Galaxy Clusters as Cosmological Probes

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1 Laboratories for the Study of the Cosmic Baryon Evolution

2 Probes for the Evolution of Large-Scale Structure and Test of Cosmological Models
Why X-ray Observations are Mandatory

X-ray observations are still the best approach to characterise galaxy clusters!

i) Compared to optical images:
   - Cluster as one continuous entity
   - Good statistics for projected structure, ICM temperature closely correlated to cluster mass

ii) For medium distant clusters: \(\sim 40,000\) cts \(\rightarrow 150 - 200\ \sigma\) Signal!
    compared to \(<\sim 10\ \sigma\) for best SZE and Lensing

Lensing signal of RXCJ1347.5-1144 (red in image) and mean ellipticity signal (profile in I and R)
Bradac et al. 05,08
1. Precise Astrophysics of clusters (z < 1) allowed by line spectroscopy

2. Detailed Astrophysics of clusters in the range z = 1 ... 2 in similar detail as currently performed for medium z (0.3 .. 0.5) clusters with XMM-Newton

This provides the means for cosmology and cosmic evolution studies!
Testing Cosmological Models & Tracing Cosmic Evolution with Galaxy Clusters

The new territory for XEUS cluster physics is the redshift

range of $z = 1 \ldots 2$
The Influence of $w$ on Cosmic Evolution

Density fluctuation growth:

$\Lambda$ w=-0.6
w=-0.2
open
Evolution of the Cluster Mass Function as a test for the cosmological model

Differential comoving cluster abundance (> Mass\textsubscript{limit}) ster\textsuperscript{-1} dz=0.1\textsuperscript{-1}

→ There are more distant clusters for small (negative) w !

Requires mass calibration to few % !

see also Haiman et al. 2001
Evolution of the Cluster Mass Function

Model constraints from the observation of the cluster mass function evolution: gas mass and Yx parameter as alternative observables (proxies)

Vikhlinin et al., Astro-ph 2008
Spatial Distribution Characterized by $P(K)$

Volume-limited samples with boxlength of: 300, 400, 500 $h^{-1}$ Mpc

Schuecker et al. 2001 - REFLEX Survey

H. Böhringer
**H₀ Determination from X-ray and SZ-Effect**

Current redshift leverage gets only good constraints on H₀. Larger redshift range necessary to constrain the matter/energy composition.

\[ H₀ = 76.9^{+3.9}_{-3.4} +10.0^{+10.0}_{-8.0} \text{ km s}^{-1} \text{ Mpc}^{-1} \]

Bonamente et al. 2006
Scientific Quests for Distant Cluster Observations

To Study the evolution of:

1. Cluster Structure (dyn. State, halo shape,...)
2. Cluster Mass Function
3. Spatial Correlation (P(k) or $\xi(r)$ normalization)
4. Evolution of the cluster ICM (entropy) and galaxy population (mass to light ratio)
5. Heavy element abundances in the ICM

X. Clusters as distance indicators: X-ray/SZ observations - baryon fraction
### How many Test Objects Do We Find?

<table>
<thead>
<tr>
<th>Redshift</th>
<th>mass</th>
<th>clusters /20000 deg²</th>
<th>X-ray luminosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>z &gt; 2</td>
<td>$&gt; 10^{14} , M_{\text{sun}}$</td>
<td>100</td>
<td>$10^{44} , \text{erg/s}$</td>
</tr>
<tr>
<td></td>
<td>$&gt; 3 \times 10^{13} , M_{\text{sun}}$</td>
<td>20000</td>
<td>$1.5 \times 10^{43} , \text{erg/s}$</td>
</tr>
<tr>
<td></td>
<td>$&gt; 10^{13} , M_{\text{sun}}$</td>
<td>$4 \times 10^5$</td>
<td>$3-4 \times 10^{42} , \text{erg/s}$</td>
</tr>
<tr>
<td>z &gt; 2.5</td>
<td>$&gt; 3 \times 10^{13} , M_{\text{sun}}$</td>
<td>3000</td>
<td>$2 \times 10^{43} , \text{erg/s}$</td>
</tr>
<tr>
<td></td>
<td>$&gt; 10^{13} , M_{\text{sun}}$</td>
<td>$1 \times 10^5$</td>
<td>$3-5 \times 10^{42} , \text{erg/s}$</td>
</tr>
<tr>
<td>z &gt; 3</td>
<td>$&gt; 3 \times 10^{13} , M_{\text{sun}}$</td>
<td>200</td>
<td>$2.7 \times 10^{43} , \text{erg/s}$</td>
</tr>
<tr>
<td></td>
<td>$&gt; 10^{13} , M_{\text{sun}}$</td>
<td>$2 \times 10^4$</td>
<td>$4-6 \times 10^{42} , \text{erg/s}$</td>
</tr>
</tbody>
</table>

→ Clusters ($>10^{14}M_{\text{sun}}$) exist up to $z \sim 2$, massive groups up to $z \sim 2.5$
New SZE-Cluster Surveys

SZE Survey with SPT (South Pole Telescope) in 4000 deg2 SZ survey

→ to determine $w$ to about ~5% time variations to about 10-20%

See also ACT and APEX Surveys
Prospects of the eROSITA Survey

![Graph showing cluster density vs. redshift for eROSITA, REFLEX, and REFLEX2 surveys.]

- **eROSITA Poles**
- **eROSITA Survey**
- **REFLEX**

**eROSITA**

- $F_x = 2 \times 10^{-12}$ erg/s/cm$^2$ (x100)
- $F_x = 5 \times 10^{-14}$ erg/s/cm$^2$
- $F_x = 5 \times 10^{-15}$ erg/s/cm$^2$
Constraints from 100K Cluster Survey

Time dependence of $w_x$

$$w_x(z) = w_0 + w_a z$$

$$p(z) = w_x(z) \times \rho(z)$$

Limitations

Already now the implications for cosmology from X-ray surveys are systematics limited:

- We need better mass measurements

- We need a better characterization of the scaling relations of cluster mass with various observables
1. Precise Astrophysics of Nearby Clusters

1. Understanding the heating of cool cores
2. Studying the structure of mergers, diagnostics of shocks, assessing turbulence
3. Precison studies of the ICM temperature structure
4. Detailed heavy element abundance measurements
5. Precise mass profiles (Dark Matter Halo evolution study)
6. Non-thermal plasma contribution to pressure (IC detect.)

Methods:

- Velocity diagnostics with (STJ and TES)
- Unvailing multi-temperature components
- Special line ratio diagnostics
- temperature, pressure, entropy, metallicity maps
Detection Turbulent or Infall Velocity Structure

Turbulence detected in the image (pressure map) of the Coma cluster with XMM-Newton (Schuecker et al. 2004). ~ 10 – 20% turbulent energy density versus thermal energy density.

Coma pseudo-pressure map

Power spectrum of pressure fluctuations

This amount of turbulence (~ 300 km/s) should also be visible in high resolution spectra!
Diagnostics of Velocity Line Broadening I

5 keV spectrum, velocity broadening 100 (blue) 600 (red) km/s (Gaussian)
uncertainty of velocity measurement in 100 ks observation: $\Delta v = \pm 20$ km/s
Diagnostics of Velocity Line Broadening II

Summary (simulations with TES detector):

[cluster z = 0.2, \( F_X = 3 \times 10^{-13} \) erg s\(^{-1}\) cm\(^{-2}\) abund. = 0.3]

- 5 keV, exp. = 100 ks \( \Delta v \sim 20 \) km/s (0 – 600 km/s)
- 5 keV, exp. = 40 ks \( \Delta v \sim 50 \) km/s
- 8 keV, exp. = 100 ks \( \Delta v \sim 40 \) km/s
- 2 keV, exp. = 100 ks \( \Delta v \sim 5-7 \) km/s

[distant cluster z = 1, \( F_X = 10^{-14} \) erg s\(^{-1}\) cm\(^{-2}\), ab=0.3]

- 5 keV, exp. = 100 ks \( \Delta v \sim 70 \) km/s

\( \rightarrow \) Velocity structure is observable even for distant clusters!

spectral fitting can be complex (to find the true minimum)
Line Broadening in Distant Clusters

Cluster: z=1, $F_\chi \sim 1.5 \times 10^{-14}$ erg s$^{-1}$cm$^{-2}$ (0.5-2 keV) $\Rightarrow \Delta v = 20 - 50$ km/s for 250 ks obs. - 70-80 km/s in 100 ks
The Influence of Multi-Temperature Structure and Turbulence on the Cluster Mass Determination

Simulations show two sources of mass underestimation (for the assumption of hydrostatic equilibrium and spherical symmetry):

1) If there is additional kinetic pressure in the ICM (turbulence) this adds to the overall ICM pressure → higher mass

2) If the plasma has locally a range of temperatures, the temperature will be biased low with respect to a mass weighted mean temperature (the weighting to estimate the overall pressure)

E.g. Rasia et al. 2006 find on average an underestimate of the mass of about 20% - half due to turbulence, half due to temperature structure. This depends on the physics used in the simulations and needs to be tested by observations!!
Diagnostics of Multi-Temperature Structure I

Half & half mixture of 4keV and 8keV ($F_X=10^{-12}$ erg s$^{-1}$ cm$^{-2}$), analysed as 1 temperature and 2 temperature model 200 ks exposure (TES detector):

In the 200 ks exposure the two temperatures can be determined with an accuracy better than 5%, they can still be clearly distinguished in a 50 ks exposure ($F_X \sim 5 \times 10^{-13}$ erg s$^{-1}$ cm$^{-2}$) at $\Delta T \sim 0.6$ keV.
**Diagnostics of Multi-Temperature Structure II**

STJ spectrum of 3 & 5 keV plasma (Em = 1:1) 50 ksec exposure:

Feasibility ($F_X = 5 \times 10^{-13}$ erg s\(^{-1}\) cm\(^{-2}\)):

4 & 8 keV plasma:
- exp = 200ks $\rightarrow$ $\Delta T \sim 0.2$ keV (TES)
- = 100ks $\rightarrow$ $\Delta T \sim 0.4$ keV
- = 100ks $\rightarrow$ $\Delta T \sim 0.3/1$ keV (STJ)

3 & 5 keV plasma:
- exp = 50 ks $\rightarrow$ $\Delta T \sim 0.3/2$ keV (TES)
- 50 ks $\rightarrow$ $\Delta T \sim 0.4/2$ keV (STJ)

3(10%) & 7(90%) keV plasma:
- Exp.: 100ks $\rightarrow$ 7 +- 0.2 keV
- 3 +- 0.3 keV

At lower temperatures things are much easier!
Cool Core Diagnostics: M87 halo

Multi-temperature-Abundance diagnostics in the radio lobe region of M87 (50ks observation TES):

- 10% cool plasma 1keV, hot Pl. 2.3 keV
- $T_1 = 0.99 \pm 0.002$, $T_2 = 2.27 \pm 0.01$
- Fe, Si, S (1) = 2.3 ± 0.14
- O, Mg (1) = 0.9 ± 0.24 (0.07)
- Fe, Si, S (2) = 0.7 ± 0.01
- O, Mg (2) = 0.3 ± 0.05 (0.01)

1 arcmin$^2$ test region with

$F_x (0.5-2) = 4.3 \times 10^{-12}$ erg s$^{-1}$ cm$^{-2}$

With XMM-Newton we can barely distinguish 2 temp., but not different abundances
Connection Between Clusters and LSS
Filiberto Braalia et al.

RXCJ0014-3023
Temperature, Pressure and Entropy Maps at z ~ 1 ... 1.5

Feasibility for a cluster with $F_X = 10^{-14} \text{ erg s}^{-1} \text{ cm}^{-2}$
$z = 1-1.4$, $5 \text{ keV}$, abund. = 0.3 solar

XEUS count rate $\sim 0.2 \text{ s}^{-1}$ 200ks $\rightarrow$ 40 000 cts

This will provide similar temperature, entropy, pressure maps as shown for the REFLEX DXL clusters (the temperature maps would even be better, due to the better spectral resolution !)

The flux limit ($F_X = 10^{-14} \text{ erg s}^{-1} \text{ cm}^{-2}$) used above corresponds to the sensitivity limit of our XMM-Newton Distant Cluster Project (XDCP) where we find about one $z>1$ cluster per deg$^2$ $\rightarrow$ we will have enough study objects of with the assumed properties !
Galaxy Group at z = 2

Surface brightness still determined to about 3.5 core radii (140 kpc)

High z extreme: Group at z = 2
- $F_X = 5 \times 10^{-16}$ erg s$^{-1}$ cm$^{-2}$
- $L_X = 7 \times 10^{43}$ erg s$^{-1}$, [0.5 -2 keV]
- centr. Sfb. ~ 2x bkg
- core radius 40 kpc = 5"

Spectroscopy:
- Temperature +- 3%
- [Fe] +- 11%
- [Si] +- 18%
- [O], [Mg] +- 30%

from M. Arnaud

H. Böhringer

IXO Science Meeting @ MPE, Garching
18. 9. 2008
Requirements for XEUS

To explore distant clusters (z = 1 .. 2.5) in detail we need:
-- large collecting area > 3 m² is good
-- at minimum 5" resolution
-- energy resolution of current response matrices
   (2.5 ev at Fe L-lines)
-- large FoV of NFI
   & WFI  is great to detect groups z > 2
-- low background and well assessed background
   (new approaches should be tried - e.g. out-of-field bkg
    monitor CCD)
Conclusion

XEUS will provide new insight in detailed astrophysics of nearby clusters

Really new territory: cluster astrophysics and cosmology with cluster at $z = 1 \ldots 2$ (2.5)

1. Precise measurements of cluster structure, thermal history, chemical evolution, formation history, mass-to-light ratio (=stellar vs total mass)

2. Precise measurements of cluster masses $\rightarrow$ required for cosmology $+$ issues above

3. Basis for testing cosmological models with (i) cluster evolution and spacial distribution and (ii) SZE/X-ray standard candles (and baryon fraction)