Profiles scaled $S \propto T^{0.65}$

- Self-similar down to 2 keV beyond core with $\sim$ standard slope
- No flat entropy core $\Rightarrow$ simple pre heating models rejected
- Larger dispersion in center $\Rightarrow$ effect of cooling/AGN/merger

Gas history depends on both cooling and SN/AGN heating

Pratt, Arnaud & Pointecouteau, 06
also Piffaretti et al, 05
The center: a laboratory of non gravitational physics (I)

Cooling in the center

\[ t_{\text{cool}} \propto T^{1/2} / n_e = t_H \]

Schmidt et al, 01

A1835

XMM/RGS

Abell 1835 and 2300 M_\odot yr^{-1} Cooling Flow + kT=8 keV Ambient Component

Standard CH

FeXVII

T_{\text{cut}} = T/3

OVII

Peterson et al, 01; 03

But not as expected
The center: a laboratory of non gravitational physics (II)

- X-ray cavities evacuated by radio source weak shocks and sound waves
- cool rims (no strong shocks) [see Blanton 03 review, but see McNamara, 05]

Complex dynamical interaction with AGN activity

Core properties not well understood!
Balance between cooling and AGN heating? effect of conduction?
Galaxy feedback: the ICM enrichment (I)

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

ICM enriched in heavy elements
Abundances other than [Fe] difficult to measure for high kT
(massive cluster, outside cool core)
Galaxy feedback: the ICM enrichment (II)

• **Constant** $M_{Fe}/L$ ratio (see also Arnaud et al 92)
  
  No abnormal low (< *) abundance in groups center *Buote et al, 02, 03*
  
  $\Rightarrow$ global yield and constraints on IMF

• Central Fe abundance peak

• $O/Fe$ increase with radius; $Si/Fe$ and $S/Fe$ flat
  
  $\Rightarrow$ In center: production by cD (and long lived cool core *Bohringer et al, 04*)
  
  by SNI and SNII and massive star formation
  
  $\Rightarrow$ In outer part: higher contribution from SNII

  AND even constraints on SNI/II yields (*Finoguenov et al, 02*)
No evolution of $[\text{Fe}]$ abundance up to $z>1.1$
Consistent with early enrichment
What about evolution of the scaling laws?
Evolution of the scaling laws

Remember (simple) expectations

- Collapse at a fixed density contrast:
  \[ \frac{GM}{R^3} = \langle \rho \rangle = 200 \rho_c(z) \]

- Evolution of the scaling laws via \( \rho_c(z) \propto h^2(z) \)
  
  e.g. \( M \propto h^{-1}(z) \, T^{3/2} \)
  \( L_X \propto h(z) \, T^2 \)

The overall picture provided by this study of the evolution of the cluster scaling relations is that within the statistical limits of the current data, the evolution of galaxy clusters out to \( z \approx 1 \) is described well by the self-similar model. “
The $L_X$-T relation does evolve

The amount of evolution is still uncertain: expected $L_X \alpha h(z) \sim (1+z)^{0.6-0.9}$ 30% (z=0.5)

- [Lumb et al]: $(1+z)^{1.52\pm0.26}$; [Vikhlinin et al] $(1+z)^{1.5\pm0.3}$; [Maughan et al] $(1+z)^{1.4\pm0.2}$ > expected
- [Ettori et al]: $(1+z)^{0.62\pm0.28}$ = expected and $h(z)^{-1} L_X \alpha (1+z)^{-1.04\pm0.32}$ < expected

!!! Systematics !!!: def integration region; ref. local relation (calibration, CF...); theor.evolution
First comparison of apples with apples

- Local M-T from Chandra ~ XMM
- High z (0.4 - 0.7) mass from: XMM/Chandra spatially resolved kT profiles

Evolution as expected

\[ M_{500} = h(z)^{1.02 \pm 0.20} T^{3/2} \]
And the entropy evolution (thermodynamical *history*)?

may be lower than expected:

\[ h(z)^{4/3} S - T = (1+z)^{-0.14\pm0.04} \]

but large scatter

*Future progresses expected on formation physics* from structures and scaling laws using larger unbiased samples

archives, LP and serendipitous surveys

⇒ Intrinsic scatter
⇒ Evolution
Conclusions II

With XMM and Chandra

• Universal mass profiles with shape as expected
  => modelling of the Cold DM collapse OK

• Gas do obey self-similarity up to high \( z \) and low mass

• But it differs from purely gravitational model
  => importance of cooling AND galaxy feedback
  => still to be better understood
X-ray cluster surveys
Detecting clusters in X-ray

The X-ray sky:
- AGN (point sources)
- Clusters (extended) [beyond the galactic plane]

Advantages of X-ray surveys
- X-ray => true DM potential well
- high contrast, no (few) confusion
- well controlled selection function => Space densities

Some difficulties
- optical follow-up (z)
- understanding selection function

Hasinger et al, 01

XMM Lockman Hole

z=1.26

z=0.34
Existing and planned X-ray cluster samples

From all sky surveys

- HEAO
- ROSAT (RASS)

=> mostly local samples
e.g: Reflex: 447 clusters

From serendipitous surveys

- Einstein: EMSS
- ROSAT:

=> high z (>0.3) samples
From 12 to 80 (120) clusters

• XMM (chandra)

Information: \( L_x \) in original catalog, some shape parameter..
(all) \( kT \) (and possibly mass) from follow-up by next generation satellite
Cluster distribution in the $L_X$-$z$ plane

Flux limited surveys $\Rightarrow$ Lower mass increases with $z$
The luminosity function

Luminous (massive) clusters are rarer

⇒ Survey area important
⇒ if $S_{\text{lim}}$ but Area => extend (low) mass coverage, not $z$ coverage!

The bright end of the XLF evolves

significant $z \gtrsim 0.5 \ L_X \gtrsim 5 \times 10^{44} \ \text{erg/s}$

Rosati, Borgani, & Norman, 02, ARAA

Mullis et al, 04
Examples of other functions

The XTF

High $z$: ASCA follow-up of EMSS
still need: $L_X$-$T$

$z > 0.3$

The $X M_{gas} F$

CHANDRA follow-up of 160SD
$L_X$-$M_{gas}$
to estimate selection function/survey volume

$z > 0.4$
The CDM cosmological scenario predictions

\[ \Omega = 0.3 \quad \Lambda = 0.7 \]

\[ \Lambda CDM \]

The XL(T, M_{gas,..})F at various z reflect the mass function and its evolution

\[ \Rightarrow \text{Clusters as cosmological probes?} \]
Cosmological parameters with X-ray observations of clusters
From cluster abundance

**Principle**

⇒ $N(M,z)$ depends on $\Omega_m$, $\sigma_8 [\Omega_b \, n, \, h, \, \Omega_\Lambda ]$

(fluctuation spectrum + cosmo)

⇒ Evolution strongly depends on $\Omega_m$

**Caveats**

use proxies for the mass: $L_x$, $T$ ...

⇒ need to know scaling laws

incl scatter & normalisation
(Illustrative) Results:

Reflex *local XLF* and M-L from Reiprich & Böhringer 02

Evolution break $\sigma_8 \Omega_m$ degeneracy

- General consistency on $\Omega_m$ between various XF studies (but see next slide)
- Complementarity with SN and CMB
- Excellent agreement of $\sigma_8$ with new WMAP3yr data

For $\Omega + \Lambda = 1$

$\Omega = 0.24 \pm 0.12$ (68%)

$\sigma_8 = 0.72 \pm 0.04$
On the importance of the knowledge of the scaling laws

Discrepancies between various published results mostly due to M-T normalization used

Main source of systematic uncertainty

Knowing and taking into account properly the scatter in the M-L (or M-T or etc..) relations is essential.
Using local cluster clustering

Breaking the degeneracy...

Reflex local XLF and M-L

Schuecker et al, 03

Power spectrum from Reflex survey

For \( \Omega + \Lambda = 1 \)

\( \Omega = 0.34 \pm 0.04 \) (68%)

\( \sigma_8 = 0.71 \pm 0.04 \)
From gas mass fraction

**Principle:**  \( f_{\text{gas}} \left( 1 + f_{\text{gal}} / f_{\text{gas}} \right) = \Omega_b / \Omega_m \)

\[
f_{\text{gas}}^{\Lambda CDM}(z) = \frac{b \Omega_b}{(1 + 0.19 \sqrt{h}) \Omega_m} \left[ \frac{d_A^{SCDM}(z)}{d_A^{mod}(z)} \right]^{1.5}
\]

Normalisation => \( \Omega_m \)
Distance indicator (as SNI) => \( \Omega_m \Omega_\Lambda \ w \)

**Caveats**

- \( f_{\text{gas}} \) increases with mass
  => high mass clusters
- Bias factor depending on radius
  => extrapolation (~20% effect)
  => compare at same \( \delta \) and \( M \)
- Assume \( f_{\text{gas}} \) do not evolve

---

*Allen et al, 02, 04*
$\Omega_m = 0.245 \pm 0.04$
$\Omega_\Lambda = 0.96 \pm 0.2 \ (68\%)$
$> 0 \ at \ 3\sigma$

**Complementary to CMB and SNI**

**Constraint on dark energy very promising**
Conclusions III

• Several independent cosmological tests from X-ray clusters

⇒ Fair sample of the Universe: $\Omega_m$
⇒ Standard candles: $H(z): \Omega_m, \Omega_{DE}, w$
⇒ Abundances $N(M,z)$: growth rate of structures: $\Omega_m, \Omega_{DE}, w, \sigma_8$
⇒ Cluster clustering: idem

• Powerful tests
⇒ Complementary with CMB, SNI, weak lensing etc..
⇒ Excellent agreement of $\sigma_8 (0.72 \pm 0.04)$
  with new WMAP data $0.74 \pm 0.06$
⇒ Low $\Omega_m$ confirmed, now measured to $\pm 20\%$
⇒ Start to give constraints on Dark energy
Some prospects
Future progresses expected:

- Formation physics from structures and scaling laws from larger unbiased samples archives, LP and serendipitous surveys
  ⇒ Intrinsic scatter
  ⇒ Evolution of scaling laws
  ⇒ Morphology evolution

- Cosmology:
  ⇒ follow-up of ROSAT surveys
  ⇒ new XMM surveys (XCS, LSS …)
New missions

**SUZAKU**, launched in 2005
Japan mission (with collaboration from US)
- Low background, e.g. cluster outskirt studies
- Better spectral resolution at low E, e.g. Ab studies
- Hard X-ray detector => non thermal emission
  also NeXT project

**Specialized missions under study for <2012 launch**
- SIMBOL-X => first spatially resolved spectroscopy up to 60 keV
  => non thermal emission
- eRosita => cluster survey for DE study.
Next generation observatories (> 2015)

Con-X (NASA) planned

XEUS (ESA/Japan)

\[ S > 5 \text{ m}^2 (\text{XMM}^*50); \Delta \theta = 5'' \]

Spatially resolved high resolution spectroscopy

The full history of the hot Universe ....

- early BHs
- from first structures -> today massive clusters
- nucleosynthesis

compl. to ‘cool’ Universe study (ALMA, JWST..)

2 kev cluster at \( z = 2 \)