Toward understanding mass proxies of galaxy clusters for modern cosmology

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Outline

- Galaxy clusters as cosmological tools
- Calibrating mass and mass proxies
- Summary
Galaxy clusters provide a powerful and well-established cosmological probe. Historically, galaxy clusters provided some of the first evidence for a low density universe (White et al. 93, Nat., 336, 429). Clusters currently receive much more attention as a potential probe of the dark energy (DE) equation of state parameter $w$. The evolution of the mass function for the sample in Vikhlinin et al. (09) constrains $w = -1.14 \pm 0.21$ assuming a constant $w$ and flat universe. The combination of the mass function and gas mass fraction of galaxy clusters, as well as CMB, SNIa, and BAO, can constrain $w$ at late and early times, $w_0 = -0.88 \pm 0.21$ and $w_{et} = -1.05^{+0.20}_{-0.36}$ (Mantz et al. 10). Current results remain statistically limited.
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**Galaxy cluster as cosmological tools**

- Self-similarity & mass proxies (more references in the next page)
Galaxy clusters as cosmological tools

- References calibrating their self-similarity and mass proxies

  - Before X-ray satellites: Mitchen et al. 77; Mushotzky et al. 78; Henry & Tucker 79; etc.
  - EXOSAT, Einstein, & Ginga X-ray data: Edge & Stewart 91; Henry & Arnaud 91; David et al. 93; etc.
  - ROSAT X-ray data: White et al. 97; Markevitch 98; Markevitch et al. 98; Arnaud & Evrard 99; Mohr et al. 99; Vikhlinin et al. 99, 02; Xue & Wu 00; Finoguenov et al. 01; Horner 01; Xu et al. 01; Ikebe et al. 02; Reiprich & Böhringer 02; Sanderson et al. 03; Ettori et al. 04; Ota & Mitsuda 05; O'Hara et al. 06; Chen et al. 07; etc.
  - Chandra & XMM-Newton data: Ettori et al. 04; Arnaud et al. 05, 07; Kotov & Vikhlinin 05; Pratt & Arnaud 05; Maughan et al. 06, 07, 08; Zhang et al. 04, 06, 07, 08, 09; Vikhlinin et al. 06, 09a, 09b; Pacaud et al. 07; Pratt et al. 09, 10; Sun et al. 09; etc.
  - Lensing + X-ray: Miralda-Escude et al. 95; Squires et al. 96; Wu & Fang 96, 97, Wu et al. 98; Allen 98; Smith et al. 05; Zhang et al. 05, 07, 08, 10; Bardeau et al. 07; Mahdavi et al. 08; Vikhlinin et al. 09; Leauthaud et al. 10; Richard et al. 10; Okabe et al. 10; etc.
  - X-ray + optical: Girardi et al. 96; Wu et al. 99; Popesso et al. 2005; Zhang et al. 11; etc.
Galaxy cluster as cosmological tools

- Scaling relation uncertainty is the dominant source of systematic error in dark energy studies

- High-precision cosmology with the mass function and baryon-mass fraction of galaxy clusters requires the knowledge of the normalization, slope, intrinsic scatter and evolution of the mass vs. mass proxy relations (e.g., Smith et al. 2003; Zhang & Wu 2003; Stanek et al. 2009, 2010; Cunha & Evrard 2009)

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**TABLE 1**

<table>
<thead>
<tr>
<th>Model</th>
<th>Cooling</th>
<th>$n_e$</th>
<th>$T$</th>
<th>Metallicity ($Z_\odot$)</th>
<th>Line Style</th>
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</thead>
<tbody>
<tr>
<td>I</td>
<td>No</td>
<td>Gas-traces-mass</td>
<td>e.h.e.</td>
<td>0.3</td>
<td>Dot-dashed</td>
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<tr>
<td>II</td>
<td>No</td>
<td>e.h.e.</td>
<td>Isothermal</td>
<td>0.3</td>
<td>Dashed</td>
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<tr>
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<td>Isothermal</td>
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<td>Dotted</td>
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<tr>
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<td>e.h.e.</td>
<td>0.3</td>
<td>Solid</td>
</tr>
<tr>
<td>V</td>
<td>Yes</td>
<td>Gas-traces-mass</td>
<td>e.h.e.</td>
<td>0.3($t/t_0$)</td>
<td>Dash-dot-dot-dotted</td>
</tr>
</tbody>
</table>

a Obtained by solving the equation of hydrostatic equilibrium.

Fig. 1.—Expected redshift distribution of SZ cluster counts with $S_p = 15$ mJy at frequency 30 GHz. Results for five models with and without radiative cooling and under different assumptions of the intracluster gas in Table 1 are shown. Inset: Minimum mass threshold against cluster redshift.
Galaxy cluster as cosmological tools

- The eROSITA Surveys (4 yrs)
  Predehl et al. 2009
  - Survey
  - Solid Angle (sq.deg)
  - Exposure time (average)
  - 0.5-2 keV flux limit (AGN)
  - 2-10 keV flux limit (AGN)
  - 0.5-2 keV flux limit (Clusters)
  - Expected AGN (0.5-2 keV)
  - Expected AGN (2-10 keV)
  - Expected **Clusters** (0.5-2 keV)

<table>
<thead>
<tr>
<th>All-Sky</th>
<th>Deep</th>
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<tbody>
<tr>
<td>42000</td>
<td>200</td>
</tr>
<tr>
<td>2-3 ks</td>
<td>20-30 ks</td>
</tr>
<tr>
<td>~1.e-14</td>
<td>~4.e-15</td>
</tr>
<tr>
<td>~1.e-13</td>
<td>~3.e-14</td>
</tr>
<tr>
<td>~3.e-14</td>
<td>~8.e-15</td>
</tr>
<tr>
<td>1.76Mi</td>
<td>60,000</td>
</tr>
<tr>
<td>130,000</td>
<td>15,000</td>
</tr>
<tr>
<td><strong>72,000</strong></td>
<td><strong>6,500</strong></td>
</tr>
</tbody>
</table>
Calibrating mass and mass proxies

- WL-to-X-ray mass ratio of 1.09+/-0.08 (Zhang et al. 08)
- An X-ray selected, volume-limited (via the L-M relation in Zhang et al. 08) sample of 67 massive clusters @z~0.2
  - XMM-Newton X-ray data (PI: Zhang)
  - Subaru weak lensing data (PI: Smith)

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For a pioneer sample of ~30 clusters in the Local Cluster Substructure Survey
Calibrating mass and mass proxies

- **X-ray to weak lensing mass ratios**

- All 7 disturbed clusters
  
  $1.06 \pm 0.12$

- 6 disturbed ones ($A1914$)
  
  $0.97 \pm 0.08$

- All 5 undisturbed ones
  
  $0.91 \pm 0.06$

  $M^X/M^{WL} = (0.908 \pm 0.004) + (0.187 \pm 0.010) \log_{10}(\Delta/500)$

- All 12
  
  $0.99 \pm 0.07$

- 11 clusters ($A1914$)
  
  $0.94 \pm 0.05$
Calibrating mass and mass proxies

- Weak lensing mass vs. $T / Y_x / M_{\text{gas}}$
  - Intrinsic scatter $\sigma_{lnM}$, $M-T>M-Y_x>M-M_{\text{gas}}$ \( (8.3^{+6.3}_{-4.6}) \% \)
  - Anti-correlation (also found in simulations in Stanek et al. 10)

Okabe, Zhang et al. 10, red – undisturbed, blue – disturbed; solid – WL mass vs. X-ray mass proxies; dashed – X-ray mass vs. X-ray mass proxies
Calibrating mass and mass proxies

- **Fitting the slopes: M vs. L / M_{gas} / Y**
  - M-T, \( \sigma_{int} = ? \), slopes: ?, ?
  - M-Y, \( \sigma_{int} = ? \), slopes: ?, ?
  - M-M_{gas}, \( \sigma_{int} = ? \), slopes: ?, ?

(Zhang et al. in prep.)
Calibrating mass and mass proxies

- Probing biases in the mass proxies: AGN feedback & substructures

AGN feedback biases **X-ray luminosity** toward low values at different levels
- Substructure biases **velocity dispersion** toward higher values

Slope 4.02+/−0.33, self-similar
Int. scatter (27+/−3)%
Norm (CC: ▲) = 2 * norm(NCC: □)
Norm (relaxed) = 1.6 * norm (disturbed)
☆/☆: w/o AGN feedback (Puchwein+10)

Zhang et al. 2011
Calibrating mass and mass proxies

- Probing biases in the mass proxies: SF & SN / radio-galaxy feedback
  - heating from merging quenches the star–formation activity of galaxies in massive systems or feedback from SN and radio galaxies drives a significant amount of \textit{gas (gas mass)} beyond $r_{500}$
Summary

- For relaxed clusters
  - WL-to-X-ray mass ratio of 0.91+/-0.06 at r500
  - Mass bias increasing with the radius, $\frac{M_X}{M_{WL}} = (0.908 \pm 0.004) + (0.187 \pm 0.010) \log_{10}(\Delta/500)$

- Fixing the slope, gas mass has the lowest intrinsic scatter as the mass proxy
  - $\sigma_{\ln M(T)} > \sigma_{\ln M(Yx)} > \sigma_{\ln M(M_{gas})} = 8.3^{+6.3}_{-4.6} \% @ r_{500}$
  - Correlation between the temperature vs. gas mass deviations as mass proxies, $r = \sigma_{\ln M(T)} / \sigma_{\ln M(Yx)} = 0.575 \pm 0.224$, in agreement with Stanek+09's Millennium gas simulations

- Slopes of the WL mass vs. X-ray observable relations may be less dependent on the cluster dynamics than predicted

- Mass bias can be probed regarding cluster dynamics and physics
  - Substructures
  - Star formation
  - AGN, SN & radio–galaxy feedback
Thank you