Galaxy Clusters in Stage 4 and Beyond
(perturbation on a Cosmic Visions West Coast presentation)

Adam Mantz (KIPAC)

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Galaxy clusters: what?

Galaxy cluster: a very massive, bound collection of dark matter, ionized gas, and galaxies ($M \gtrsim 10^{14} \, M_\odot$, $kT \gtrsim 1 \, \text{keV}$).
Galaxy clusters: why?

Primary cosmological use is as a tracer of the growth of cosmic structure.

This constrains:

- Dark energy
- Gravity on large scales
- Neutrino masses
- etc.

(Image from Cole 2005)
Cluster cosmology currently – X-ray version

constant-\(w\) models

Clusters alone:

\[
\begin{align*}
\Omega_m &= 0.261 \pm 0.031 \\
\sigma_8 &= 0.831 \pm 0.036 \\
w &= -0.98 \pm 0.15
\end{align*}
\]

growth index (modified gravity) models

Clusters alone:

\[
\begin{align*}
\Omega_m &= 0.257 \pm 0.030 \\
\sigma_8 &= 0.833 \pm 0.048 \\
\gamma - 0.55 &= -0.07 \pm 0.19
\end{align*}
\]
Galaxy clusters: how?

Three main observing techniques

- X-ray: intracluster medium (ICM) density and temperature
- optical/IR
  - Imaging: cluster galaxies and lensed background galaxies
  - Spectroscopy: galaxy velocities
- mm: ICM pressure (SZ effect)

Abell 1835 as seen by Chandra, Subaru, and SZA
Galaxy cluster cosmology: how?

1. Predicted halo mass function from simulations
2. Observed number of clusters as a function of $z$ and survey signal
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Stage 4 cluster surveys will open up a vast discovery space!
Galaxy cluster cosmology: how?

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2. Observed number of clusters as a function of $z$ and survey signal
3. Stochastic relation between mass and observable signal(s)
   - Astrophysics-dependent (limited ability to simulate)
   - Data driven modeling – need to measure masses
   - No single mass proxy is simultaneously accurate and precise!
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Accuracy: weak lensing

Average mass constraint to $\sim 7\%$, down to 1–2% within years.
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precision: X-ray gas mass, temperature

Relative masses of individual clusters to $\sim 10\%$
What next?

Stage 4 programs (esp. LSST and CMB-S4) will straightforwardly provide cluster catalogs at all redshifts, and photo-$z$’s and mass calibration at $z \lesssim 1$. To *fully* exploit these data, we need a bit more:

- Confirmation and photo-$z$’s at high redshifts
- Absolute mass calibration at high redshifts
- Relative mass calibration (mass proxies for new detections)
Photo-$z$’s at $z \gtrsim 1$

Better photo-$z$’s (for lensed galaxies and clusters) are key for pushing galaxy-cluster lensing to higher $z$ than LSST alone allows.

- sources are close behind lenses
- need to avoid contamination by cluster members
- Deep NIR photometry (WFIRST/Euclid) and spectroscopic follow-up will be essential
- SNOWmass white paper (Jeff Newman et al.)
  
  *Spectroscopic needs for imaging dark energy experiments*
  
  – high-$z$ cluster fields ideal targets for 30 m class telescopes
Absolute mass calibration at $z \gtrsim 1$

We expect LSST lensing to be excellent (good to 1–2%) out to $z \lesssim 1$. For $z \gtrsim 1$, we need another solution.

- CMB-cluster lensing (CMB-S4; resolution/depth dependent)
- space-based NIR galaxy-cluster lensing (WFIRST)
- velocity dispersions (DESI et al.)?
Relative mass calibration

Utility of a mass proxy depends on the complexity and intrinsic scatter of its scaling with mass.

X-ray observables \((M_{\text{gas}}, T_X, Y_X)\) set a high standard, with intrinsic scatters of 10–15%.

- Chandra/XMM-Newton (currently operating)
- eROSITA (2018 launch; 4 yr survey followed by pointed phase)
- ATHENA (2028 launch; 30 Ms survey followed by pointed phase)
- X-ray Surveyor (early 2030’s launch)
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Clusters provide tight cosmological constraints, and are one of the main probes enabled by large stage 4 surveys. The science return of these new cluster catalogs can be significantly enhanced by the right set of complementary observations. Effective coordination across multiwavelength projects is essential.