Precision Cosmology from Future Galaxy Cluster Surveys

How do we control various systematics from observations and theory?

Hao-Yi Wu
KIPAC, Stanford University, USA

(in collaboration with Risa Wechsler, Eduardo Rozo, and Andrew Zentner)

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Cosmology from Galaxy Cluster Counts

- Galaxy clusters probe:
  - Structure growth
  - Expansion rate

Figure: Haiman ‘01 (w= -1; -0.6; -0.2; no DE)
Current Cosmological Constraints from Clusters

Mantz et al. ‘09 for ROSAT and Chandra Clusters; also see Vikhlinin ‘09

Rozo et al. ‘09 for SDSS Clusters; also see Gladders ‘07 for RCS Clusters
Outline

• Introduction
• Part I: Follow-ups and observable-mass distribution
  • External constraints from follow-up observations
  • Properties of follow-up mass tracers
  • Optimization of the follow-up target selections
• Part II: Theoretical uncertainties in mass function and halo bias
  • Requirements for future surveys
  • Comparison of different mass and redshift regimes
The Dark Energy Survey

• Galaxy clusters selected from optical imaging (~10⁵), 40% scatter
• Survey area = 5000 deg²; overlap with the South Pole Telescope (SZ survey)
• Survey depth: \( M_{\text{th}} = 10^{13.7} \, h^{-1}M_{\odot} \) and \( z_{\text{max}} = 1 \)

Self-calibration Analysis

• Using sample variance (clustering of galaxy clusters) to self-calibrate the observable-mass distribution (Lima & Hu ‘04, ‘05).

The Dark Energy Figure of Merit (FoM)

• \( \text{FoM} := 1/[(\sigma(w_a)\sigma(w_p))] \propto 1/(\text{area of the error ellipse of } w_0, w_a) \)
• Current Data (WMAP5+SNe+BAO+X-ray clusters): 15.5 (Mantz ‘09)
• DETF Report (Albrecht ‘06): Stage III CL+Planck prior:
  • Optimistic: 35.21
  • Pessimistic: 6.11
Part I: Follow-ups for DES-like Optical Surveys

Cluster Counts

Follow up part of the sample in a bin (measure the mass more precisely)

- The mean and variance of the follow-up mass measurements can further constrain the O-M distribution. The variance is particularly crucial for constraining the scatter.
- Optimized follow-up strategy can further improve the FoM.
- With 100 follow-up clusters, FoM can be improved by 77%

Wu, Rozo, and Wechsler, arXiv:0907.2690; Also see Majumdar and Mohr ‘03, ‘04
Complications: Scatter and Bias of Follow-up Mass Tracers

Scatter: mild degradation

Bias: strong degradation

- Lowing the scatter in survey sample can further improve the power of follow-ups.
- The bias in follow-up mass measurements needs to be controlled at 5% level.

Also see Cunha ‘08 for cross-calibration; Nagai ‘07, Rudd ‘09 for possible bias...
Optimization: Different Strategies for X-ray and SZ

- Clusters are weighted by their observational cost $\propto 1 / \text{Flux}$
- X-ray follow-ups
  - Cost is sensitive to redshift
  - Small program: low-z clusters
  - Large program: clusters span a redshift range
- SZ follow-ups
  - Cost is sensitive to mass
  - Small program: massive clusters span over a redshift range
  - Large program: some less-massive clusters
Optimization: Different Strategies for X-ray and SZ

- X-ray cost proxy
- SZ cost proxy

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- X-ray, $d_{\text{XMM}}=47.1\%$, cost = 1640 (210 ks with XMM)

- SZ, $d_{\text{SPT}}=109.9\%$, cost = 64640 (8400 ks with XMM)
Optimization: FoM as a function of Telescope Time

• Optimizing the FoM at a given cost can significantly improve the FoM. To achieve a given FoM, the optimization can reduce the cost by an order of magnitude over random selection.

Cost proxy $\propto 1 / \text{Flux}$; corresponding telescope time is shown on the top.
Part II: Theoretical Uncertainties in Halo Mass Function and Halo Bias

• How does the uncertainty in mass function and halo bias impact the cosmological constraints from clusters? What are the required accuracies of them in future cluster surveys?

• Current theoretical uncertainties in the shape of mass function (~20%) can lead to significant systematic errors in future surveys. We compare Sheth-Tormen ‘99 and Tinker ‘08 fitting formulae as an example.

Wu, Zentner, and Wechsler, arXiv: 0910.3668

Also see Wu et al. ‘08 for the effects of assembly bias
Modeling the Uncertainties in Mass Function and Halo Bias

- We discretize the mass function and halo bias to describe the uncertainty in a parameterization-independent way.
- The Tinker function is used as the fiducial model.
- We include $f_i$’s and $g_i$’s as additional nuisance parameters and study their impacts.

Also see Cunha & Evrard ‘09 for the study of parameters in the Tinker function.
Degradation in the Dark Energy Figure of Merit

Top: unknown O-M
Bottom: known O-M
Left: DES assumption
Right: SPT assumption

• For DES, percent-level accuracy on MF is required.
• The requirement on halo bias is less stringent.

Uncertainty in halo bias
Uncertainty in mass function

DES assumptions: \( M_{th} = 10^{13.7} \, M_{\text{sun}}/h; \) Scatter = 0.4; Area = 5000 deg\(^2\)
SPT assumptions: \( M_{th} = 10^{14.1} \, M_{\text{sun}}/h; \) Scatter = 0.2; Area = 2000 deg\(^2\)
Effects of Survey Area

- Future full-sky optical surveys will require sub-percent level accuracy in mass function.
- The required constraints are almost independent of $z_{\text{max}}$ and assumptions of observable--mass distribution.
- Optical surveys have more stringent requirements than X-ray and SZ surveys.

Most stringent requirement will come from a full-sky optical survey.
Comparing Bins

- We tighten the MF in one bin at a time and calculate the FoM improvement.
- This pattern reflects the CMB prior, cluster counts, and degeneracy between scatter and MF.
- Improving the mass function accuracy in low redshift and low mass will be the most beneficial.

Lowest z: longest lever arm for dark energy constraints

Lowest mass: greatest cluster counts
Comparing Bins

More general O-M assumption
Summary

• We studied how follow-ups for future optical galaxy cluster surveys can improve the dark energy constraints.

• The systematic errors of the follow-up mass tracers need to be controlled at ~5% to avoid significant degradation in FoM.

• Optimization can reduce the observational cost by up to an order of magnitude. Less than 200 X-ray or SZ clusters can improve the FoM by 50% in DES-like surveys.

✓ **Note for observers:** Follow-ups over a wide range of mass and redshift are the most effective!

• We studied the impact of theoretical uncertainties in mass function on future surveys.

• Future optical surveys will require percent-level accuracy in mass function to avoid severe degradation in the FoM.

✓ **Note for simulators:** The low mass and low redshift regimes are the most important to accurately calibrate mass function.