Precision Cosmology From Galaxy Cluster Surveys: Observational and Theoretical Challenges

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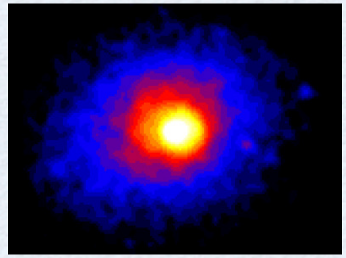
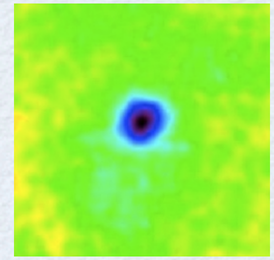
Berkeley Cosmology Seminar, September 14, 2010

Optical: DES, Pan-STARRS, LSST

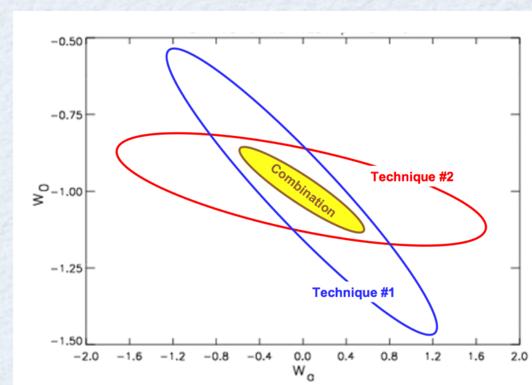
X-ray: Chandra, eROSITA, WFXT

Sunyaev-Zel'dovich: SPT, ACT, Planck





- How do we control various systematics to achieve precision cosmology?
- How do we combine multi-wavelength observations of galaxy clusters?



Cosmology from Galaxy Cluster Counts

- Galaxy clusters probe
  - Expansion of the universe
  - Growth rate of cosmic structures

- In a survey, we measure cluster number as a function of
  - Mass proxy M_{obs} (e.g. optical richness, X-ray properties, SZ signals, weak lensing)
  - Redshift
- Then we infer
  - M_{obs}-M distribution (scaling relation, scatter)
  - Dark matter halo mass function
  - Constraints on cosmological parameters

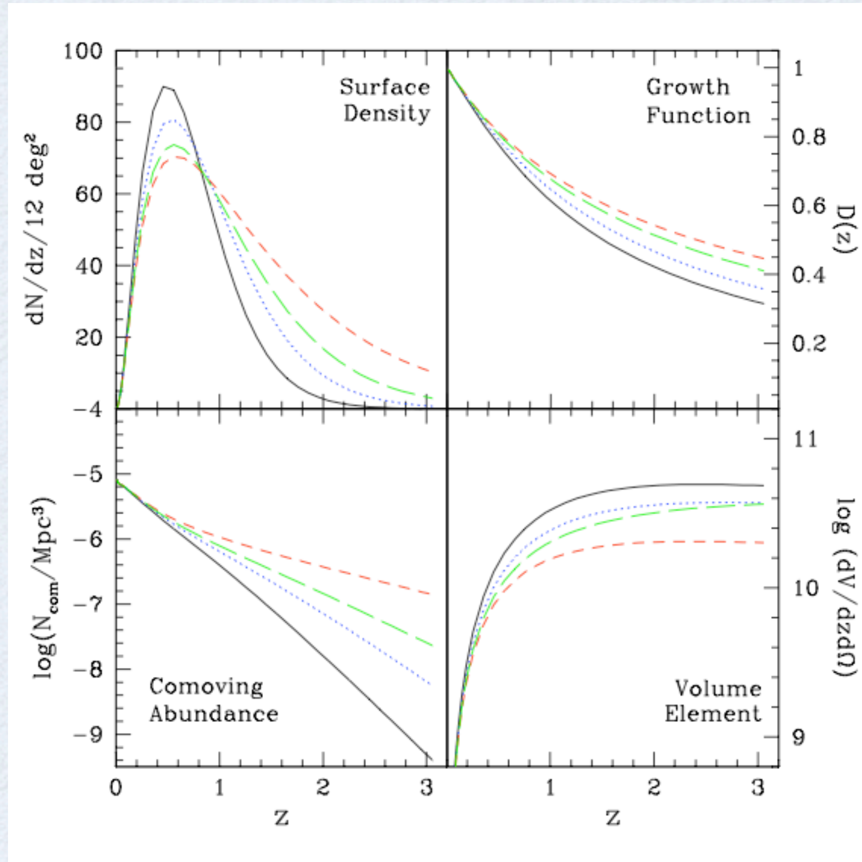
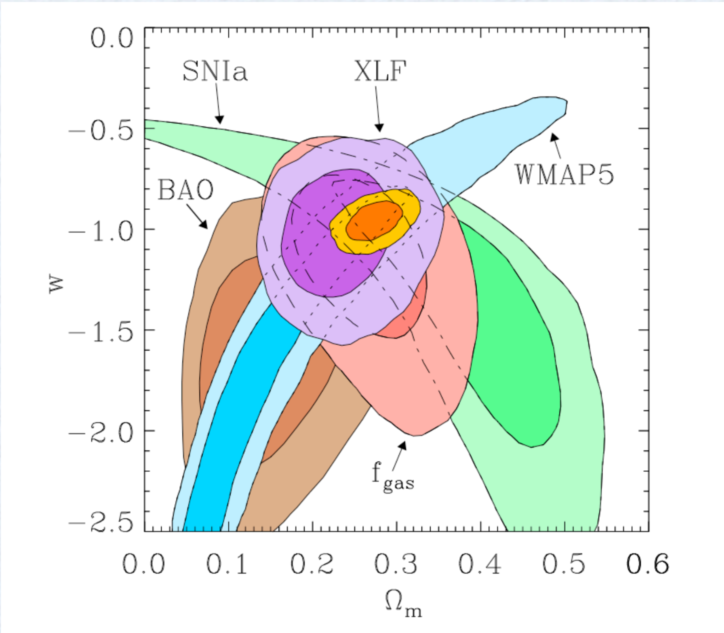
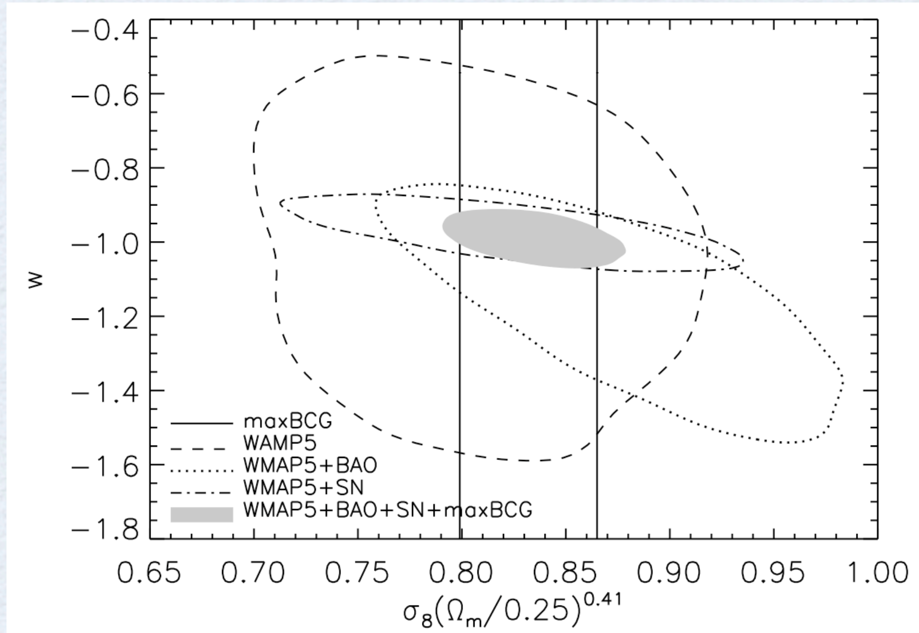


Figure: Haiman '01 (w= -1; -0.6; -0.2; no DE)
Also see Levine '02; Gladders 07; Rozo '08

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

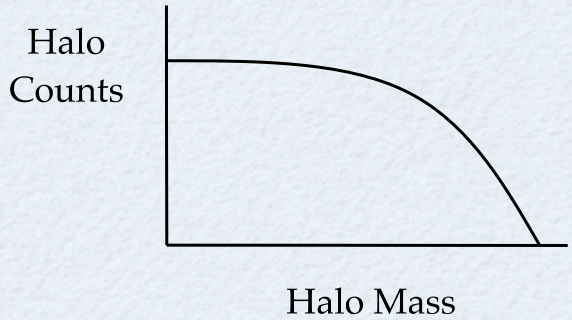
Outline

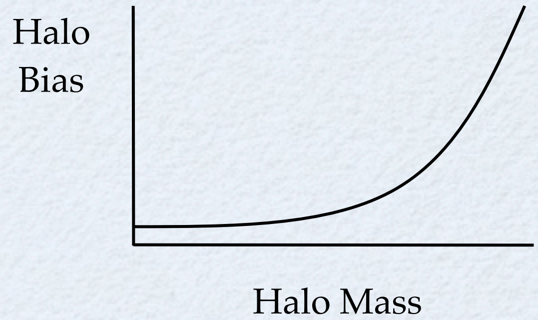
- Introduction
- Part I: Observable-mass distribution
  - Self-calibration
  - Follow-up mass calibrations
- Part II: Theoretical uncertainties
  - Theoretical uncertainties in mass function and halo bias
  - The effect of assembly history

PART 1: Observable-Mass Distribution

- Self-calibration
  - Statistical errors in scatter
  - Systematic errors in scatter
- Follow-up mass calibrations
  - X-ray and SZ follow-up strategies
  - Stacked weak lensing

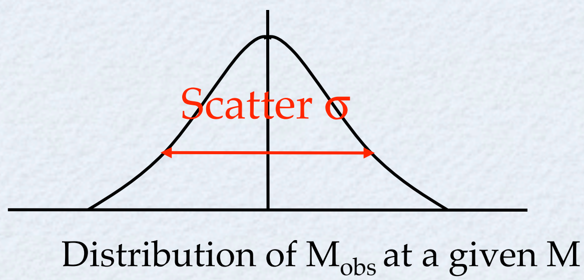
A Cartoon Picture of Self-Calibration





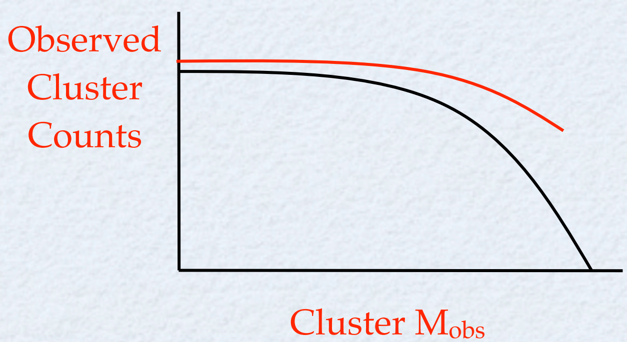
Halo bias definition:
$b = \delta_{halo} / \delta_{dark\ matter}$

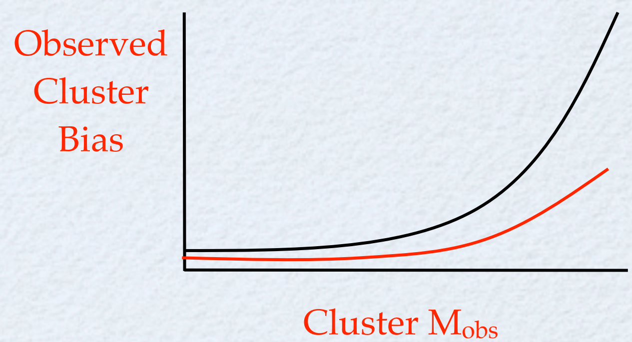
+



and other complications e.g., survey selection, completeness, and purity

=>

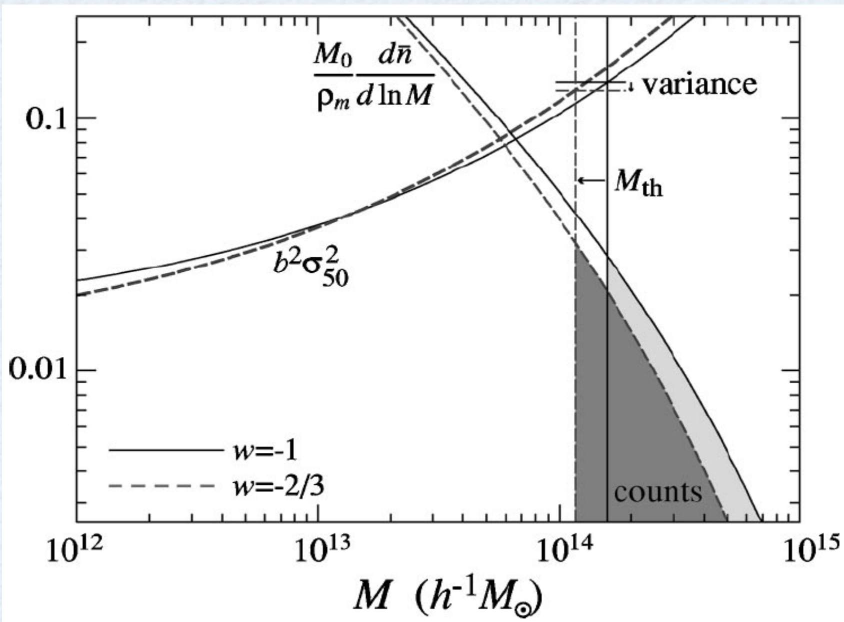


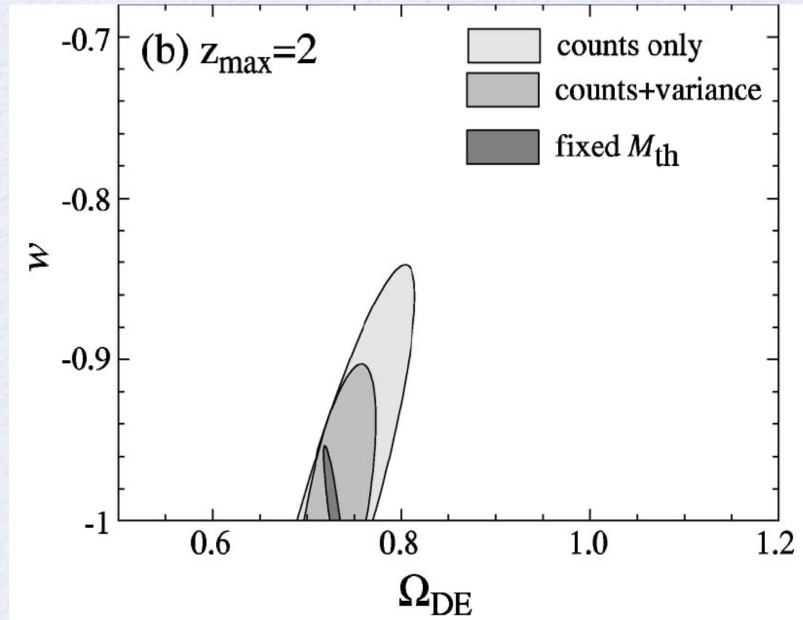


Fitting scatter and other nuisance parameters to match both cluster counts and bias will provide a consistency check and also improve the cosmological constraints.

Self-Calibration for Cluster Observable-Mass Relation

In a counts-in-cells analysis, counts and variance (halo bias) can self-calibrate observable-mass distribution and improve dark energy constraints

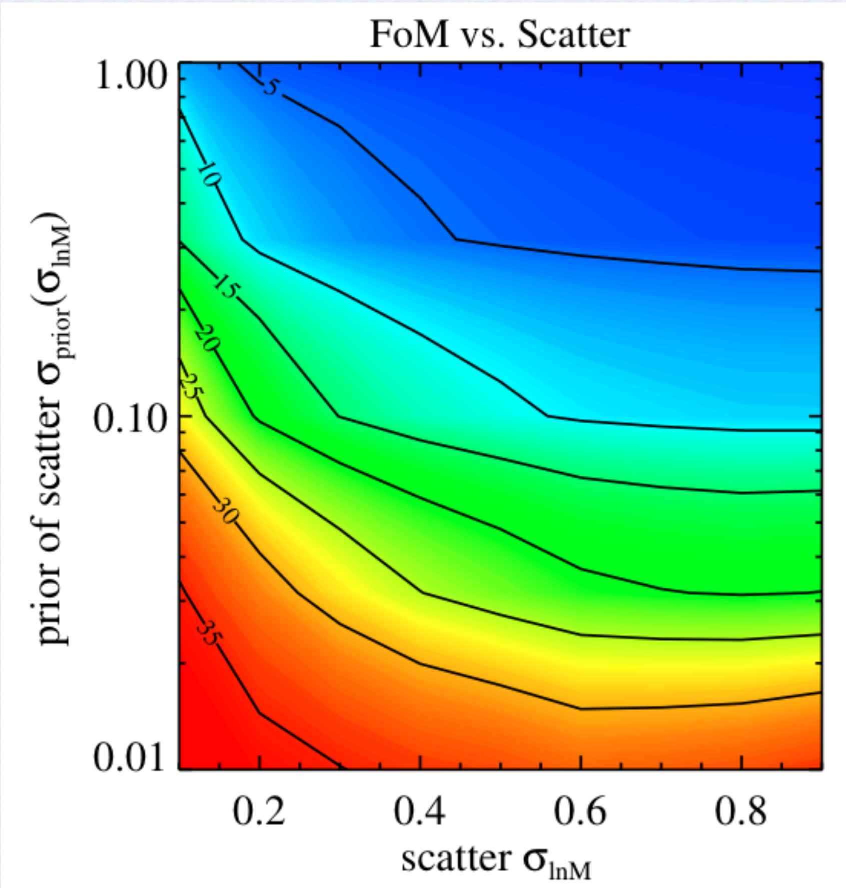




$$n(M^{obs}) \propto \int dM n(M) P(M^{obs}|M)$$
$$b(M^{obs}) \propto \int dM b(M) n(M) P(M^{obs}|M)$$

Figures from Lima and Hu '04, '05; also see Hu and Cohn '06; Holder '06, etc.

The Effect of Scatter: Statistical Errors

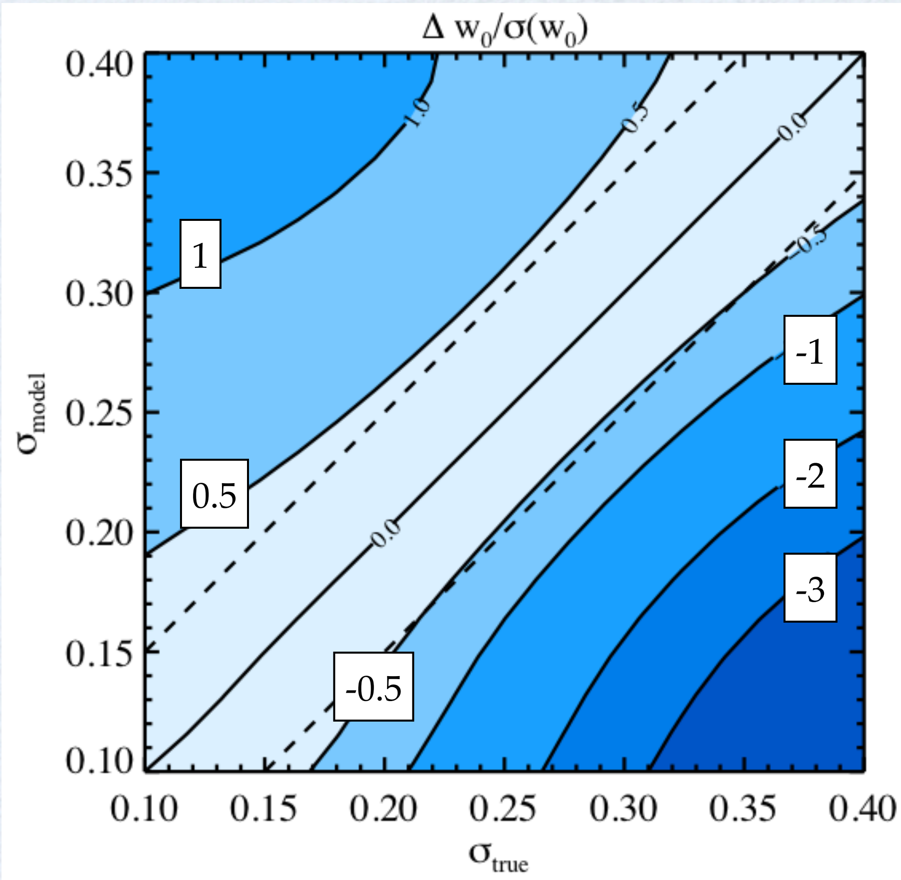


- Tightening the prior of scatter is more important than tightening the scatter itself.
- Optical surveys tend to have better statistics but also bigger scatter -- thus the key is to constrain the scatter!

DES-like survey: cluster sample: $M_{th} = 10^{13.7}\ M_{\odot}/h$ and $z_{max} = 1$ (~10^5 clusters)

Dark Energy Figure of Merit: FoM := $[\sigma(w_a)\ \sigma(w_p)]^{-1}$

The Effect of Scatter: Systematic Errors

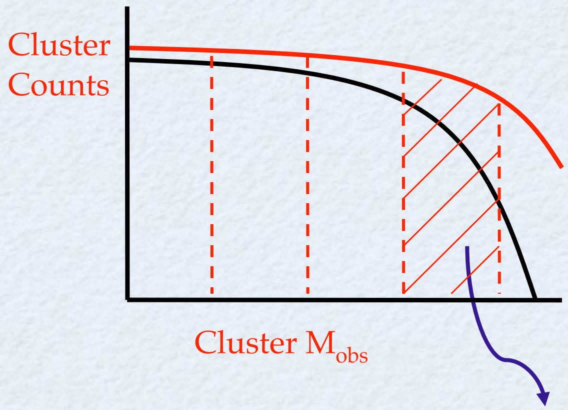


- If our estimate in scatter (σ_{model}) differs from the true scatter (σ_{true}), the inferred cosmological parameters will be biased.
- The scatter needs to be unbiased at 5% level to avoid significant bias in the inference of w_0 (similar for w_a).

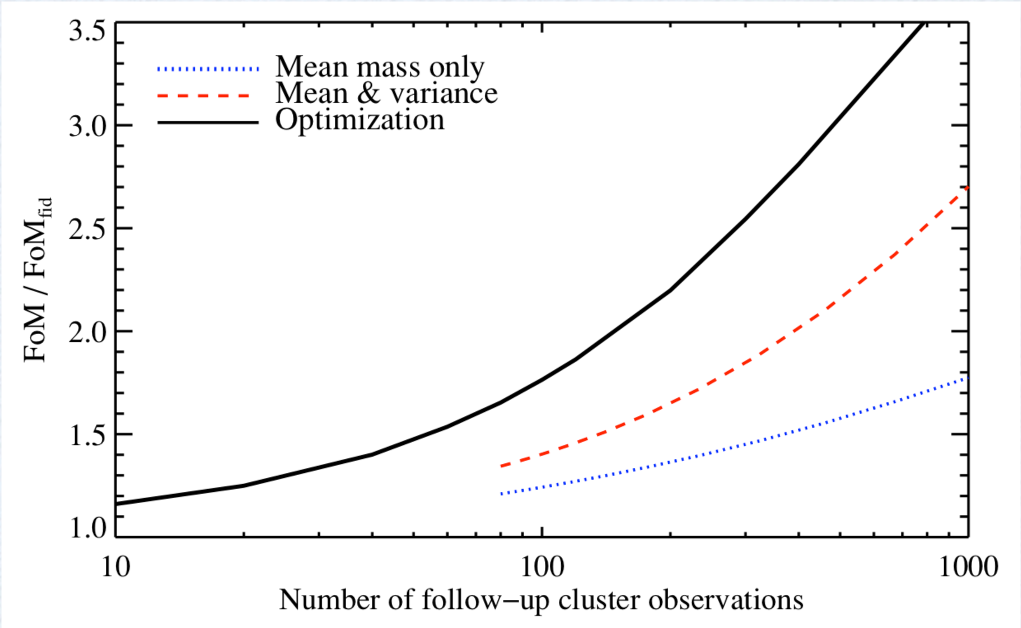
DES-like survey: cluster sample: $M_{th} = 10^{13.7}\ M_\odot/h$ and $z_{max} = 1$ (~10^5 clusters)

Coming soon: see Rozo et al. '10 (in prep) for various sources of error for scatter

External Mass Calibration from Follow-ups



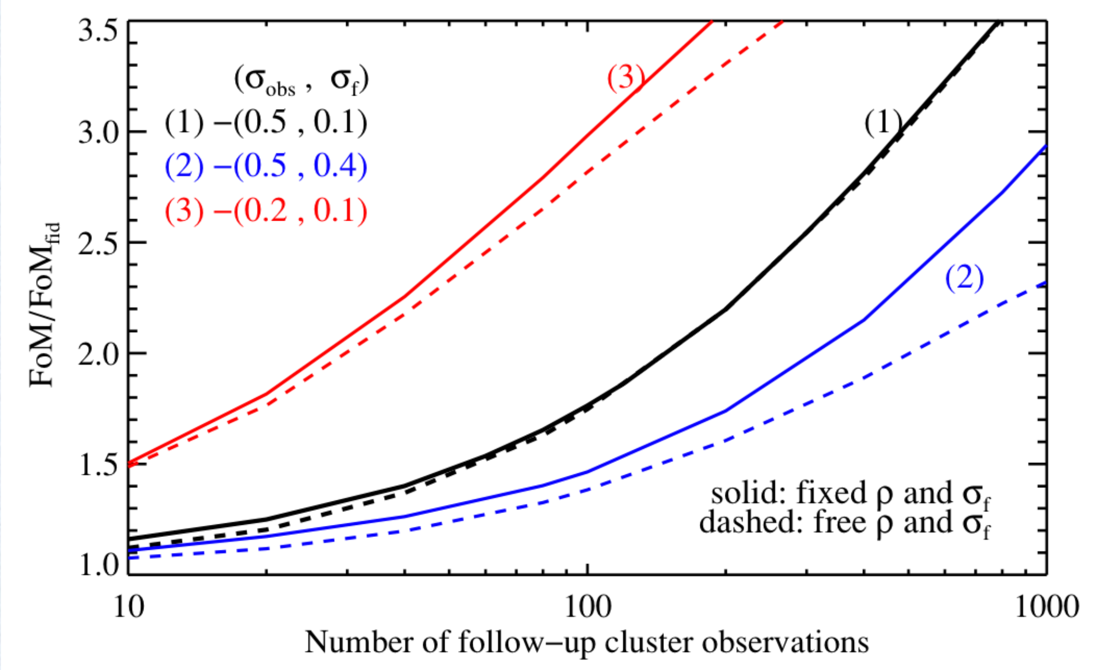
Follow up part of the sample in a bin
(measure the mass more precisely)



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

Wu, Rozo, and Wechsler 2010, ApJ, 713, 1207 (arXiv:0907.2690)
Also see Majumdar and Mohr '03, '04

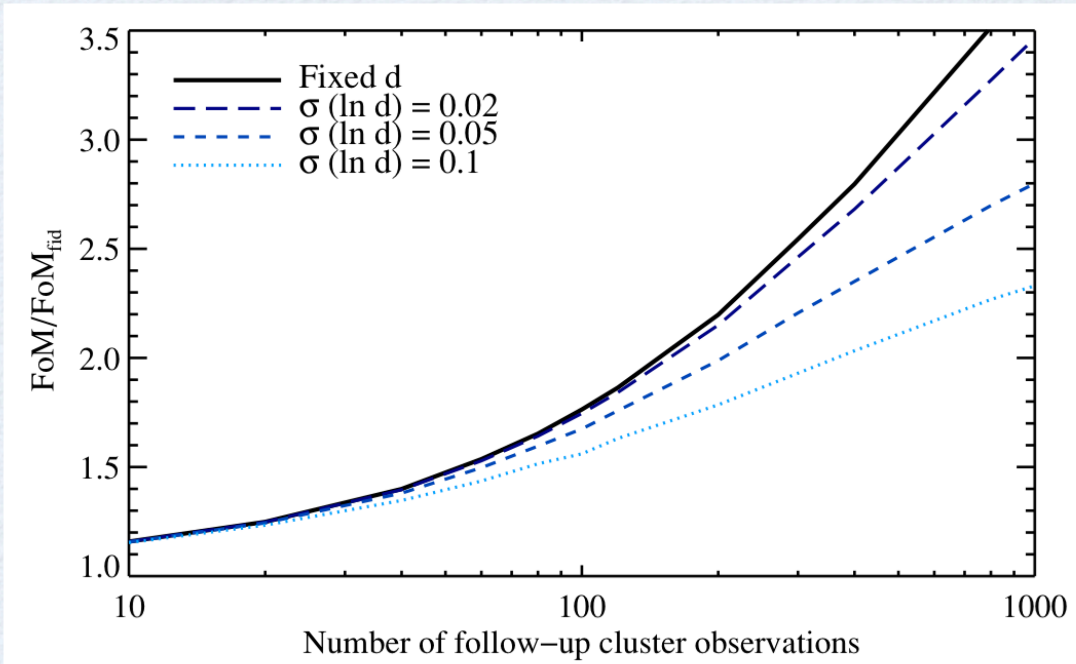
Statistical Errors of Follow-up Mass Tracers



- The FoM is barely degraded when the ϱ is uncertain.
- Large scatter in follow-ups: FoM is slightly lower.
- Small scatter in optical richness: FoM is further improved, because the (optically-selected) follow-ups are less noisy.

Also see Cunha ‘08 for cross-calibration

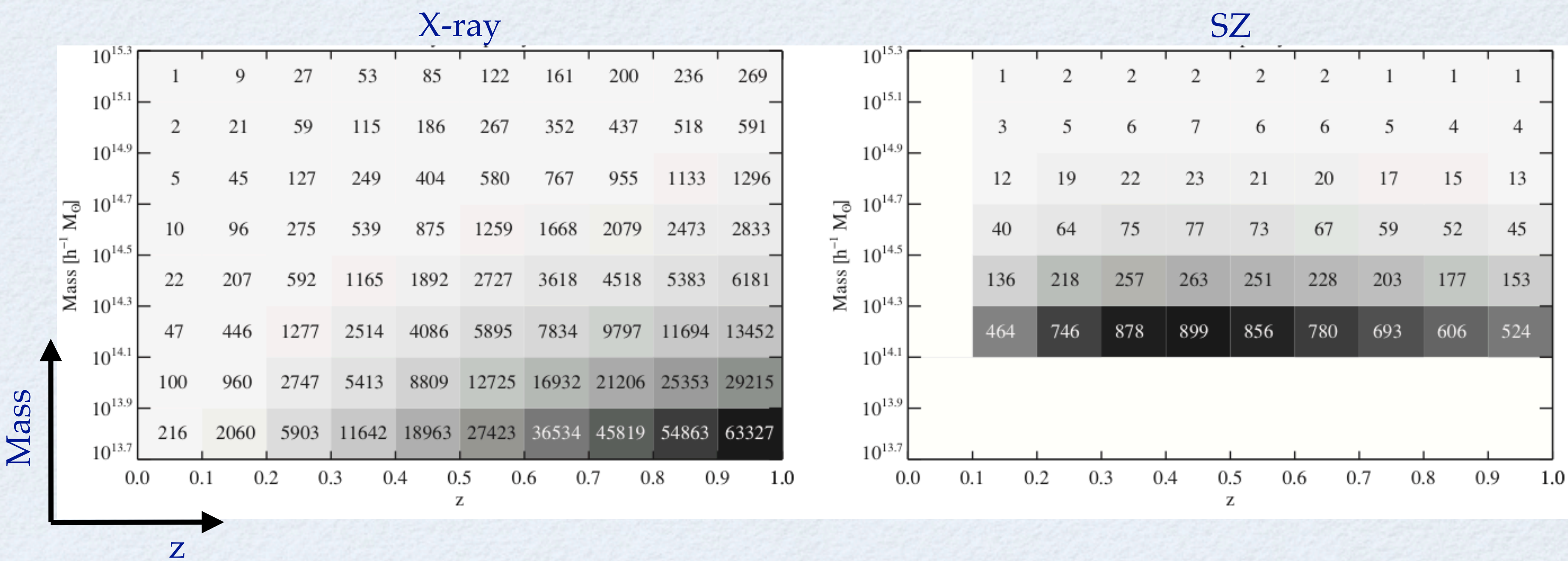
Systematic Errors in Follow-up Mass Tracers



- Systematic bias ($M_f = d\, M_{true}$) can largely degrade the efficacy of follow-ups if d is not well constrained.
- Modestly-sized program requires ln d to be constrained at 5% level.

Also see Nagai '07, Rudd '09 for possible sources of systematic bias

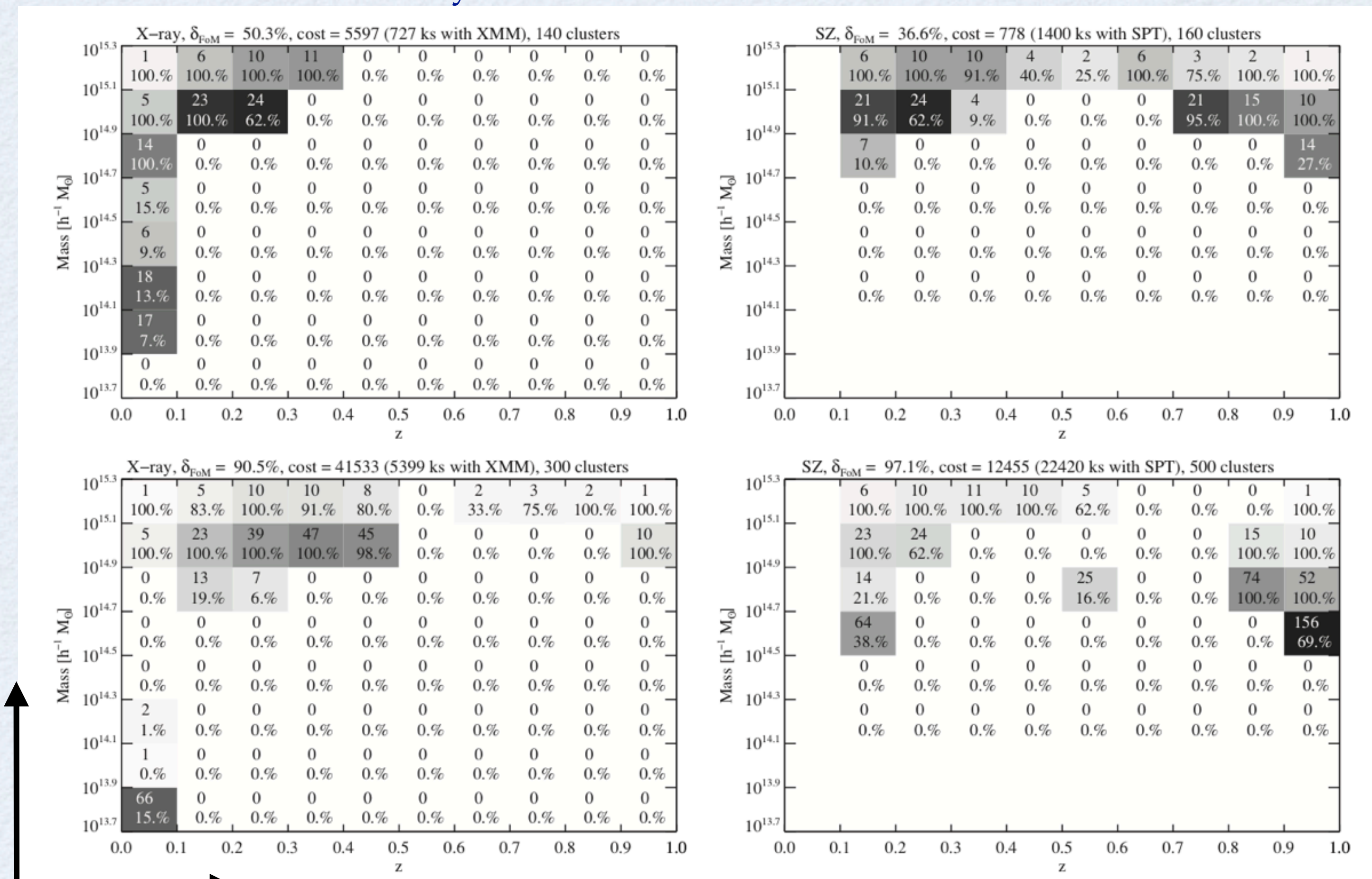
Optimization: Different Strategies for X-ray and SZ



- Clusters are weighted by their observational cost ∝ 1 / Flux
  - X-ray follow-ups: Cost is most sensitive to redshift
  - SZ follow-ups: Cost is most sensitive to mass
- Maximizing FoM at a given total observational costs:
  - Simulated annealing
  - Metropolis algorithm

Optimization: Different Strategies for X-ray and SZ

X-ray SZ



Small program: ~ 150 clusters

Large program: ~ 500 clusters

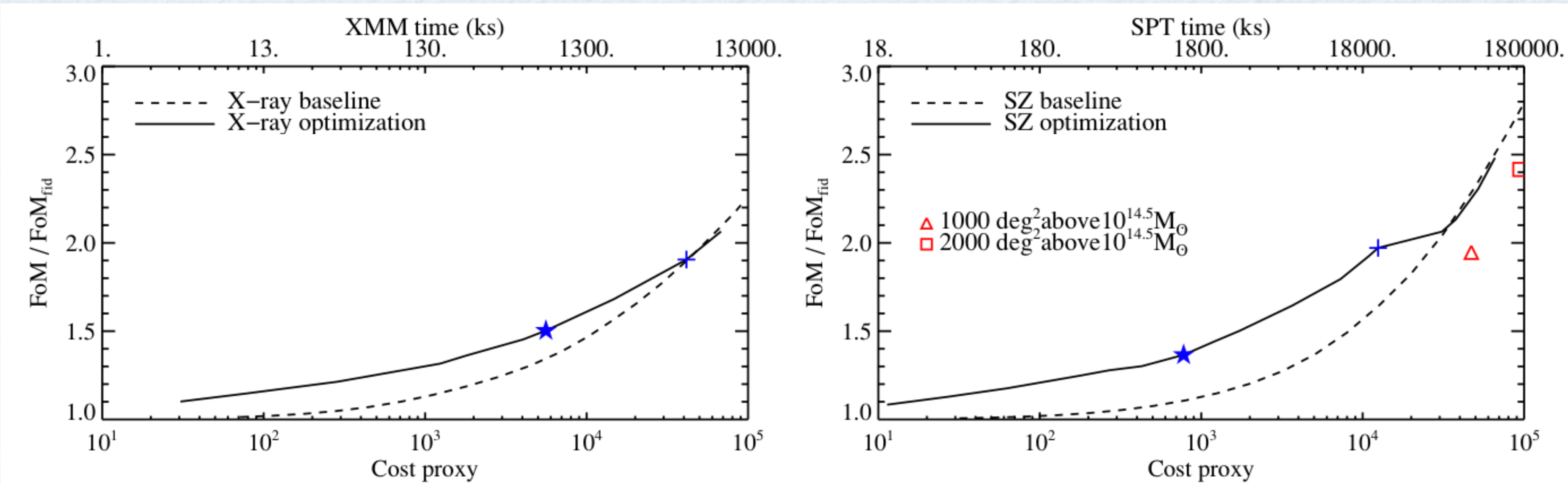
Mass

z

- X-ray: Small program: low-z clusters; large program: clusters span a redshift range
- SZ: Small program: massive clusters span over a redshift range; large program: some less-massive clusters

Optimization: FoM as a function of Telescope Time

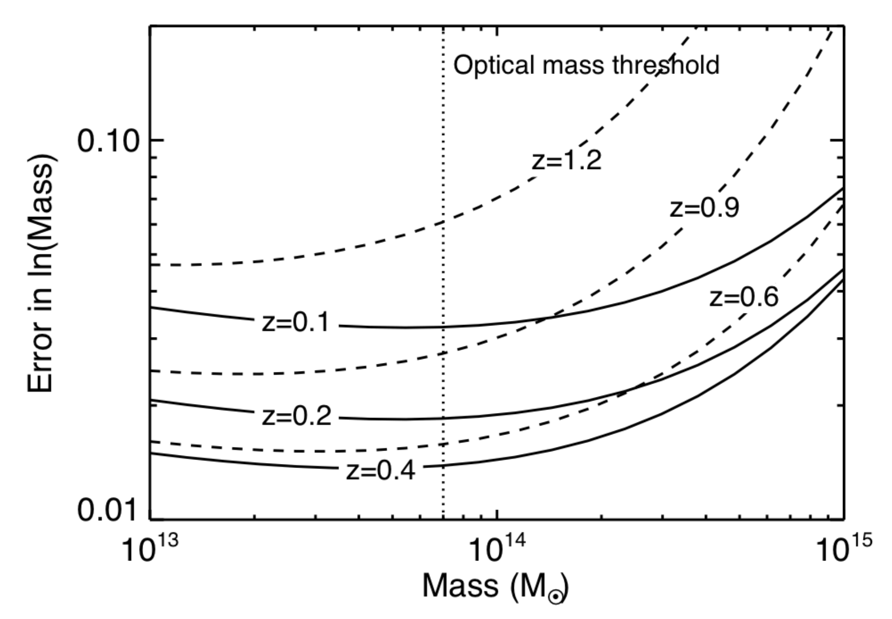
Cost proxy ∝ 1 / Flux; corresponding telescope time is shown on the top



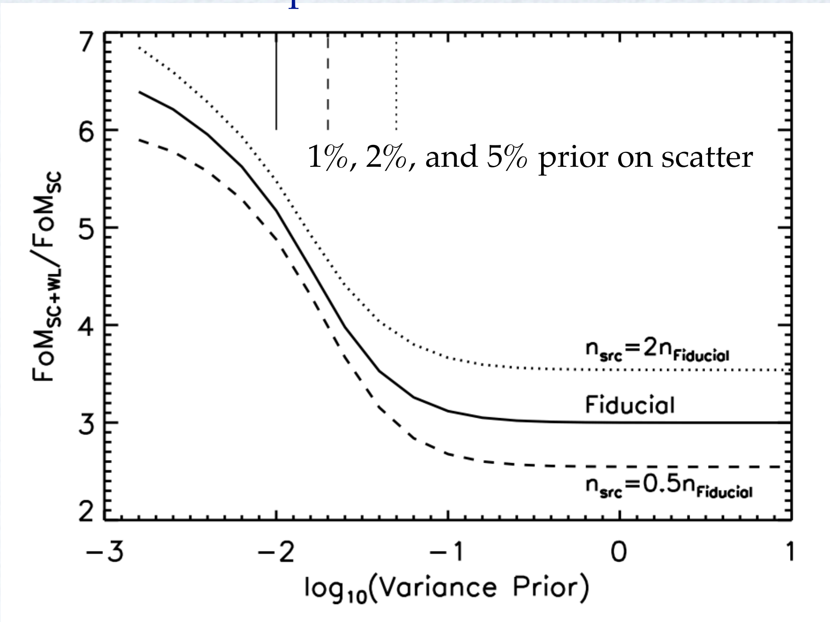
- Optimizing the FoM at a given cost can significantly improve the FoM.
- To achieve a given FoM, the optimization can reduce the cost by an order of magnitude over random selection.
- Slope changes are related to switch of strategies; blue points correspond to the strategies in the previous slide.

Stacked Weak Lensing Mass Calibration

Constraints on Mean Mass



Improvement in FoM



- Stacked weak lensing can probe relatively low-mass systems and constrain the mean mass at a given richness.
- Stacked weak lensing can constrain mean mass to 2%; this will improve FoM by approximately a factor of 3.
- Further constraints on the scatter will boost the efficacy of stacked weak lensing.

Rozo, Wu, and Schmidt 2010, submitted (arXiv: 1009.0756)

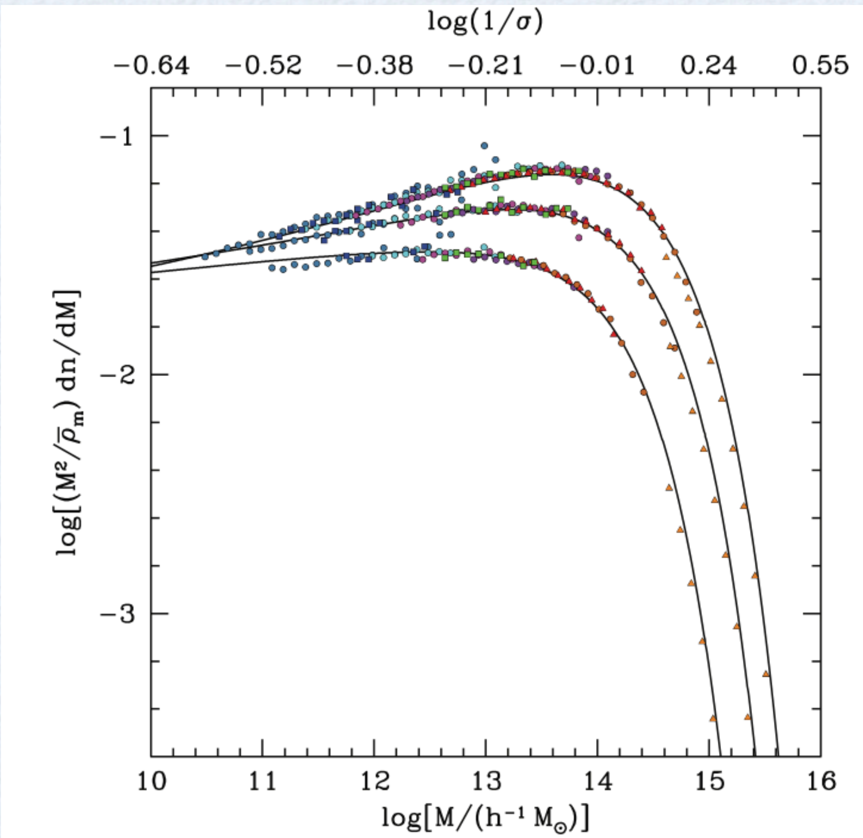
Ongoing Projects

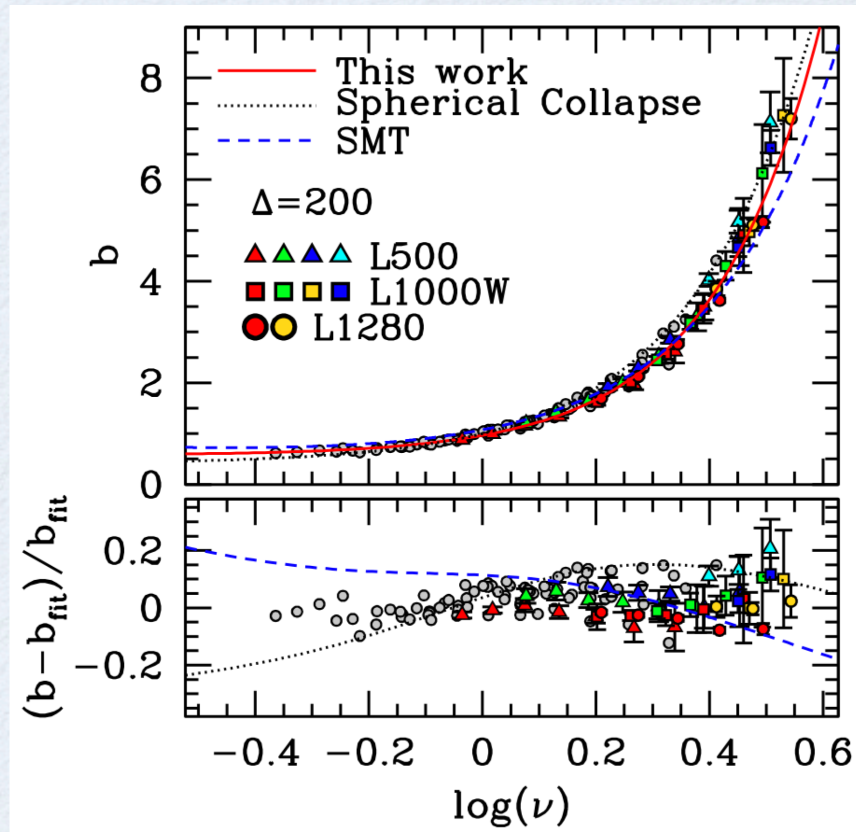
- Assessing the constraining power of the Wide Field X-ray Telescope (WFXT) (with Adam Mantz)
  - 20,000 deg^2 survey; partially core-excised L_X (10% scatter) and T_X (10% scatter)
  - 3,000 deg^2 fully followed up with core-excised L_X
- Optimizing the spectroscopic follow-ups for DES clusters (with Brian Gerke)
  - Velocity dispersion measurements from different scenarios
  - Impact on dark energy constraints

Part II: Theoretical Uncertainties

- Theoretical uncertainties in mass function and halo bias
  - Required precision for future surveys
  - Comparison between different mass and redshift ranges
- The effect of halo assembly history
  - The impact of secondary dependence of halo bias on self-calibration
  - Potential systematic errors in cosmology

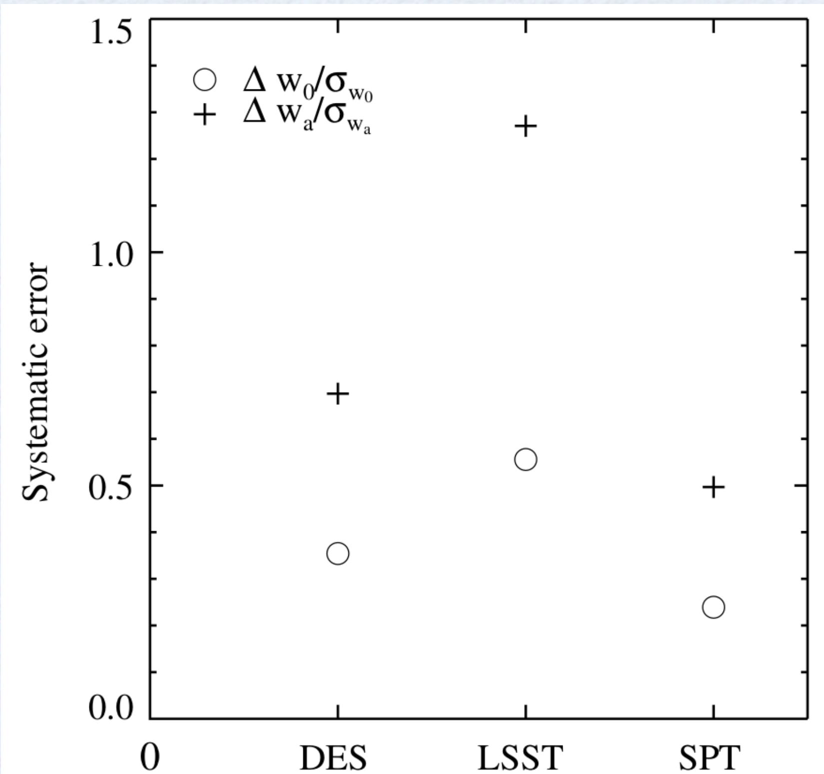
Current Calibrations of Halo Mass Function and Halo Bias from N-body Simulations





Tinker et al. ‘08, ‘10; also see Bhattacharya et al. ‘10

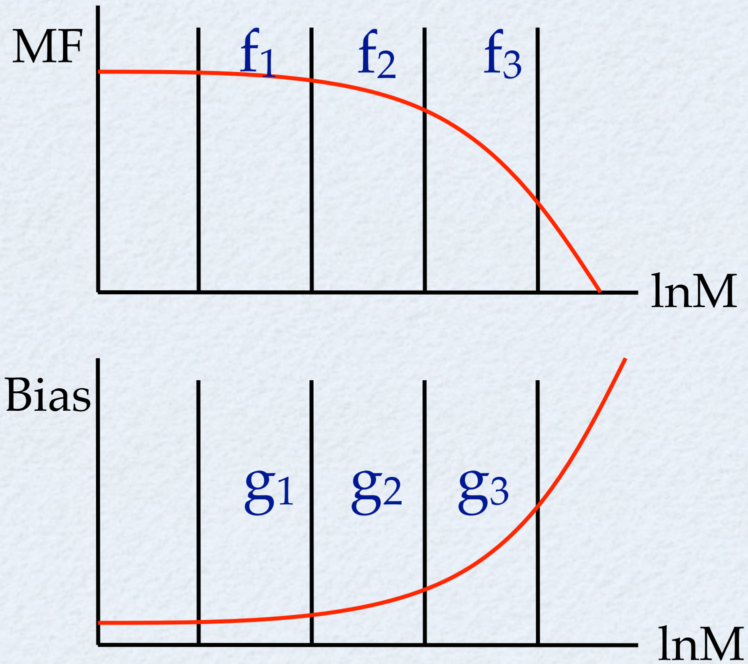
Systematic Errors Caused by Inaccurate Modeling of Mass Function



- 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 2010, ApJ, 716, 856 (arXiv:0910.3668)

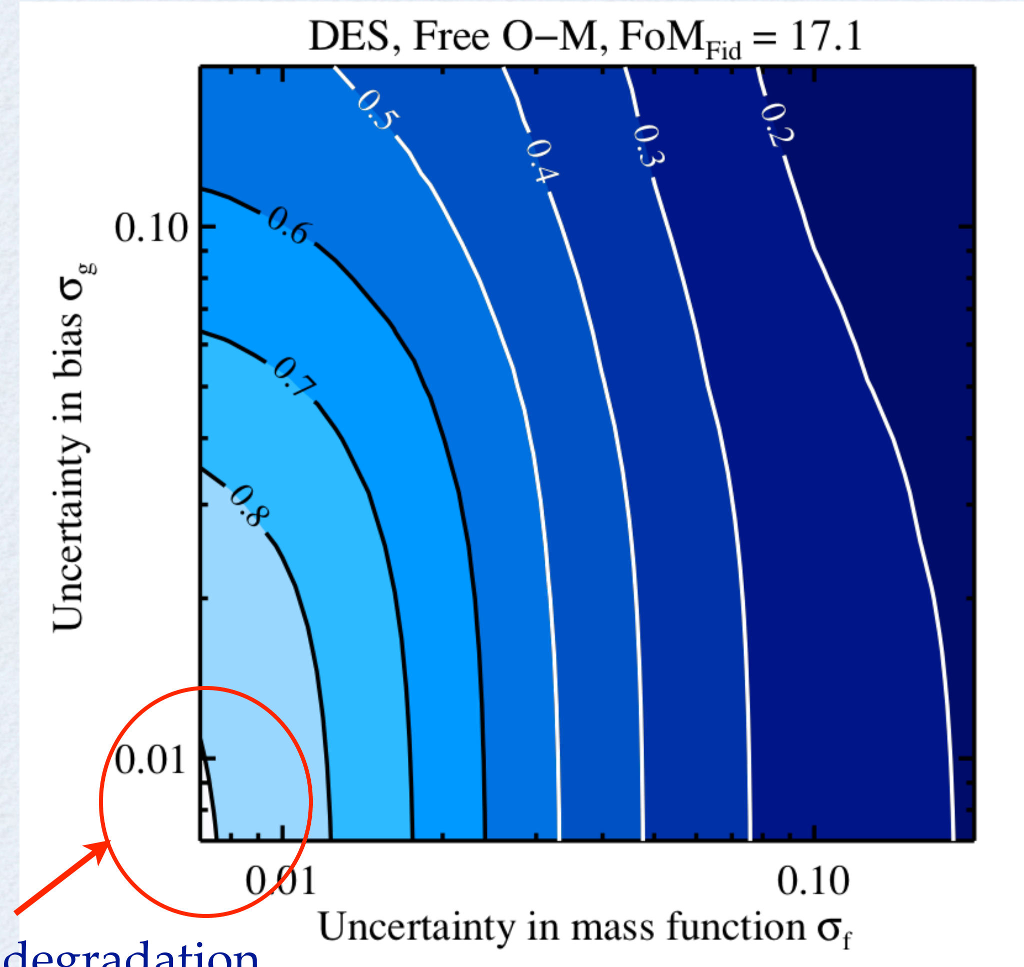
Modeling the Uncertainties in Mass Function and Halo Bias



- 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 and Evrard '09 for the study of parameters in the Tinker function

Degradation in the Dark Energy Figure of Merit

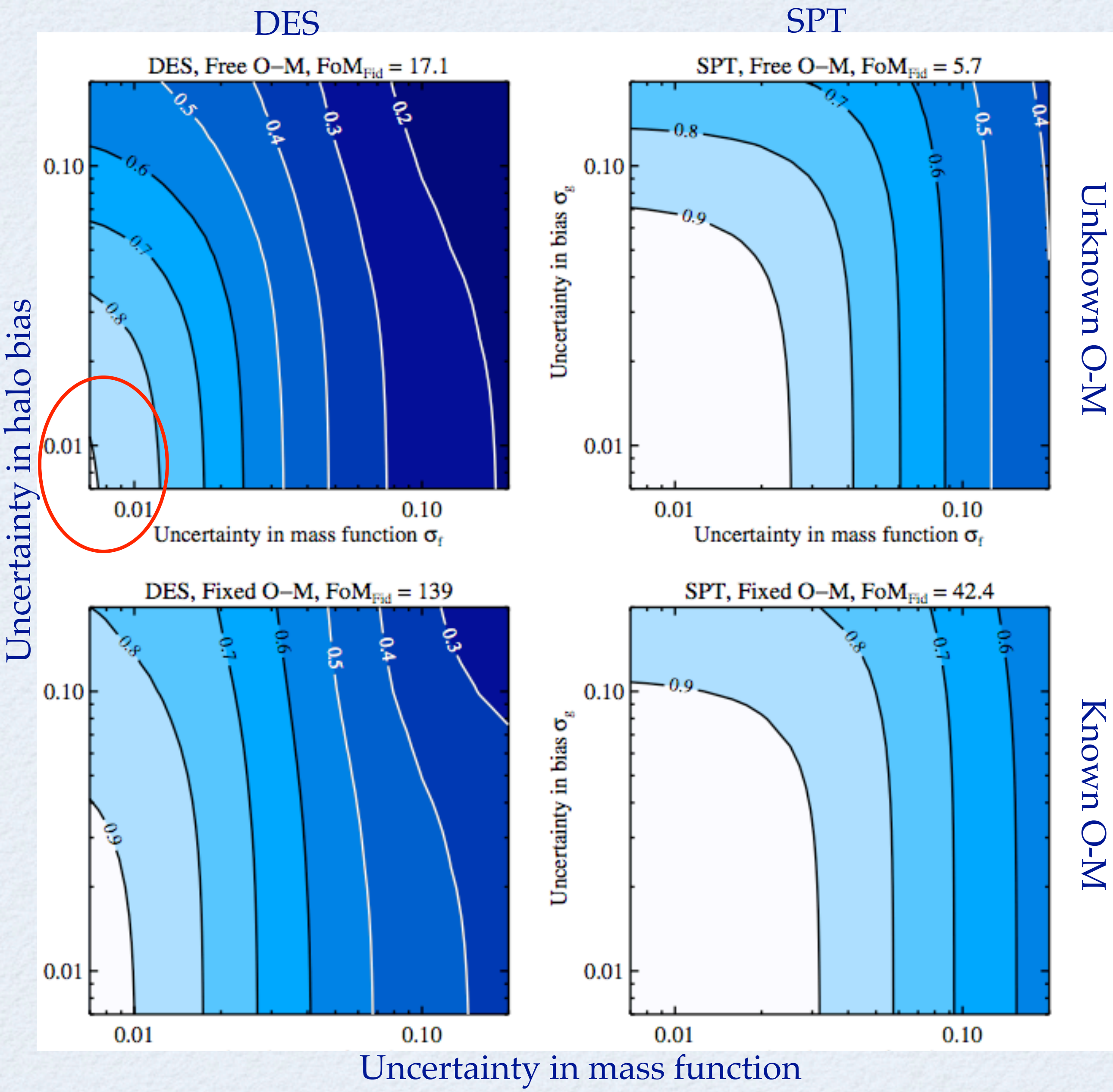


10% degradation in FoM

- DES assumptions: $M_{th} = 10^{13.7}\ M_\odot/h$; Scatter = 0.4; Area = 5000 deg^2
- For DES, percent-level accuracy on mass function and halo bias is required to avoid 10% degradation in FoM.
- The requirement on halo bias is less stringent.

Wu, Zentner, and Wechsler 2010, ApJ, 716, 856 (arXiv:0910.3668)

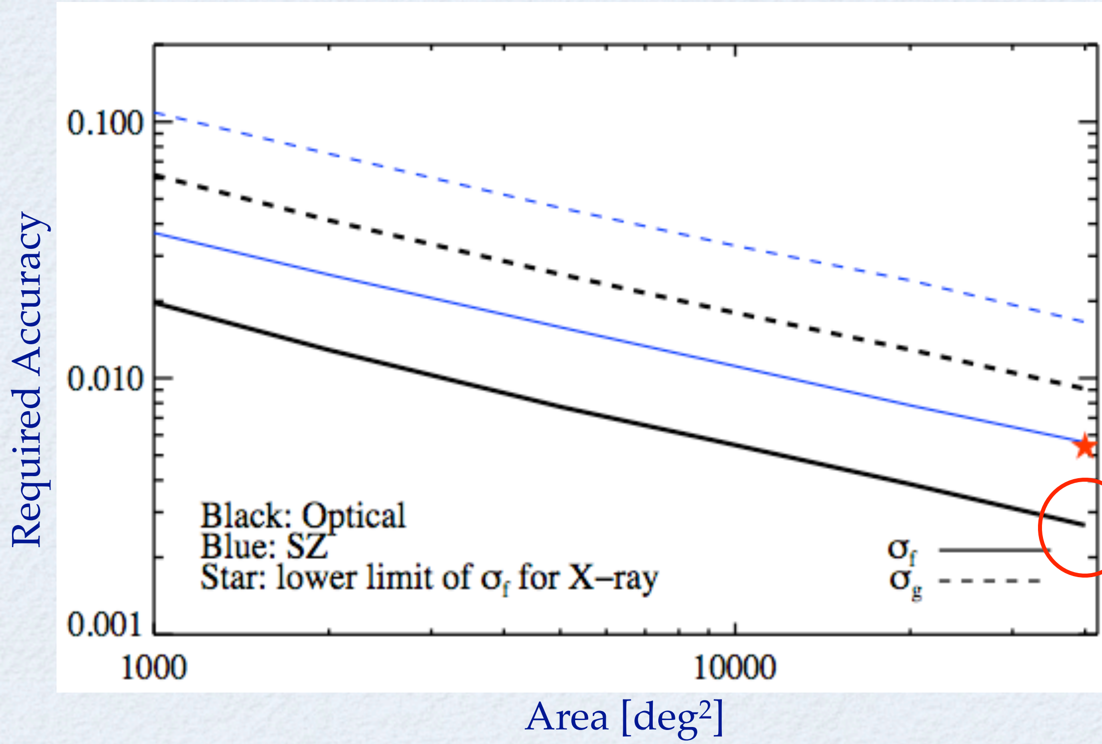
Degradation in the Dark Energy Figure of Merit



- An SPT-like survey will require less accuracy.
- When observable-mass distribution is well constrained, the required accuracy on halo bias is less stringent.

- DES assumptions:
$M_{th} = 10^{13.7}\ M_{\odot}/h$; Scatter = 0.4;
Area = 5000 deg^2
- SPT assumptions:
$M_{th} = 10^{14.1}\ M_{\odot}/h$; Scatter = 0.2;
Area = 2000 deg^2

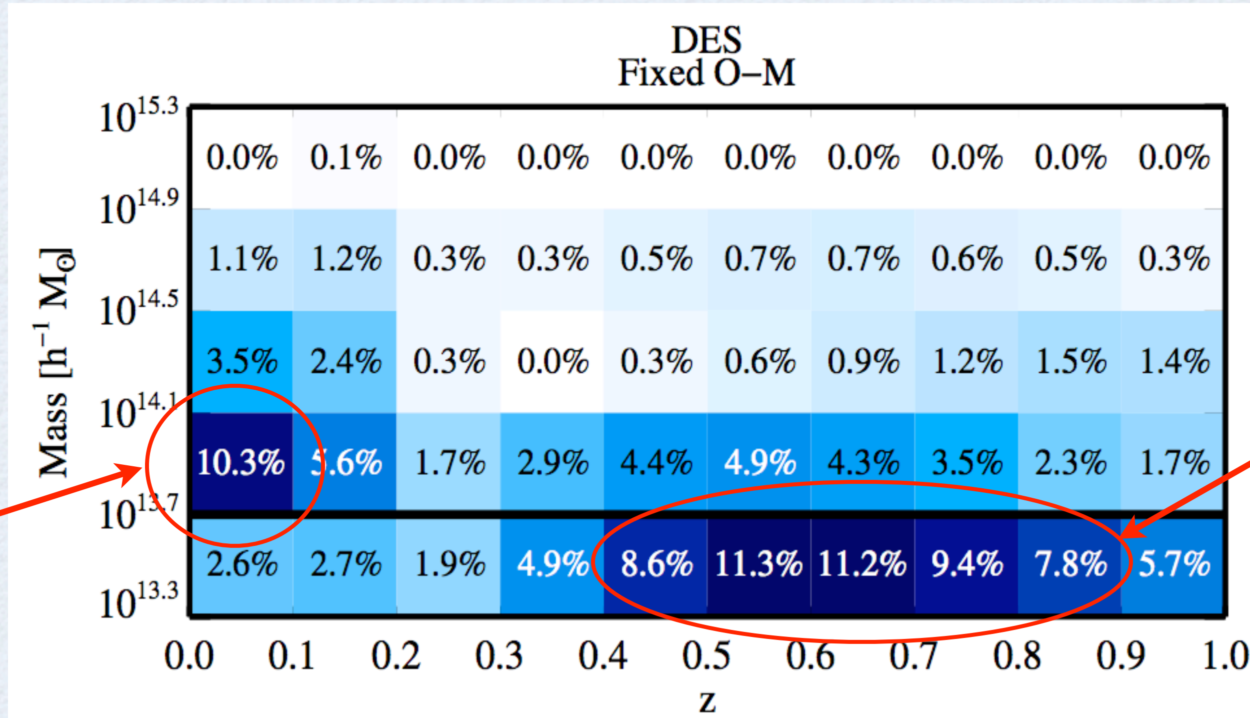
The Effect of Survey Area



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

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

Comparing Bins

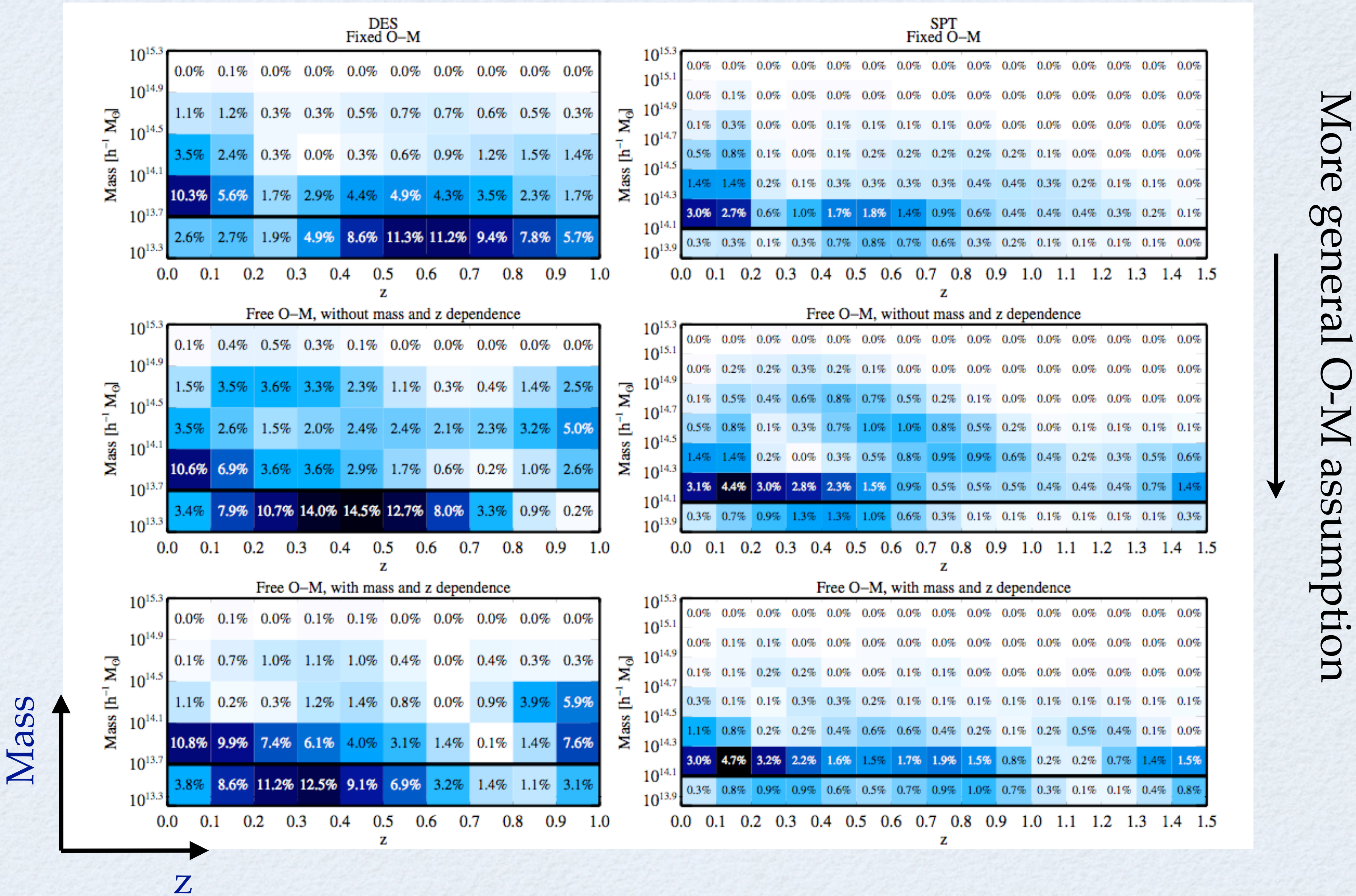


Lowest z: longest lever arm for dark energy constraints

Lowest mass: greatest cluster counts

- 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.

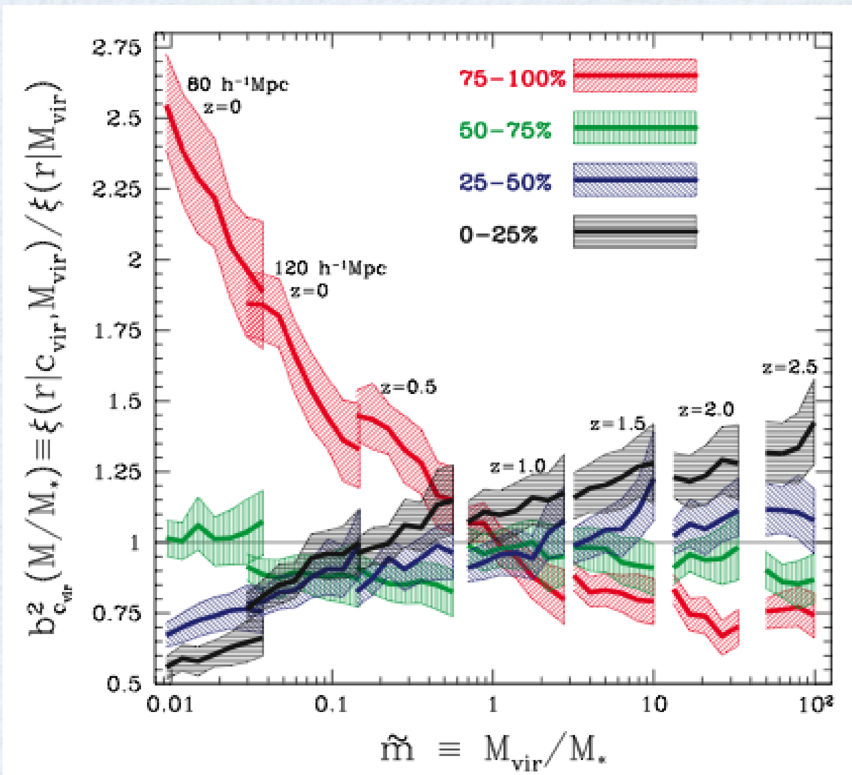
Comparing Bins

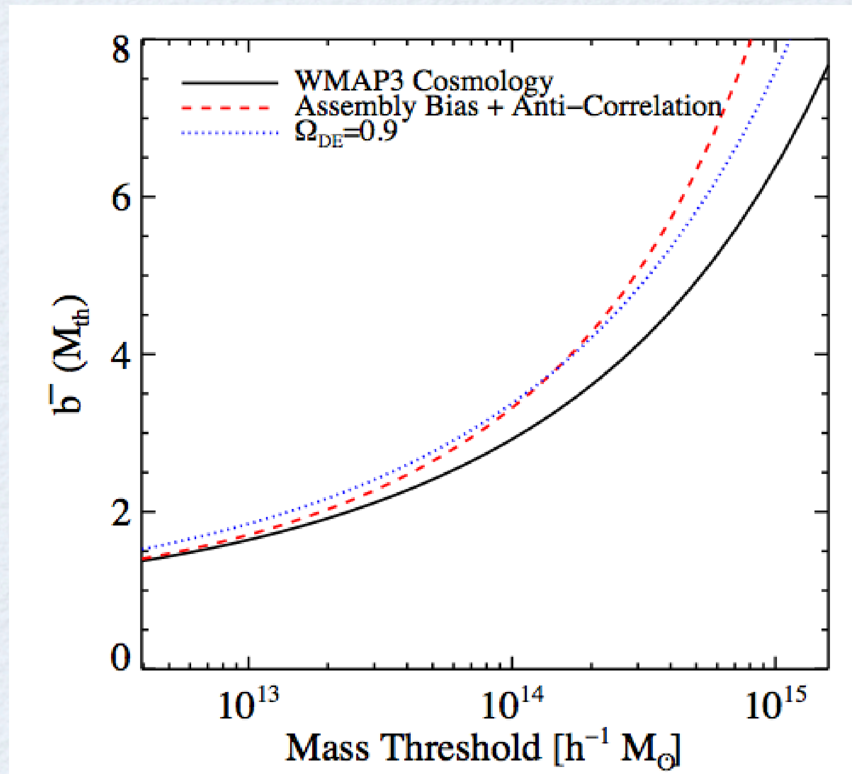


The Effect of Halo Assembly Bias

Halo bias also depends on secondary parameters, e.g. concentration.

Relative bias^2

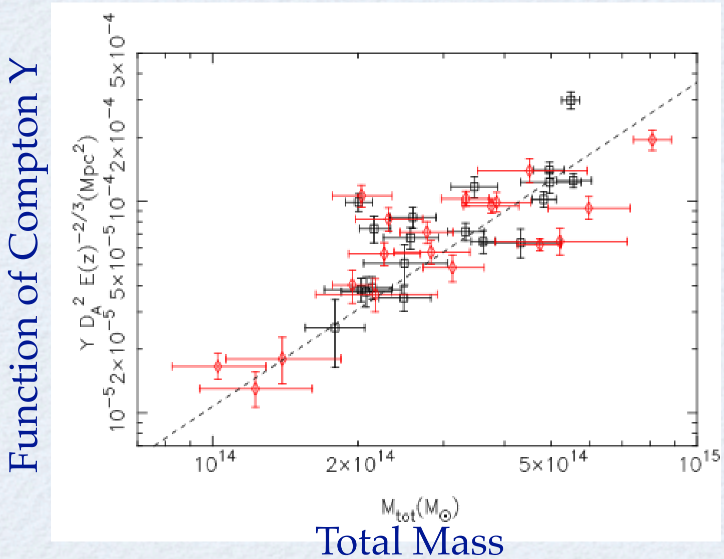


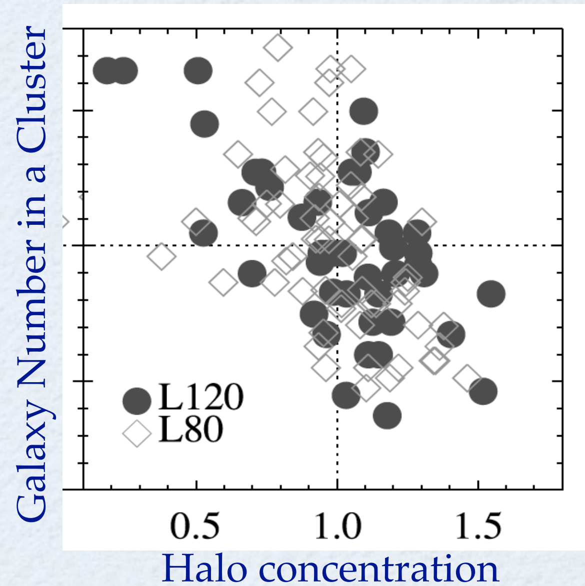


Wechsler et al. ‘06; Gao et al. ‘06, ‘07; Wetzel et al. ‘07;
Croton et al. ‘07; Dalal et al. ‘08 etc.

Wu, Rozo, and Wechsler 2008, ApJ, 688, 729 (arXiv:0803.1491)

Modeling the M_{obs}-M-c Distribution





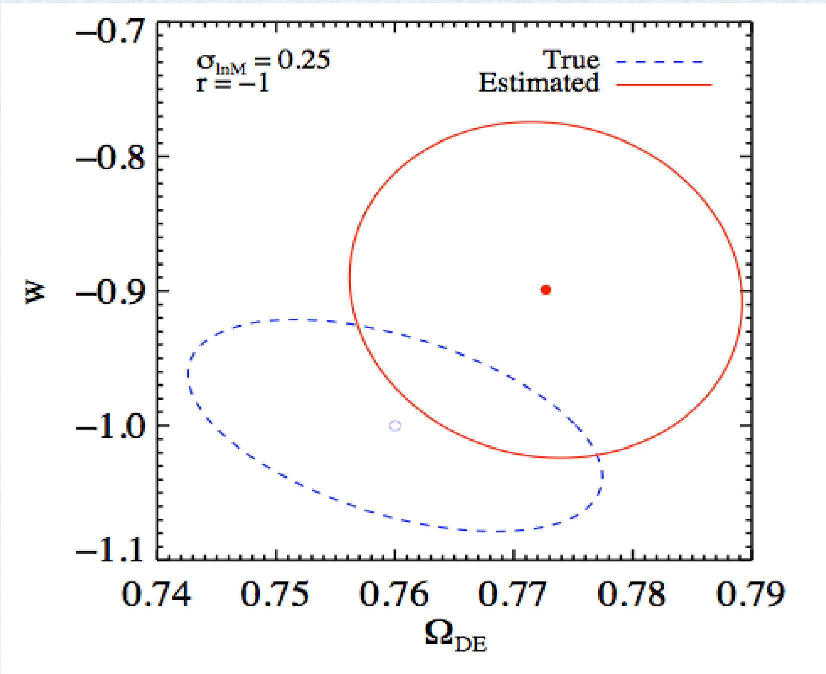
$$b^{ab}(M^{obs}) \propto \int dM \int dc\, n(M) P(c|M) b^{ab}(M,c) P(M^{obs}|M,c)$$

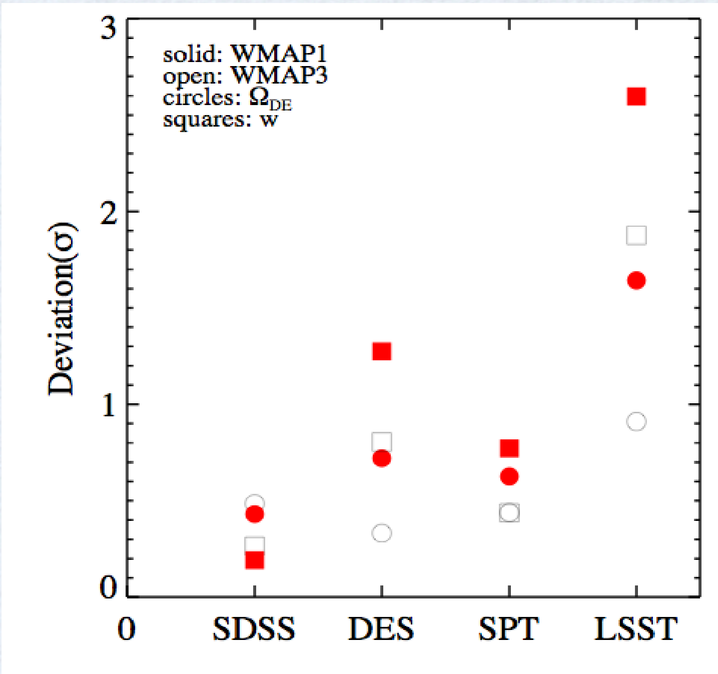
$$\langle \ln M^{obs} | \ln M, c \rangle = \ln M + r\sigma_{\ln M} c$$

- M_{obs}-M: log-nomal with scatter σ_{lnM}
- M_{obs}-c: modeled with correlation coefficient r
- Estimated values: r= -0.5 for optical, r = 0.4 for SZ

Bonamente et al. ‘07; Wechsler et al. ‘06; Rudd ‘08

Systematic Errors Caused by Ignoring Assembly Bias





- Blue: correct model that properly includes the effect of assembly bias
- Red: biased parameter estimates caused by ignoring assembly bias

- Optical: larger scatter + negative correlation
- SZ: small scatter + positive correlation
- The impact is stronger for optical surveys

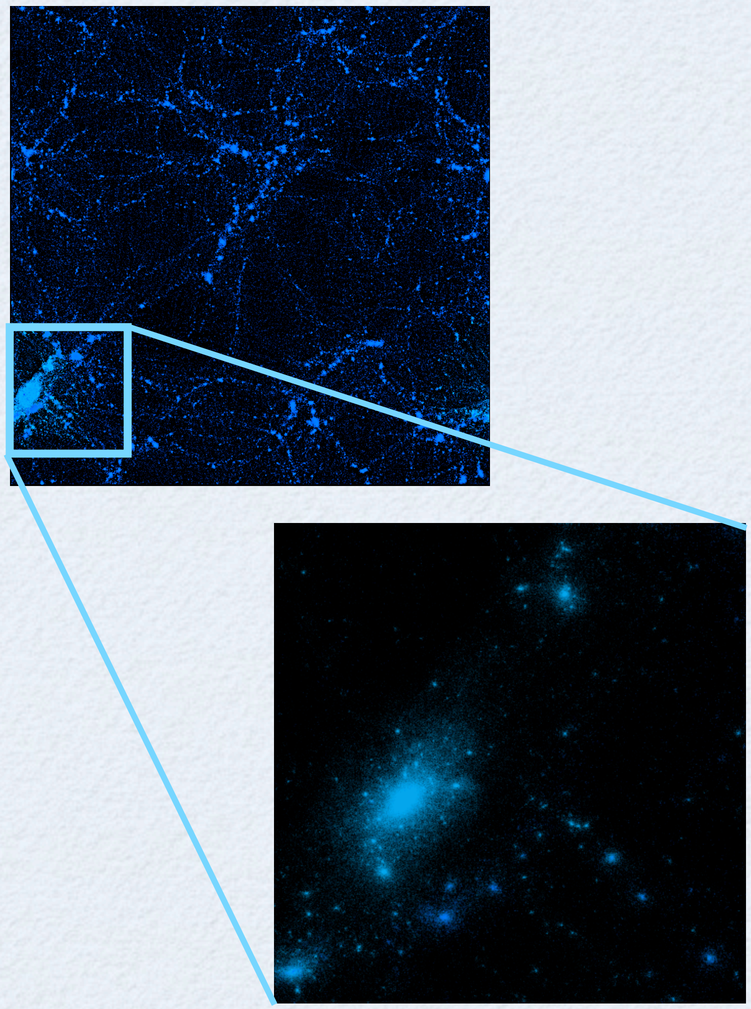
Wu, Rozo, and Wechsler 2008, ApJ, 688, 729 (arXiv:0803.1491)

Ongoing Projects

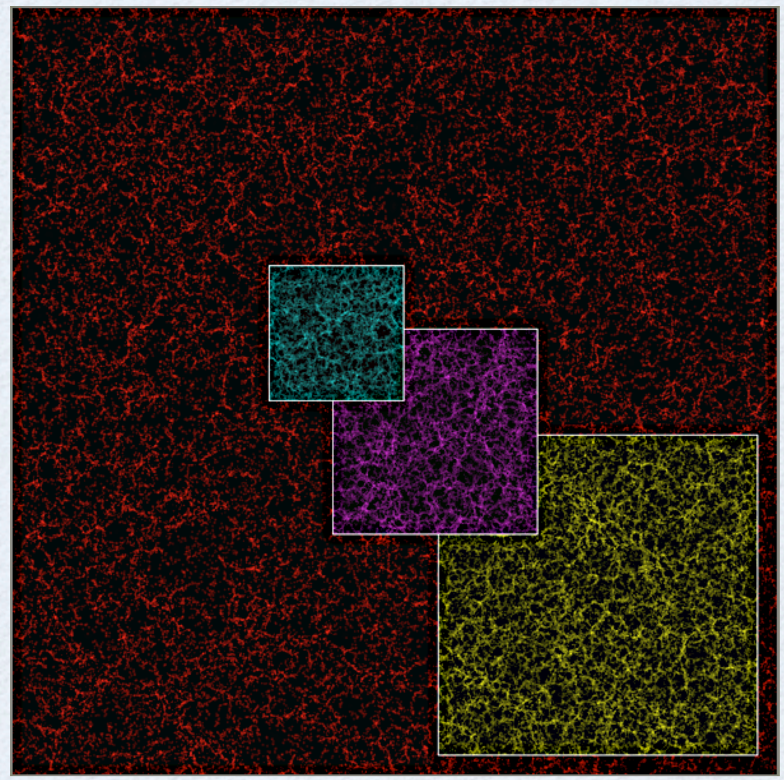
- Re-simulations of halos in a Gpc Box (with Oliver Hahn and Michael Busha)
  - Characterizing assembly bias at high mass regime
  - Aiming for studying large-scale halo bias and small-scale substructure properties simultaneously
  - Understanding the origin of scatter
- Small scale halo bias for constraining cluster mass (with Jeremy Tinker and the LasDamas Collaboration)

Ongoing Projects

Re-simulations of Massive Halos in a Cosmological Volume



Large Suite Dark Matter Simulations (LasDamas)



LasDamas website:
http://lss.phy.vanderbilt.edu/lasdamas
McBride et al.

Summary

• The constraining power of galaxy cluster surveys will depend on how various systematic errors are controlled. Here we assume DES as an example.

• **PART I: Constraining Observable-Mass Distribution**

- The follow-up mass tracers need to be **unbiased at 5% level**.
- Optimized **X-ray** and **SZ** follow-ups: less than 200 X-ray or SZ clusters can improve the FoM by 50%.
- **Stacked weak lensing** can provide 2% constraints on mean mass, which will improve FoM by a factor of 3.

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

• **PART II: Theoretical Uncertainties in Modeling Halo Distribution**

- A full-sky optical survey will require **<1% accuracy in mass function** to avoid severe degradation in the FoM.
- **Halo assembly bias** needs to be properly modeled to avoid systematic errors in cosmological parameters.

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