# Galaxy Cluster Cosmology: Enhancing Upcoming Surveys

Adam Mantz (KIPAC)

Cosmic Visions Dark Energy

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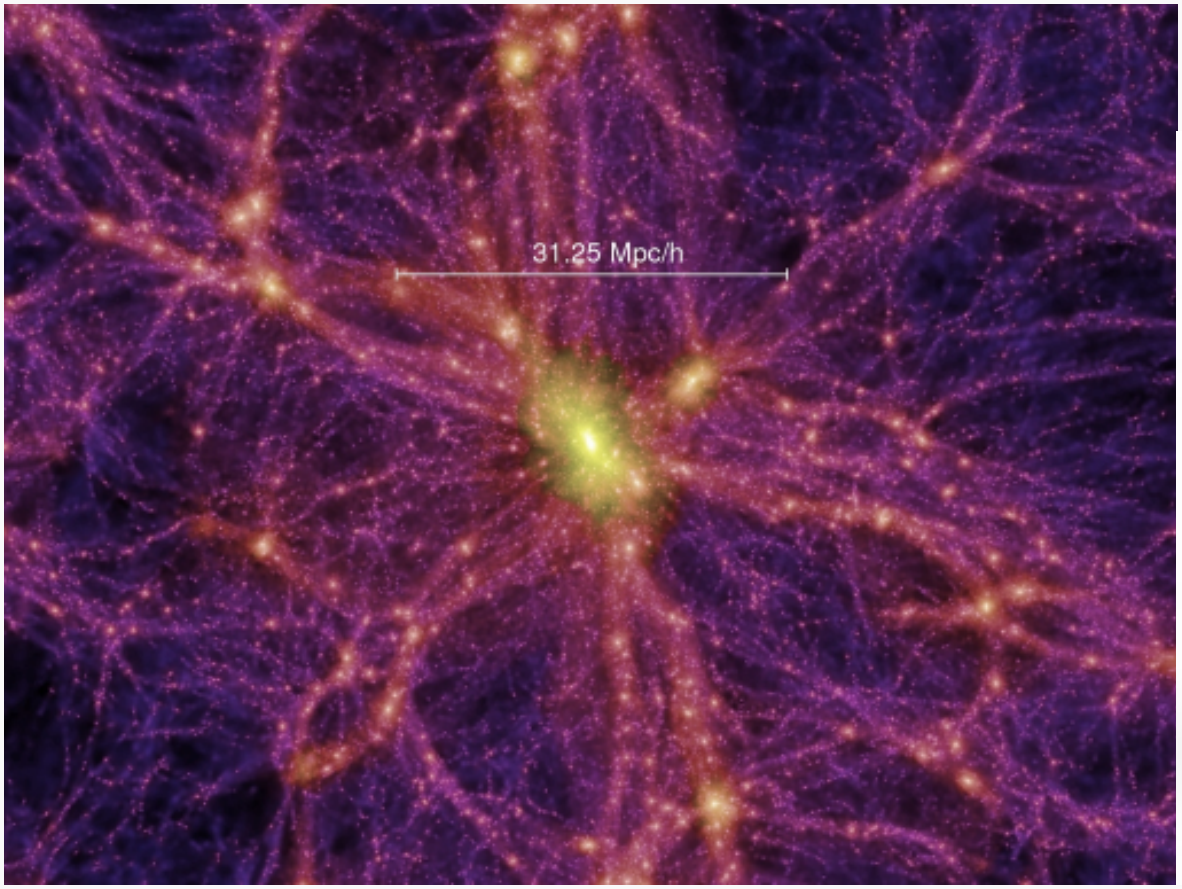
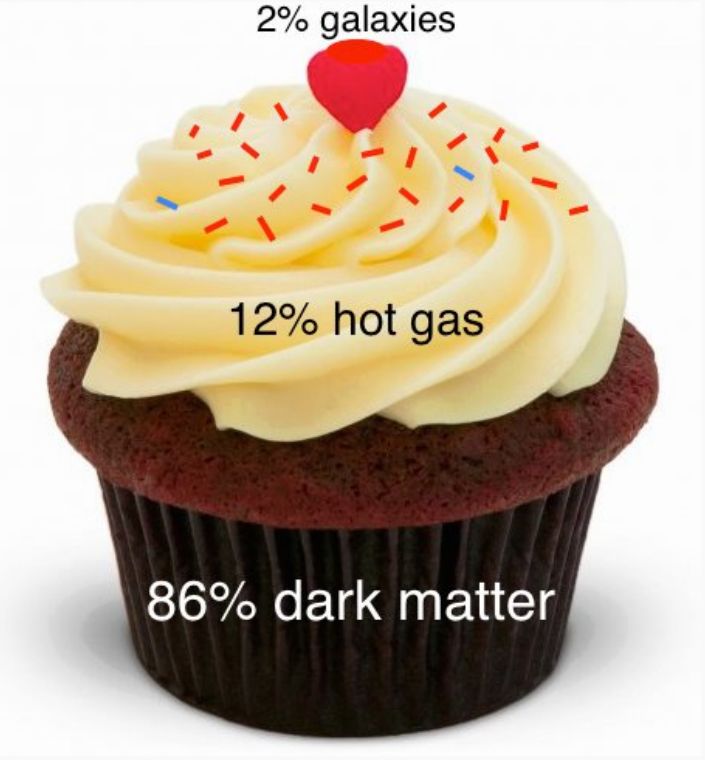
# Outline

1. Cluster cosmology overview
2. Where things stand
3. Upcoming surveys
4. **Data that can magnify the impact of upcoming surveys**

# What are clusters of galaxies?

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



# What do clusters do for cosmology?

- Mass function $\leftarrow$ growth of structure, expansion, neutrino mass
- Gas-mass fractions (standard quantity) $\leftarrow$ cosmic expansion and $\Omega_{\rm m}$
- Clustering of clusters $\leftarrow$ growth of structure, expansion
- X-ray and mm pressure measurements $\leftarrow$ cosmic expansion
- Bulk flows $\leftarrow$ growth of structure, expansion
- Merger statistics $\leftarrow$ dark matter cross section
- Internal structure $\leftarrow$ dark matter, gravity
- ...

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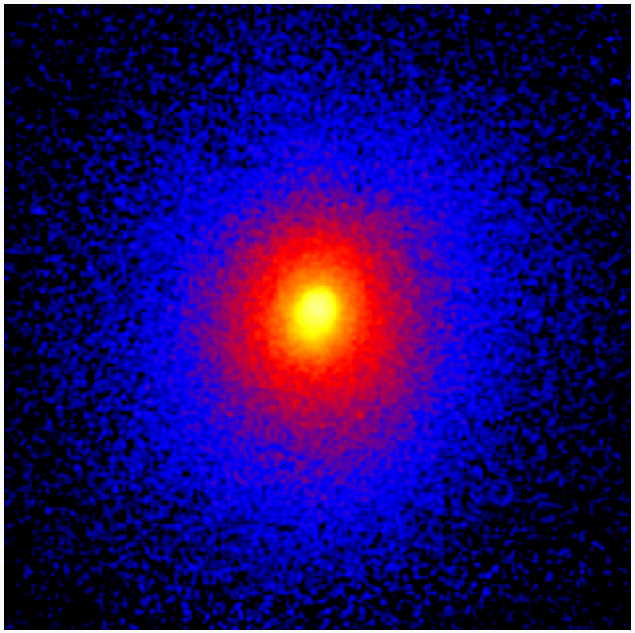
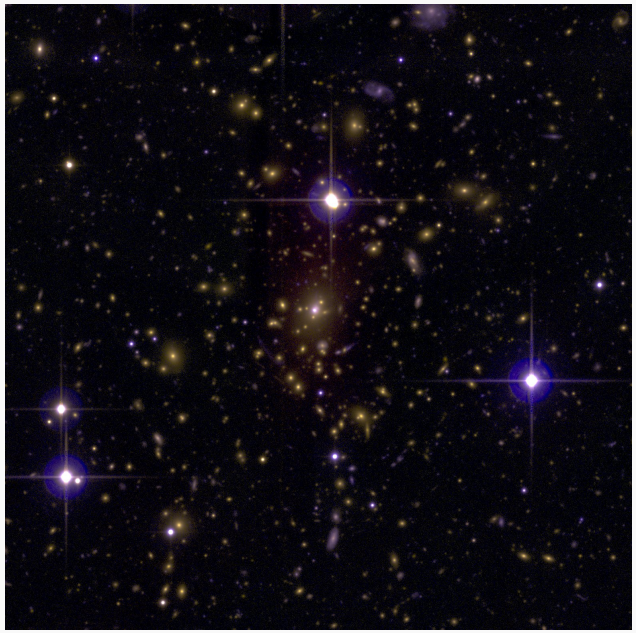
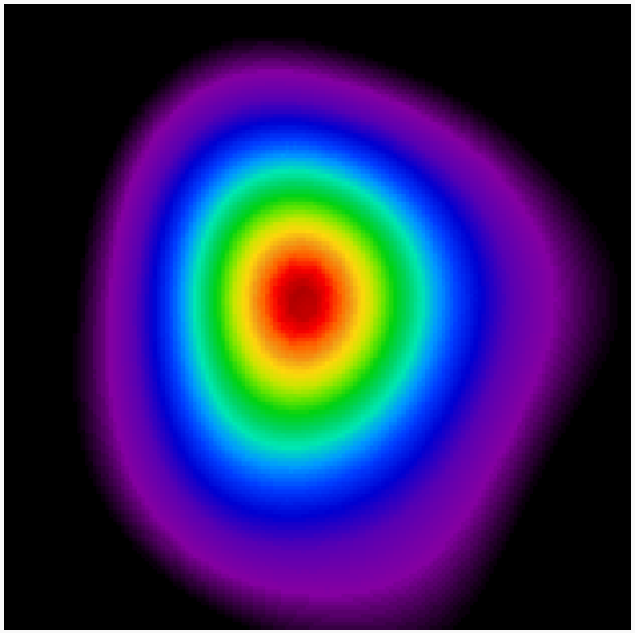
# How it works

Three preferred survey strategies (increasing wavelength order):

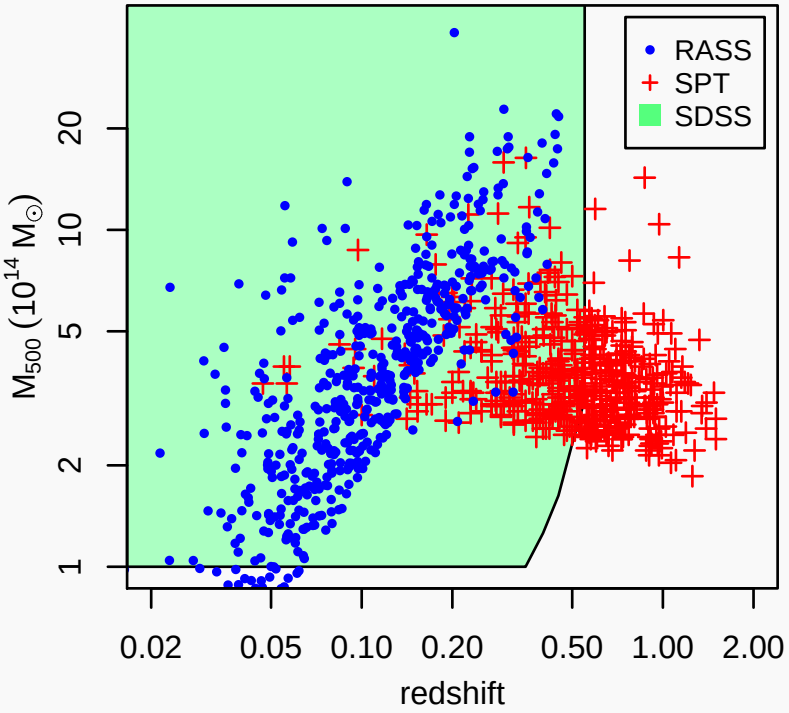
- X-ray: emission from hot intracluster medium (ICM)
- optical/IR: cluster galaxies and lensed background galaxies
- mm: SZ effect (CMB spectral distortion) due to ICM

# How it works

Three preferred survey strategies (increasing wavelength order):

- X-ray: emission from hot intracluster medium (ICM)
  $\rightarrow$ Most massive clusters to high $z$, groups at lower $z$
- optical/IR: cluster galaxies and lensed background galaxies
  $\rightarrow$ High completeness to low masses
- mm: SZ effect (CMB spectral distortion) due to ICM
  $\rightarrow$ Massive clusters at any redshift



# Ingredients

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)
   - More astrophysics-dependent than mass function
   - Data driven modeling – need to measure masses
   - No mass proxy is simultaneously accurate and precise!

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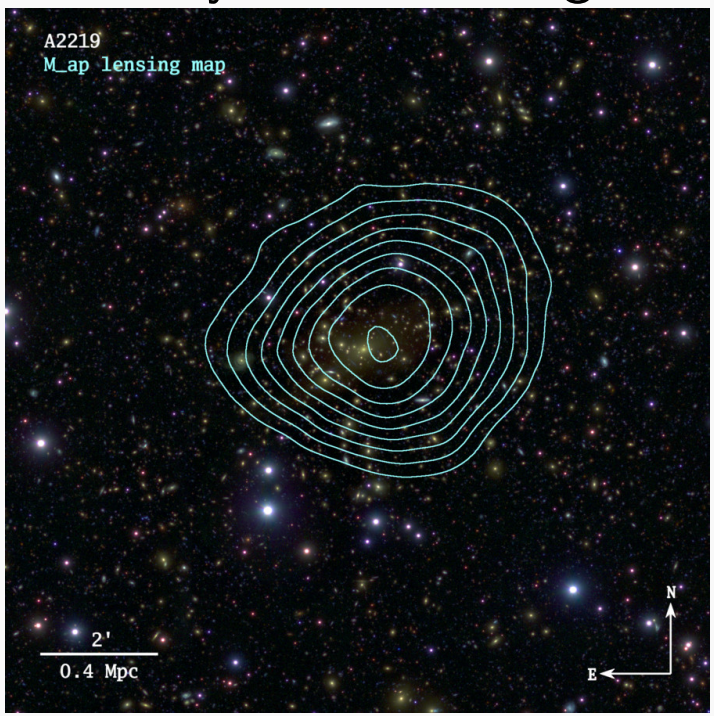
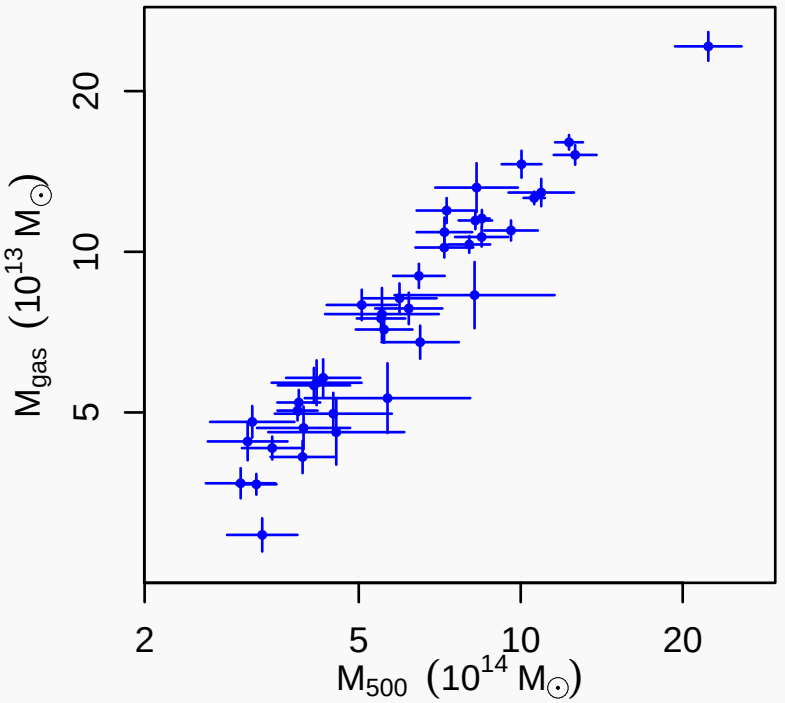
Accuracy: weak lensing




Precision: gas mass, temperature

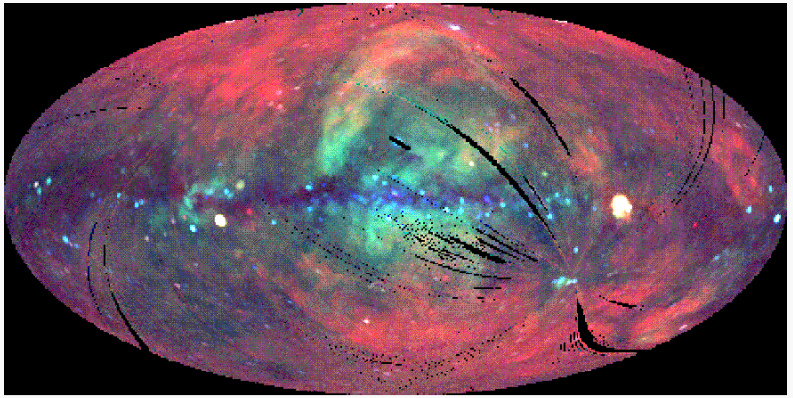


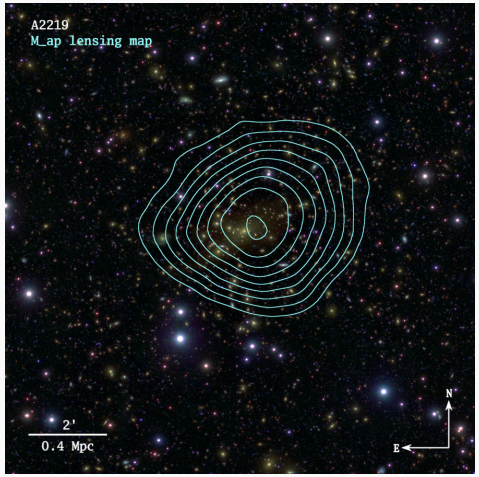
# Current status

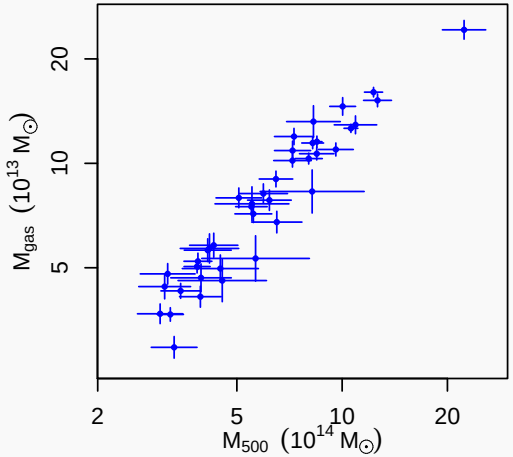
(from your local Stanford group)

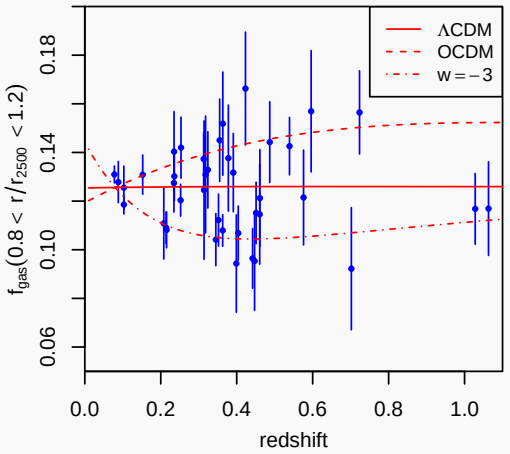
Combining:

1. ROSAT All-Sky X-ray survey
2. Weighing the Giants weak lensing
3. Chandra X-ray mass proxies
4. $f_{\rm gas}$ expansion data



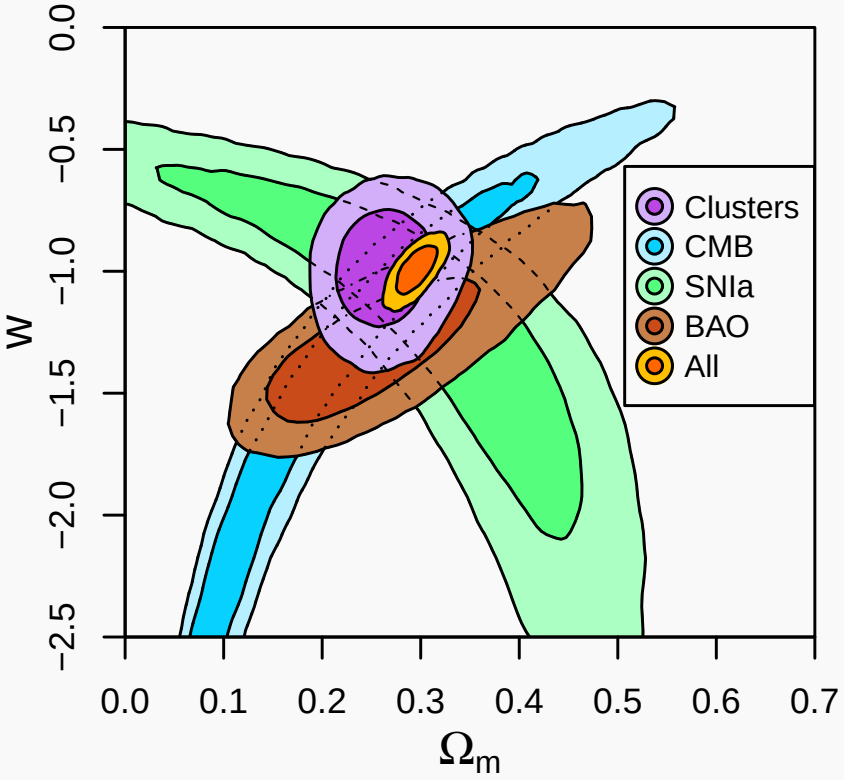


# Current status

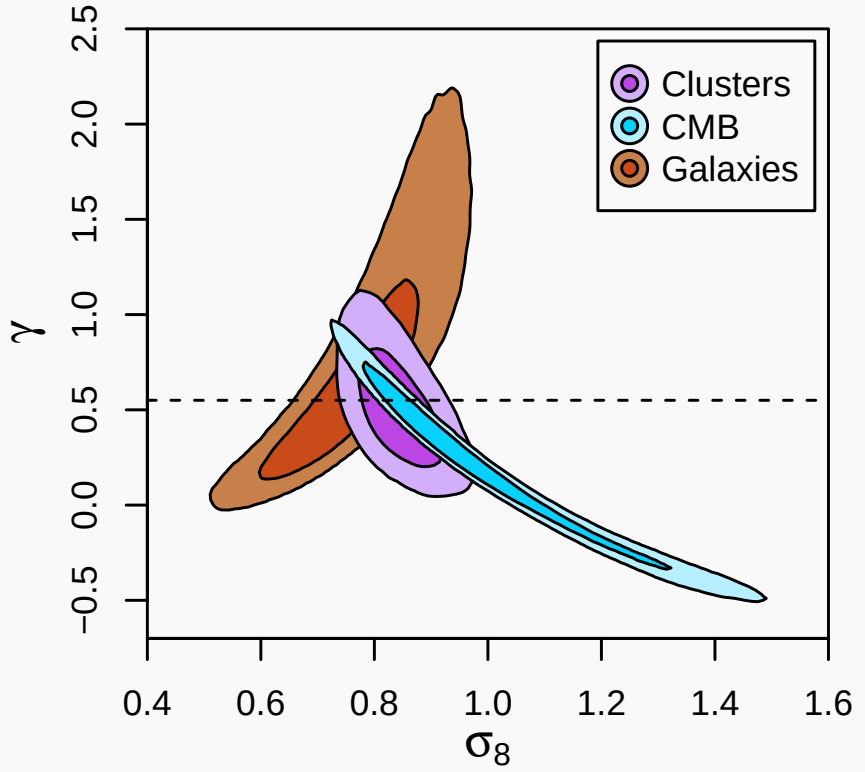
constant-$w$ models




Clusters alone:

$$\Omega_{\rm m} = 0.261 \pm 0.031$$
$$\sigma_8 = 0.831 \pm 0.036$$
$$w = -0.98 \pm 0.15$$

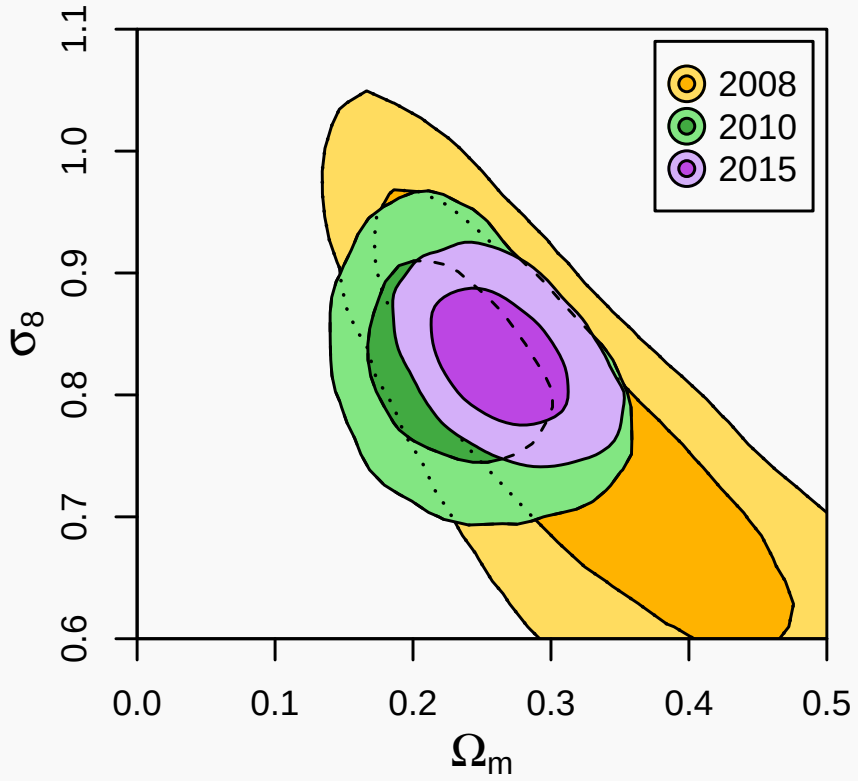
growth index (modified gravity) models

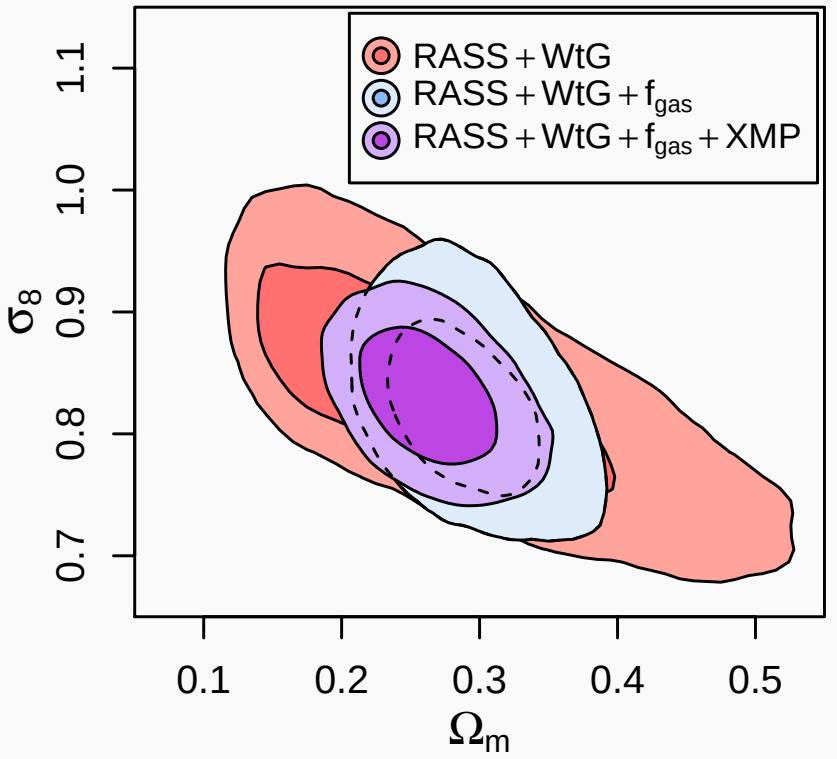



Clusters alone:

$$\Omega_{\rm m} = 0.257 \pm 0.030$$
$$\sigma_8 = 0.833 \pm 0.048$$
$$\gamma - 0.55 = -0.07 \pm 0.19$$

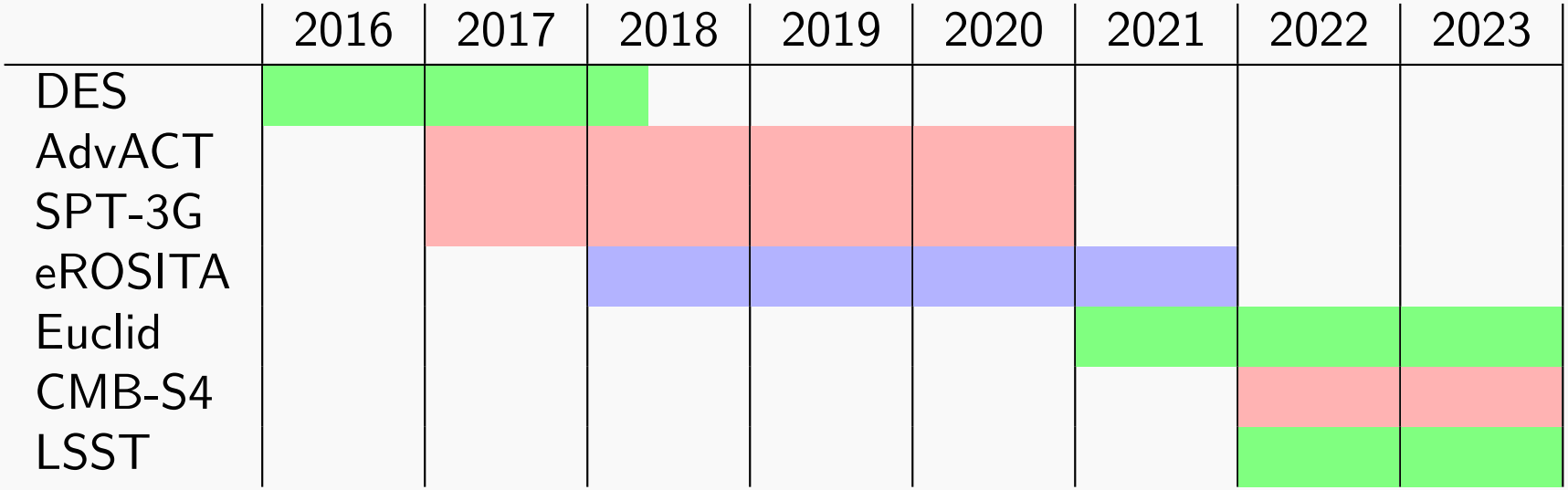
# Current status

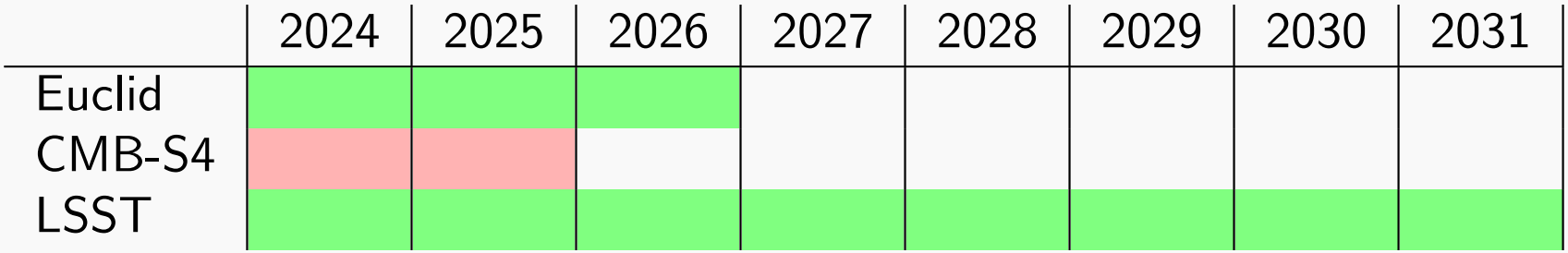



- Improvement has been rapid
- Significant gains to be had from both improving absolute mass calibration (accuracy) and obtaining precise relative masses (precision).

# The road ahead for big cluster surveys




. . . lots!

# What other data would we like?

- (Simulations for mass function and lensing systematics)
- Confirmation and photo-$z$'s at high redshifts
- Absolute mass calibration at high redshifts
- Relative mass calibration (mass proxies for new detections)
- Even more surveys?

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- **Confirmation and photo-$z$'s at high redshifts**
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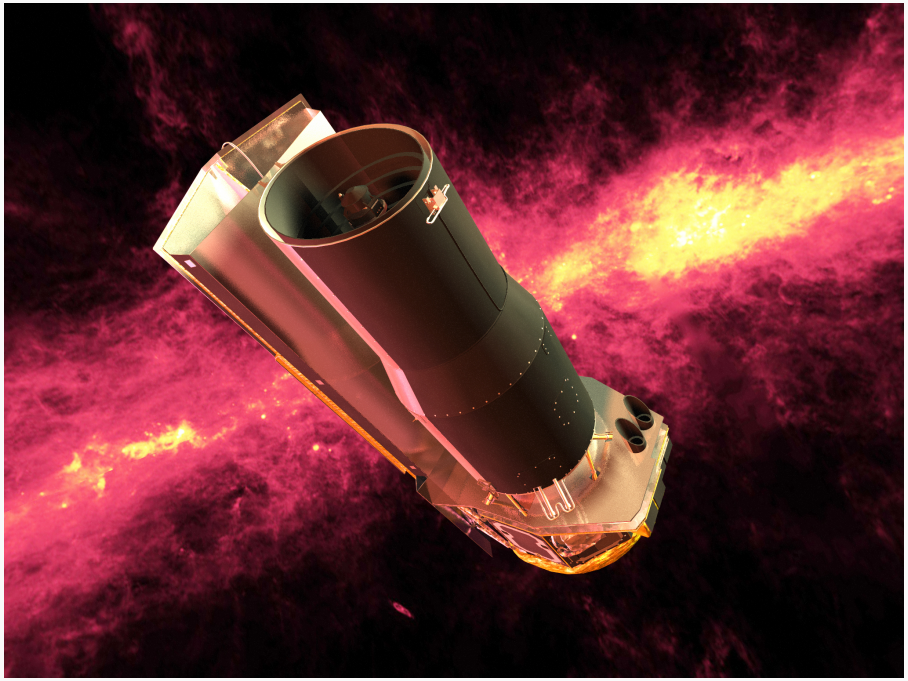
Proper forecasts of their impacts are high on the to do list. . .

# NIR imaging

- Confirmation and photo-$z$'s at high redshifts
- Galaxy-cluster lensing (absolute masses) at high redshifts?

Need continuing access to large ground-based and space-based facilities (e.g. VLT, Magellan, Keck, TMT/GMT, Spitzer, Hershel, WFIRST, . . . )



# Spectroscopy

- Photo-$z$ training sets for faint galaxies behind and in clusters
- Impacts cluster finding and (especially) mass calibration

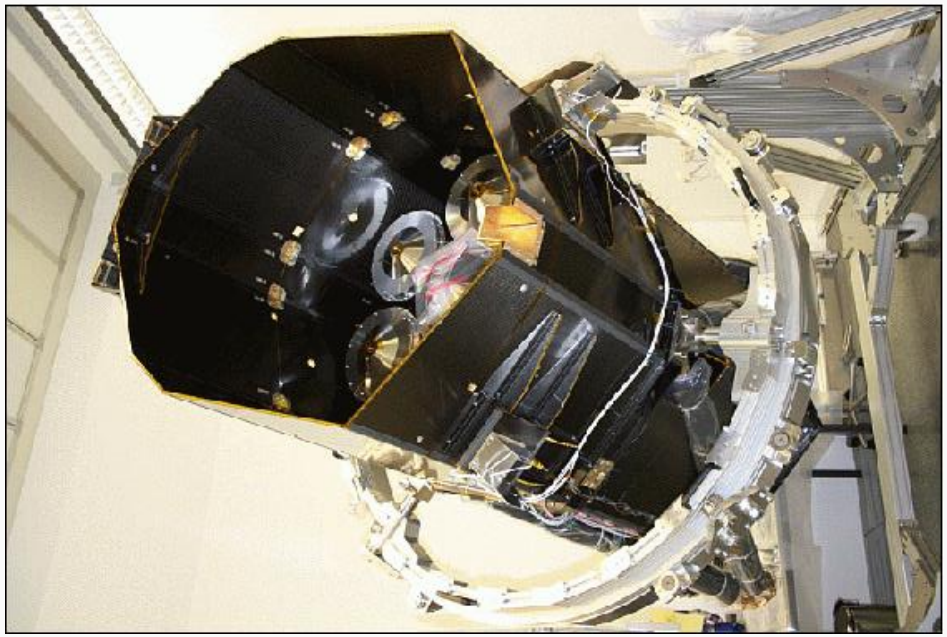
Need continuing access to ground- and space-based facilities, plus future projects like DESI, HSC-PFS (, SPHEREx?)

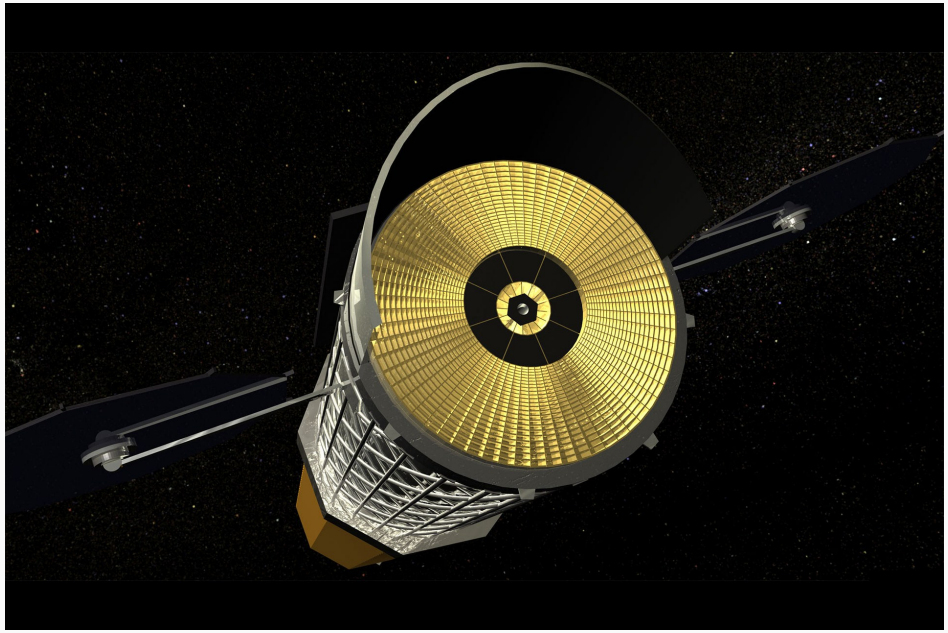
# X-ray imaging spectroscopy

- Provides precise relative mass calibration
- Constrains mis-centering/projection systematics (lensing and optical cluster-finding)

Current facilities: Chandra, XMM-Newton
Upcoming missions:

- eROSITA (2016 launch; 4 yr survey followed by pointed observations)
- ATHENA (2028 launch; 30 Ms survey + pointed observations)



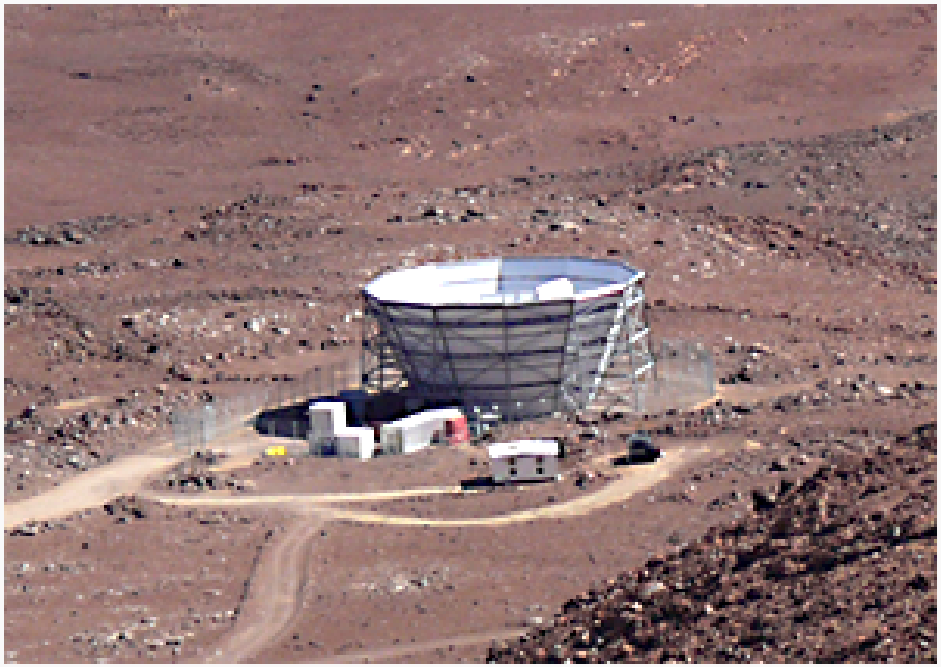


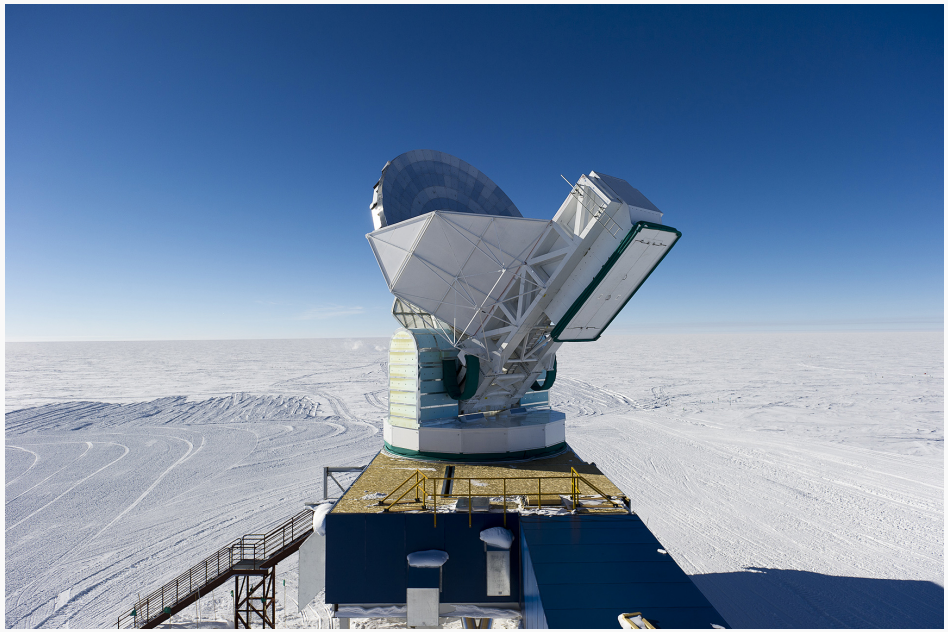
# mm observations

- Best survey for finding clusters at the highest redshifts
- CMB-cluster lensing (high-$z$ absolute mass calibration)

Upcoming project:

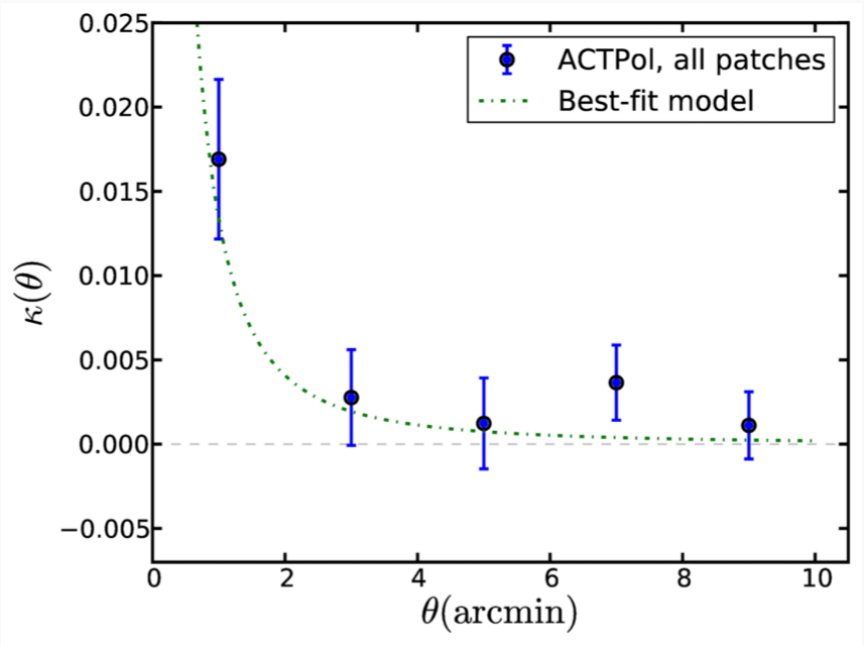
- CMB Stage-4: survey combining multiple ground-based sites



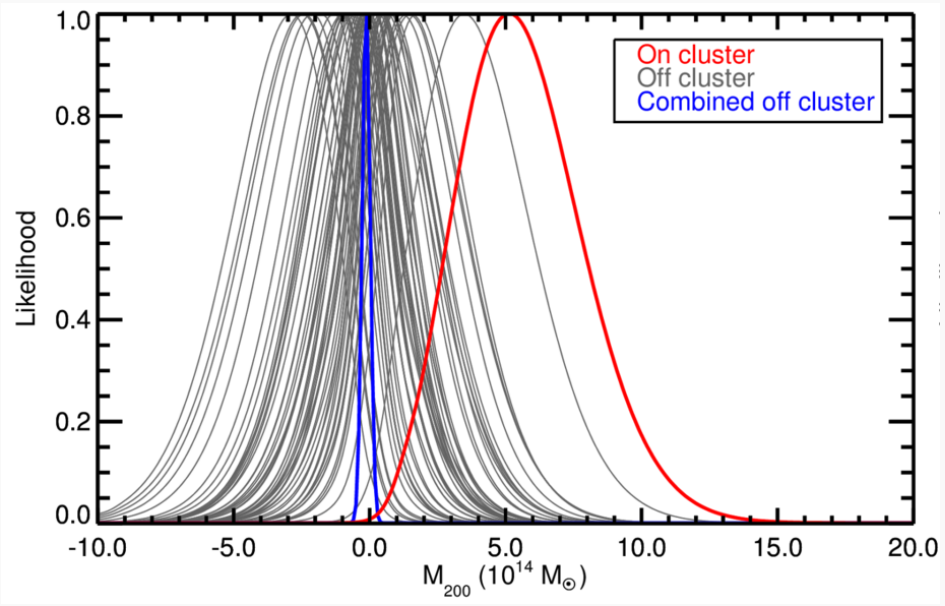


# CMB-cluster lensing

- Recent $\sim 3\sigma$ stacked detections by ACT and SPT.
- Potentially a great resource for absolute mass calibration at high $z$, but more work needed to understand systematics.



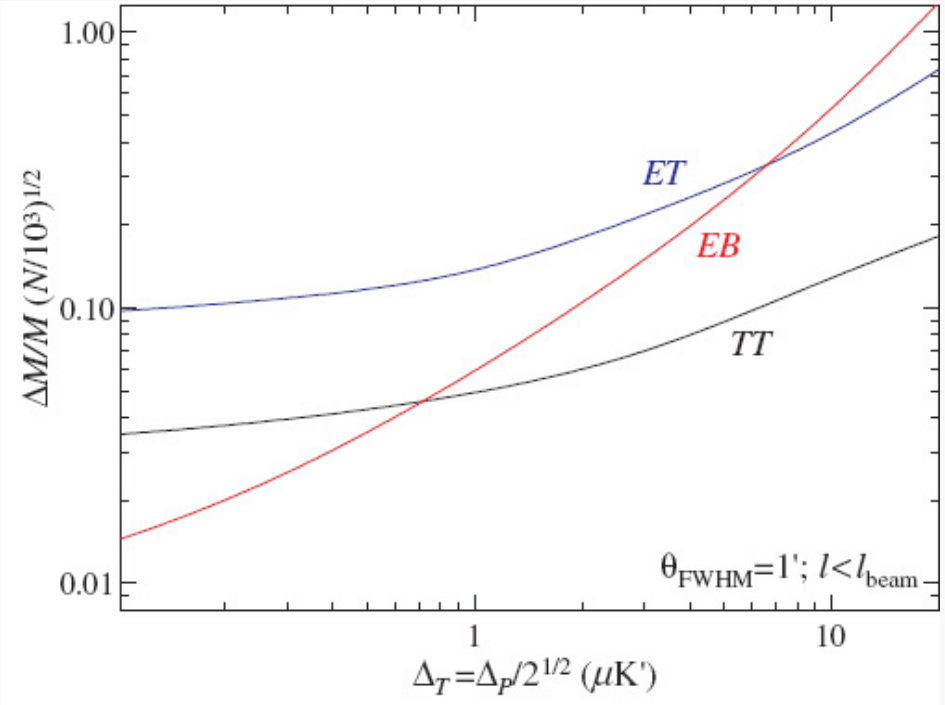

ACT: stacked on 12,000 galaxies
Madhavacheril+ 2015




SPT: stacked on 500 clusters
Baxter+ 2015

# CMB-cluster lensing

- Long-term, polarization signals are more sensitive due to being less contaminated by primary CMB and the SZ effect
- Even so, the Stage 4 survey is not quite as deep as one would like
- Case for a dedicated camera and deep cluster observations? TBD




Hu+ 2007

# Summary

- Clusters provide tight cosmological constraints, and are one of the main probes enabled by large stage 4 surveys.
- Targeted investment in supporting observations can significantly enhance the science return of these new cluster catalogs.
- Much of what we'd like to do is completely straightforward, but there are also some exciting new avenues.