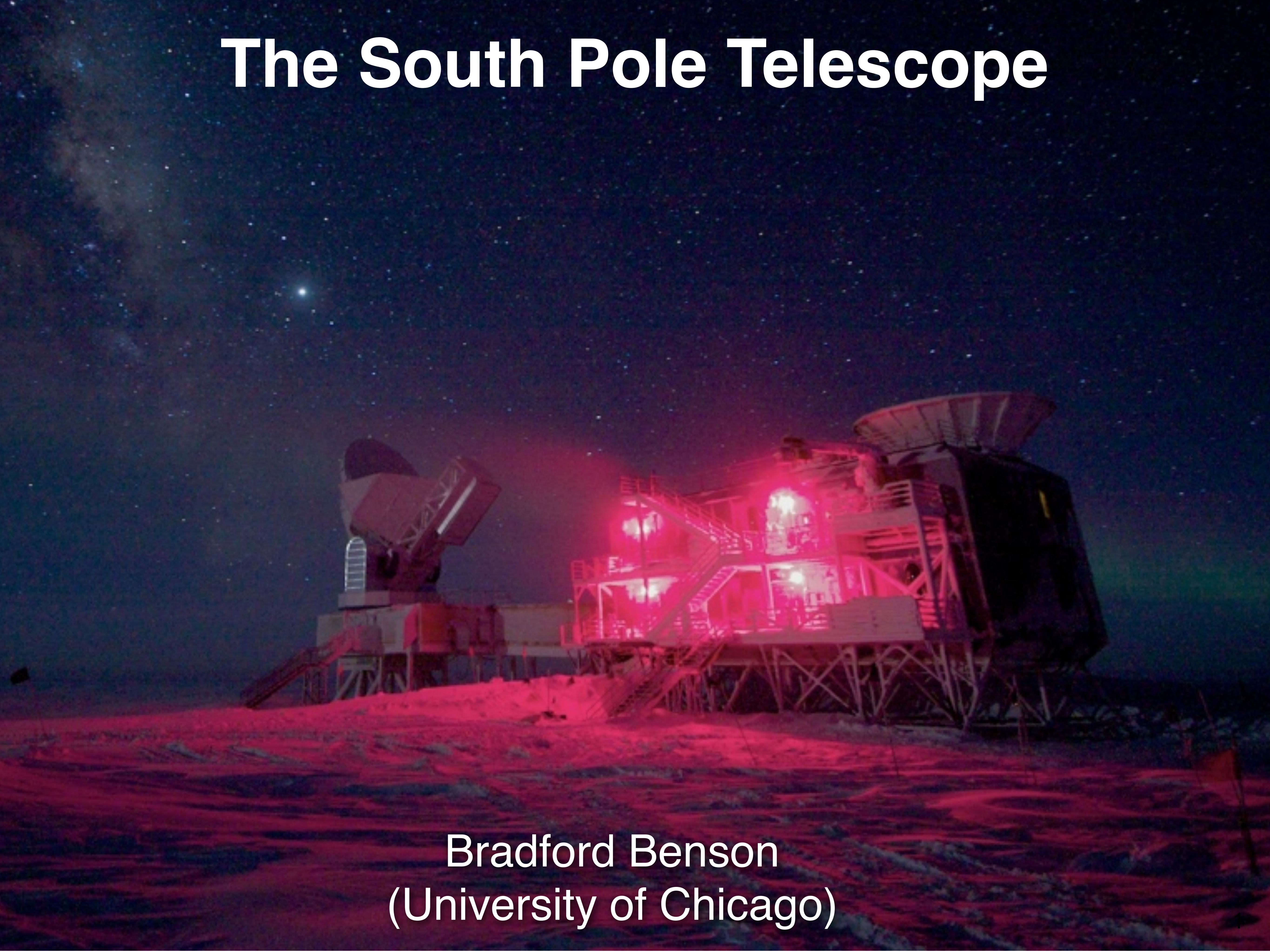
The South Pole Telescope



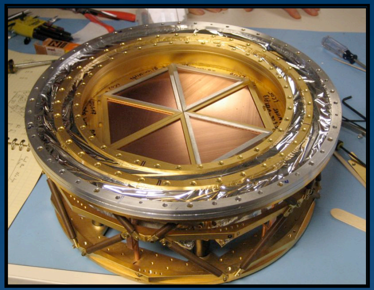
Bradford Benson
(University of Chicago)

The South Pole Telescope Collaboration

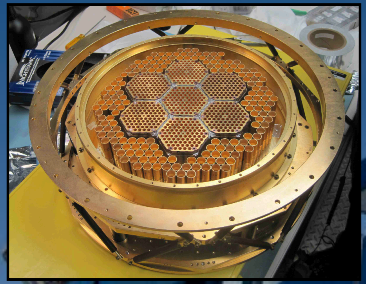
The South Pole Telescope (SPT)

- 10-meter sub-mm quality wavelength telescope
- At 100, 150, 220 GHz, angular resolution of 1.6, 1.2, 1.0 arcmin

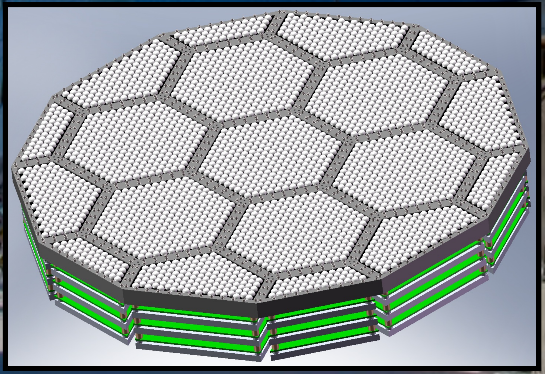
2007: SPT-SZ
960 detectors
100,150,220 GHz



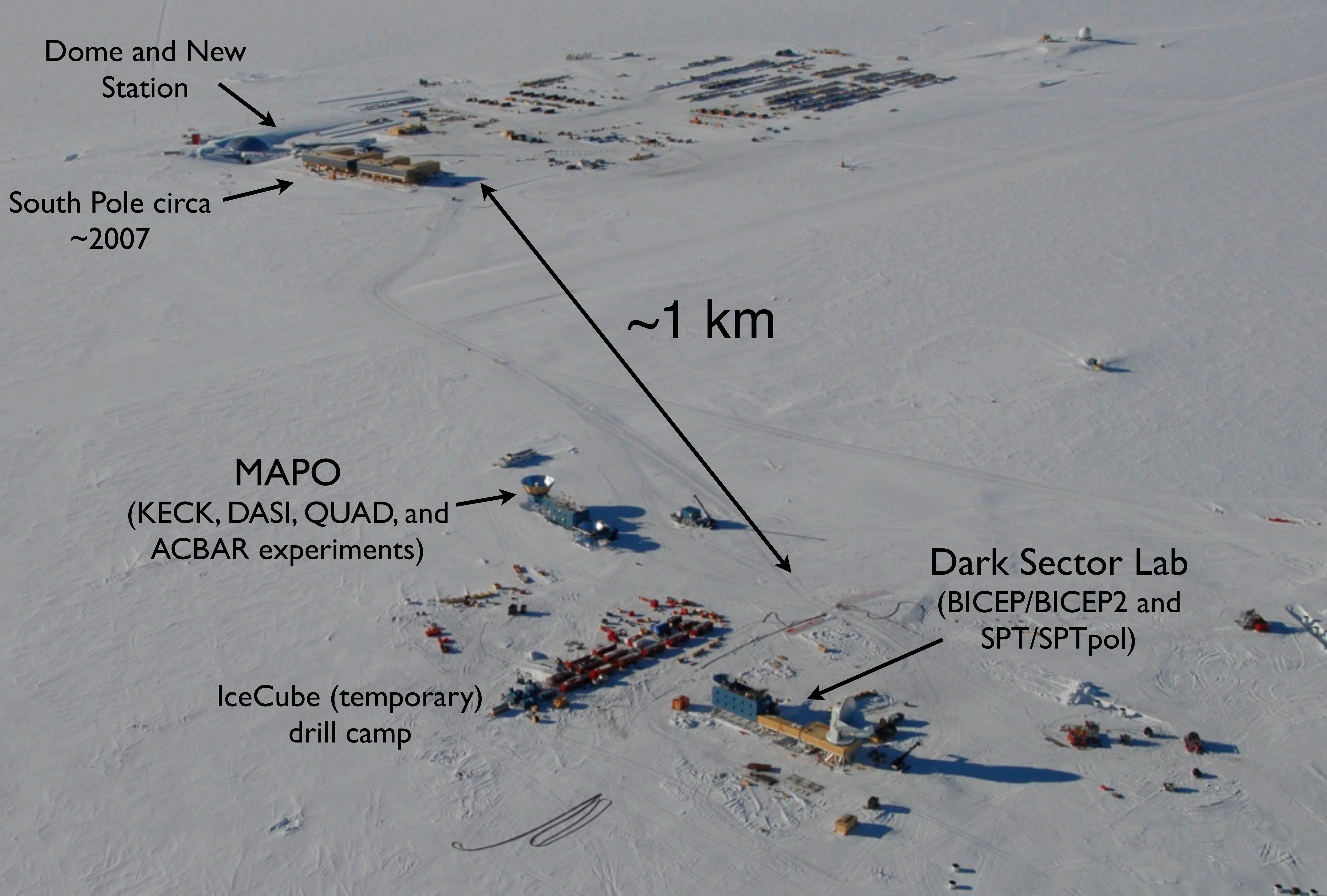
2012: SPTpol
1600 detectors
100,150 GHz
+Polarization



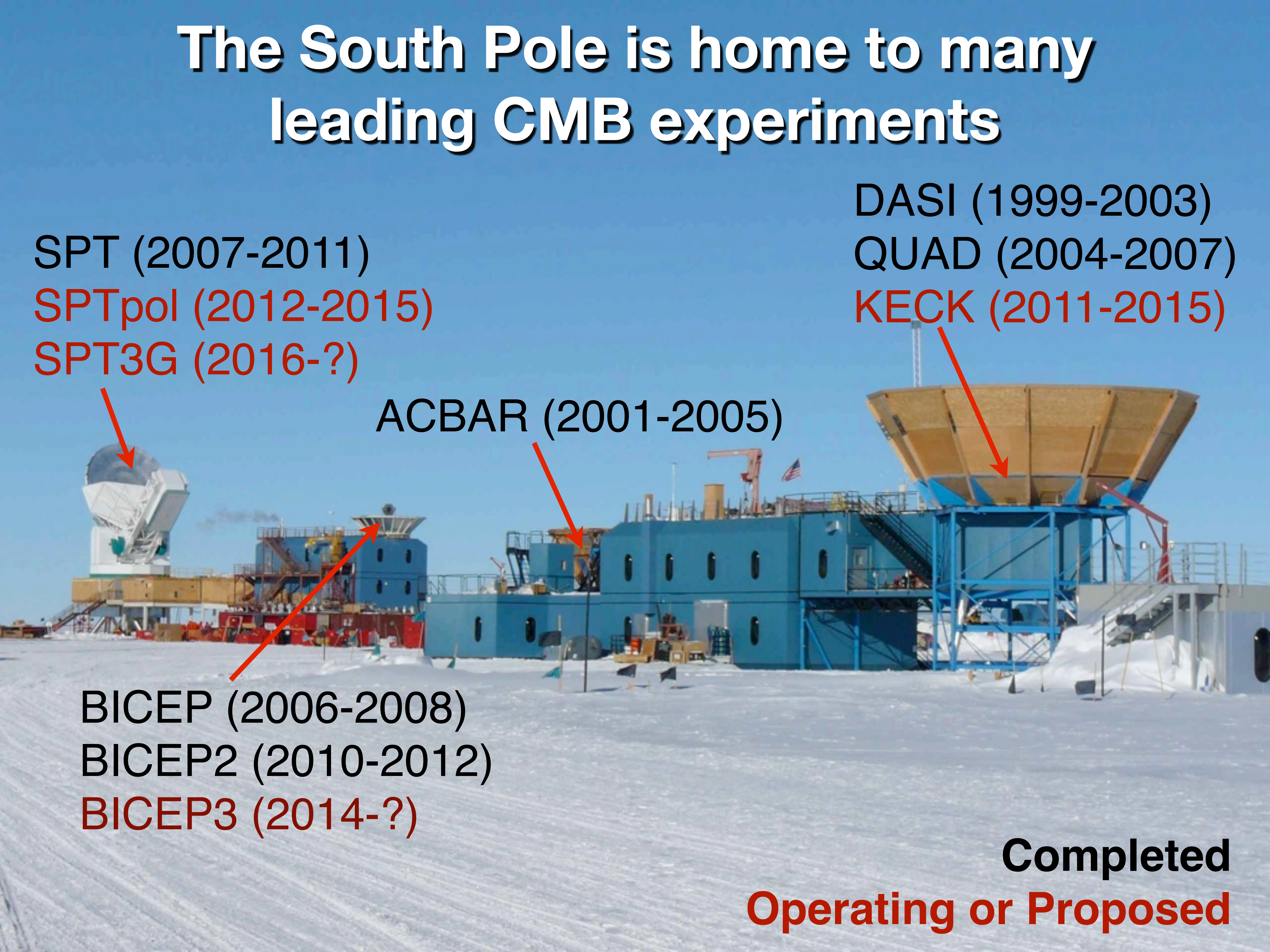
2016: SPT-3G
~15,200 detectors
100,150,220 GHz
+Polarization



February 3, 2007: South Pole



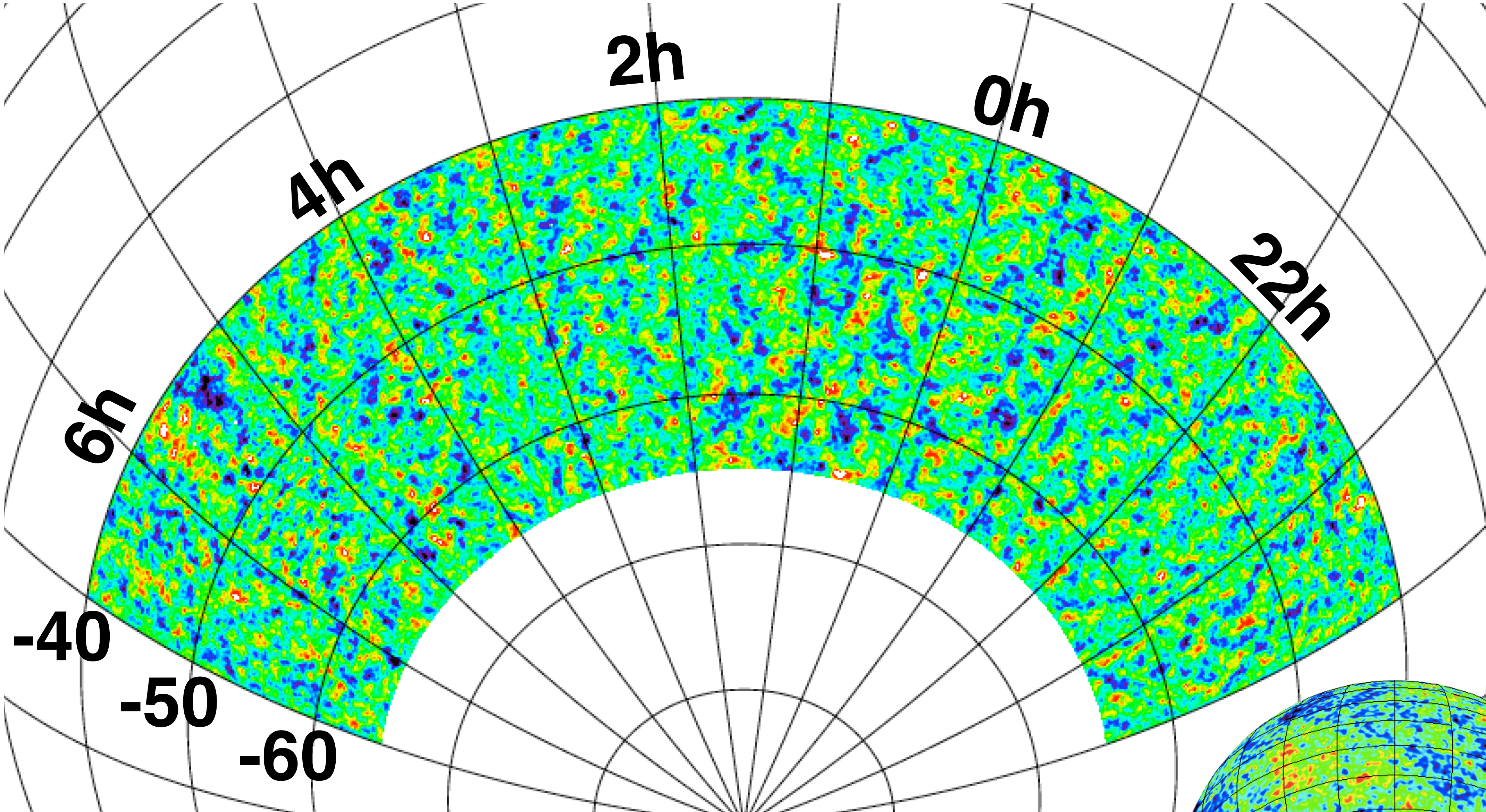
The South Pole is home to many leading CMB experiments



The SPT-SZ Survey (2007-2011):

The highest resolution and sensitivity map of the CMB

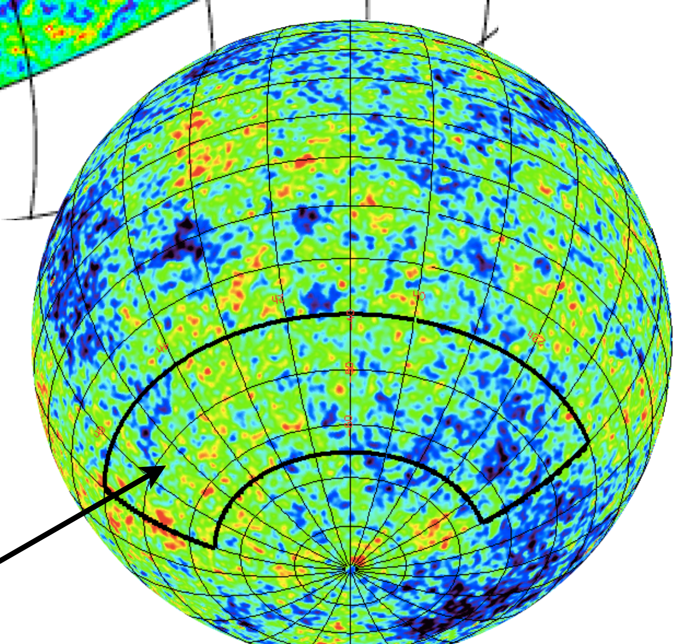
(covering 2500 deg² ~ 6% of sky)



Final survey depths of:

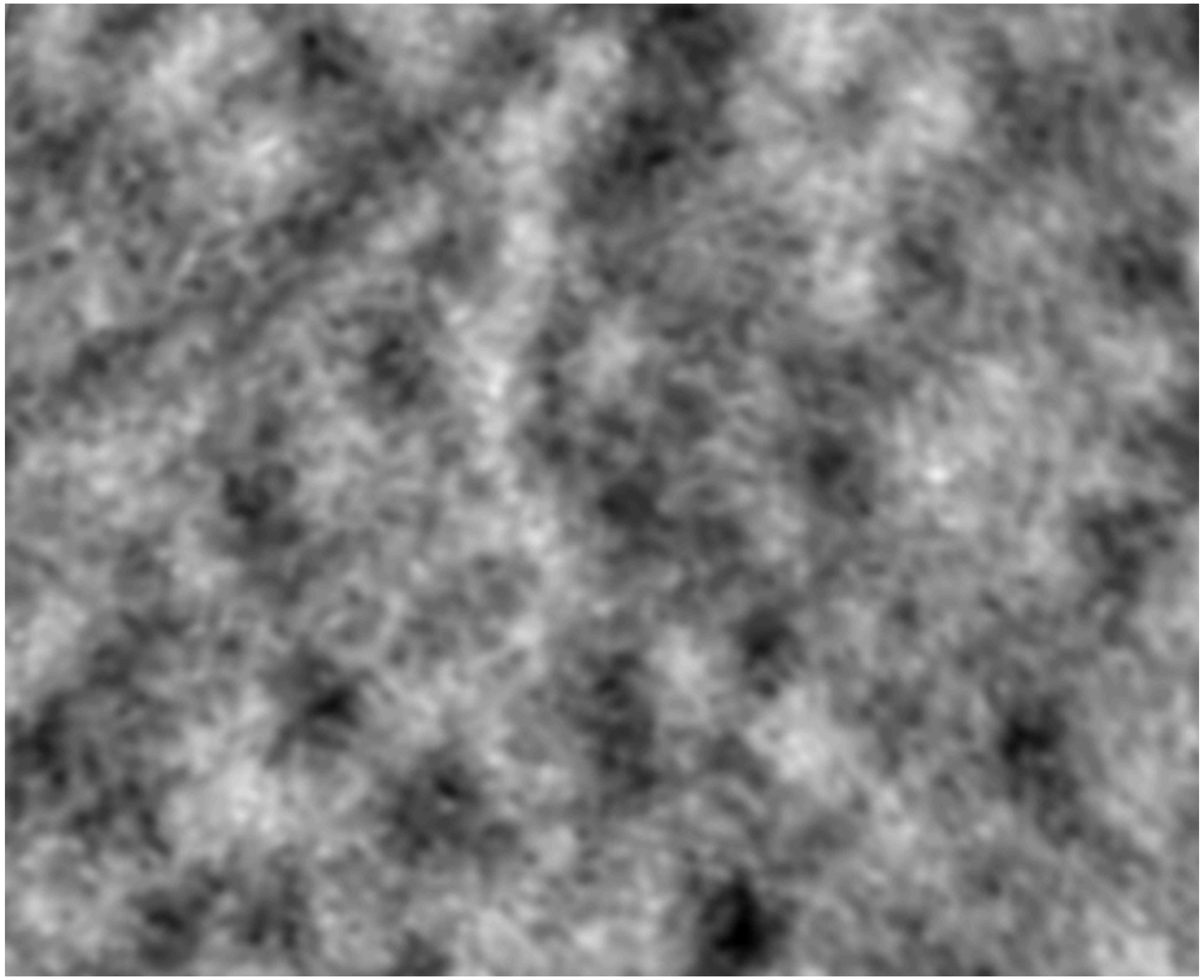
- 90 GHz: 40 uK_{CMB}-arcmin
- 150 GHz: 17 uK_{CMB}-arcmin
- 220 GHz: 80 uK_{CMB}-arcmin

WMAP lower resolution full sky map with SPT area marked

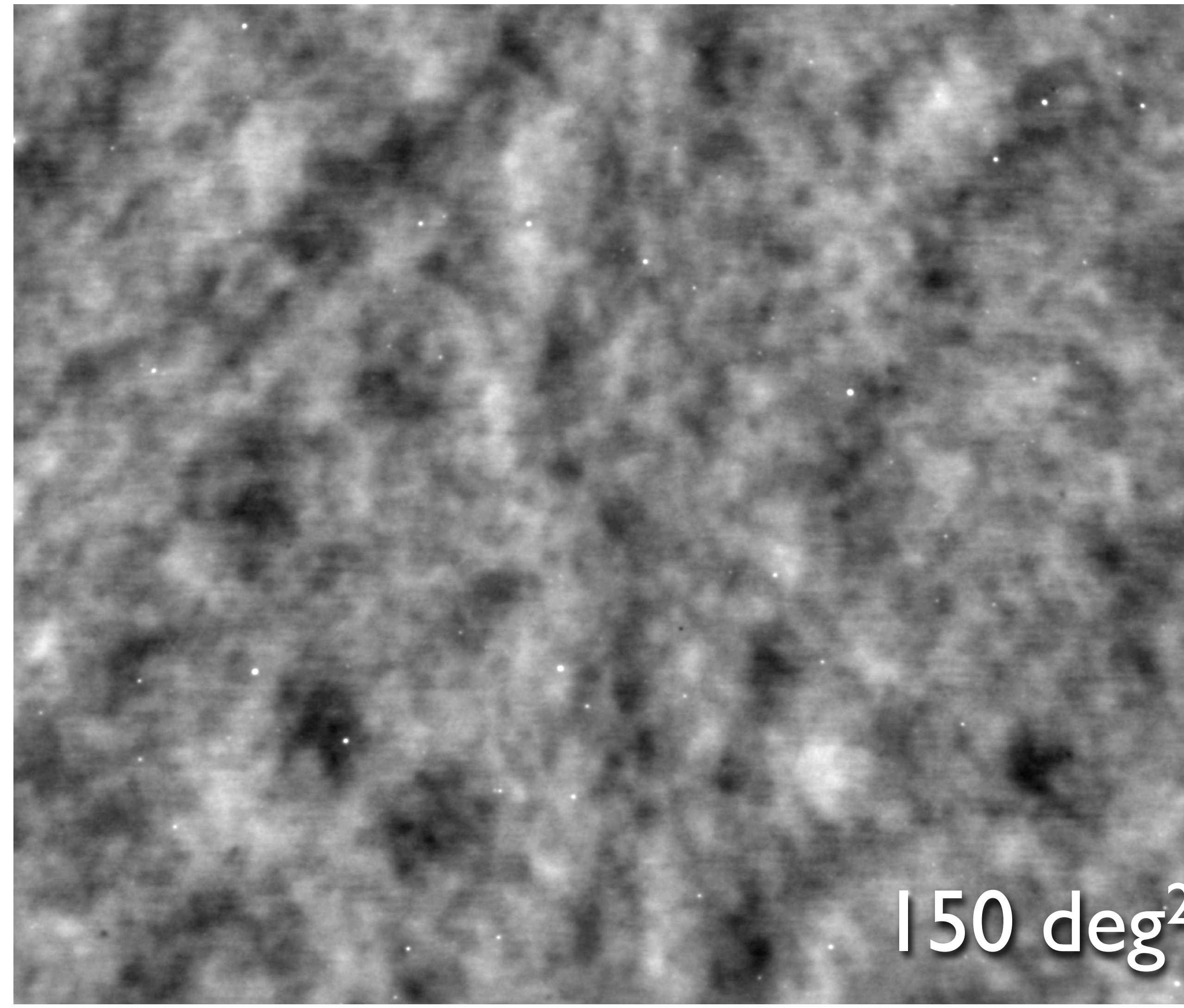


The CMB as observed by WMAP and SPT

WMAP



SPT

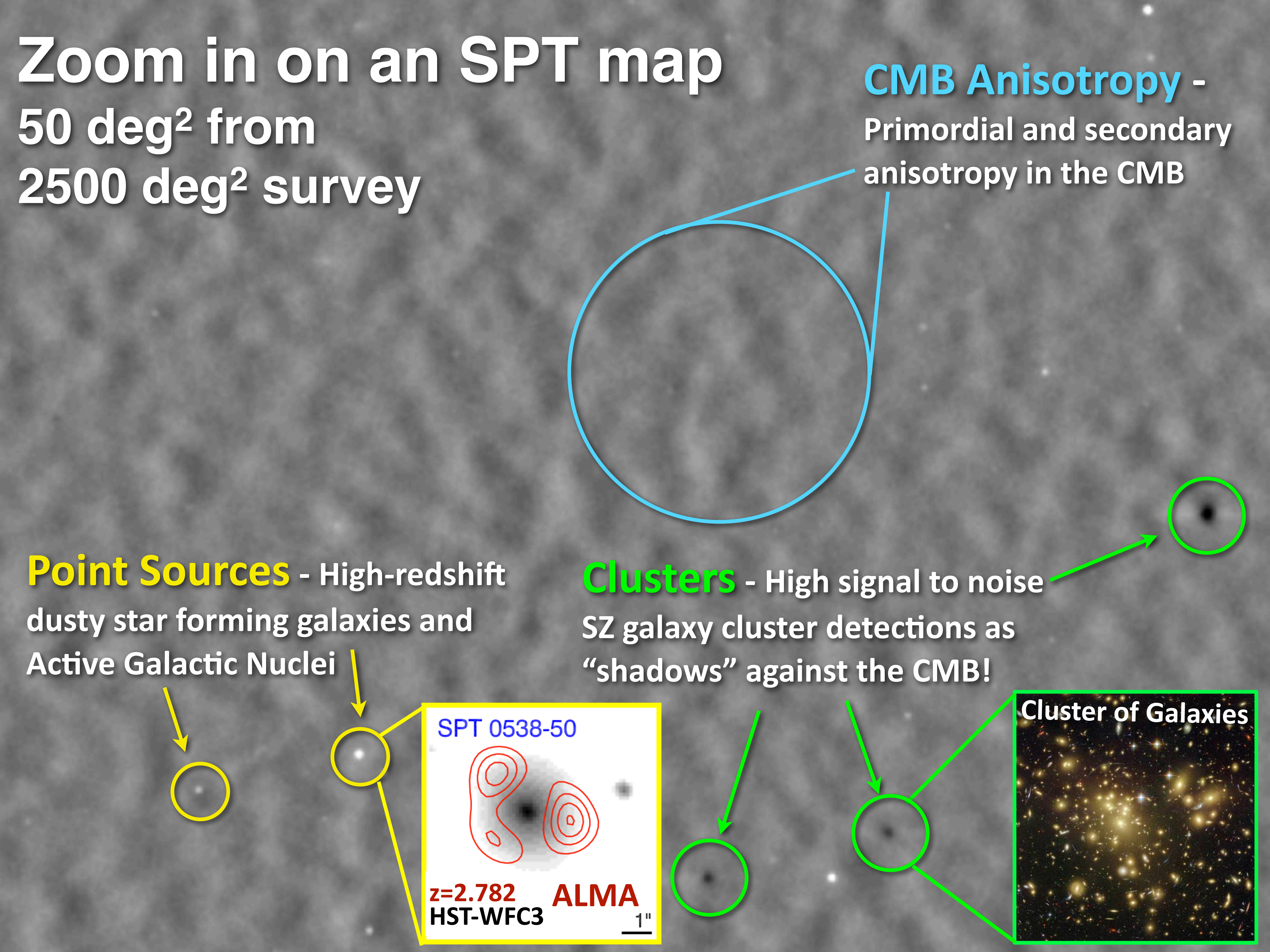


SPT relative to WMAP:

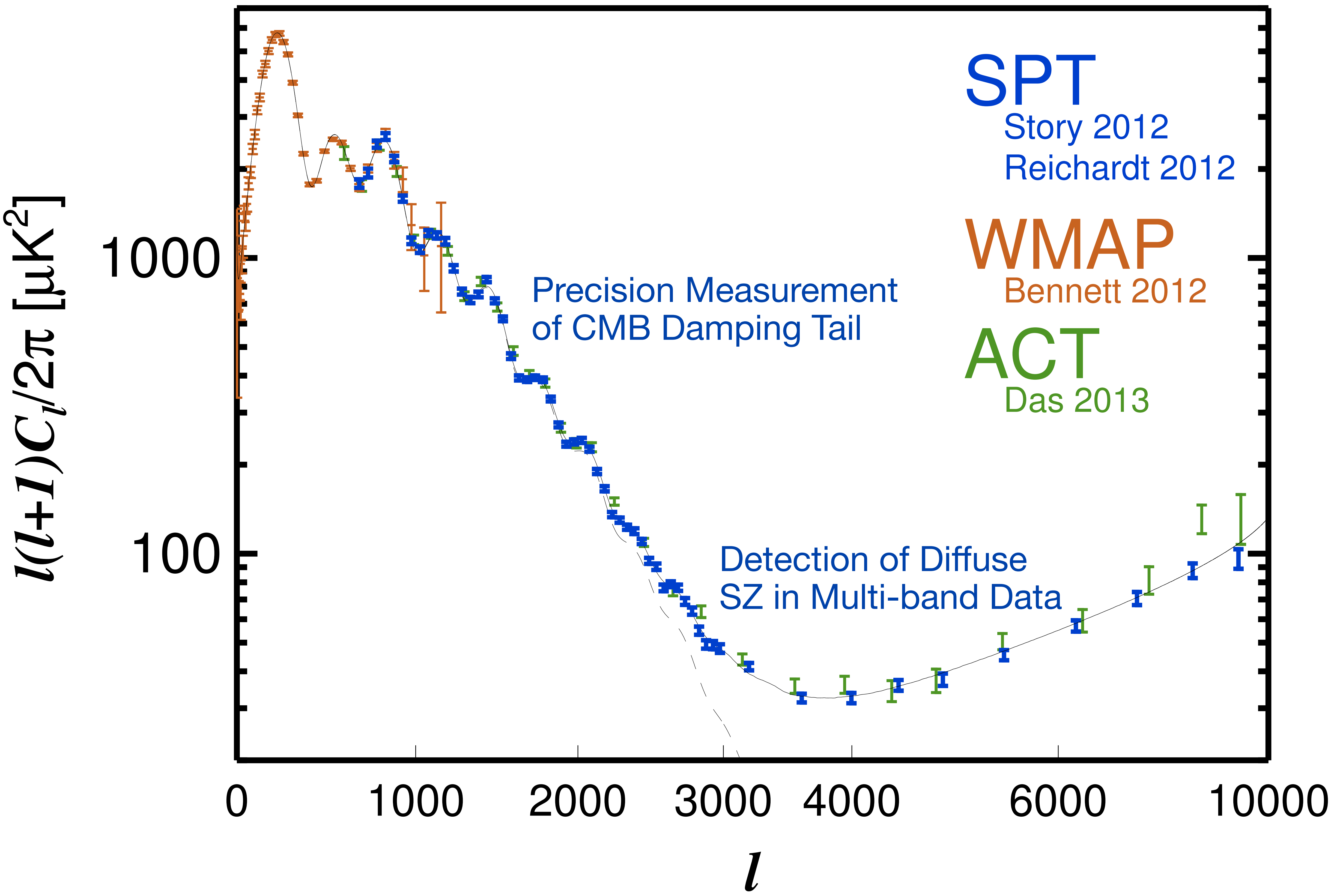
SPT has 13x smaller beam (13' vs 1')

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

(Planck DR1 has a depth of ~45 uK-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

The "pre-Planck" CMB Power Spectrum



Outline

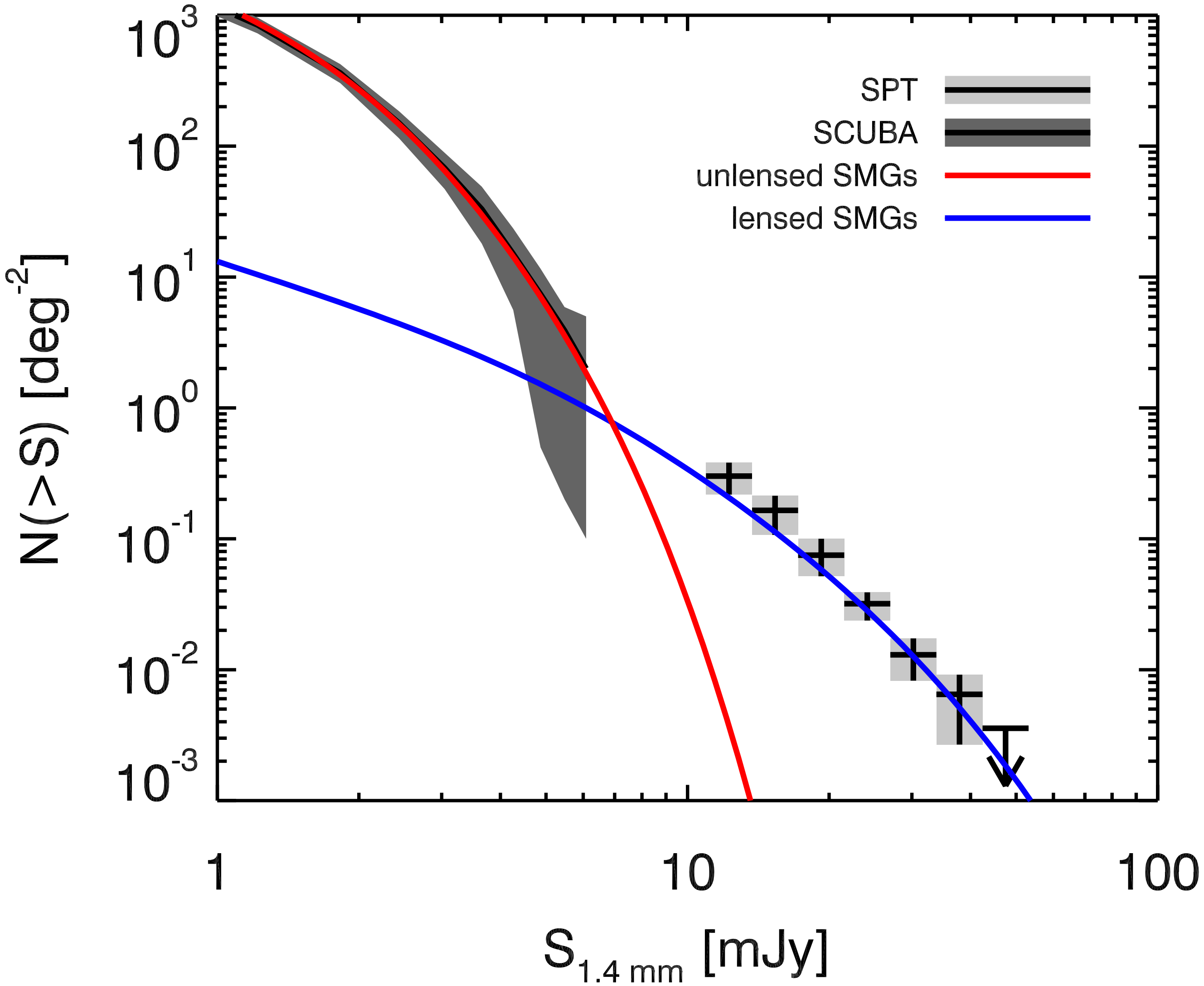
1. **Astronomy & Astrophysics with SPT-SZ**
   - ***High-redshift galaxies***
   - ***Clusters of galaxies***

2. **Cosmological Constraints from SPT-SZ**
   - Planck vs. SPT, Clusters, etc.

3. **Whats next for the SPT and the CMB?**
   - Measuring CMB polarization with SPTpol, SPT-3G, and CMB-S4

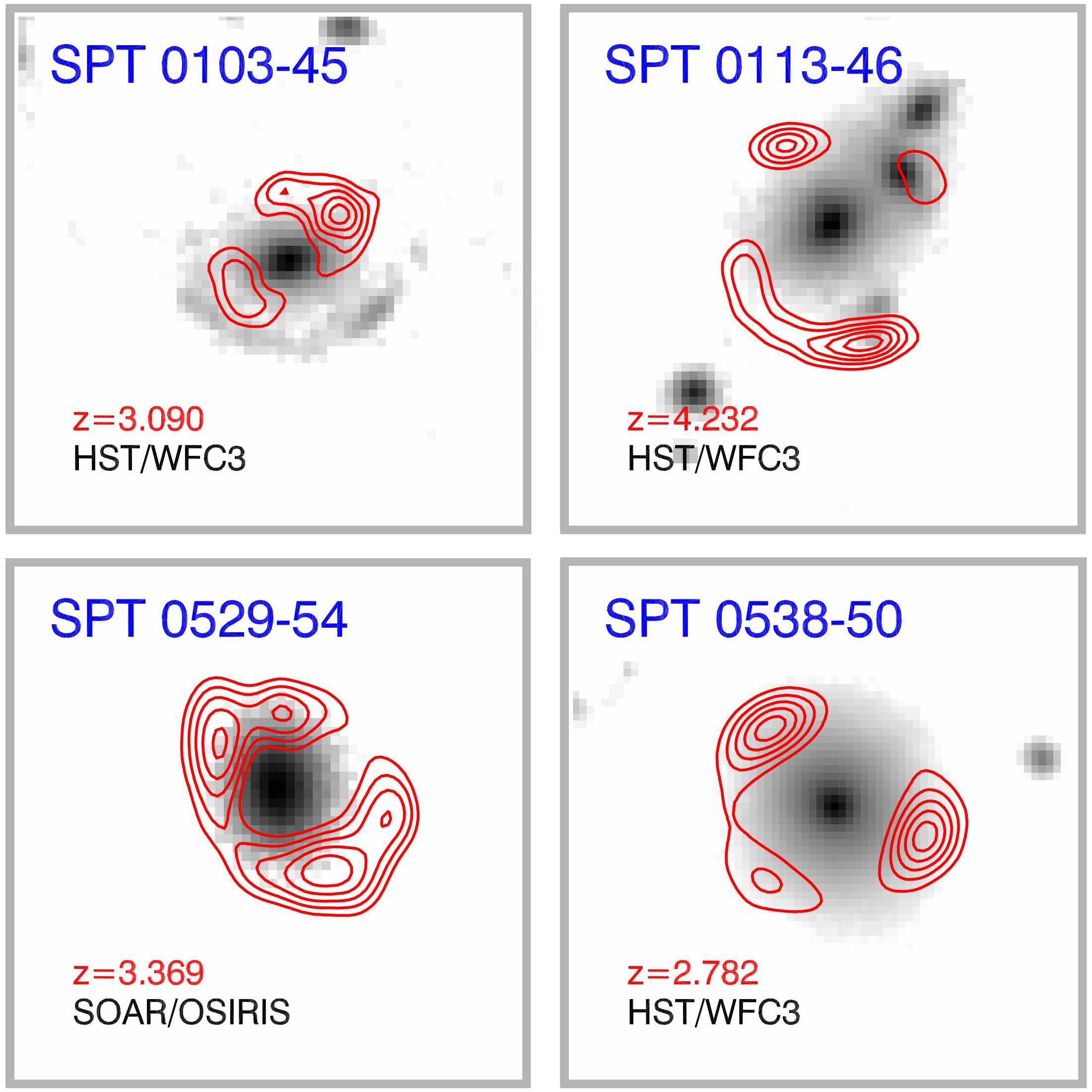
SPT-SZ: ***Lensed Sources in SPT-SZ Survey***

mm-wavelength Source Number Counts



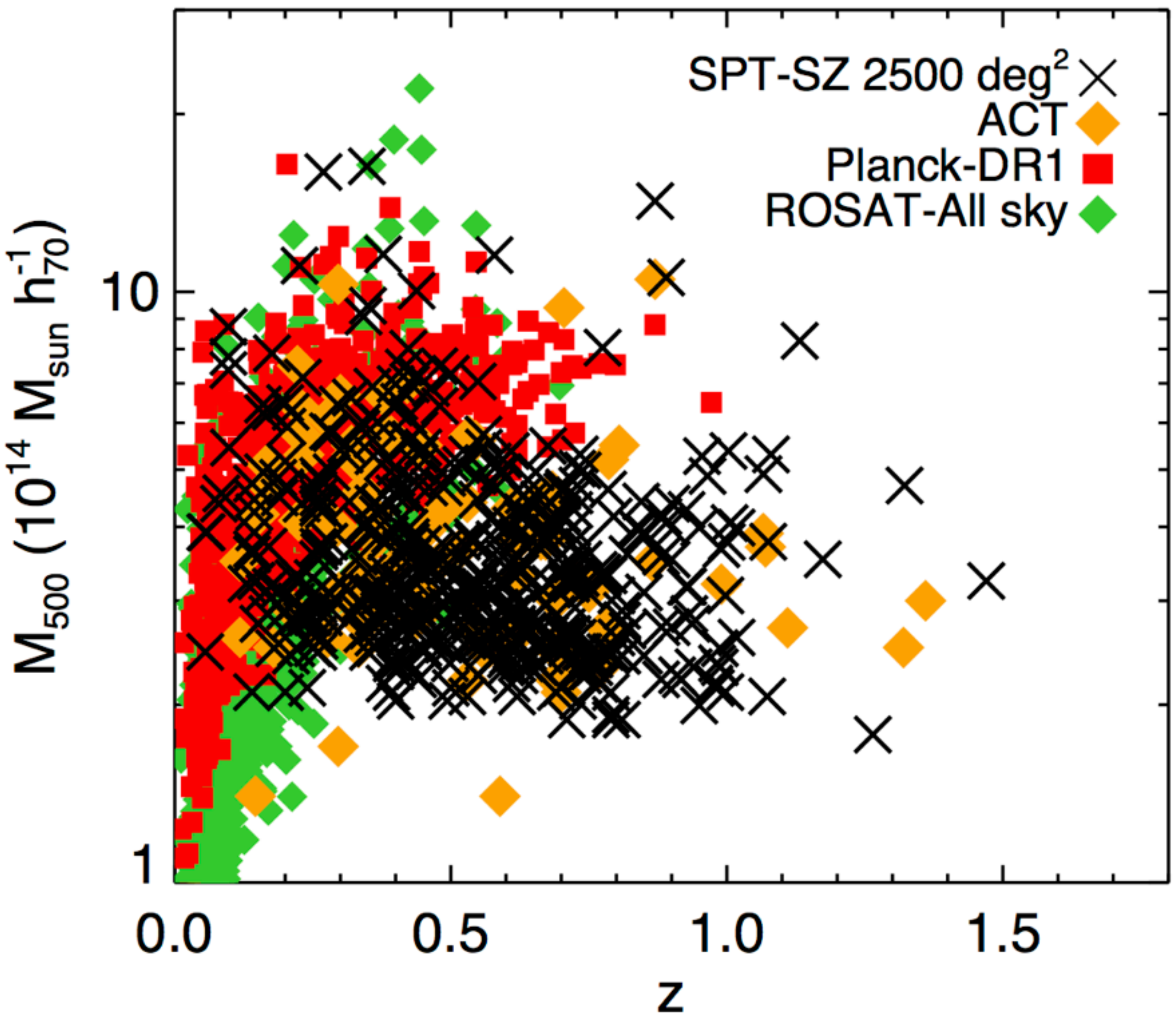
Negrello *et al.* 2007 model
Vieira *et al.* 2010 source counts

SPT lensed high-z ($2 < z < 6$) galaxies resolved by ALMA



See:
- Vieira *et al.* 2013 Nature
- Hezevah et al. 2013
- Weiss et al. 2013
- Mocanu et al. 2013

SZ Cluster Surveys: ***Mass vs Redshift***



	Area (deg²)	**Depth** (uK-arcmin)	**$N_{clusters}$**
Planck	All-sky	45	861
SPT	2500	17	465
ACT	950	23-40	91

First SZ-discovered cluster was in 2008 by SPT *(Staniszewski et al);* ***5 years later there are > 1300 SZ-identified clusters!***

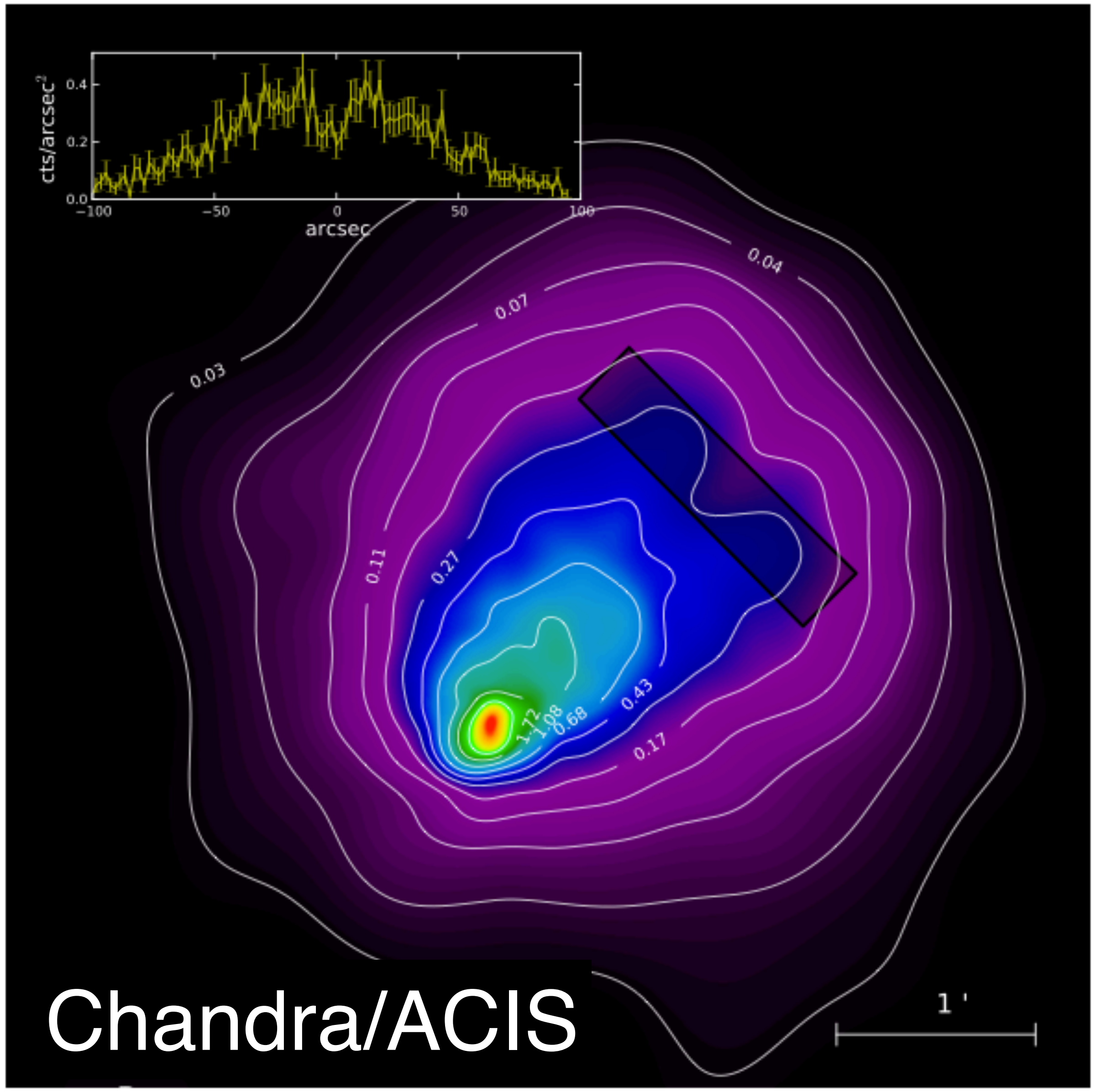
Notes:

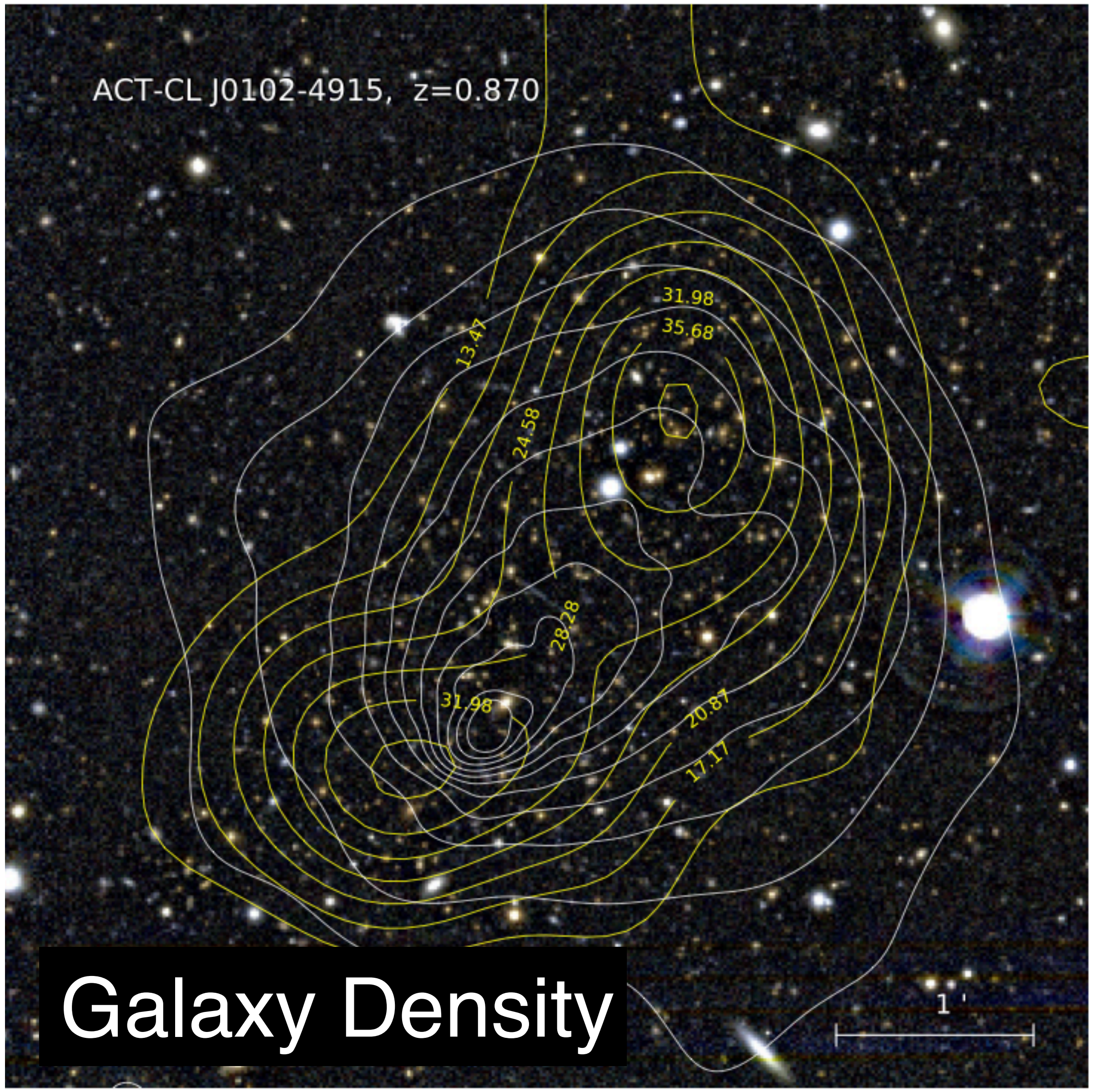
- For each experiment, the 150 GHz depth is given, most important band for cluster counts
- Planck based on ~1/2 survey, cluster counts should ~double for full survey
- $N_{clusters}$ highly dependent on completeness of optical follow-up, which varies between each experiment

ACT-CL/SPT-CL J0102-4915: ***"El-Gordo"***

"Rarest" cluster in universe; provides test of LCDM and non-Gaussianity (e.g., Mortonson et al. 2011, Shandera et al. 2013):

Mass ~ 3 x 10^{15} M_{sun}/h_{70} at z=0.87

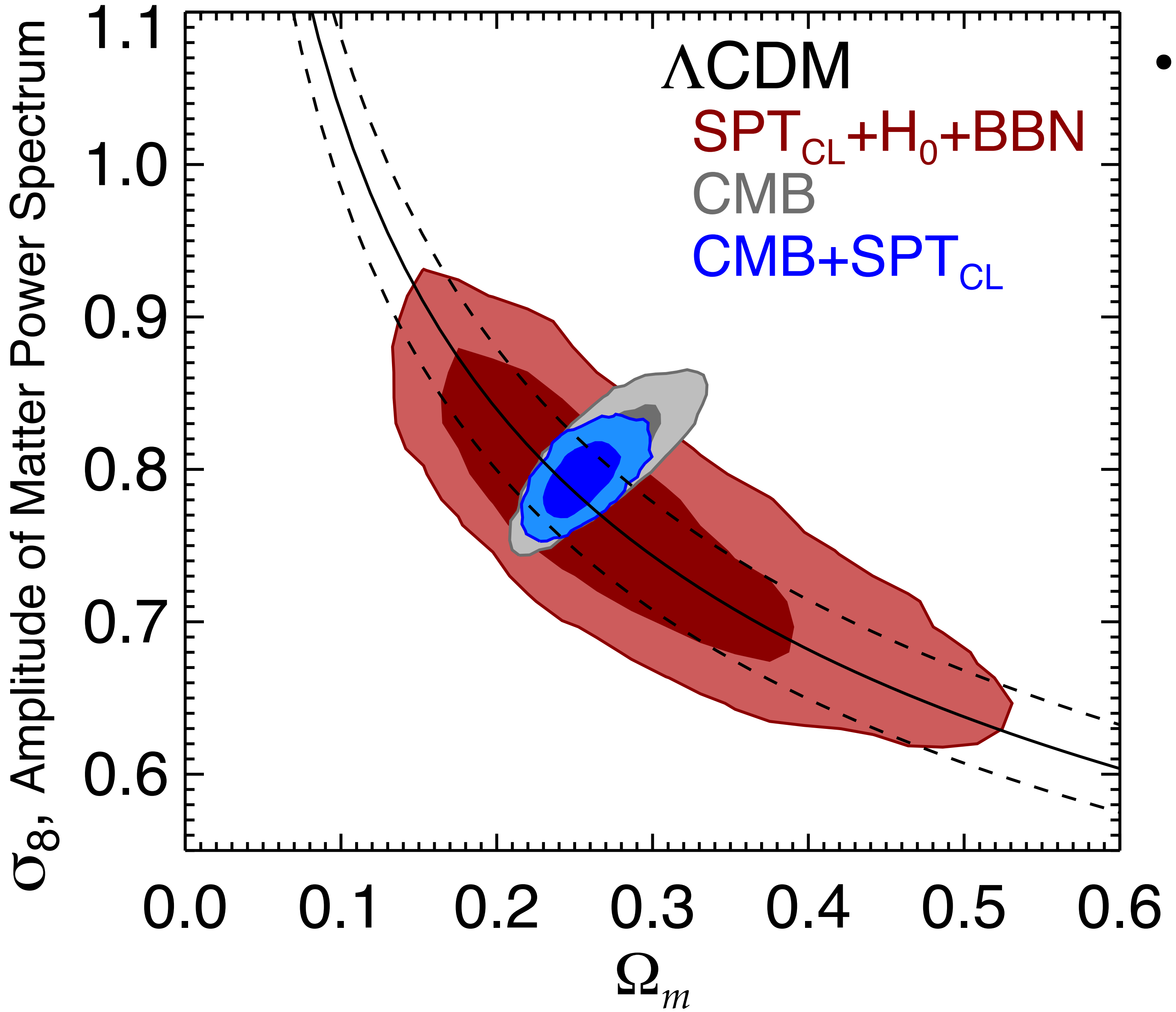




Menanteau et al. (2011)

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!***
  - *Uncertainty in scaling relation slope, scatter, redshift evolution are all significantly sub-dominant*

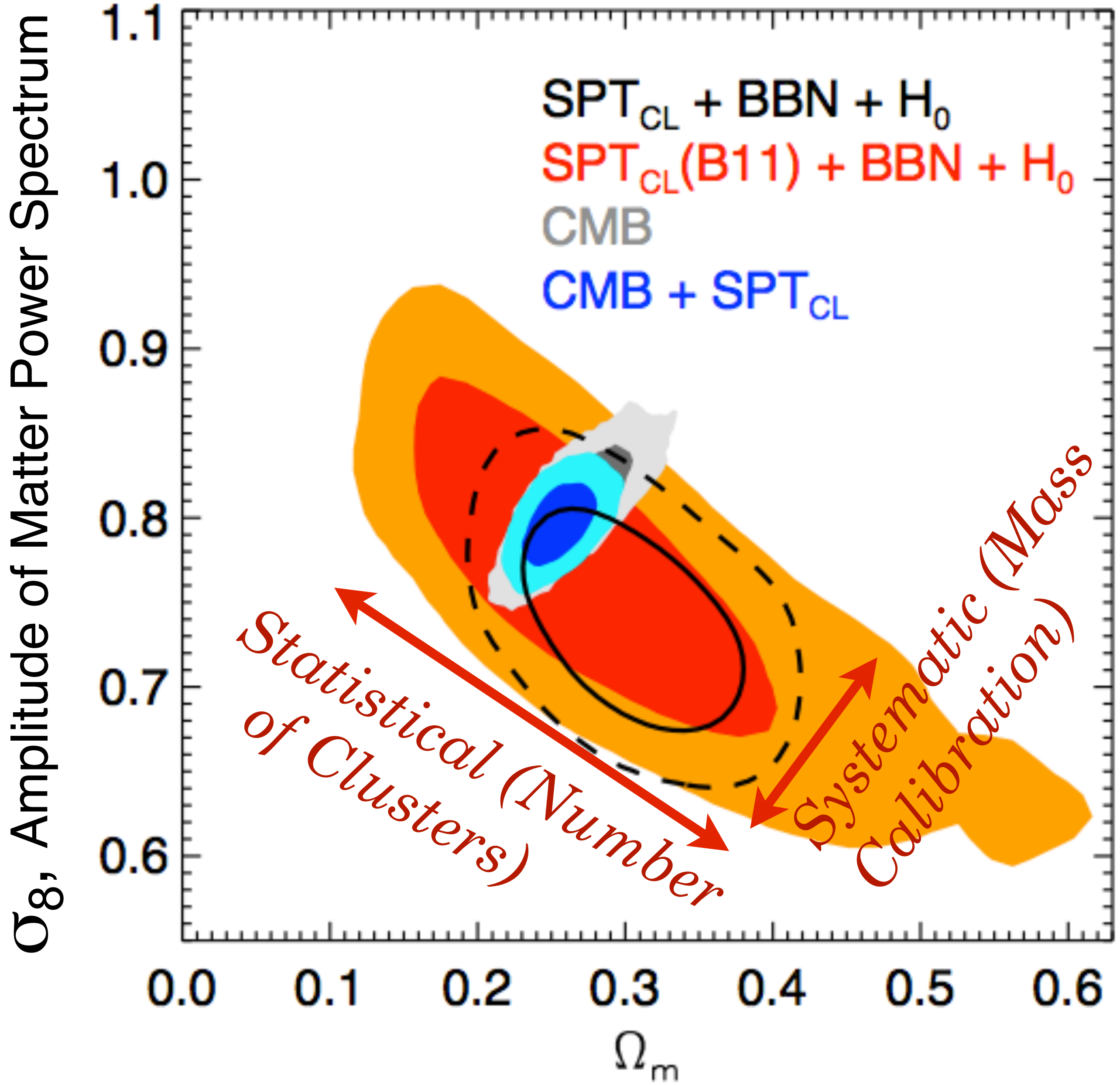
σ_8, Ω_m - 68, 95% Confidence Contours

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:

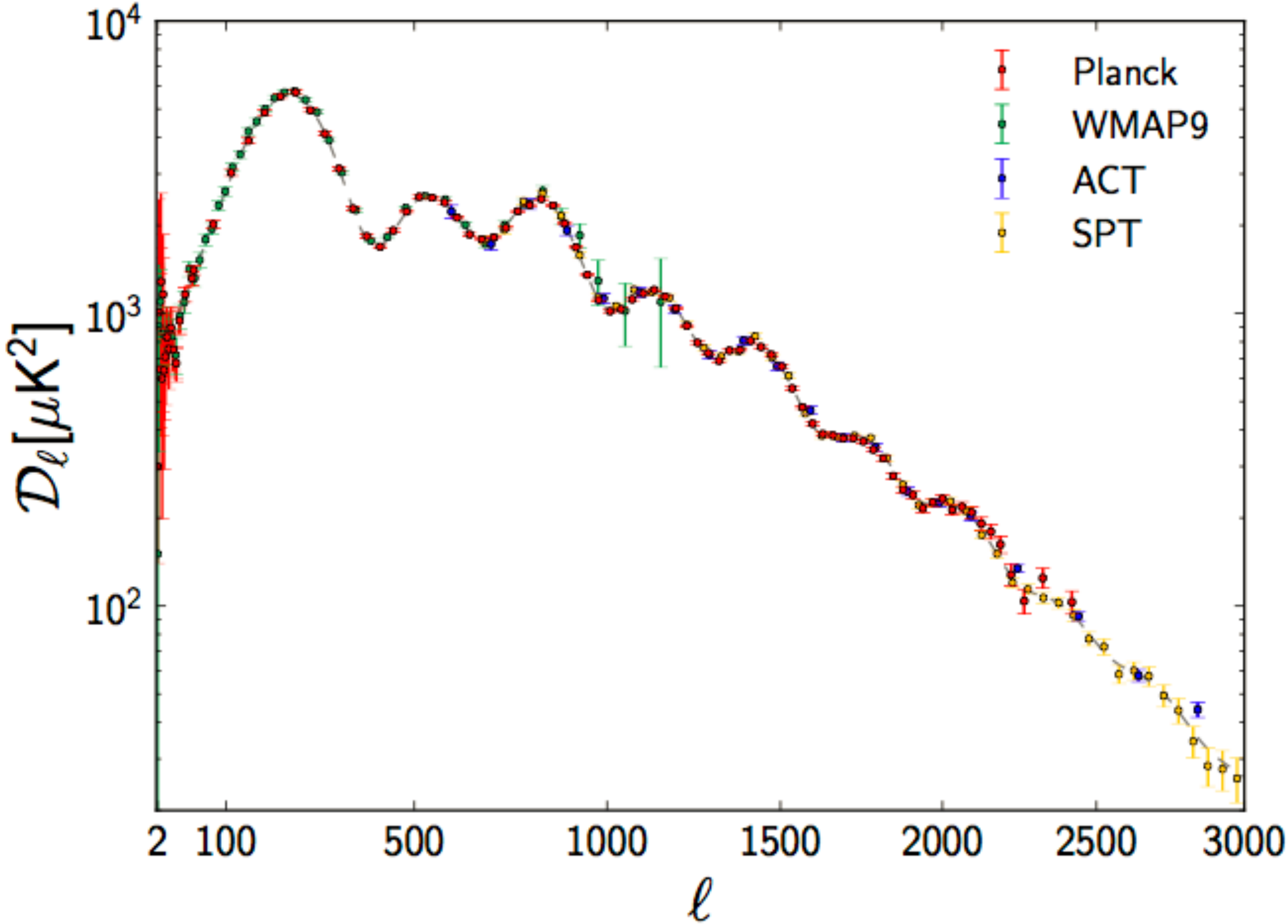
Now use 100 clusters (Reichardt et al. 2012)



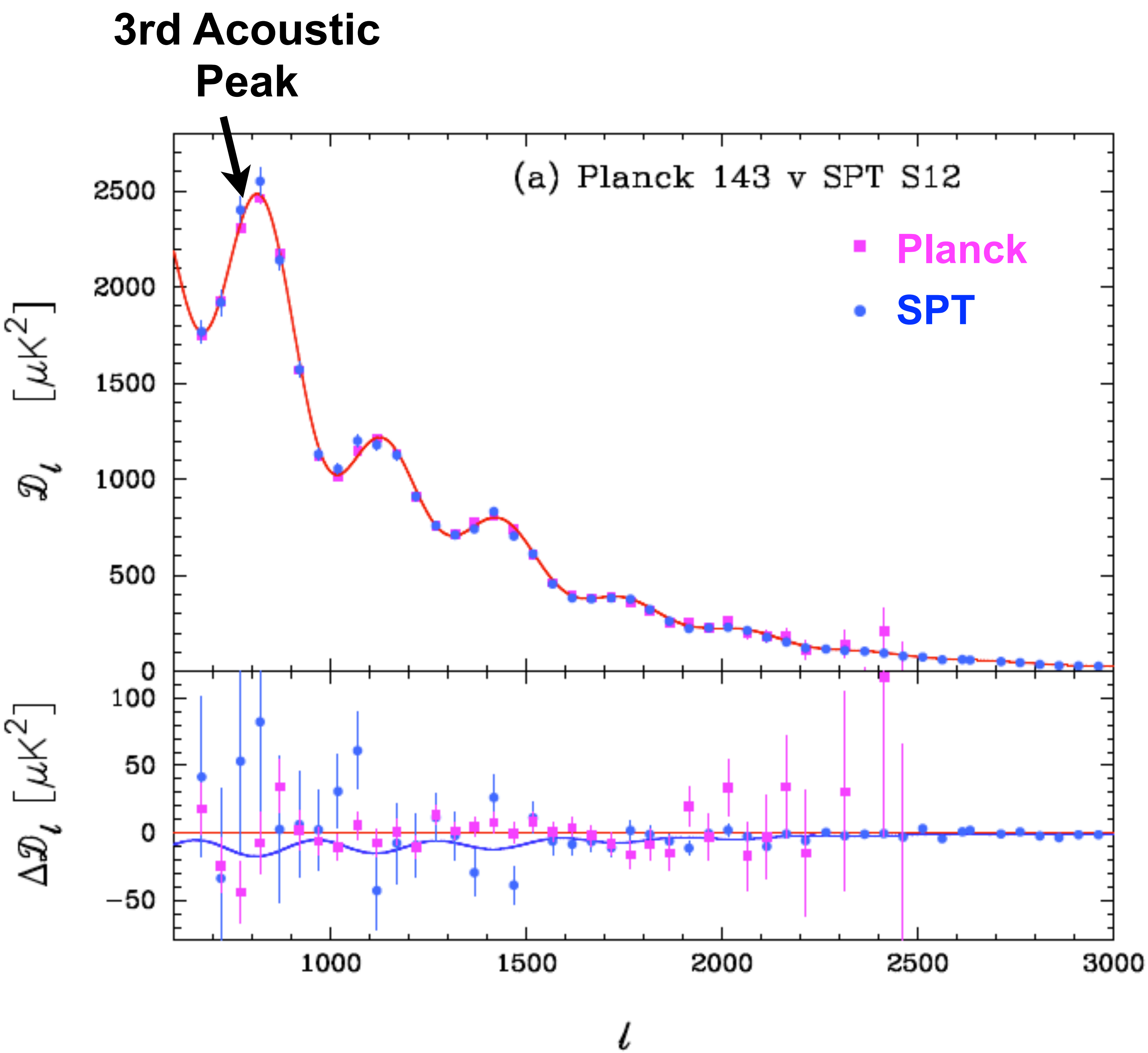
- SPT increased cluster sample by ~5x in Reichardt et al. (2012) improving constraints in σ_8-Ω_m plane by 1.8x in area
- ***In direction orthogonal to CMB constraints, cluster constraints limited by mass calibration***

Reichardt et al 2012, arXiv:1203.5775

Outstanding agreement between CMB power spectrum measurements



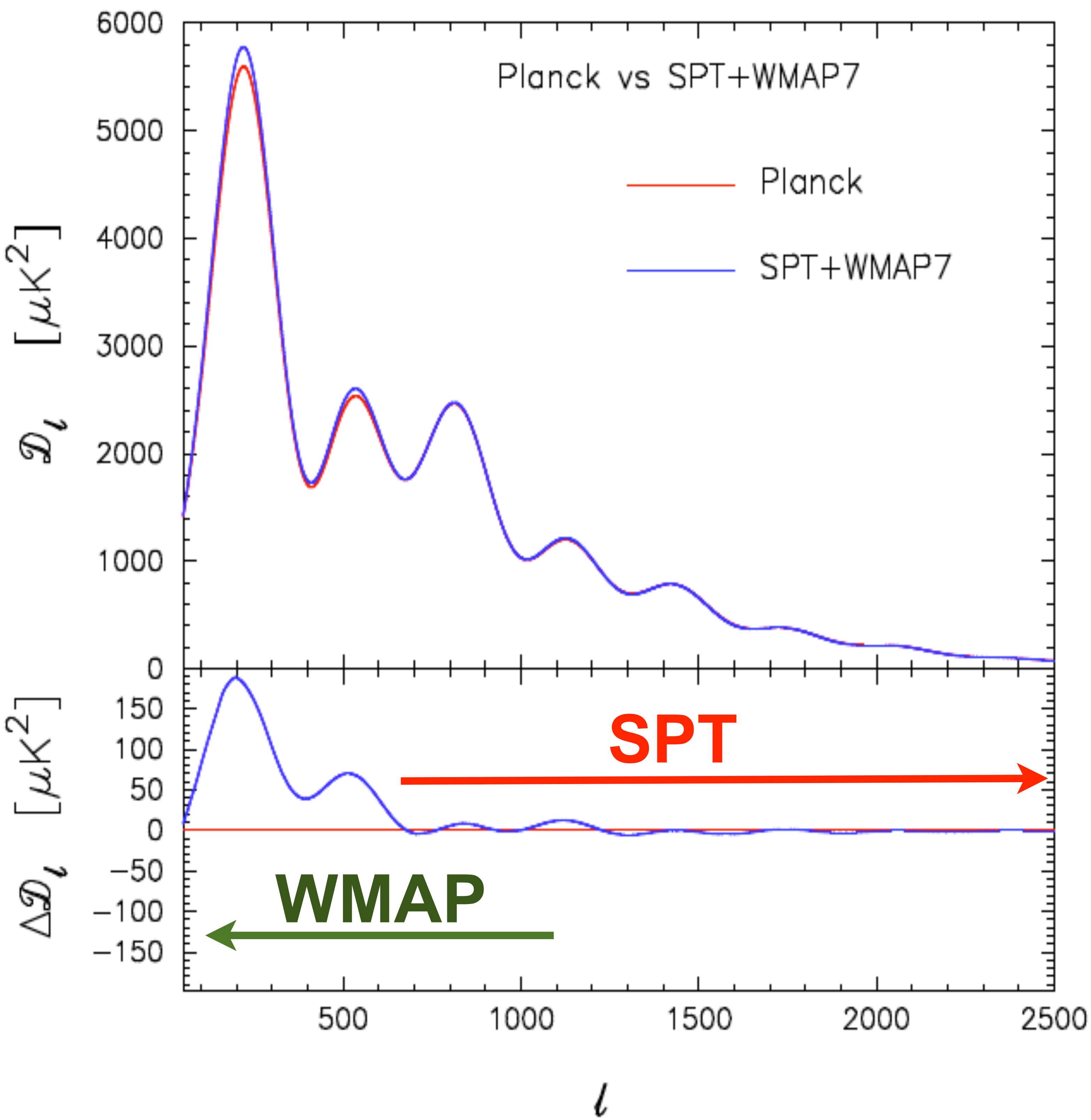
CMB Power Spectrum: ***Planck and SPT***



- ***Planck improved on SPT band powers at ell < 1850***
- ***SPT and Planck agree very well!*** (despite what Planck appendix says)
  - **$\Delta\chi^2$ = 3 for the 47 SPT data points, comparing best-fit (WMAP9+SPT) vs (Planck+SPT) cosmology**

Planck Collaboration XVI (2013)

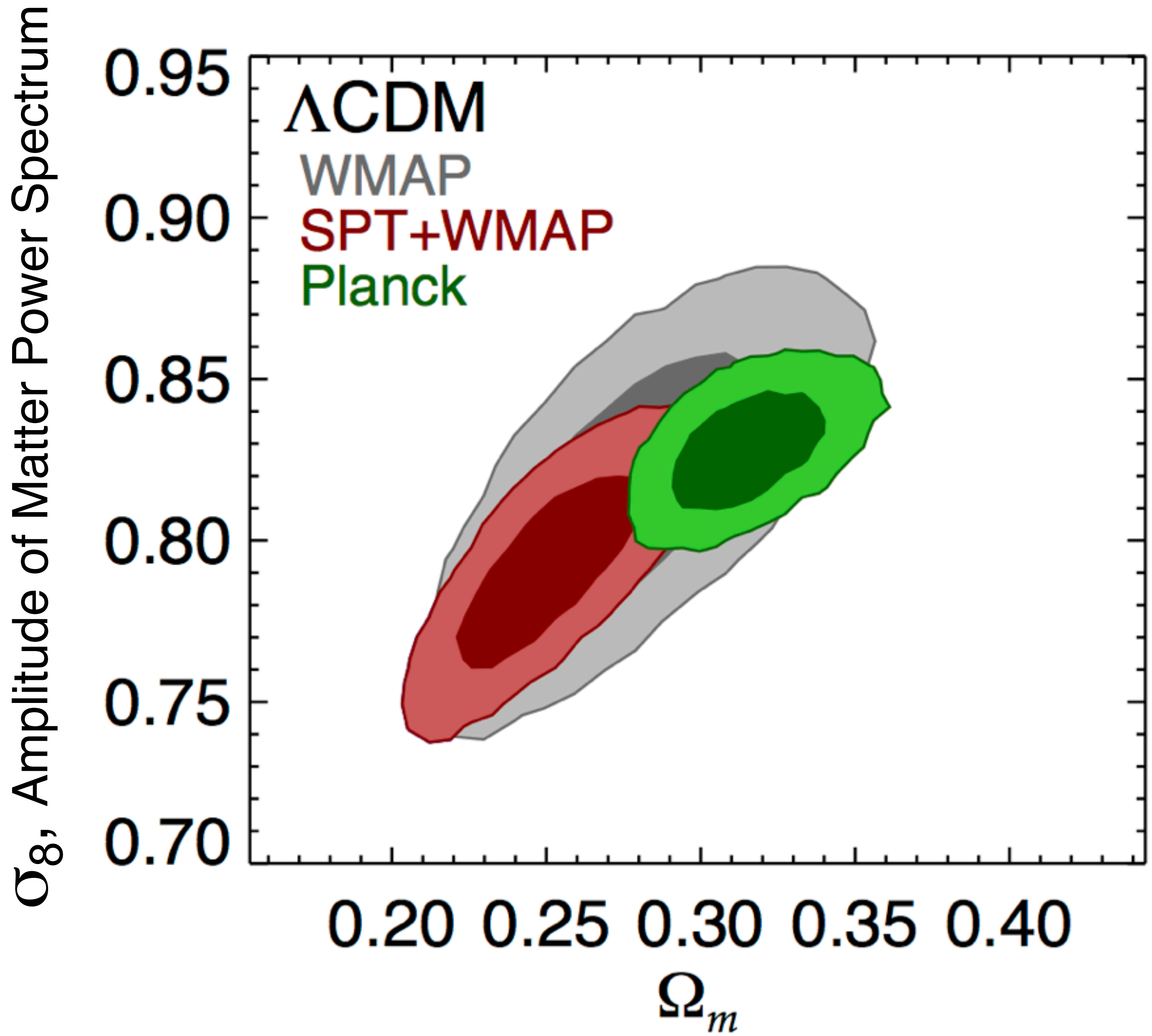
CMB Power Spectrum: ***Planck and WMAP***



- ***Planck and WMAP best-fit models disagree by 2.6% in power of 1st acoustic peak (5-sigma calibration discrepancy)***
- *SPT calibrated off of WMAP at 650 < ell < 1100*
- *At ell > 700, the Planck and WMAP+SPT models largely agree*

Planck Collaboration XVI (2013)

CMB Constraints on σ_8, Ω_m



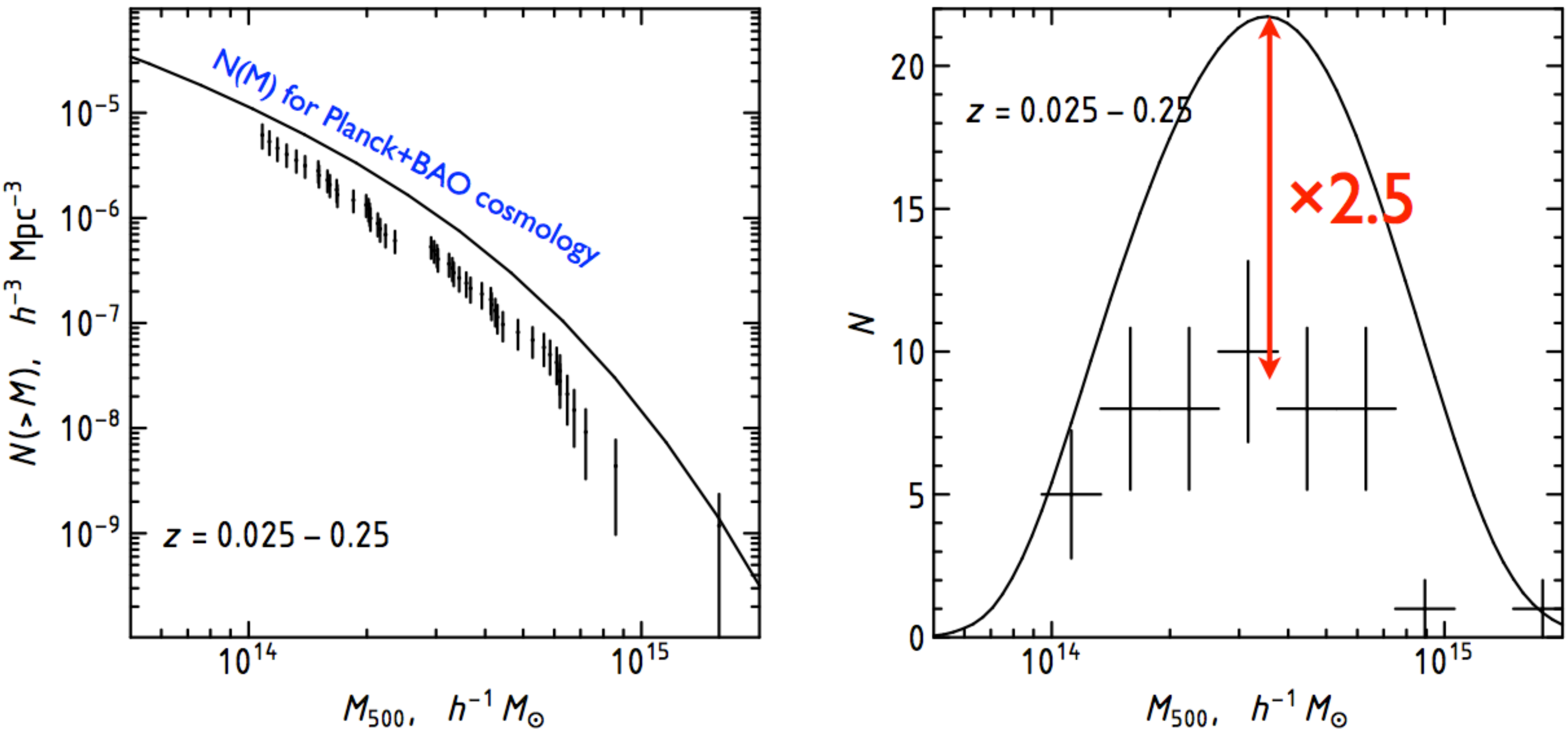
Planck measurements favor a shift in σ_8 and Ω_m Driven by:

- 1st/3rd acoustic peak power ratio
- Gravitational lensing in the CMB power spectrum (Ω_m goes down by ~1σ when A_{Lens} is free)

	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

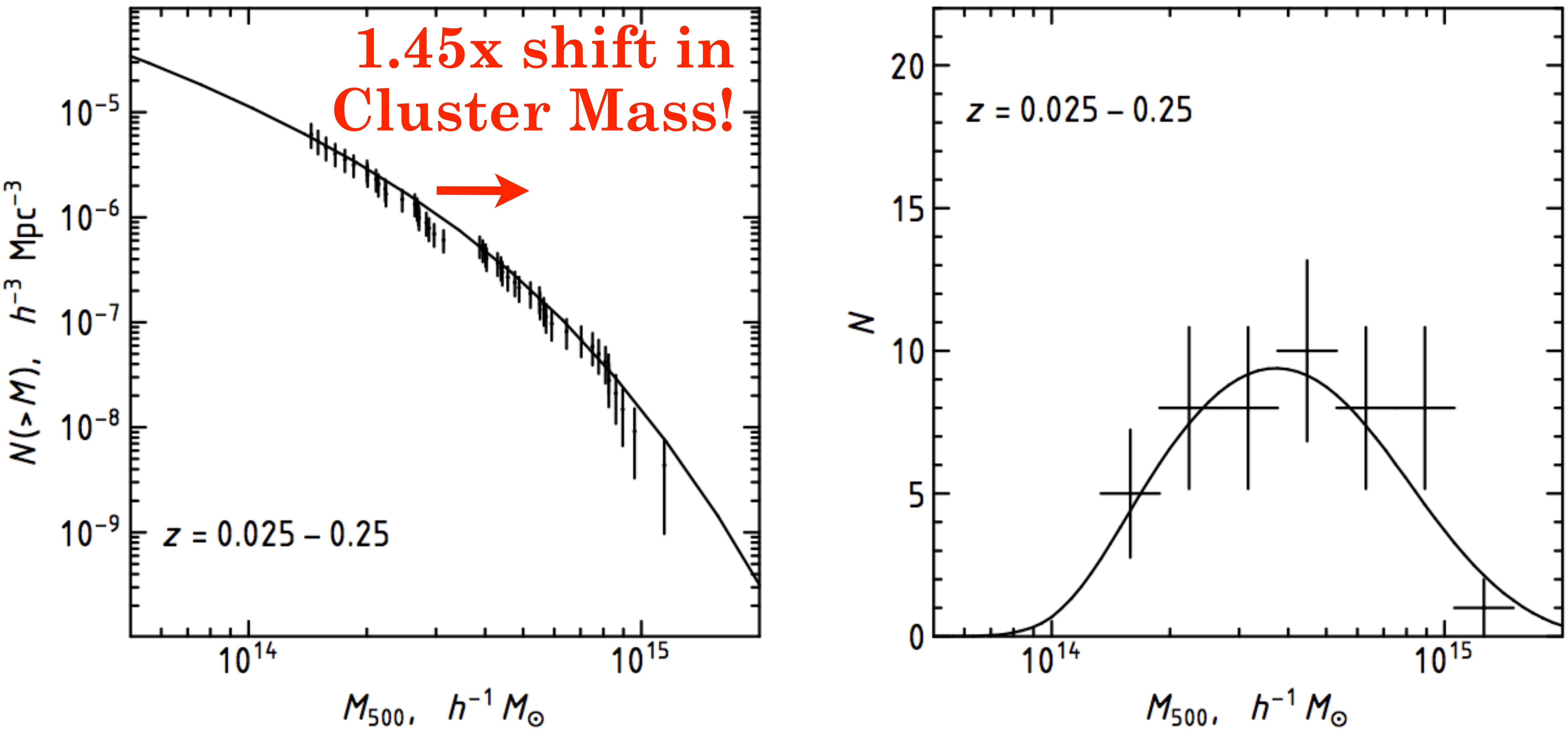
Planck Cosmology has ***profound*** mismatch with Cluster Abundance



$$\text{Cluster counts} \sim (\boldsymbol{\sigma}_8)^{10}$$

Vikhlinin et al. 2009 (CCCP, X-rays)

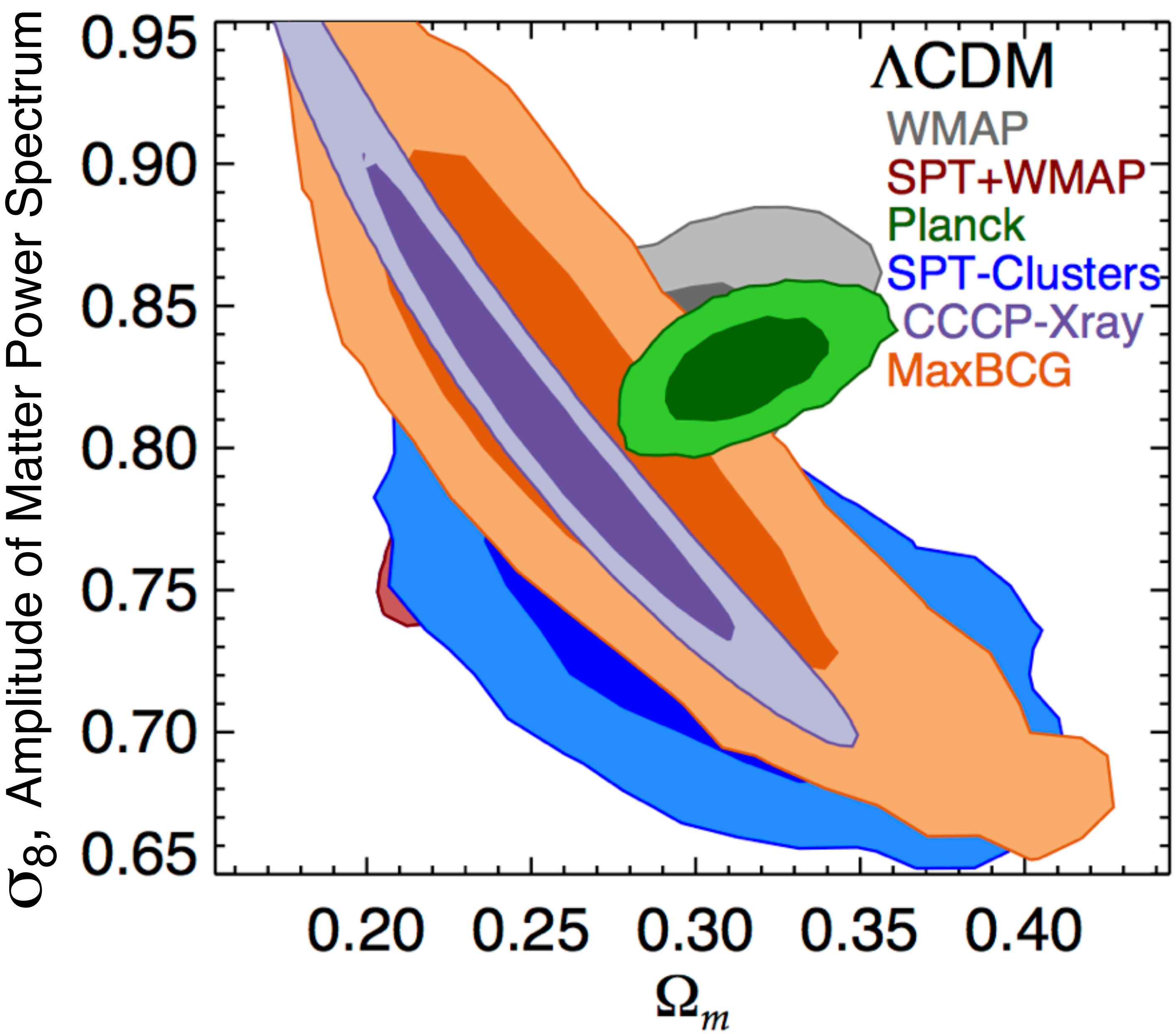
Planck Cosmology has ***profound*** mismatch with Cluster Abundance



Cluster counts ~ $(\sigma_8)^{10}$

Vikhlinin et al. 2009 (CCCP, X-rays)

Tension exists for ***SZ, X-ray, Optical*** cluster surveys and other probes of structure



- ***SZ, X-ray, and optical cluster surveys all favor lower σ_8, Ω_m*** (Reichardt+13, Vikhlinin +09, Rozo+10, etc.)
- **Other probes of structure are consistent with clusters**:
  - Weak lensing surveys (e.g, CFHTLS, Kilbinger+13)
  - Redshift space distortions (Macaulay+13)
  - Planck CMB lensing power spectrum (PlanckXVII)
- *A neutrino mass of $\Sigma m_\nu \sim 0.3$ eV would relieve this tension.*

However, I think there is still room to question evidence for high σ_8, Ω_m from Planck CMB.

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
3. Energy scale of inflation

Temperature Survey:

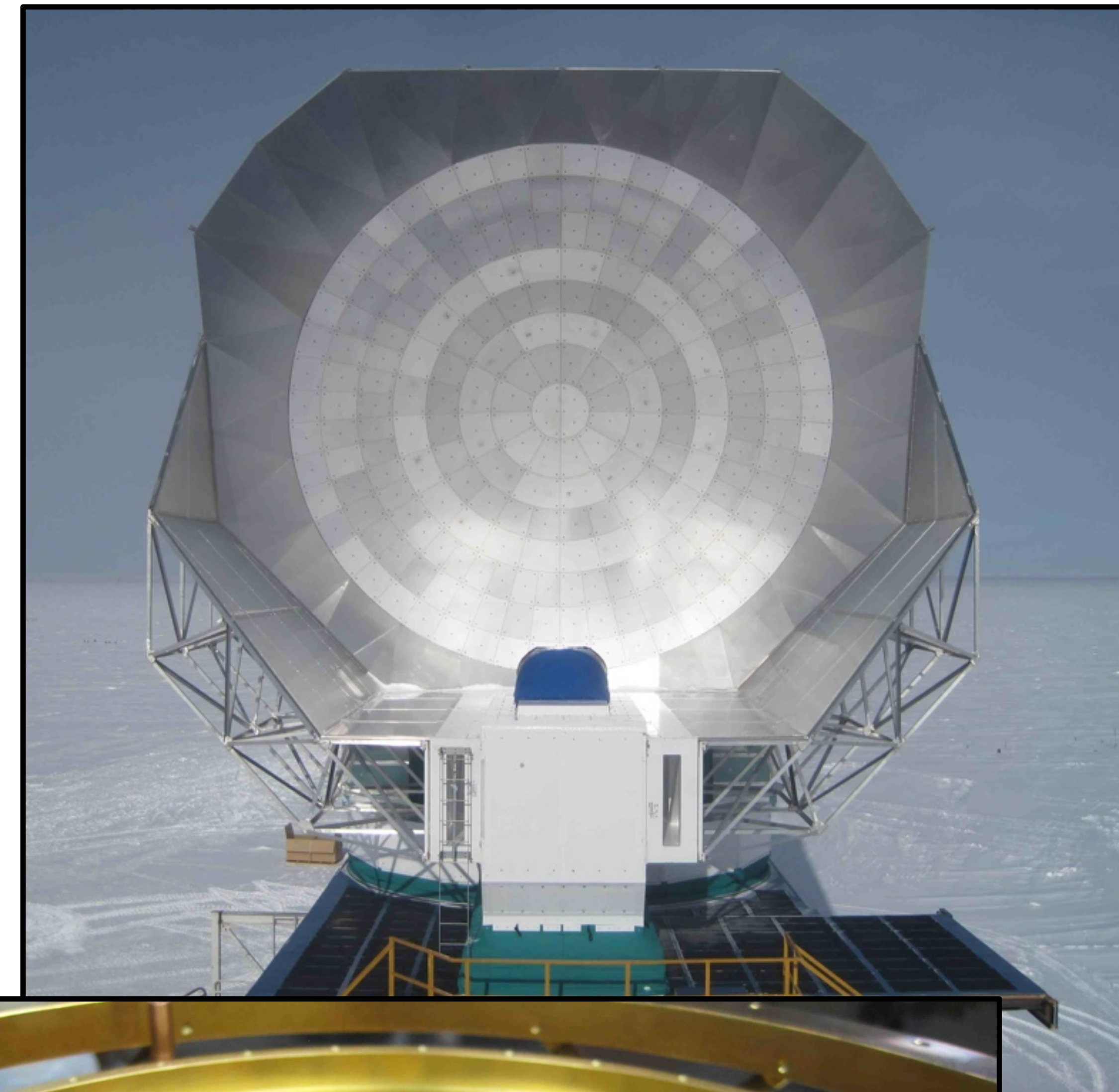
4. Deeper cluster survey

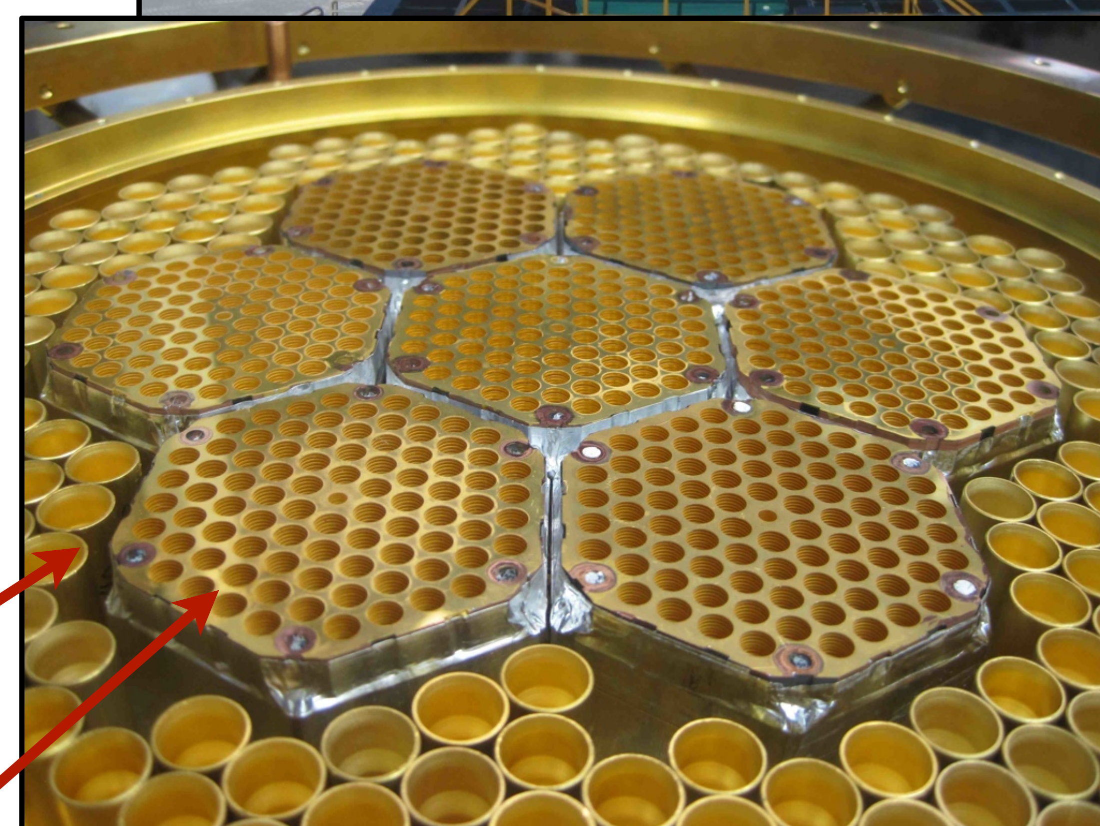
Status:

- First light Jan. 26, 2012

- 500 deg^2 survey to 6 uK-arcmin depth *(3x deeper than SPT-SZ)*

- Finished ~2 years of survey

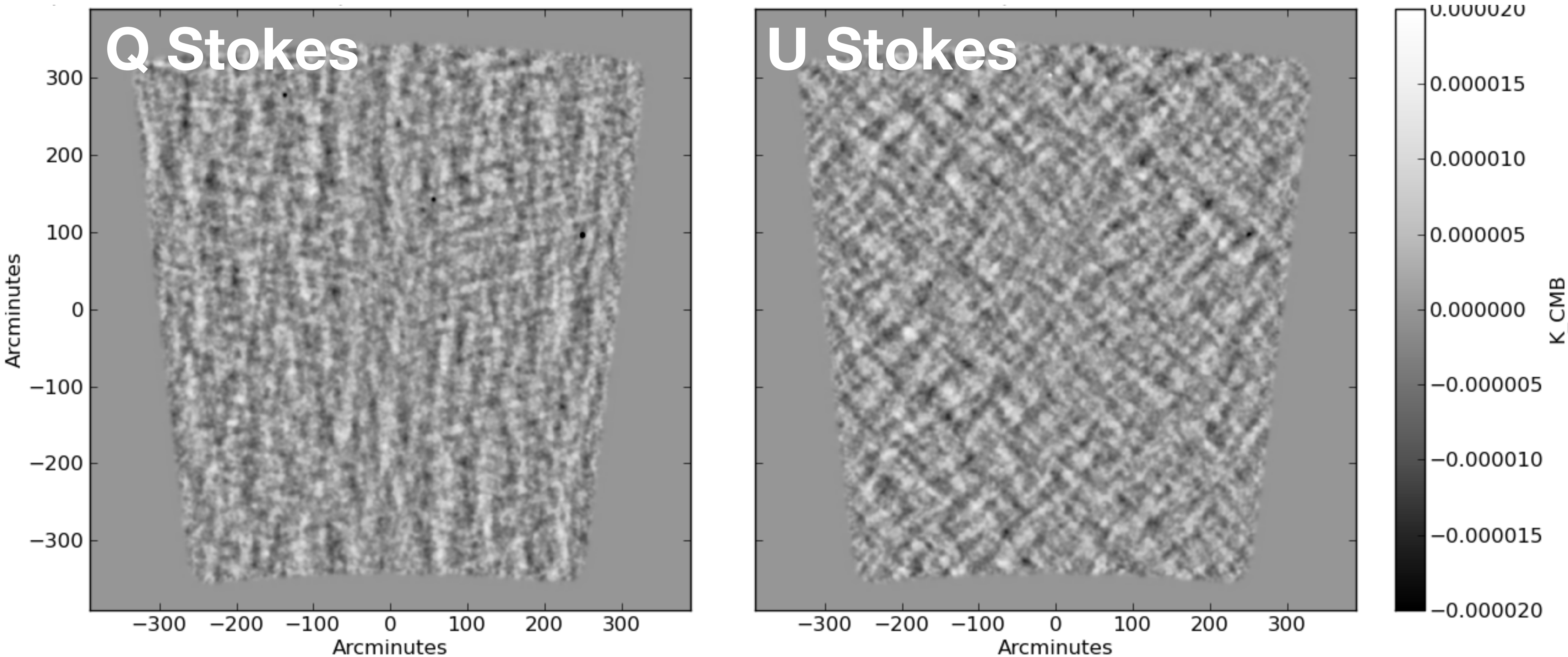




(360x) **100 GHz** detectors, (Argonne National Labs)

(1176x) **150 GHz** detectors (NIST)

SPTpol (2012): 100 deg^2 CMB Polarization Maps



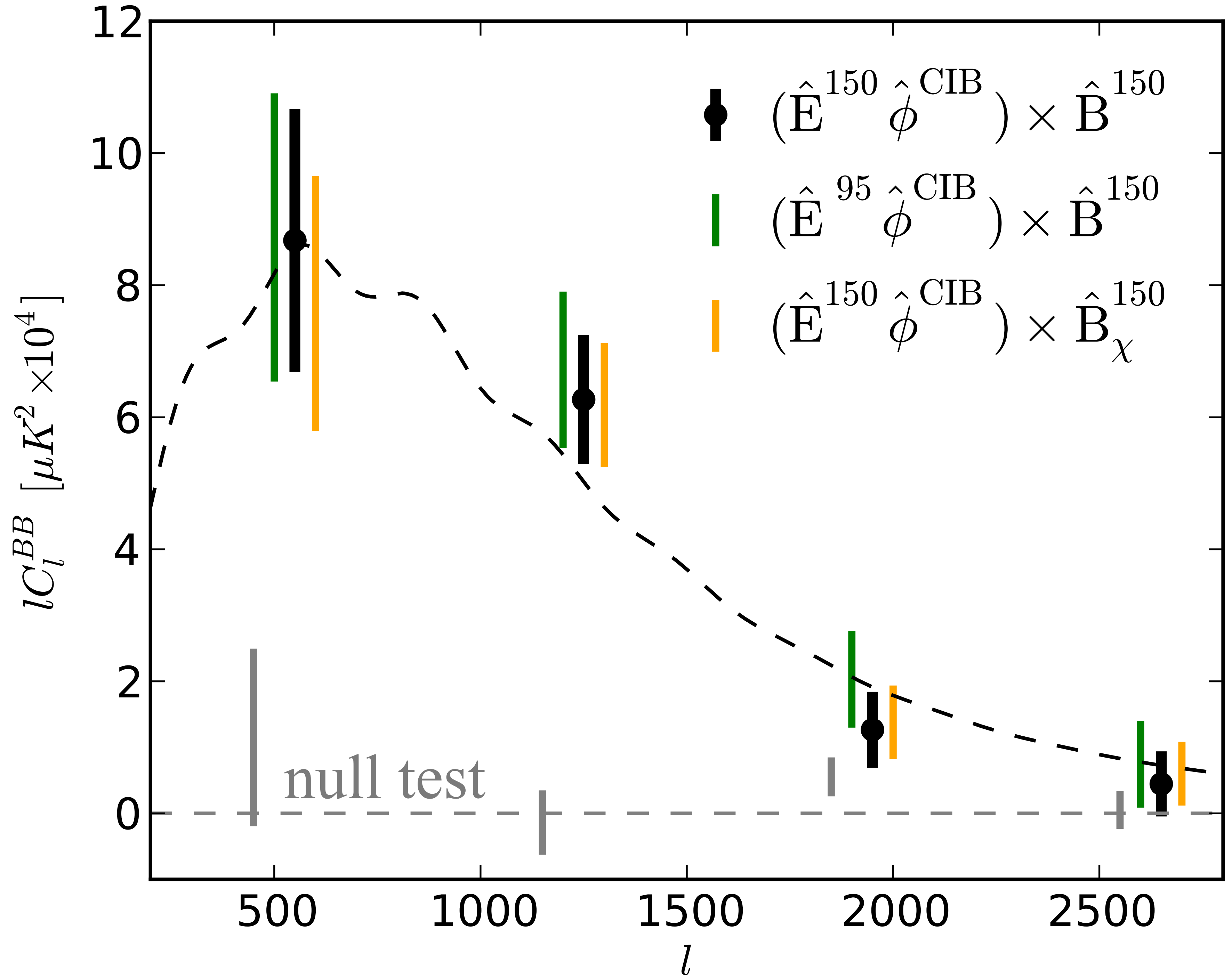
2012 to mid-2013: Observed 100 deg^2 SPT "deep" field to 6 uK-arcmin

- ***E-modes obvious in SPTpol maps***
- *Significant multi-wave (IR, sub-mm, radio, X-ray) overlap for lensing and cluster science*

2013-2015: Observe 500 deg^2 to constrain inflationary B-modes

- ***Collaboration with BICEP2/KECK/BICEP3 team to de-lens large angular scales***

Detection of B-mode Polarization in the CMB with Data from SPTpol

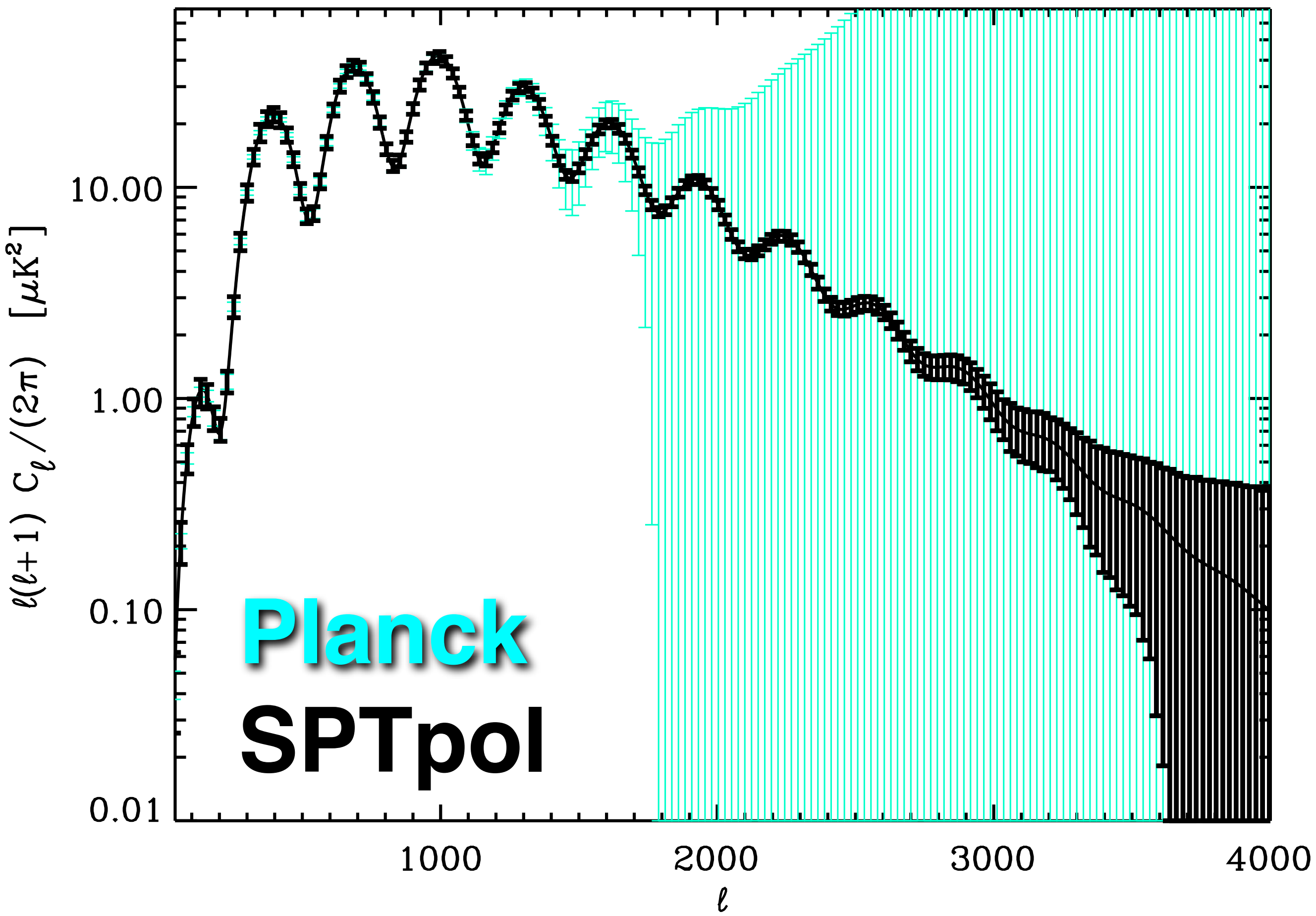


7.7-σ detection of lensing B-modes!

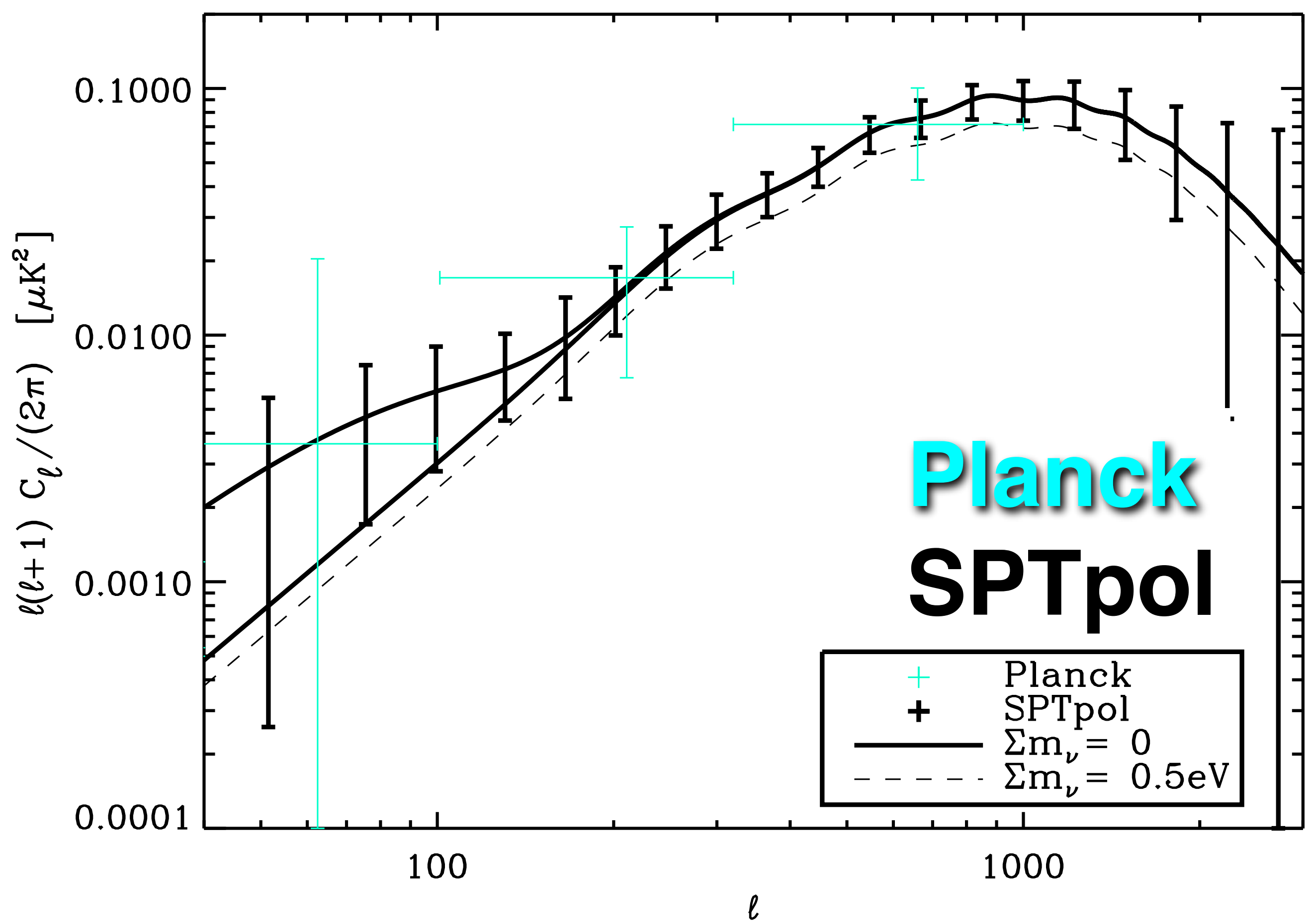
SPTpol, Hanson et al. (2013)

SPTpol: 500 deg² Projected Polarization Power Spectra

EE-Spectrum



BB-Spectrum



- *Expected ~40-σ detection of lensing of CMB*
- With Planck priors, ***SPTpol will constrain:***
  - ***Sum of neutrino masses to $\delta(\Sigma m_\nu)=0.09$ eV***
  - ***Tensor-to-scalar ratio to $\delta(r)=0.03$***

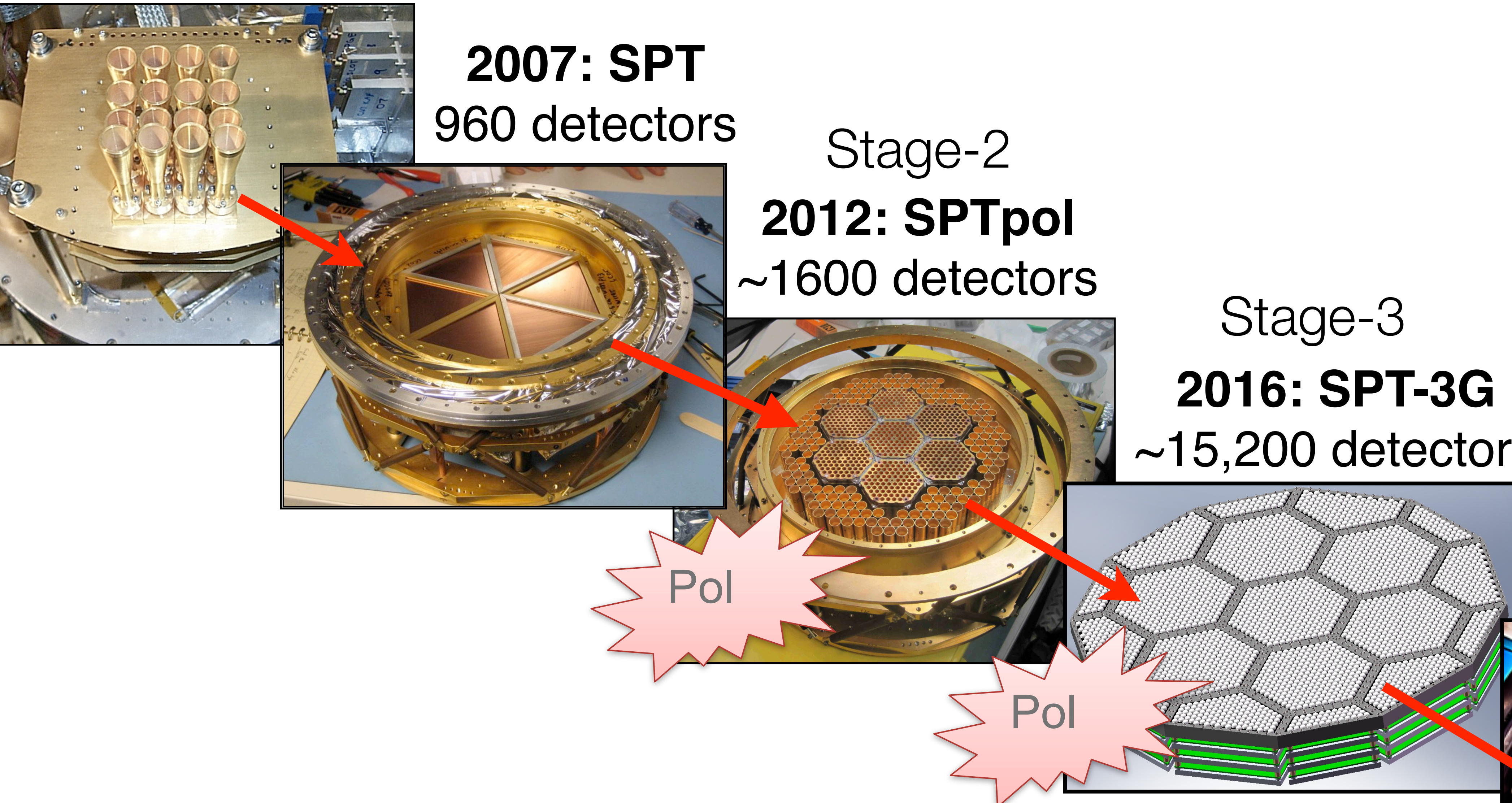
What's Next? Evolution of CMB Focal Planes

2001: ACBAR
16 detectors

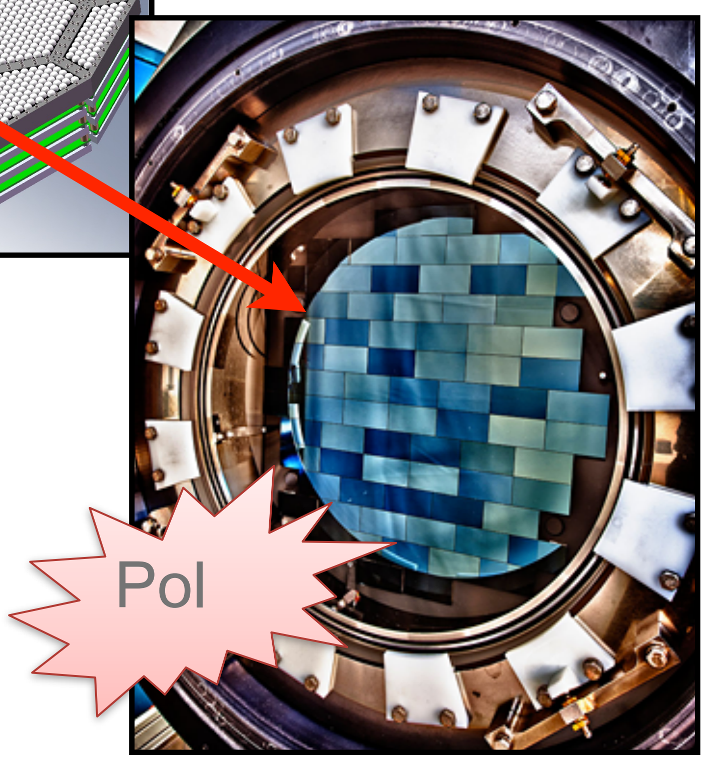
2007: SPT
960 detectors

Stage-2
2012: SPTpol
~1600 detectors

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

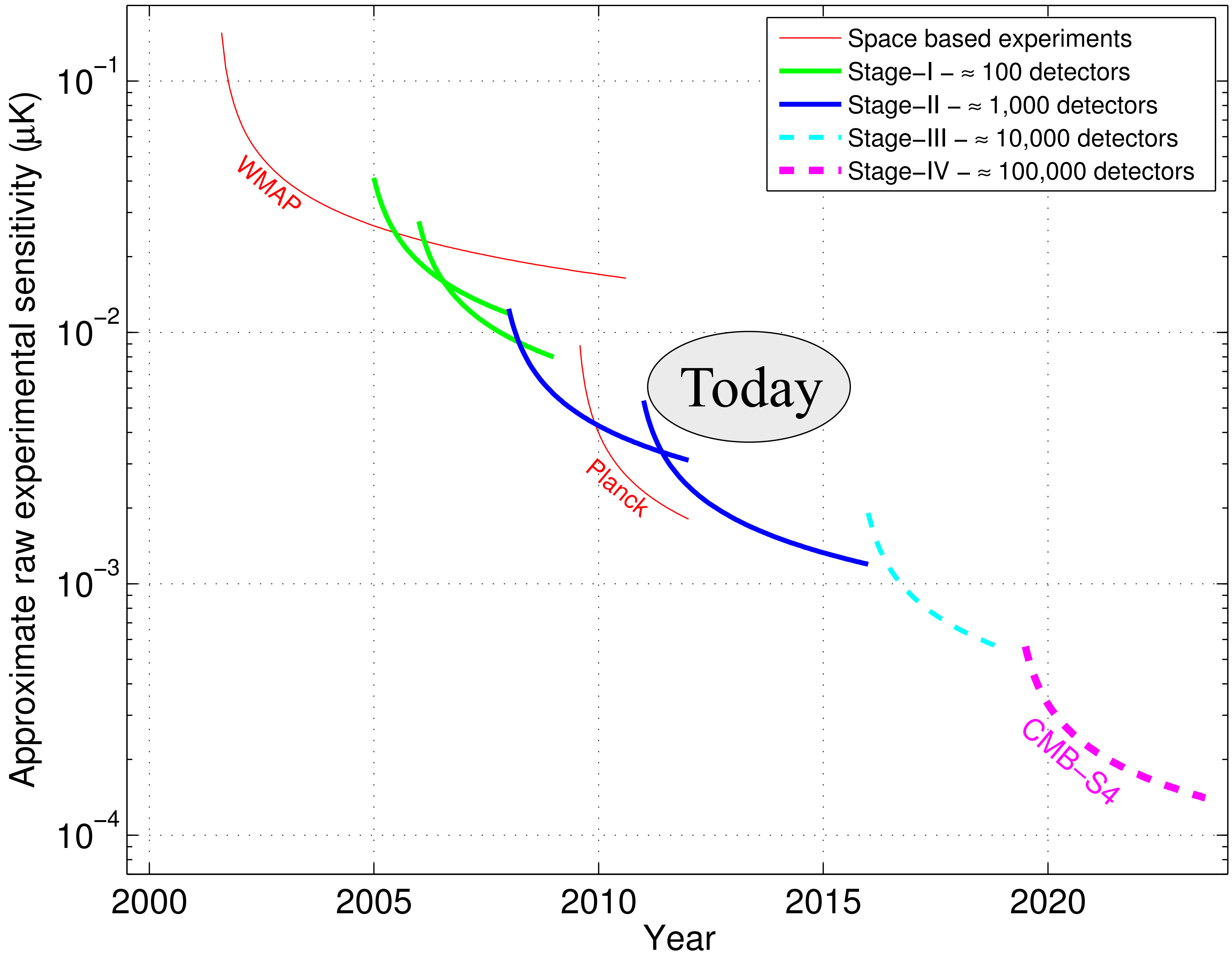


Stage-4
2020?: CMB-S4
100,000+ detectors



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

CMB Experimental Stages



Stage-IV CMB experiment = **CMB-S4**

~200x faster than today's Stage 2 experiments

Snowmass: CF5 Neutrinos Document
arxiv:1309.5383 (on the arxiv today!)

CMB-S4: A CMB Stage 4 Experiment

- **Two Surveys:**
  - Inflation survey (~few% of sky)
  - Neutrino survey (~half of sky)

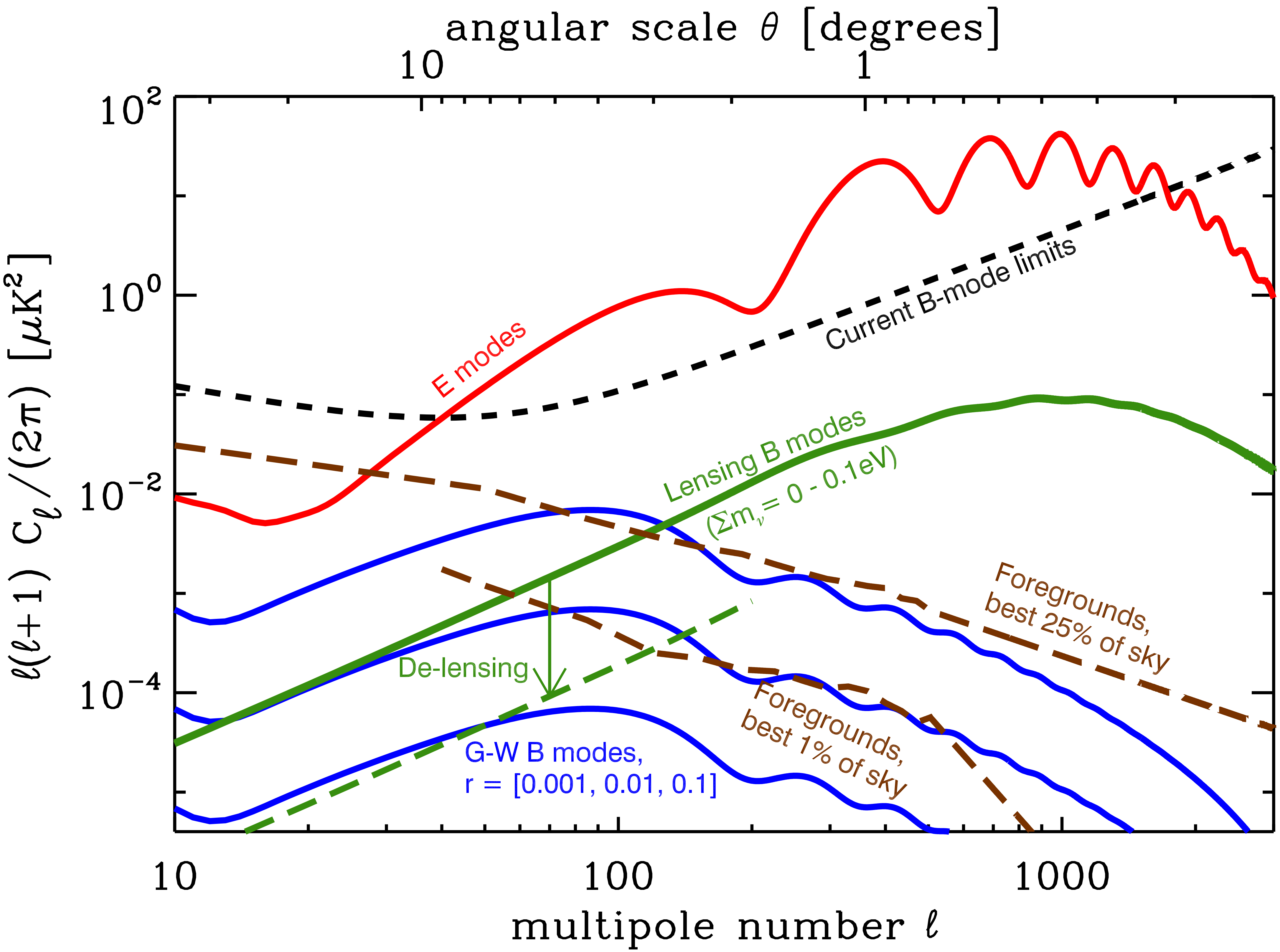
- **Experimental Configuration:**
  - 100,000 - 500,000 detectors on multiple platforms
  - Spanning 40 - 240 GHz for foreground removal
  - < 3 arcmin resolution required for CMB lensing, neutrino science

- **Target noise of ~1 uK-arcmin depth over half the sky, starting in 2020**

Primary technical challenge will be from the scaling of the CMB detector arrays

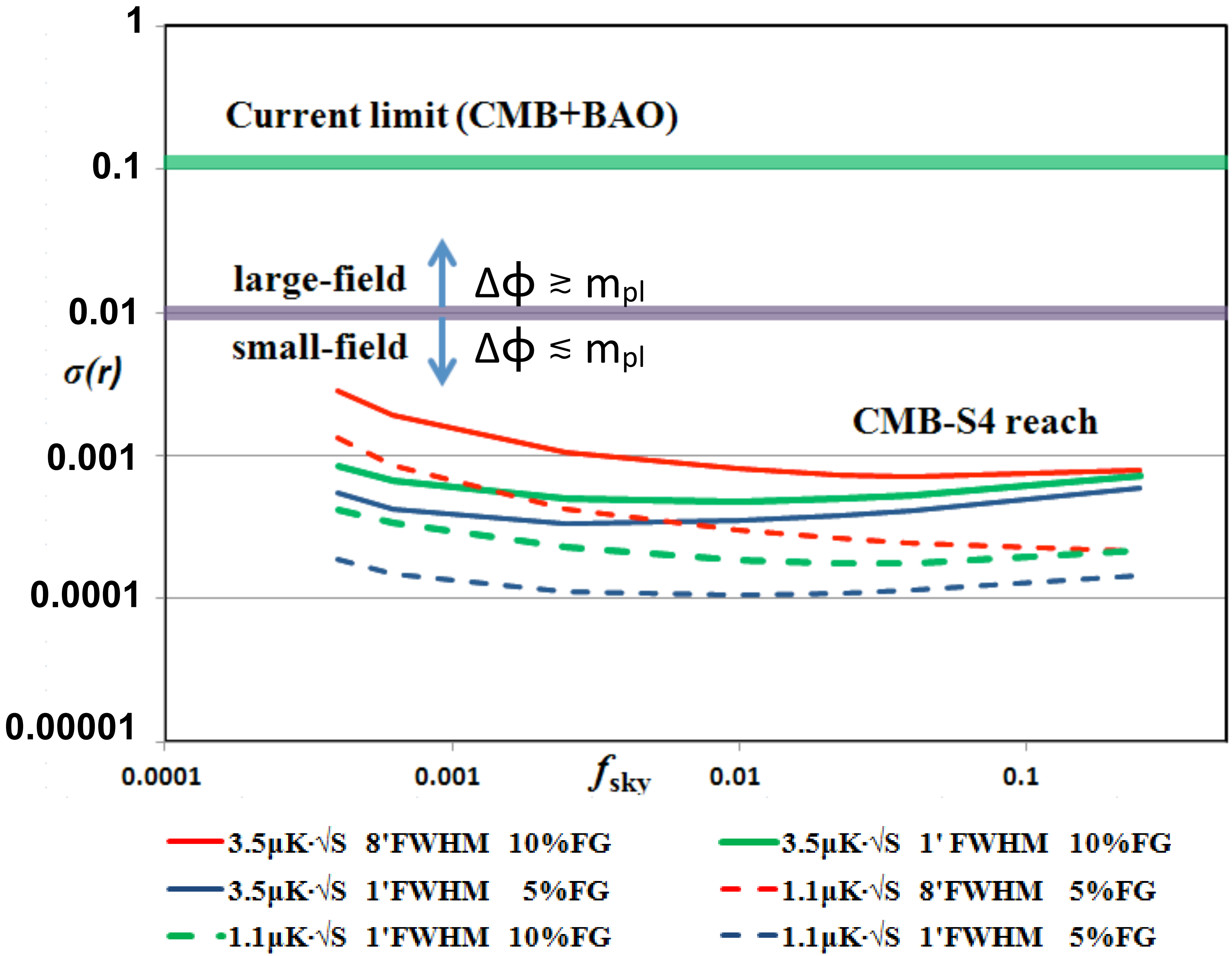
Snowmass: CF5 Neutrinos Document
arxiv:1309.5383

CMB Polarization Power Spectrum



Snowmass: CF5 Inflation Document
arxiv:1309.5381

CMB-S4 Constraints on Tensor-to-Scalar Ratio

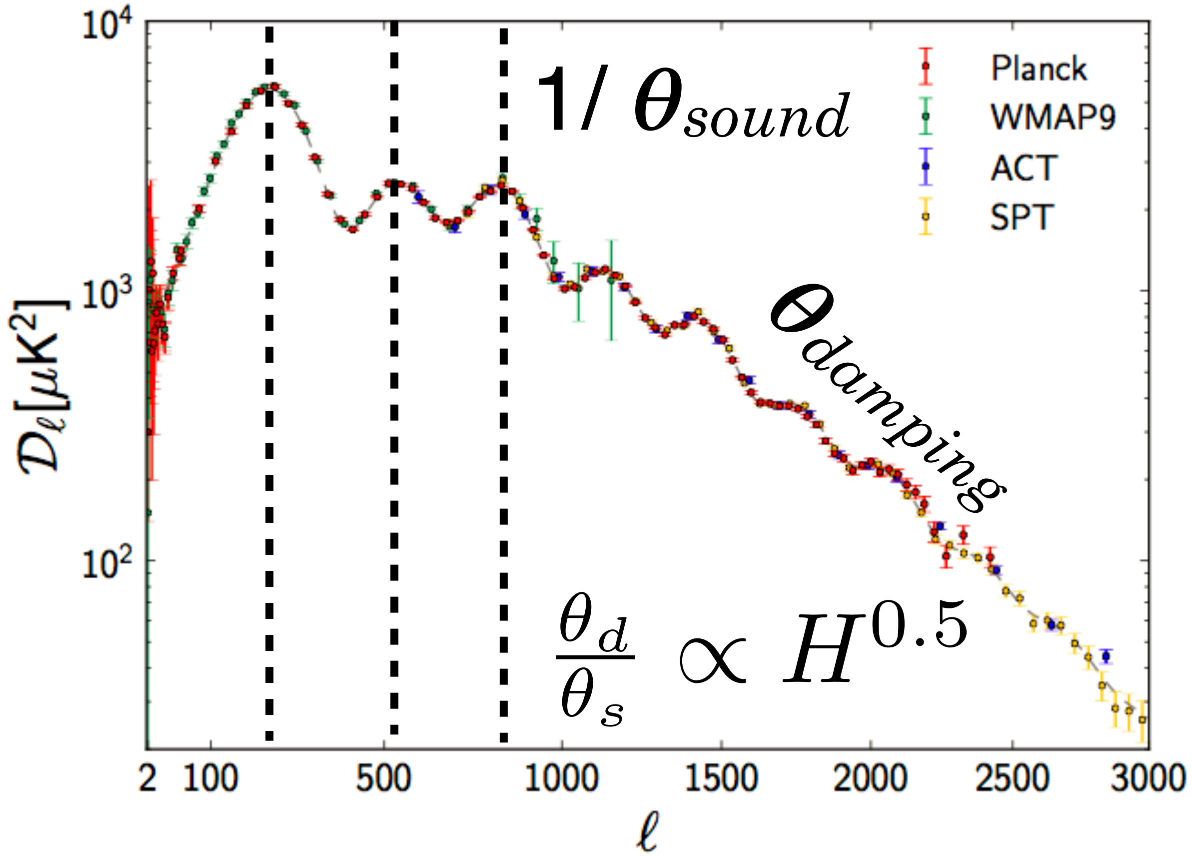


$\sigma(r) \sim 0.001$ will be attainable for a broad range of configurations for CMB-S4

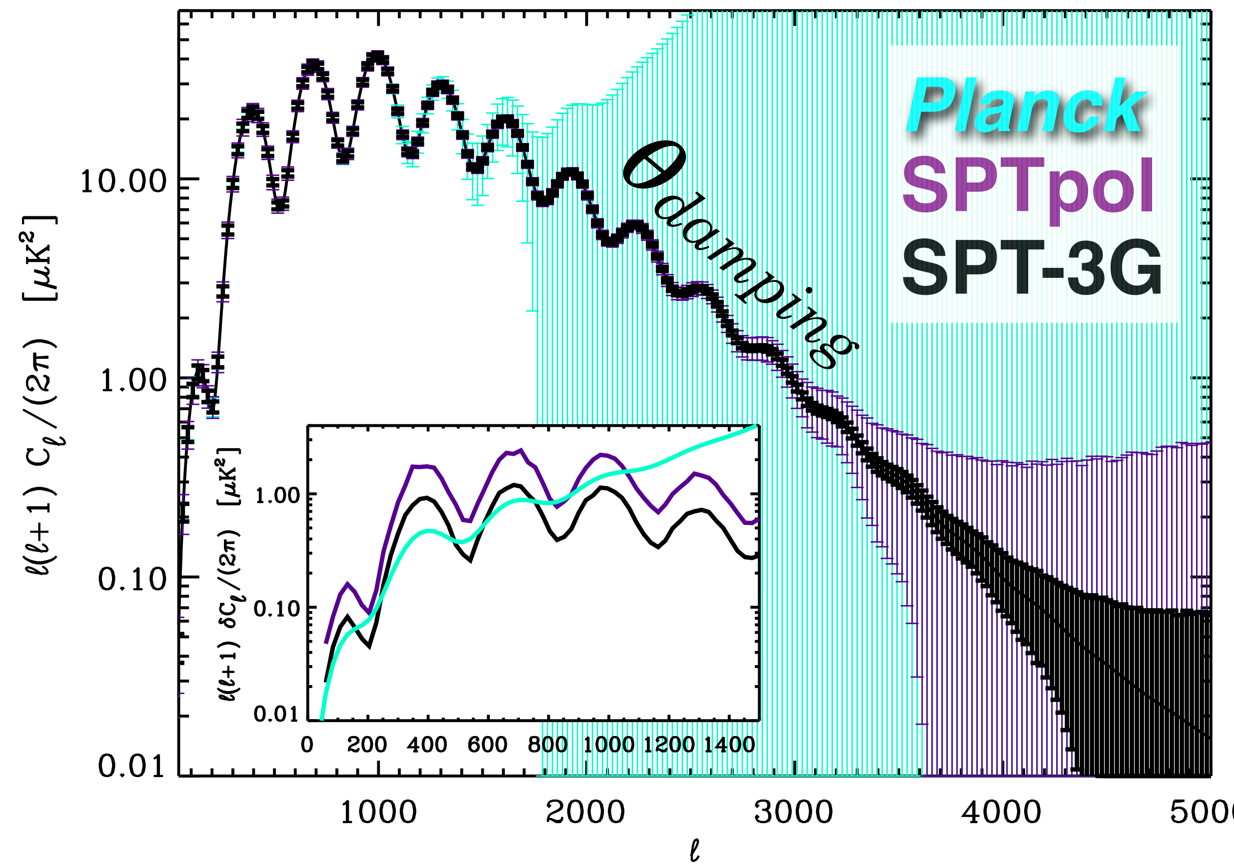
Snowmass: CF5 Inflation Document
arxiv:1309.5381

CMB-S4 Constraints on Effective Number of Relativistic Species, Neff

CMB Temperature (***Current***)



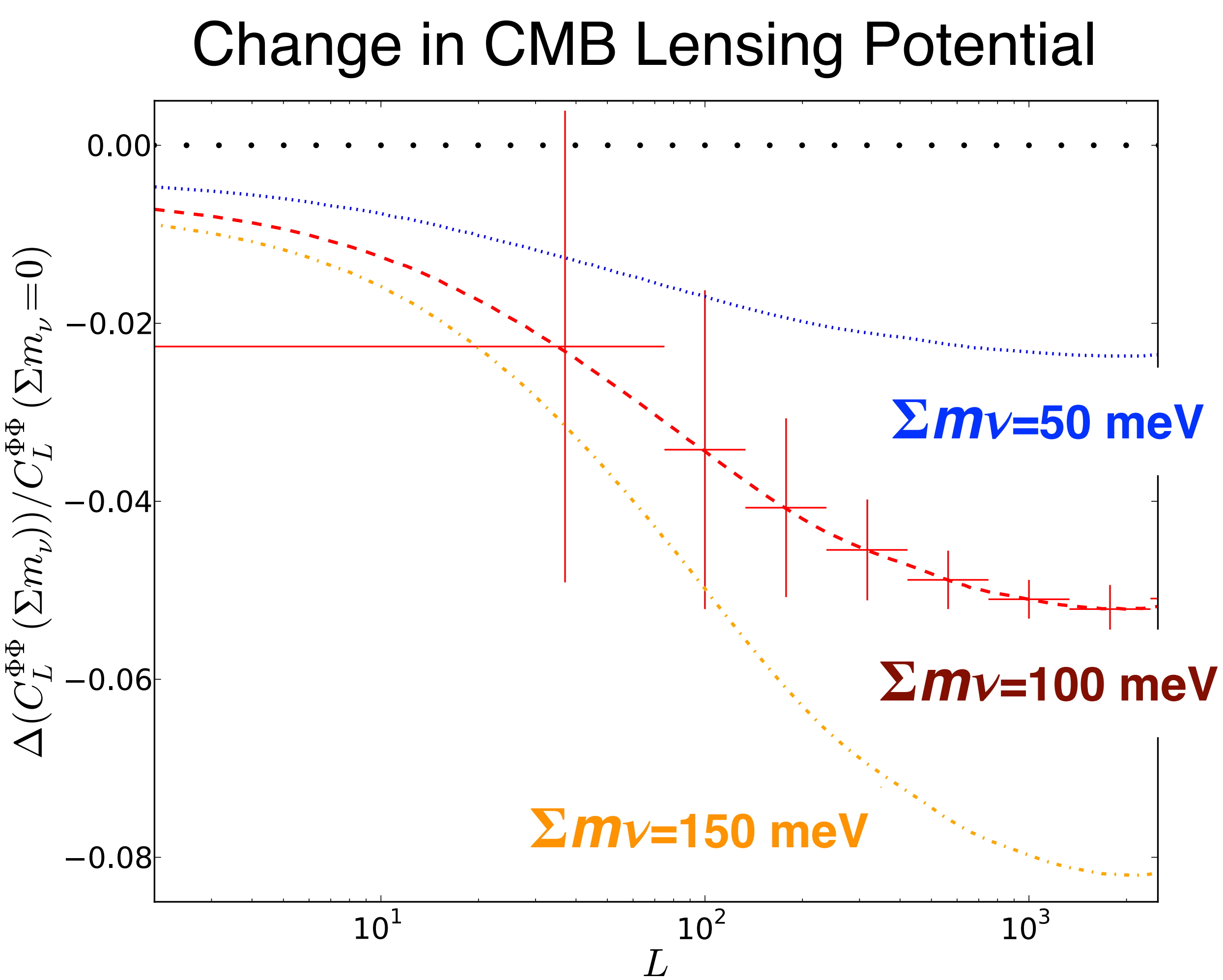
CMB E-mode Polarization (***Projected***)

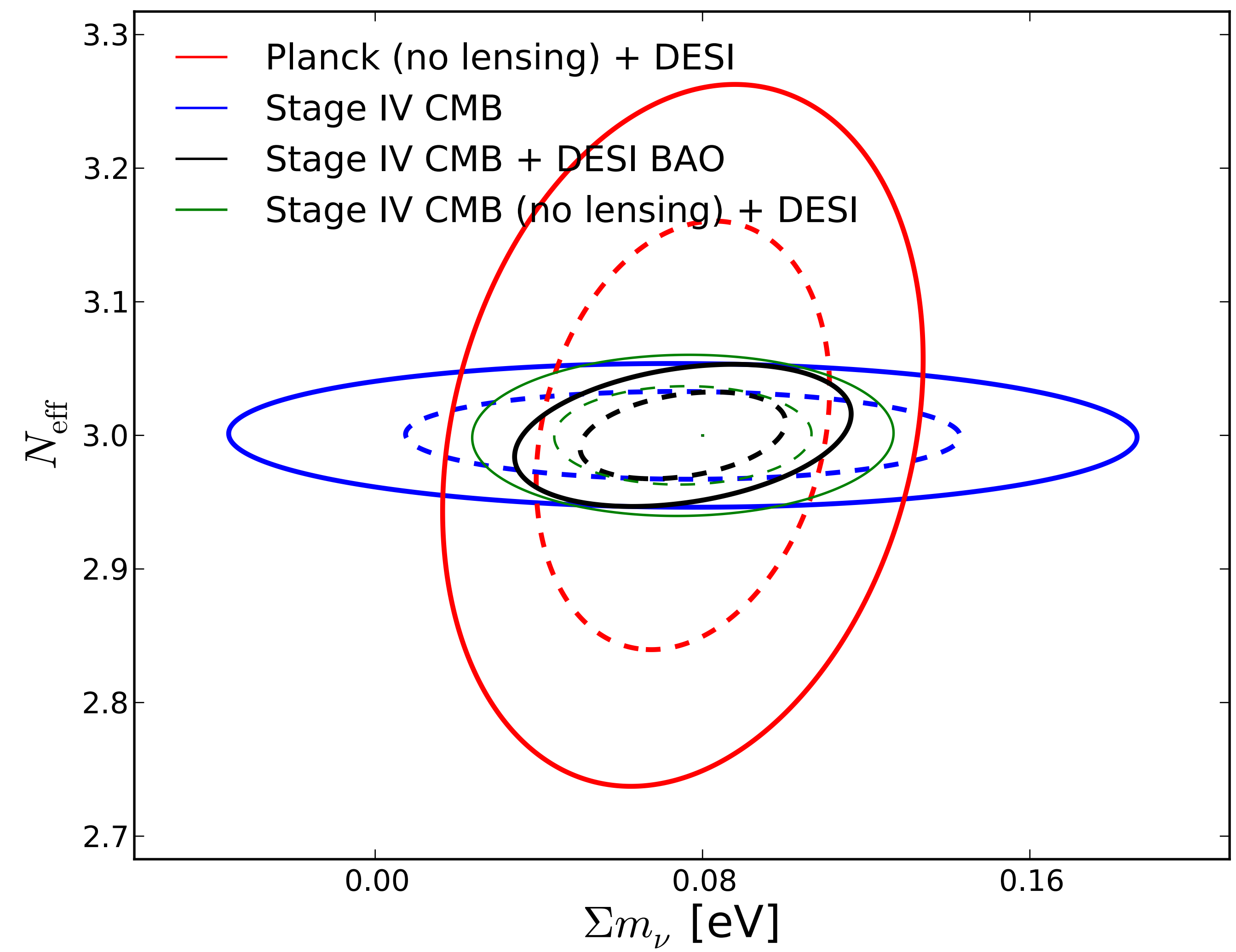


Current CMB: $N_{\rm eff}$ = 3.36 +/- 0.34
SPTpol (Stage 2): $\sigma(N_{\rm eff})$=0.12
SPT-3G (Stage 3): $\sigma(N_{\rm eff})$=0.06
CMB+BAO (Stage 4): $\sigma(N_{\rm eff})$=0.02

Precision test of standard model prediction of Neff=3.046

CMB-S4 Constraints on Neff and the Sum of the Neutrino Masses, Σmν





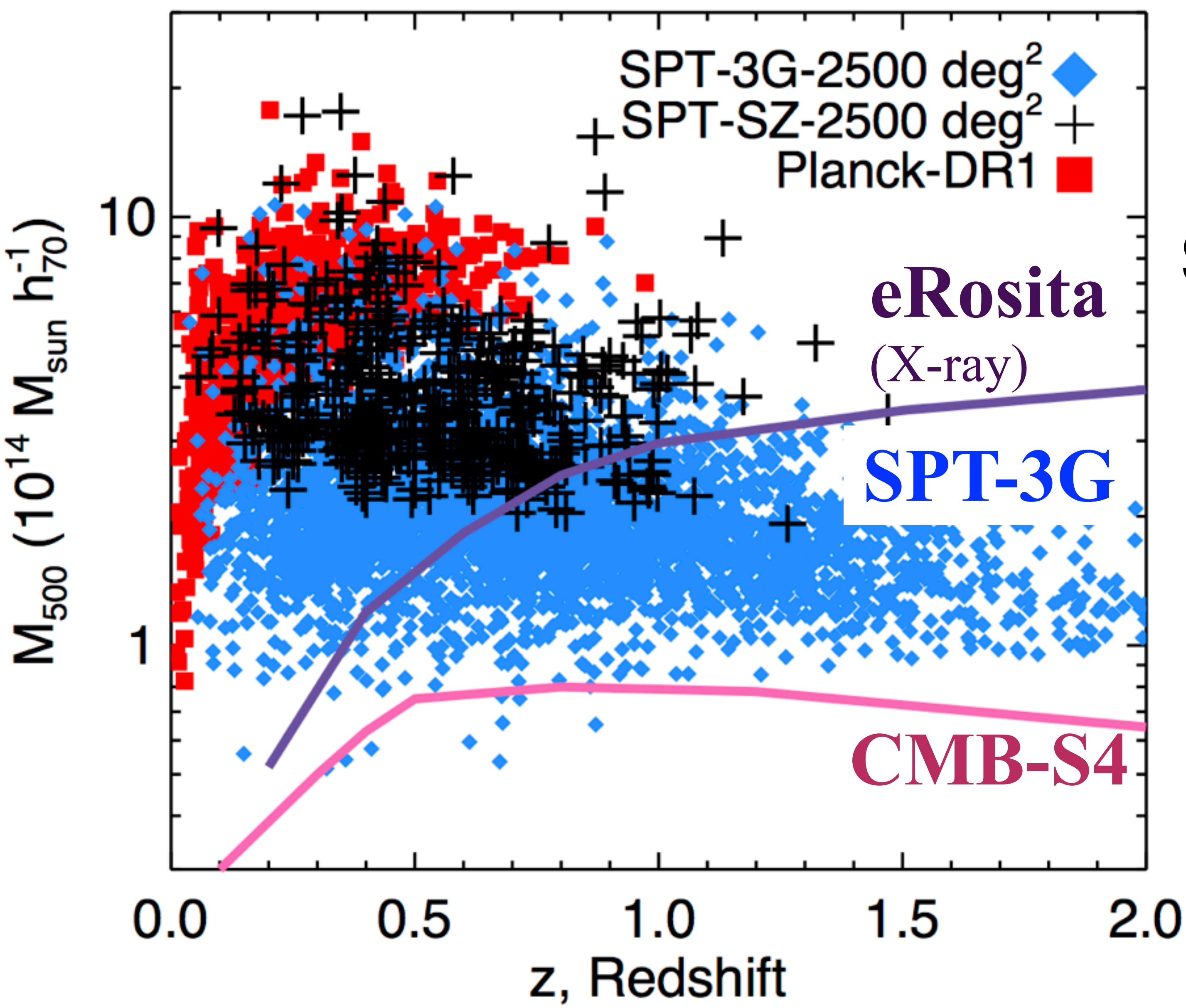
Planck (2014):	**σ(Σmν)= 117 meV**
SPTpol (Stage 2):	σ(Σmν)= 96 meV
SPT-3G+BOSS (Stage 3):	σ(Σmν)= 61 meV
CMB+BAO (Stage 4):	**σ(Σmν)= 16 meV**

Will detect neutrino mass at > 3.5-σ at lower limit of 58 meV from oscillation experiments

Snowmass: CF5 Neutrinos Document
arxiv:1309.5383

CMB Sunyaev-Zel'dovich Cluster Survey

Cluster Mass vs Redshift for CMB/SZ Experiments



CMB measurements detect clusters through the "shadows" they make in the CMB, the Sunyaev-Zel'dovich (SZ) effect:

SPT-SZ/pol: N_{clust} **~ 1,000**
SPT-3G: N_{clust} **~ 10,000**
CMB-S4: N_{clust} **~ 100,000+**

CMB lensing measured from individual clusters, can directly calibrate cluster mass:

SPT-3G: σ(M) ~ 3%

CMB-S4: σ(M) < ~0.1%

Summary

- **SPT-SZ survey complete with broad spectrum of science results:**
  - Astrophysics and cosmology from high-z galaxies, clusters
  - CMB power spectrum measurements consistent with Planck
  - Interesting shifts in σ_8, Ω_m worth watching; will CMB polarization change anything?
- **SPTpol is ~2 years into 4-year survey, and has detected B-modes!**
  - Detection of B-modes via cross-correlation
  - Polarization experiments are on the verge of improving neutrino mass and tensor-to-scalar ratio constraints
- **SPT-3G and Stage 4 CMB experiments will be at an exciting threshold where they can constrain, or detect, new physics:**
  - $\sigma(r) \sim 0.001$; large vs small field inflation?
  - $\sigma(N_{\mathrm{eff}}) \sim 0.02$; new physics in neutrino sector?
  - $\sigma(\Sigma m_\nu) \sim 16$ meV ; with DESI and LSST, detect neutrino mass?