Galaxy Cluster Cosmology with the Atacama Cosmology Telescope (ACT)

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For the ACT Collaboration

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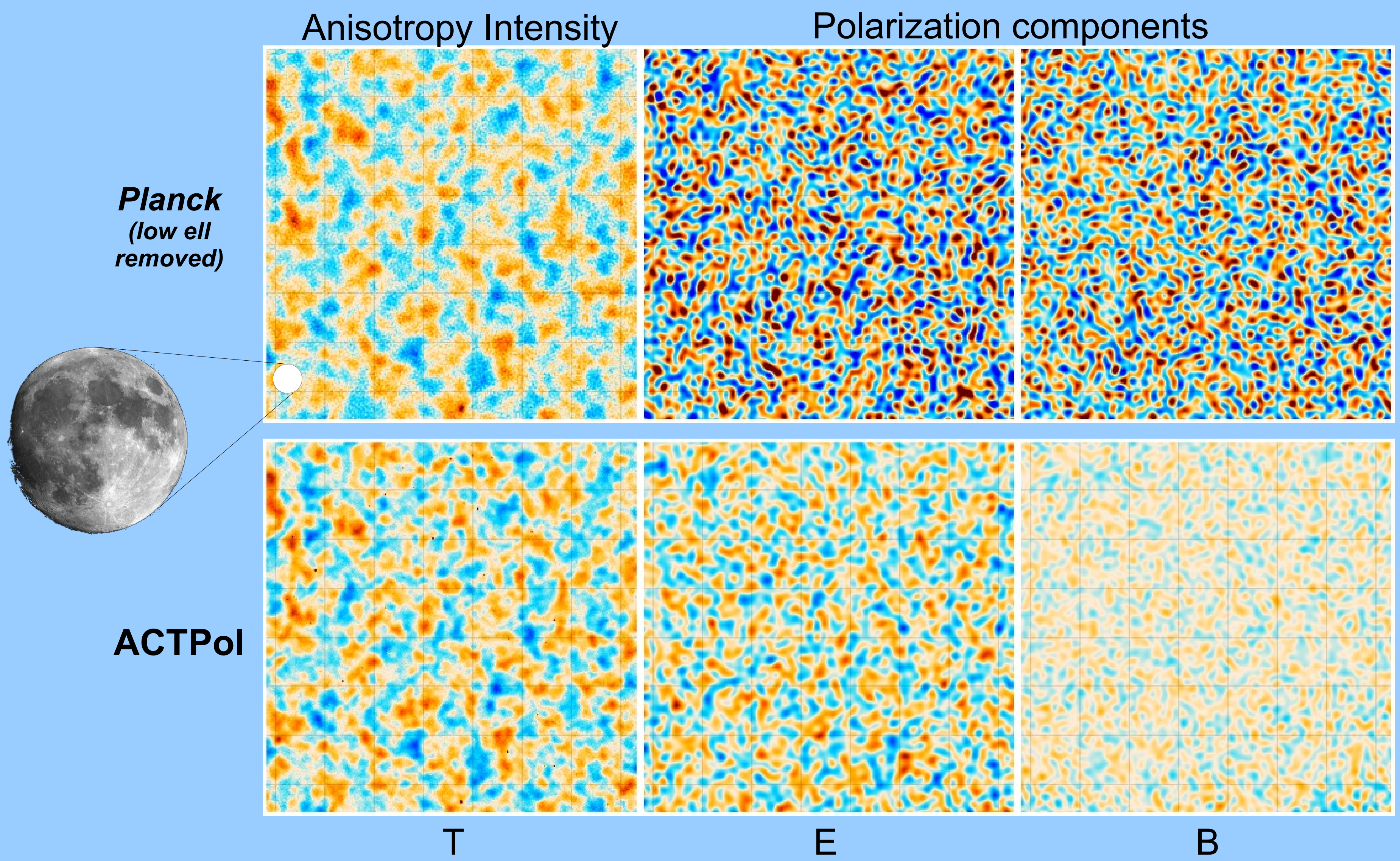
What is ACT

- **Atacama Cosmology Telescope** is a ground-based CMB observatory. The ACT collaboration makes maps from the data and extracts cosmological information.
- Compared to ***Planck***: ACT observes (slightly) smaller regions of sky, with finer spatial resolution, to lower noise levels (in some frequencies).



Galaxy Clusters

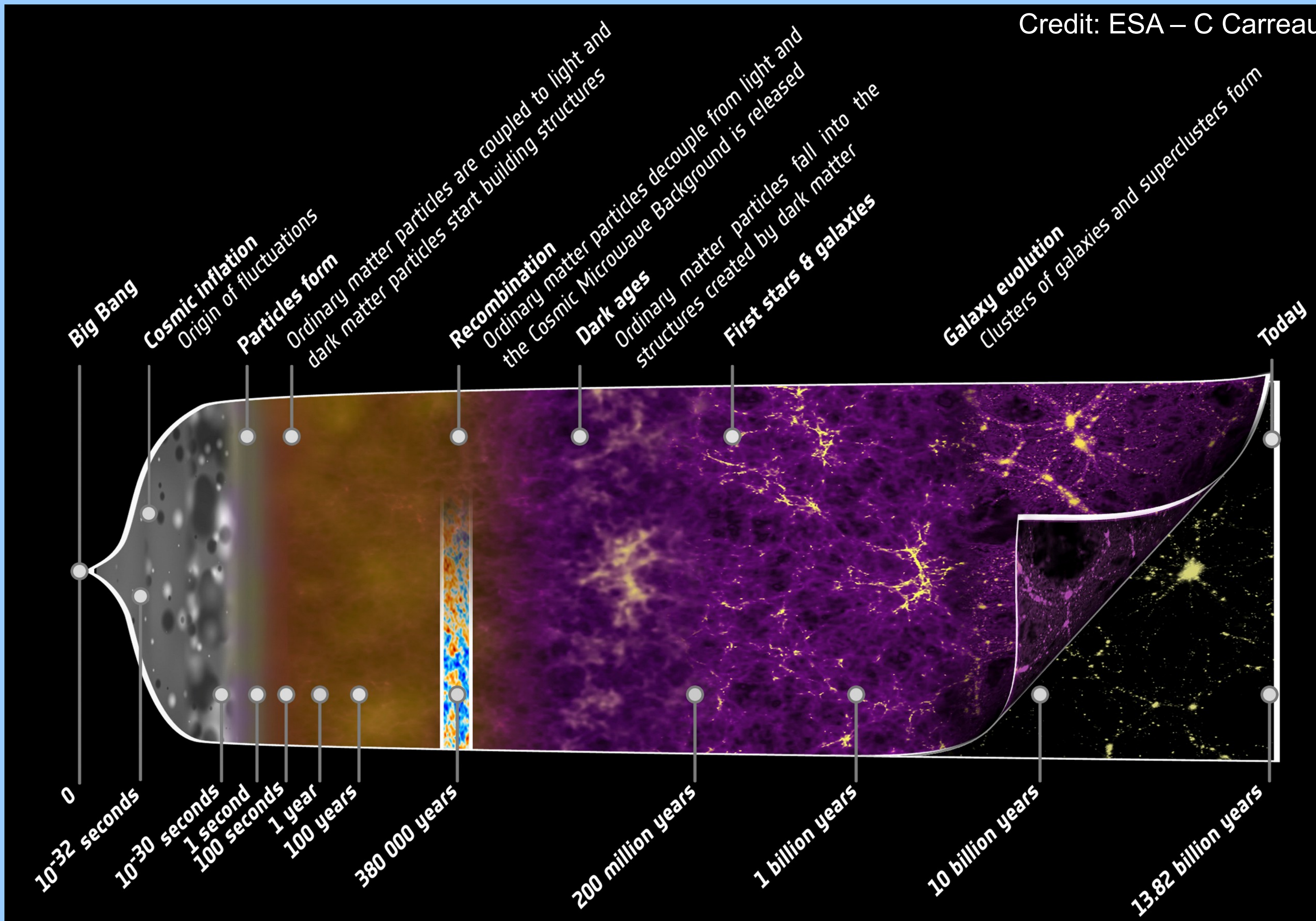
- In addition to the CMB power spectrum… ACT also detects Galaxy Clusters, and can measure their masses (more on this later).
- Galaxy Clusters are the most massive gravitationally collapsed objects in our Universe.
- For cosmology, what we are interested in is: how many galaxy clusters are there (as a function of redshift), and how massive are they? This is the *abundance*.

(These are optical / X-ray images of galaxy clusters… not like ACT images!)

Abell 370; note gravitational lensing arcs (HST).

Abell 644, showing X-ray signal from intracluster medium (Chandra).

What determines cluster abundance?



This history sets bounds on how small and how large a collapsed object can be.

Initial spectrum of fluctuations...

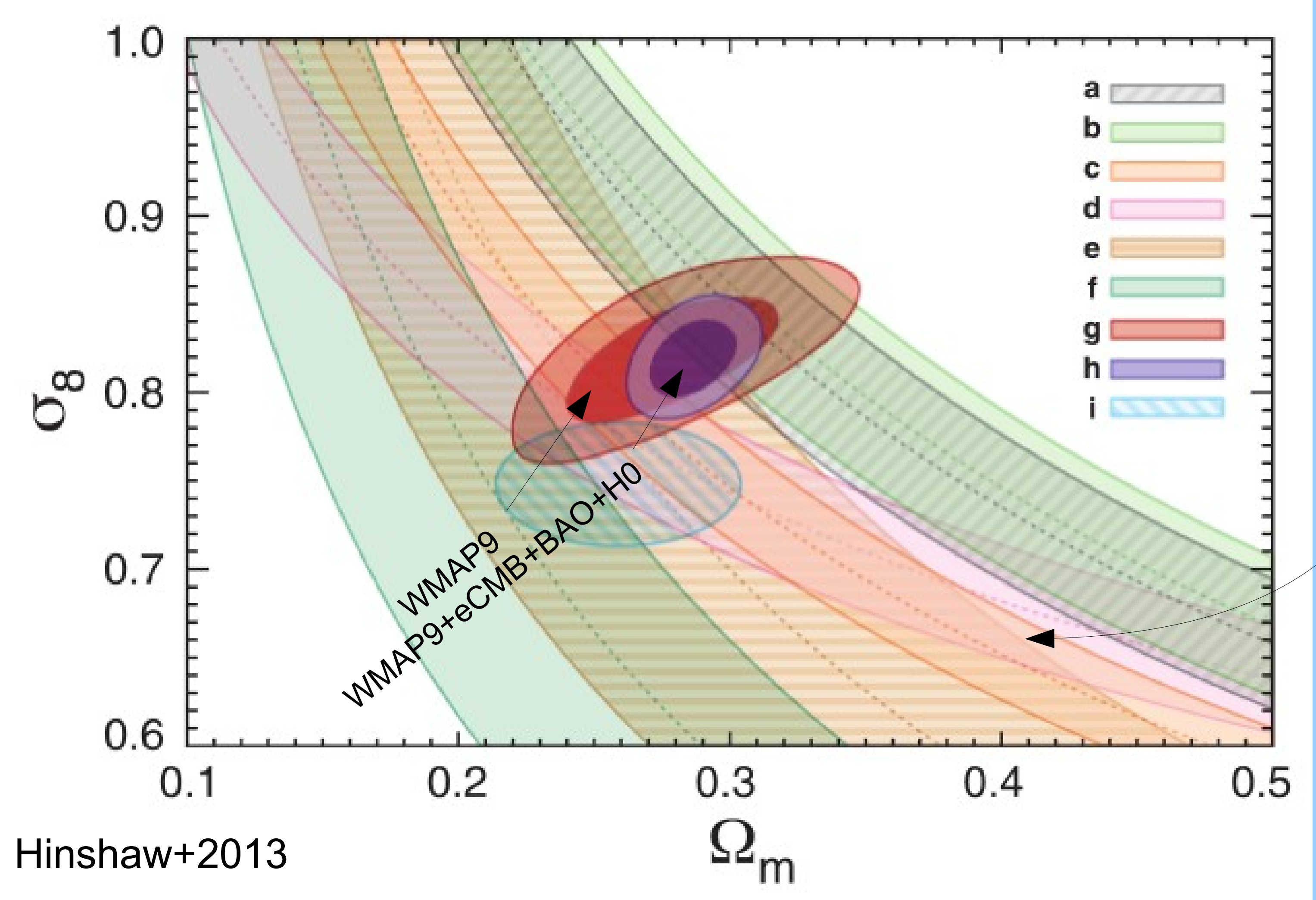
Overdensities are enhanced, by gravitational instability…

… resisted by radiation pressure

… fighting the expansion.

Clusters and cosmology

- Cluster abundance constraints are strongly degenerate in sigma8 – Omega_M… but they are still complementary to other probes.



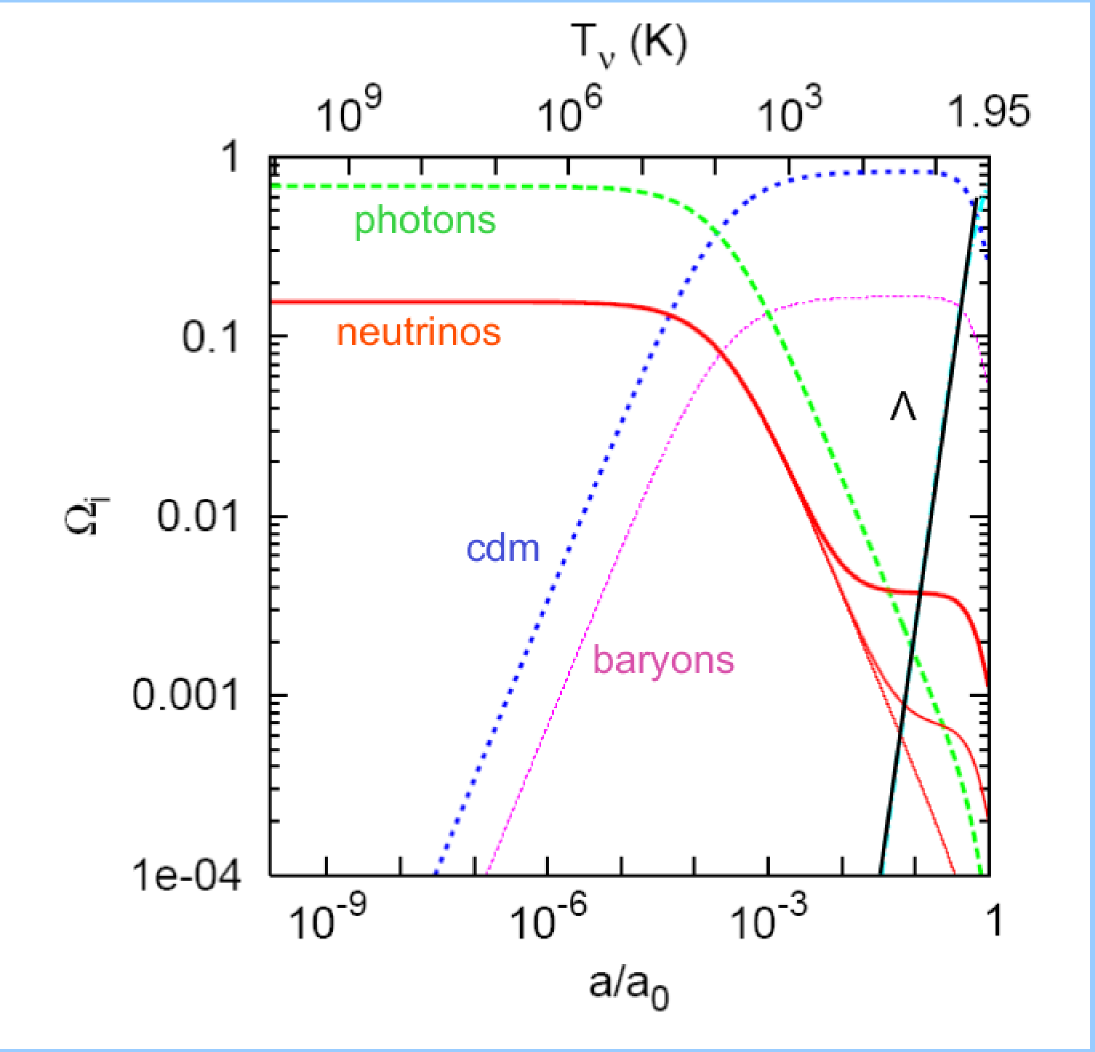
Cluster constraints including optical, X-ray, SZ.

Clusters and cosmology

- When it comes to extensions to LCDM, a potential role for clusters is to aid in constraining the **neutrino masses**.
- Primordial neutrinos have an interesting history – depending on mass, they transition from relativisitic to non-relativistic behavior at some point since the CMB was emitted.
- Non-relativistic neutrinos make up some of the Dark Matter now. But at earlier times their free-streaming served to smooth out the density field.
- The current matter density of non-relativistic neutrinos is roughly:

$$\Omega_\nu h^2 = \sum_\nu m_\nu / (93\ \text{eV})$$

Supposing the masses total 50 meV, and h=0.7… then Omega_nu ~ 0.1%. That will be hard to measure! Current cosmological upper bound is ~200 meV.

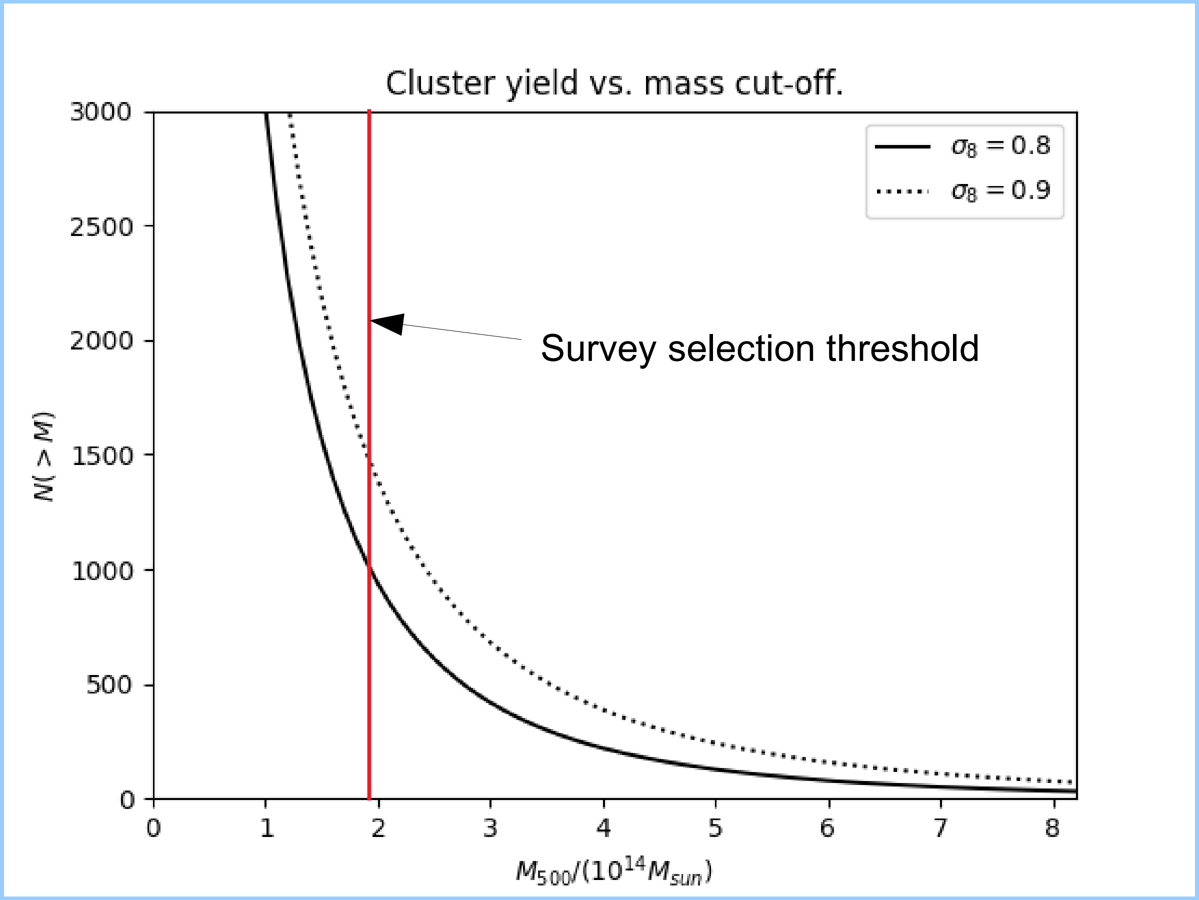


From Lesgourges & Pastor (2014)

Constraint Technique

- In cluster abundance studies, a catalog of clusters is compared to some model prediction.
  - The models are constrained by N-body simulations and predict n(>M,z) – the number density of clusters in mass-redshift space.
  - In a cosmological likelihood analysis, the model is re-generated as cosmological parameters are varied; simple or complex comparisons are performed.

- Supposing our catalog can be formed to include only clusters above some threshold mass…
  - Then the cluster count is very sensitive to cosmological parameters.



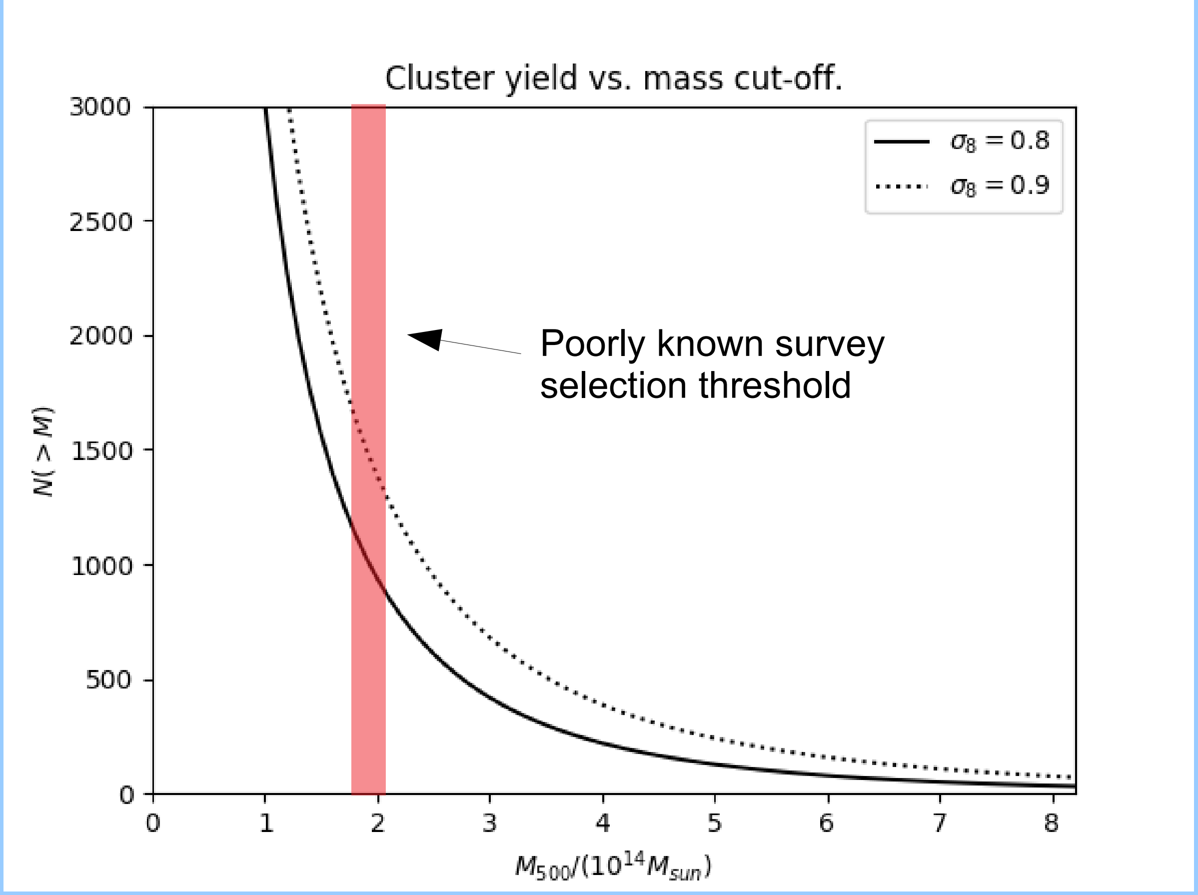
Constraint Technique

- But if we do not understand our "selection function"…

  e.g. if the "Mass" cut-off is not known well, or is based on some noisy proxy measurement

  … then the cosmological constraining power is greatly affected.

  This problem is due to the steep cluster abundance is falling steeply with mass.



- Modern cluster cosmology pays much attention to ***selection*** effects, and especially to ***mass calibration***.

Era of Precision Cosmology...

- From N. Bahcall & R. Cen "*Galaxy Clusters and Cold Dark Matter: A Low Density Unbiased Universe?*" (1992)
  - Factor of ~10 discrepancy in galaxy cluster abundance, vs. simulations, suggests a Universe with sub-critical matter density.

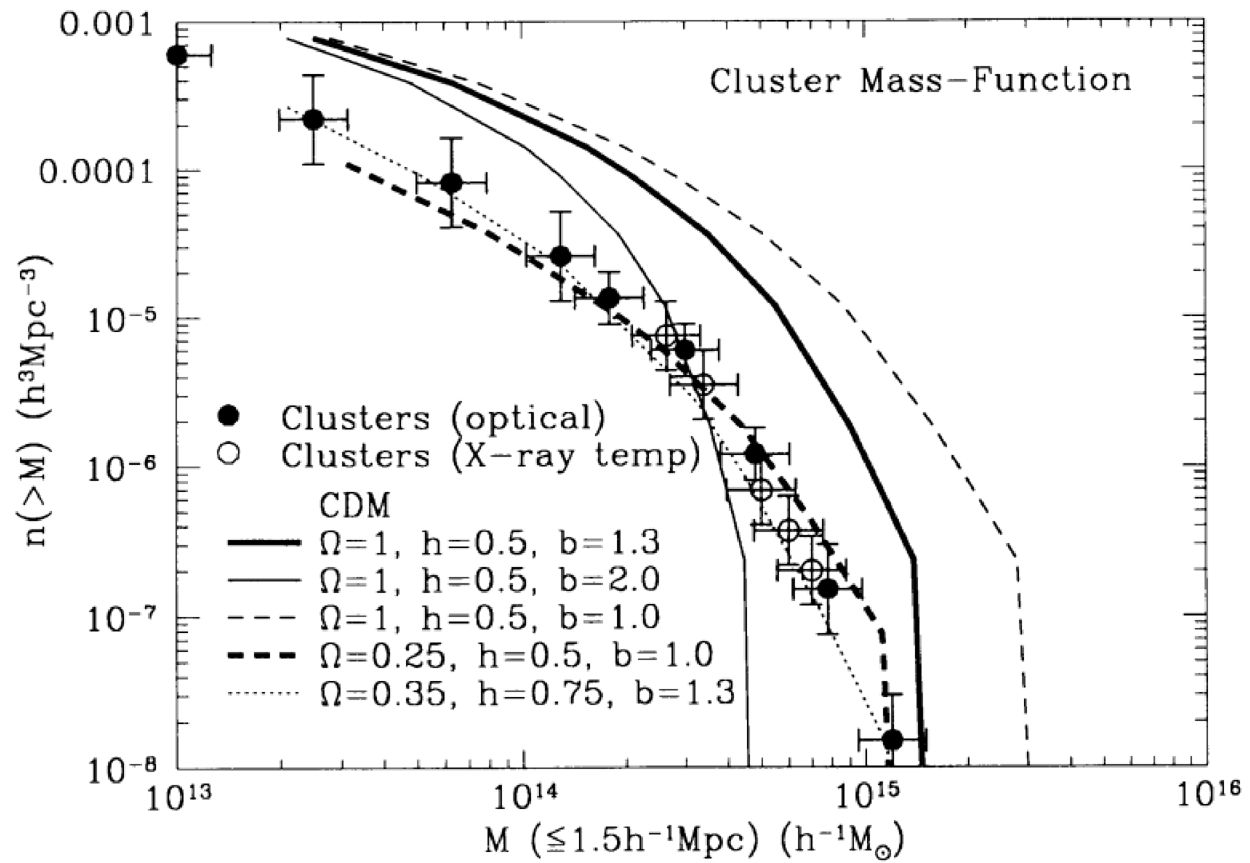


FIG. 1.—Cluster mass functions from observations (Bahcall & Cen 1992) and from our CDM simulations.

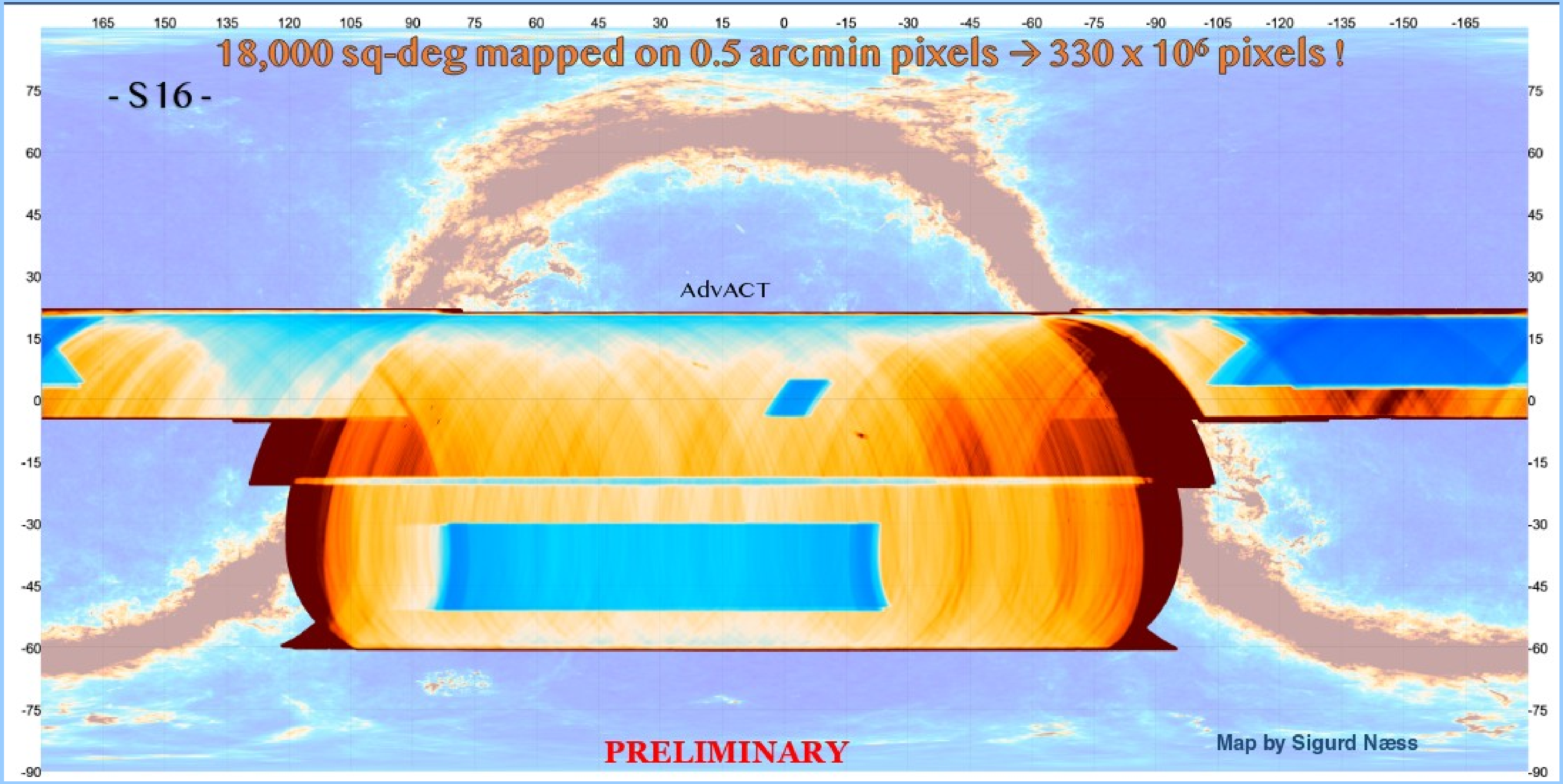
The Atacama Cosmology Telescope

- High resolution CMB observatory
  - Northern Chile, near ALMA site, at 5200m altitude
  - 6m primary, off-axis Gregorian design (< 1.5 arcmin FWHM at 150GHz)

- MBAC camera, 2007-2010:
  - 2500 bolometers in wide
    148, 218, 277 GHz bands
- ACTPol, 2013-2015
  - 2500 bolometers, 90+145 GHz.
  - Polarization sensitive.
- Advanced ACTPol 2016-pres.
  - 4500 bolometers
  - 90+145+225 GHz on sky now
  - 2 low-freq bands coming

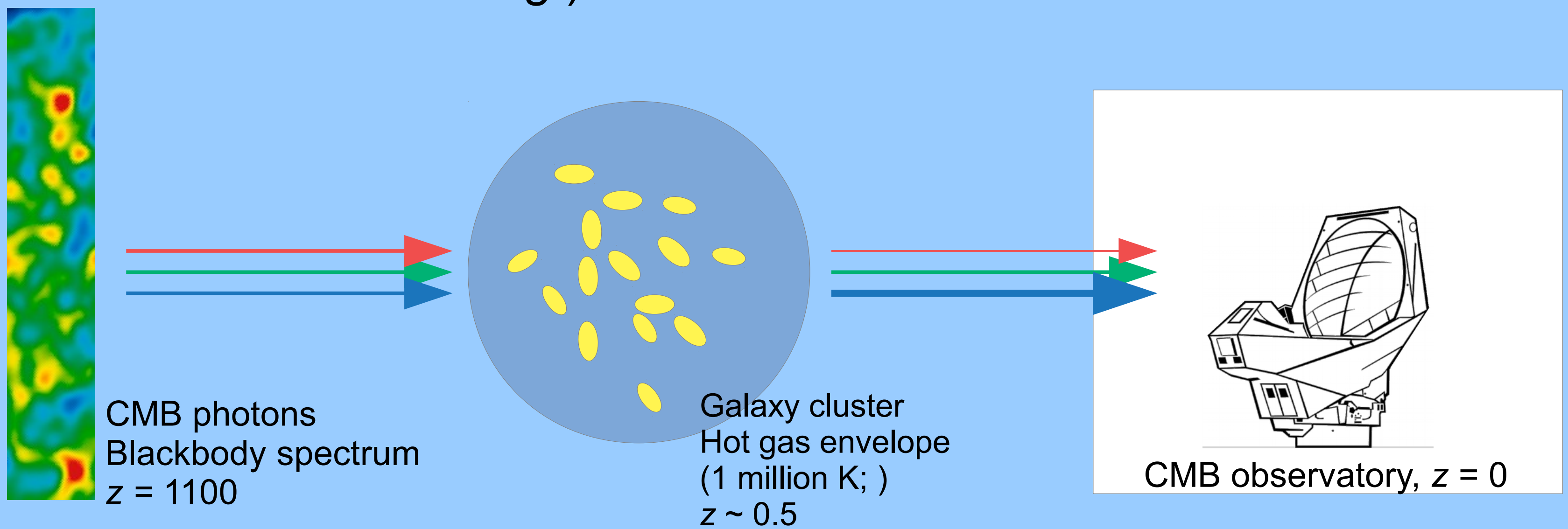
The Atacama Cosmology Telescope

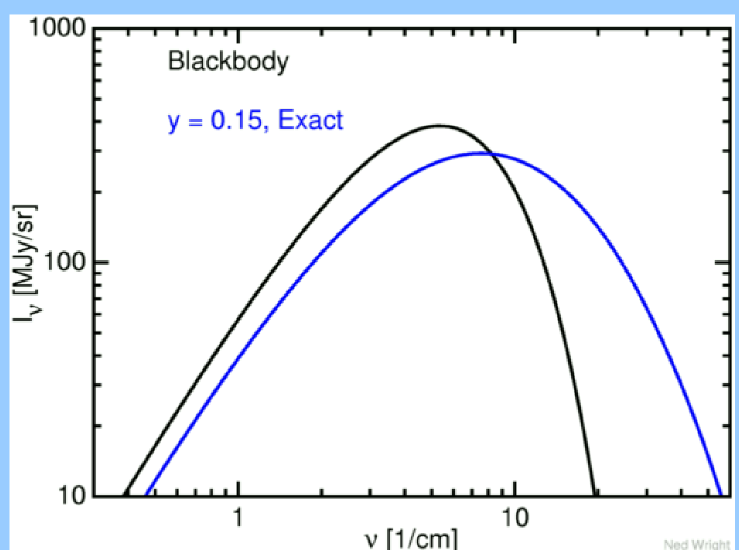
- Published results so far are for early, deep patches covering 800 sq. deg...
- But the current phase of the survey covers 35-45% of the sky.
  - Spreading the weight broadly maximizes returns from correlation studies, e.g. with BOSS and DES.



Sunyaev Zeldovich Effect

- Sunyaev Zeldovich effect: CMB photons passing through a galaxy cluster are scattered to higher energies by electrons in the hot intracluster medium. (Inverse Thomson scattering.)





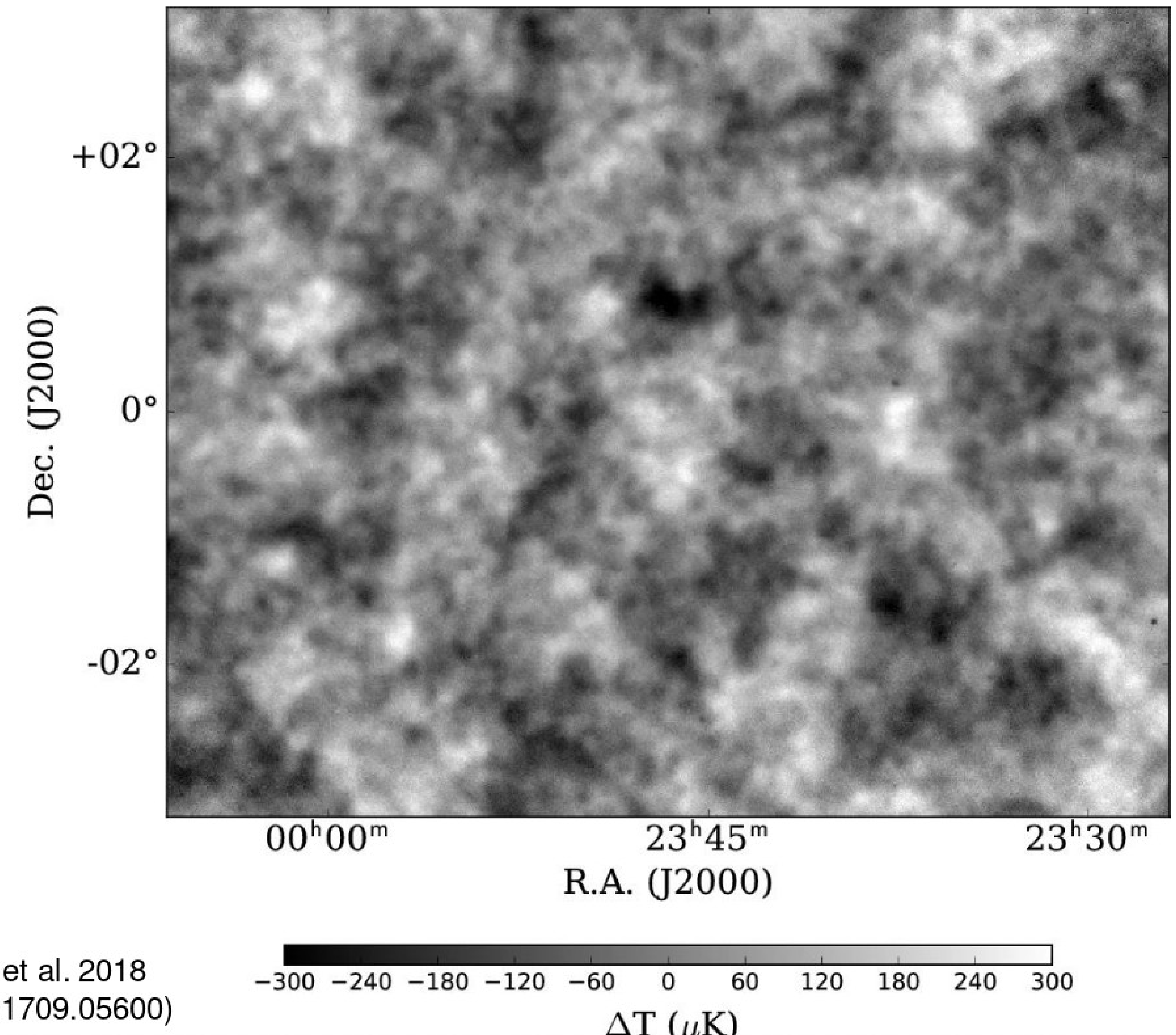
http://www.astro.ucla.edu/~wright/SZ-spectrum.html

→ Net intensity of sky is enhanced / suppressed, at CMB wavelengths, in the directions of hot cluster gas.

The surface brightness of this effect is *independent of distance.*

ACT Surveys and Maps

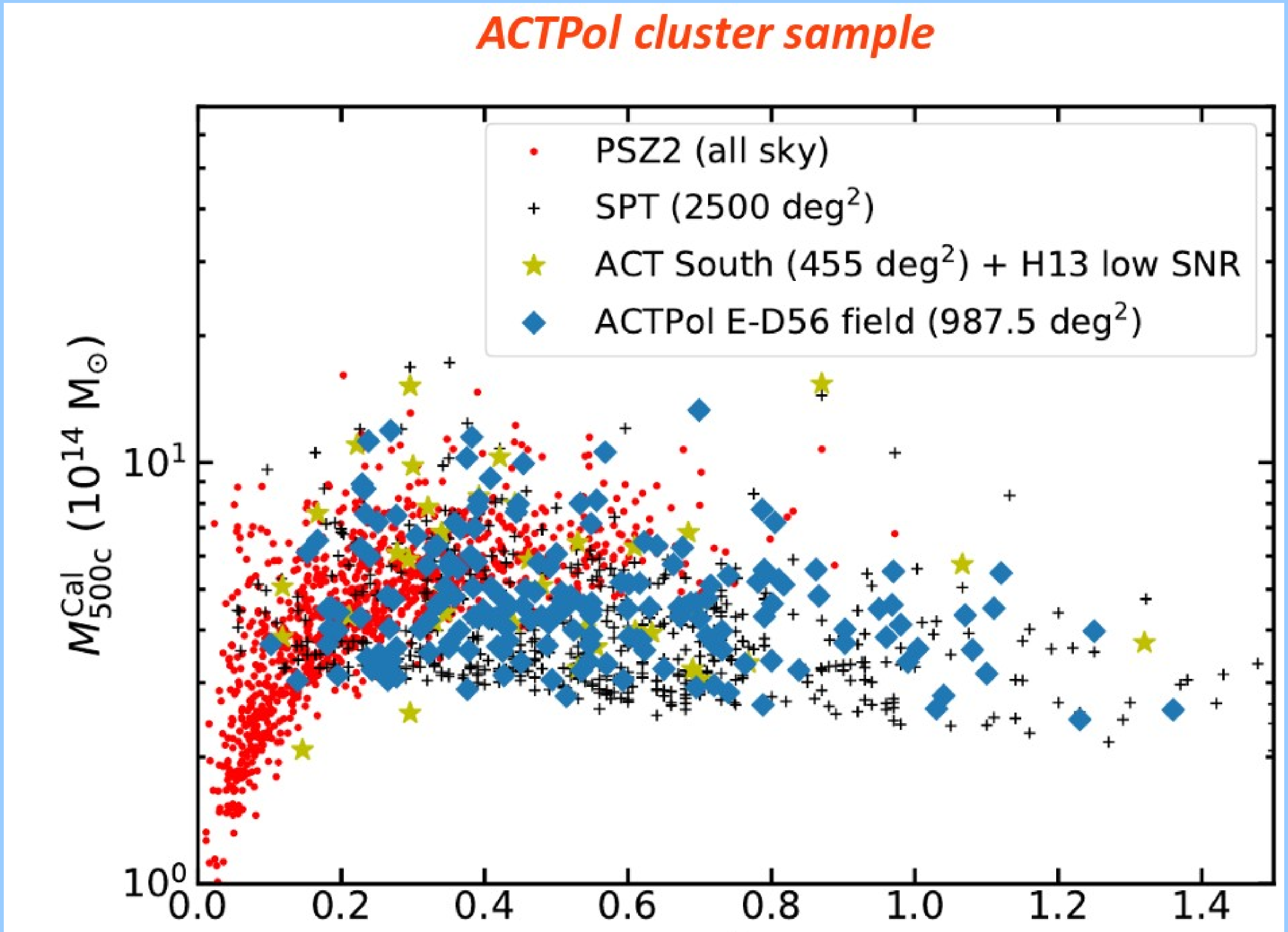
- 150 GHz map of a particularly deep ACT region (79 sq. deg)…
- Match-filtering with a cluster template reveals 21 clusters (in this region).



Hilton et al. 2018
(arXiv:1709.05600)

ACT Surveys and Maps

- Latest published ACT cluster catalog (from combination of ACT 2008-2010 and ACTPol 2013-2014 maps): sample of 182 clusters

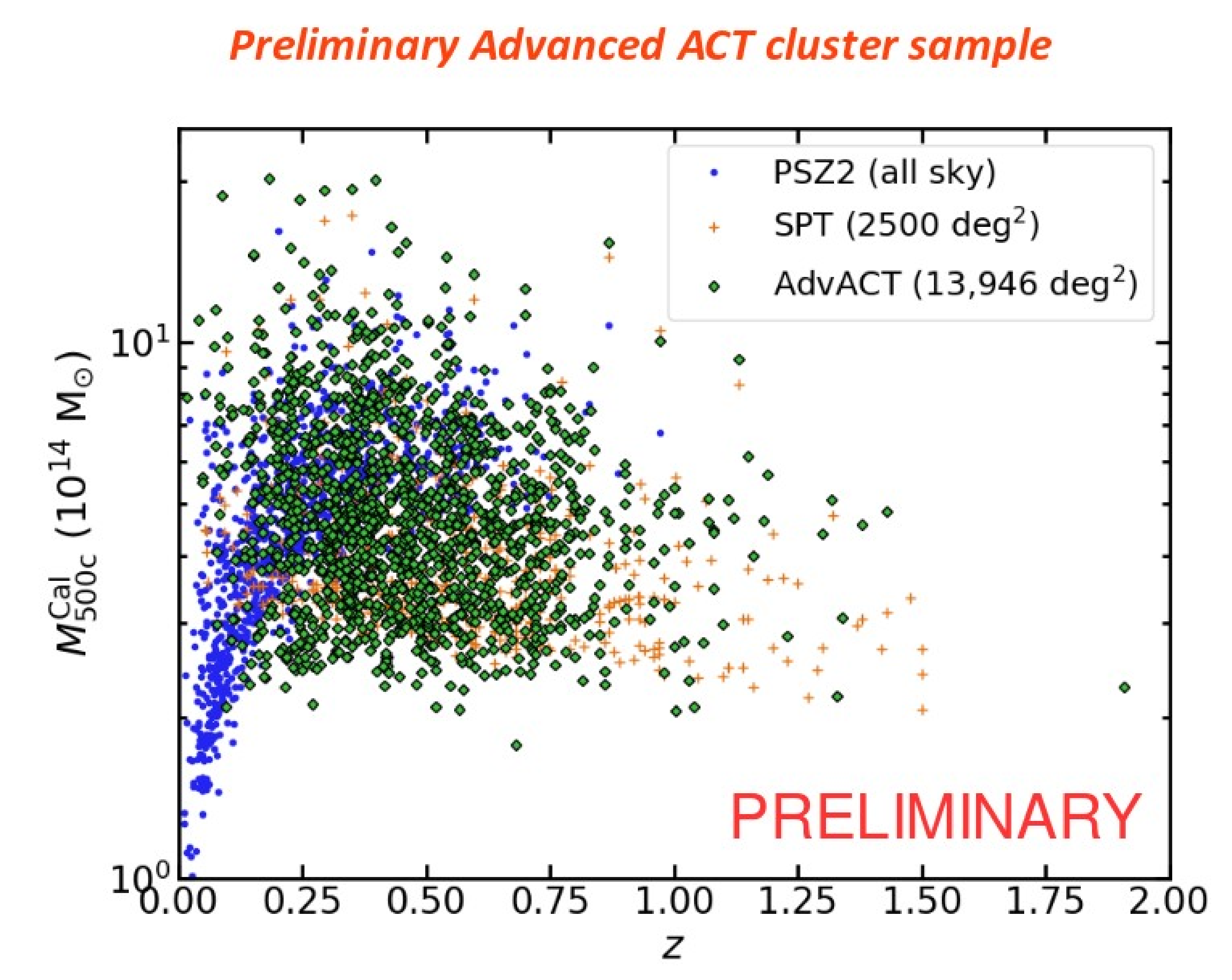


Hilton et al. 2018 (arXiv:1709.05600)

High-resolution telescopes such as ACT and SPT have no high-redshift limit on cluster detection.

ACT Surveys and Maps

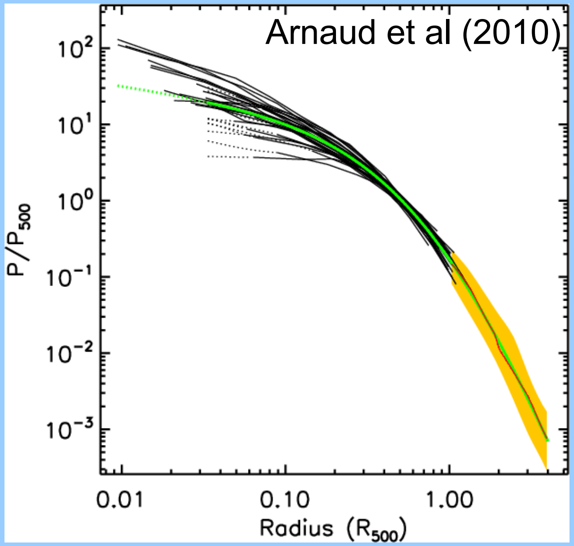
- Preliminary catalog from full survey area – all data through 2016: 1,400 clusters.

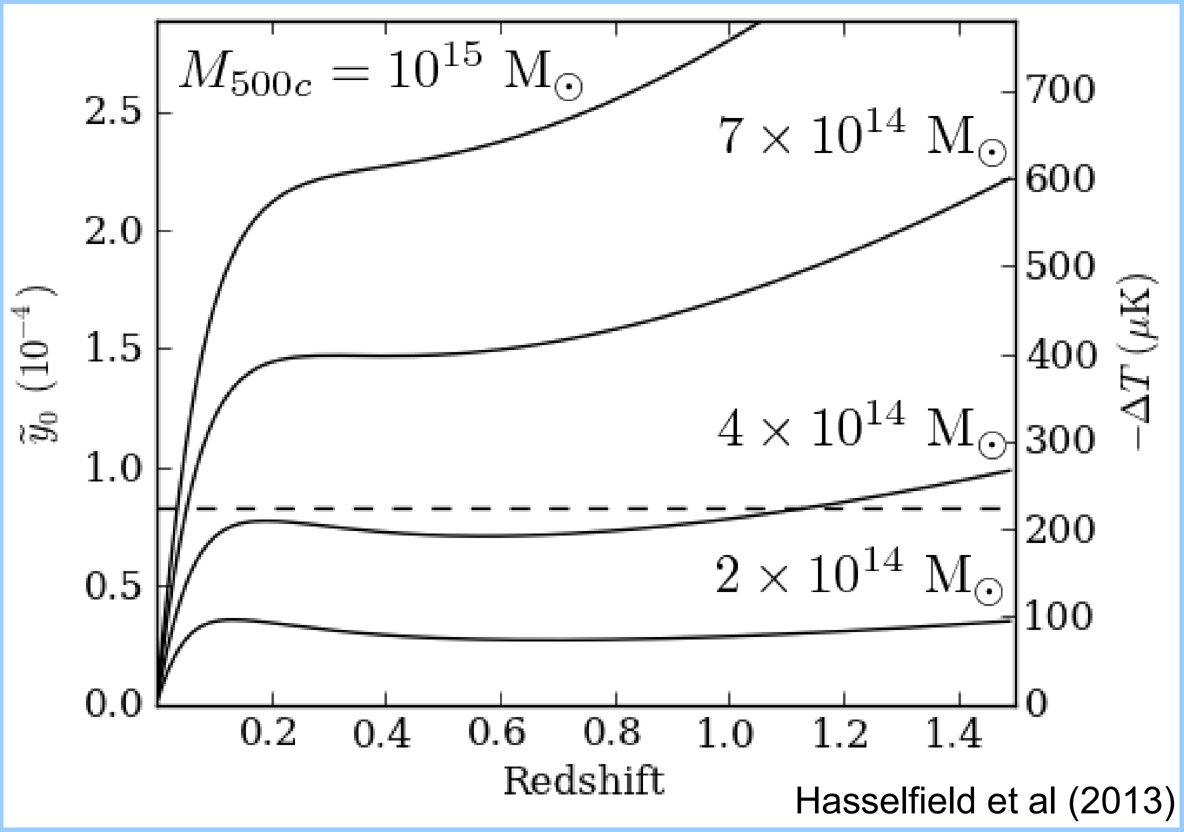


From Matt Hilton

ACT Cluster Mass Calibration

- The SZE signal is closely connected to cluster mass – the Compton scattering parameter scales with gas pressure, and a cluster should be close to hydrostatic equilibrium.
- The total SZE flux, once corrected for angular diameter distance, should scale like $M^{5/3}$. In practice, this "Y" parameter is difficult to measure directly.
- All experiments rely on some combination of a "universal pressure profile" or extensive simulations to assign "SZ masses" to their catalogued clusters.
- ACT analyses have historically leaned on "pressure profile" approaches to relate our observable parameter ($\tilde{y}_0$) to mass.



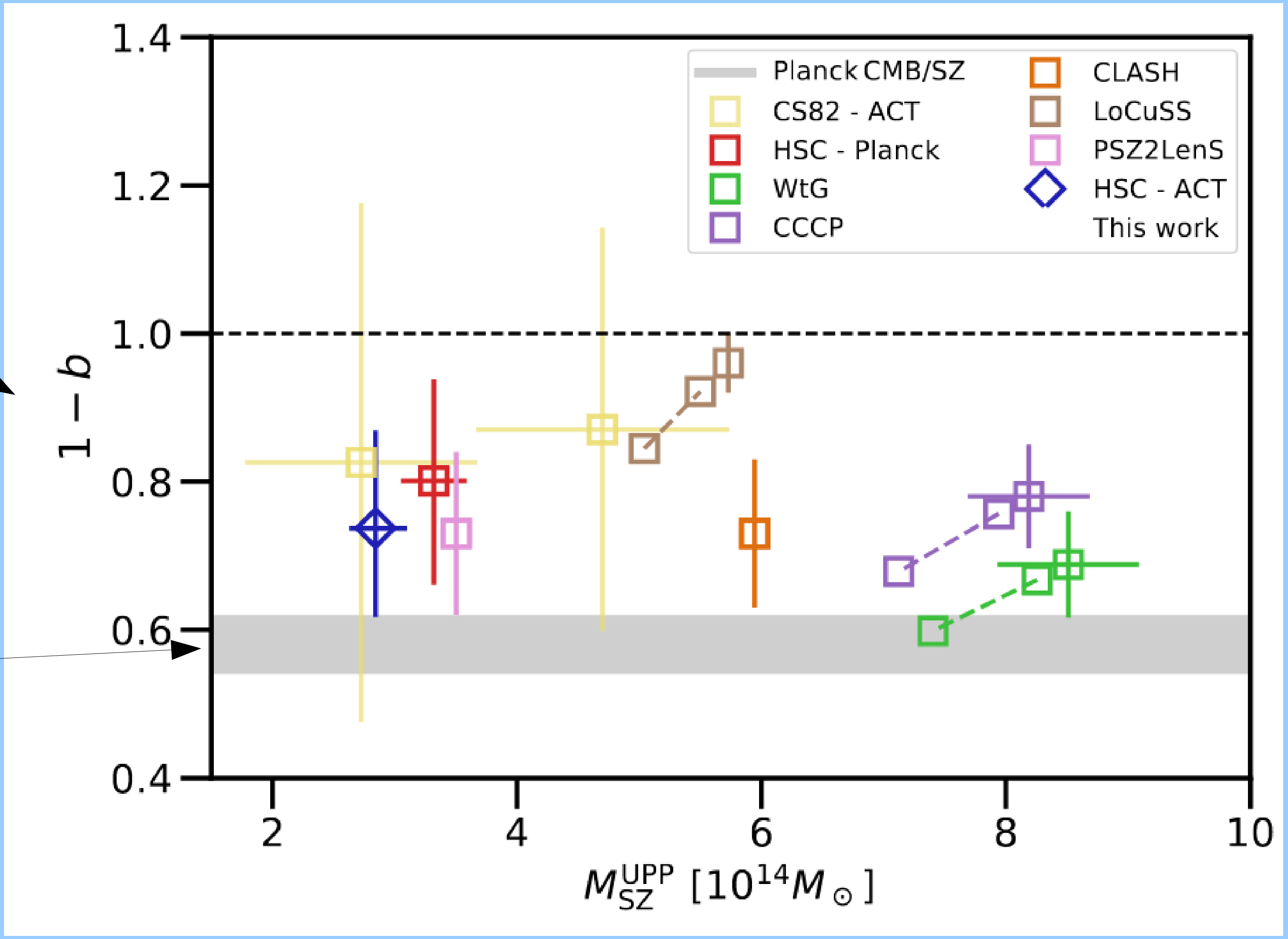


ACT Cluster Mass Calibration

- Model/simulation masses are systematically overpredicted – the cluster community is performing extensive *weak-lensing mass* measurements in order to better calibrate this systematic offset.
- Is the mass bias consistent, across instruments and across the mass range?

Bias parameter of SZ masses
$1\text{-b} = M_{SZ} / M_{WL}$

Value preferred by CMB-only cosmology



ACT Cluster Mass Calibration

- In order to have confidence in cosmological constrainst, clusters must be internally consistent.
  - Hilton et al (2018) connects ACT SZ measurements to the Weak Lensing calibration of RedMapper clusters.

The mess of data here is as expected in the case of a sharp selection function on a steep mass function.

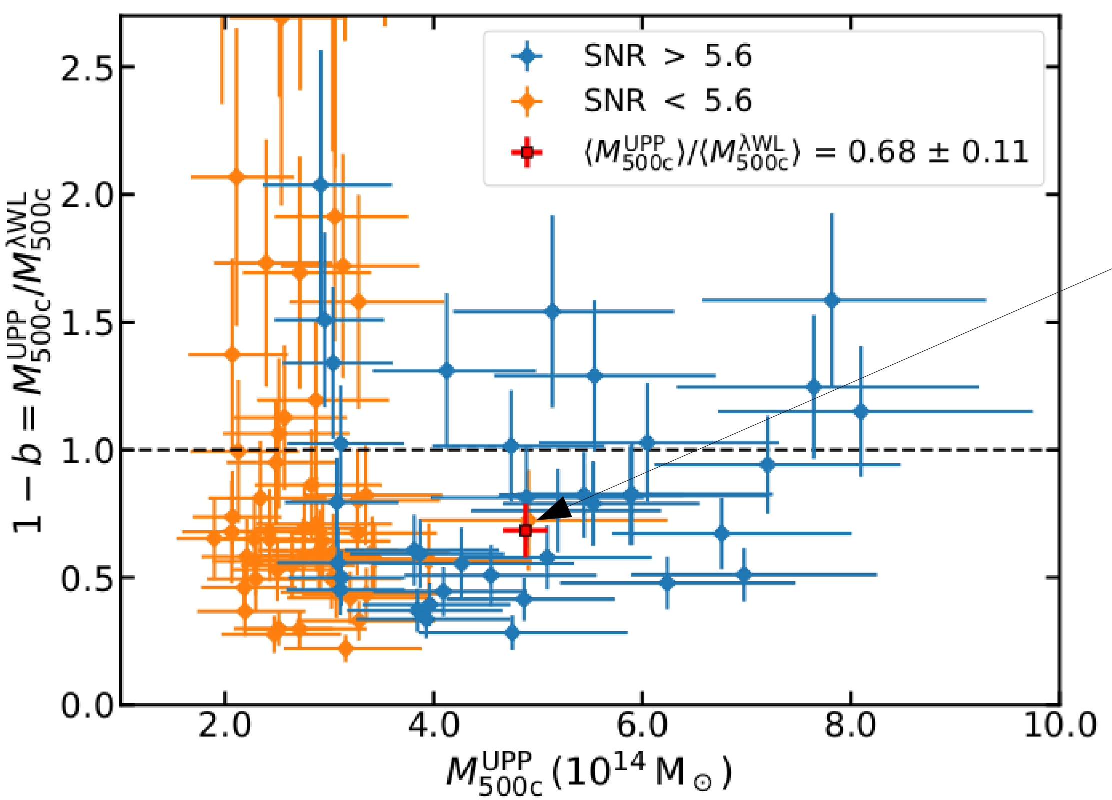


Figure 24. Comparison of richness-based weak-lensing masses ($M_{500c}^{\lambda WL}$), derived from applying the Simet et al. (2017) scaling relation to ACTPol clusters in common with redMaPPer, with ACTPol UPP/A10 SZ masses. The red

The ratio of average masses is plotted here.

ACT Cluster Mass Calibration

- An important consistency check – does ACT agree well with other high-resolution SZE measurements?
  - Compare to South Pole Telescope (masses calibrated throug multiple follow-up probes) – analysis techniques are quite different, but yield very compatible masses.

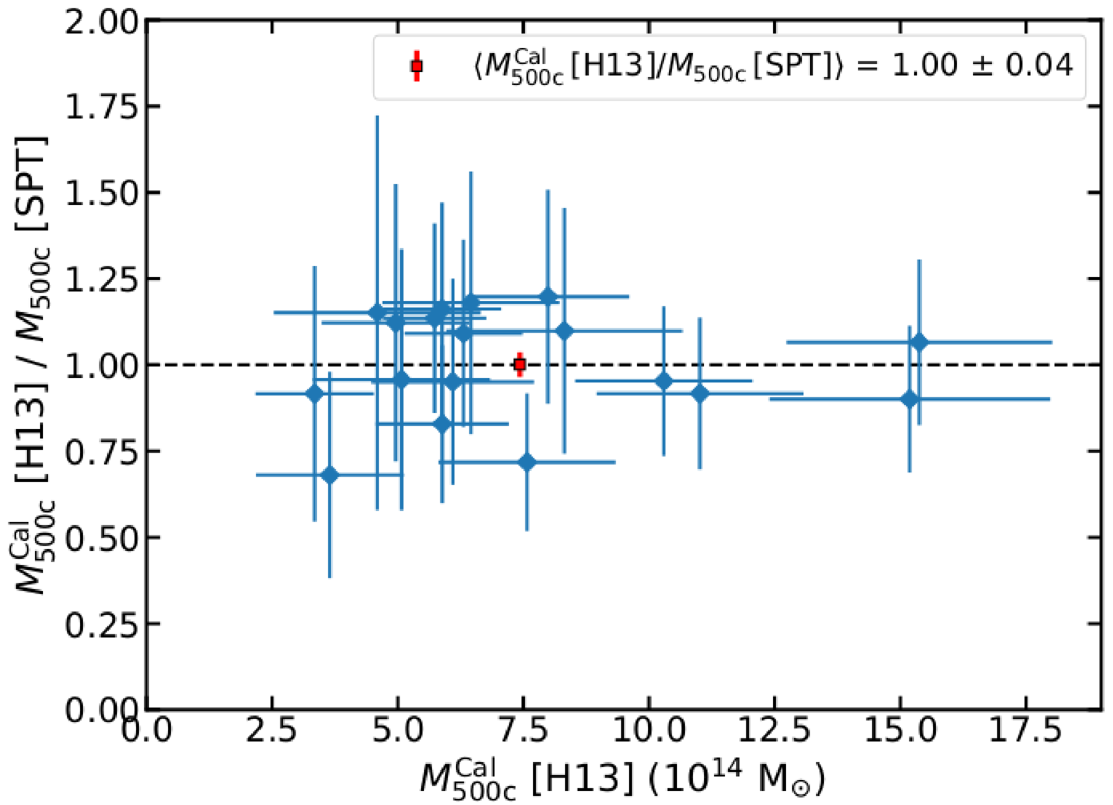


Figure 25. Comparison of the ratio of SPT masses reported in Bleem et al. (2015) to the ACTPol UPP-based masses, re-scaled using the richness-based weak-lensing mass calibration ($M^{\rm Cal}_{\rm 500c}$; Section 6.1), for southern ACT clusters in H13, for 18 objects cross matched between the samples. The red square

Next steps for ACT Cluster Cosmo

- The mass bias issue will be sorted out by new lensing measurements, and increasing statistical power of latest samples.
- The next frontier will be to better understand other aspects of the selection function – things more subtle than the mass bias. What information can we extract about the mean pressure profile, and deviations from it?
- We are planning an updated cluster cosmology paper. Since our last major effort, we have significant improvements to work with:
  - Weak-lensing mass calibration.
  - Sample size increase by factor of at least 10.
  - Improvements in other CMB data, including *Planck* and ACTPol anisotropy results.

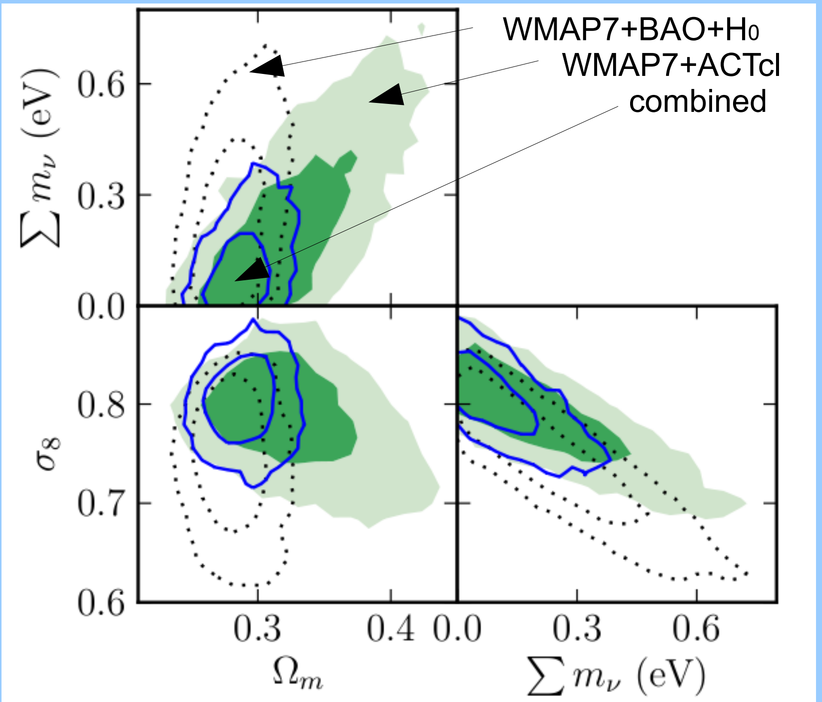


Figure 18. Constraints within an extension to ΛCDM that allows for non-zero neutrino density. The data sets shown are WMAP7+BAO+H0 (dotted black lines), WMAP7+ACTcl(dyn) (green contours), and WMAP7+ACTcl(dyn)+BAO+H0 (solid blue lines). The total number of relativistic species is fixed to $N_{\rm eff} = 3.046$.

ACT cluster cosmo analysis – Hasselfield et al (2013)