Galaxy Clusters in Stage 4 and Beyond

(perturbation on a Cosmic Visions West Coast presentation)

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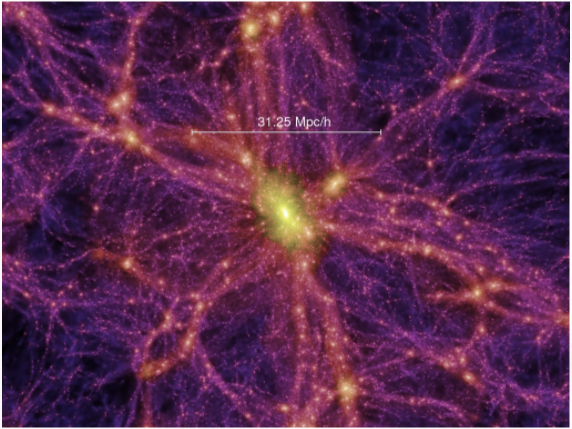
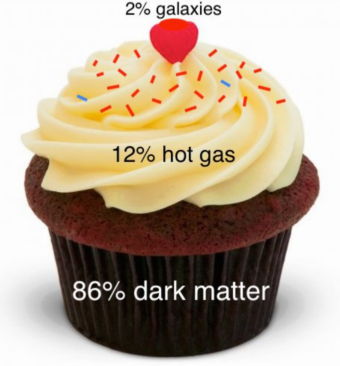
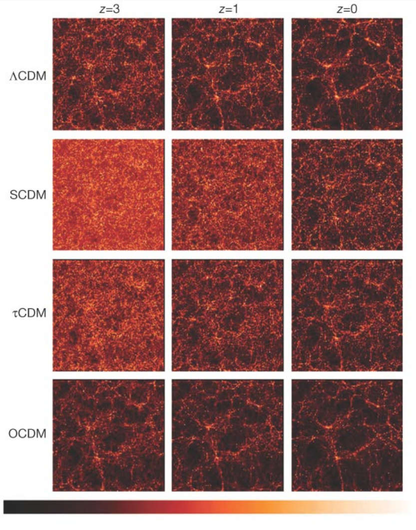
Galaxy clusters: what?

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





Galaxy clusters: why?



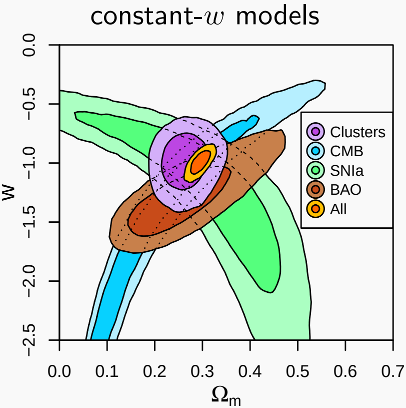
Primary cosmological use is as a tracer of the growth of cosmic structure.

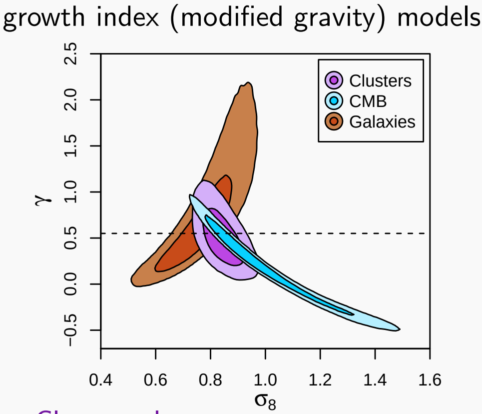
This constrains:

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

(Image from Cole 2005)

Cluster cosmology currently – X-ray version





Clusters alone:

$$\Omega_m = 0.261 \pm 0.031$$
$$\sigma_8 = 0.831 \pm 0.036$$
$$w = -0.98 \pm 0.15$$

Clusters alone:

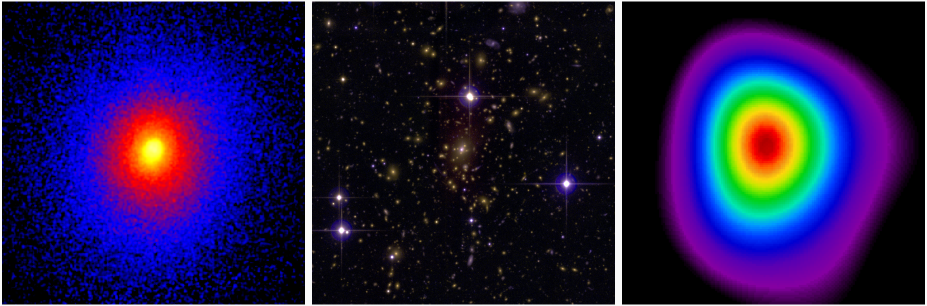
$$\Omega_m = 0.257 \pm 0.030$$
$$\sigma_8 = 0.833 \pm 0.048$$
$$\gamma - 0.55 = -0.07 \pm 0.19$$

AM+ 2015

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?

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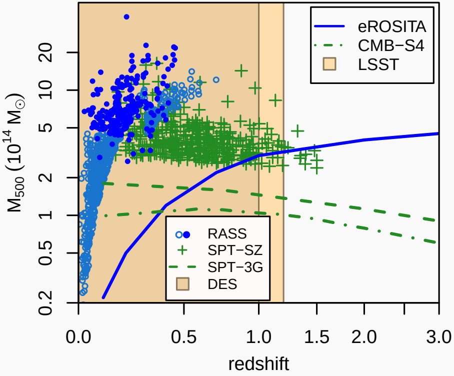

Stage 4 cluster surveys will open up a vast discovery space!

Galaxy cluster cosmology: how?

1. Predicted halo mass function from simulations
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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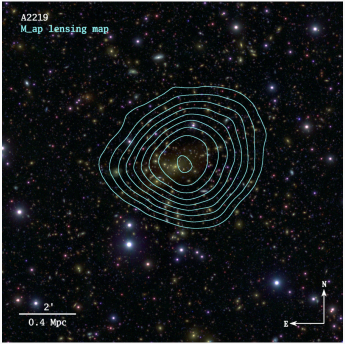

Accuracy: weak lensing

Average mass constraint to $\sim 7\%$, down to 1–2% within years.

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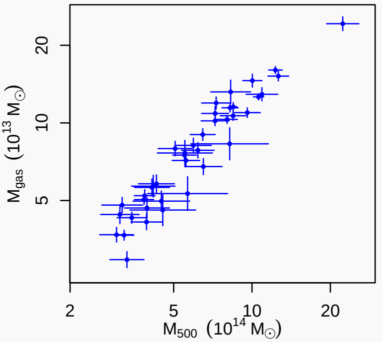


Precision: X-ray gas mass, temperature

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 $z \gtrsim 1$

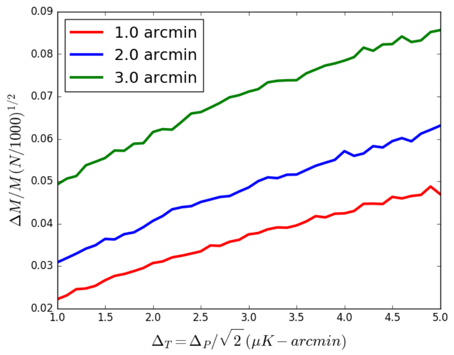
Better photo-z's (for lensed galaxies and clusters) are key for pushing galaxy-cluster lensing to higher z than LSST alone allows.

- 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 ($M_{\rm gas}$, $T_{\rm X}$, $Y_{\rm X}$) 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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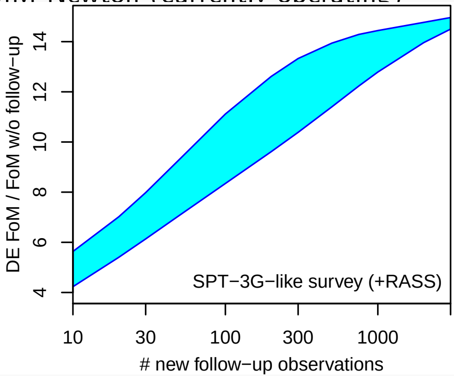

Summary

- 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.