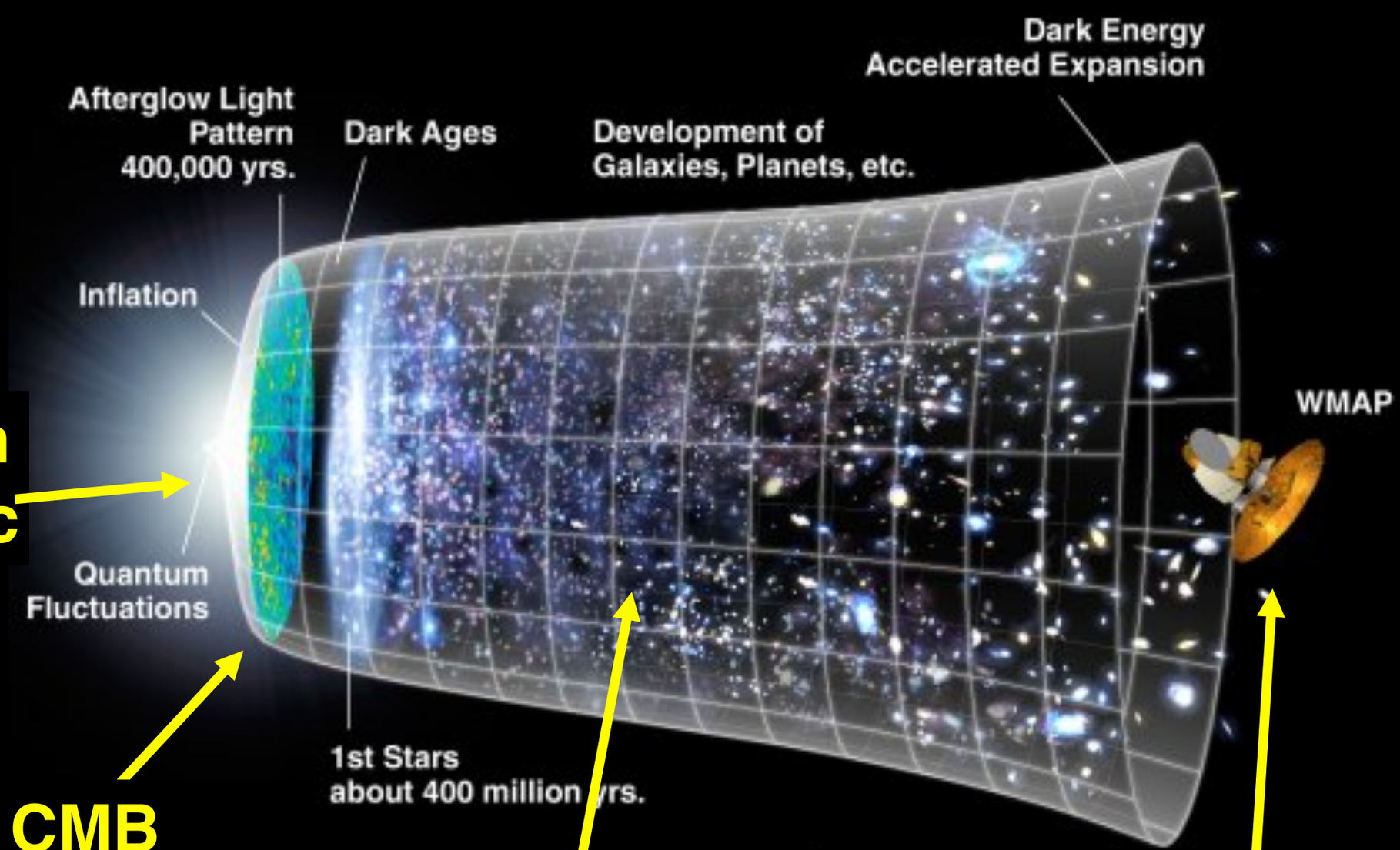
Synergies with Cosmic Microwave Background, and other data sets

Bradford Benson
(Fermilab / U. Chicago)

The CMB as a Backlight

(time since Big Bang)



Inflation
10^{-34} sec

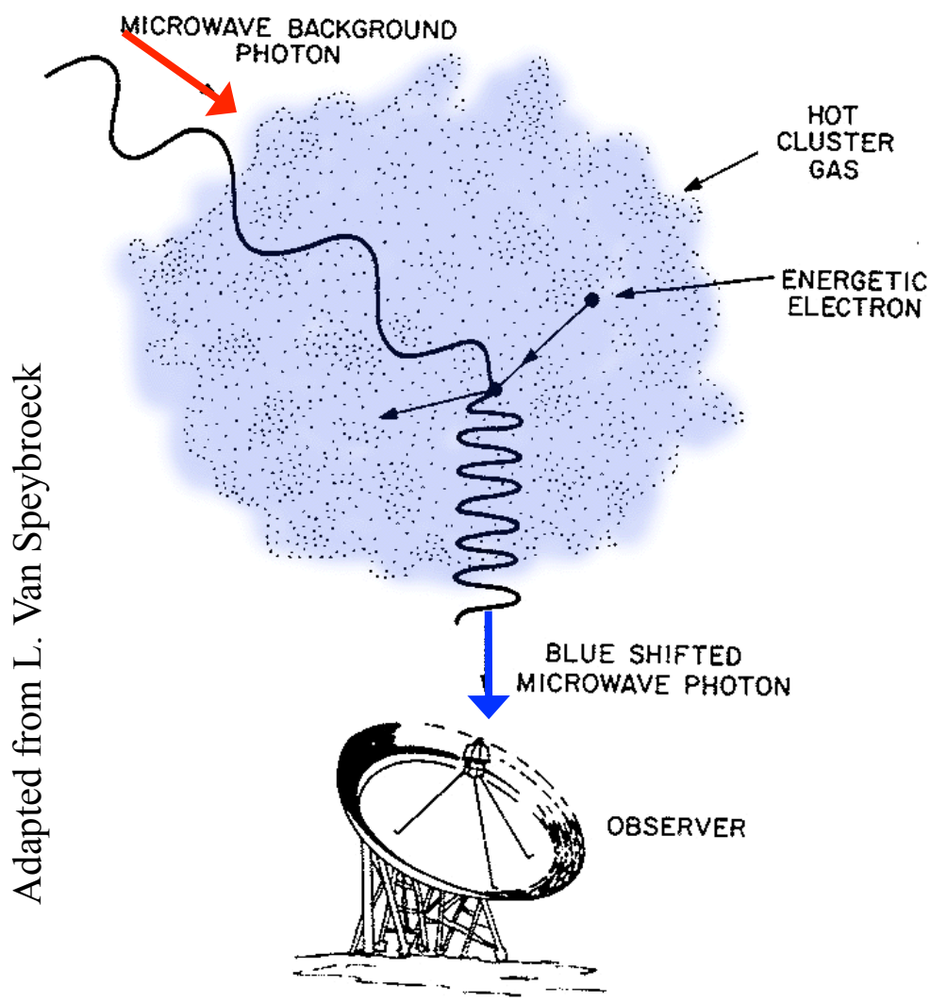
The CMB
400,000 years

First clusters of galaxies
~4 billion years

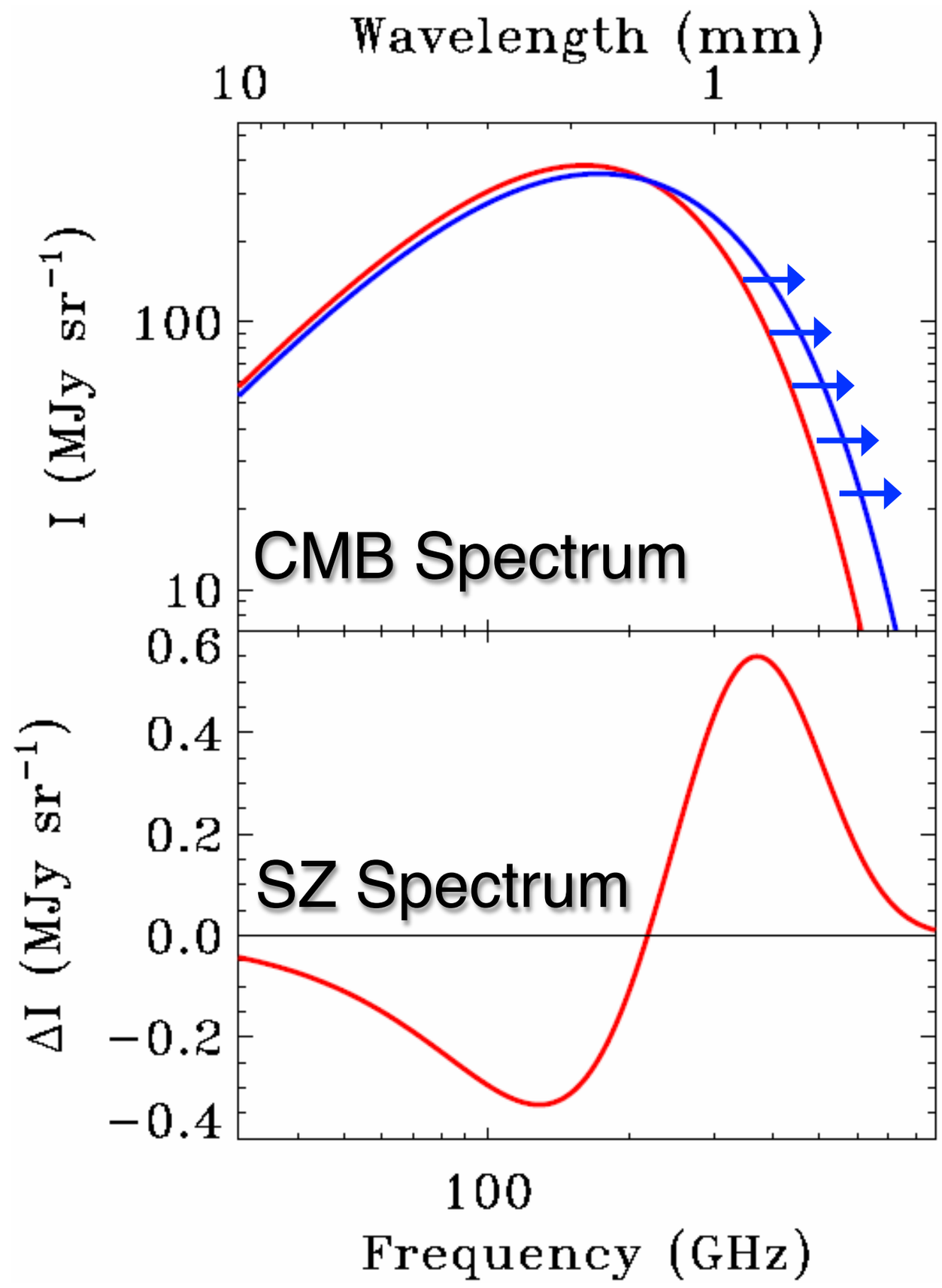
Today
14 billion years

graphic from NASA/WMAP

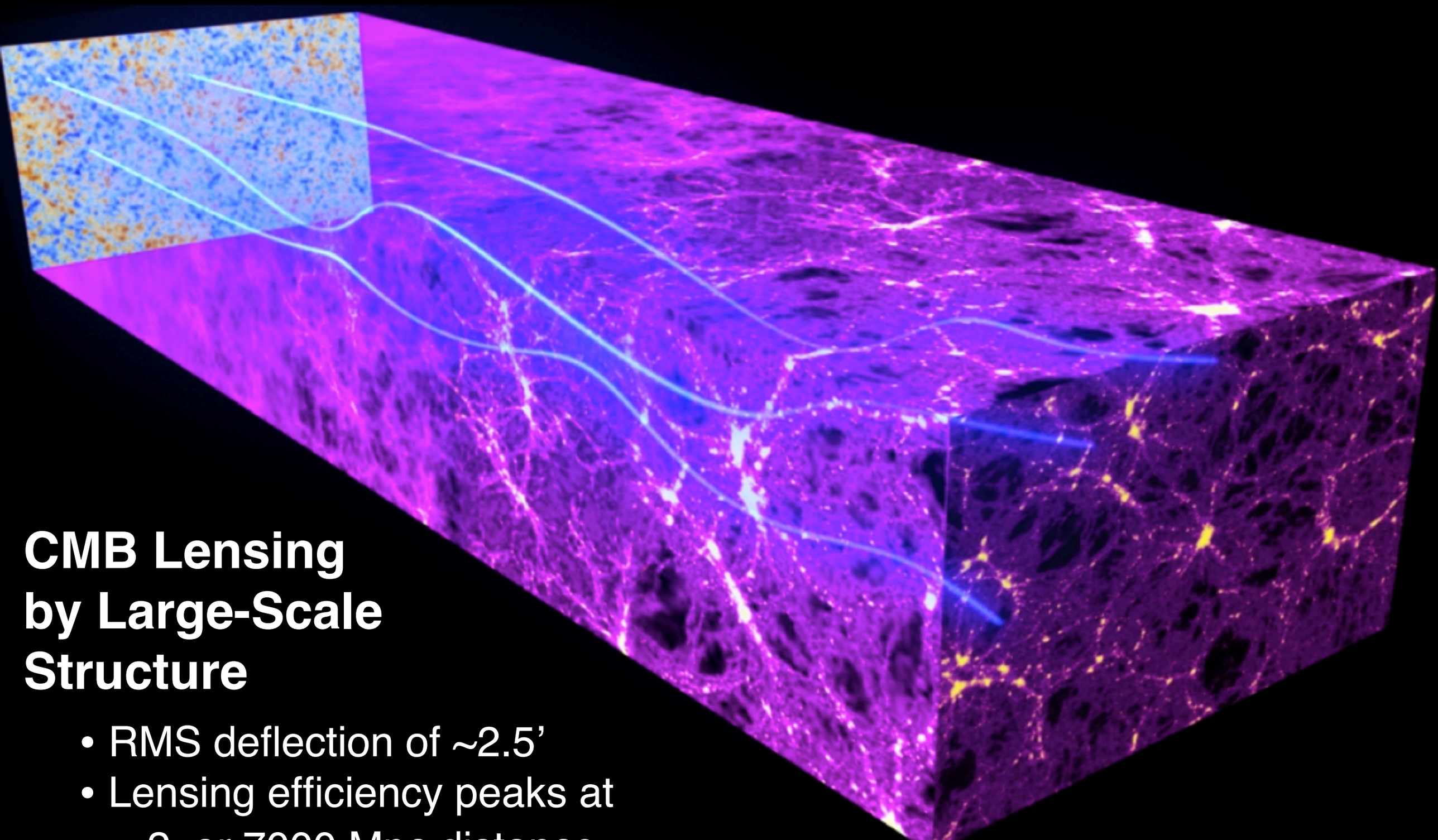
The Sunyaev Zel'dovich (SZ) Effect



Adapted from L. Van Speybroeck



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



CMB Lensing by Large-Scale Structure

- RMS deflection of ~2.5’
- Lensing efficiency peaks at $z \sim 2$, or 7000 Mpc distance
- Coherent on ~degree (~300 Mpc) scales

graphic from Planck/ESA

Cross-Correlation Science from SPTxDES

DES x SPT	CMB Lensing Convergence (κ) Map	SZ Temperature Profile	CMB Polarization	Small-scale CMB Lensing
Galaxy Map	Measure galaxy bias; the relationship between galaxy stellar and halo mass	Calibrate SZ and optical cluster observables to improve constraints on cosmology and cluster evolution	Gravitational potential from DES galaxies convolved with E-modes to estimate their B-mode contribution	CMB cluster lensing will calibrate DES cluster masses to improve cosmological constraints
Shear Map	Constrain systematics in galaxy shape measurements (e.g., linear and magnification bias)	Probes baryonic pressure as a function of distance from halos	Gravitational potential from DES shear convolved with E-modes to estimate their B-mode contribution	Measure CMB lensing around DES shear peaks, tomographic measurement of large-scale structure
Tangential Shear [galaxy-galaxy or cluster lensing]	Measure tangential shear of DES galaxies around SZ-selected lensing peaks	Lensing mass estimates of SZ-selected clusters to improve cluster cosmological constraints		

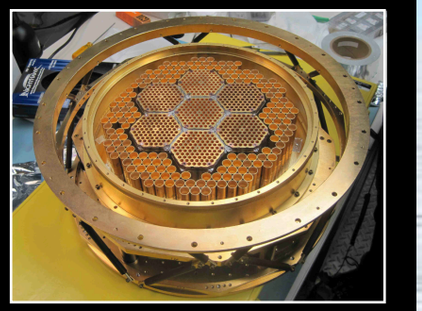
The South Pole Telescope (SPT)

10-meter sub-mm quality wavelength telescope

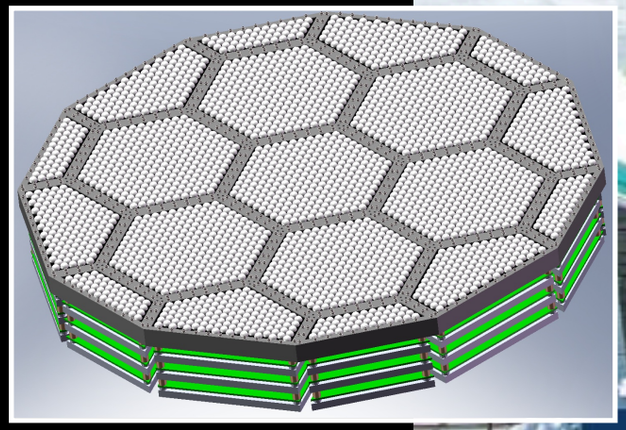
100, **150**, **220** GHz and
1.6, **1.2**, **1.0** arcmin resolution

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:

POLARBEAR

2.5-meter aperture on
Atacama Plateau, Chile

100, **150** GHz and
5.0, **3.5** arcmin resolution

2012: Polarbear
1200 detectors
150 GHz

2014: Polarbear2
~7000 detectors
100,150 GHz

ACT

2007: ACT
~3000 detectors
150,220,280 GHz

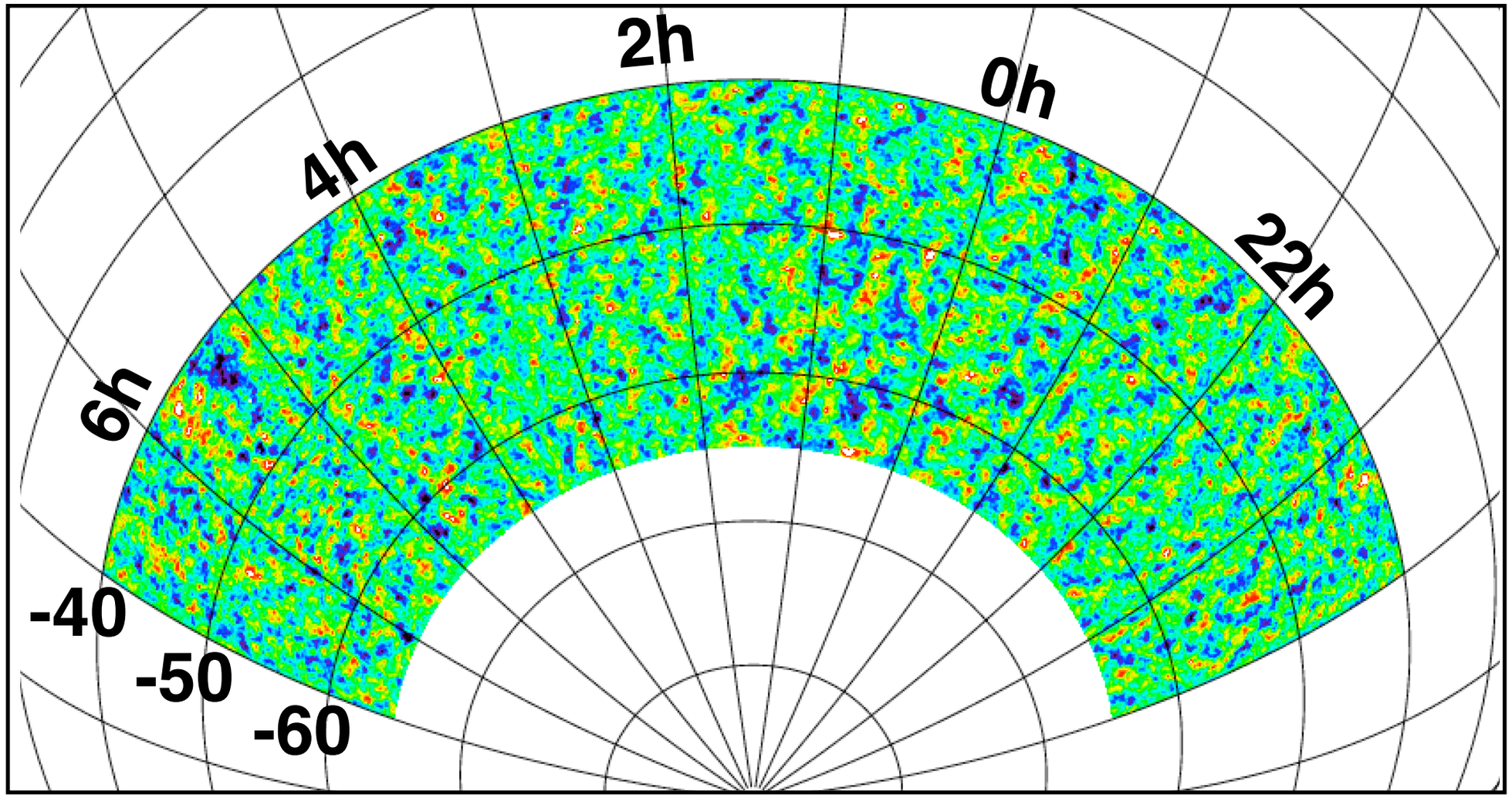
2013: ACTpol
~3000 detectors
90, 150 GHz
+Polarization

6 meter telescope
17,000 feet, Atacama Desert
148 GHz, 217 GHz, 277 GHz
Each with 1024 superconducting transition edge sensors at 0.3 K.

Planck

- 9 frequencies from 30-850 GHz
- SZ sensitivity mostly from HFI 100, 143, 217 GHz, with ~7 arcmin effective beam
- 29 months of survey data in hand, only first ~14 months released

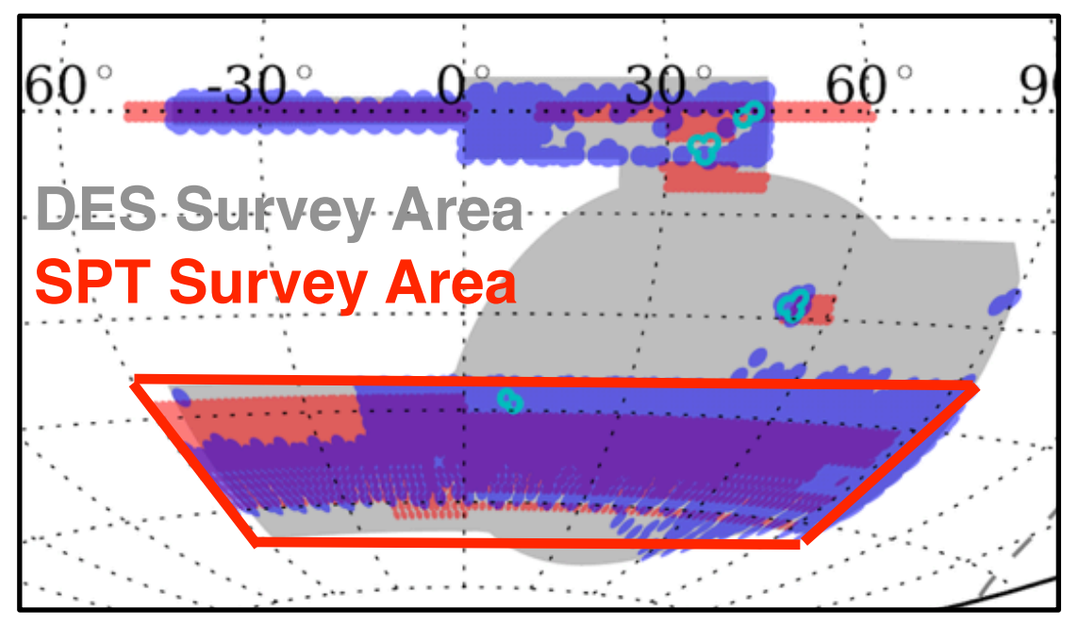
The 2500 deg² SPT-SZ Survey (2007-2011):

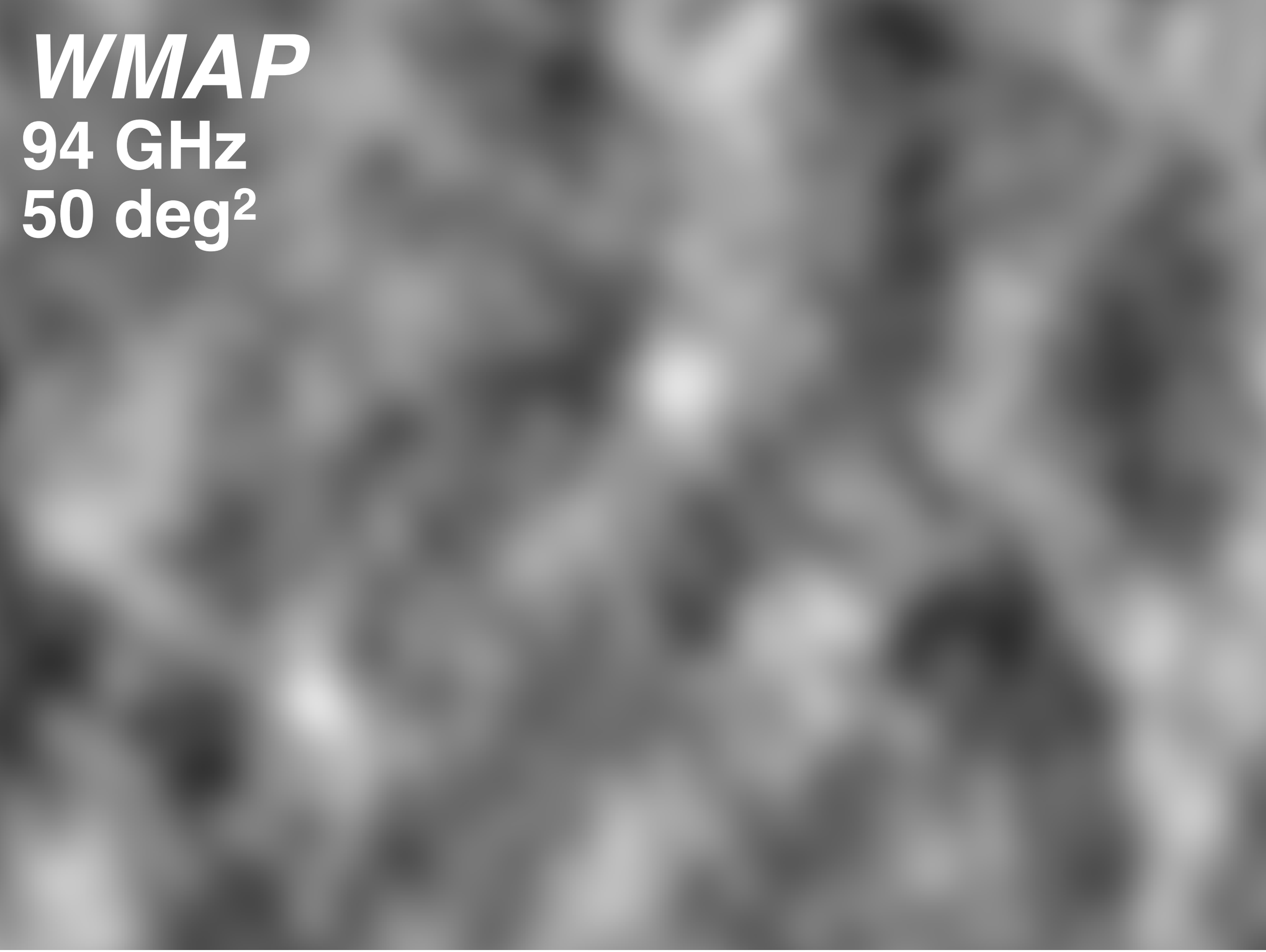


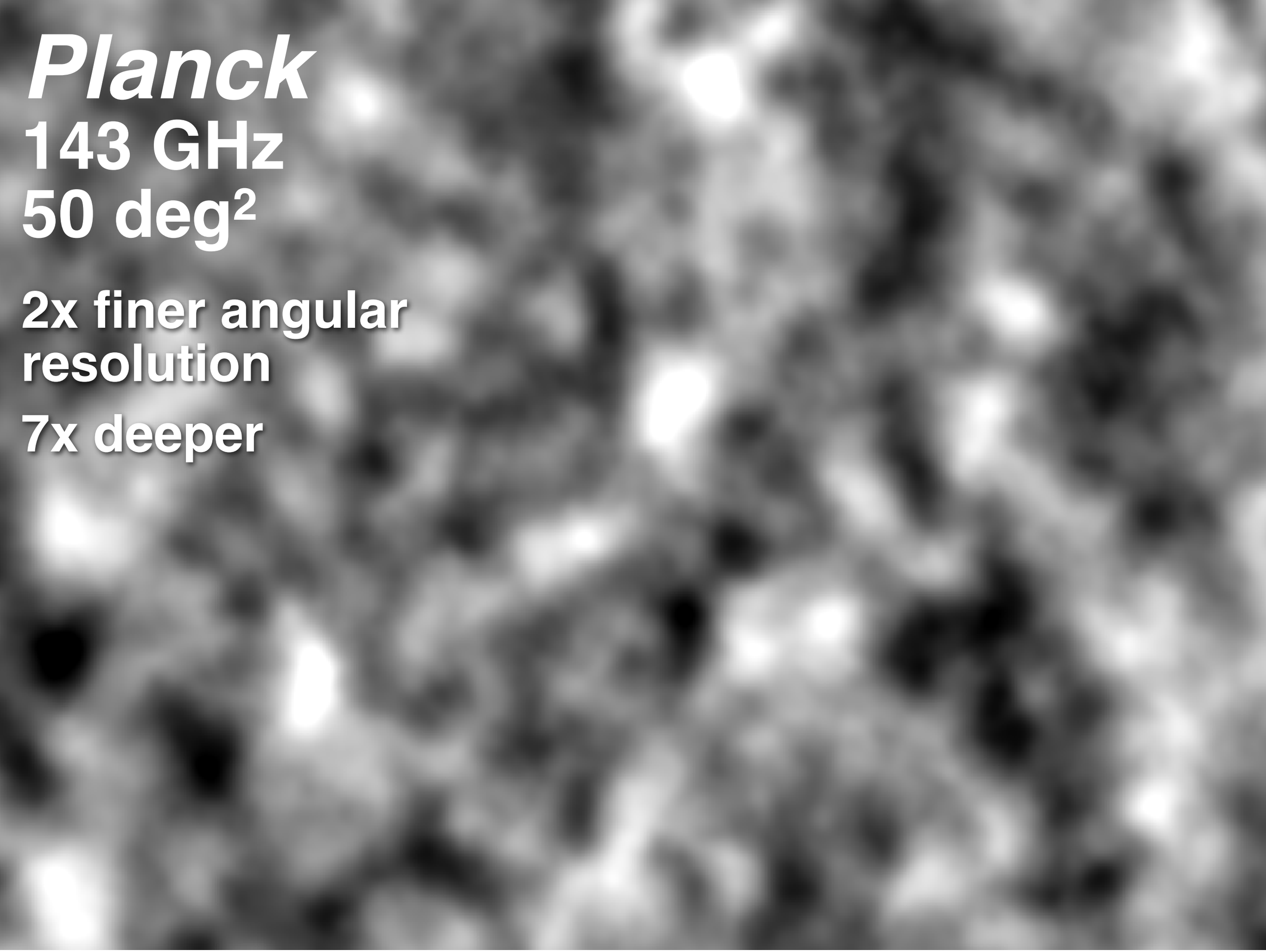
Final survey depths of:

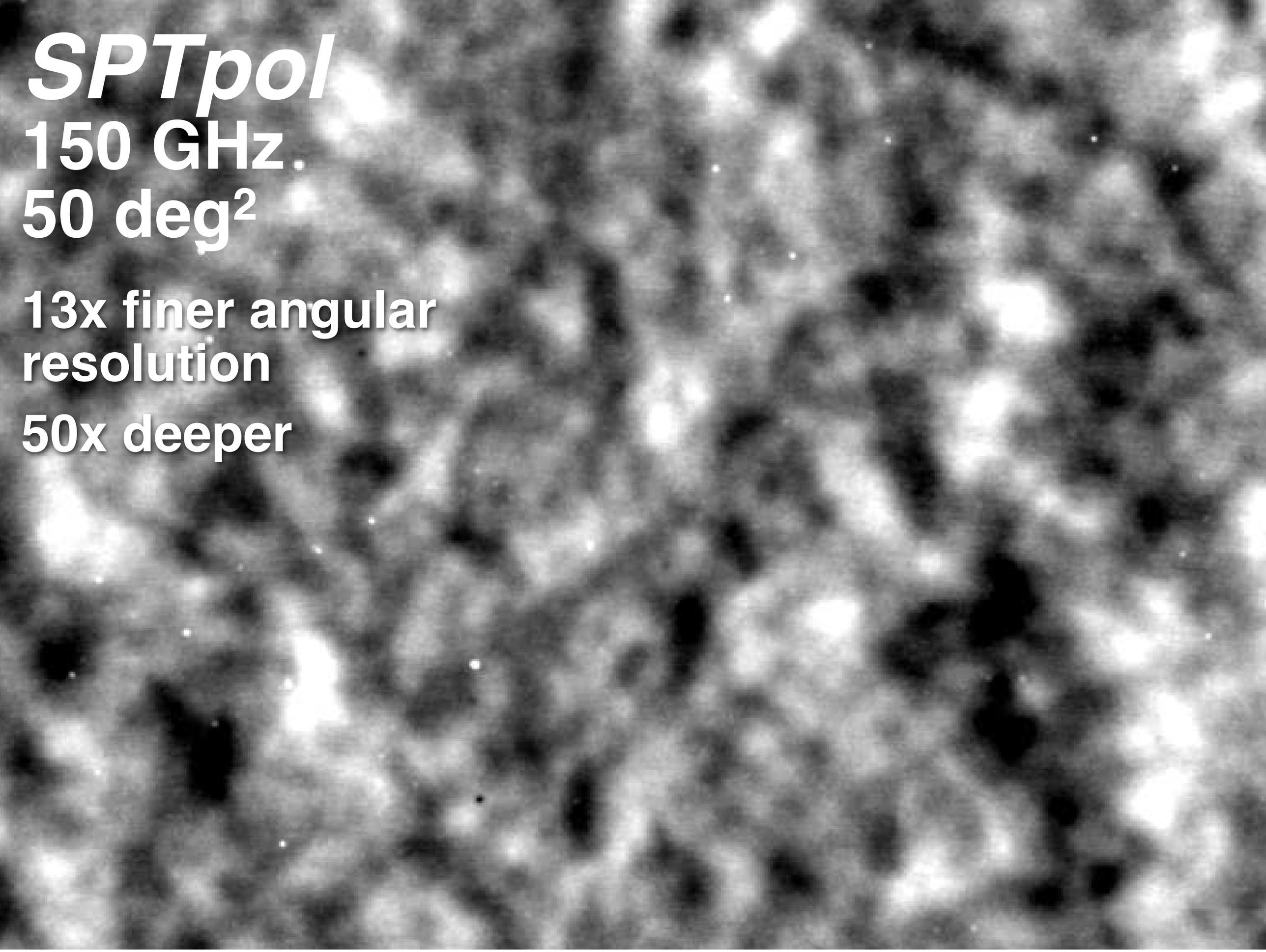
- **90 GHz:** 40 uK_{CMB}-arcmin
- **150 GHz:** 17 uK_{CMB}-arcmin
- **220 GHz:** 80 uK_{CMB}-arcmin

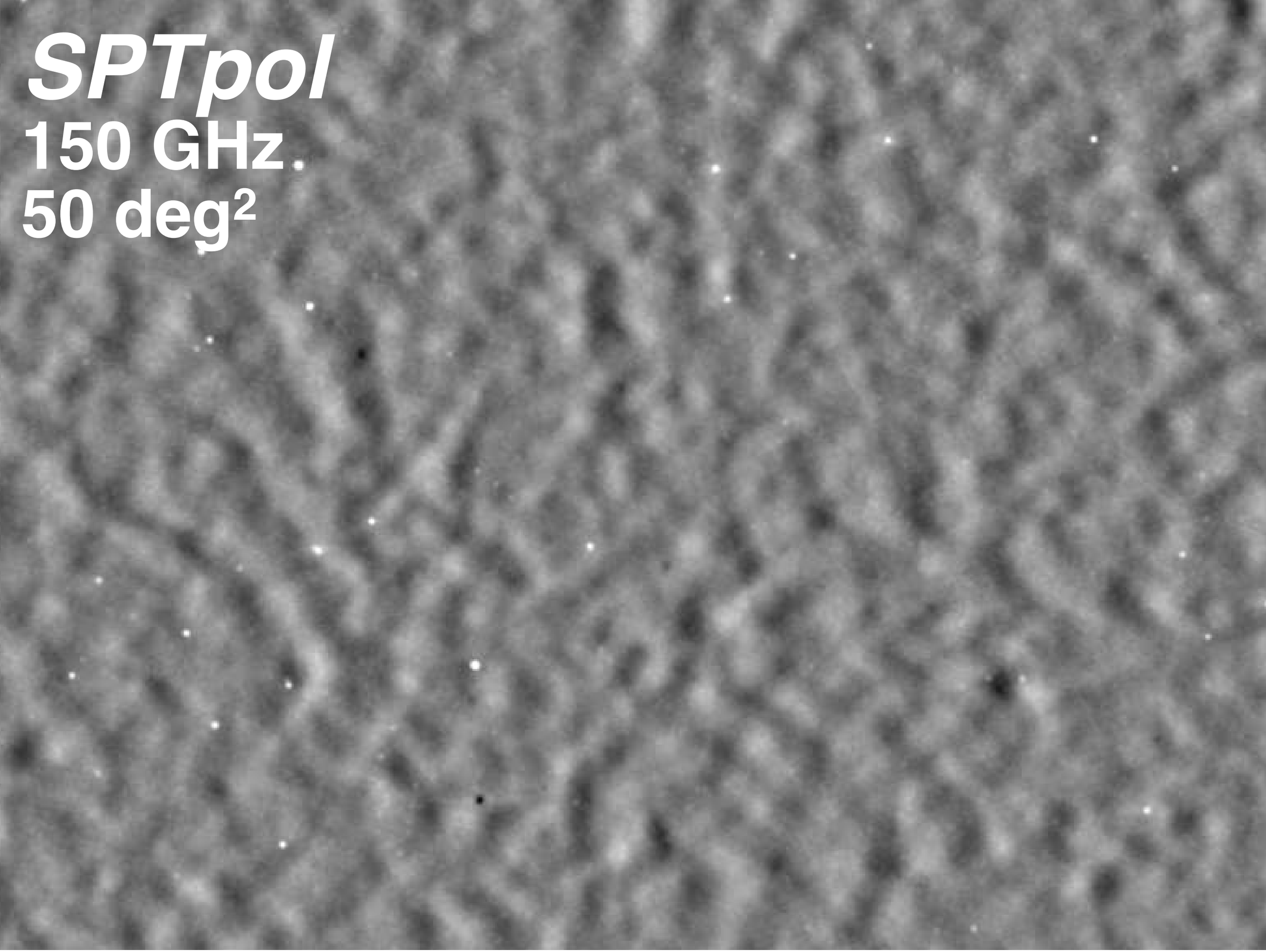
Complete overlap with DES survey

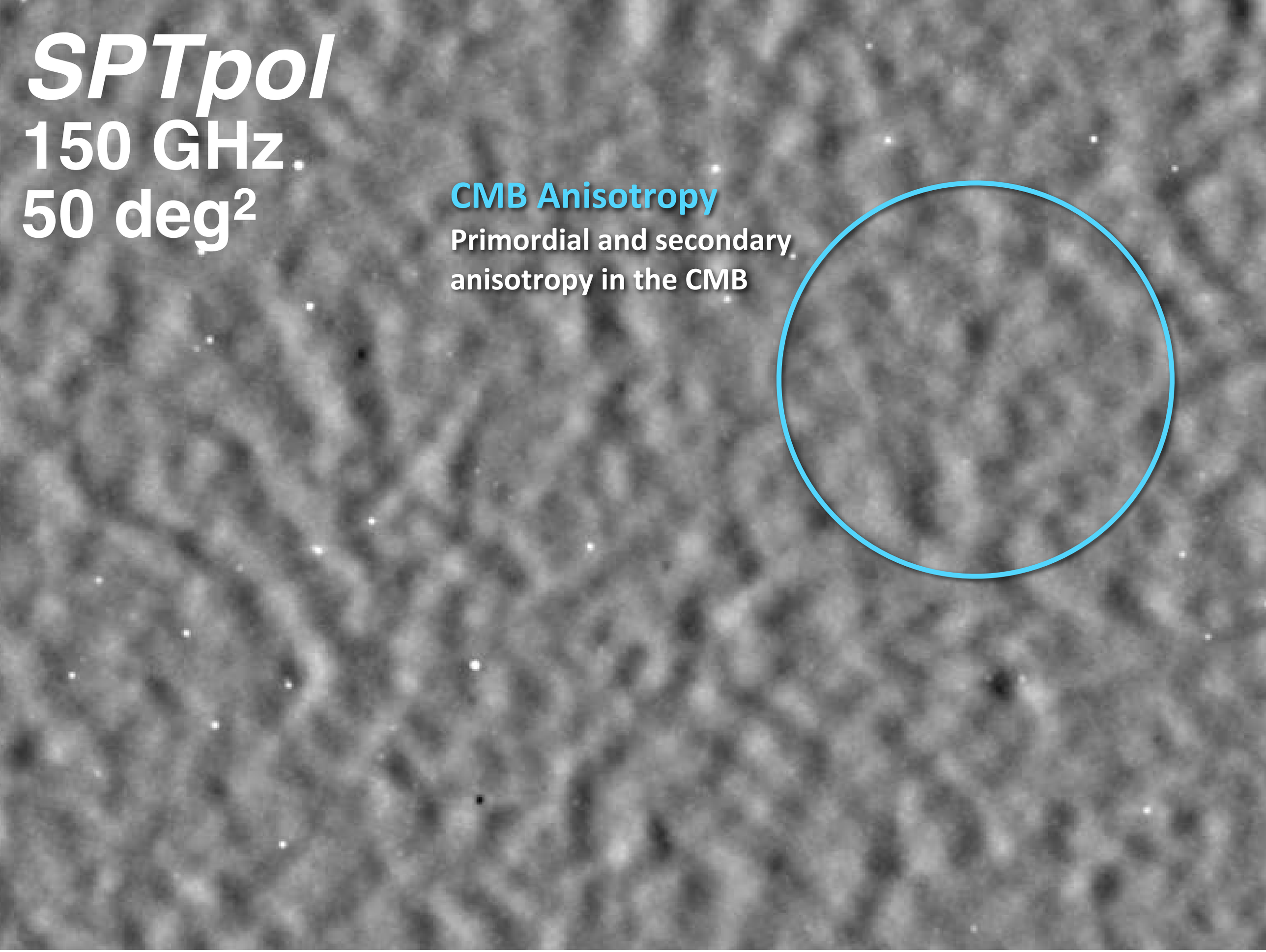



WMAP
94 GHz
50 deg²


Planck
143 GHz
50 deg²
2x finer angular resolution
7x deeper


SPTpol
150 GHz
50 deg²
13x finer angular resolution
50x deeper

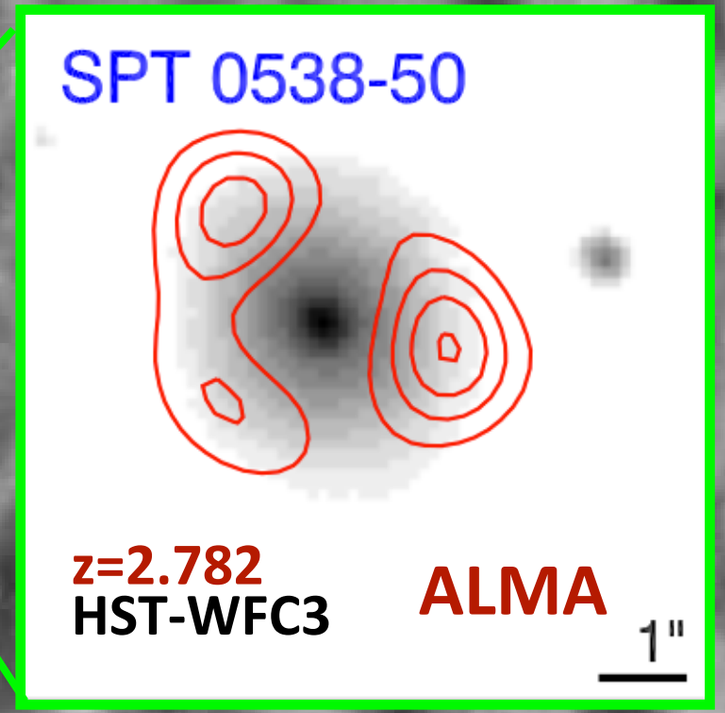

SPTpol
150 GHz
50 deg²

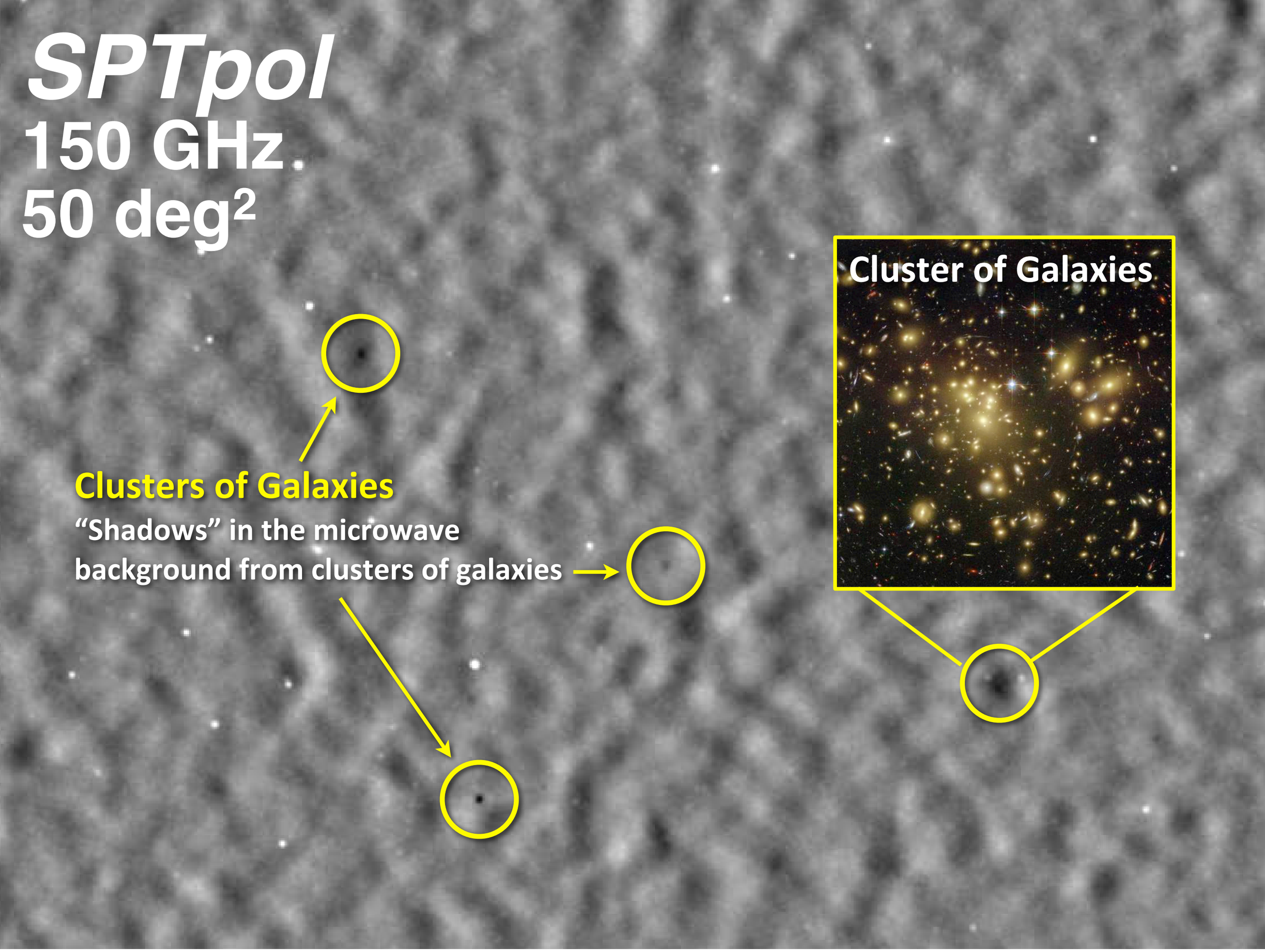

SPTpol
150 GHz
50 deg²
CMB Anisotropy
Primordial and secondary anisotropy in the CMB

SPTpol
150 GHz
50 deg^2

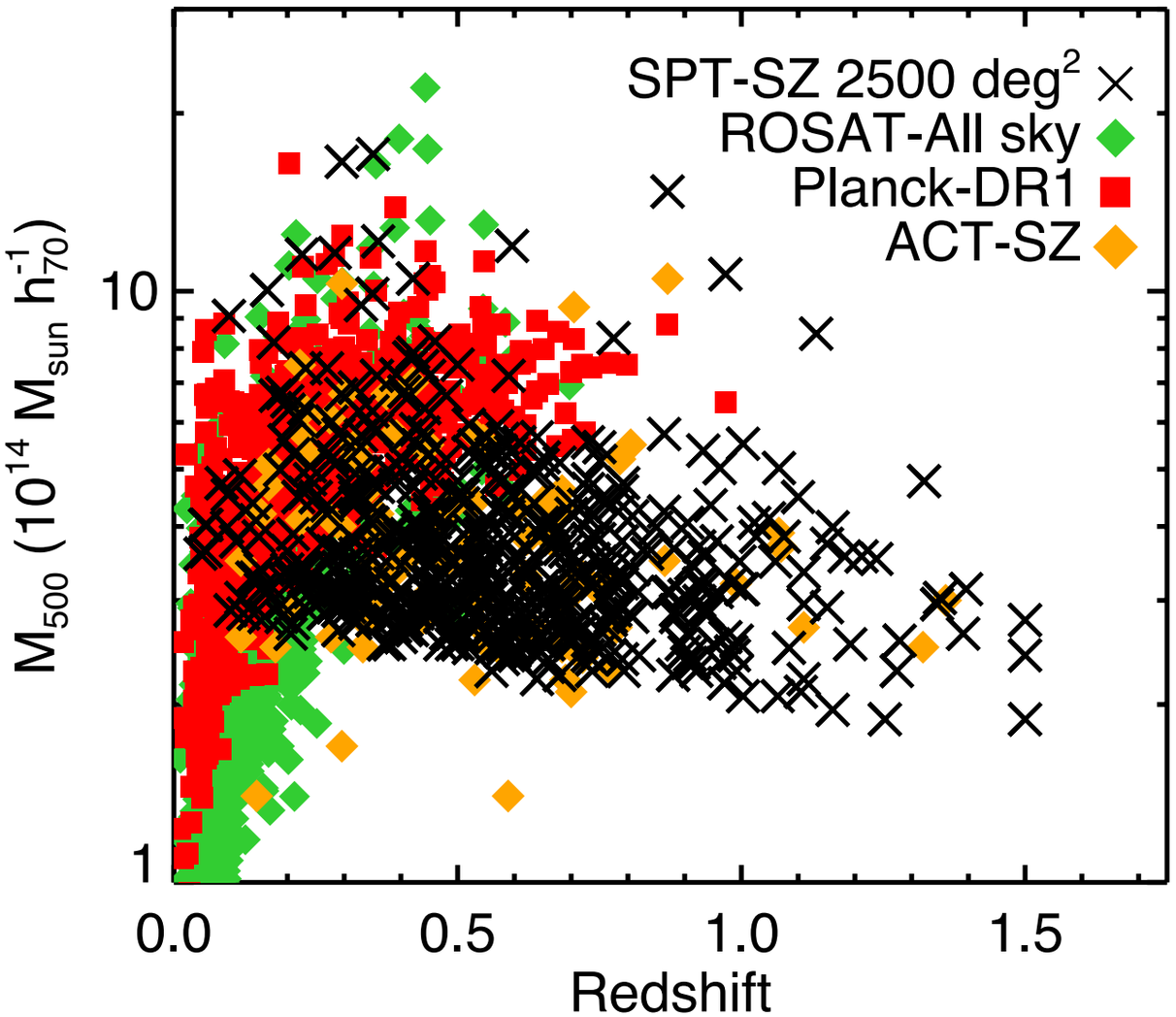
Point Sources

Active galactic nuclei, and the most distant, star-forming galaxies




SPTpol
150 GHz
50 deg²
Cluster of Galaxies
Clusters of Galaxies
"Shadows" in the microwave
background from clusters of galaxies

SZ Cluster Surveys: Mass vs Redshift

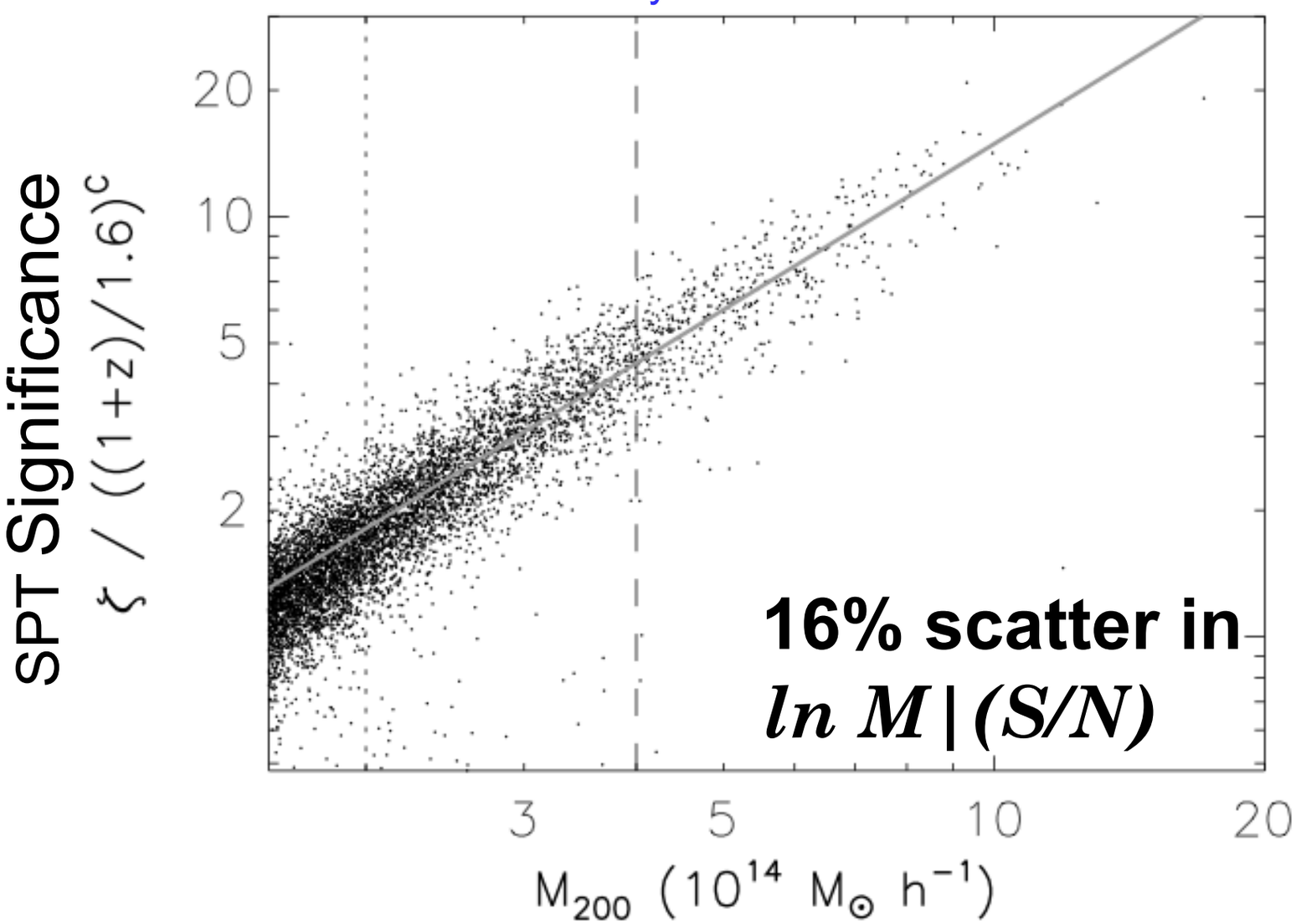


	Area (deg^2)	**Depth** (uK-arcmin)	**$N_{clusters}$**
Planck	All-sky	45	861
SPT	2500	17	524
ACT	950	23-40	91

- The SZ effect uniquely finds the most massive, high-redshift clusters in the Universe.
- ***First SZ-discovered cluster found in 2008*** *(SPT, Staniszewski et al)*; ***5 years later there are > 1300 SZ-identified clusters!***

SZ Significance as a Mass Proxy

From Simulations by Laurie Shaw

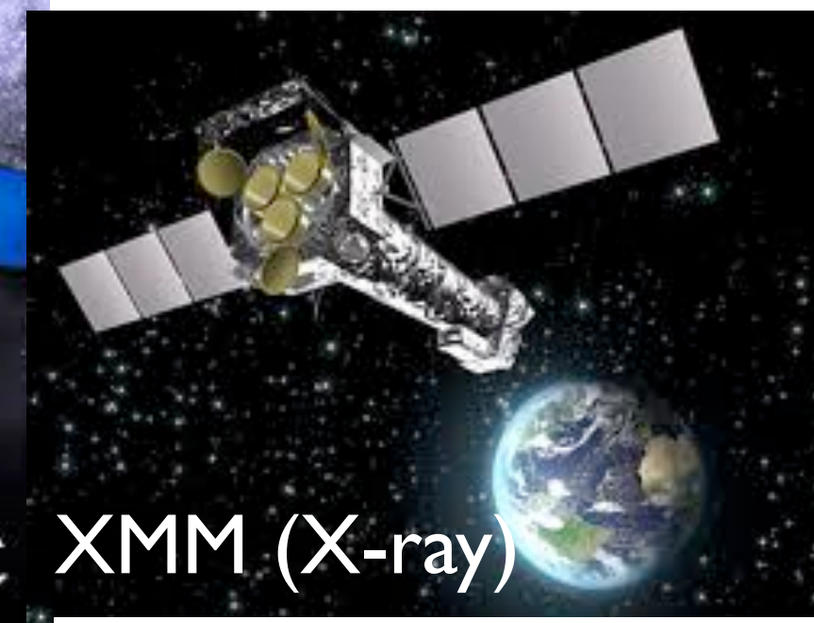


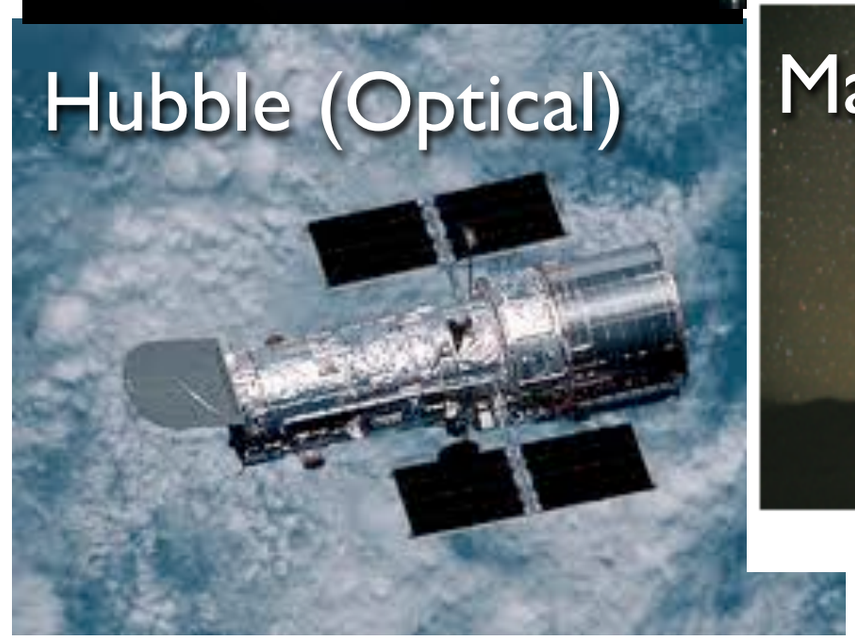
- For any cluster survey, challenge is to link cluster "observable" to cluster mass
- ***The SZ effect measures the total thermal energy of the cluster***, and is robust to astrophysical processes (Kravstov 2006, Fabjan 2011, Battaglia 2012)
- Signal-to-noise in filtered SPT map is a low-scatter mass proxy (Vanderlinde+10)
- **Scatter in $ln\ M$**
  - **~7% given Ysz**
  - ***~16% given SPT S/N***
  - ***~25% given X-ray Lx***
  - ***~25% given Richness***

Multi-wavelength Observations:
SPT Mass Calibration Strategy

1. **X-ray** with Chandra and XMM
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 ($0.3 < z < 0.8$), and VLT at ($z > 0.8$)

>100 clusters with proposed or approved measurements with each method





http://obs.carnegiescience.edu/Magellan/

Cosmological Analysis:

Combine multi-wavelength observations

Markov-Chain Monte Carlo (MCMC) methods can vary cosmology and cluster observable-mass relation simultaneously, while accounting for cluster selection in a self-consistent way

6 Cosmology Parameters (plus extension parameters)

- ΛCDM Cosmology
  - $\Omega_{\rm m}h^2, \Omega_{\rm b}h^2, A_{\rm s}, n_s, \boldsymbol{\theta}_s$
- Extension Cosmology
  - $w, \Sigma m_\nu, f_{NL}, N_{eff}$

9 Scaling Relation Parameters

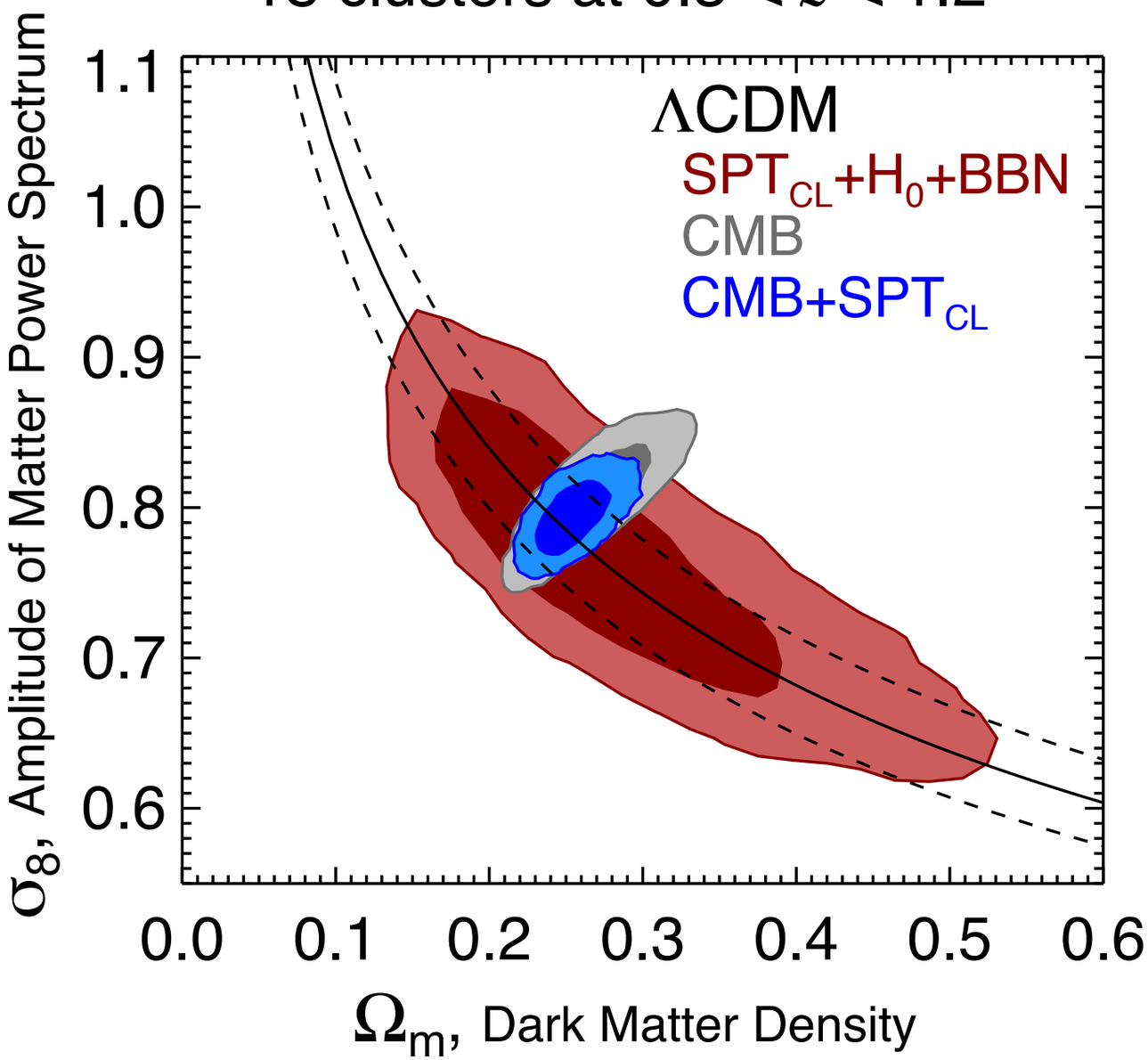
- X-ray (Yx-M) and SZ (ζ-M) relations (4 and 5 parameters):
  - A) normalization,
  - B) slope,
  - C) redshift evolution,
  - D) scatter,
  - F) correlated scatter

Benson et al 2011

ΛCDM Cosmological Constraints from Clusters Currently

SPT (SZ) *(Benson et al. 2011)*

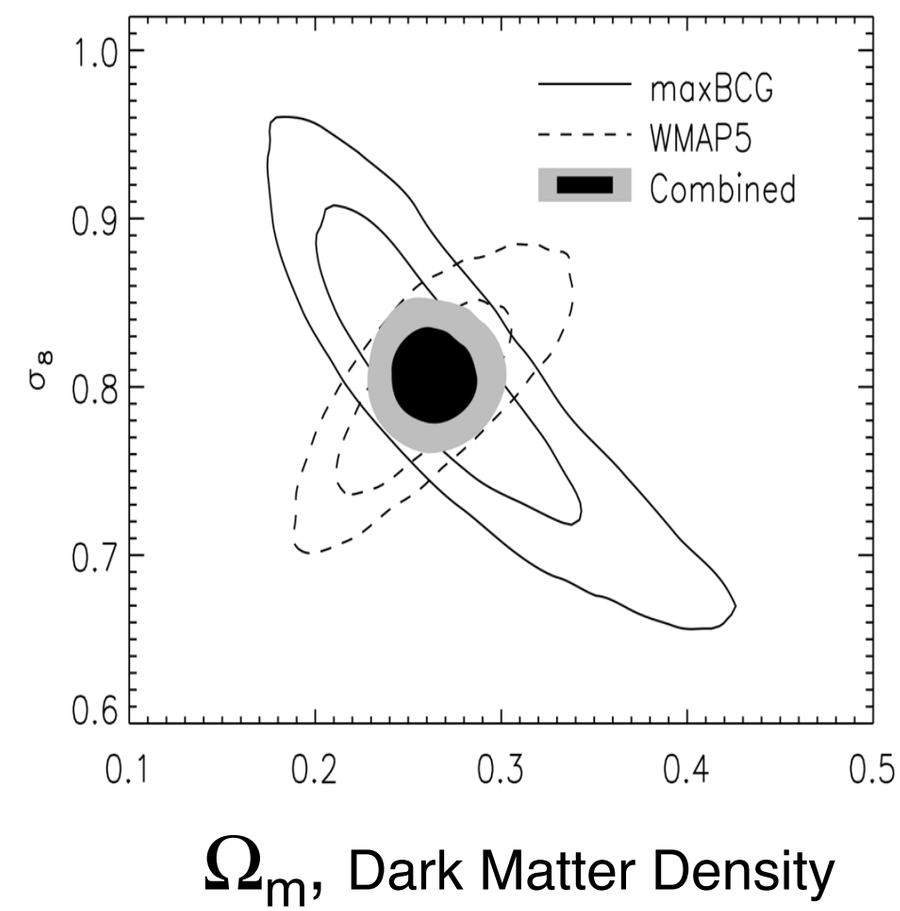
- ~18 clusters at $0.3 < z < 1.2$



Limited by uncertainty in mass calibration

SDSS (Optical) *(Rozo et al. 2010)*

- ~10,000 clusters at $z < 0.3$

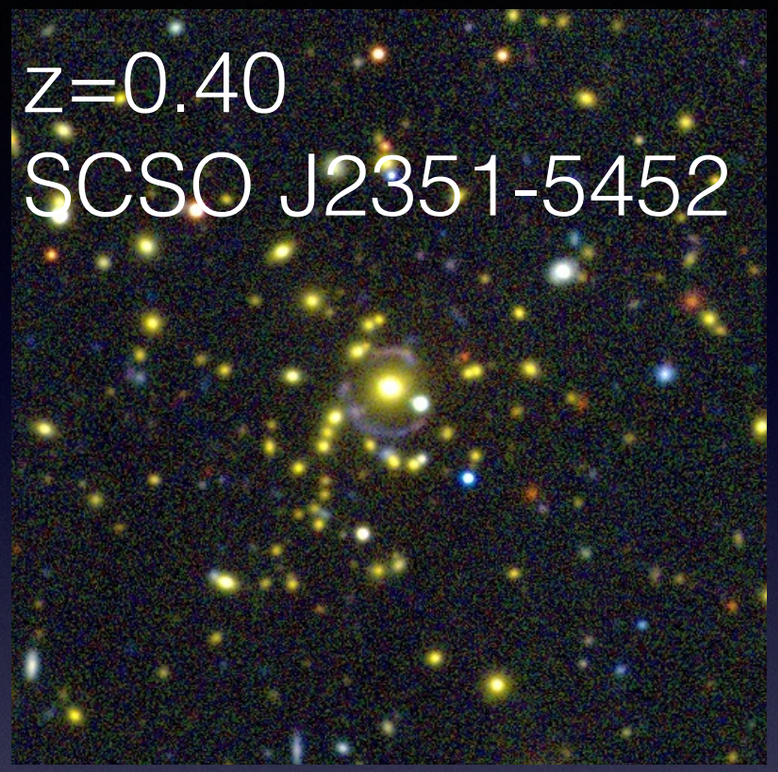


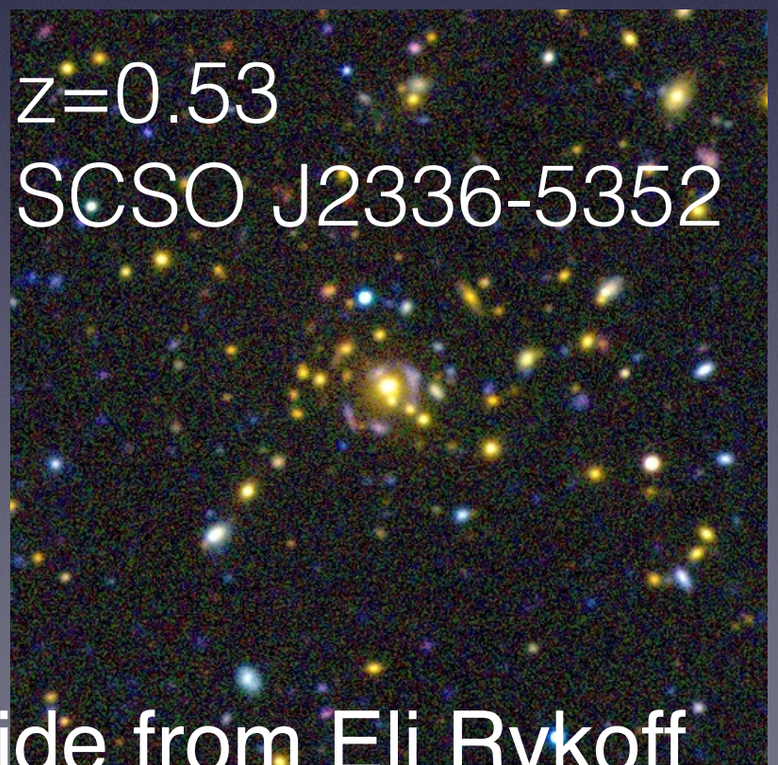
Limited by uncertainty in scatter of richness with mass

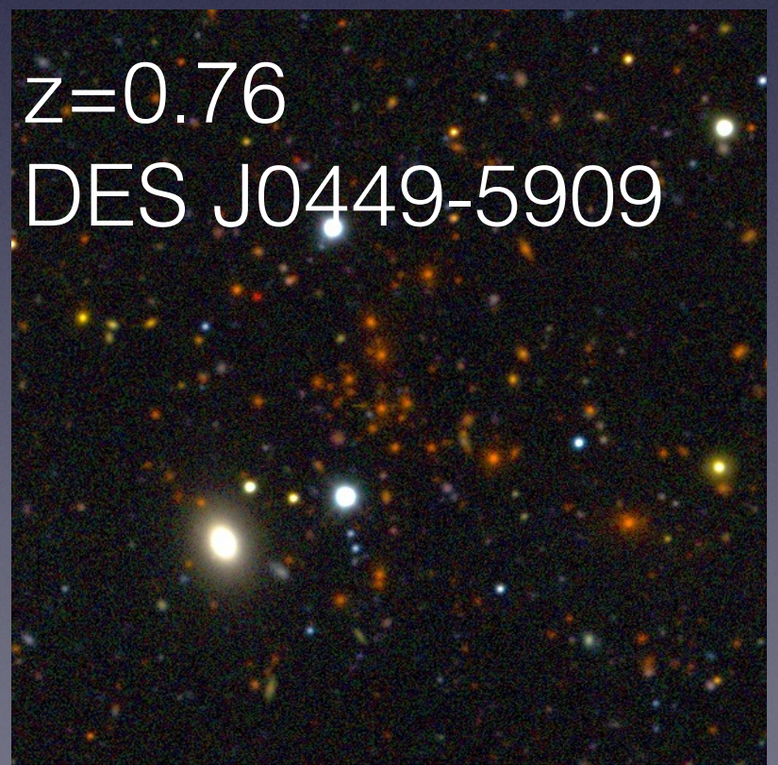
Dark Energy Survey (DES) and SPT

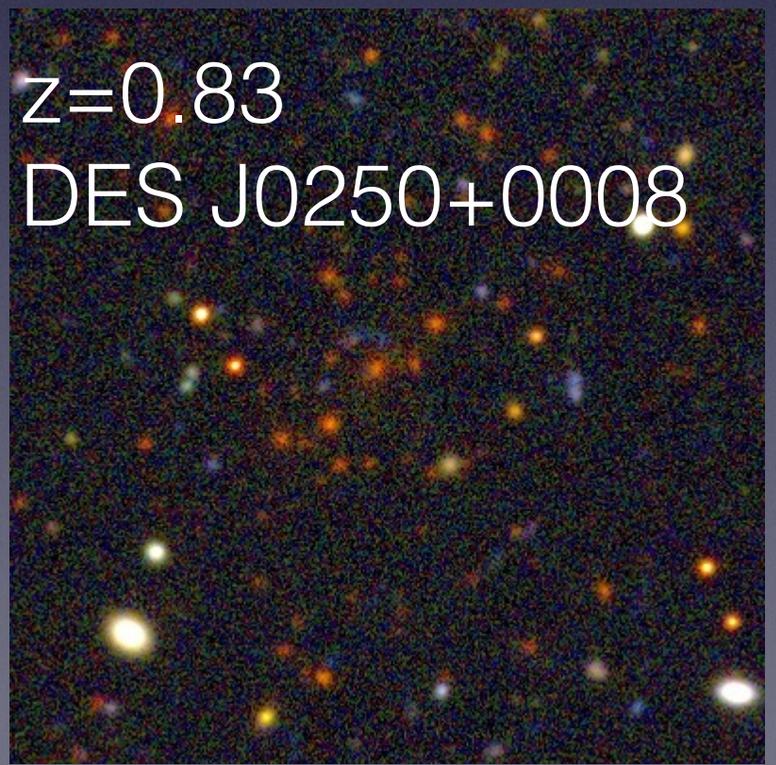
- 5-year optical survey to image 5000 deg^2, including entire SPT-SZ survey area
- **The DES Survey began on August 31, 2013!**
  - DES will detect ~100,000 clusters at $0 < z < 1$
  - ***Strong complementarity with SPT cluster survey; the combination will improve current cluster constraints on dark energy by ~100x***

Rogue's Gallery



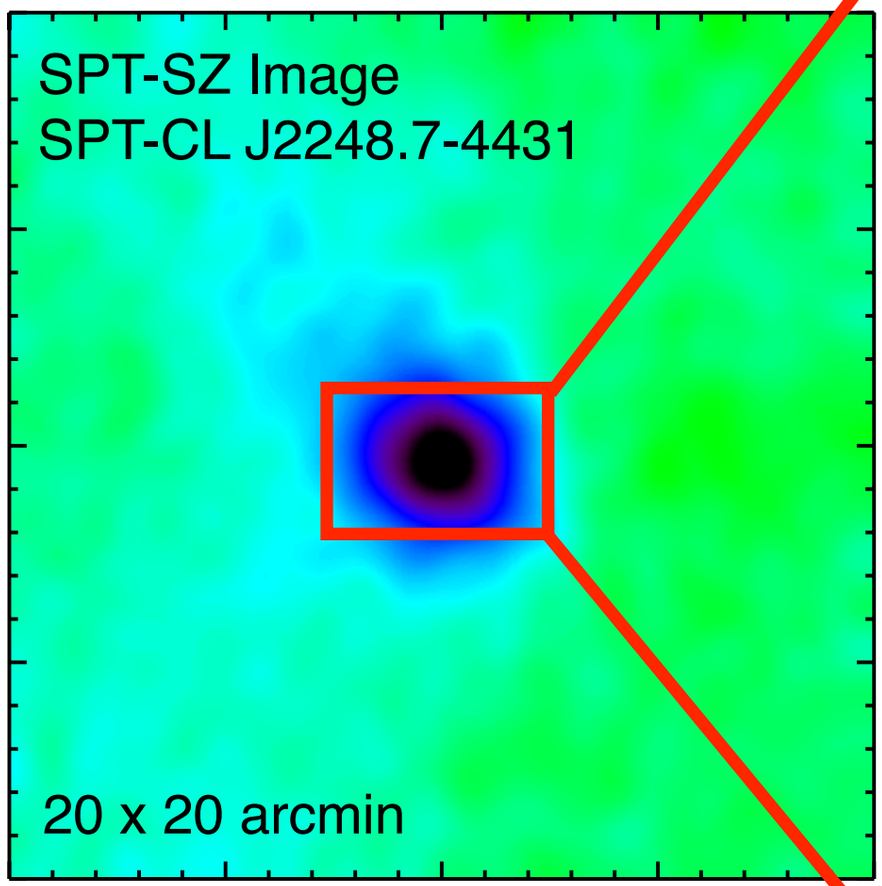






Slide from Eli Rykoff

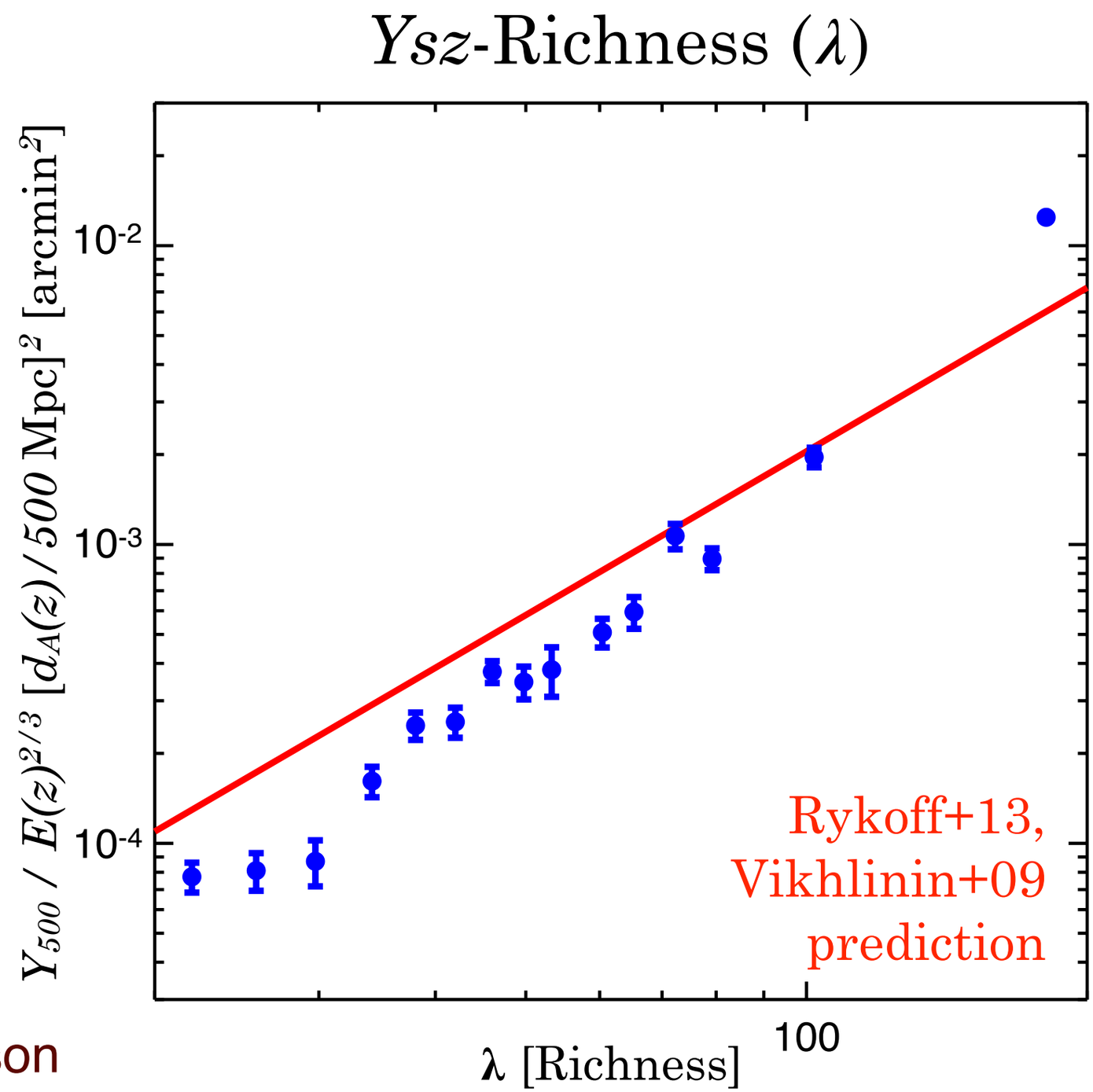
SPT-CL 2248-4431 (AS1063)



DES and SPT Cluster Stacking

Using 150 deg^2 of DES-SV data, stack SPT-SZ data on 602 DES-selected clusters from Rykoff & Rozo (Redmapper algorithm):

- ***High S/N detection of Ysz-Optical Richness relation***

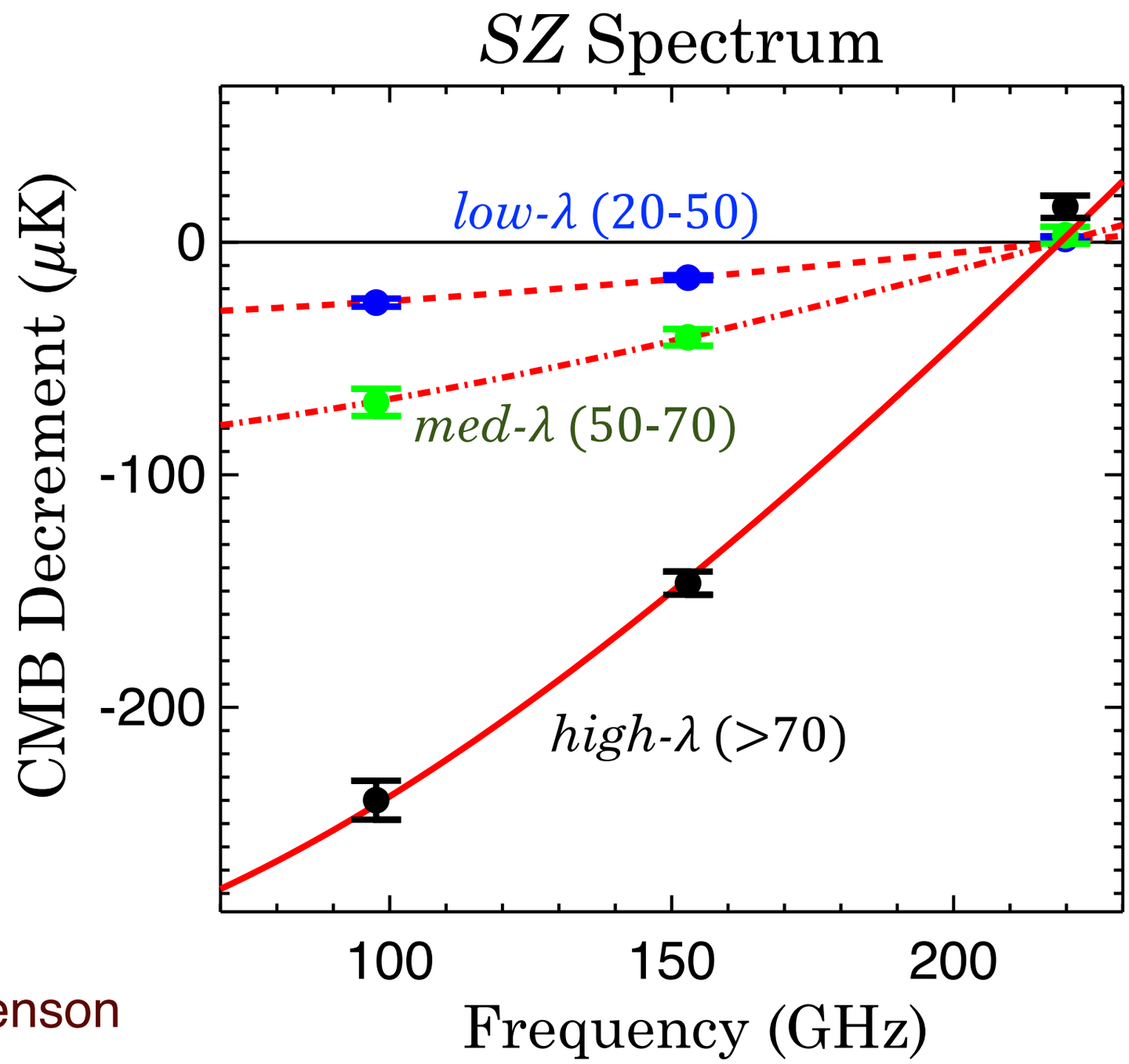


Plot by B. Benson

DES and SPT Cluster Stacking

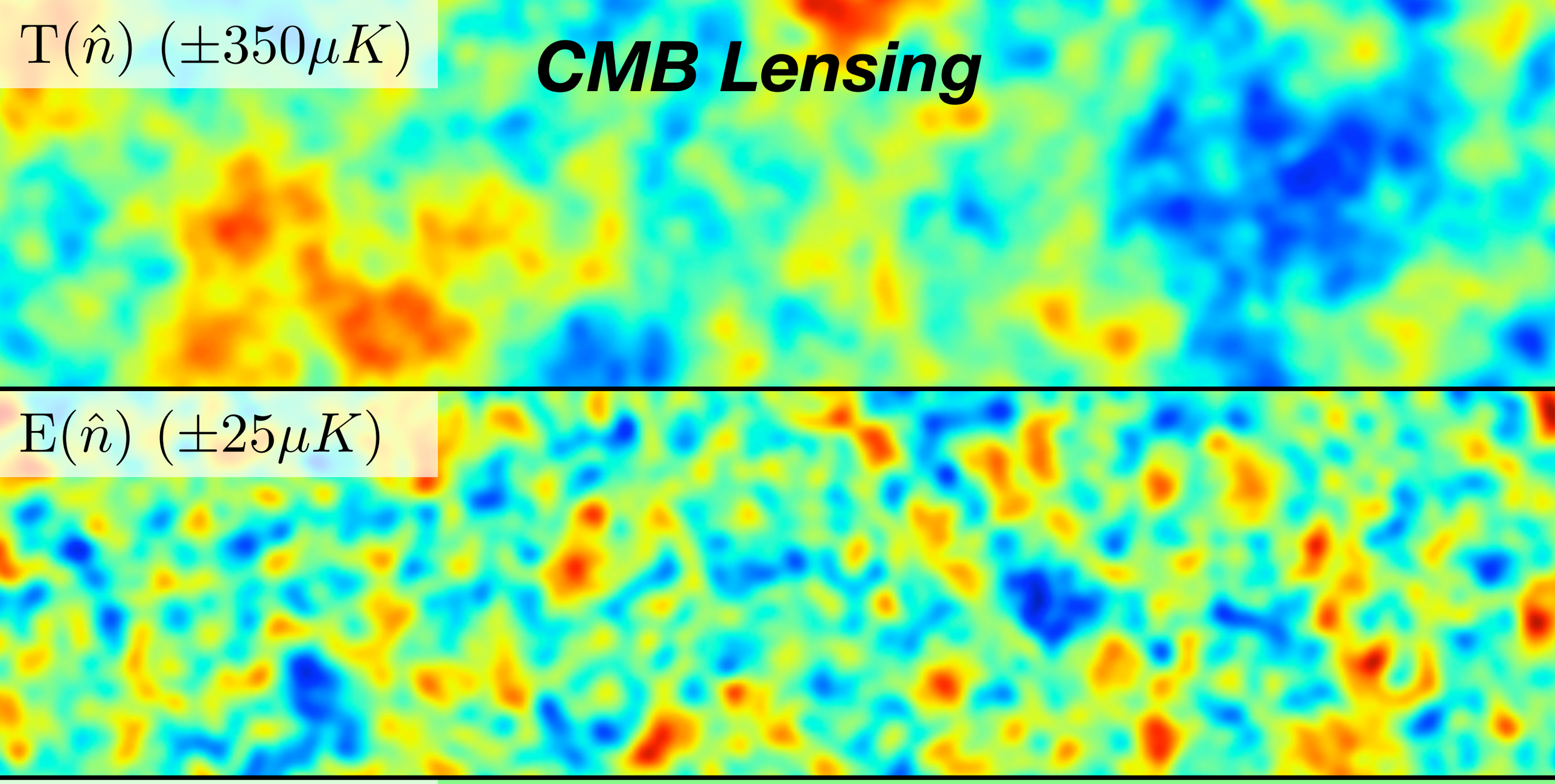
Using 150 deg^2 of DES-SV data, stack SPT-SZ data on 602 DES-selected clusters from Rykoff & Rozo (Redmapper algorithm):

- ***220 GHz flux implies dusty sources are <3% of SZ signal at 150 GHz for λ > 20 (cluster mass > ~1e14 Msun)***



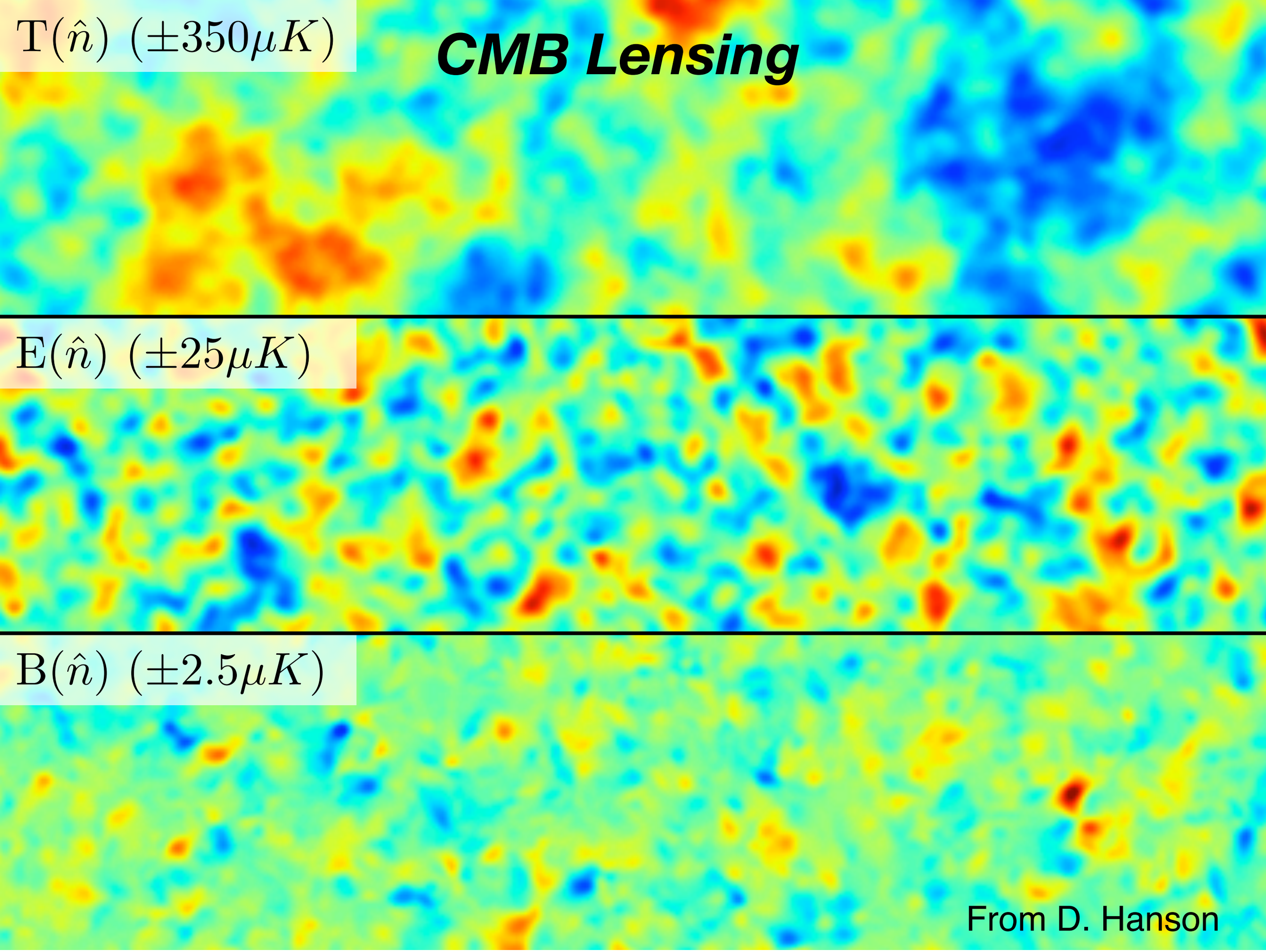
Plot by B. Benson

CMB Lensing



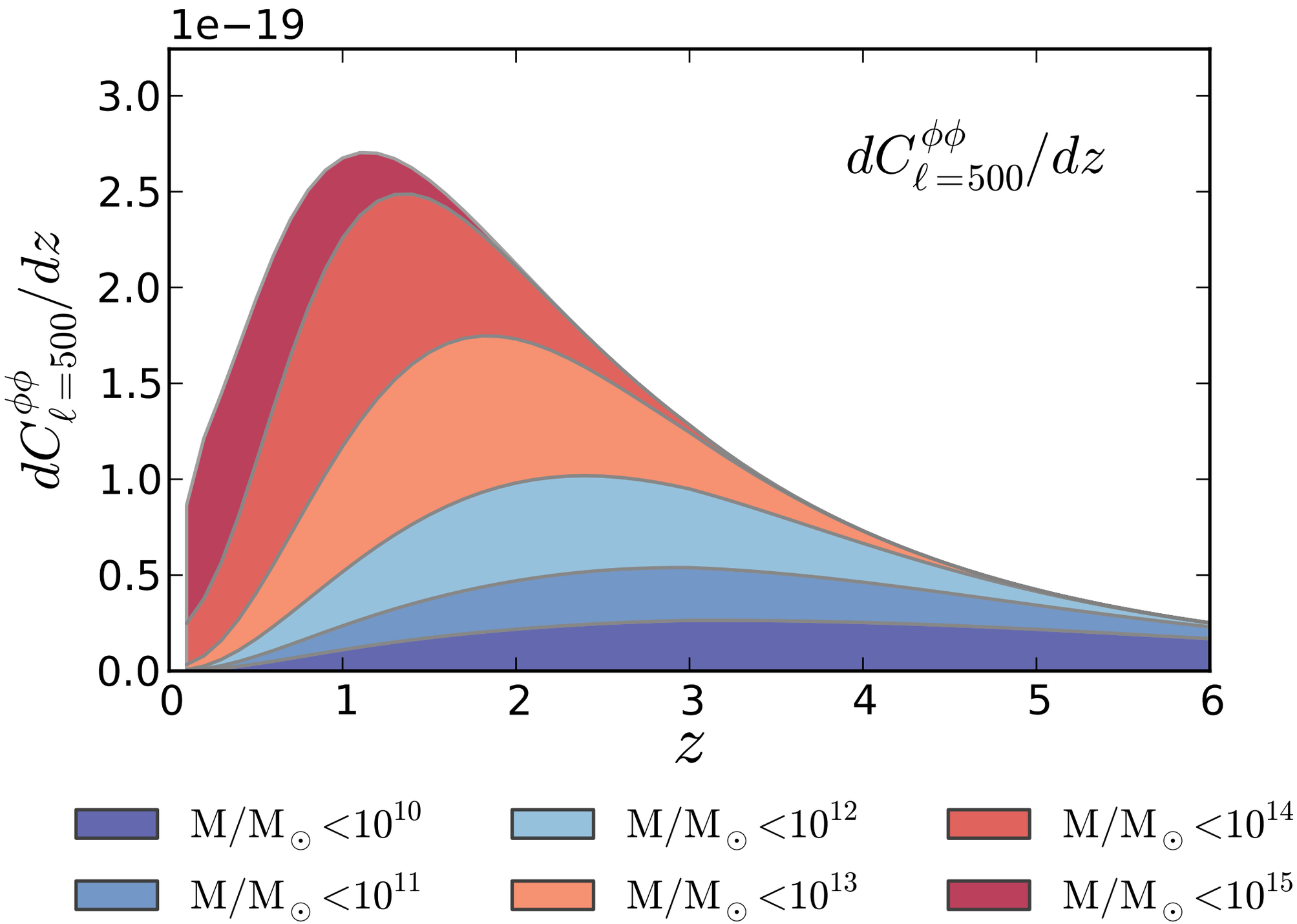
From D. Hanson

CMB Lensing



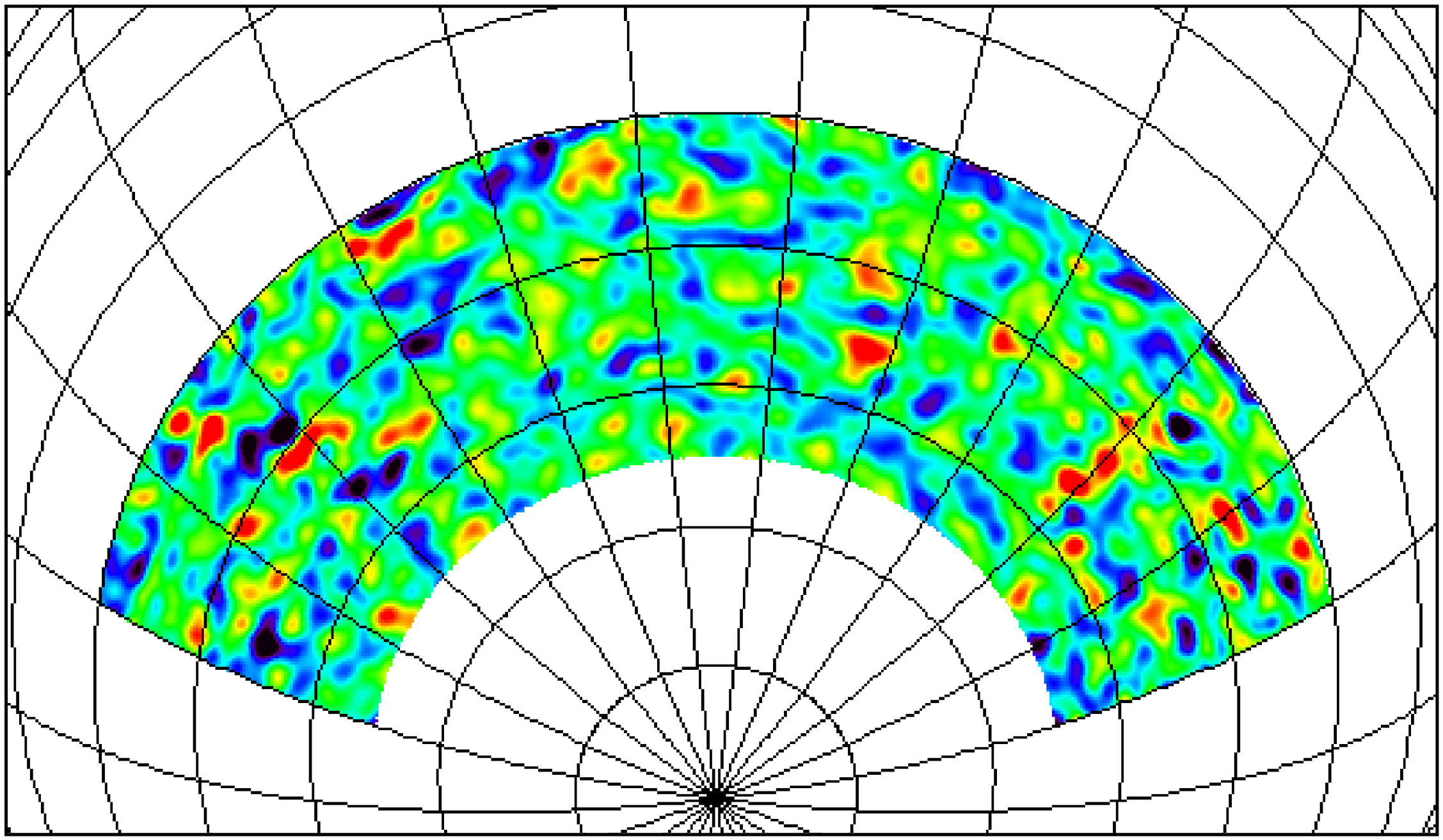
From D. Hanson

CMB Lensing has a Broad Redshift Kernel



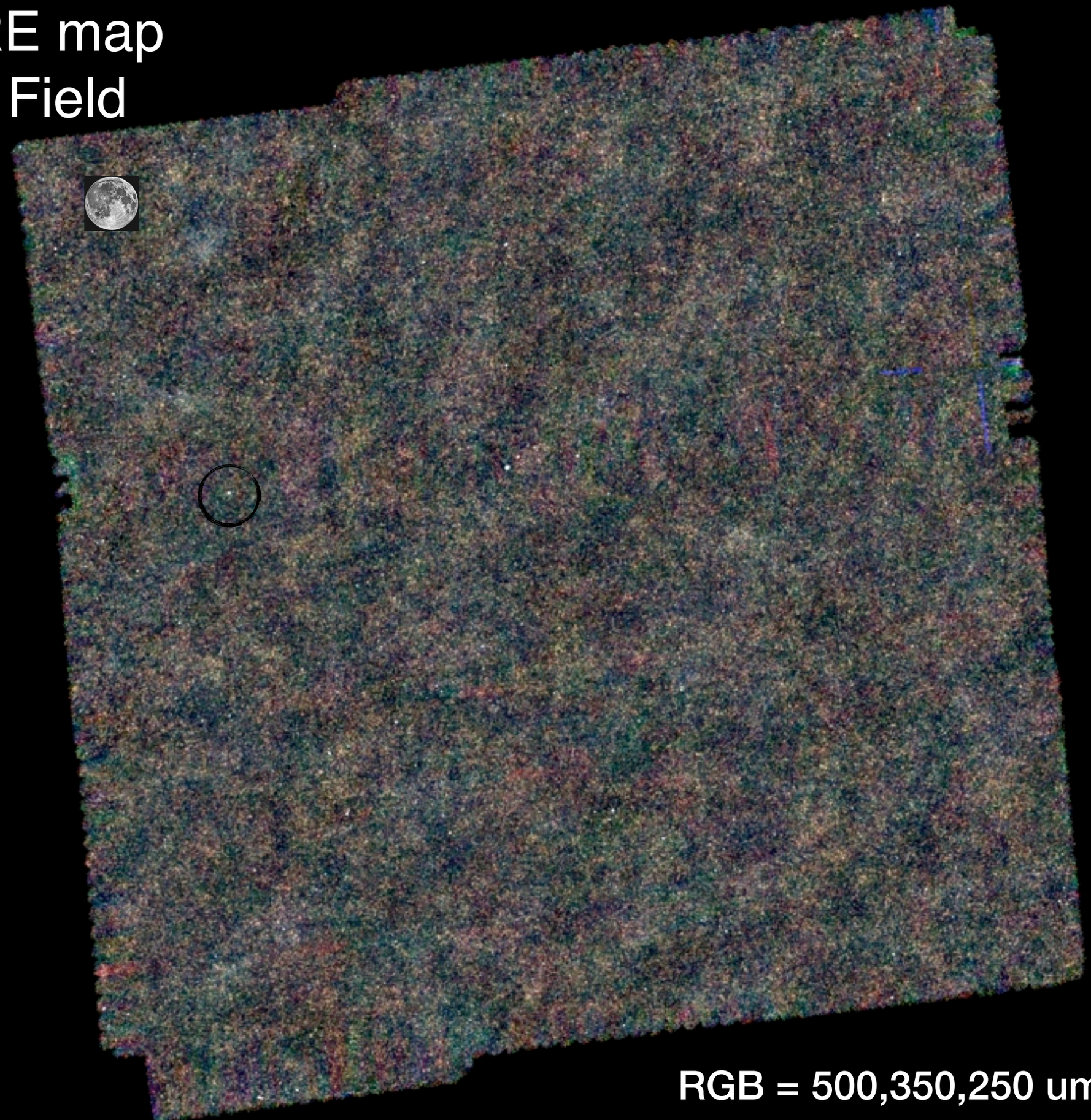
SPT-SZ: CMB Lensing "Weighs" the Universe

Mass fluctuation map smoothed to 1 deg resolution from CMB lensing analysis of SPT-SZ 2500 deg^2 survey



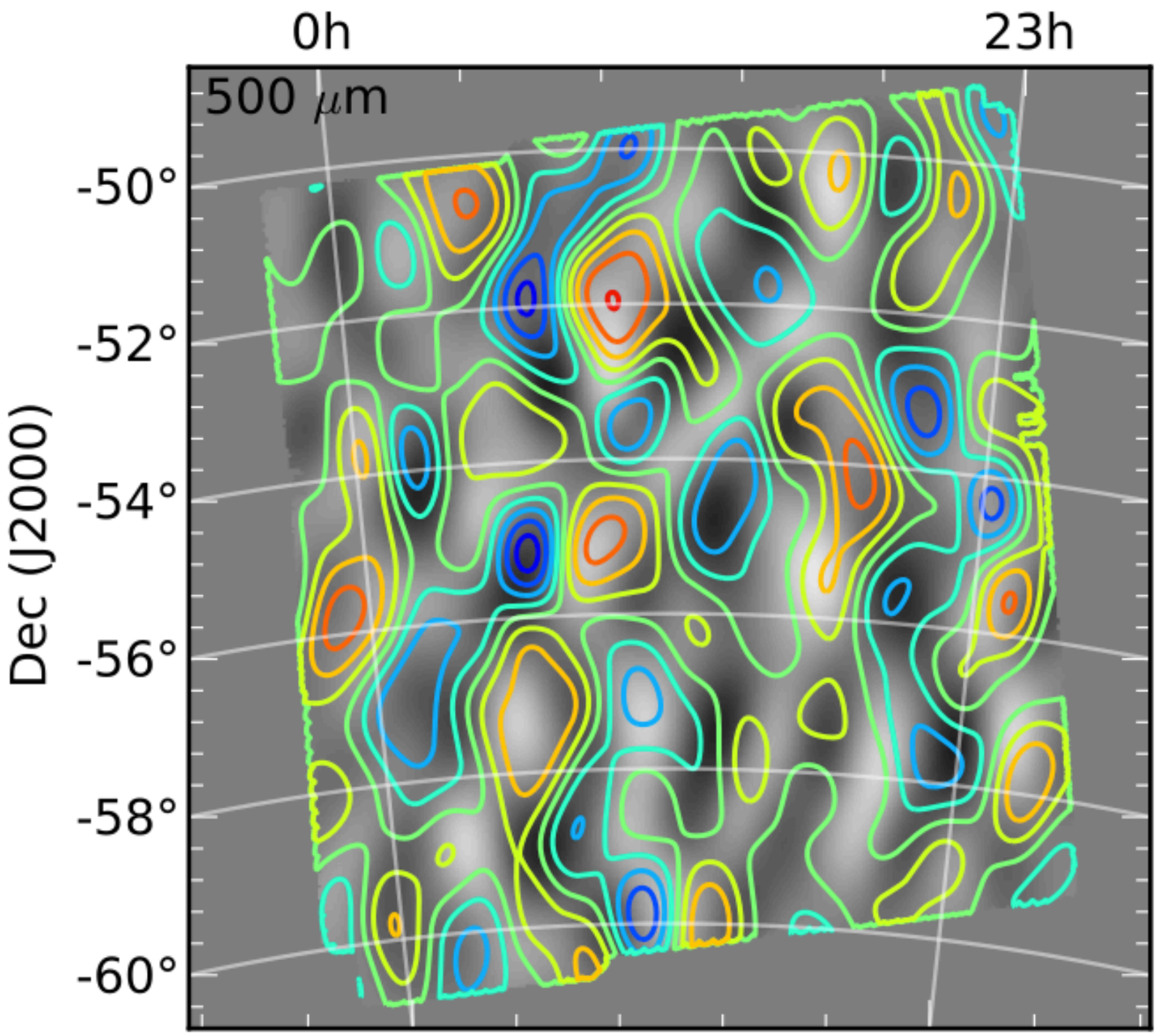
(SPT) Holder et al., in prep

100 deg^2 SPIRE map of SPT Deep Field



RGB = 500,350,250 um

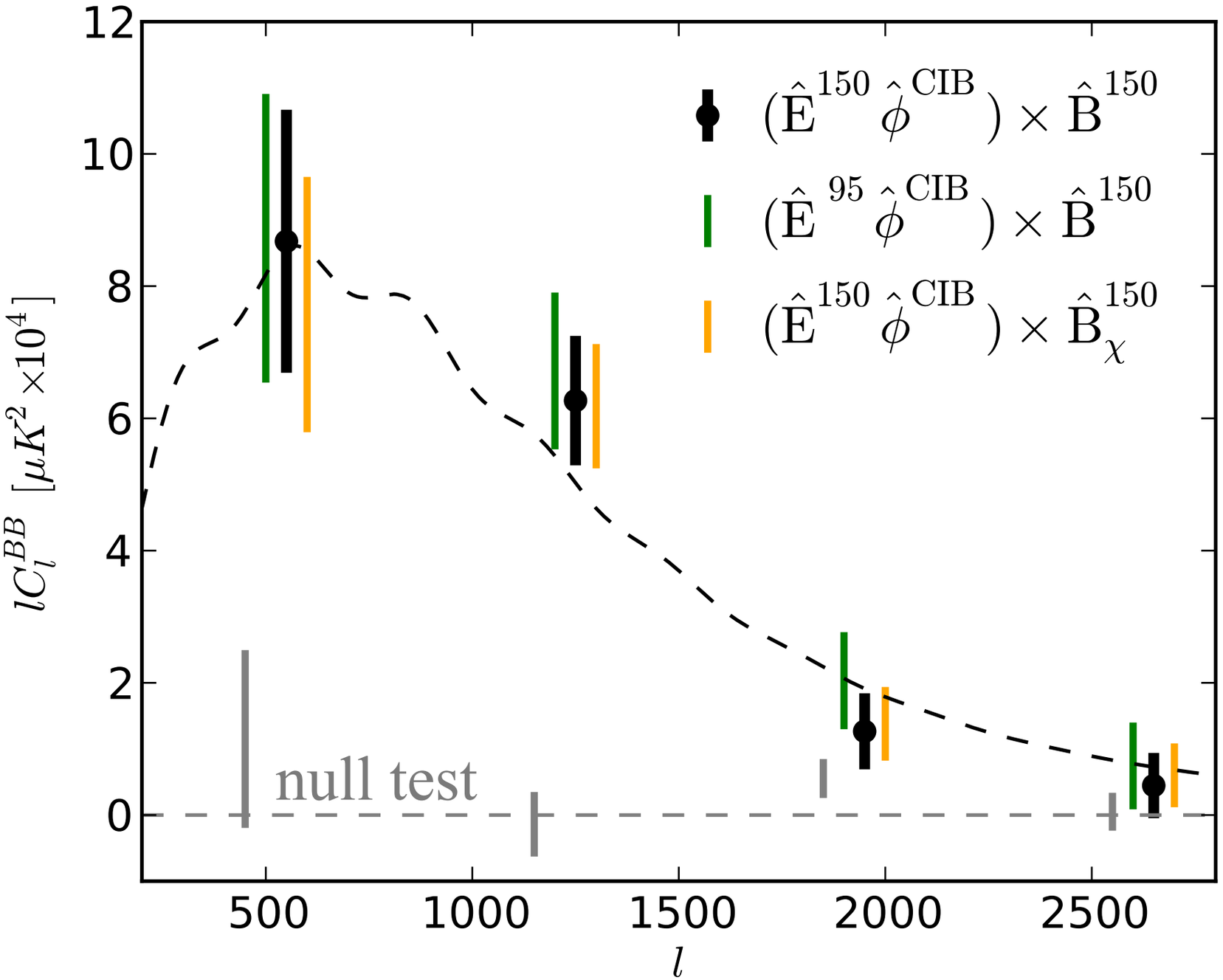
SPT-SZ: *CMB Lensing and the CIB*



- *Mass contours* from SPT CMB lensing.
- Add smoothed 500um map to ~1 degree scales (~100 Mpc scales)
- ~10σ correlation signal
- Galaxy bias constrained to be 1.3 < b < 1.8, model dependent
- CMB lensing is well calibrated in *mass* and probes how CIB traces dark matter distribution

Holder et al. 2013, arXiv: 1112.5435

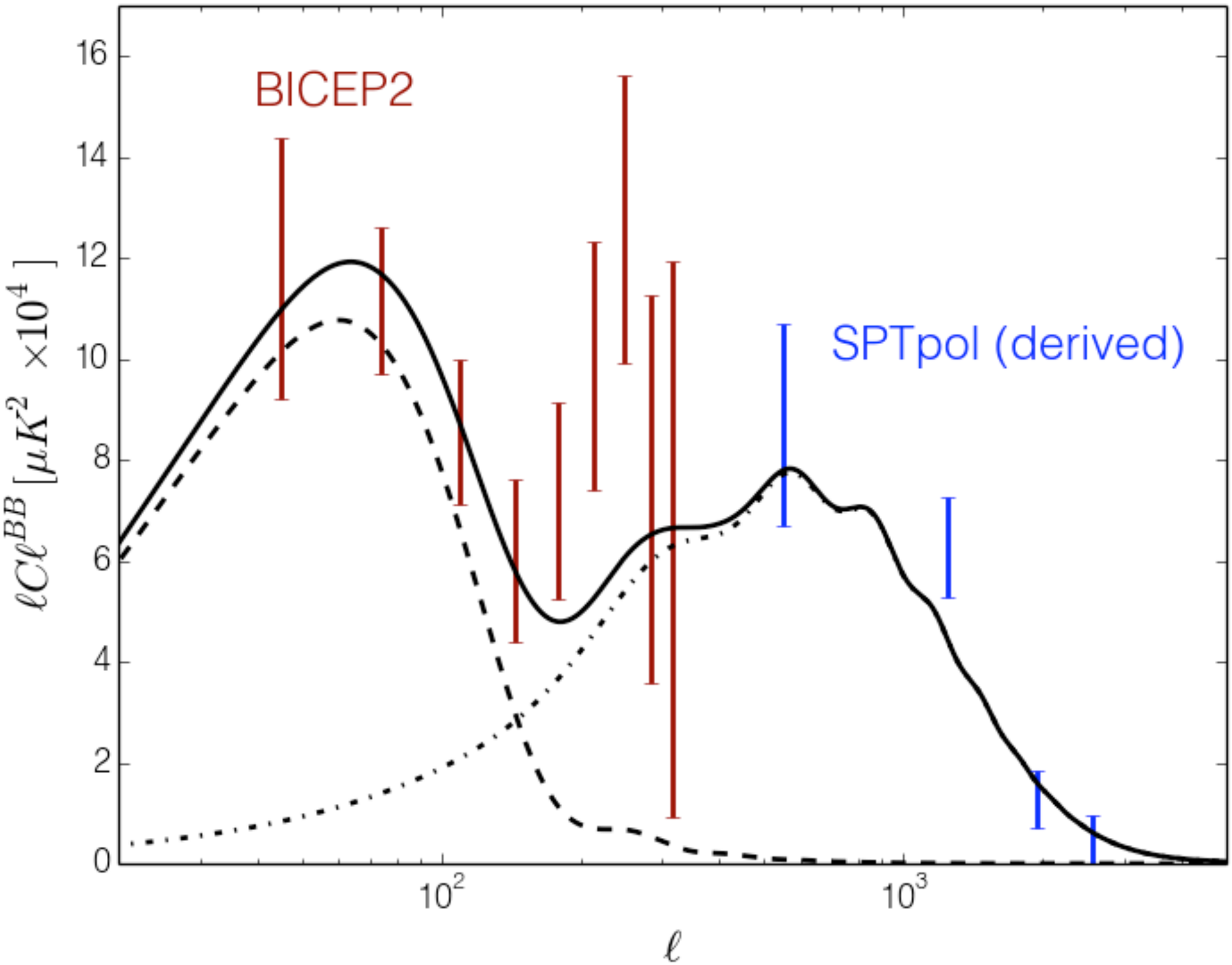
Detection of B-mode Polarization in the CMB with 100 deg^2 of SPTpol data



7.7-σ detection of lensing B-modes!

(SPTpol) Hanson et al. (2013)

Characterizing the Lensing Signal is Important for Measuring Shape of Inflationary B-modes

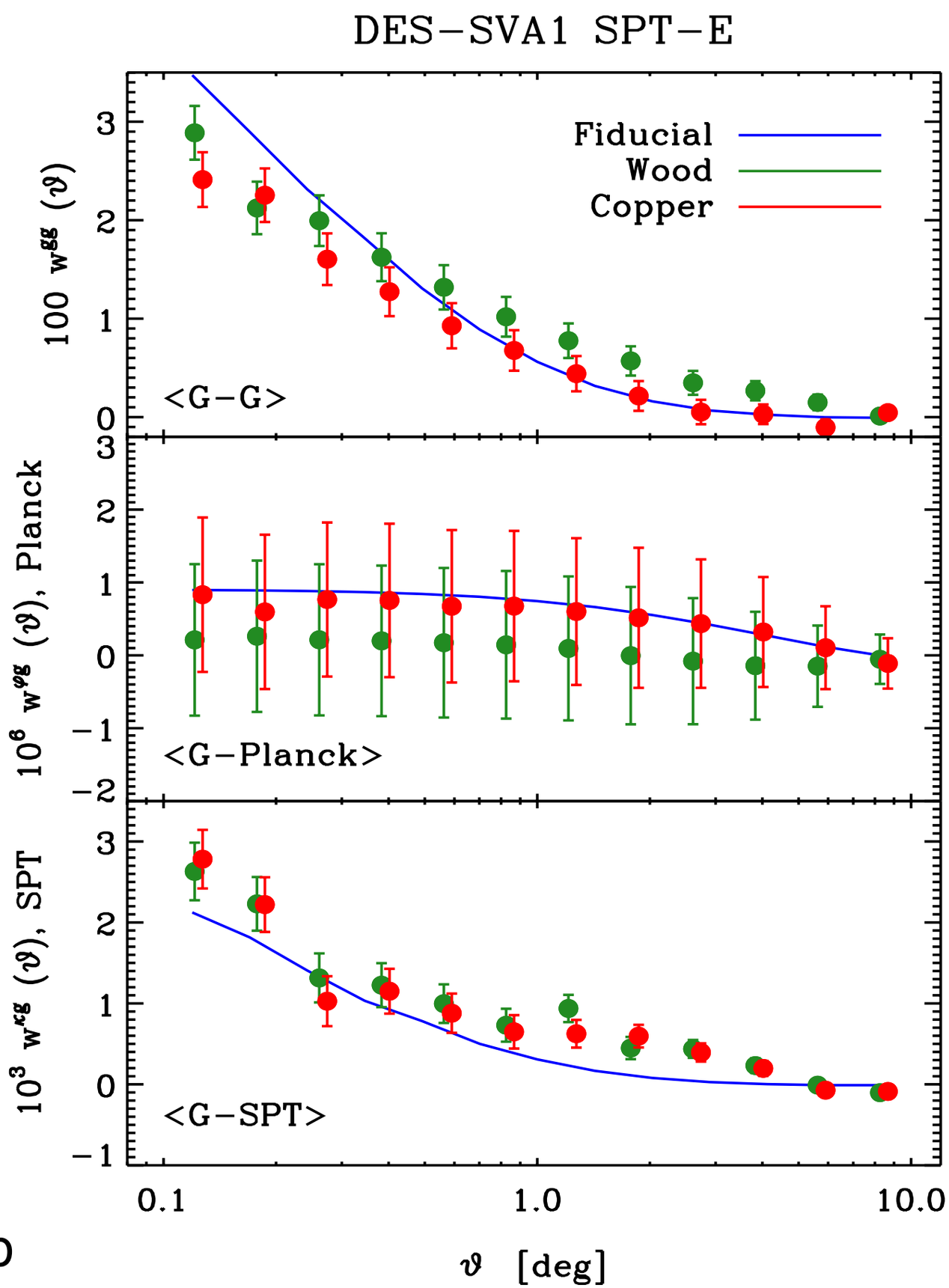


DES Galaxies x SPT Lensing

Galaxy x
Galaxy

Galaxy x
Planck-CMB Lensing

Galaxy x
SPT-CMB Lensing

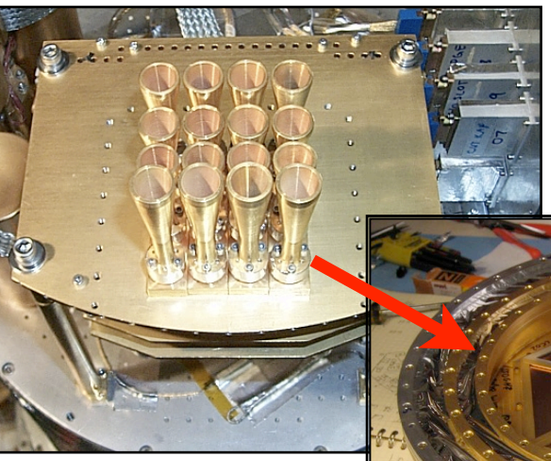


Using ~140 deg² of DES-SV data

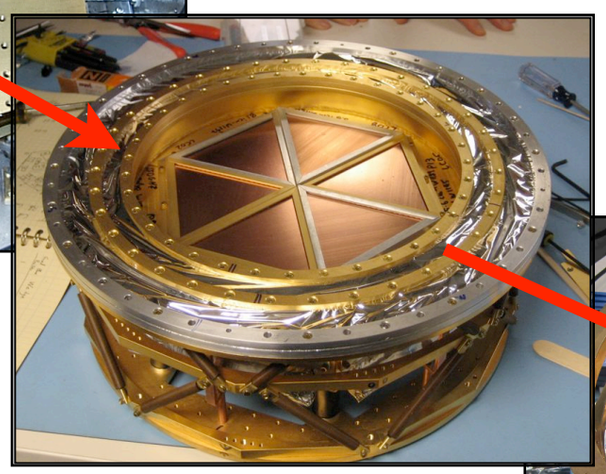
From DES-LSS Group

Whats next? Evolution of CMB Focal Planes

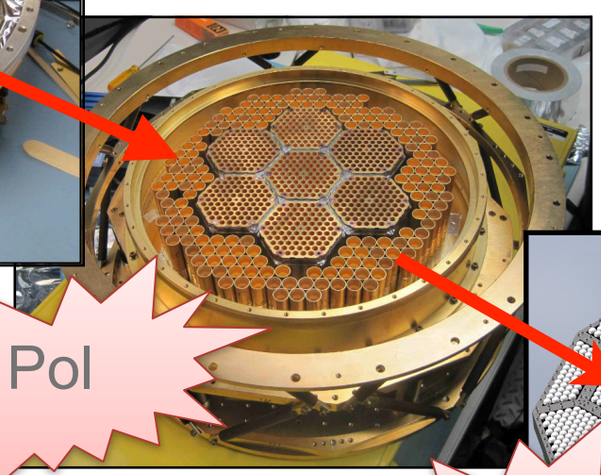
2001: ACBAR
16 detectors



2007: SPT
960 detectors

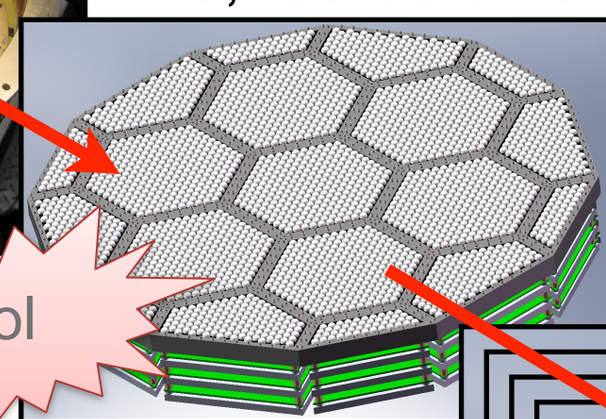


Stage-2
2012: SPTpol
~1600 detectors



Pol

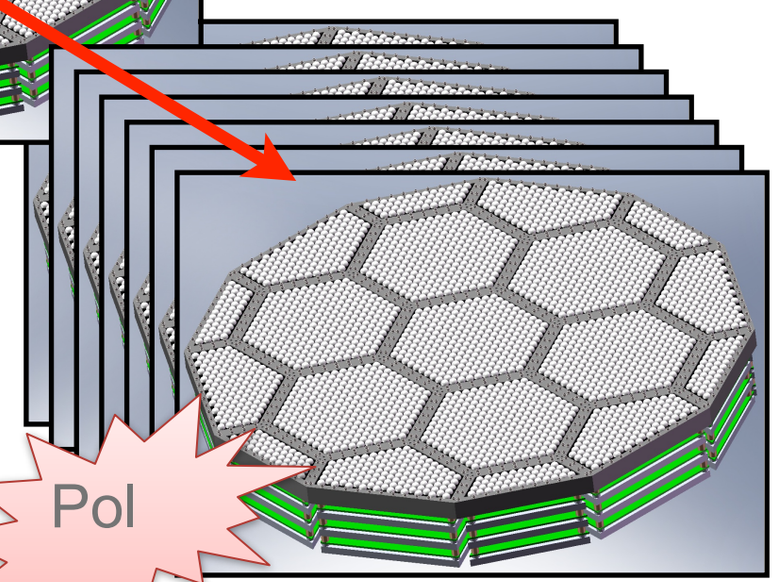
Stage-3
2016: SPT-3G
~15,200 detectors



Pol

CMB Stage-4 Experiment
Described in Snowmass CF5:
Neutrinos: arxiv:1309.5383
Inflation: arxiv:1309.5381

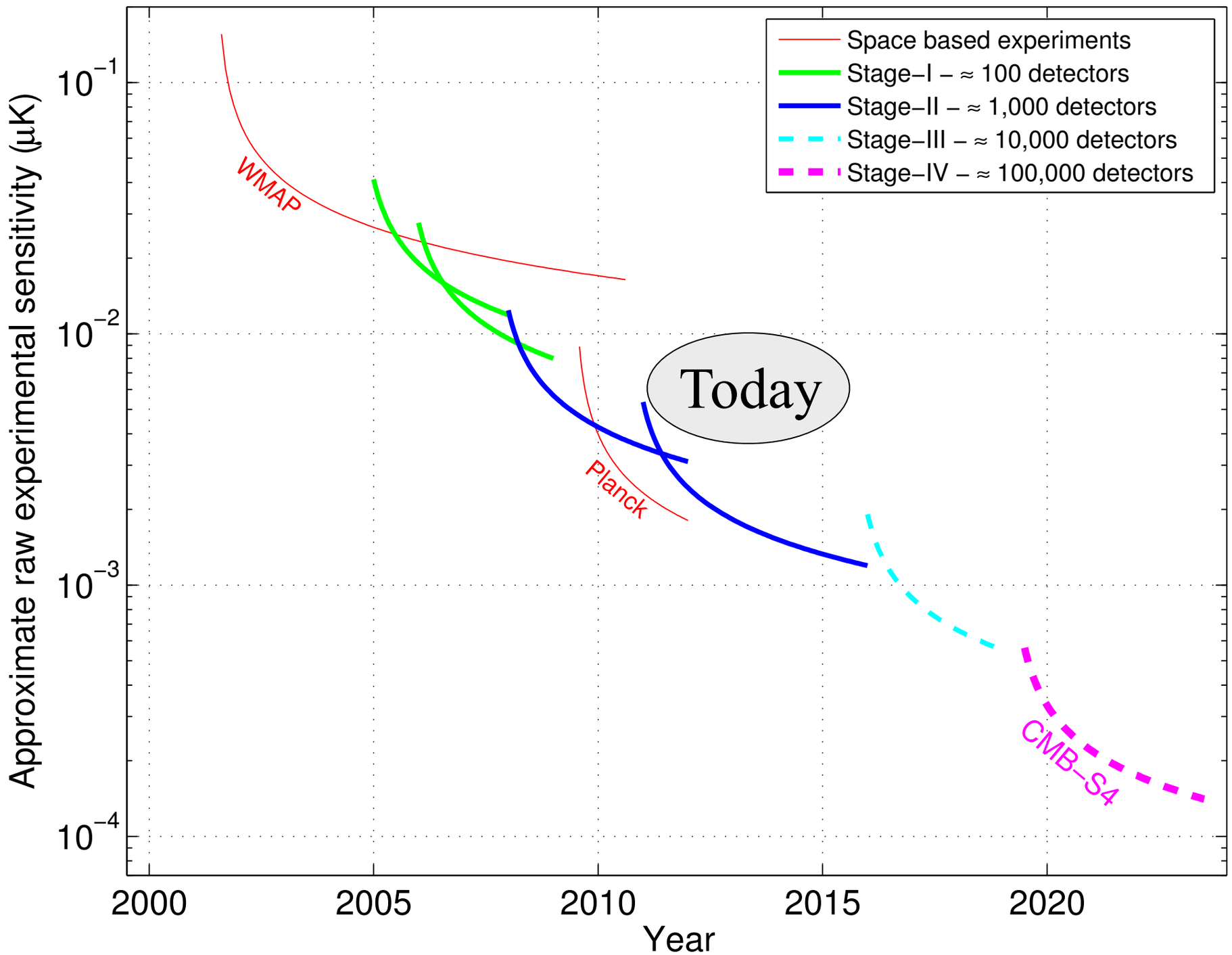
Stage-4
2020?: CMB-S4
100,000+ detectors



Pol

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



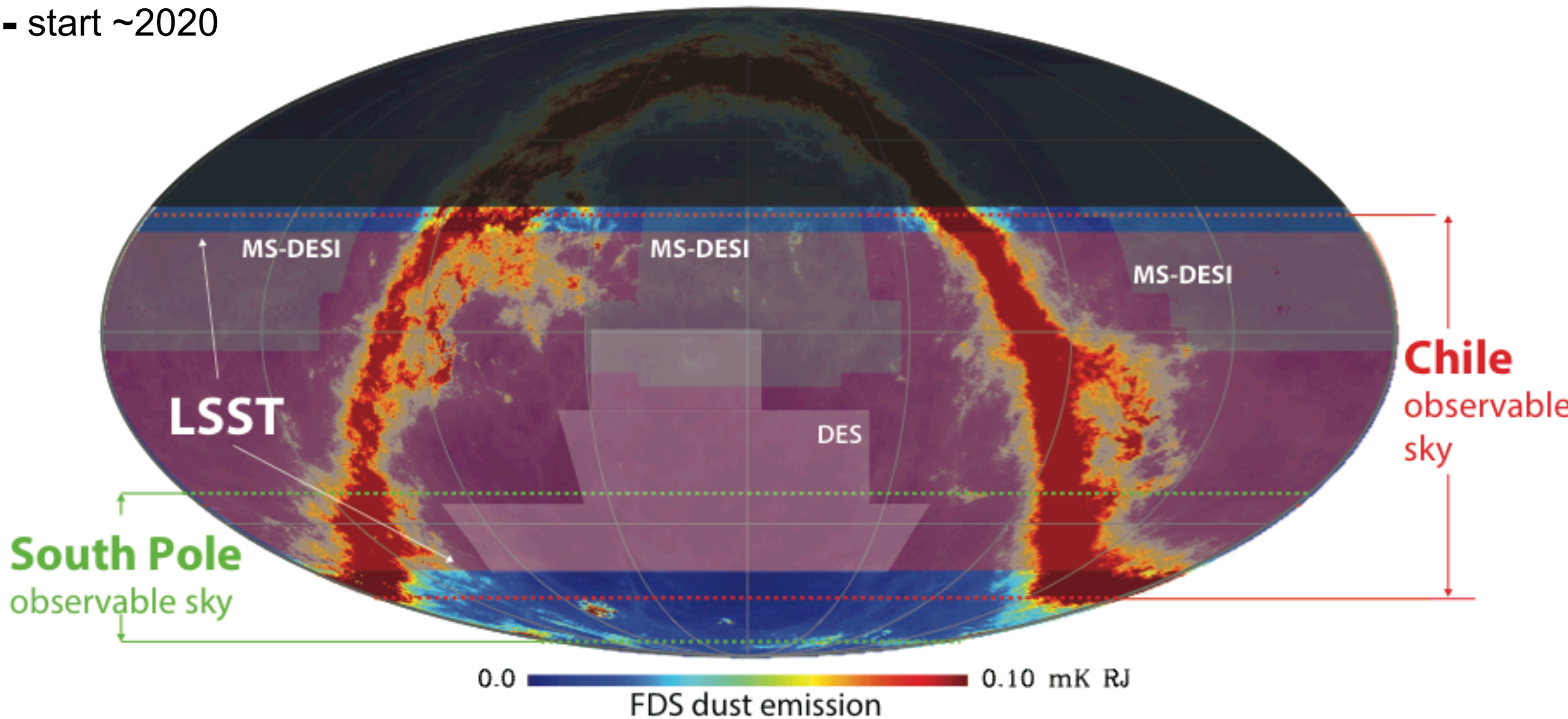
Stage-IV CMB experiment = **CMB-S4**

~200x faster than today's Stage 2 experiments

Snowmass: CF5 Neutrinos Document
arxiv:1309.5383

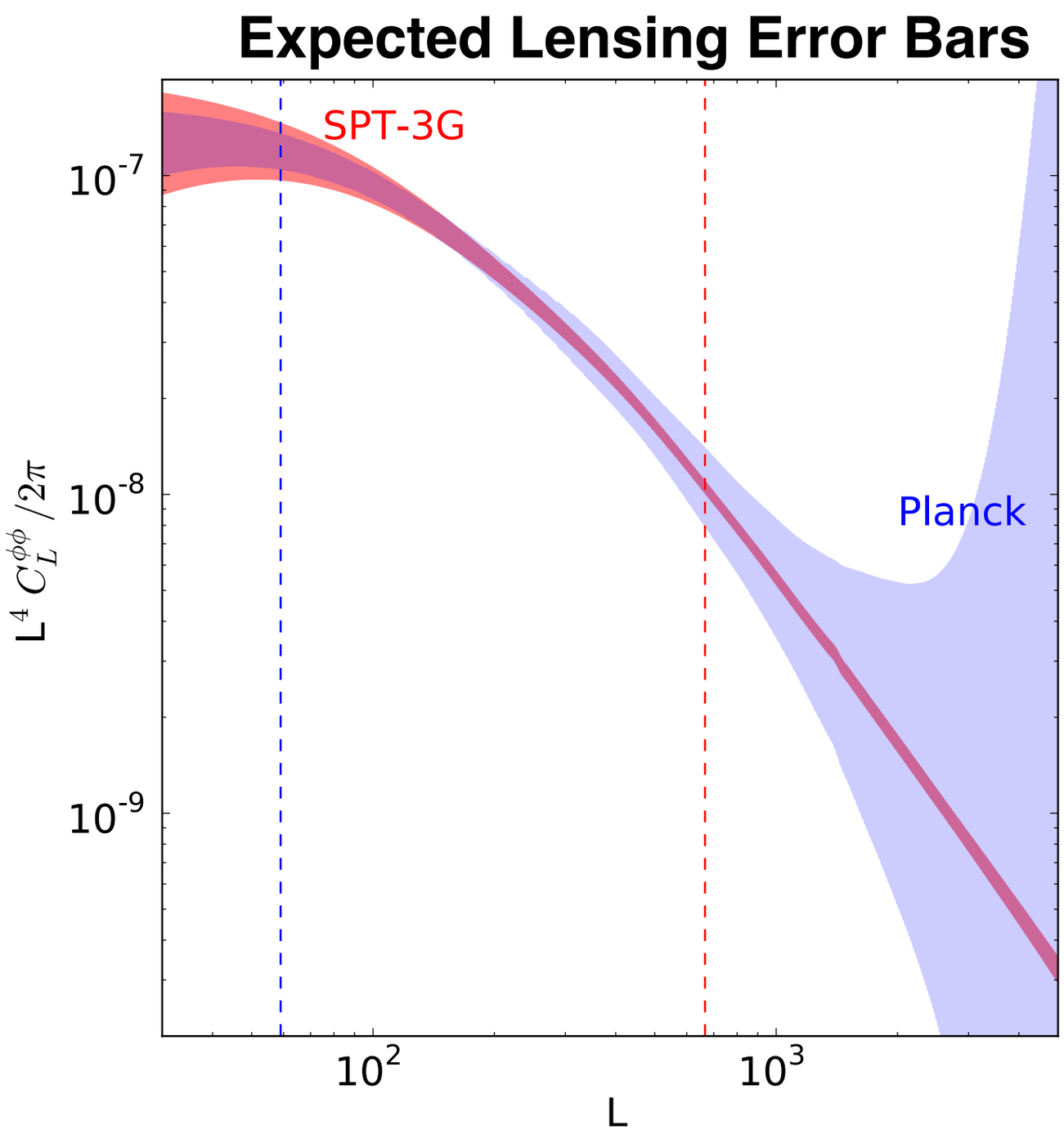
‘CMB-S4’ Stage 4 CMB experiment
(footprint overlap with DES, LSST, MS-DESI, etc)

- 200,000 - 500,000 detectors on multiple platforms
- span 40 - 240 GHz for foreground removal
- target noise of ~1 uK-arcmin depth over half the sky
- start ~2020



Primary technical challenge will be the scaling of the detector arrays

CMB Lensing Power Spectrum Constraints



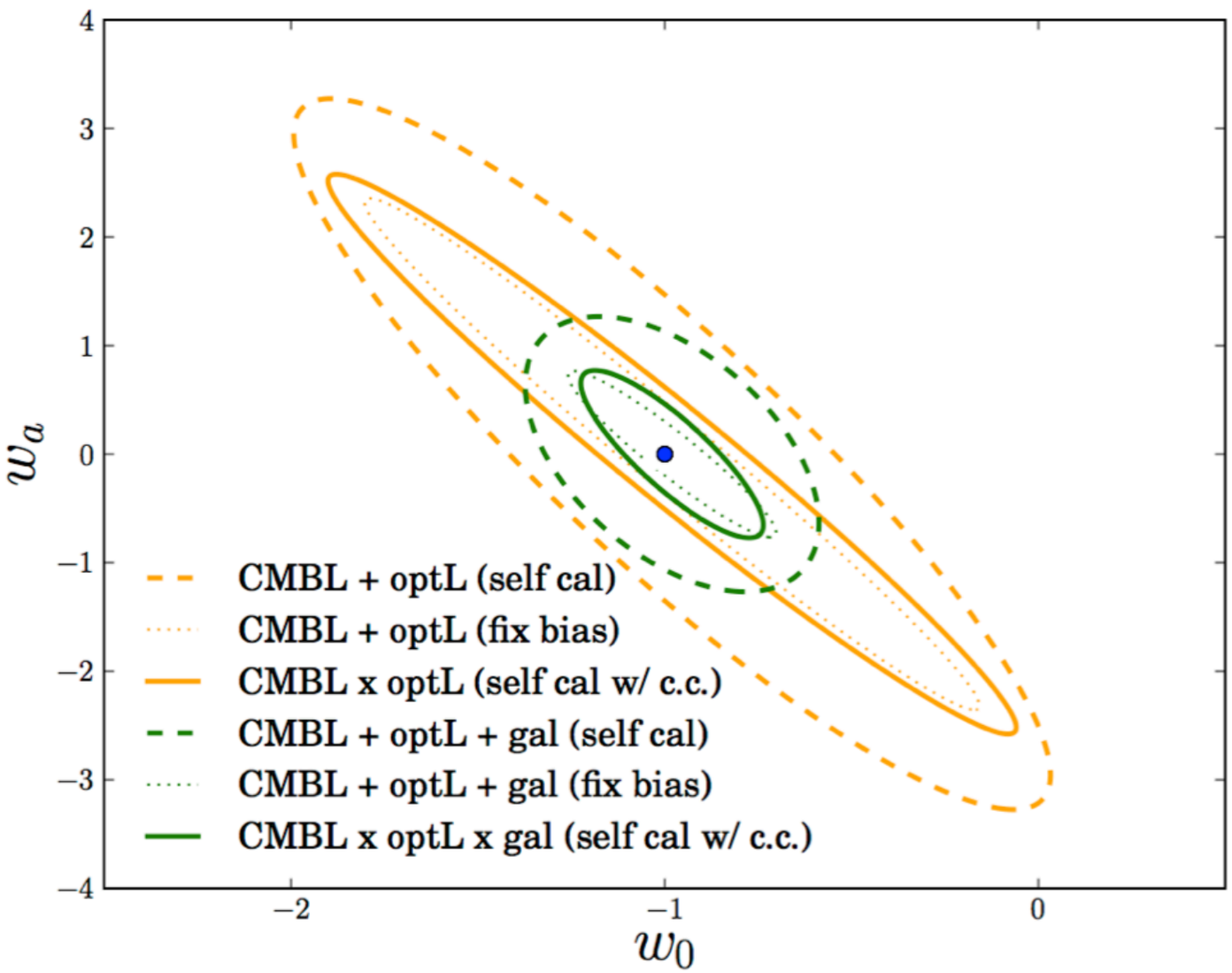
Credit: G. Holder

- CMB Lensing Detection Significance:
  - **SPT-SZ:** 20-σ
  - **Planck:** 30-σ
  - **SPTpol:** 40-σ
  - **SPT-3G:** 150-σ
  - **CMB-S4:** 400-σ

- ***SPT-3G will measure individual lensing modes on ~10 arcmin scales*** (Planck is ~3 deg scales)

- ***Cross-correlating with DES will measure galaxy bias to better than ~1%***

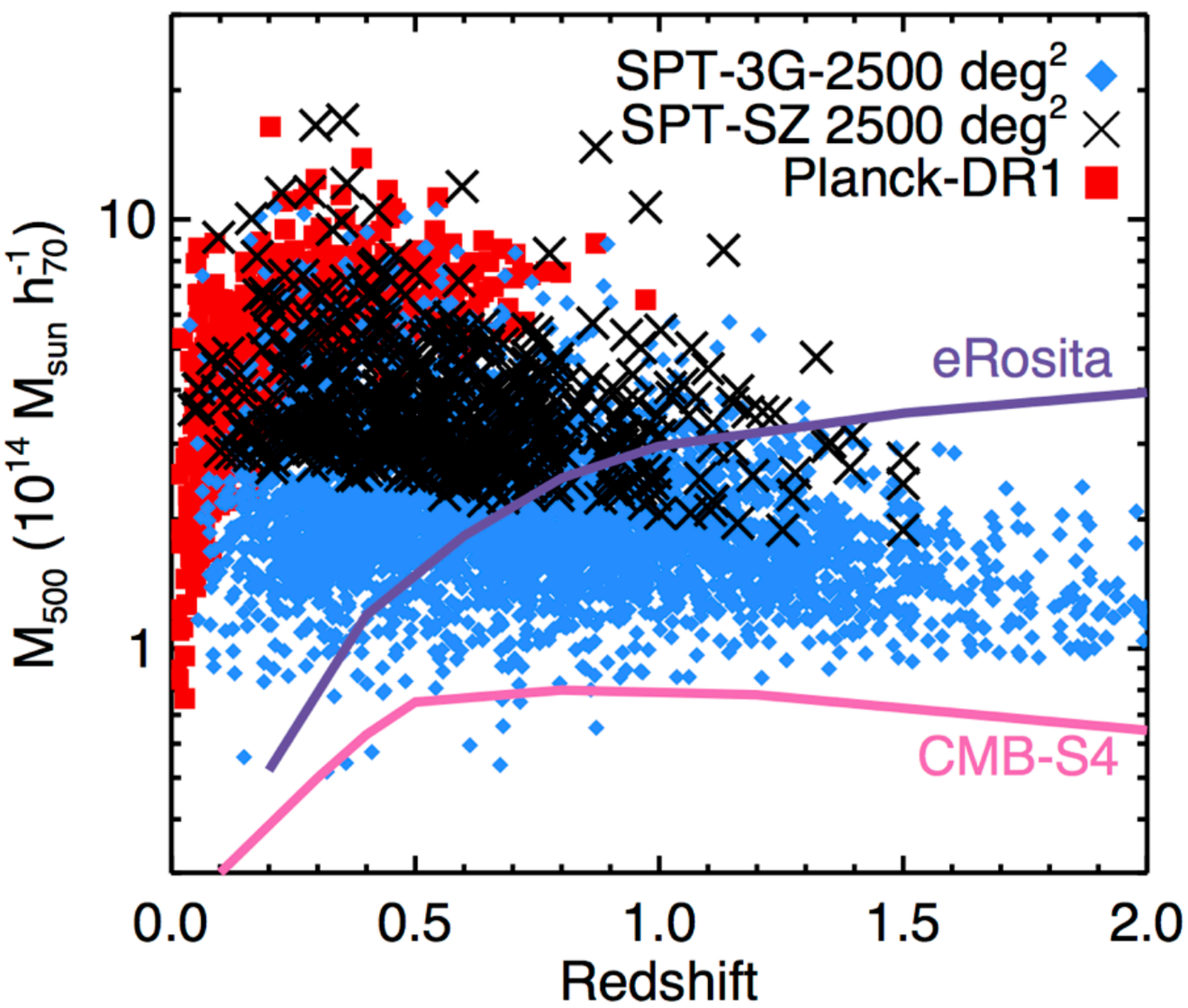
CMB Lensing x Galaxy Lensing



- **CMB lensing provides a powerful calibration for galaxy lensing surveys (DES,LSST)**
- For ACTpol and HSC (SPTpol and DES-like) lensing surveys, adding CMB lensing will:
  - ***Improve dark energy constraints by ~25%***
  - ***Reduces uncertainty on multiplicative bias by a factor of ~3-10***

Das, Errard, & Spergel (2013)

Future SZ Cluster Surveys



Cluster counts scale roughly as number of CMB detectors:

SPT-SZ/pol: $N_{\rm clust}$ **~ 1,000**

SPT-3G: $N_{\rm clust}$ **~ 10,000**

CMB-S4: $N_{\rm clust}$ **~ 100,000+**

Deep CMB data also enables CMB cluster lensing as a competitive mass calibration tool for cluster DE science:

SPT-3G: $\sigma(M) \sim 3\%$

CMB-S4: $\sigma(M) < \sim 0.1\%$

Especially promising tool for cluster masses at $z > 1$

Cross-Correlation Science from SPTxDES

DES x SPT	CMB Lensing Convergence (κ) Map	SZ Temperature Profile	CMB Polarization	Small-scale CMB Lensing
Galaxy Map	Measure galaxy bias; the relationship between galaxy stellar and halo mass	Calibrate SZ and optical cluster observables to improve constraints on cosmology and cluster evolution	Gravitational potential from DES galaxies convolved with E-modes to estimate their B-mode contribution	CMB cluster lensing will calibrate DES cluster masses to improve cosmological constraints
Shear Map	Constrain systematics in galaxy shape measurements (e.g., linear and magnification bias)	Probes baryonic pressure as a function of distance from halos	Gravitational potential from DES shear convolved with E-modes to estimate their B-mode contribution	Measure CMB lensing around DES shear peaks, tomographic measurement of large-scale structure
Tangential Shear [galaxy-galaxy or cluster lensing]	Measure tangential shear of DES galaxies around SZ-selected lensing peaks	Lensing mass estimates of SZ-selected clusters to improve cluster cosmological constraints		

Summary

This science is just beginning!

- **2008**: First CMB (SZ) discovered cluster
- **2012**: First 5-σ detection of CMB lensing
- **2013**: DES survey begins

SZ-discovered clusters of galaxies and CMB lensing have a strong complimentary with upcoming optical surveys to probe structure growth:

Cosmology from the Cluster Abundance

Dark energy and neutrino mass from cross-correlations

(Galaxy density and lensing) X CMB lensing

Gravitational potentials on ~100 Mpc scales

CMB-S4 Cosmological Constraints

	$\sigma(r)$	$\sigma(N_{\rm eff})$	$\sigma(\Sigma m_\nu)$ (meV)
Current CMB	**0.05**	**0.34**	**117**
Stage 2: SPTpol	0.02	0.12	96
Stage 3: SPT-3G	0.01	0.06	61*
Stage 4: CMB-S4	**0.001**	**0.02**	**16****

* Includes BOSS prior
** Includes DESI prior

The CMB-S4 sensitivity would achieve important benchmarks:

- $\sigma(r) \sim 0.001$; large vs small field inflation?
- $\sigma(N_{\rm eff}) \sim 0.02$; new physics in neutrino or dark sector?
- $\sigma(\Sigma m_\nu) \sim 16$ meV ; cosmological detection of neutrino mass?

Snowmass: CF5 Neutrinos + Inflation Document
arxiv:1309.5383, 1309.5381