Galaxy Cluster Cosmology

1. Clusters as cosmological probes (tracing structure growth and providing distance indicators)

2. Importance of IXO for calibration of underlaying scaling relations

3. Synergy with other missions for cluster cosmology

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Why X-ray Observations are Mandatory

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

For medium distant clusters: ~ 40 000 cts → 150 – 200 $\sigma$ Signal!

compared to <~ 10 $\sigma$ for best SZE and Lensing

We are interested in exploring and understanding the physics in its original complexity before making simplifying generalizations!

Lensing signal of RXCJ1347.5-1144 (red in image) and mean ellipticity signal (profile in I and R)
Bradac et al. 05,08

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Cosmological Tests with Galaxy Clusters

1. Evolution of the cluster mass function [tests LSS growth $g(z)$ – and $H(z)$]

2. Evolution of $P(k)$ or $\xi(r)$ of the cluster clustering

3. Cluster ICM observations as standard candles
go mass fraction or SZE (depend on diameter dist.)

4. Shape of DM halos (formation history, details of DM interaction)
Cosmological Challenge Baseline

WMAP++ Results reported in Komatsu et al. 2008

\[ \Delta w < 15 \text{%} \text{ (~7\% for w const.)} \quad \Delta w' \sim 50 - 70\% \]

\[ \Delta w \sim 6-7\% \quad \Delta w' \sim 50 \% \]

\[ \Delta w < 5\% \quad \Delta w' \sim 40-50 \% \text{ (conserv.)} \]
**Cosmological Distance Indicators ($f_{\text{gas}}$)**

Gas mass fraction as function of redshift - deduced for different cosmologies (Concordance model, Einstein-deSitter model).

Universal gas mass fraction expected! (Allen et al. 2008)

Prospected cosm. Constraints from 500 hot (> 5keV) clusters ($z = 0..2$) with 2%, 5% or 10% mass measurement accuracy (Rapetti et al. 2008)
Current redshift leverage gets only good constraints on $H_0$ - larger redshift range necessary to constrain the matter/energy composition
The Role of Galaxy Clusters in the Hierarchy of Large-Scale Structure

Statistics of the peaks (Cluster Population) is closely connected to the statistical properties of the fluctuation field, $P(k)$ or $\xi(r)$

Therefore the increase of the cluster abundance with time measures the structure growth function, $g(z)$

where: $P(k,z) = g(z)/g(0) \ P_0(k)$

mass of galaxy clusters $\sim 10^{14} - 10^{15} \ M_{\odot}$
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}

$\Rightarrow$ There are more distant clusters for small (negative) $w$ !

Requires mass calibration to few % !

see also Haiman et al. 2001
Details Cluster Evolution I

Approximately:

\[
\frac{d \log N}{d \log w} = 0.85 \quad (z > 1) \quad = \quad 1.75 \quad (z > 1.4)
\]

\[\Delta N \ 10\% \ \rightarrow \ \Delta w \ 10\%
\]

\[
\frac{d \log N}{d \log m} = -3 \quad (z > 1) \quad = -3.5 \quad (z > 1.4)
\]

\[\Delta m_{\text{cal}} \ 3\% \ \rightarrow \ \Delta w \ 10\%
\]

\[\rightarrow \ \text{Scatter in M is less of a problem than bias (calibration of the mean)}\]
Details of Cluster Evolution II

\[ \Delta N \ 10\% \rightarrow \Delta w \ 10\% \]

one needs few hundred clusters in the critical \( M - z \) regime

\[ \Delta m_{cal} \ 3\% \rightarrow \Delta w \ 10\% \]

calibration should be better than 2%

Scatter in \( m \) has to be known for the mass proxy used (e.g. \( L_x, T_x, Y_x \))

few hundred clusters help to reduce shot and scatter in similar way
### 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>$10^{44}$ erg/s</td>
</tr>
<tr>
<td></td>
<td>$&gt; 3 \times 10^{13} M_{\text{sun}}$</td>
<td>20000</td>
<td>$2 \times 10^{43}$ erg/s</td>
</tr>
<tr>
<td></td>
<td>$&gt; 10^{13} M_{\text{sun}}$</td>
<td>$4 \times 10^5$</td>
<td>$3-5 \times 10^{42}$ erg/s</td>
</tr>
</tbody>
</table>

| z > 2.5  | $> 3 \times 10^{13} M_{\text{sun}}$ | 3000                | $2 \times 10^{43}$ erg/s |
|          | $> 10^{13} M_{\text{sun}}$ | $1 \times 10^5$     | $3-5 \times 10^{42}$ erg/s |

| z > 3    | $> 3 \times 10^{13} M_{\text{sun}}$ | 200                  | $2.7 \times 10^{43}$ erg/s |
|          | $> 10^{13} M_{\text{sun}}$ | $2 \times 10^4$      | $4-6 \times 10^{42}$ erg/s |

$\Rightarrow$ **Clusters ($>10^{14} M_{\text{sun}}$) exist up to $z \sim 2$, massive groups up to $z \sim 2.5$**
High z extreme: Group at $z = 2$

- $F_X = 5 \times 10^{-16} - 1 \times 10^{-15} \text{erg s}^{-1} \text{cm}^{-2}$
- $L_X = 3 \times 10^{43} \text{erg s}^{-1}$, [0.5 -2 keV]
- centr. Sfb. $\sim 3-6 \times \text{bkg}$
- core radius $\sim 40 \text{kpc} = 5''$

**Spectroscopy:**
- Temperature $\pm 5\%$
- Abundance $\Delta < 0.05$
- [$\text{Fe}$] $\pm 11\%$
- [$\text{Si}$] $\pm 18\%$
- [$\text{O}$], [$\text{Mg}$] $\pm 30\%$
**External Calibration of the Cluster Masses**

To be better than 10% in $\Delta w$ requires:

- Mean mass calibration better than 2%  \[ > 500 – 1000 \text{ lensing cl.} \]
- Abundances better 5 - 7%  \[ > 400 \text{ strategically strong clusters} \]
- Mass scatter < 20 - 30% (uncritical)
- $M > 10^{14} \, M_\odot \, (z > \sim 1)$ or e.g. $M > 3 \times 10^{13} \, M_\odot \, (z > \sim 1.4)$

Mass bias for X-rays:

~ - 12%  \(\pm\) 12%

Zhang et al. 2008
(LoCuSS project G. Smith ea.)
Precise Diagnostics

1. Studying the structure of mergers, diagnostics of shocks, assessing turbulence
2. Precision studies of the ICM temperature structure
3. Velocity Broadening as a third parameter for observable mass relations
5 keV spectrum, velocity broadening 100 (blue) 500 (red) km/s (Gaussian)
uncertainty of velocity measurement in 100 ks observation: $\Delta v \leq \pm 20$ 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)
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

→ 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_X \sim 1.0 \ 10^{-14} \text{ erg s}^{-1}\text{cm}^{-2} \ (0.5\text{-}2 \text{ keV}) \rightarrow \Delta v \sim 30 \ - \ 40 \ \text{ km/s} \ \text{ for} \ 200 \ \text{ ks obs.} \ - \ (50 \ - \ 70 \ \text{ km/s} \ \text{ in} \ 100 \ \text{ ks})
Diagnostics of Multi-Temperature Structure II

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

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

4 & 8 keV plasma:
- exp = 200ks $\rightarrow$ $\Delta T \sim 0.2$ keV
- exp = 100ks $\rightarrow$ $\Delta T \sim 0.4$ keV

3 & 5 keV plasma:
- exp = 50 ks $\rightarrow$ $DT \sim 0.3/2$ keV

At lower temperatures things are much easier!

3(10%) & 7(90%) keV plasma:
- Exp. = 100ks 7 +- 0.2 keV
- 3 +- 0.3 keV
Comparison to Simulations
Calibration of Scaling Relations

Simulation

Initial condition → distant cluster → nearby cluster

Calibration of scaling rel.
Relying in correct physics

Comparison in great detail
Calibration of simul.-physics

Observation:

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Narrowing Down the M-T Relation with Structure Parameters (example)

Ventimiglia et al. 2008: deviation, $\Delta M$, from the mean $M-T_X$ relation for simulated clusters (Borgani et al. 2004). The fitted trend with substructure parameters can be used to produce a correction factor which reduces the scatter of the relation.

I believe that the velocity broadening of X-ray lines is an even better diagnostics!
Differences Between Simulations and Observations (in Substructure Measures)

Distribution of power ratios $P_2/P_0$ and $P_3/P_0$ for the representative cluster sample REXCESS (colored points) and simulated clusters (Borgani et al. 2004). There are more extremely substructured clusters in the simulations – they have more extreme cool cores. The right panel gives a few examples (X-ray surf. brightn.) of extremely structured clusters. (Böhringer et al. 2009).
Serendipitous Discoveries @ High z

For a 20 x 20 arcmin² FoV for WFI

1 year of observations (50% eff.) = 300 x 50 ks obs.

assuming a ration of 1.5 : 1 for NFI and WFI observations

→ 5 year archive (30% useful obs.) 20 deg²

10 year „ „ „ „ 40 deg²

We expect about 1-2 cluster T>= 2 keV z>~ 2 per deg²

which can be identified in 50 ks exposures (300 – 1000) cts

This will provide a new territory for follow-up studies in confirmed-evolved distant clusters ! (Unless SZE experiements make an enormous progress, there is no other way to find these groups/clusters !)
Conclusion

IXO will provide the detailed insight into cluster structure and evolution necessary to put the results from forerunning cluster surveys on precise footing to allow stringent cosmological tests.

Cluster cosmological tests provide complementary information on cosmology by probing the growth of structure in the Universe (which depends on DM + DE).

We will reach a new territory for cluster astrophysics and cosmology with clusters at $z \geq 1.5 - 2$ (... 2.5).

IXO has a discovery potential for clusters/groups at redshifts $\geq 2$. 