Cluster Science with CMB-S4
Cluster Science with CMB-S4 will be extraordinary!
(given a sufficiently small beam)
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 catalogs constructed at X-ray (ROSAT), optical (SDSS, DES) and mm (SZ) wavelengths (SPT, ACT, Planck).

[MASS-OBSERVABLE RELATION] Well-calibrated scaling relation linking survey observable (e.g. Lx, richness, SZ flux) and M,z.

Separate into: 1) relative mass calibration (X-rays) 2) absolute mass calibration (weak lensing)
Current constraints (clusters only): $\sigma_8$, $\Omega_m$

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.)

224 ROSAT All-Sky Survey (X-ray) clusters, $z<0.5$. 
+ Chandra X-ray follow-up (139/224) + Weighing the Giants WL (27/224)
Comparison: X-ray vs. SZ cluster surveys

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

Also consistent with earlier X-ray and optical 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.
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.
Dark energy: clusters vs. independent techniques

Flat, constant $w$ mode:

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

Combined constraint (68%)

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

Cluster constraints from 224 massive clusters at $z<0.5$ (+ Chandra X-ray + WTG weak lensing) competitive with other leading cosmological methods.
The landscape of new cluster surveys
Surveys on the near and mid-term horizons (2017-2023)

Projects:
- Optical/NIR: (DES, HSC), Euclid, LSST
- mm: SPT3G, AdvACT/Simons Obs, 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.**
The discovery space of near and mid-term surveys
The discovery space for CMB-S4
CMB-S4: cluster cosmology perspective

The primary discovery space for cluster cosmology with CMB-S4 will be high-z.

- CMB-S4 will provide the first large, clean, complete catalog of massive clusters at high-z, reaching back to z~3 (when massive clusters first formed).
- while current catalogs have just a few clusters at z>1.5, CMB-S4 will provide thousands.
- As well as finding high-z clusters, CMB-S4 will provide robust absolute mass calibration for these systems, via CMB lensing.

Leveraging the low-z anchor and complementary multi-wavelength data provided by other experiments, CMB-S4 has the potential to transform studies of dark energy with clusters*

*Caveat: this is dependent on CMB-S4 having sufficient spatial resolution.
The need for high spatial resolution

The primary discovery space for (all) cluster science with CMB-S4 is high-z (z>1.5). To enable it, we need the best spatial resolution possible.

With a 1’ beam, CMB-S4 will find thousands of clusters at high-z, and have sufficient sensitivity to provide absolute cluster mass calibration from CMB lensing for these systems to 1-2% (comparable to LSST at low-z). With a 3’ beam, essentially all of this science would be lost.
Cluster/galaxy astrophysics with CMB-S4

As with the cosmological studies, the primary contributions of CMB-S4 to astrophysics will stem from finding large samples of virialized halos out to high-z.

CMB-S4 will provide the definitive target list for studying, e.g.

- The impact of cluster/group environments on the triggering and quenching of star formation and AGN activity (with measurements spanning the peaks of SF/AGN activity).
- The evolution of feedback processes in groups and clusters.
- The integrated history of star formation (metallicity of the ICM).
- and much more ....

Substantial synergies with, e.g. JWST, WFIRST, Athena, ALMA, SKA, 30m telescopes, NASA Surveyors ...
Publications from high-resolution CMB experiments

- SPT papers
- Anisotropies
- Other cosmology
- Cluster astrophysics
- Galaxy astrophysics

Credit: Adam Mantz
Summary

Given a sufficiently small beam (~1 arcmin), CMB-S4 will be transformative for cluster cosmology and cluster/galaxy astrophysics.

With a ~1 arcmin beam, CMB-S4 will unveil the high-z cluster population out to z~3 (when massive clusters first formed) and provide robust absolute mass calibration for these systems from CMB lensing (with a precision comparable to LSST at low-z).

Enabled by CMB-S4, galaxy clusters may indeed “emerge as the most powerful cosmological probe” (Cosmic Visions Dark Energy Science report, arXiv:1604.07626).

With a ~1 arcmin beam, CMB-S4 will also provide a treasure trove for astrophysics, being highly synergistic with other major projects in the 2020s.