Cluster Cosmology: WFIRST + LSST (+SZ)

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Cosmic Visions Report (2016): “The number of massive galaxy clusters could emerge as the most powerful cosmological probe if the masses of the clusters can be accurately measured.”

• Cluster weak-lensing is the most promising observational method to calibrate cluster masses.

• LSST’s weak-lensing and photo-z capabilities will yield a precise and accurate cluster mass calibration to at least $z_{\text{cluster}} \leq 0.8$ (note: DES and HSC already detect cluster lensing signals at higher redshifts)

• WFIRST: better shape + photo-z estimates allow high-quality mass calibration to higher redshifts → esp. important for dark energy
**State of the Art**

*Weighing the Giants IV* alone places 15% constraint on \( w \); one of the tightest single-probe constraints today

competitive constraints also on neutrino masses - nearly independent of cosmological model

+ modified gravity, evolving \( w \), ...
State of the Art

Weighing the Giants based on

• only(!) \(\sim 200\) X-ray-selected (ROSAT) clusters at \(z<0.5\),
• 50 with weak-lensing masses,
• 90 with \textit{Chandra} imaging
• generous marginalization over systematic uncertainties

competitive constraints also from optical and SZ cluster surveys; DES constraints coming next year

\(\sim\) next decade: 100 000s of clusters, multiple selection methods (optical, SZ, X-ray), to \(z\sim 2\) \(\rightarrow\) tremendous statistical power
Ingredients for cluster counts cosmology

1. prediction for halo mass function
2. cluster survey (X-rays, SZ, optical) with well understood selection function
3. relation between survey observable and cluster mass
4. self-consistent statistical framework
Mass proxies: Precision vs. Accuracy

- survey observables (X-ray luminosity, SZ decrement, optical richness) do not measure cluster mass directly
  - correlate with mass, but with considerable scatter, (30-40)%

- follow-up (X-ray) observations can provide a number of precise low-scatter (≤10%) mass proxies:
  - ICM temperature $T_X$; gas mass $M_{\text{gas}}$; $Y_X = M_{\text{gas}} \times T_X$
  - essential for measuring shape and scatter of M-O relation
  - do not provide absolute mass calibration

absolute masses?

- X-ray hydrostatic masses
  - non-thermal bias, $T_X$ calibration

- galaxy dynamics
  - large scatter and bias

- weak lensing
  - small bias: accurate
  - scatter ~30%

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Calibration by cluster weak lensing

- there are multiple methods of finding clusters (see later)

- cosmological constraining power will depend on precision of weak-lensing mass calibration

- limited by how well we can control systematic uncertainties

- LSST+WFIRST will yield the best cluster WL constraints by a significant margin
Ingredients for cluster mass measurements

Shear induced on background galaxy depends on:

- cluster mass (distribution)
- redshift

To measure cluster mass, need

1. reduced shear measurements
2. (some) assumption on mass distribution
3. redshifts / redshift distribution

...and need to understand the systematics of each!
(1) Shear measurements

- bias in shear estimates $\rightarrow$ bias in cluster mass estimate

- cluster-specific issues:
  - shear in clusters is larger
  - dense fields: deblending, background subtraction
  + need to calibrate to (only) $\sim 1\%$, cf. $\sim 10^{-4}$ for cosmic shear

$\rightarrow$ significant improvements with WFIRST imaging to $\sim$LSST depth

DESC Clusters Key Project: image simulations (ARCLETS) specifically for cluster fields to quantify shear bias
(2) Shear - redshift scaling

- shear on background galaxy depends on redshift
- shear($z$) is a steep function right behind the cluster, then flattens out $\rightarrow$ error in mass from photo-z’s depends on cluster redshift

- limitations of ground-based lensing / photo-z’s:
- redshift distribution of resolved galaxies peaks at $z \sim 0.8$ (though deeper data adds high-$z$ tails)
- “good” photo-z’s require coverage of 4000Å break; $z \leq 1.4$ with LSST’s $y$-band
(2) **Photo-z’s**

- cluster-specific concern: dilution by cluster members
- cluster galaxies not sheared
- (and no empirical evidence for intrinsic alignments, e.g. Sifon et al. 2015)
- any contamination of lensing sample causes mass underestimate

- if cluster galaxies are “simple”, then this can be tuned with adjusting photo-z priors (add peak at cluster redshift); probably ok at low-z (z<0.8)
- **what are the properties of cluster galaxies at z>1?** At WFIRST / LSST depth? In “typical” clusters?
- LSST DESC Clusters WG: efforts to obtain deep multi-object spectroscopy of cluster fields (NOT red-sequence galaxies); would benefit significantly from joint efforts with WFIRST / Euclid
- WFIRST spectroscopy: high-purity lensing galaxy sample
(2) Photo-z's

“clean” photo-z region for LSST for \( z \sim 0.7 \) cluster

dilution problem?

can gain a lot of high-z background galaxies!

from Jain et al. 2015
(3) Mass model

- lensing sensitive to all mass along line-of-sight
  - measures projected 2D masses
  - for relation to halo mass function, need to infer 3D mass

- galaxies are intrinsically elliptical → weak lensing is noisy
  - can typically measure only one parameter reliably

- fit spherically symmetric profile (also breaks mass-sheet degeneracy)

- inferred (3D) mass depends on cluster triaxiality / orientation / substructure, structure along LOS
  e.g. Meneghetti et al. 2010, Hoekstra 2003, 2011

- (3D) lensing masses have intrinsic irreducible scatter of ≳ 20%
  (ground-based: scatter from shape noise also ~20% ⇒ total scatter: ~30%)
  (e.g. Becker & Kravtsov 2011)
Is the average lensing mass (un-)biased calibratable?

- methodology can be well tested on N-body (+hydro) simulations
- need to quantify mass bias as function of mass, radius, redshift, fitting method, miscentering, cosmology, ...
- significant efforts underway within LSST DESC; machinery will be available to extend to WFIRST

Becker & Kravtsov 2011

Applegate et al., in prep.
(0) Finding clusters

- X-rays: thermal bremsstrahlung from Intra-Cluster Medium (ICM)
- millimeter: Sunyaev-Zeldovich effect - inverse Compton scattering of CMB photons on ICM
- optical: galaxy population - overdensity of (red) galaxies
(0) Finding clusters

optical / NIR
✓ highest completeness, to relatively low masses
- subject to projection effects
- red sequence finding works very well at $z \leq 1$, but RS not well populated at higher redshifts

X-rays:
✓ in principle, very high purity and completeness (every extended extragalactic source is a cluster)
- in practice: limited angular resolution leads to impurity / incompleteness due to AGN confusion
- large scatter $L_x$ - mass of $\sim 40\%$

SZ
✓ nearly redshift-independent mass selection threshold
✓ high purity and completeness
✓ relatively small scatter in SZ signal - mass of $\sim 20\%$
current proposal by CMB groups

- full-sky (or half-sky)
- low-noise
- main driver: inflation
- could be a fantastic cluster finder (some dependence on resolution)
- 2020-2025

WFIRST goal for cluster detection: $>10^{14}M_{\odot}$

same as CMB-S4 with $1'$ resolution, 1 $\mu K$-arcmin

thin lines: CMB-S4 mass thresholds (50% completeness) for 3', 2', 1' resolution
noise: 1 $\mu K$-arcmin
Impact of Angular Resolution

SZ mass sensitivity limited by noise + angular resolution

increased angular resolution especially important for:

• cluster finding at z>1
• CMB cluster lensing (mass calibration)

exactly the regime where things become difficult even for WFIRST +LSST:

• cannot rely on red sequence for cluster finding
• have to rely on high-redshift source galaxies for weak lensing
CMB Cluster Lensing Overview

- To date, most cross-correlations between CMB lensing and tracers of the matter density field probe *two-halo regime*
- Recently, CMB lensing in the *one halo regime* has been measured

CMASS galaxies (Madhavacheril et al. 2015)

![CMASS galaxies plot]

SPT-SZ clusters (Baxter et al. 2015)

![SPT-SZ clusters plot]

Planck clusters (Planck XXIV 2015)

![Planck clusters plot]
Possibilities & Challenges
with CMB Cluster Lensing

Potentially powerful

• Study cluster masses at high $z$
  – Galaxy lensing at high-$z$ is difficult because high-$z$ source galaxies are faint and hard to measure

• When combined with galaxy lensing...
  – Test for systematics in other weak lensing measurements
  – Constrain cosmology using distance ratios when combine with galaxy weak lensing (Hu, Holz, Vale 2007)

Challenges

• Small scales $\geq$ beam is a problem
• Potential biases due to e.g. tSZ and kSZ
Results on Simulations

Mock clusters
- NFW profile
- $M_{200} = 3 \times 10^{14} \, M_{\text{sun}}$
- $z = 0.7$
- $c = 3$
- $N = 5000$

Mock CMB maps
- Realistic fields, noise, beam, transfer function, foregrounds

E. Baxter
details still to be decided

possible scenario: incorporate existing telescopes: SPT 10-m, ACT 6-m, Simons Observatory 6-m

existing facilities already provide ~1’ resolution

good for clusters!

in particular, SPT-3G survey very similar to CMB-S4 goals:
1’ resolution; 2 μK-arcmin noise level (cf. 1 μK-arcmin for CMB-S4)
2500 \degree survey, entirely within LSST (and DES) footprint
2016-2019

within SPT-3G footprint, we will already know large fraction of clusters with \( >10^{14} M_\odot \) by 2020
ACTpol and Advanced ACT

larger-area surveys, ~1.5’ resolution, higher noise level

ACTpol: overlap with HSC, ~15 μK-arcmin (similar to SPT-SZ), completed

AdvACT: ~half-sky, ~10 μK-arcmin, overlap with DESI + DES
Synergy SZ - WFIRST+LSST

1. use SZ as cluster finder (and mass proxy)
2. use WFIRST+LSST for confirmation + redshift determination (and secondary mass proxy)
3. use WFIRST+LSST to identify additional (lower-mass) clusters; verify through SZ stacking
4. two avenues for mass calibration:
   • galaxy-based shear from WFIRST+LSST
   • CMB-cluster lensing (especially useful for high-z; only a stacked measurement)
   • some joint systematics (e.g. miscentering), some independent systematics (photo-z’s)
   • systematics for both are difficult to control at required precision → great cross-check
5. inform all-sky surveys (LSST+Euclid+AdvACT)
In practice

CMB-S4 will be “most-sky”; should we just wait for it?

- Not necessarily: the final design might be lower angular resolution than current instruments → significant impact on both cluster finding and CMB cluster lensing

Advantages to considering overlap with current surveys: can utilize follow-up data gathered for SPT and ACT clusters

- X-ray imaging (low-scatter mass proxies! very expensive for high-redshift clusters)
- multi-object spectroscopy
- Spitzer follow-up
Ideal Case for Clusters

complete overlap between SPT-3G and WFIRST HLS footprints (both are ~2500 °); or at least complete coverage of overlap region between SPT-3G and AdvACT

+ pointed observations of the most massive ACT clusters with LSST or HSC coverage (rare in SPT field)

this would:

• ensure good coverage over wide mass range (from $10^{14} \, M_{\odot}$ to the rarest, most massive clusters)

• be highly informative for all cluster surveys (including both LSST’s and WFIRST’s cluster finders), and LSST +Euclid

• yield highly competitive cosmology constraints!
Synergy in Preparation

Can / should / will join efforts on:

1. **Calibrating shear measurements**
   - good news: less stringent than CS (≈1% vs. ≈0.01%)
   - complications:
     - shear is large
     - dense fields
     - calibrate on cluster-specific simulations

2. **Mass model**
   - need to calibrate on simulations

3. **Photo-z’s**
   - sources close behind lenses → good photo-z’s are critical!
   - contamination from cluster galaxies
   - need more data, including spectroscopy and NIR imaging

*new postdoc (Ying Zu) starting with David Weinberg this fall for WFIRST clusters work, DESC member*
Cluster Structure

- Internal structure of an N-body cluster: subhalos and splashback
- Tests of cluster physics and dark matter interactions
- Lensing, galaxy counts and SZ probe this physics

Diemer, Kravtsov; More et al; Adhikari et al; DES, in prep
Discussion topics

- Pixel-level joint processing is essential for deblending, photoz, shear calibration. Challenges for cluster fields?
- Other uncertainties: reduced shear, magnification, projection...How critical is joint processing?
- How much can joint analysis expand redshift range of cluster sample?
Discussion topics: research areas

• Finding the most massive clusters at high-z: with WFIRST and CMB SZ. Can a joint analysis help - validation and evolution?

• Cluster physics, gravity and dark matter interactions: synergies need further study

• Strong lensing, kinetic SZ, other probes?