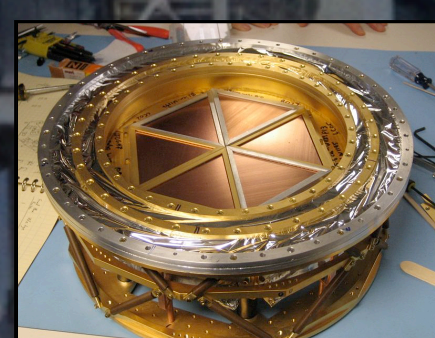
The South Pole Telescope (SPT)

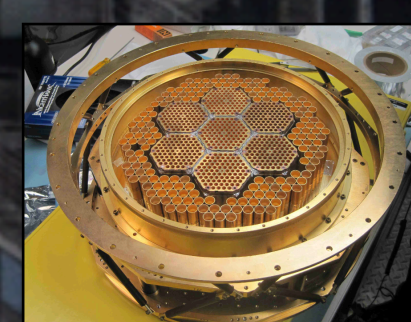
Bradford Benson
(University of Chicago)

The South Pole Telescope (SPT)

- 10-meter sub-mm quality wavelength telescope
- At 100, 150, 220 GHz, angular resolution of 1.6, 1.2, 1.0 arcmin
  - Well-matched to high-z clusters, e.g., r_{500} $(z=1.0)$ ~ 2 arcmin
- **Three Surveys**: SPT-SZ, SPTpol, SPT-3G

2007: SPT-SZ	**2012: SPTpol**	**2016: SPT-3G**
960 detectors	1600 detectors	~15,200 detectors
100,150,220 GHz	100,150 GHz	100,150,220 GHz
	+Polarization	*+Polarization*





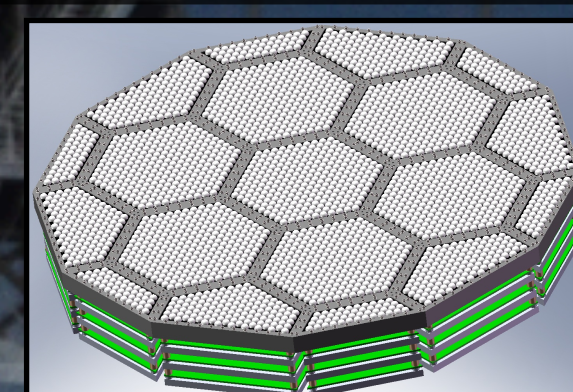
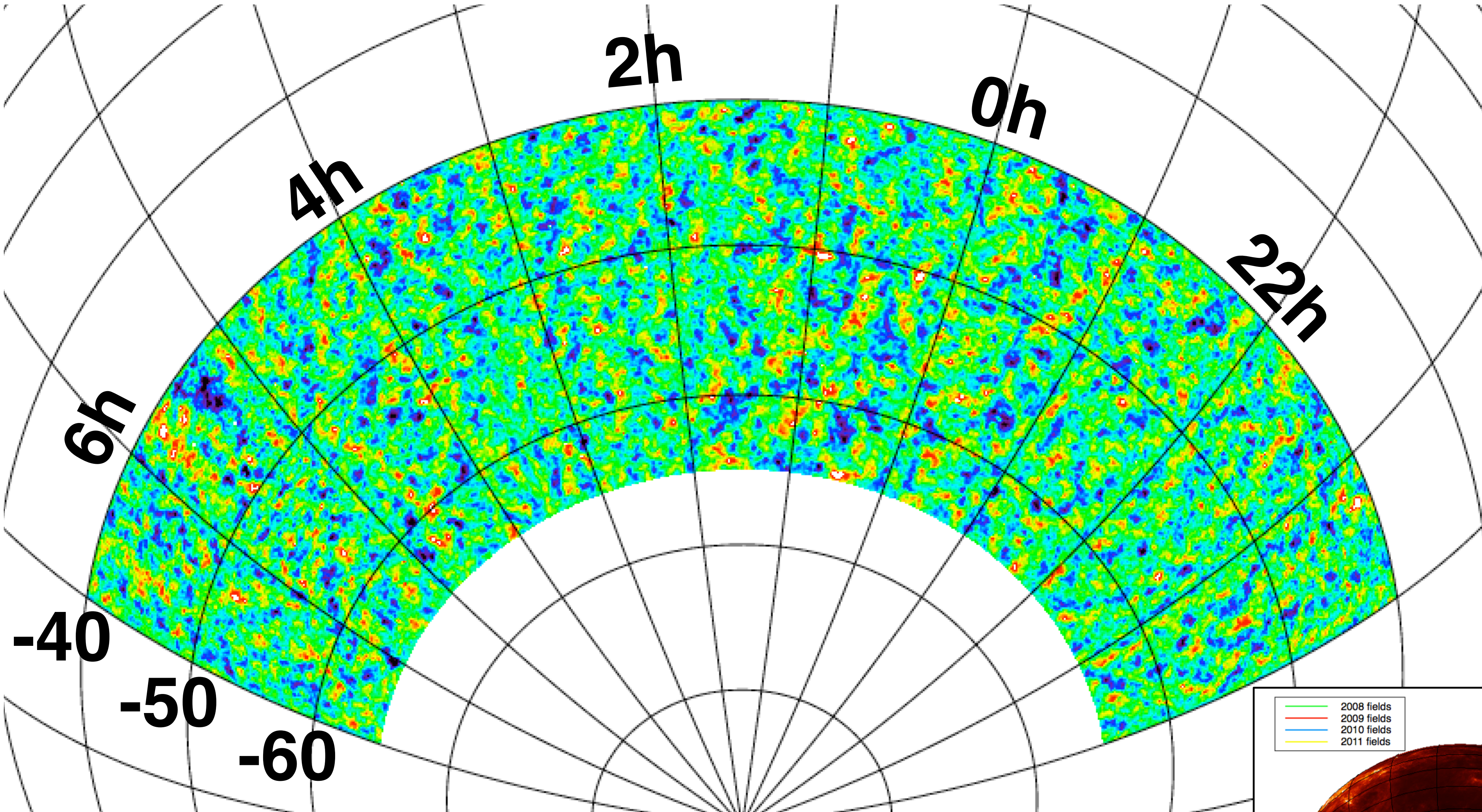


photo by Dana Hrubes

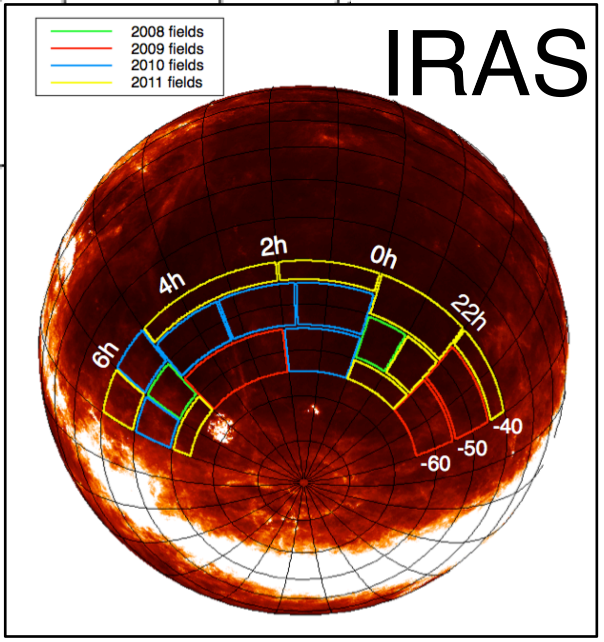
The SPT-SZ Survey (2007-2011):

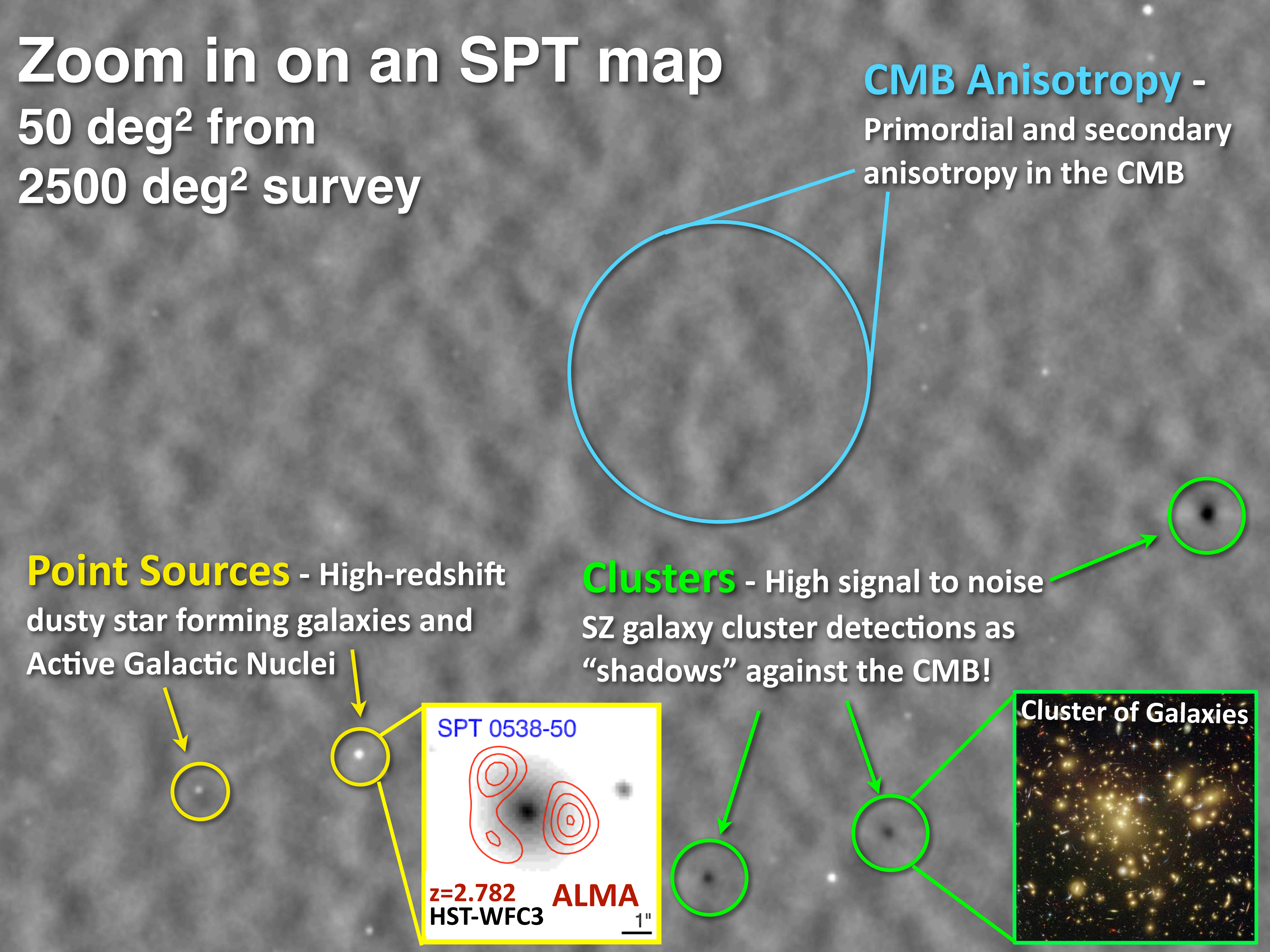
Covering 2500 deg^2 ~ 6% of sky



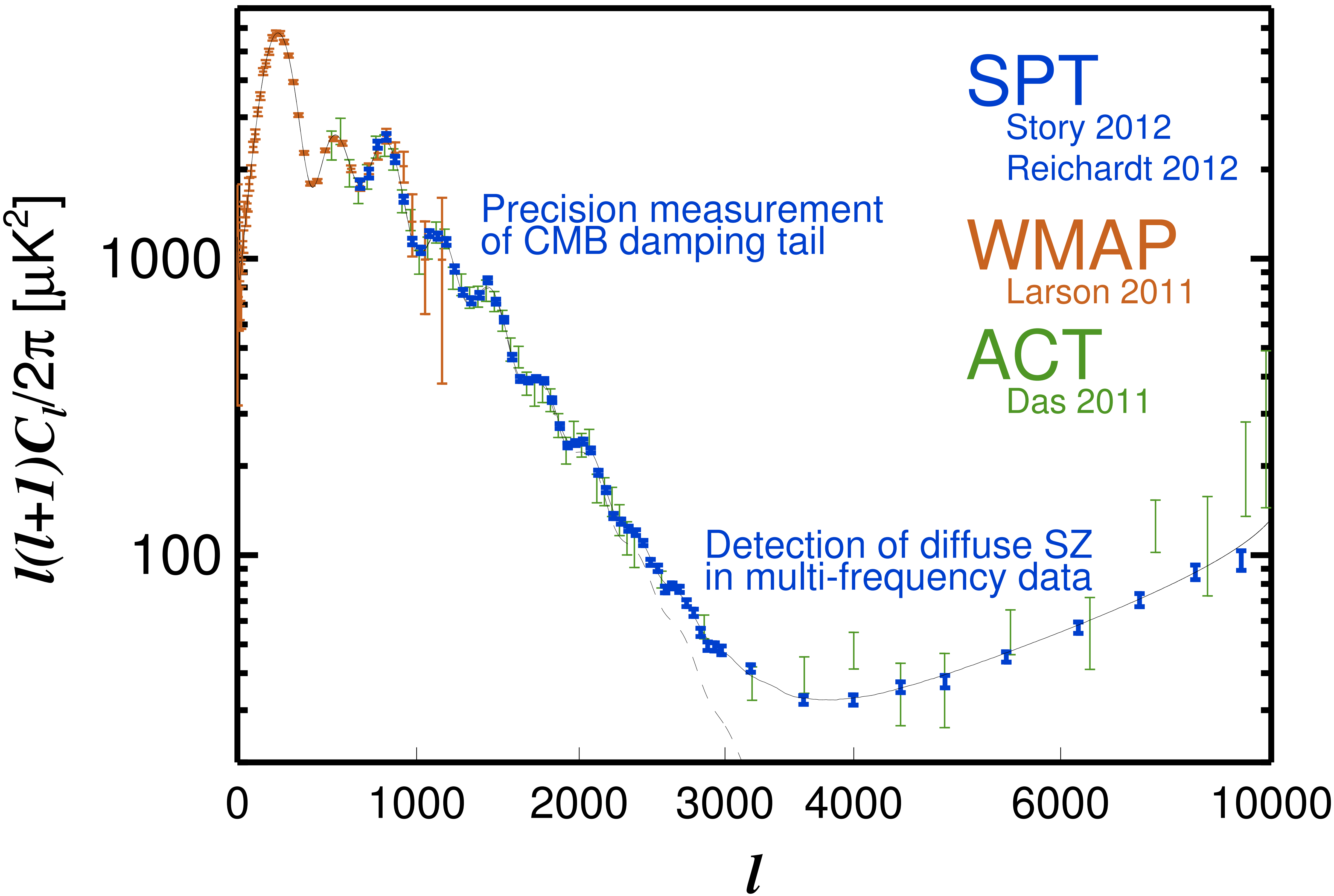
Final survey depths of:

- **100 GHz:** < 40 uK_{CMB}-arcmin
- **150 GHz:** < 18 uK_{CMB}-arcmin
- **220 GHz:** < 80 uK_{CMB}-arcmin



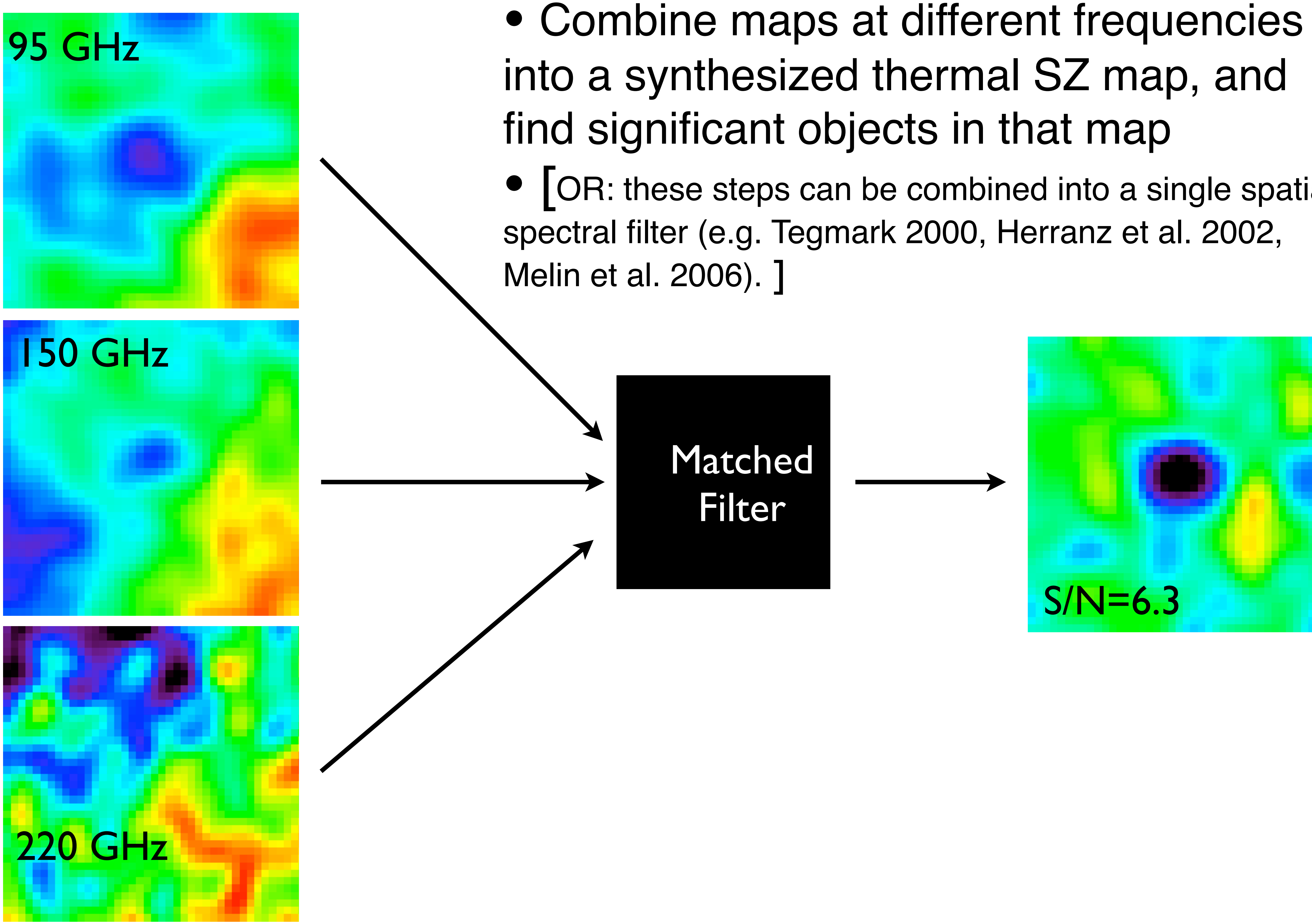

Zoom in on an SPT map
50 deg² from
2500 deg² survey
CMB Anisotropy - Primordial and secondary anisotropy in the CMB
Point Sources - High-redshift dusty star forming galaxies and Active Galactic Nuclei
SPT 0538-50
z=2.782
HST-WFC3
ALMA
1"
Clusters - High signal to noise SZ galaxy cluster detections as "shadows" against the CMB!
Cluster of Galaxies

SPT: CMB Power Spectrum



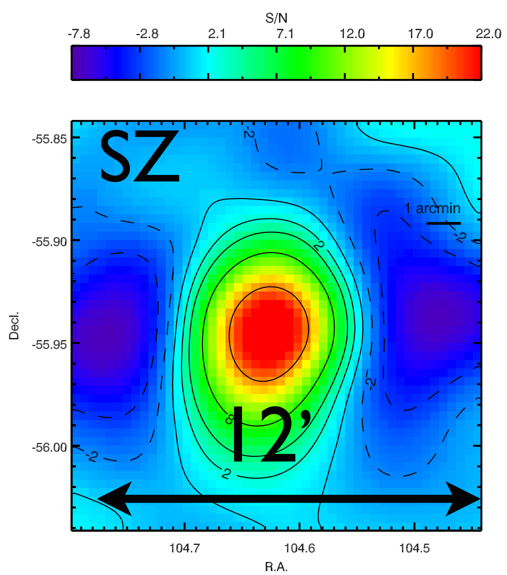
Finding Clusters in the SPT Survey

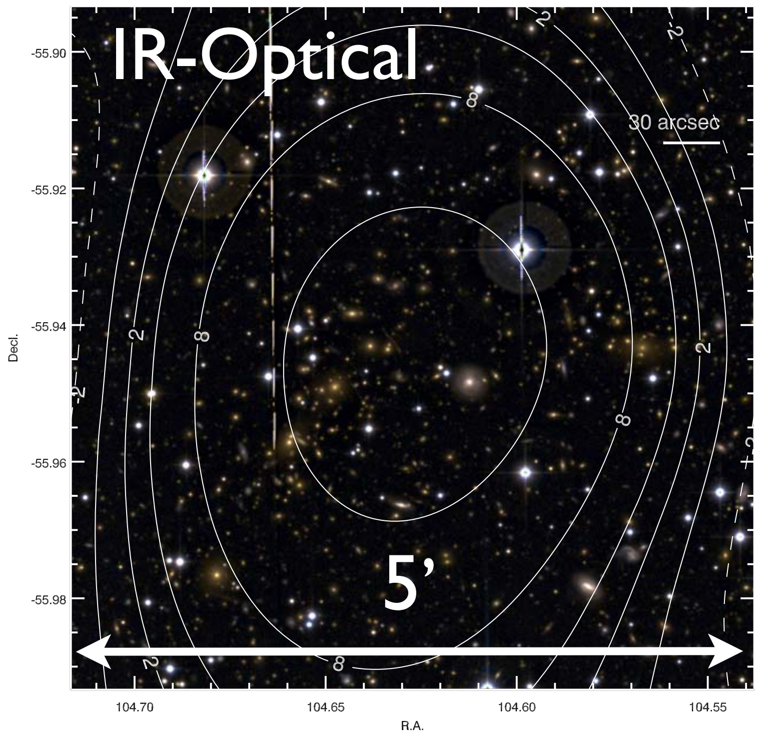
- Combine maps at different frequencies into a synthesized thermal SZ map, and find significant objects in that map
- [OR: these steps can be combined into a single spatial-spectral filter (e.g. Tegmark 2000, Herranz et al. 2002, Melin et al. 2006).]



Example Massive SPT Clusters

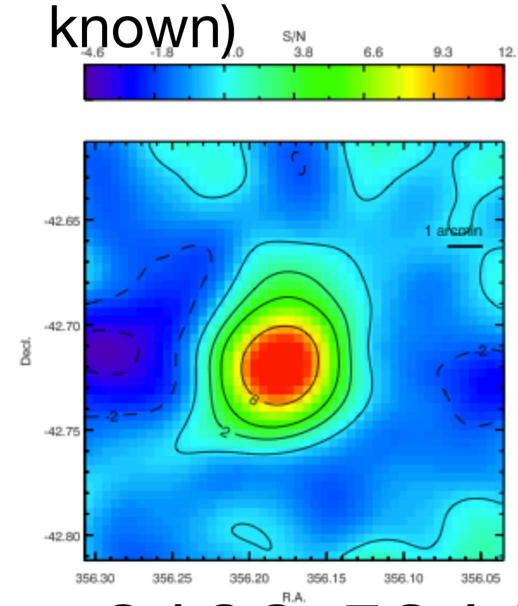
0658-5358 (z=0.30) (Bullet)

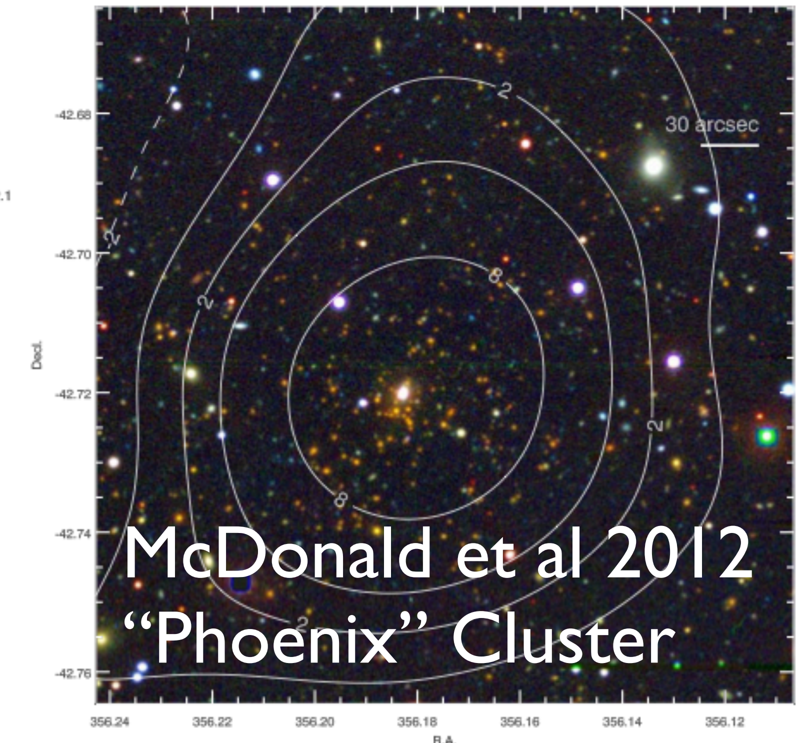




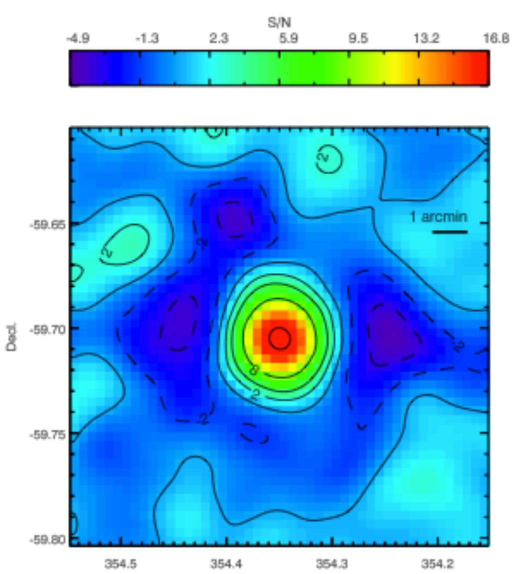
2344-4243 (z=0.60)

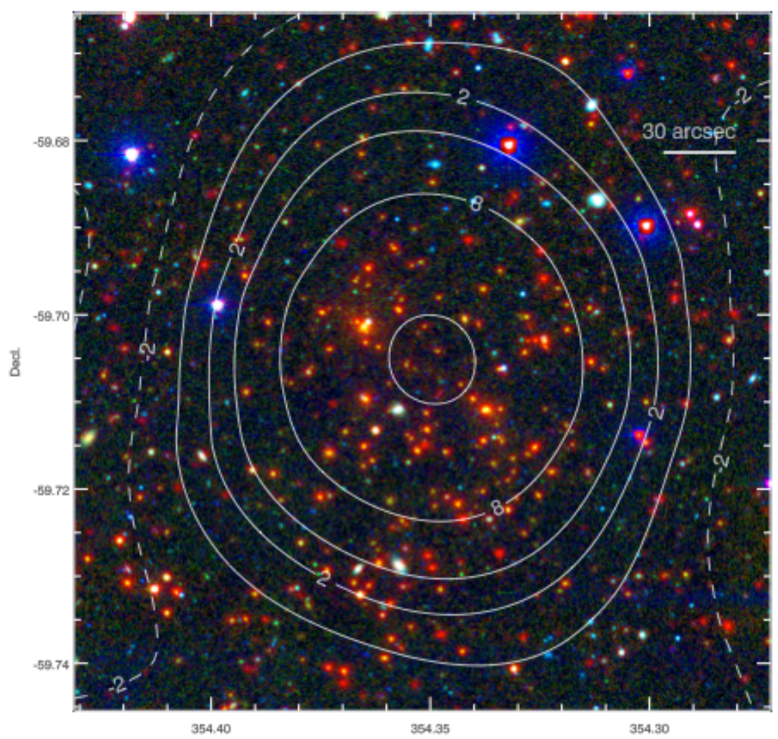
(Most X-ray luminous cluster known)





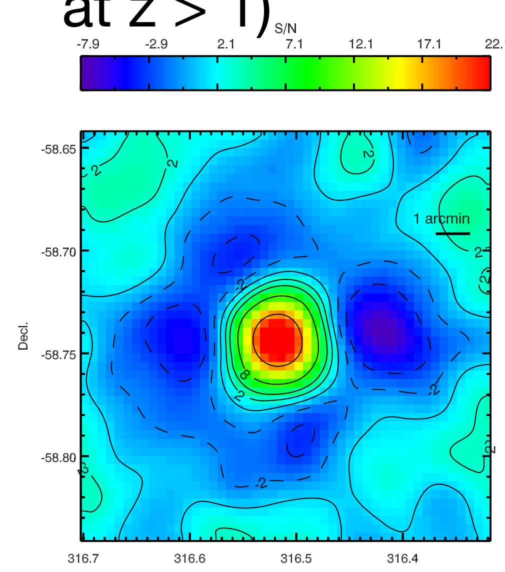
2337-5942 (z=0.78)

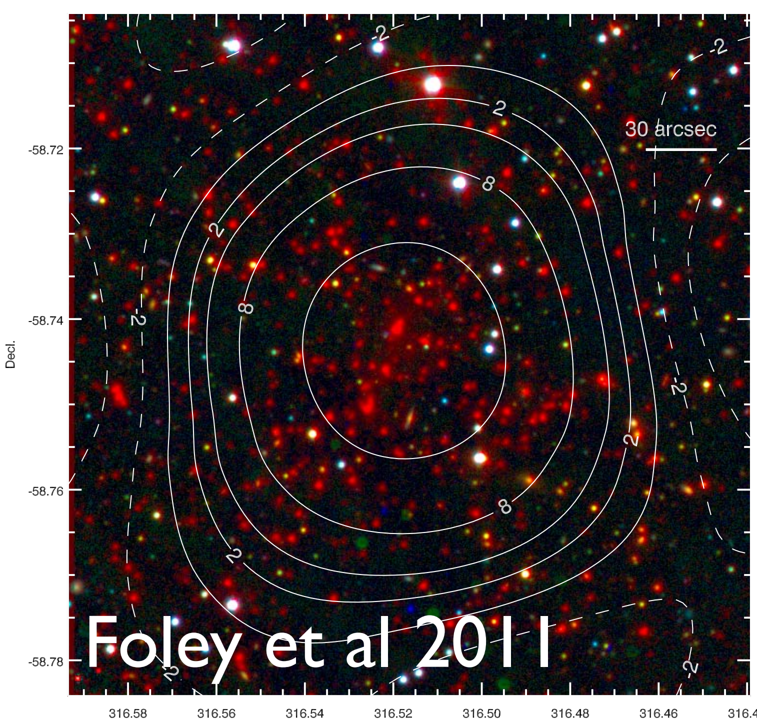




2106-5844 (z=1.13)

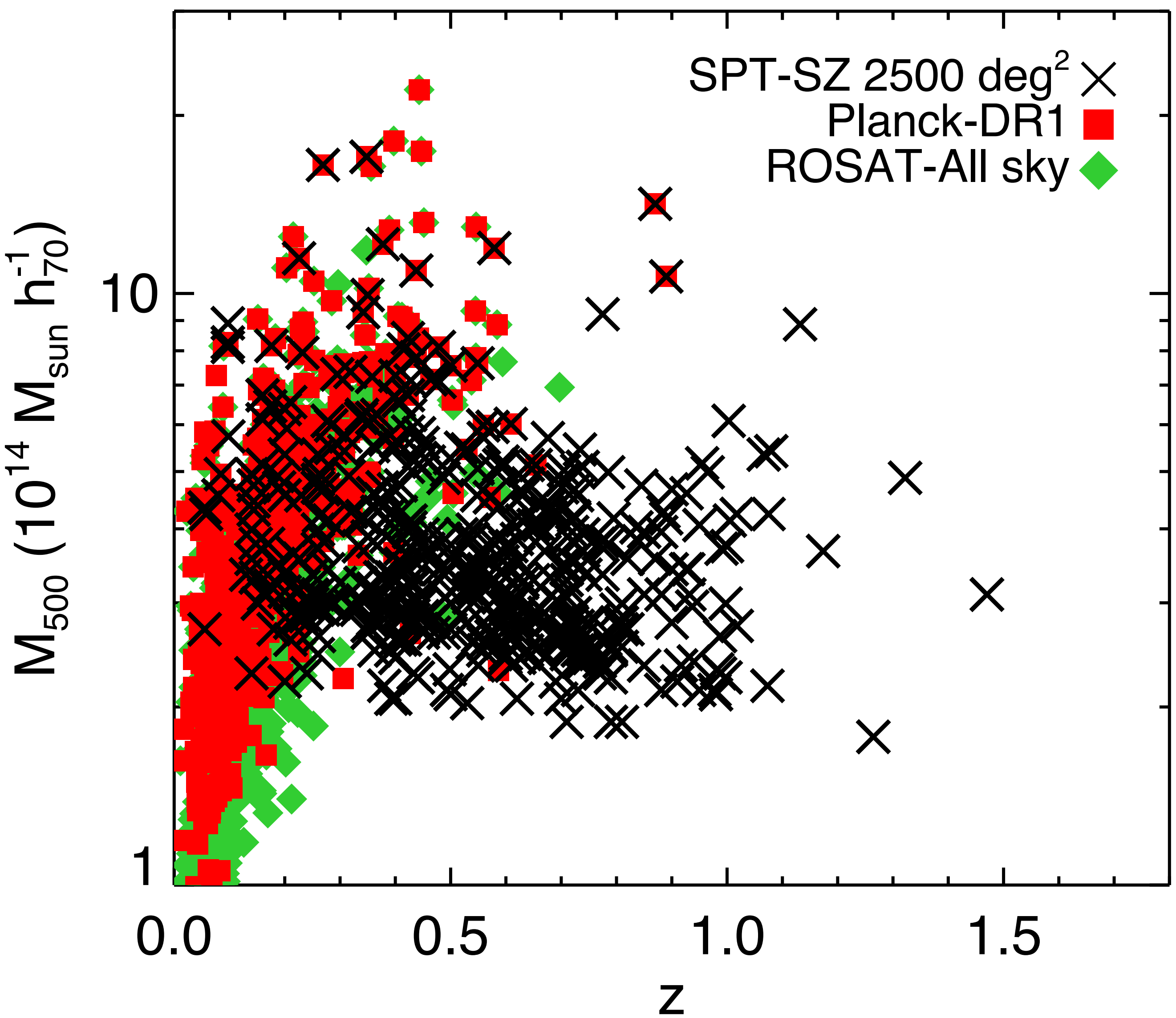
(Most massive cluster known at z > 1)





SPT Cluster Sample Properties

Cluster Mass vs Redshift

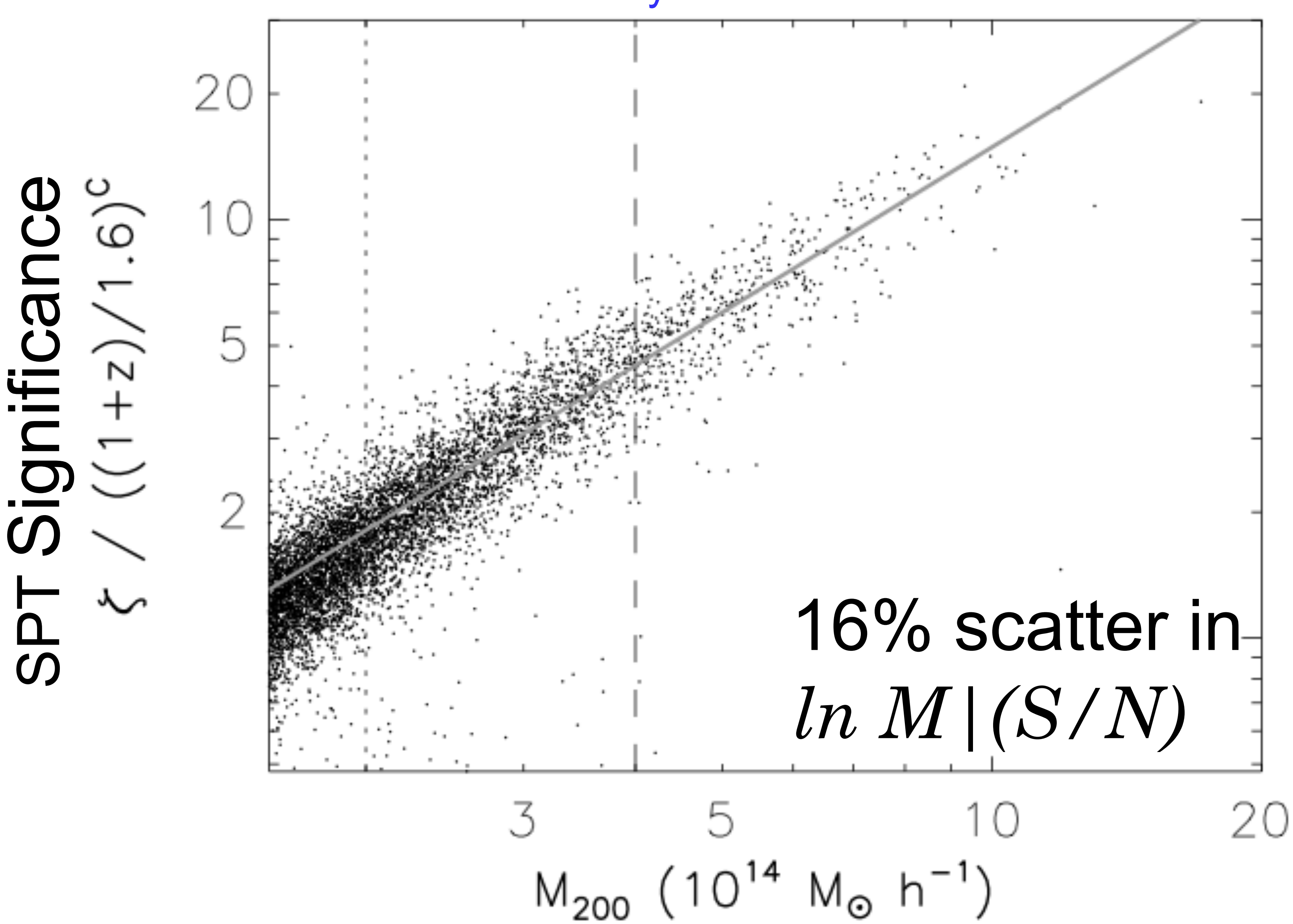


- **SPT has nearly redshift independent selection for M_{500} > 2.5 x 10^{14} M_{sun}/h_{70}**
- **440 clusters with measured redshifts and SPT S/N > 4.0** (~400 at S/N > 5; ~95% purity level)
  - **~75% are newly SZ-discovered clusters**
- Optical analysis on-going; full 2500 deg^2 catalog due out summer 2013

Bleem et al. (in prep)

SPT Significance as a Mass Proxy

From Simulations by Laurie Shaw

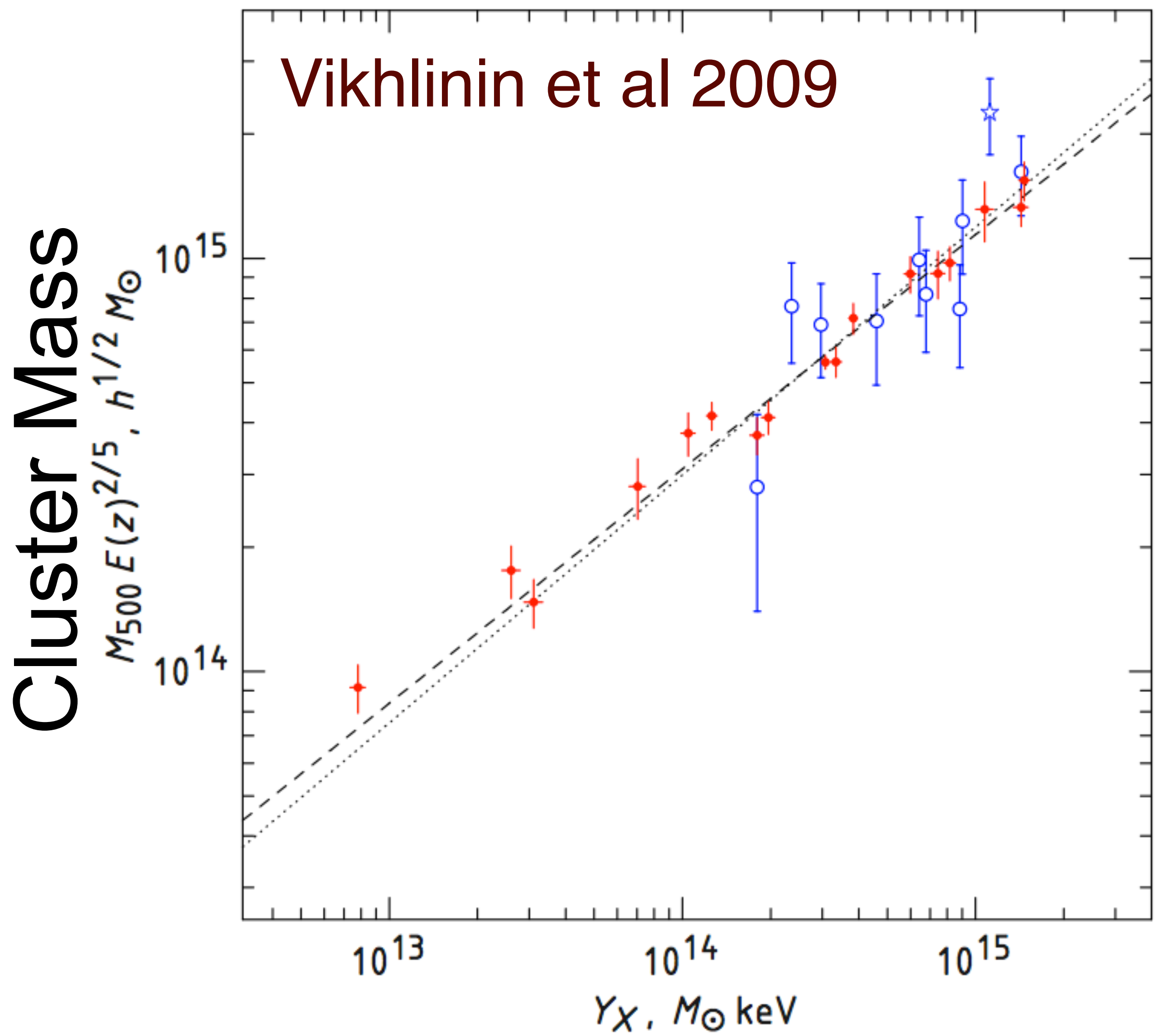


- For any cluster survey, challenge is to link cluster "observable" to cluster mass
- Ysz should have low scatter (Kravstov 2006, Battaglia 2012)
- From simulations, signal-to-noise in spatial filtered SPT map is a relatively good mass proxy (Vanderlinde et al 2010)
- **Need to calibrate SZ significance to cluster mass!**

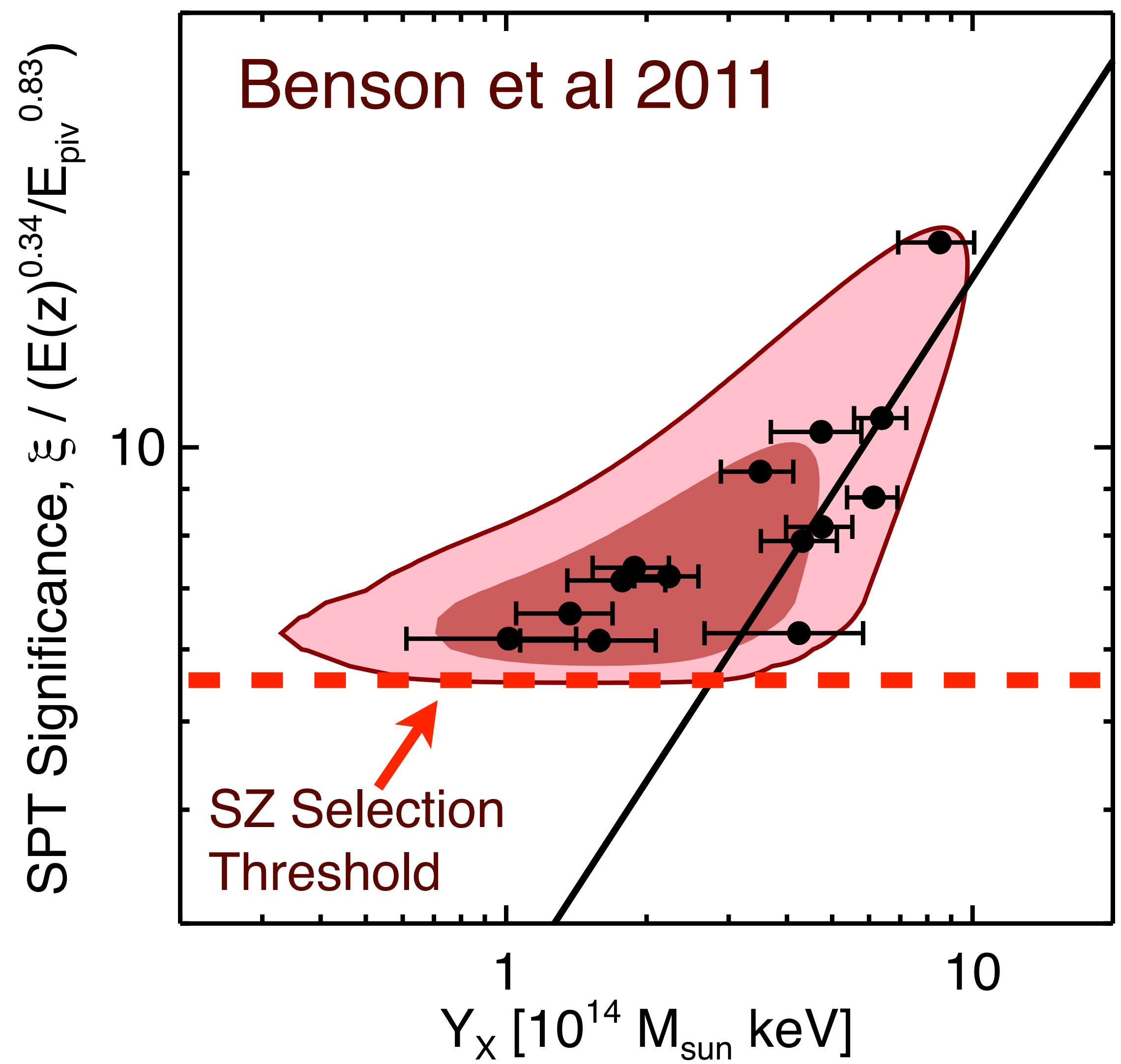
SPT Significance-Mass Calibration

Use X-ray (Yx-M) relation to calibrate SPT significance-mass relation:

- ***X-ray observations calibrate slope, scatter, redshift evolution***
- ***Weak Lensing calibrates mass normalization (~10-15% accuracy)***



X-ray Pressure, $Yx(=M_{gas}Tx)$

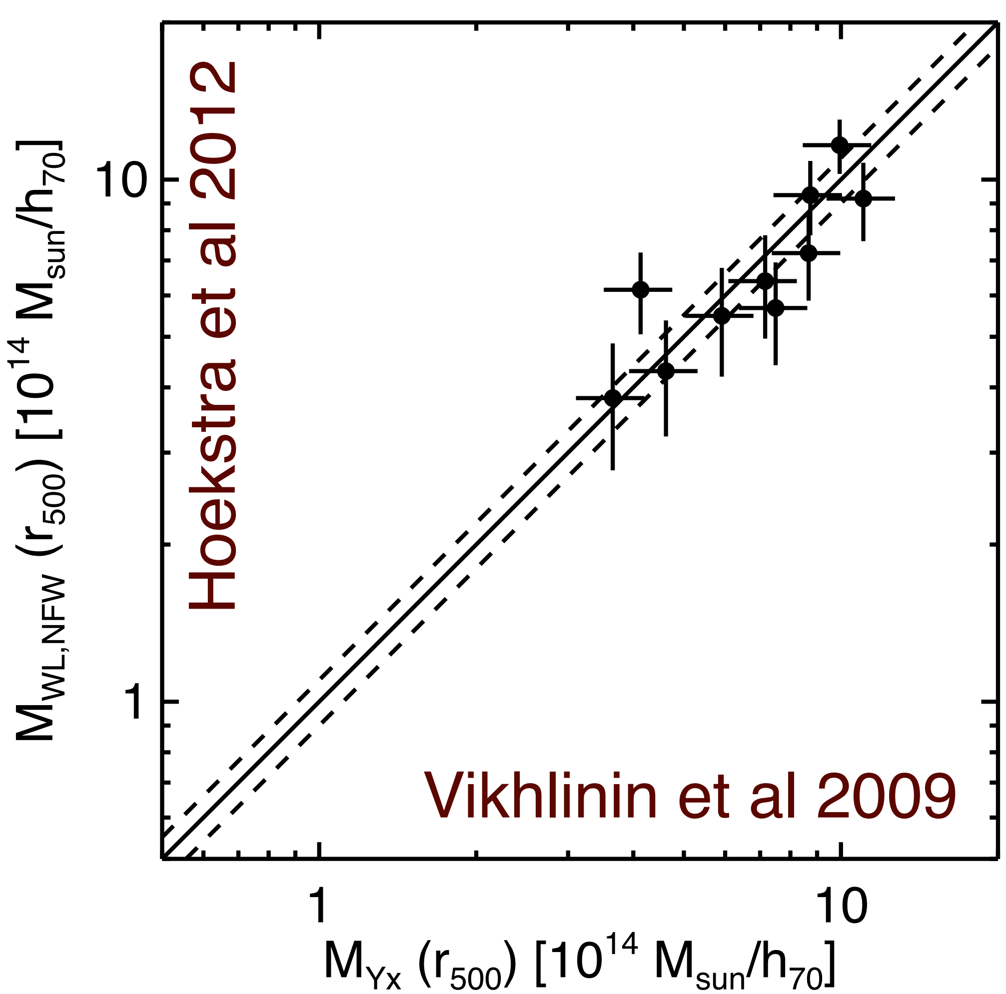


X-ray Pressure, Yx

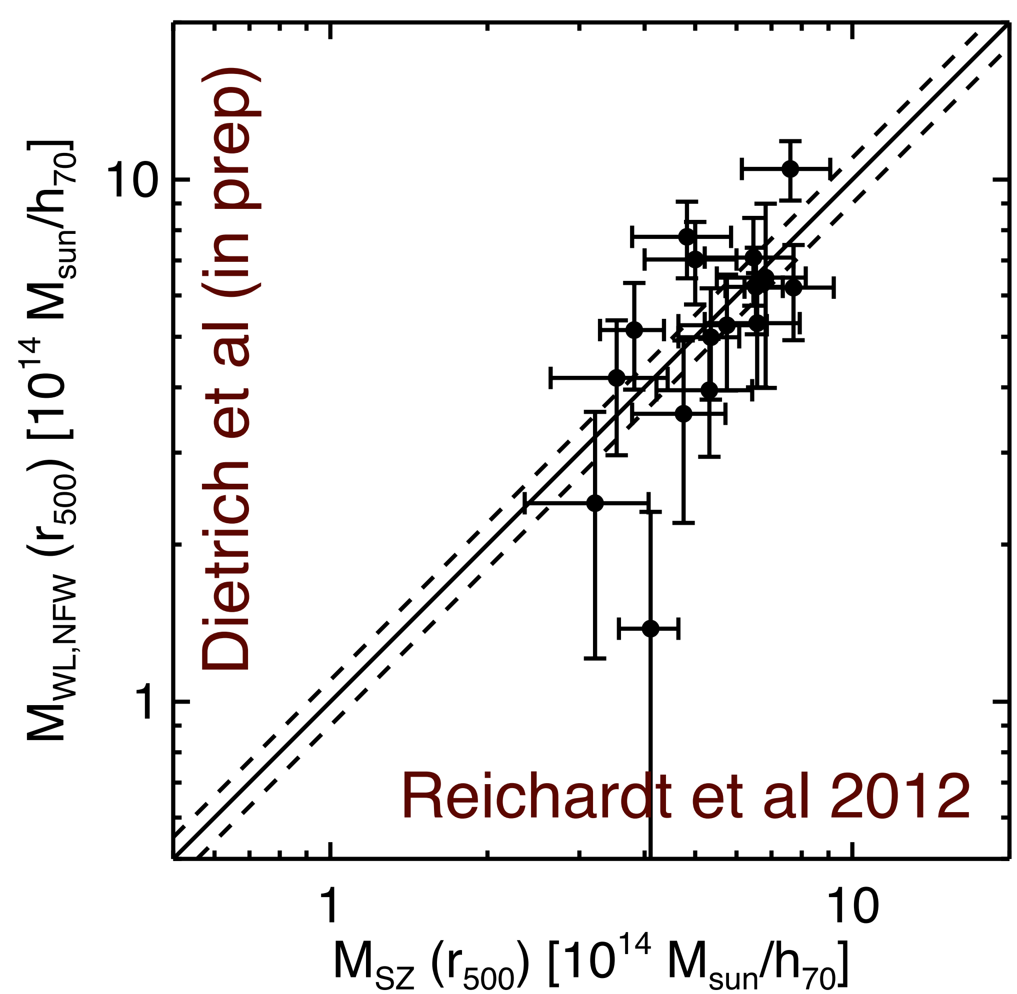
Weak Lensing Mass Calibration

$M_{500}(Yx) = (1.02 \pm 0.08)\, M_{500}(WL)$

$M_{500}(SPT) = (1.00 \pm 0.08)\, M_{500}(WL)$



X-ray (Yx) Mass



SPT-SZ Mass

Cosmological Analysis:

Combine X-ray Measurements with SZ Cluster Survey

Developed 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

6 Cosmology Parameters (plus extension parameters)

- ΛCDM Cosmology
  - $\Omega_{\mathrm{m}}h^2$, $\Omega_{\mathrm{b}}h^2$, A_{s}, n_s, τ, θs
- Extension Cosmology
  - w, Σm_ν, f_{NL}, N_{eff}

9 Scaling Relation Parameters

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

  A) normalization,

  B) slope,

  C) redshift evolution,

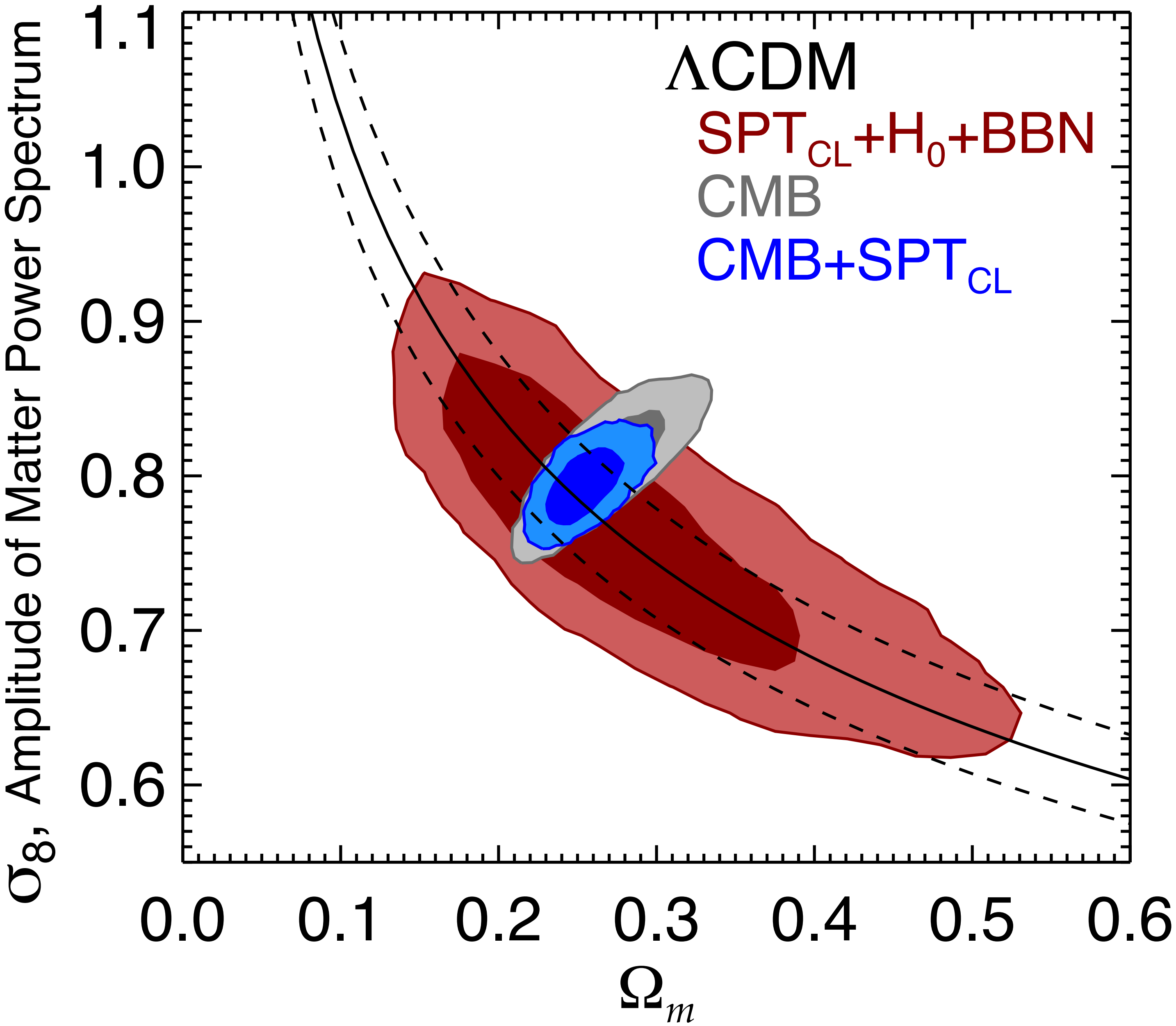
  D) scatter,

  F) correlated scatter

Benson et al 2011,
arXiv: 1112.5435

ΛCDM Constraints:

Test X-ray Mass Calibration on 18 clusters (Benson et al. 2011)



- SPT$_{CL}$+H$_0$+BBN ΛCDM fit best constrains:
  - $\sigma_8(\Omega_m/0.25)^{0.30}$=0.785 +/- 0.037
  - ***Limited by accuracy of cluster mass calibration!***
- Adding SPT$_{CL}$ to CMB improves σ_8 and Ω_m constraint by factor of 1.5:
  - σ_8 = 0.795 +/- 0.016
  - Ω_m= 0.255 +/- 0.016

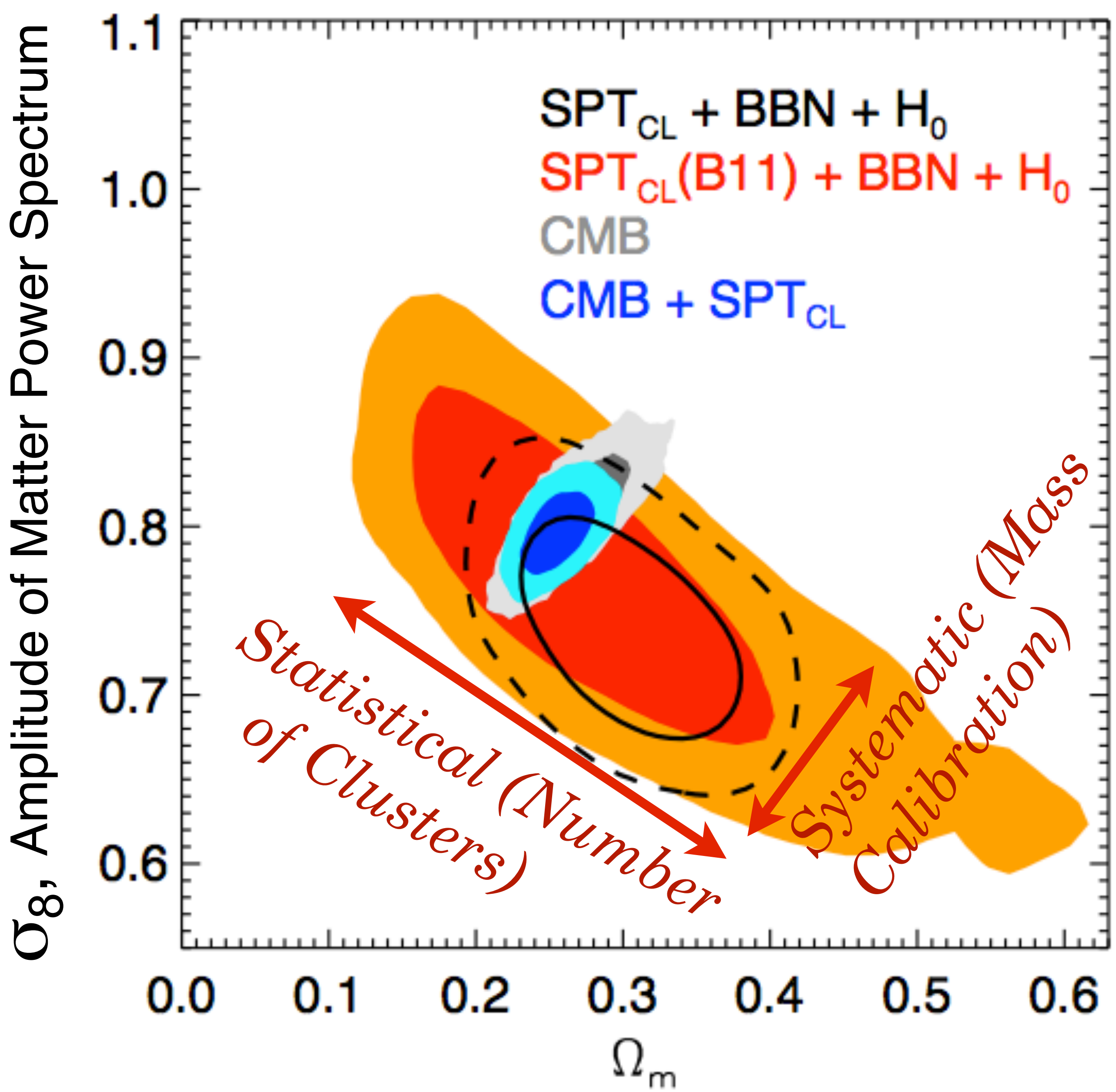
σ_8, Ω_m - 68, 95% Confidence Contours

H_0 = 73.8 +/- 2.4 km / s Mpc (Riess et al 2011)
CMB: WMAP7 + SPT (Komatsu et al 2011, Keisler et al. 2011)
BBN: $\Omega_b h^2$ = 0.022 +/- 0.002 (Kirkman et al. 2003)

Benson et al 2011, arXiv: 1112.5435

ΛCDM Constraints:

Now use 100 clusters (Reichardt et al. 2012)



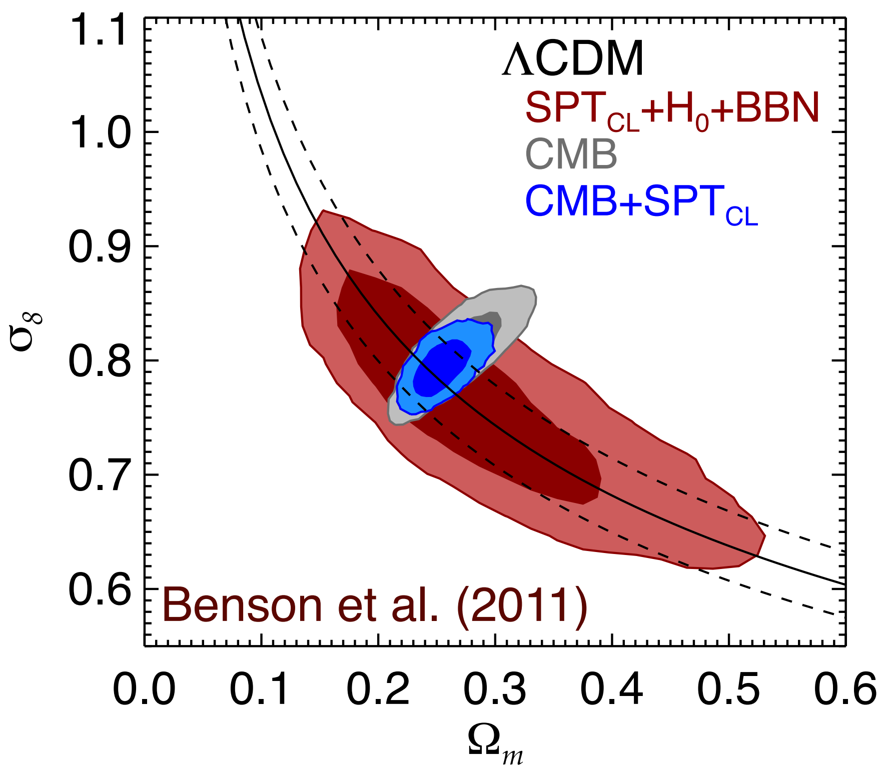
- SPT increased cluster sample by ~5x in Reichardt et al. (2012) improving constraints in σ_8-Ω_m plane by 1.8x in area
- ***In direction orthogonal to CMB constraints, cluster constraints limited by mass calibration***
- However, cluster data is an independent “growth of structure” based cosmological constraint (tests “new physics”, e.g., dark energy, gravity, neutrino mass, etc.)

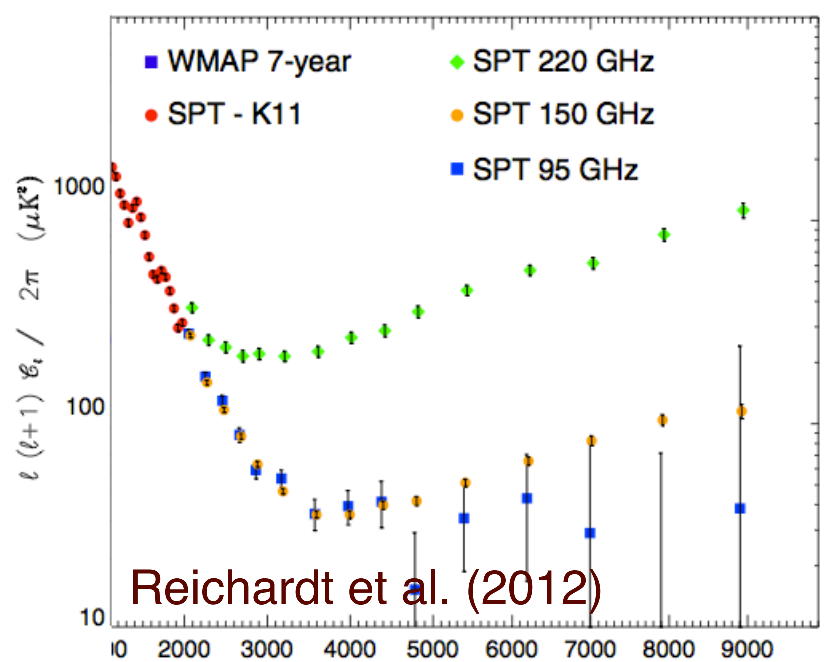
Reichardt et al 2012, arXiv:1203.5775

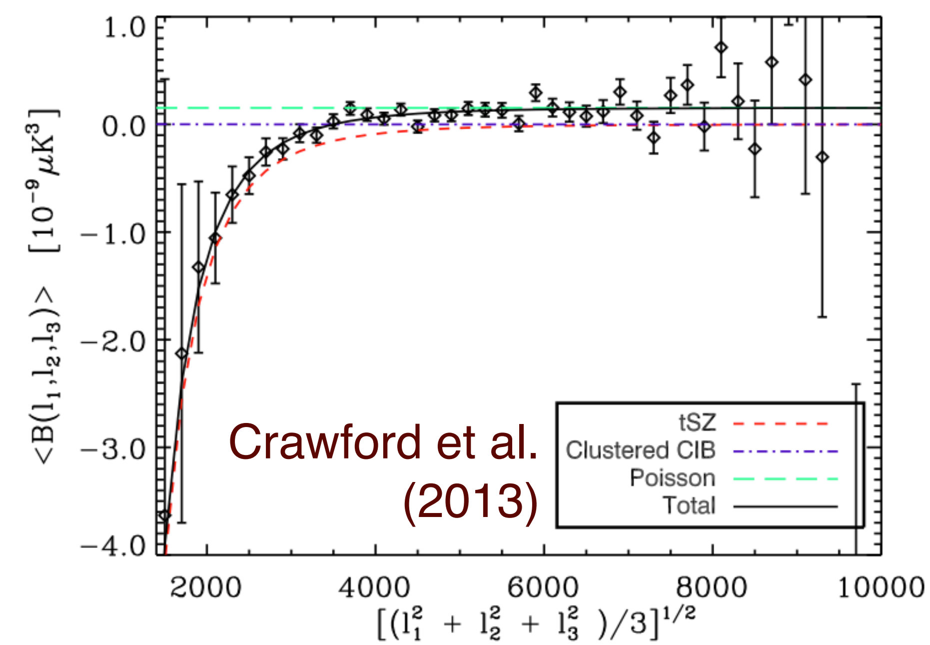
SZ Constraints on σ_8:

SZ Cluster Survey, SZ Power Spectrum, SZ Bispectrum

SZ data measures σ_8 three different ways, each with different systematic uncertainties and cosmological dependences







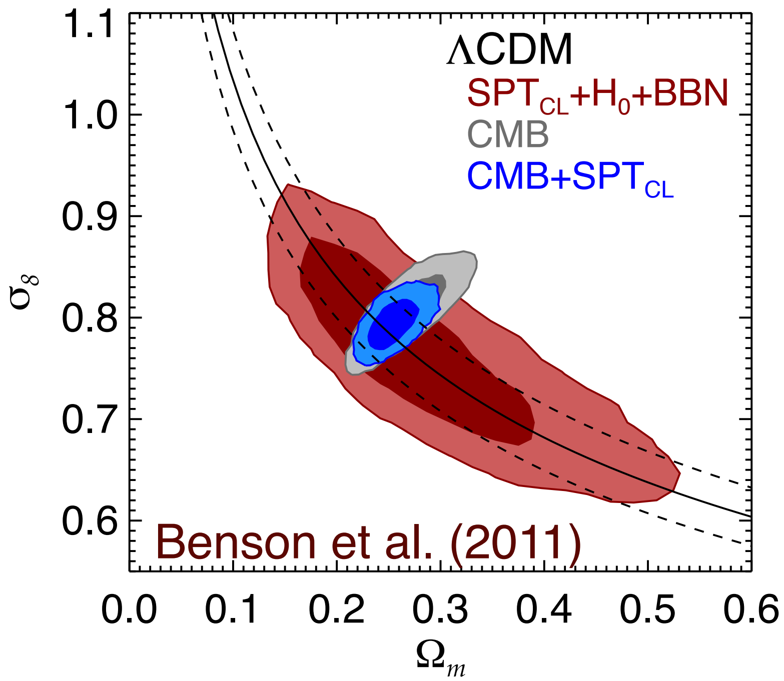
- **High-mass** clusters (>3e14 Msun) at **all redshifts** ($z > 0.3$)
  - Limited by uncertainty of weak-lensing mass calibration (Hoekstra+2012)

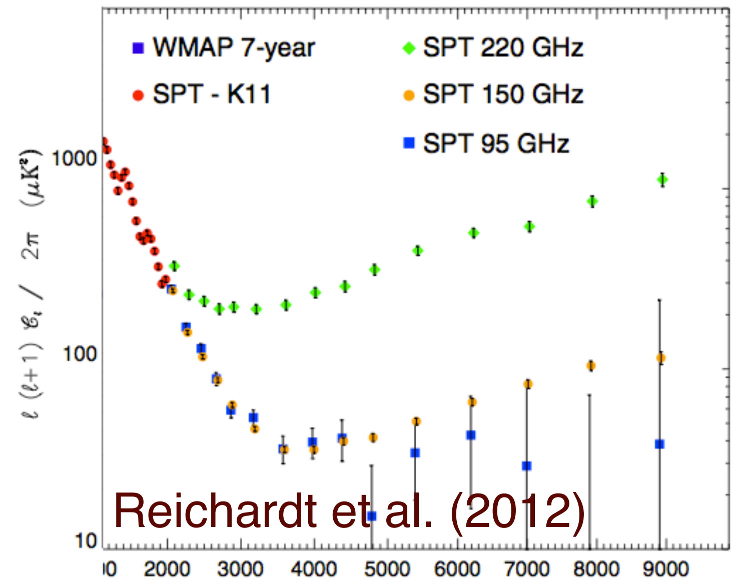
- **Low-mass** clusters (~1.5e14 Msun) at **high-z** ($0.5 < z < 1.0$)
  - Limited by uncertain gas physics (Shaw+2010, Battaglia+2010)

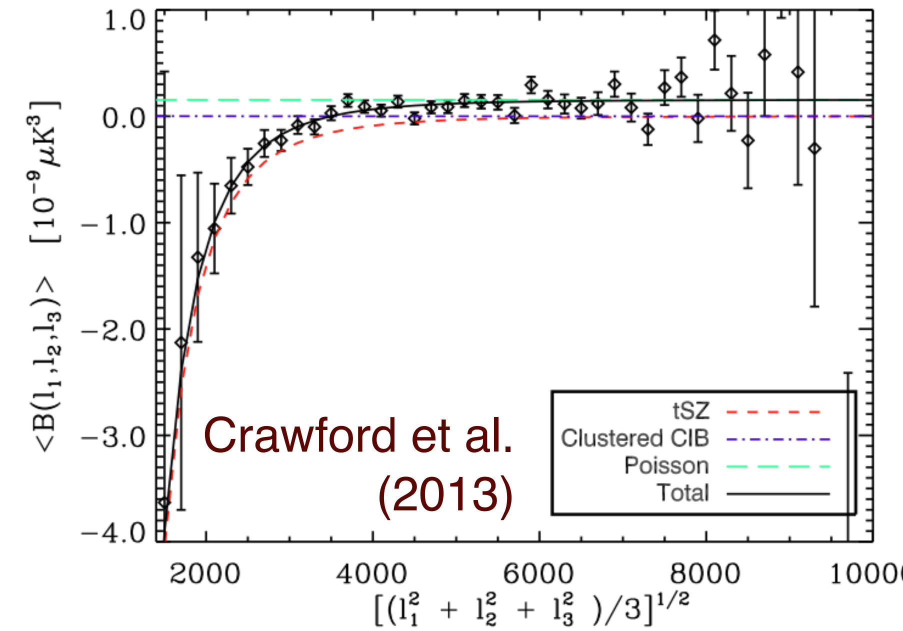
- **High-mass** clusters (~6e14 Msun) at **mid-z** ($0.3 < z < 0.5$)
  - (Less) limited by uncertain gas physics (Bhattacharya +2012)

SZ Constraints on σ_8:

SZ Cluster Survey, SZ Power Spectrum, SZ Bispectrum







$$\sigma_8(\Omega_m/0.25)^{0.30}$$

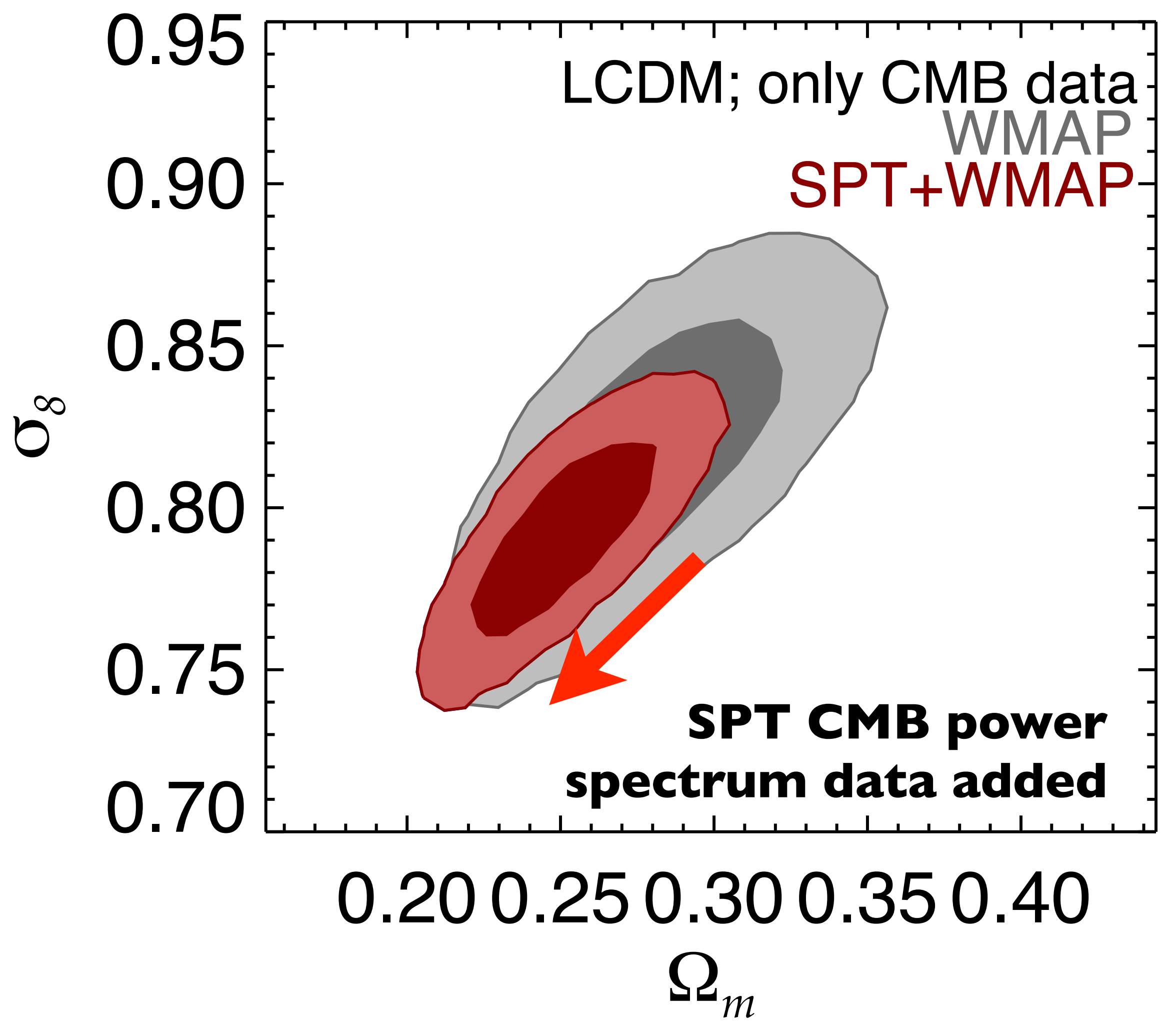
$$D^{\rm tSZ} \propto \left(\frac{\sigma_8}{0.80}\right)^{8.3}\left(\frac{\Omega_b}{0.044}\right)^{2.8}$$

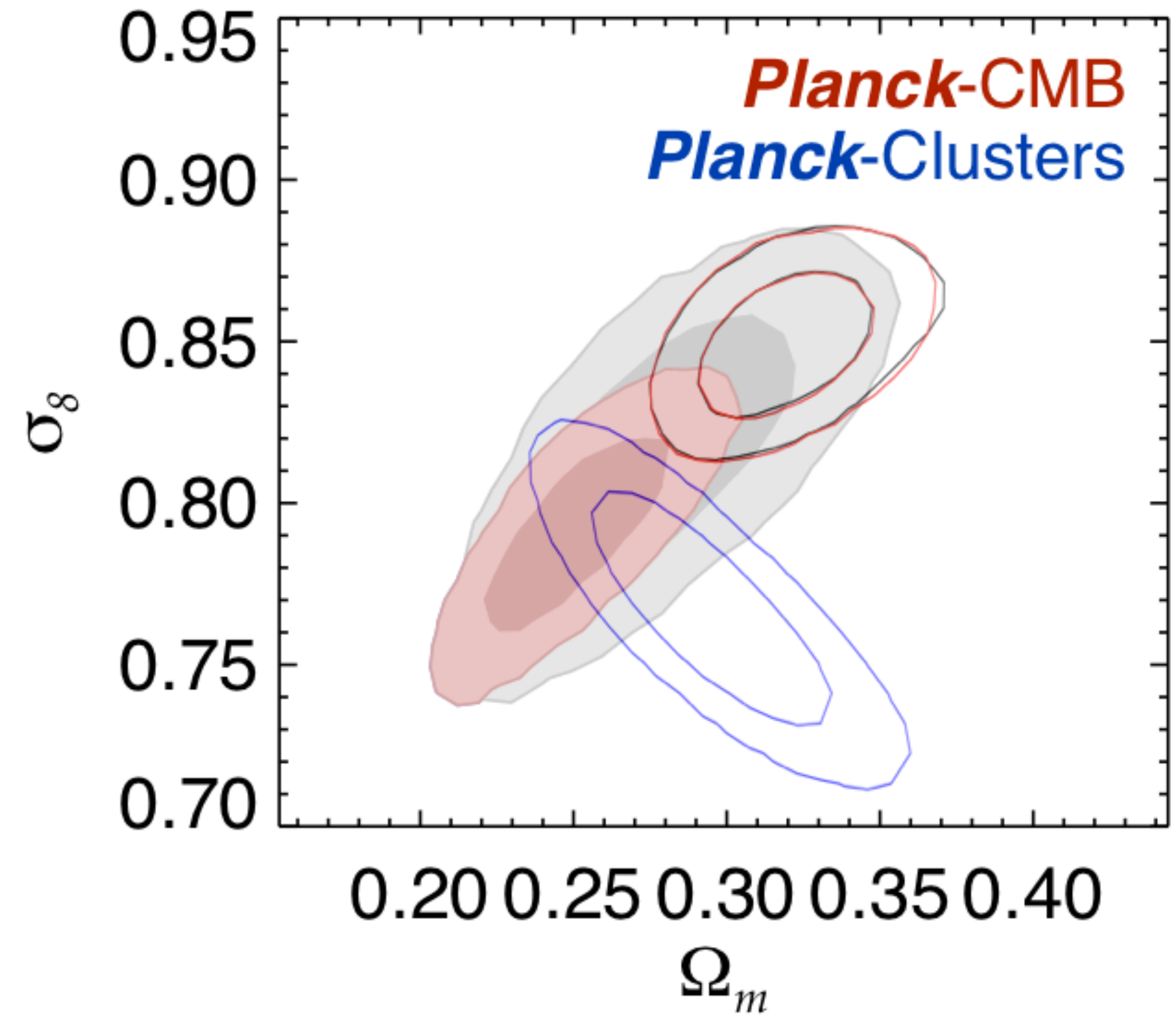
$$B_{\rm tSZ} \propto \left(\frac{\sigma_8}{0.8}\right)^{9.1}\left(\frac{\Omega_b}{0.045}\right)^{3.82}$$

σ_8 = 0.785 +/- 0.037 (Benson et al. 2011)	σ_8 = 0.797 +/- 0.030 (Reichardt et al. 2012)	σ_8 = 0.786 +/- 0.031 (Crawford et al. 2013)

- SZ data measures different cluster populations and has different cosmological degeneracies, allowing systematic check of constraints
- ***How do these results change for new Planck cosmology?***

CMB Constraints on σ_8, Ω_m

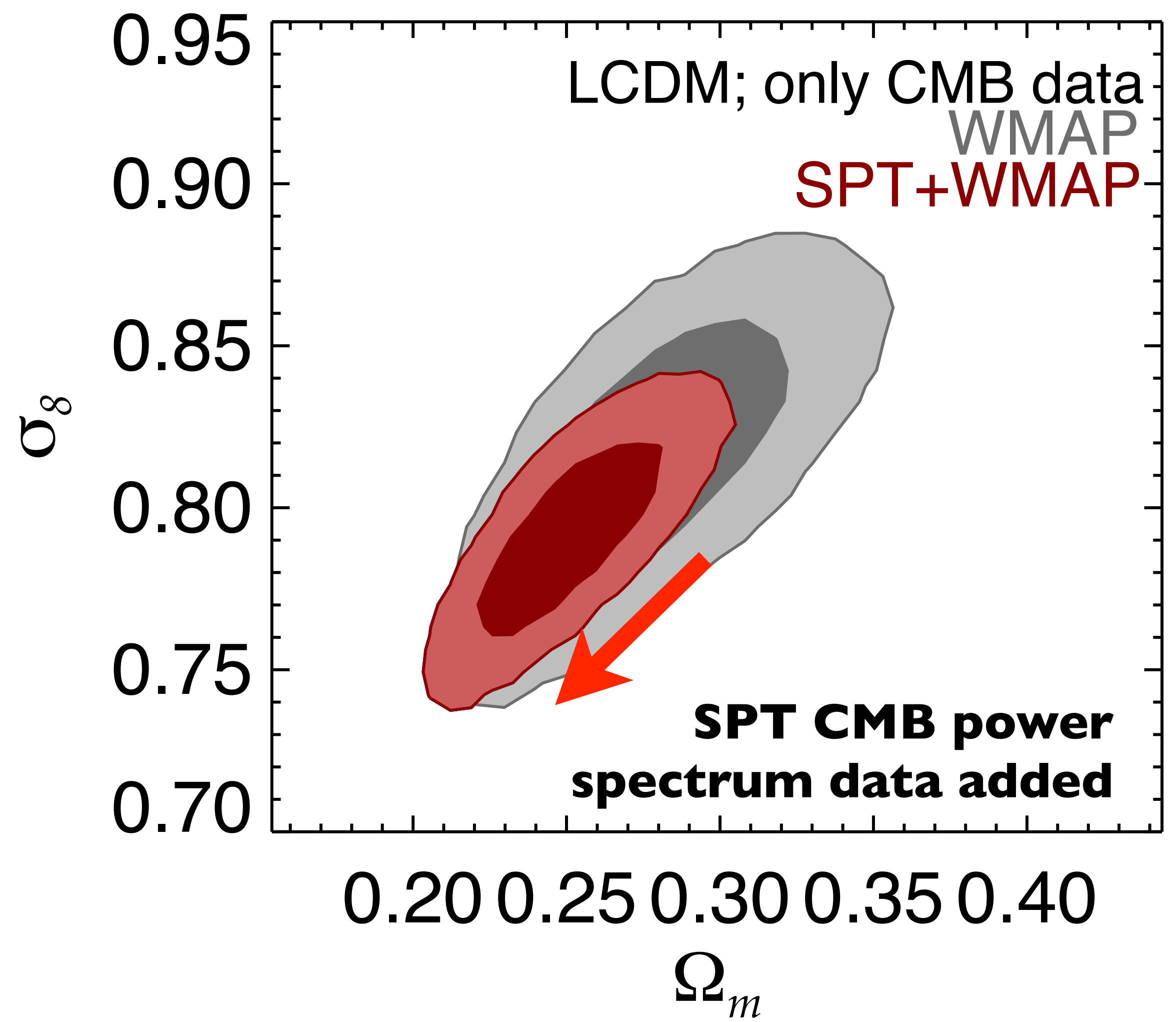


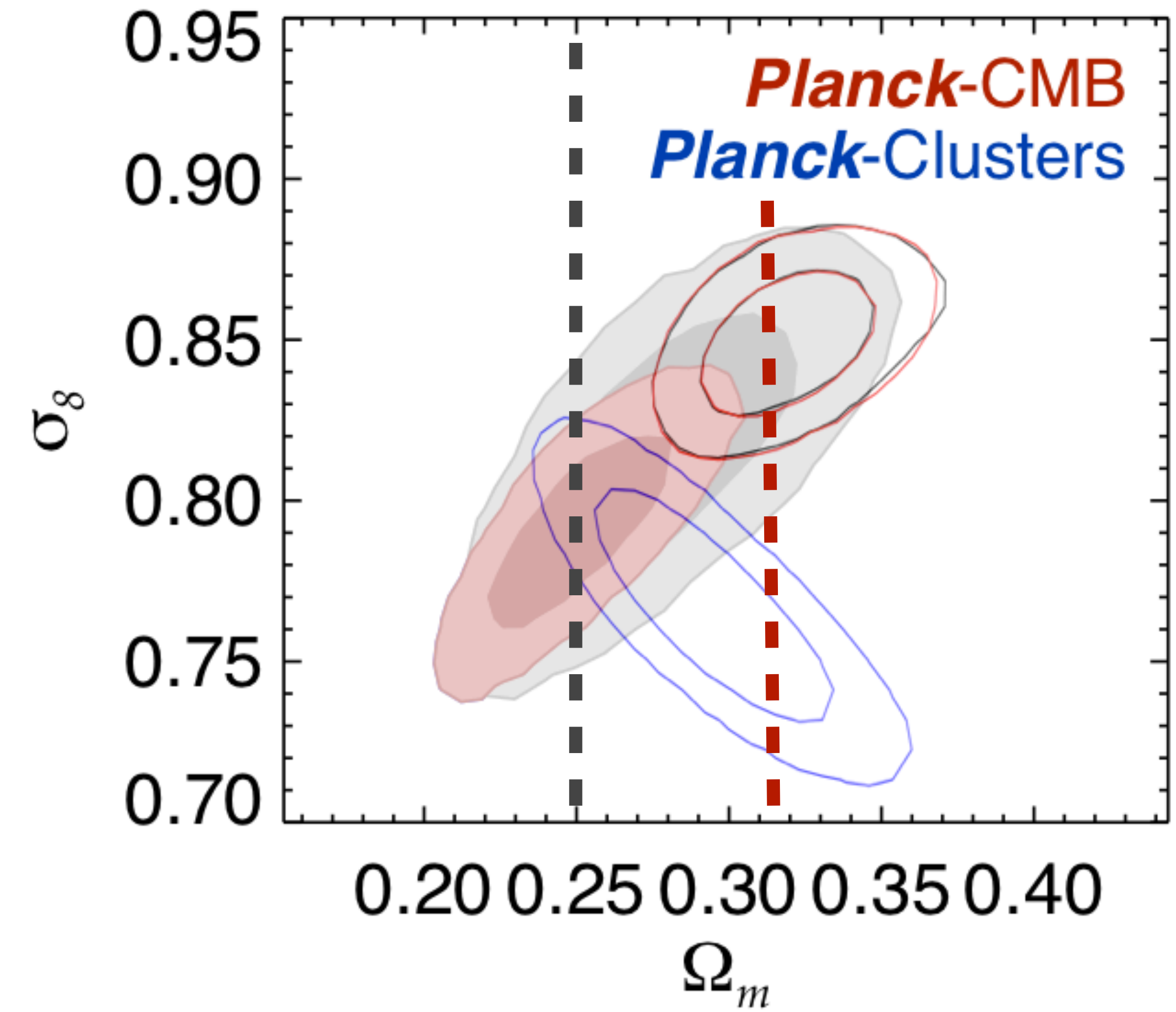


	WMAP7	WMAP7+SPT	Planck-CMB
σ_8	0.819 +/- 0.031	**0.795 +/- 0.022**	**0.829 +/- 0.012**
Ω_m	0.276 +/- 0.029	**0.250 +/- 0.020**	**0.315 +/- 0.016**

(WMAP7) Komatsu +2011
(SPT) Story+2012
Planck XX 2013
Planck XVI 2013

CMB Constraints on σ_8, Ω_m





	WMAP7	WMAP7+SPT	Planck-CMB
σ_8	0.819 +/- 0.031	0.795 +/- 0.022	0.829 +/- 0.012
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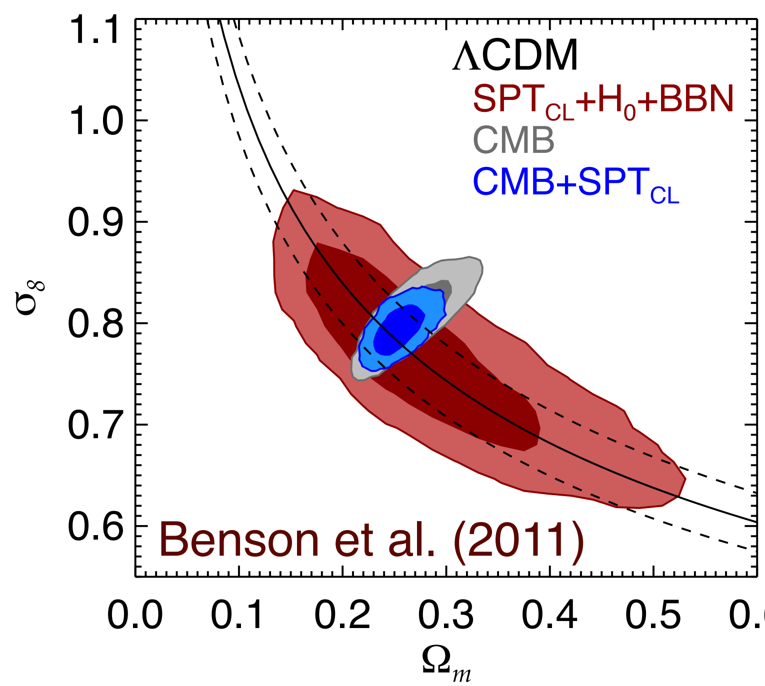
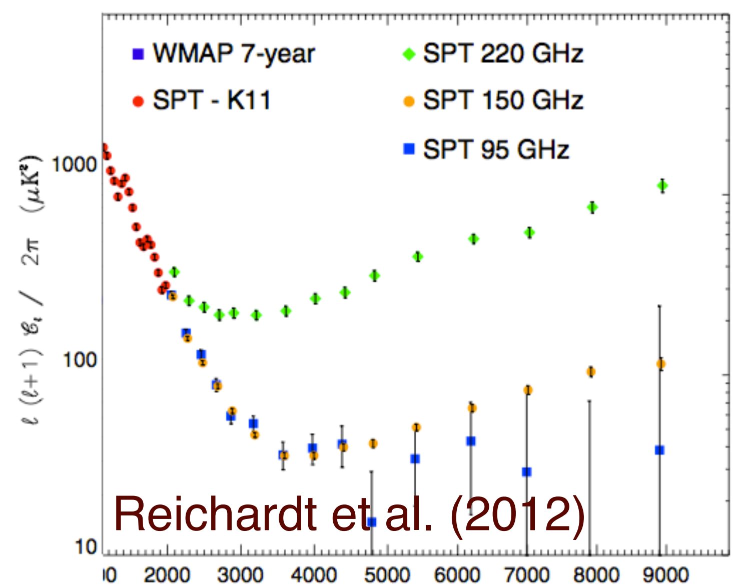
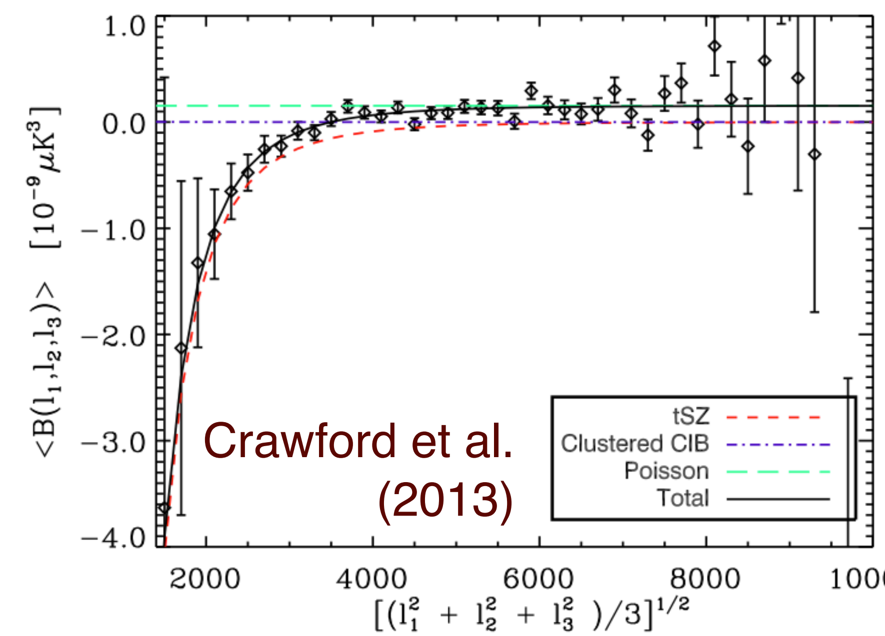
(WMAP7) Komatsu +2011
(SPT) Story+2012
Planck XX 2013
Planck XVI 2013

Constraints adjusted for Planck Cosmology:

SZ Cluster Survey, SZ Power Spectrum, SZ Bispectrum







$$\sigma_8 (\Omega_m / 0.315)^{0.30}$$

$$D^{tSZ} \propto \left(\frac{\sigma_8}{0.80}\right)^{8.3} \left(\frac{\Omega_b}{0.049}\right)^{2.8}$$

$$B_{tSZ} \propto \left(\frac{\sigma_8}{0.8}\right)^{9.1} \left(\frac{\Omega_b}{0.049}\right)^{3.82}$$

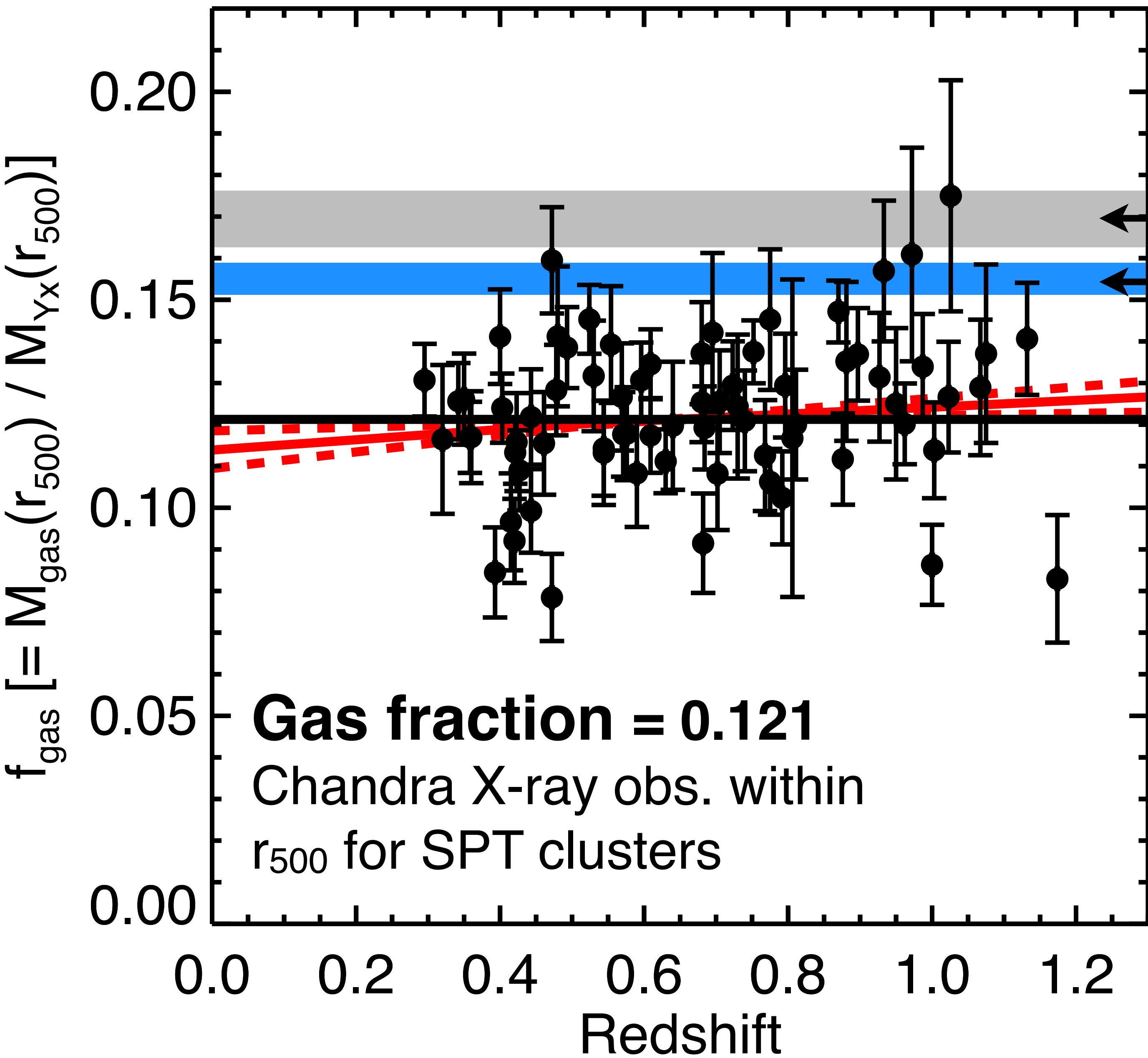
σ_8 = 0.732 +/- 0.035 (Benson et al. 2011)	σ_8 = 0.777 +/- 0.029 (Reichardt et al. 2012)	σ_8 = 0.772 +/- 0.030 (Crawford et al. 2013)

***Planck*-CMB: σ_8 = 0.828 +/- 0.012**

- SZ measurements consistently low by ~2-3-sigma -> would require a factor of 1.5x cluster mass bias across all masses and redshifts

“Missing” Baryons and the Gas Fraction

Cosmic Baryon Fraction inferred from CMB data, compared to clusters



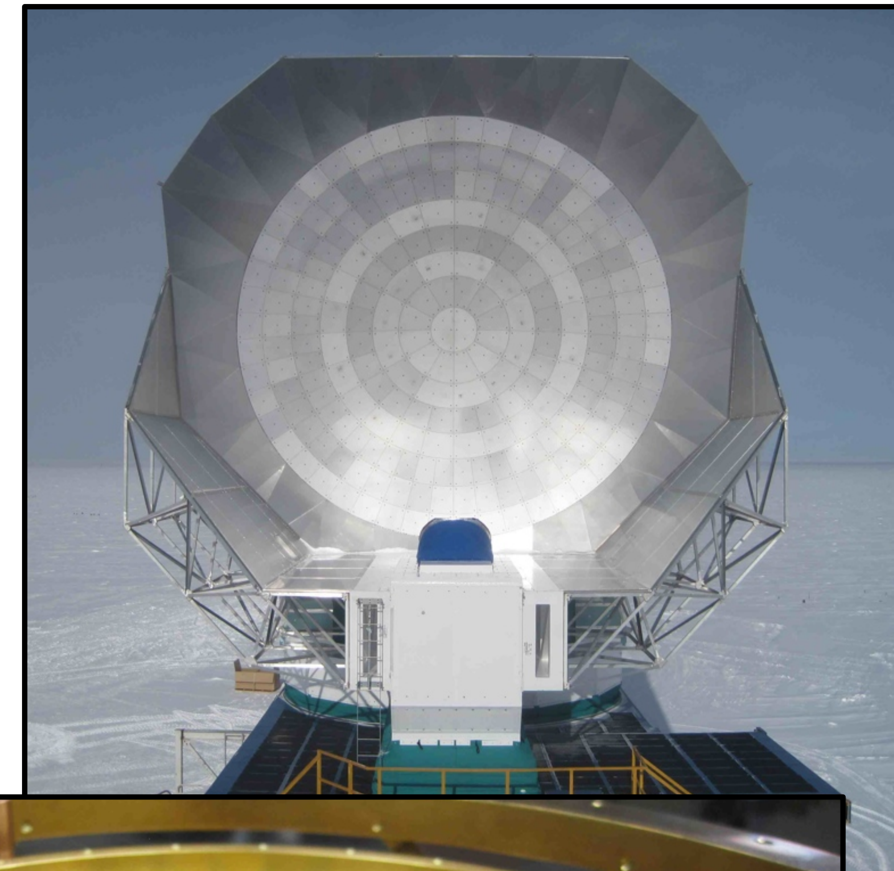
WMAP7+SPT: **($\Omega b/\Omega m$) = 0.169**

Planck: **($\Omega b/\Omega m$) = 0.155**

Correction to gas fraction from stars and gas profile shape ***lowers*** measured value relative to cosmic (“gas depletion”)

- *X-ray gas fraction implies a baryon fraction of* ***~0.151, consistent with new Planck value! (i.e., no “missing” baryons)***
- *However, a factor of 1.5x cluster mass re-calibration would screw this up!*

SPTpol:
A *new* polarization-sensitive camera for SPT



Science from SPTpol -

“B-mode” CMB Polarization:

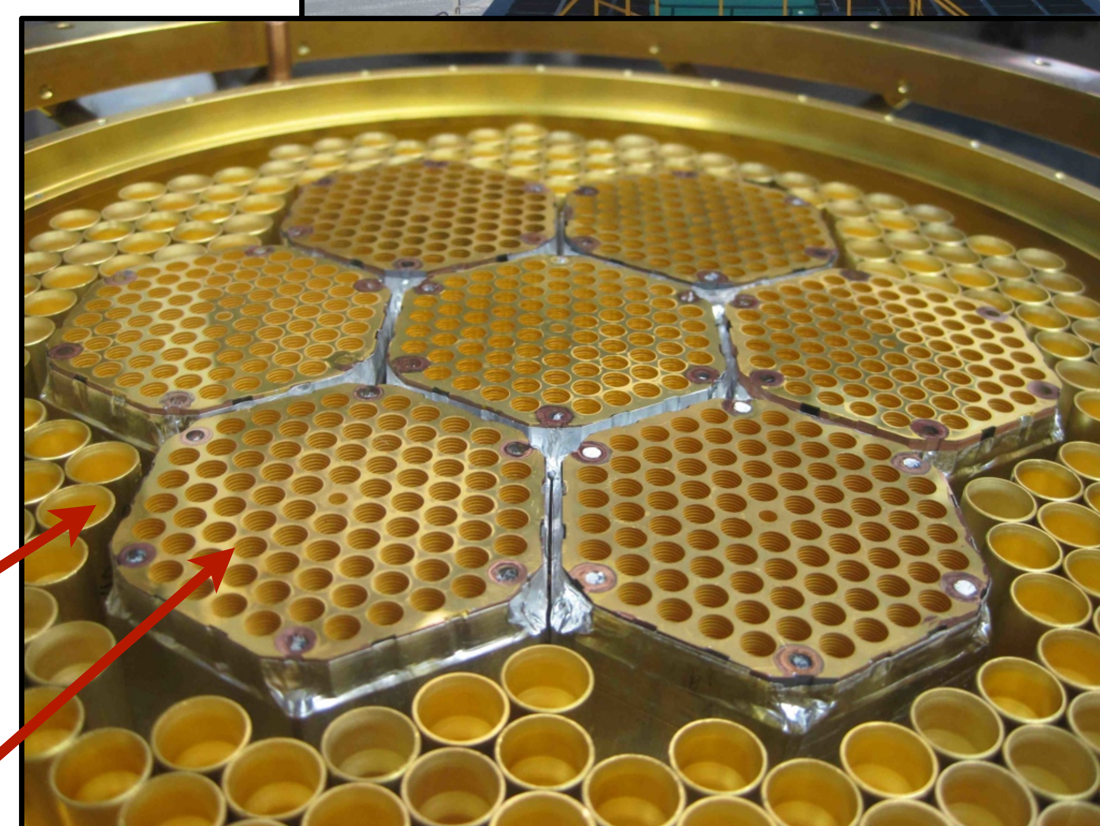
1. Detection of “B-mode” power spectrum
2. Neutrino mass from CMB lensing
   +/- 0.1 eV constraint from CMB alone!
3. Energy scale of inflation

Temperature Survey:

4. Deeper cluster survey

Status:

- First light Jan. 26, 2012.
- Started a 4-year, 500 deg^2 survey
- **Finished 1st year of survey!**

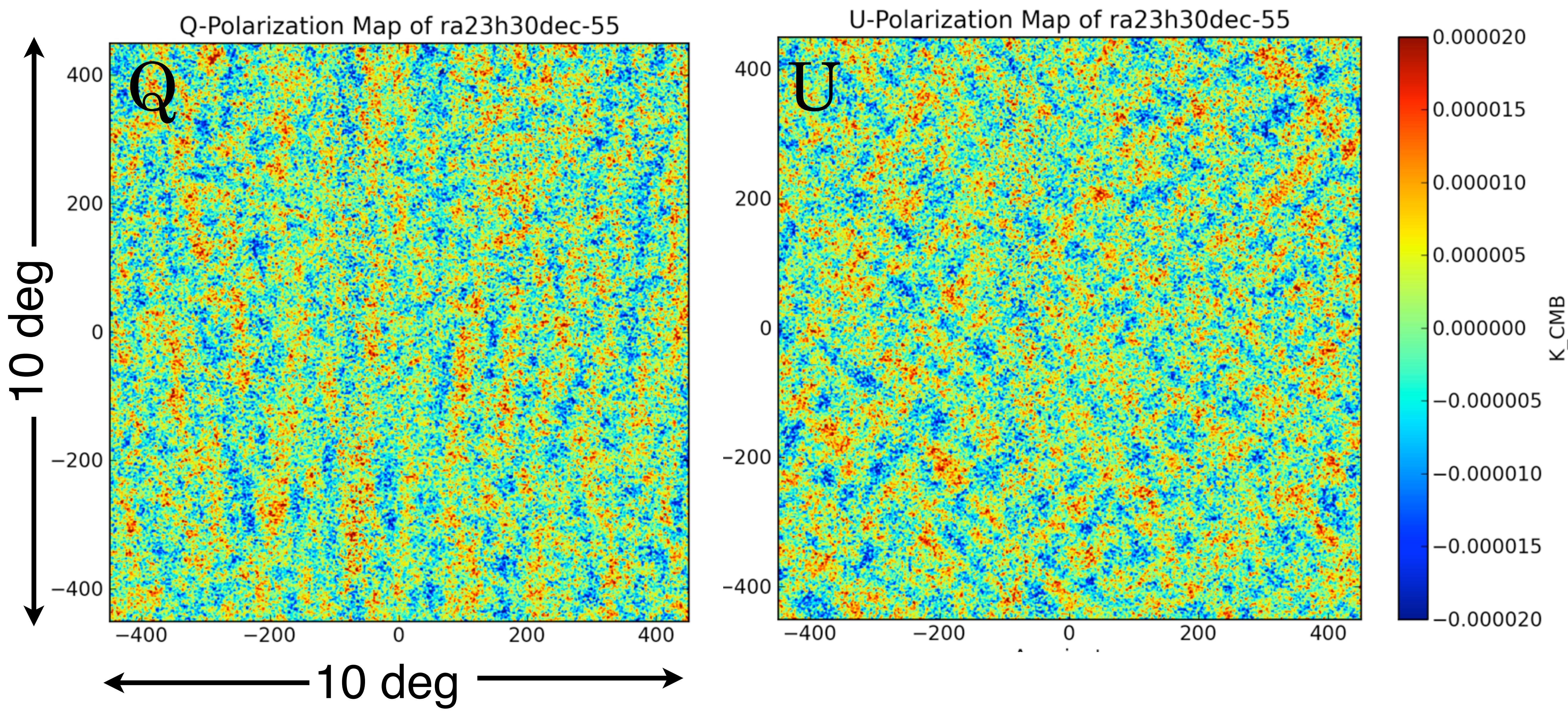


(360x) 100 GHz detectors, (Argonne National Labs)

(1176x) 150 GHz detectors (NIST)

SPTpol 1st Year: ***100 deg² CMB Polarization Maps***

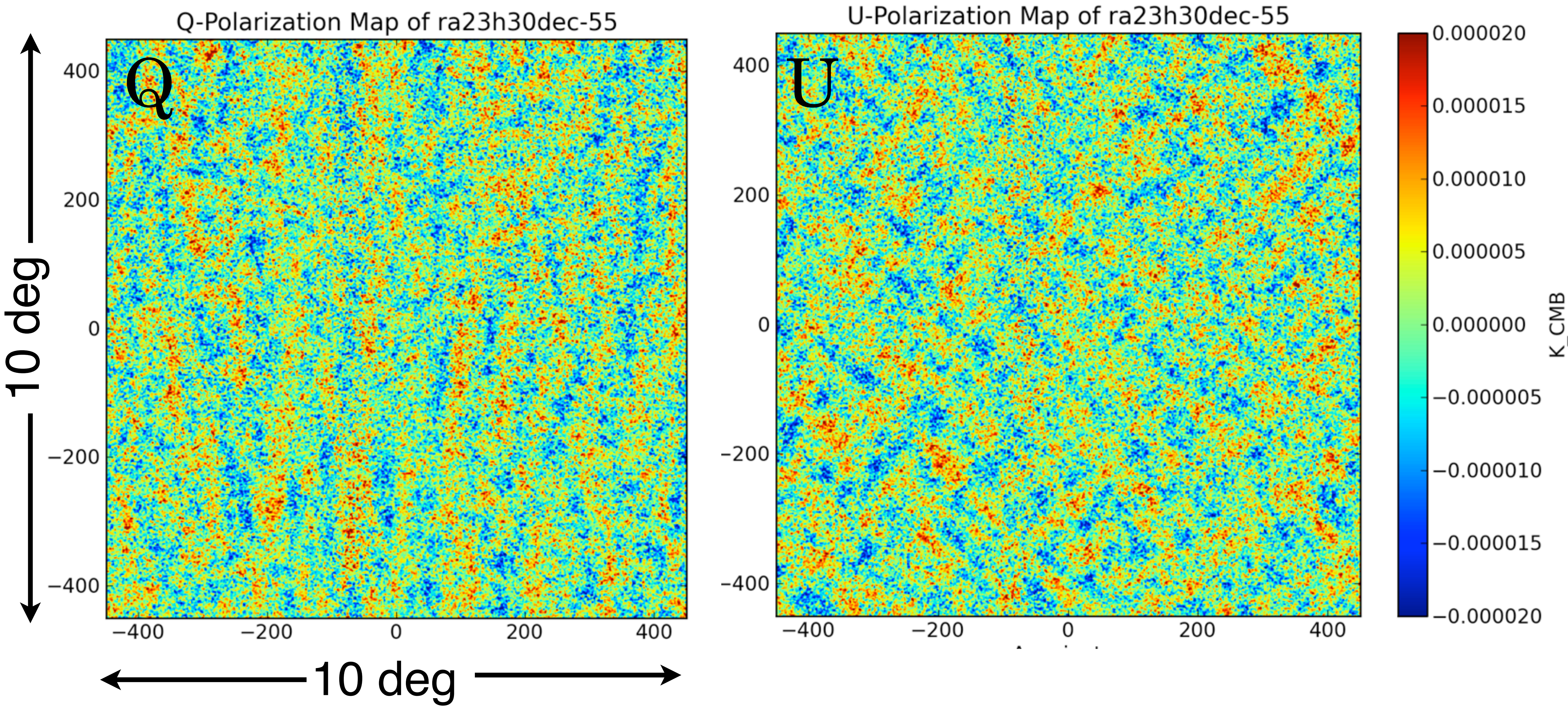
- **Visible detection of E-modes in SPTpol maps!**
- 3x deeper than SPT-SZ survey, ~6 uK-arcmin; will eventually cover 500 deg² to similar depth
  - **Projected 40-σ detection of CMB lensing!**
  - **Tensor-to-scalar ratio, $r < 0.03$ at 95% confidence**



Maps by Abby Crites

SPTpol 1st Year: ***100 deg² CMB Polarization Maps***

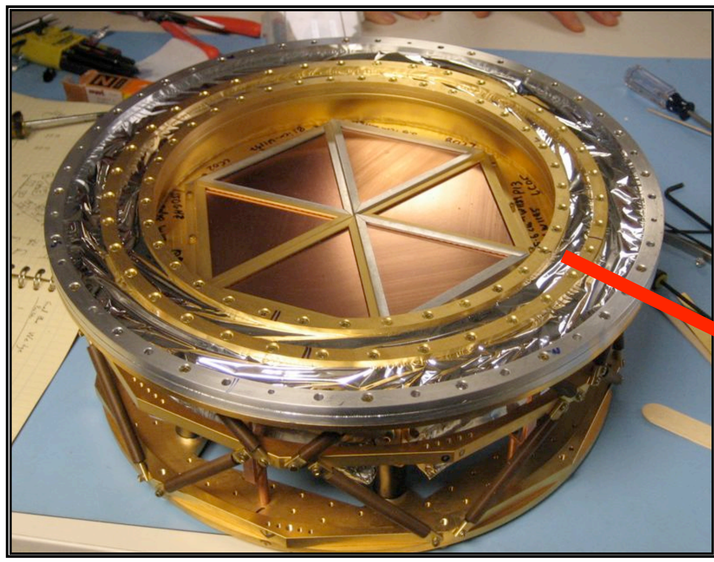
- **Cluster density ~6x SPT-SZ;**
  - ➡ **Expect ~100 clusters in 100 deg² SPTpol map**
- Overlap with XMM-XXL (25 deg²), Spitzer (100 deg²), Herschel (100 deg²), DES (4000 deg²)



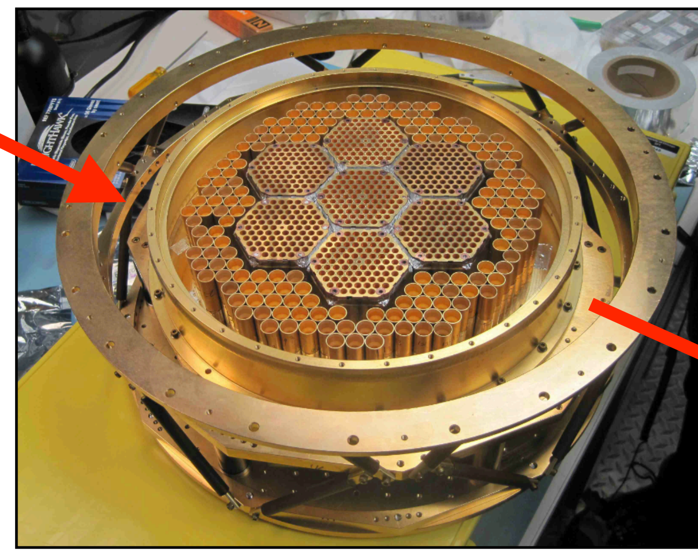
Maps by Abby Crites

SPT-3G: The Next Generation Camera for the SPT

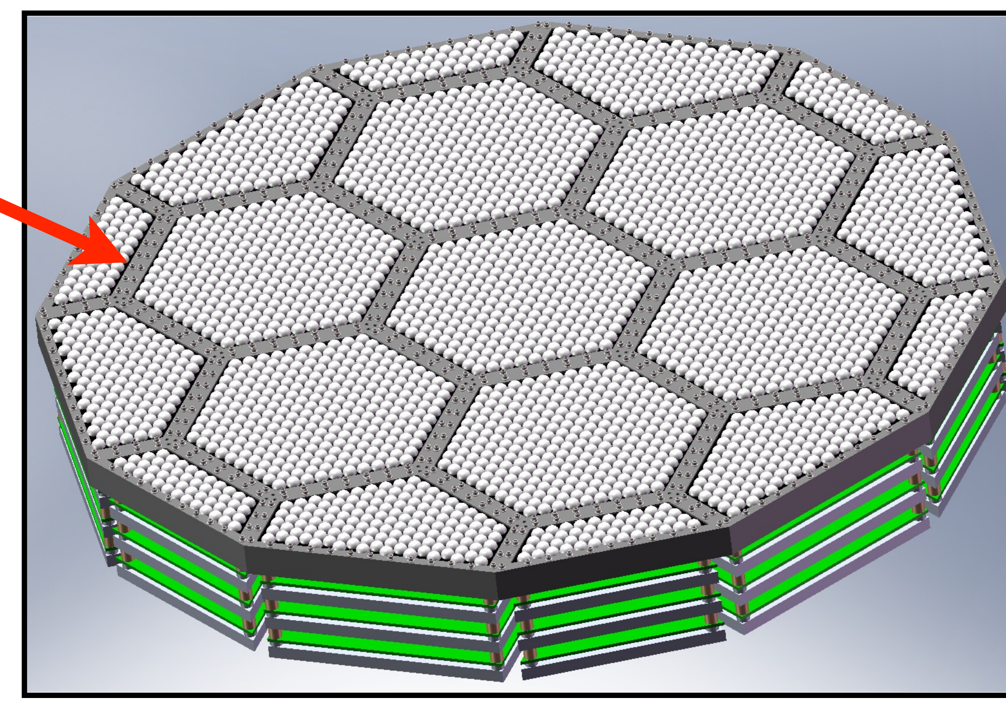
2007: SPT
960 detectors



2012: SPTpol
~1600 detectors

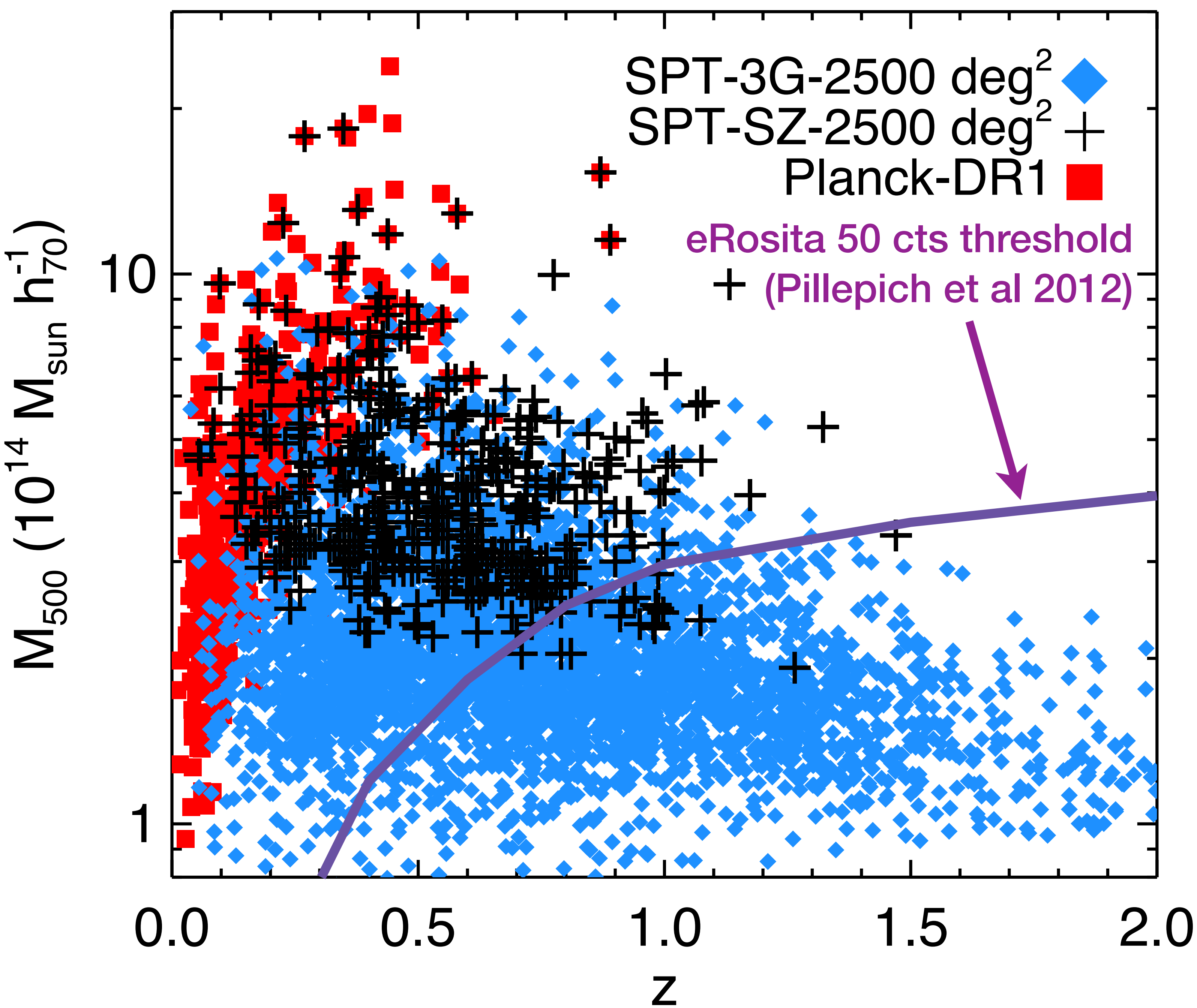


2016: SPT-3G
~15,200 detectors



SPT-3G will increase SPT detector count by order of magnitude! Increase driven by multi-choric detectors; ***each SPT-3G pixel simultaneously measures 100, 150, 220 GHz***

SPT-3G:
Cluster Survey



- SPT-3G will survey 2500 deg^2 to a level 10x deeper than SPT-SZ survey
- >10x increase in number of clusters over SPT-SZ
  - 4000 clusters at 99% purity threshold
- CMB-cluster lensing would provide a 3% cluster mass calibration
  - competitive with stacked weak-lensing (Rozo et al. 2011)

Credit: B. Benson

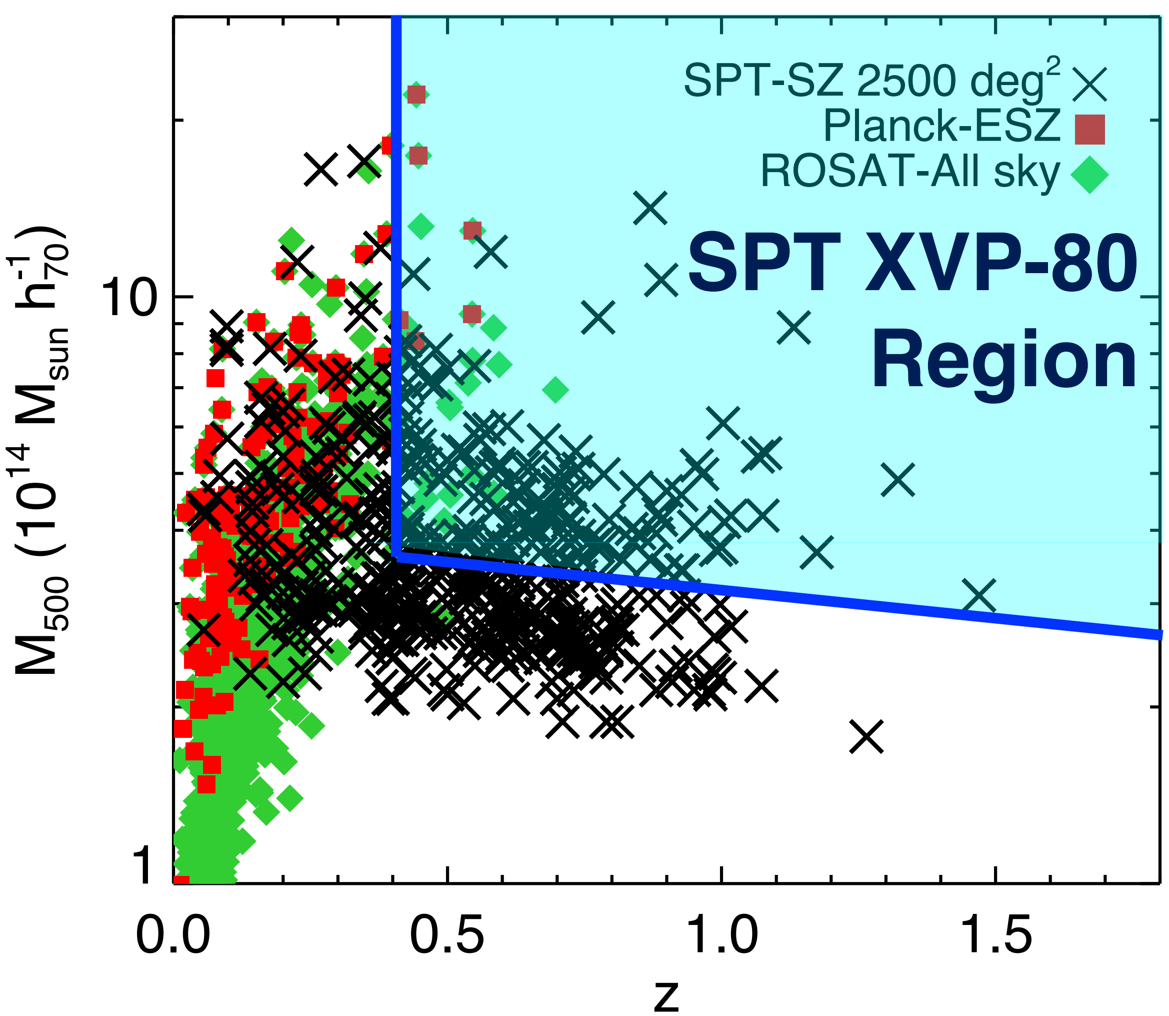
Summary

- **SPT-SZ Survey Complete!**
  - ~500 cluster catalog of massive ($M_{500} > 3x10^{14}$ M_{sol}/h_{70}), high-redshift ($0.05 < z < 1.5$) clusters; ***catalog due out summer 2013*** **!**
- **SZ Measurements give multiple probes of cosmology; all have some tension with the high-Ω_m,σ_8 universe suggested by Planck CMB:**
  - Naively, would suggest clusters masses are low by a factor of 1.5x across all masses ($>1x10^{14}$ M_{sol}/h_{70}) and redshifts
  - However, this would be in significant tension with X-ray and weak lensing measurements
  - Would also imply a significant “missing” baryon problem
- **CMB polarization experiments will weigh in; SPTpol has completed first year of four year survey:**
  - CMB lensing measurements will check / confirm high-$\Omega_m h^2$ universe
  - Will also provide ever larger catalogs of high-z, massive clusters


Thank You!

SPT Cluster Mass Calibration:
X-ray XVP-80 Sample

Chandra X-ray observations of 80 most significant clusters at $z > 0.4$ from SPT-SZ survey



Primary Goals:

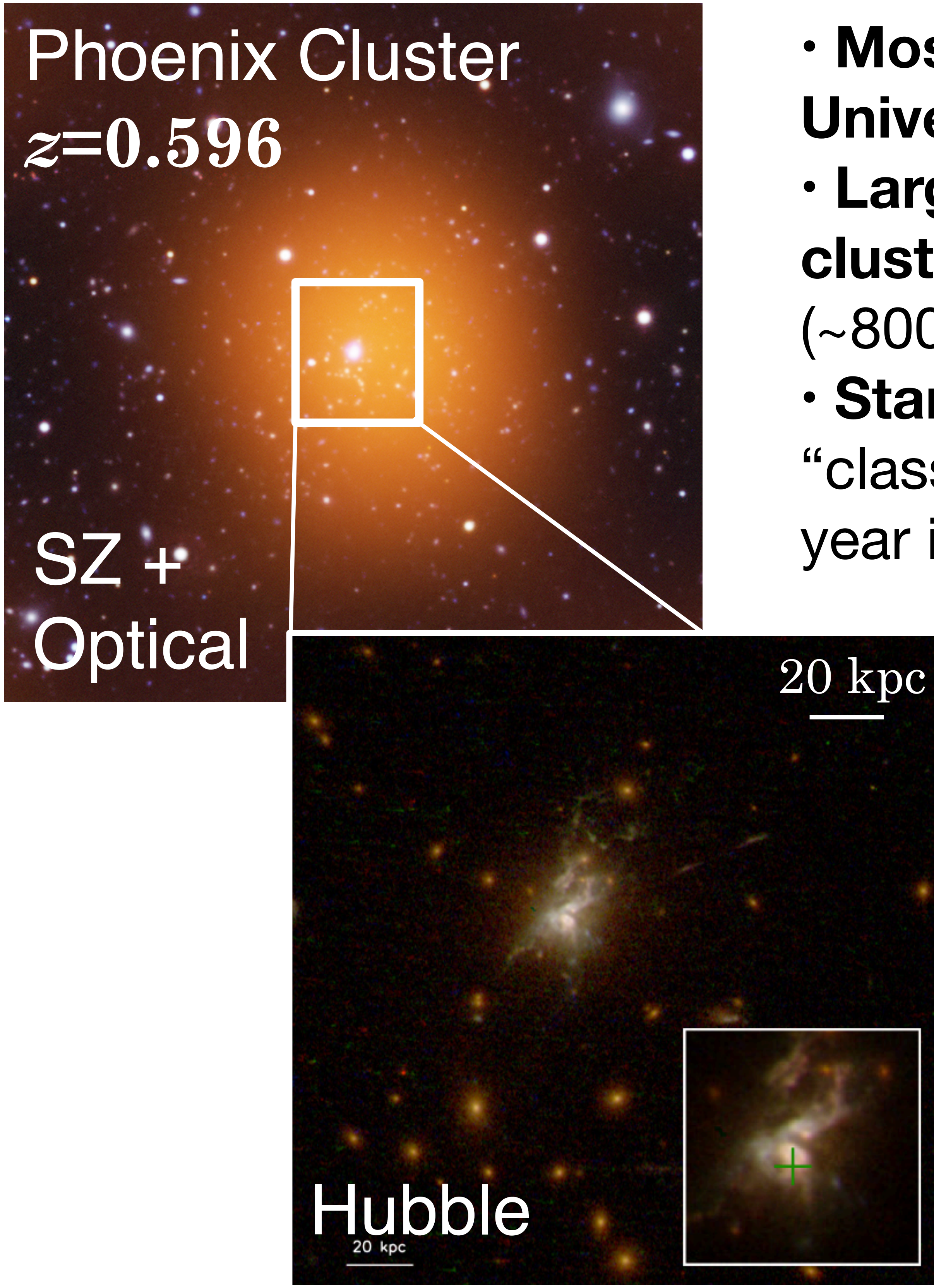
1) **Dark Energy, w** - Calibrate SPT cluster mass with ~10% accuracy to obtain systematics limited constraint on w of ~15%

2) **Angular Diameter Distance** relation - Combine Ysz, Yx to use clusters as "standard ruler", constrain geometry of universe to high-z

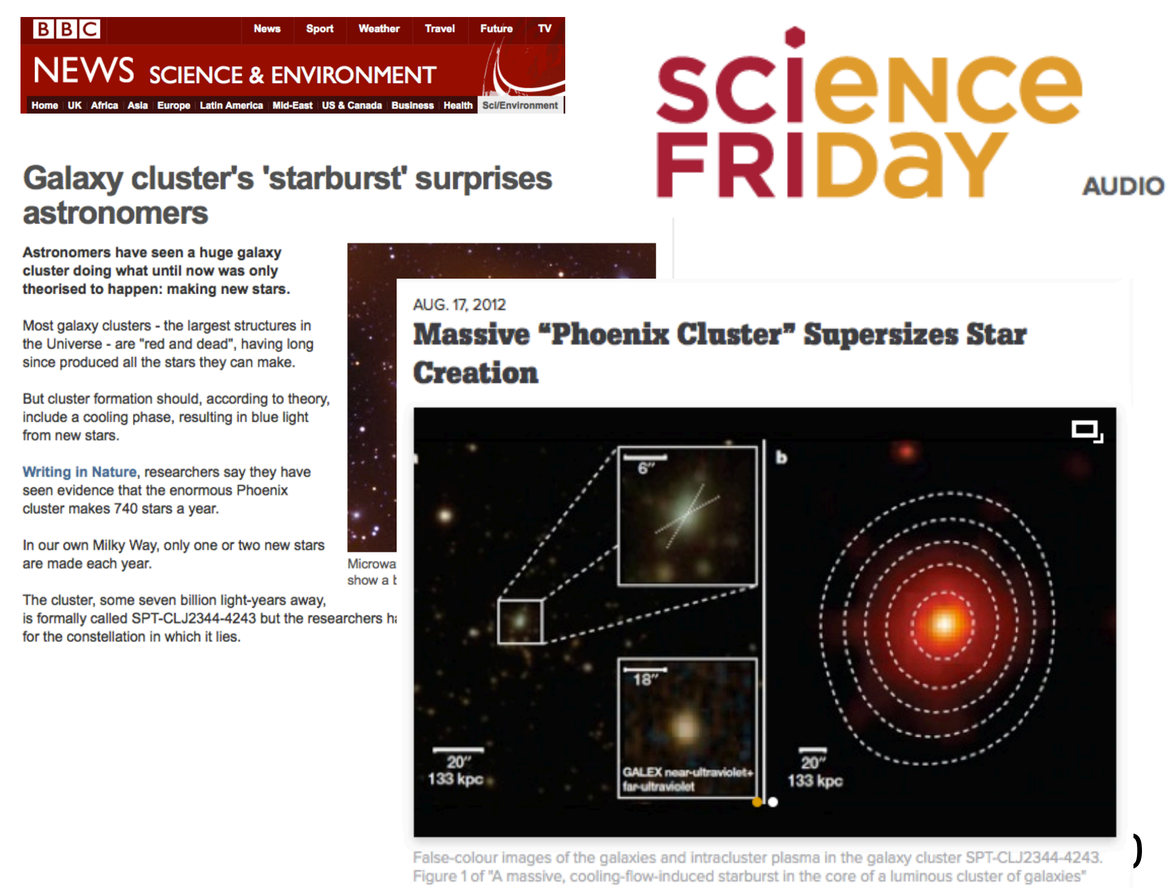
3) **Cluster Evolution** - High-redshift properties of massive clusters; e.g., cool core fraction, evolution of gas observables, metallicity, ...

Chandra observations finished Feb 2013!

SPT-CL J2344-4243: *The "Phoenix Cluster"*



- **Most X-ray luminous cluster known in the Universe**
- **Largest star formation rate observed in a cluster's brightest central galaxy**: (~800 +/- 40 Msun / year)
- **Star formation efficiency of ~30%;** "classical" X-ray cooling rate of 2850 Msun / year is efficiently turning into stars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Galaxy cluster's 'starburst' surprises astronomers

Astronomers have seen a huge galaxy cluster doing what until now was only theorised to happen: making new stars.

Most galaxy clusters - the largest structures in the Universe - are "red and dead", having long since produced all the stars they can make.

But cluster formation should, according to theory, include a cooling phase, resulting in blue light from new stars.

Writing in Nature, researchers say they have seen evidence that the enormous Phoenix cluster makes 740 stars a year.

In our own Milky Way, only one or two new stars are made each year.

The cluster, some seven billion light-years away, is formally called SPT-CLJ2344-4243 but the researchers h[...] for the constellation in which it lies.

Science Friday AUDIO

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Massive "Phoenix Cluster" Supersizes Star Creation

False-colour images of the galaxies and intracluster plasma in the galaxy cluster SPT-CLJ2344-4243. Figure 1 of "A massive, cooling-flow-induced starburst in the core of a luminous cluster of galaxies" published in *Nature* Vol 488, 349-352 (August 16, 2012).

McDonald et al. (2012, 2013)