High-redshift, massive, galaxy clusters in LCDM.

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Shaun Hotchkiss University of Helsinki.

Overview

- Galaxy Cluster surveys as cosmological probes
- The XMM Cluster Survey
- Individual Galaxy Clusters as extreme objects
- Early analysis $\Delta M, \Delta z$ & misunderstandings
- A critical look at the $\Delta M, \Delta z$ question
- Updated analysis and results
- Exclusion curves
- Conclusions + future work
The theoretical Cluster Mass Function

The mass function describes the number of clusters per unit mass, per unit redshift as a function of cosmological parameters.

\[ n_G(M, z) = \sqrt{\frac{2}{\pi}} \left( \frac{\bar{\rho}}{M^2} \right) \left\{ \frac{d}{d \ln M} \ln \sigma_M \right\} \nu \exp(-\nu^2/2). \]

\[ \nu = \delta_{sc}/\sigma(M, z) \]

\[ \sigma = \int P(k)\hat{W}(kR)k^2 dk, \]

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Now, fitting functions are calibrated to large N-body dark matter only simulations (e.g., Tinker et al 2008, Bhattacharya & Wagner et al 2010)

\[ f(\sigma) = A \left[ \left( \frac{\sigma}{b} \right)^{-a} + 1 \right] e^{-c/\sigma^2} \]

\[ \frac{dn}{dM} = f(\sigma) \frac{\bar{\rho}_m}{M} \frac{d \ln \sigma^{-1}}{dM}. \]
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Or from first principles + fitting one parameter: Corasaniti & Ixandra Achitouv (PRD submitted) arXiv: 1107.1251 (& 1012.3468)
Cosmological constraints with many clusters

\[ \sim 100 \text{ X-ray selected clusters: Vikhlinin et al. 2008} \]

\[ \sim 13,000 \text{ maxBCG (SDSS DR5) optically selected clusters: Rozo et al. 2009} \]
Cosmological constraints with many clusters

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Future cluster catalogues
PanStarrs, DES ~100,000 optical
eROSITA ~10,000 X-ray
Identifying and classifying extended sources

X-ray photon map + automated pipeline to detect point sources (red) extended sources (green).

The extended X-ray emission is produced by a cluster’s ICM. However, we need optical identification and redshifts before the fluxes can be converted to temperatures/masses, and used for cosmology.

Algorithms paper, Lloyd-Davies et al. 2010
Cluster zoo

Optical imaging from NOAO XCS = expensive,
Data from SDSS = free
Cluster zoo

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Redshift histograms  Color-Magnitude diagrams
XCS: Future Cluster zoos

Cluster Zoo with XCS & PanStarrs Full sky data (Johannes, Tommaso, Jochen + others?)

High redshift optical + photoz + X-ray masses

HOD, mass-optical scaling relations for medium/high redshift X-ray selected clusters, with ~temperature/mass estimates
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Recent Data release, Mehrtens et al. 2011
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Was the highest redshift X-ray selected cluster, z=1.46 (Stanford et al. 2006, Hilton et al. 2007, 2008)
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**XMMXCS J2215**
*Was the highest redshift X-ray selected cluster, z=1.46 (Stanford et al. 2006, Hilton et al. 2007, 2008)*

**Now z=2.07, Gobat et al. 2011**

**Some XCS papers**

- The interplay between the BCG and the ICM via AGN feedback: Stott et al. 2012
- Predicted overlap with the Planck Clusters: Viana et al. 2011
- AGN and Starburst Galaxies in XMMXCS J2215.9-1738 at z=1.46: Hilton et al 2010
- The build up of stellar mass in BCG at high redshift: Stott et al. 2010
- Forecasting cosmological and cluster scaling-relation parameter constraints: Sahlen et al. 2008
Individual clusters as extreme objects
Cluster catalogues with many hundreds or thousands of clusters can be to constrain cosmology, but so can individual “pink elephant” or extreme clusters. If observations of such clusters are statistically very unlikely to have occurred, maybe there is some tension with our understanding of the cosmological model.
Individual clusters as extreme objects

The observations of XMMJ2235 appeared to cause tension with the LCDM model + WMAP priors on the cosmological parameters. A very massive clusters of galaxies at high redshift, was statistically unlikely to exist.

\[ M_{200} = 7.7 \pm 1.3 \times 10^{14} \, M_\odot \]
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How likely was this cluster to exist \( >M >z \)?

• How many clusters would do we expect to find at \( >M, >z \)?
• The expected number in the full sky \( \sim 7 \).
• Footprint was 11 square degrees XMM X-ray survey, 0.02% of sky.
• Poisson sample from \( (0.0002 \times 7) \) \( >1 \) only 1.4%

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Jee at al 2009

Jimenez & Verde 2009 showed \( \text{fnl}\sim 150 \) relieves tension.

Cayon et al 2010 \( \text{fnl}=360, \text{fnl}>0 \) at 95%.
Observations of more “rare” clusters

SPT CL J0546-5345

\[ M_{200} \sim 10^{15} M_\odot \]

\[ z = 1.05 \]

Brodwin et al 2010

• Expect to see one 18% of time in the \( >M, >z \) sense

We just got lucky.
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**XMMUJ0044.0-2033**

\[ 3.5 < M < 5 \times 10^{14} M_\odot \]

\[ z = 1.57 \]

Santos et al 2011

- Expect to see one
- <10% of time in the
- \( >M,>z \) sense

We just got lucky.

We got very lucky.

Hey, we also got lucky!
The $M,z$ analysis (uncalibrated)

Quantifying luck.

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+ conservative assumptions
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BH, Jimenez, Verde 2011

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Jee et al (2011) updated cluster sample.
The $>M,>z$ analysis

The $>M,>z$ analysis begins by assuming that we would have also observed any cluster with greater mass, or greater redshift than an observed cluster.
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A_s = \int_{M_S}^{\infty} \int_{z=z_{\text{cluster}}}^{z=2.2} n(m, z, f_{\text{NL}}, C) \, dm \, dz
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We Poisson sample from $A_s$ many ($1e4$) times. If the Poisson sample is $>1$, the cluster exists in this realisation. If the Poisson sample is $<1$ the cluster does not exist in this realisation.
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The “existence probability” $R$, is given by

$$R = \frac{\text{Number}(P^O(A_s) \geq 1)}{10^4}$$
The bias in a nutshell: In previous literature, the quantity R, the probability of finding a cluster in this \( \text{>M,>z} \) box, has been used as a proxy for what we actually want to know, “What is the probability of this cluster existing in our cosmological model?”

When stated like this, one can see that one does not imply the other. (see Hotchkiss 2011)
Unbiasing/Calibrating the $>M,>z$ statistic

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**Why this is wrong**

Why should we restrict ourselves to the easily calculated, but arbitrary, $>M,>z$ contours, e.g., what dictates that the box should be placed at right angles to the $(M,z)$ axis, or have straight instead of curved boundaries? One could simply modify the $>M,>z$ box and obtain a new “existence probability” $R^*$ which would be equally as ‘justified’ as the original existence probability $R$.

The Universe doesn’t care what we call “existence probability”.

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Once the above is understood, we can calculate the distributions of $R$ found in simulations, compare it with $R$ from observations, and then use the calibrated $R$ to test for tension with LCDM.

(see Hotchkiss 2011)
Notes on the $>M,>z$ statistic

Playing the $>M,>z$ game is only necessary if we don’t know the selection function (sf) of a survey. For example Jee et al (2011) published a list of X-ray (actually SNe) selected clusters with weak lensing masses. They have a very complicated sf. Only the existence, not the absence, of clusters can constrain cosmology (contrast with e.g., SPT, maxBCG, R400d).
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Not all X-ray extended sources identified, (noise)
Extended sources not followed up => no redshifts or mass estimates.
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But we still want to infer something!
Identify sets of “rare” simulated clusters assuming LCDM (e.g. low R values) and compare their R values with the observed clusters.

- Lowest R clusters $\Rightarrow$ LP

Note: To calibrate $M,z$ analysis using simulated clusters, we must assume which part of the (M,z) plane has been “observed” (i.e., a sf).

Ongoing work to recover cosmological constraints using weaker assumptions about the selection function (Hoyle et al, in prep)
Observations progressed

X-ray survey footprint of 100 sq. deg. (Jee et al 2011)

Redshift range of Jee $1.0<z<2.2$

Still use the $(>M,>z)$ R statistic but calibrate to simulations.

<table>
<thead>
<tr>
<th>Cluster Name</th>
<th>Redshift</th>
<th>$M_{200} \times 10^{14} M_\odot$</th>
<th>Method</th>
<th>$\tilde{R}$</th>
<th>Mass reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>RCS0221-0321</td>
<td>1.02</td>
<td>$1.80^{+1.30}_{-0.70}$</td>
<td>WL</td>
<td>0.992</td>
<td>[15]</td>
</tr>
<tr>
<td>WARPSJ1415+3612</td>
<td>1.03</td>
<td>$4.70^{+2.00}_{-1.40}$</td>
<td>WL</td>
<td>0.706</td>
<td>[15]</td>
</tr>
<tr>
<td>RCS0220-0333</td>
<td>1.03</td>
<td>$4.80^{+1.80}_{-1.30}$</td>
<td>WL</td>
<td>0.709</td>
<td>[15]</td>
</tr>
<tr>
<td>RCS2345-3632</td>
<td>1.04</td>
<td>$2.40^{+1.10}_{-0.70}$</td>
<td>WL</td>
<td>0.989</td>
<td>[15]</td>
</tr>
<tr>
<td>XLSSJ022403.9-041328*</td>
<td>1.05</td>
<td>$1.66^{+1.15}_{-0.38}$</td>
<td>X-ray</td>
<td>0.997</td>
<td>[31]</td>
</tr>
<tr>
<td>RCS2156-0448</td>
<td>1.07</td>
<td>$1.80^{+2.50}_{-1.00}$</td>
<td>WL</td>
<td>0.916</td>
<td>[15]</td>
</tr>
<tr>
<td>RCS0337-2844</td>
<td>1.10</td>
<td>$4.90^{+2.80}_{-1.70}$</td>
<td>WL</td>
<td>0.567</td>
<td>[15]</td>
</tr>
<tr>
<td>RDGSJ0910+5422</td>
<td>1.11</td>
<td>$5.00^{+1.20}_{-1.00}$</td>
<td>WL</td>
<td>0.595</td>
<td>[15]</td>
</tr>
<tr>
<td>ISCSJ1432+3332</td>
<td>1.11</td>
<td>$4.90^{+1.20}_{-1.60}$</td>
<td>WL</td>
<td>0.603</td>
<td>[15]</td>
</tr>
<tr>
<td>XMMUJ205-0159</td>
<td>1.12</td>
<td>$3.00^{+1.60}_{-1.00}$</td>
<td>WL</td>
<td>0.888</td>
<td>[15]</td>
</tr>
<tr>
<td>RXJ1053.7+5735(West)</td>
<td>1.14</td>
<td>$2.00^{+1.60}_{-0.69}$</td>
<td>X-ray</td>
<td>0.989</td>
<td>[31]</td>
</tr>
<tr>
<td>XLSSJ0223-0436</td>
<td>1.22</td>
<td>$7.40^{+2.50}_{-1.80}$</td>
<td>WL</td>
<td>0.119</td>
<td>[15]</td>
</tr>
<tr>
<td>RDGSJ1252-2927</td>
<td>1.24</td>
<td>$6.80^{+1.20}_{-1.00}$</td>
<td>WL</td>
<td>0.094</td>
<td>[15]</td>
</tr>
<tr>
<td>ISCSJ1429+3437</td>
<td>1.26</td>
<td>$2.50^{+2.20}_{-1.10}$</td>
<td>WL</td>
<td>0.806</td>
<td>[15]</td>
</tr>
<tr>
<td>ISCSJ1429+3437</td>
<td>1.26</td>
<td>$5.40^{+2.40}_{-1.60}$</td>
<td>WL</td>
<td>0.327</td>
<td>[15]</td>
</tr>
<tr>
<td>RDGSJ0849+4452</td>
<td>1.26</td>
<td>$4.40^{+1.10}_{-0.90}$</td>
<td>WL</td>
<td>0.517</td>
<td>[15]</td>
</tr>
<tr>
<td>RDGSJ0848+4453</td>
<td>1.27</td>
<td>$3.10^{+1.00}_{-0.80}$</td>
<td>WL</td>
<td>0.839</td>
<td>[15]</td>
</tr>
<tr>
<td>ISCSJ1432+3436</td>
<td>1.35</td>
<td>$5.30^{+2.60}_{-1.70}$</td>
<td>WL</td>
<td>0.265</td>
<td>[15]</td>
</tr>
<tr>
<td>ISCSJ1434+3519</td>
<td>1.37</td>
<td>$2.80^{+2.90}_{-1.40}$</td>
<td>WL</td>
<td>0.636</td>
<td>[15]</td>
</tr>
<tr>
<td>XMMUJ2235-2557</td>
<td>1.39</td>
<td>$7.30^{+1.70}_{-1.40}$</td>
<td>WL</td>
<td>0.035</td>
<td>[15]</td>
</tr>
<tr>
<td>ISCSJ1438+3414</td>
<td>1.41</td>
<td>$3.10^{+2.60}_{-1.40}$</td>
<td>WL</td>
<td>0.584</td>
<td>[15]</td>
</tr>
<tr>
<td>XMMXCSJ2215-1738</td>
<td>1.46</td>
<td>$4.30^{+3.00}_{-1.70}$</td>
<td>WL</td>
<td>0.335</td>
<td>[15]</td>
</tr>
<tr>
<td>XMMUJ0044.0-2033**</td>
<td>1.57</td>
<td>$4.25^{+0.75}_{-0.75}$</td>
<td>X-ray</td>
<td>0.152</td>
<td>[30]</td>
</tr>
</tbody>
</table>

Marginalize over the mass error by sampling from each clusters’ mass and error many times and calculate $R$ for each sampled mass. This produces a distribution in $R$ for each cluster.

BH, Jimenez, Verde, Hotchkiss (2011 JCAP)
1) 450 sets of simulations made from Poisson sampling the mass function, varying cosmological parameters, assuming WMAP7 priors.
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2) Assign each simulated cluster a 40% mass error and re-sampled the cluster mass. This accounts for the Eddington bias (see Mortonson et al 2011).

3) Calculate R for each cluster, identify the LP clusters in each simulation.
We assumed that the combined R values, for an ensemble of N clusters is

\[ R_N = \Pi_N R_i \]
Calibrated analysis/comparison with sim.

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This analysis assumes the survey geometry of Jee et al. $l<z<2.2$; footprint=100 sq. deg.
Main results

The calibrated $R (>M, >z)$ statistic for the observed ensemble of clusters are consistent with $R$ values for simulated clusters drawn from LCDM mass function, once the Eddington bias is considered.

However, we are be too conservative in the modeling of the survey geometry. More work needed to understand what this means for LCDM.
Related work, exclusion curves

Curves in the mass-redshift plane can be used to signal tension with individual ‘rare’ clusters, but can rule out a cosmological model. The (biased) idea was introduced in Mortonson et al (2010).

Harrison & Hotchkiss 2012 released (de-biased) code to create these curves in future claims of tension with individual clusters.

They also need to make assumptions about survey geometry.

The observed clusters provide no tension, e.g. with exclusion curves, with LCDM *assuming* the survey geometries examined here.

Figure 4. Rareness of currently observed clusters (using the > $mdV$ measure described in the text) corresponding to an idealised all-sky survey which is complete at masses above $m_{\text{min}} = 10^{14} M_\odot/h$ out to $z = 2$.

Harrison & Hotchkiss
arXiv: 1210.4369
Summary

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• More high-redshift, massive clusters are being found ~weekly. Planck/XCS/Panstarrs/DES, and will likely be found with future surveys (eROSITA).

• In these cases when high z selection functions can be difficult to quantify. we have begun to build a statistical framework to understand what individual or ensembles of clusters tell us about cosmological models.

Follow up work: Panstarrs/XCS/other matching, and to use samples of clusters with an unknown selection function to bound cosmological parameters (in prep.)
**z<1.6 survey geometry**

All clusters have $z<1.6$. Perhaps we were too conservative, comparing the observed clusters ($z<1.6$) with simulated clusters between $1<z<2.2$. We now modify the assumed survey geometry, by imposing a hard cut to the simulations.
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But, this line is arbitrary!

Any inferred exclusion significance must be quoted together with the metric.

(see also Hotchkiss 2011, and Harrison & Hotchkiss 1210.4369)
The CMF with cosmological parameters/models

Shapiro, BH, et al 2010
The CMF with cosmological parameters/models

\[ R_{NG}(S_{3,M}, M, z) = \frac{n(M, z, f_{NL})}{n_G(M, z, f_{NL} = 0)} \]

E.g., Ixandra Achitouv & Corasaniti 2012, Wagner et al 2010
Exclusion curves (uncalibrated)

Furthermore, we can define lines of constant $R (>M, >z)$ in the mass-redshift plane, and use them to create exclusion curves. The exclusion curves can only be used for individual ‘rare’ clusters, but can rule out a cosmological model (Mortonson et al 2010).
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Given the (w)LCDM model with WMAP7 cosmological priors, we do not expect any cluster to sit above the curve at 95% or some other specified confidence.

These lines were created by tracing lines of constant $R$ (existence probability $>M, >z$).
More $M_z$ analysis (uncalibrated)

Jee et al 2011

Improved (HST WL) cluster mass estimates & less conservative (more realistic) survey footprints.
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Jee et al 2011

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Are these clusters really in tension with LCDM, or have we been goofing up? What’s going on?
XCS: Comparison with other X-ray surveys

![Graph showing comparison between XCS and other surveys](image)
Comparison with other X-ray surveys

The Future
• XMM lifetime extended to work past 2013
• Analyzing more XMM photon maps
• Obtaining more cluster redshifts
• Future data releases soon
• Cosmology from XCS DR1

Data available: http://www.xcs-home.org/
Why use clusters, when we have WMAP? Clusters probe the growth of structure, and so are complementary to geometry probes such as CMB.