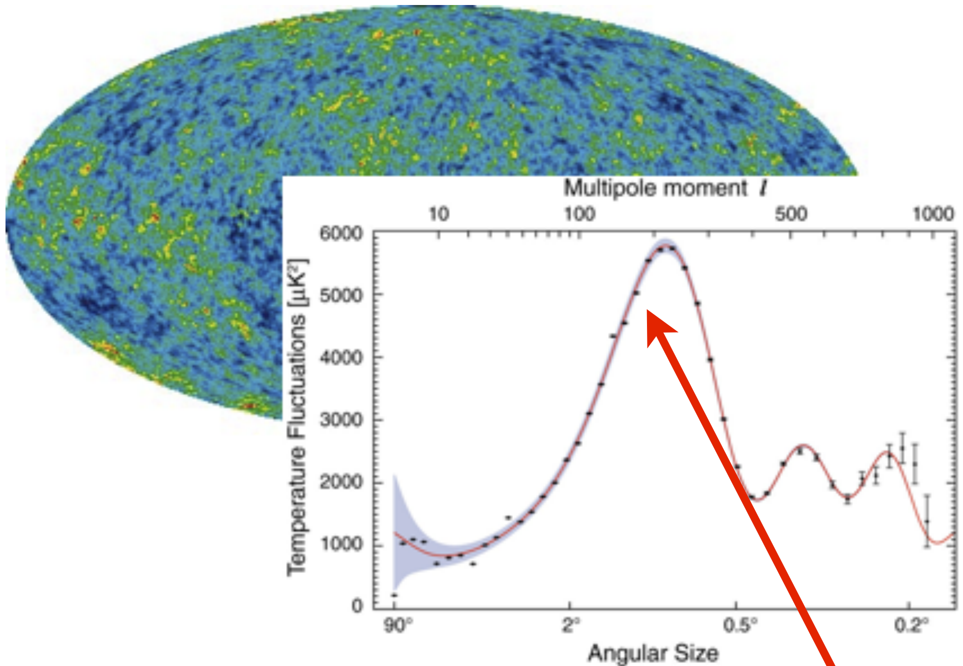
Constraining Cosmology with Galaxy Clusters Discovered by the South Pole Telescope

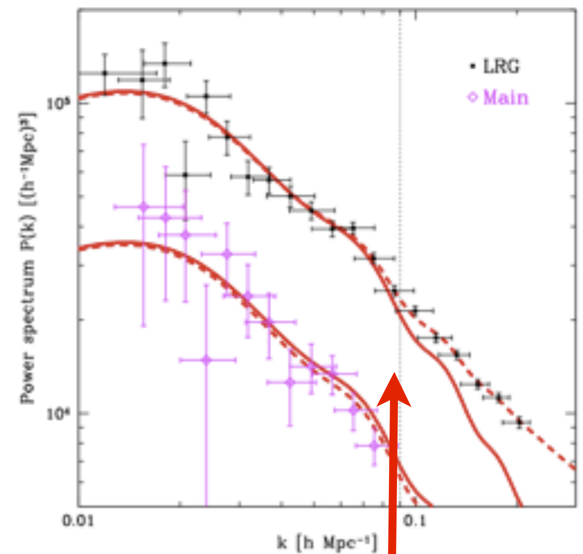
Lindsey Bleem
Argonne National Laboratory
July 31, 2019

DPF 19

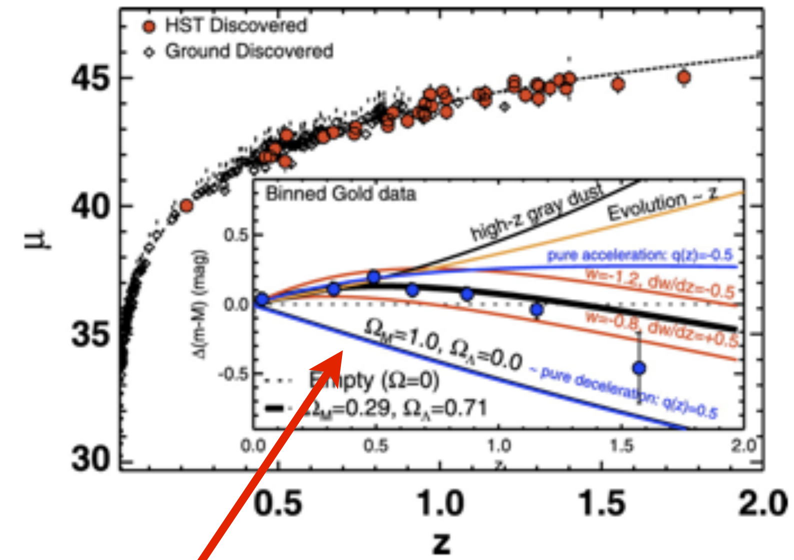
Photo credit: Keith Vanderlinde



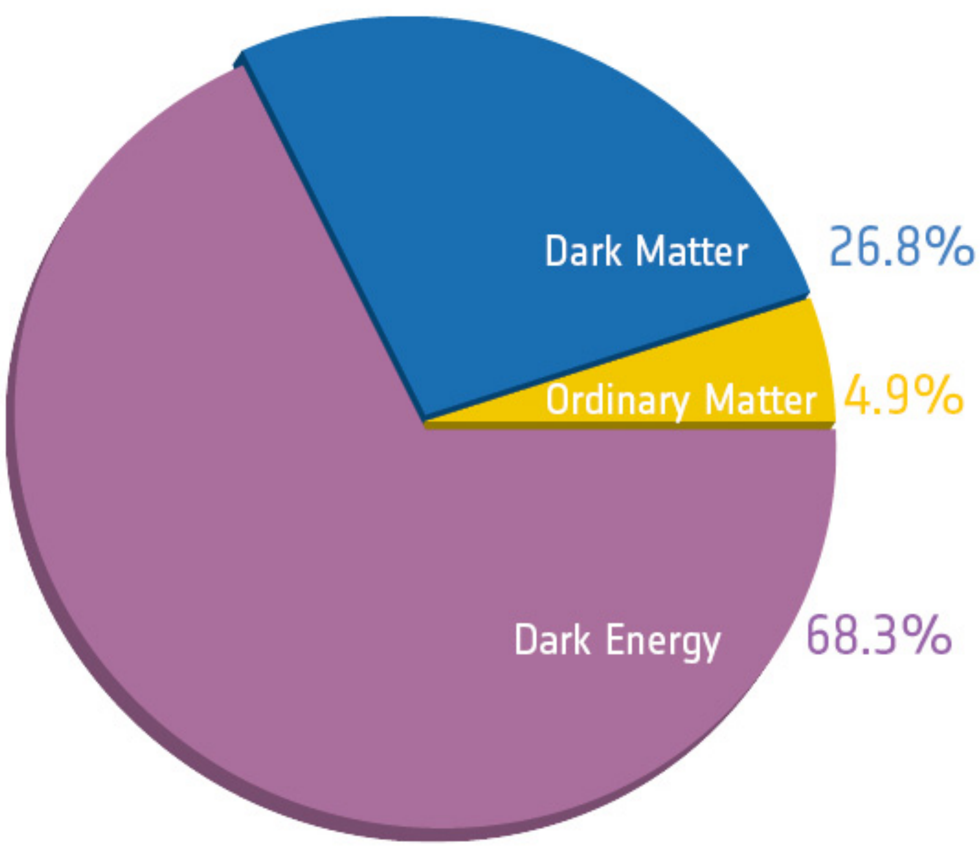
Tegmark et al 2006



Riess et al 2007

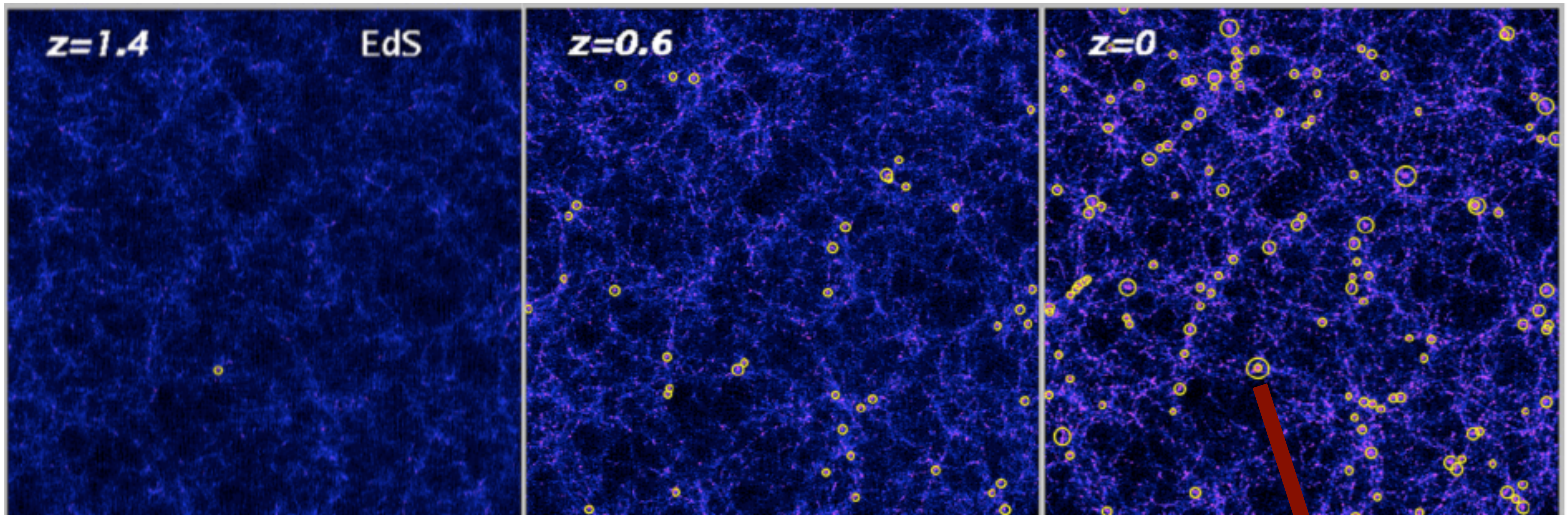


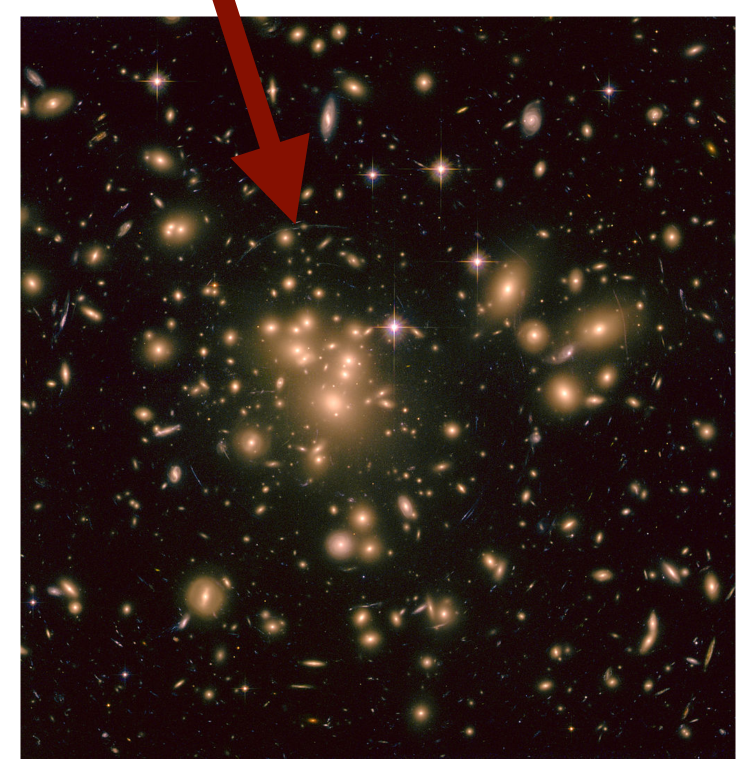
CMB + Large Scale Structure + SNe Ia



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

Matter Dominated, No dark Energy





Source Borgani and Guzzo 2001

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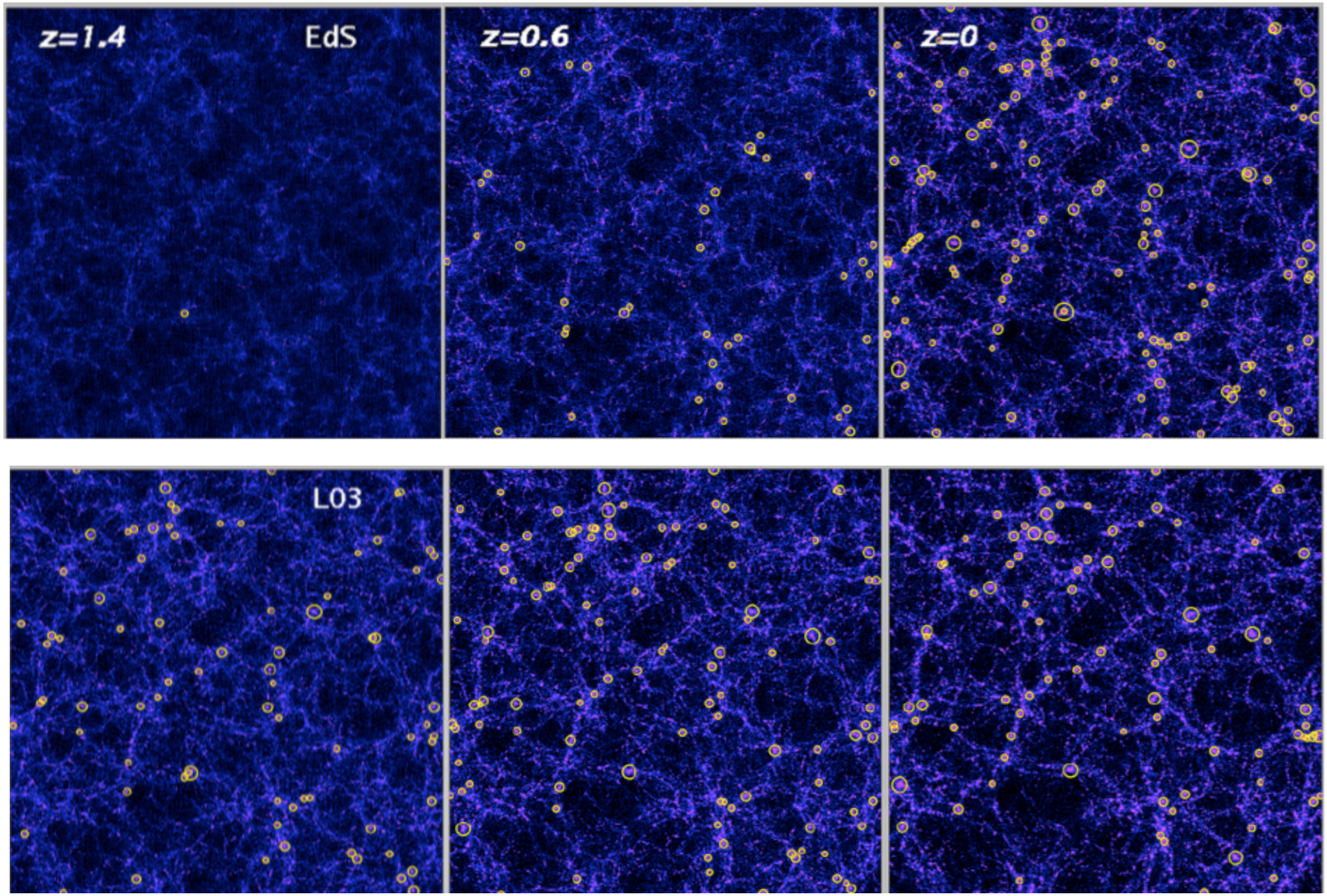

70% Dark Energy, 30% Matter

Source Borgani and Guzzo 2001

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)*

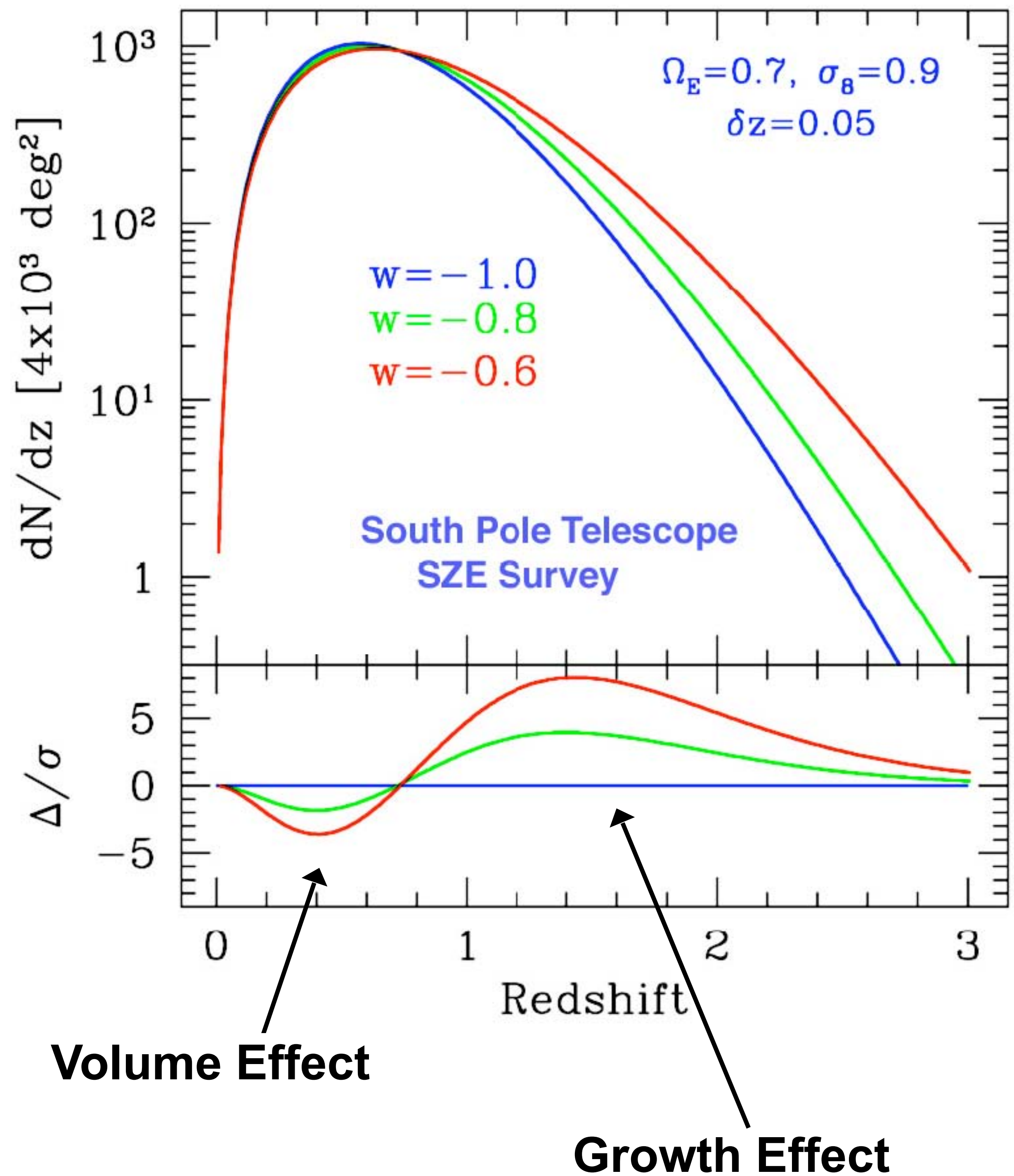

Figure: J Mohr

Dark Energy and Cluster Cosmology

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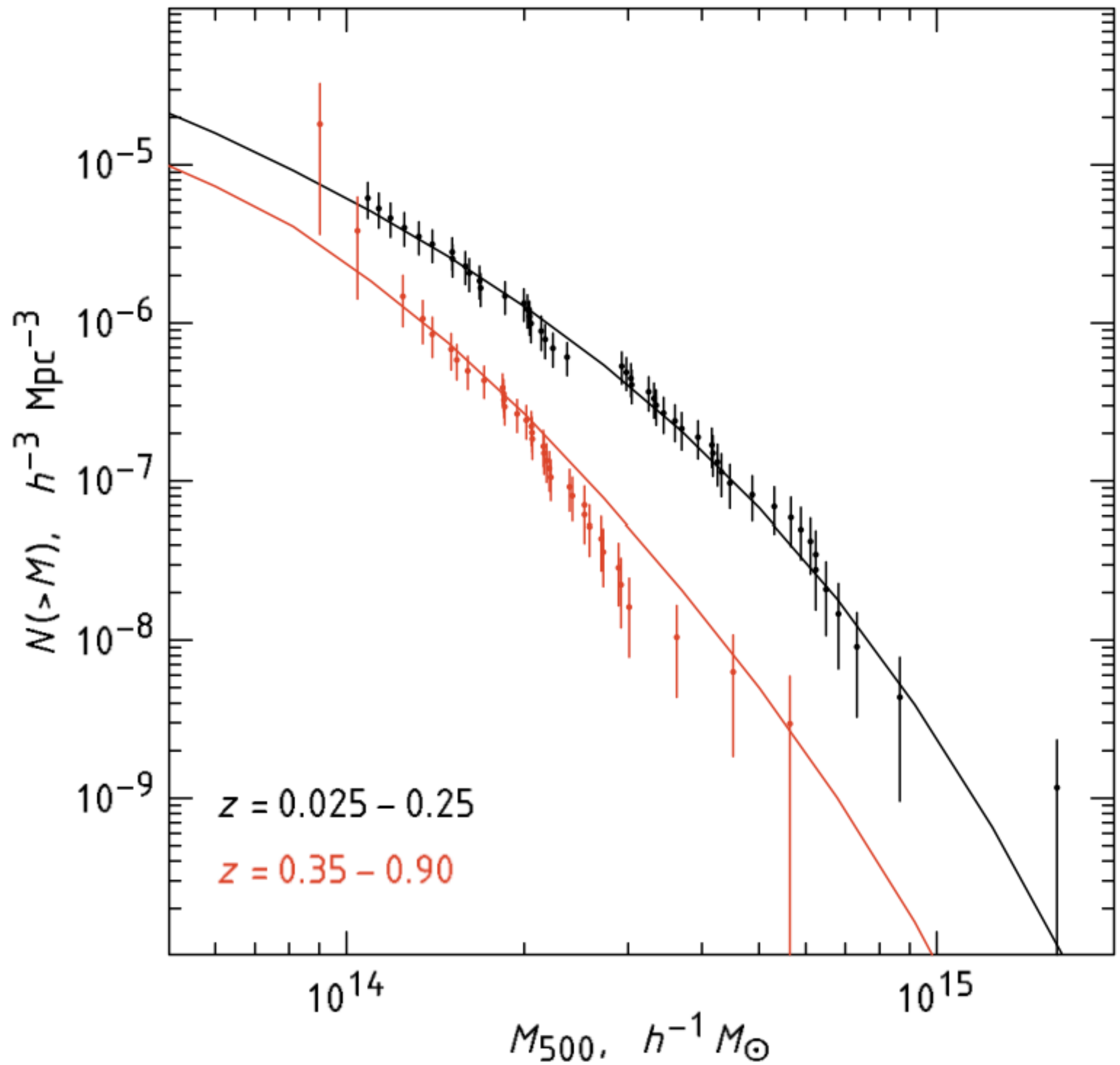


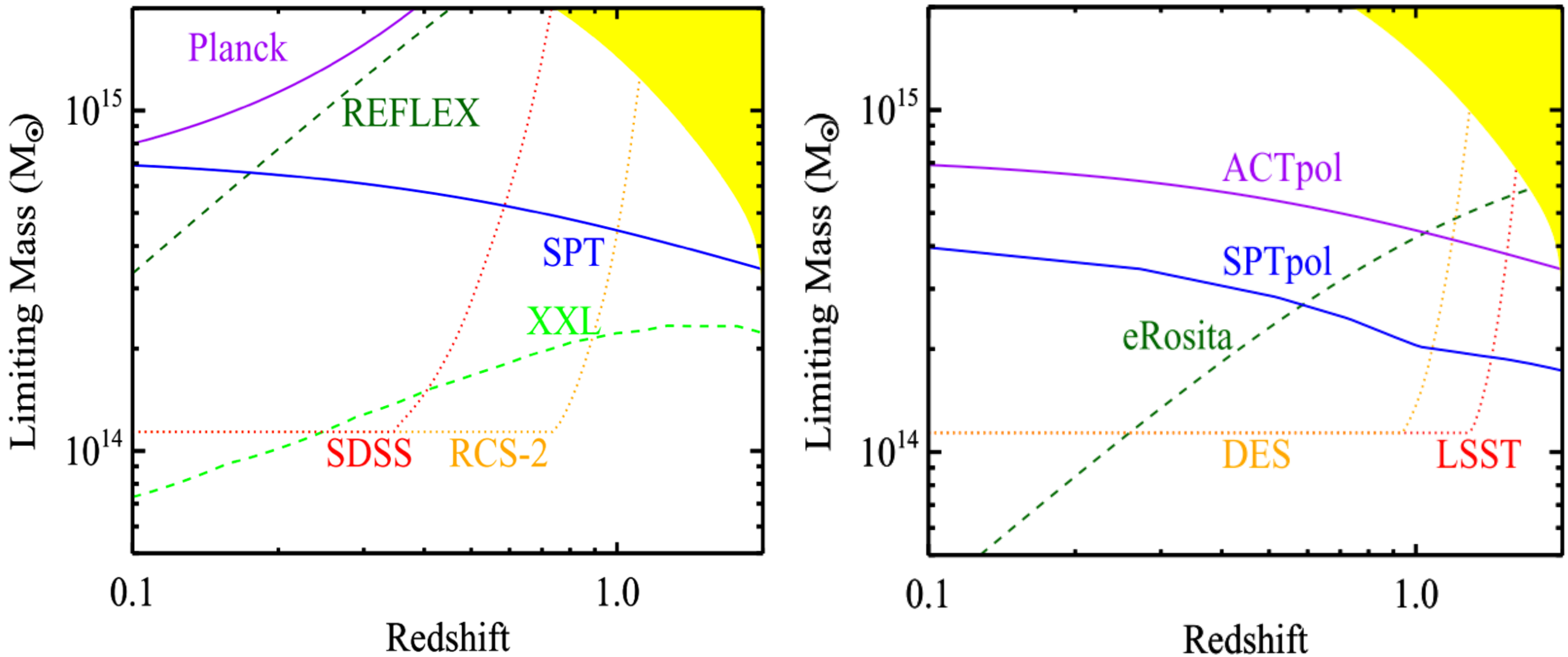
Vikhlinin et al, ApJ 692, 1060V, (2009)

For Cosmology with Clusters We Need To

Find Them.

“Weigh” Them.

3 Approaches: Optical, X-ray, SZ



Recent/Ongoing/Near Future Surveys

Weinberg et al. PhR 520, 87W (2013)

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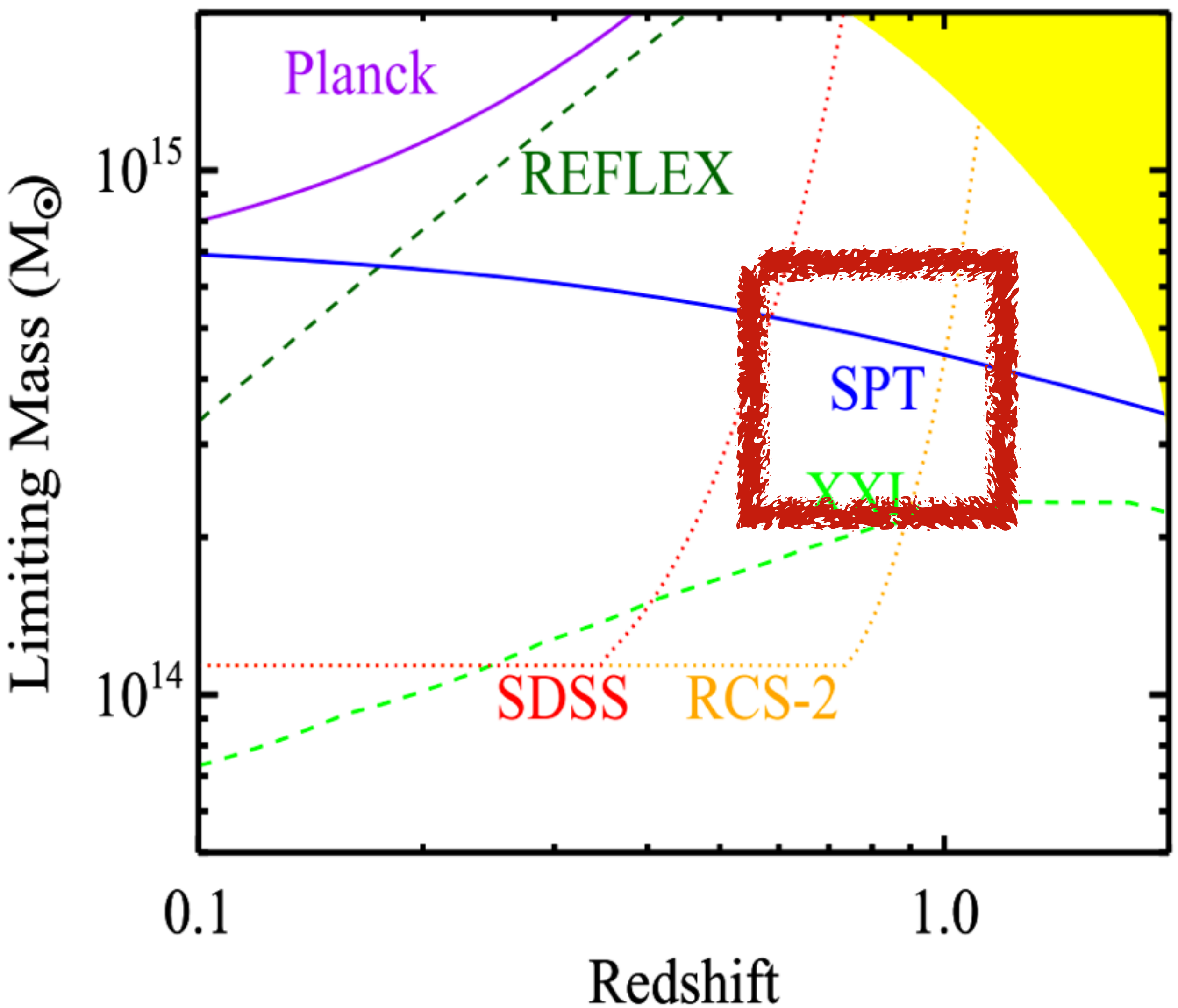
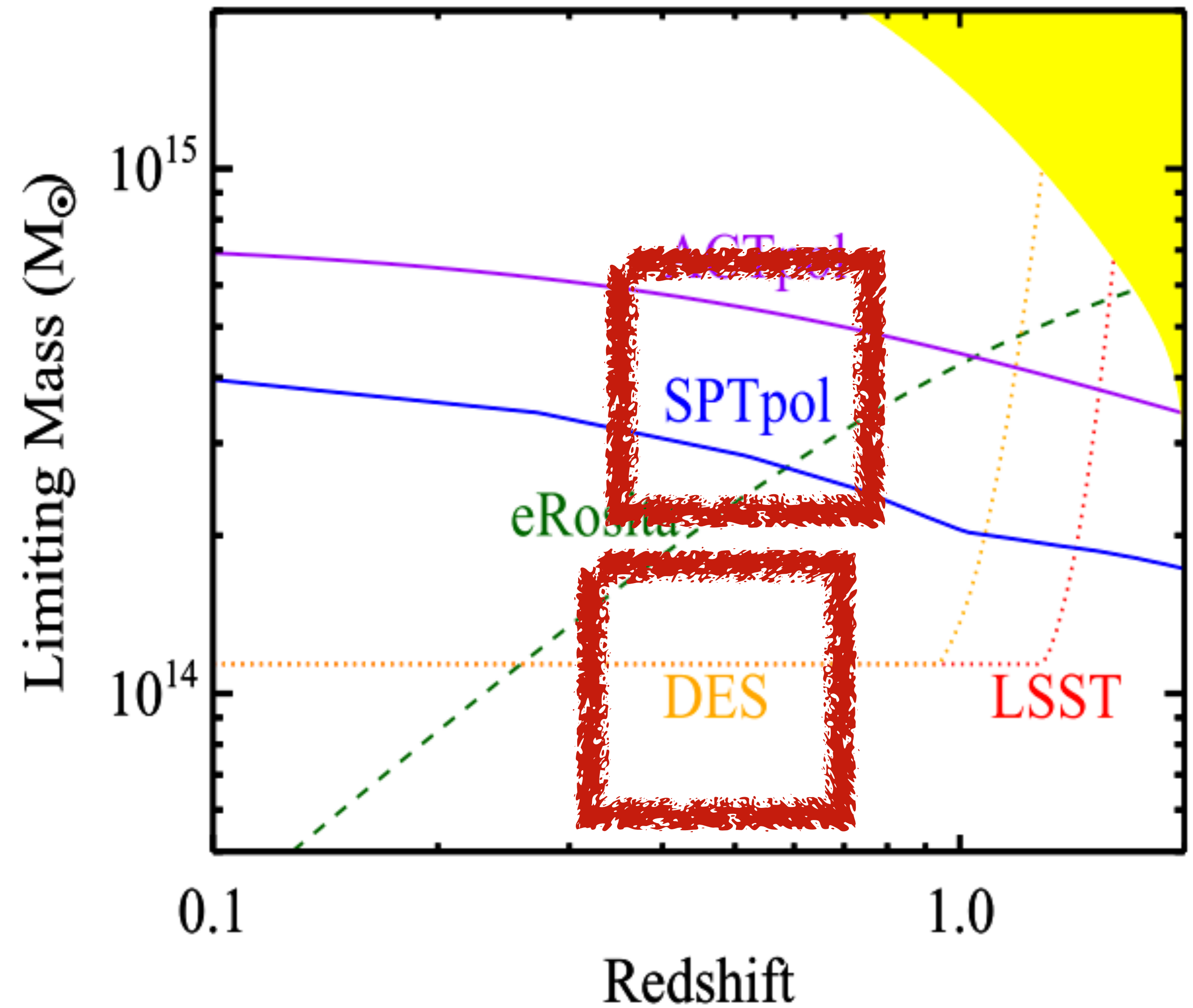
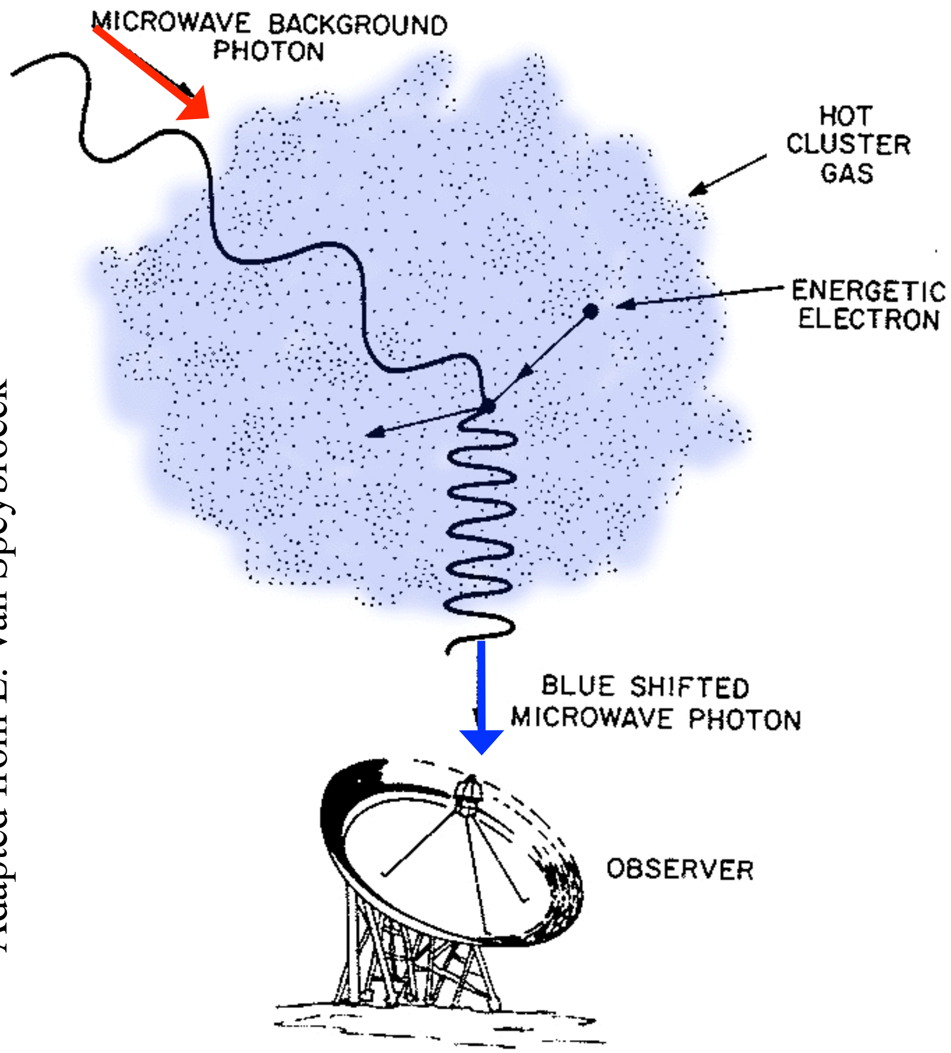




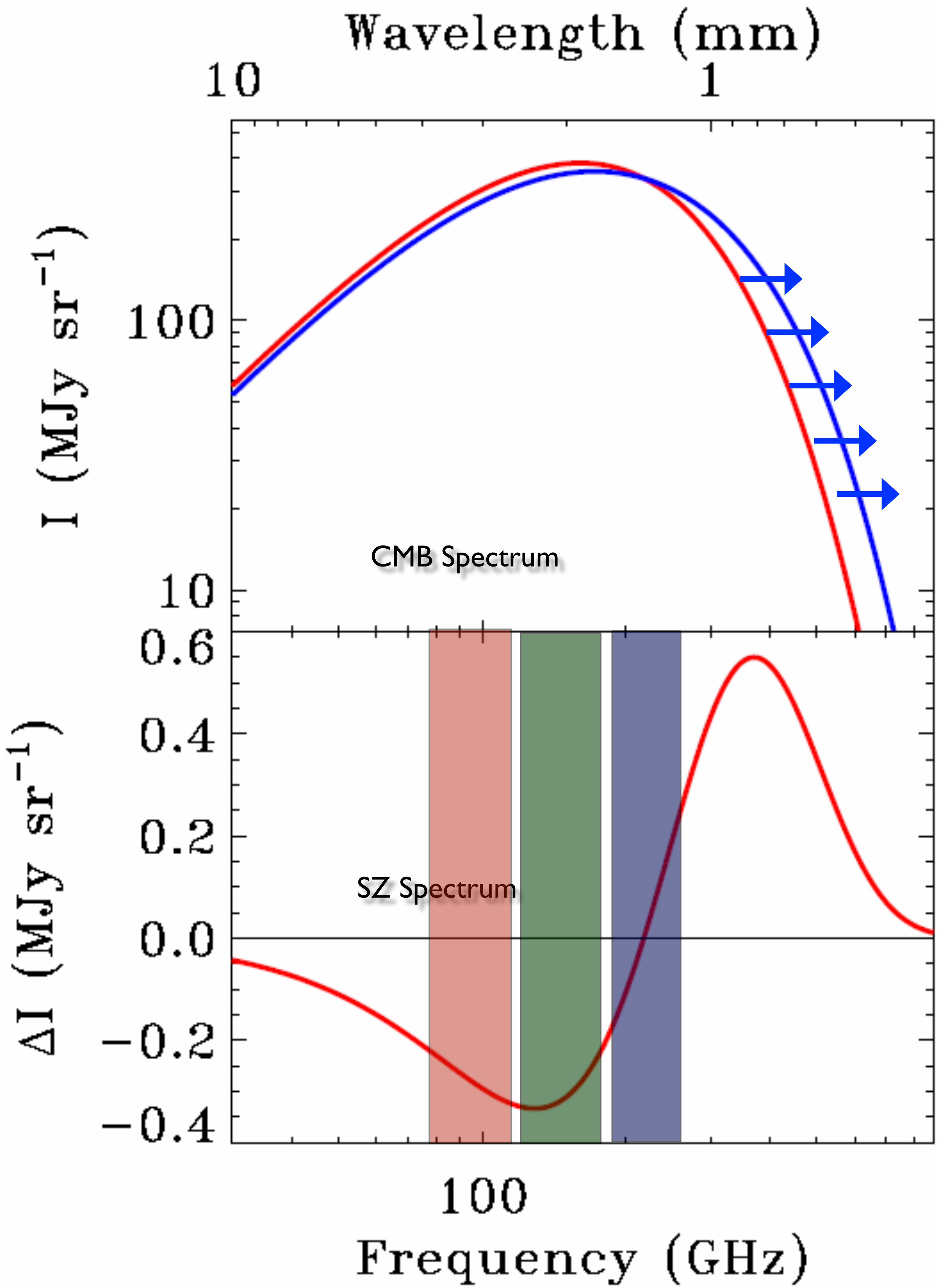
Recent/Ongoing/Near Future Surveys

Weinberg et al. PhR 520, 87W (2013)

The Sunyaev Zel'dovich (SZ) Effect



Adapted from L. Van Speybroeck

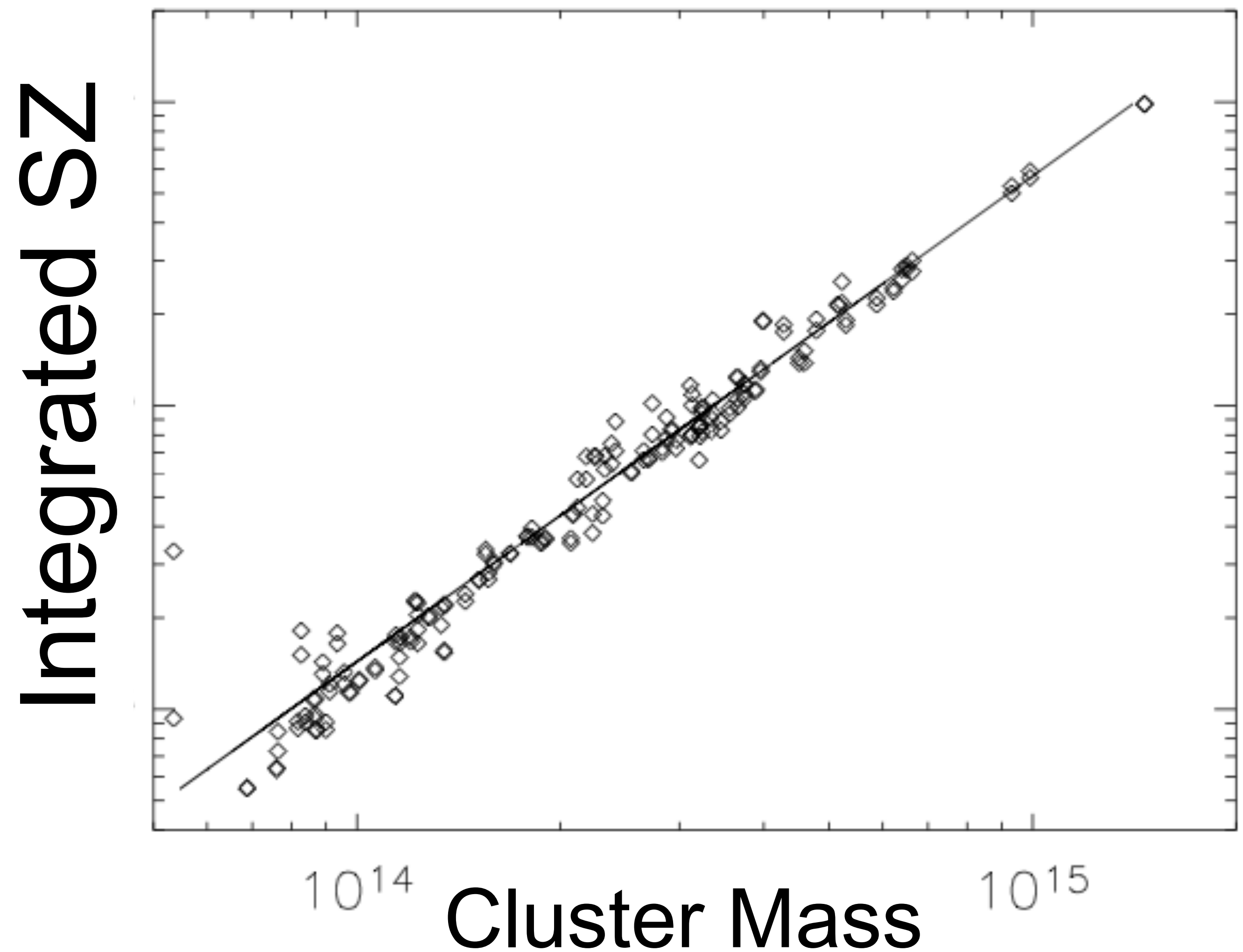


Towards a massive cluster, ~1% of CMB photons scatter off of intra-cluster gas

The SZ-observable is tightly correlated with mass.

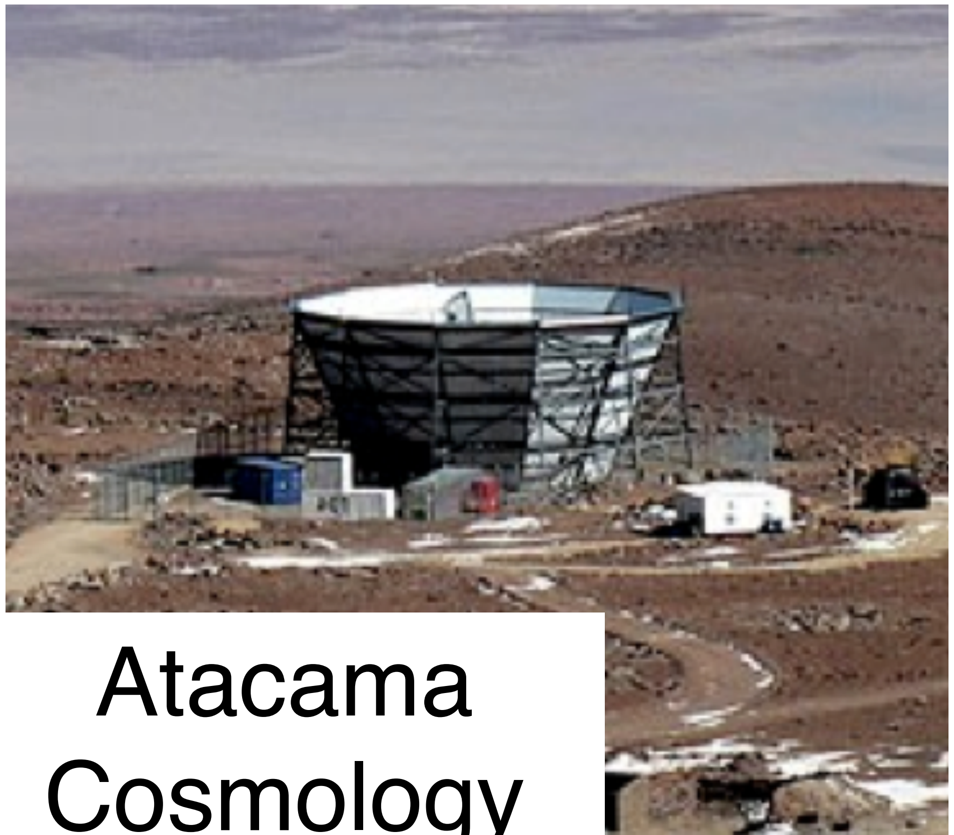
$$\int y d\Omega \propto \frac{k_B T_e}{m_e c^2} \sigma_T \frac{N_e}{D_a^2}$$

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

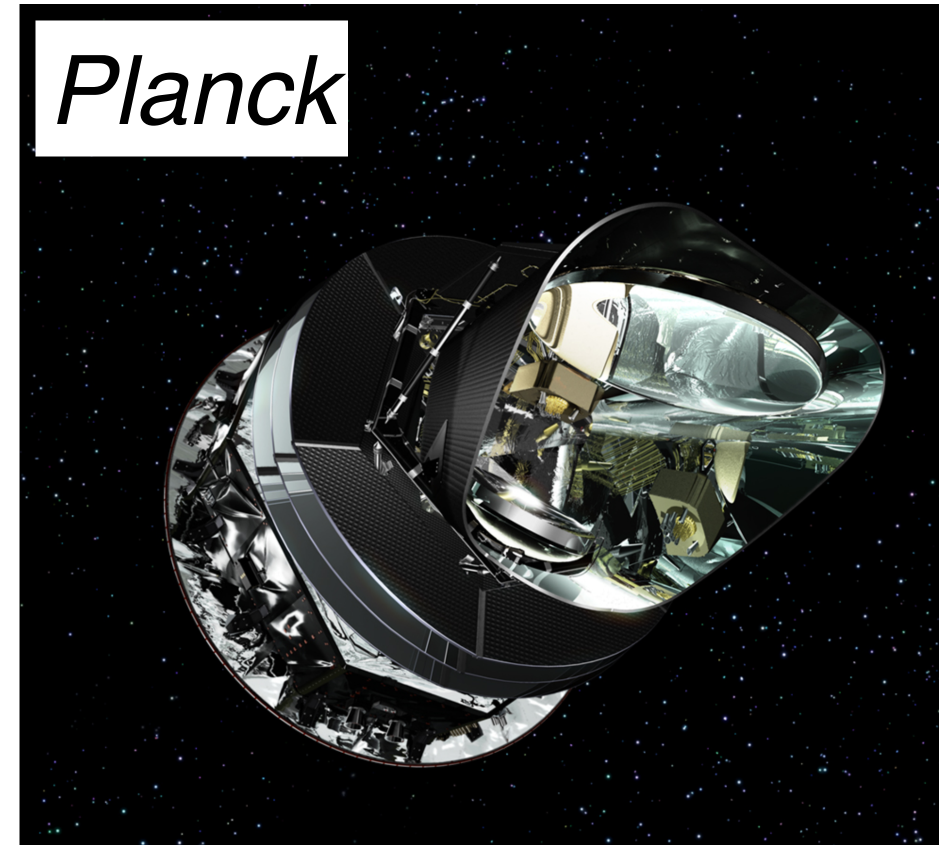


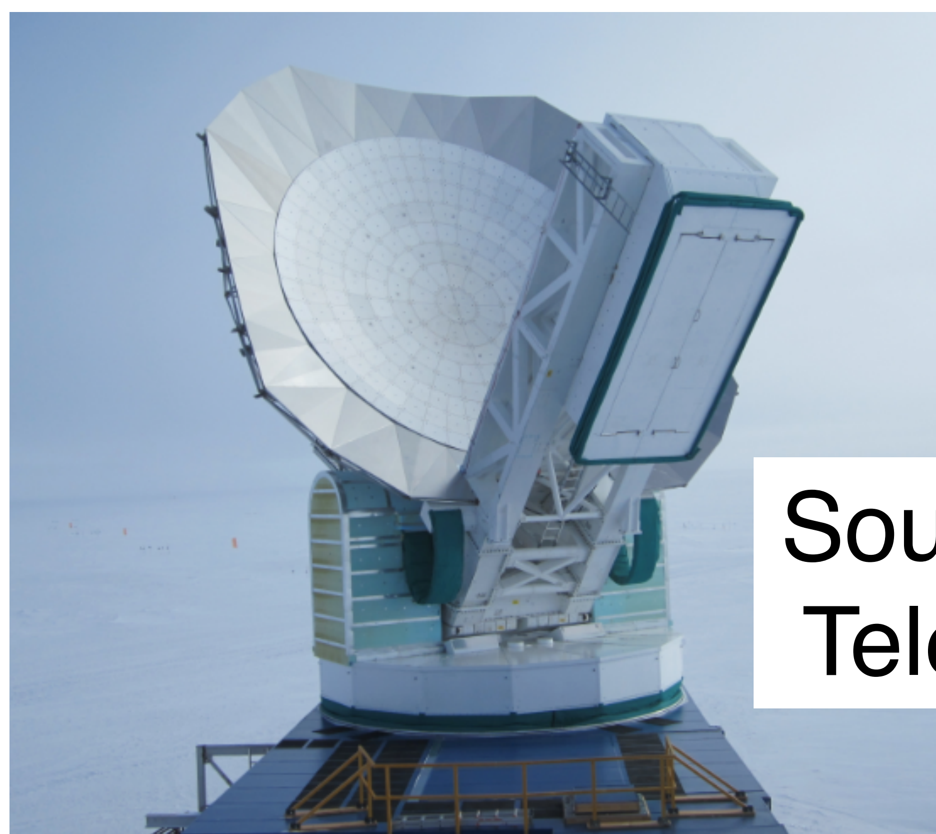
Motl et al 2005

We require high-resolution, wide-area surveys to discover significant numbers of clusters.



Atacama Cosmology Telescope





South Pole Telescope

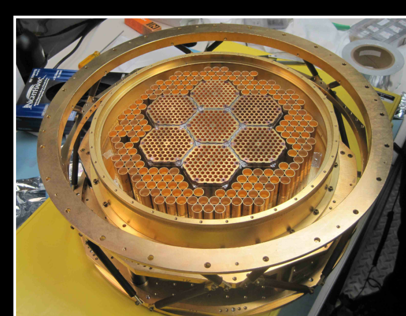
The South Pole Telescope (SPT)

10-meter sub-mm quality wavelength telescope

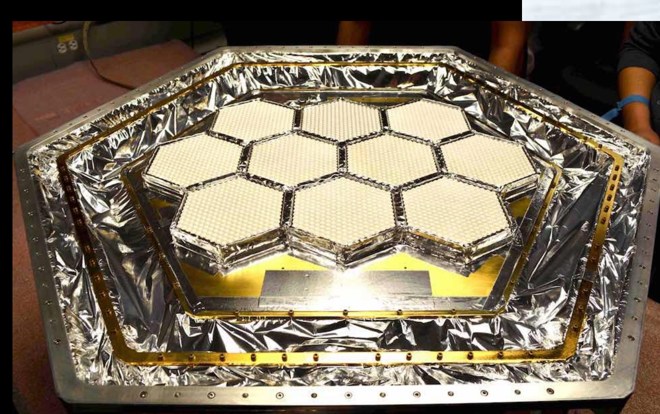
90, 150, 220 GHz and
1.6, 1.2, 1.0 arcmin resolution

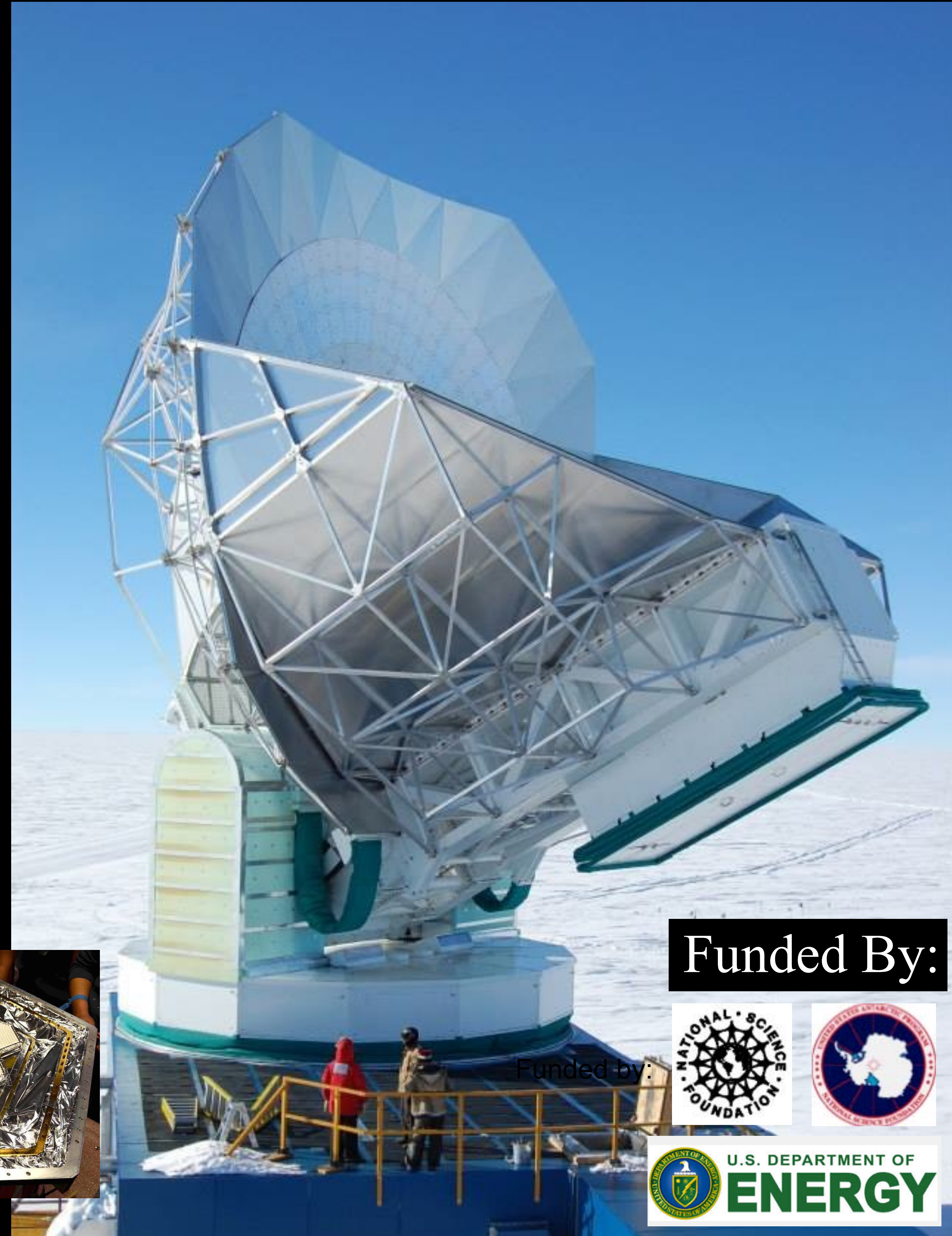
2007: SPT-SZ
960 detectors
90,150,220 GHz

2012: SPTpol
1600 detectors
90,150 GHz
+Polarization



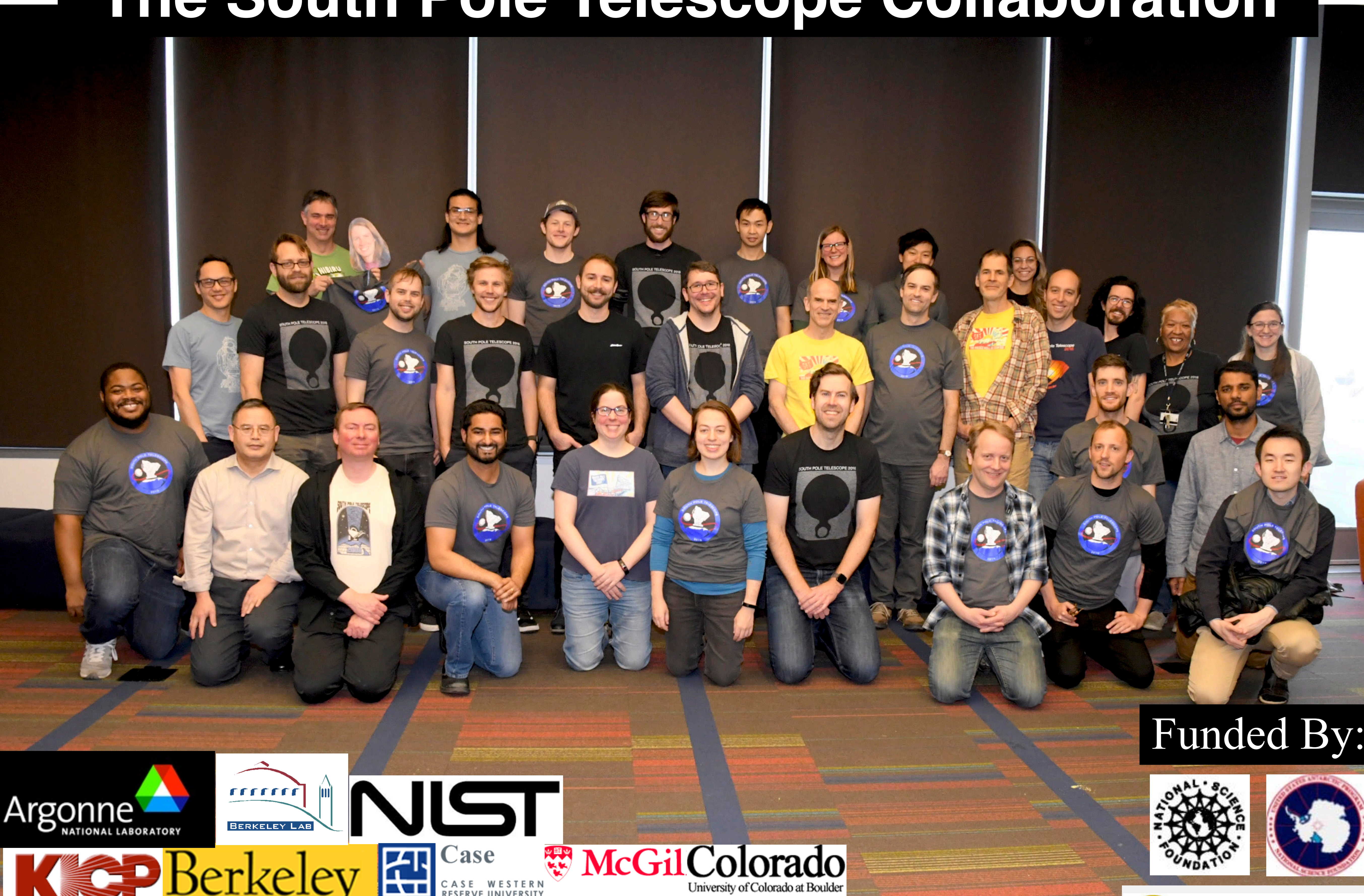
2017: SPT-3G
~15,200 detectors
90,150,220 GHz
+Polarization





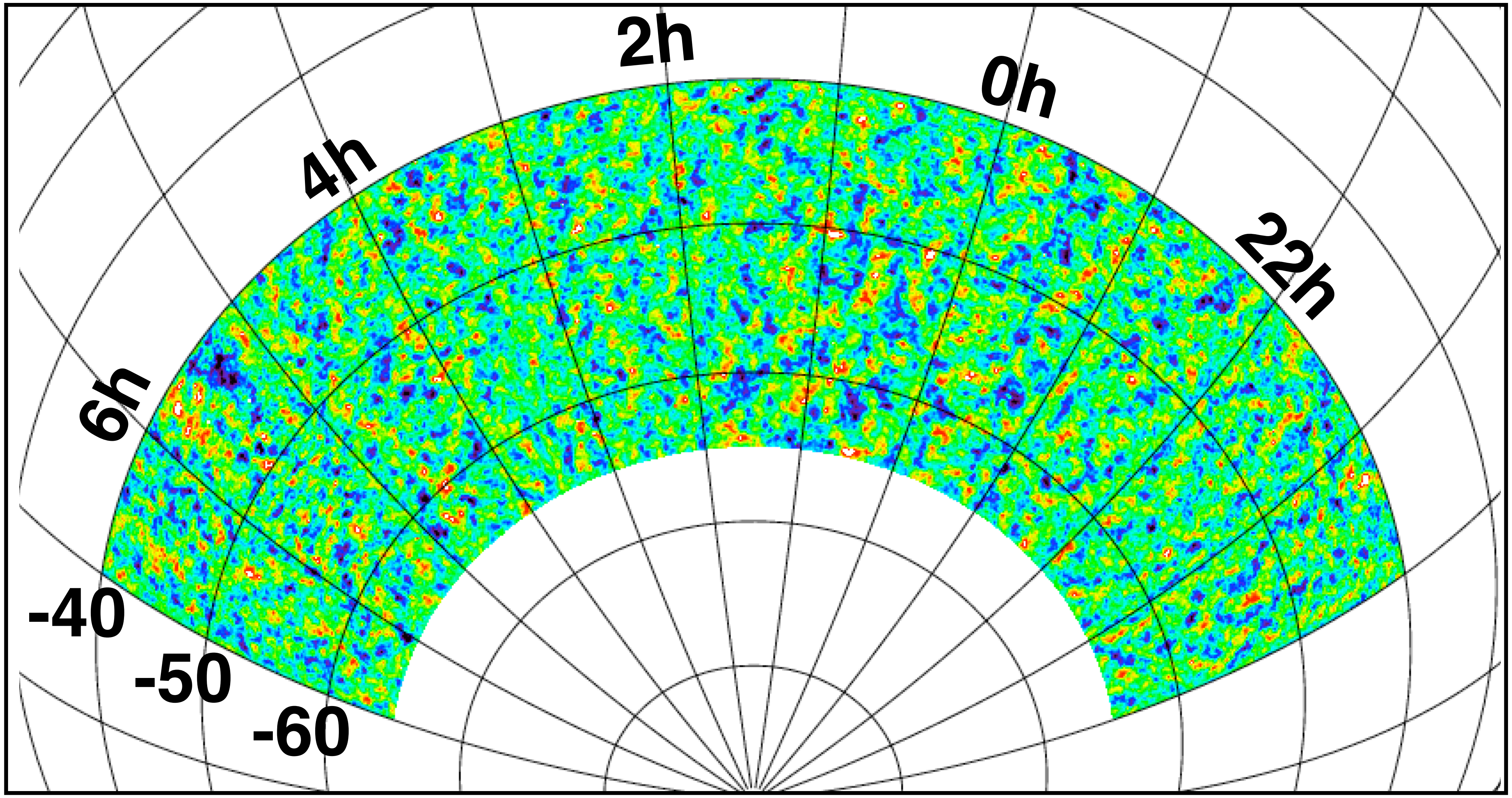
Funded By:
NATIONAL SCIENCE FOUNDATION
U.S. DEPARTMENT OF ENERGY

The South Pole Telescope Collaboration

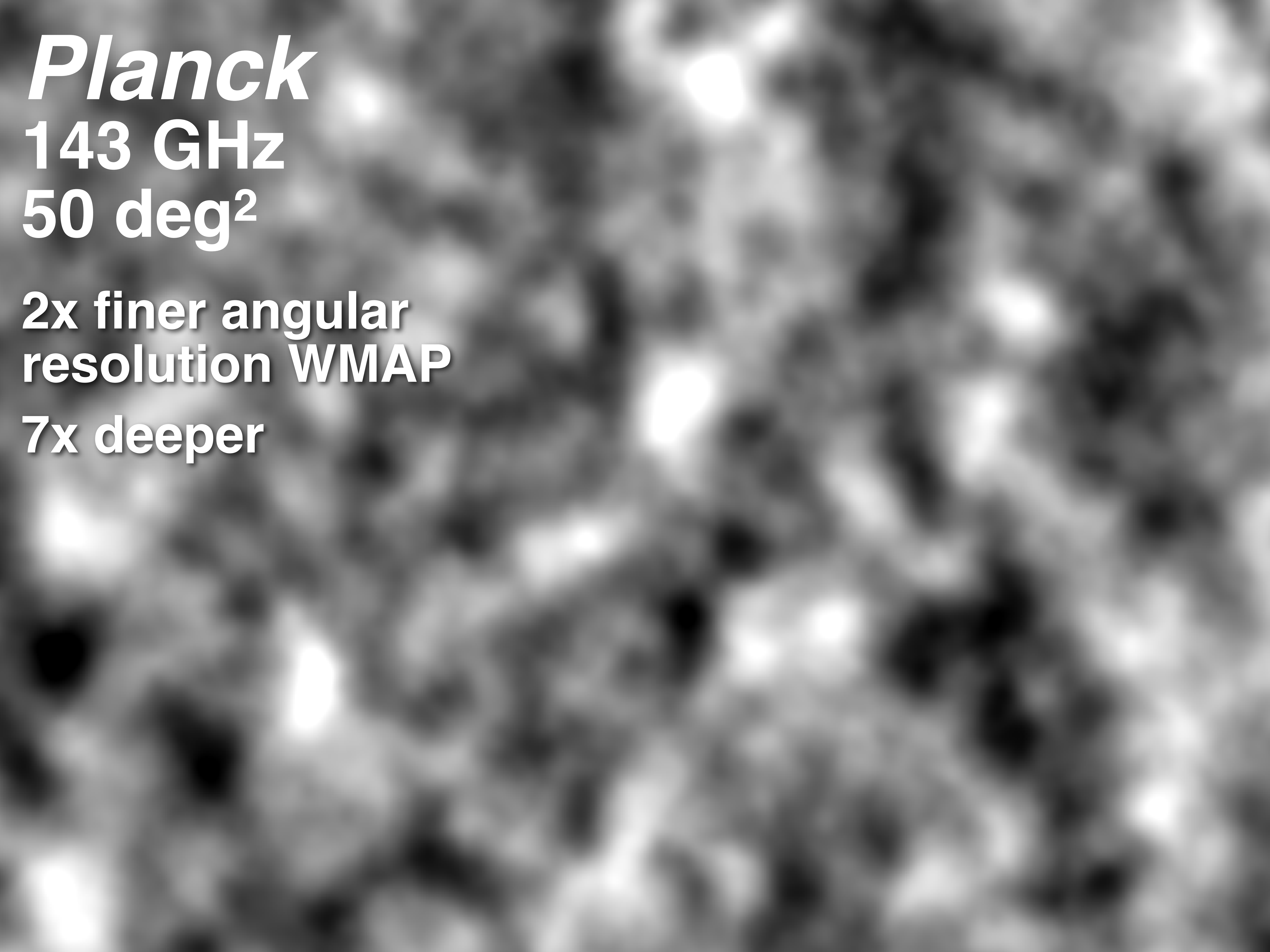


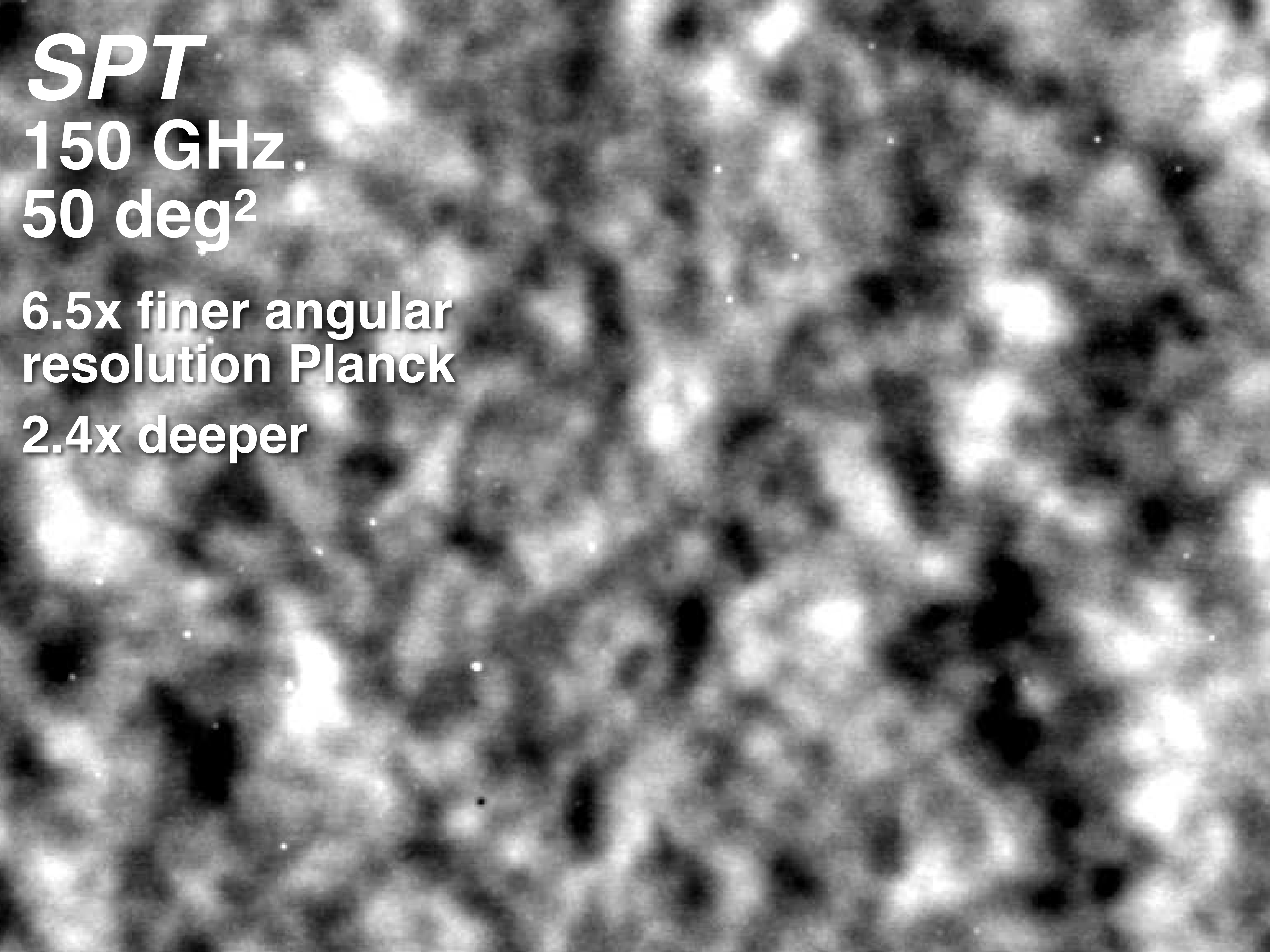
Funded By:

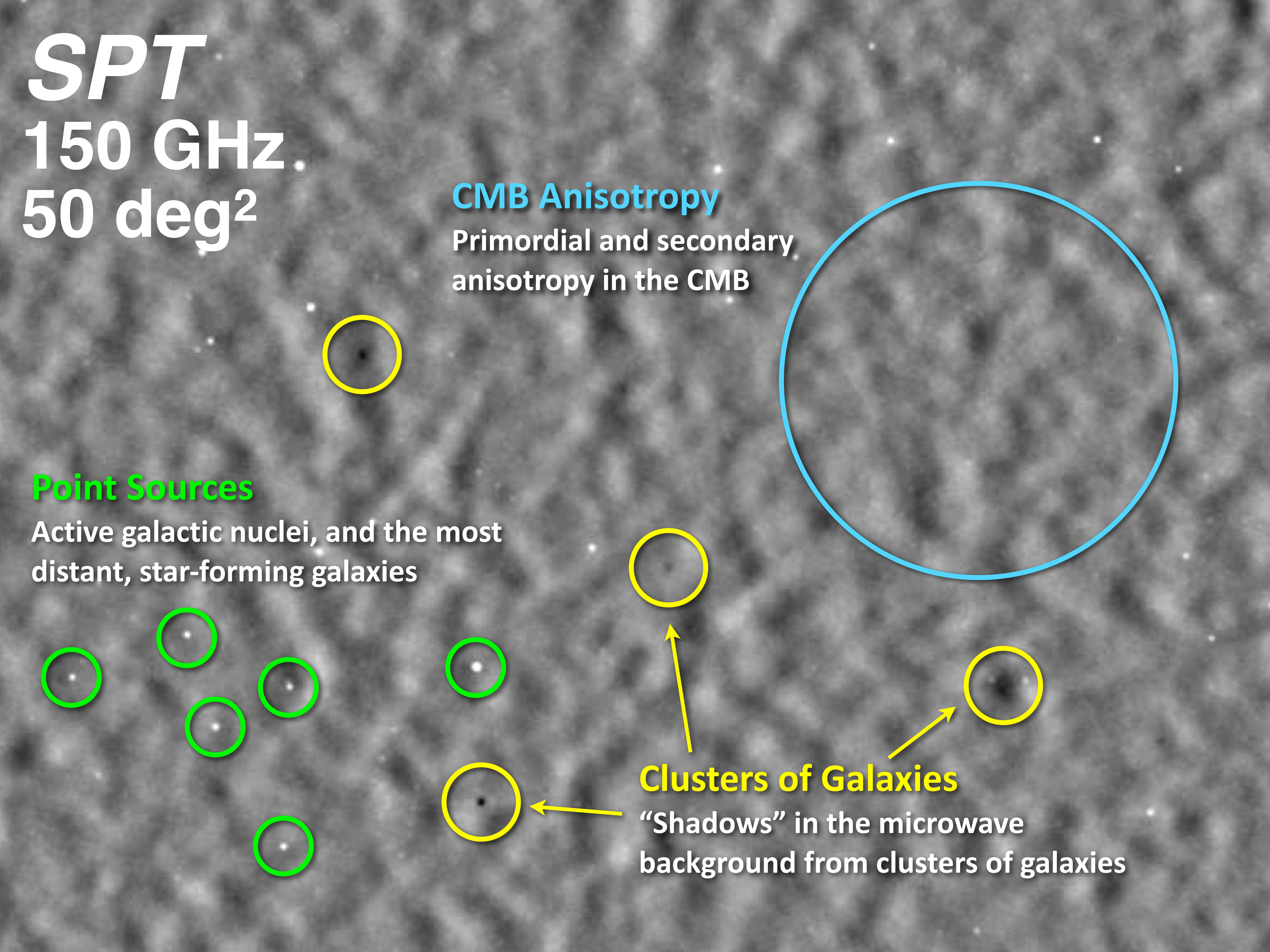
The 2500 deg² SPT-SZ Survey (2007-2011):



Final survey depths of:
90 GHz: 40 uK_{CMB}-arcmin
150 GHz: 17 uK_{CMB}-arcmin
220 GHz: 80 uK_{CMB}-arcmin

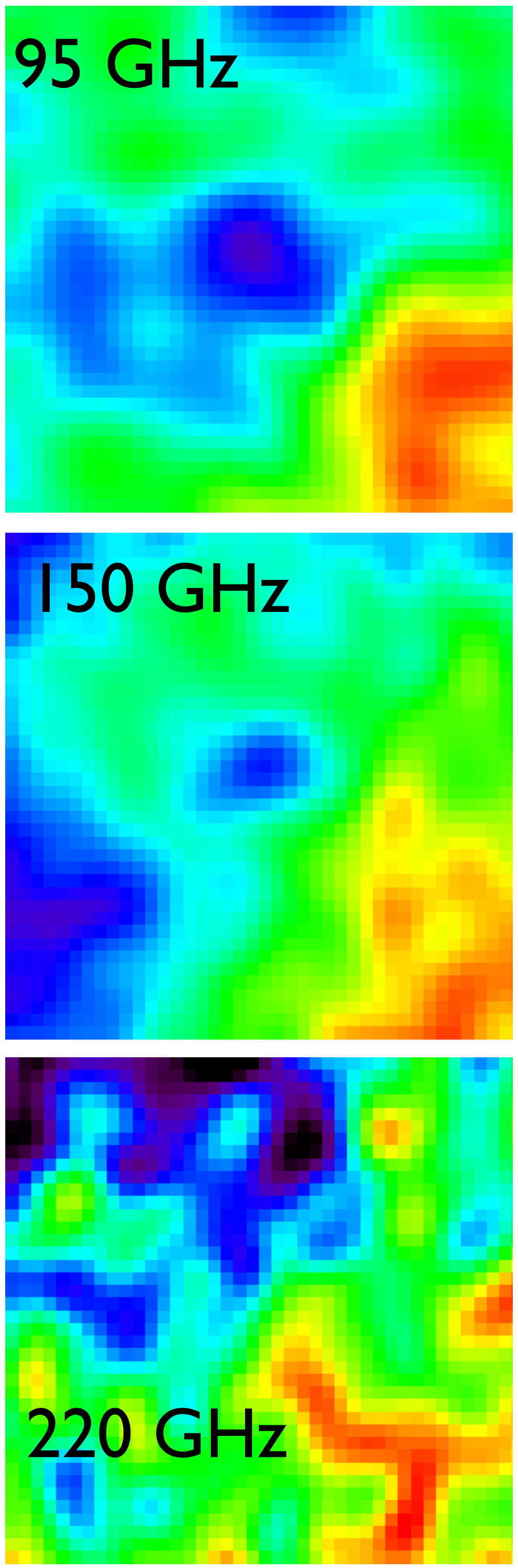

Planck
143 GHz
50 deg^2
2x finer angular resolution WMAP
7x deeper

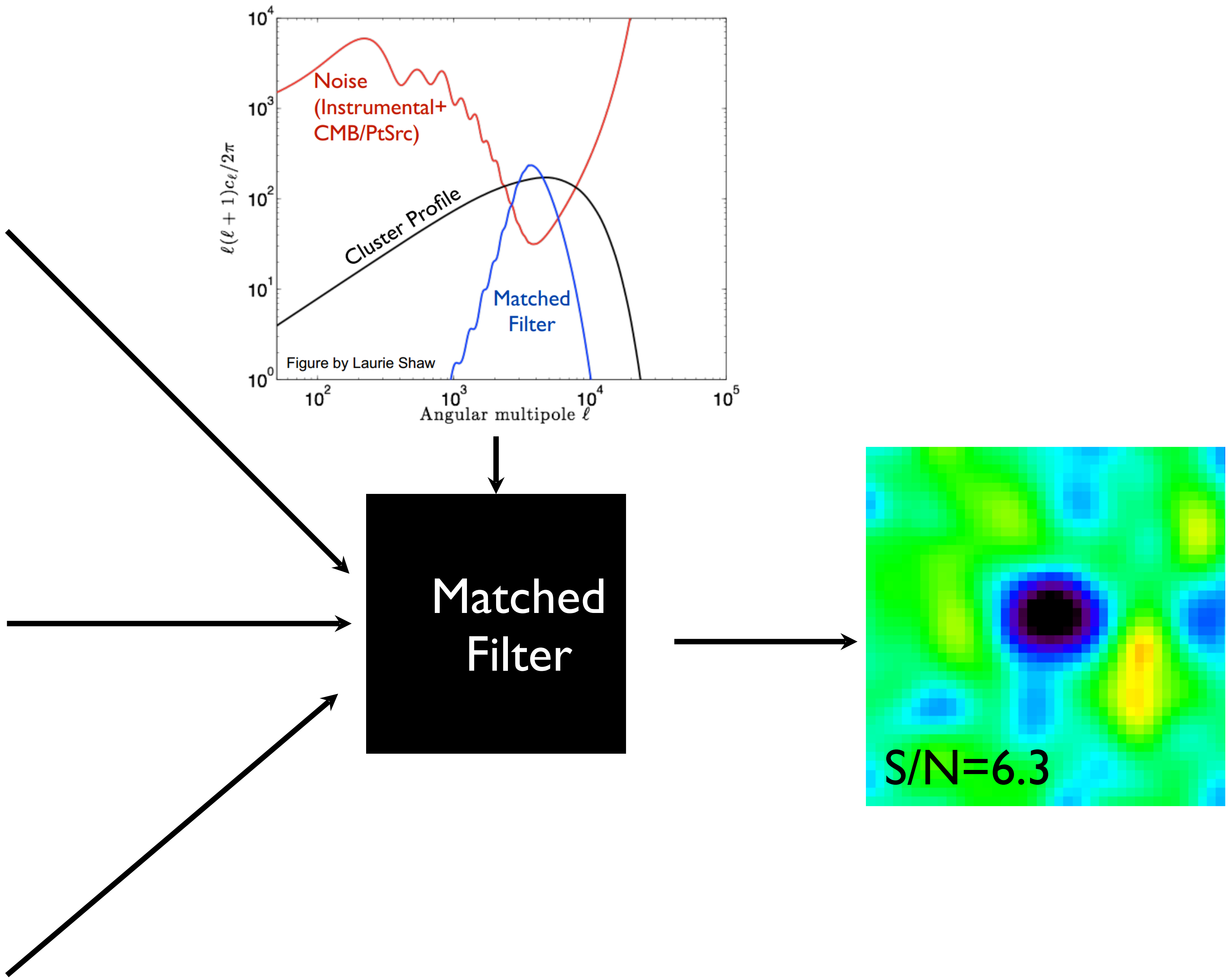

SPT
150 GHz
50 deg²
6.5x finer angular resolution Planck
2.4x deeper



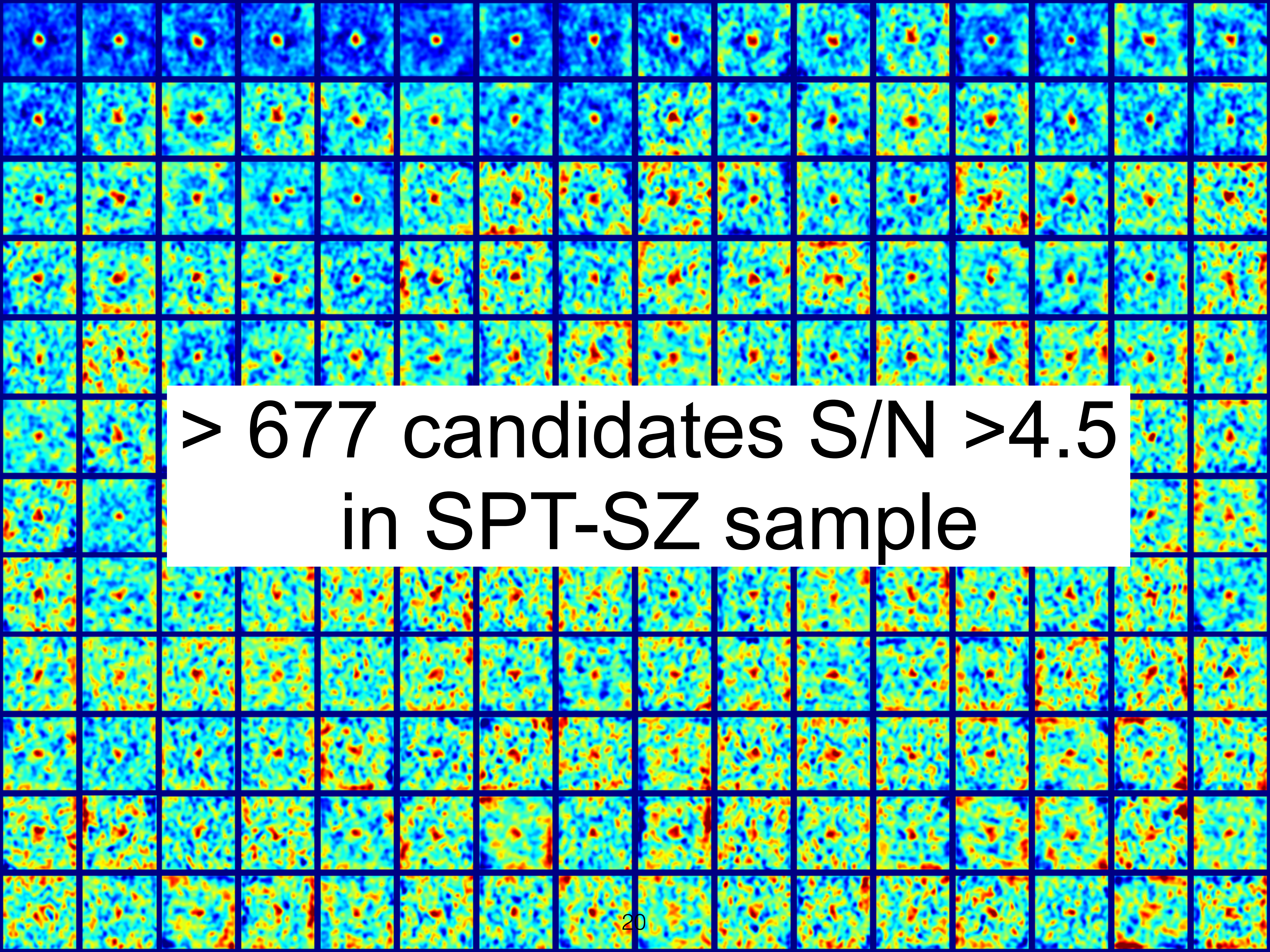
SPT
150 GHz
50 deg²
CMB Anisotropy
Primordial and secondary anisotropy in the CMB
Point Sources
Active galactic nuclei, and the most distant, star-forming galaxies
Clusters of Galaxies
"Shadows" in the microwave background from clusters of galaxies

Finding Clusters in the SPT Survey

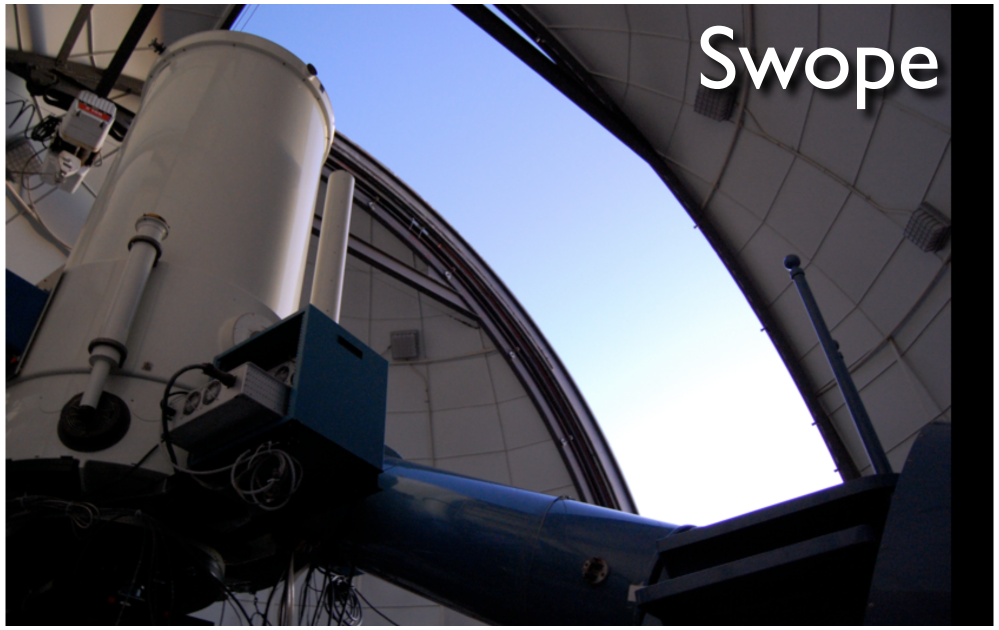


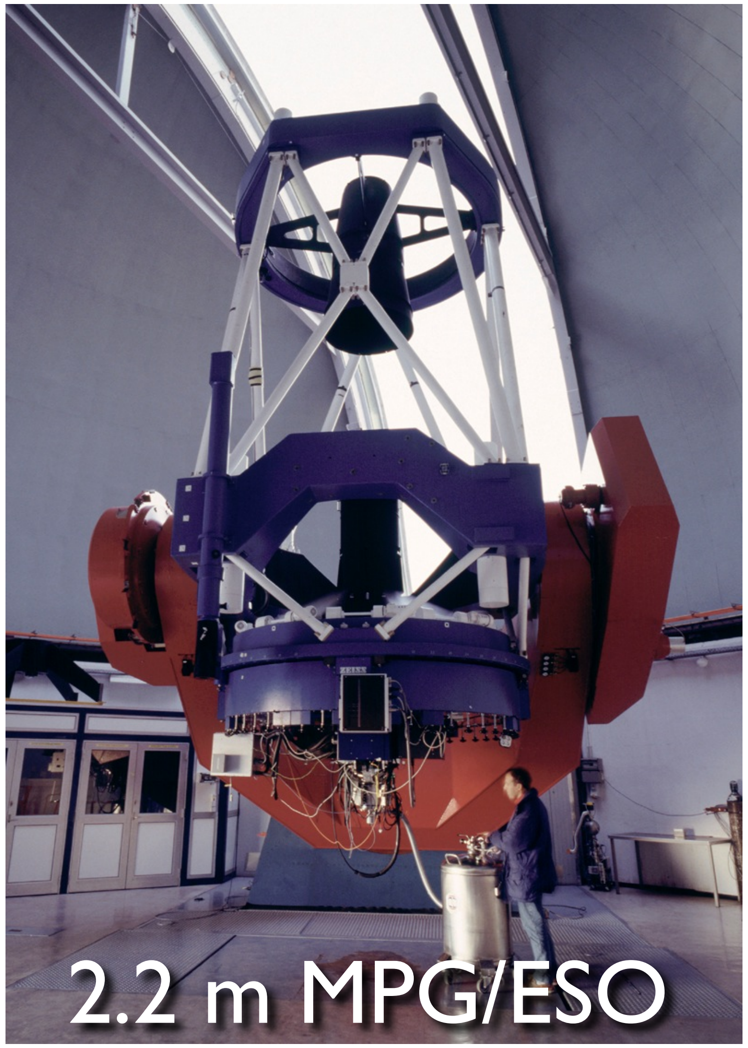


- Matched-filter multi-frequency cluster finder (Melin et al. 2006)



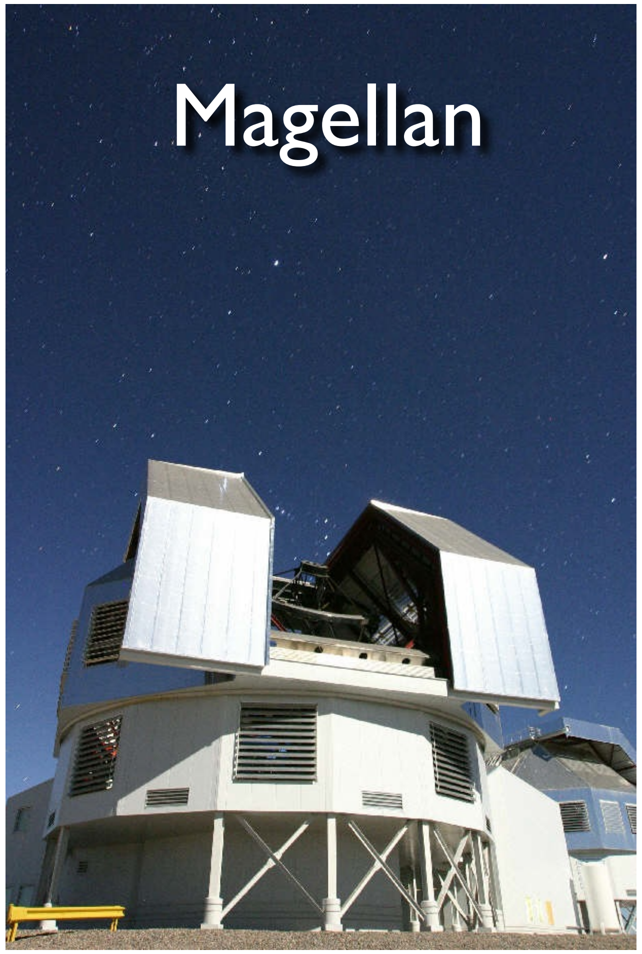
> 677 candidates S/N >4.5
in SPT-SZ sample



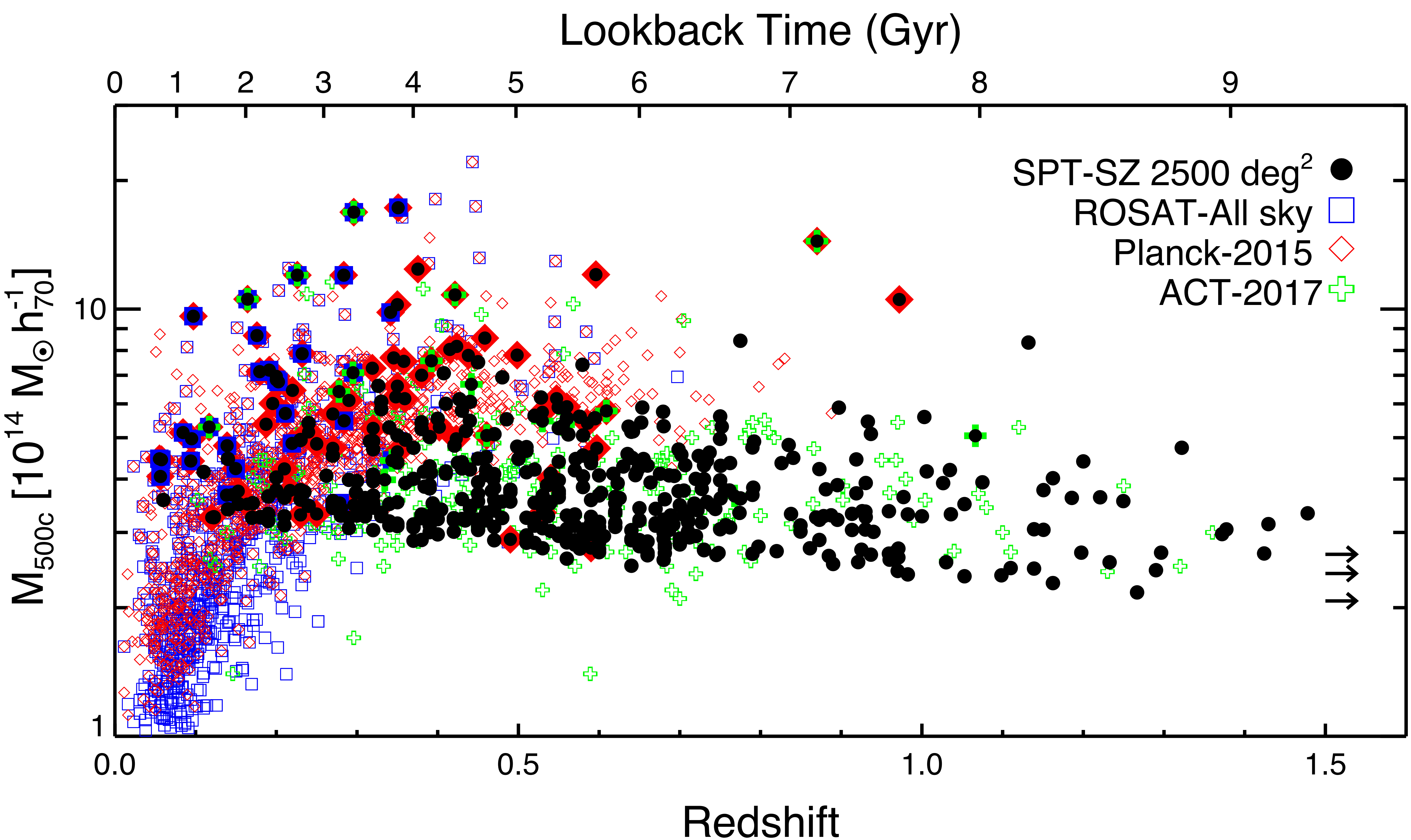


Multiple-facility Imaging Campaign for Cluster Confirmation →

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)

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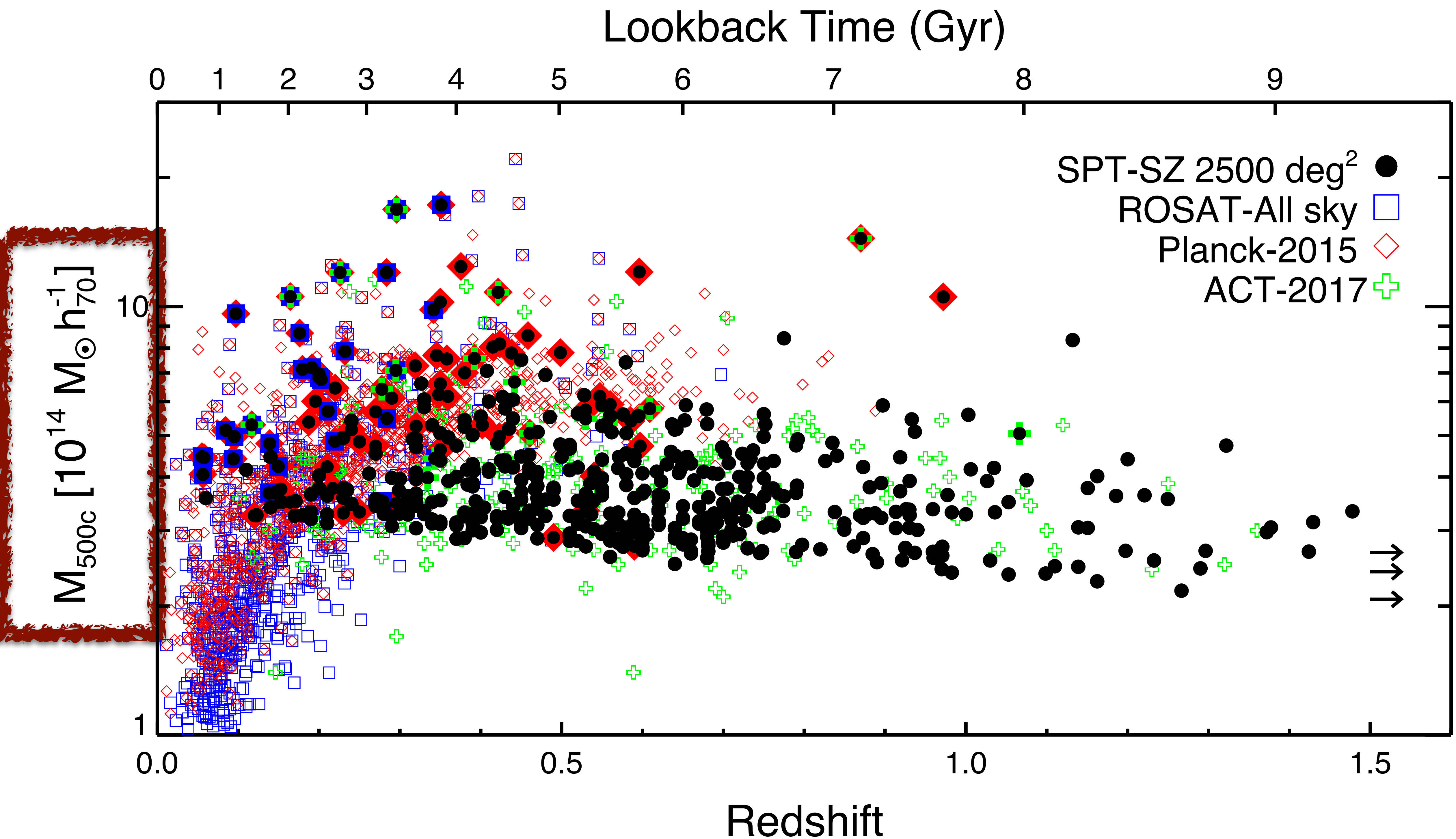

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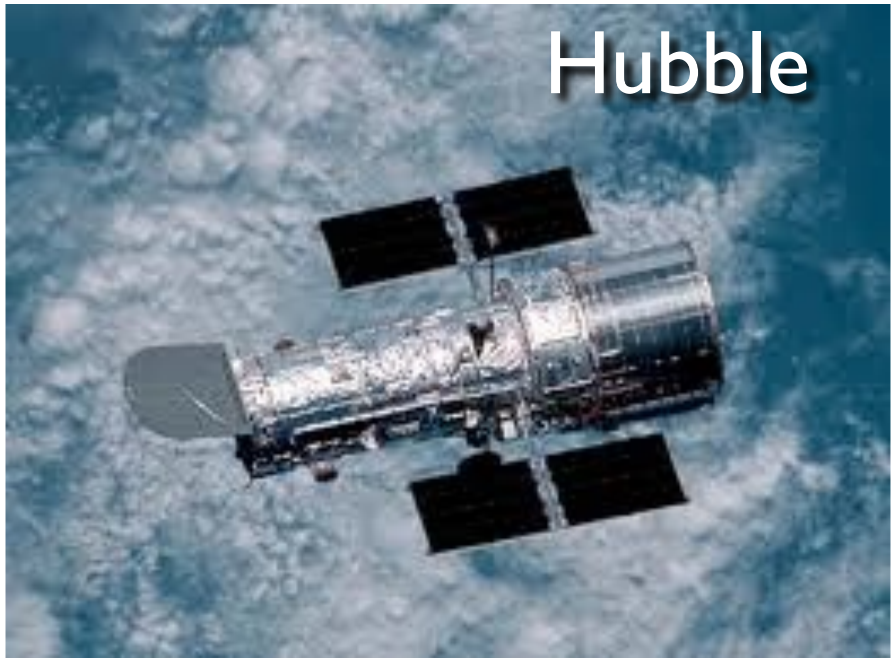
Bleem et al, ApJS, 216, 27 (2015)

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)



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

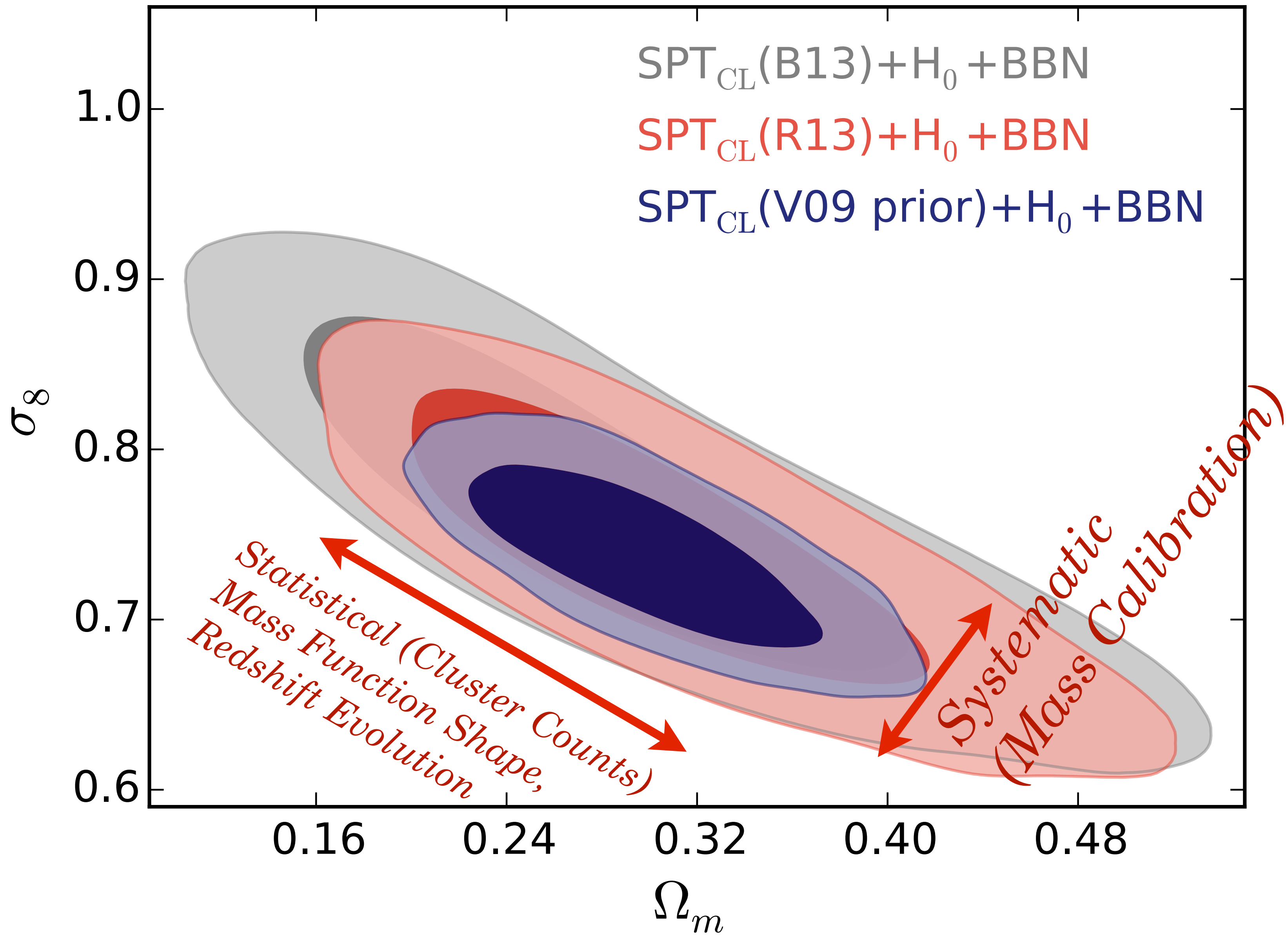
- X-ray (Y_X-M) and SZ (ζ-M) relations (4 and 5 parameters):
  - A) normalization,
  - B) slope,
  - C) redshift evolution,
  - D) scatter,
  - F) correlated scatter

6 Cosmology Parameters (plus extension parameters)

- ΛCDM Cosmology
  - $\Omega_m h^2$, $\Omega_b h^2$, A_s, n_s, θ_s
- Extension Cosmology
  - w, Σm_ν, f_{NL}, N_{eff}

Benson et al, ApJ 763, 147 (2013)

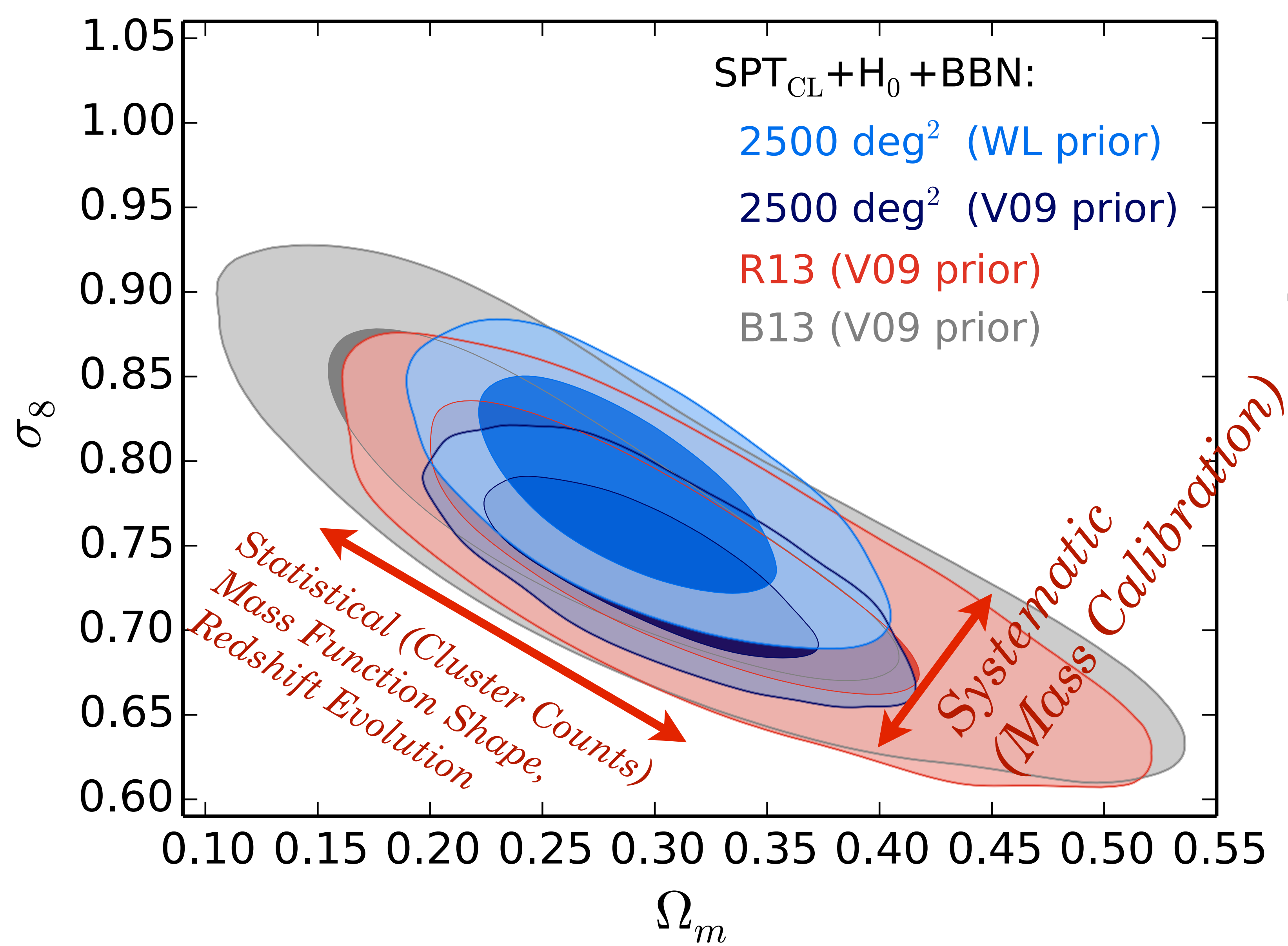
ΛCDM Constraints:



- From Benson+13 to de Haan+16, area in σ_8-Ω_m likelihood space reduced by ~4x
- Biggest improvement is in direction of parameter space helped by cluster counts

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:



- 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
  - Next step is to increase sample and extend to higher redshift

Benson et al., ApJ 763, 147 (2013) (21 clusters in cosmo sample)
Reichardt, Stalder, Bleem, et al., ApJ 763, 127 (2013) (100 clusters)
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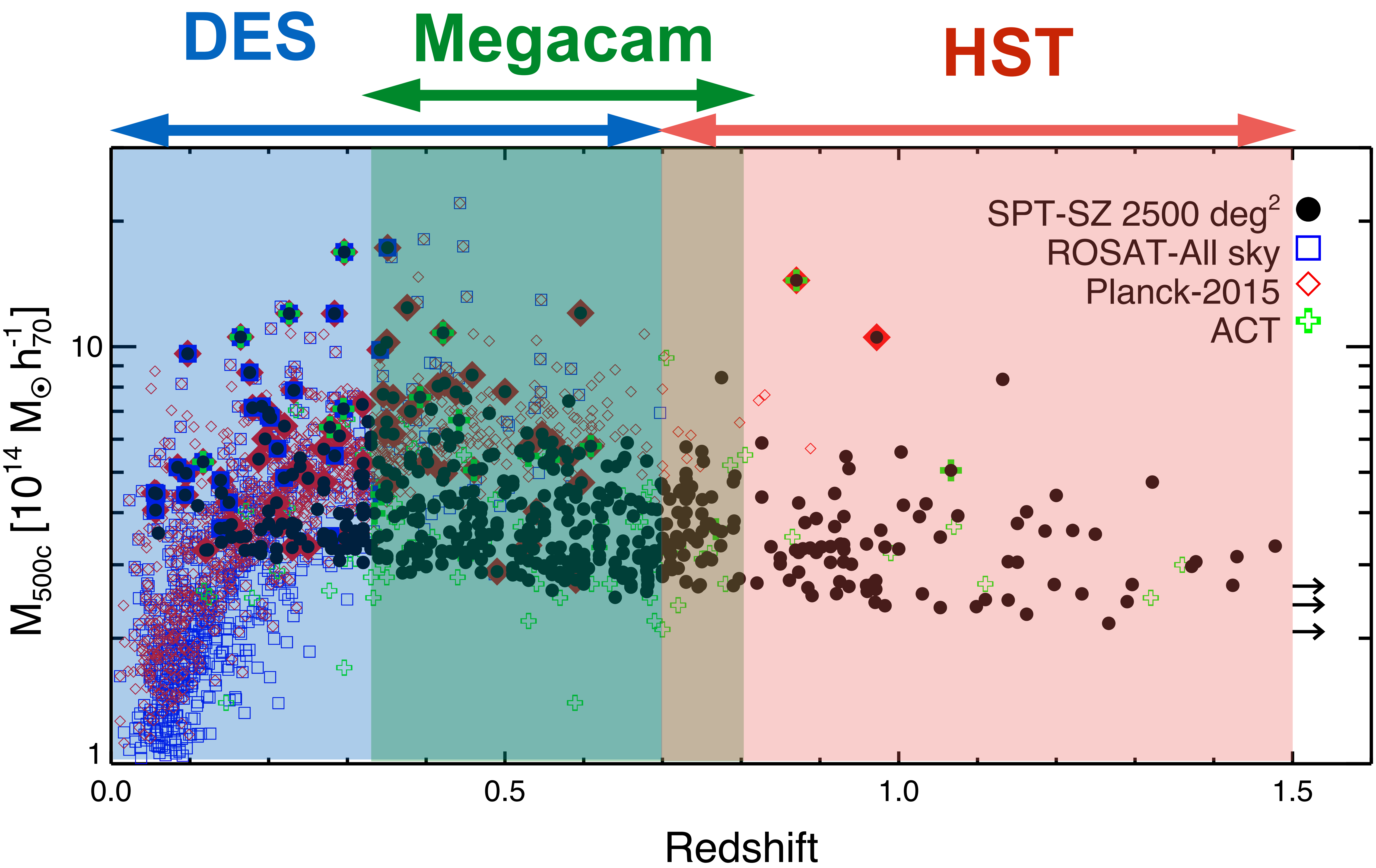
The Next Steps: [lensing, lensing, & more lensing!]



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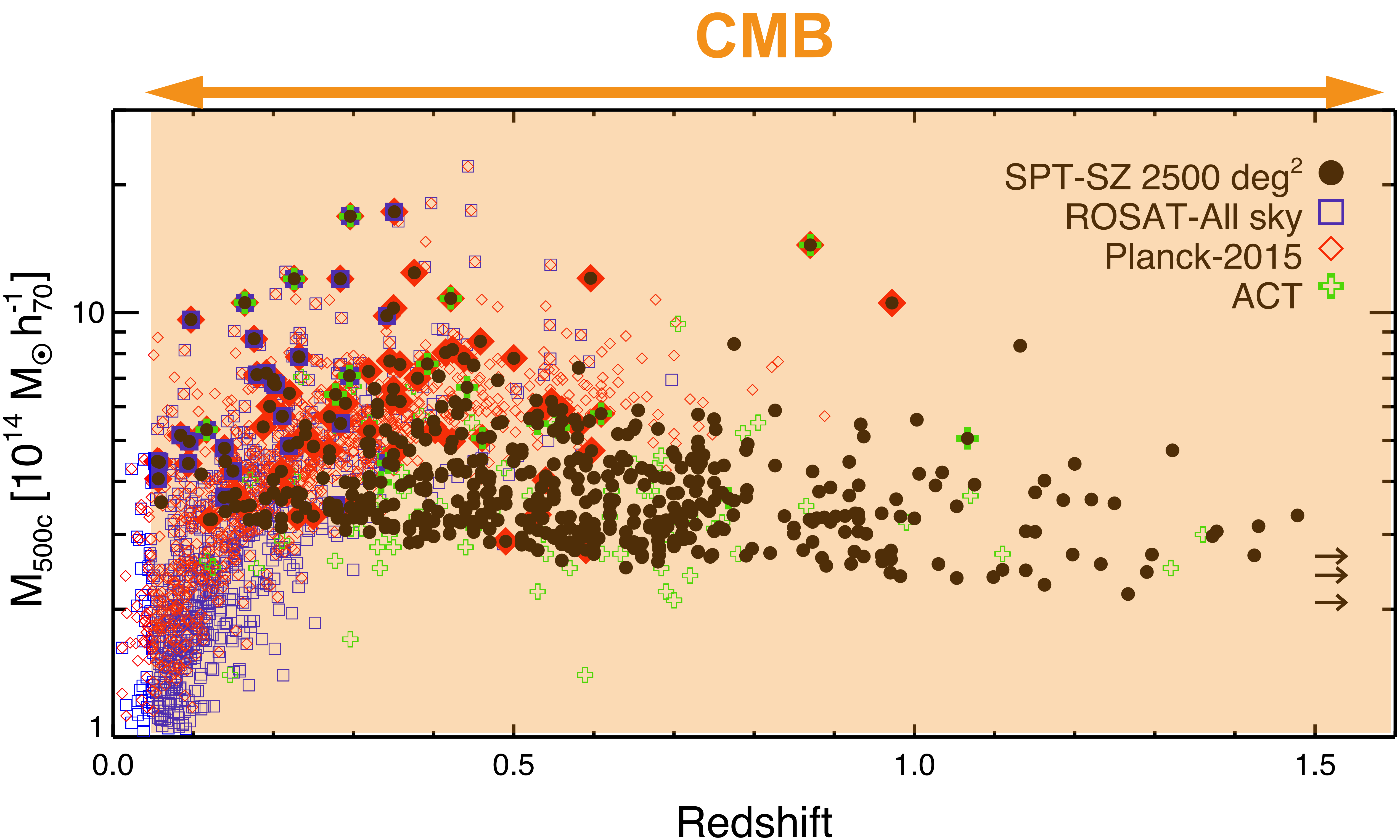
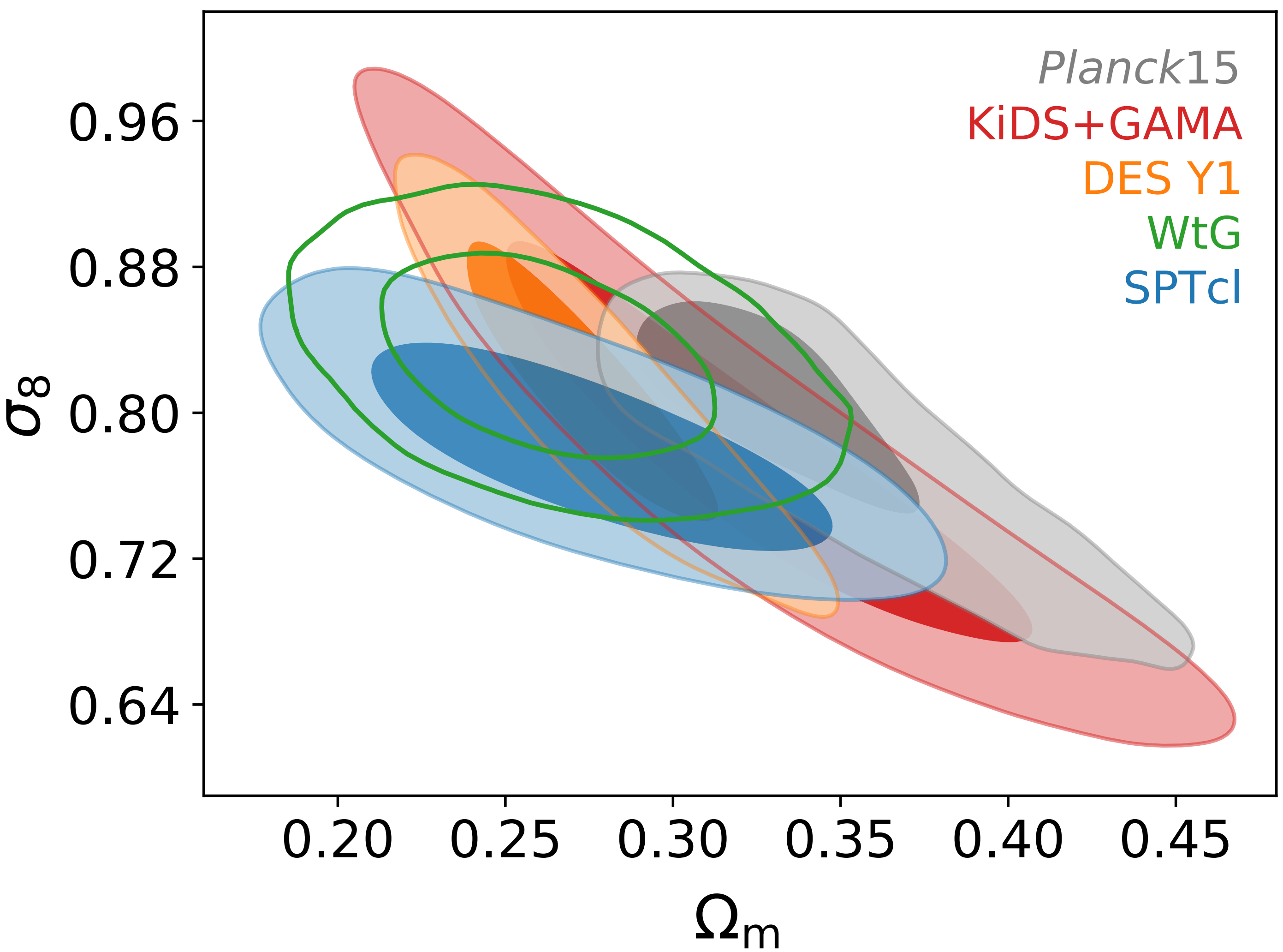
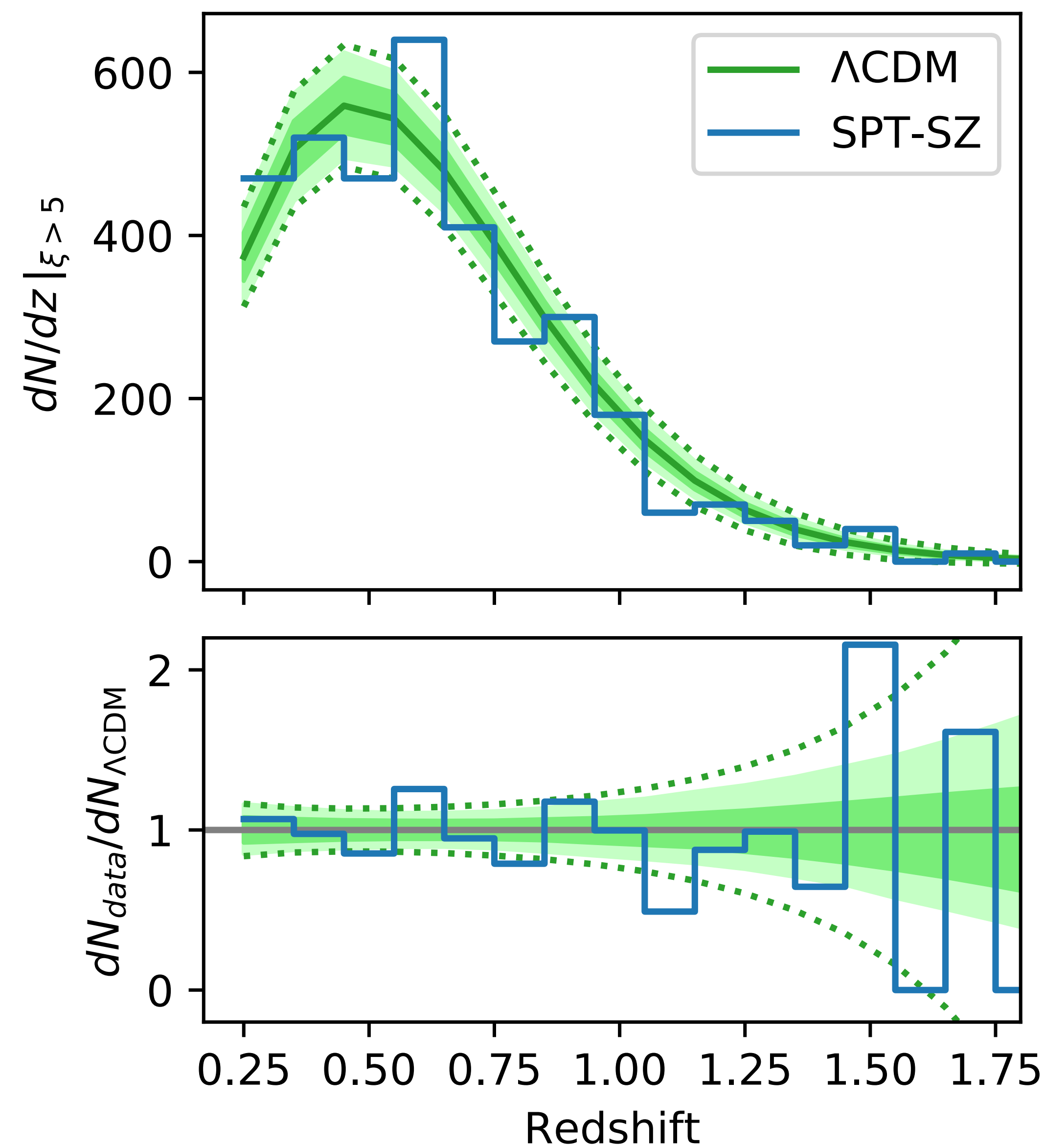


First “Internal” WL Cosmology Results from SPT

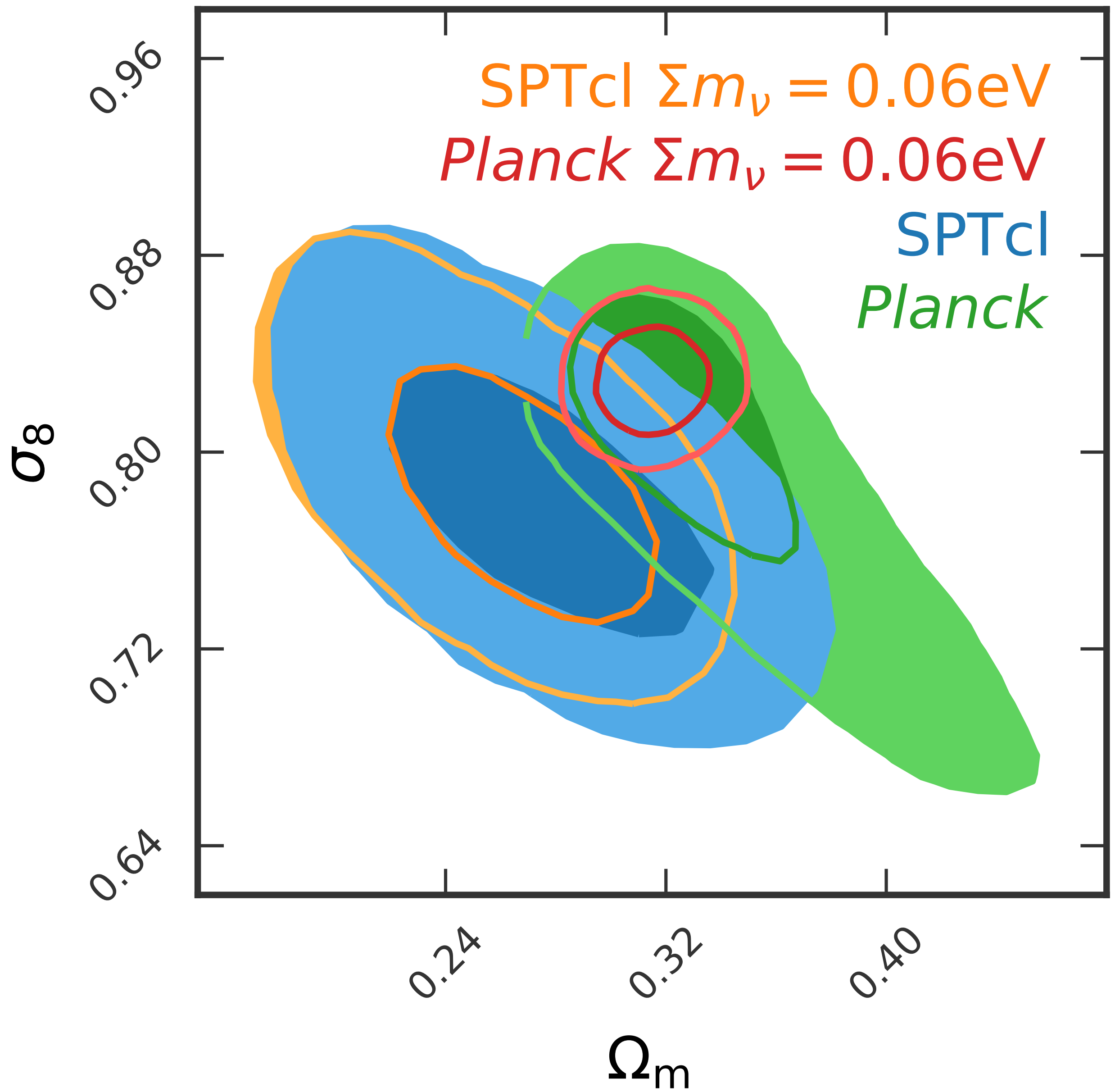


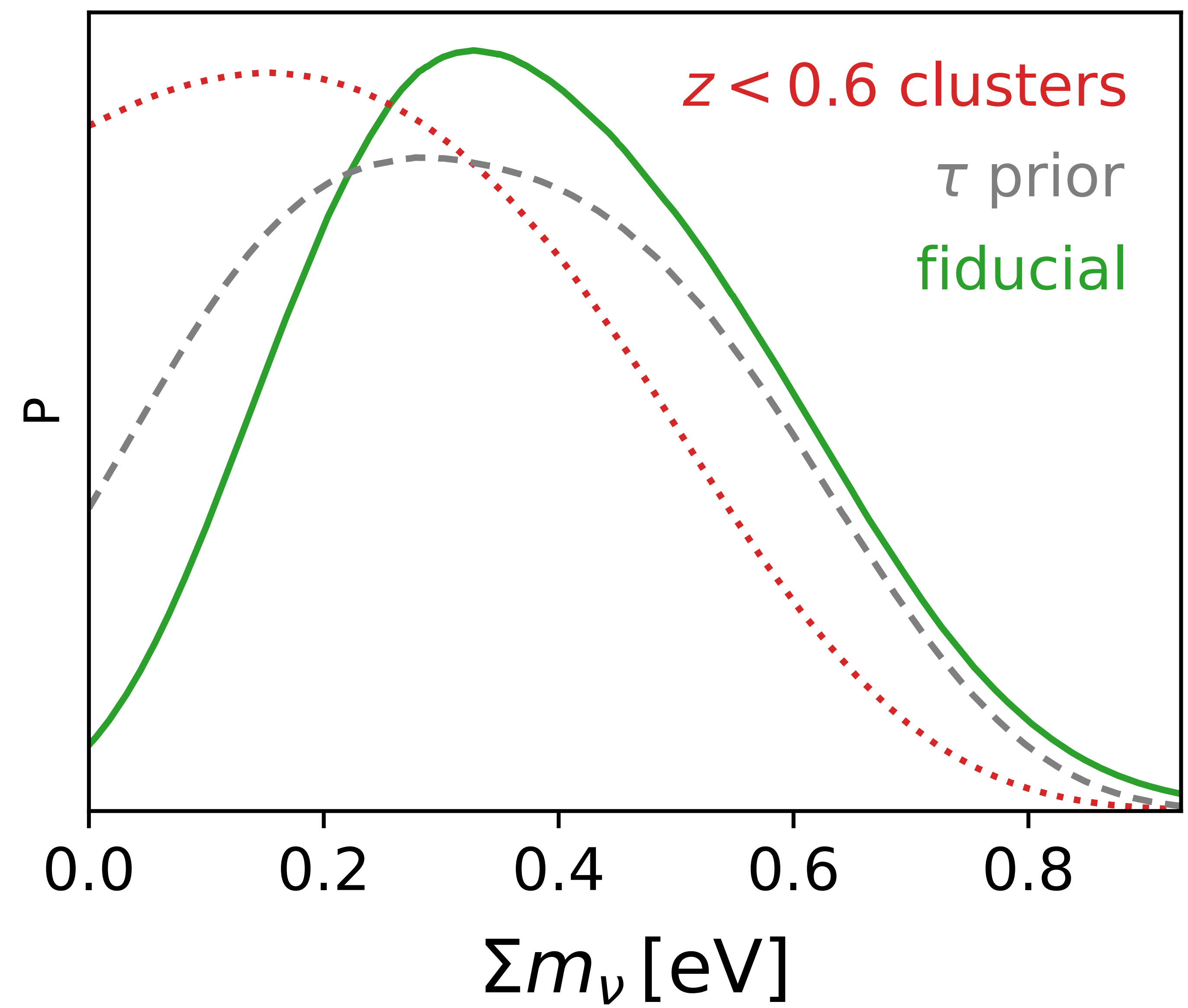


Consistent with previous SPT cluster cosmology results as well as other surveys; can constrain scaling relations without priors

S Bocquet et al; ApJ 878, 55 (2019)

Interesting internal pulls as we test consistency of the dataset





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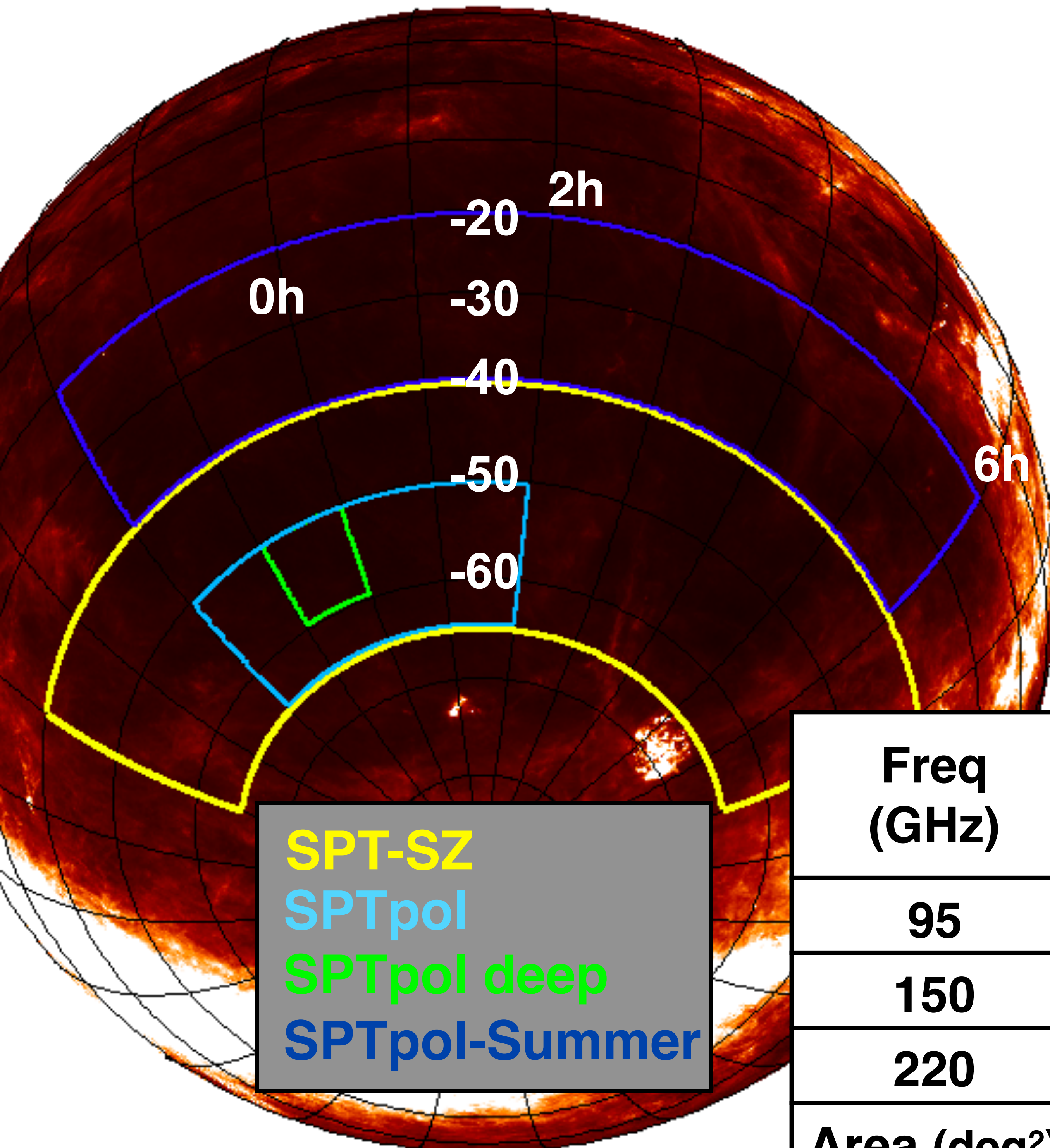
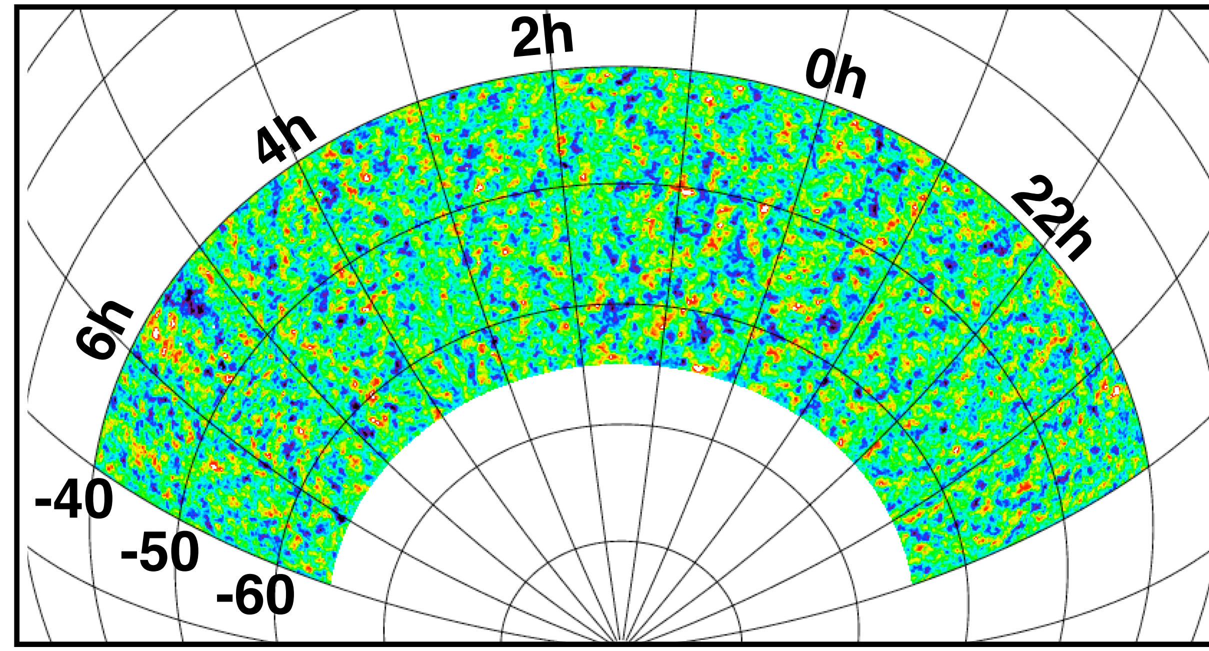
The SPT Surveys



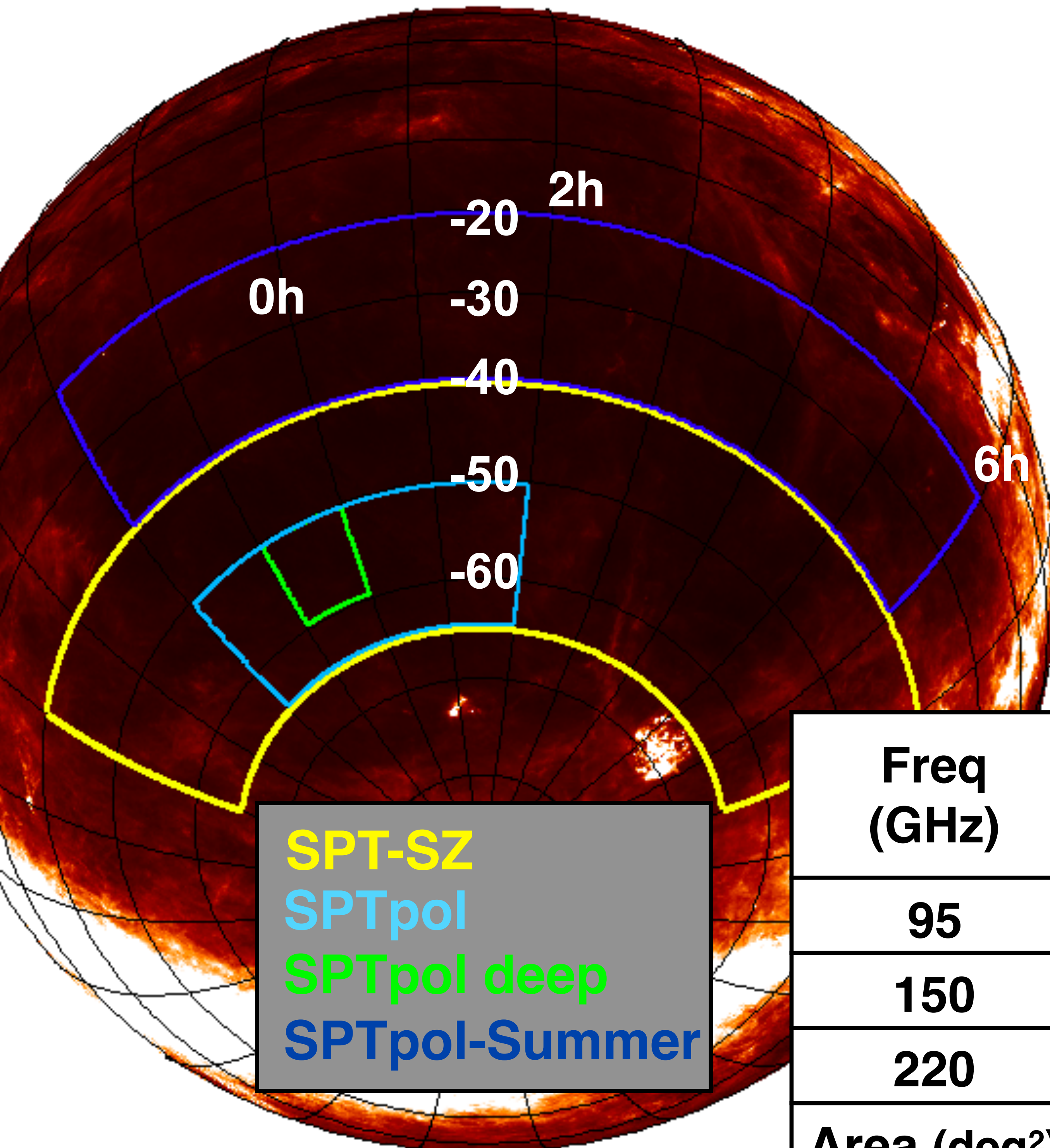


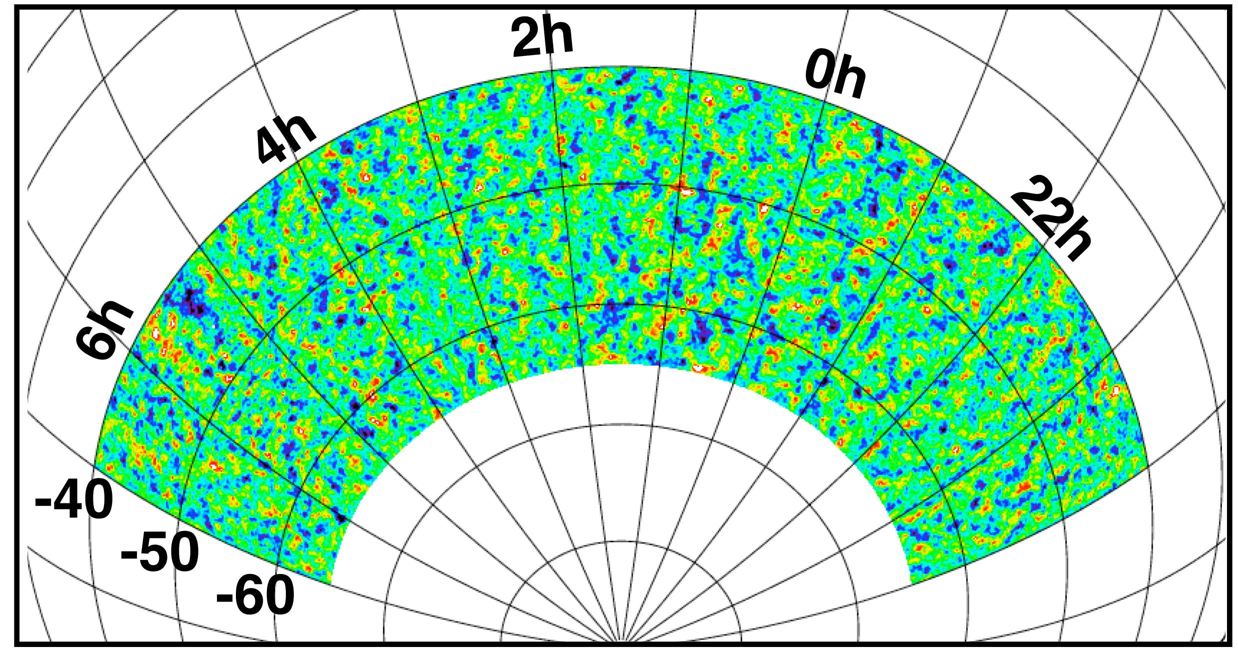
Freq (GHz)	SPT-SZ	SPTpol deep	SPTpol	SPTpol Summer
95	40	10	12	50
150	17	5/3.5	5	25-30
220	80	40	40/80	-
Area (deg²)	2500	100	500	2700
Status	*Complete*	*Complete*	*Complete*	*Complete*

5000 deg² 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 Surveys





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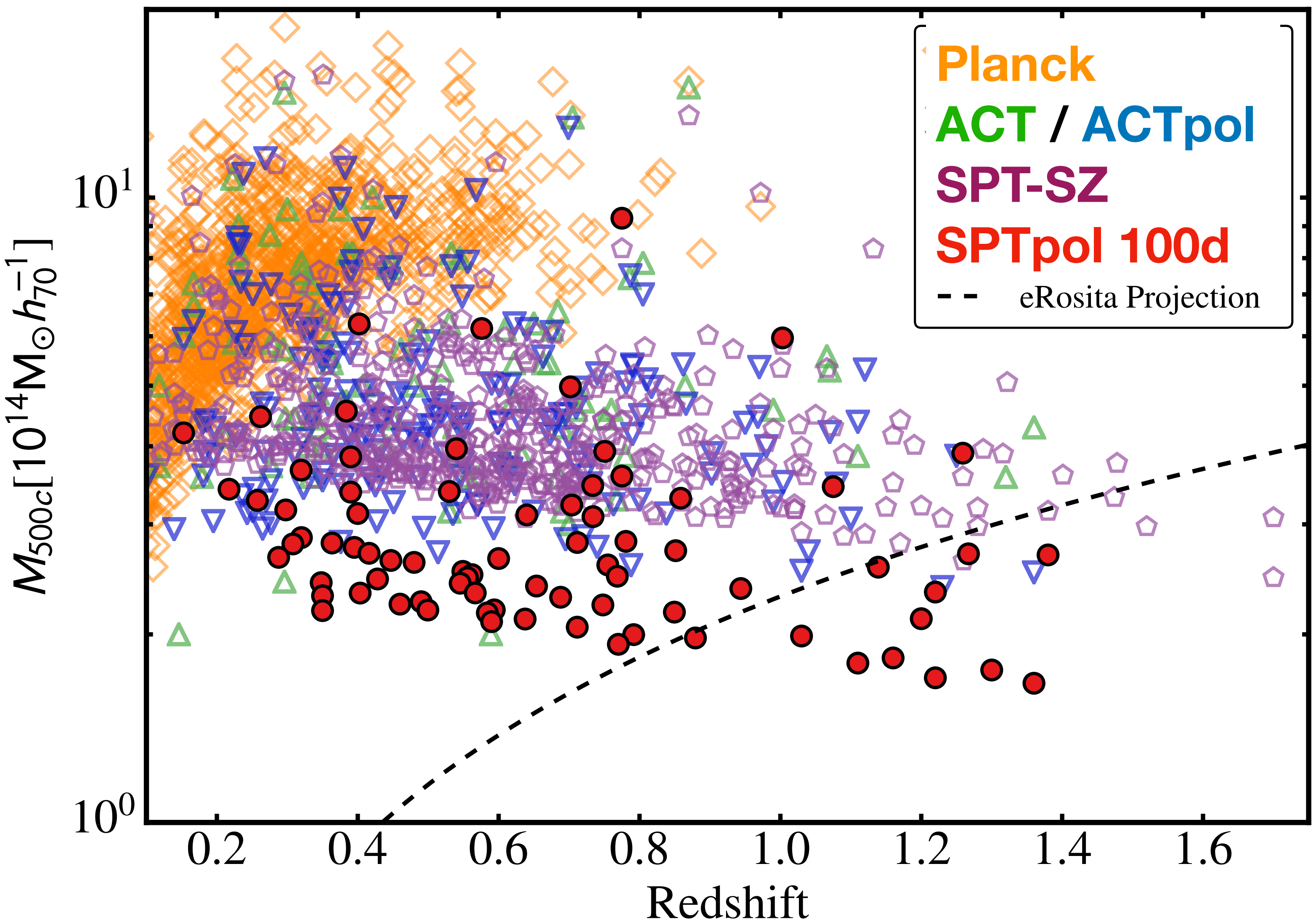
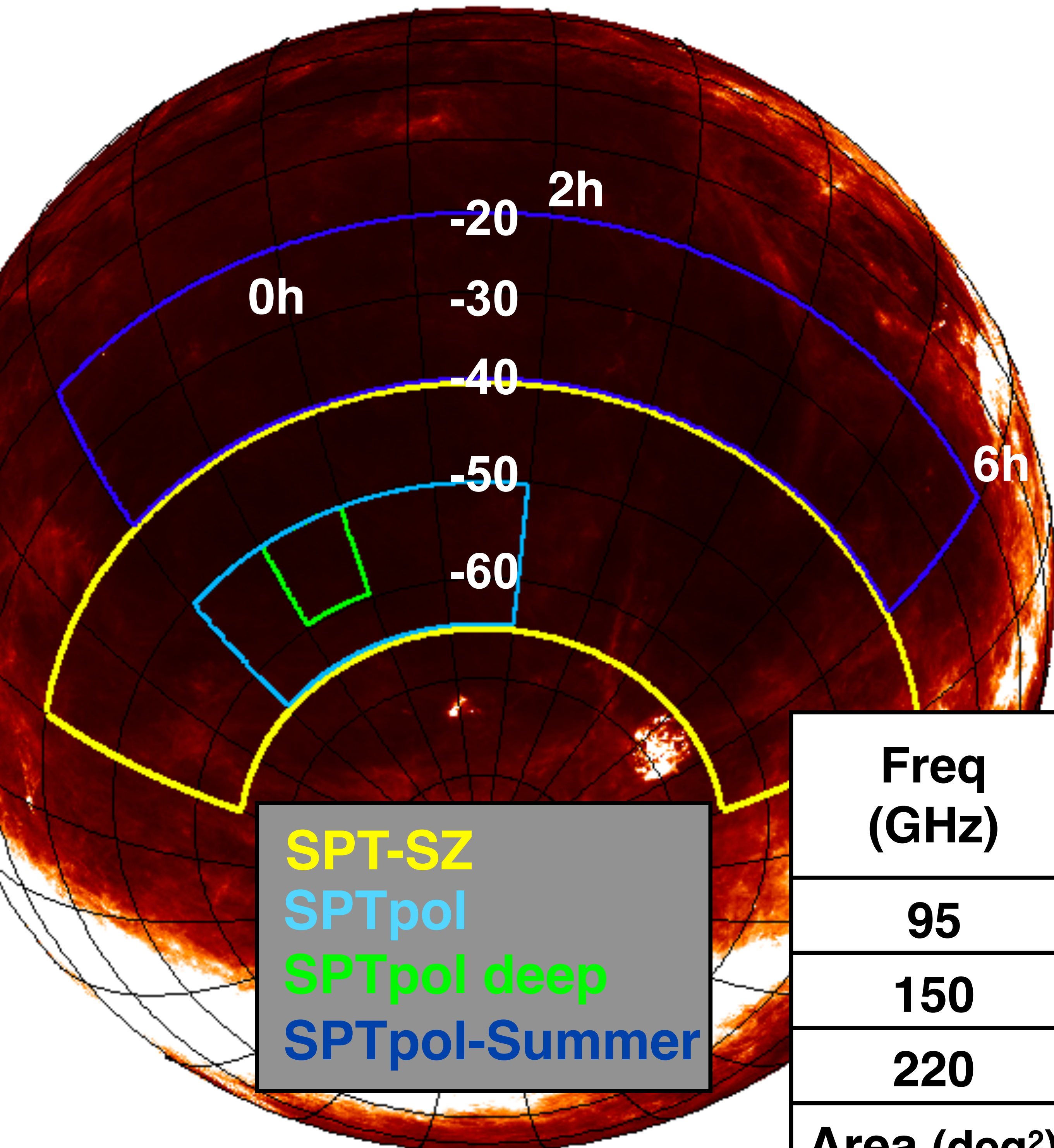
SPTpol-100d: Deep Survey

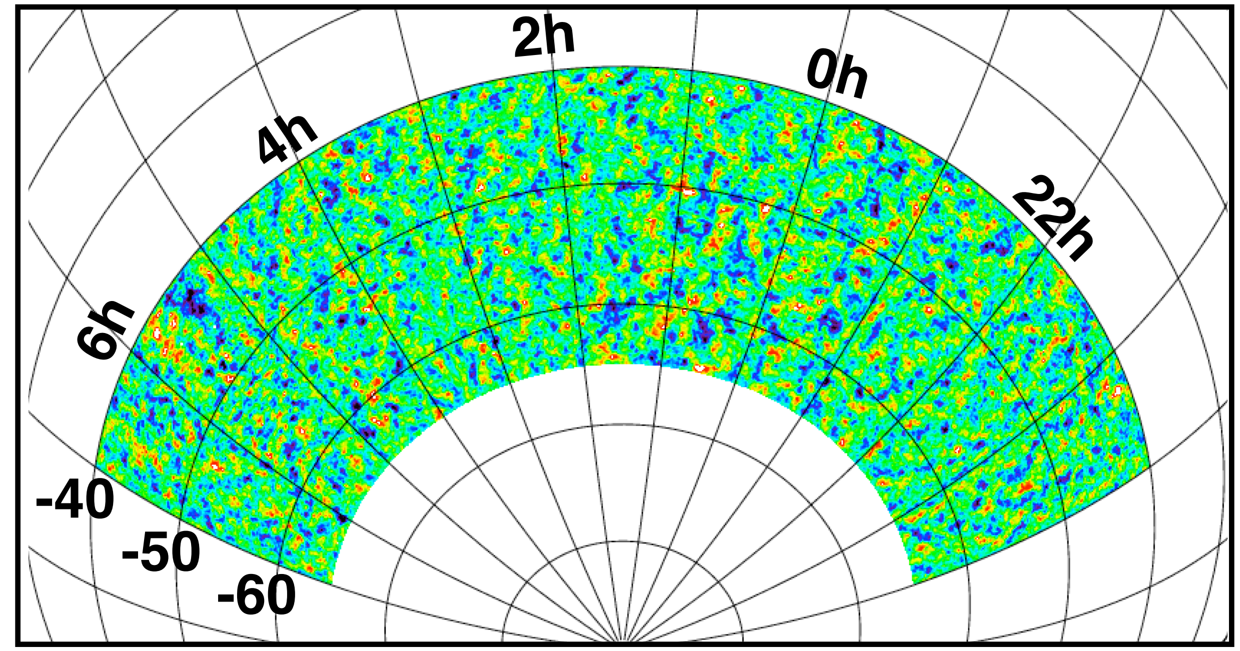


- SPTpol 100d "deep field" is 3-4x deeper than SPT-SZ survey
- 81 clusters (~1 per deg²)
  - 15 clusters at $z > 1$ (~19% of sample)
- SPTpol-deep 100d field overlaps with multi-wave surveys:
  - **Herschel** SPIRE (250, 350, 500 um) (Viero et al., 1810.10643)
  - **Spitzer** SSDF (3.6, 4.5 um) (Ashby et al., 1308.0201)
  - **ATCA** (1.8 GHz) (Tothill et al., 2013atnf.prop.5598T)
  - **XMM-XXL** (25 deg²) (Pierre et al.)
  - **Targeted Chandra** (LP PI: McDonald) on 18 clusters at $0.8 < z < 1.4$; hi-z pre-cursors to the Perseus cluster

Huang, Bleem, Stalder et al. 1907.09621

The SPT Surveys





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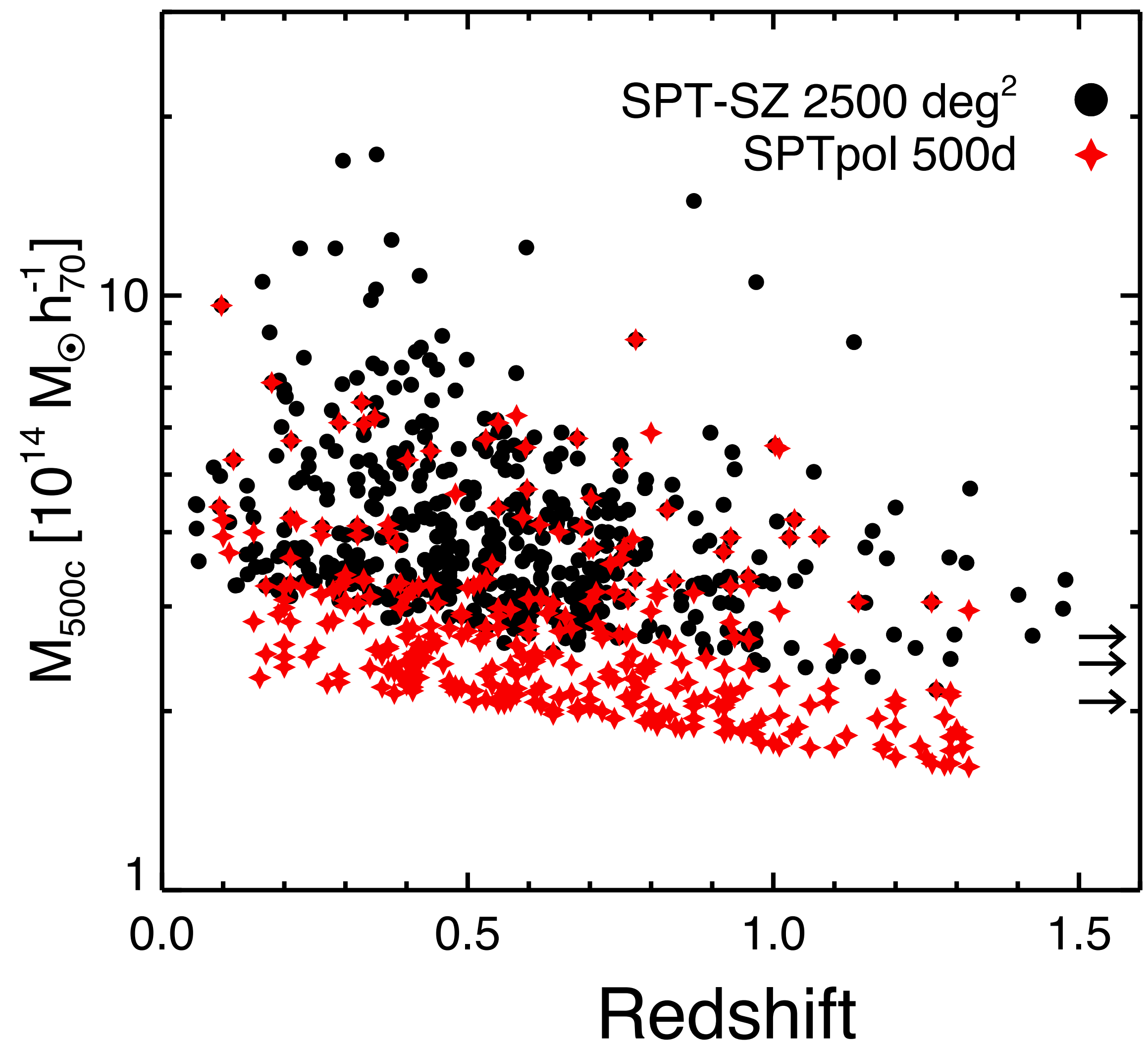
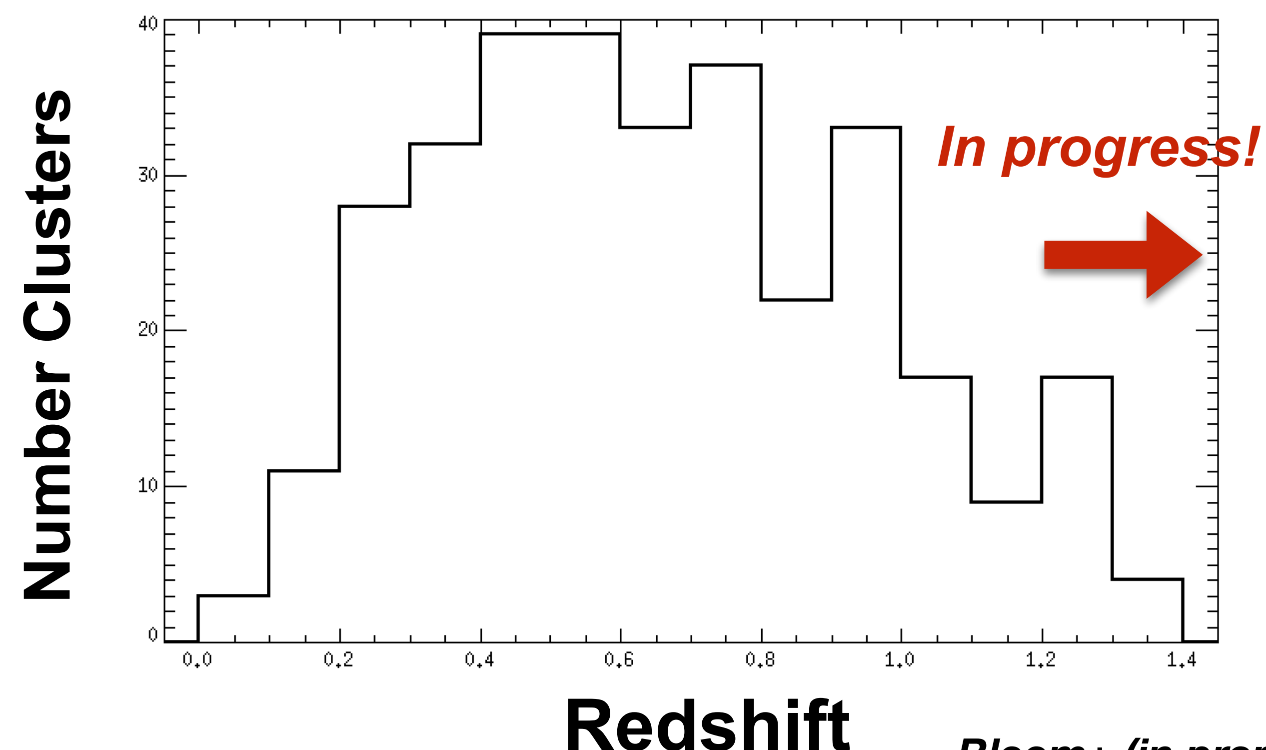
500d Catalog Construction well underway!

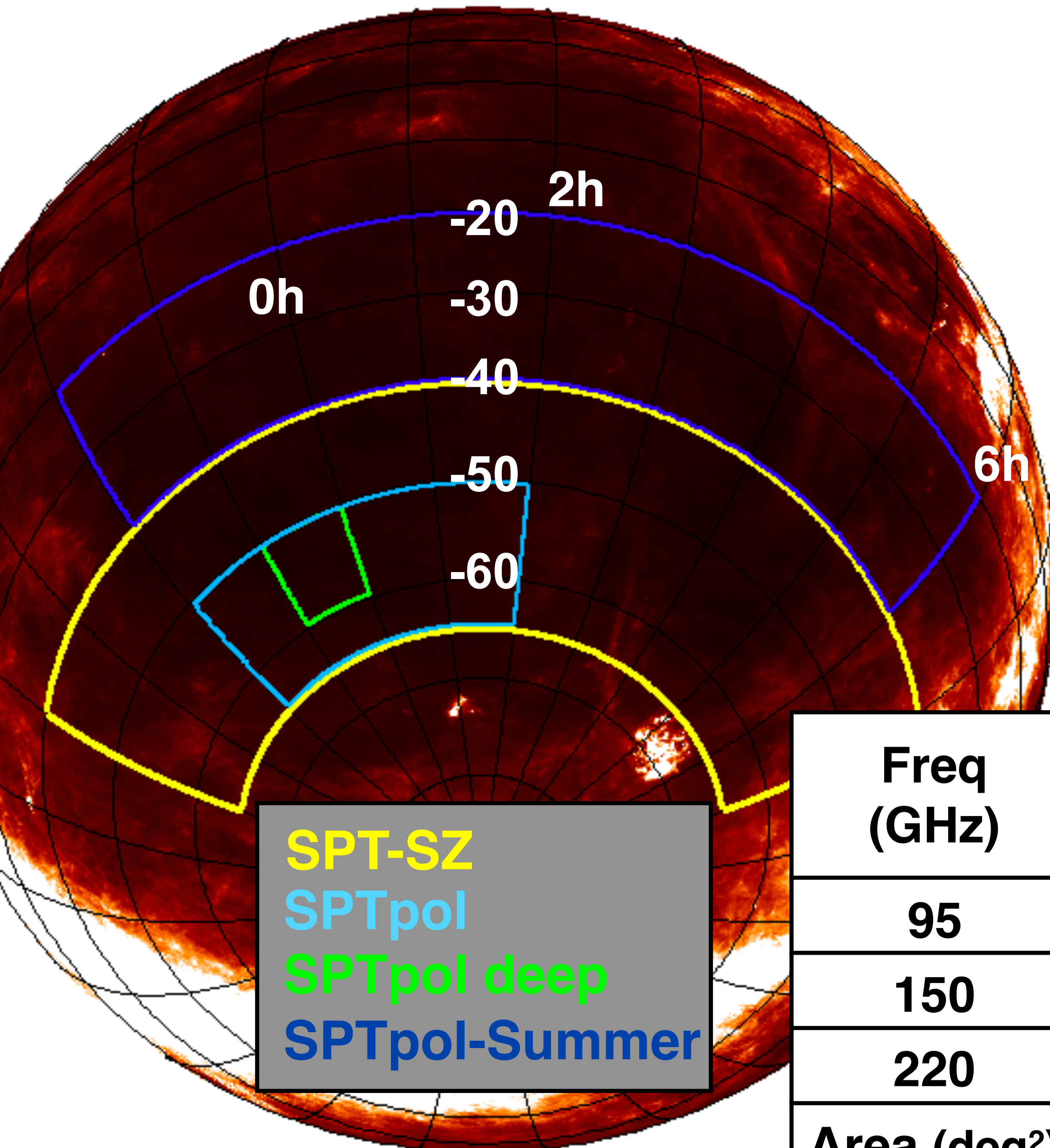
- Incorporating all SPTpol 500d data; Final 150 GHz map depth ~5 uK-arcmin
- Ongoing DES-SPT projection for cluster confirmation
- 2 Spitzer programs complete
- NIR imaging on Magellan/ FourStar

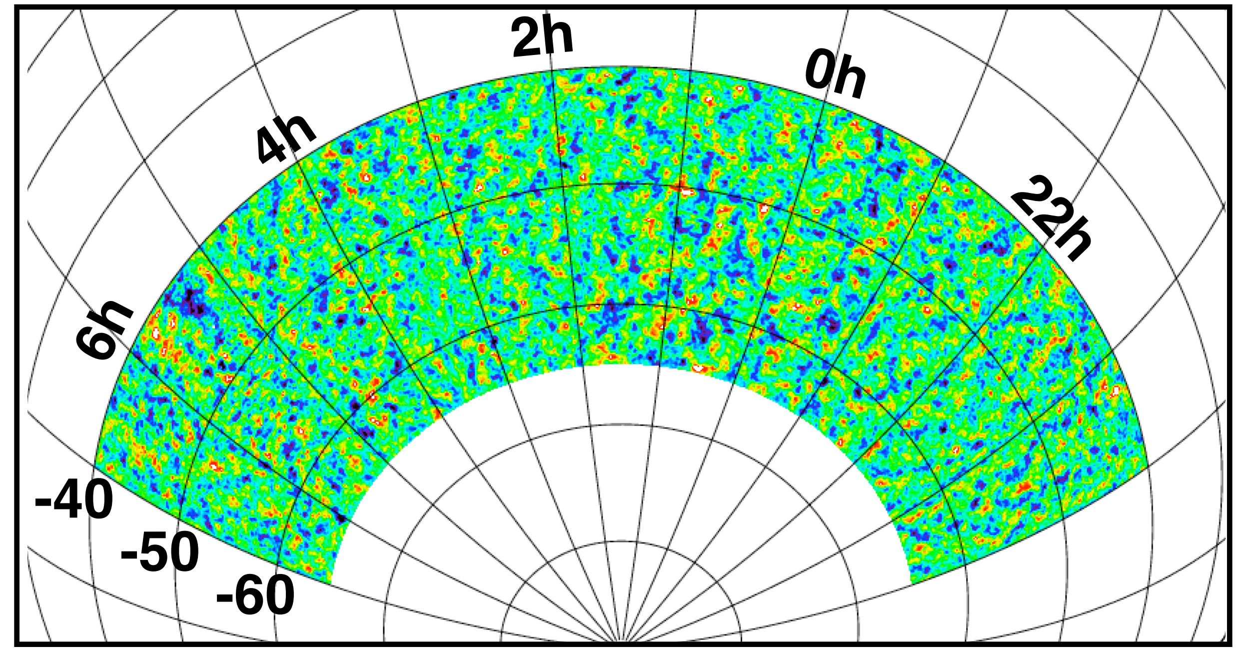




Bleem+ (in prep)

The SPT Surveys



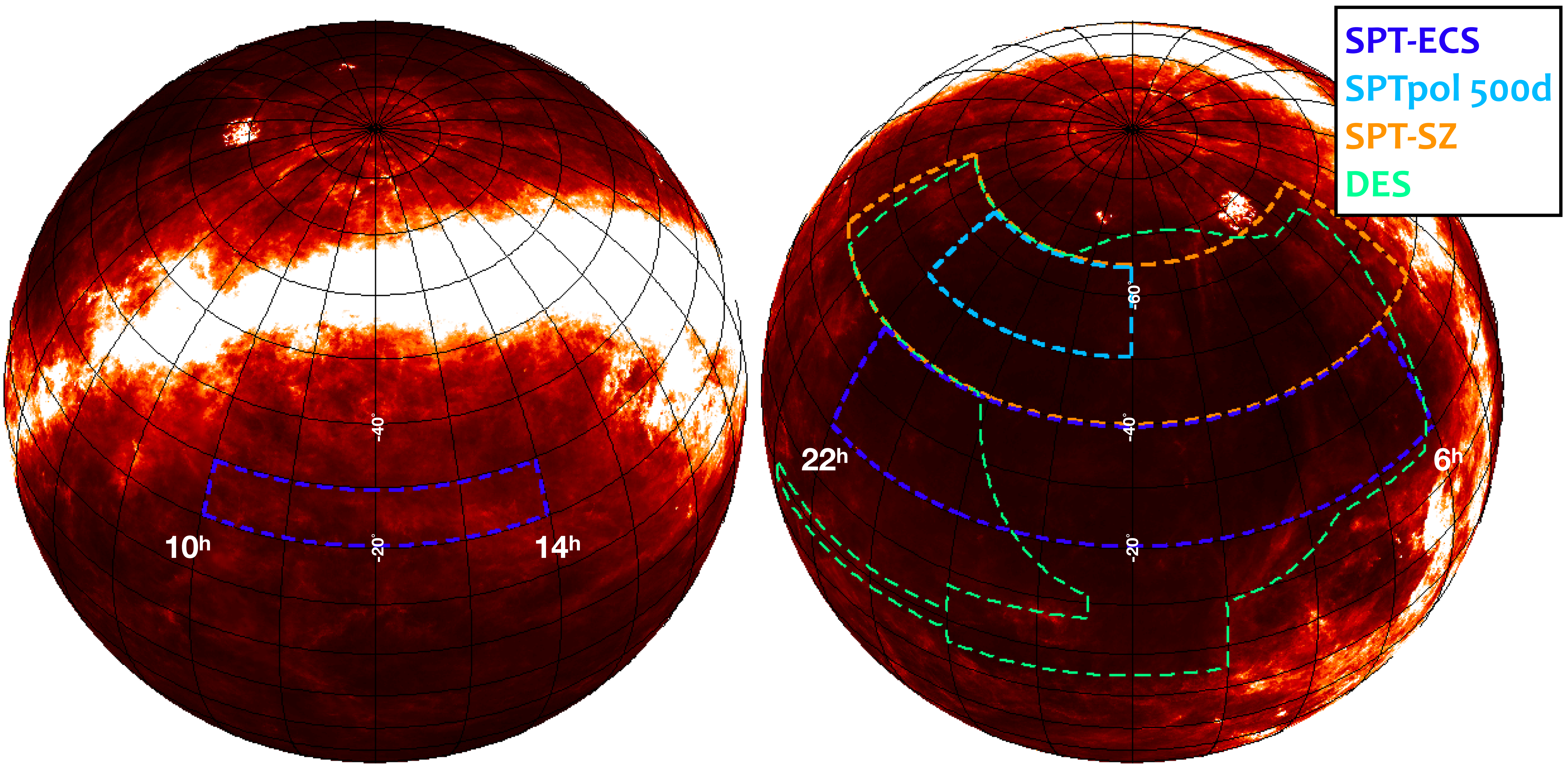


Freq (GHz)	SPT-SZ	SPTpol deep	SPTpol	SPTpol Summer
95	40	10	12	50
150	17	5/3.5	5	30
220	80	40	40/80	-
Area (deg²)	2500	100	500	2700
Status	*Complete*	*Complete*	*Complete*	*Complete*

5000 deg² surveyed in total by SPT-SZ and SPTpol

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

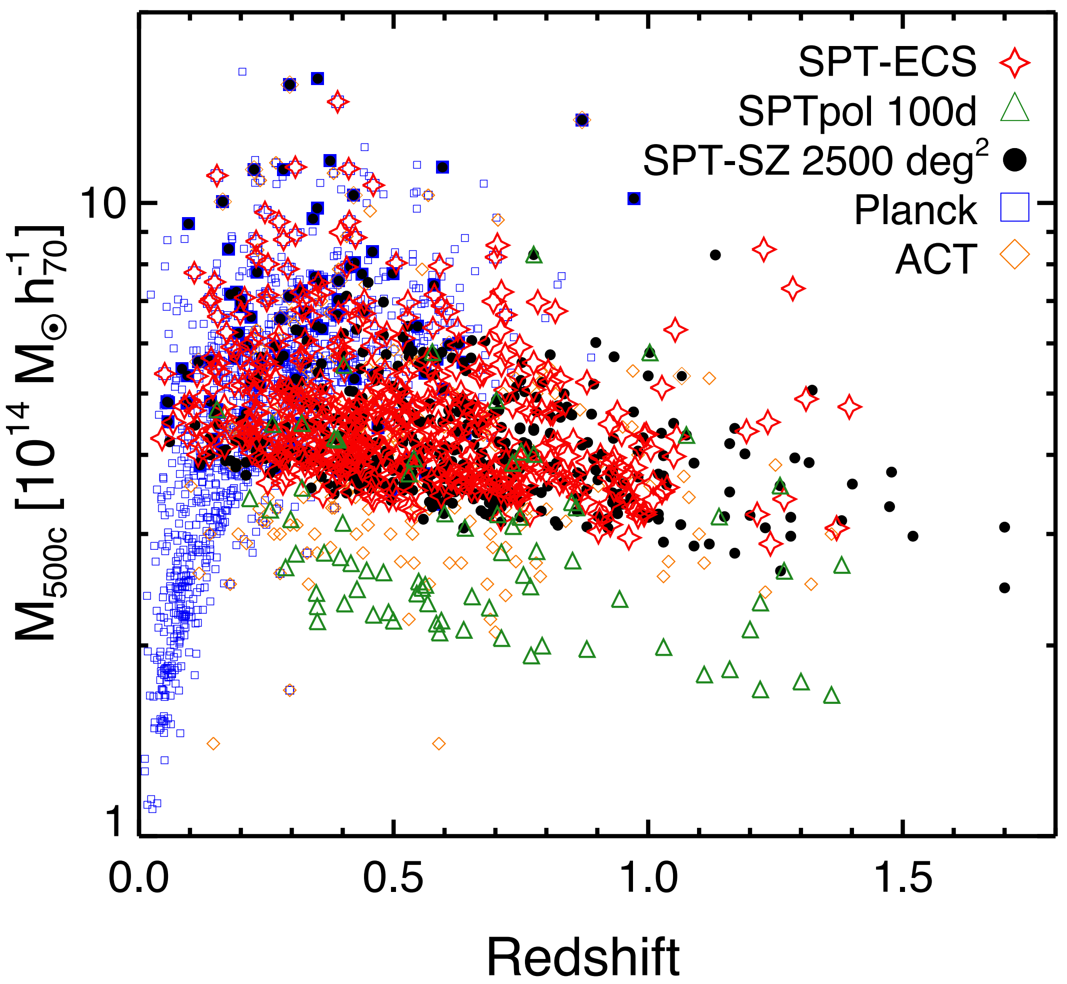
The SPTpol Extended Cluster Survey

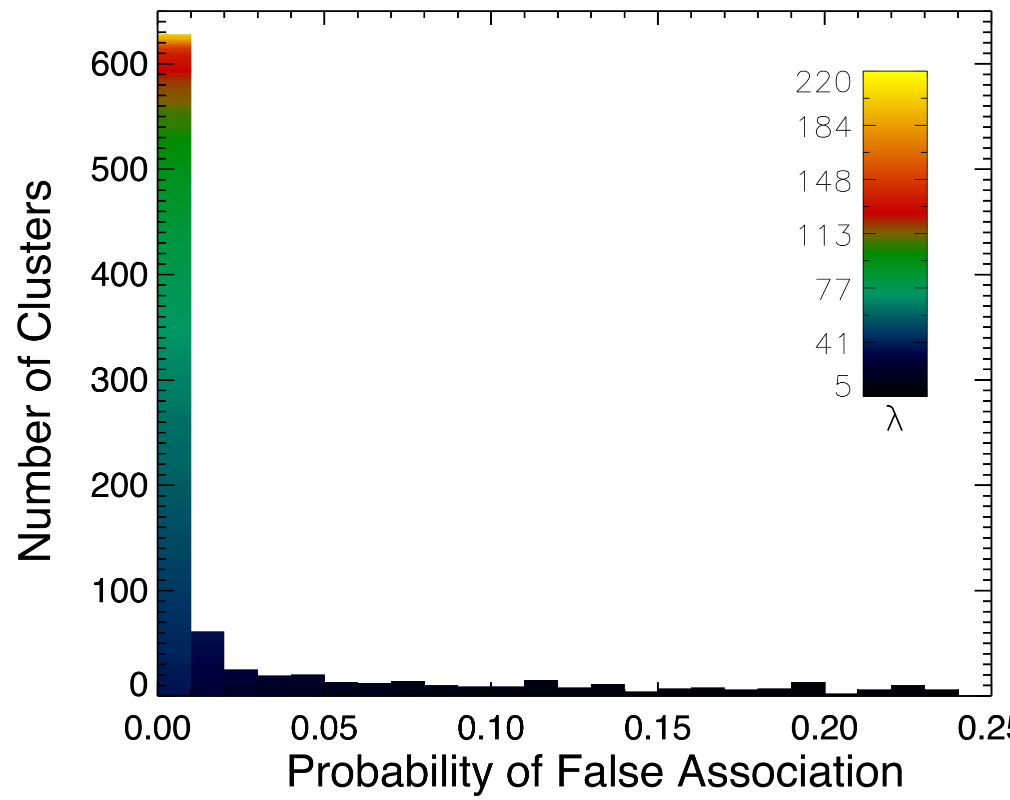


~2700 sq-degree survey, approximately *Planck* depths at arcmin resolution

New SZ-Selected catalog from 2700d of SPTpol Data!

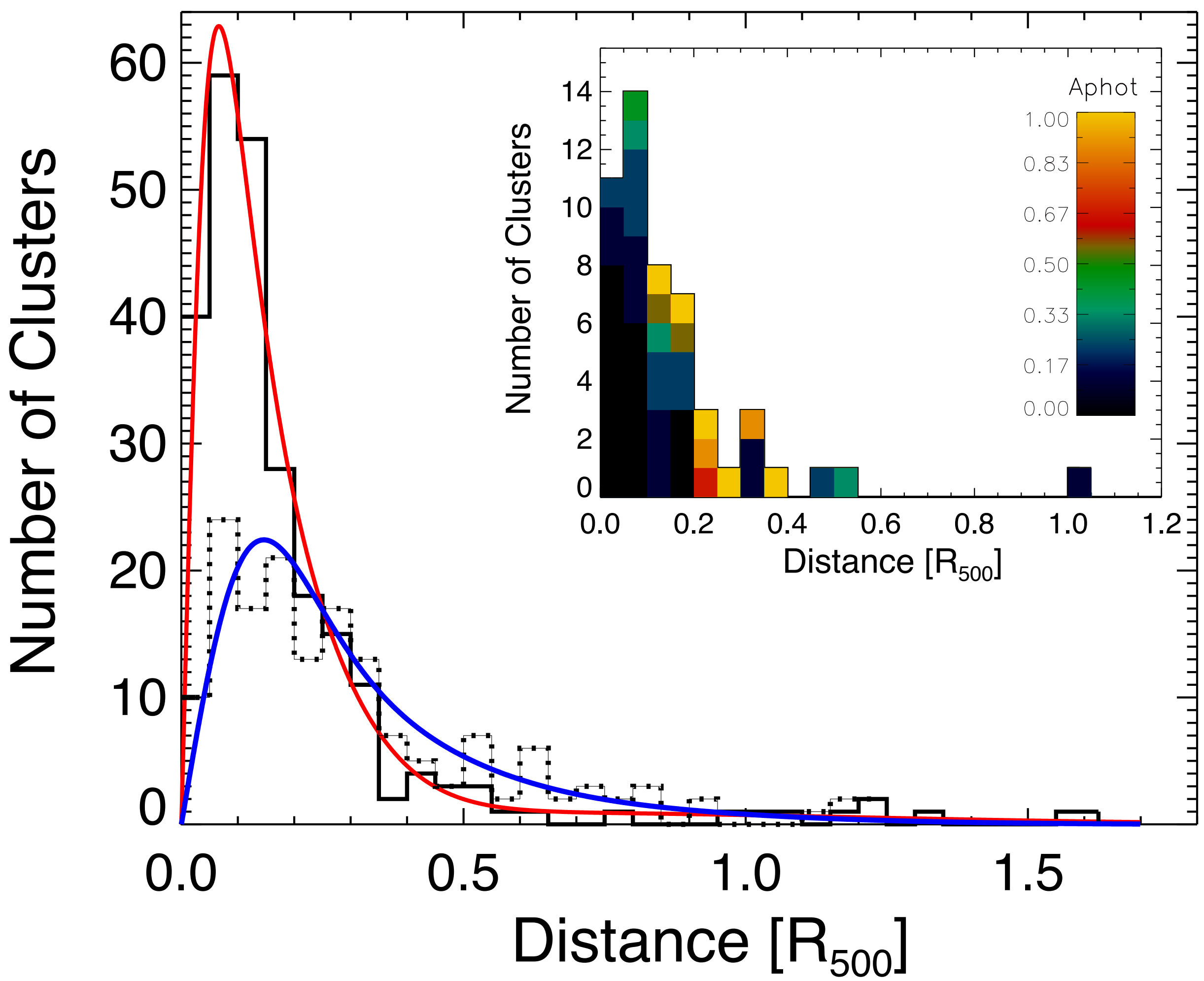
- 447 SZ-selected clusters, with SPTpol 100d and SPT-SZ brings total number of clusters selected by SPT to >1,000
- Median redshift z=0.49, median mass M_{500c} ~4.4 x 10^{14} M_{sun}/h_{70}
- DES redMaPPeR confirmation for clusters to z~1
- PanStarrs, WISE, & targeted imaging of clusters (Magellan/ PISCO) outside of DES survey & of the highest redshift systems (FourStar, *Spitzer*)



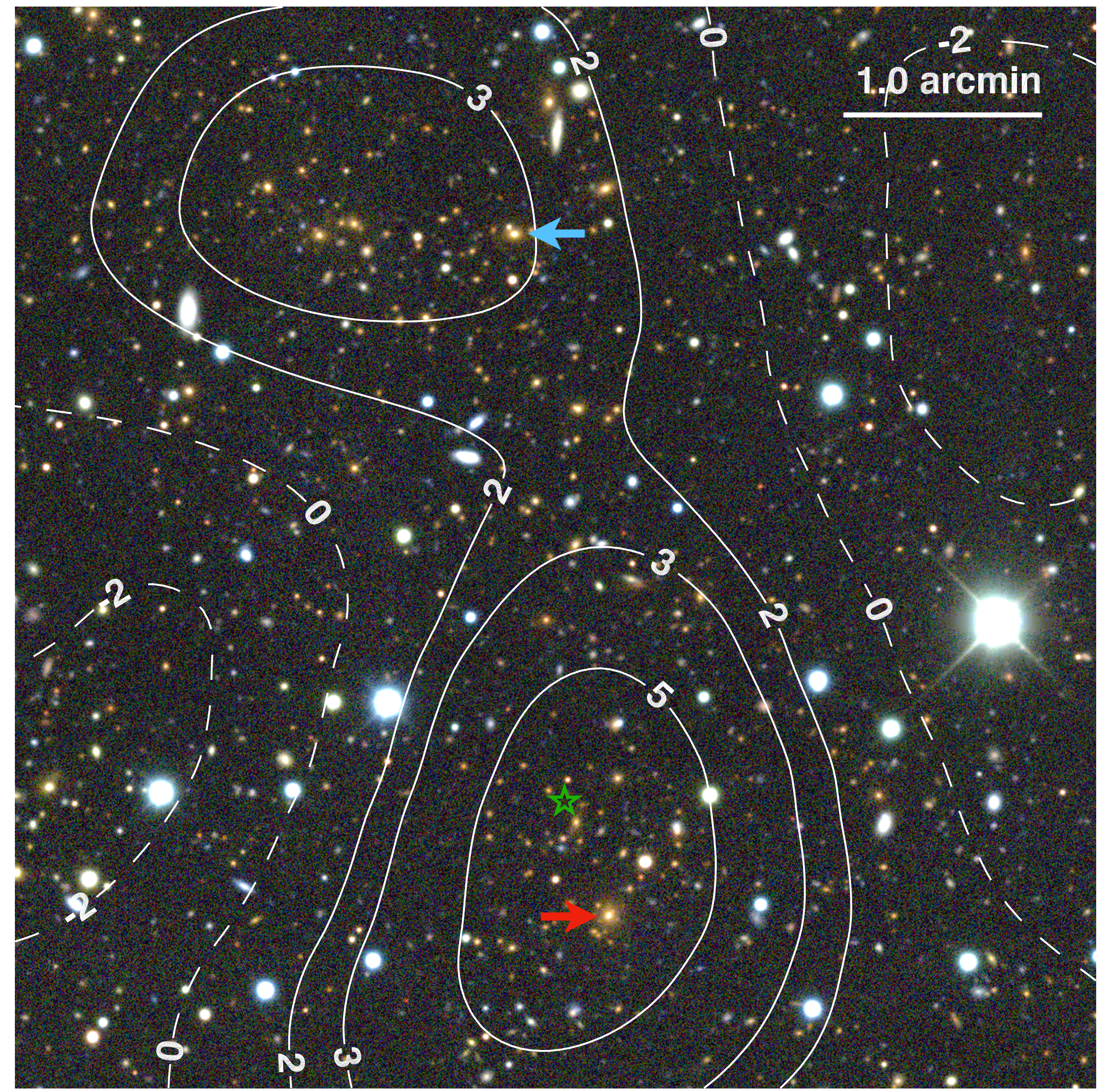


Bleem+ (in prep)

At the high mass end, we can leverage SPT cluster data to characterize optically-selected clusters from DES.

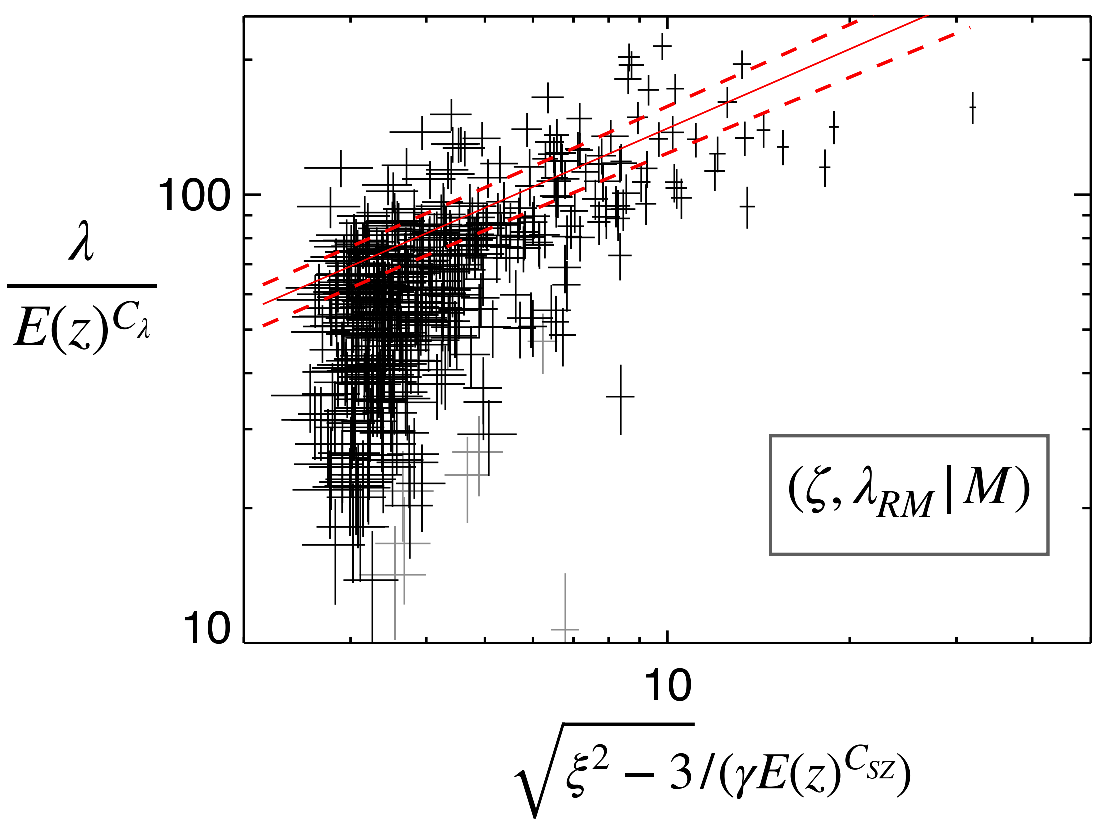


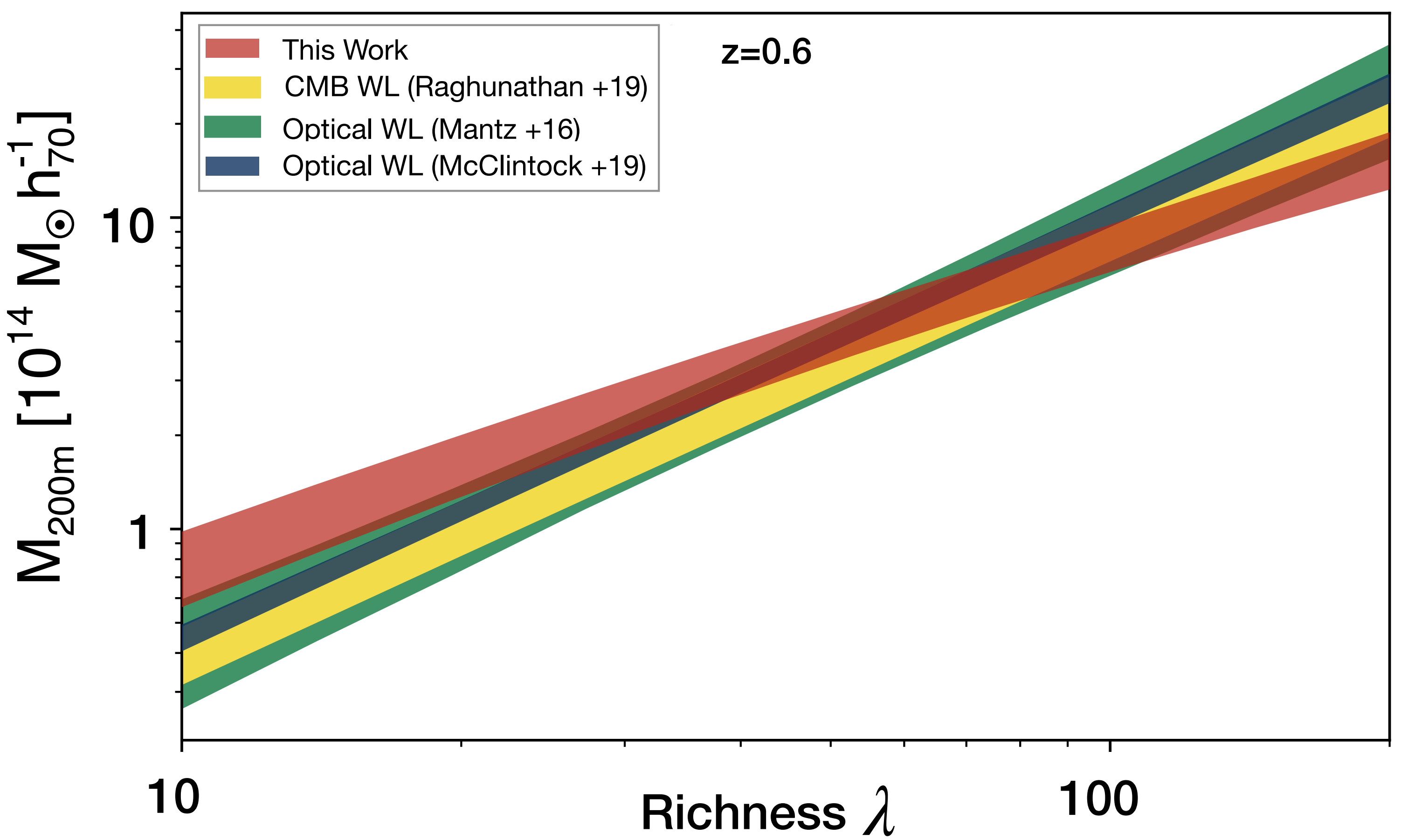
BCG - gas centroid separation



Bleem+ (in prep)

At the high mass end, we can leverage SPT cluster data to characterize optically-selected clusters from DES.





Mass-Richness Relation

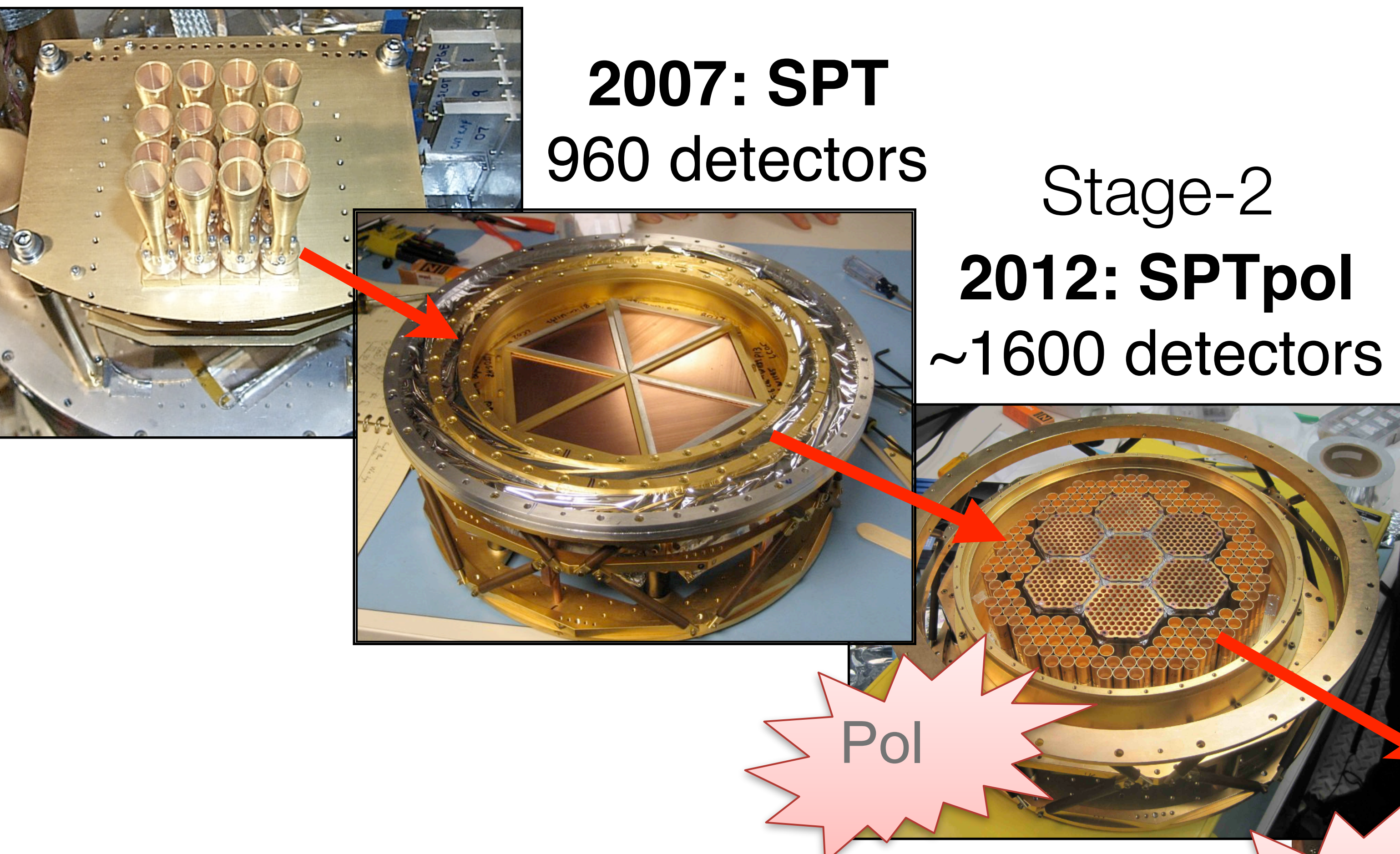
Bleem+ (in prep)

Whats next? Evolution of CMB Focal Planes

2001: ACBAR
16 detectors

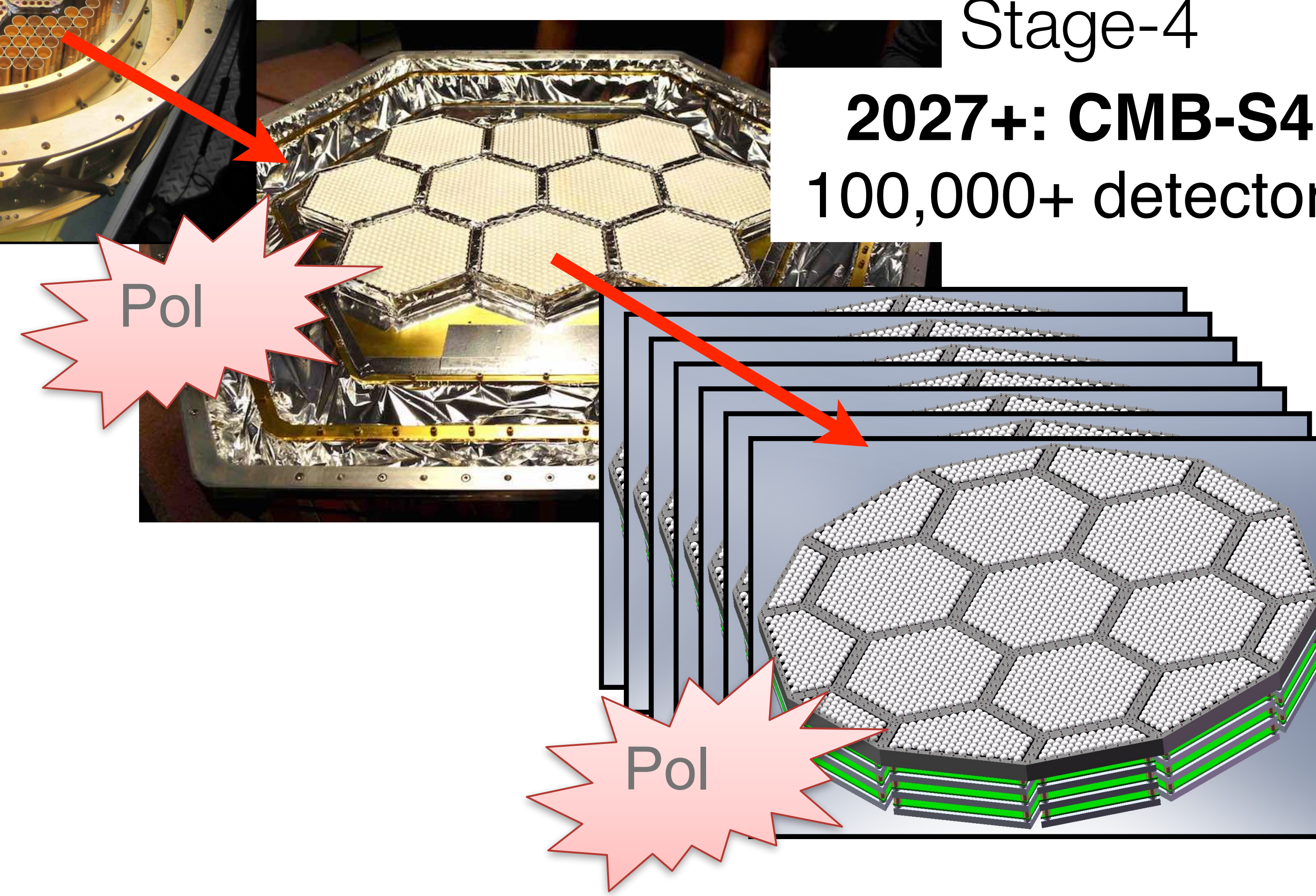
2007: SPT
960 detectors

Stage-2
2012: SPTpol
~1600 detectors



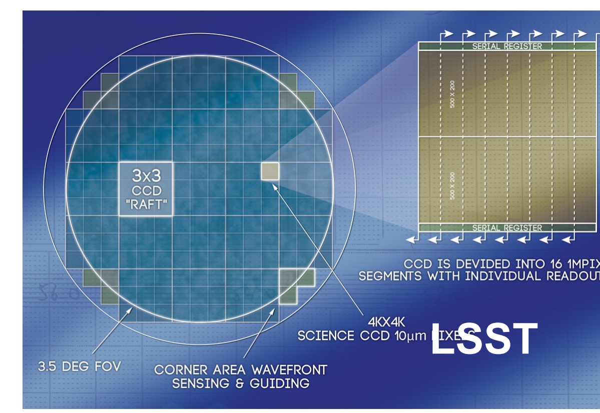
Stage-3
2017: SPT-3G
~15,200 detectors

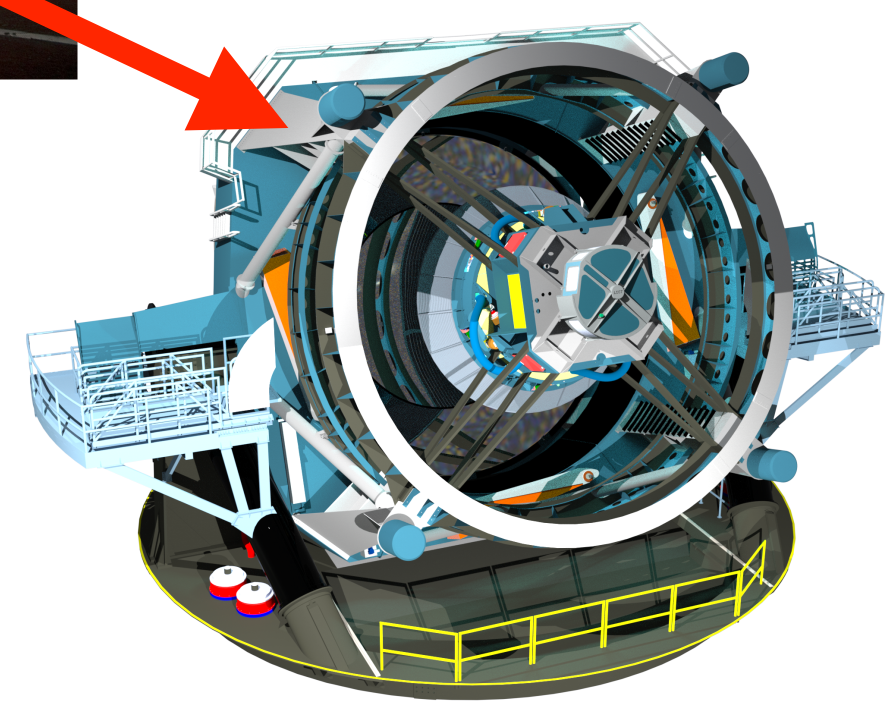
Stage-4
2027+: CMB-S4
100,000+ detectors



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

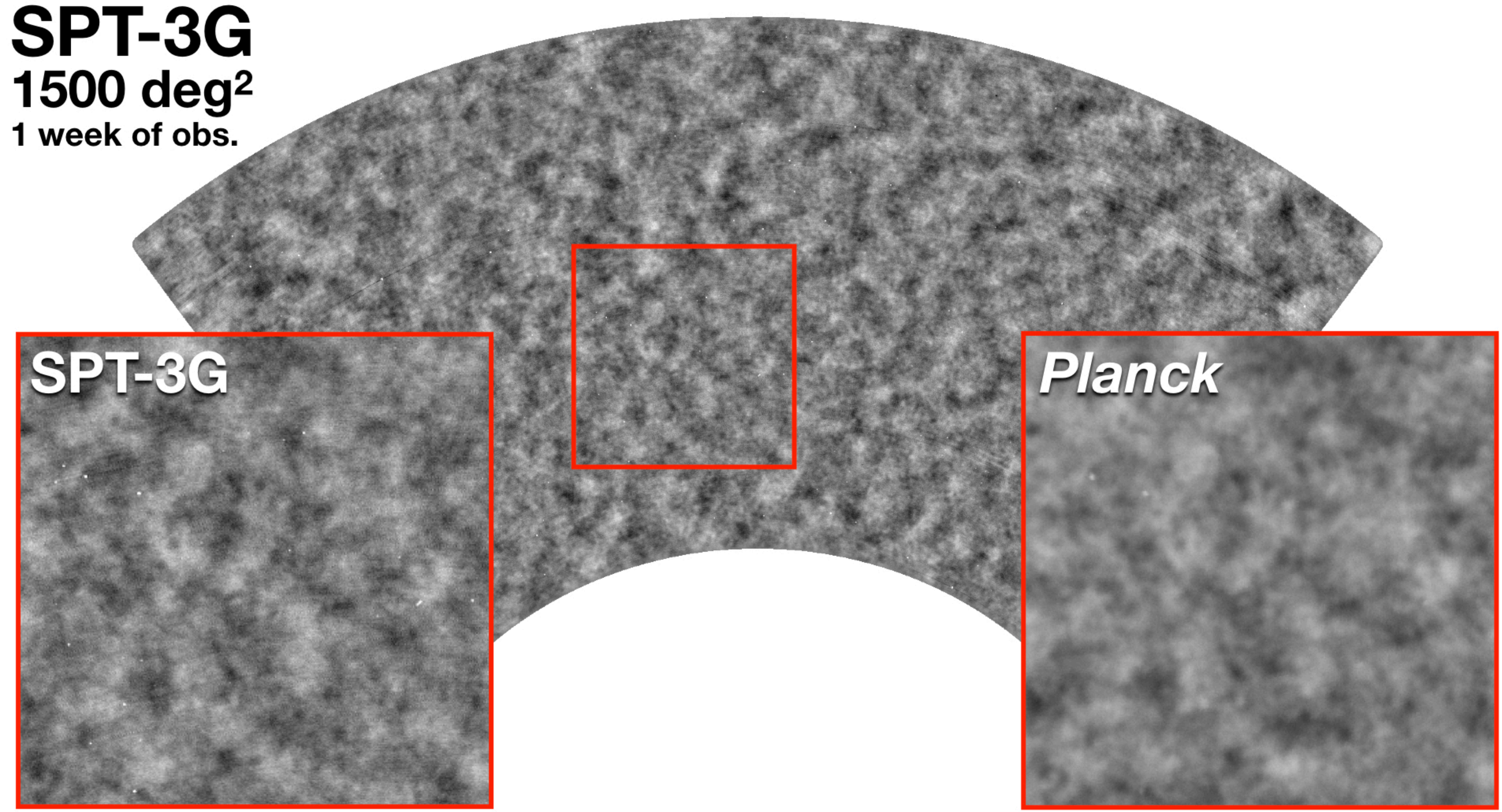
Whats next? Evolution of Focal Planes





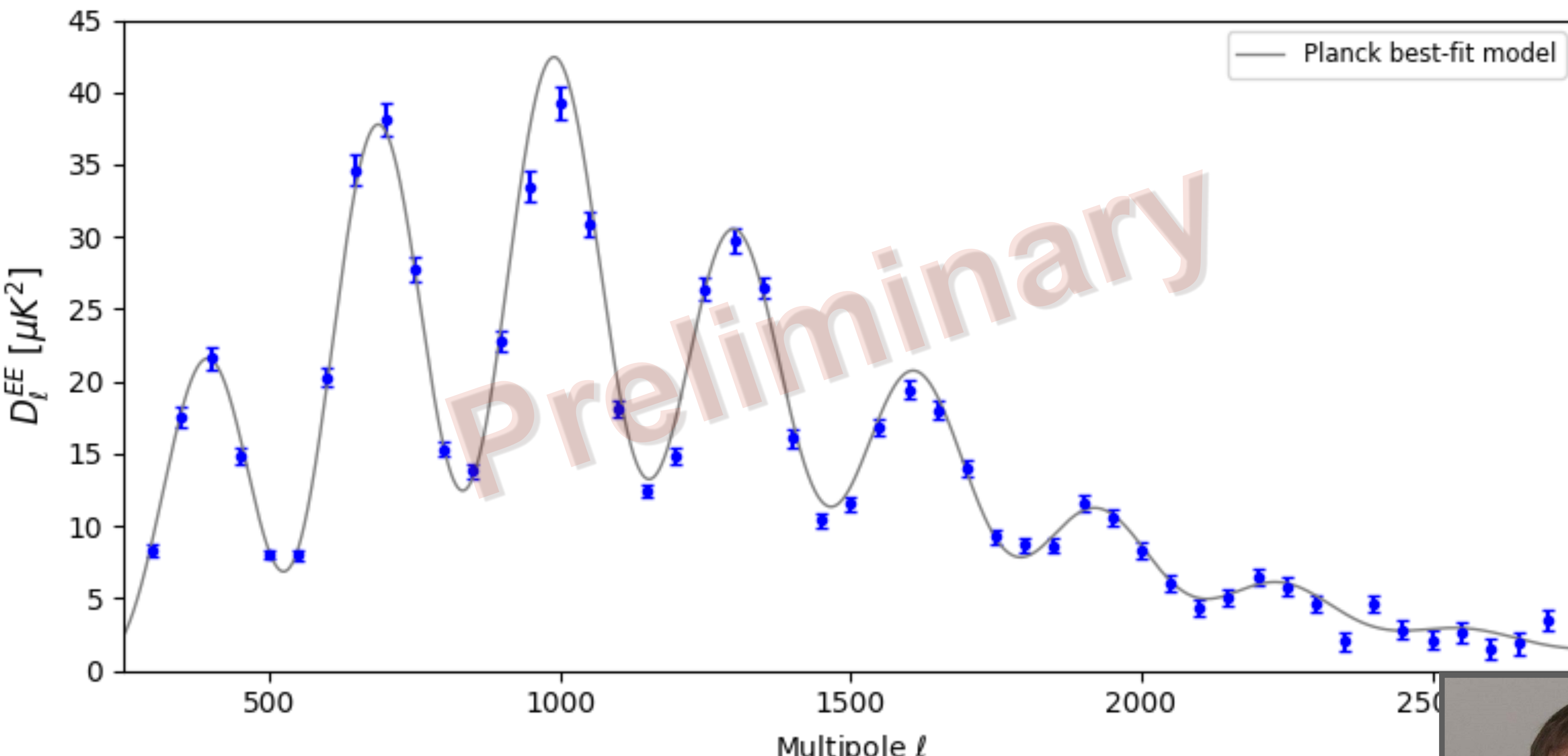
More detectors!

(and bigger telescopes)



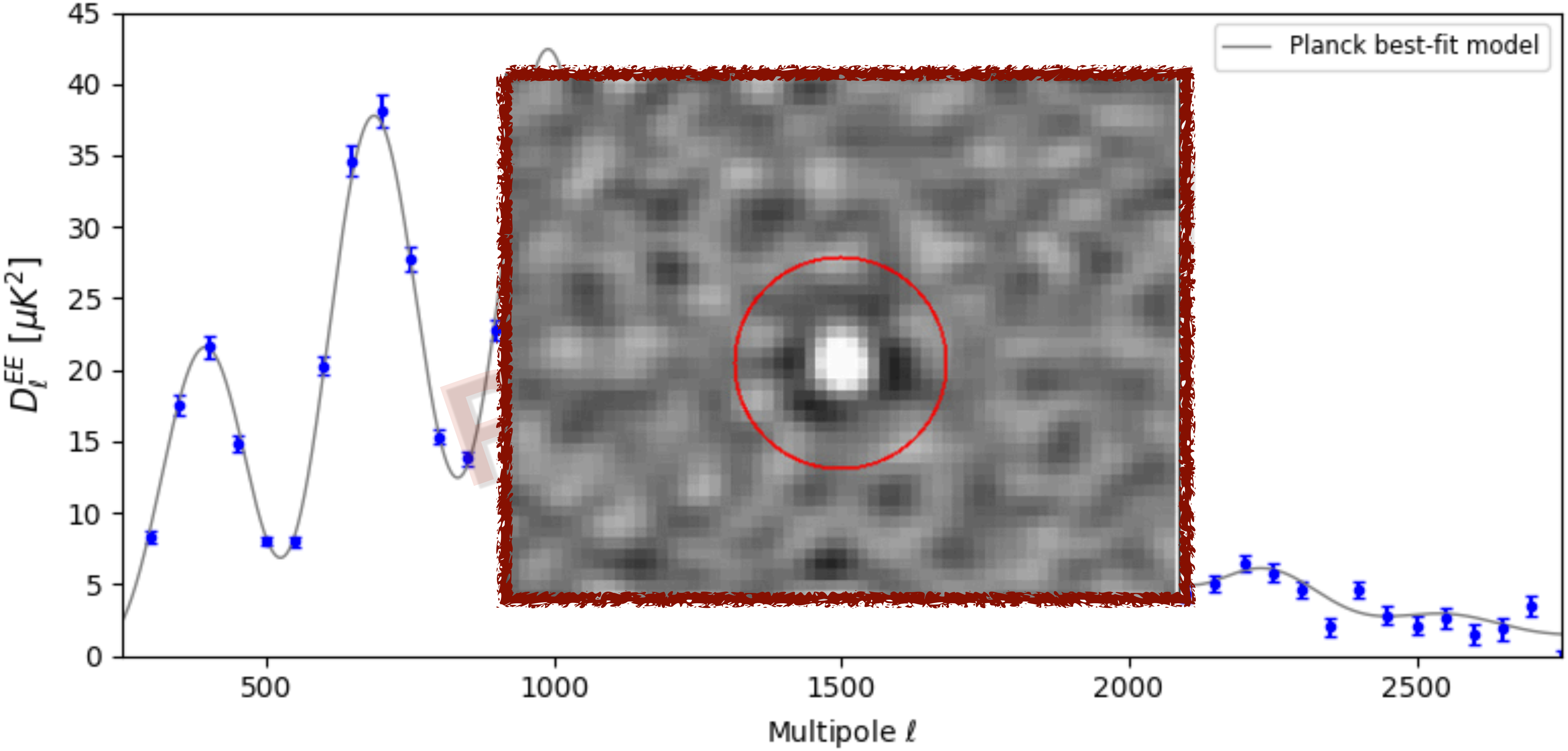
- ***SPT-3G data gets to ~Planck depth on 1500d field with a ~week of data.***
- ***Observe 1500d field every ~2 days for 6 years***

Preliminary SPT-3G EE Power Spectra:



Knox error bars shown

Preliminary SPT-3G EE Power Spectra:



Knox error bars shown

CMB-S4
Next Generation CMB Experiment

Enhance Future Surveys science by overlapping coverage

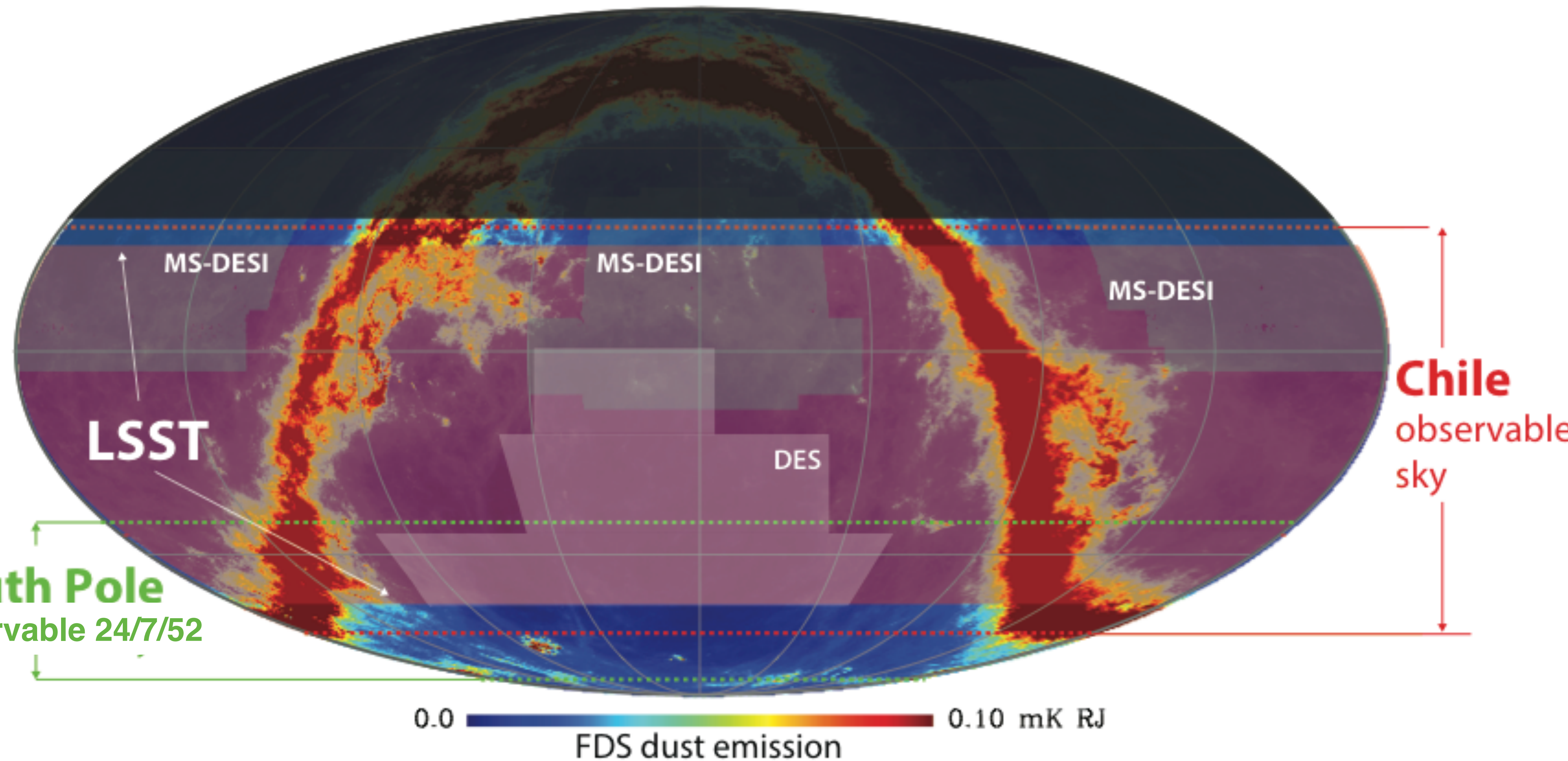
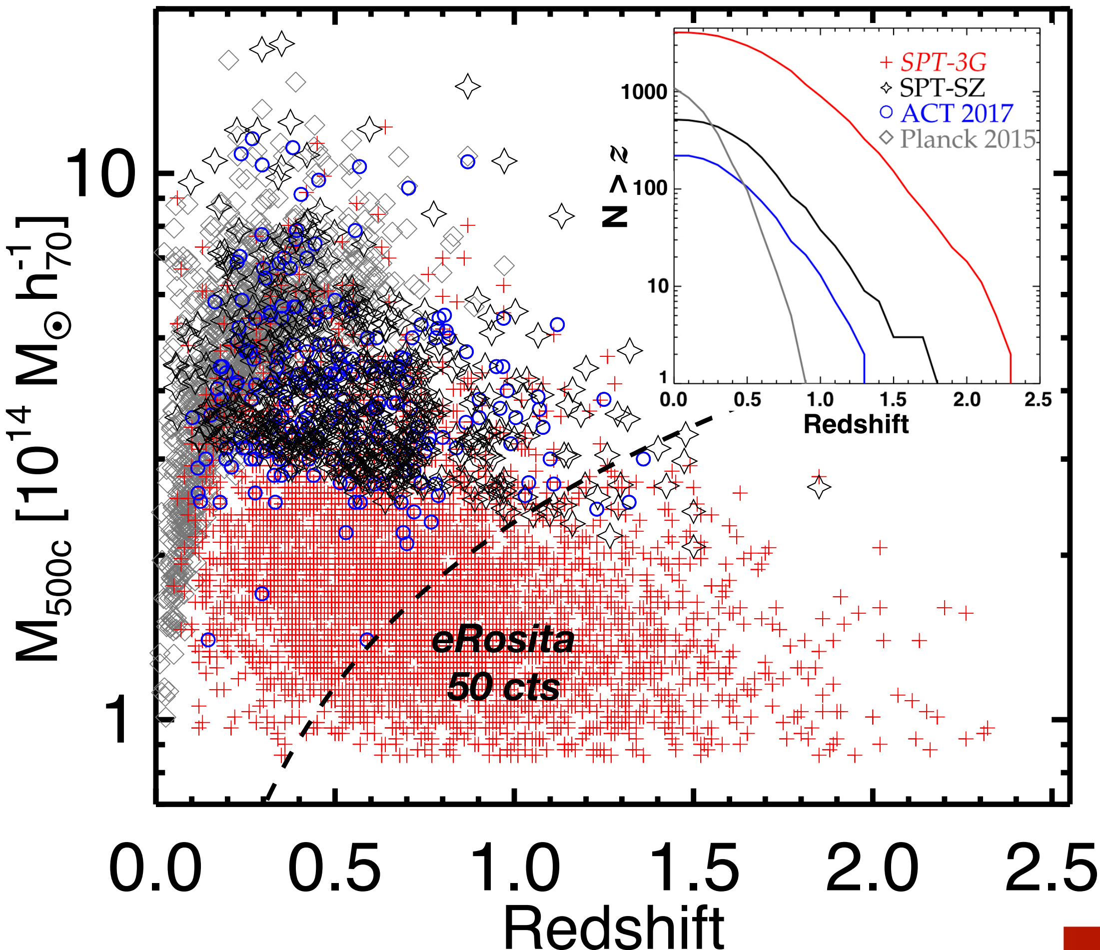


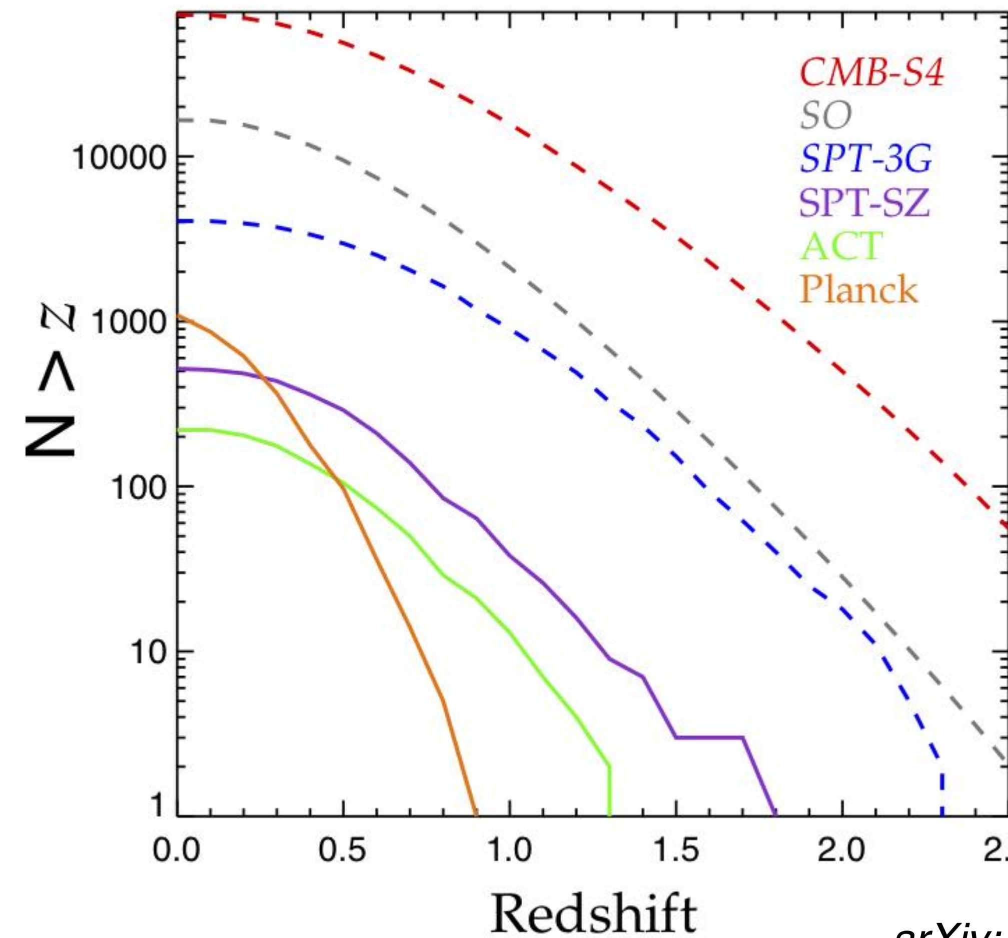
Figure from Jeff McMahon

Cluster Forecasts

SPT-3G

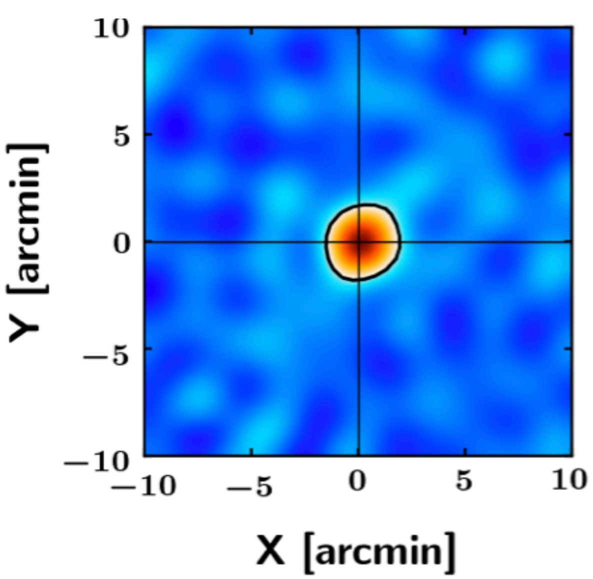


Stage 4

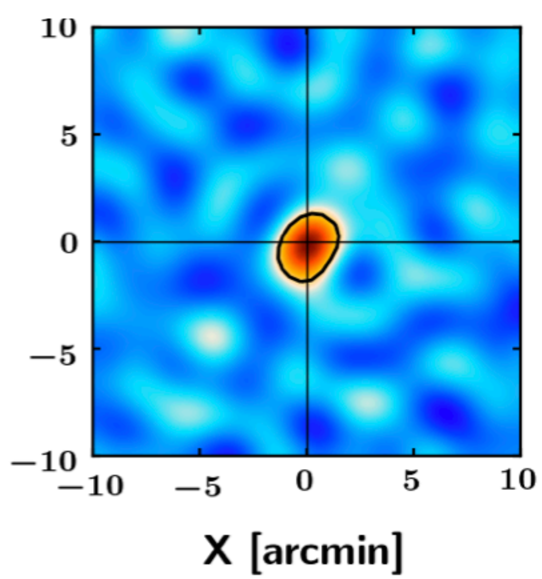


arXiv:1907.04473

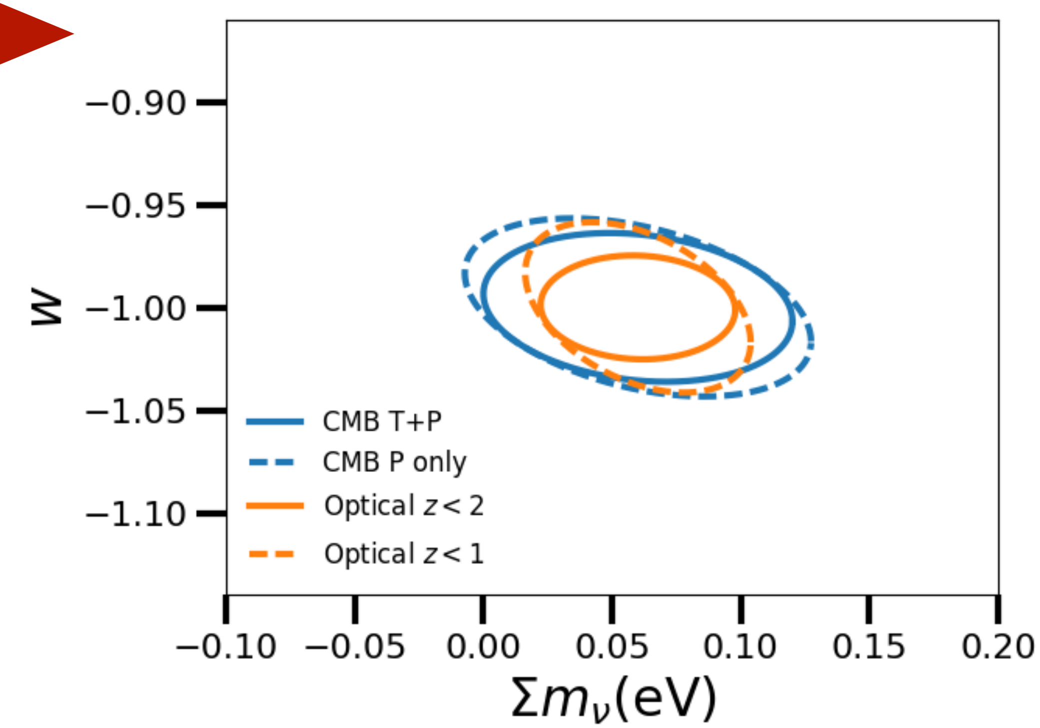
z<1



z>1



High S/N (25-30σ) detection of CMB cluster lensing!



Stage 4: Madhavacheril, Battaglia, Miyatake 2017

Summary

- SPT has found hundreds of massive galaxy clusters spanning a redshift range $0.05 < z < 1.72$.
- 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-3G is deployed and observing.
- CMB-S4 will survey ~70% of the sky, detecting >70,000 SZ clusters.