Cosmological and Large-Scale Structure Studies with X-ray Galaxy Clusters

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Overview

1. Galaxy Clusters in X-rays
2. Galaxy Clusters in the Large-Scale Structure
3. The CLASSIX Cluster Survey
4. Implication for Neutrino Masses
5. The Local Underdensity and the Hubble Constant
6. Magnetic Fields in Clusters
7. Conclusions
Optical and X-ray Image of the Coma Galaxy Cluster

The X-ray emission originates from a hot intracluster plasma with temperatures of a few 10 Million degrees.

Clusters of galaxies are the largest, clearly defined objects in our Universe.
Structure and composition of galaxy clusters

Gas thermalised
Galaxies virialised
Hardly any energy dissipation

Mass from hydrostatic equation:

\[
\frac{1}{\rho} \frac{dP}{dr} = - \frac{GM(r)}{r^2}
\]

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

Matter composition:

- Dark Matter \( \sim 84\% \)
- Gas \( \sim 14\% \)
- Galaxies \( \sim 2\% \)

Clusters from REXCESS sample [Böhringer et al. 2007]
\( L_X - M \) Relation for REXCESS Clusters

M estimated from \( Y_X \)

\textbf{Scatter} \sim 40\%

\textbf{Scatter} \sim 18\%

Formation of Galaxy Clusters

- Galaxy clusters form from peaks in the density fluctuation field.

- The number density and the spatial distribution of the density peaks in a Gaussian fluctuation field can be calculated statistically → prediction for the number density of galaxy clusters

Mass of galaxy clusters $\sim 10^{14} - 10^{15} \, M_{\text{sun}}$
The CLASSIX Galaxy Cluster Survey
Cosmic Large-Scale Structure in X-rays cluster survey
REFLEX & NORAS Cluster Survey

REFLEX II 911 clusters, NORAS II 860 clusters $F > 1.8 \times 10^{-12}$ erg s$^{-1}$ cm$^{-2}$

3-dimensional distribution of the REFLEX/NORAS clusters
X-ray luminosity function obtained from CLASSIX Survey

Prediction for a flat $\Lambda$CMD model $\Omega_m = 0.27$ and $\sigma_8 = 0.80$

Böhringer et al. 2014
model predicted X-ray luminosity function

Flat $\Lambda$CMD model with variation of $\Omega_m$ (15%) and $\sigma_8$ (12%)

Böhringer et al. 2014
L_x – M scaling relations

HIFLUGCS sample

ext. HIFLUGS

REXCESS sample

Reiprich & Böhringer 2002

Bohringer et al. 2007


Mass determination from X-ray observations (assumption: hydrostatic)
Influence of the scaling relation on cosmological constraints

Figure: slope +- 5%, normalization +- 10%, scatter +- 10%
Marginalization: slope +- 7%, normalization +- 14%, scatter 30%
Assume hydrostatic mass bias of -10%
Cosmological constraints by REFLEX and NORAS

Böhringer, Chon et al. 2014, 2017
Cosmology: REFLEX and PLANCK Galaxy Clusters as well as PLANCK and WMAP CMB Results

Planck Collaboration 2013
Hinshaw et al. 2013

Böhringer et al. 2014
Böhringer et al. 2014
Effect of Massive Neutrinos
Relativistic neutrinos can diffuse out the density fluctuations (peaks)

Power spectrum of the matter density fluctuations

Neutrino mass: $\sum(m_{\nu}) = 0, 0.06, 0.17, 0.4, 0.6$ eV

CMB normalisation

clusters
Fit to the observations for $M_\nu = 0.17$ eV (and mass bias = 24%)

Formal consistency for $M_\nu = 0.17 - 0.7$ eV

Böhringer & Chon 2015; Böhringer 2018
Redshift space distortions (brown) and gravitational lensing (green & grey) also show a lower amplitude of the density fluctuations than expected.
Planck CMB lensing

Planck Collaboration 2015

\[ \sigma_8 \Omega_m^{0.25} = 0.622 \pm 0.013 \]

\[ \sigma_8 \Omega_m^{0.25} = 0.592 \pm 0.021 \]

\[ \sigma_8 h^{-1} \Omega_m^{-1/4} = 1.59 \pm 0.05 \]
Aspects of Large-Scale Structure
Cluster Mass Function

Böhringer, Chon, Fukugita 2017
Cluster Mass Function and Mass Fraction using different parametrised recipes

a = Despali et al. 2016
b = Watson et al. 2013
c = Tinker et al. 2008 with cosmological marginalisation
d = Tinker et al. 2008 with marginalisation and $H_0$ variation

Böhringer, Chon, Fukugita 2017
Cluster Mass Fraction of Cosmic Matter

14 \pm 1\% \text{ in groups and clusters} \quad M_{200} > 10^{13} M_{\odot}

4.4 \pm 0.4\% \text{ in clusters} \quad M_{200} > 10^{14} M_{\odot}
Fraction of Cosmic Matter in Collapsed Objects

Using results from the Sloan Survey (SDSS) we compare the matter in clusters at larger scale to those in galaxy halos.

From galaxy number counts in SDSS we get the light density (Blanton et al. 2001, Masaki et al. 2012)

The mass-to-light ratio comes from lensing measurements in the halos of galaxies confirmed by similar results from galaxy dynamics (McKay et al. 2001, 2002)

\[(M/L_r)_{r200} = 90 \pm 20 \, h^{-1}\]
Fraction of Cosmic Matter in Collapsed Objects

assumed $\Omega_m = 0.282$

Asymptotic mass fraction = 28%

Fukugita & H.B. 2019
Most of the mass in Dark Matter halos is in the mass range $10^{12} - 10^{14} \, M_{\odot}$

Fukugita & H.B. 2019
Spatial modulation of the density of peaks (clustering):

The cluster distribution traces the matter distribution in a „biased“ (amplified) way

Biasing:

\[ \tilde{P}(k) = b^2 \cdot P_{DM}(k) \]

\[ b(M, z) = 1 + \frac{\Delta_*}{\sigma^2(M, z)} - \frac{1}{\Delta_*} \]

biased (amplified) probe of very large scales

Mo & White 1996
Sheth & Tormen 1999
Tinker et al. 2010
The lines give the prediction of the Concordance Cosmological Model with WMAP 5yr parameters.

Balaguera-Antolinez et al. 2010
The amplitude of the $P(k)$ increases with increasing lower mass limit. Increase of the amplitude (above) for 6 volume limited subsamples.
Local Cosmography
Mimicking an accelerating Universe

SN Ia in the nearby Universe are closer and appear brighter for high $H_0$ for given $z$ – correcting to higher magn. \( \Rightarrow \) less curvature in the plot \( \Rightarrow \) lower $\Lambda$

For $\Lambda \sim 0$ one would need an at least 300 Mpc large void with a density deficit of about 50% - our results shown in the following can rule this out!

Perlmutter et al. 1999
Mimicking an accelerating Universe

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## Different Hubble constants

<table>
<thead>
<tr>
<th>Source</th>
<th>Hubble constant</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Planck (2018)</td>
<td>67.4 ± 0.5</td>
<td>km/s/Mpc</td>
</tr>
<tr>
<td>Freedman et al. 2012 (HST-KP)</td>
<td>74.3 ± 1.5 ± 2.1</td>
<td>km/s/Mpc</td>
</tr>
<tr>
<td>Riess et al. 2011</td>
<td>73.8 ± 2.4</td>
<td>km/s/Mpc</td>
</tr>
<tr>
<td>Tully et al. 2014</td>
<td>75.2 ± 3.0</td>
<td>km/s/Mpc</td>
</tr>
<tr>
<td>Riess et al. 2018</td>
<td>73.24</td>
<td>km/s/Mpc</td>
</tr>
<tr>
<td>Riess et al. 2019</td>
<td>74.03 ± 1.42</td>
<td>km/s/Mpc</td>
</tr>
</tbody>
</table>

Currently hot debate between Riess et al. (2018,19) and Shanks et al. (2018, 19a,b):

**Shanks:** zero point offsets of Gaia Cepheid paralaxes  
“calibrated” with AGN  
local underdensity  
⇒ $H_0 = 73.4 \rightarrow 68.9$ km/s/Mpc

**Riess:** both claims are wrong, (complex dependence of zeropt. offsets)
Galaxy clusters: excellent tracers of the large-scale matter distribution

2 slices through the Millenium dark matter simulations
black points = clusters    colour scale = matter density
Cluster bias in the Millenium simulation for counts in cells (L = 89.3 Mpc [left] and 178.6 Mpc [right]) for clusters with $M_{200} > 0.5 \times 10^{44}$ M$_{\text{sun}}$. Bias factor is about 2.1.

\[
\text{Overdensity : } \Delta = \frac{\rho - \bar{\rho}}{\bar{\rho}}
\]

Böhringer, Chon, et al. (2019)
CLASSIX (all extragal. Sky)

Red square: excluding the Virgo-cluster region  
Böhringer, Chon, et al. 2019
We can avoid the ambiguity problem by constructing the density distribution for different volume limited sub-surveys:

![Combined cluster density distribution]

Cumulative density profile for cluster and matter

Matter density in CLASSIX: $-30 \pm 15\%$ for radius $< 100$ Mpc

Böhringer et al. 2019
Local underdensity in the galaxy distribution in the South Galactic Cap

Whitbourn & Shanks 2014

(see also Keenan et al. 2012)
REFLEX cluster density distribution in the North and South Galactic Cap (in the southern sky)

South galactic cap region

North galactic cap region in South

Böhringer, Chon, et al. 2015
Change of $H_0$ with Underdensity

An underdensity of -30 % $\Rightarrow$ change in Hubble parameter by 5.5 (+2.1 – 2.5)%

$$H_0 = 67.4 + 0.5 \Rightarrow 71 (+1.5) \text{ km/s/Mpc} \Rightarrow 74.0 \text{ km/s/Mpc}$$

Planck Collaboration 2016

Riess et al. 2019

Note: that the $H_0$ measurement of Riess et al. covers a larger volume, in which this effect is diluted (smaller)!

Size of the local underdensity: $\sim 100 \text{ Mpc}$

in comoving coordinates $\sim 90 \text{ Mpc}$

Variance at 90 Mpc („spherical top-hat“) radius $\sim 10 – 12$

$\Rightarrow$ a -30 +- 15% underdensity is a 1.3 – 3.7 sigma effect
Probing the Magnetic Field in Galaxy Clusters
Through Faraday Rotation of Polarised Background Radio Sources

Hans Böhringer, Gayoung Chon, Philipp Kronberg
Introduction

We probe magnetic fields through rotation measures in polarised radio signal of background radio sources.

\[ RM = 811.9 \left( \frac{n_e}{1 \text{ cm}^{-3}} \right) \left( \frac{B_{\parallel}}{1 \mu \text{G}} \right) \left( \frac{L}{1 \text{ kpc}} \right) \text{ rad m}^{-2}. \]

Galaxy cluster sample: CLASSIX (NORAS and REFLEX)
- 8.25 ster of the sky \(|b_{\|}| > 20\) deg
- 1722 clusters (flux limit \(1.8 \times 10^{-12}\) erg s\(^{-1}\) cm\(^{-2}\))
  - cluster mass = \(0.02 - 19.1 \times 10^{14}\) M\(_{\odot}\)
  - total cross section (<\(r_{500}\)) = 208.3 deg\(^2\)

Radio source sample: 1383 RM\(s\) \(z > 0.05\) (several frequencies)

92 Radio sources in the sightlines of 65 clusters \((r < R_{500})\)
Corrected RM as a Function of Scaled Cluster Radius

\[ r_{500} = 0.957 L_{X,500}^{0.207} E(z)^{-1} \]

\[ M_{200} \text{ (median)} = 1.4 \times 10^{14} M_{\odot} \]

\[ RM \ (M_{200} > M_{\text{median}}) = 158 \text{ rad m}^{-2} \]
\[ RM \ (M_{200} < M_{\text{median}}) = 62 \text{ rad m}^{-2} \]

Böhringer, Chon, Kronberg (2016)
RM as a Function of Electron Column Density

assuming $L \sim 1$ Mpc
$I \sim 10$ kpc

$B \sim 0.18 \pm 0.05$ $\mu$G

magnetic fields of few $\mu$G

\[
\left( \frac{B_{\parallel}}{1 \mu G} \right) = 3.801 \times 10^{18} \left( \frac{\sigma(RM)}{\text{rad m}^{-2}} \right) \left( \frac{N_e}{\text{cm}^{-2}} \right)^{-1} \Lambda
\]

\[
\Lambda = (L/I)^{1/2}
\]

Böhringer, Chon, Kronberg (2016)
RM as Function of los integrated $n_e \times B$

$\frac{B^2}{8\pi} = \frac{3}{2} n k_B T$

ratio of magnetic to thermal energy density in the ICM:

$3-10 \times 10^{-3} (l/10 \text{kpc})^{-1/2}$

→ B-Field energy density is not much larger than 1% on average

Böhringer, Chon, Kronberg (2016)
Conclusion

- Galaxy Clusters are powerful probes for the study of the LSS and for cosmological tests
- Constraining $\Omega_m$ and $\sigma_8$ we find a discrepancy with the Planck results
- This may point to the effect of massive neutrinos
- We can reproduce the predicted halo mass function and biasing
- The cosmographical cluster distribution suggest a significant local underdensity of 100 – 140 Mpc size
- Magnetic fields contribute not much more than 1% on average to the energy content of the intracluster medium