Cluster Cosmology with the South Pole Telescope

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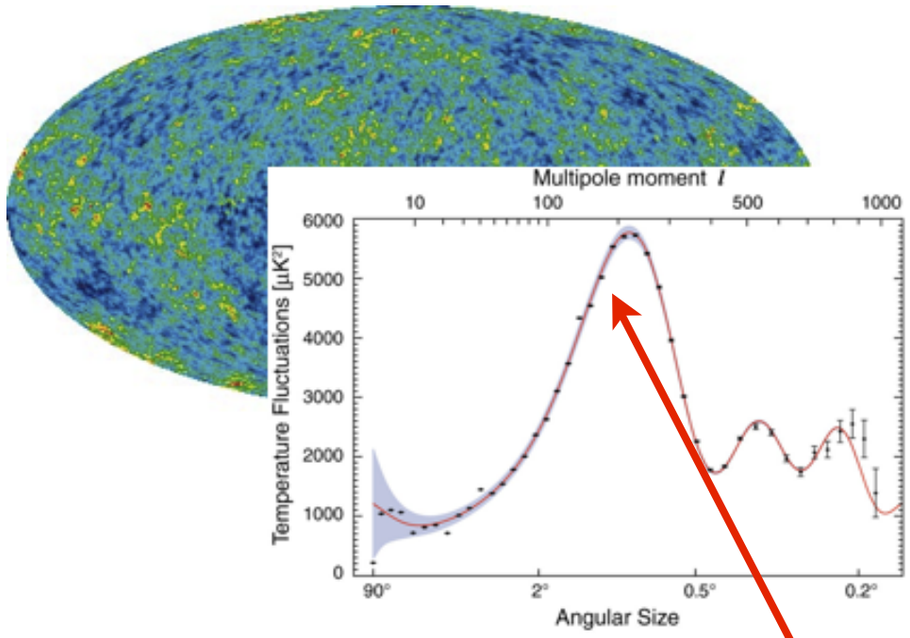
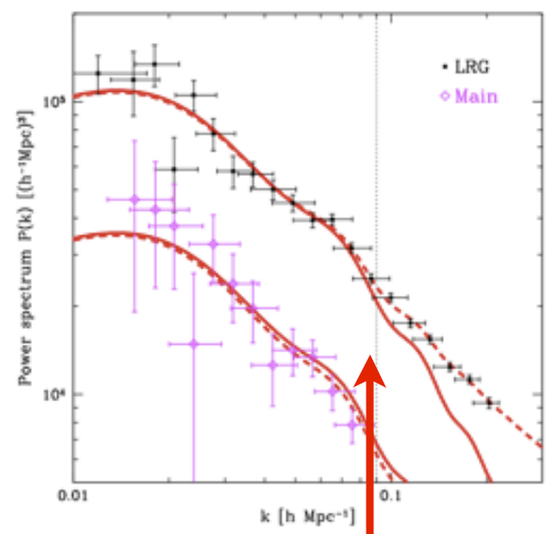
Argonne National Laboratory
August 1, 2017

APS DPF

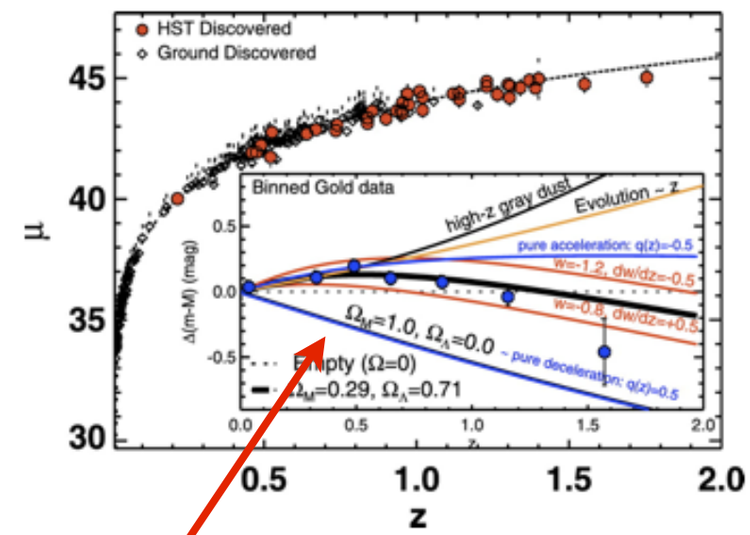
Photo credit: Keith Vanderlinde



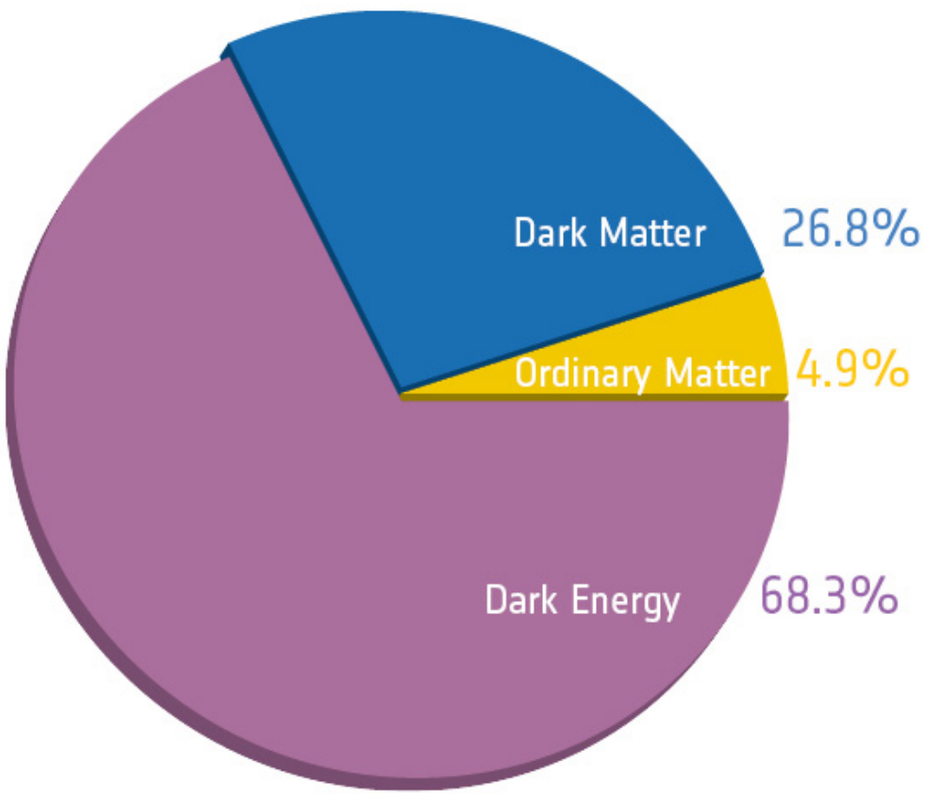
Tegmark et al 2006



Riess et al 2007



CMB + Large Scale Structure + SNe Ia



We live in a flat universe whose density is dominated by dark energy

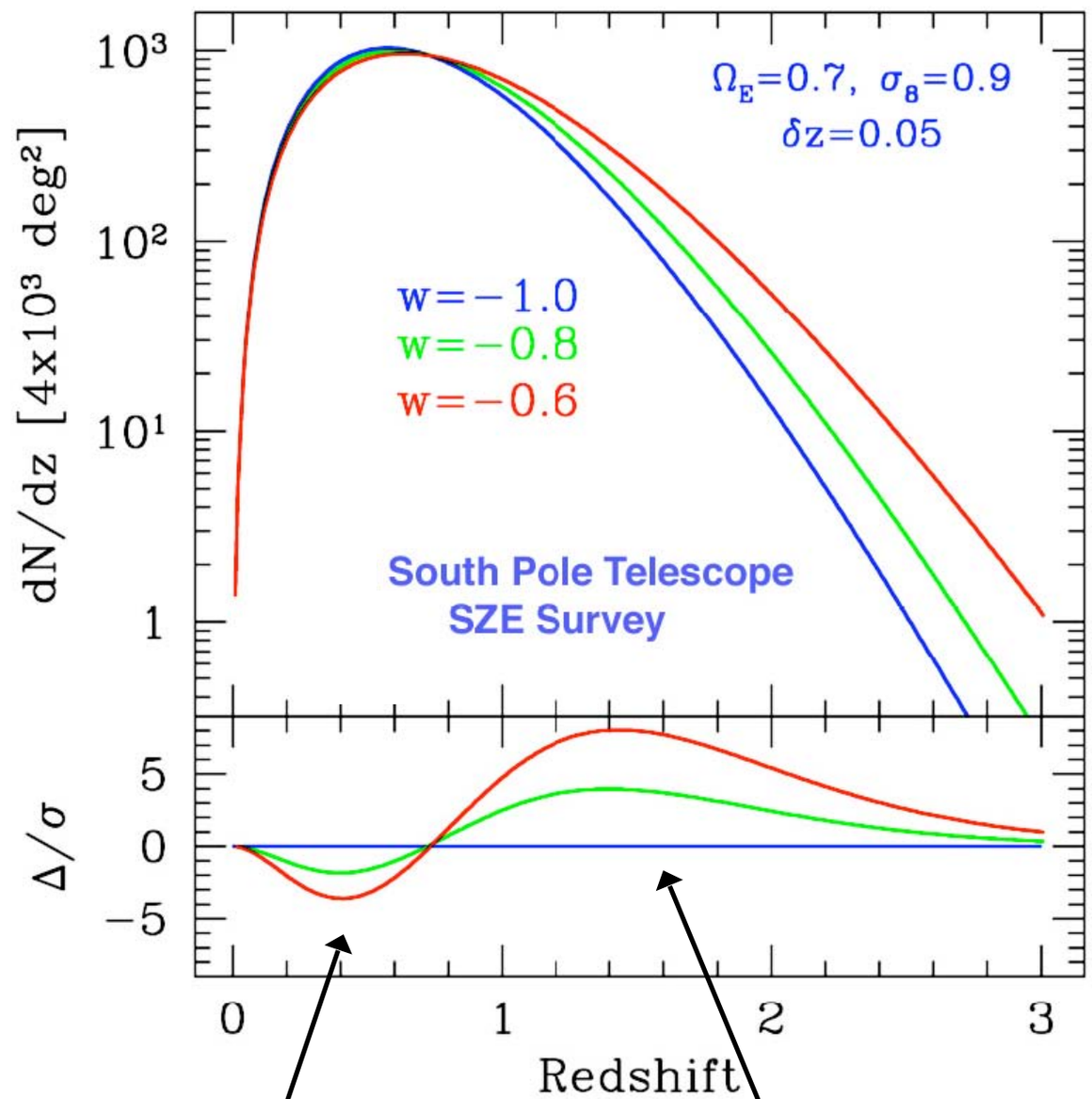
Dark Energy and Cluster Cosmology

Cluster Abundance: dN/dz

$$\frac{dN}{d\Omega dz} = n(z)\frac{dV}{d\Omega dz}$$

Depends on:
Matter Power Spectrum, σ_8
Growth Rate of Structure, *D(z)*

Depends on:
Rate of Expansion, *H(z)*

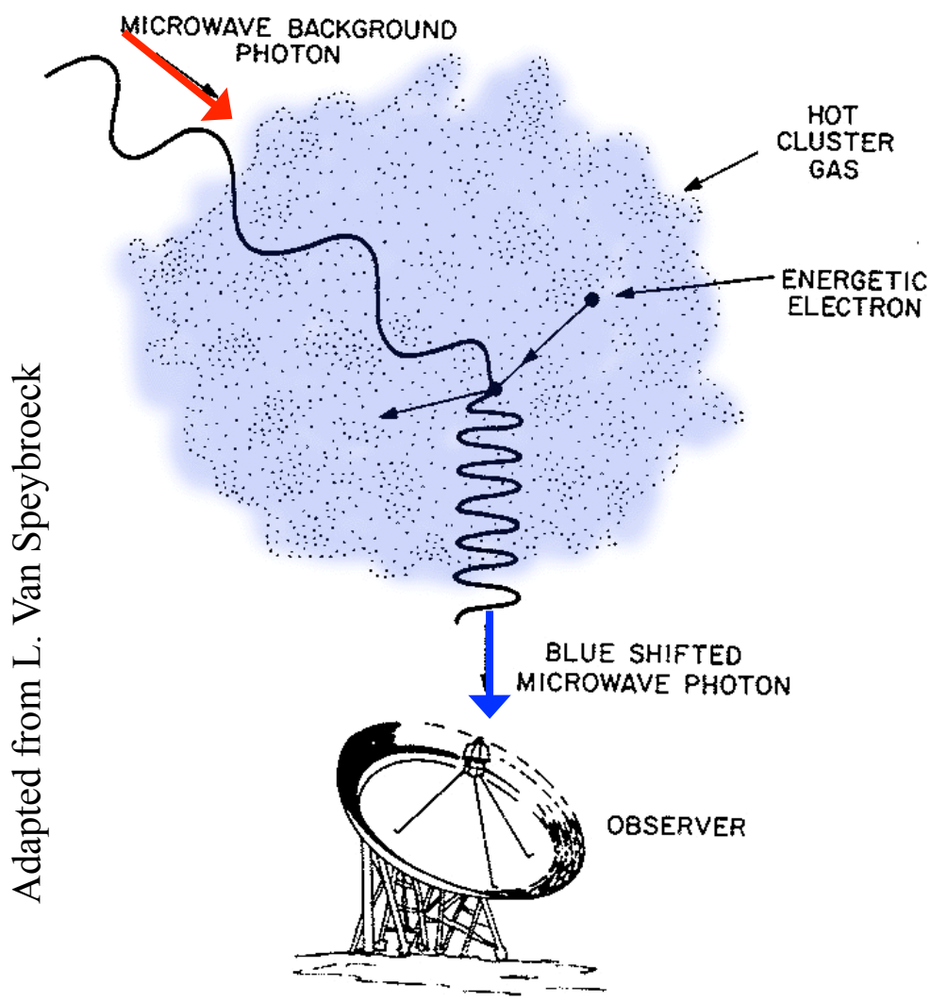


Volume Effect

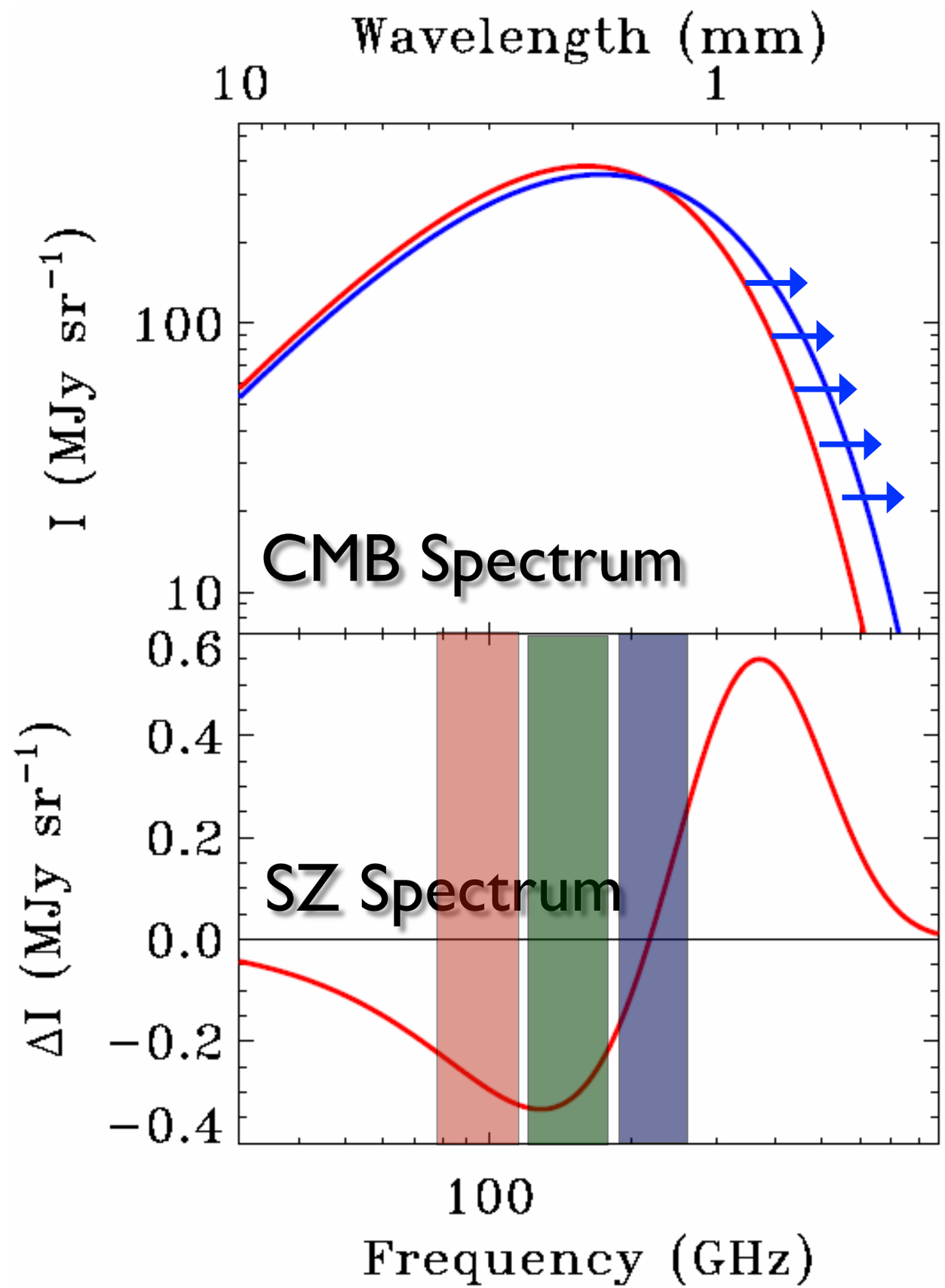
Growth Effect

Figure: J Mohr

The Sunyaev Zel'dovich (SZ) Effect

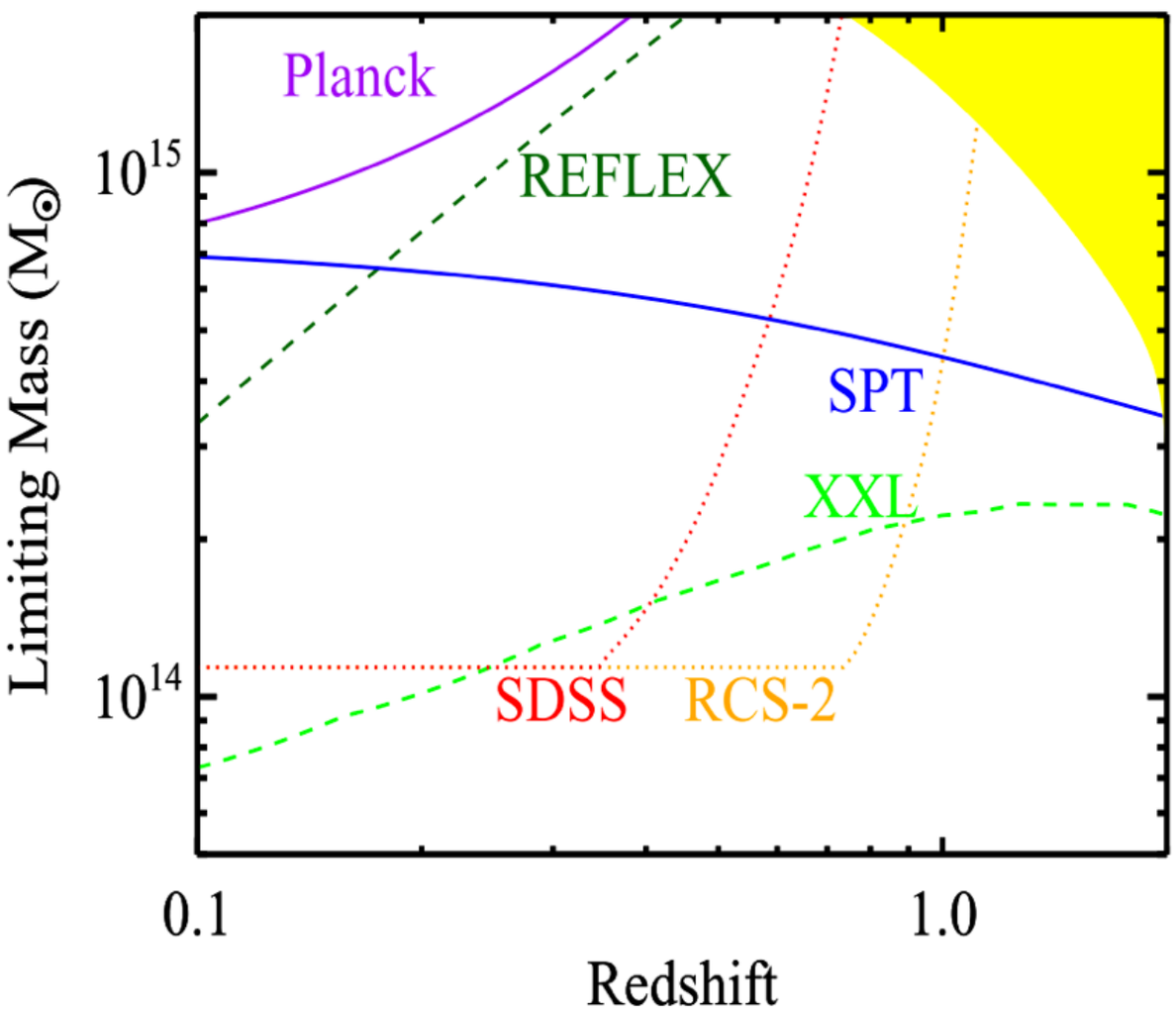


Adapted from L. Van Speybroeck

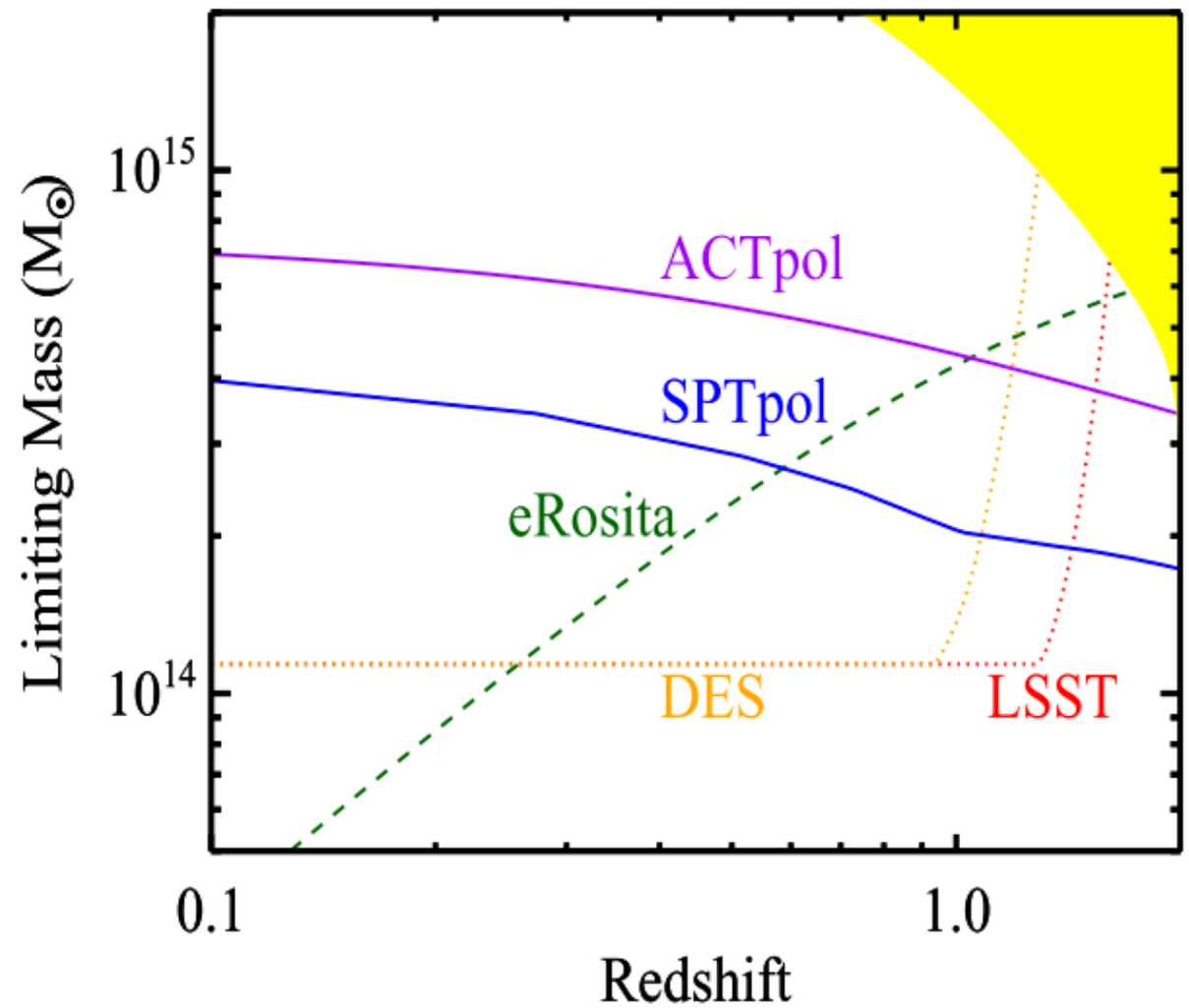


Towards a massive cluster, ~1% of CMB photons scatter off of intra-cluster gas

3 Approaches: Optical, X-ray, SZ



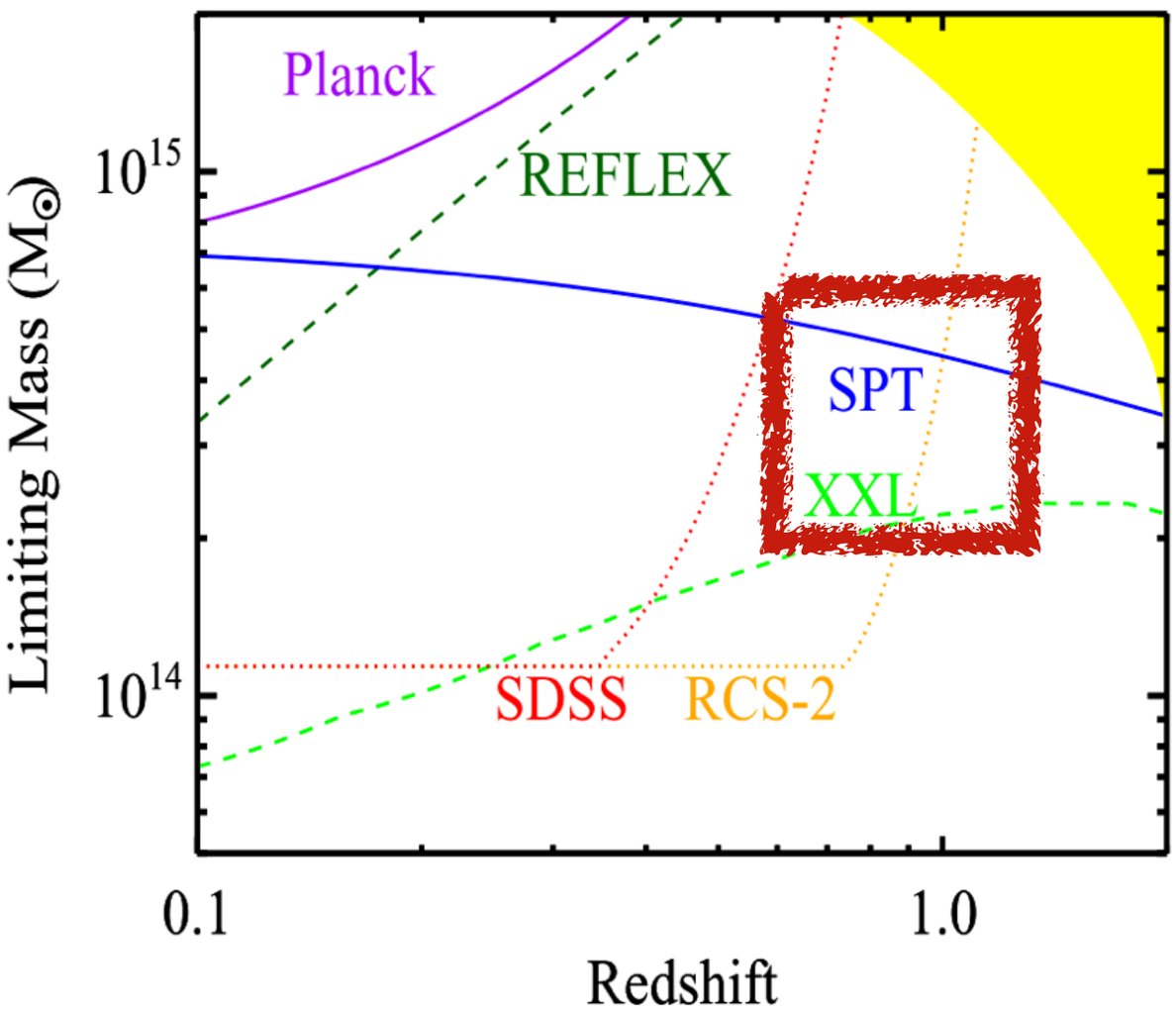
The Past



Recently Completed /Near Future

Weinberg et al. 1201.2434

3 Approaches: Optical, X-ray, SZ



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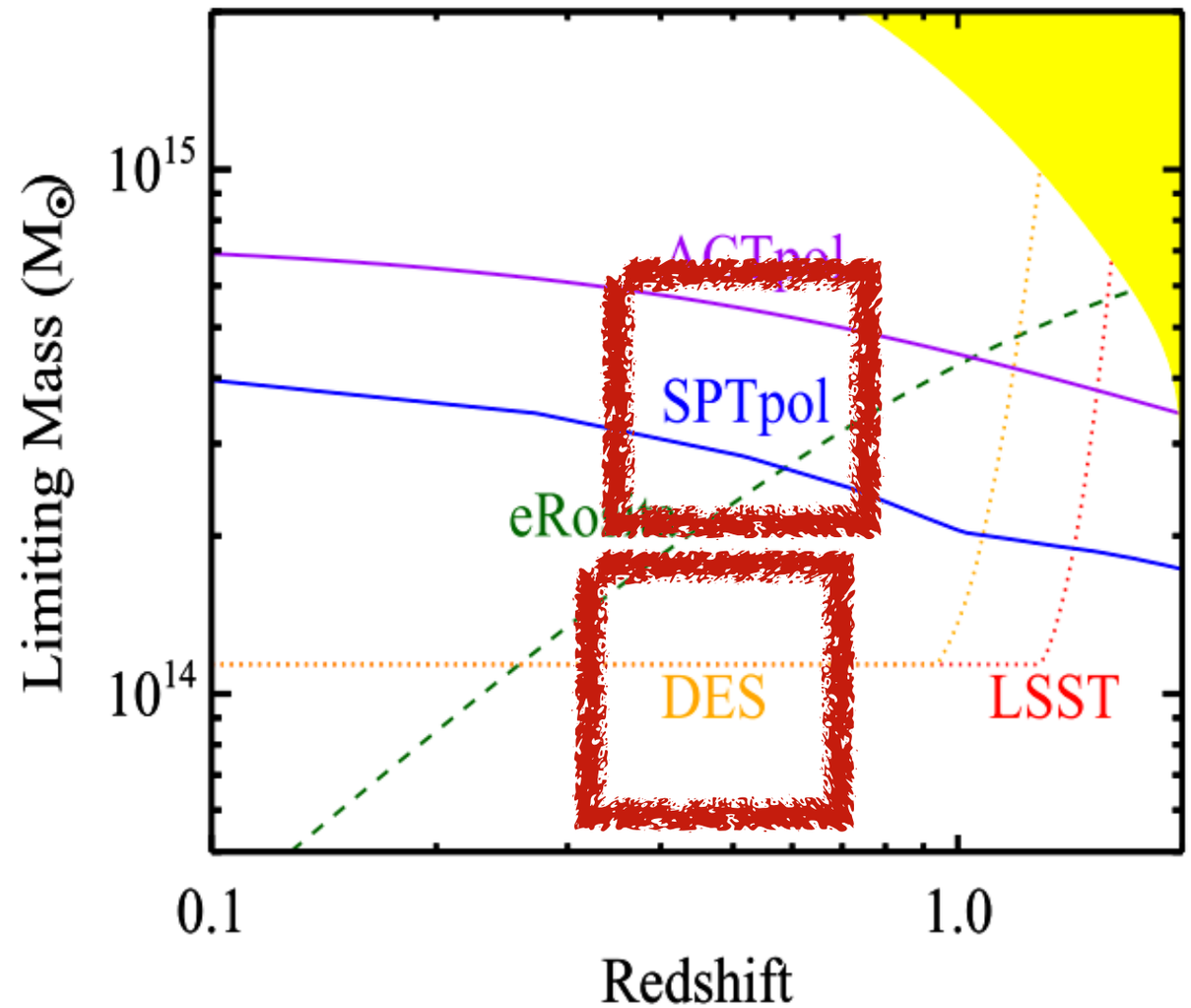

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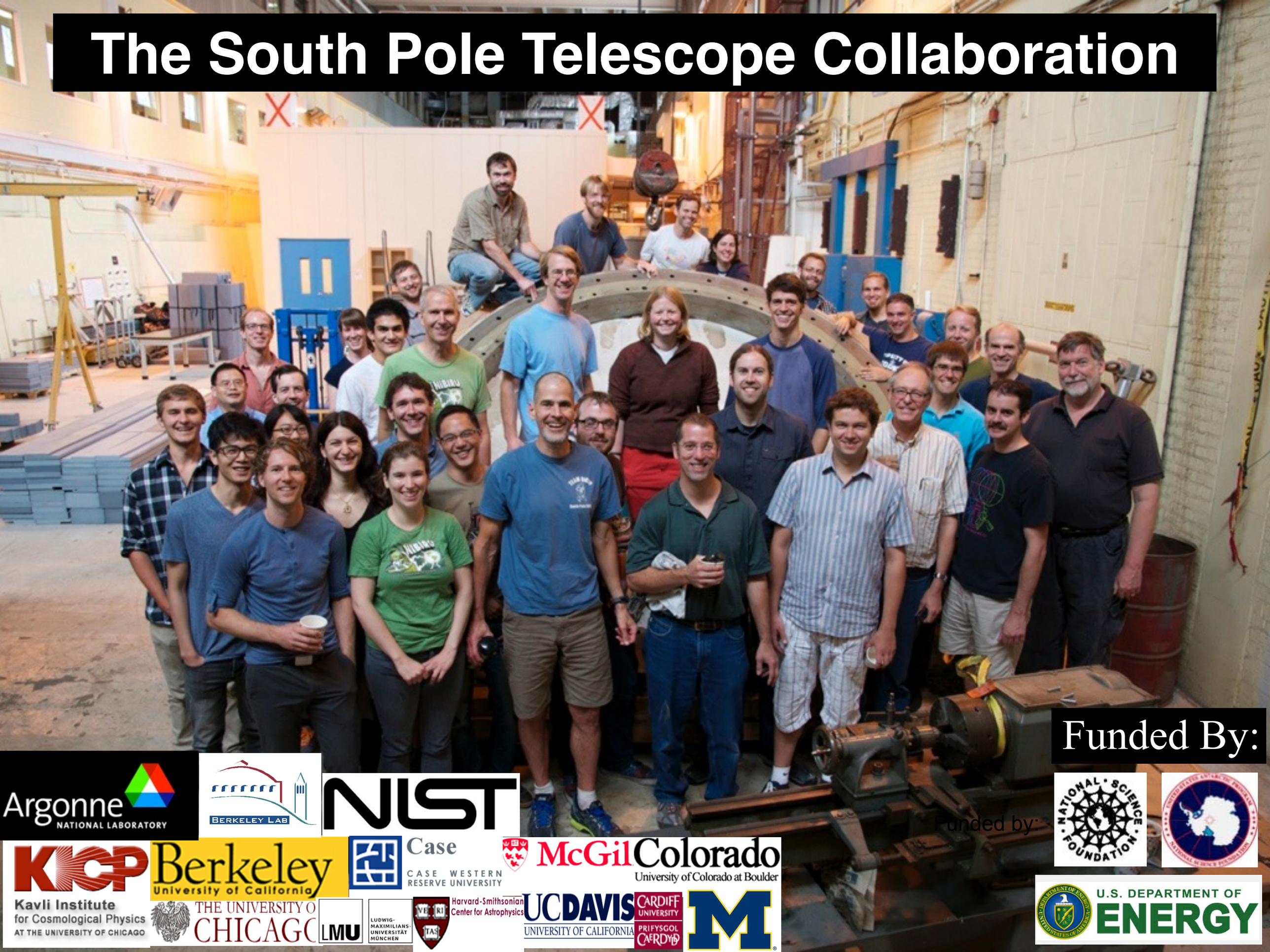
The South Pole Telescope Collaboration



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M

NATIONAL SCIENCE FOUNDATION

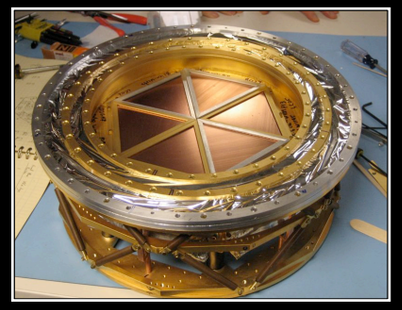
U.S. DEPARTMENT OF ENERGY

The South Pole Telescope (SPT)

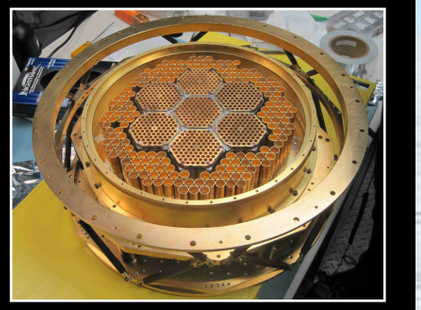
10-meter sub-mm quality wavelength telescope

90, **150**, **220** GHz and
1.6, **1.2**, **1.0** arcmin resolution

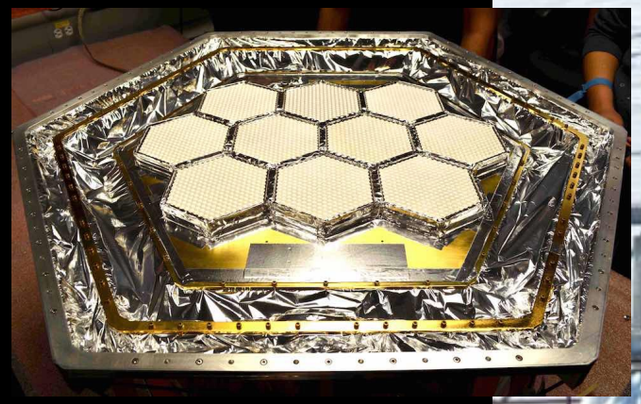
2007: SPT-SZ
960 detectors
90,150,220 GHz



2012: SPTpol
1600 detectors
90,150 GHz
+Polarization



2017: SPT-3G
~15,200 detectors
90,150,220 GHz
+Polarization



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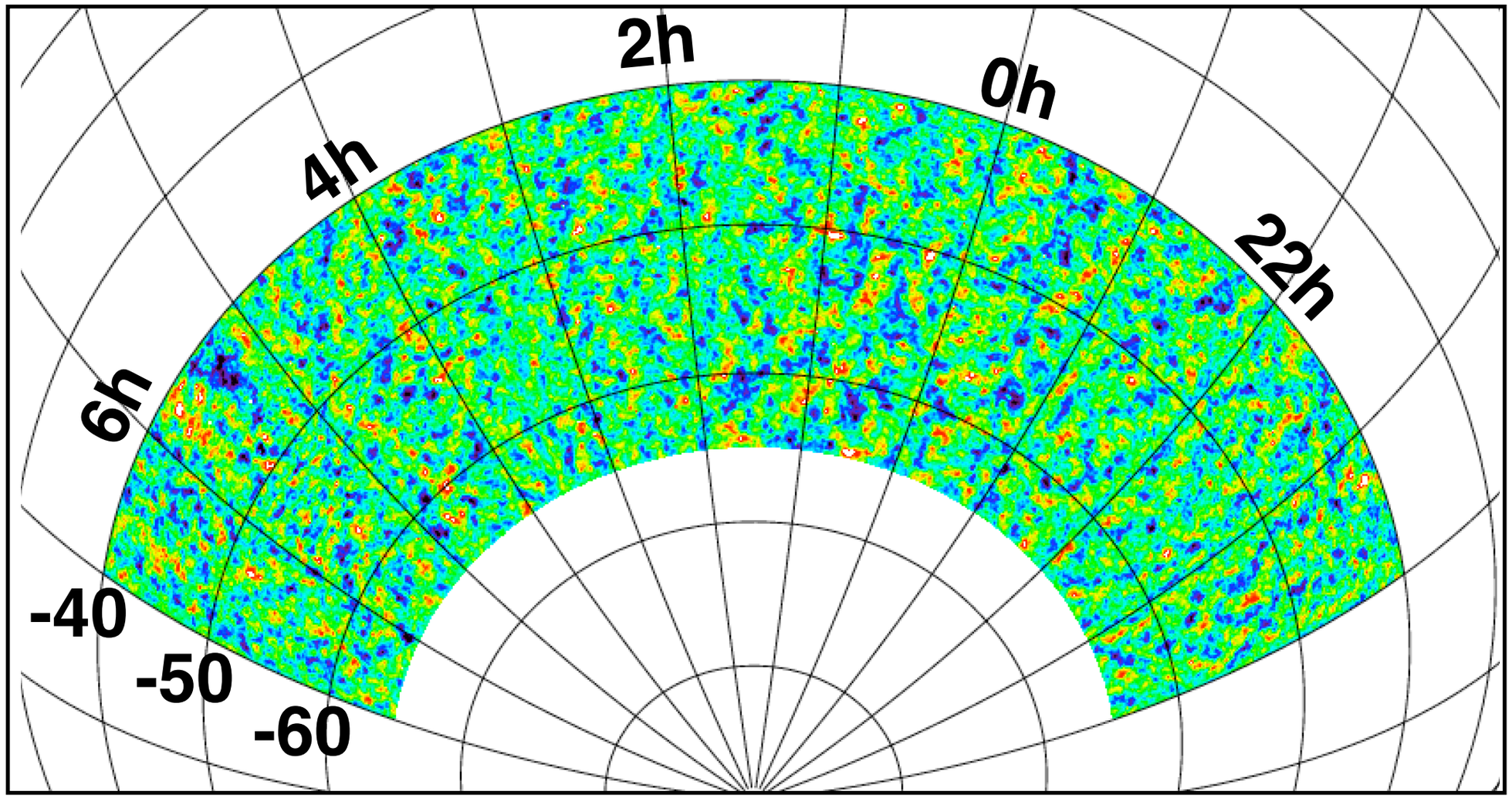
The 2500 deg^2 SPT-SZ Survey (2007-2011):

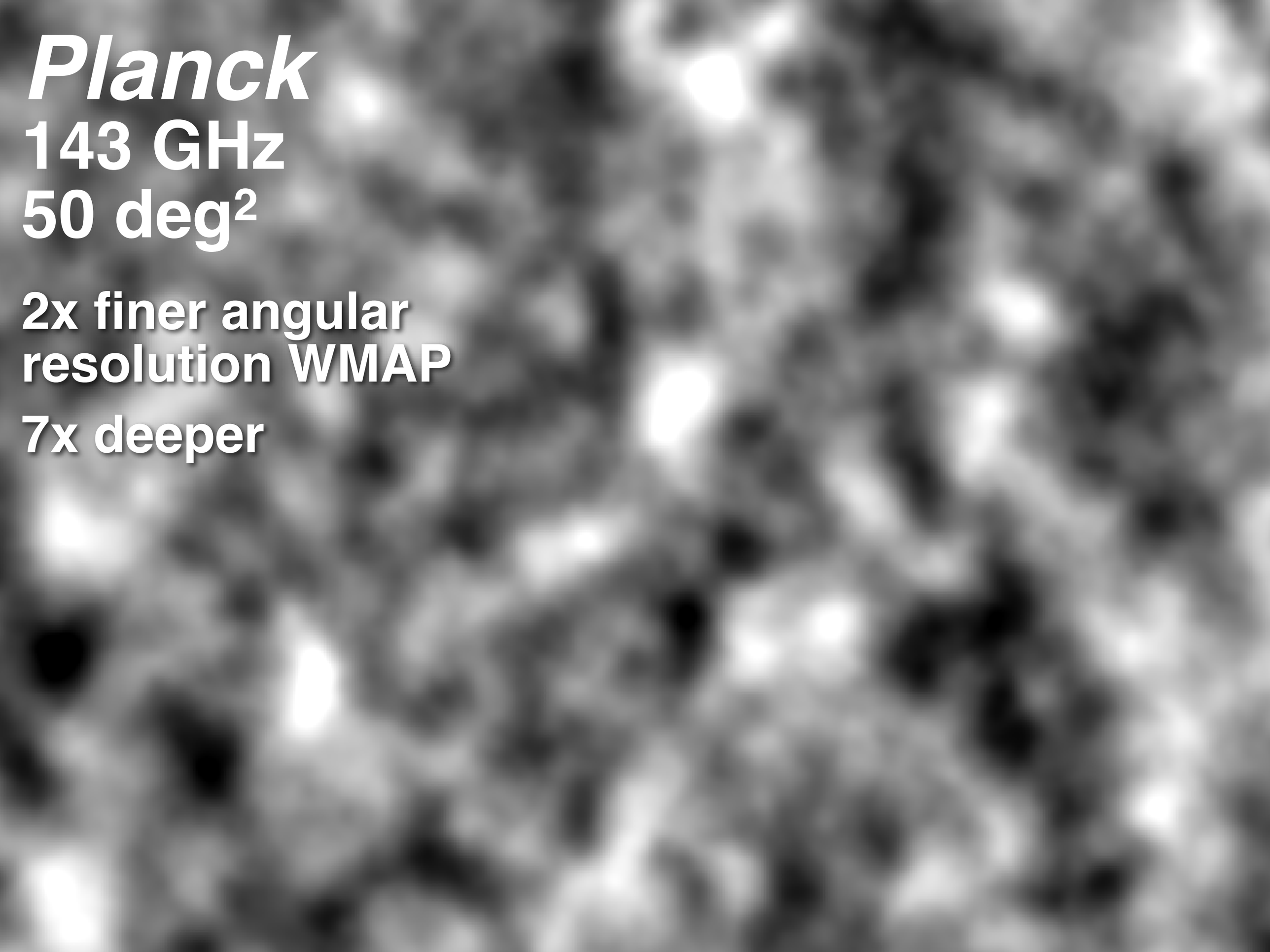


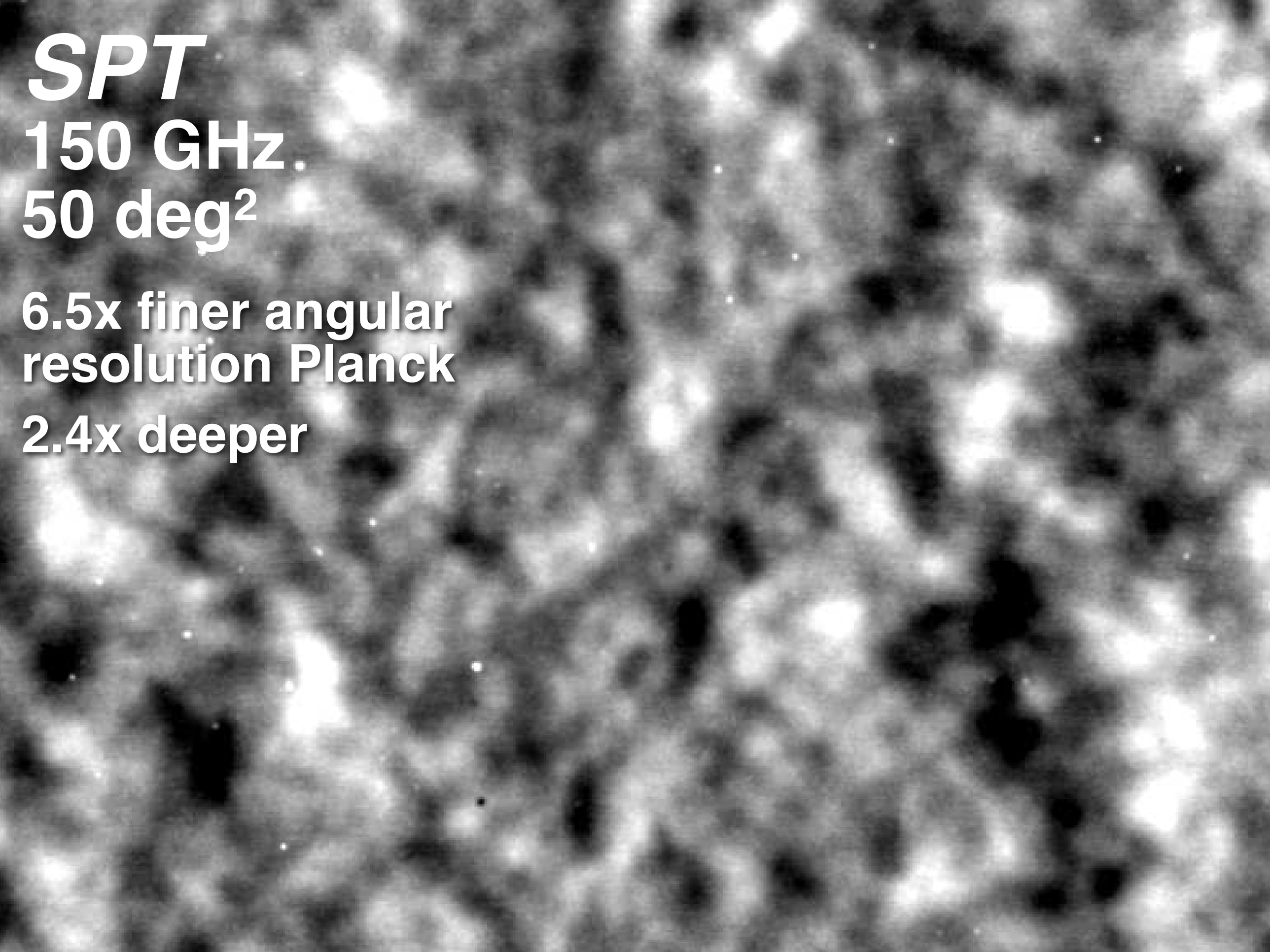
Final survey depths of:

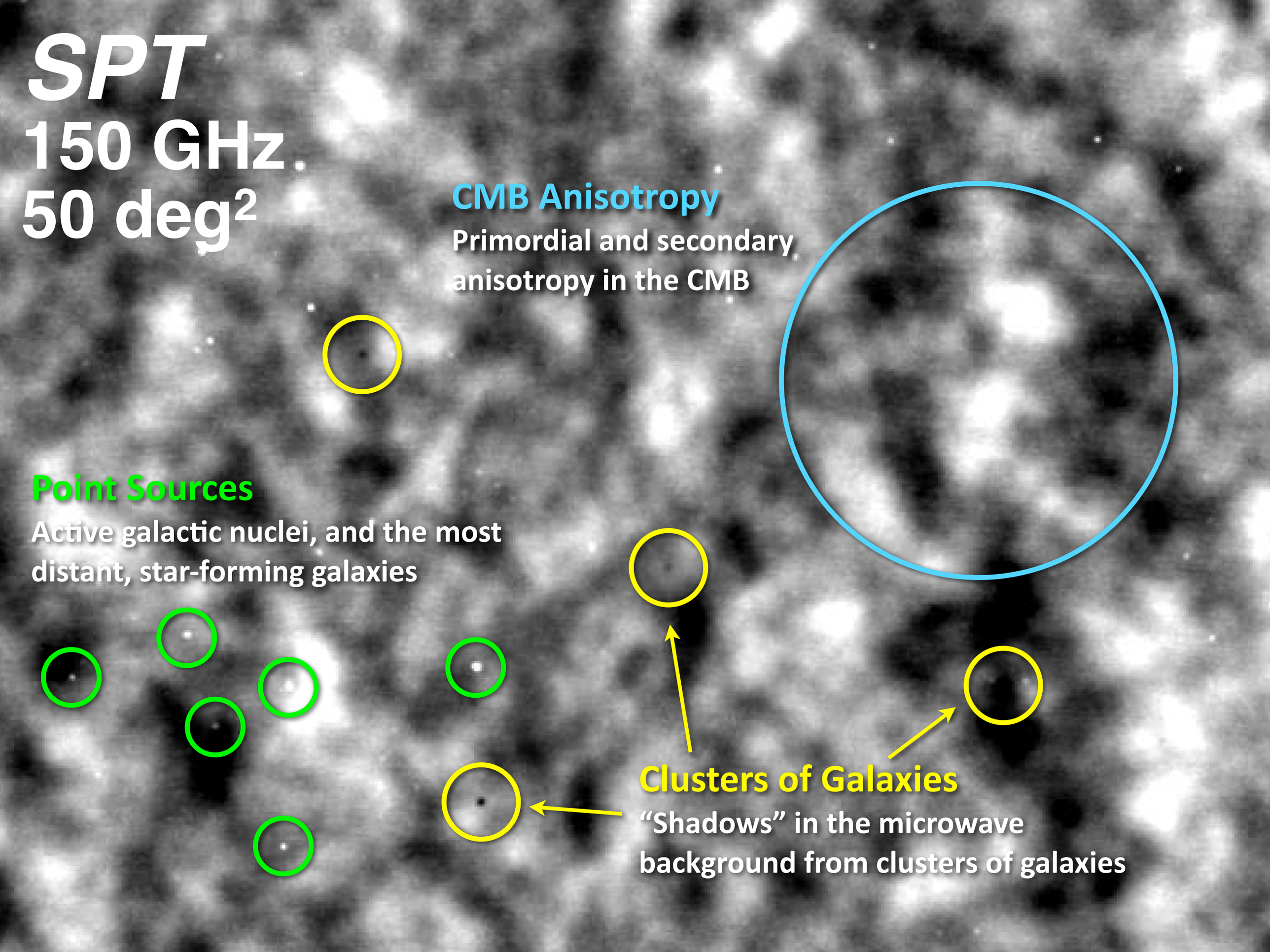
90 GHz: 40 uK_{CMB}-arcmin

150 GHz: 17 uK_{CMB}-arcmin

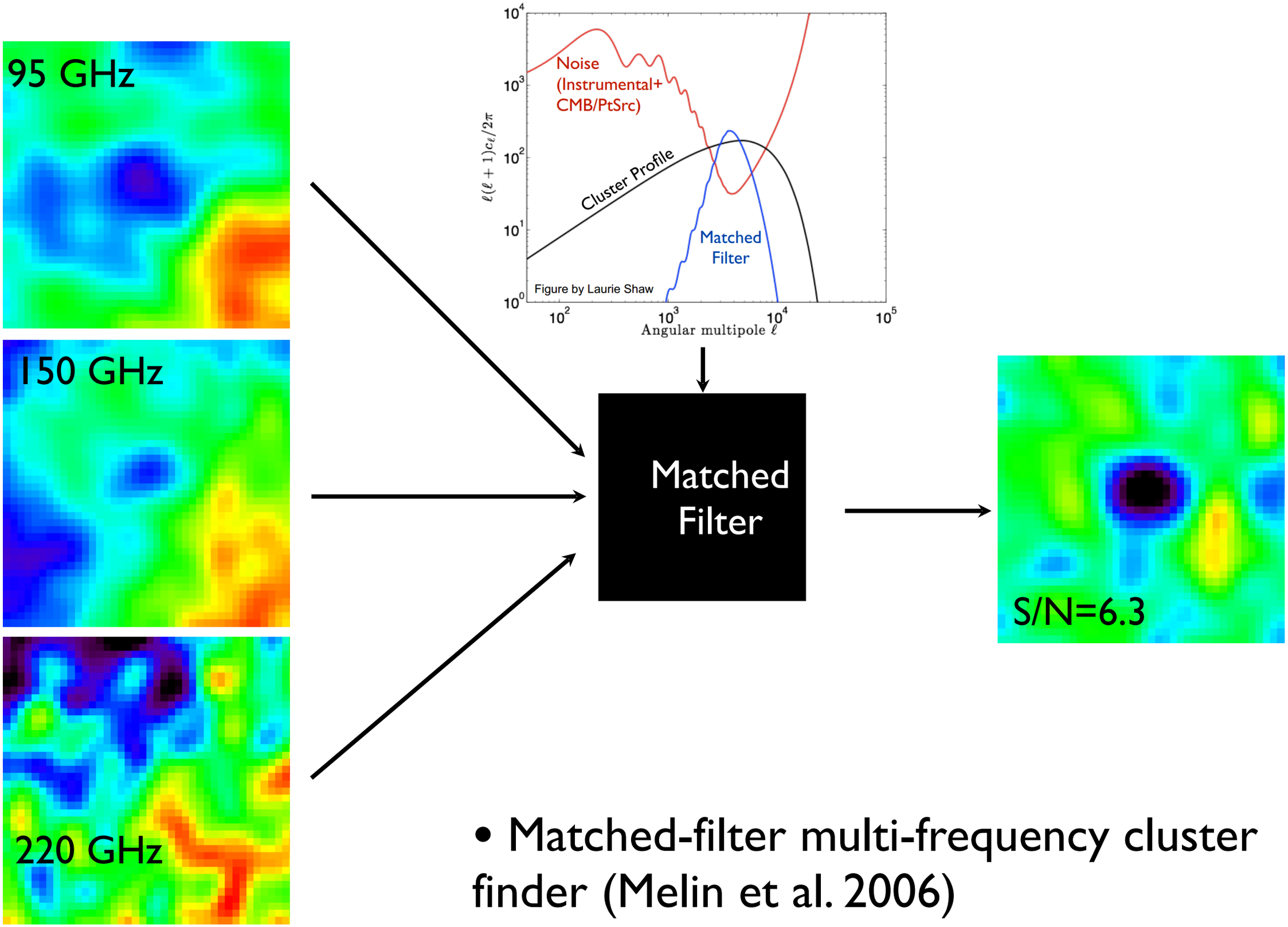
220 GHz: 80 uK_{CMB}-arcmin


Planck
143 GHz
50 deg²
2x finer angular resolution WMAP
7x deeper

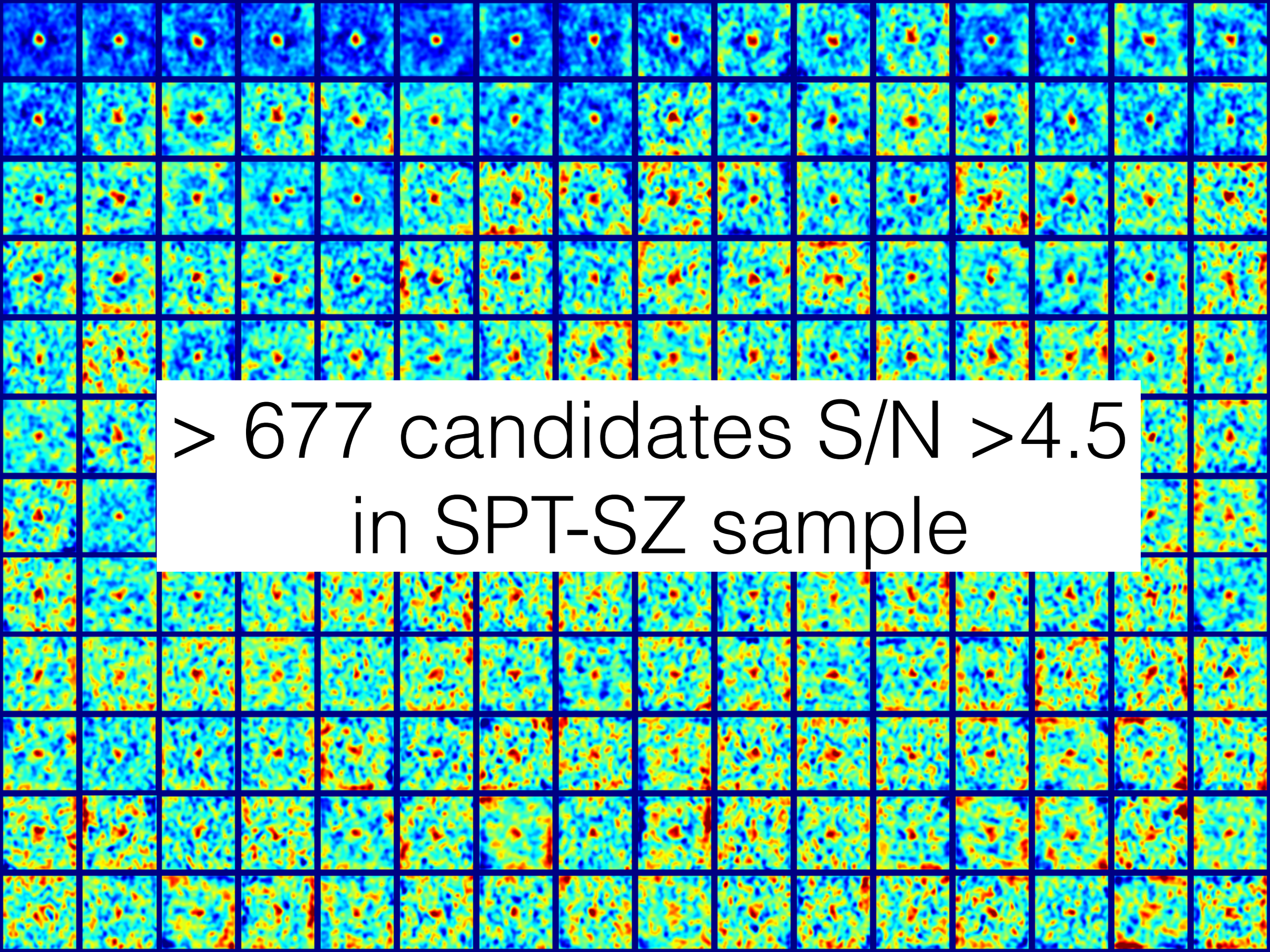

SPT
150 GHz
50 deg²
6.5x finer angular resolution Planck
2.4x deeper


SPT
150 GHz
50 deg²
CMB Anisotropy
Primordial and secondary anisotropy in the CMB
Point Sources
Active galactic nuclei, and the most distant, star-forming galaxies
Clusters of Galaxies
"Shadows" in the microwave background from clusters of galaxies

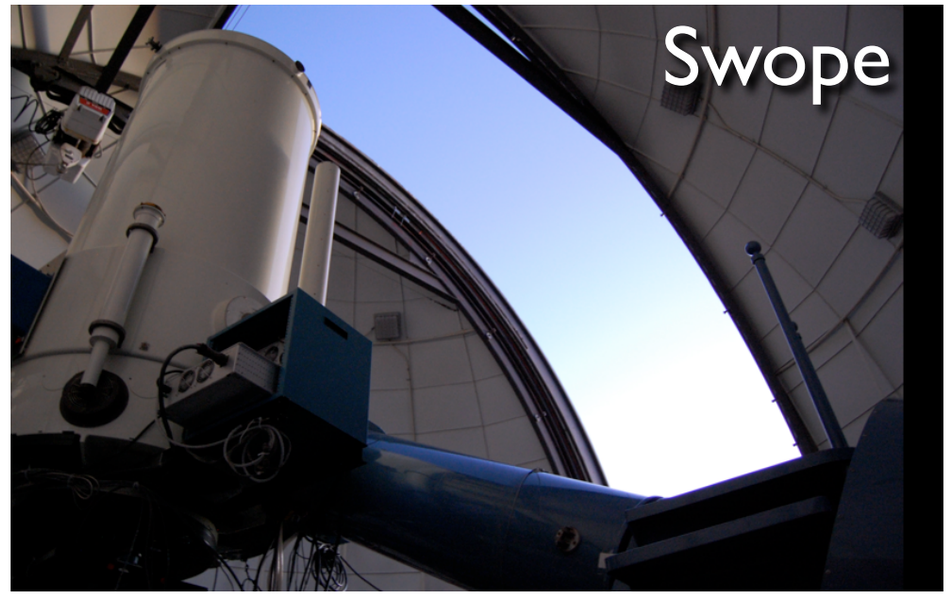
Finding Clusters in the SPT Survey

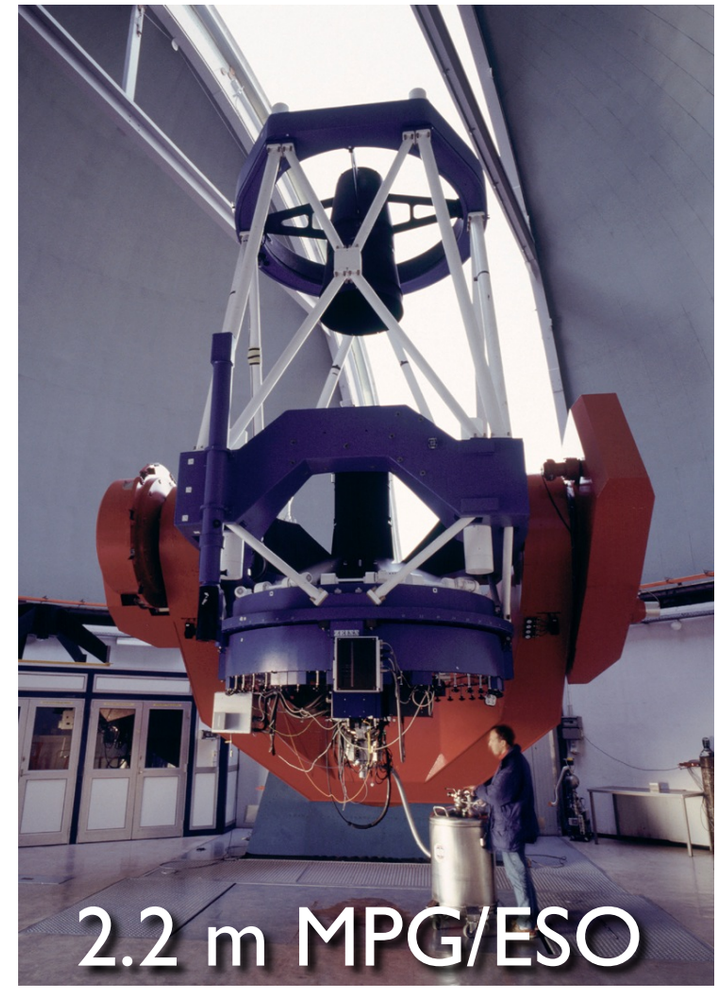


- Matched-filter multi-frequency cluster finder (Melin et al. 2006)



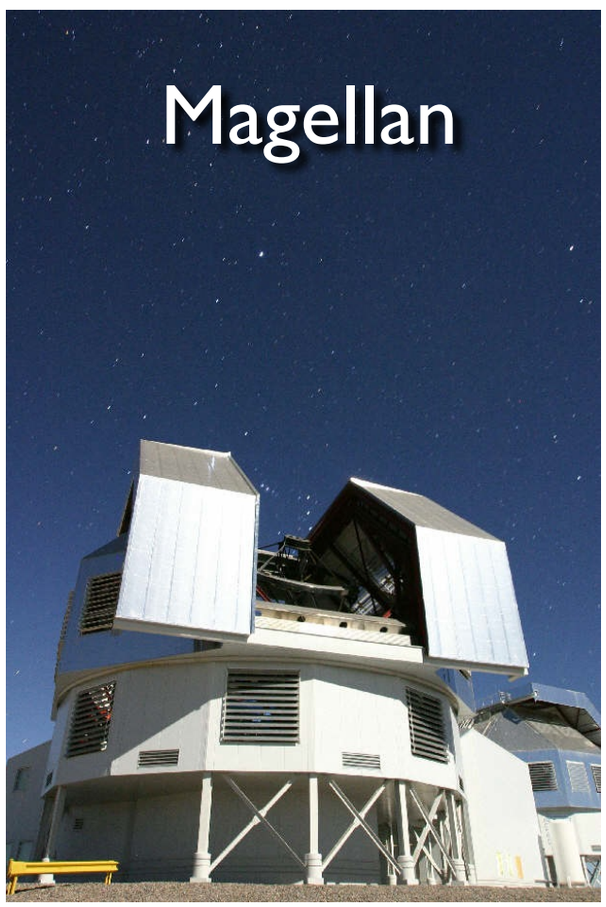
> 677 candidates S/N >4.5 in SPT-SZ sample



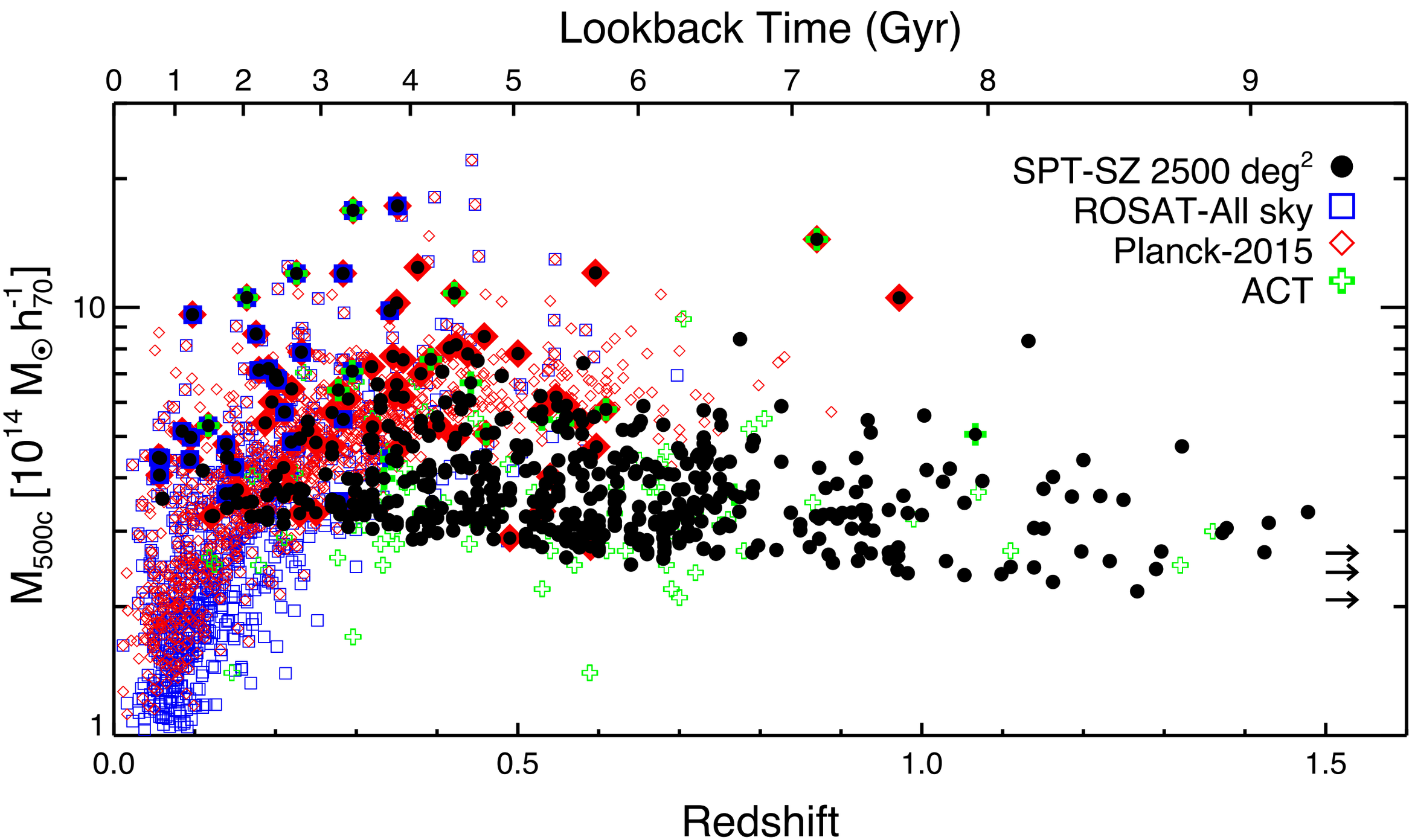


Multiple-facility Imaging Campaign for Cluster Confirmation →

516 Confirmed Clusters



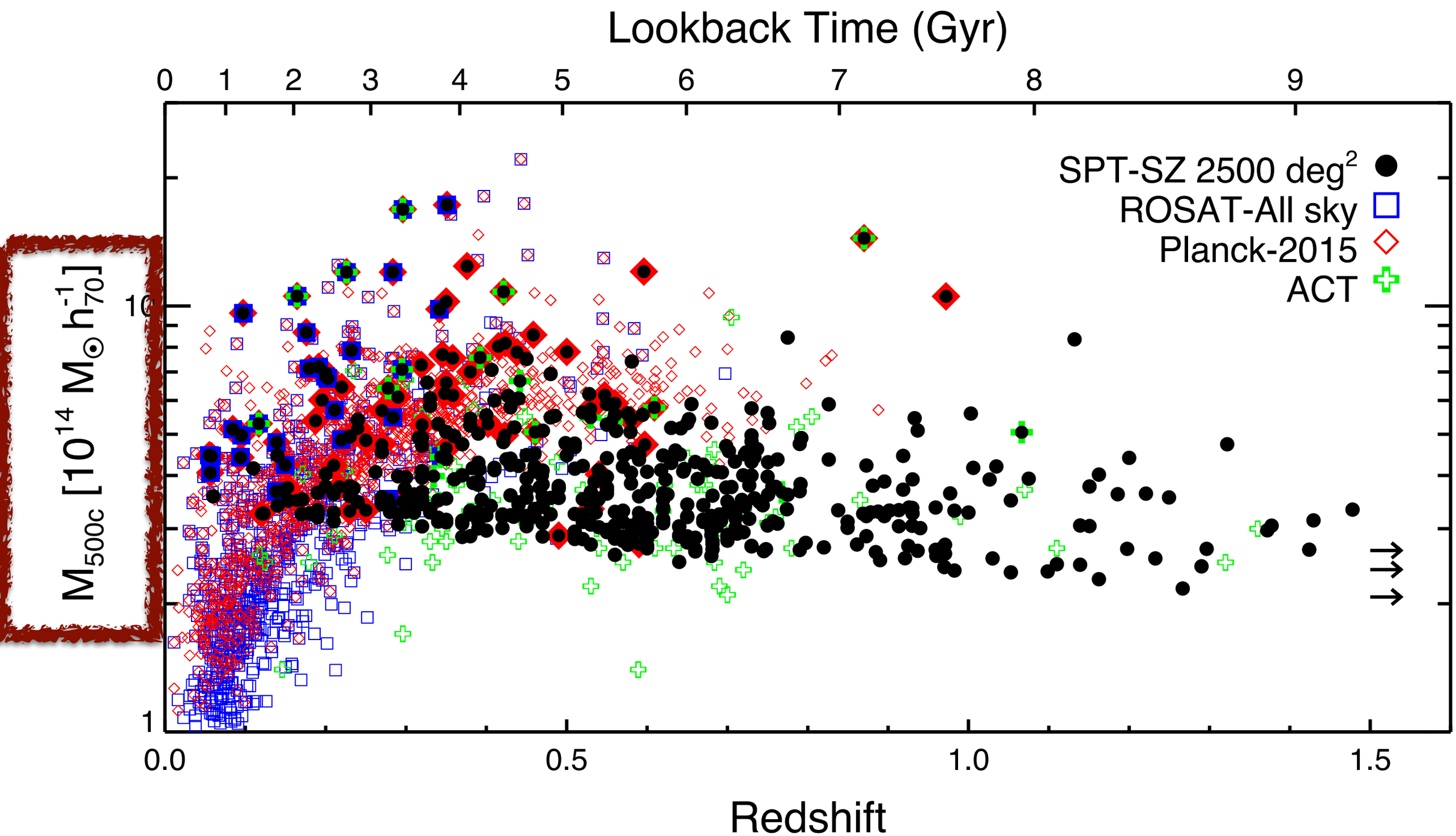
The 2500d SPT-SZ Cluster Sample



- Median M_{500} ~ 3×10^{14} M_{sun}
- z_{median} =0.55

Bleem et al, ApJS, 216, 27 (2015)

The 2500d SPT-SZ Cluster Sample



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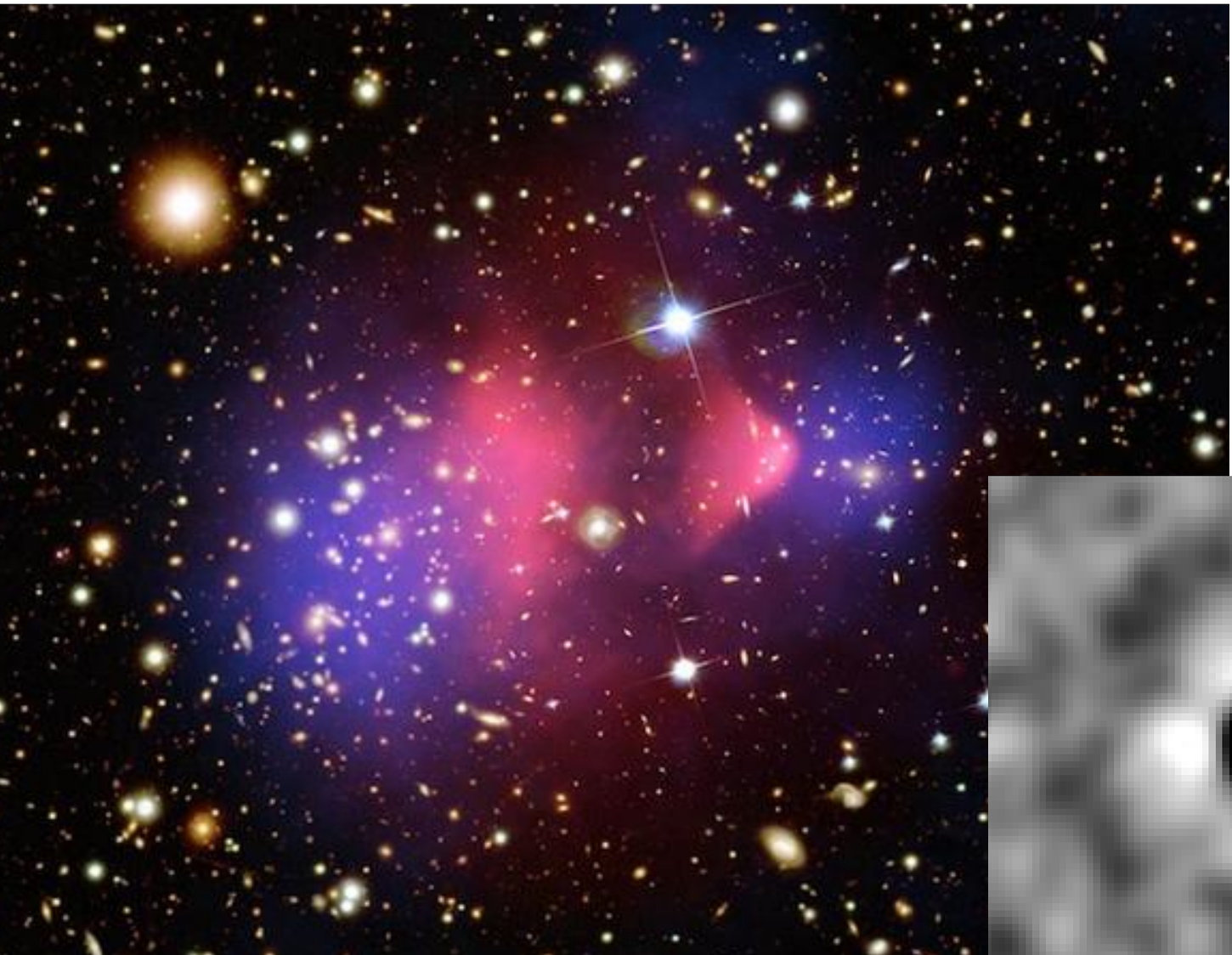
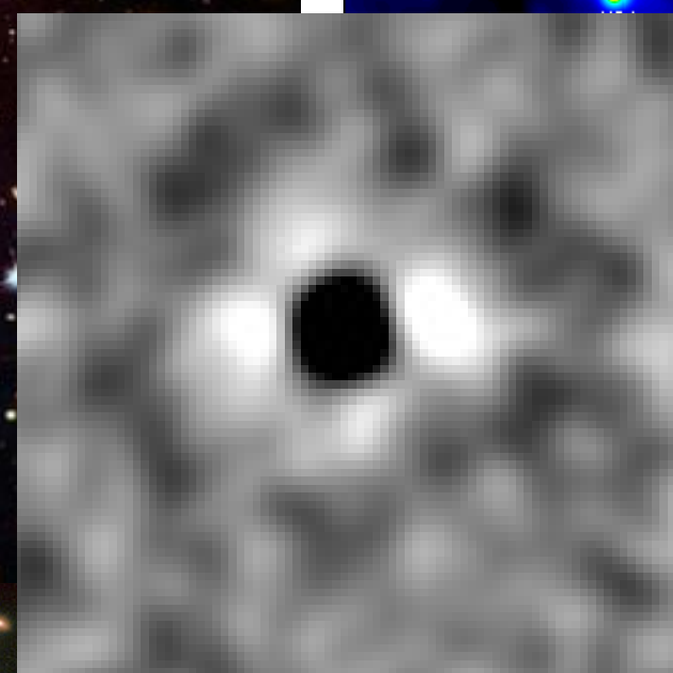
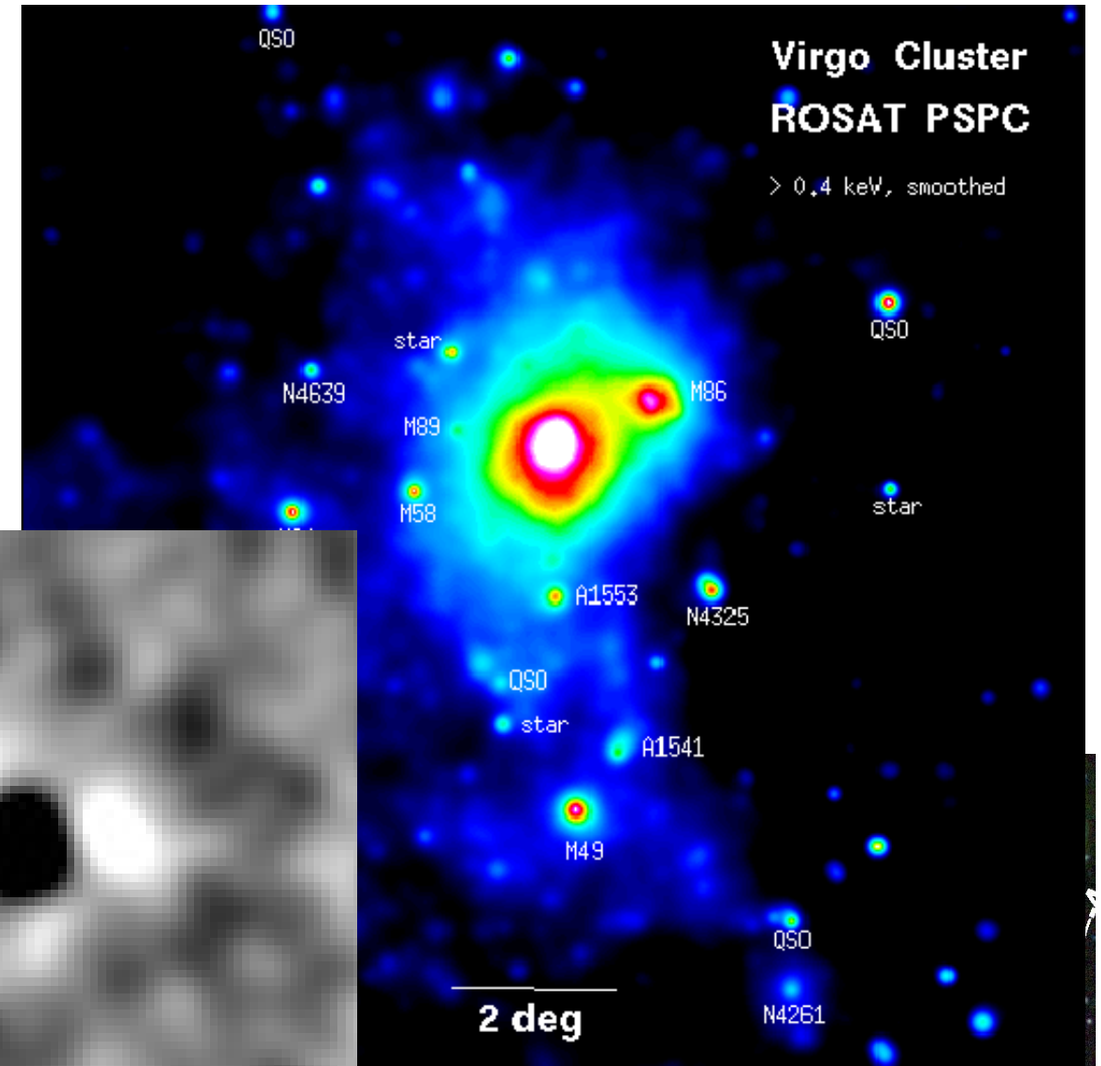
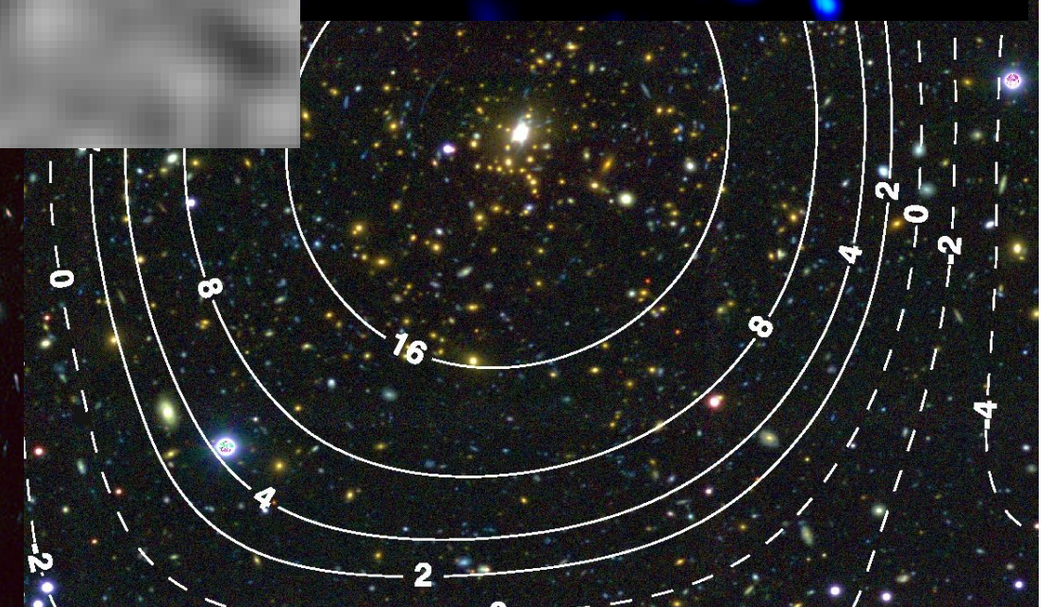
What is the mass of this object?







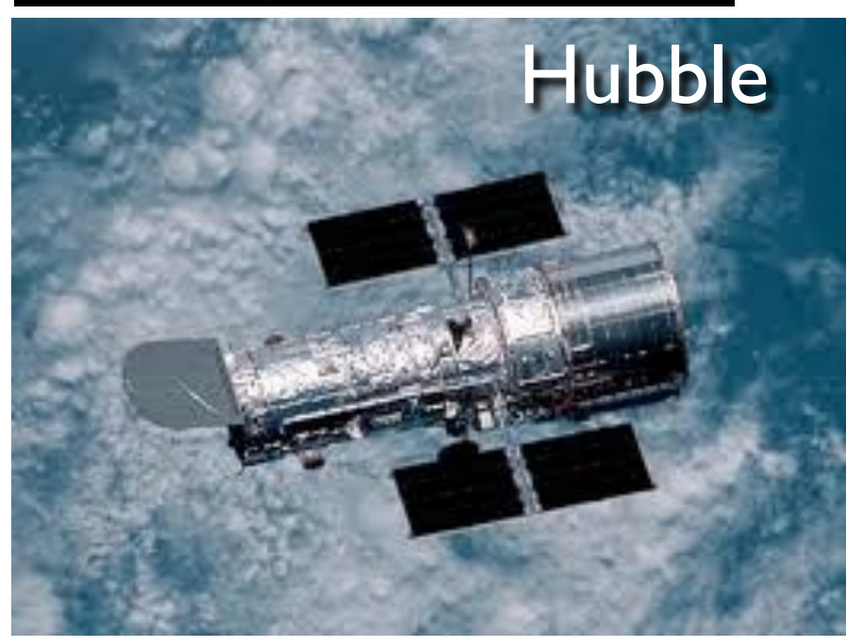


Multi-wavelength Observations:
Mass Calibration

- **Multi-wavelength mass calibration campaign, including:**

1. **X-ray** with Chandra
2. **Weak lensing** from Magellan ($0.3 < z < 0.6$) and HST ($z > 0.6$)
3. **Dynamical masses** from NOAO 3-year survey on Gemini ($0.3 < z < 0.8$), VLT, Magellan at ($z > 0.8$)

Bocquet et al. ApJ, 799, 214 (2015)



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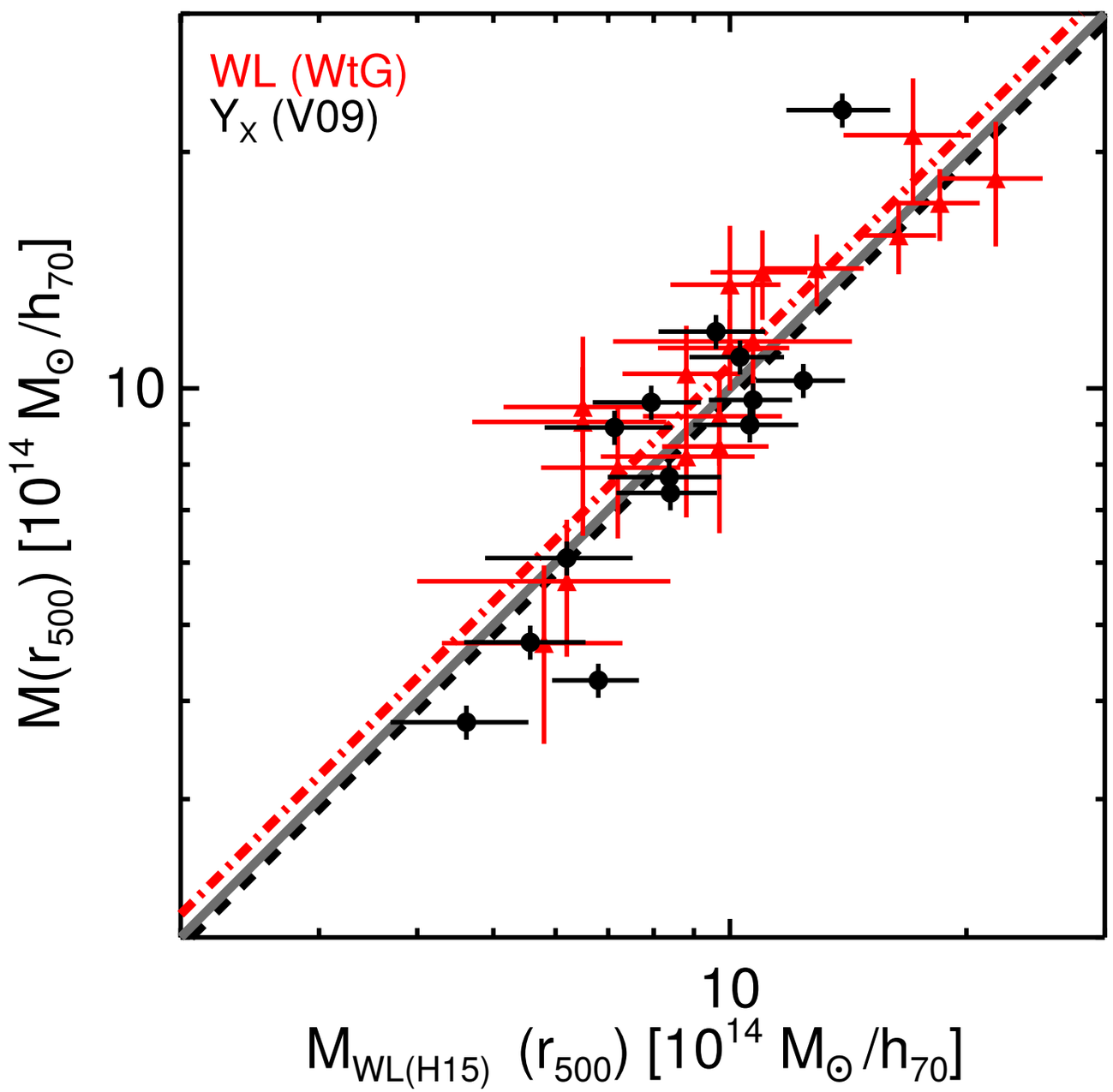


de Haan, Benson, Bleem, et al., (2016)

Cosmological Analysis:

Combine X-ray Observables with SPT Cluster Survey

Use Markov-Chain Monte Carlo (MCMC) method to vary cosmology and cluster observable-mass relation simultaneously, while accounting for SZ selection in a self-consistent way

9 Scaling Relation Parameters

- X-ray (Yx-M) and SZ (ζ-M) relations (4 and 5 parameters):
  - A) normalization,
  - B) slope,
  - C) redshift evolution,
  - D) scatter,
  - F) correlated scatter

6 Cosmology Parameters (plus extension parameters)

- ΛCDM Cosmology
  - $\Omega_m h^2, \Omega_b h^2, A_s, n_s, \boldsymbol{\theta}_s$
- Extension Cosmology
  - $w, \Sigma m_\nu, f_{NL}, N_{eff}$

Benson et al, ApJ 763, 147 (2013)
Reichardt, Stalder, Bleem, et al., ApJ 763, 127 (2013)
de Haan, Benson, Bleem, et al., ApJ 832, 95 (2016)

Cosmological Analysis:

Combine X-ray Measurements with SZ Cluster Survey

9 Scaling Relation Parameters

- X-ray (Yx-M) and SZ (ζ-M) relations (4 and 5 parameters):

A) Normalization:

- Effectively set by weak-lensing calibration

B) Slope:

- Effectively set by prior based on Vikhlinin+09 /Hoekstra+15

C) Redshift evolution:

- Prior of self-similar evolution, with an uncertainty corresponding to an additional ~10% mass uncertainty at z=1.0

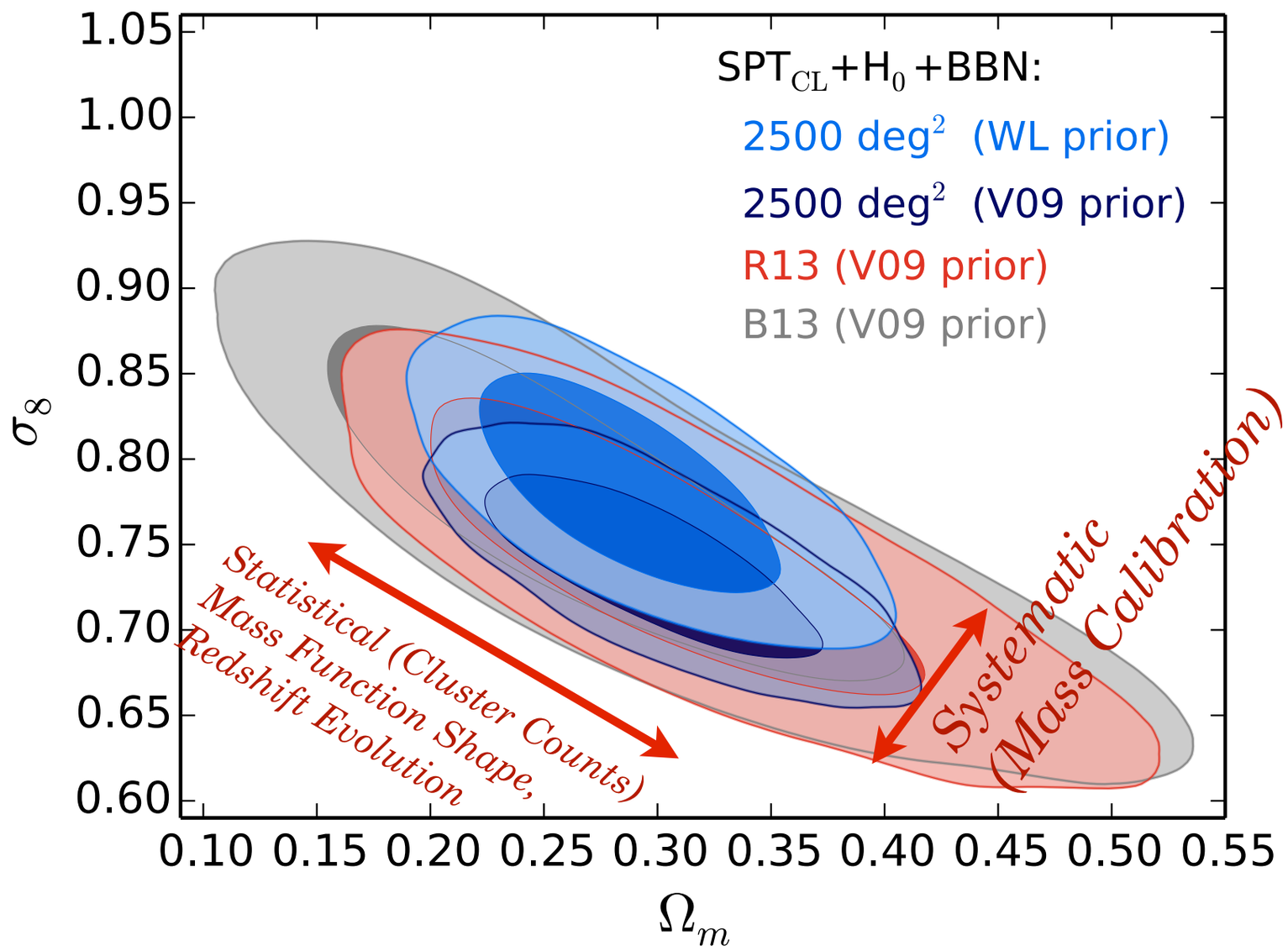
D) Scatter:

- Log-normal scatter of (0.12+/-0.08) in mass given Yx

F) Correlated scatter:

- Uniform prior from -1 to 1 (not important for constraints)

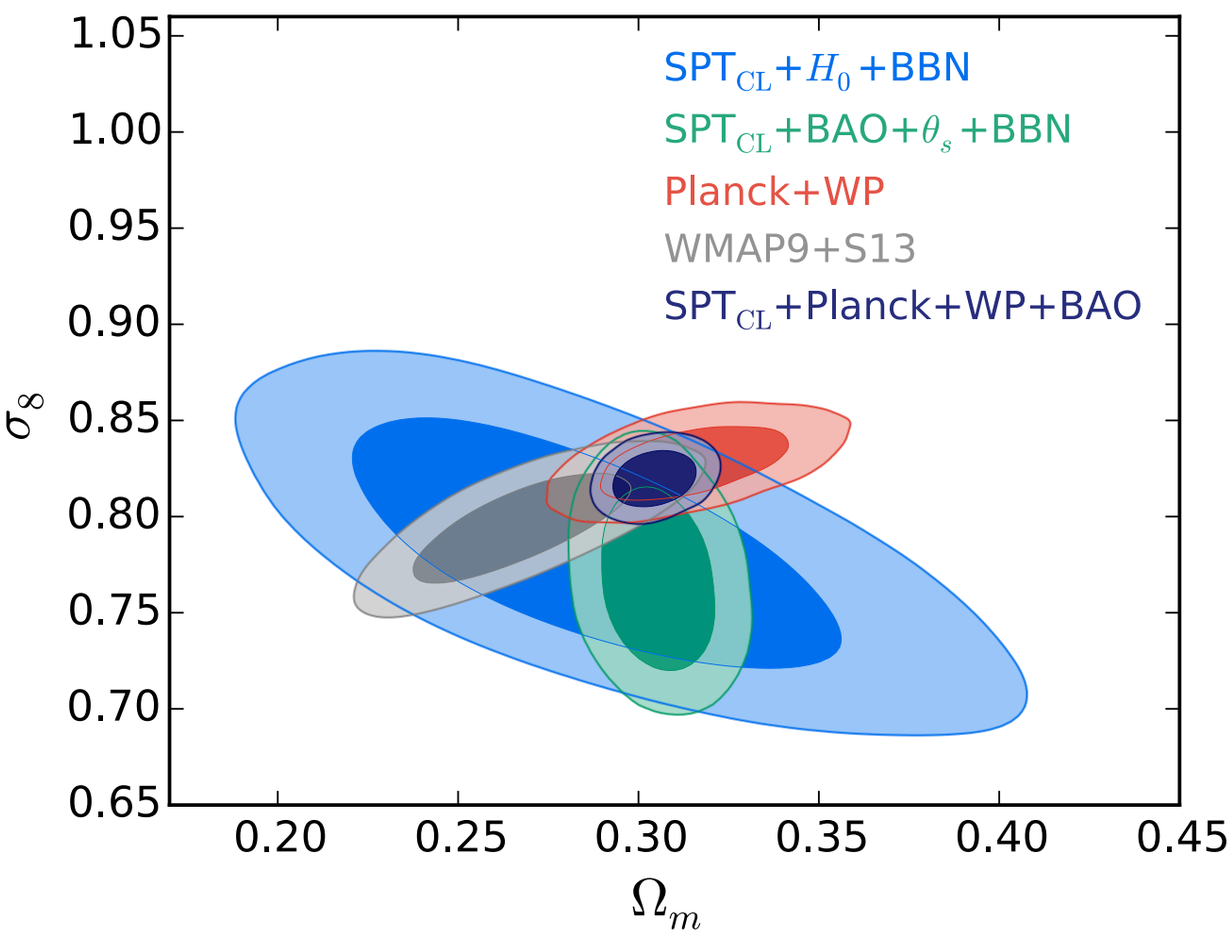
ΛCDM Constraints:

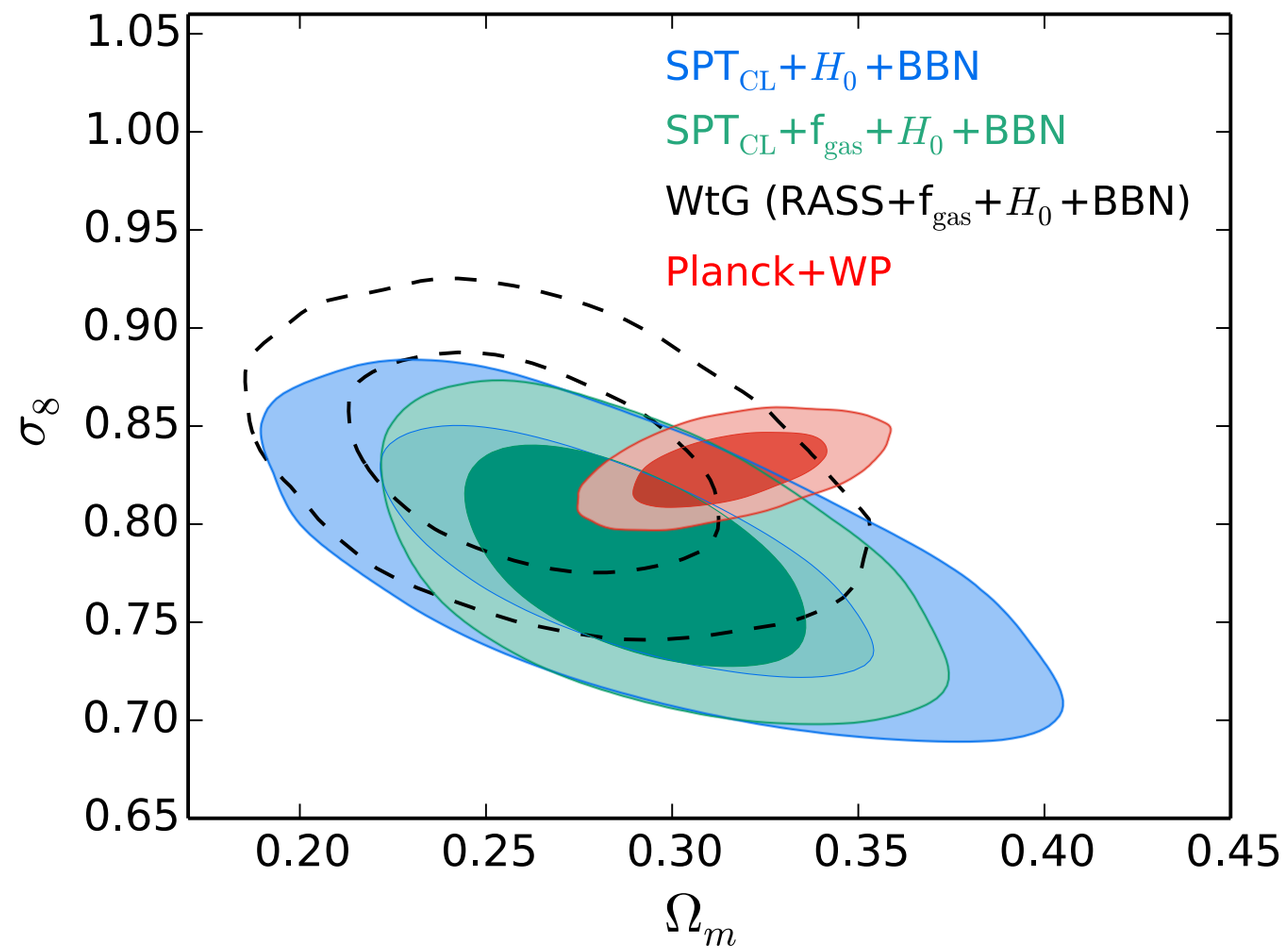


- From Benson+13 to de Haan+16, area in σ_8-Ω_m likelihood space reduced by ~4x
- Updated weak lensing calibration increases mass calibration by 10% (relative to Vikhlinin+09)
- Mass calibration assumes a 10% uncertainty in mass at z=0
  - Limited by small sample (10 clusters) in Vikhlinin+09, Hoekstra+15 comparison

Benson et al., ApJ 763, 147 (2013) (21 clusters in cosmo sample)
Reichardt, Stalder, Bleem, et al., ApJ 763, 127 (2013) (100 clusters)
de Haan, Benson, Bleem, et al., ApJ 832, 95 (2016) (356 clusters)

ΛCDM Constraints:



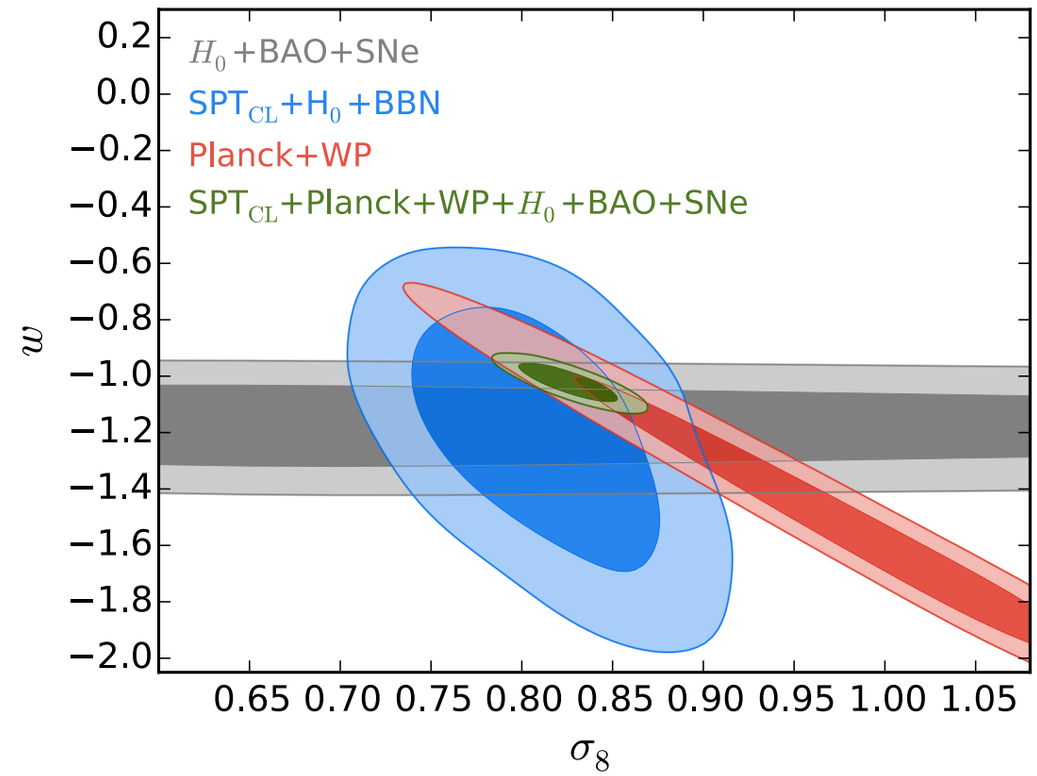


- Consistent with CMB cosmological measurements
- As well as constraints from other cluster surveys

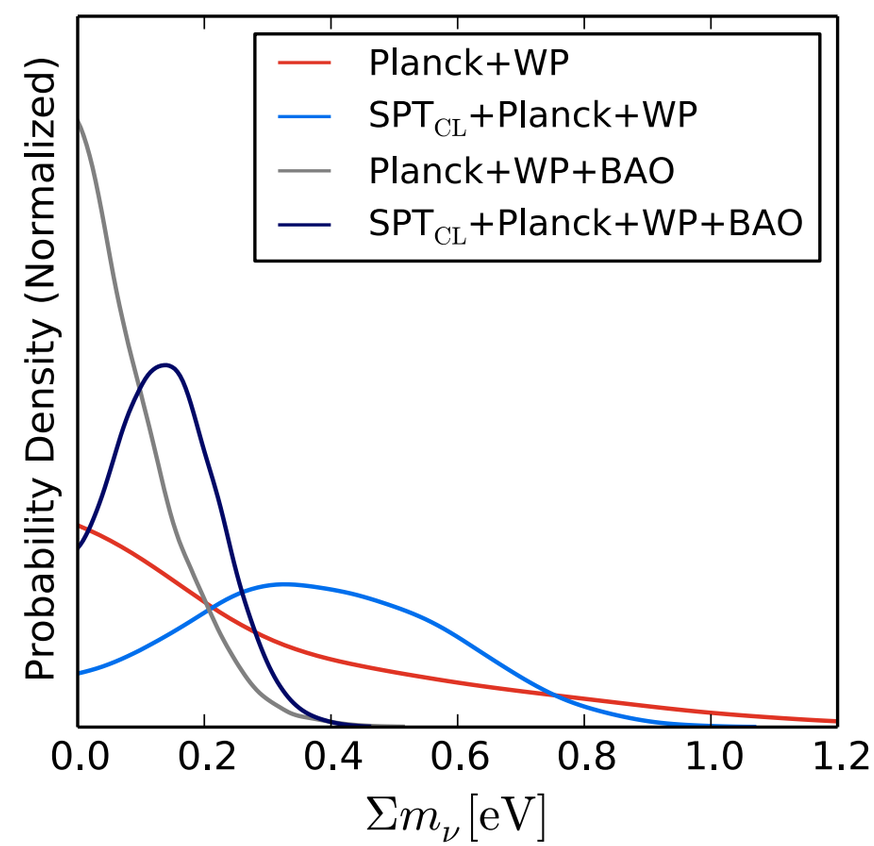
de Haan, Benson, Bleem, et al., (2016)

Extensions to ΛCDM

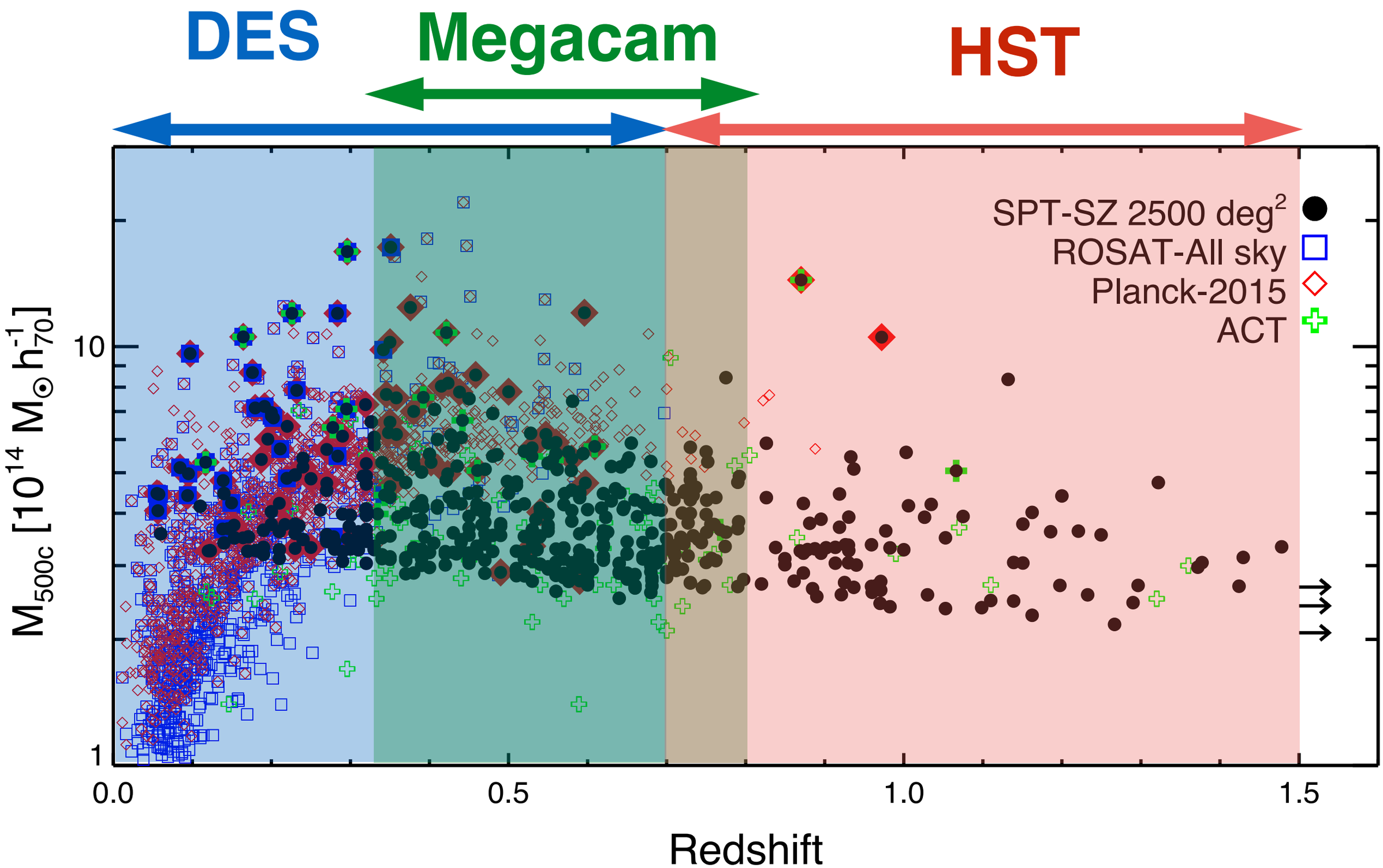
- Clusters break degeneracies in other datasets; Combination of Clusters, CMB, geometric probes: *w = -1.023 +/- 0.042*



- CMB strong degeneracy σ_8-Σm_ν so even modest σ_8 can improve constraints



The Next Steps: [lensing, lensing, & more lensing!]



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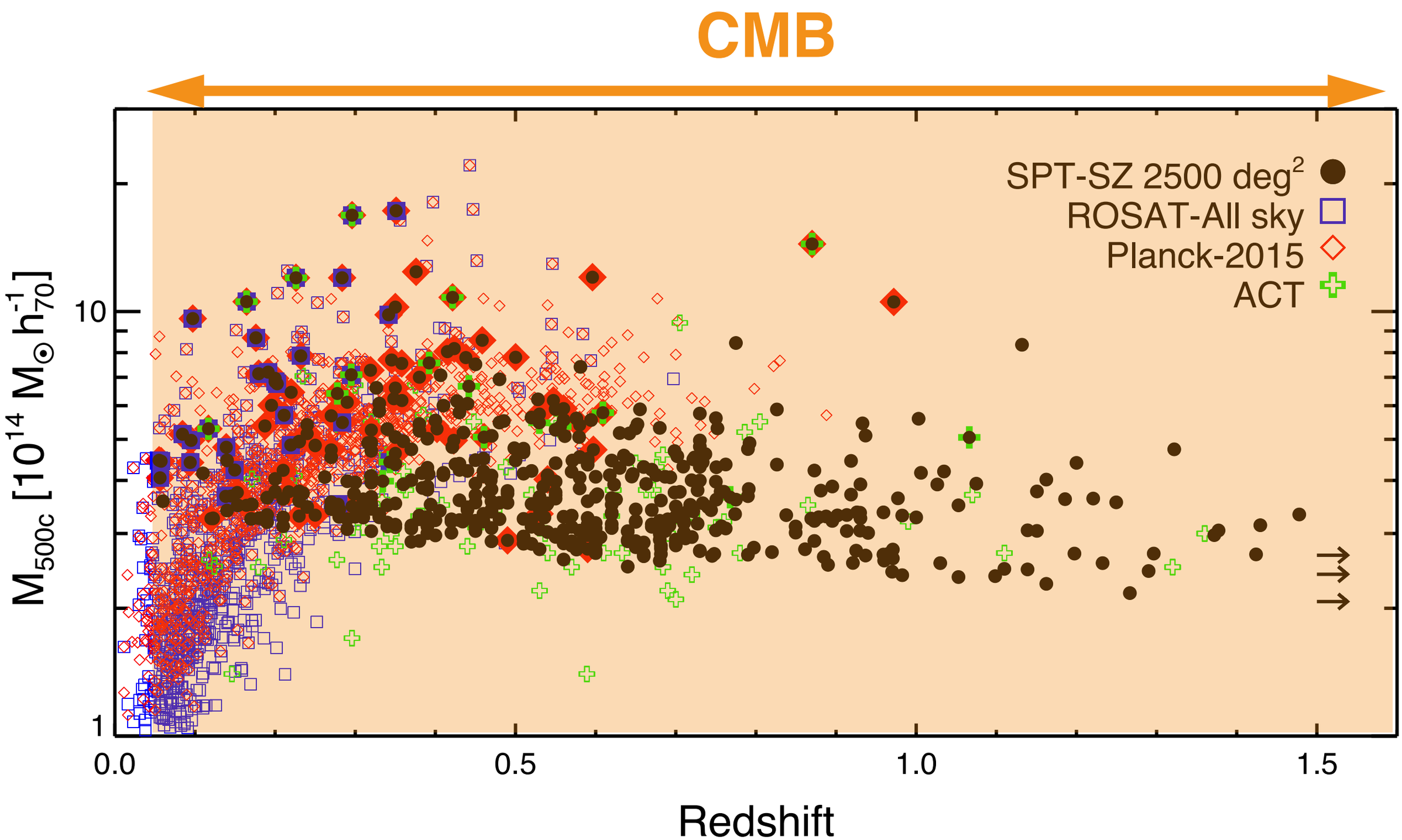
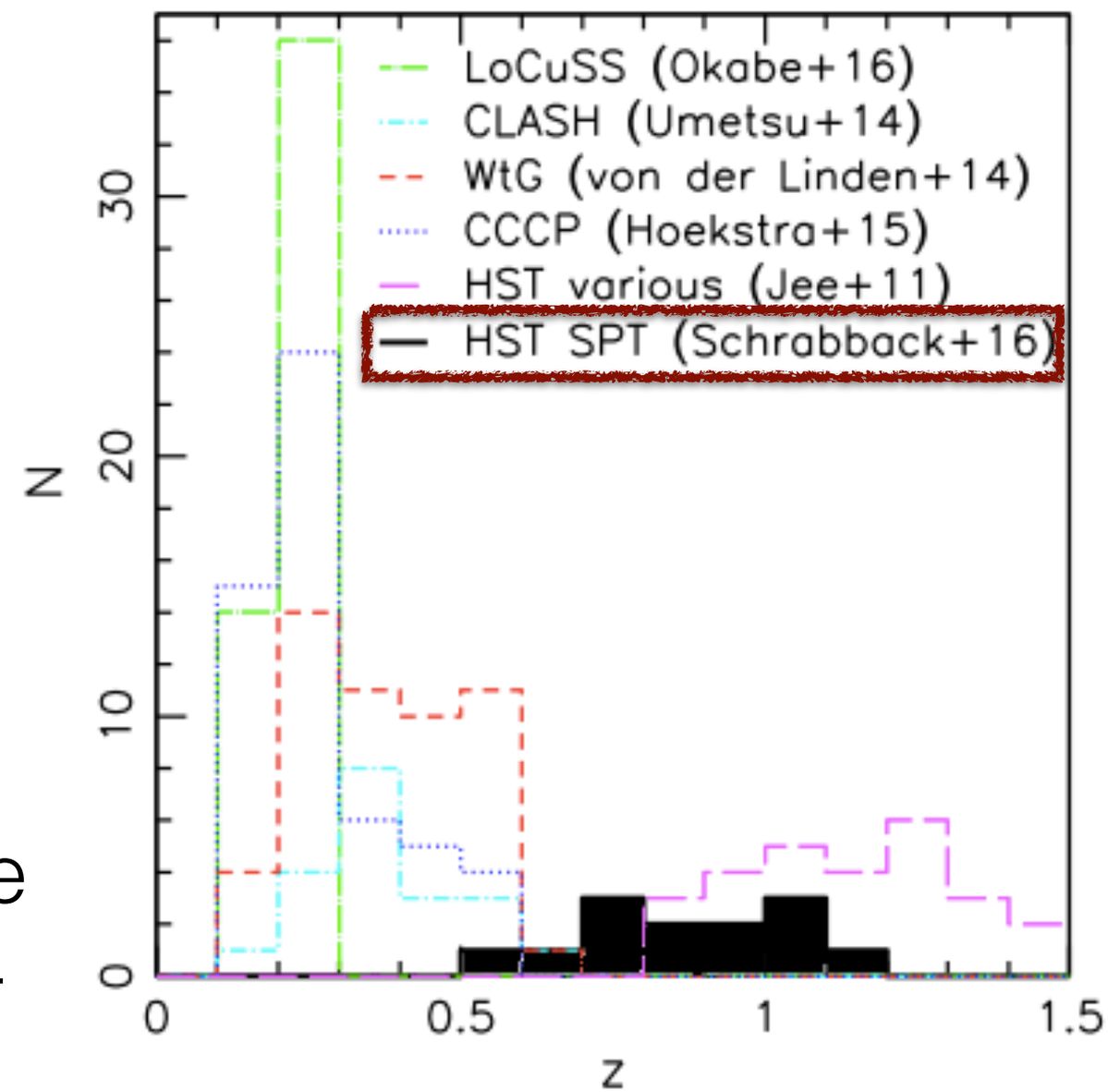


Next Steps: SPT-HST 13 Sample

- HST + VLT imaging of 13 massive SPT clusters $\langle z \rangle_{med} = 0.88$
- First step in creating high-redshift anchor for SPT WL calibration
- Careful study of role of WL systematics: photo-zs, source selection, miscentring, mass-concentration relation



Schrabback et al. (2016; *1611.03866*)

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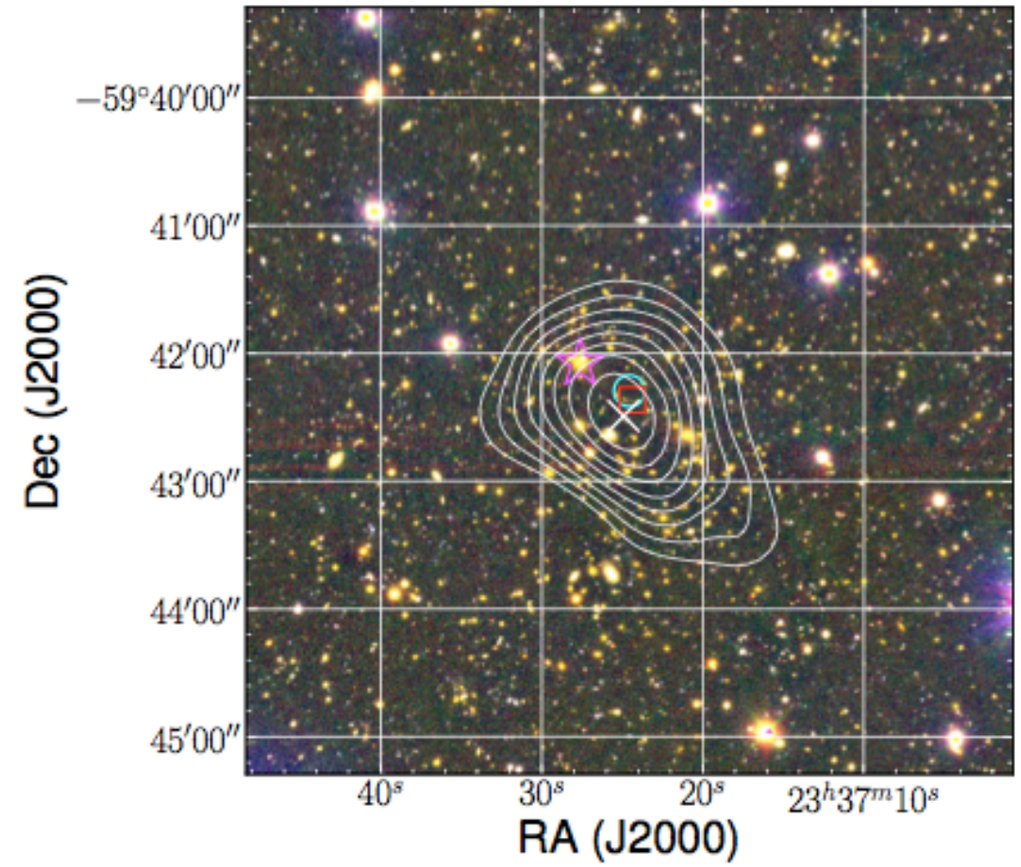
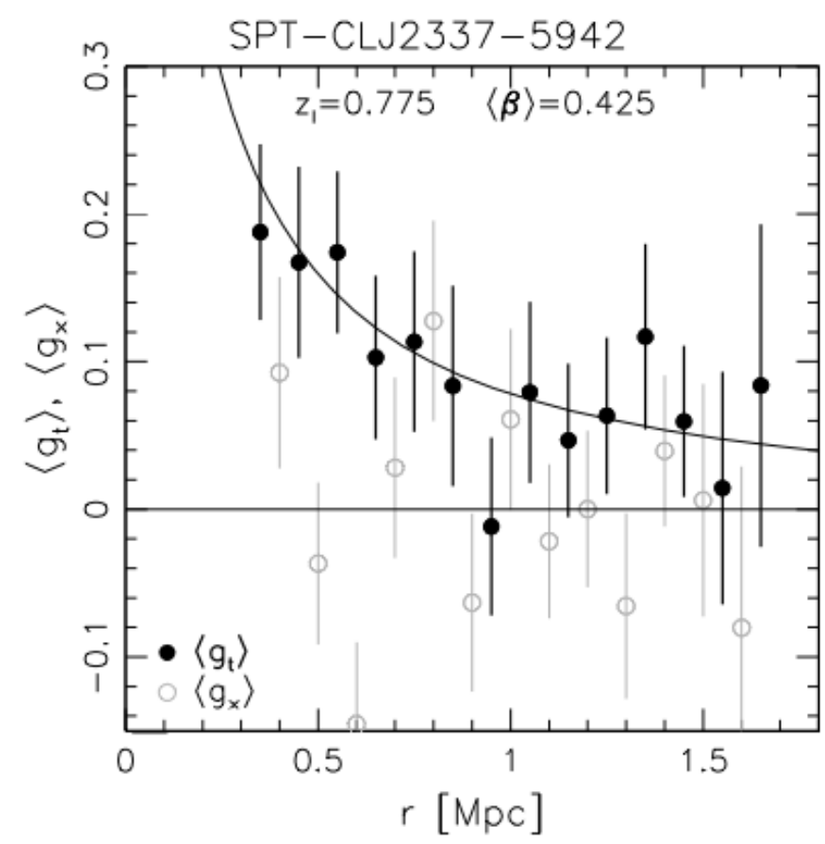
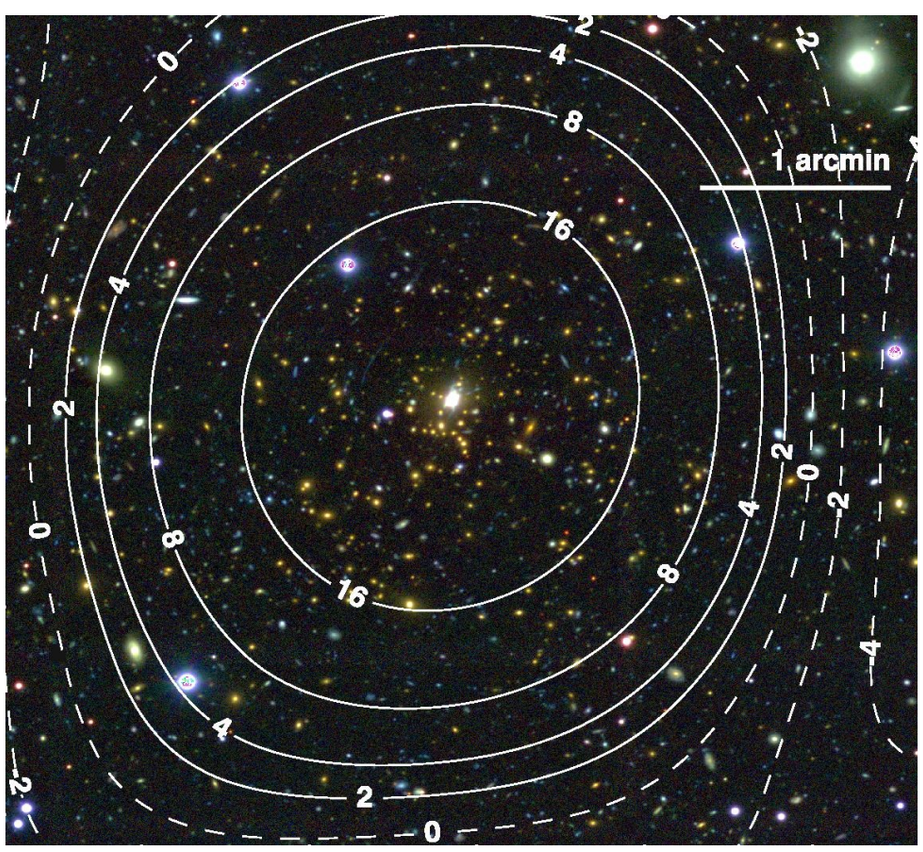


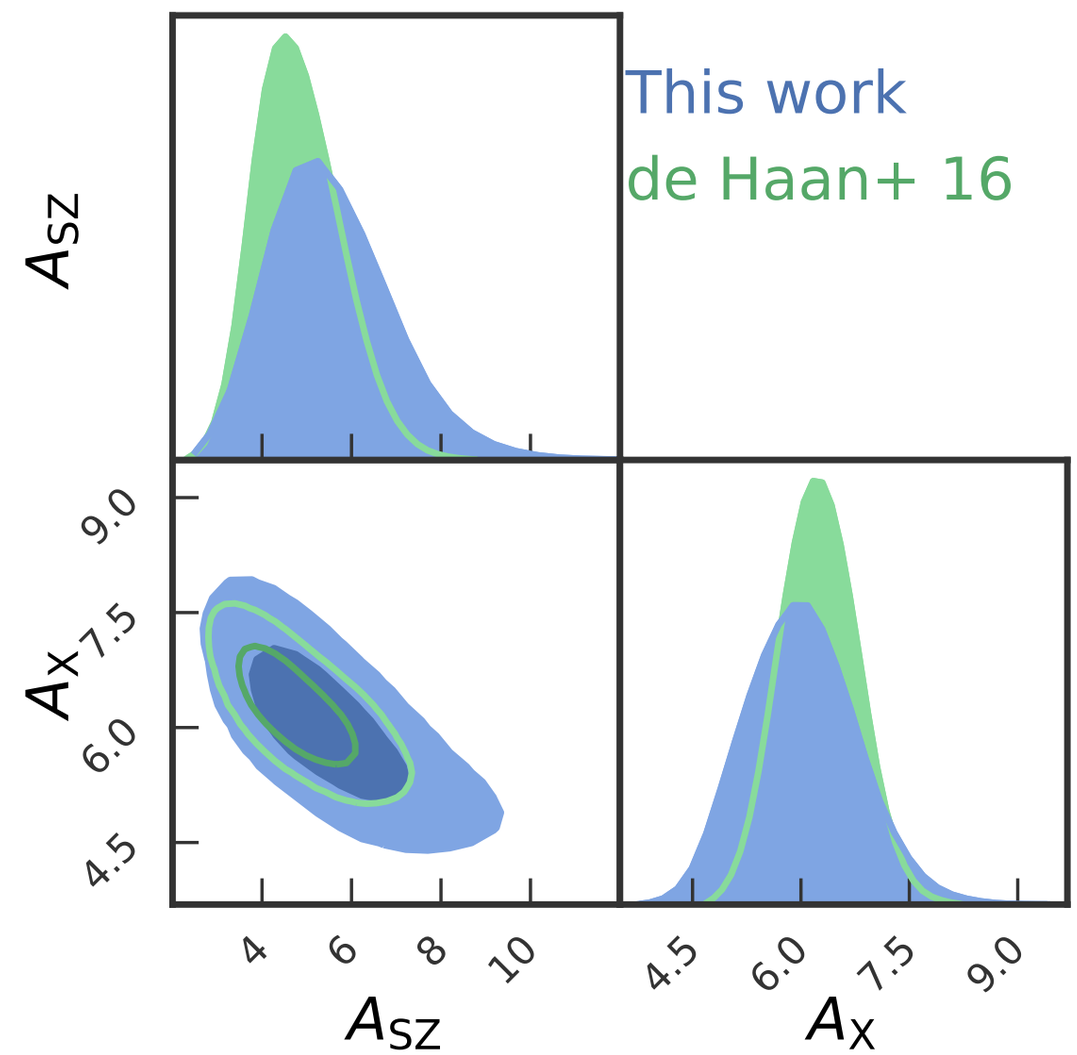


Schrabback et al. (2016; *1611.03866*)

Next Steps: + SPT-Megacam 19

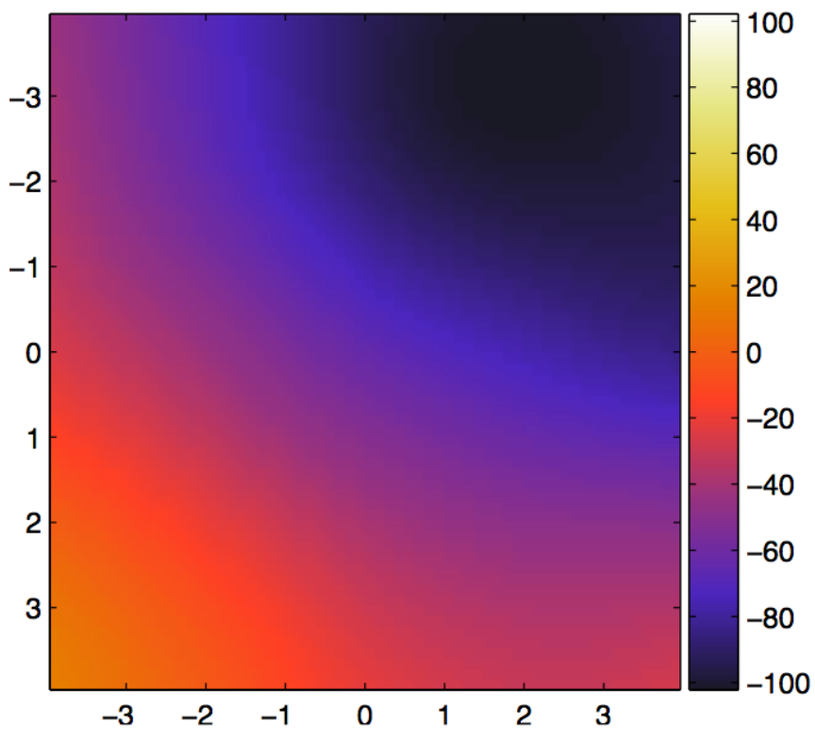
- Analysis of first SPT Megacam + HST WL datasets
- Fit SZ, X-ray Mass observable scaling relation
- X-ray results consistent with previous studies



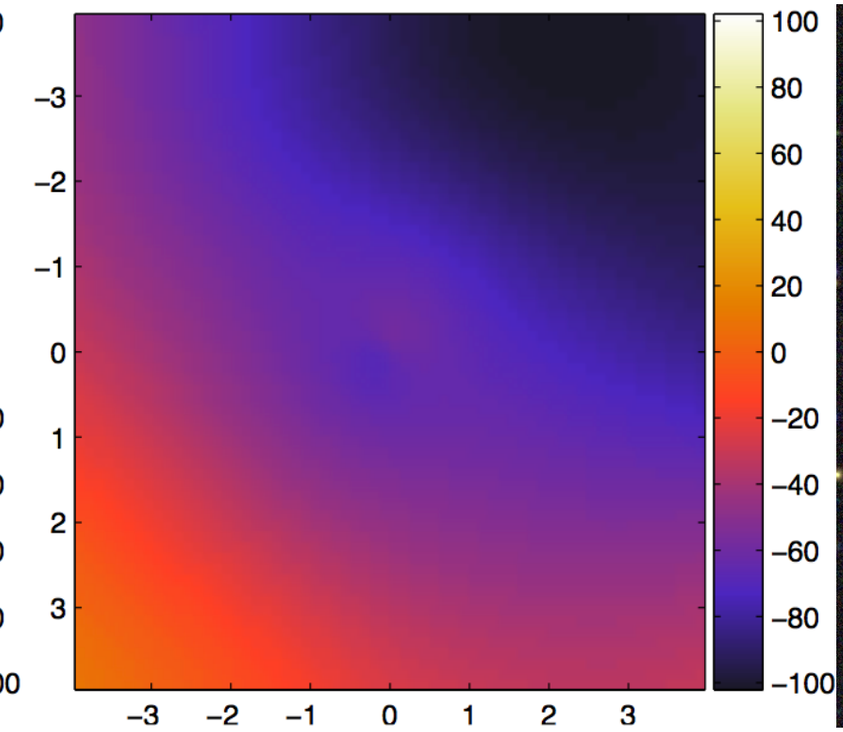


Dietrich, Bocquet, Applegate et al. (in prep)
Bocquet et al. (in prep)

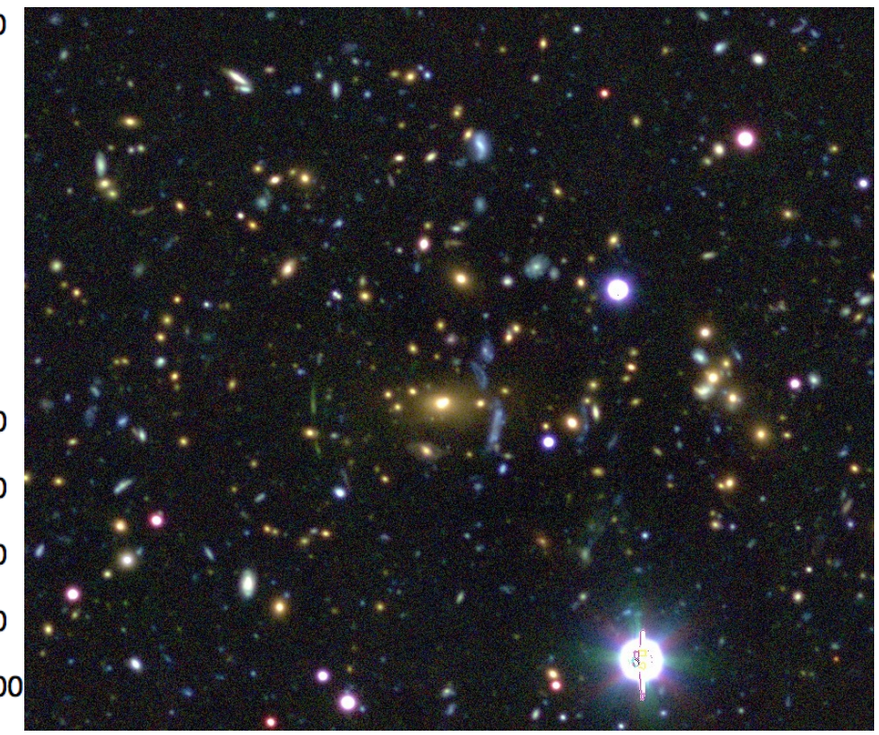
CMB lensing will be a powerful tool for constraining the masses of high-z clusters.



Unlensed CMB



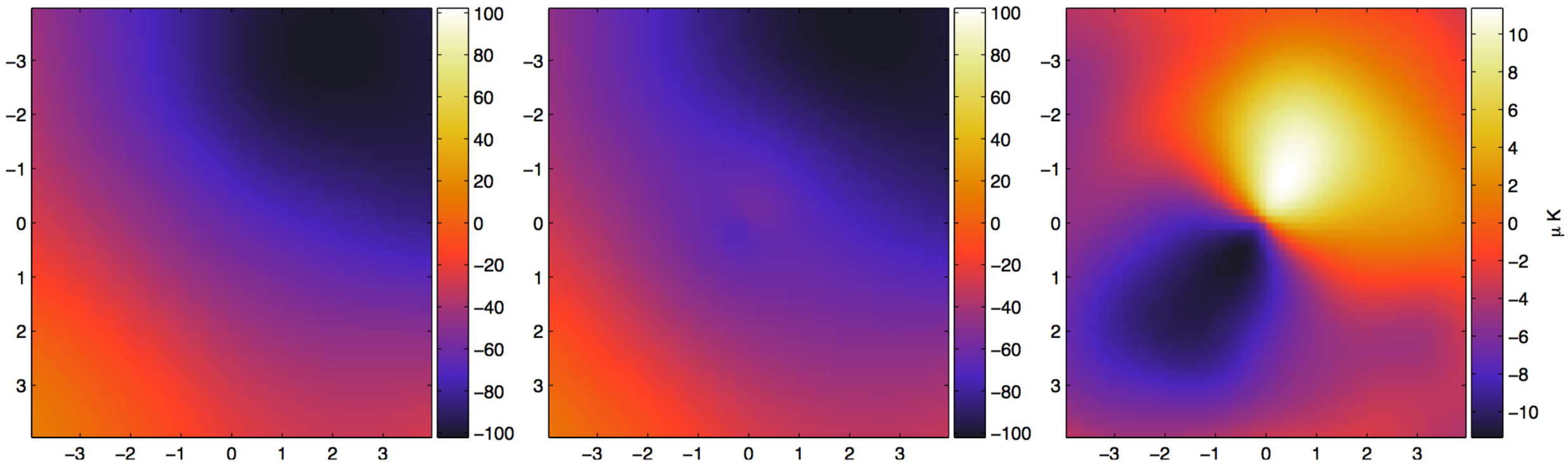
Lensed CMB



$M_{200} \sim 1e15\ M_\bullet$

Lewis & Challinor, 2006

CMB lensing will be a powerful tool for constraining the masses of high-z clusters.



Unlensed CMB

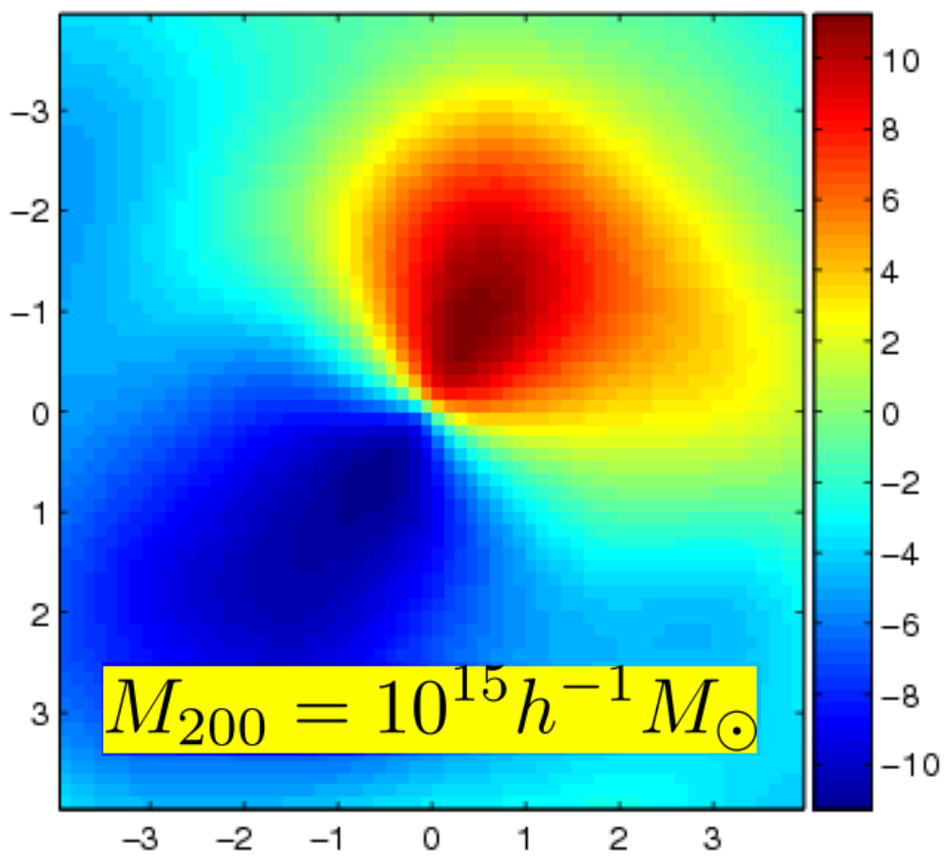
Lensed CMB

Difference

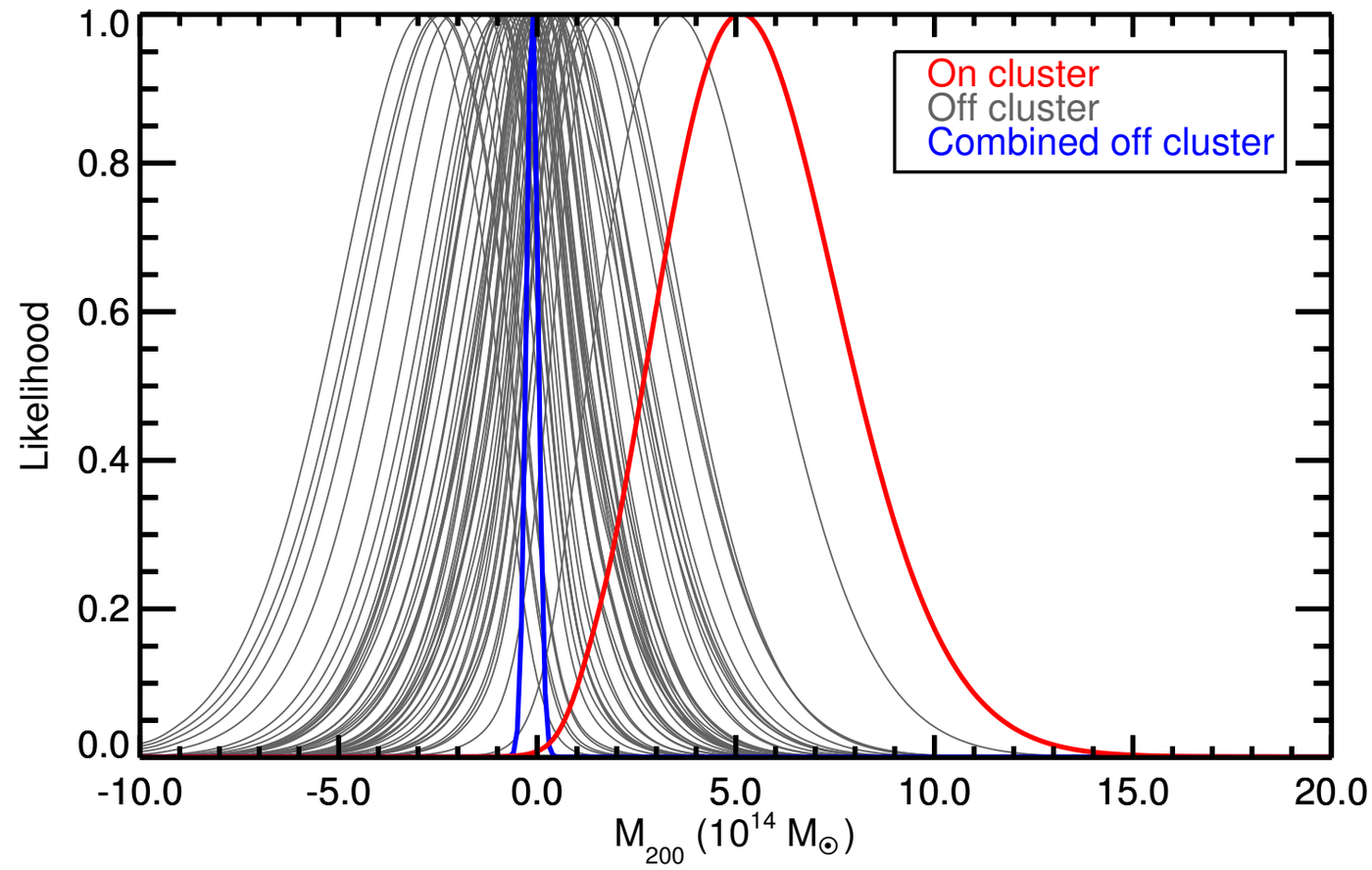
Lewis & Challinor, 2006

CMB Cluster Lensing with SPT-SZ

Lensed-Unlensed



A ~few $u\mathrm{K}$ "dimple" in the CMB caused by lensing of a ~10^{15} solar mass cluster



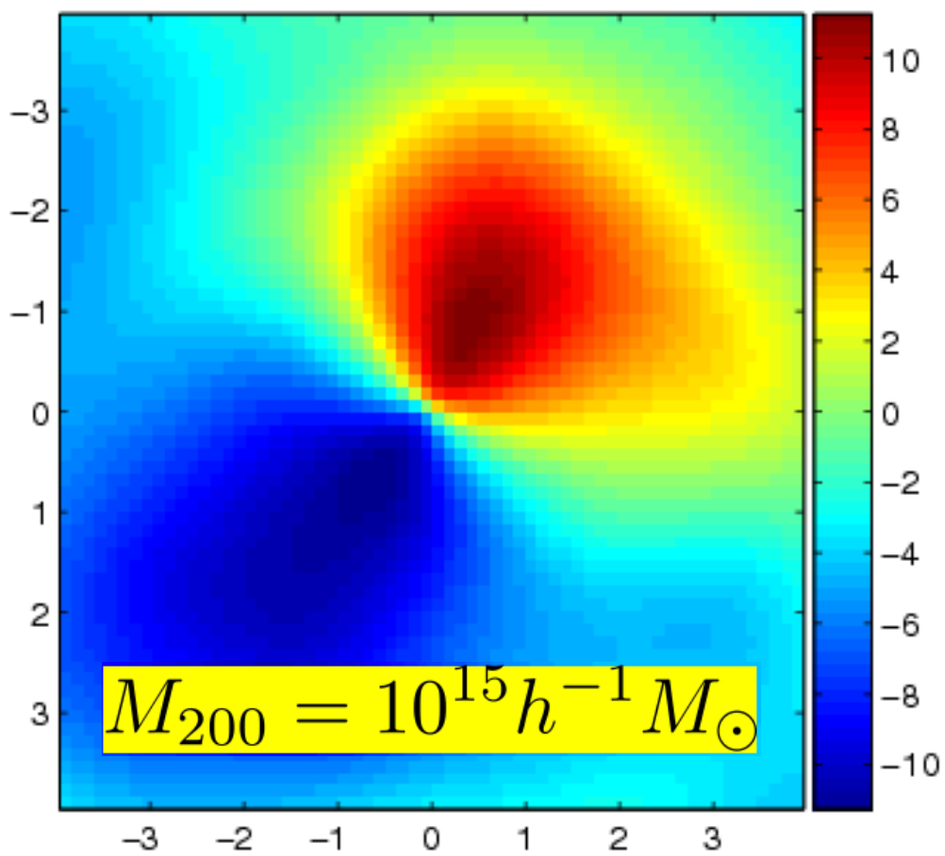
A 3.1-σ detection of CMB lensing using ~500 clusters measured by SPT-SZ

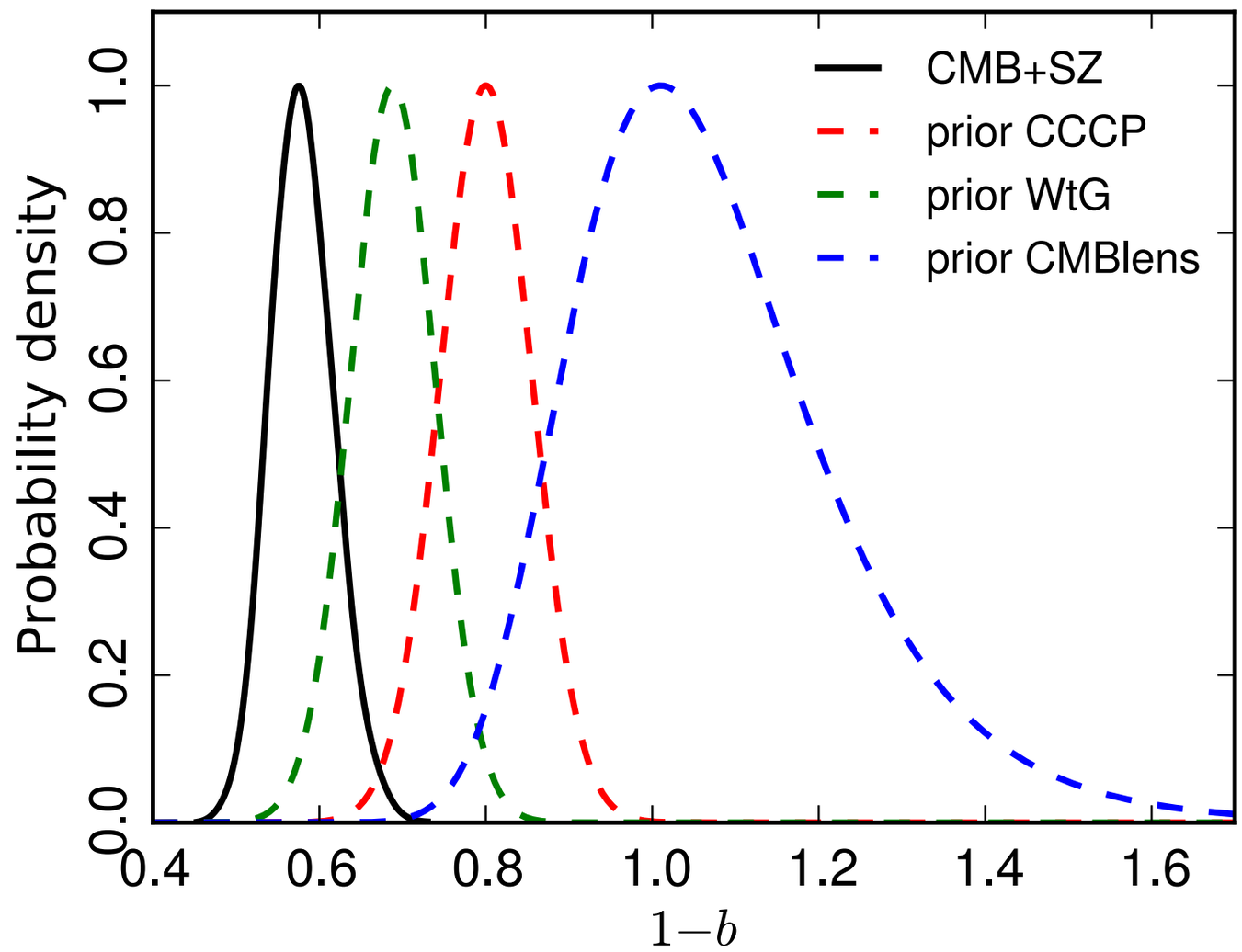
Baxter et al. 2015, ApJ, 806, 247

See also: Madhavacheril et al. PRL 114, 2015.

CMB Cluster Lensing with SPT-SZ

Lensed-Unlensed





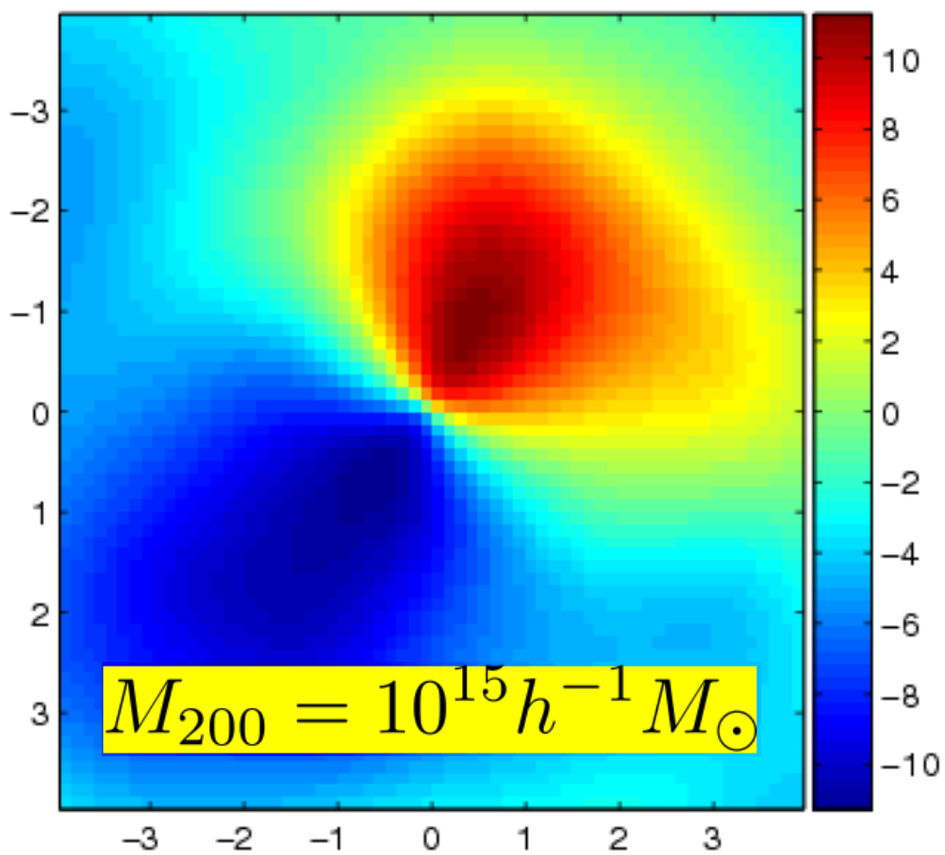
A ~few $u\mathrm{K}$ "dimple" in the CMB caused by lensing of a ~10^{15} solar mass cluster

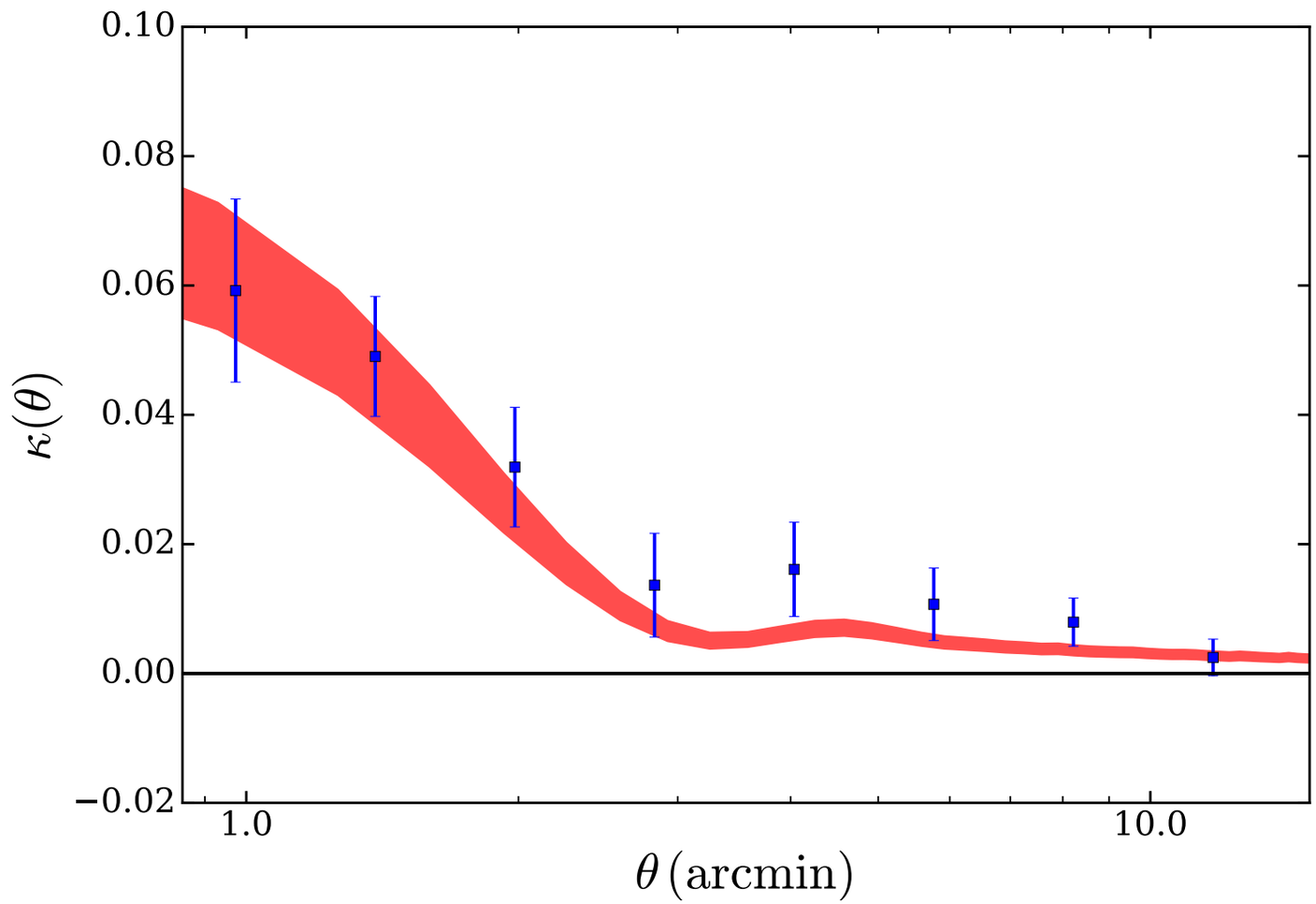
Planck Collab. XXIV, 2016 A&A 594, A24

See also: Madhavacheril et al. PRL 114, 2015.

CMB Cluster Lensing with SPT-SZ

Lensed-Unlensed





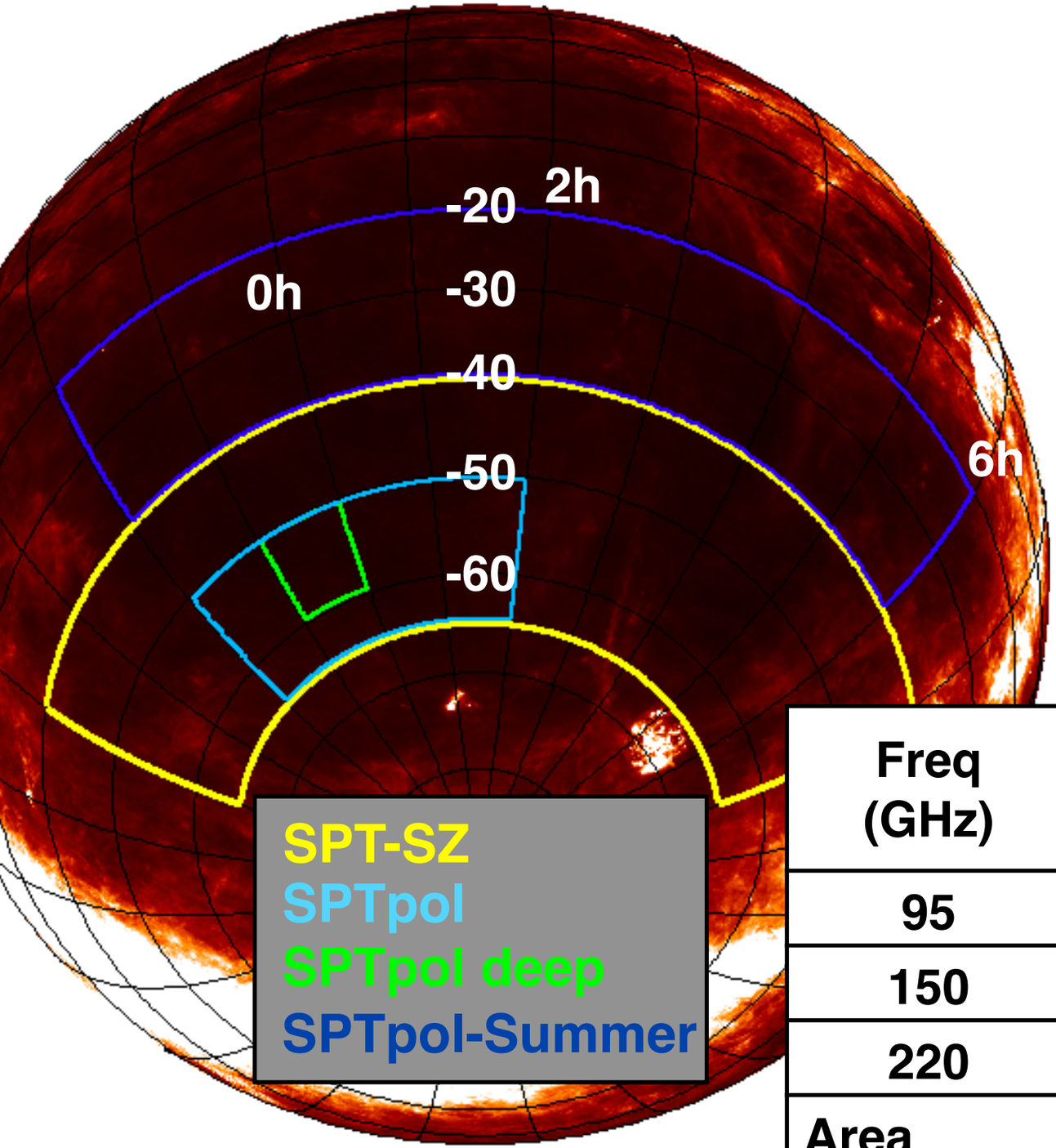
A ~few uK "dimple" in the CMB caused by lensing of a ~10^{15} solar mass cluster

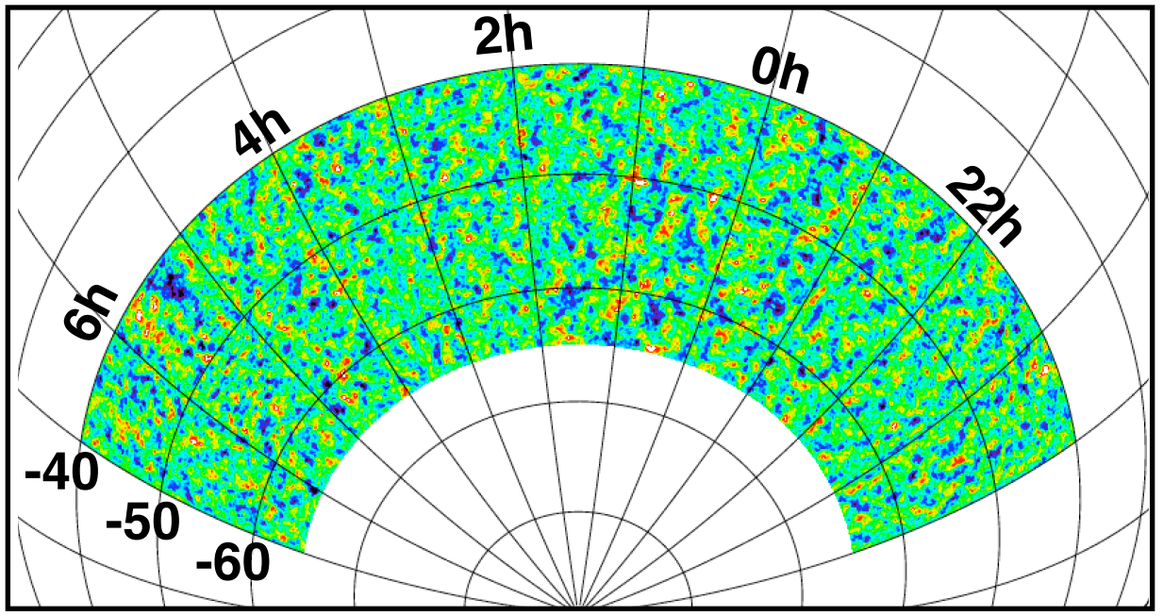
Baxter+ 2017

6.5σ detection CMB Cluster Lensing

3697 optically-selected clusters at $\langle z_{med} \rangle = 0.47$

The SPT Surveys



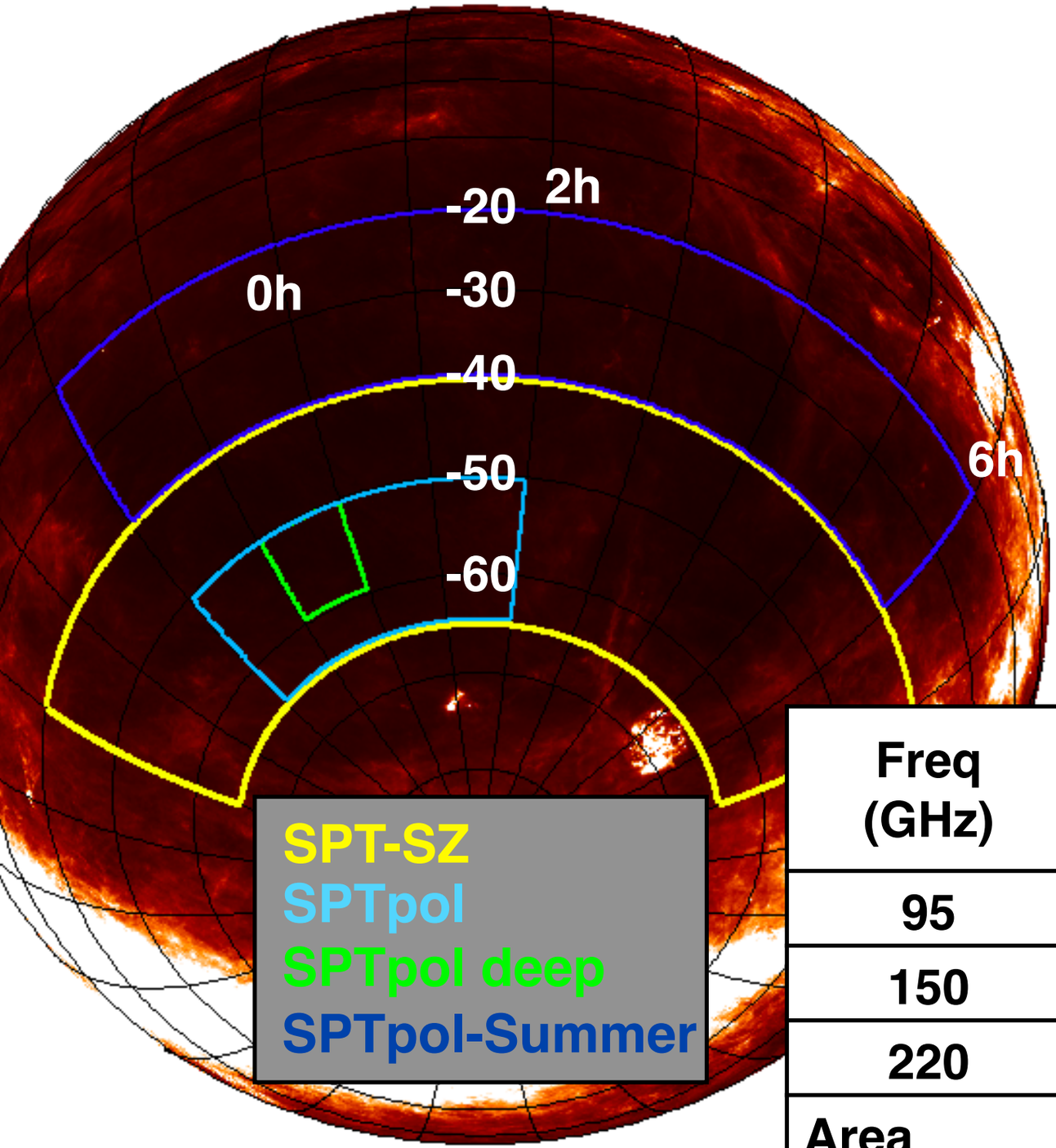


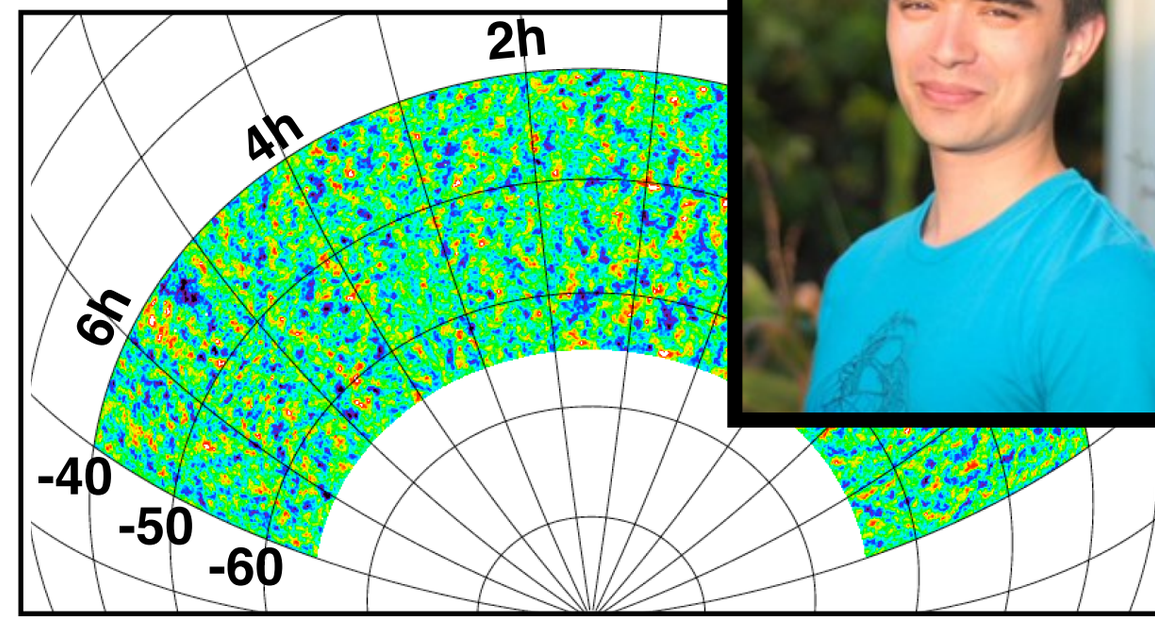
Freq (GHz)	SPT-SZ	SPTpol deep	SPTpol	SPTpol Summer
95	40	10	13	50
150	17	5/3.5	5	30
220	80	40	40/80	-
Area	2500	100	500	2500
Status	*Complete*	*Complete*	*Complete*	*Complete*

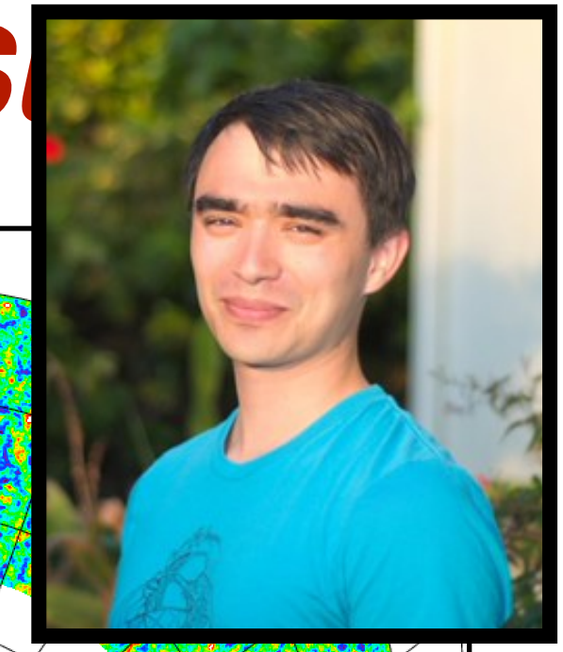
5000 deg^2 surveyed in total by SPT-SZ and SPTpol

- 150 GHz depths between 4-30 uK-arcmin (from ~Planck depth, to ~7 times deeper)

The SPT Su







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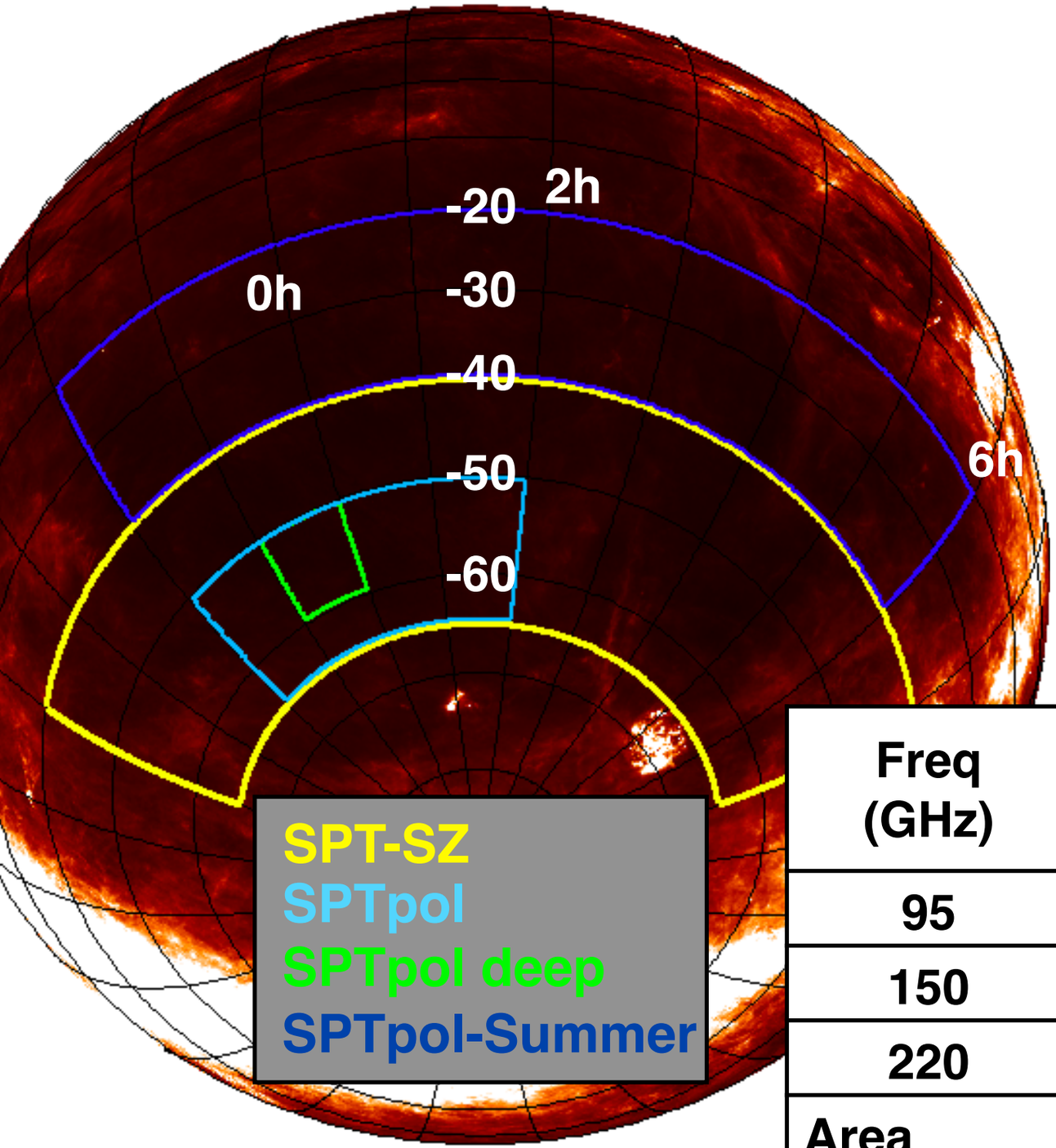

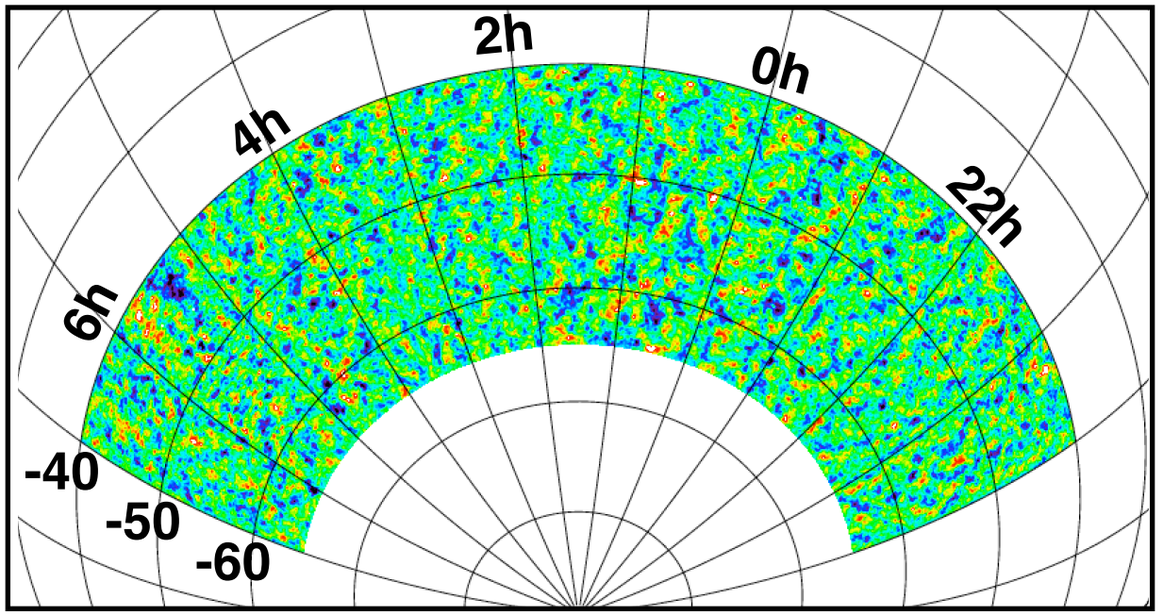

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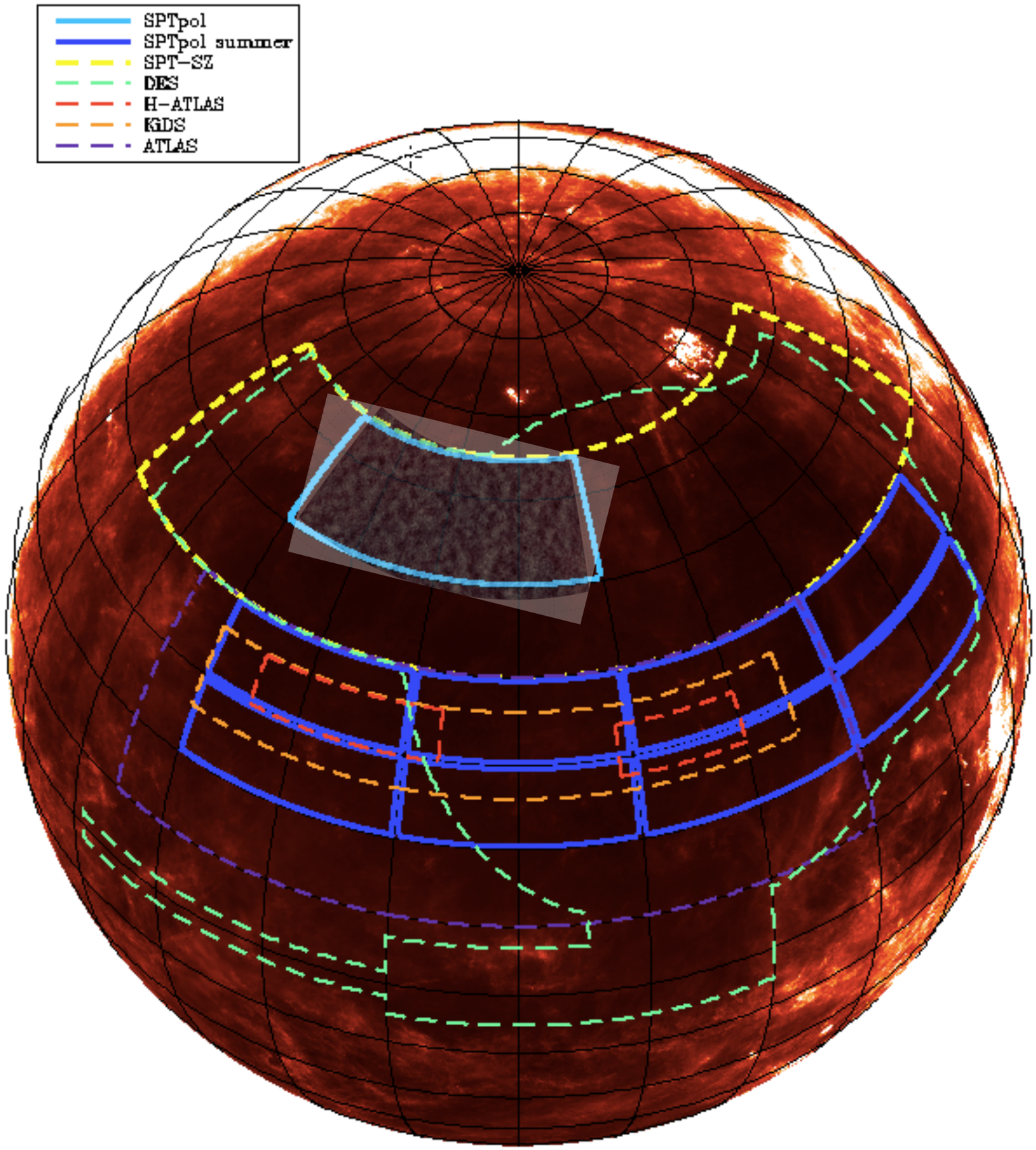
5000 deg^2 surveyed in total by SPT-SZ and SPTpol

- 150 GHz depths between 4-30 uK-arcmin (from ~Planck depth, to ~7 times deeper)

Dark Energy Survey (DES) and SPT



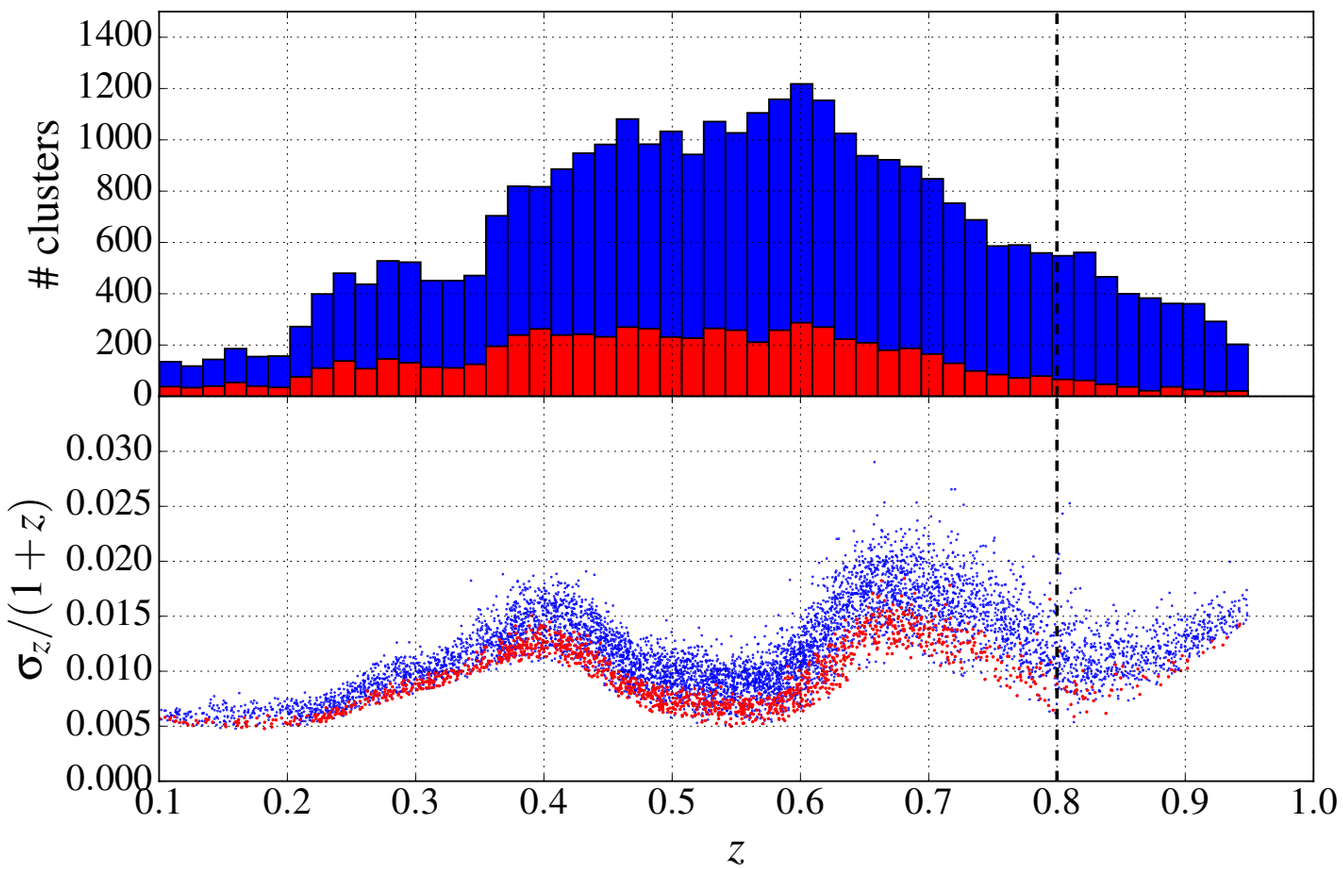
- **Ongoing Optical Survey to cover ~5000 deg² which will detect ~100,000 clusters out to *z*=1**

- Multiple probes of dark energy (cluster survey, weak lensing, BAO, SNe)

- **Coordinated** to overlap with SPT

500d Catalog Construction well underway!

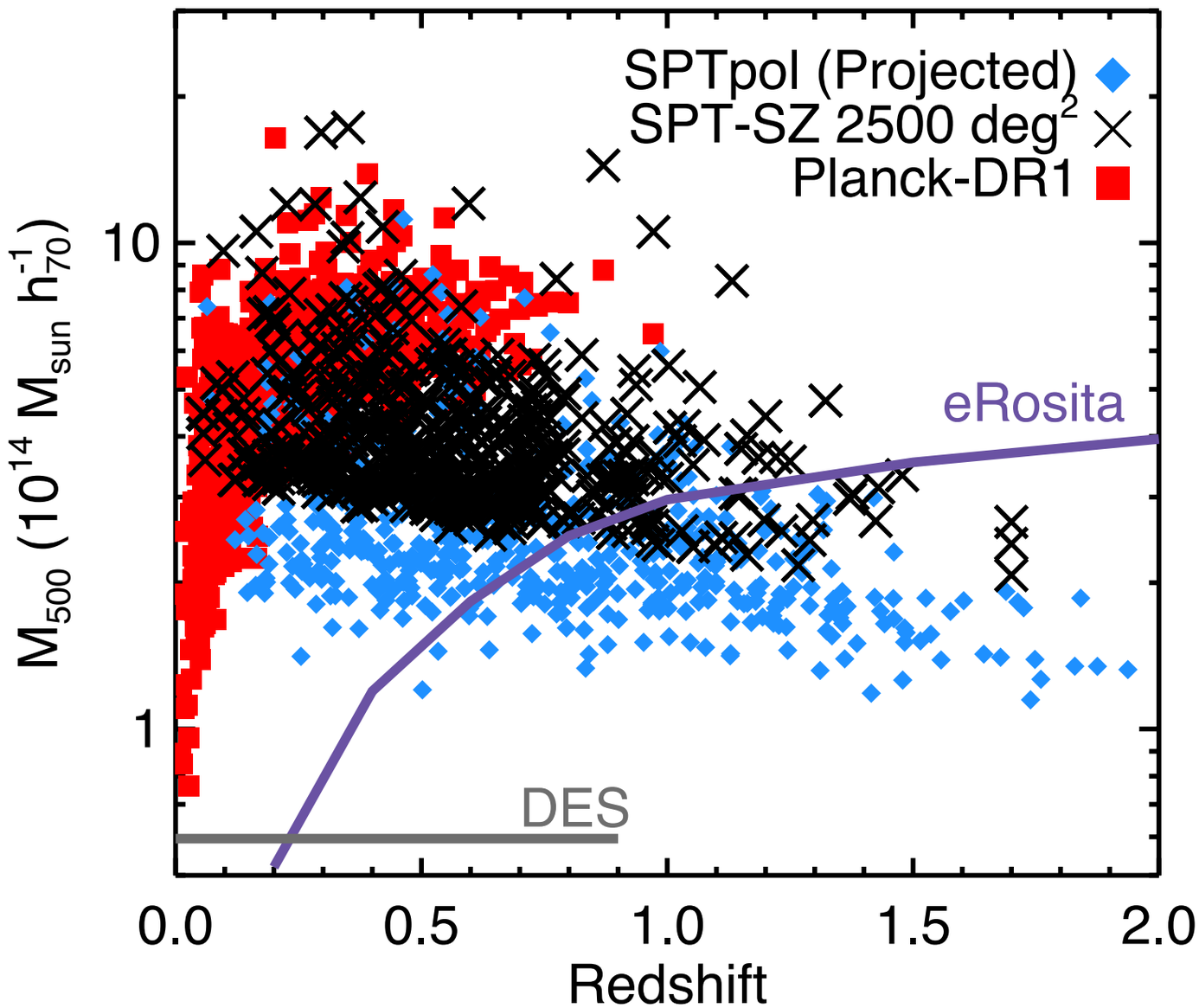
- Incorporating **all** SPTpol 500d data; Final 150 GHz map depth ~5 uK-arcmin
- >500 cluster candidates at >4 sigma (~80% purity)
- Ongoing DES-SPT projection for cluster confirmation



(Soergel+2016;MNRAS.461.3172S)

500d Catalog Construction well underway!

- Incorporating **all** SPTpol 500d data; Final 150 GHz map depth ~5 uK-arcmin
- Ongoing DES-SPT projection for cluster confirmation
- 2 Spitzer programs complete
- Approved NIR imaging on Magellan/FOURSTAR to finish imaging of high-z candidates



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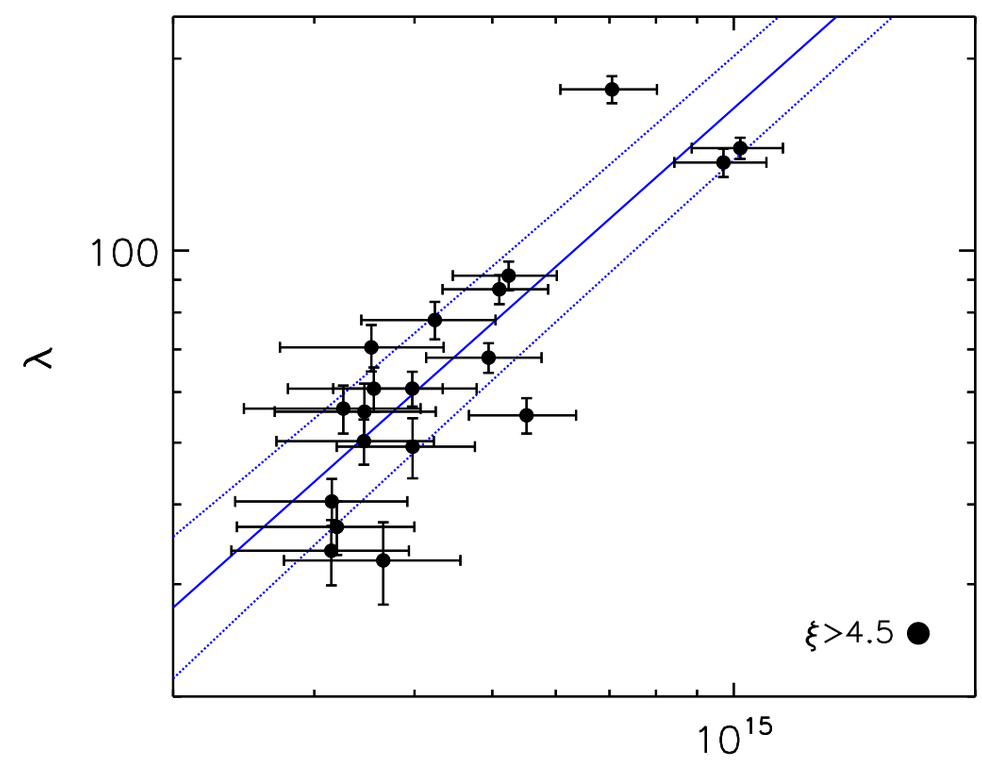
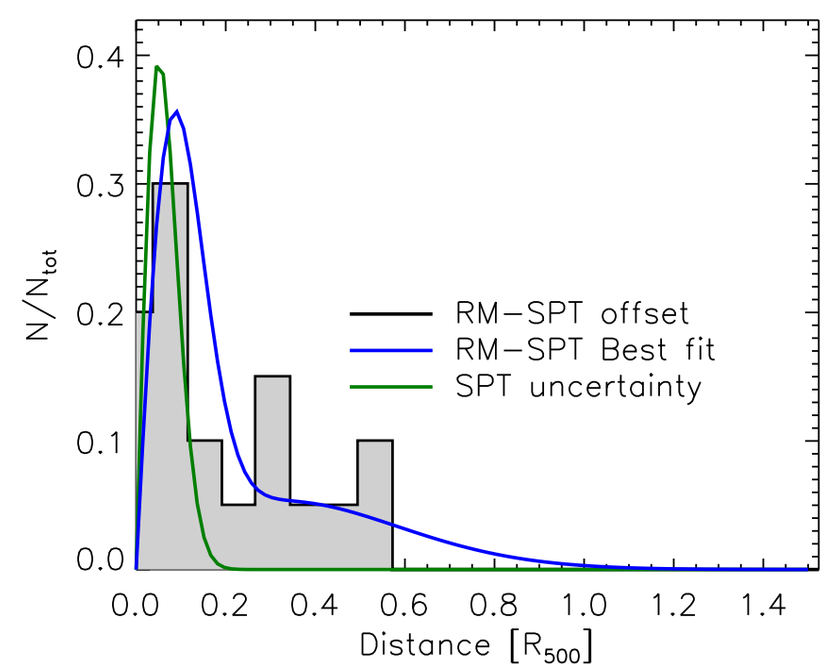
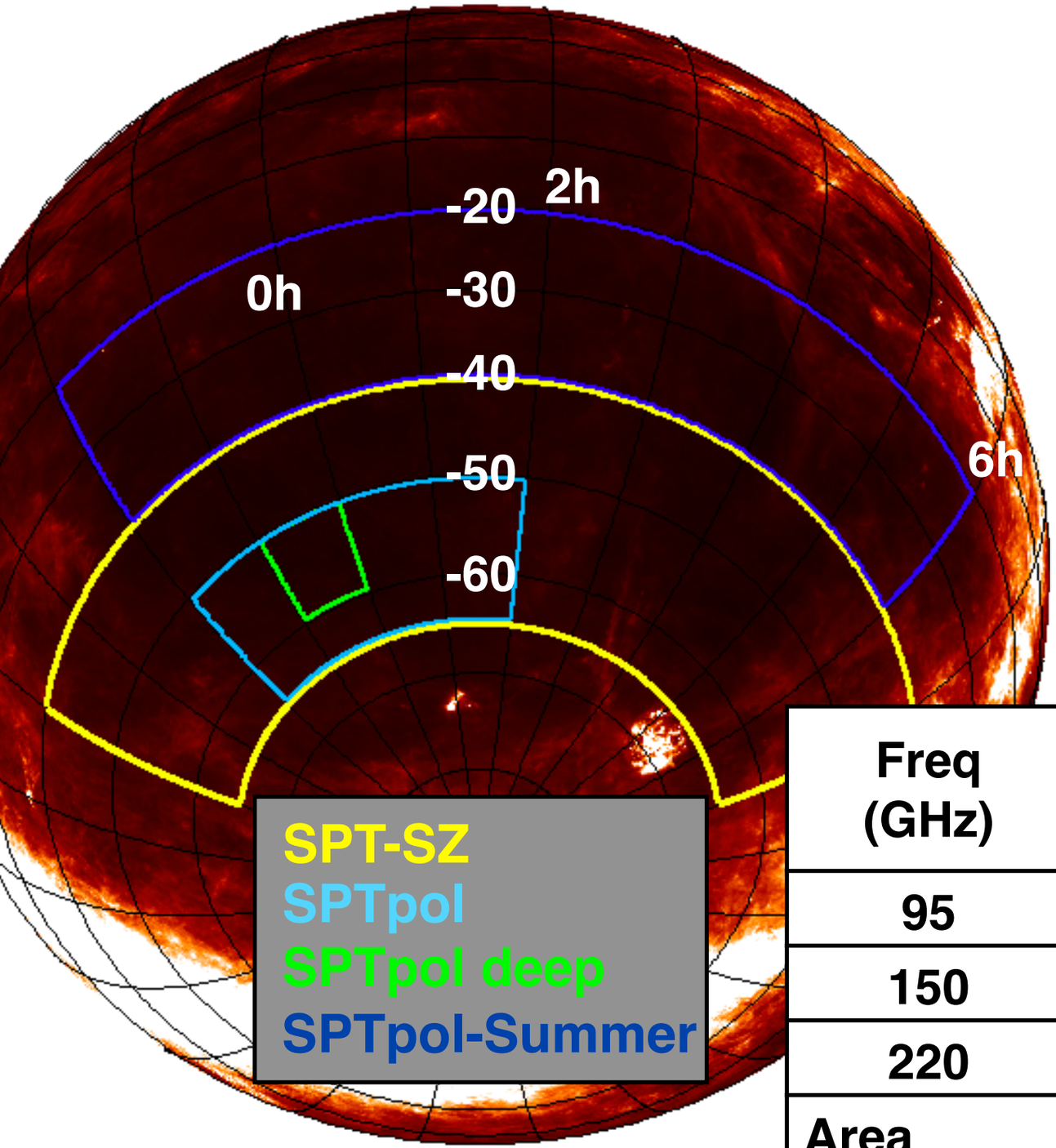
SPT-SZ + DES SV:

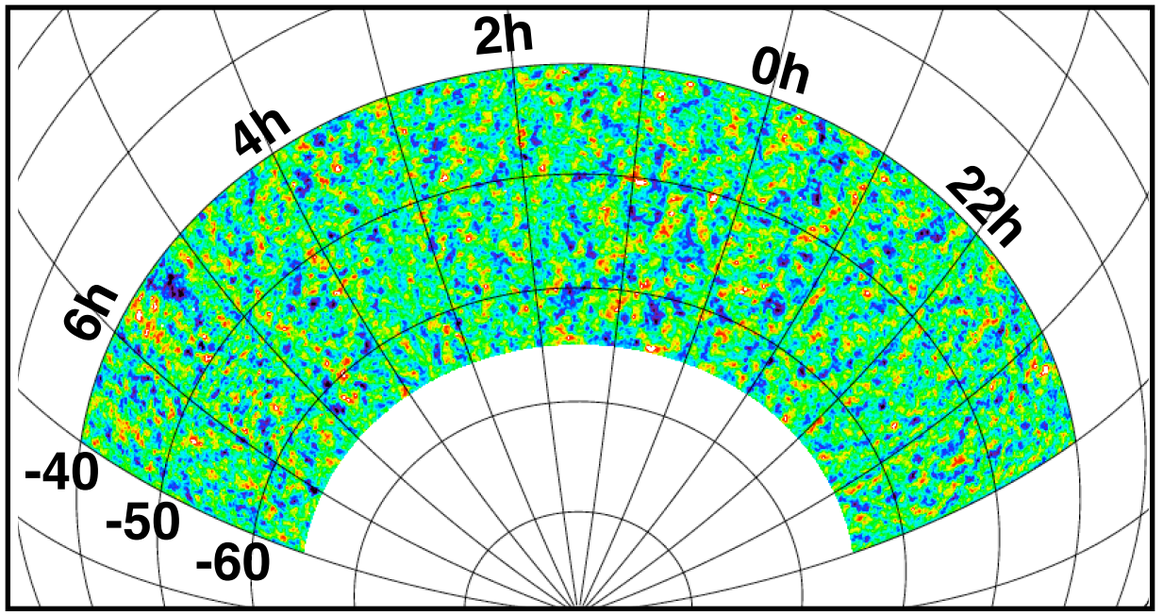




Saro+ MNRAS, 454, 3 2015

The SPT Surveys





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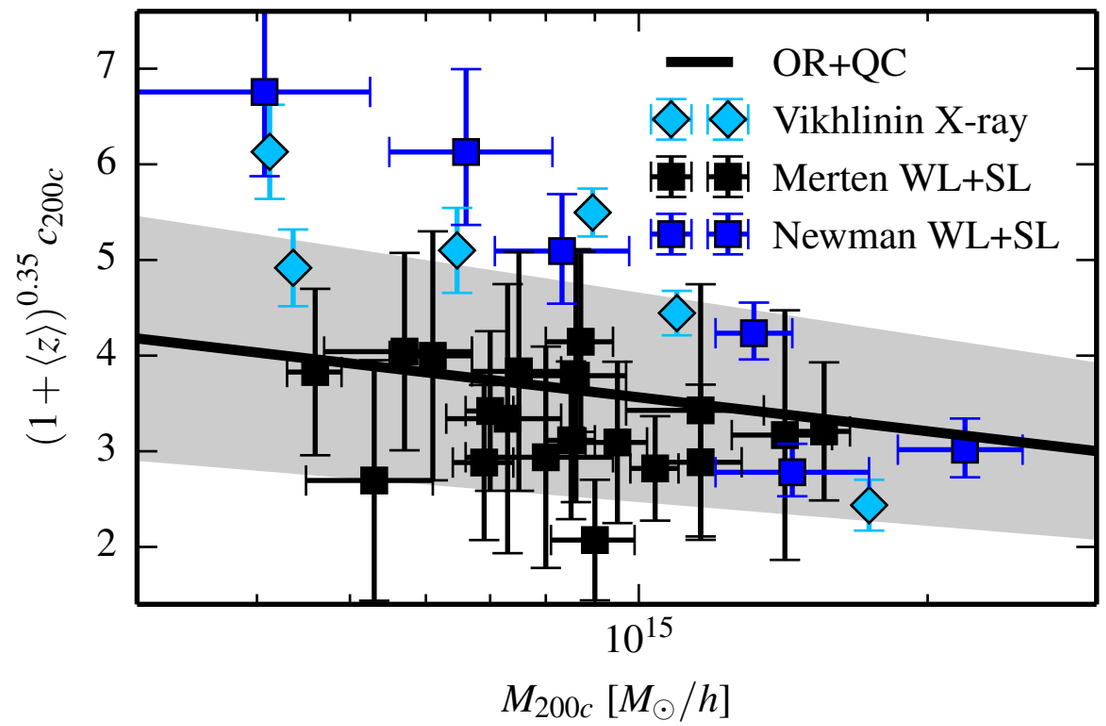
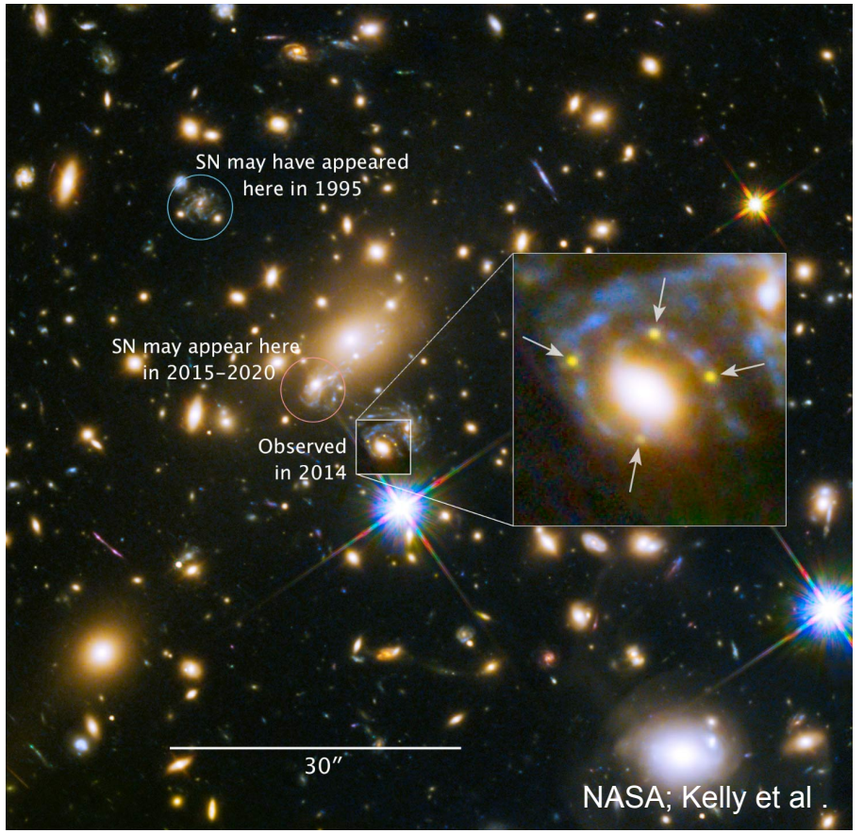
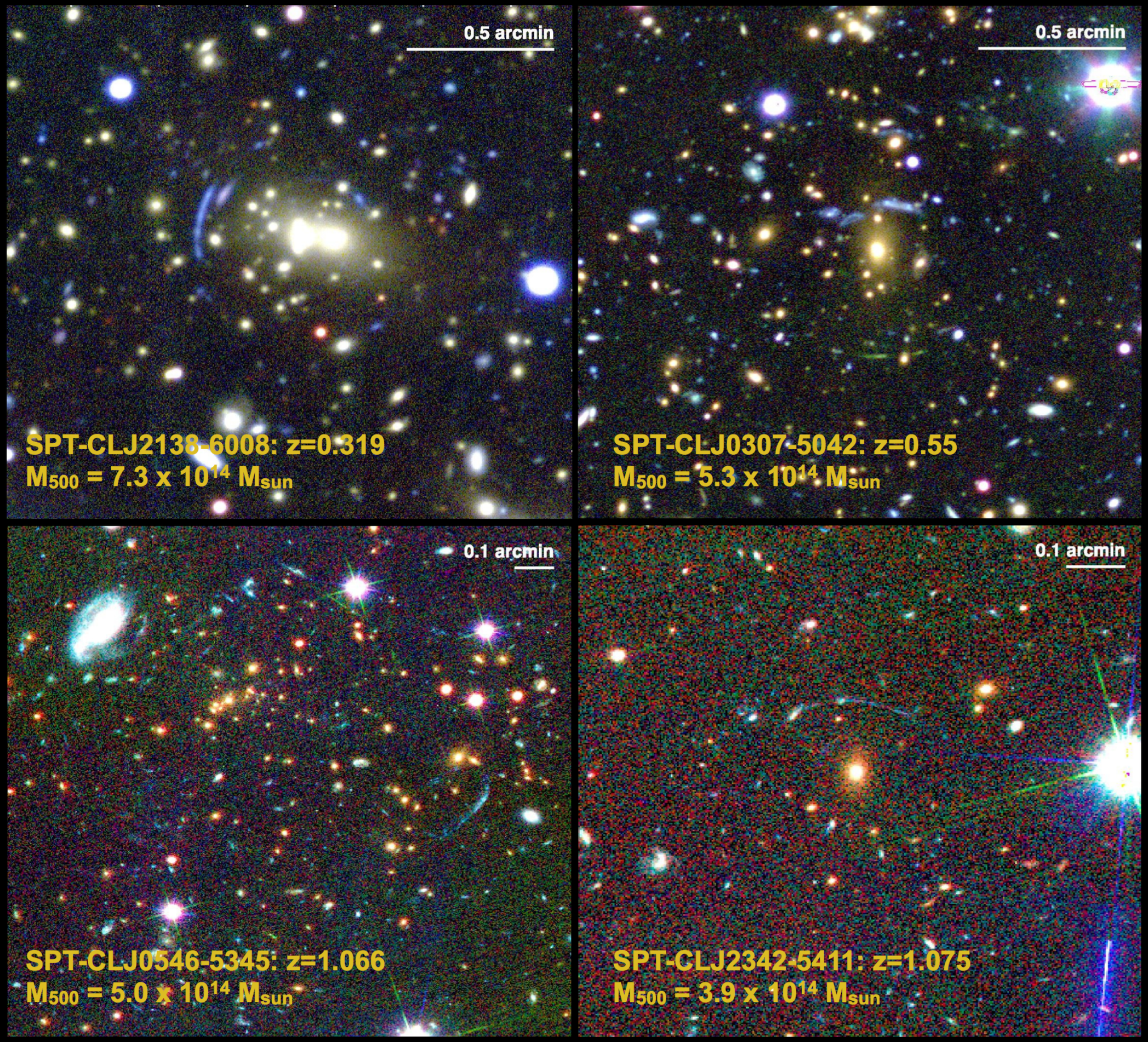
Strong Lensing Science

- **Direct test of structure formation:** Large N-body simulations provide predictions for the properties of Dark Matter haloes that are directly testable by using Strong Lensing as a probe the cores of massive systems
- **Improved Dark Energy Constraints from Cluster Surveys:** Joint Strong + Weak Lensing provides the best constraints on cluster masses
- **Cosmic Telescopes** - Strong lensing is a powerful tool with which to study the distant Universe
  - *Earliest galaxies (reionization!)*
  - *Expansion Rate of the Universe (e.g., SN Refsdal)*
  - *Dark Matter Substructure (SPT + ALMA)*



H. Child+ (submitted)



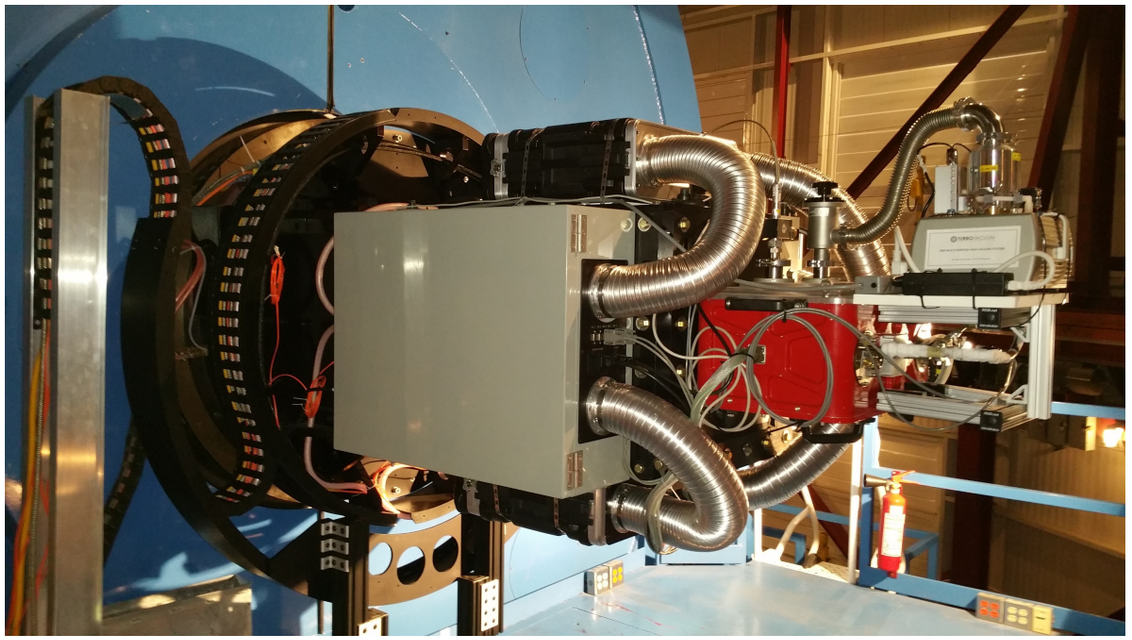

0.5 arcmin
SPT-CLJ2138-6008: z=0.319
M500 = 7.3 x 10^14 Msun
0.5 arcmin
SPT-CLJ0307-5042: z=0.55
M500 = 5.3 x 10^14 Msun
0.1 arcmin
SPT-CLJ0546-5345: z=1.066
M500 = 5.0 x 10^14 Msun
0.1 arcmin
SPT-CLJ2342-5411: z=1.075
M500 = 3.9 x 10^14 Msun

The SPT Strong Lensing Sample

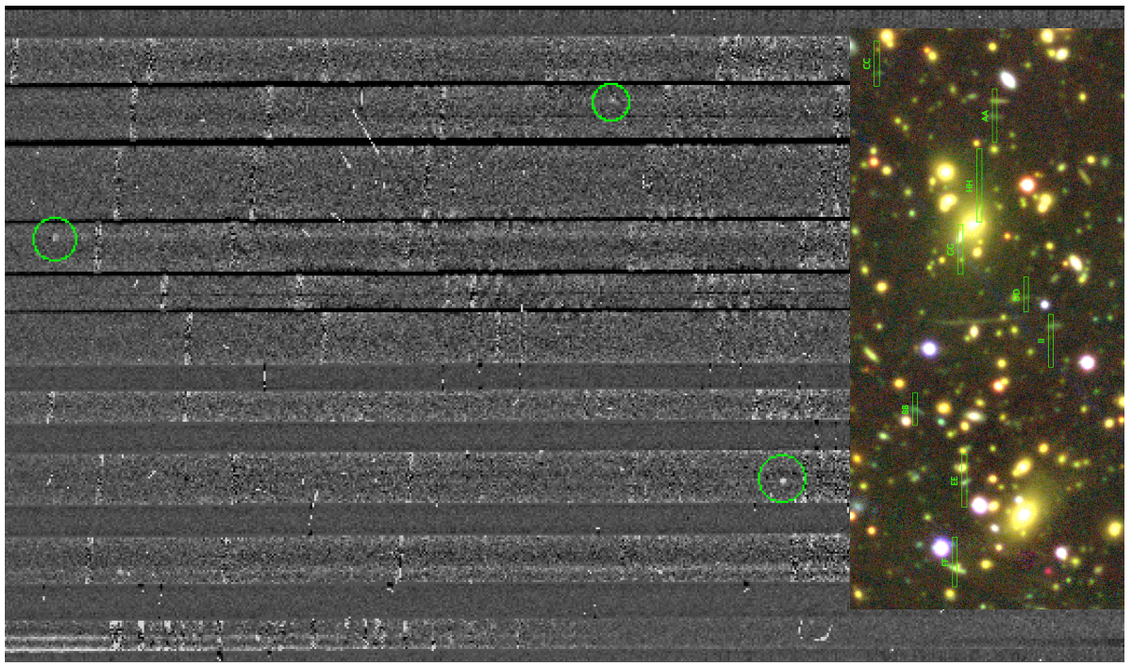
- **Uniform** coverage of this **uniformly-**selected sample

- Imaging Program with PISCO
  - simultaneous ***griz'*** imager installed on Magellan/Clay
  - Adaptive exposures strategy compensating for airmass, seeing, lunar brightness
  - Fast cadence; broad RA range of SPT enables optimization of target ordering
    - 120 clusters in a good night!

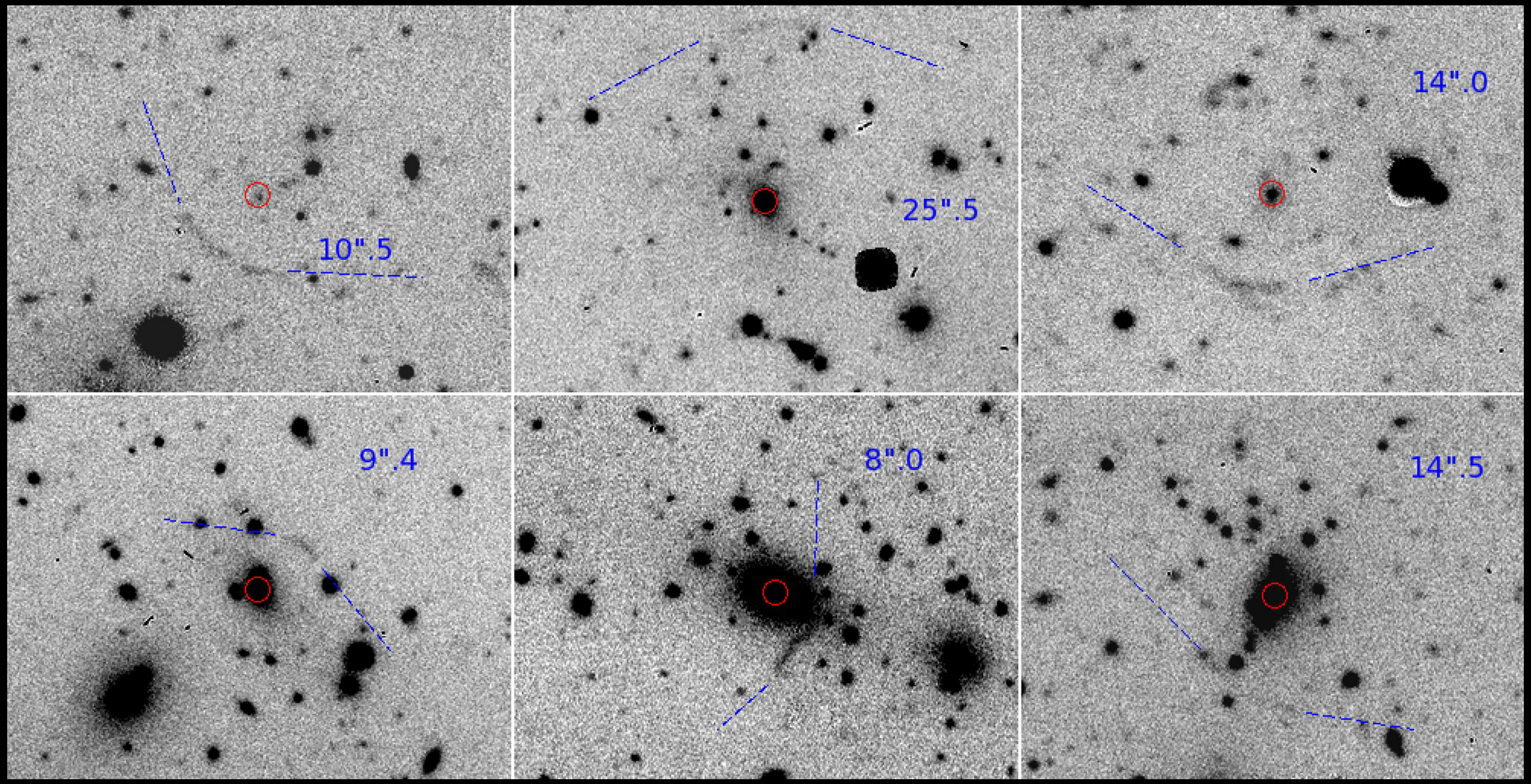
- Spectroscopic Campaign targeting lensed galaxies (K. Sharon)



PISCO imager
Stalder et al. SPIE 91473Y (2014)



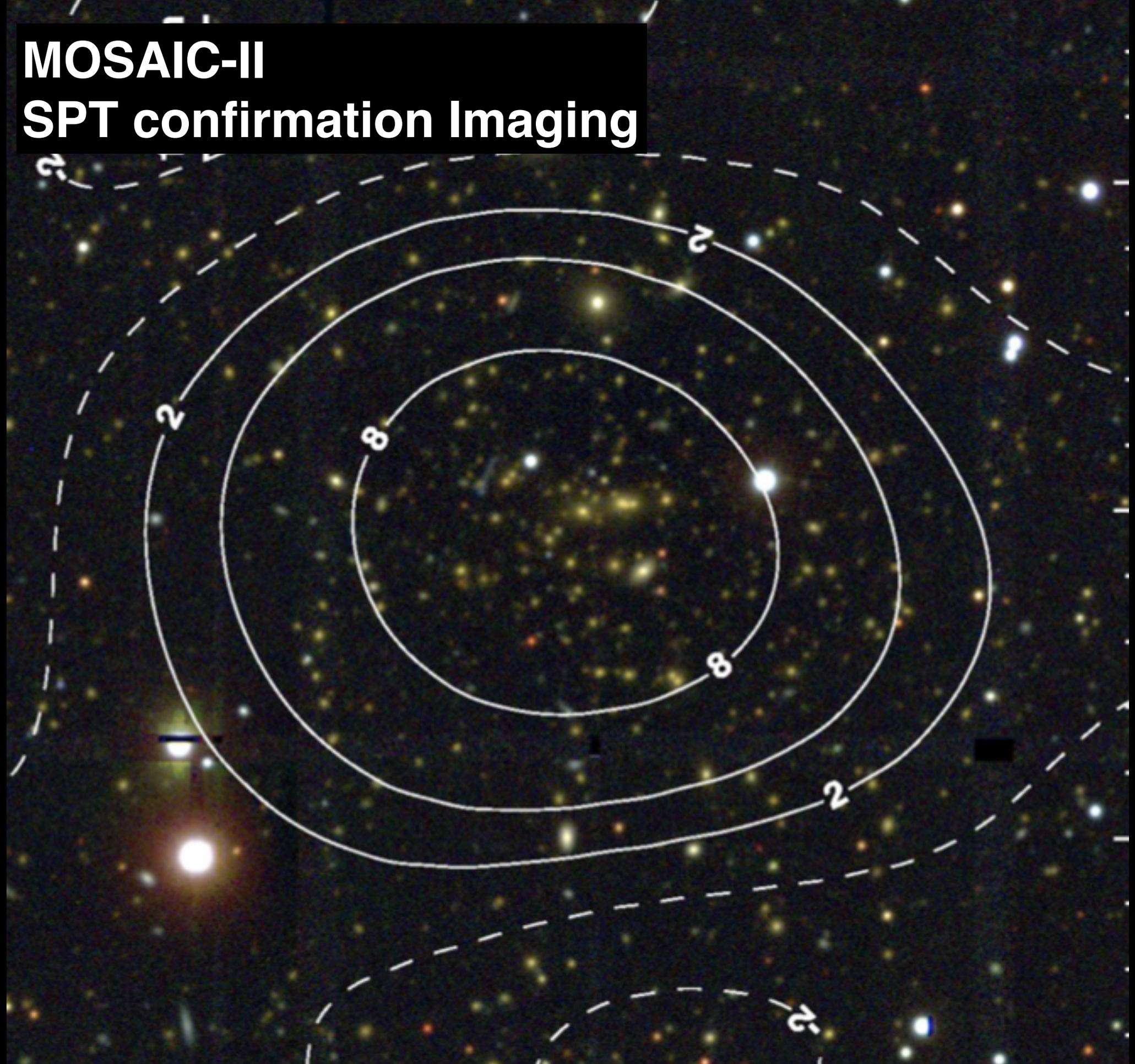
Emission line search IMACs



>400 clusters observed with Magellan/PISCO with <0.9” seeing + 130 with HST or Magellan/Megacam

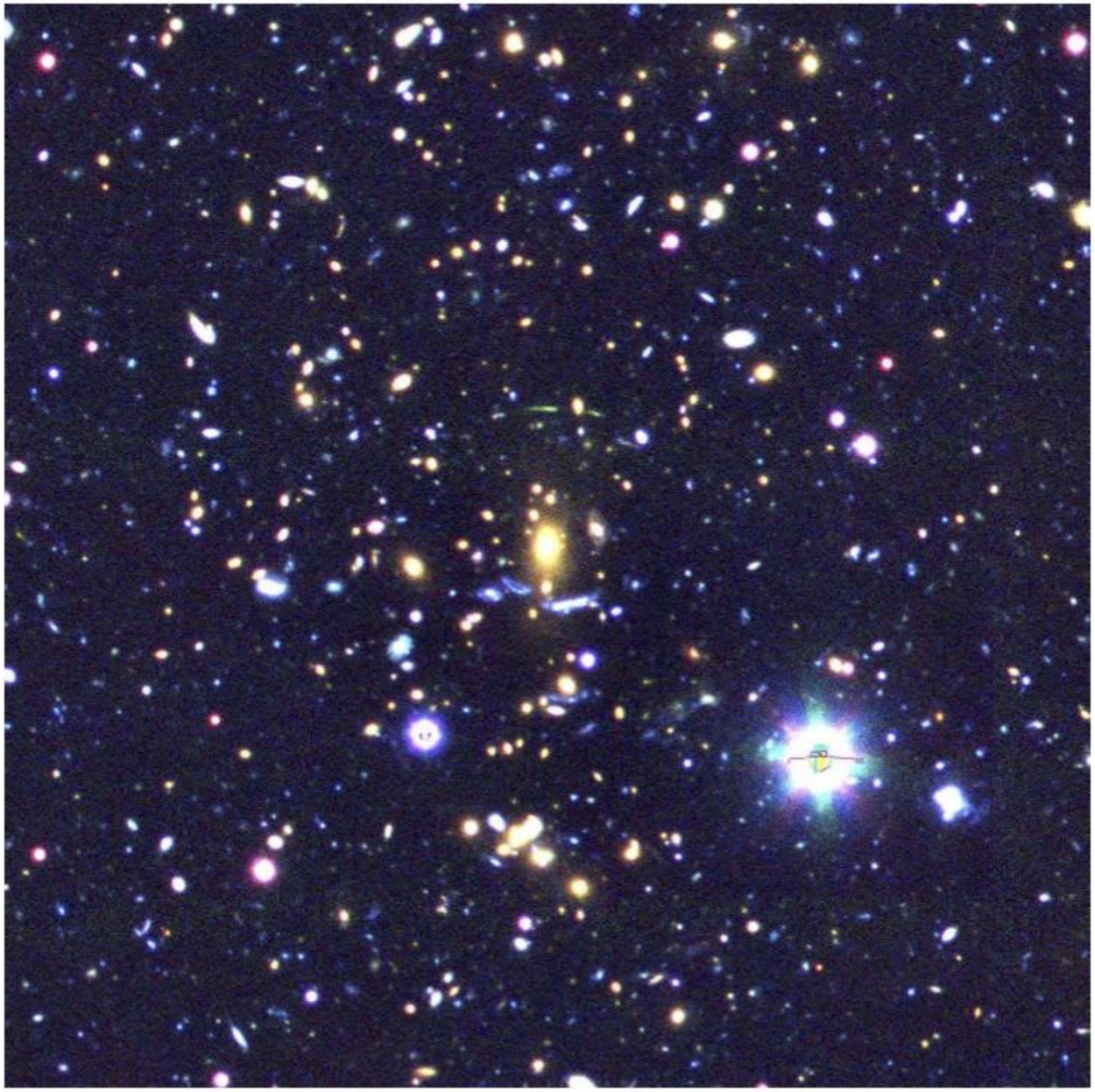
Bleem+ (in prep)

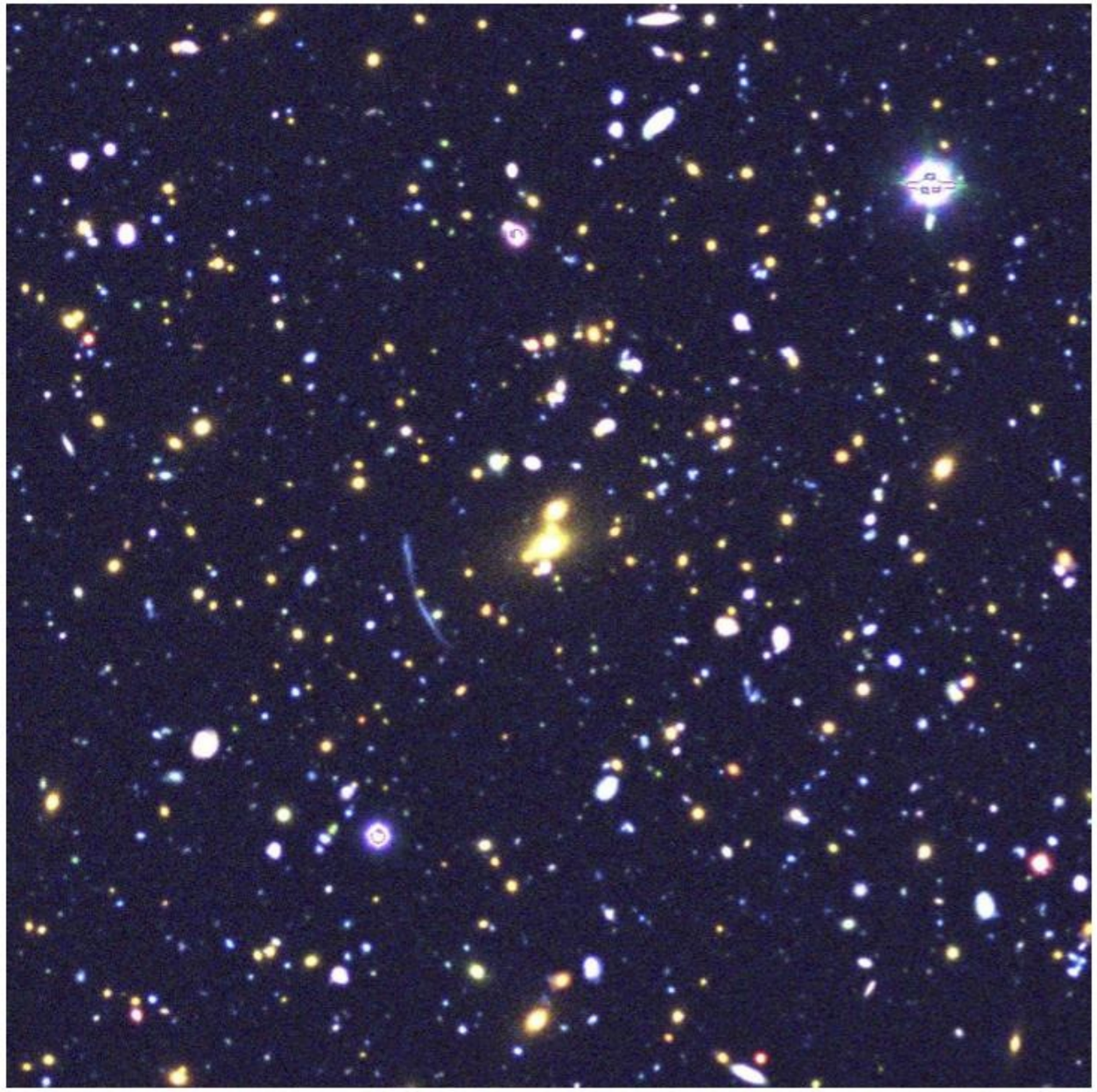
MOSAIC-II
SPT confirmation Imaging



PISCO - 300 s

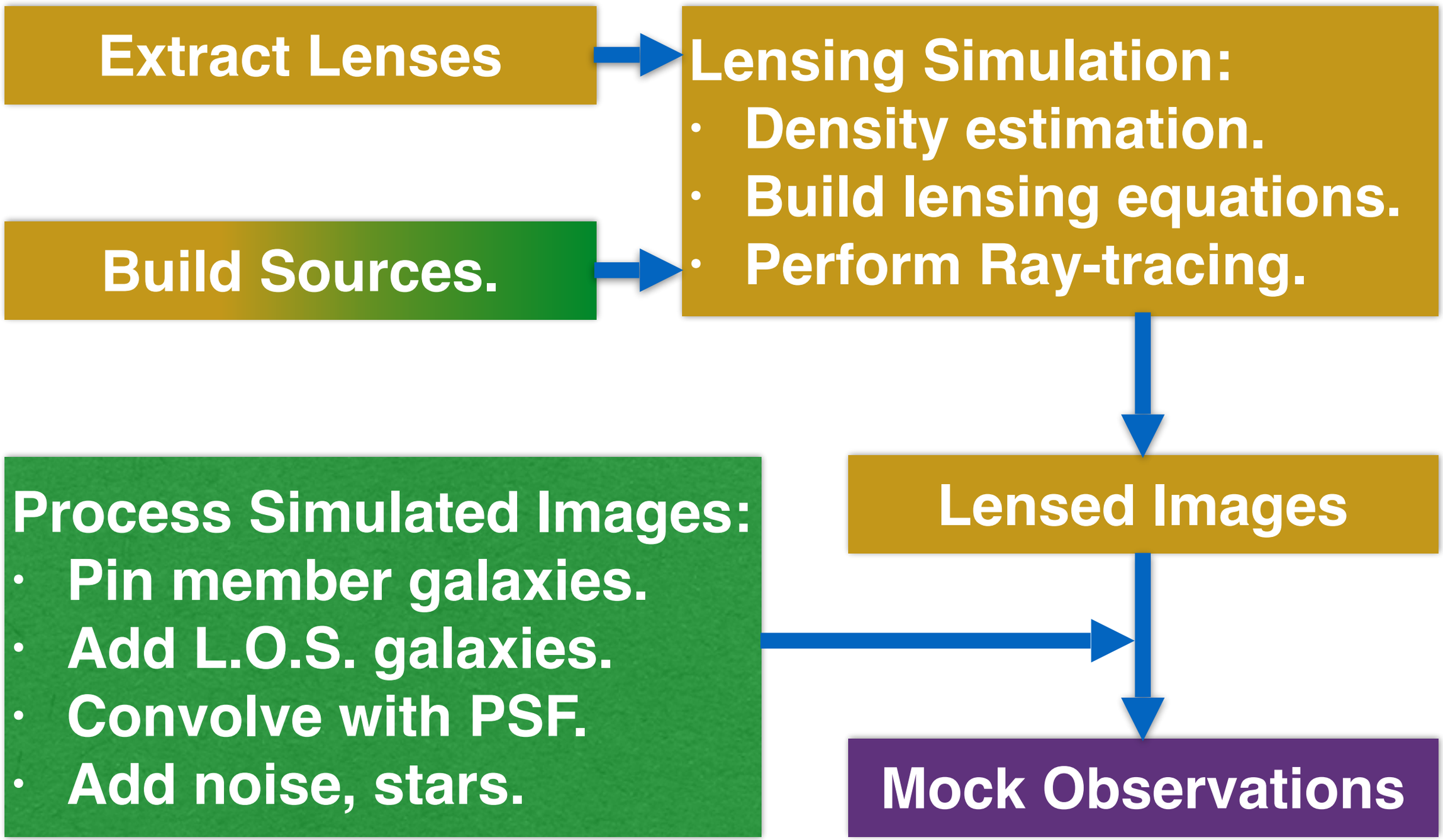
Contrasting Simulations with Observations: Cluster-scale Strong Lensing



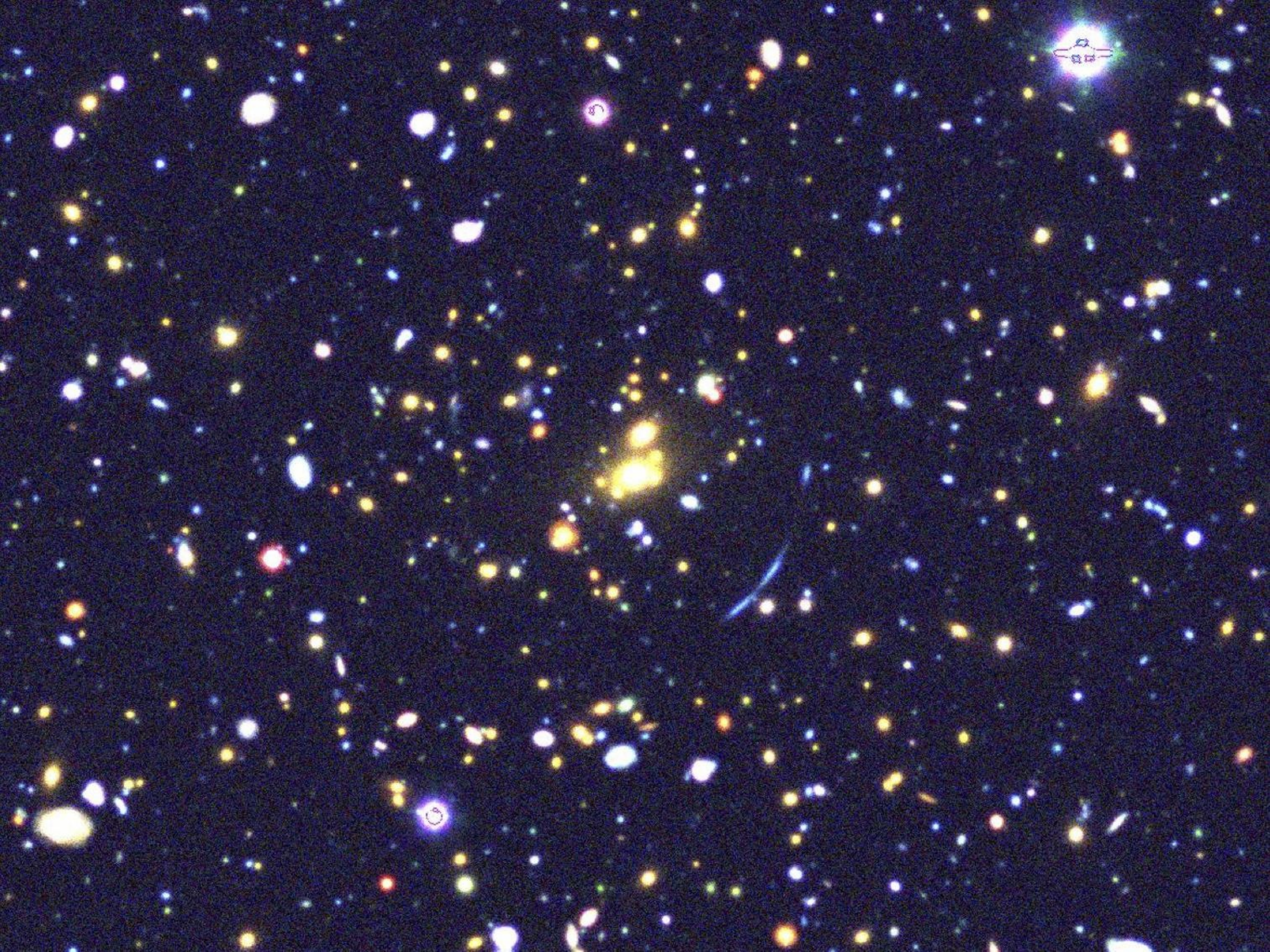


Nan Li et al. (with LB)
ApJ 828,1, 54 (2016)

Strong Lensing Pipeline



Nan Li et al.
ApJ 828,1, 54 (2016)



The SPT Strong Lensing Sample:

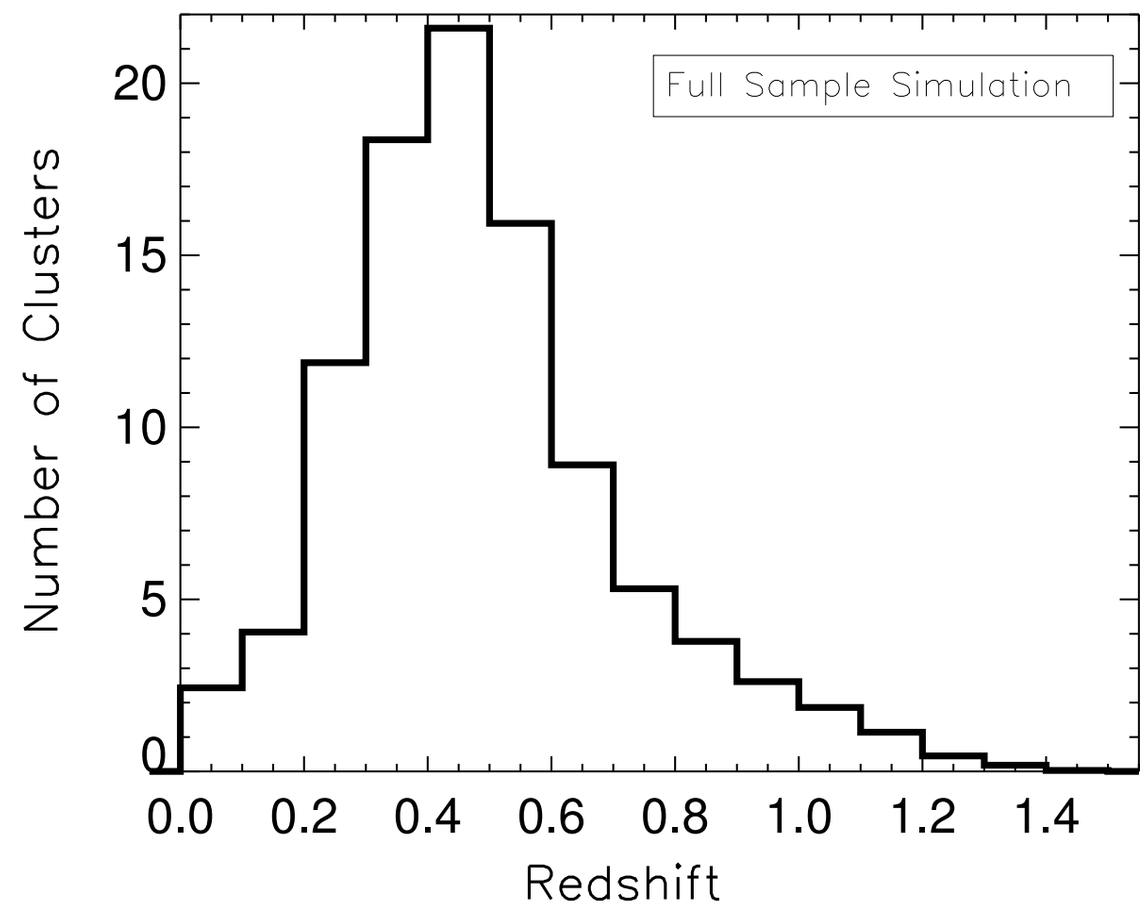
- On-going simulation efforts to interpret observations:
  - "Outer Rim" simulation (HACC code; Habib+16, NewAst,42,49H)
  - 1.1 trillion particles with mass $2.6 \times 10^9\ M_\odot$
  - (4.225 Gpc)^3 Volume

- Expect >100 strong lenses to be detected in SPT cosmology sample with reasonable (<0.75") ground-based imaging.

- Will be possible to measure the mean mass-concentration relation of massive halos to ~5%, and constrain its scatter to ~10% precision ***(statistical)***.

- Large Volume Hydrodynamic simulations coming (2017/2018!)

Preliminary Predicted Lens Redshift Distribution

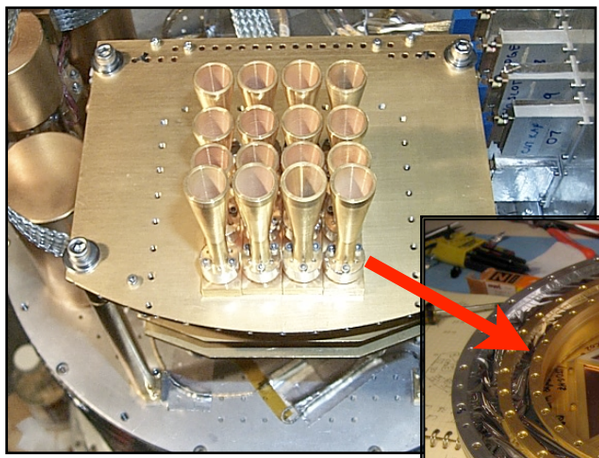


Li+ (in prep)

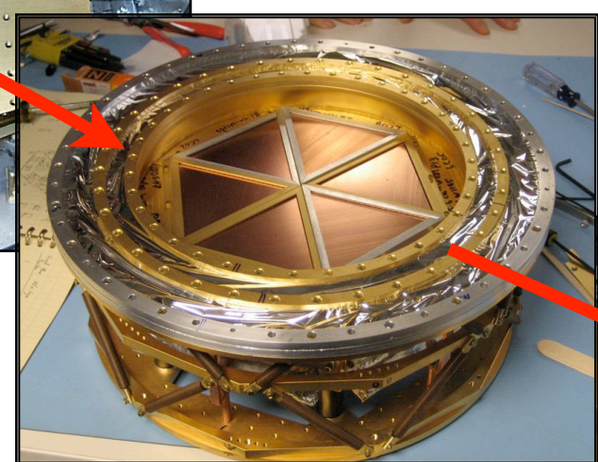
Whats next? Evolution of CMB Focal Planes

CMB Stage-4 Experiment
https://arxiv.org/abs/1610.02743

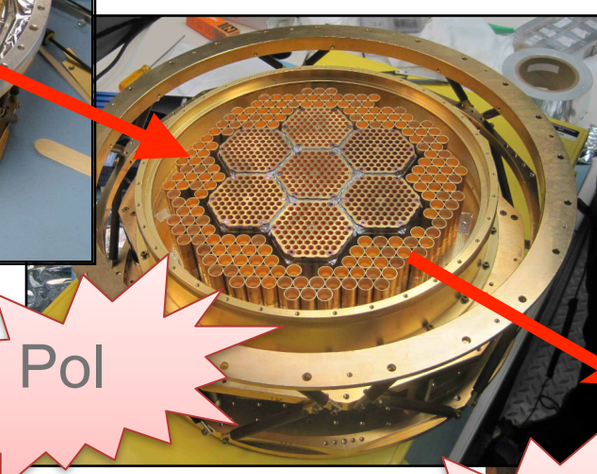
2001: ACBAR
16 detectors



2007: SPT
960 detectors

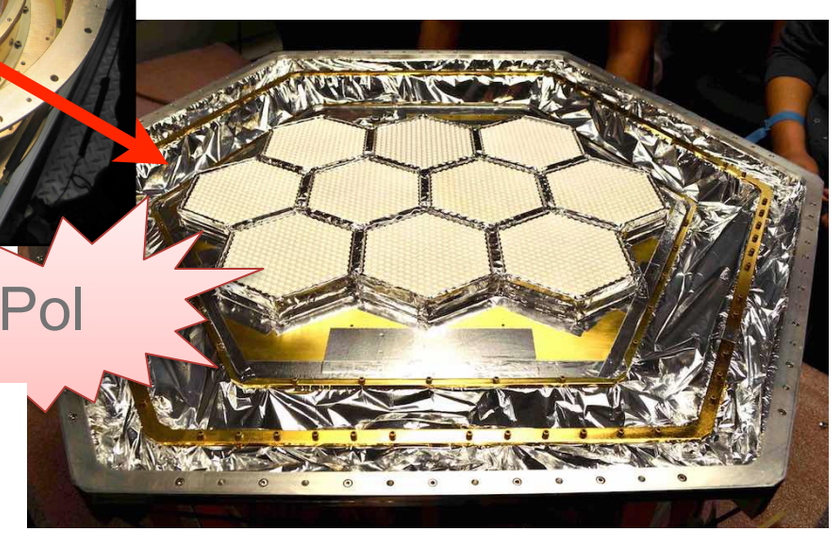


Stage-2
2012: SPTpol
~1600 detectors



Pol

Stage-3
2016: SPT-3G
~15,200 detectors

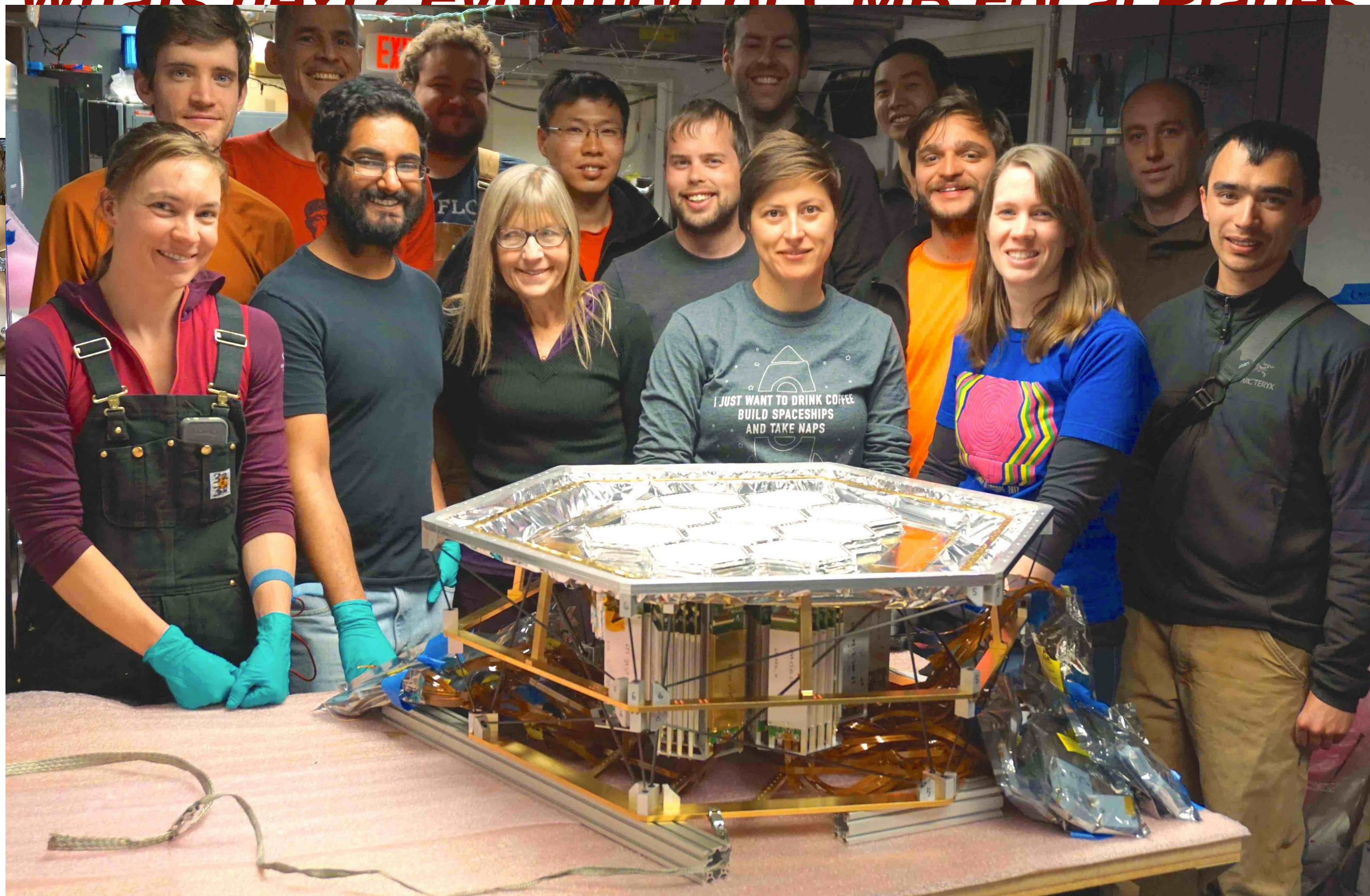


Pol

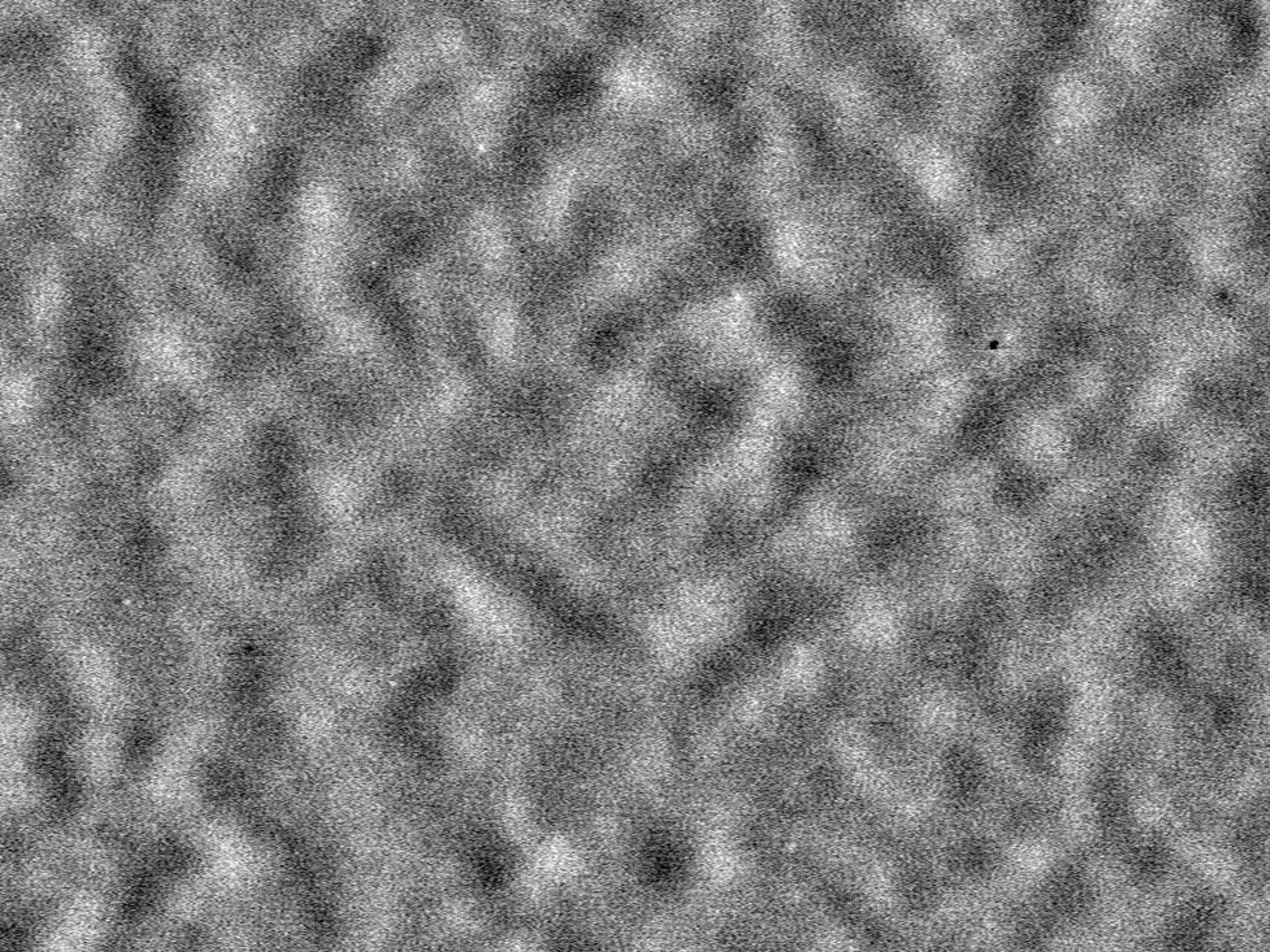
Detector sensitivity has been limited by photon "shot" noise for last ~15 years; further improvements are made only by making ***more detectors!***

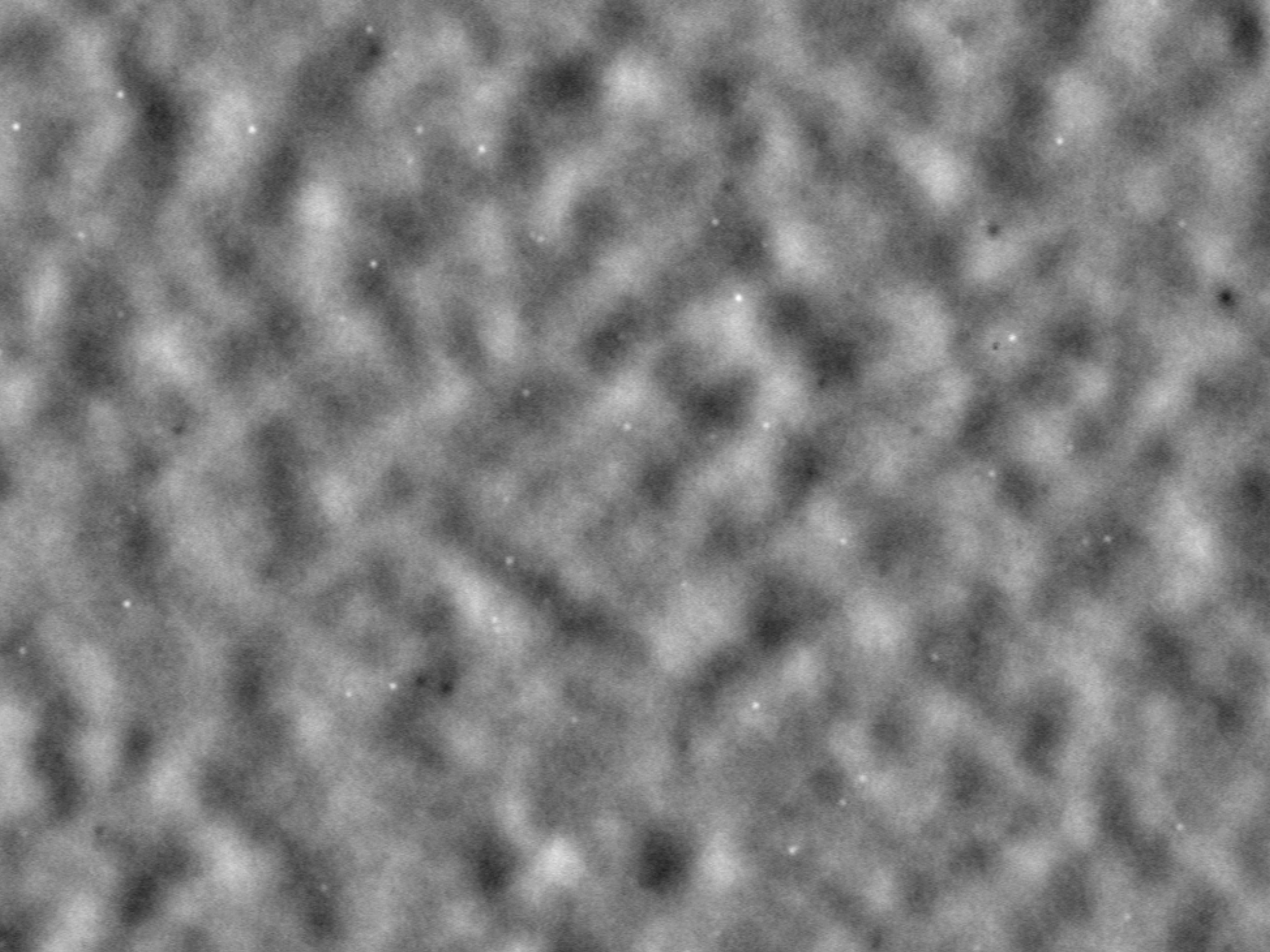
See A Bender's talk this afternoon!

Whats next? Evolution of CMB Focal Planes

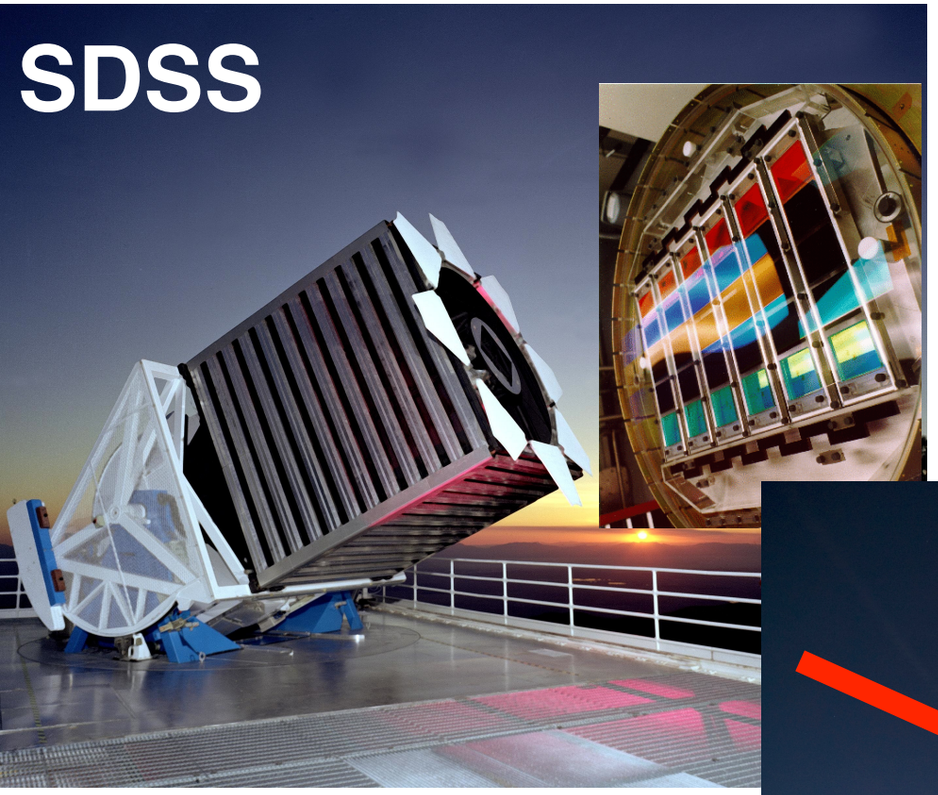


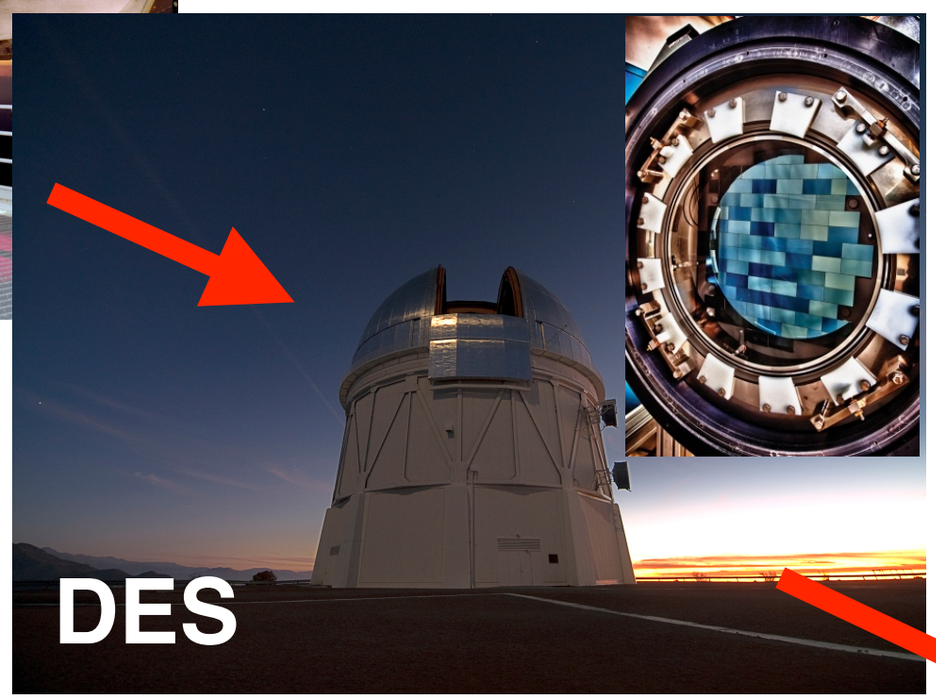
making ***more detectors!***

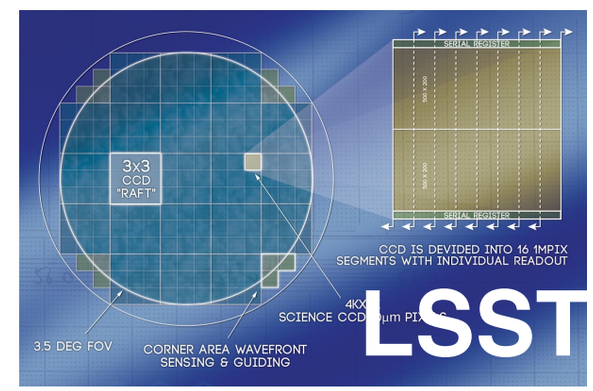


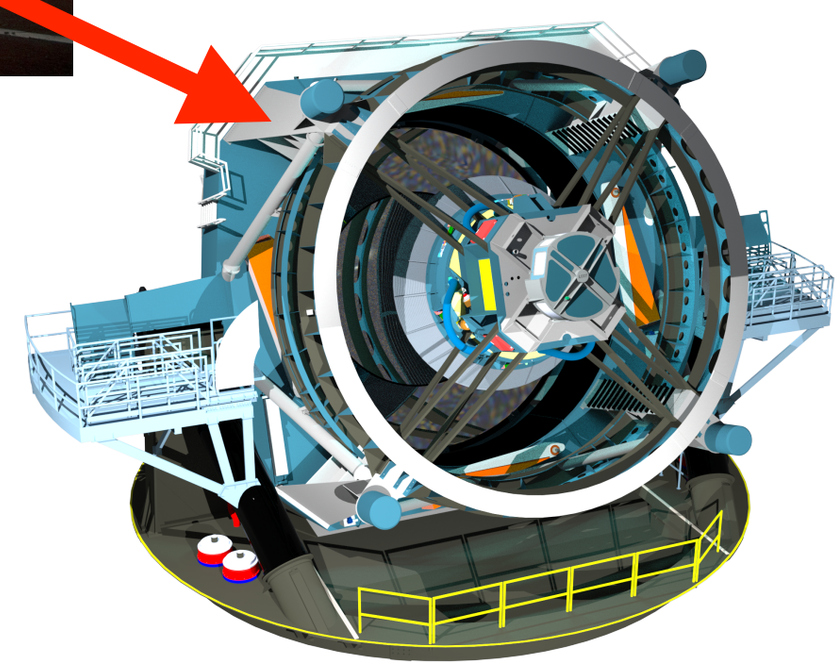


Whats next? Evolution of Focal Planes





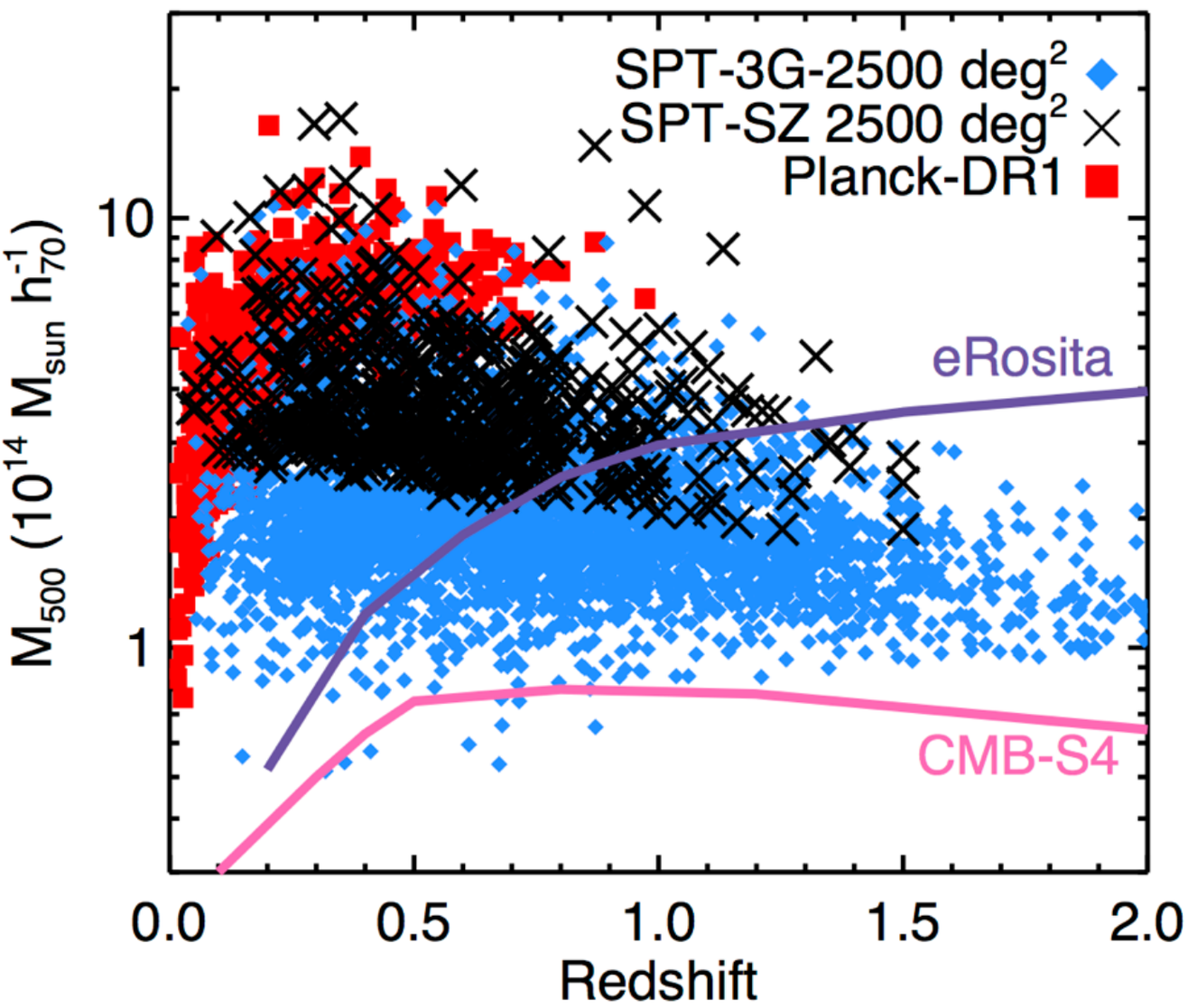




More detectors!

(and bigger telescopes)

Future Cluster Surveys



SPT-SZ/pol: $N_{\rm clust}$ **~ 1,000**

SPT-3G: $N_{\rm clust}$ **~ 10,000**

CMB-S4: $N_{\rm clust}$ **~ 100,000+**

- Optical Surveys WL all clusters at z<1

- Deep CMB data also enables CMB cluster lensing as a competitive mass calibration tool for cluster DE science:

SPT-3G: $\sigma(M) \sim 3\%$

Especially promising tool for cluster masses at $z > 1$

*eRosita 50 cts threshold (Pillepich et al 2012)

Summary

- SPT has found hundreds of massive galaxy clusters spanning a redshift range $0.05 < z < 1.85$.
- Clean, mass-limited selection leads to a fantastic sample for cosmological and astrophysical studies.
- Cosmological analysis consistent with other cluster studies & CMB Cosmology
- Better mass calibration required to tighten constraints (and work is ongoing!).
- SPT Strong lensing program will identify ~175 lensing clusters; constraints on the mass-concentration relation, valuable sample to study cores of clusters
- SPT-3G is deployed and observing!

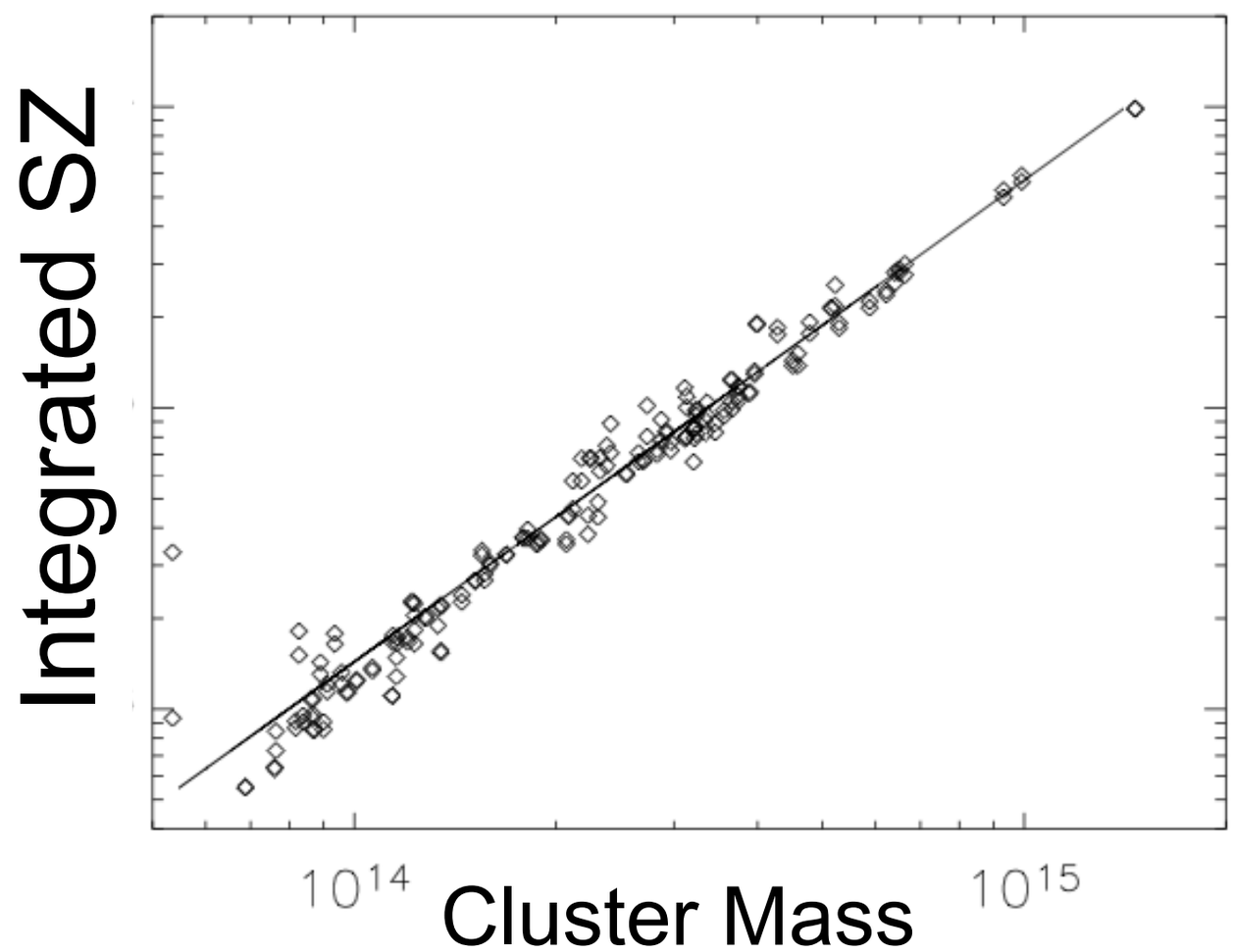
Thanks!

Photo credit: Keith Vanderlinde

The SZ-observable is tightly correlated with mass.

$$\int y d\Omega \propto \frac{k_B T_e}{m_e c^2} \sigma_T \frac{N_e}{D_a^2}$$

Integrated Signal proportional to total thermal energy, should faithfully track cluster mass



Motl et al 2005