Cluster Cosmology for the Next Decade

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+ many more ...
Cosmology with cluster counts

1. Where we stand today

Mantz et al., in prep.

See also e.g. Vikhlinin et al. 09ab; Mantz et al. ’08, ’10abc; Henry et al. ’09; Rozo et al. ’10; Allen et al. ’11; Kravtsov & Borgani ’12; Weinberg et al. ‘13; Benson et al. ’13; Planck Collaboration et al. ’13, ’15; de Haan et al. ’16.
Cosmology with cluster counts

Measurements of the number counts of galaxy clusters, as a function of mass and redshift, provide powerful constraints on cosmological parameters (“... galaxy clusters could emerge as the most powerful cosmological probe”, DOE Cosmic Visions Dark Energy Science report, arXiv:1604.07626)
Ingredients for cluster count experiments

[THEORY] The predicted mass function of clusters, \( n(M,z) \), as a function of cosmological parameters (\( \sigma_8, \Omega_m, w \) etc).

[CLUSTER SURVEY] A large, clean, complete cluster survey with a well defined selection function.

Current leading work spans X-ray (ROSAT), optical (Sloan Digital Sky Survey) and SZ surveys (SPT, ACT, Planck).

[MASS-OBSERVABLE RELATION] Well-calibrated scaling relation linking survey observable (e.g. \( L_x \), richness, SZ flux) and \( M,z \).
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Cluster surveys based on RASS

BCS (Ebeling et al. ’98, ’00). $z<0.3, \ F_x > 4.4 \times 10^{-12} \ erg \ cm^{-2} \ s^{-1}$  
[northern sky: 201 clusters]

REFLEX (Bohringer et al ’04). $z<0.3, \ F_x > 3.0 \times 10^{-12} \ erg \ cm^{-2} \ s^{-1}$  
[southern sky: 447 clusters]

Bright MACS (Ebeling et al. ’09) $z>0.3, \ F_x > 2.0 \times 10^{-12} \ erg \ cm^{-2} \ s^{-1}$.  
[all-sky: 34 clusters]

All three surveys based on ROSAT All-Sky Survey (RASS) (0.1-2.4keV). To minimize systematics, we use conservative flux limits and only the most luminous systems, with $L_x > 2.5 \times 10^{44} \ h_{70}^{-2} \ erg \ s^{-1}$ (224 clusters total).
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Separate into: 1) precise relative mass calibration 2) accurate absolute mass calibration

Vikhlinin et al. ’09
Mantz et al. ‘10
Precise relative mass calibration from X-ray data

10Ms of pointed Chandra and ROSAT observations for 139/224 survey clusters → re-measure $L_x$ + measure $M_{\text{gas}}$, $T_x$, $Y_x$ at $r_{500}$ (<15% scatter mass proxies)

Low scatter mass proxies → tight relation between survey observable and mass.

- $L_x$-$M$: ~40% scatter
- $M_{\text{gas}}$-$M$: ~10% scatter
- $T_x$-$M$: ~10-15% scatter

Mantz et al. 2016
Robust absolute mass calibration from weak lensing

Deep, high quality, multi-filter (BVRIZ) Subaru imaging for 50 massive clusters → accurate absolute mass calibration from weak lensing (WL) methods

WL masses (measured appropriately) expected to be approximately unbiased on average, with residual bias being calibrate-able with simulations

Bottom line: → ± 8% absolute mass calib. (2x better) + path forward.

Weighing the Giants (WtG)

A. von der Linden et al. 2014
P. Kelly et al. 2014
D. Applegate et al. 2014

Improved techniques for cluster WL +(critically) employ **BLIND ANALYSIS**.
Analysis method

To determine robust cosmological constraints one should solve simultaneously for the cosmology+scaling relations, accounting fully for survey biases and all covariance, and marginalizing over systematic uncertainties.

Such analyses can be carried out efficiently using Markov Chain Monte Carlo (MCMC) methods.

Conservative allowances for systematic uncertainties

The results in the following slides include conservative allowances for systematic uncertainties associated with e.g. the survey construction, mass function, and mass-observable scaling relations.

Dominant systematic: ±8% uncertainty in absolute mass calibration
Cosmology: results on $\sigma_8$, $\Omega_m$

**Flat $\Lambda$CDM model:**

$\Omega_m = 0.260 \pm 0.030$

$\sigma_8 = 0.830 \pm 0.035$

68% confidence limits, marginalized over all systematic uncertainties.
(Standard priors on $\Omega_b h^2$ and $h$ included.)
The impact of improving mass calibration

Addition of Chandra + WL mass calibration → substantial boost in cosmological constraining power.

Key advances:


2010→2014: inclusion of Weighing the Giants weak lensing mass calibration.
Comparison: RASS vs. other cluster experiments

Good agreement between X-ray and SZ cluster counts when employing consistent absolute mass calibration.

Also consistent with optical (Rozo et al. 10) + earlier X-ray (Vikhlinin et al. ‘09) results.

Comparison vs. primary CMB

No tension between constraints from cluster counts and primary CMB (either WMAP or Planck) when employing full statistical framework and robust WL mass calib.

Agreement maintained with recent update on Planck optical depth to reioniz., $\tau$ (arXiv:1605.02985)
Results on dark energy (clusters only)

Flat, constant $w$ model:

- $\Omega_m = 0.261 \pm 0.031$
- $\sigma_8 = 0.831 \pm 0.036$
- $w = -0.98 \pm 0.15$

68% confidence limits, marginalized over all systematic uncertainties. (Standard priors on $\Omega_b h^2$ and $h$ included.)

Clear detection of the effects of dark energy on cluster growth (suppression).

Mantz et al. 2015
Cluster counts vs. independent techniques

Flat, constant w model:

- Clusters (Mantz et al. ‘15)
- CMB (WMAP9+SPT+ACT)
- SNIa (Suzuki et al. ’12)
- BAO (Anderson et al. ‘14)

Combined constraint (68%)

- $\Omega_m = 0.295 \pm 0.013$
- $\sigma_8 = 0.819 \pm 0.026$
- $w = -0.99 \pm 0.06$

Independent techniques all consistent with cosmological constant.
Cluster constraints highly competitive with other leading methods.
Cosmology with cluster counts

2. The road ahead
The first next step

While X-ray and optical studies have laid down a robust low-z anchor, SZ surveys are now delivering unparalleled cluster catalogs at high-z.

Current RASS (X-ray) and SPT (SZ) catalogs together trace the growth of massive clusters out to $z \sim 1.5$.

To date these catalogs have been analysed separately.

Their optimal combination (+Chandra +WL) should → significant near term boost in DE constraints (expect 2017).
Surveys on the near and mid-term horizons (2017-2023)

Projects:
- Optical/NIR: (DES, HSC), Euclid, LSST
- mm: SPT3G, AdvACT, CMB-S4
- X-ray: eROSITA

Strengths:
- Optical/NIR: cluster finding, photo-zs, WL mass cal.
- mm: high-z cluster finding, CMB-WL mass cal.
- X-ray: cluster finding, low-scatter mass proxies.

These projects are each powerful (finding $10^5$ clusters) but also exceptionally synergistic: far stronger in combination than alone $\rightarrow$ essential to coordinate.
The discovery space of near and mid-term surveys
The (continuing) need for Chandra

The prime discovery space for cluster science is high-z (z>1). Chandra follow-up essential to provide precise relative mass calibration (XMM-Newton/eROSITA PSFs insufficient to resolve point sources from diffuse X-ray emission at high-z).

Ideally we would gather \( M_{\text{gas}}, T_x, Y_x \) for a reasonable subsample (few hundred) clusters at \( z>1 \).

But gathering the necessary counts (1000-2000/target) is expensive (\( \geq 100 \text{ks/cluster} \)).

How can we do this within a reasonable total Chandra budget?
A low-cost mass proxy for cluster cosmology

The center-excised X-ray luminosity, $L_{ce}$, can serve as an efficient low-scatter (<20%) mass proxy for massive clusters, being far `cheaper’ to measure than $M_{gas}$, $T_x$, $Y_x$ (100-200 vs. 1000-2000 counts).

Moreover the relatively short exposures needed to measure $L_{ce}$ would also enable a rich array of AGN science (see R. Canning talk).
So how well could we do?

Assume: Chandra investment of 0.5-1.0Ms/yr over 5-10 years (for ~5Ms new data, c.f. current ~10Ms at z<1) → Lce for ~250 clusters at z>1.

Fisher matrix forecast for improvement in DETF FoM for SPT-3G-like survey as number of follow-up targets increases.

Targets can be optimized for a given question but should be somewhat representative.

Substantial FoM boost.

The full astrophysical exploitation of high-z clusters (detailed thermodynamic properties and metal content) will need to await Athena/X-ray surveyor.
Conclusions

Measurements of cluster counts provide powerful constraints on dark energy and fundamental physics, competitive with the best other techniques.

The results on $\sigma_8$ and $\Omega_m$ from current X-ray/SZ/optical surveys agree well with each other, and with the primary CMB, when a consistent, rigorous absolute mass calibration is adopted.

The prospects for (rapid) improvement are outstanding.

A significant but reasonable investment of Chandra time over the next 5-10 years could have a significant impact, opening up the $z>1$ universe to cluster cosmology + cluster AGN science.