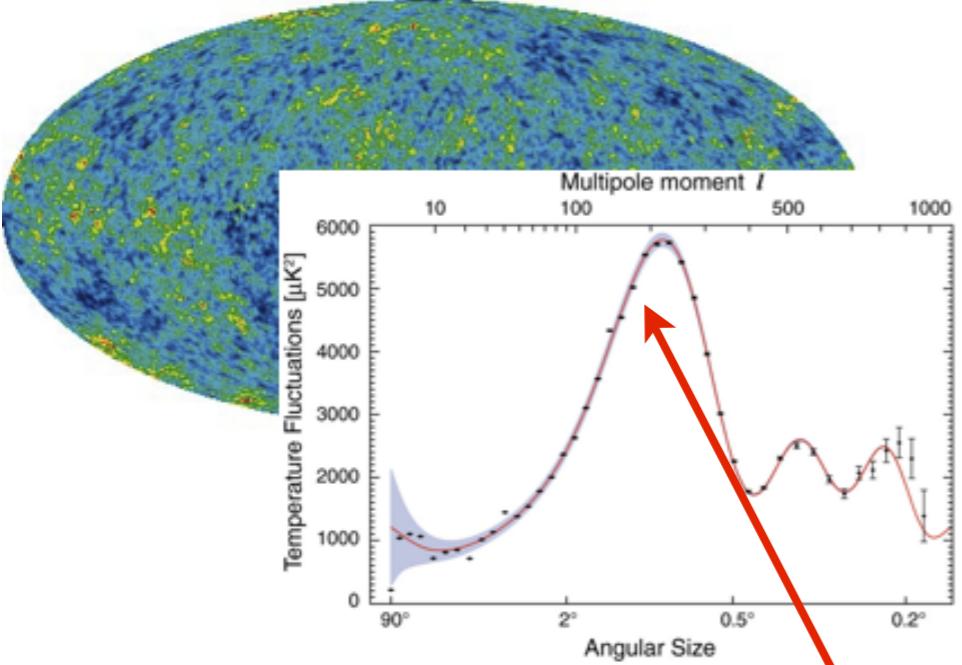


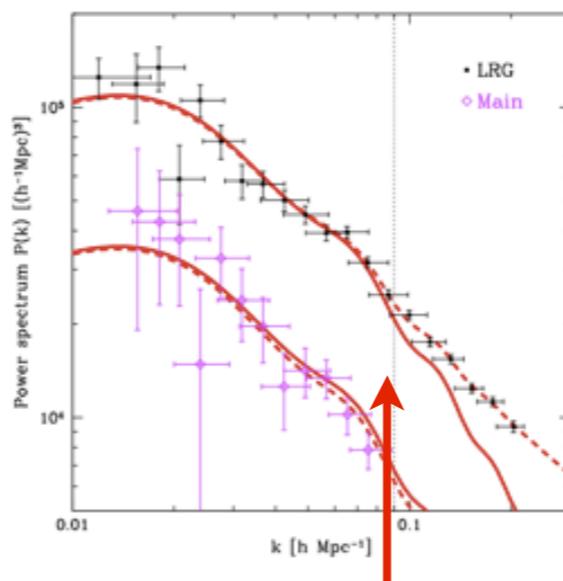
# Cosmology from Clusters and Joint SPT-DES Analyses of Clusters in the SPT-SZ survey

Lindsey Bleem  
Argonne National Laboratory  
August 5, 2016

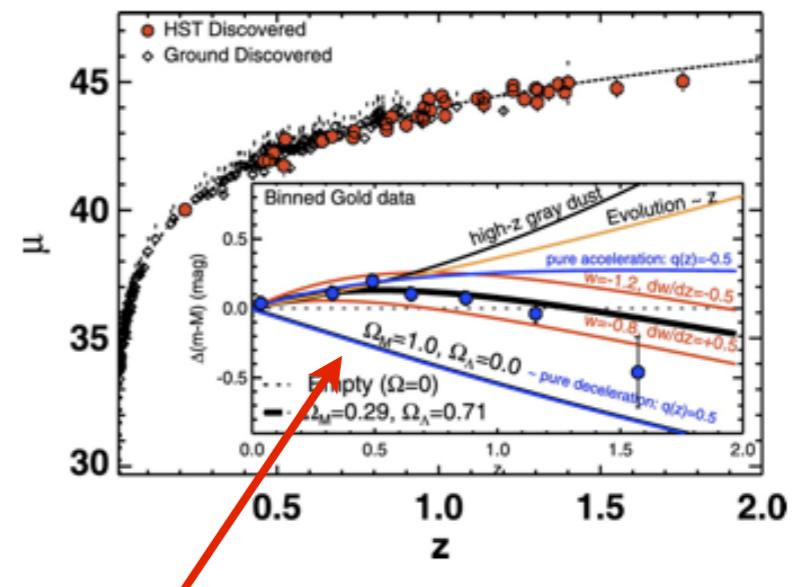




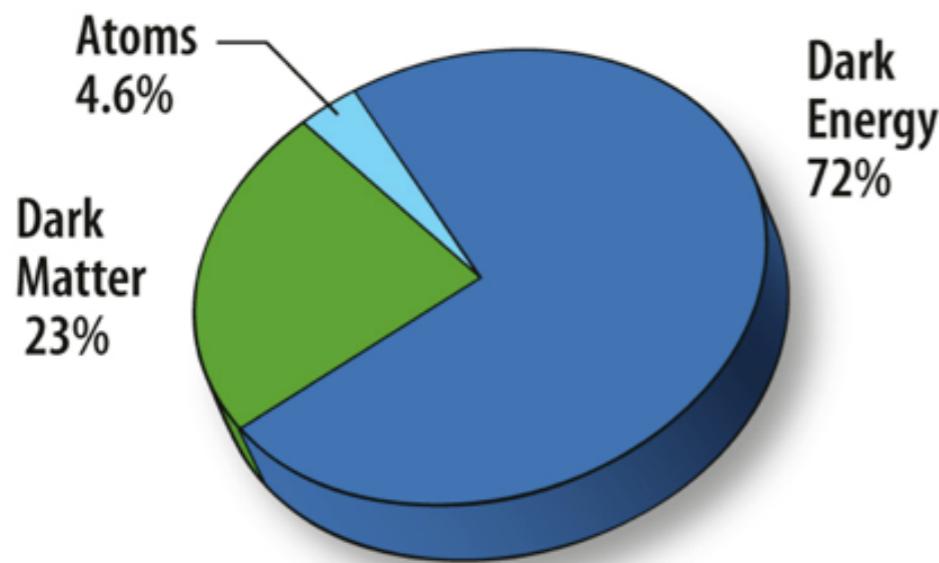
Tegmark et al 2006



Riess et al 2007

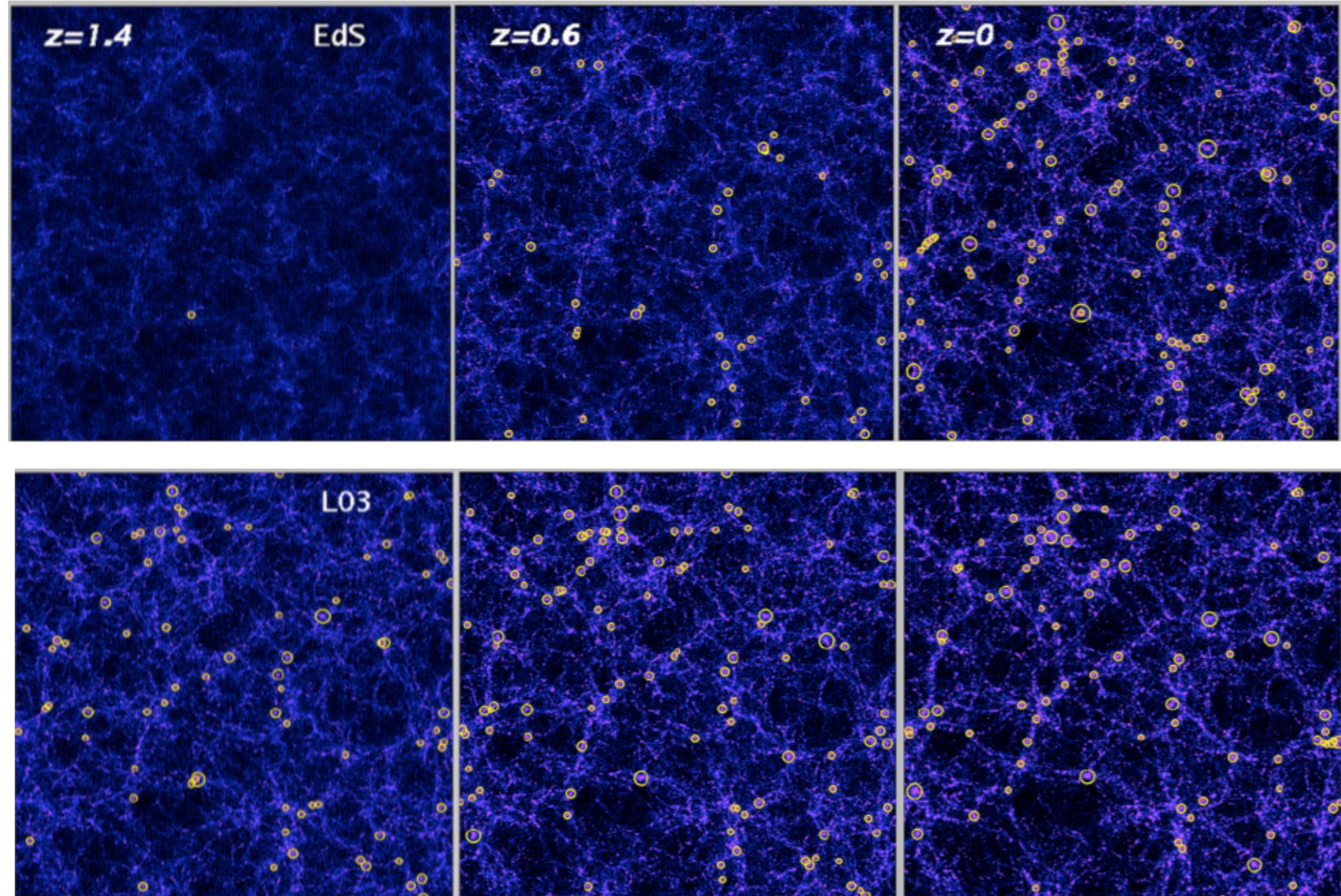


CMB + Large Scale Structure + SNe Ia



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

# Matter Dominated, No dark Energy



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,  $\sigma_8$

Growth Rate of Structure,  $D(z)$

Depends on:

Rate of Expansion,  $H(z)$

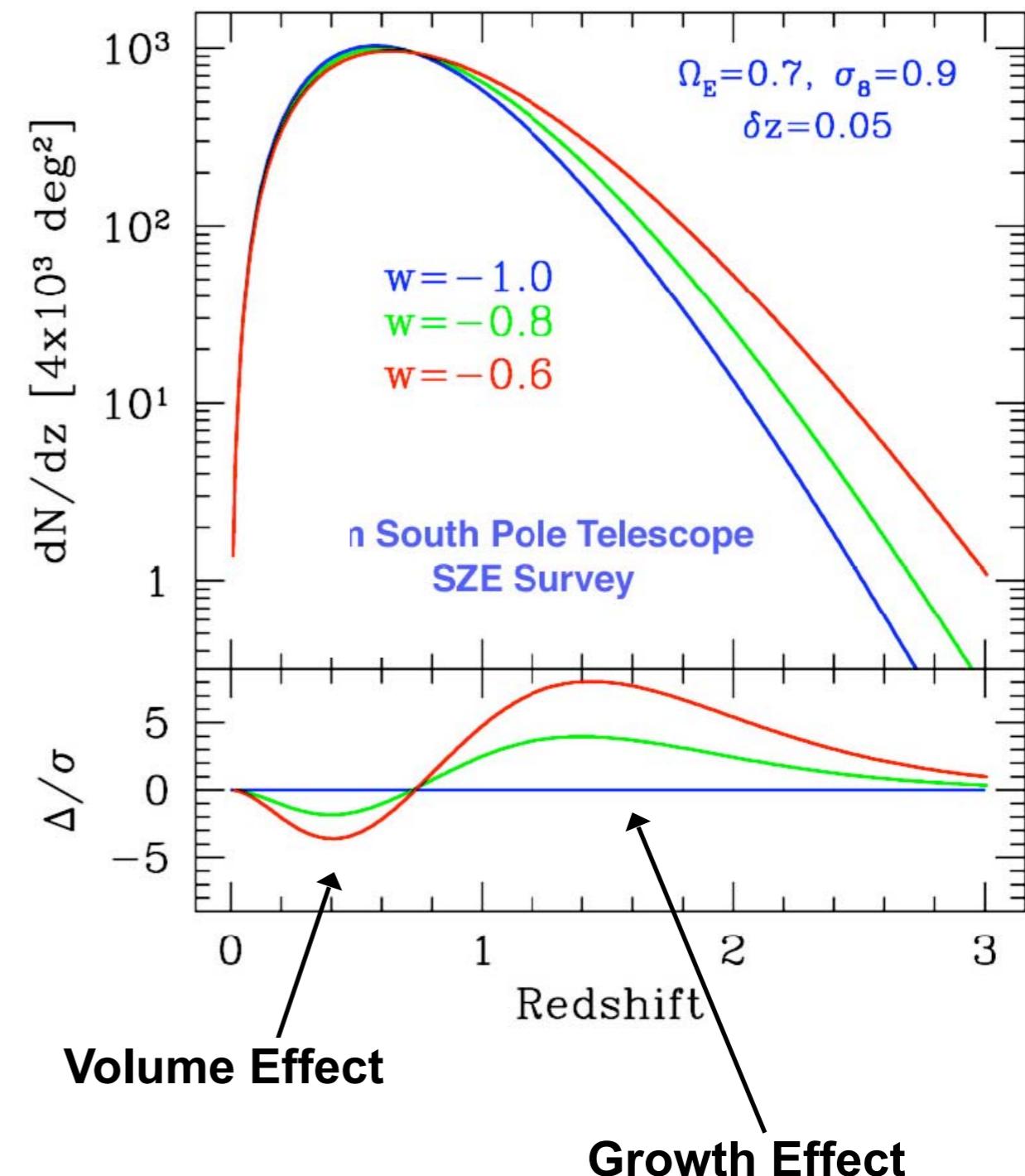
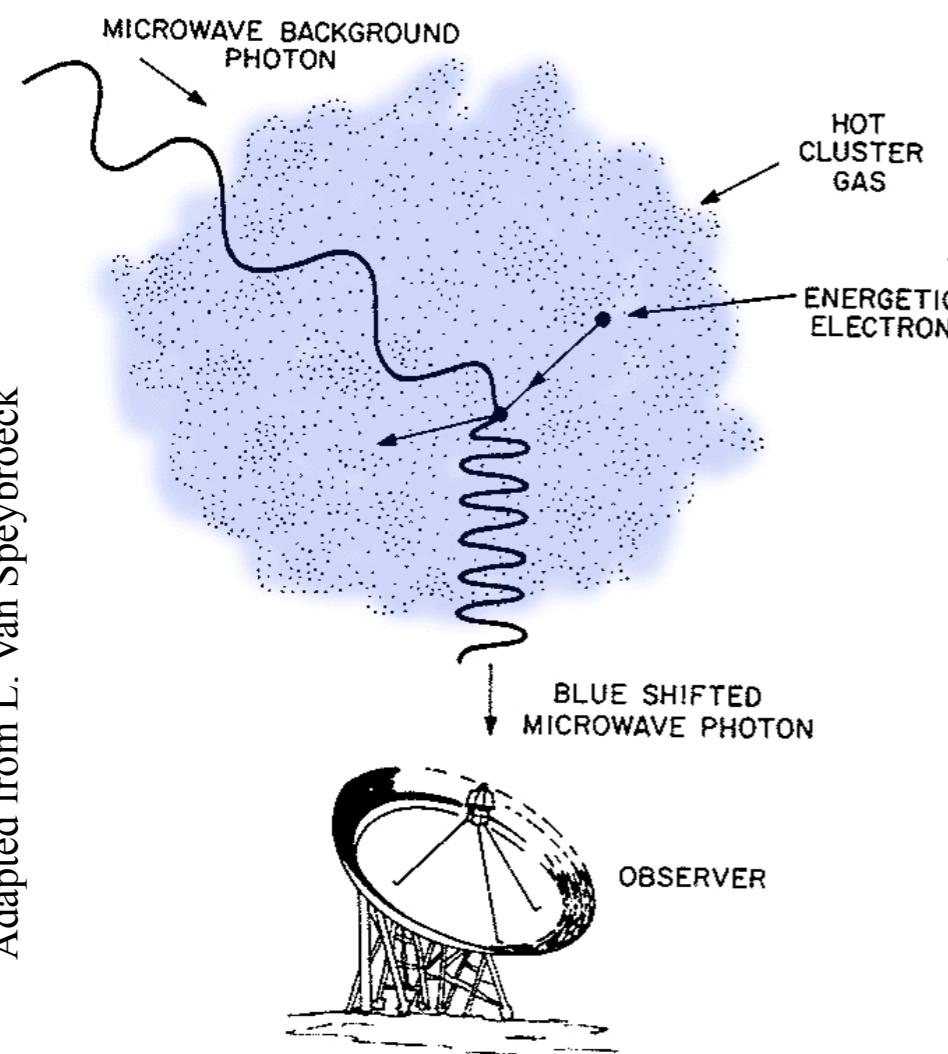


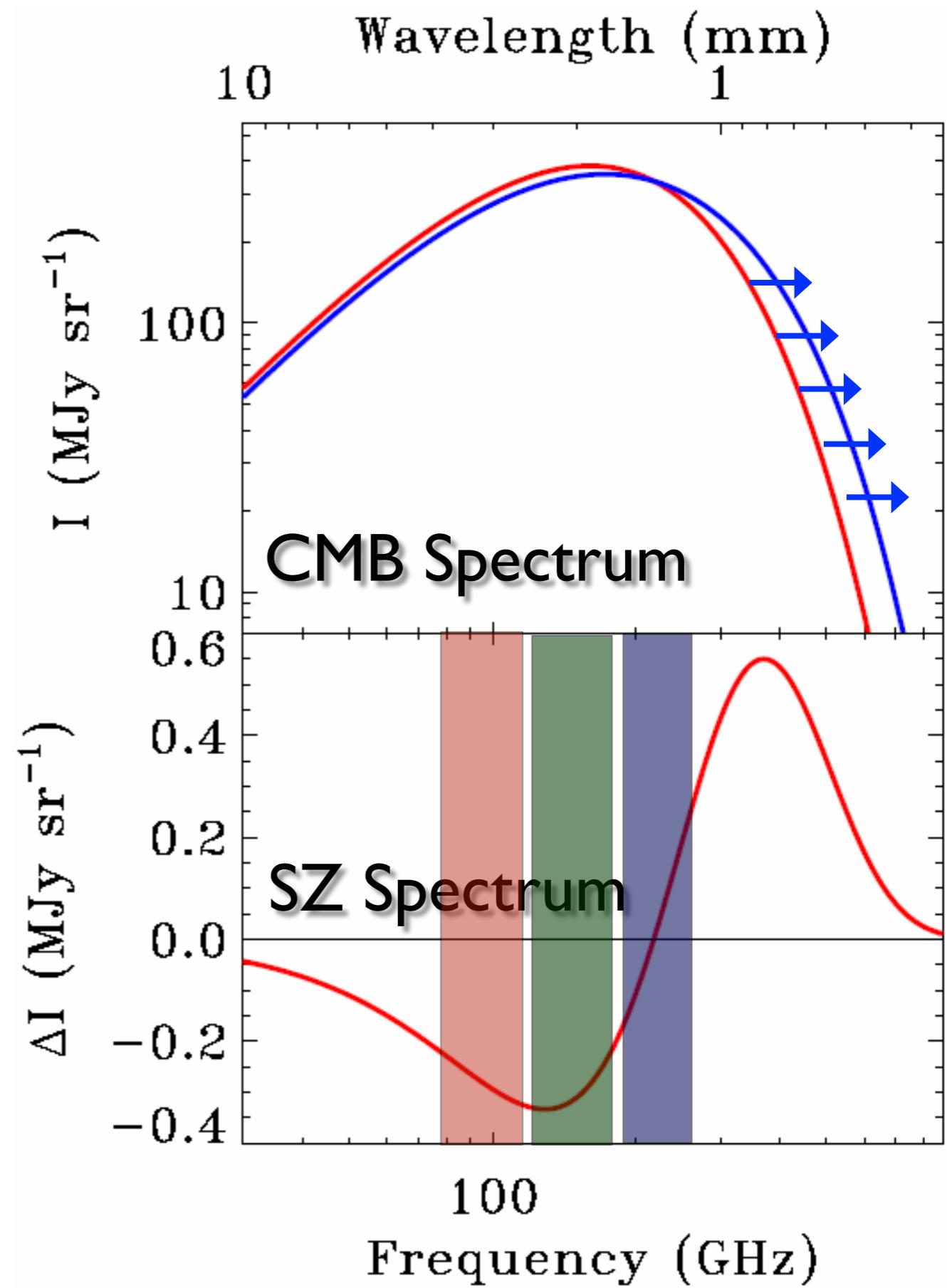
Figure: J Mohr

# The Sunyaev Zel'dovich (SZ) Effect

Adapted from L. Van Speybroeck



The SPT-SZ survey imaged the sky at 100, 150 and 220 GHz.



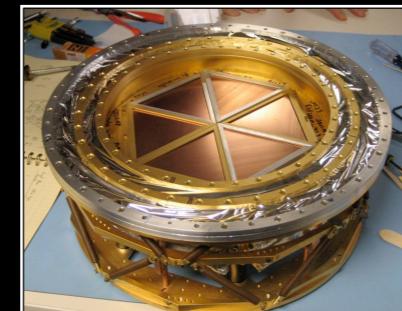
# The South Pole Telescope (SPT)

10-meter sub-mm quality wavelength telescope

100, 150, 220 GHz and  
1.6, 1.2, 1.0 arcmin resolution

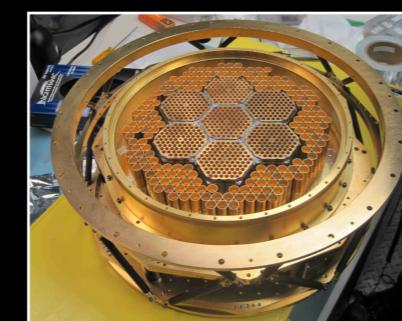
## 2007: SPT-SZ

960 detectors  
100,150,220 GHz



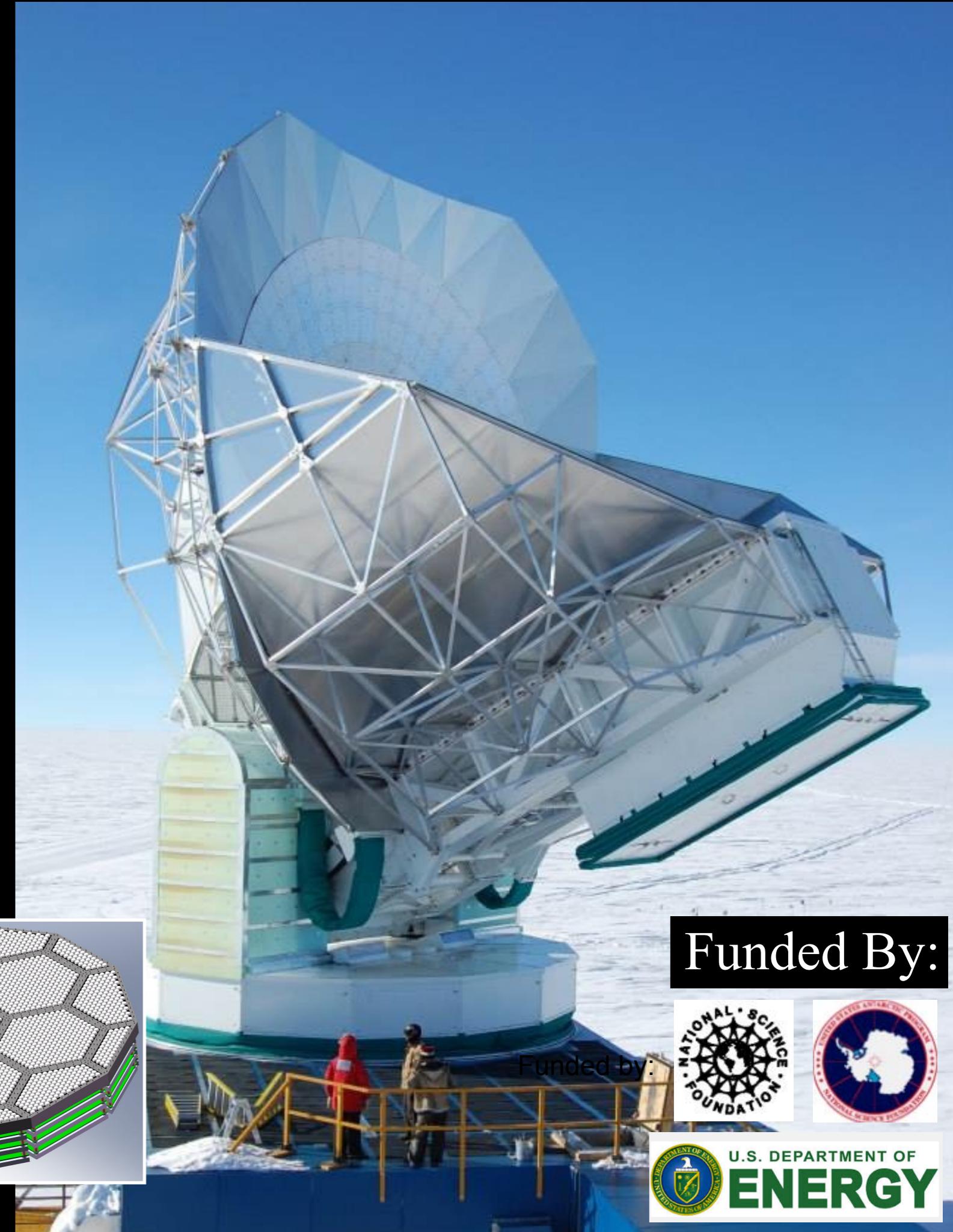
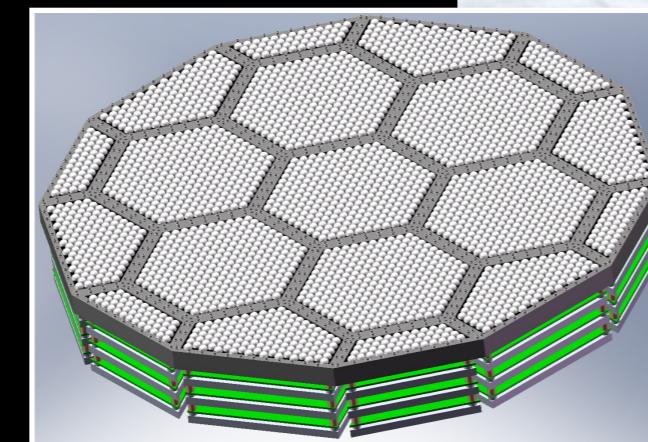
## 2012: SPTpol

1600 detectors  
100,150 GHz  
*+Polarization*



## 2016: SPT-3G

~15,200 detectors  
100,150,220 GHz  
*+Polarization*

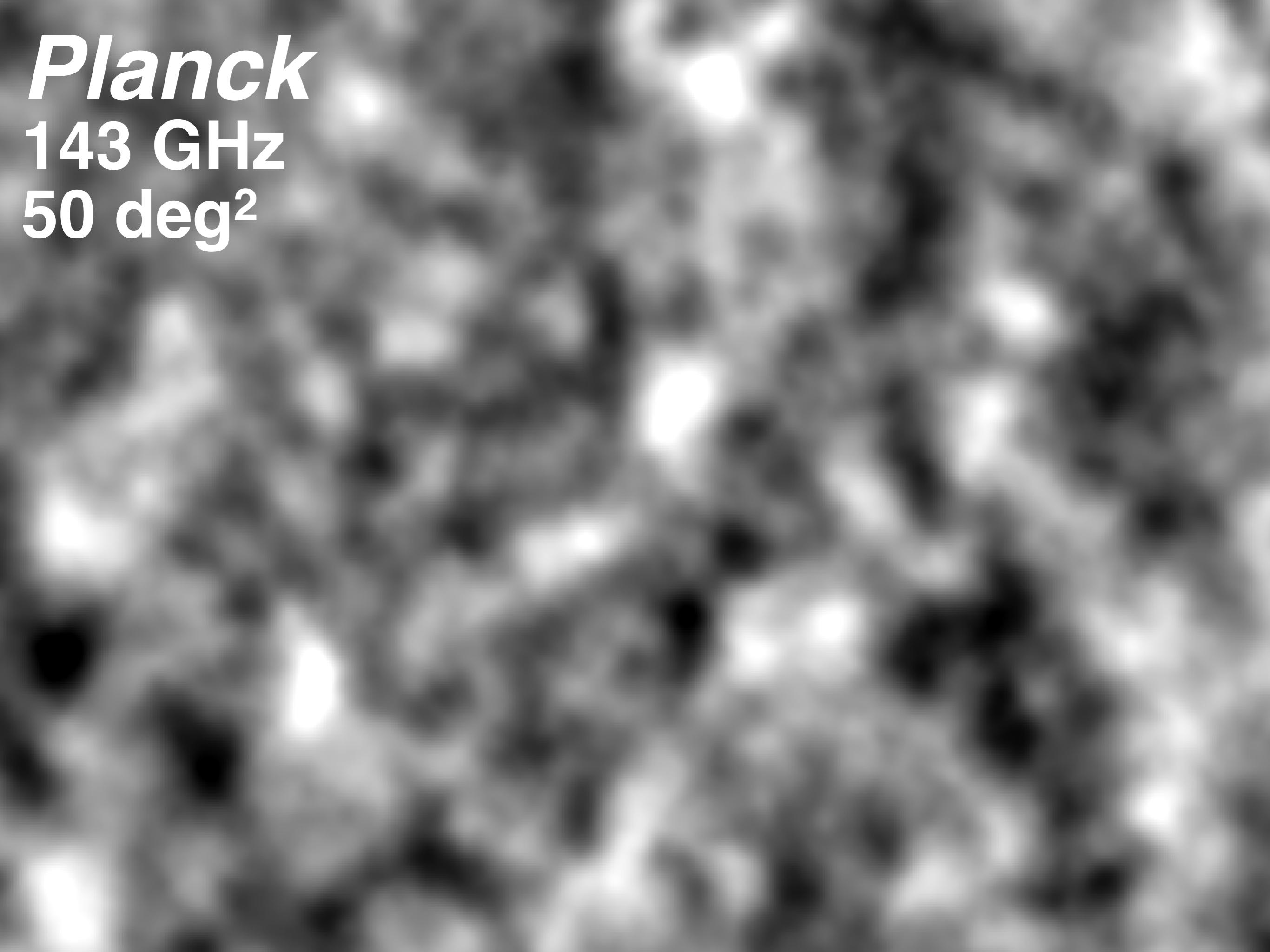


Funded By:

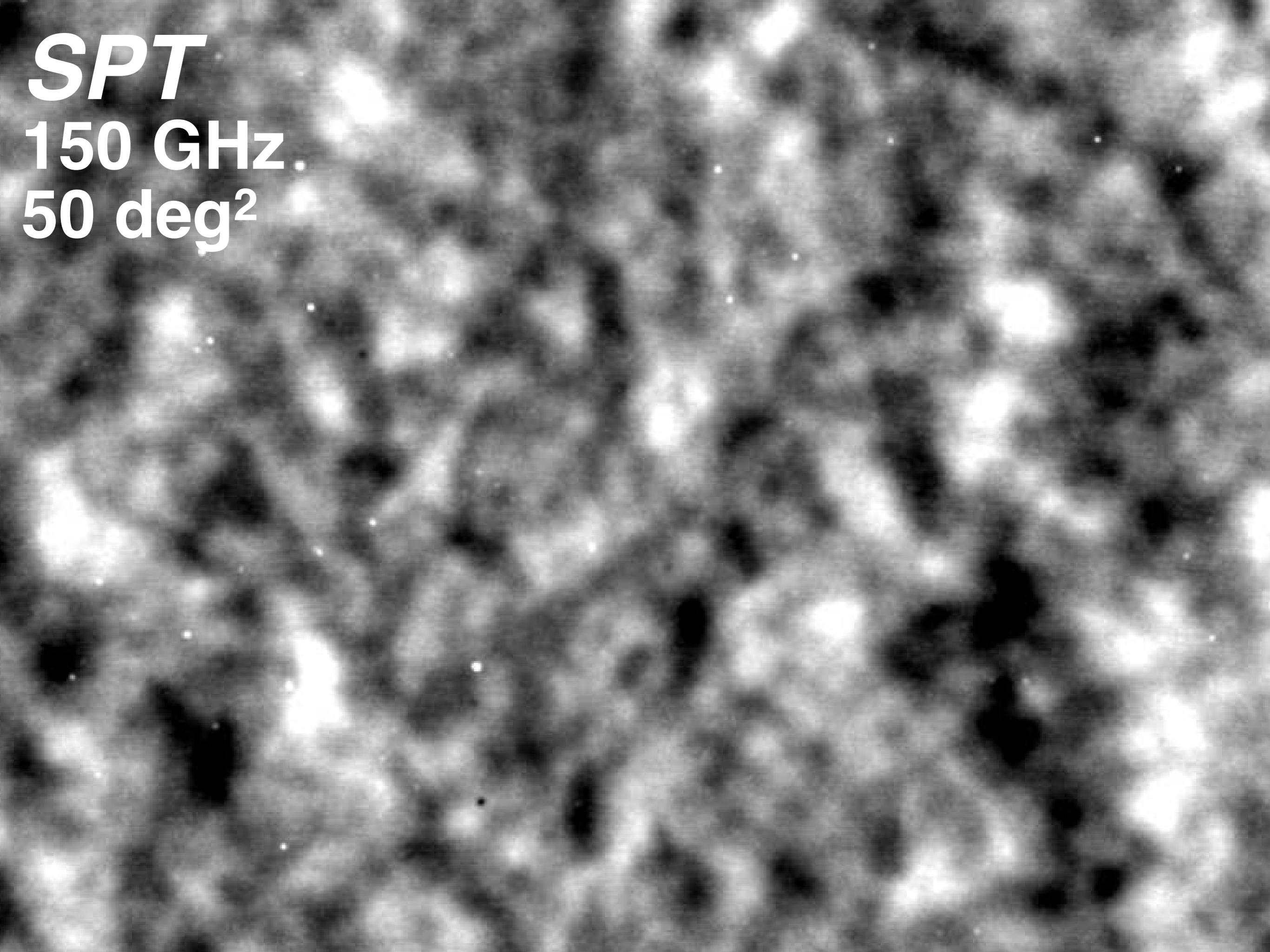


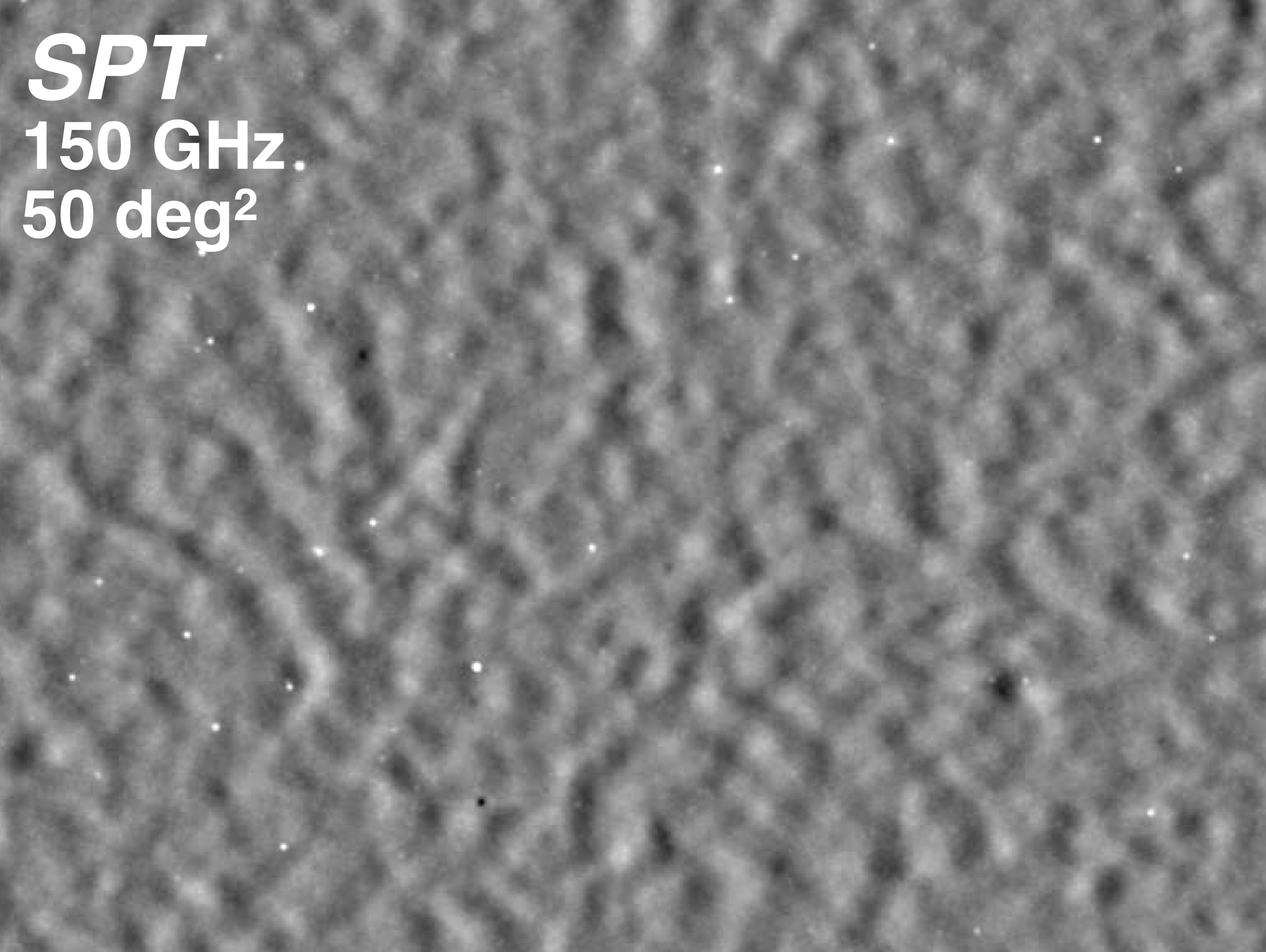
Funded by:

*Planck*  
143 GHz  
50 deg<sup>2</sup>



*SPT*  
150 GHz.  
50 deg<sup>2</sup>



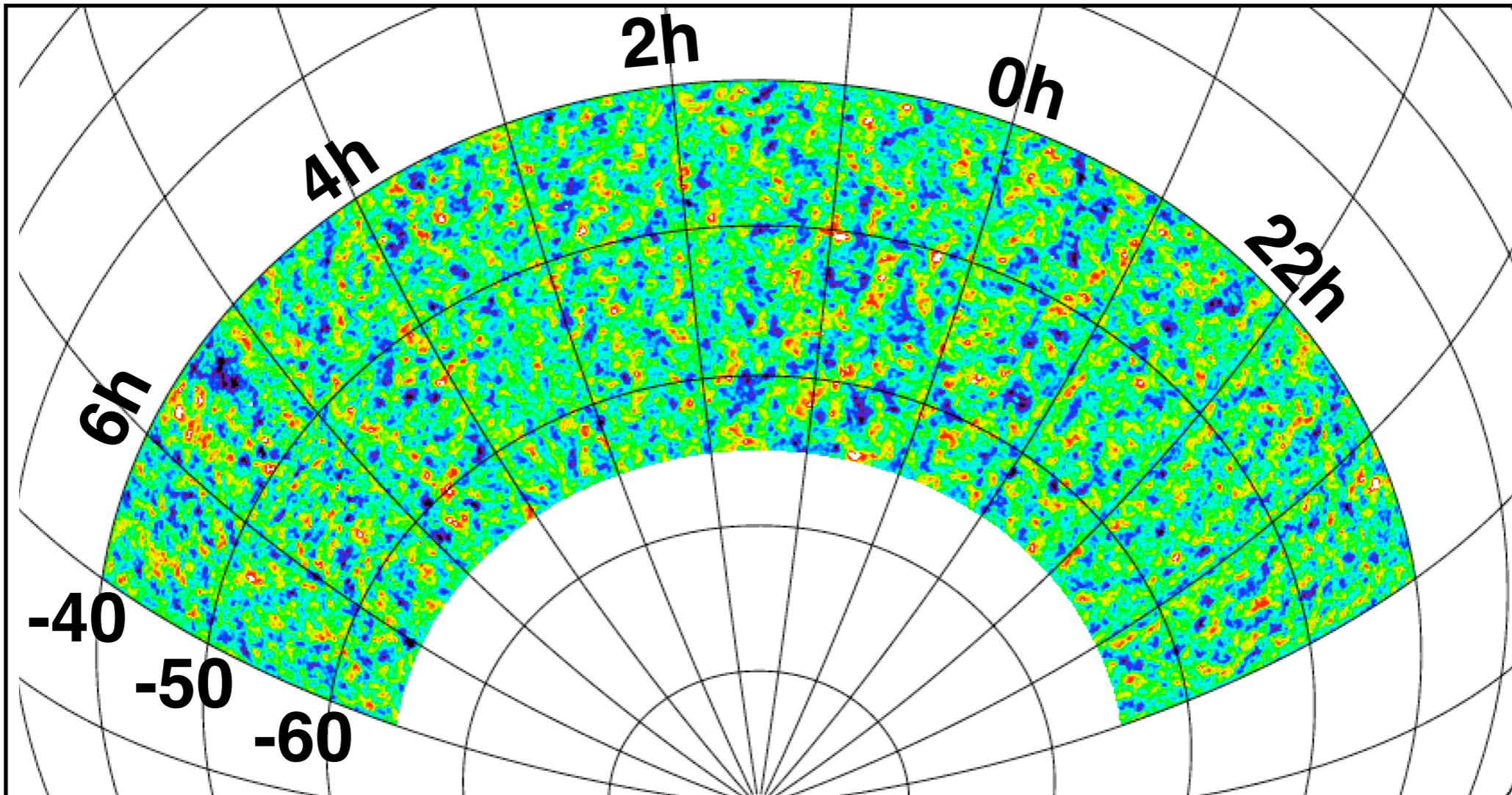


SPT  
150 GHz.  
50 deg<sup>2</sup>

*SPT*  
150 GHz.  
50 deg<sup>2</sup>

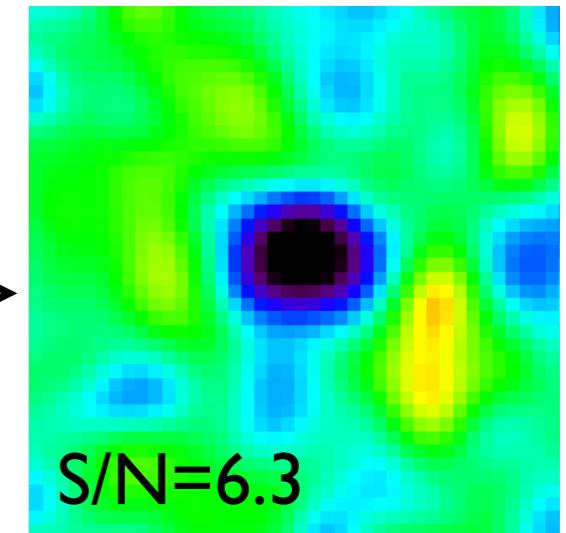
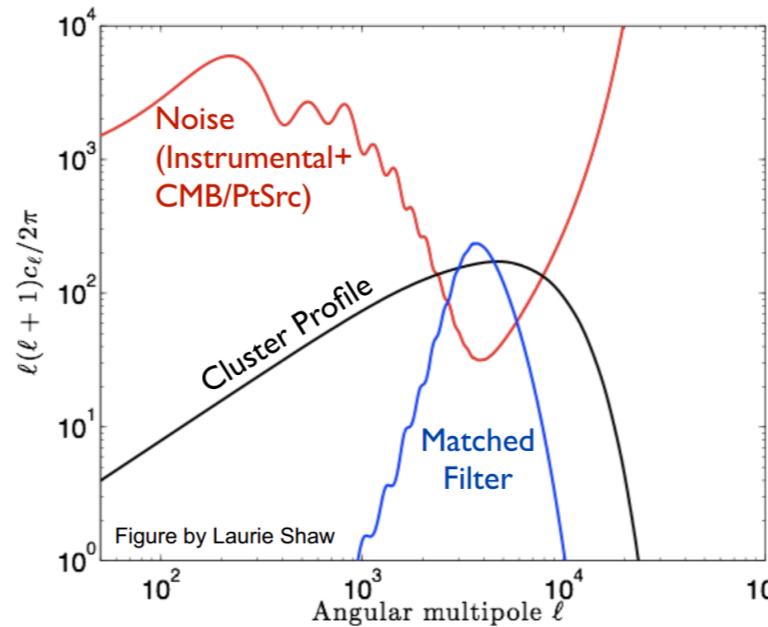
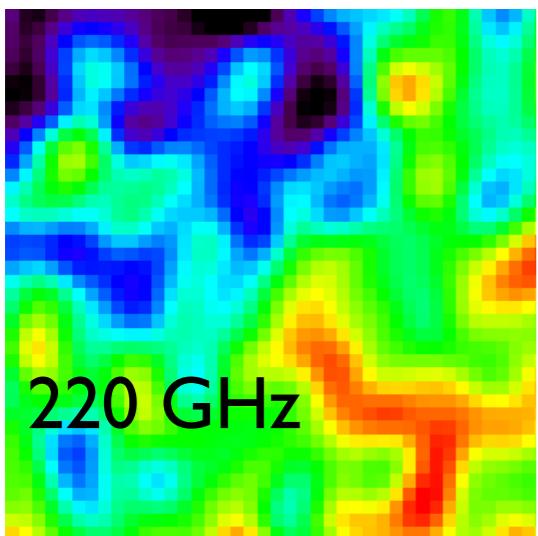
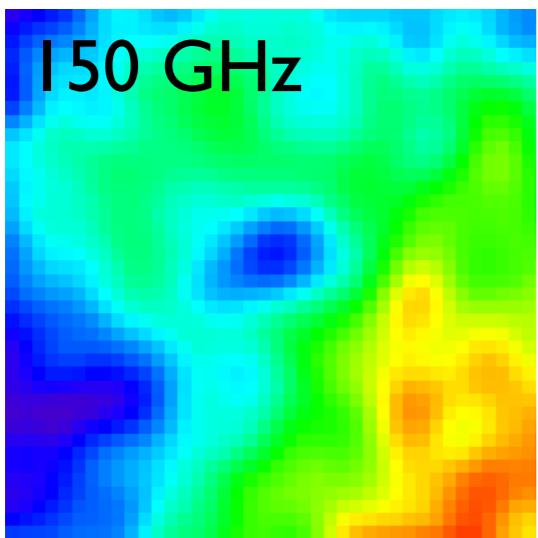
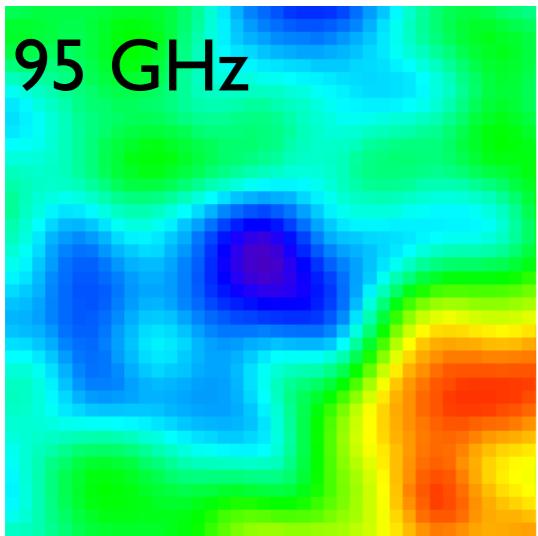
**Clusters of Galaxies**  
“Shadows” in the microwave background from clusters of galaxies

# *The 2500 deg<sup>2</sup> SPT-SZ Survey (2007-2011):*



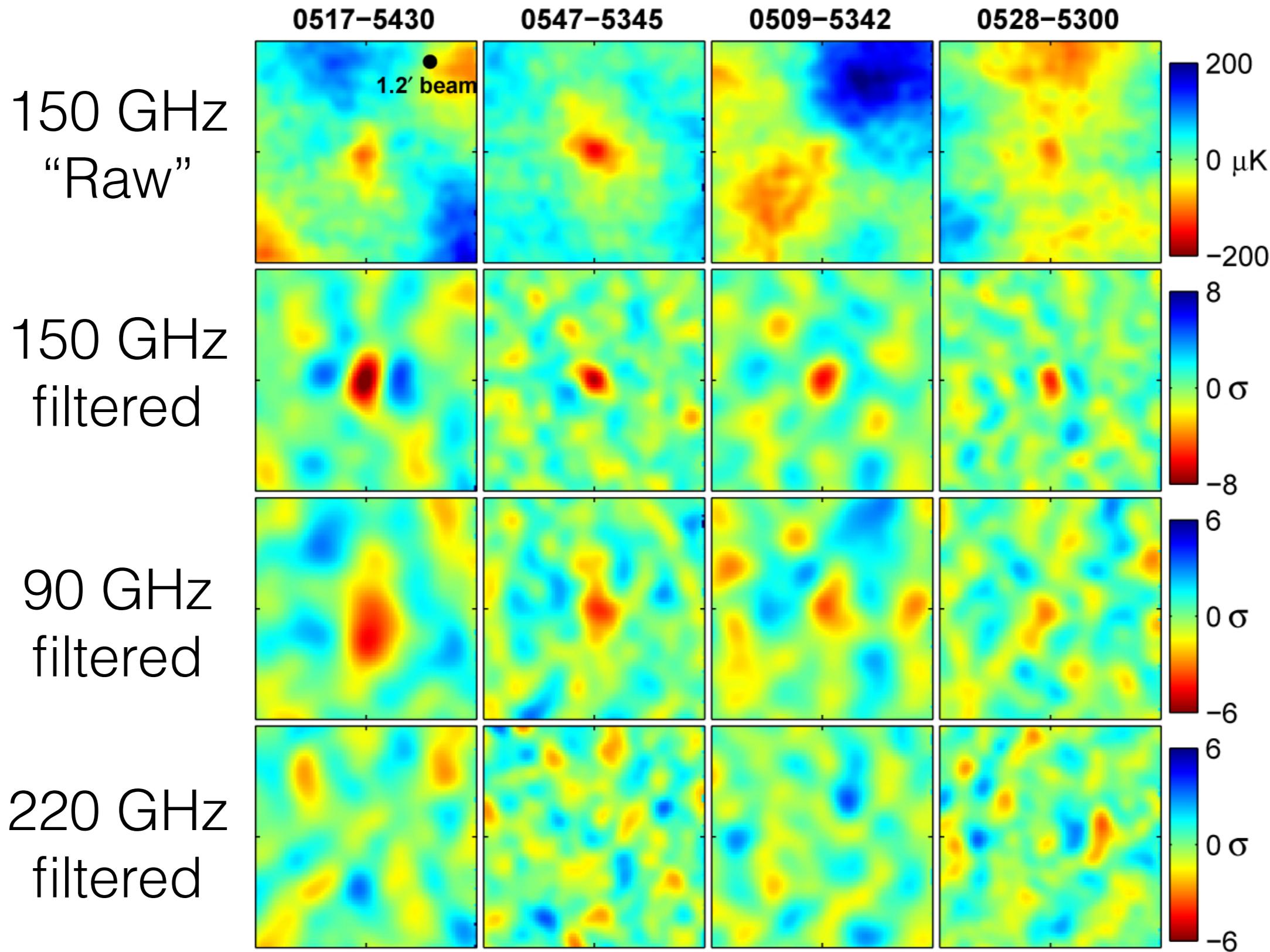
Final survey depths of:  
**90 GHz:** 40 uK<sub>CMB</sub>-arcmin  
**150 GHz:** 17 uK<sub>CMB</sub>-arcmin  
**220 GHz:** 80 uK<sub>CMB</sub>-arcmin

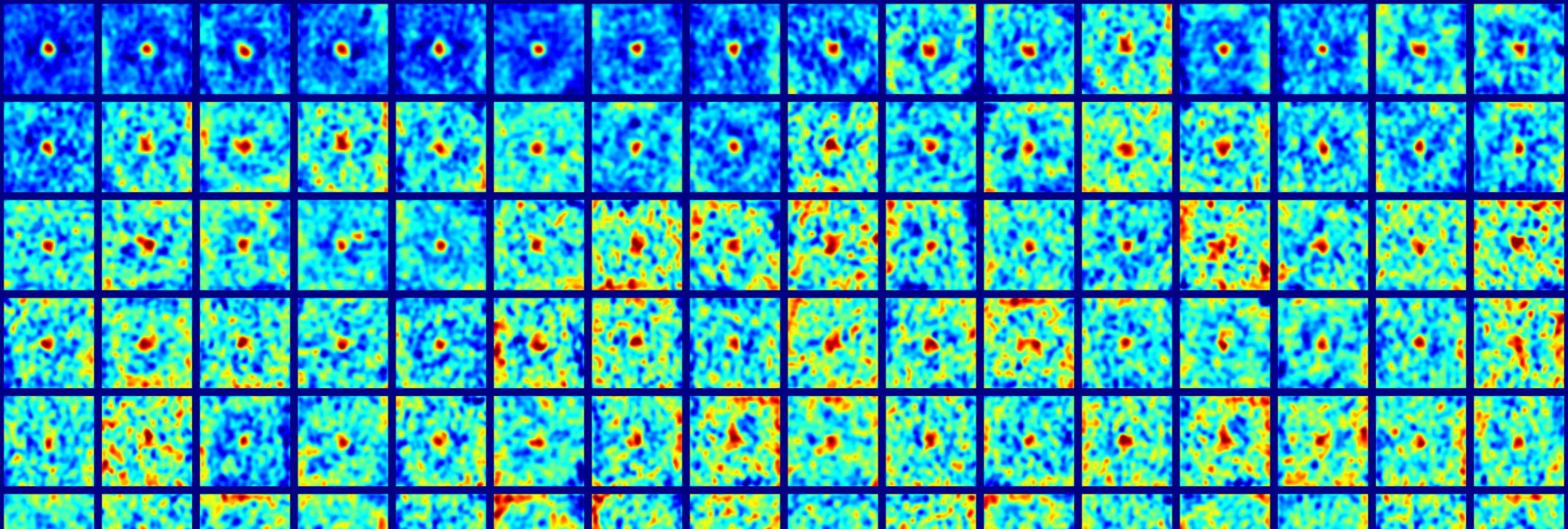
# Finding Clusters in the SPT Survey



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

# First “Blind” SZ detection : 2008!

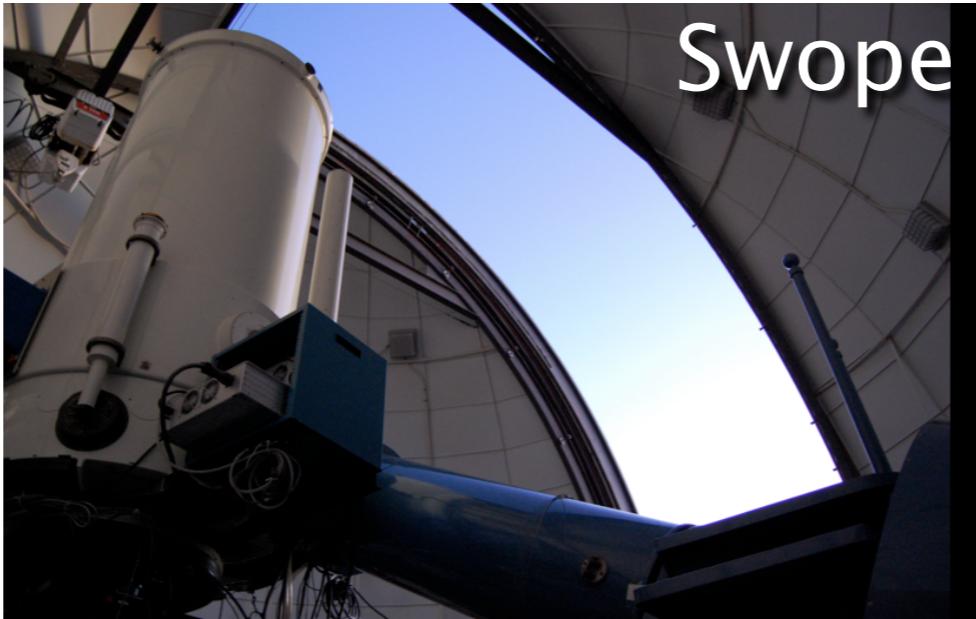




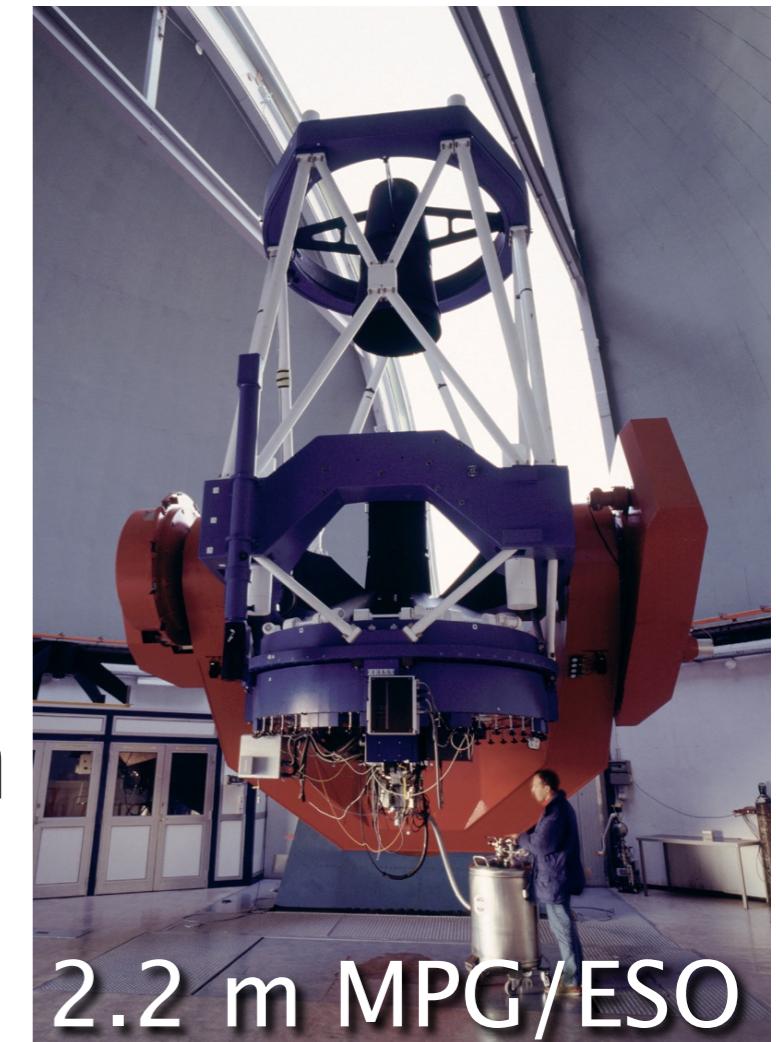
> 500 Clusters in SPT-SZ sample



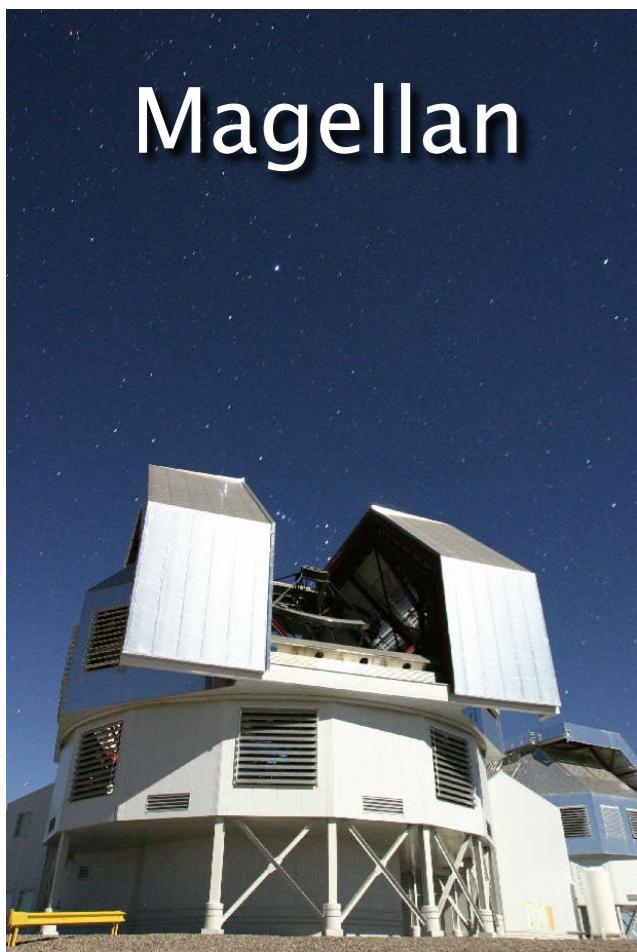
Spitzer



Swope



2.2 m MPG/ESO



Magellan



Blanco

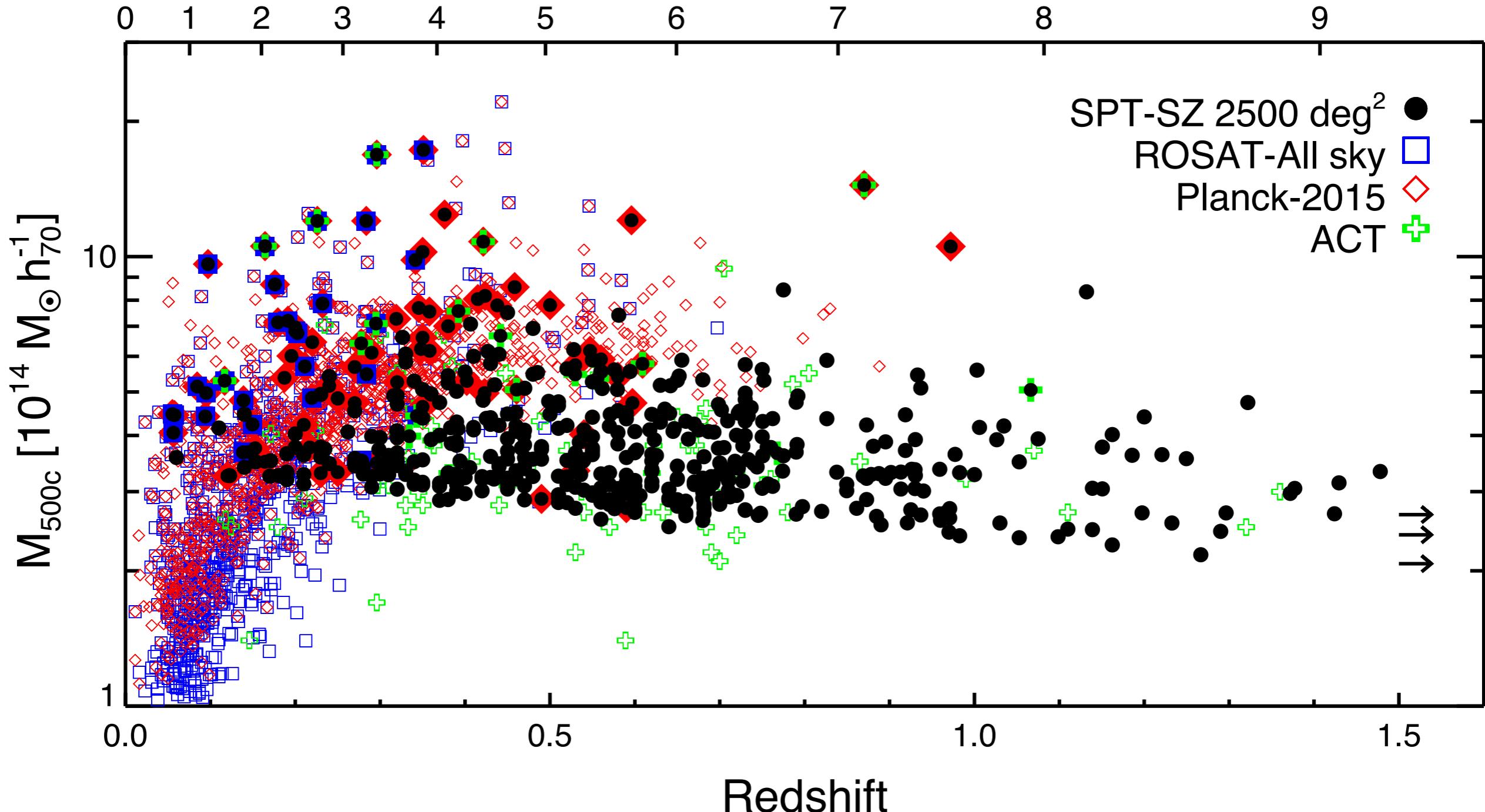


NTT

Multiple-facility Imaging Campaign  
for Cluster Confirmation

# The 2500d SPT-SZ Cluster Sample

Lookback Time (Gyr)



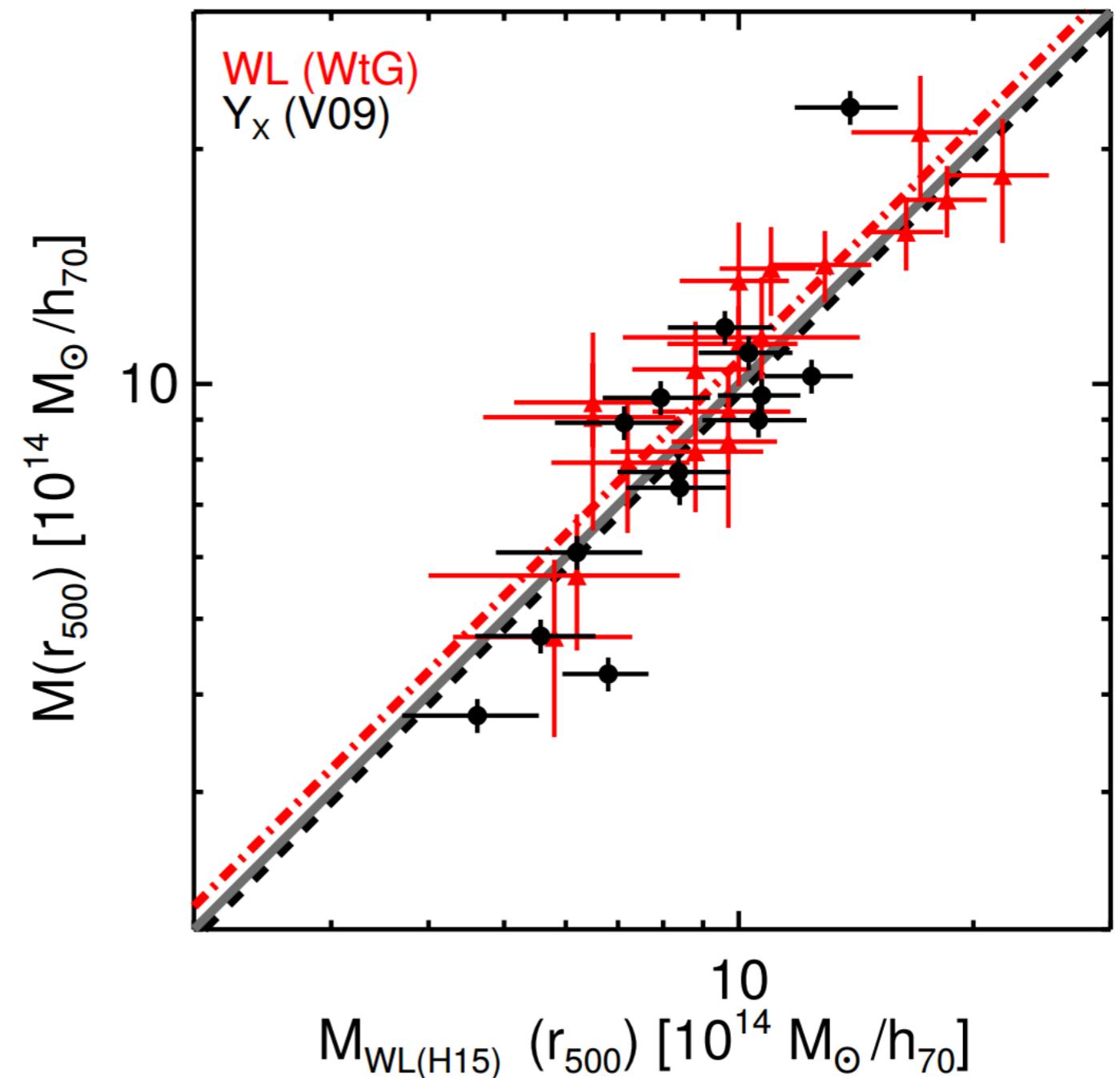
# Multi-wavelength Observations: Mass Calibration

- 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 ( $z > 0.8$ )



# **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

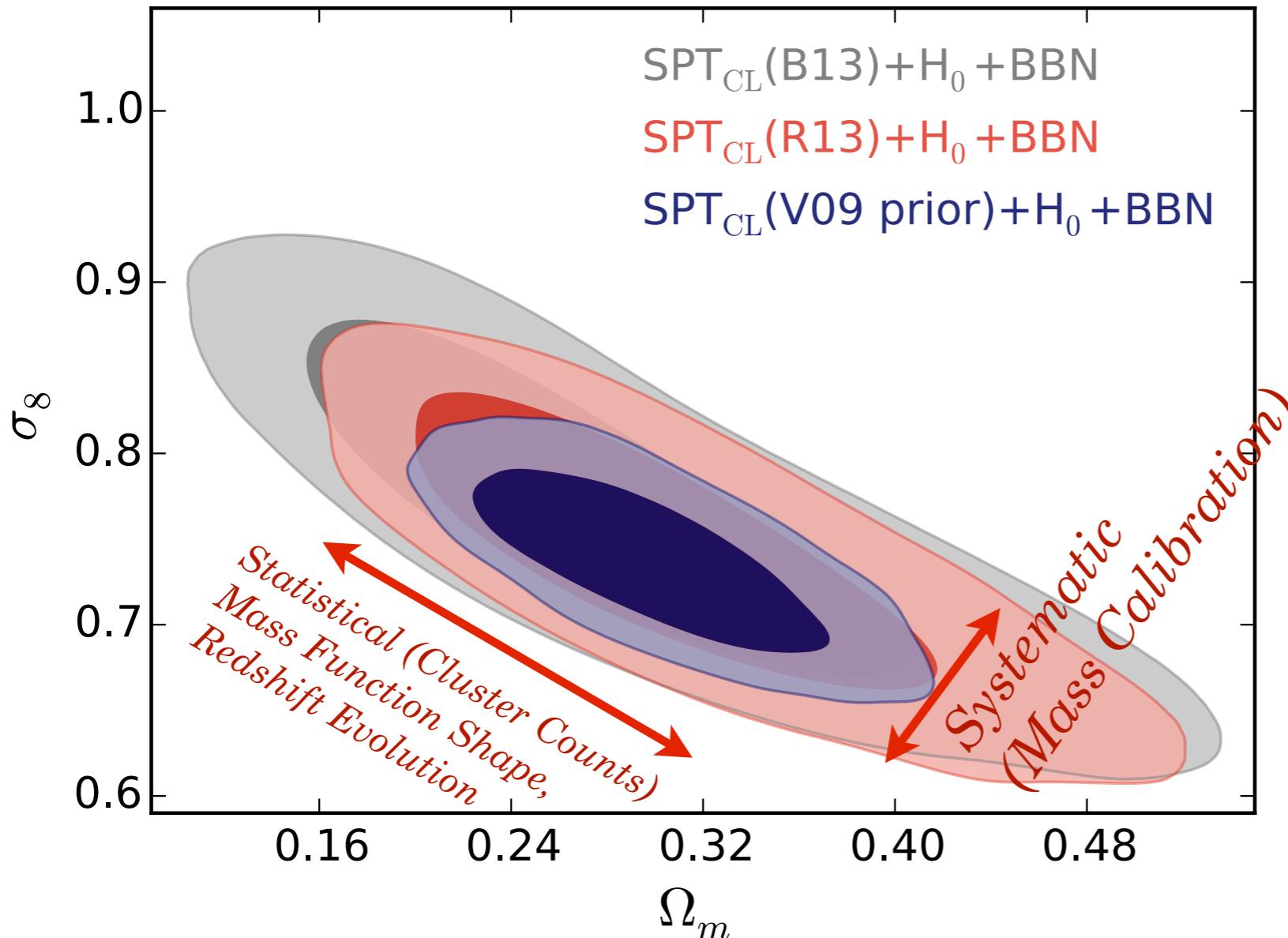
## **9 Scaling Relation Parameters**

- X-ray ( $Y_{x\text{-}M}$ ) and SZ ( $\zeta\text{-}M$ ) relations (4 and 5 parameters):
  - A) normalization,
  - B) slope,
  - C) redshift evolution,
  - D) scatter,
  - F) correlated scatter

## **6 Cosmology Parameters (plus extension parameters)**

- $\Lambda$ CDM Cosmology
  - $\Omega_m h^2, \Omega_b h^2, A_s, n_s, \theta_s$
- Extension Cosmology
  - $w, \Sigma m_\nu, f_{NL}, N_{eff}$

# $\Lambda$ CDM Constraints:



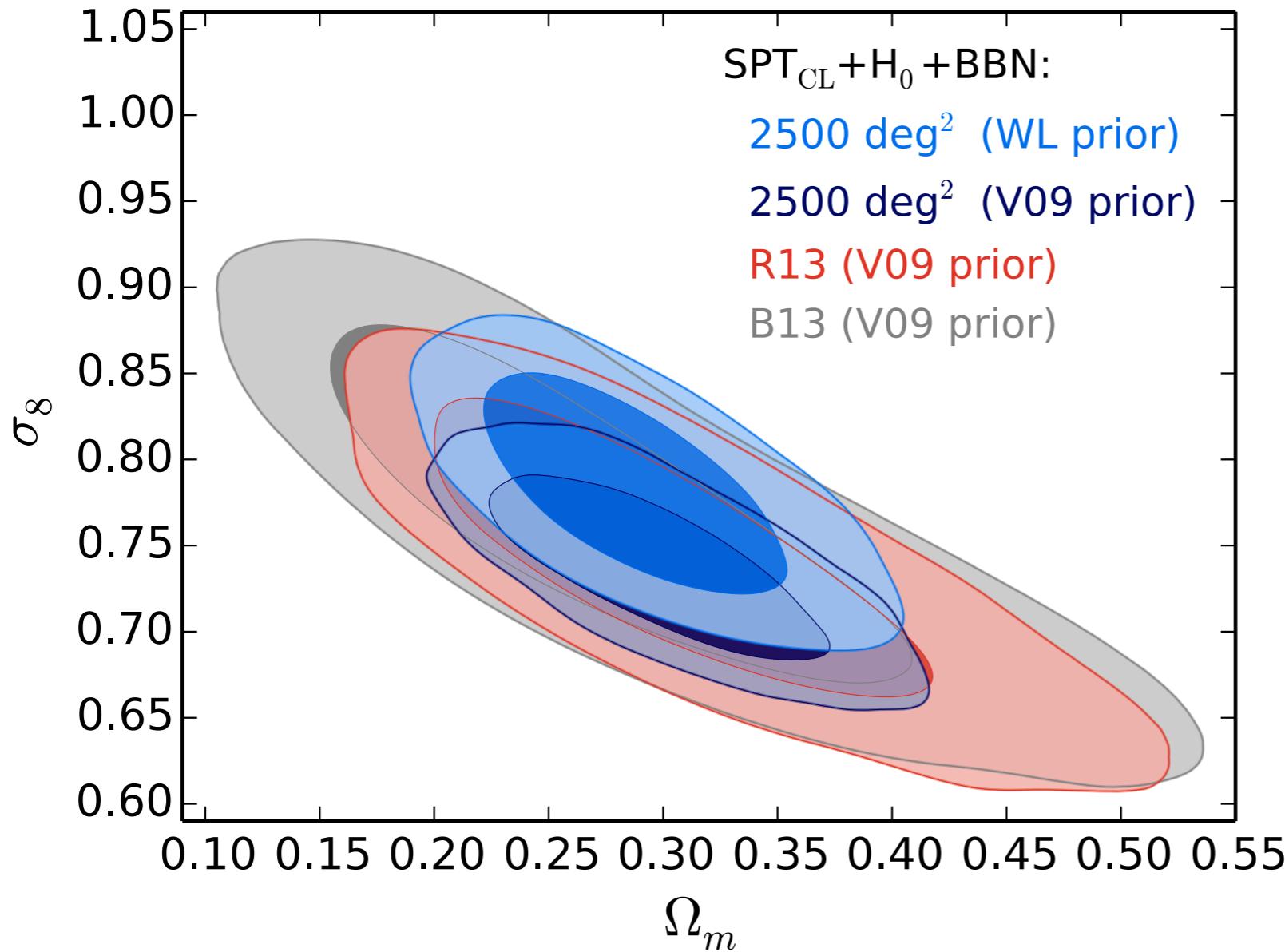
- From Benson+13 to de Haan+16, area in  $\sigma_8$ - $\Omega_m$  likelihood space reduced by  $\sim 4x$
- Biggest improvement is in direction of parameter space helped by cluster counts

Benson et al., ApJ 763, 147 (2013)

Reichardt, Stalder, Bleem, et al., ApJ 763, 127 (2013)

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

# $\Lambda$ CDM Constraints:



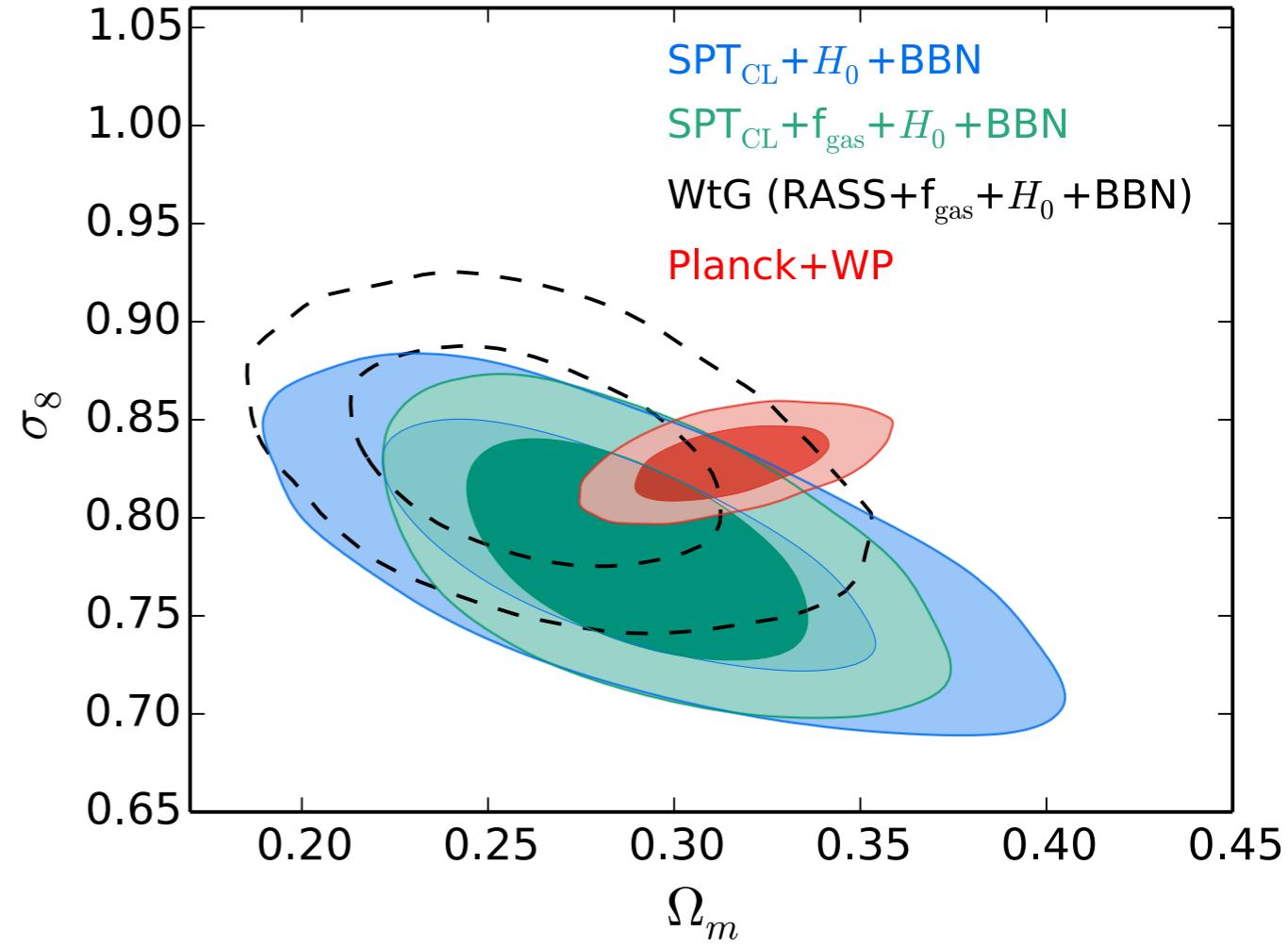
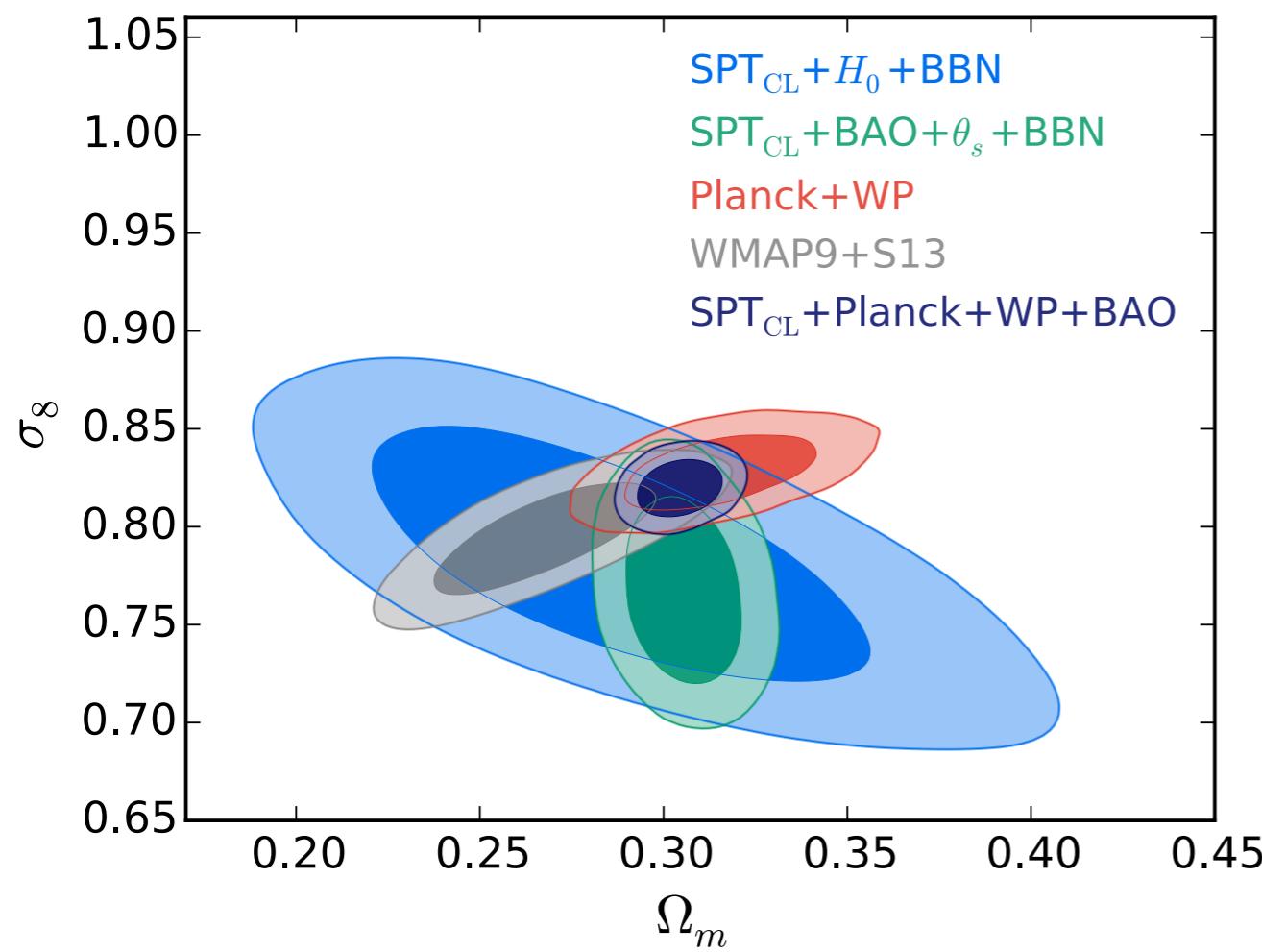
- Updated weak lensing calibration increases mass calibration by 10% (relative to Vikhlinin+09)
- Mass calibration assumes a 10% uncertainty in mass at z=0
  - Limited by small sample (10 clusters) in Vikhlinin+09, Hoekstra+15 comparison
  - Next step is to increase sample and extend to higher redshift

Benson et al., ApJ 763, 147 (2013)

Reichardt et al., ApJ 763, 127 (2013)

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

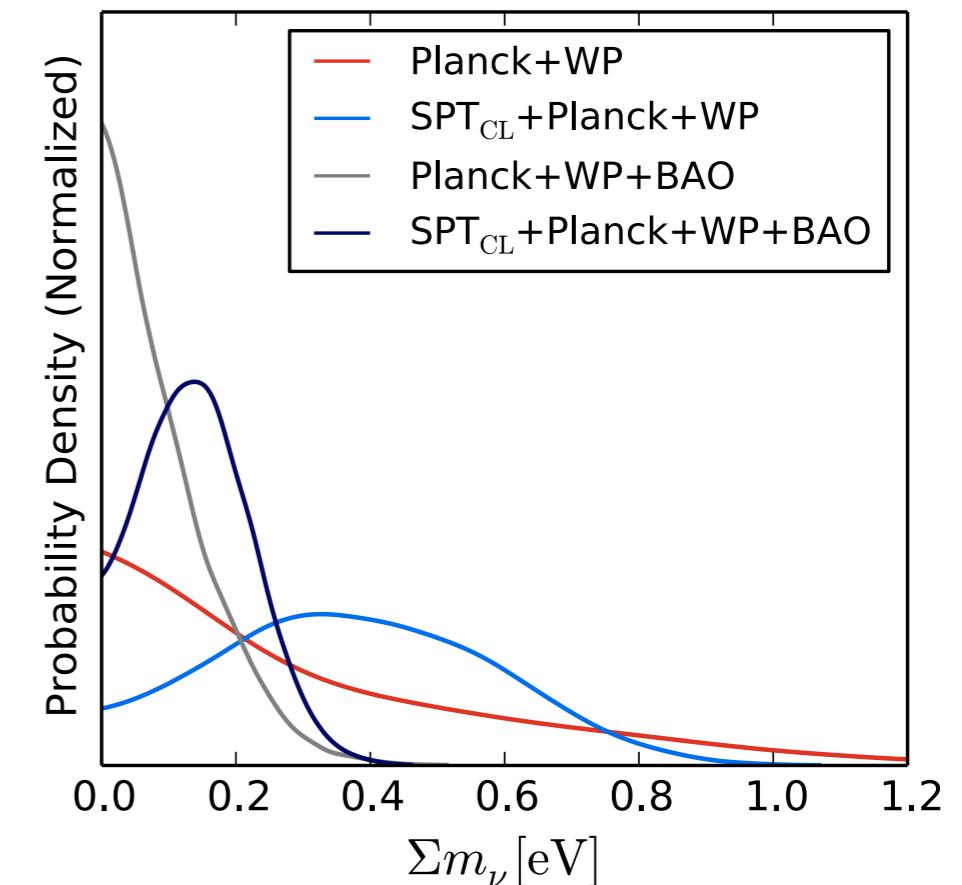
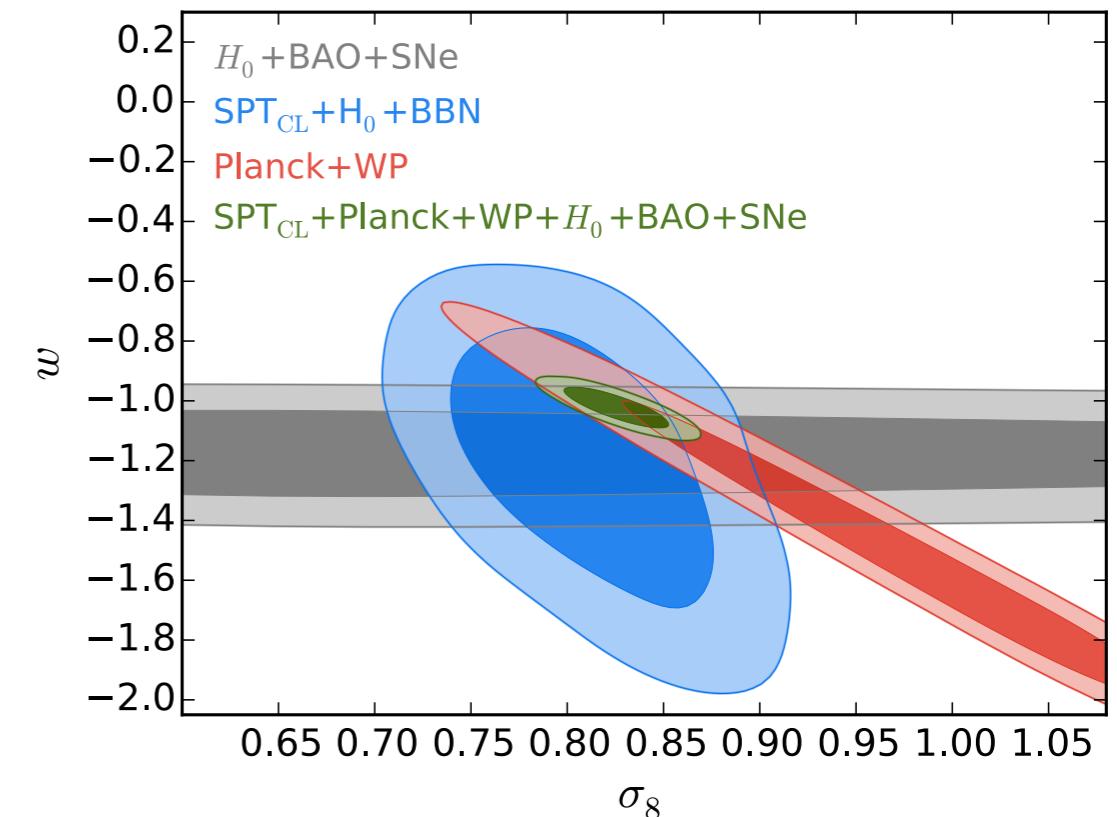
# $\Lambda$ CDM Constraints:



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

# *Extensions to $\Lambda$ CDM*

- Clusters break degeneracies in other datasets; Combination of Clusters, CMB, geometric probes:  $w = -1.023 \pm 0.042$
- CMB strong degeneracy  $\sigma_8$ - $\Sigma m_\nu$  so even modest  $\sigma_8$  can improve constraints



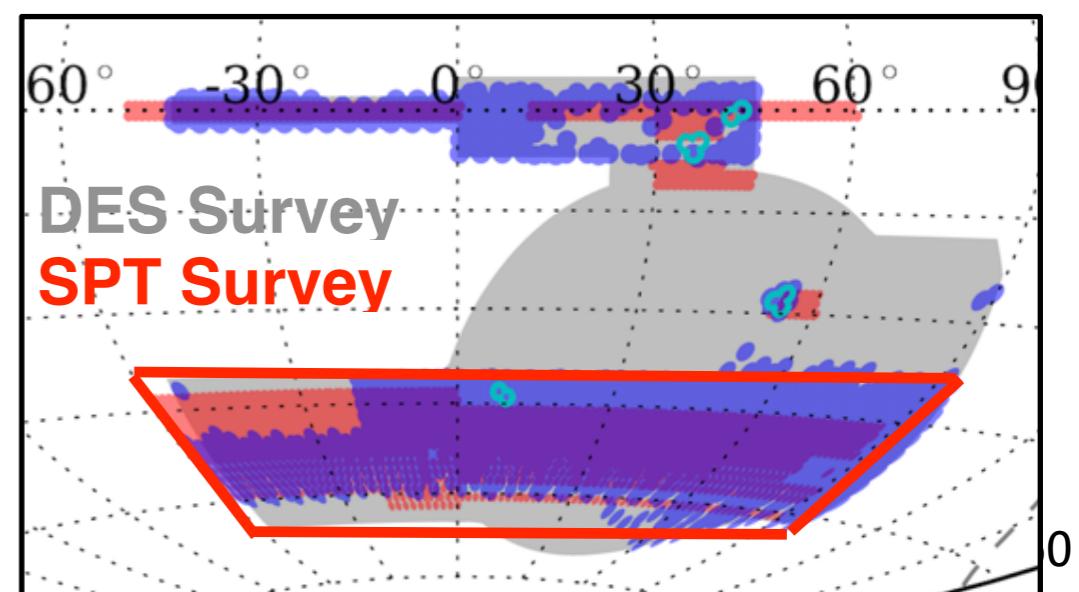
# *Dark Energy Survey (DES) and SPT*



Image credit: Roger Smith/NOAO/AURA/NSF

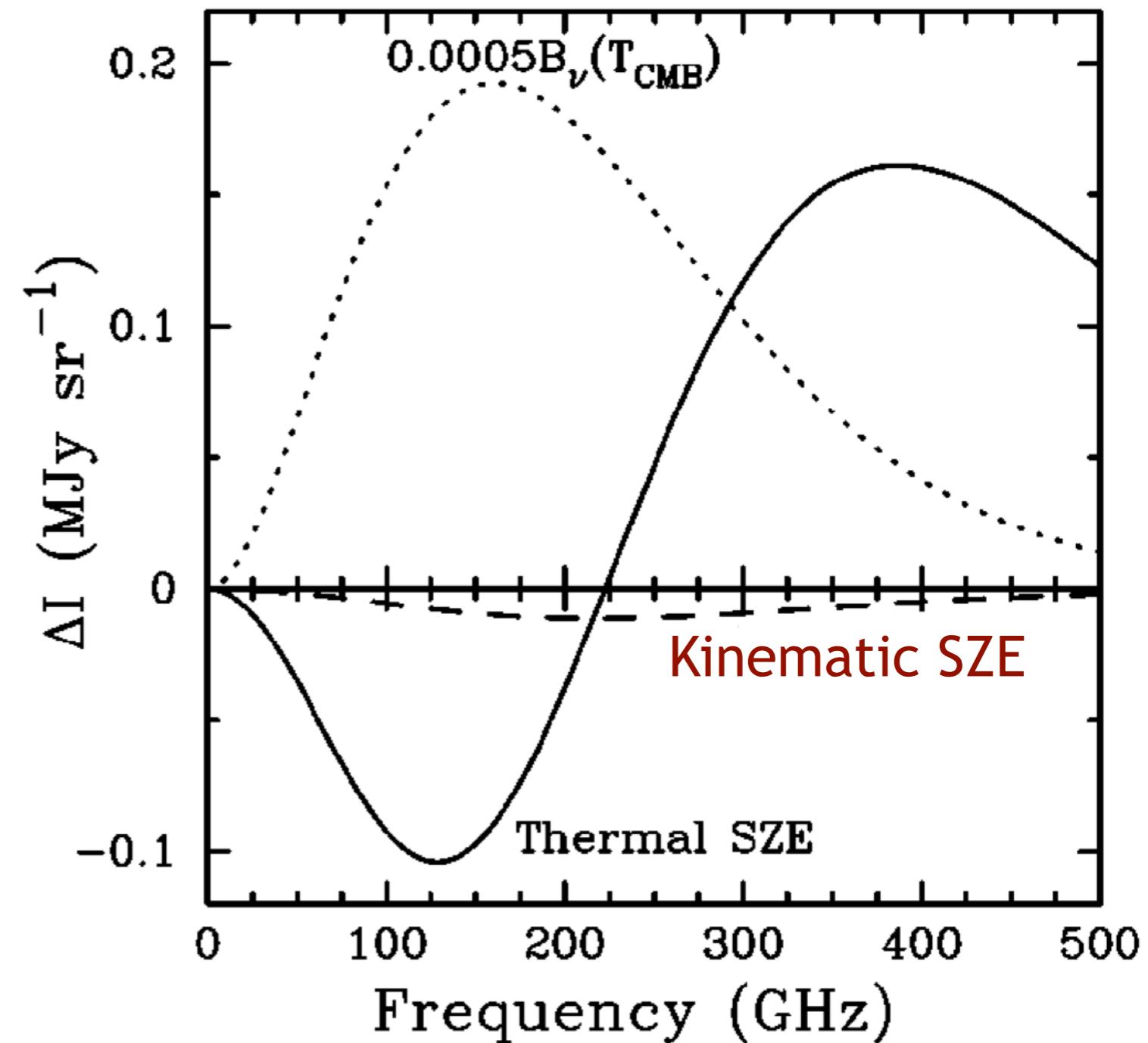
Blanco 4m. Cerro Tololo, Chile

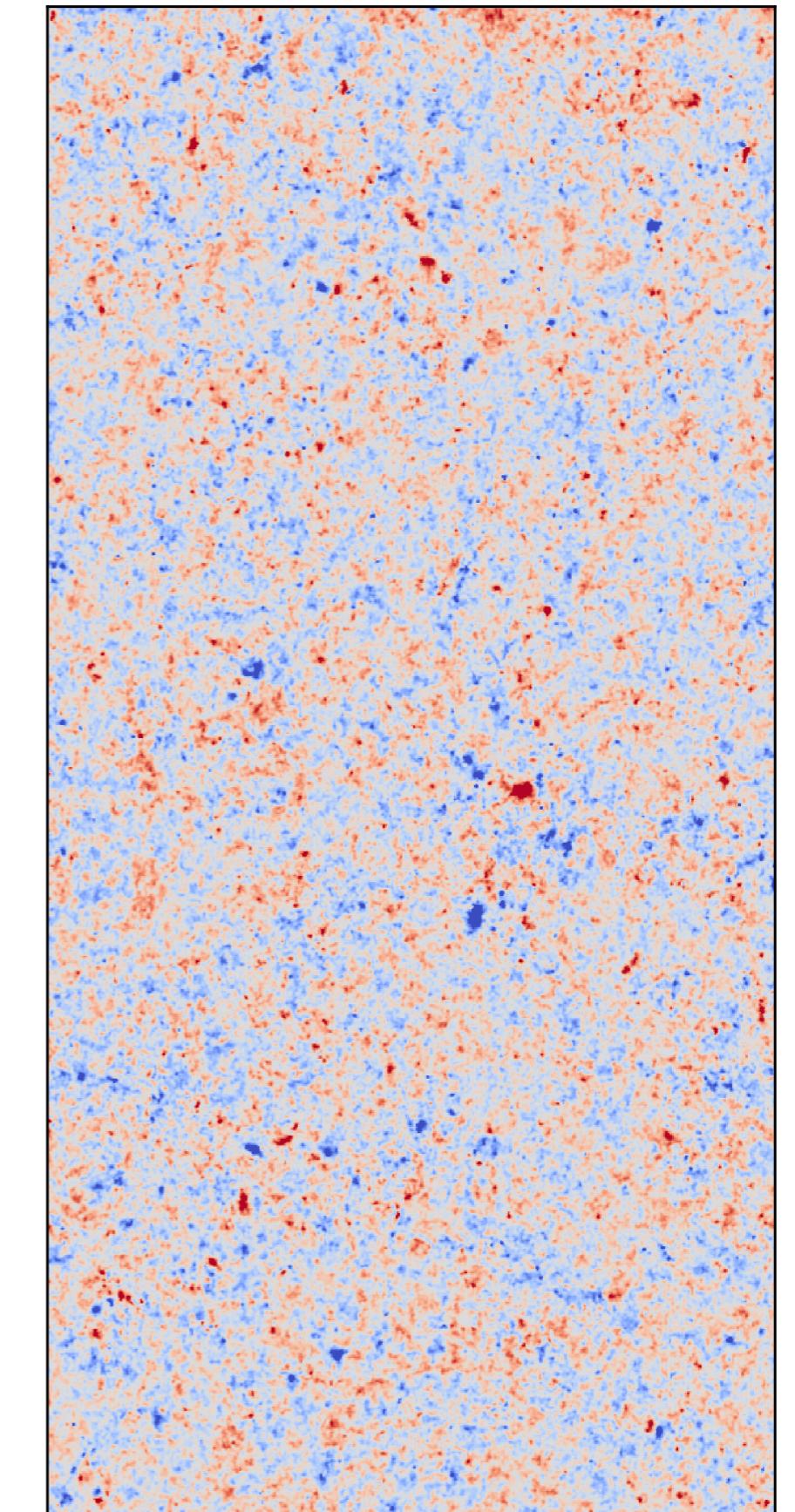
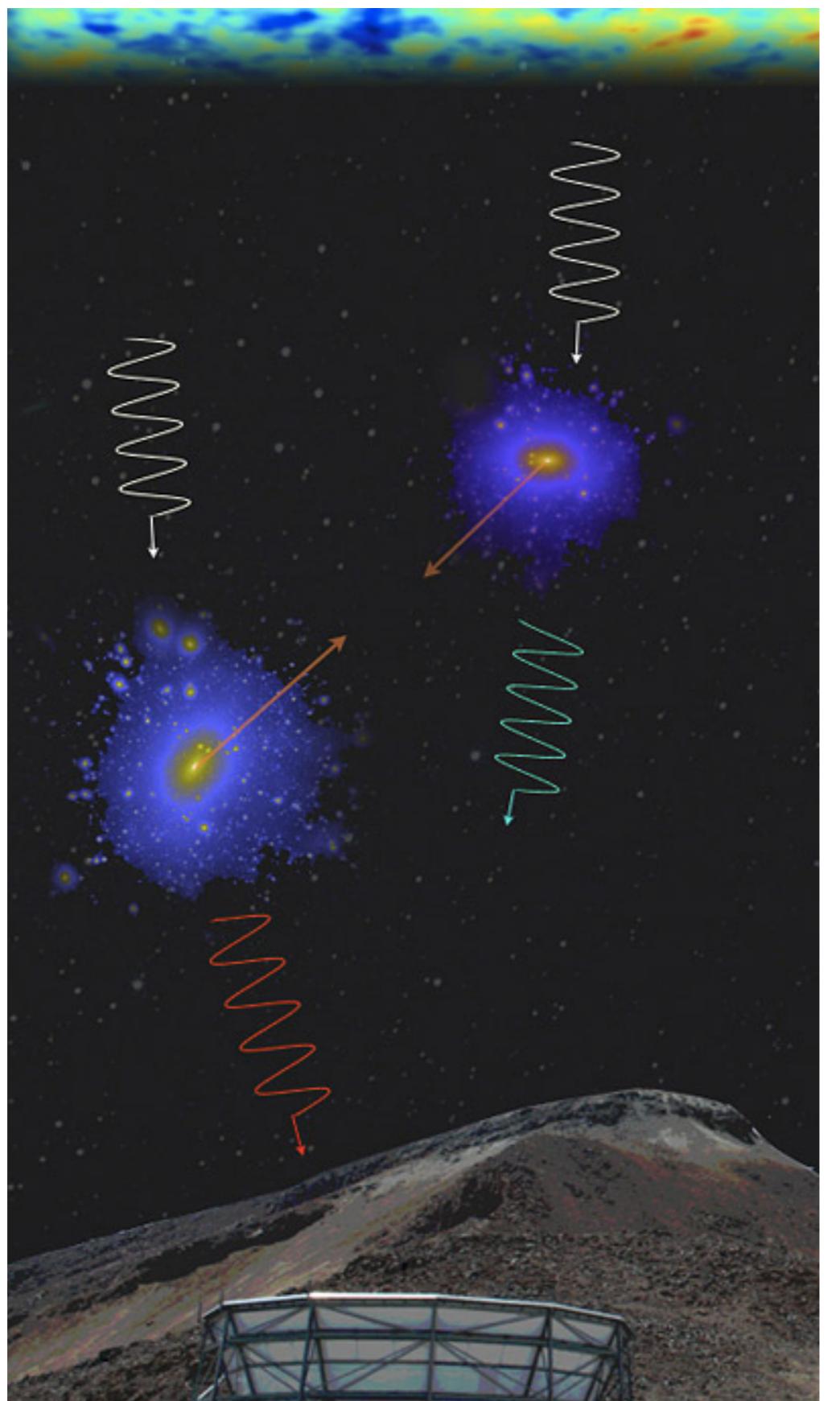
- **Ongoing Optical Survey to cover ~5000 deg<sup>2</sup> which will detect ~100,000 clusters out to z=1**
- Multiple probes of dark energy (cluster survey, weak lensing, BAO, SN)
- **Coordinated** to overlap with SPT



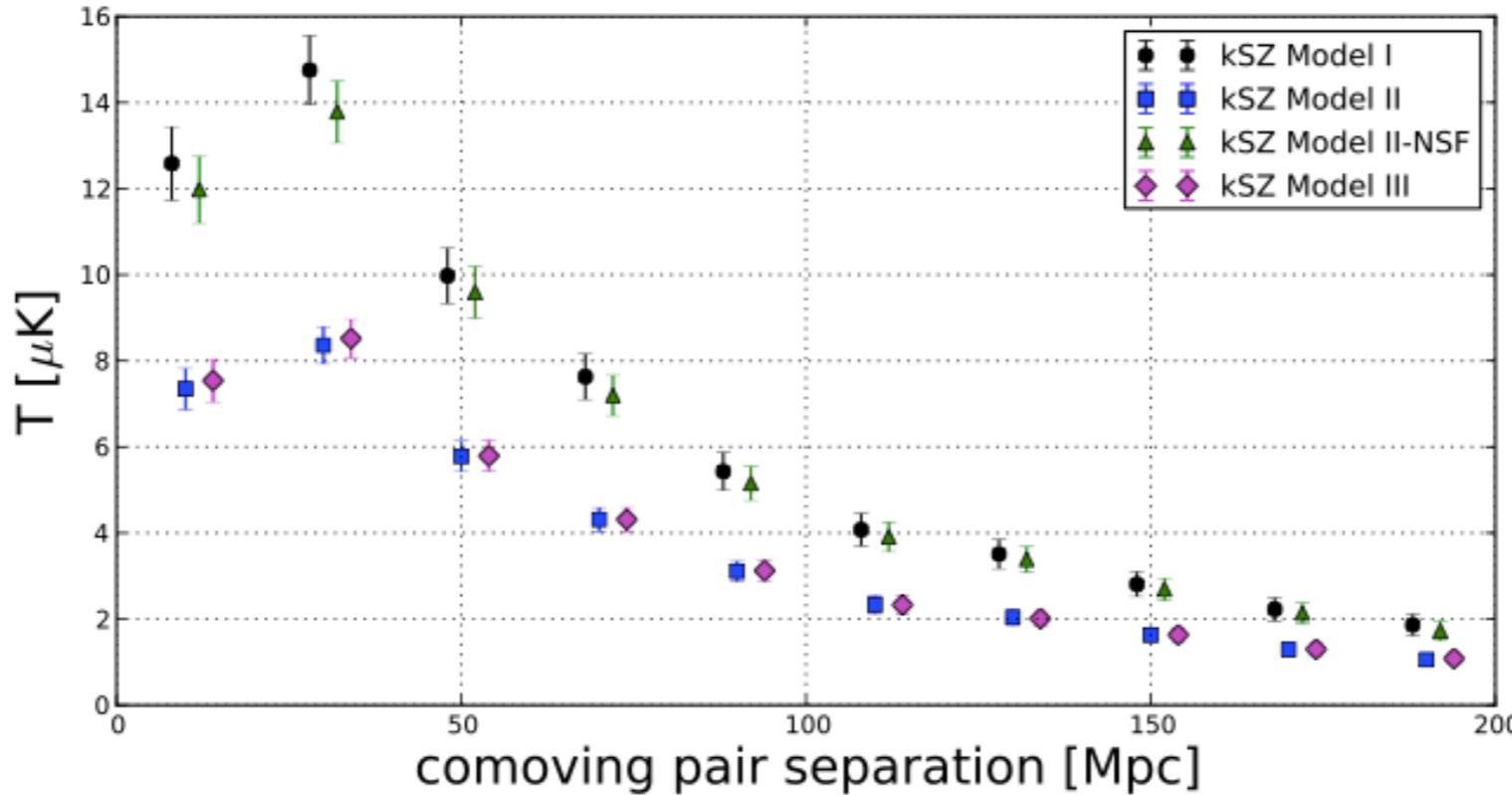
# The Kinematic Sunyaev-Zel'dovich Effect

- CMB photons scatter off electrons with peculiar velocities with respect to the CMB rest frame
- No spectral dependence; signal can be +/- depending on cluster motion
- **Much** weaker (~20x) than tSZE for high mass clusters, comparable for low mass groups

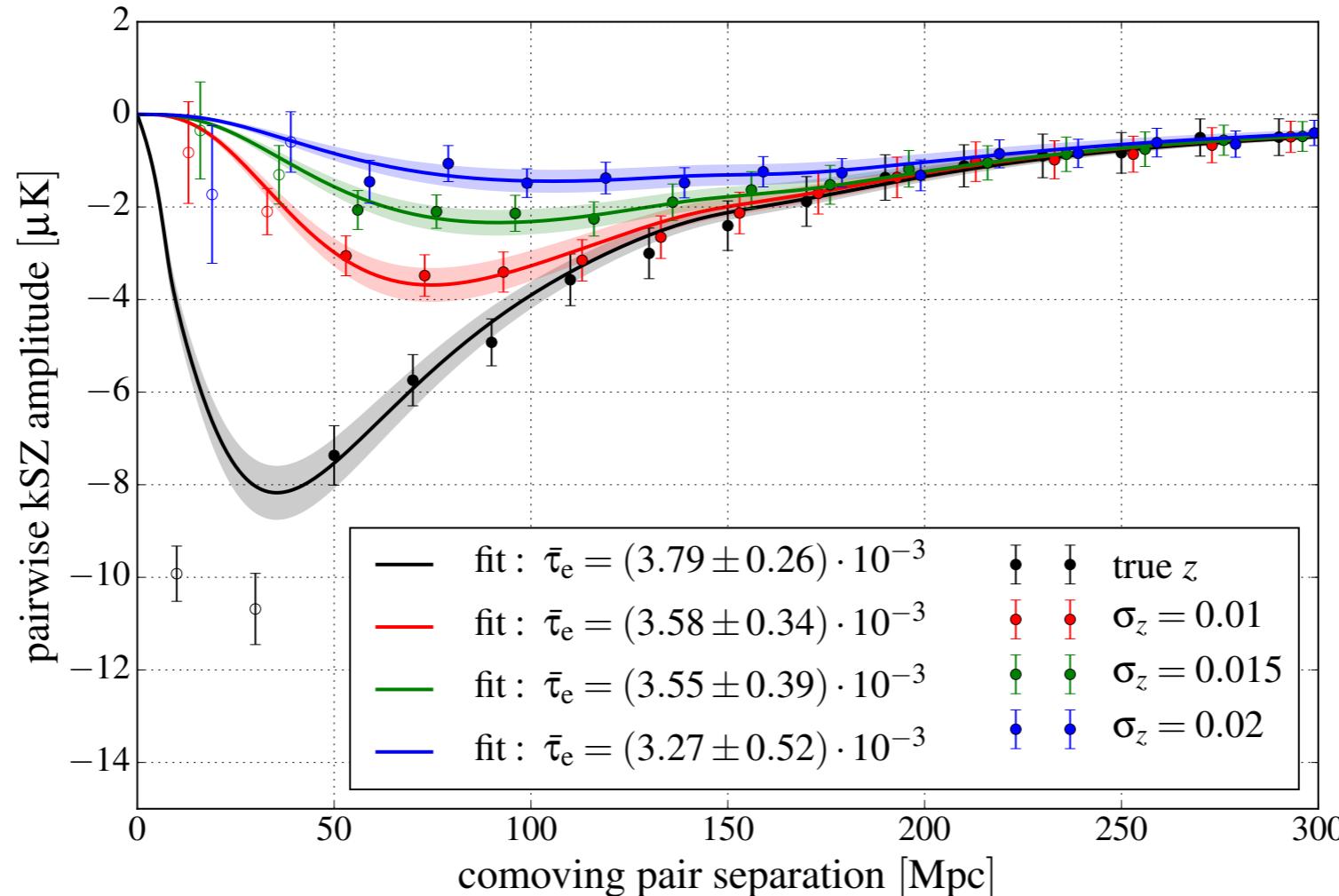




# Simulations are key for Understanding Biases/Interpreting Results

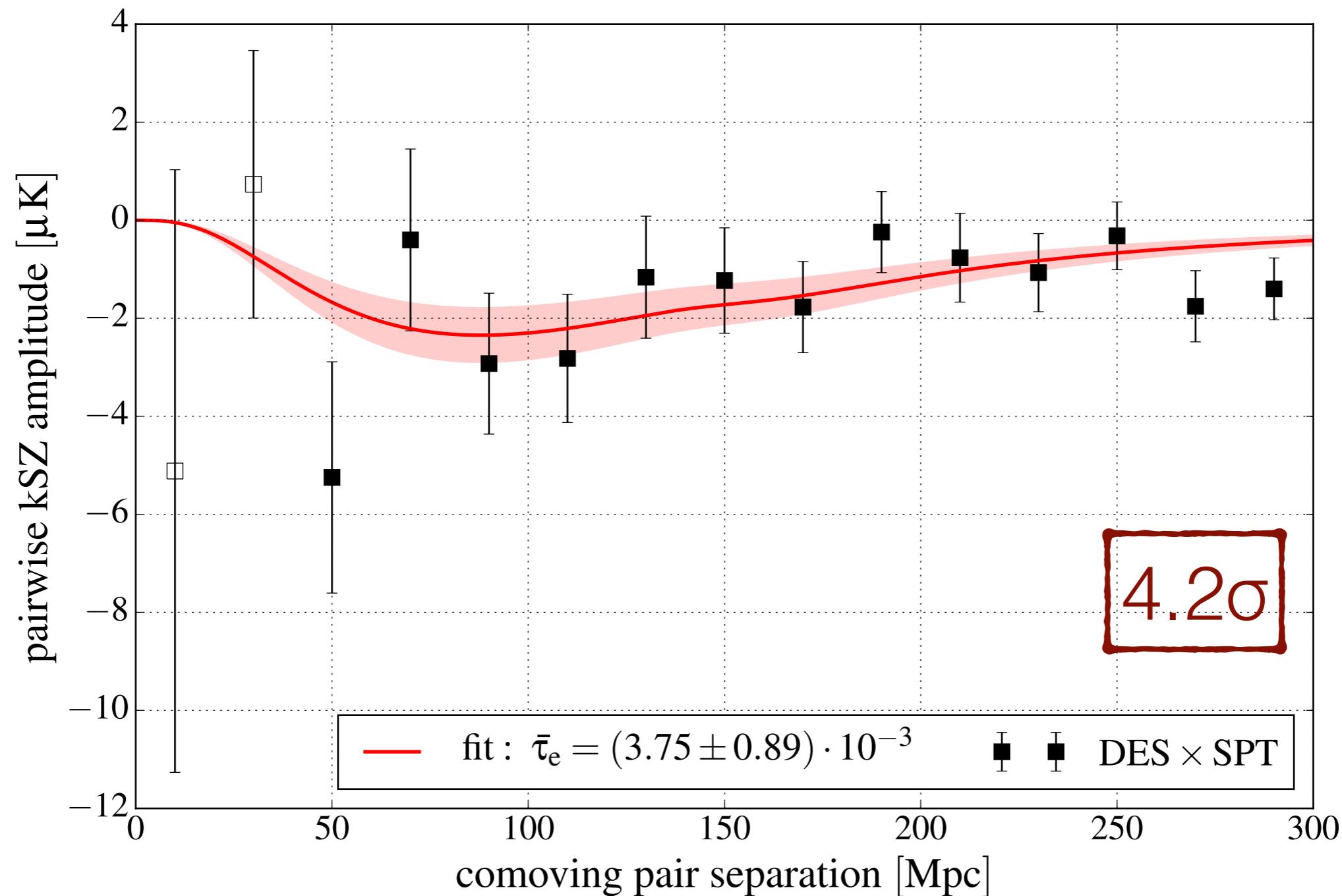


Flender et al.  
ApJ 826, 98 (2016)



Soergel et al.  
MNRAS (2016) 461 (3)

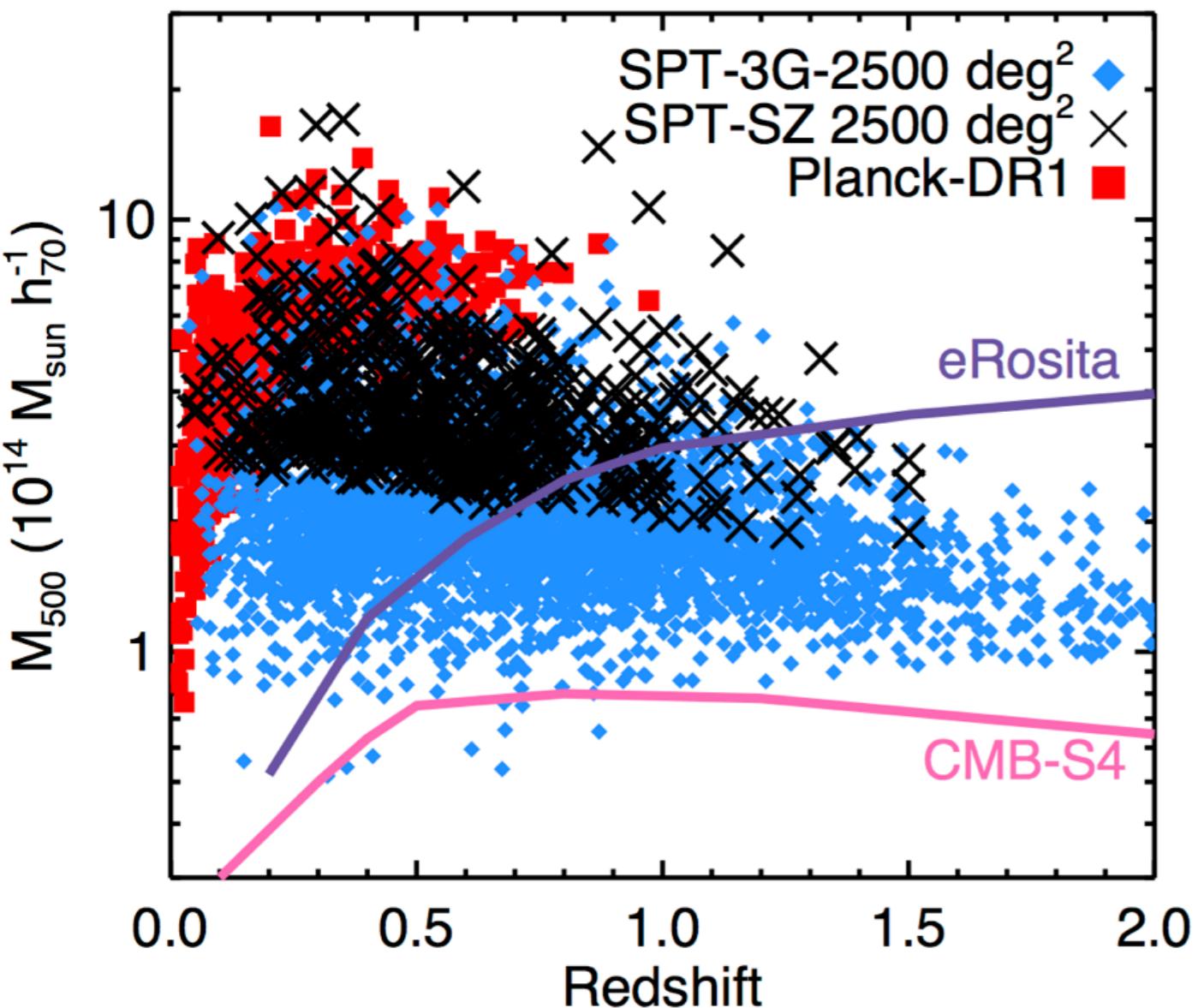
# Measurement of the Pairwise kSZ signal from DES Y1 and SPT-SZ data.



Soergel et al.  
MNRAS (2016) 461 (3)  
1603.03904

See also Planck Collab. arXiv:  
1504.0333,  
Hill+ arXiv:1603.01608, De  
Bernardis+ arXiv:1607.02139

# Future Cluster Surveys



**SPT-SZ/pol:**

$N_{\text{clust}} \sim 1,000$

**SPT-3G:**

$N_{\text{clust}} \sim 10,000$

- 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  $0.05 < z < 1.7$ .
- 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!).
- Joint DES-SPT analyses promise to improve cosmological constraints, provide powerful systematic tests, and enable new cosmological probes