Precision Cosmology from Future Galaxy Cluster Surveys

How do we control various systematics from observations and theory?

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Cosmology from Galaxy Cluster Counts

- Galaxy clusters probe:
  - Structure growth
  - Expansion rate

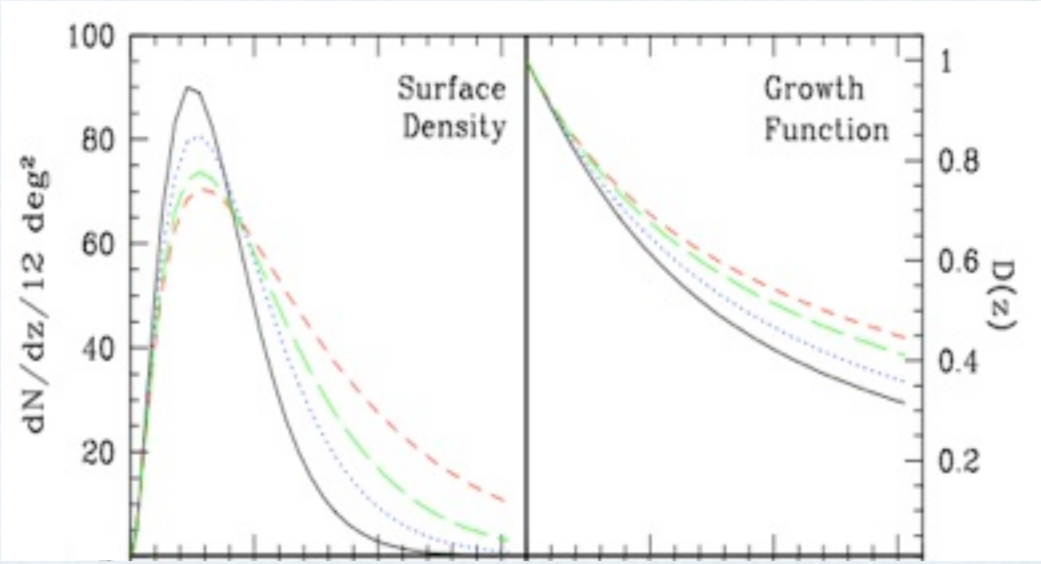
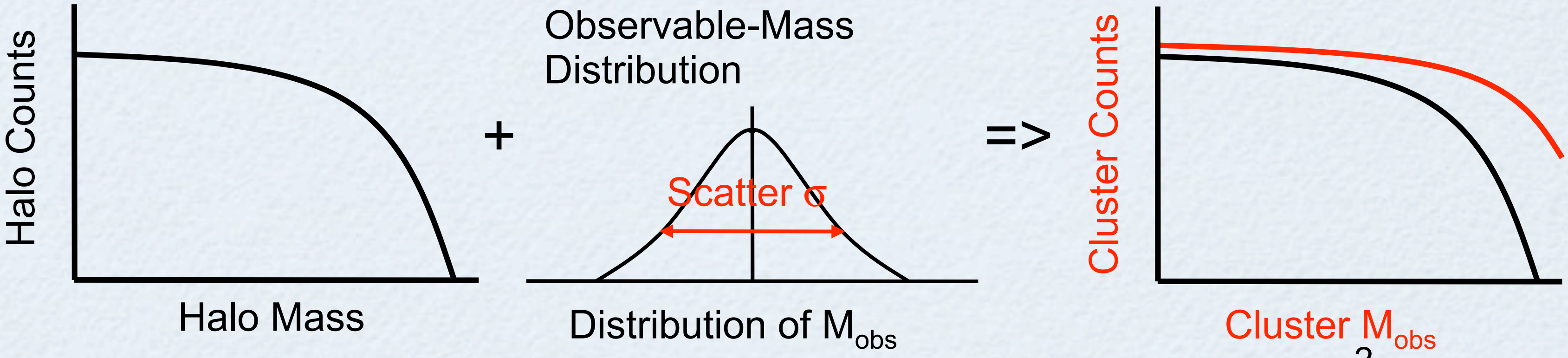
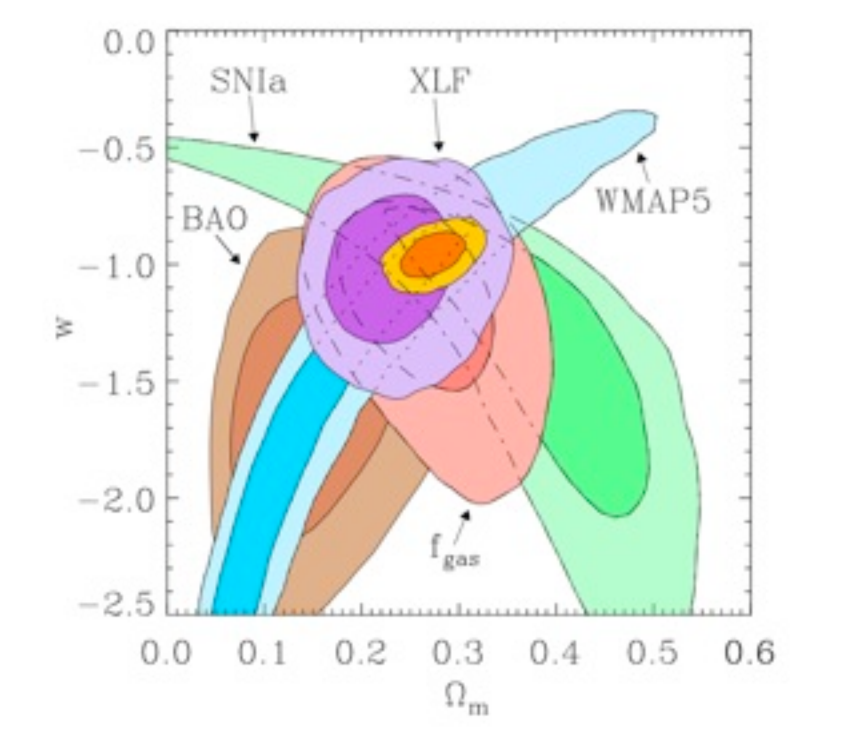
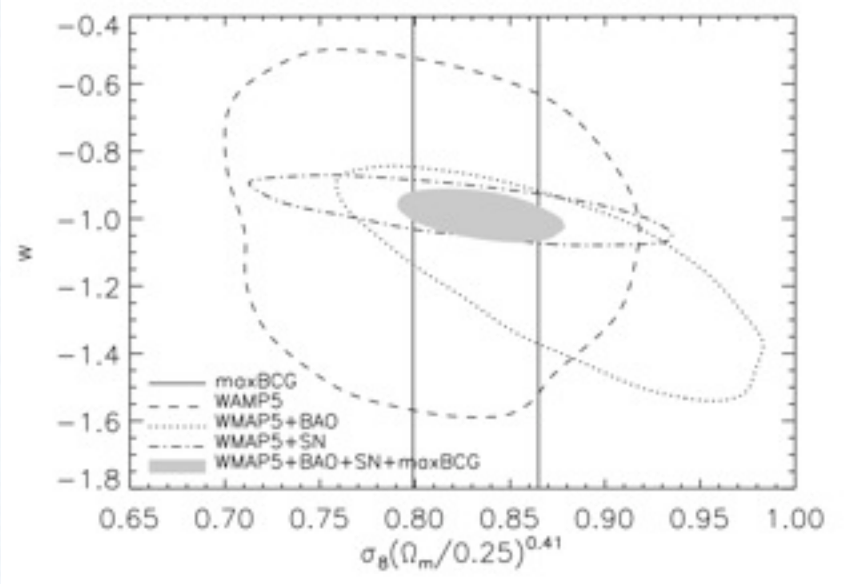


Figure: Haiman '01 (w= -1; -0.6; -0.2; no DE)



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 (~10^5), 40% scatter
- Survey area = 5000 deg^2 ; overlap with the South Pole Telescope (SZ survey)
- Survey depth: $M_{th} = 10^{13.7}\ h^{-1}M_{sun}$ and $z_{max} = 1$

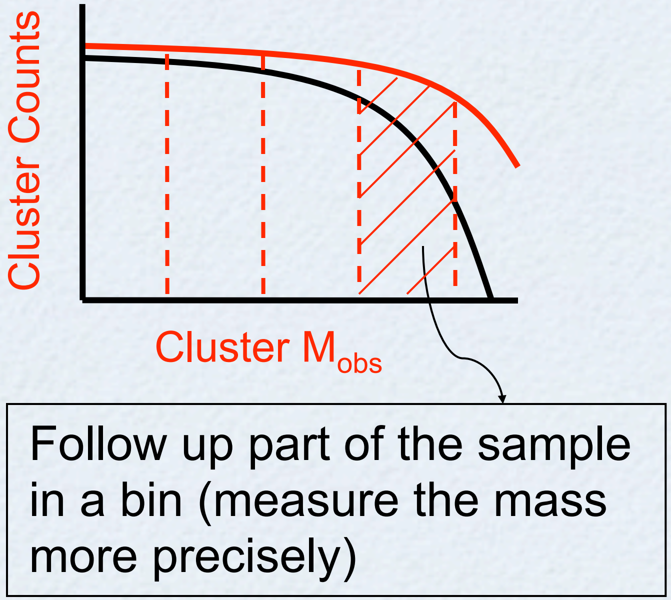
Self-calibration Analysis

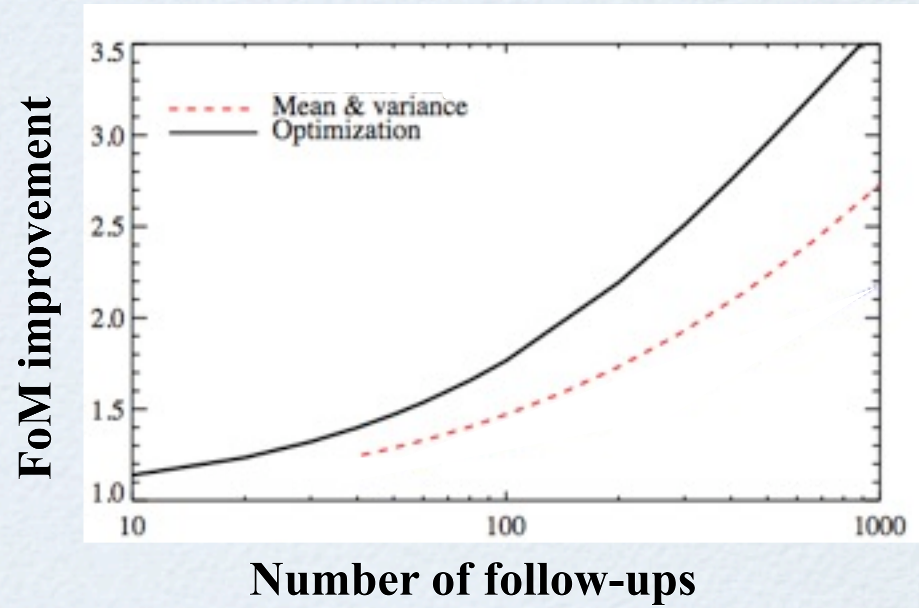
- Using sample variance (clustering of galaxy clusters) to self-calibrate the observable-mass distribution (Lima & Hu '04, '05).

The Dark Energy Figure of Merit (FoM)

- FoM :=$1/[\sigma(w_a)\sigma(w_p)] \propto 1/$(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





- 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.

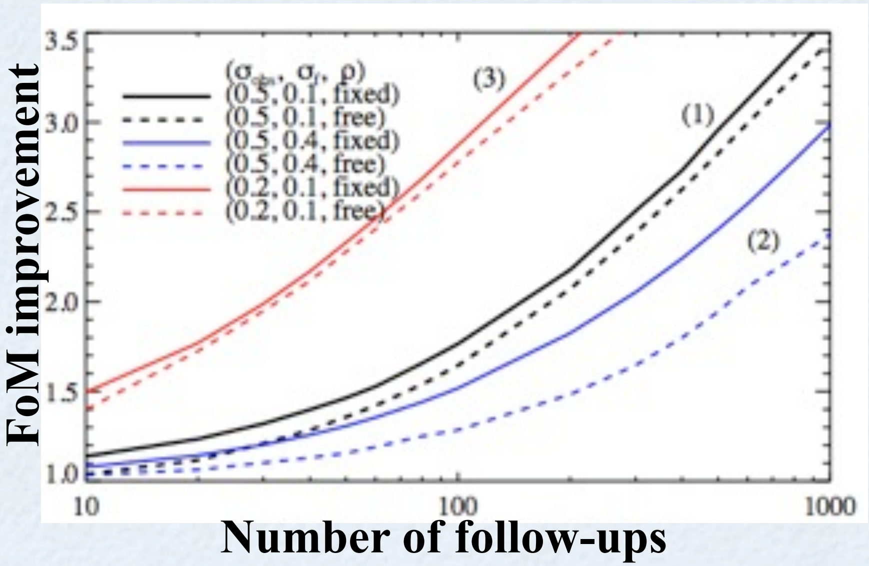
- Optimized follow-up strategy can further improve the FoM.

- With 100 follow-up clusters, FoM can be improved by 77%

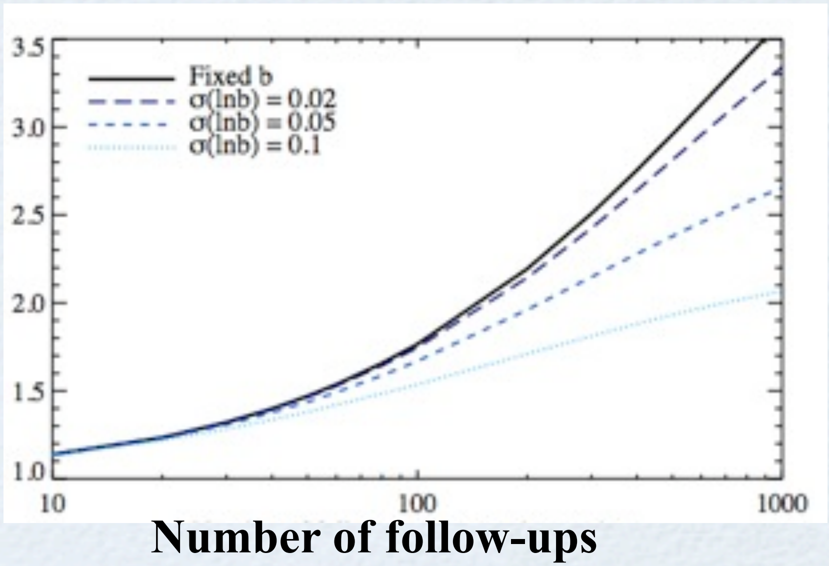
Wu, Rozo, and Wechsler, arXiv:0907.2690; Also see Majumdar and Mohr ‘03, ‘04

Complications: Scatter and Bias of Follow-up Mass Tracers

Scatter: mild degradation



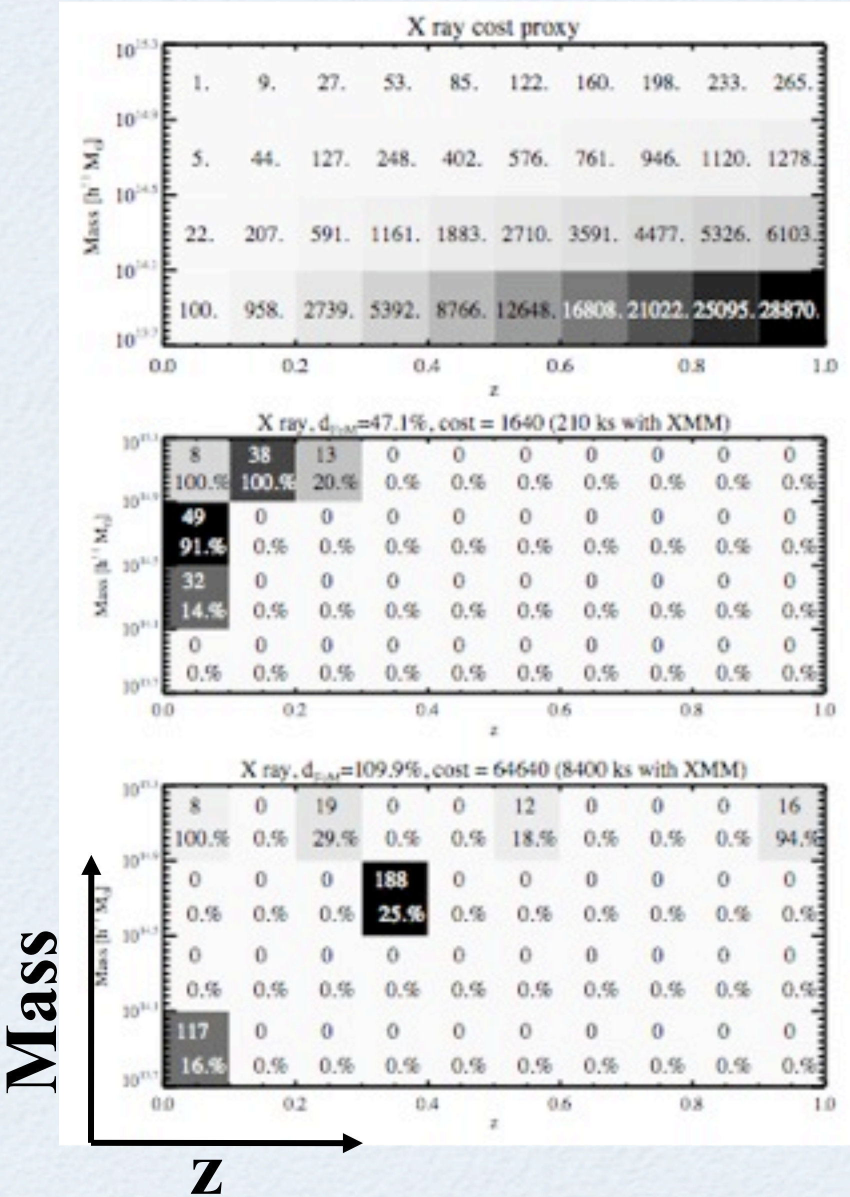
Bias: strong degradation



- 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.

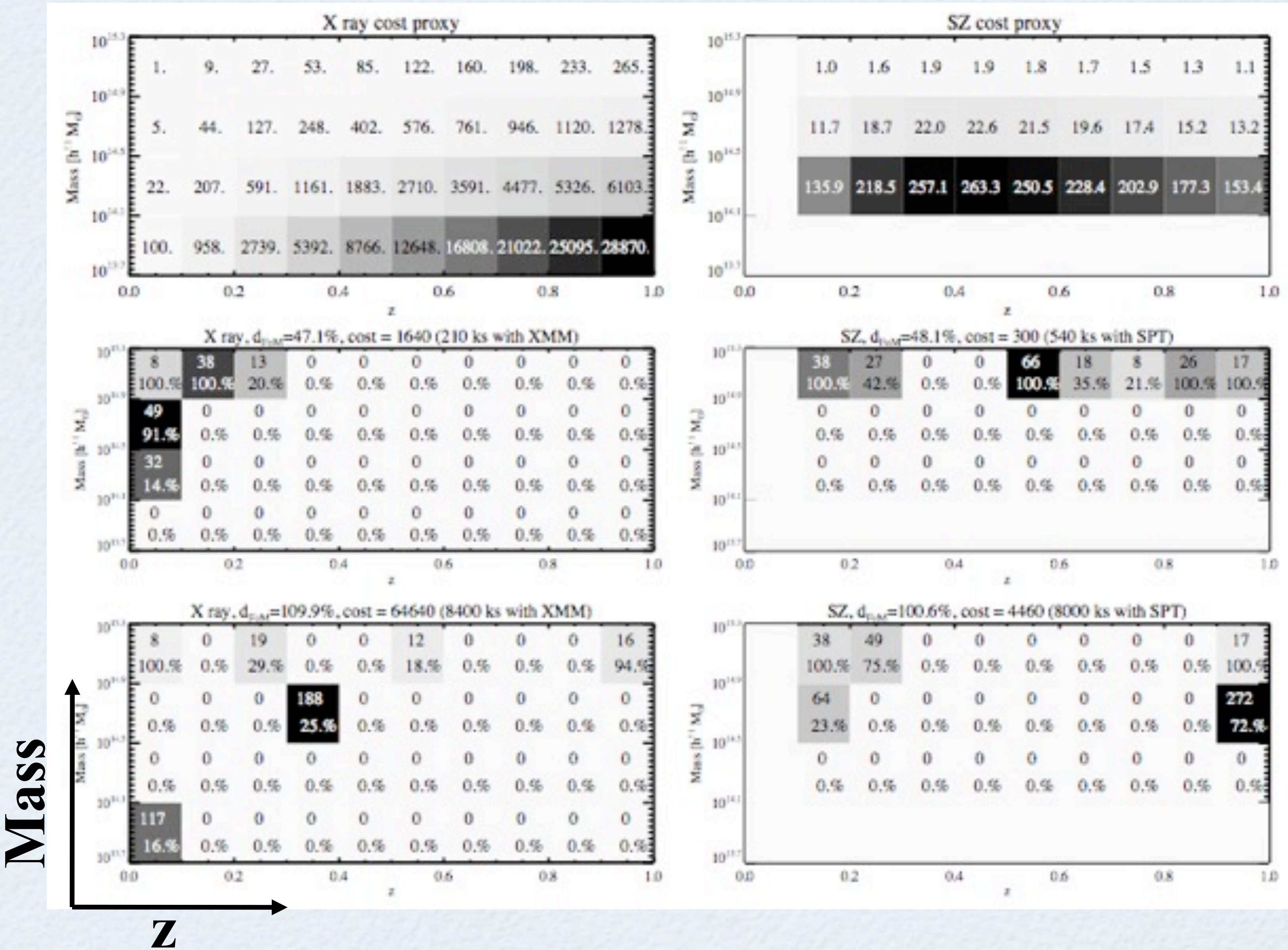
Also see Cunha '08 for cross-calibration; Nagai '07, Rudd '09 for possible bias

Optimization: Different Strategies for X-ray and SZ

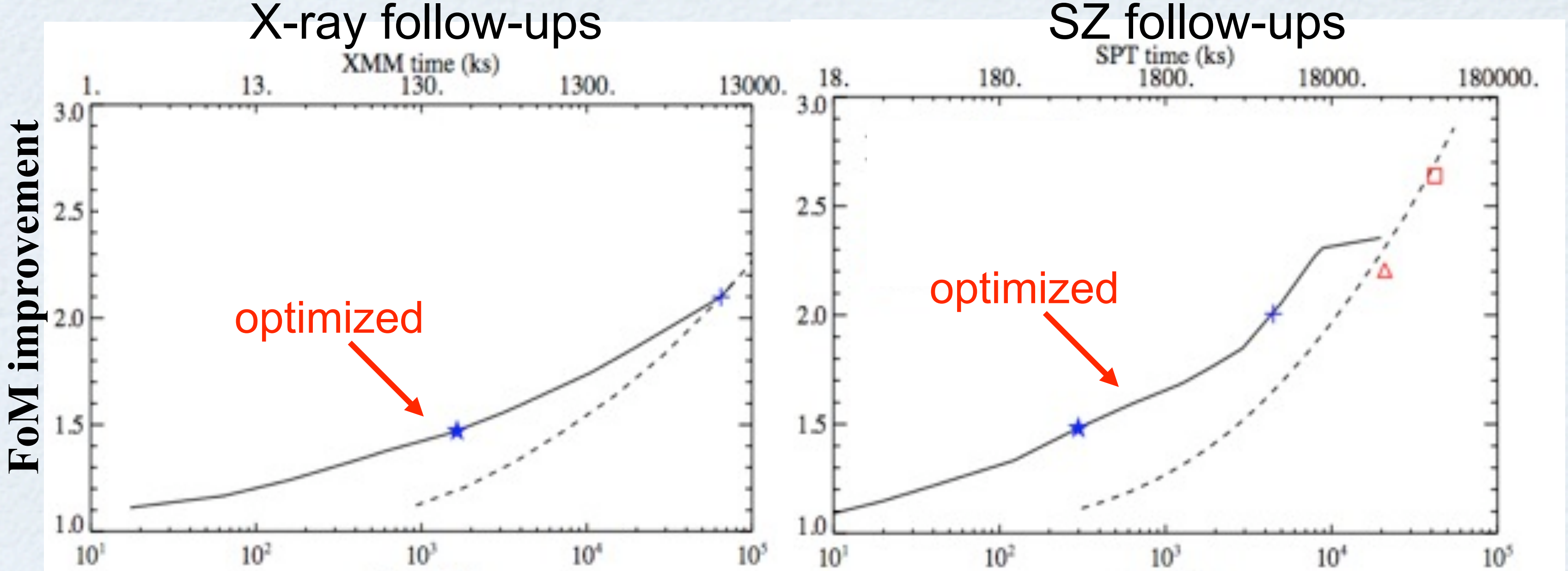


- Clusters are weighted by their observational cost ∝ 1 / Flux
- X-ray follow-ups
  - Cost is sensitive to redshift
  - Small program: low-z clusters
  - Large program: clusters span a redshift range
- SZ follow-ups
  - Cost is sensitive to mass
  - Small program: massive clusters span over a redshift range
  - Large program: some less-massive clusters

Optimization: Different Strategies for X-ray and SZ



Optimization: FoM as a function of Telescope Time

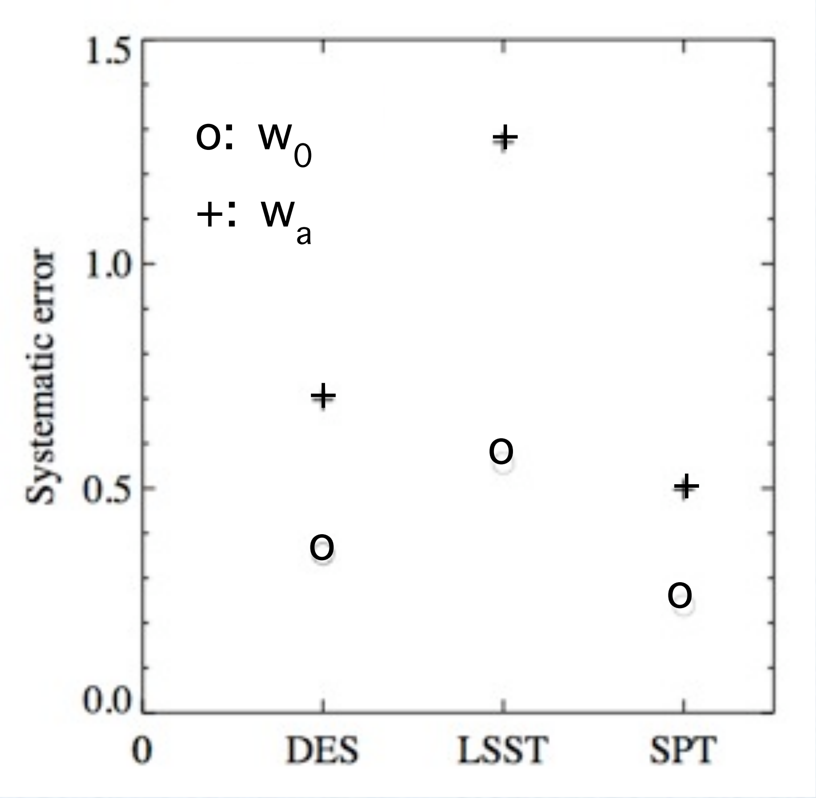


Cost proxy ∝ 1 / Flux; corresponding telescope time is shown on the top

- 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.

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.

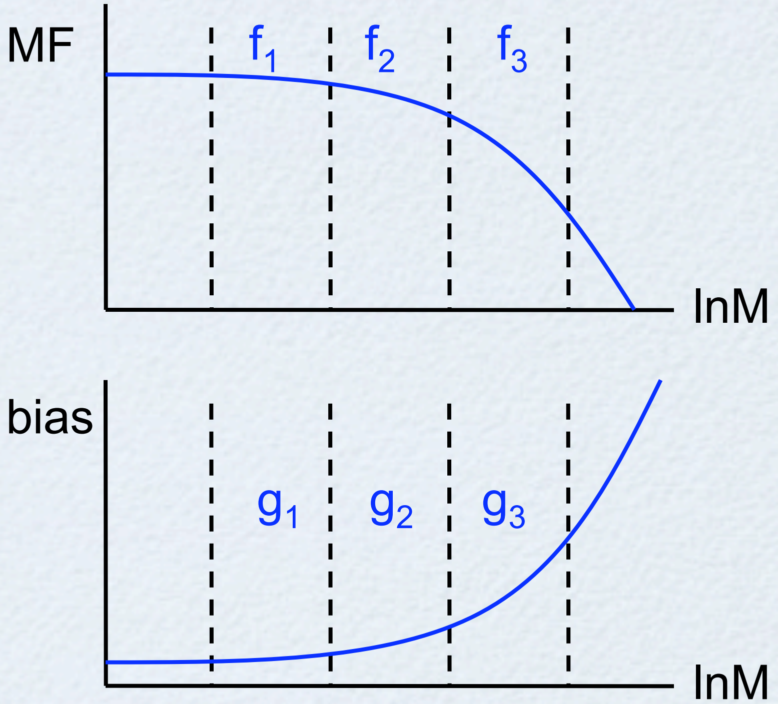


Wu, Zentner, and Wechsler, arXiv: 0910.3668

Also see Wu et al. '08 for the effects of assembly bias

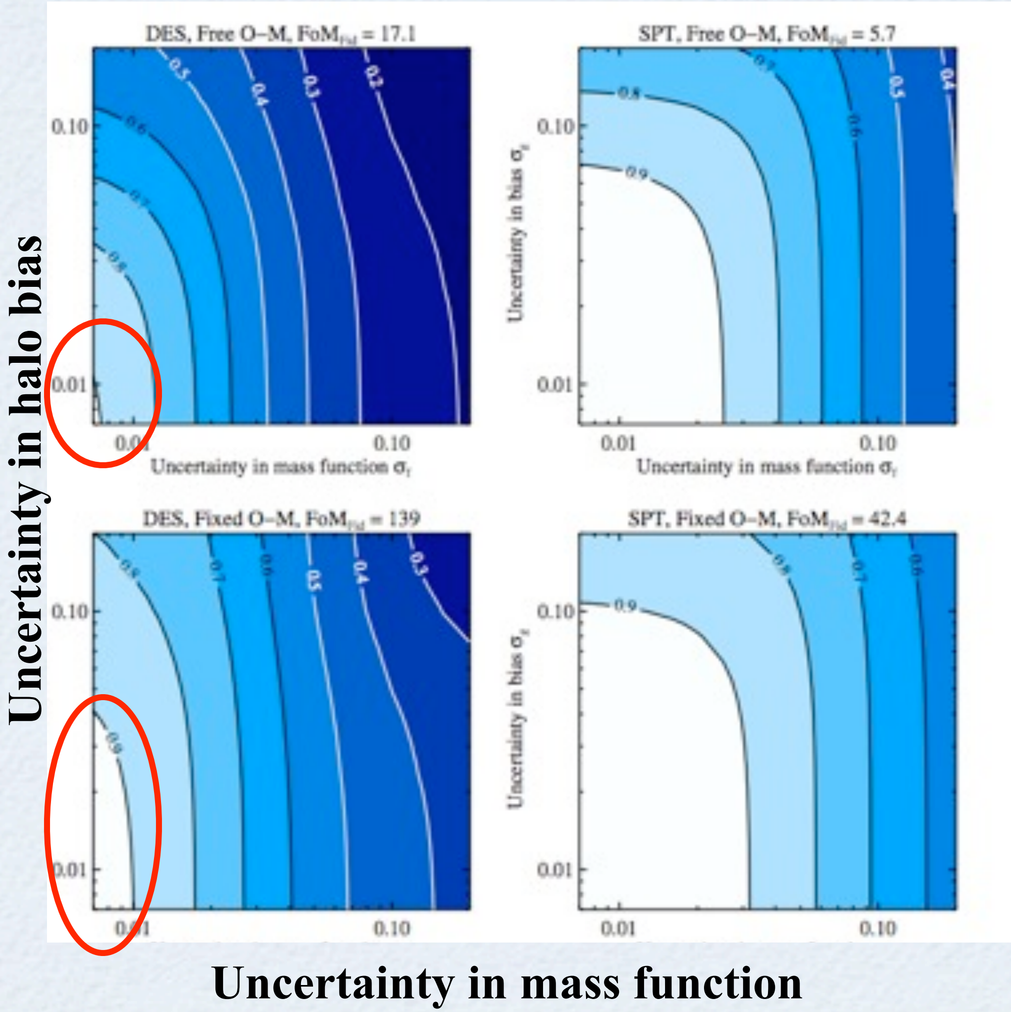
Modeling the Uncertainties in Mass Function and Halo Bias

- 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

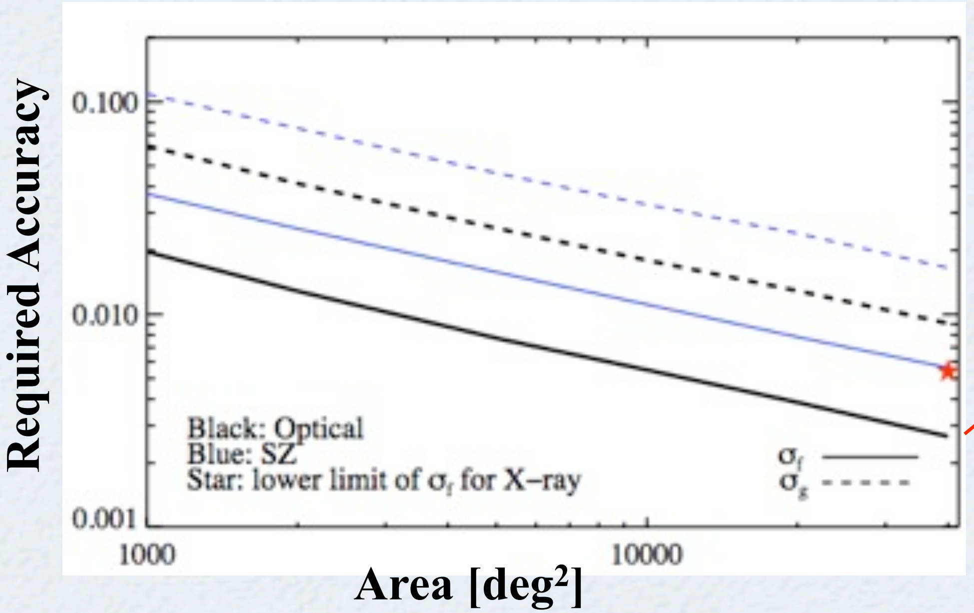
Right: SPT assumption

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

DES assumptions: $M_{th} = 10^{13.7}\ M_{sun}/h$; Scatter = 0.4; Area = 5000 deg^2

SPT assumptions: $M_{th} = 10^{14.1}\ M_{sun}/h$; Scatter = 0.2; Area = 2000 deg^2

Effects of Survey Area

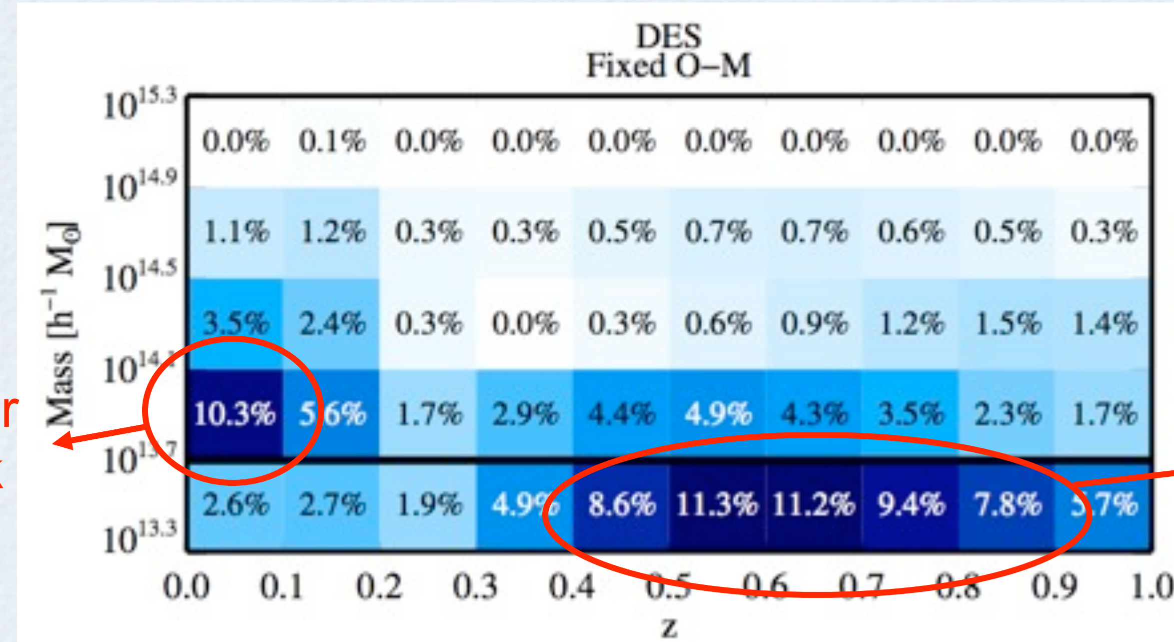


Most stringent requirement will come from a full-sky optical survey.

- Future full-sky optical surveys will required 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

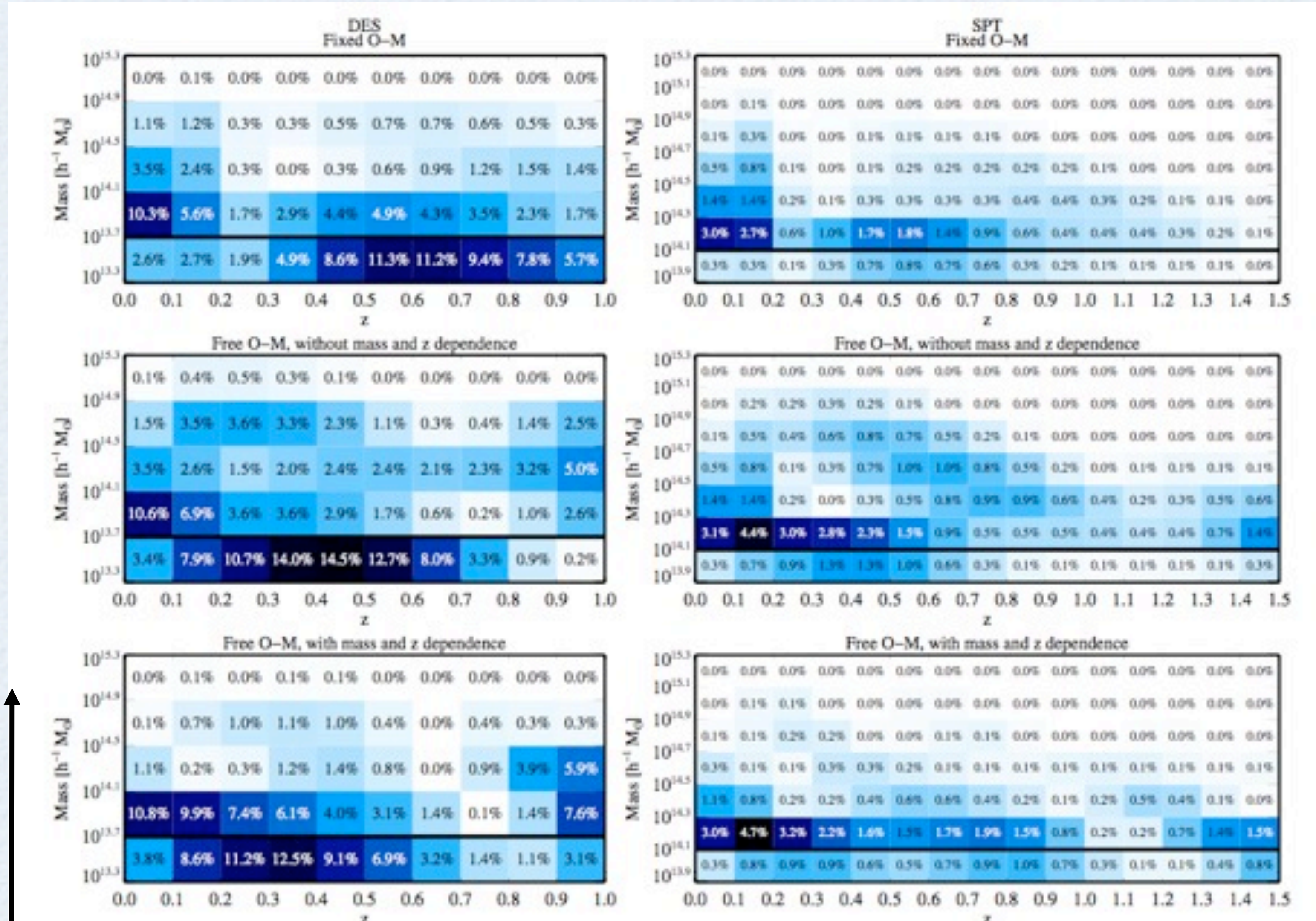
Lowest z: longest lever arm for dark energy constraints



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



More general O-M assumption

Mass

z

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.