The Abdus Salam International Centre for Theoretical Physics

2419-13

Workshop on Large Scale Structure

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The South Pole Telescope: The Sunyaev-Zel'dovich Cluster Survey and Future Plans

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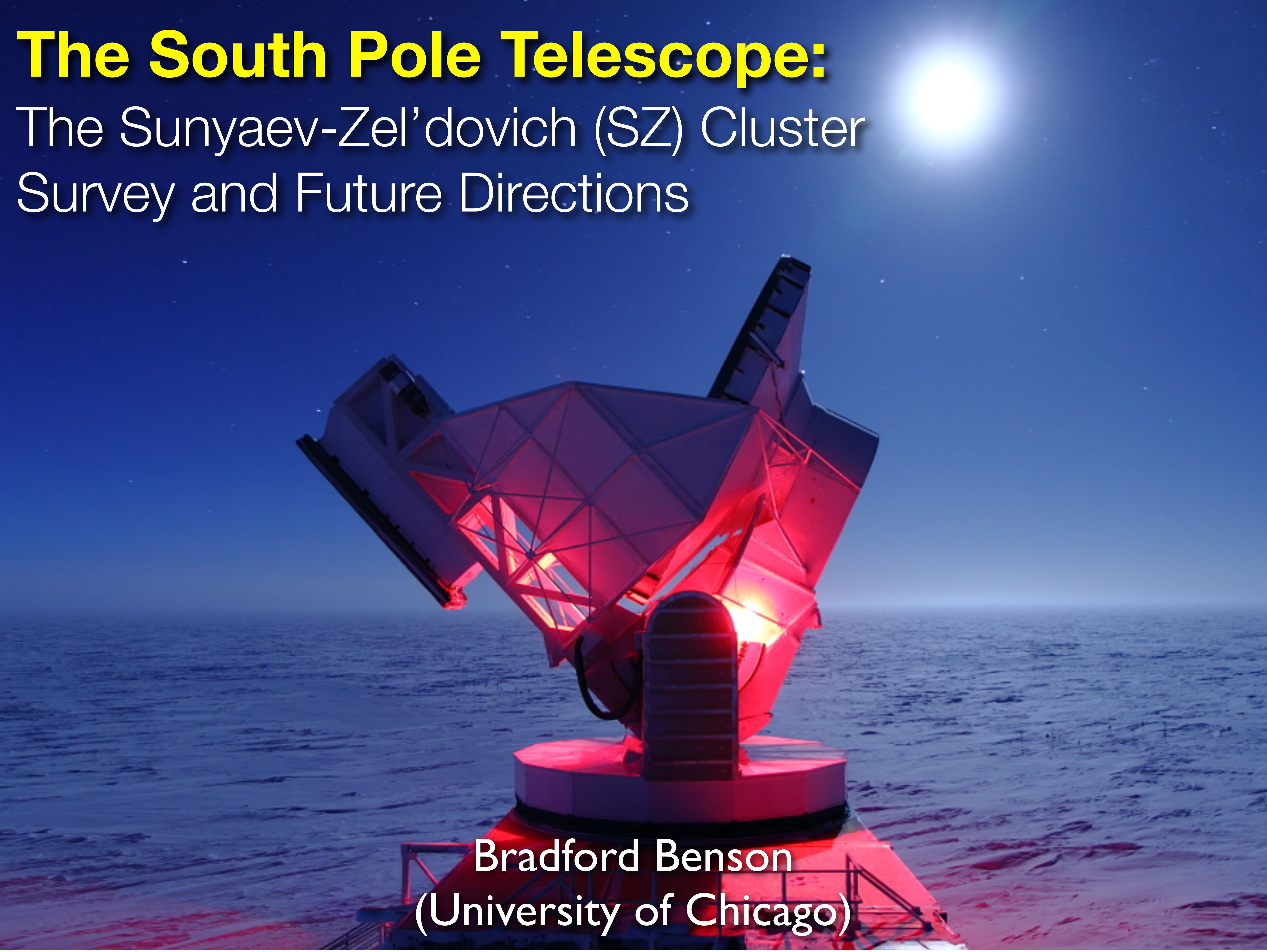
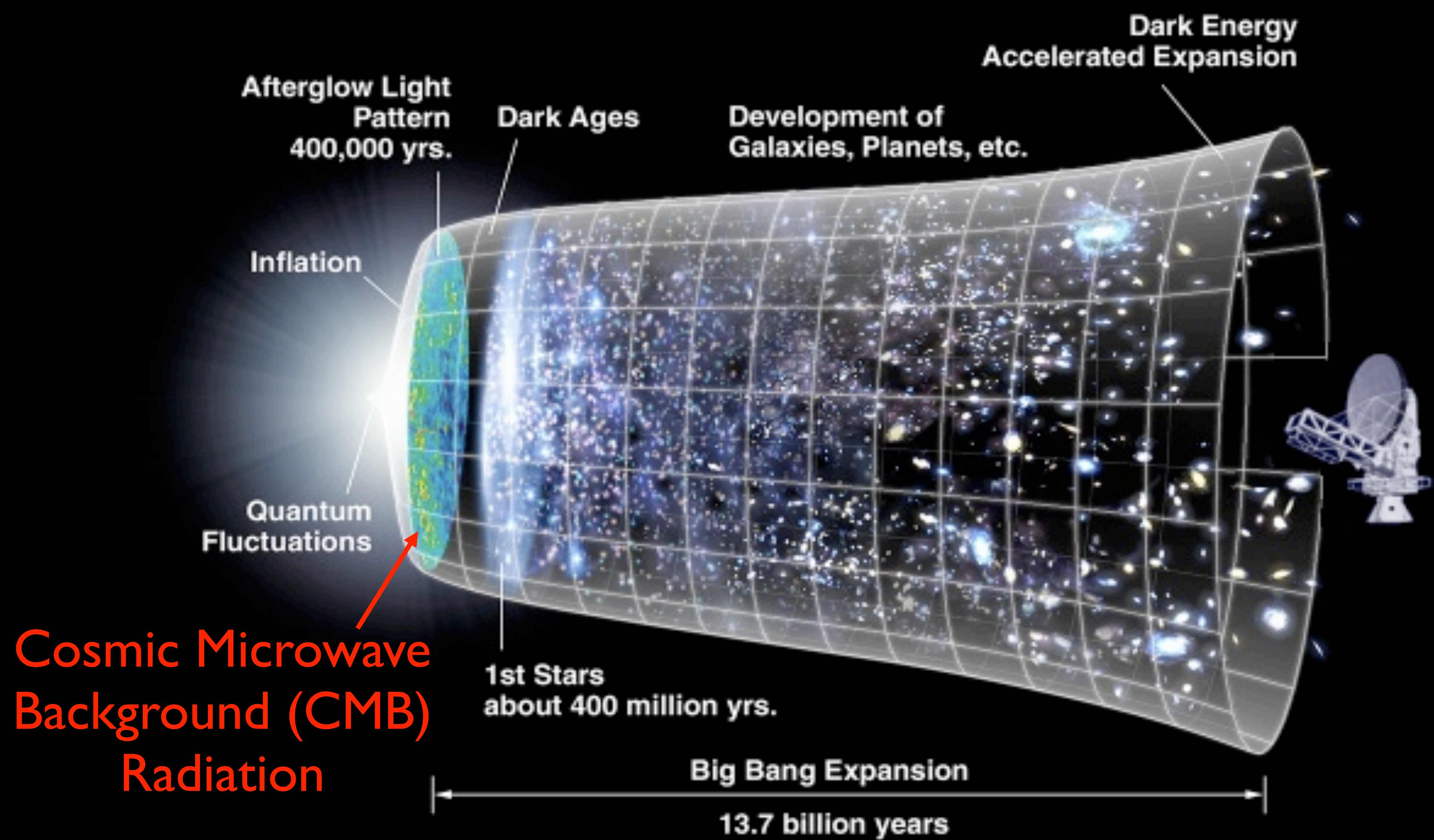
The South Pole Telescope:

The Sunyaev-Zel'dovich (SZ) Cluster Survey and Future Directions



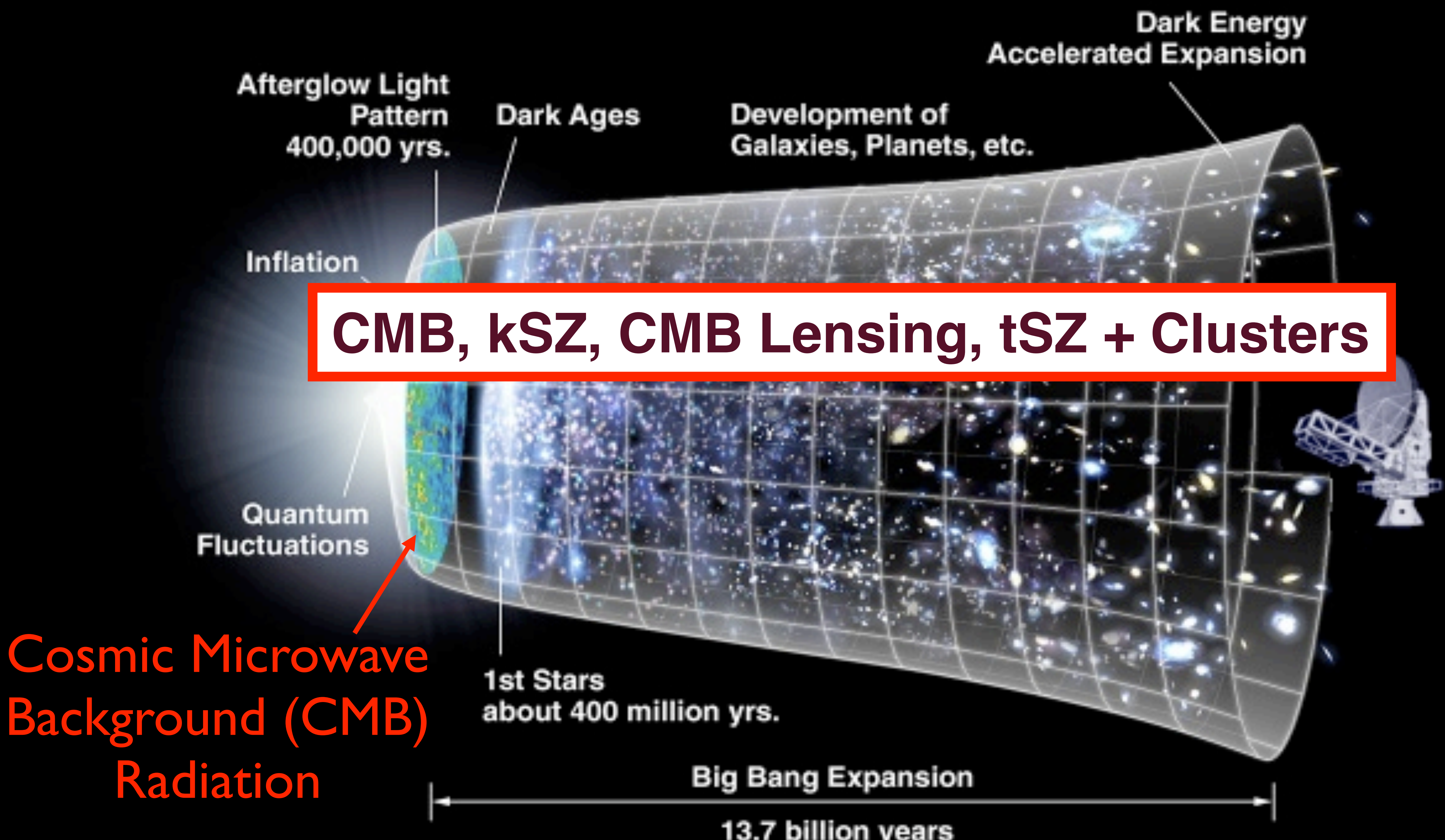
Bradford Benson
(University of Chicago)

The CMB as a Backlight to the Universe



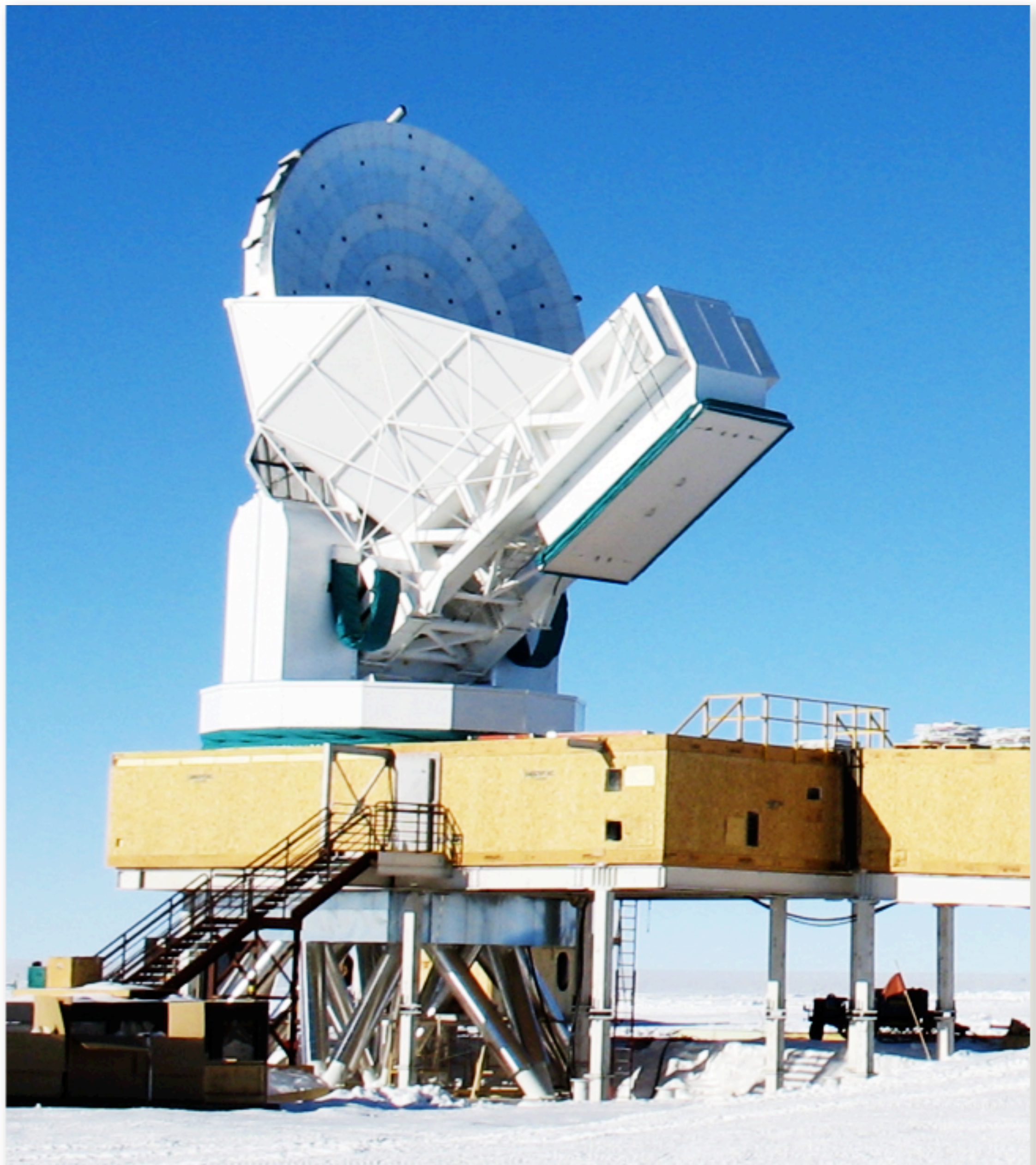
(image modified from NASA/WMAP)

The CMB Measures Structure Formation



(image modified from NASA/WMAP)

The South Pole Telescope (SPT)

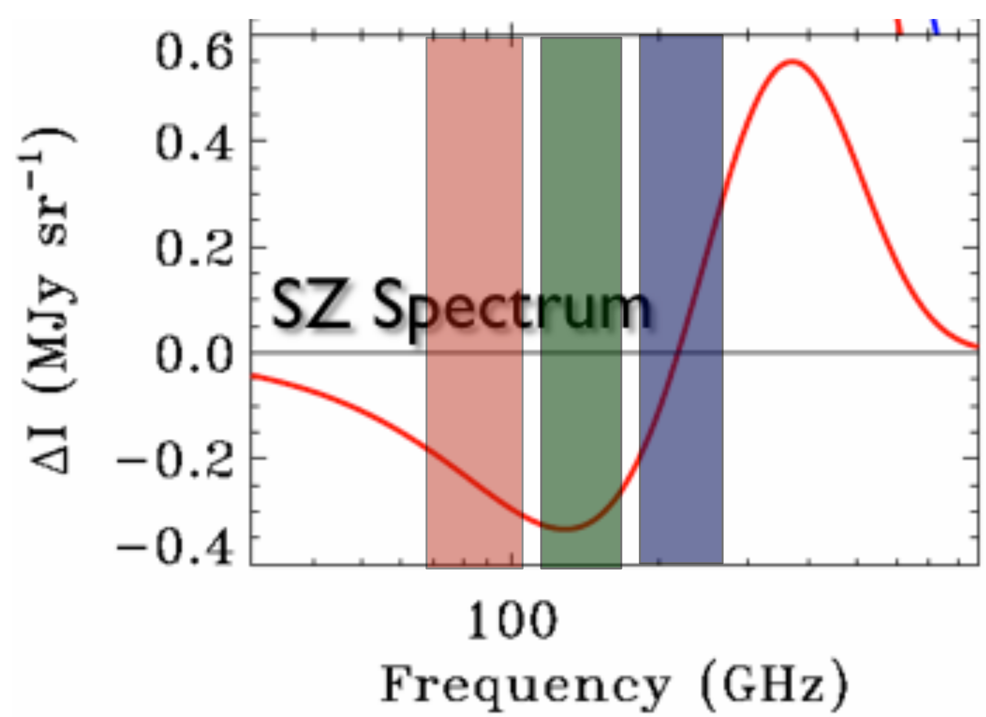


Millimeter-Wavelength Telescope

- 10 meter primary mirror
- 1 deg^2 field of view

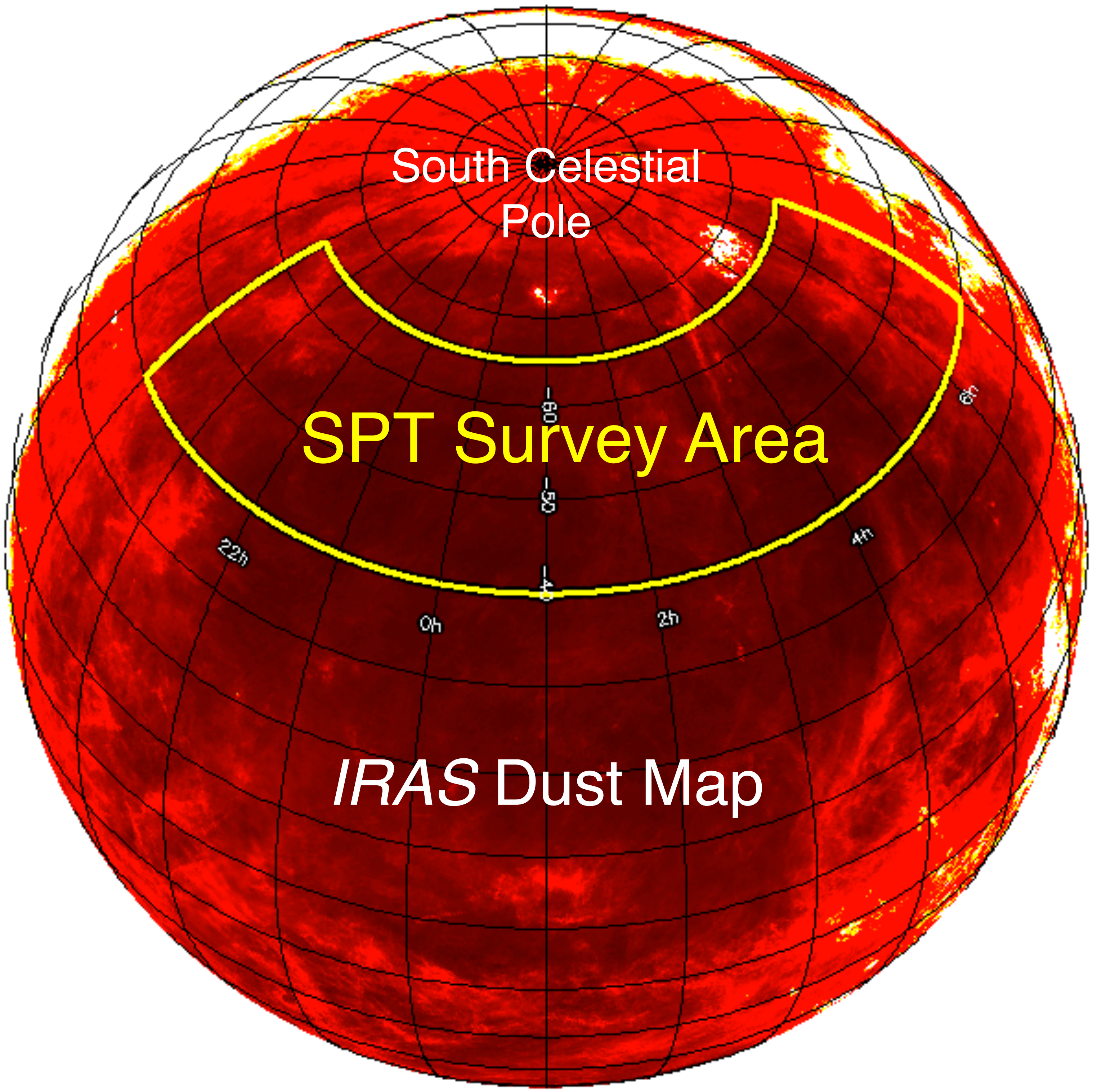
SPT-SZ Receiver Camera

- ~960 bolometers
- 3-colors: 100, 150, 220 GHz
- Resolution of 1.6, 1.2, 1.0 arcmin (well-matched to high-z clusters, r_{500} $(z=1.0) \sim 2$ arcmin)



Funded by NSF

The 2500 deg^2 SPT-SZ Survey



- **Status**: 5-year survey finished (!!!) Nov. 2011

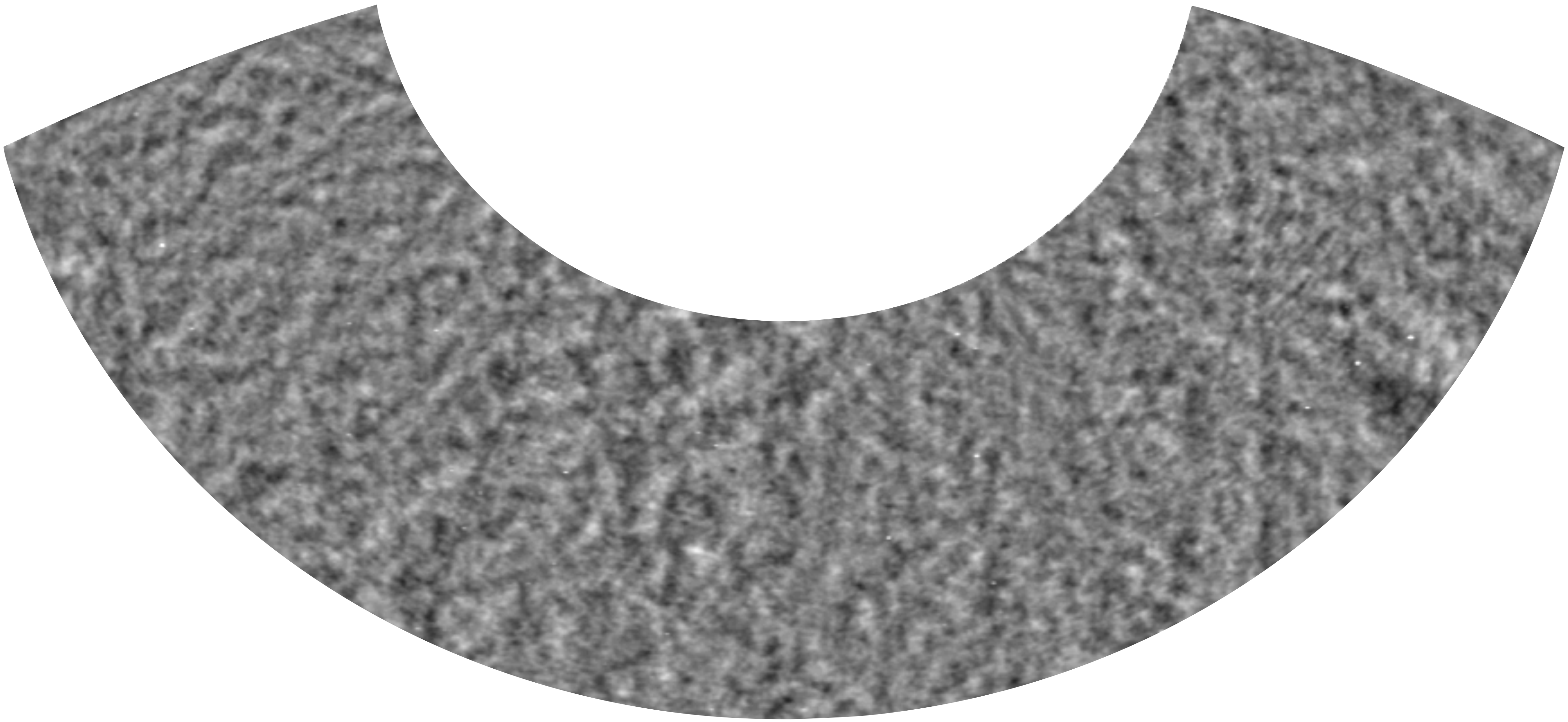
- 2500 deg^2 at high galactic latitude in Southern Sky.

Final survey depths of:

- 90 GHz: 40 uK_{CMB}-arcmin
- 150 GHz: 18 uK_{CMB}-arcmin
- 220 GHz: 70 uK_{CMB}-arcmin

(In these units, thermal Sunyaev-Zel'dovich (SZ) effect is 1.7 times brighter at 90 GHz than at 150 GHz.)

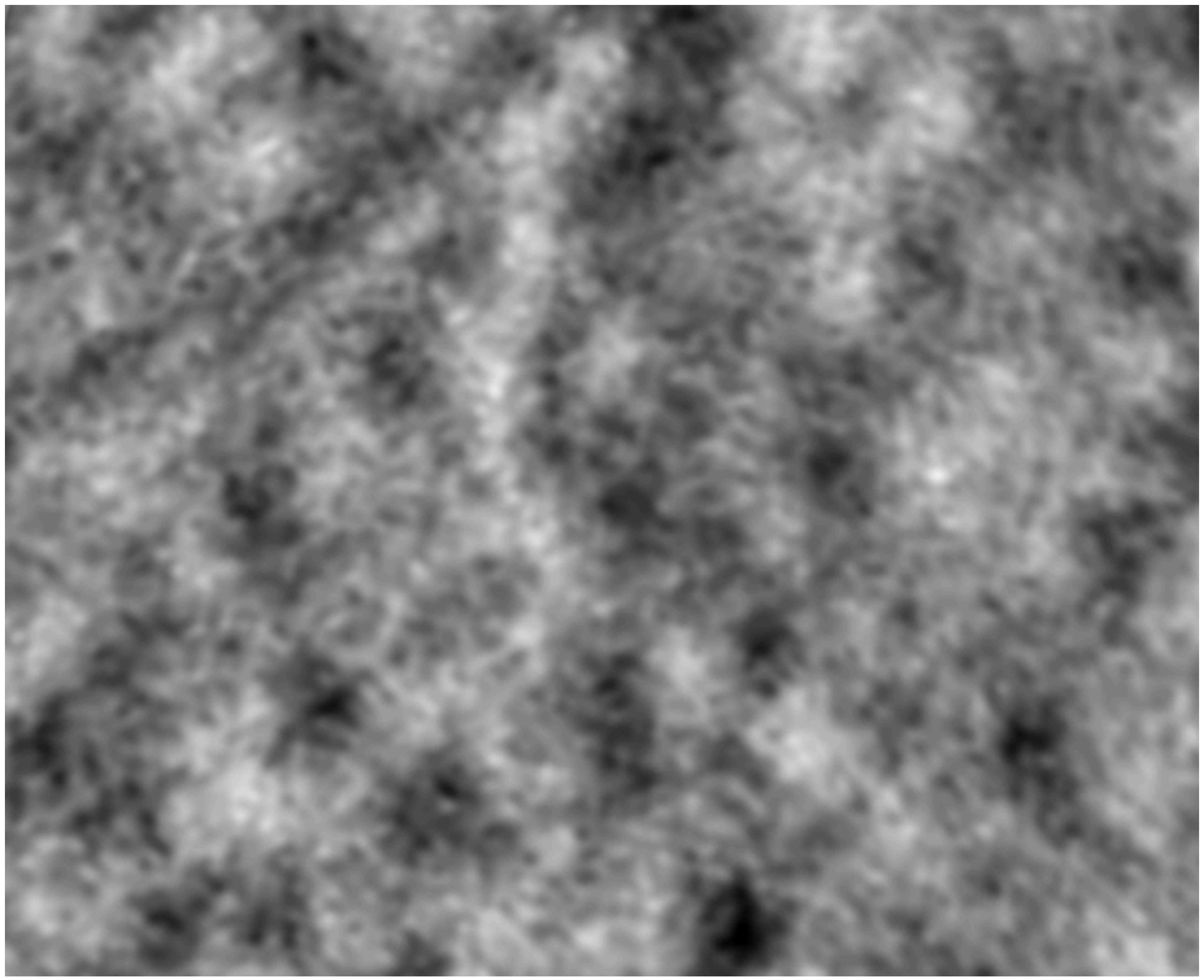
SPT 2500 deg^2 SZ Survey



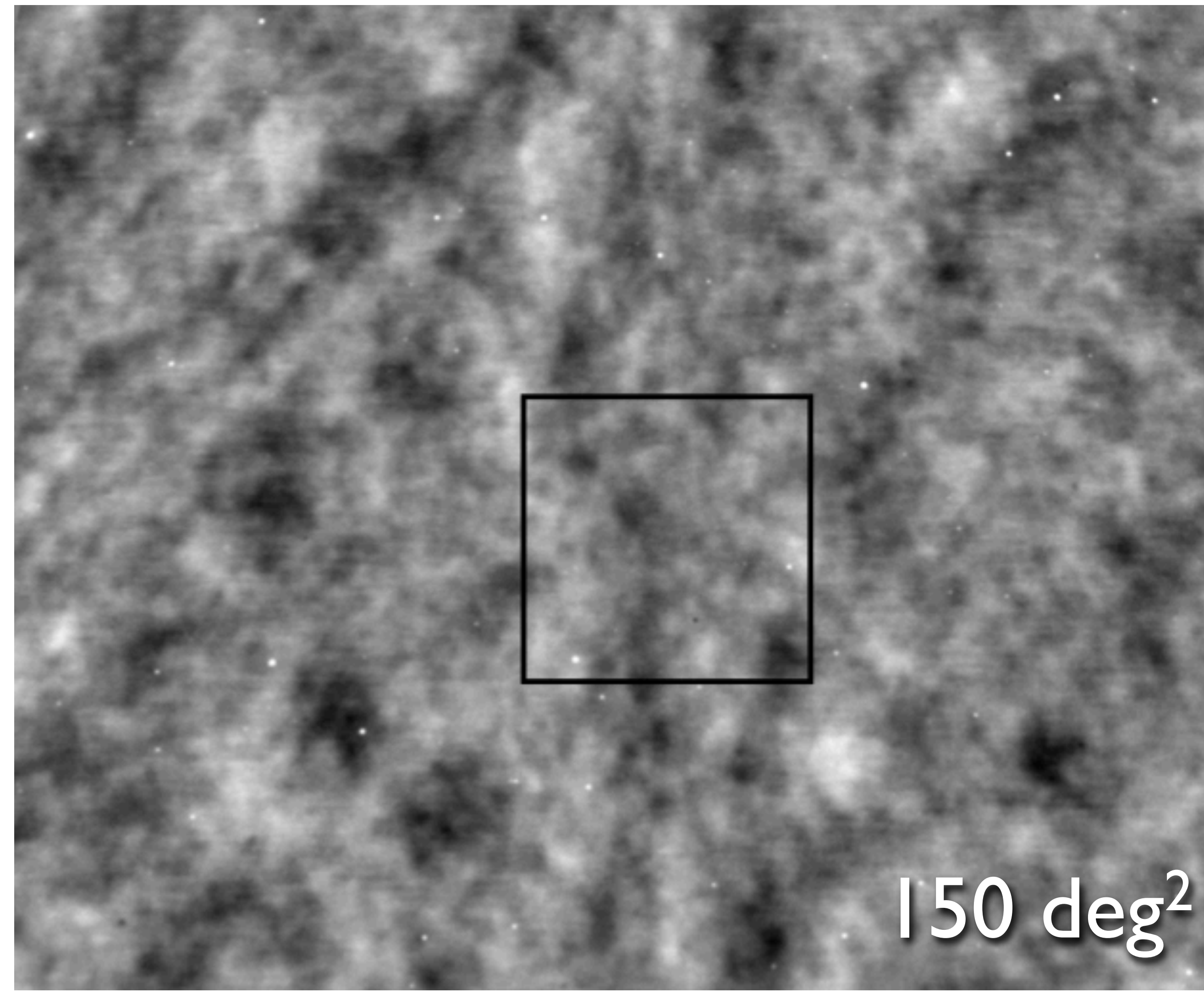
Status: finished in *Nov. 2011*.
Most results shown today use **1/3** of this data.

The CMB as observed by WMAP and SPT

WMAP



SPT

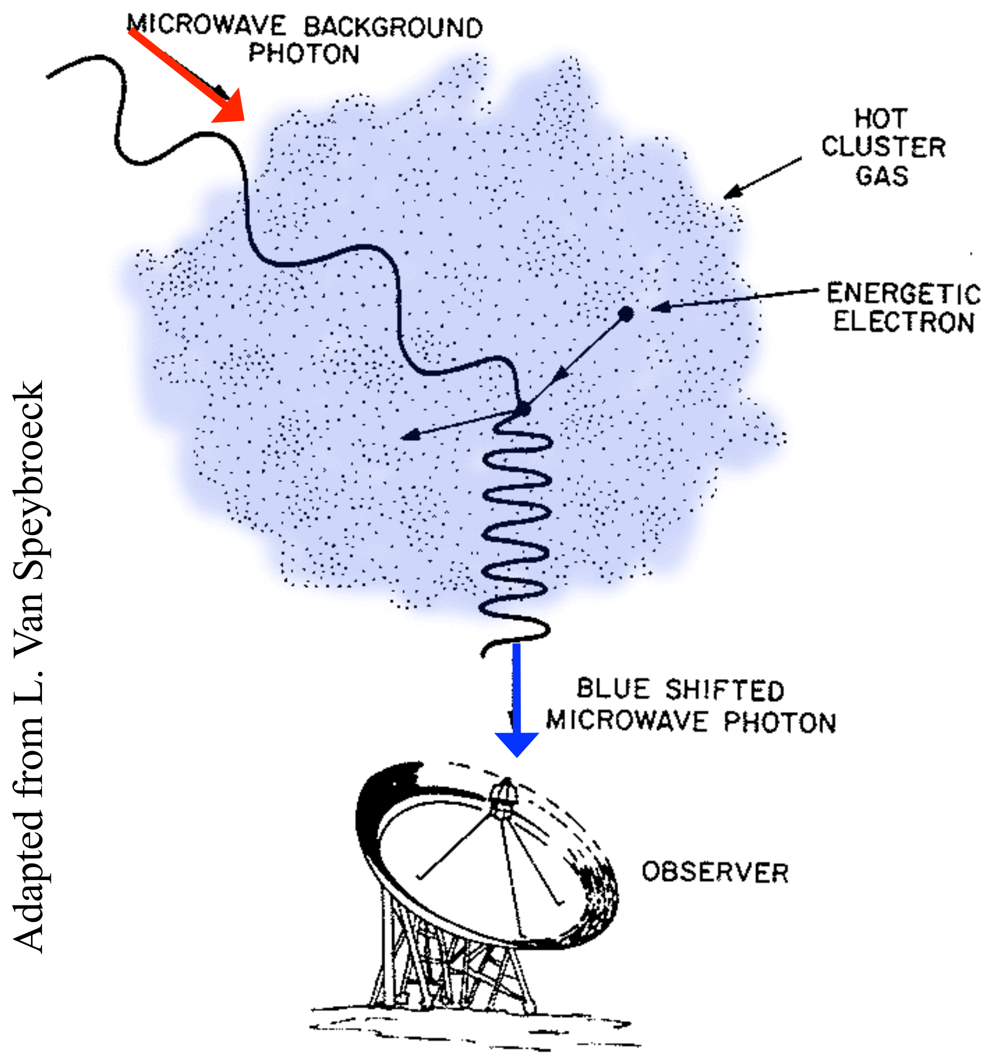


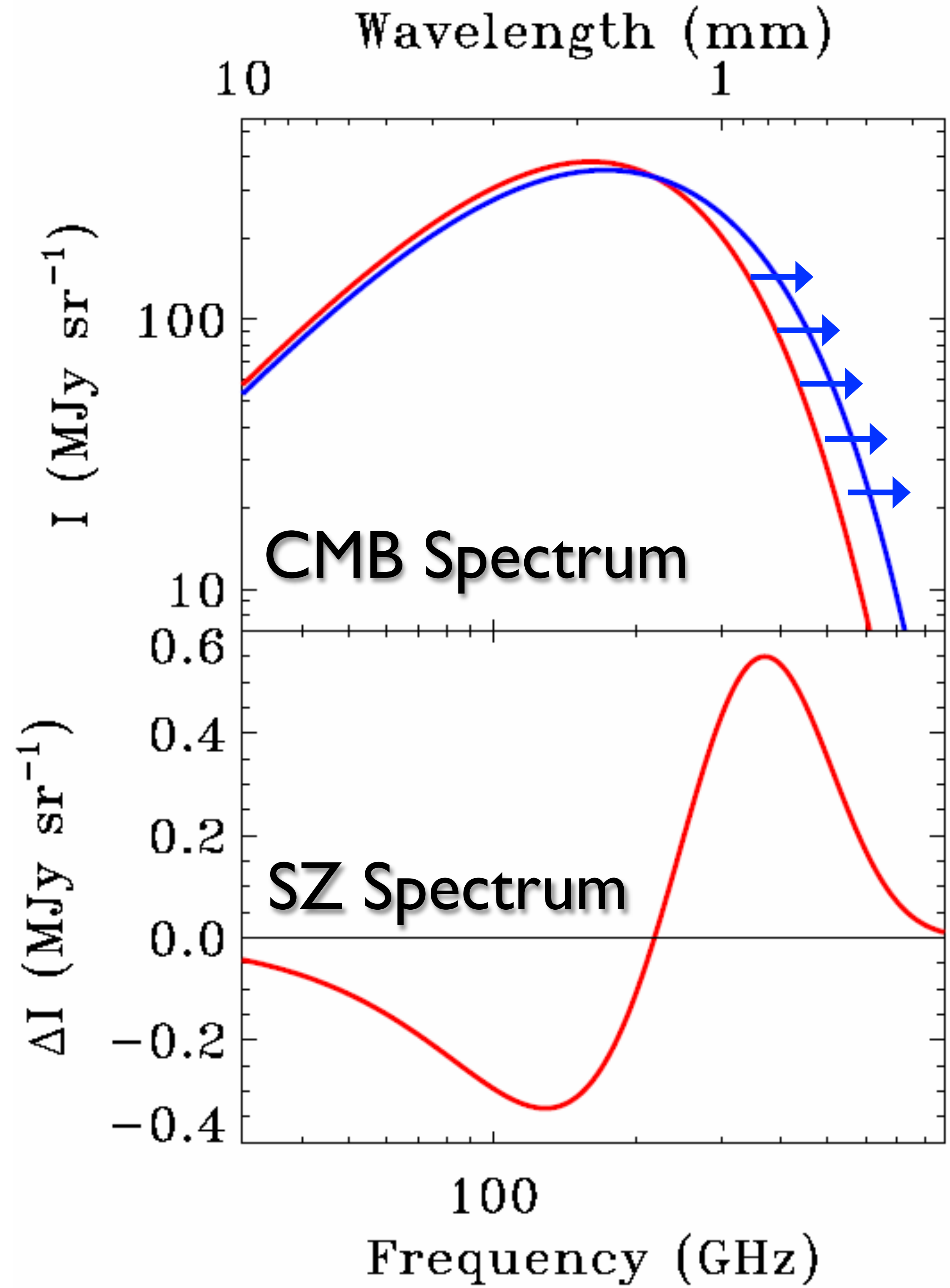
SPT relative to WMAP:

13x smaller beam (13’ vs 1’)

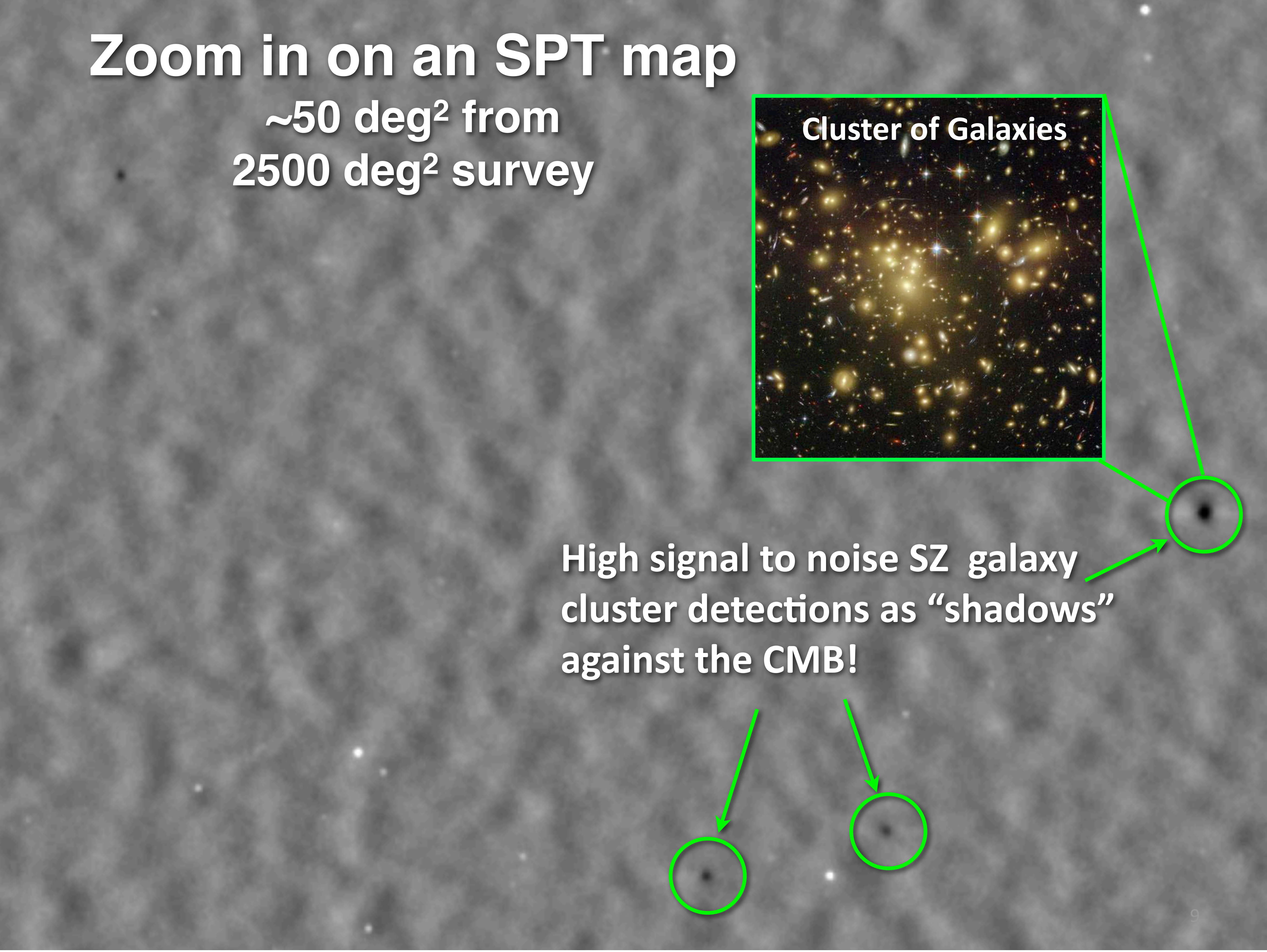
17x deeper (300 uK-arcmin vs 18 uK-arcmin)

The Sunyaev Zel'dovich (SZ) Effect

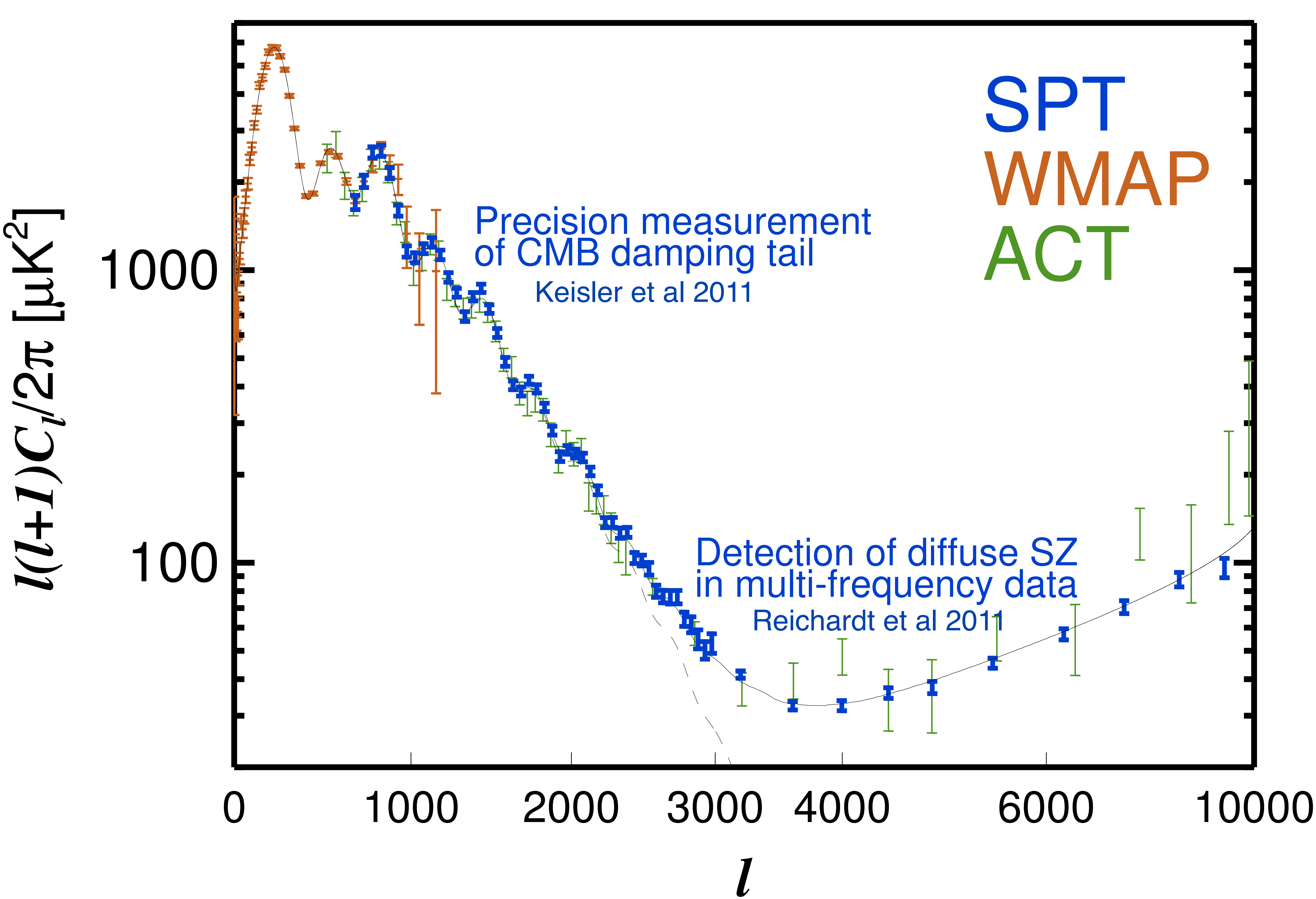




- Towards a massive cluster, ~1% of CMB photons scatter off of intra-cluster gas
- SZ Surface Brightness is redshift independent


Zoom in on an SPT map
~50 deg² from
2500 deg² survey
Cluster of Galaxies
High signal to noise SZ galaxy
cluster detections as "shadows"
against the CMB!

SPT: CMB Power Spectrum



Cosmology from the CMB

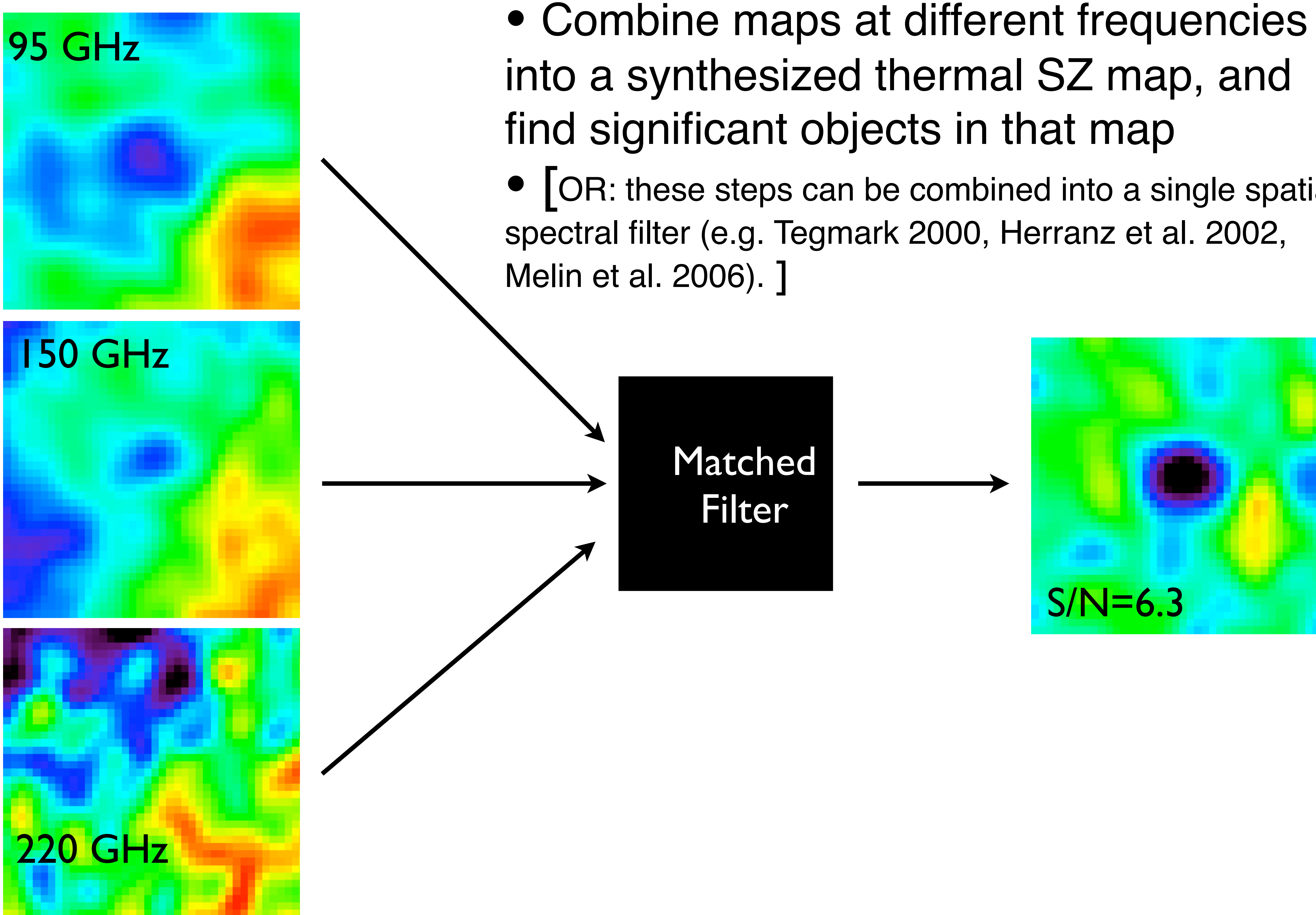
1. SZ Cluster Survey
2. SZ Anisotropy
3. Future SZ Science

Cosmology from the CMB

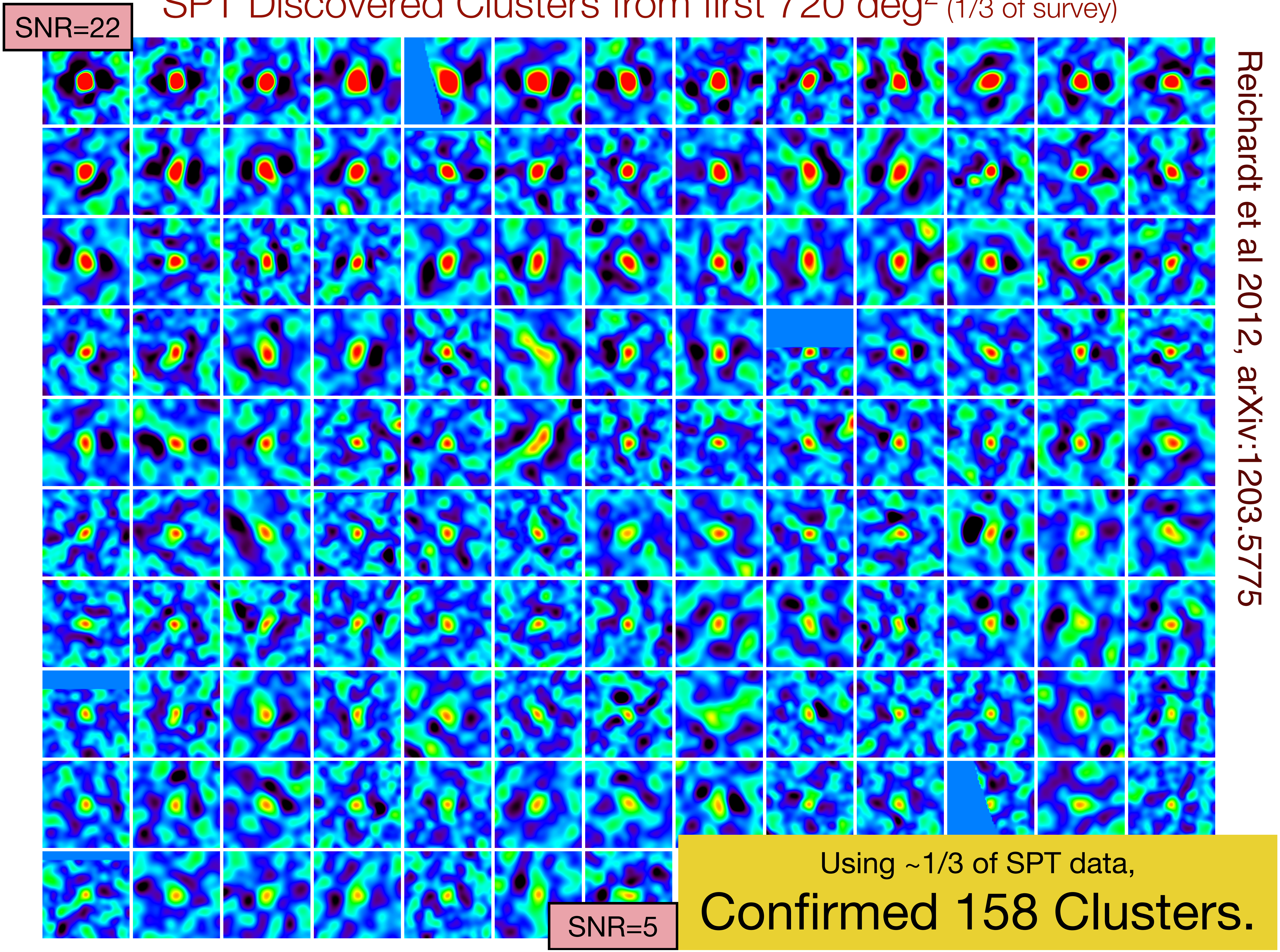
1. **SZ Cluster Survey**
2. SZ Anisotropy
3. Future SZ Science

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).]



SPT Discovered Clusters from first 720 deg^2 (1/3 of survey)



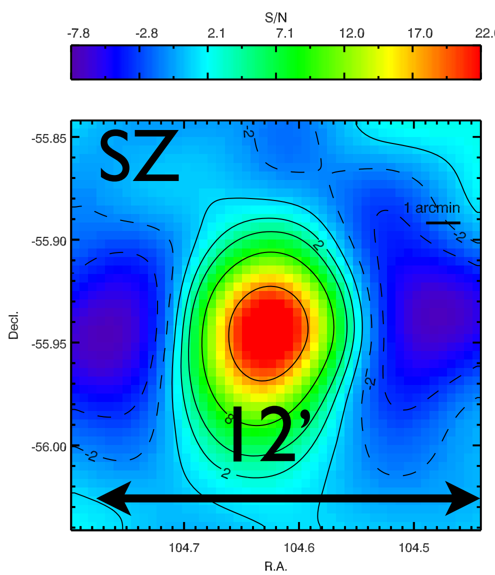
Reichardt et al 2012, arXiv:1203.5775

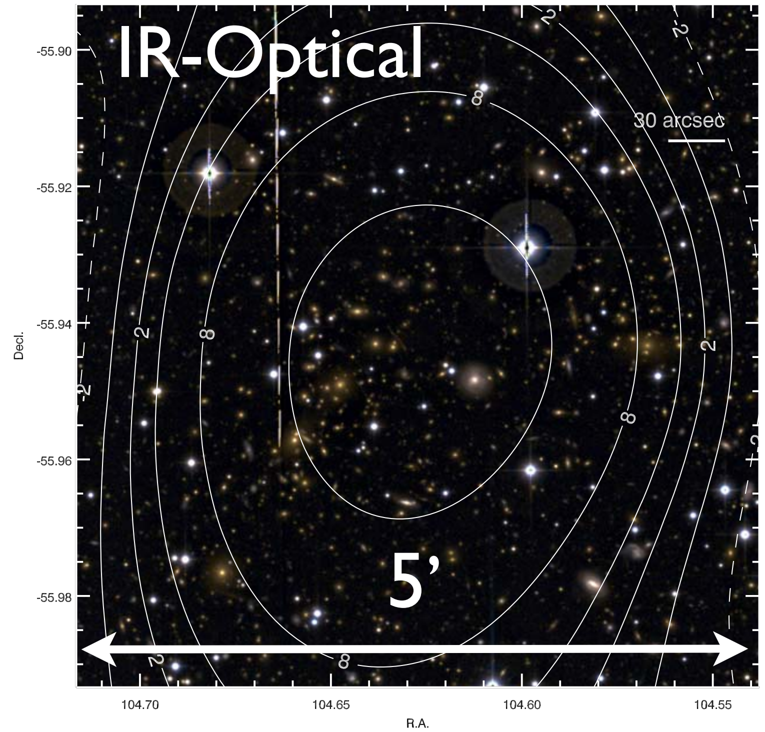
Using ~1/3 of SPT data,

Confirmed 158 Clusters.

Example Massive SPT Clusters

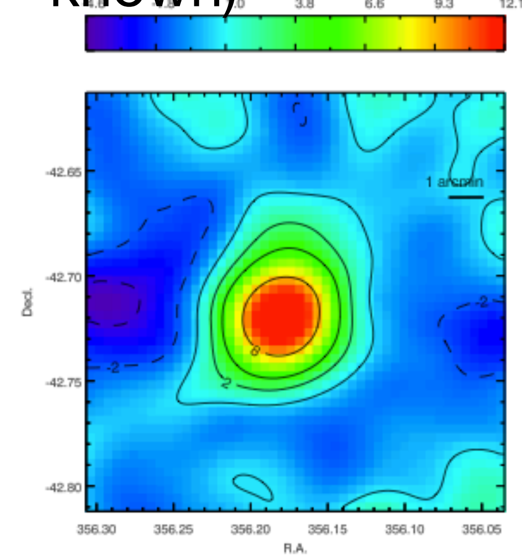
0658-5358 (z=0.30) (Bullet)

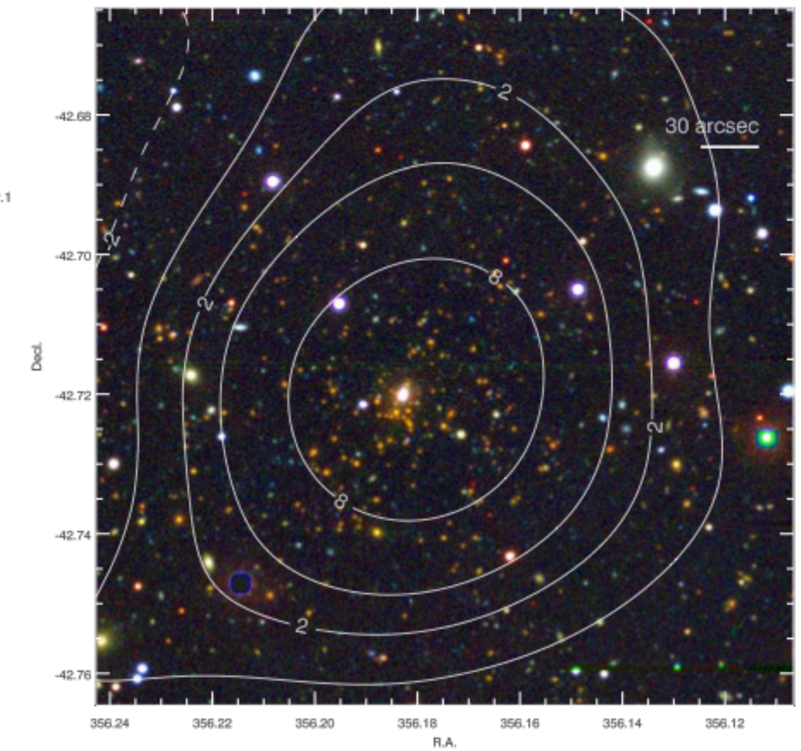




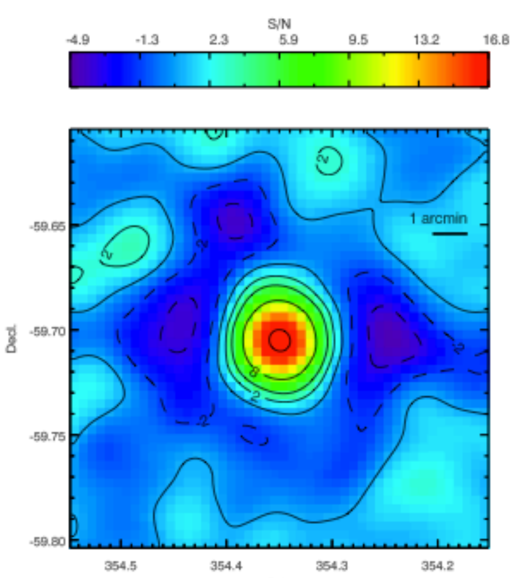
2344-4243 (z=0.60)

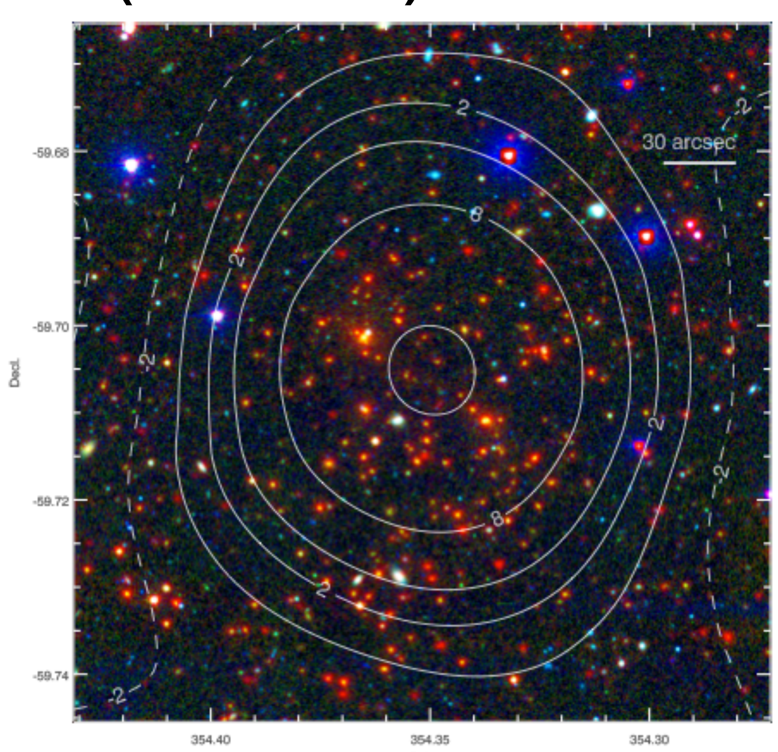
(Most X-ray luminous cluster known)





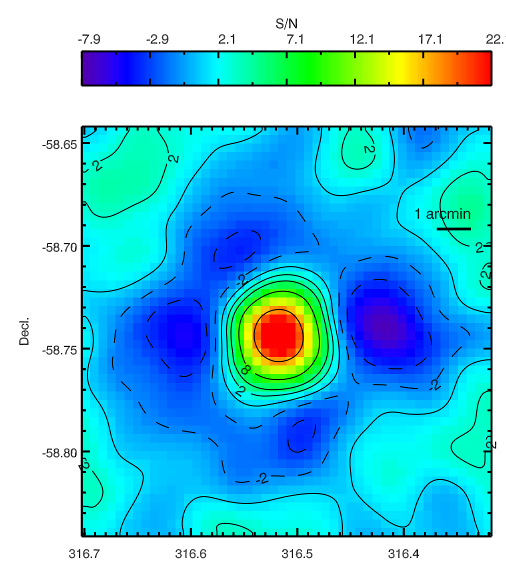
2337-5942 (z=0.78)

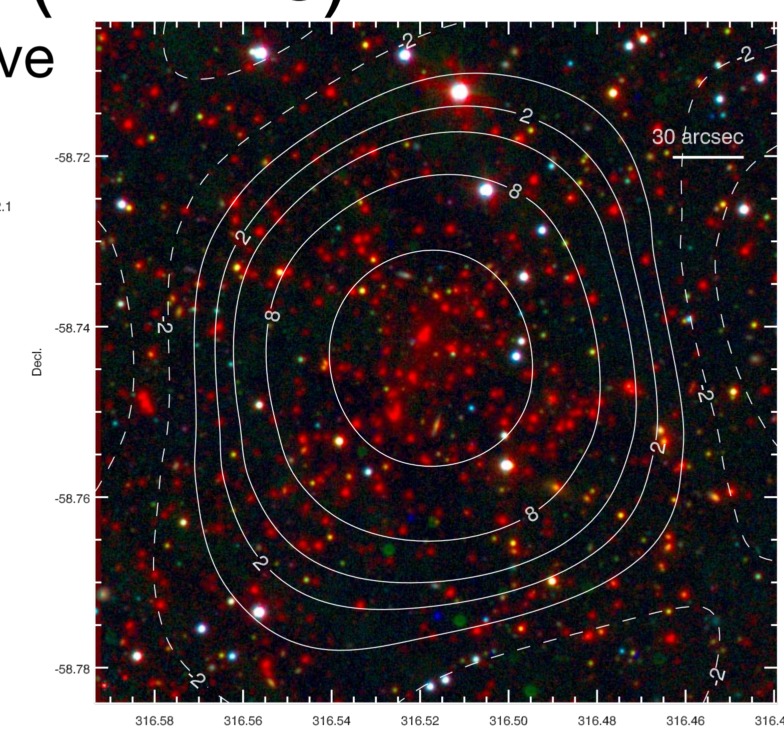




2106-5844 (z=1.13)

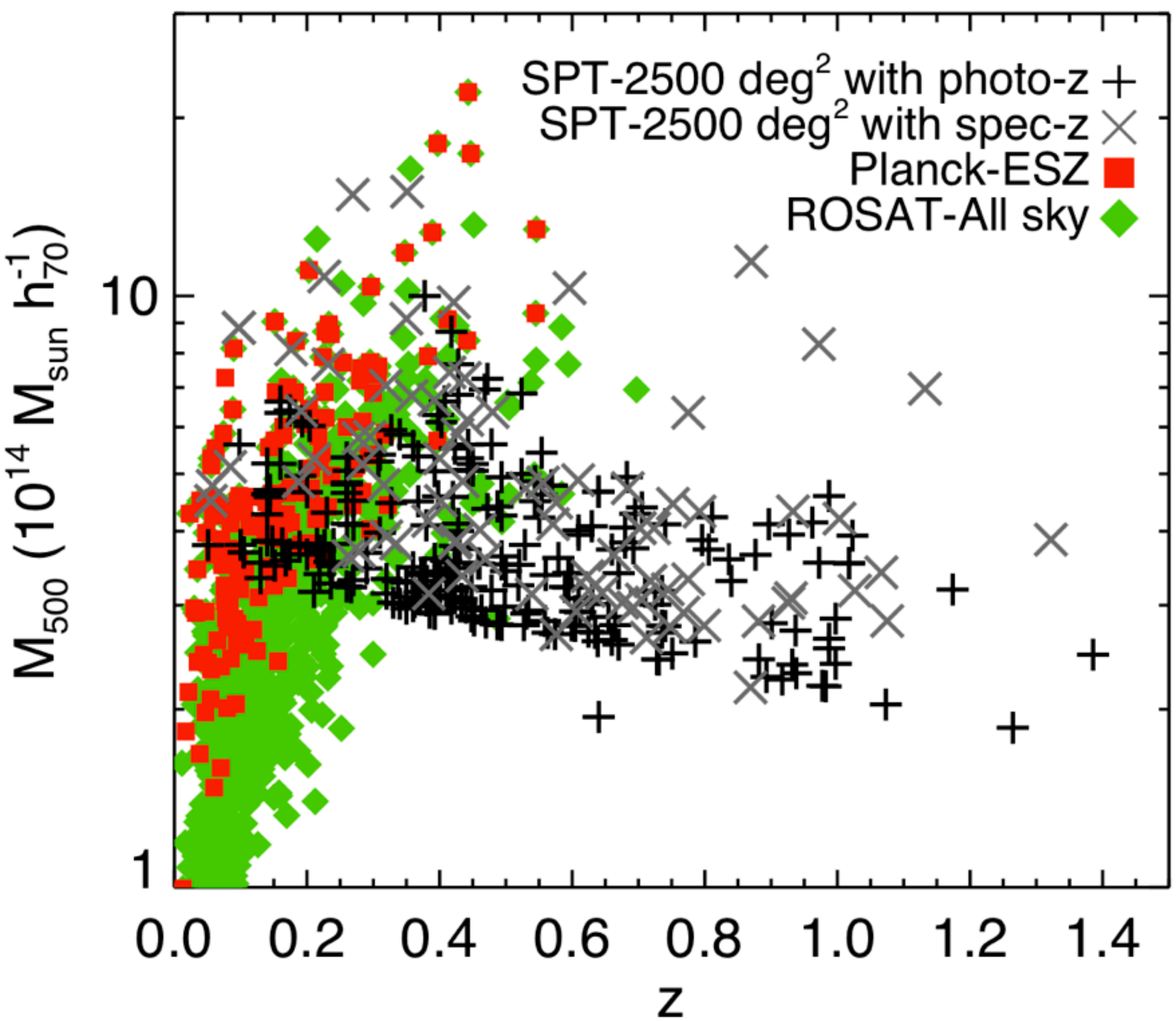
(The most massive cluster at z > 1)





SPT Cluster Sample Properties

Cluster Mass vs Redshift

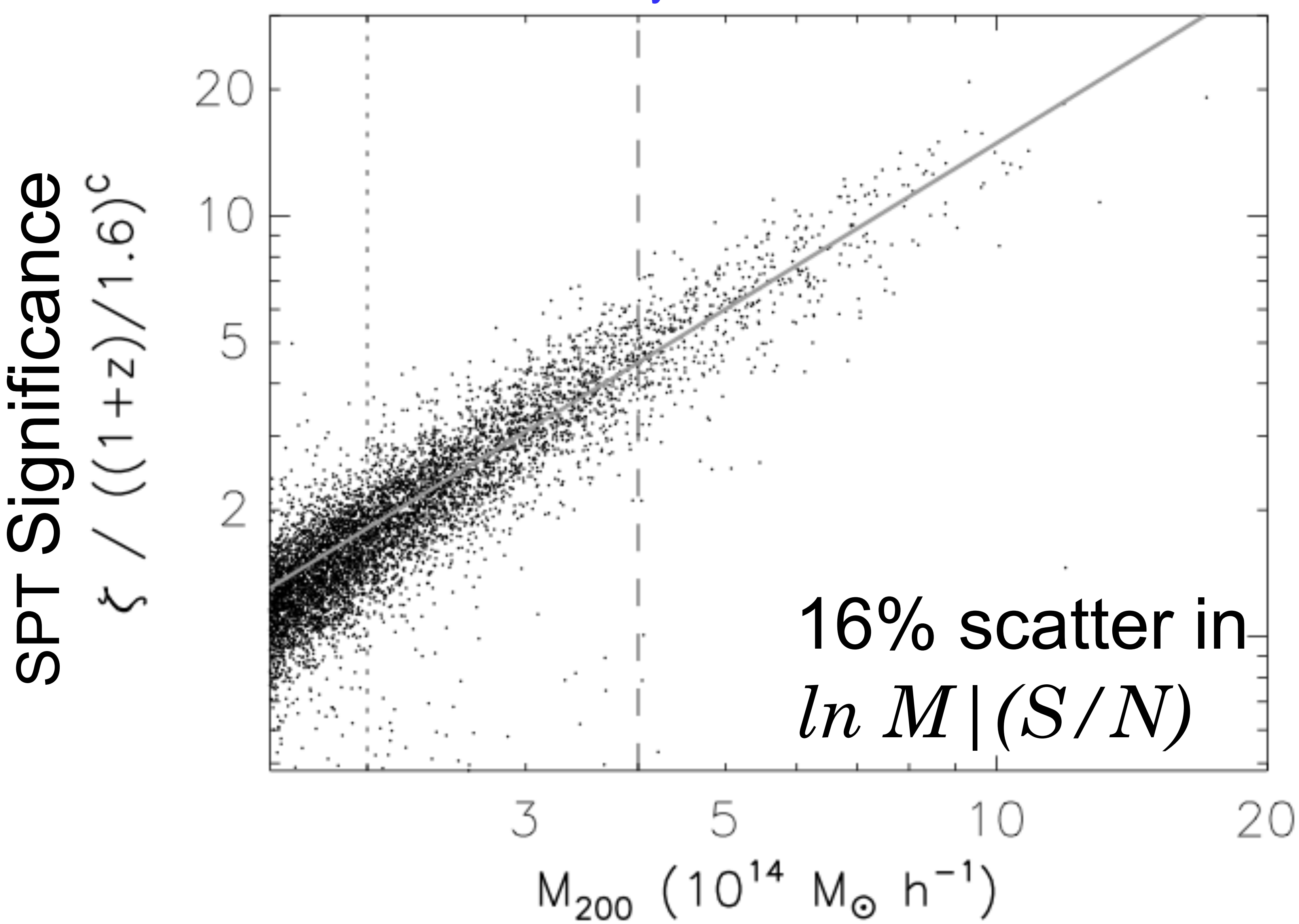


- About 500 clusters in SPT 2500 deg^2 catalog
- Over 325 SPT clusters have measured redshifts; 80% are newly discovered clusters.
- High redshift: <z> ~ 0.55 (20% of clusters at $z > 0.8$)
  - ***SPT has found more massive clusters at $z > 0.4$ than previously known***
- SPT mass threshold falls with redshift, but with **$M_{500}(z=0.6) > 3\times10^{14}\ M_{sol}/h_{70}$**

See, Reichardt et al 2012, arXiv:1203.5775

SPT Significance as a Mass Proxy

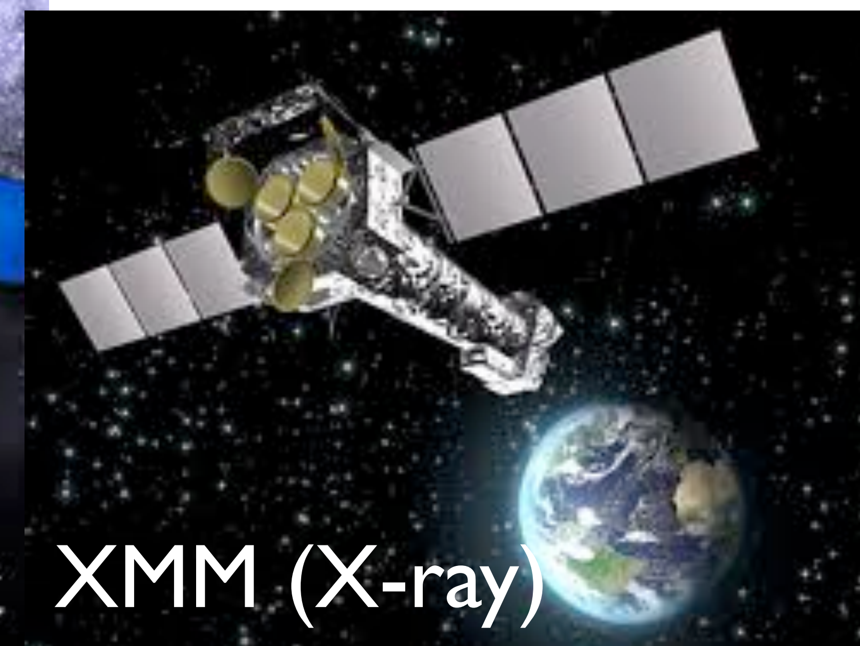
From Simulations by Laurie Shaw

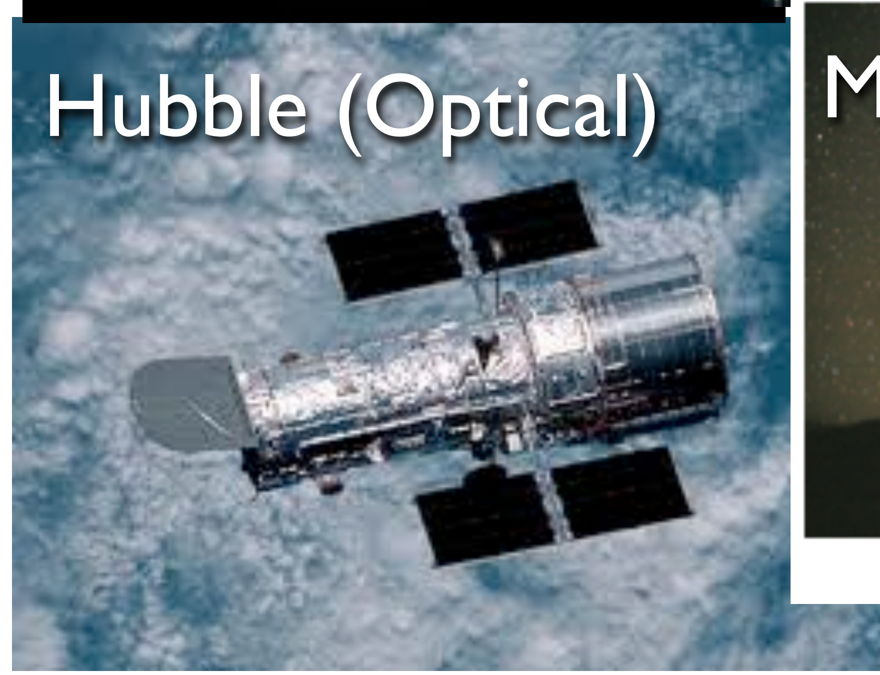


- For any cluster survey, challenge is to link cluster “observable” to cluster mass
- Ysz should have low (~7%) scatter with Mass (Kravstov, Vikhlinin, Nagai 2006)
- From simulations, signal-to-noise in spatial filtered SPT map is a relatively good mass proxy (Vanderlinde et al 2010)
- **Need to calibrate SZ significance to cluster mass!**

Multi-wavelength Observations:
Mass Calibration

- **Multi-wavelength mass calibration campaign, including:**
  1. **X-ray** with Chandra and XMM **(PI: Benson**, Vikhlinin**)**
  2. **Weak lensing** from Magellan ($0.3 < z < 0.6$) and HST ($z > 0.6$) **(PI: High,** Hoekstra)
  3. **Dynamical masses** from NOAO 3-year survey on Gemini ($0.3 < z < 0.8$) (PI:Stubbs), also VLT at ($z > 0.8$) **(PI: Bazin**, Mohr)

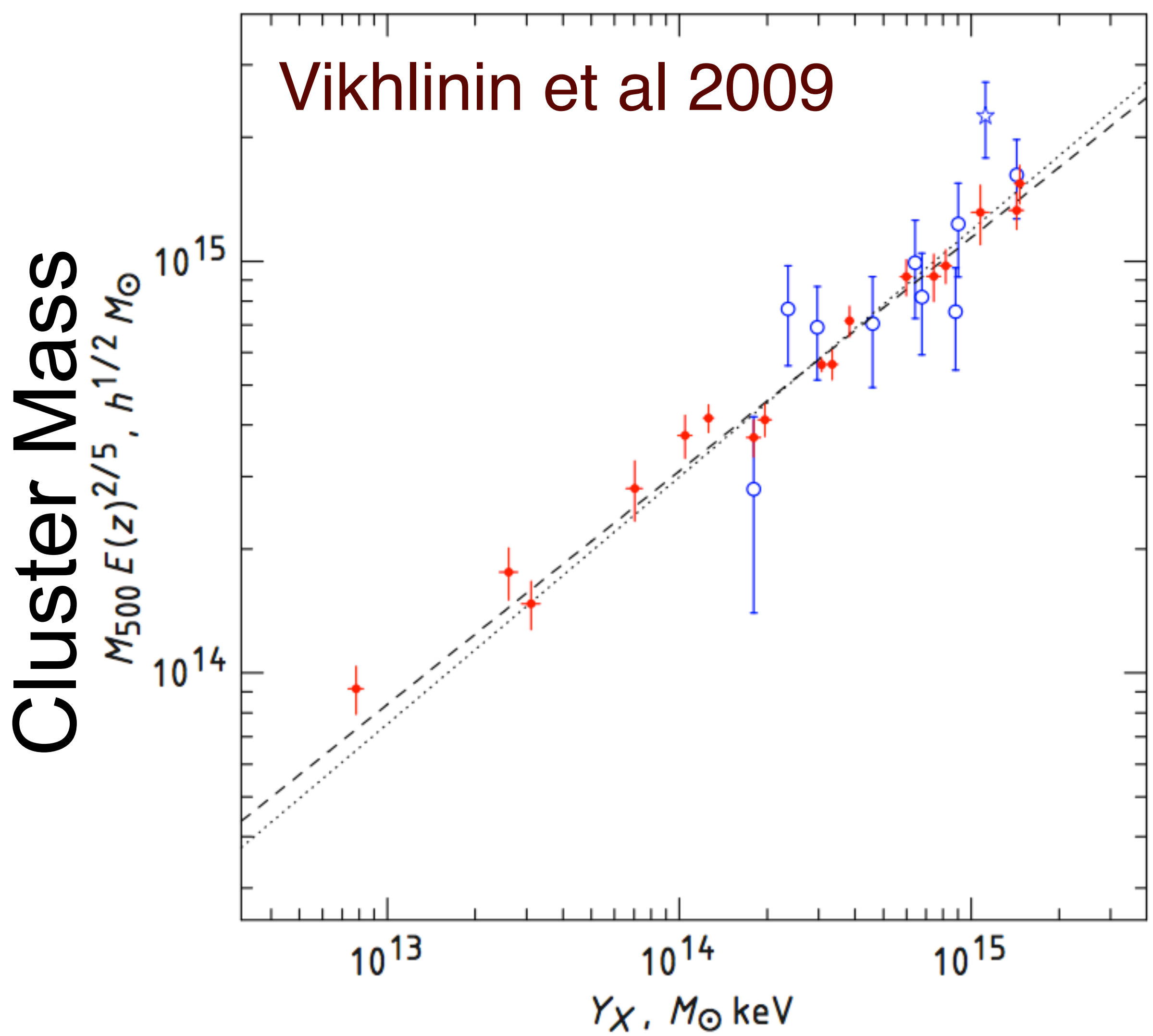




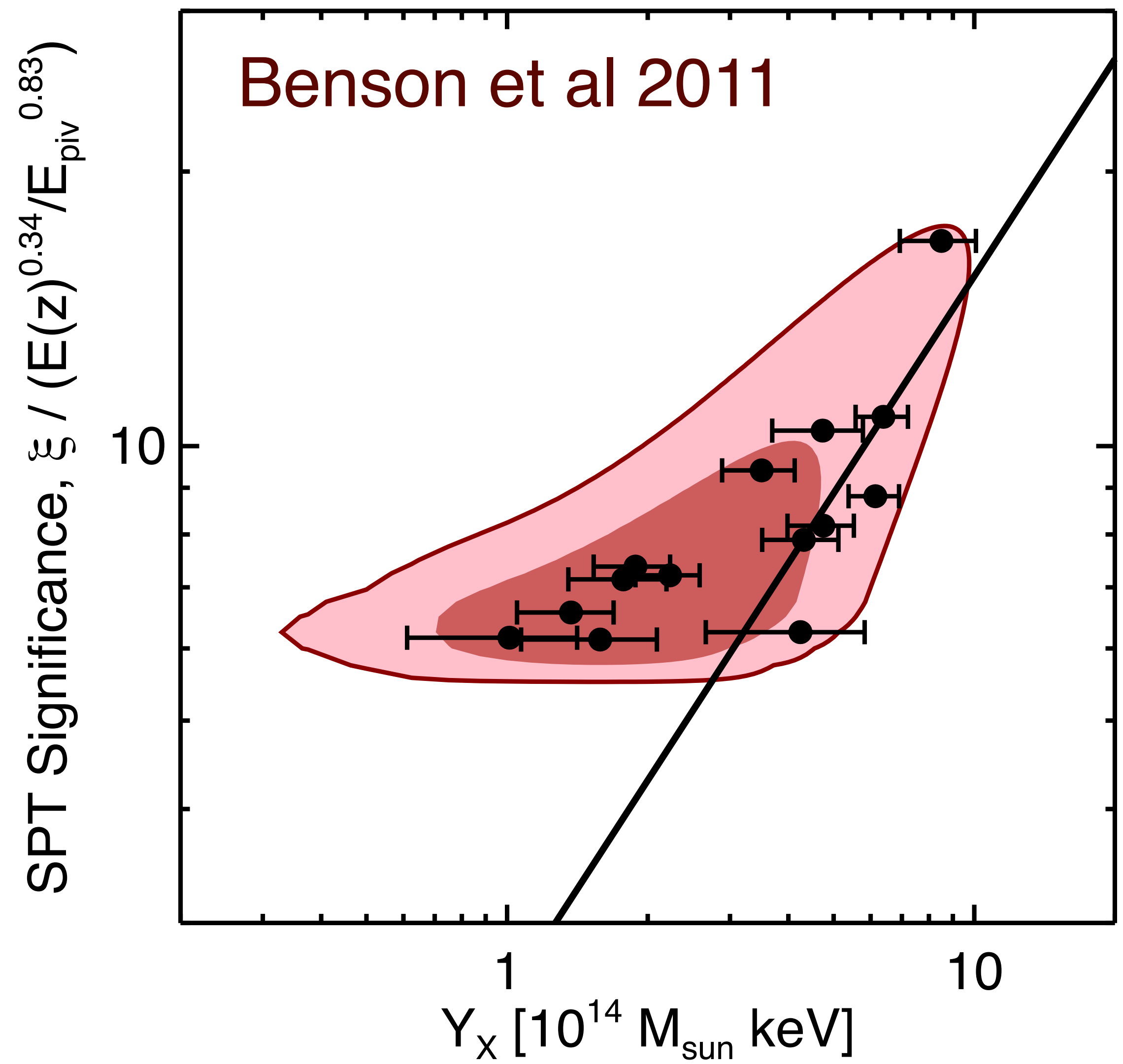
SPT Significance-Mass Calibration

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

- X-ray masses are calibrated with ~10-15% accuracy using measurements of low-redshift relaxed clusters assuming hydrostatic equilibrium (and cross-checked by weak lensing observations)



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



X-ray Pressure, Yx

Cosmological Analysis:

Test X-ray Method on 18 clusters (<10% of 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
  - $\Omega_{\mathrm{m}} h^2, \Omega_{\mathrm{b}} h^2, A_{\mathrm{s}}, n_s, \tau, \theta s$
- Extension Cosmology
  - $w, \Sigma m_\nu, f_{NL}, N_{eff}$

9 Scaling Relation Parameters

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

A) normalization,

B) slope,

C) redshift evolution,

D) scatter,

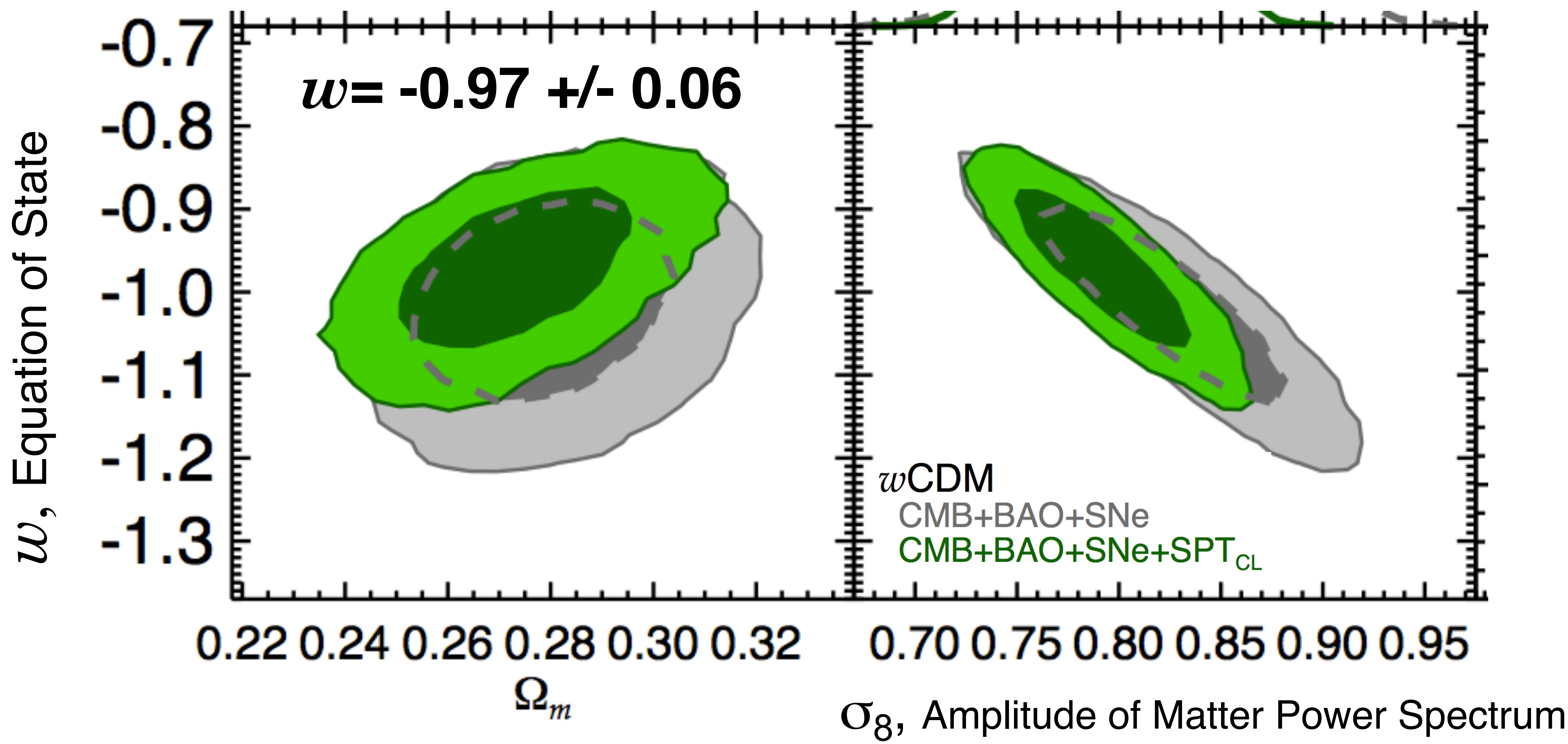
F) correlated scatter

Benson et al 2011, arXiv: 1112.5435

wCDM Constraints

Test X-ray Method on 18 clusters (<10% of survey)

SPT$_{CL}$ data improves dark energy (w,Ω_m) constraints by factor of 1.5



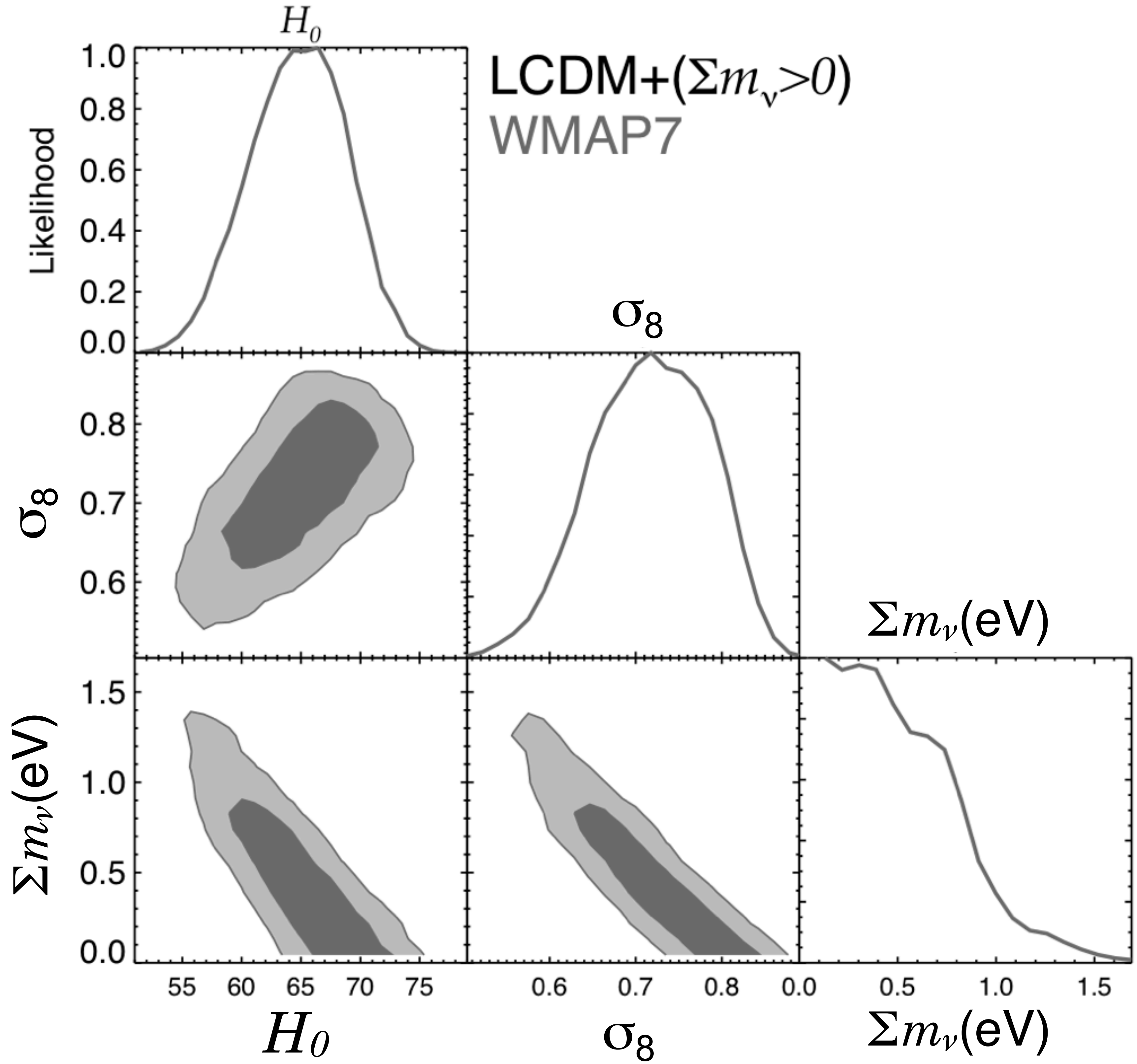
w, σ_8, Ω_m - 68, 95% Confidence Contours

CMB: WMAP7 + SPT (Komatsu et al 2011, Keisler et al. 2011)
BAO: (Percival et al. 2010)
SNe: (Amanullah et al. 2010)

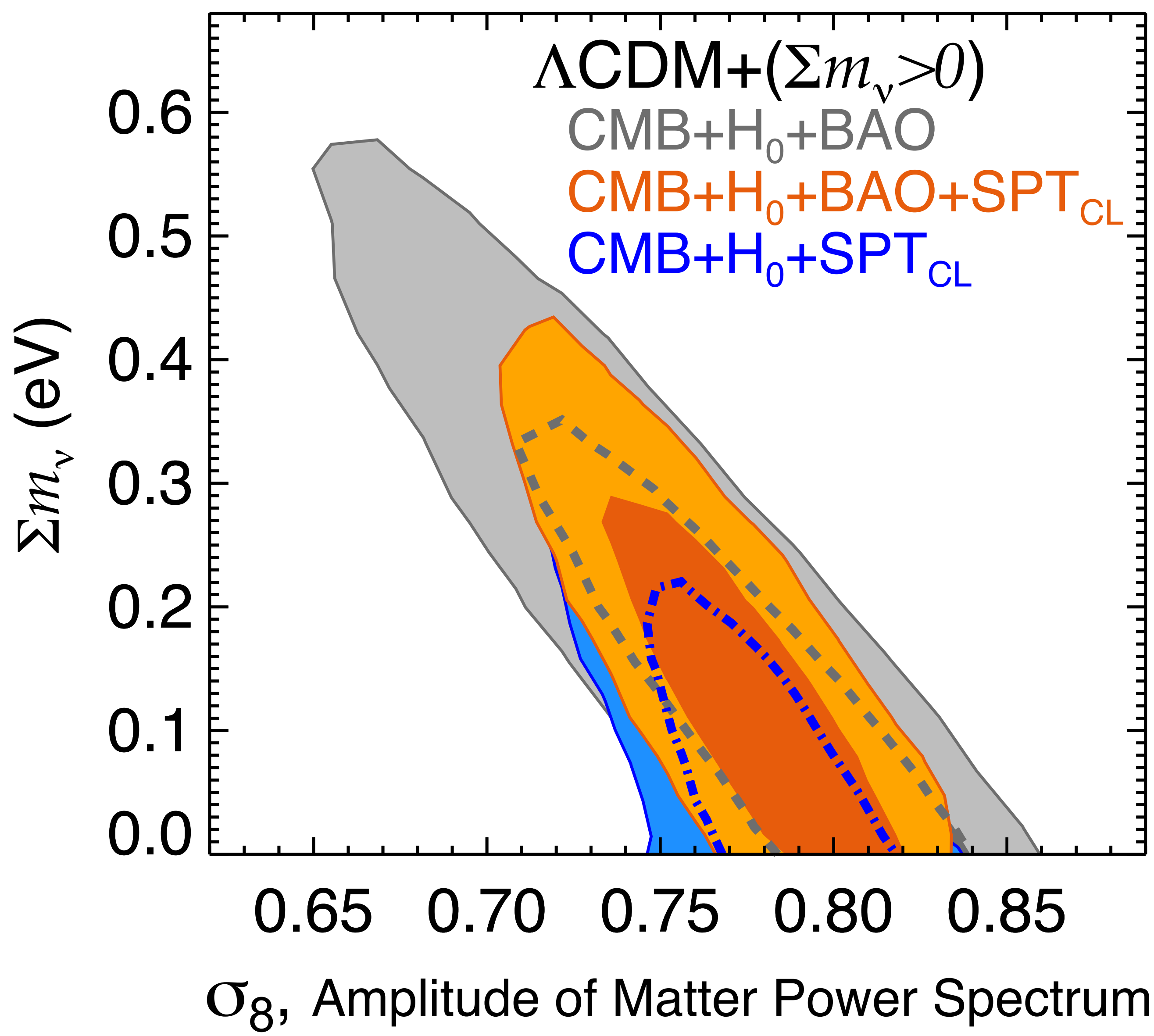
Benson et al 2011, arXiv: 1112.5435

Neutrino Mass (Σm_ν) Constraints

Constraints on neutrino mass from the CMB are improved most significantly by breaking degeneracies with H_0 and σ_8



Neutrino Mass (Σm_ν) Constraints



- 95% upper limit on the sum of the neutrino masses (Σm_ν) of:

CMB	< 1.1 eV
+H_0+BAO	< 0.45 eV
+H_0+SPT_{CL}	< 0.28 eV

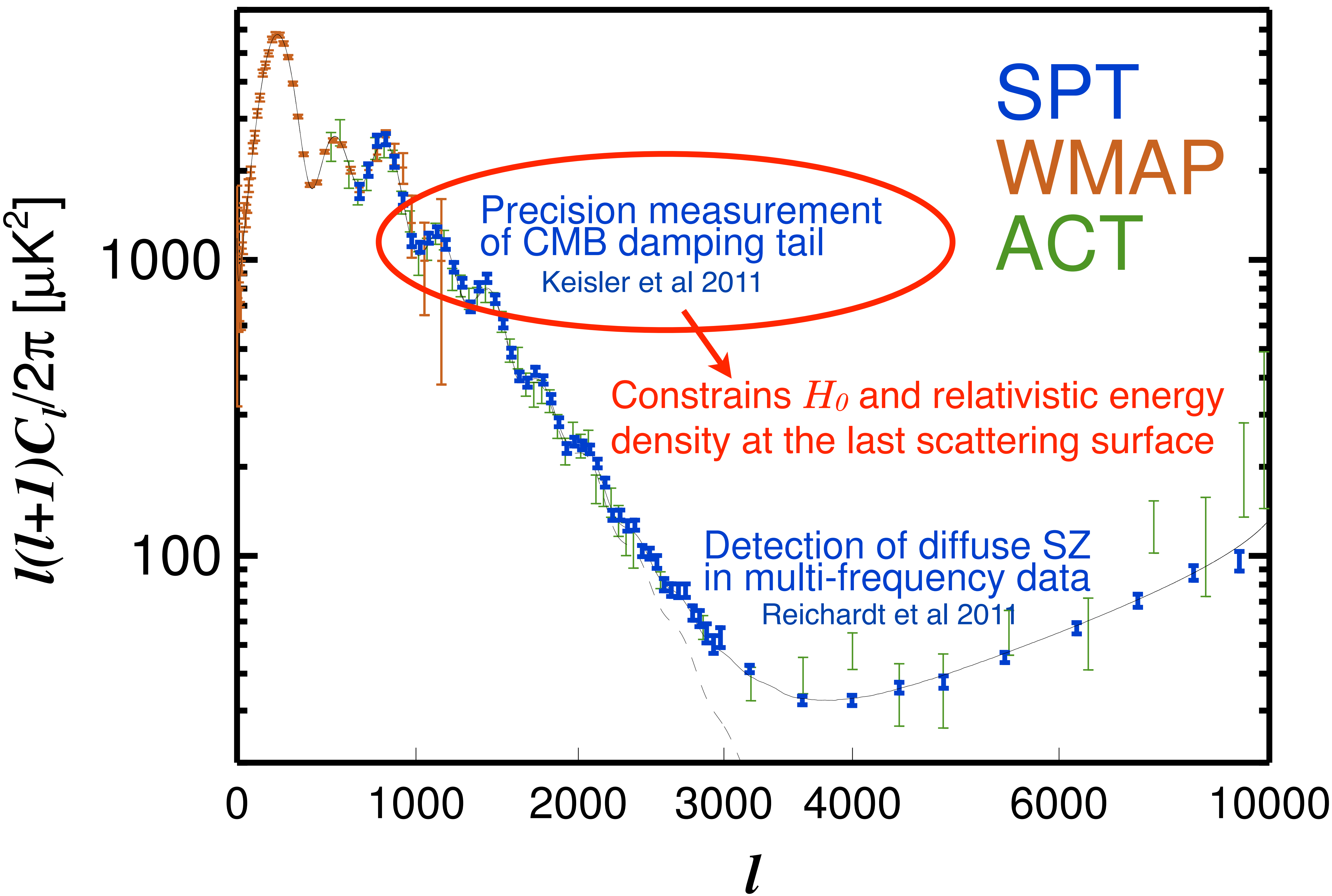
- With CMB+H_0+SPT_{CL} data 1-sigma standard deviation of +/- 0.09 eV
- Nearing > 0.05 eV mass limit from neutrino oscillations

Σm_ν, σ_8 - 68, 95% Confidence Contours

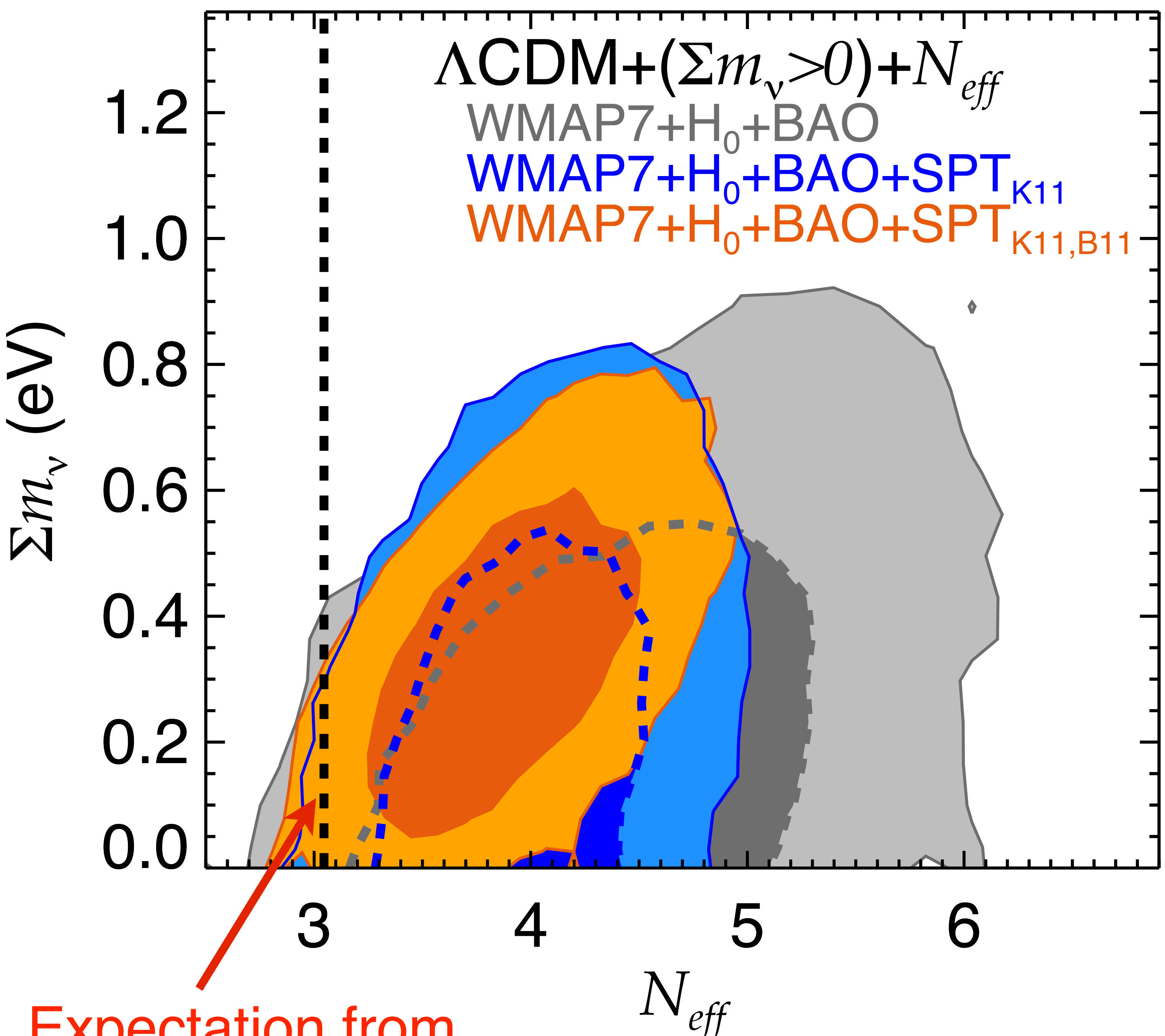
CMB: WMAP7 + SPT (Komatsu et al 2011, Keisler et al. 2011)
BAO: (Percival et al. 2010)
H_0 = 73.8 +/- 2.4 km / s Mpc (Riess et al 2011)

Benson et al 2011, arXiv: 1112.5435

SPT: CMB Power Spectrum



SPT: Neutrino Mass and the Number of Relativistic Species



Expectation from 3 neutrino species

CMB "damping tail" constrains effective number of relativistic particle species:

- $N_{\rm eff}$ = 3.91 +/- 0.42
- Σm_ν < 0.63 eV (at 95% confidence)
- Σm_ν = 0.34 +/- 0.17 eV

2-sigma preference for non-zero neutrino mass and an extra particle species

Keisler et al 2011, ApJ, 743, 28 (K11)

Benson et al 2011, arXiv: 1112.5435 (B11)

Cosmology from the CMB

1. **SZ Cluster Survey**
   - Thats with 18 clusters, what about for the full survey?
2. SZ Power Spectrum
3. Future SZ Science

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

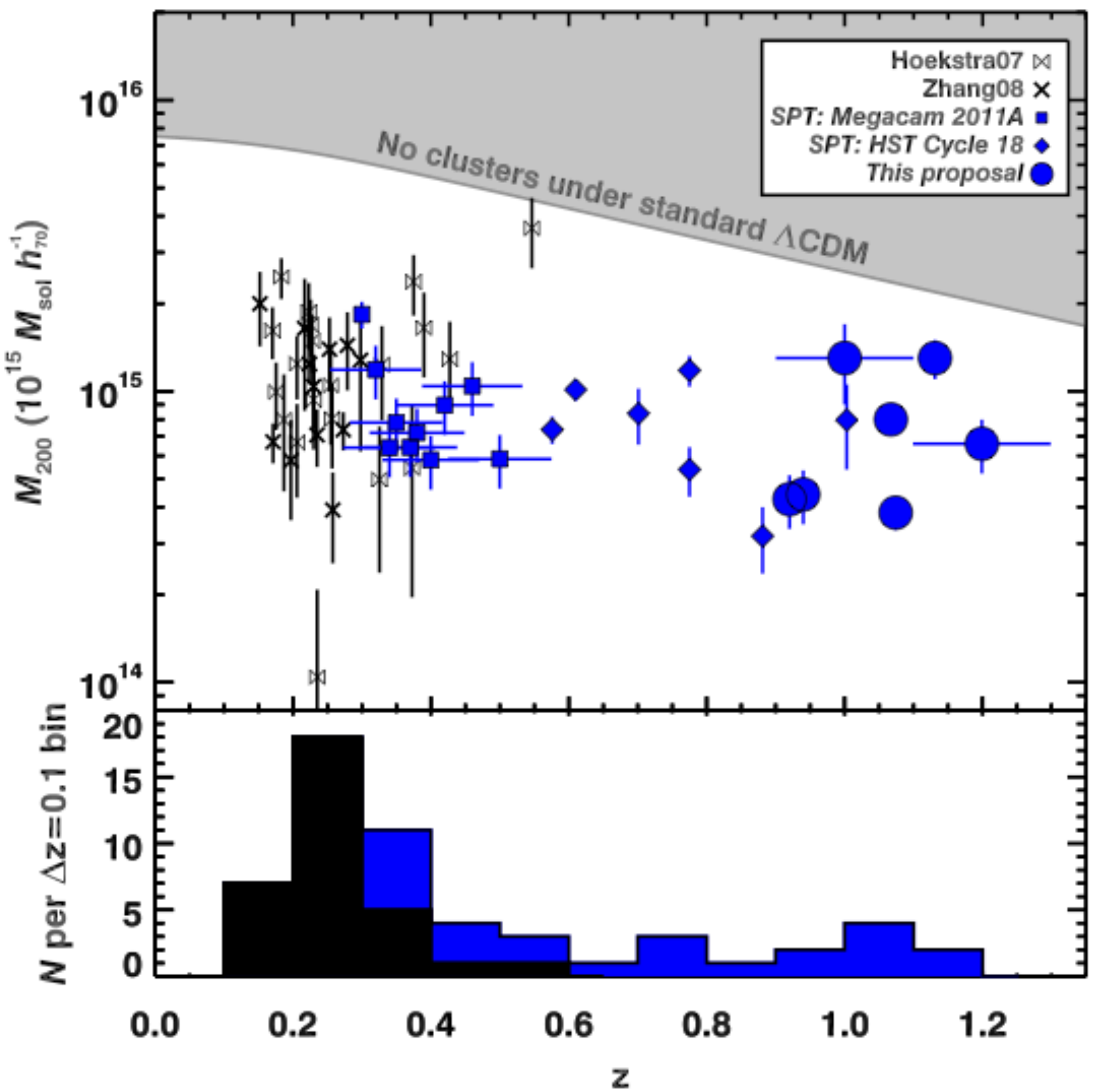
Chandra X-ray observations of 80 most significant clusters at $z > 0.4$ from SPT survey

- 2.1 Msec Proposal (PI: Benson), ~1% of Chandra's total lifetime
- **Primary Cosmology 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 Y_{SZ}, Y_X to use clusters as "standard ruler", constrain geometry of universe to high-z

Weak Lensing: Magellan, Hubble

Weak lensing measures gravitational deflection of light from background galaxies to measure total cluster mass

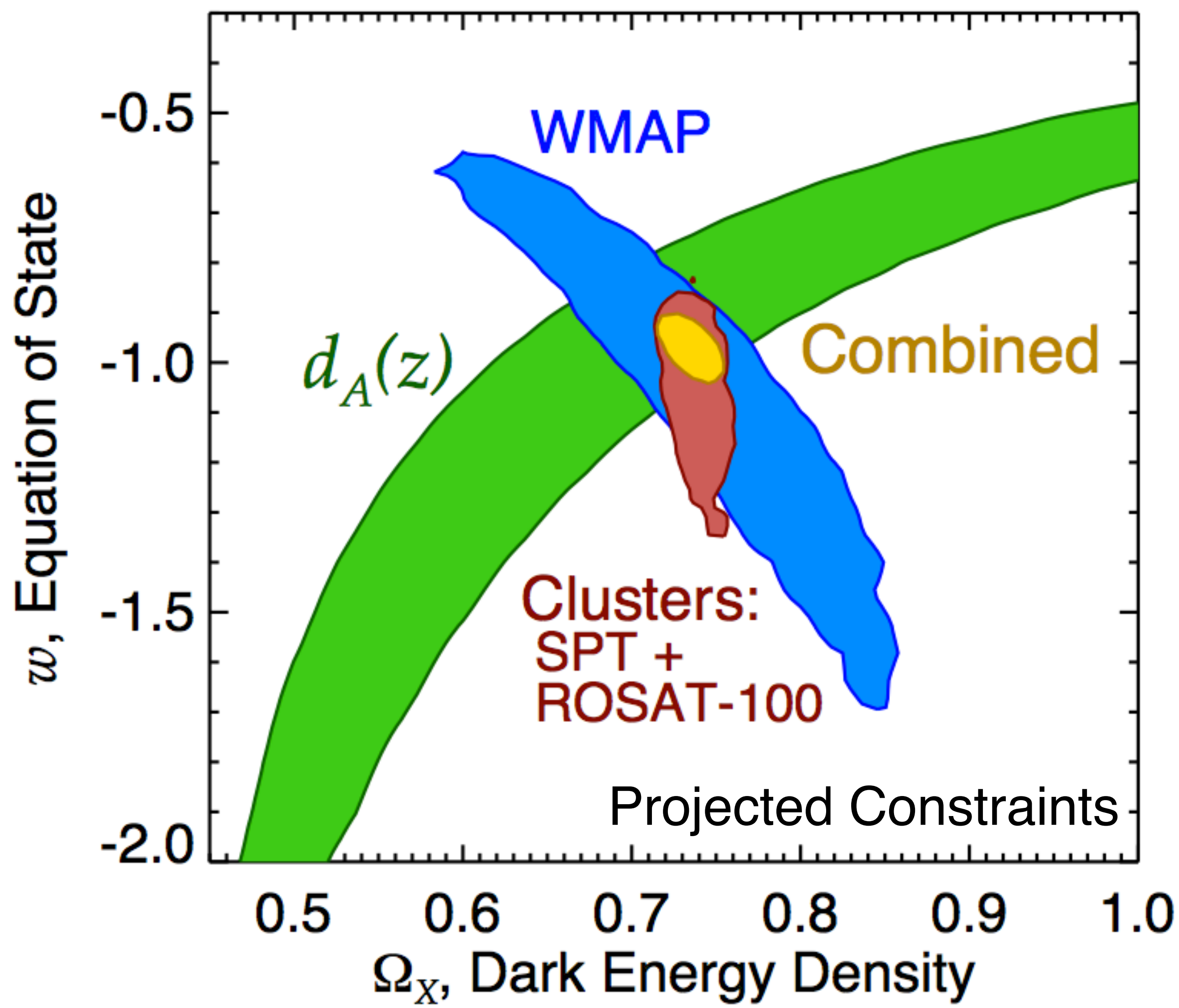
HST Weak Lensing Sample (PI: High)



- **Magellan** - 19 clusters ($0.3 < z < 0.6$)
- **Hubble** - 14 clusters ($0.6 < z < 1.4$)
- **Primary Goal**
  1. **Mass Calibration** of the SPT survey (~5% mean, ~10% redshift evolution)

Test weak lensing analysis on 220 deg^2 mock catalogs from Dark Energy Survey (DES) (see High et al. 2012, 1205.3103)

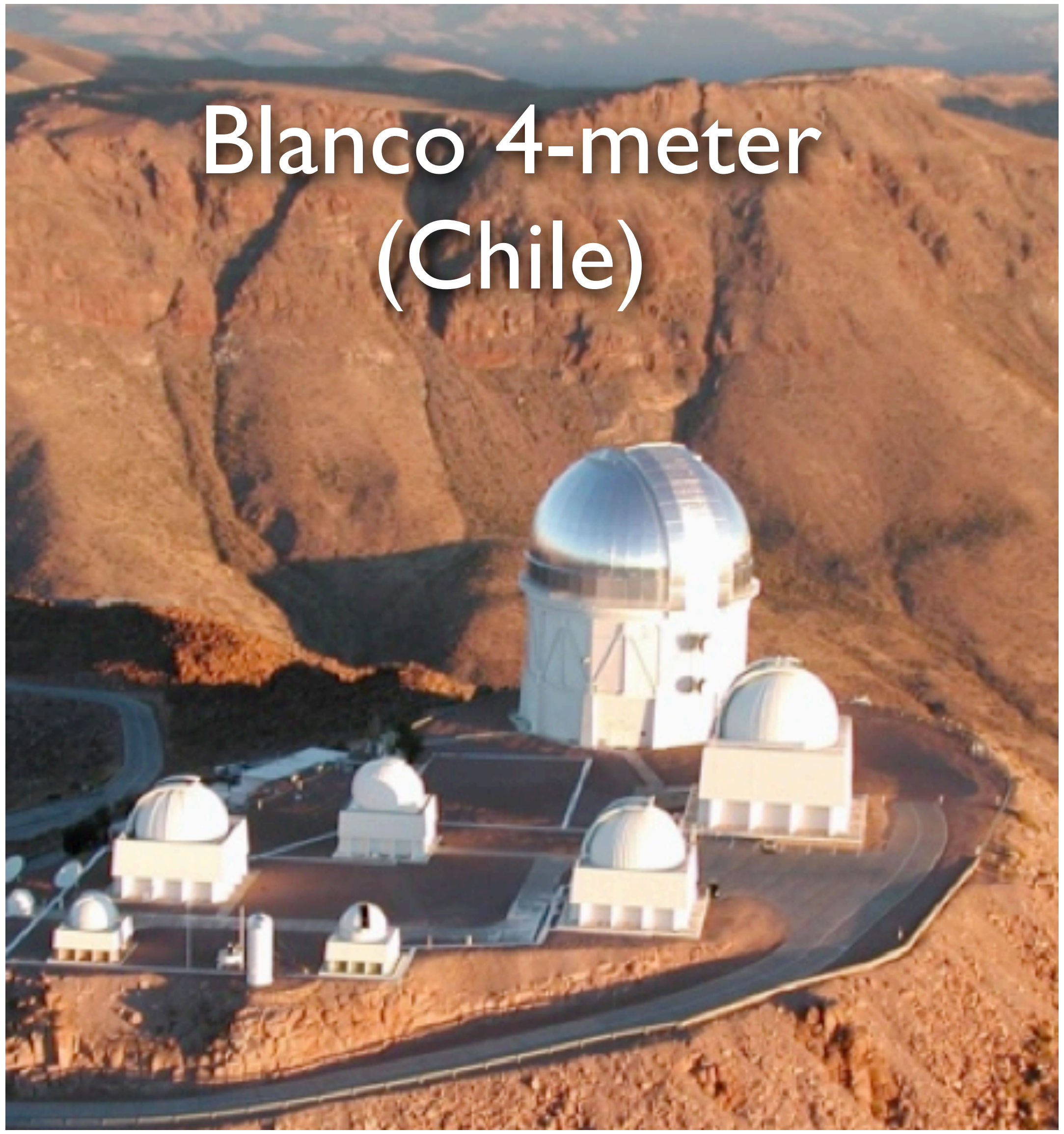
SPT Cosmological Constraints:
2500 deg^2 (projected)



SPT 2500 deg^2 survey will detect ~500 clusters, assuming mass calibration expected with X-ray and Lensing programs then:

- **Combined CMB + SPT cluster survey will constrain δw ~ 5%, **independent* of geometric cosmological constraints from SNe, BAO***

Dark Energy Survey (DES) and SPT

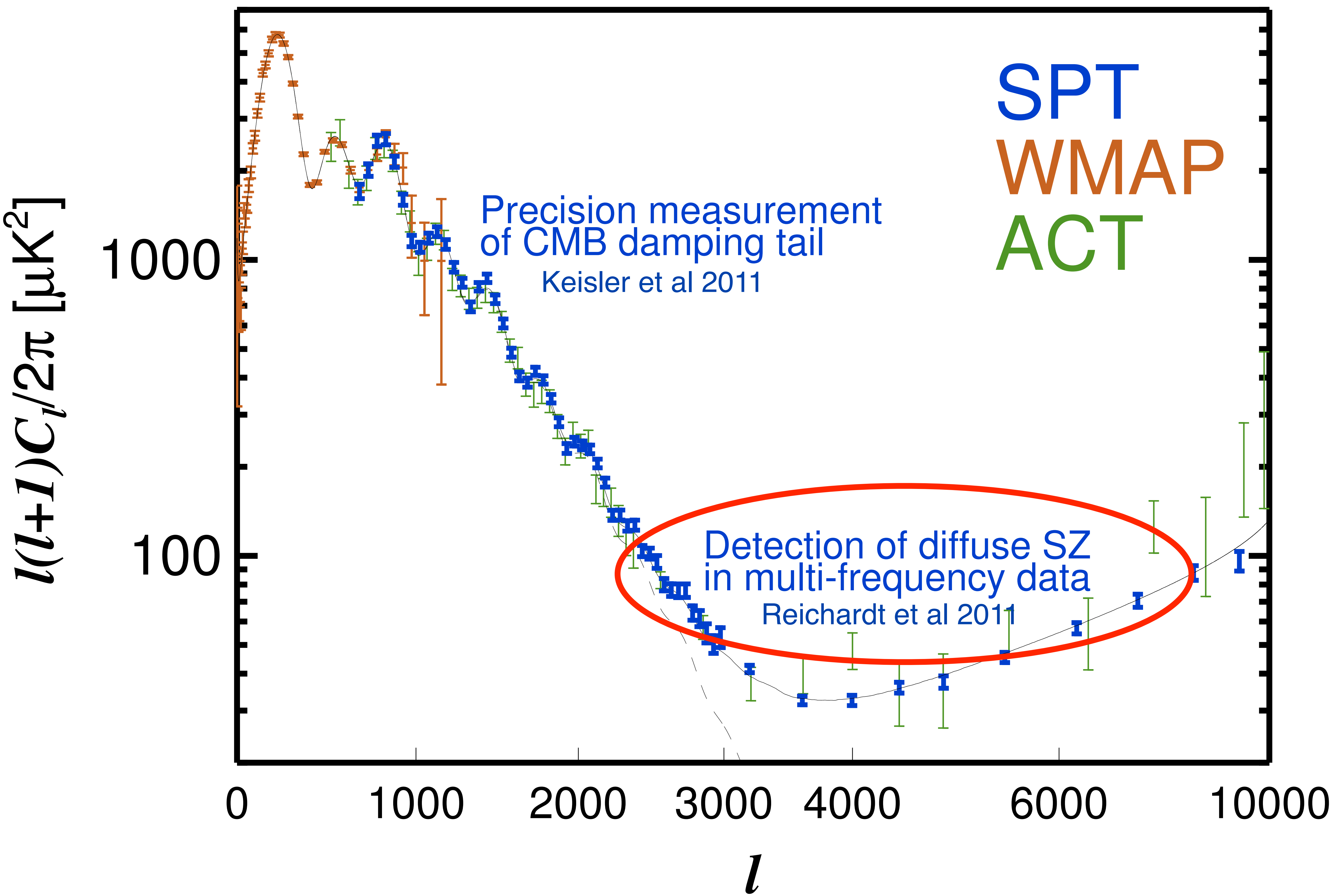


- Wide field (2.2 deg^2) optical camera for 4-meter Blanco telescope (Chile)
- **5-year optical survey (2012-2016) to cover ~5000 deg^2 which will detect ~100,000 clusters out to *z*~1**
- Multiple probes of dark energy (cluster survey, weak lensing, BAO, SN)
  - Coordinated to overlap with SPT
  - **Combined DES + SPT cluster survey will improve DES dark energy figure-of-merit by ~3** (Wu, Rozo, Wechsler 2009)

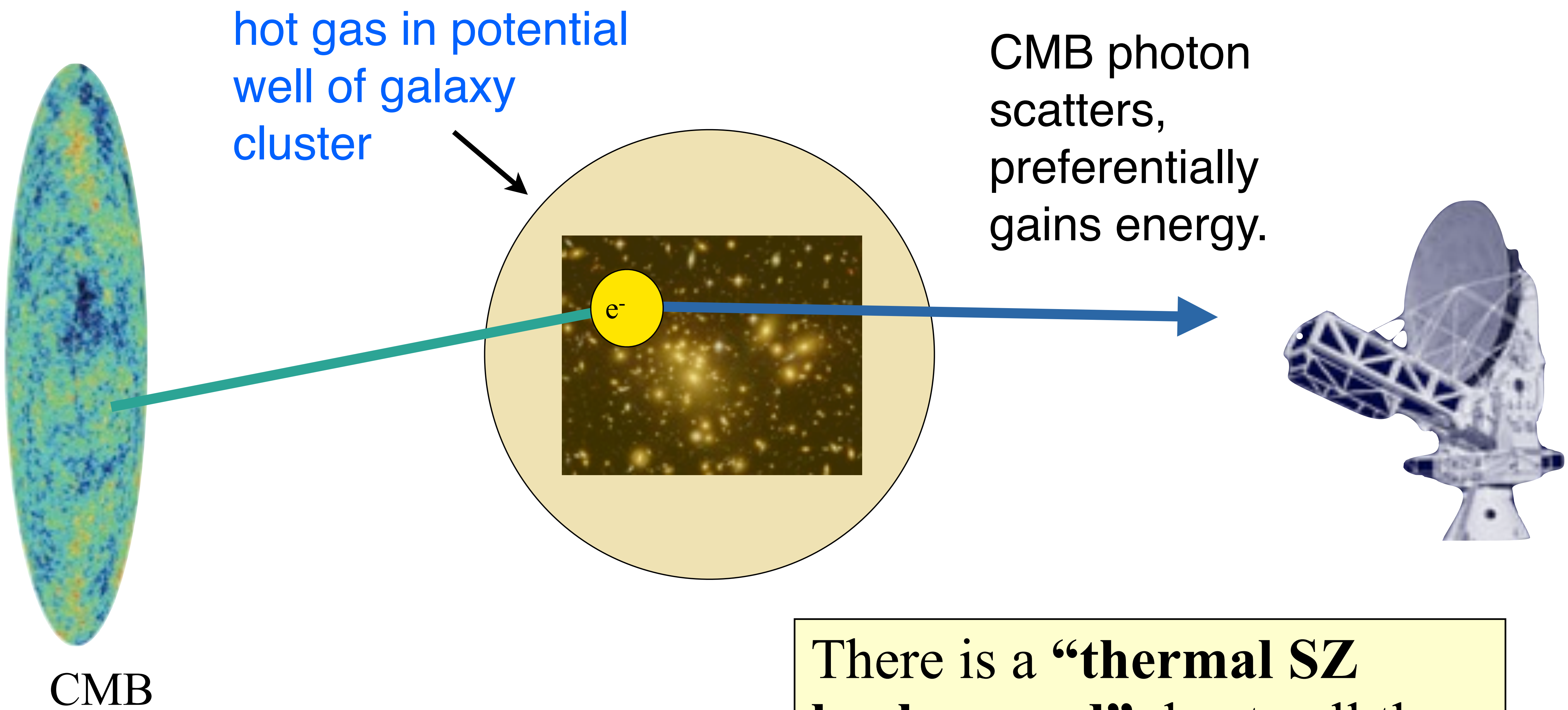
Cosmology from the CMB

1. SZ Cluster Survey
2. **SZ Anisotropy**
3. Future SZ Science

SPT: CMB Power Spectrum

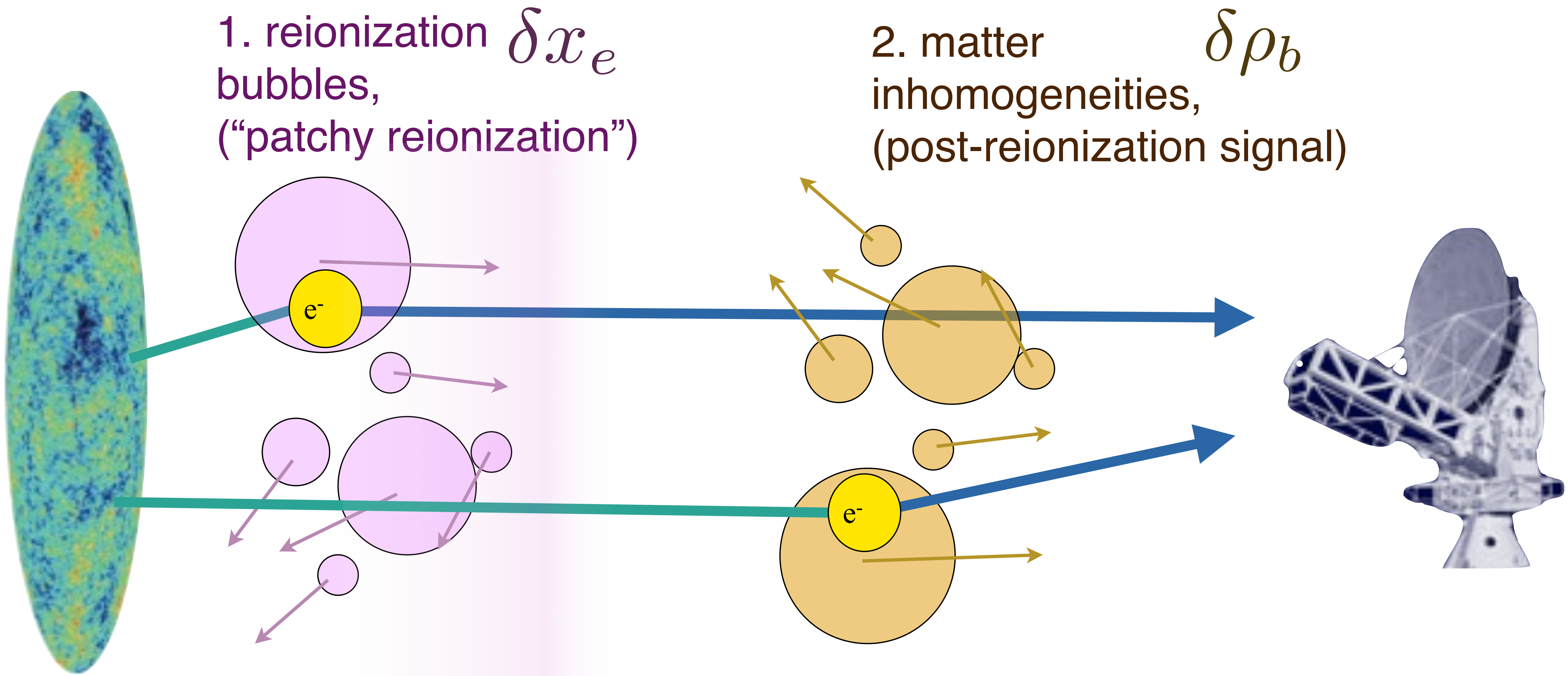


thermal Sunyaev-Zel'dovich (tSZ) effect



There is a **"thermal SZ background"** due to all the hot gas in groups and clusters along the lines of sight: **SZ Power ~ $(\sigma_8)^{8.3}$**

kinetic Sunyaev-Zel'dovich (kSZ) effect



CMB

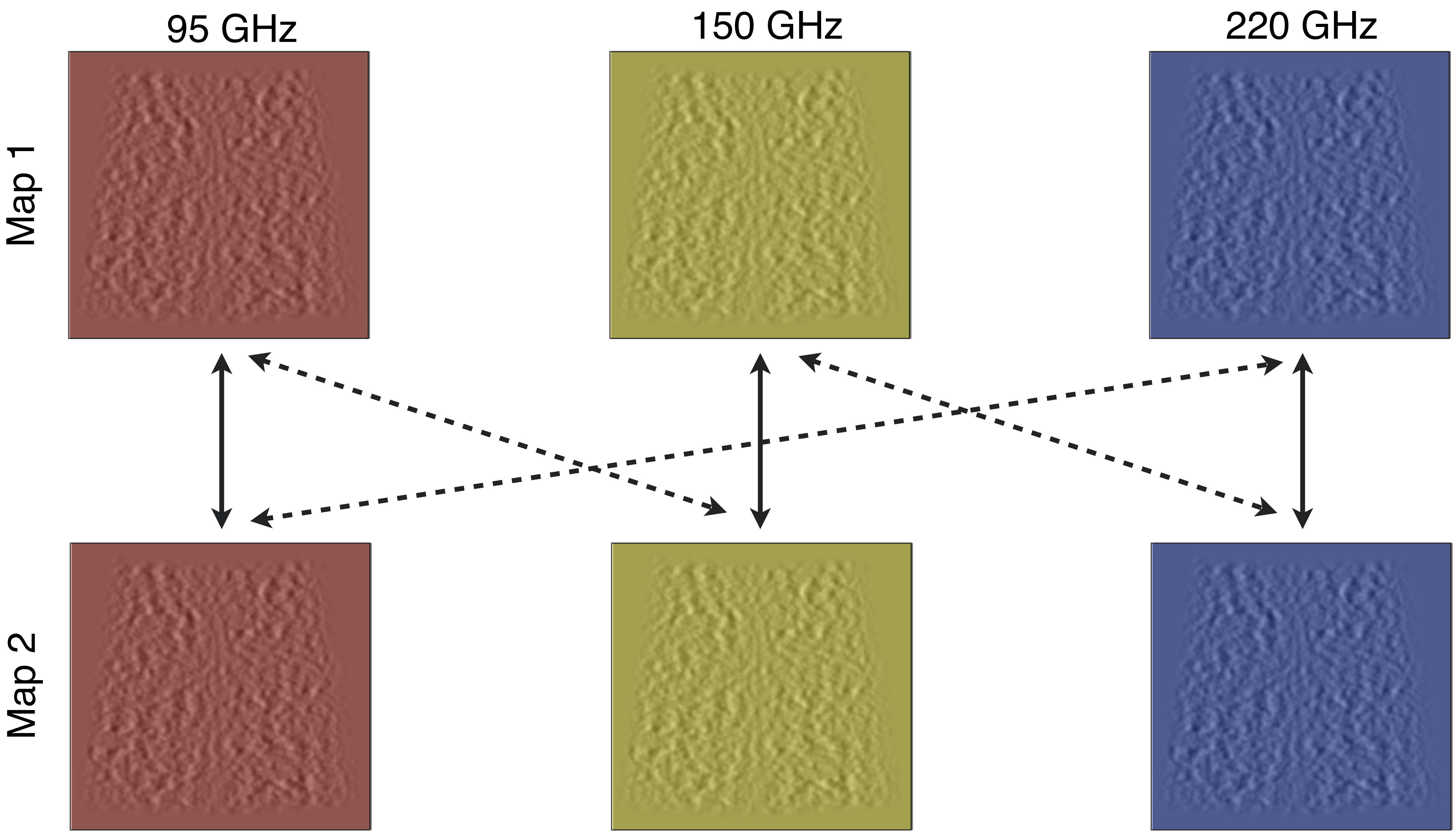
CMB photon scatters on free electrons moving with respect to the CMB.

"Doppler" signal.

There is a **"kinetic SZ background"** due to both of these effects, **sensitive to duration of reionization**.

SPT 3-band Power Spectrum Analysis

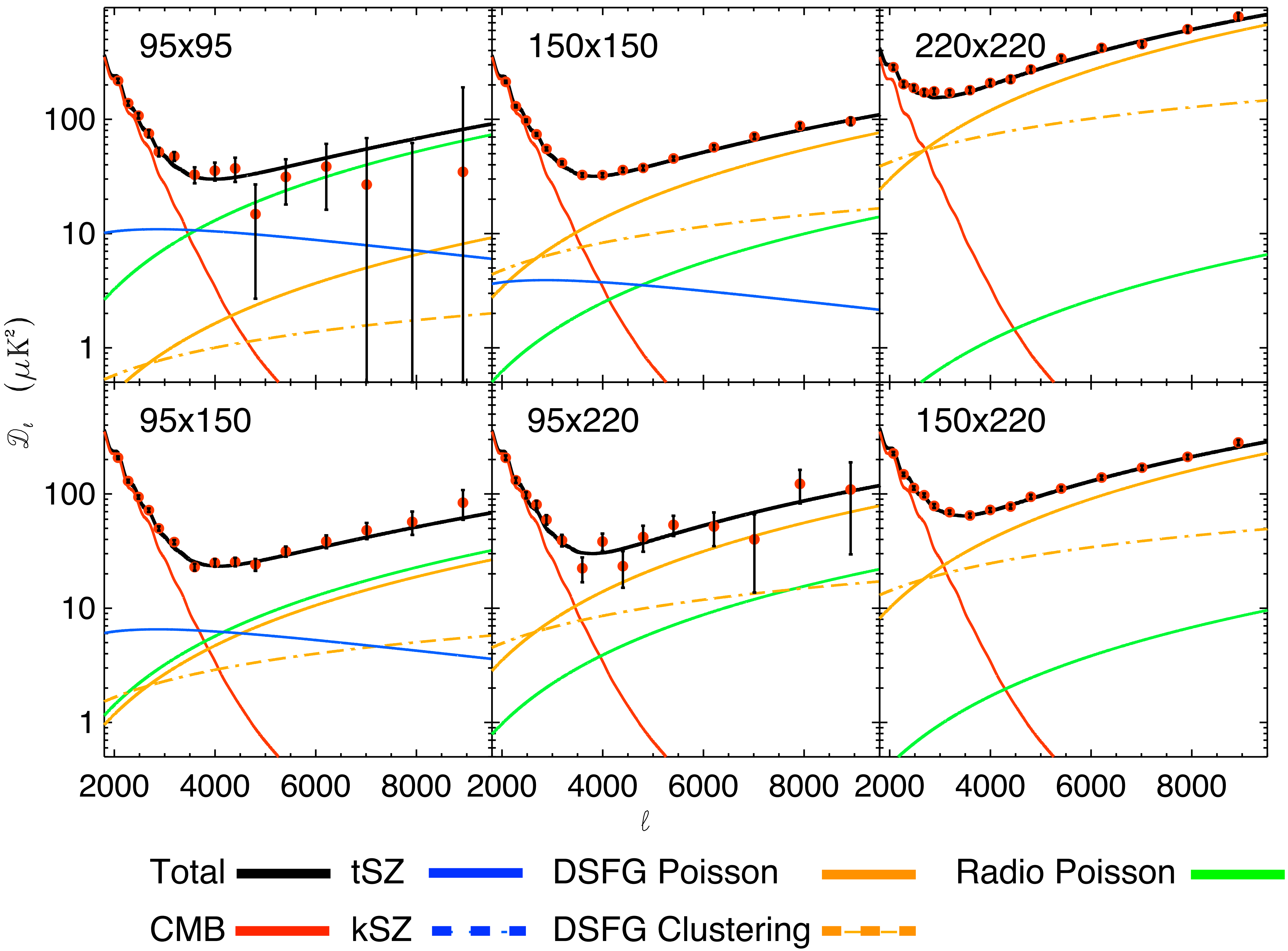
Reichardt et al. 2011, astro-ph/1111.0932



6 unique spectra

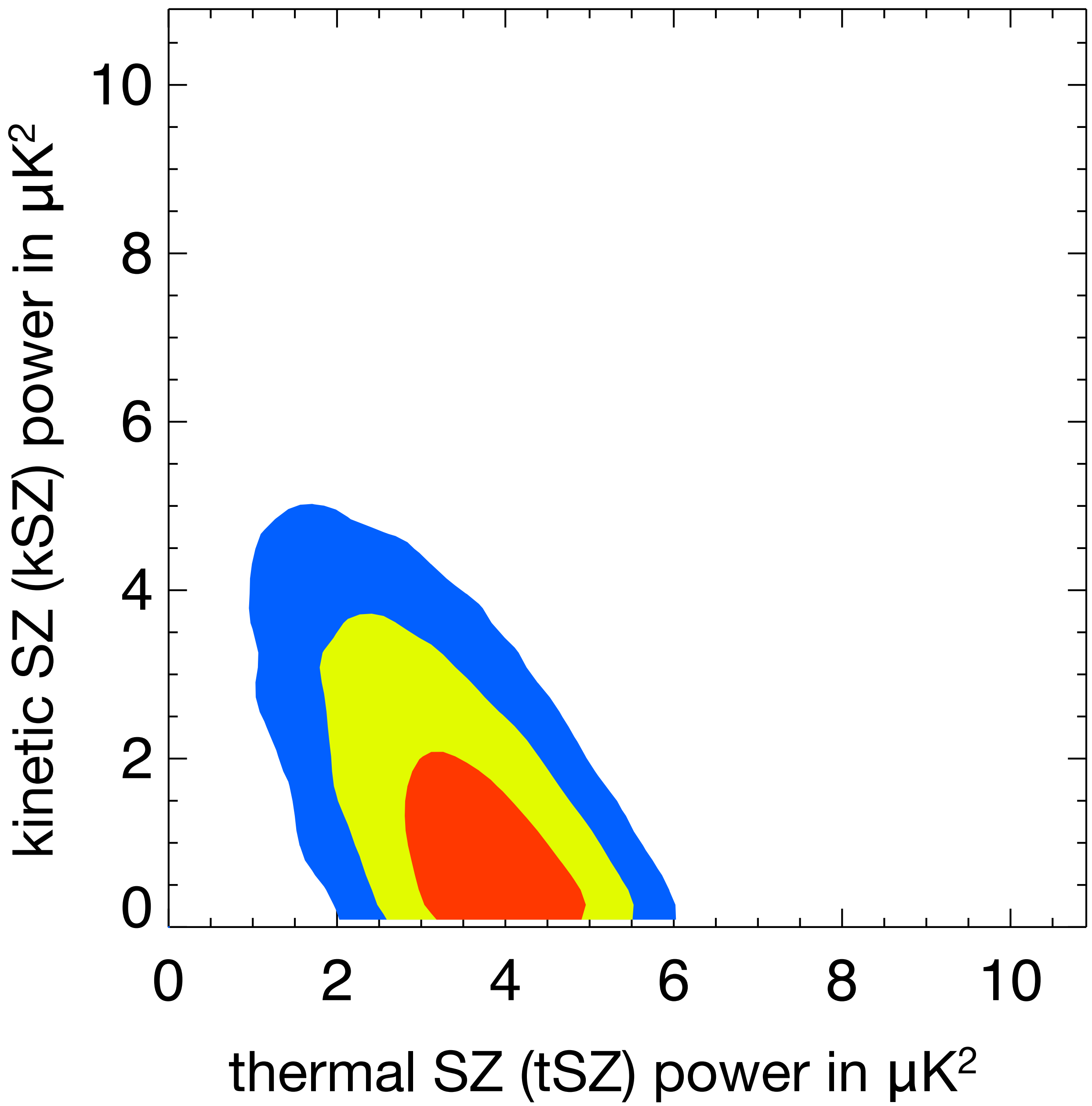
SPT Power Spectrum: Model Fitting

Reichardt et al. 2011, astro-ph/1111.0932



SZ Power Spectrum Constraints

kSZ vs tSZ Constraints



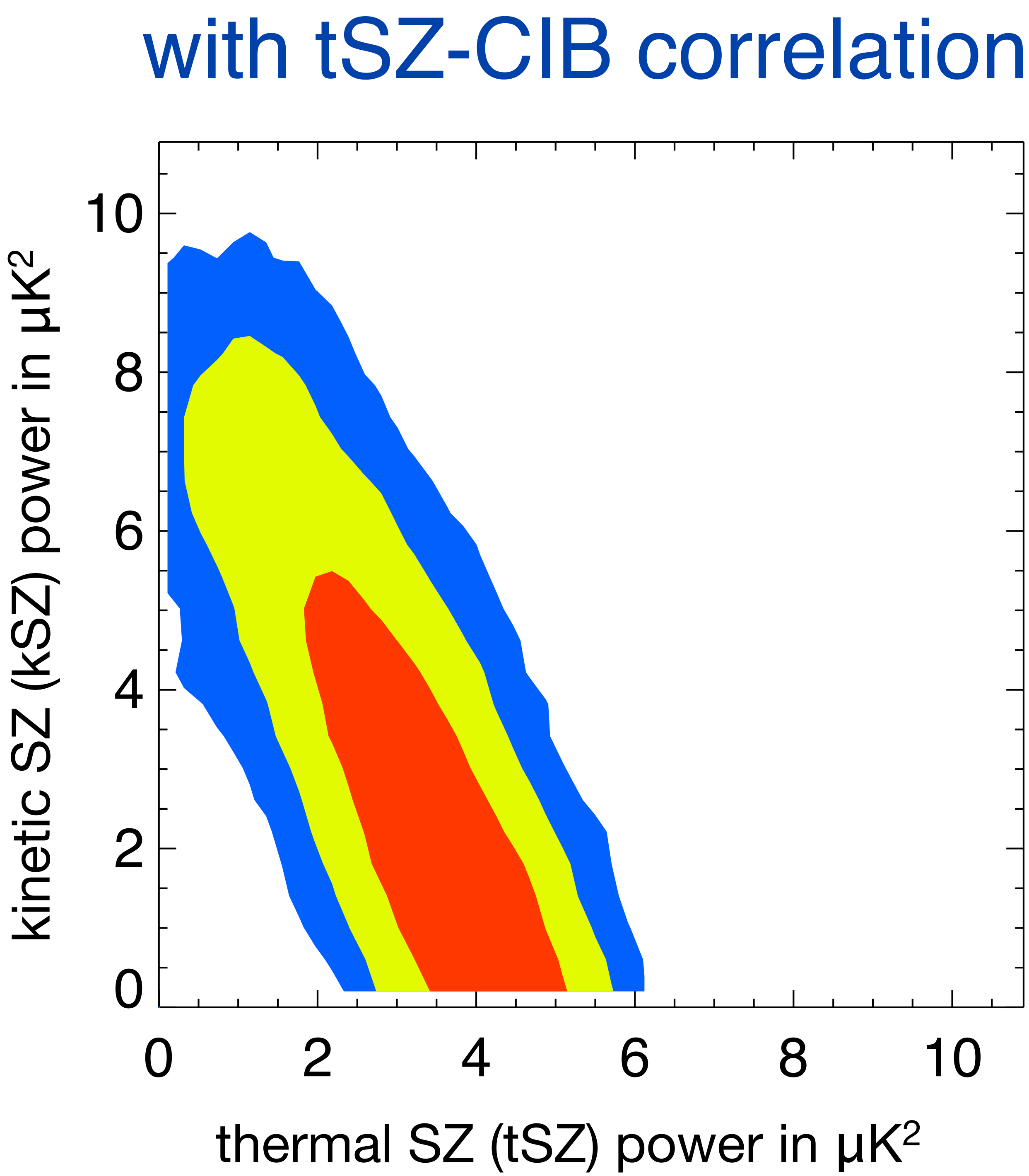
- SPT SZ power spectrum constraints:

  tSZ = 3.65 +/- 0.69 μK²
  kSZ < 2.8 μK² (at 95% CL)

- tSZ power ~2x low relative to predictions (Sehgal et al 2010)
- Several possible explanations: e.g., astrophysical feedback (AGN, etc.), non-thermal pressure support, (see, e.g, Shaw et al. 2010)
- kSZ power is also low (expect ~2 μK² from post-reionization kSZ)

Reichardt et al 2011, arXiv: 1111.0932

SZ Power Spectrum Constraints



- Including a free parameter for a tSZ-CIB correlation weakens constraints:

  tSZ = 3.26 +/- 1.06 μK^2
  kSZ < 6.7 μK^2 (at 95% CL)
  tSZ-CIB correlation = -0.18 +/- 0.11

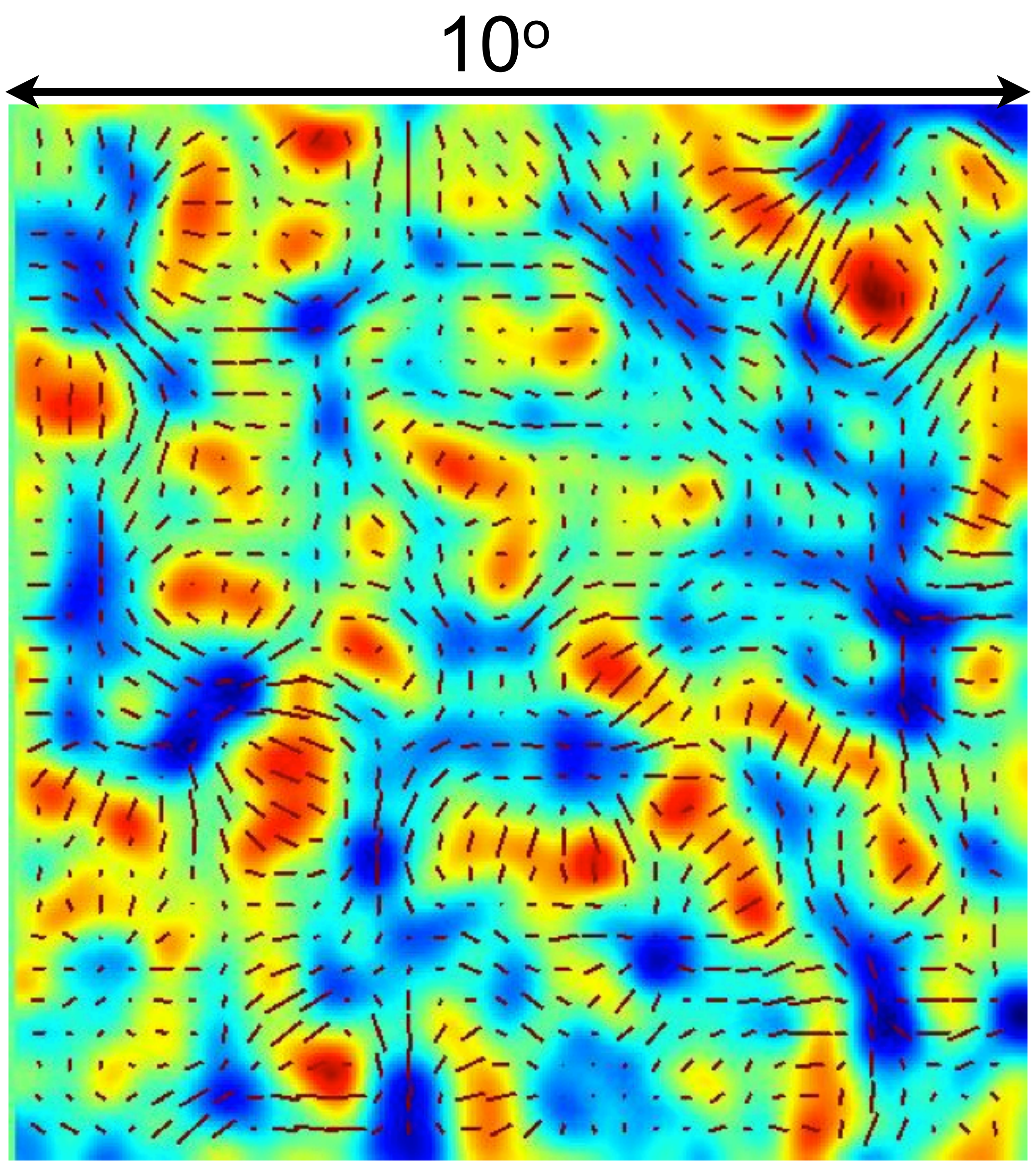
- kSZ still provides useful constraint on duration of reionization (Zahn et al. 2011): $\Delta z < 8$ at 95% confidence
- CIB measurements needed to break tSZ-CIB degenercy (SPT 100 deg² Herschel survey finished last month to do this)

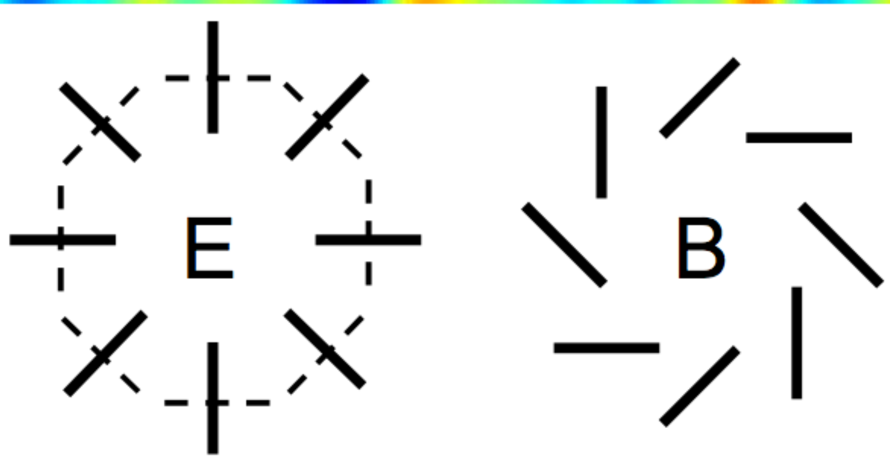
Reichardt et al 2011, arXiv: 1111.0932

Cosmology from the CMB

1. SZ Cluster Survey
2. SZ Anisotropy
3. **Future of SZ Science**

The Next Frontier:
The Polarization of the CMB



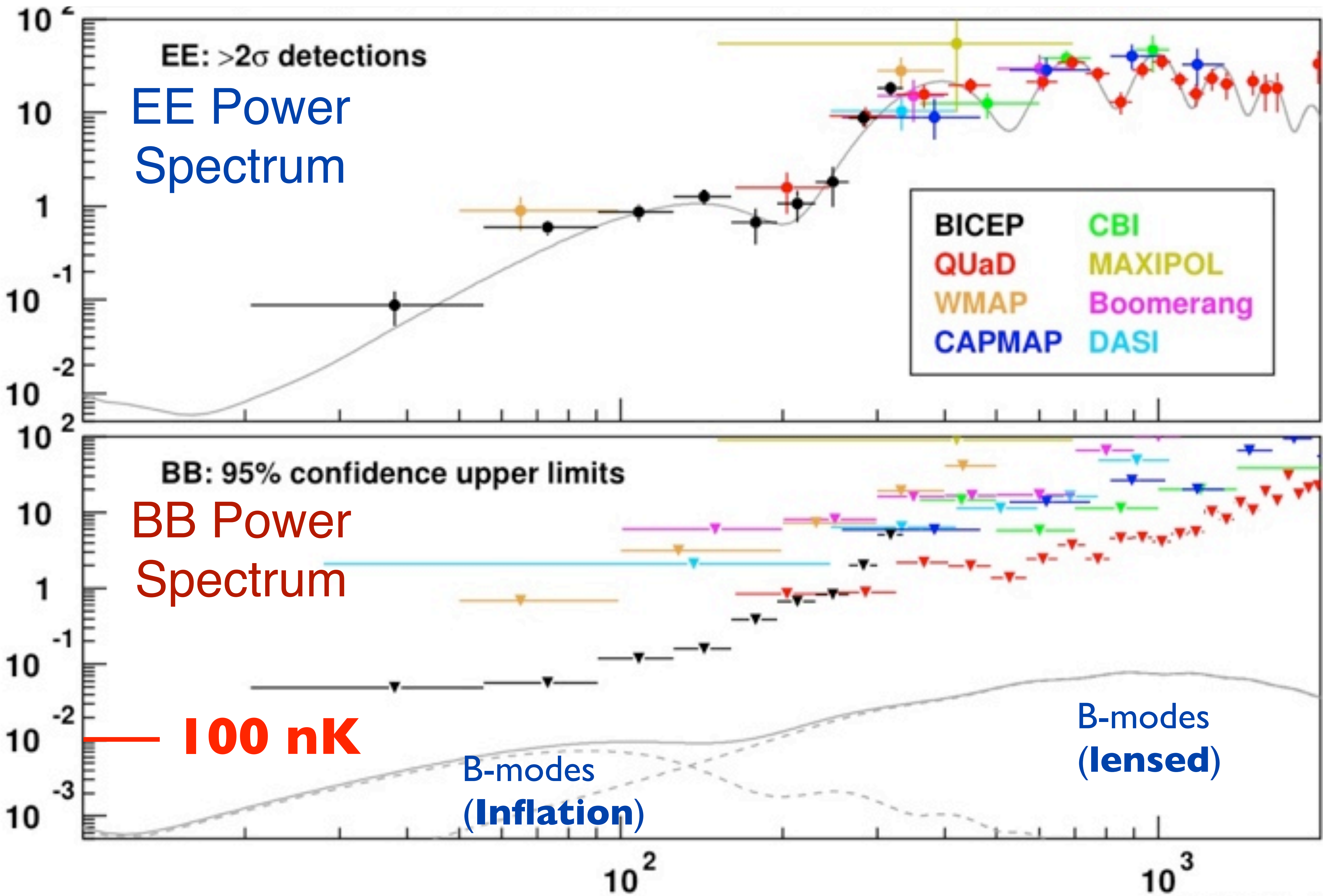


Smith et al 2008

- Quadrupole anisotropy introduces a polarization from Thomson scattering near surface of last scattering
- Polarization pattern can be decomposed into "E" and "B" modes, that have only grad and curl components
- Density fluctuations produce only "E" modes, no handedness

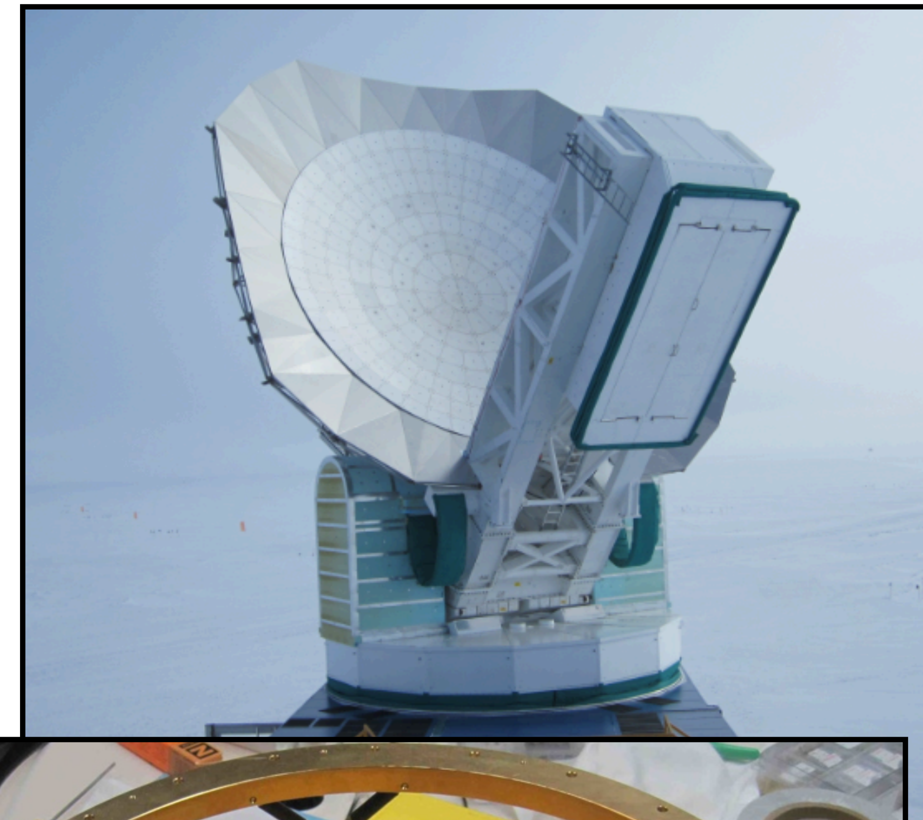
- "B" modes can be created by:
  – primordial gravity waves from Inflation
  – lensing of the CMB from large scale structure

CMB Measurements so far:
Closing in on Inflation!



see (QUAD) Brown et al., arXiv:0906.1003 & (BICEP) Chiang et al., arXiv:0906.1181

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
   - “de-lens” large angular scales
3. Energy scale of inflation

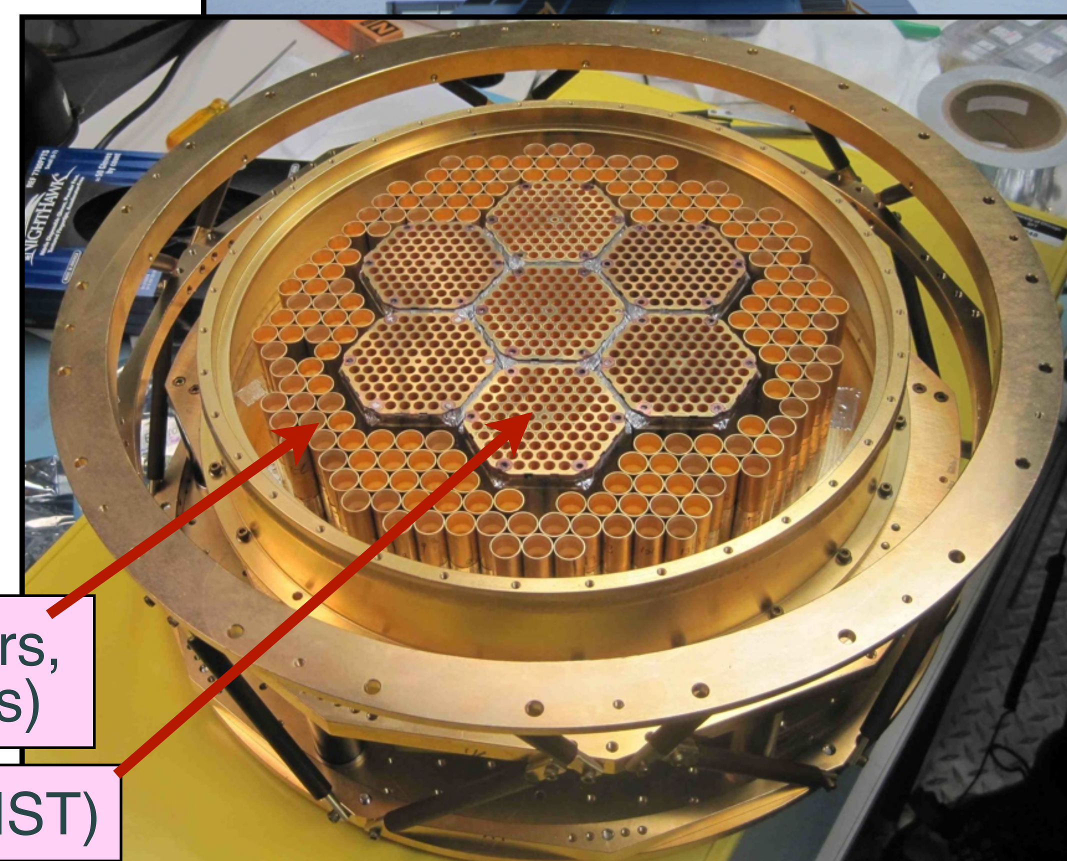
Temperature Survey:

4. Deeper cluster survey

Status:

- First light Jan. 26, 2012.

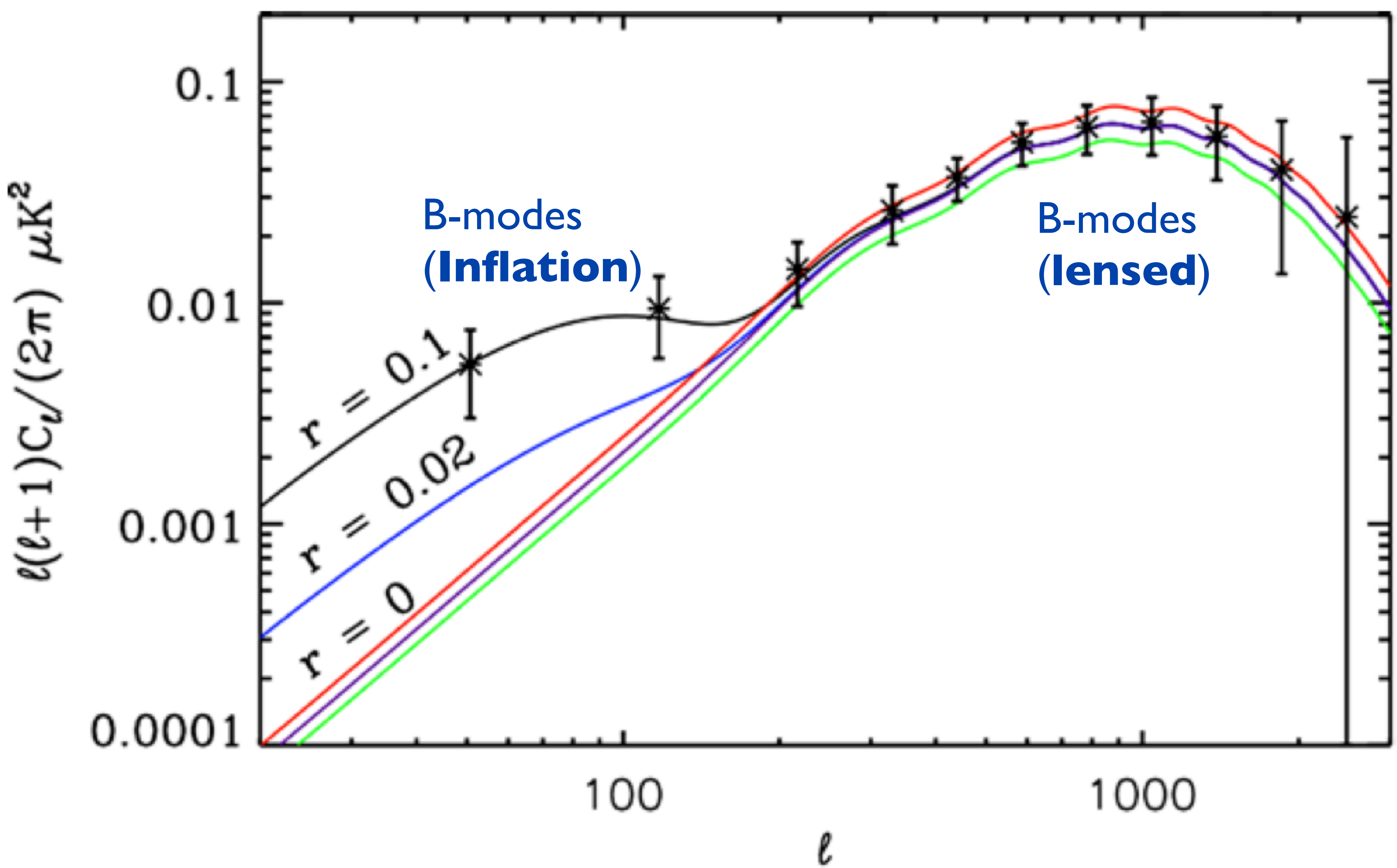
- Started a 4-year, 625 deg^2 survey



SPTpol: Projected B-mode Power Spectrum

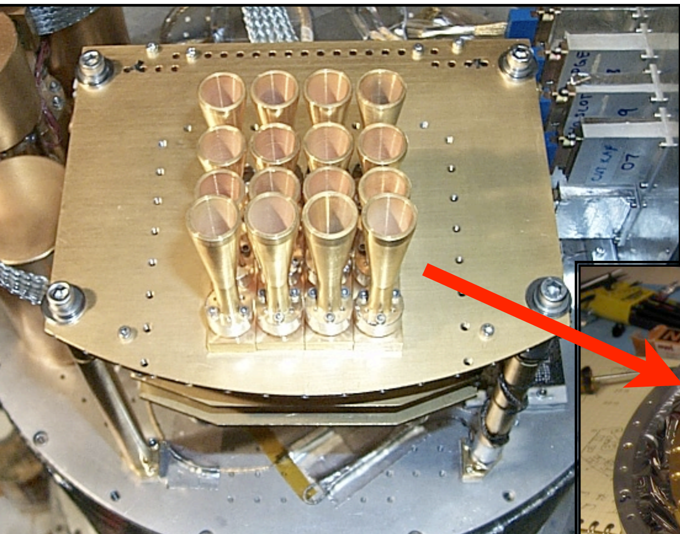
SPTpol will make a high signal-to-noise detection of the lensing B-modes

With Planck priors; the 4-year 625 deg² SPTpol survey expects to constrain δr=0.028 and $\delta(\Sigma m_\nu)$=0.09 eV

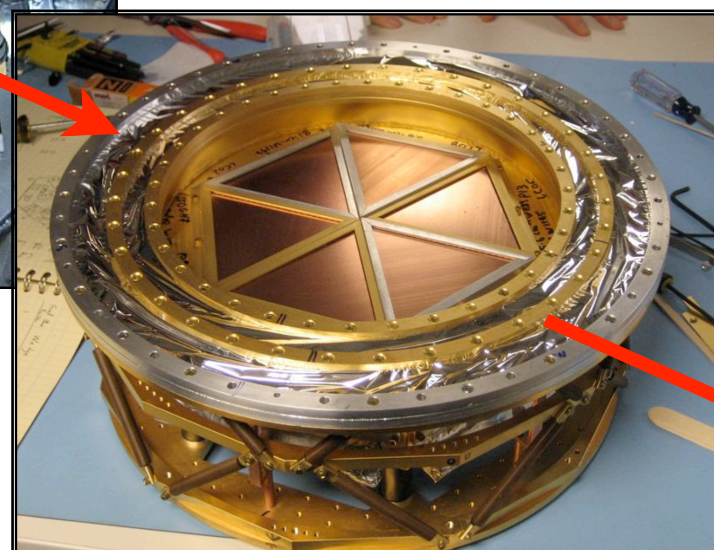


SPT-3G: The Next Generation Camera for the SPT

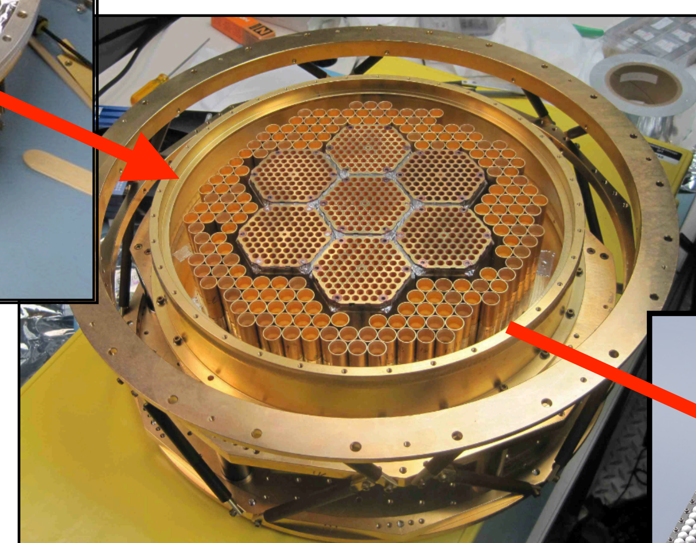
2001: ACBAR
16 detectors



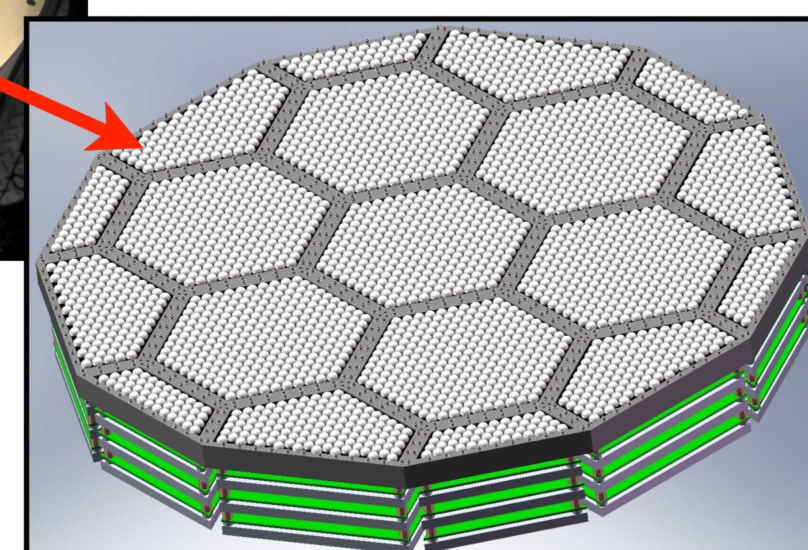
2007: SPT
960 detectors



2012: SPTpol
~1600 detectors



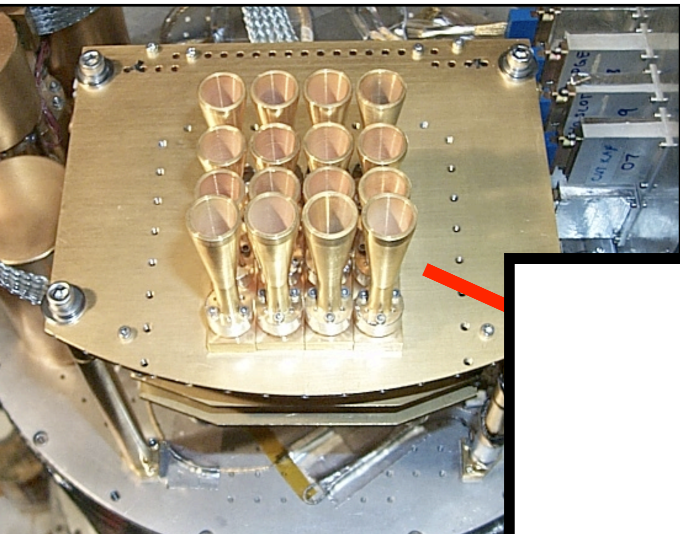
2016: SPT-3G
~15,200 detectors



ACBAR was the first experiment to make a “background limited” detector, since then we’ve just been trying to make more of them

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

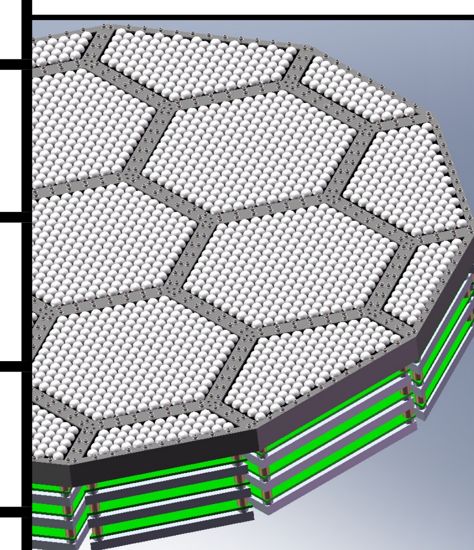
2001: ACBAR
16 detectors



2007: SPT
960 detectors

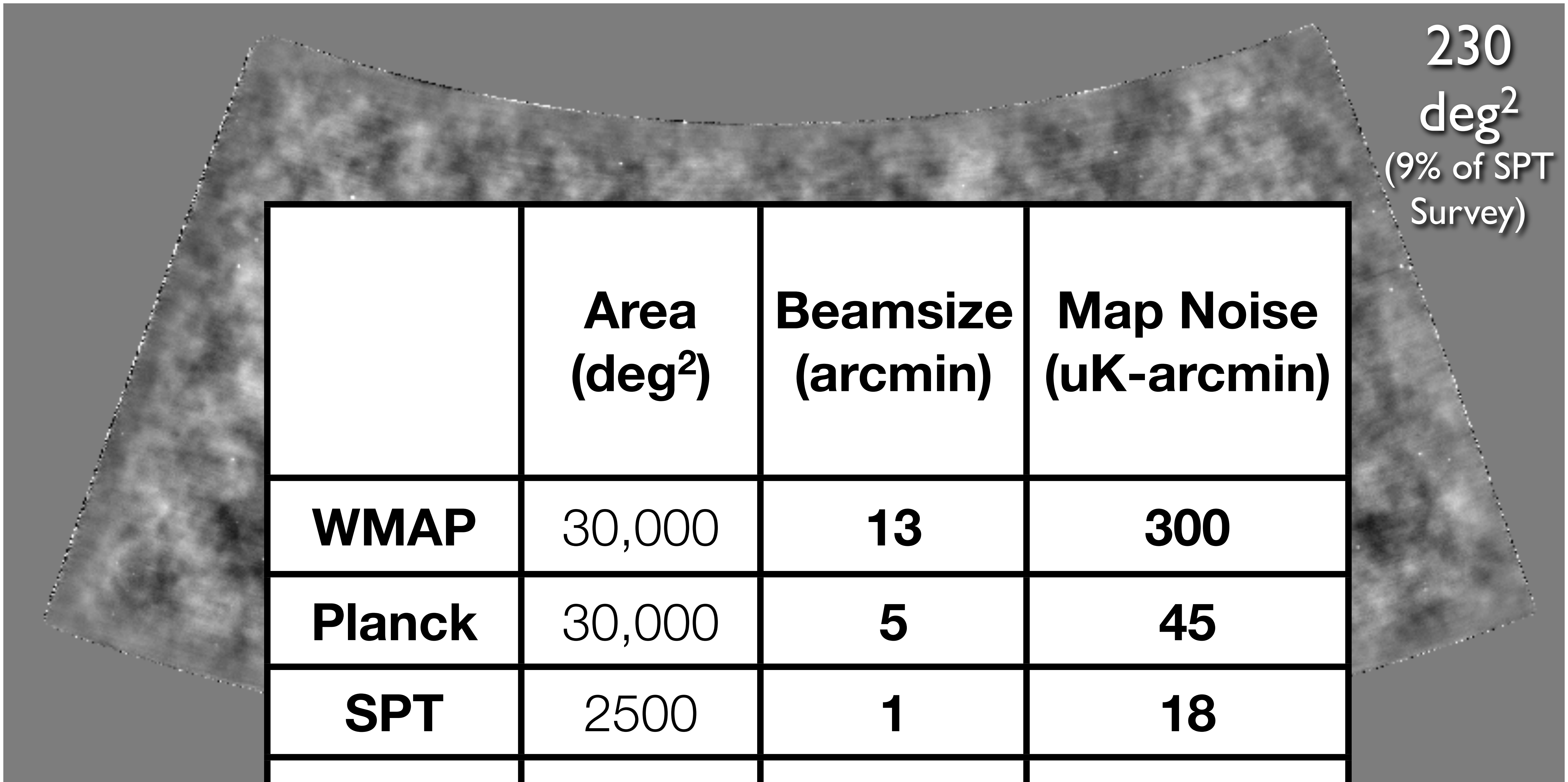
	NET (noise equivalent temperature) (uK CMB $s^{0.5}$)	**SZ Mapping Speed**
ACBAR	90	**1**
ACT	30	**9**
SPT	18	**25**
SPTpol	~14	**40**
SPT-3G	~3.5	**850**

: SPT-3G
) detectors



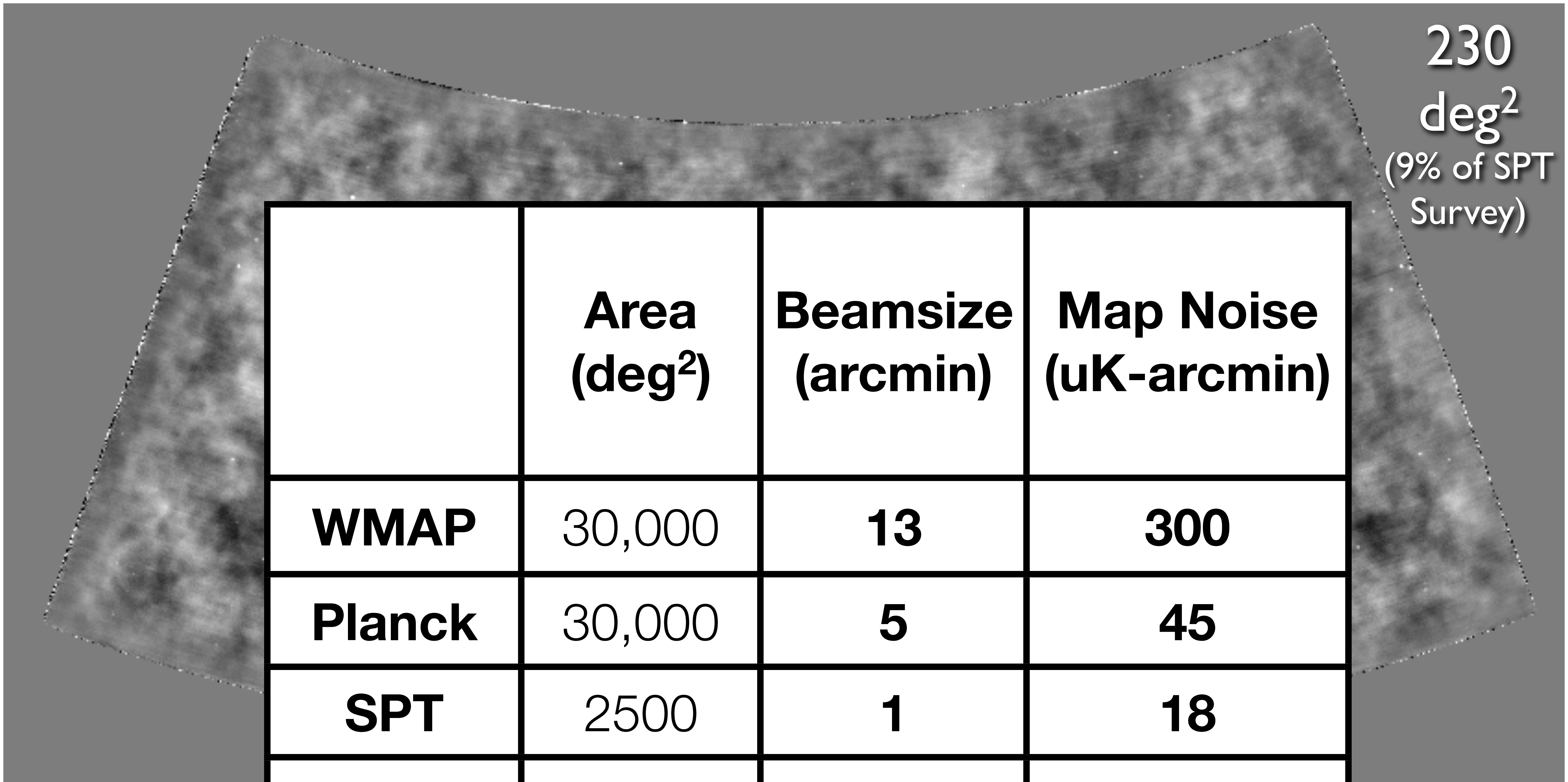
ACBAR w
make a “b
since then
make mor

SPT



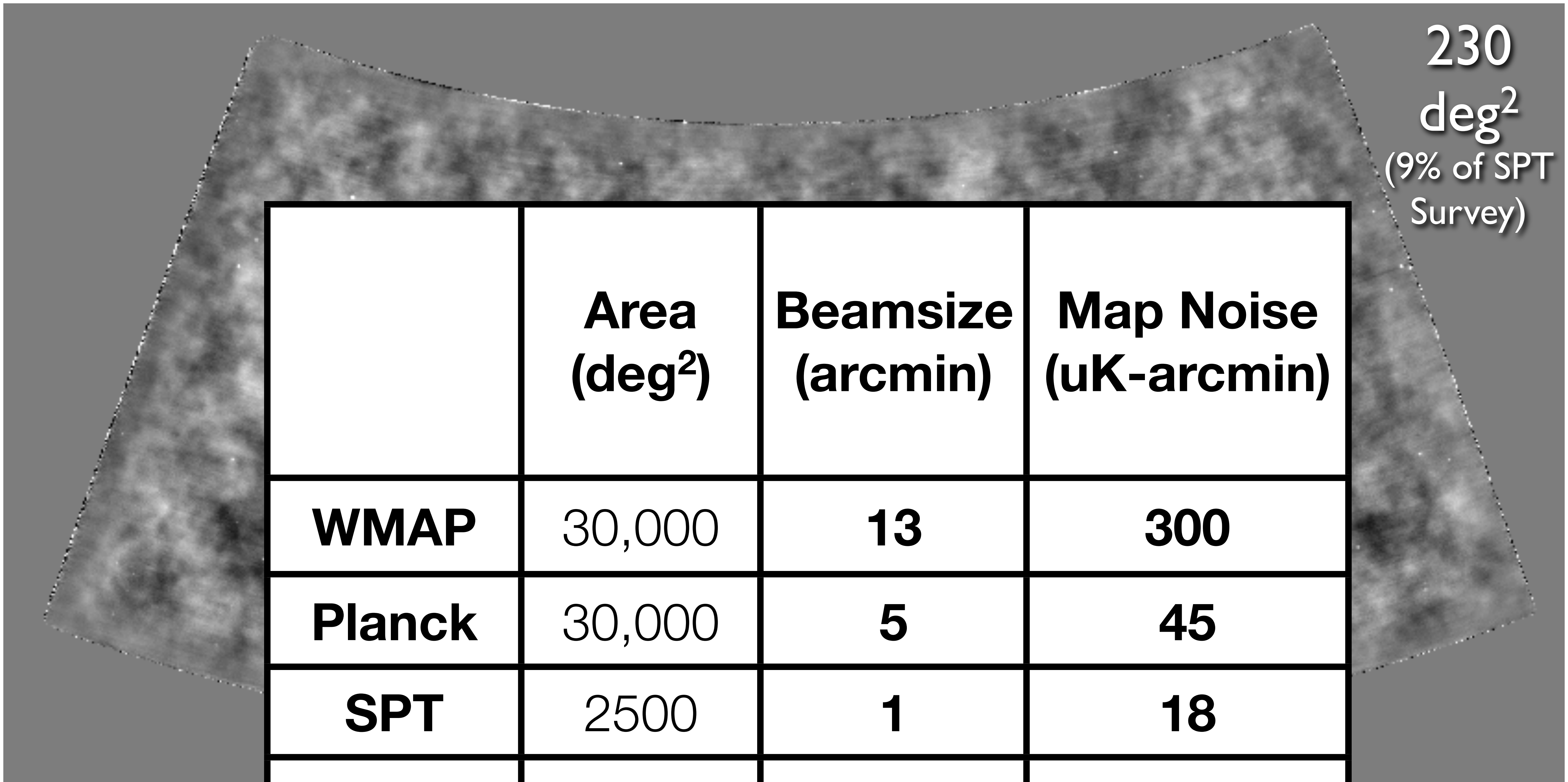
	Area (deg^2)	Beamsize (arcmin)	Map Noise (uK-arcmin)
WMAP	30,000	**13**	**300**
Planck	30,000	**5**	**45**
SPT	2500	**1**	**18**

SPT



	Area (deg^2)	Beamsize (arcmin)	Map Noise (uK-arcmin)
WMAP	30,000	**13**	**300**
Planck	30,000	**5**	**45**
SPT	2500	**1**	**18**
SPTpol	600	**1**	**5**

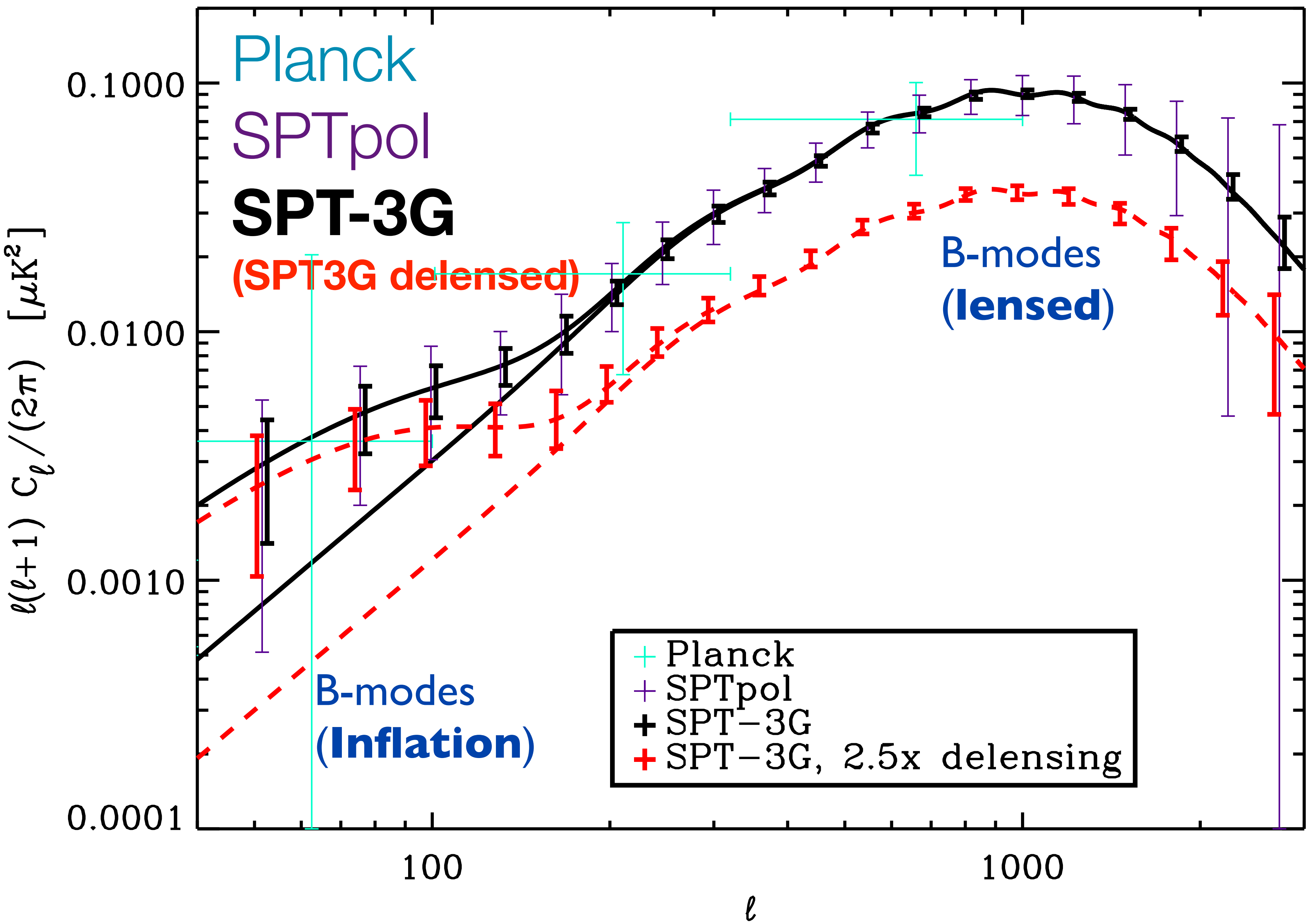
SPT



	Area (deg^2)	Beamsize (arcmin)	Map Noise (uK-arcmin)
WMAP	30,000	**13**	**300**
Planck	30,000	**5**	**45**
SPT	2500	**1**	**18**
SPTpol	600	**1**	**5**
SPT-3G	2500	**1**	**2**

10x deeper than SPT!

SPT-3G:
Projected B-mode Power Spectrum



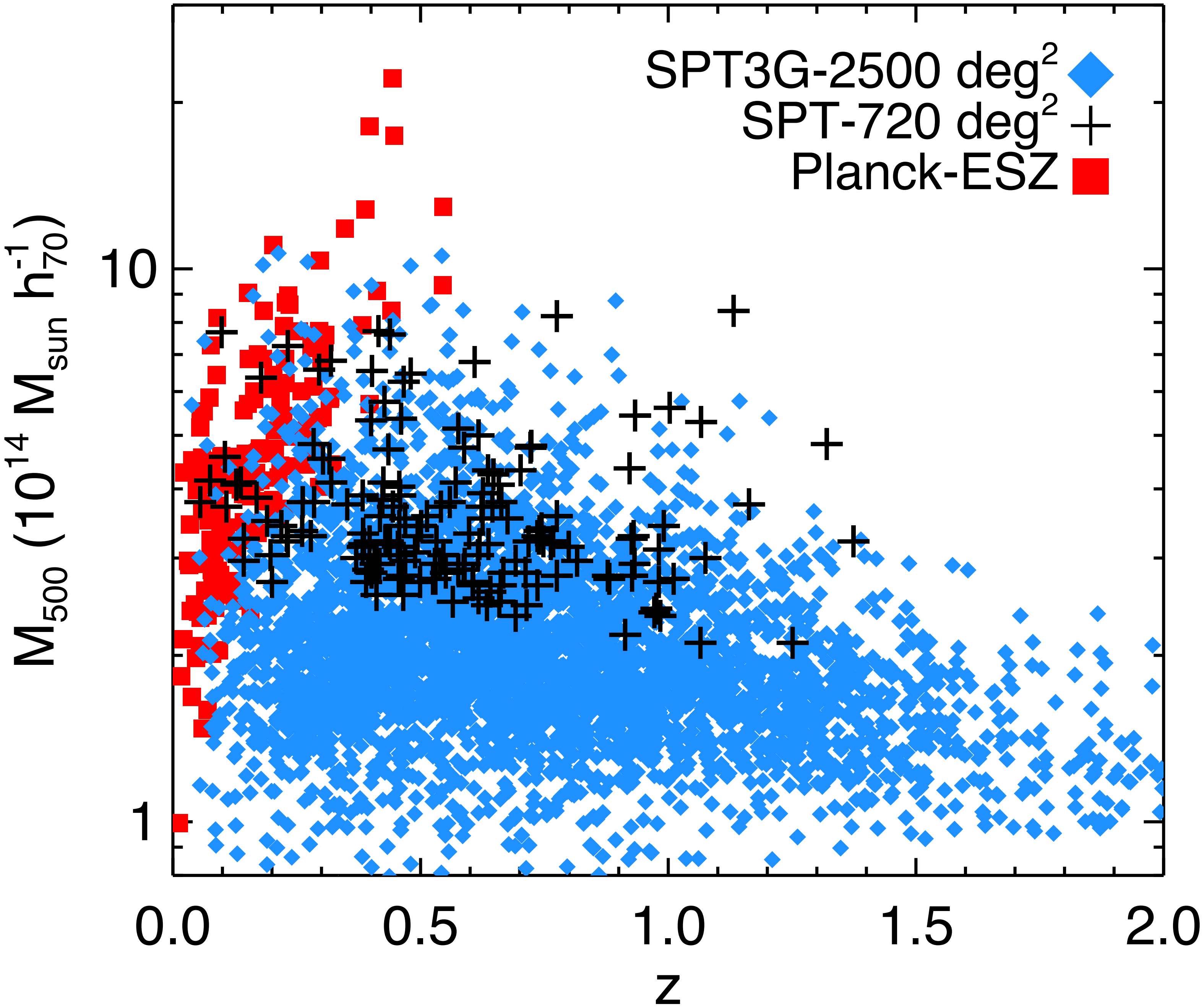
- Planck, in principle, will only make weak B-mode detection

- SPTpol will make pioneering B-mode measurements

- SPT-3G will be deep enough to:
  - improve neutrino mass constraints (over Planck)
  - “de-lens” at large-scales and improve “r” constraint

Credit: T. Crawford

SPT-3G:
Cluster Survey



- -10x increase in number of clusters over SPT
  - 4000 clusters at 99% purity threshold
- -Could improve DES dark energy figure of merit by ~4 by calibrating scatter in richness-mass relation (Wu et al. 2010)
- -CMB-cluster lensing should provide a 3% cluster mass calibration (per 4000 clusters)
  - competitive with mass calibration from stacked weak-lensing (Rozo et al. 2011)

Credit: B. Benson

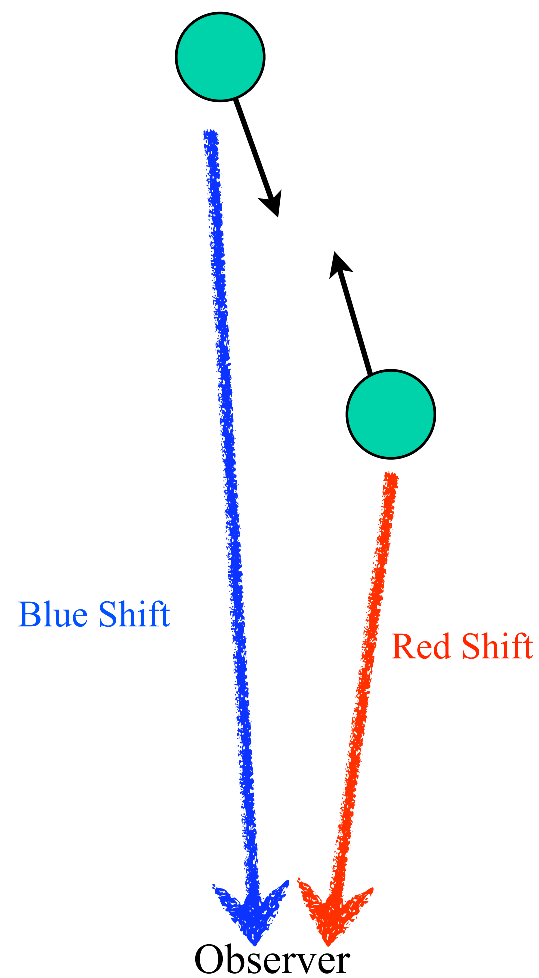
SPT-3G:
Testing Gravity on Large-scales

kSZ Pairwise Velocity Signal

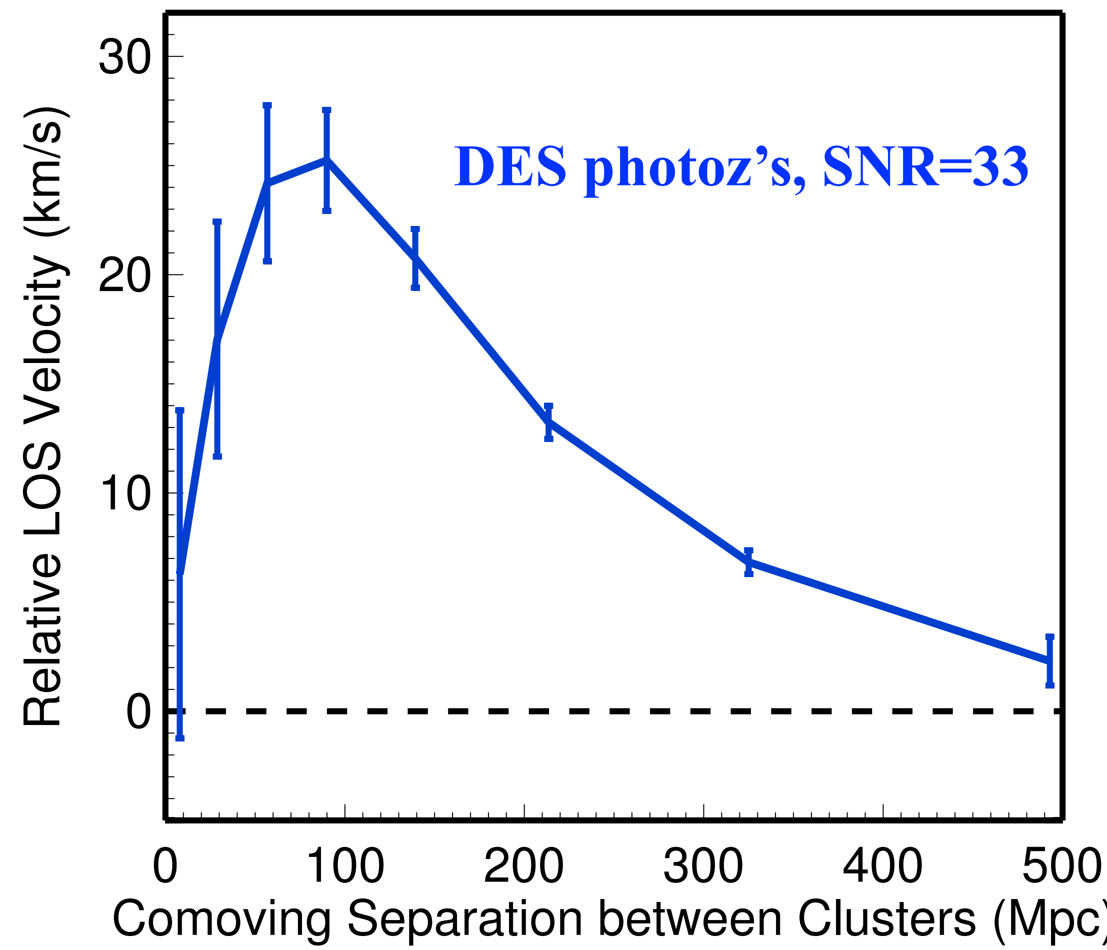
(Hand et al., ACT Collaboration, 1203.4219)

Galaxy clusters tend to fall towards each other (w.r.t. Hubble flow).

For a given pair, the high-z (low-z) cluster tends to move towards (away from) us
=>
differential CMB signal from kSZ effect.



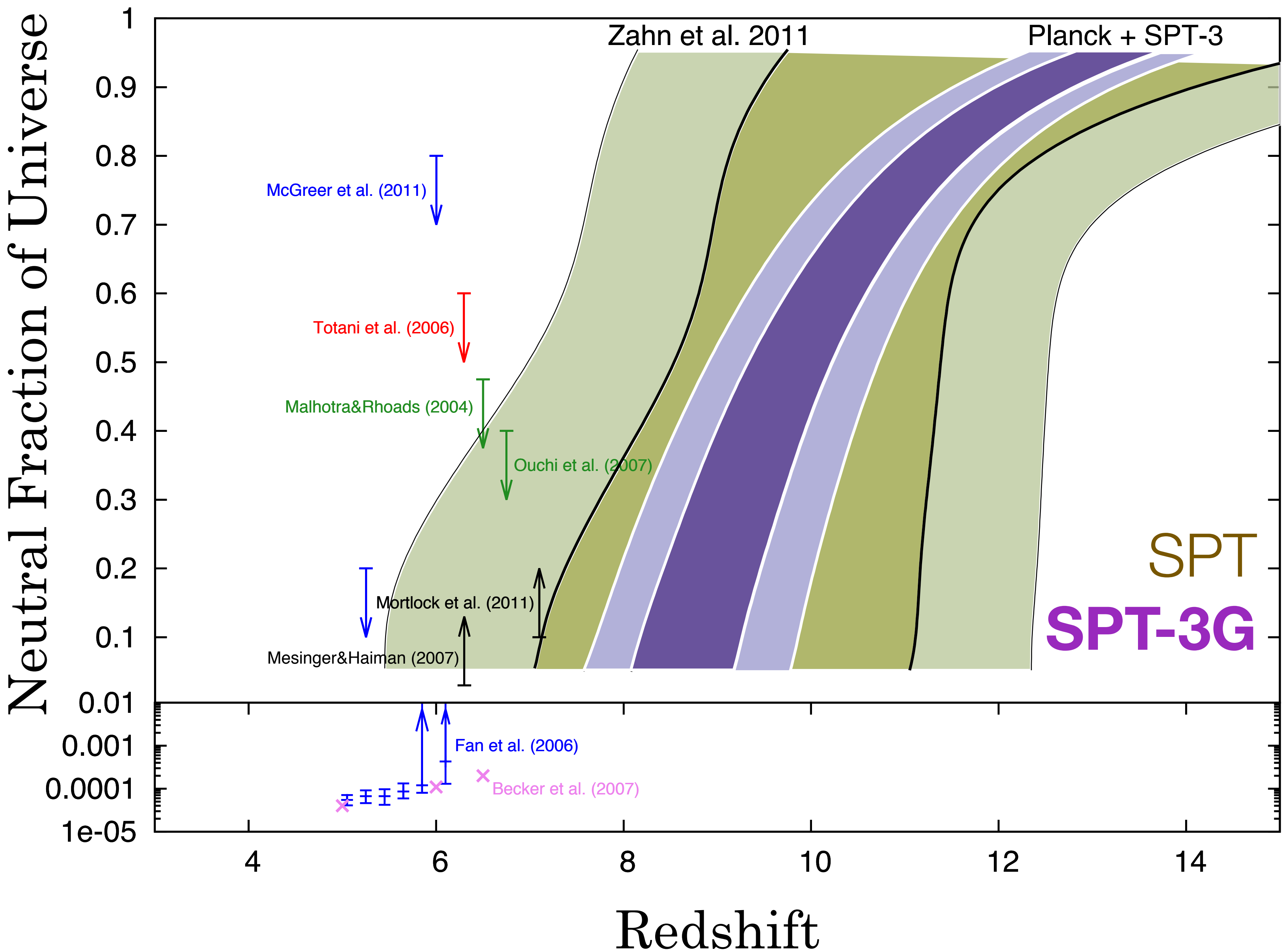
Project a **33-sigma** detection of the pairwise kSZ signal for SPT-3G and a DES-like cluster sample with photoz errors.



This provides a novel probe of gravity on **~50-200 Mpc** scales and competitively constrains modified theories of gravity (f(R)/chameleon and DGP) on very large length scales.

Credit: R. Keisler

SPT-3G:
Measuring the Duration of Reionization



- Reionization induces kSZ signal from contrast in ionized bubble size

- Planck constrains mean redshift (z~10), SPT-3G constrains duration

- Can constrrain duration of epoch of reionization to $\delta z \sim 1$

-Shape of kSZ spectrum can also test reionization models

Credit: C. Reichardt

Summary

- **Exciting data sets coming out of SZ surveys: SPT, ACT, and Planck**
- **SZ surveys are now providing large cluster samples that are useful for studying the astrophysics of massive cluster formation and also providing interesting cosmological constraints**
- **Mass calibration is critical to realizing full power of surveys:**
  - need to incorporate multiwave information (X-ray, WL, dispersions)
  - simulations key to understanding bias and correlations of observables
  - strong synergies with future optical surveys (e.g., DES, LSST), both from clusters and CMB lensing (Gil Holder's talk)
- **SZ anisotropy cosmological constraints are currently limited by combination of uncertain astrophysics in low-mass clusters and correlation with CIB (will be improved soon via Herschel)**
- **Current and future CMB polarization experiments will continue to improve on all of the above, also allowing new measurements of:**
  - CMB-cluster lensing, pairwise velocities, SZ polarization, etc.


Thank You!