Galaxy Cluster Scaling Relations for Cosmology

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EAYAM 2015
Galaxy Cluster Cosmology: How Does Dark Energy Affect The Growth of Large-Scale Structure?

Instead of measuring the rate of recession, measure the rate of growth → Galaxy Cluster Mass Function.

Freedman Solution

\[ R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R + g_{\mu\nu} \Lambda = \frac{8\pi G}{c^4} T_{\mu\nu} \]

A. Kravtsov

http://cosmicweb.uchicago.edu/filaments.html

43 Mpc/h70/side
From Cosmology to Astrophysics

A rich collection of observables allows for self-calibration...

Credit: Volker Springel
Simulation code: Gadget-2
http://www.mpa-garching.mpg.de/galform/data_vis/

Dark Matter Halo
Significant amount of structure.
Lensing

kSZE
Proper velocity.

Temperature
Shallow Radial Dependence.

tSZE
Smooth and Uniform

Shocked gas
From merger activity.
The Sunyaev-Zel’dovich Effect

\[ Y_{\text{cyl}} = \int y \, d\Omega \, dl \]

\[ d\Omega = 2 \times R_{2500} \]

\[ Y_{\text{sph}} = \int y \, dV \]

\[ \Delta T_{\text{SZE}} / T_{\text{CMB}} = f(x) \, y = f(x) \int n_e \frac{k_B T_e}{m_e c^2} \sigma_T \, dl, \]


2/10/2015

N. Czakon: EAYAM 2015
Why SZE?
Mass Limit Constant with Redshift

- Lensing can eventually help with calibration
- X-Ray and SZE detect a lot of clusters! More to come with eROSITA!
- Need to find a way to calibrate observables with mass....

Planck 2013 XXIX. SZE Catalog

M_{500} | Y_{500}?
Why SZE?

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Planck 2015 XXVII. SZE Catalog

N. Czakon: EAYAM 2015
Why SZE? Self-Similarity Seems to Work... Insensitive to Cluster Astrophysics.....


Simulations and observations agree, Ysz is a low scatter mass proxy.

Can make a similar proxy with X-Rays:

\[ Y_X = M_{gas} \times T_X \]
BOXSZ: Bolocam XSZ

12-14' Ø maps 1' PSF
140 GHz (& 268 GHz)

45 clusters, 2006-2012
\langle z \rangle = 0.4
k_B T \geq \approx 5 \text{ keV}
Decade in mass

Corrected for selection effects. No redshift, mass, or morphology dependence….


**$Y_{sz}$ vs. $M_{tot}$: Comparison with Other Analyses**

**Czakon, 2014**

**Bonamente, 2008**

**Andersson, 2011**

**Planck Early results, 2011**

Bender, 2014.  
$Y_{sz}$ : APEX-SZ vs. $M_{gas}$  
P11/B08 measure $\sim 1.4$


How can we compare these results independent of $M_{tot}$?  
Compare the mass proxies directly:

$Y_{sz}$ vs. $M_{gas}$ or $Y_{sz}$ vs. $Y_X$ ......

| Name          | SZE data | X-ray data | Proxy | $\Delta$ | $\beta^y|m$   |
|---------------|----------|------------|-------|---------|--------------|
| this work     | Bolocam  | CXO        | $M_{gas}$ | 2500    | 1.06 ± 0.12  |
| B08           | OVRO/BIMA| CXO        | HSE   | 2500    | 1.66 ± 0.20  |
| A11           | SPT      | CXO/XMM    | $Y_X$ | 500     | 1.67 ± 0.29  |
| P11           | Planck   | XMM        | $Y_X$ | 500     | 1.74 ± 0.08  |
Systematic Differences in Fit Method

OVRO/BIMA vs. Bolocam

Our Fitting Method
-> Similar Results

B08 Fitting Method
-> B08 Results

Sensitive to assumptions of intrinsic scatter...

![Graph showing comparison between different fitting methods and sources of uncertainty in $f_{\text{gas}}$ measurements.](image)

**Sources of Uncertainty in $f_{\text{gas}}$ Measurements**

<table>
<thead>
<tr>
<th>Source</th>
<th>X-Ray $f_{\text{gas}}$ (%)</th>
<th>SZE $f_{\text{gas}}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statistical Effects</td>
<td></td>
<td></td>
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<tr>
<td>Kinetic SZE</td>
<td>...</td>
<td>±4</td>
</tr>
<tr>
<td>Radio point sources</td>
<td>...</td>
<td>±4</td>
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<tr>
<td>Asphericity</td>
<td>±20</td>
<td>±10</td>
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<td>Systematic Effects</td>
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<tr>
<td>Instrument calibration</td>
<td>±6</td>
<td>±8</td>
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<td>X-ray background</td>
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<td>...</td>
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<tr>
<td>HSE</td>
<td>−10</td>
<td>−10</td>
</tr>
<tr>
<td>Isothermality</td>
<td>−5</td>
<td>−10</td>
</tr>
</tbody>
</table>

\( Y_{sz} \) vs. \( Y_x = M_{gas} T_x \) : Consistent Between Analyses

- Bender, 2014.
- \( Y_{sz} \) : APEX-SZ vs. \( M_{gas} \)

\[ 0.98 \pm 0.07 \]

- Czakon, 2014
- Bonamente, 2008
- Andersson, 2011
- Planck Early results, 2011

Systematic Differences in the X-ray Data
XMM vs. Chandra

(Schellenberger, 2014, arXiv:1407130)

Favors Chandra because of consistent self-calibration and calibration of column density measurements from 21 cm.

Possible culprit? XMM PSF....

From IM Stewart’s website: http://www.ast.uct.ac.za
Broken Power Law in $f_{\text{gas}}$...
Broken Power Law in $f_{\text{gas}}$....

\[ f_{\text{gas},2500} = f_0 \left( \frac{M_{2500}}{6 \times 10^{14} M_\odot} \right)^\alpha \]
Conclusion

• We measured the $Y_{\text{SZE}} - M_{\text{tot}}$ scaling relations for 45 massive clusters using Bolocam SZE data and Chandra X-ray data

  http://irsa.ipac.caltech.edu/Missions/bolocam.html

  – These are much shallower than other observational analyses and predicted by simulations.

• Systematic differences between different analyses make it difficult to get to the root of the problem:
  – Different mass and redshift ranges for various cluster samples.
  – Non-uniform fitting methodologies.
  – Inconsistent Chandra and XMM temperature measurements.

• The inconsistencies between our results and other analyses could be partially explained by an $f_{\text{gas}} - M_{\text{tot}}$ model with a broken power law...which is not well constrained observationally in the region $10^{14} M_{\odot}$.

• Possible astrophysics? Too soon to tell...