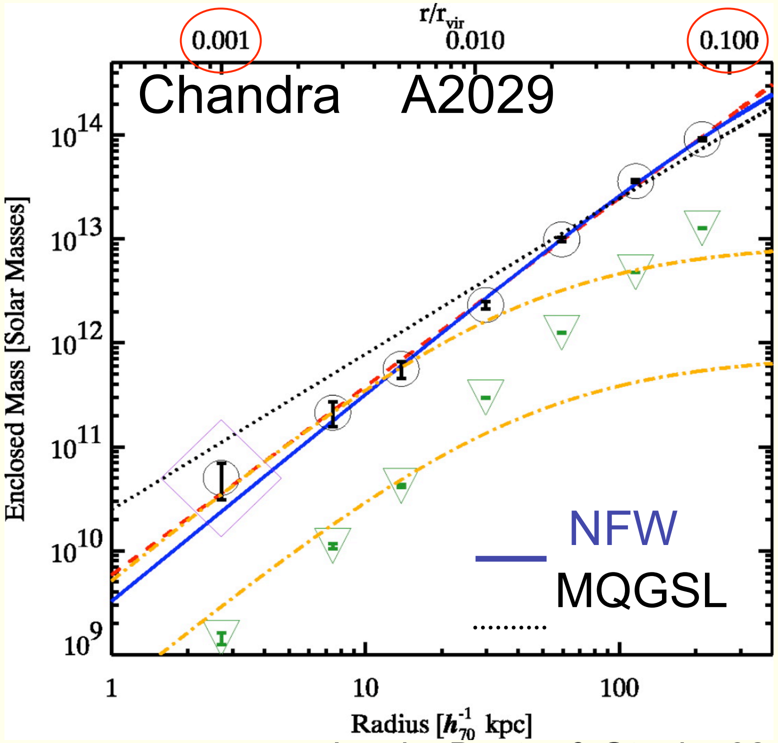
$$M(r) = -\frac{kT}{G\mu m_p}\left[\frac{d\ln n_e}{d\ln r} + \frac{d\ln T}{d\ln r}\right]$$

<== XMM/Chandra
*for*
*local relaxed clusters*

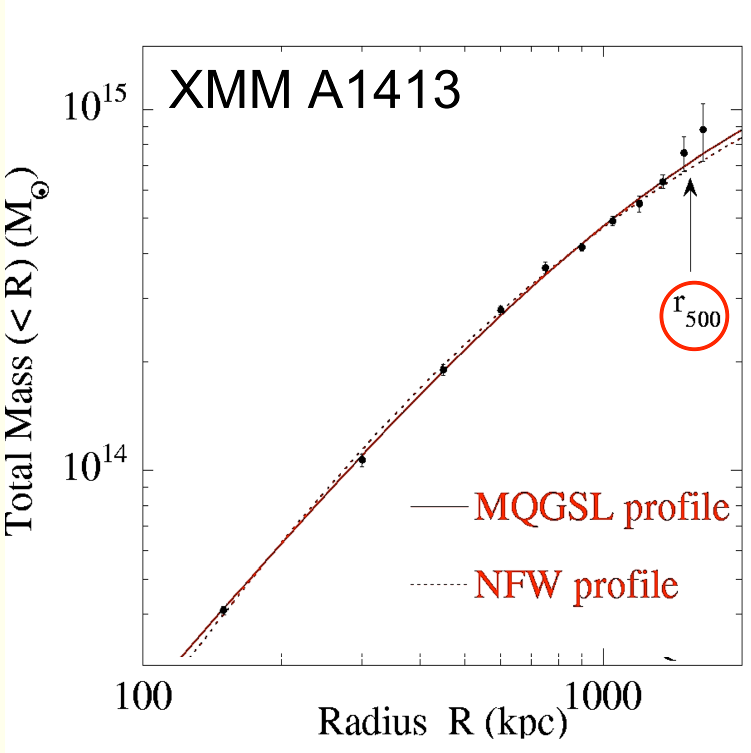
• Open question: exact slope in the center: $\rho_{DM} \propto r^{-\alpha}$

e.g $\alpha$= 1 [*NFW 95*]; $\alpha$ = 1.5 [*Moore et al 99*]; see [*Navarro et al 04*]

# The dark matter: cusped profiles as expected




*Lewis, Buote & Stocke 03*

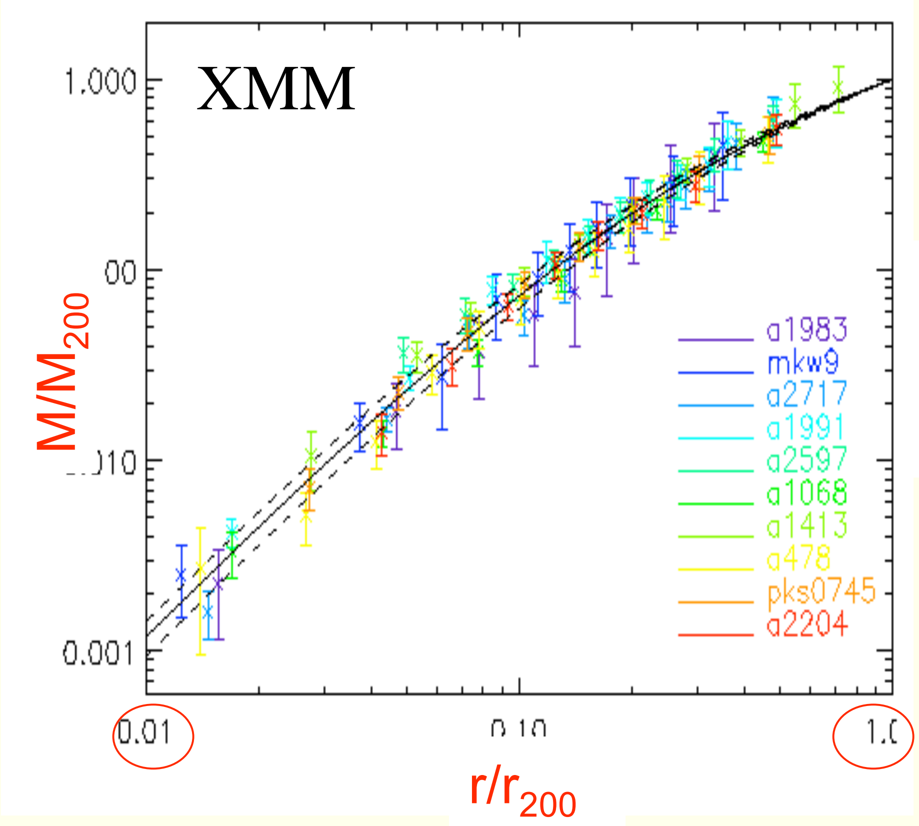



*Pratt & Arnaud 02*

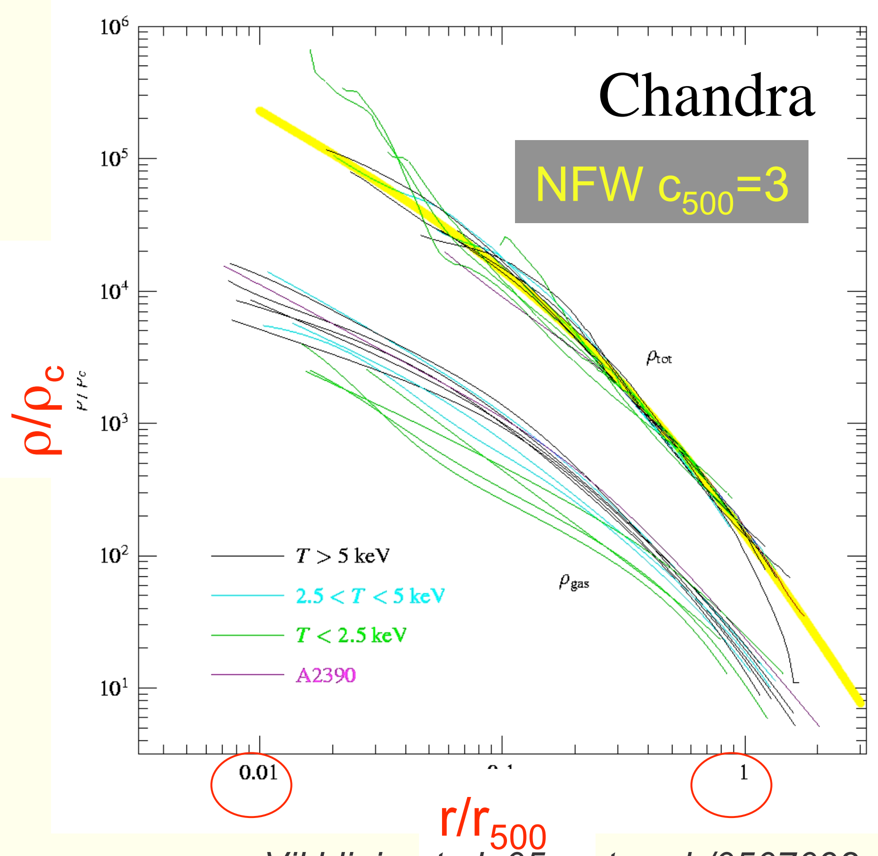
NFW profile preferred

$\alpha$ = -1.19±0.04, inconsistent with SIDM

# The dark matter: an universal profile down to low mass




*Pointecouteau, Arnaud & Pratt, 05, A&A*




*Vikhlinin et al, 05, astro-ph/0507092*

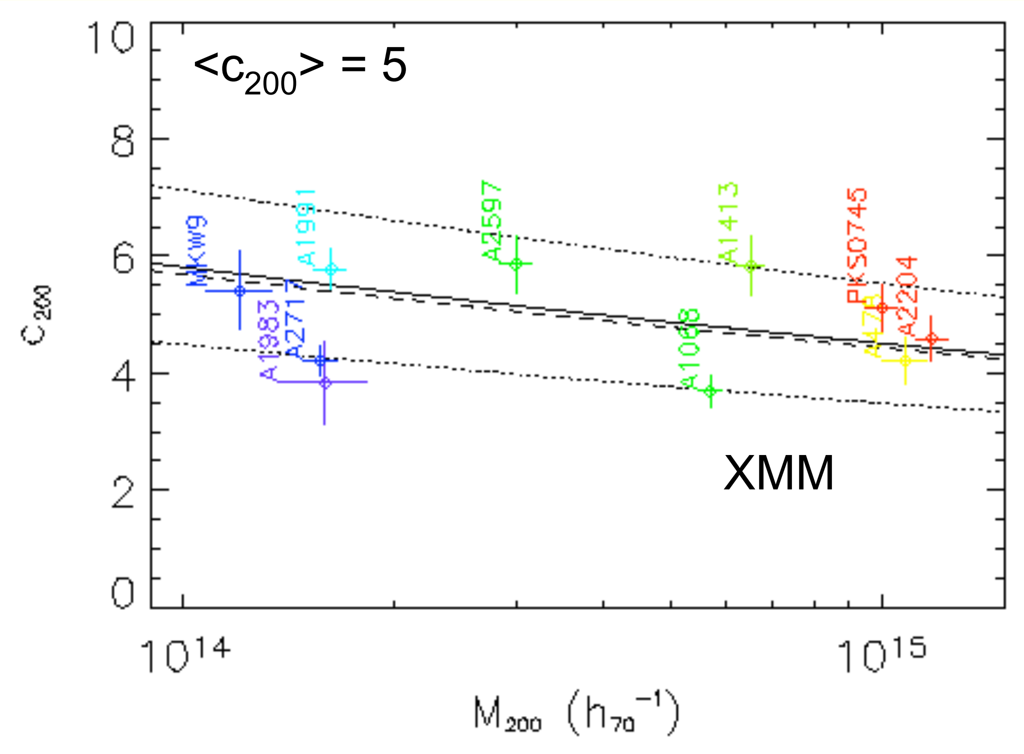
10 clusters kT = 2 -9 keV

13 clusters kT = 0.7 -9 keV

Dispersion <15%

# The dark matter: concentration parameter as expected

*c-M: [Dolag et al. 04];*




*Pointecouteau, Arnaud & Pratt, 05, A&A*

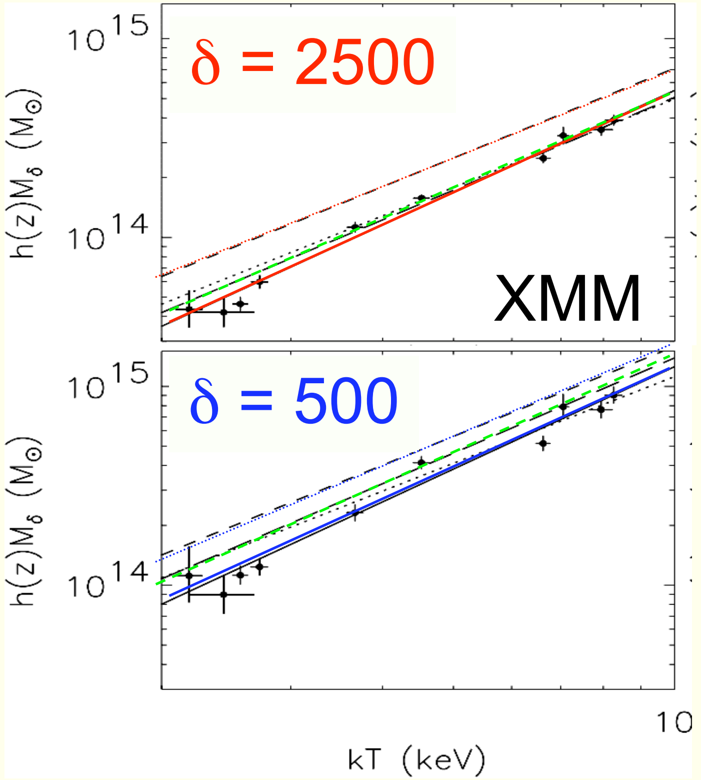
Validity of the current
$\Lambda$**CDM** modeling
of the DM collapse
at cluster scale

*Confirmed:*

*with Chandra: Vikhlinin et al, 05, astro-ph/0507092*

*down to group scale: Gastadello et al, astro-ph/0510192*

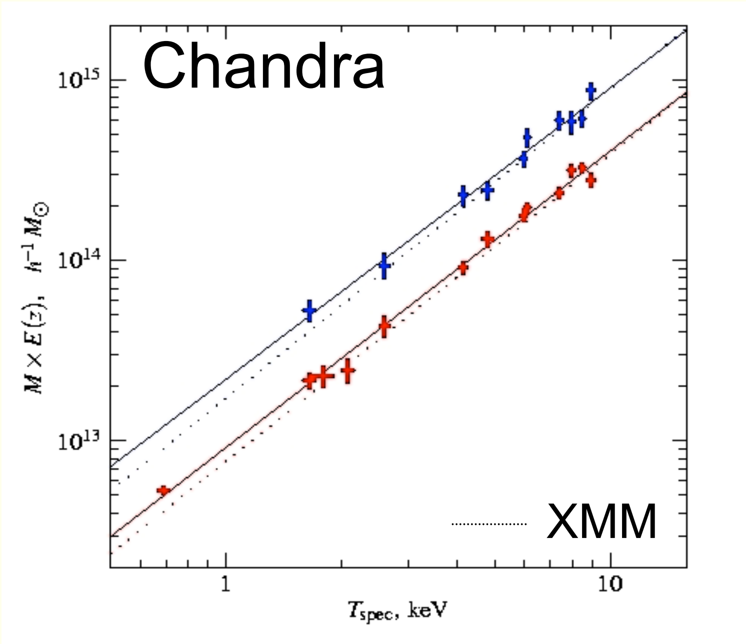
# The DM- ICM connection: the local M-T relation




*Arnaud,Pointecouteau & Pratt,05*

- normalisation offset
- $\alpha$ = 1.5±0.1 (T>3.5)
- $\alpha$ ~ 1.7 (T>2 keV)

  !!!! T definition !!!!!



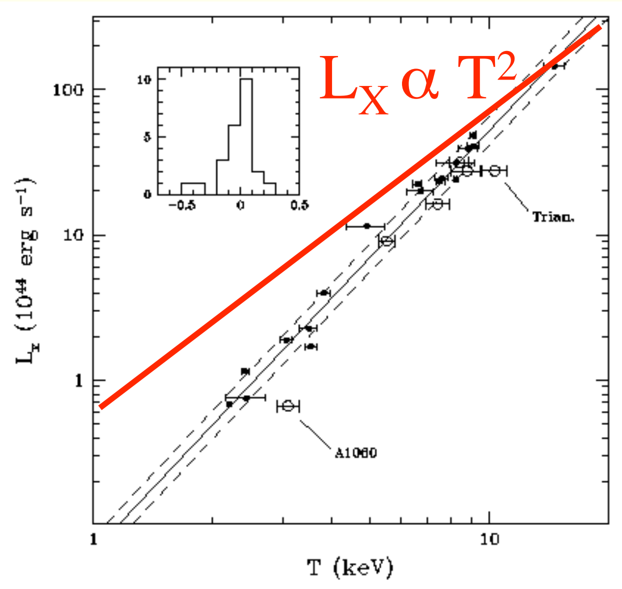

*Vikhlinin et al, 05, astro-ph/0507092*

Precise converging calibration

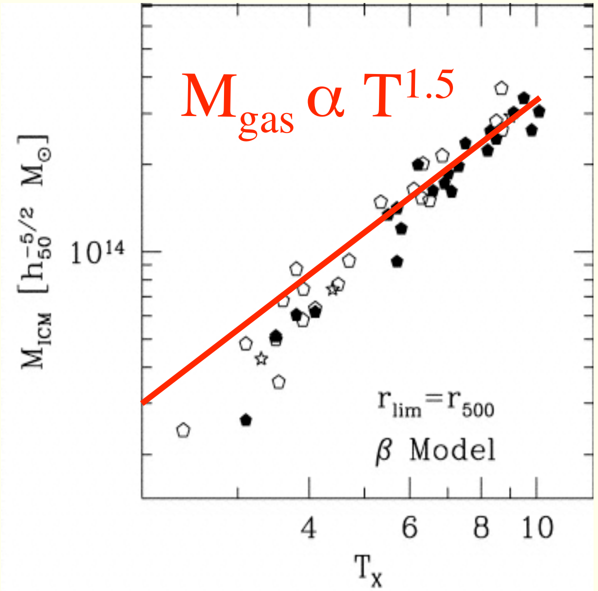
for relaxed clusters; syst possible

Effect on non-gravitational physics

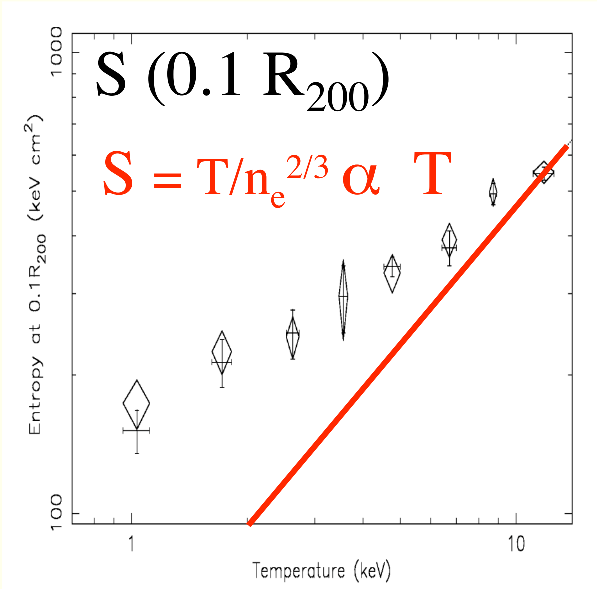
# The ICM local scaling laws




*Arnaud & Evrard, 99*




*Mohr et al, 99*




*Ponman et al, 03*

Steeper than expected

Entropy excess

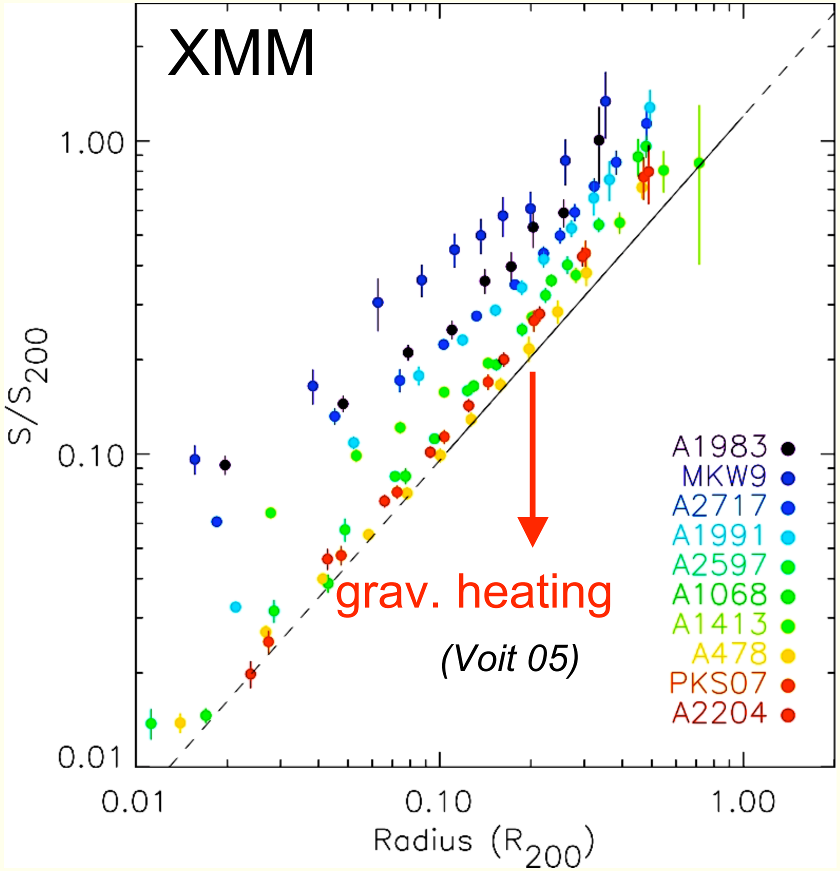
Higher at low T (M)

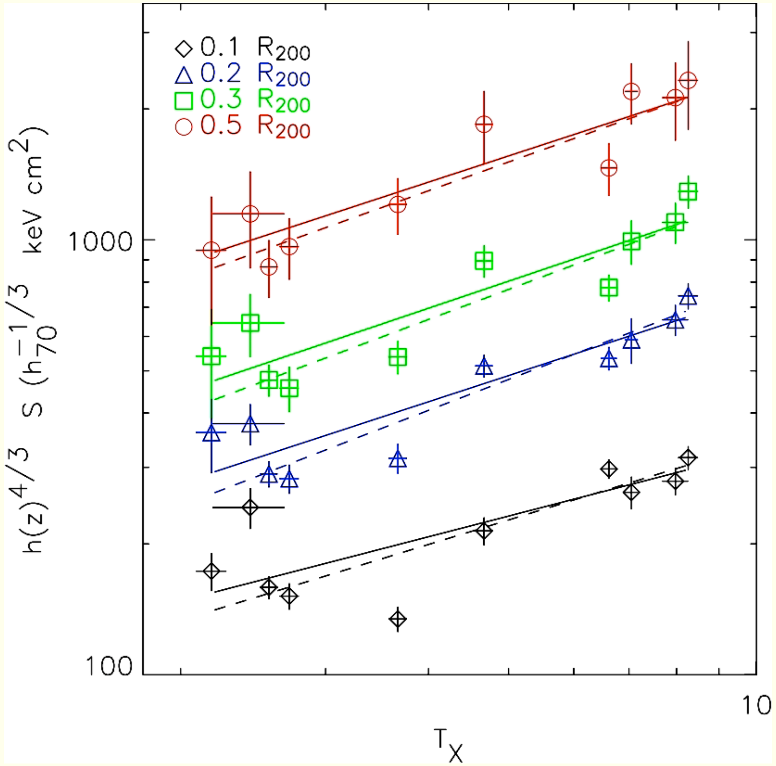
$S \alpha T^{\sim 0.65}$

ICM is not purely governed by gravitational effects

(pre) heating (SN, AGN); cooling ?

# The ICM entropy: key to thermodynamical history




*Pratt, Arnaud & Pointecouteau, 06*

$S\ (0.2\text{-}0.5r_{200})\ \alpha\ \ T^{0.64\pm0.11}$

Entropy excess (larger at low mass) confirmed at all radii