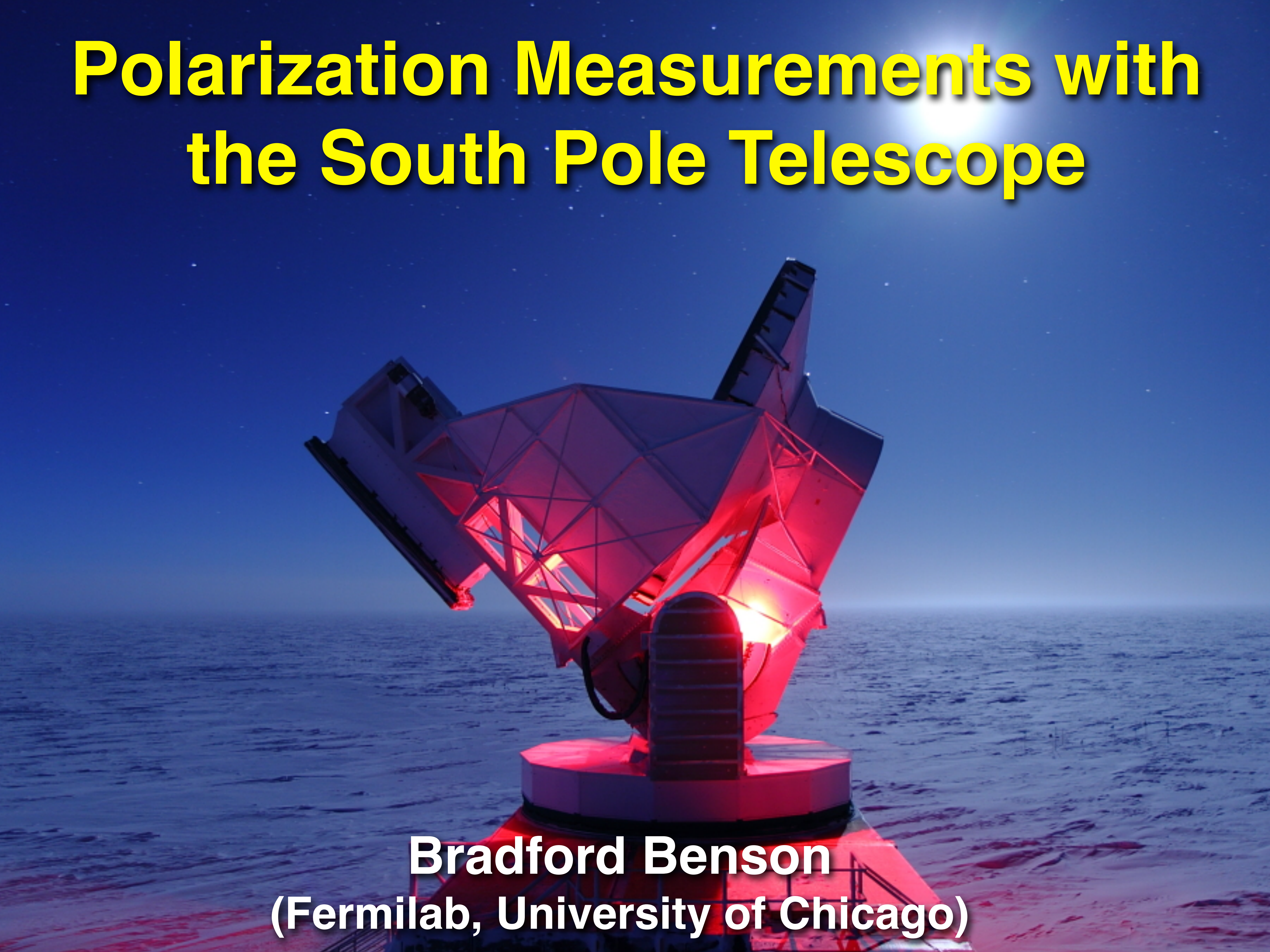
# Polarization Measurements with the South Pole Telescope



**Bradford Benson**
(Fermilab, University of Chicago)

# The South Pole Telescope Collaboration

Funded By:

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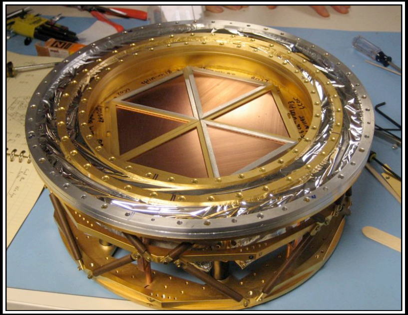
# The South Pole Telescope (SPT)

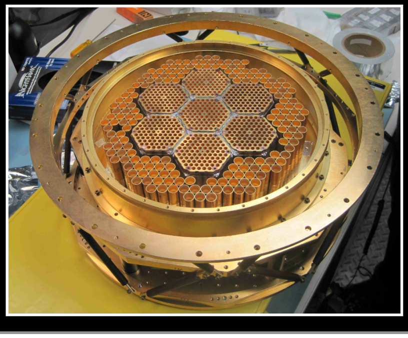
10-meter sub-mm quality wavelength telescope

95, 150, 220 GHz and
1.6, 1.2, 1.0 arcmin resolution

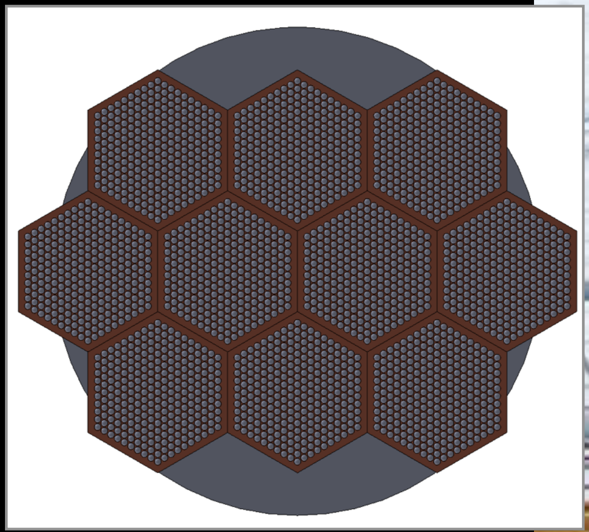
**2007: SPT-SZ**
960 detectors
95,150,220 GHz

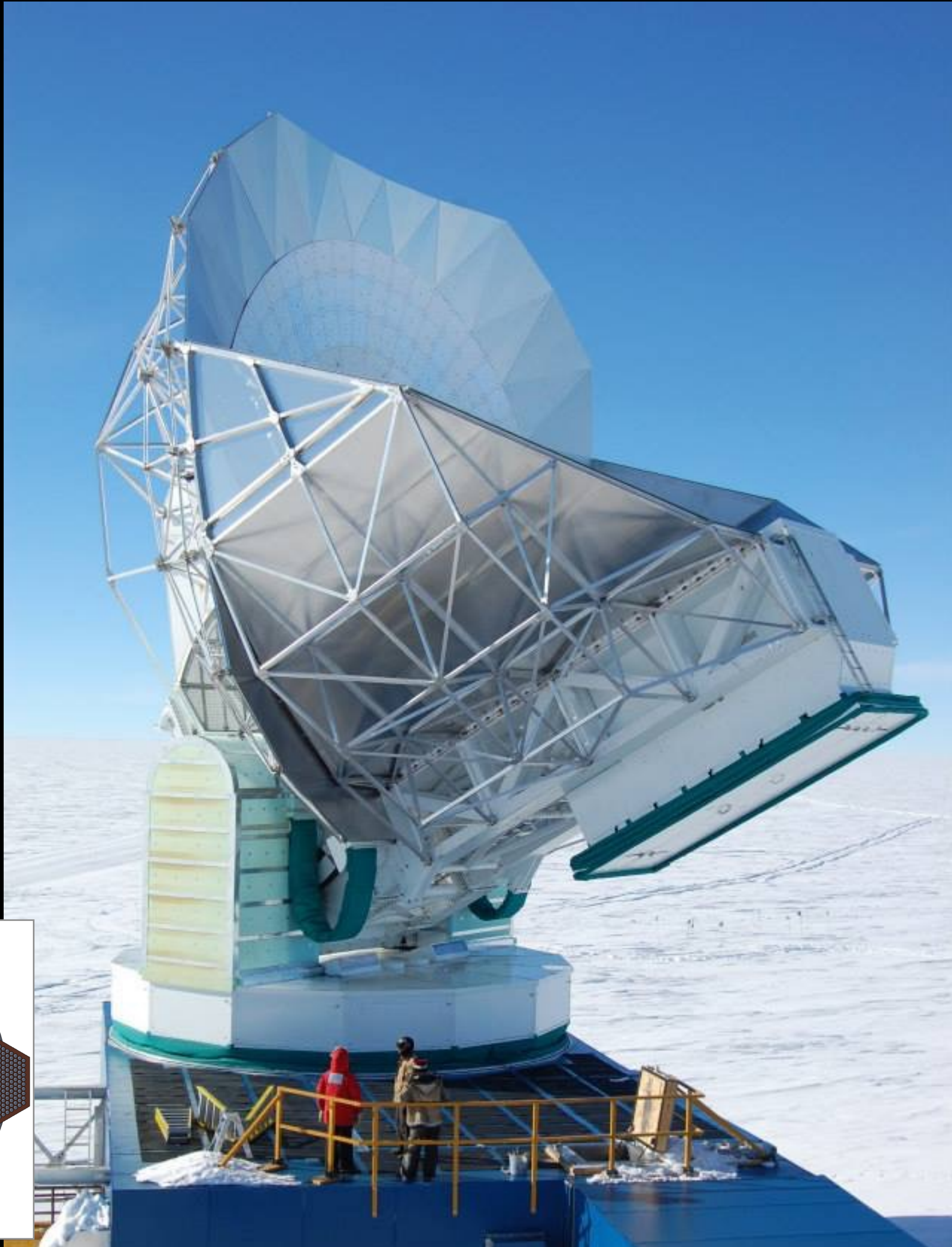


**2012: SPTpol**
1600 detectors
95, 150 GHz
***+Polarization***

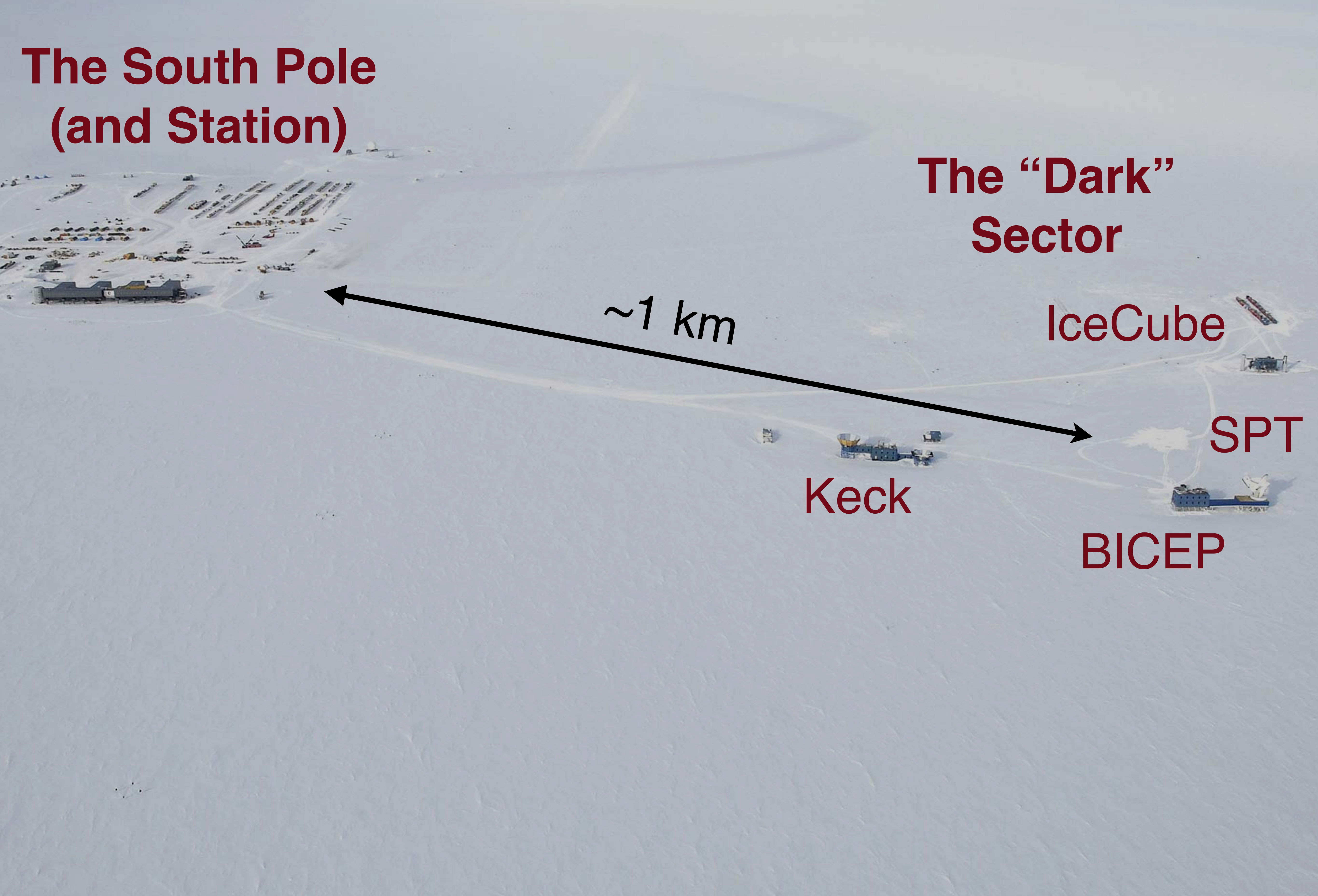


**2016: SPT-3G**
16,260 detectors
95,150,220 GHz
***+Polarization***

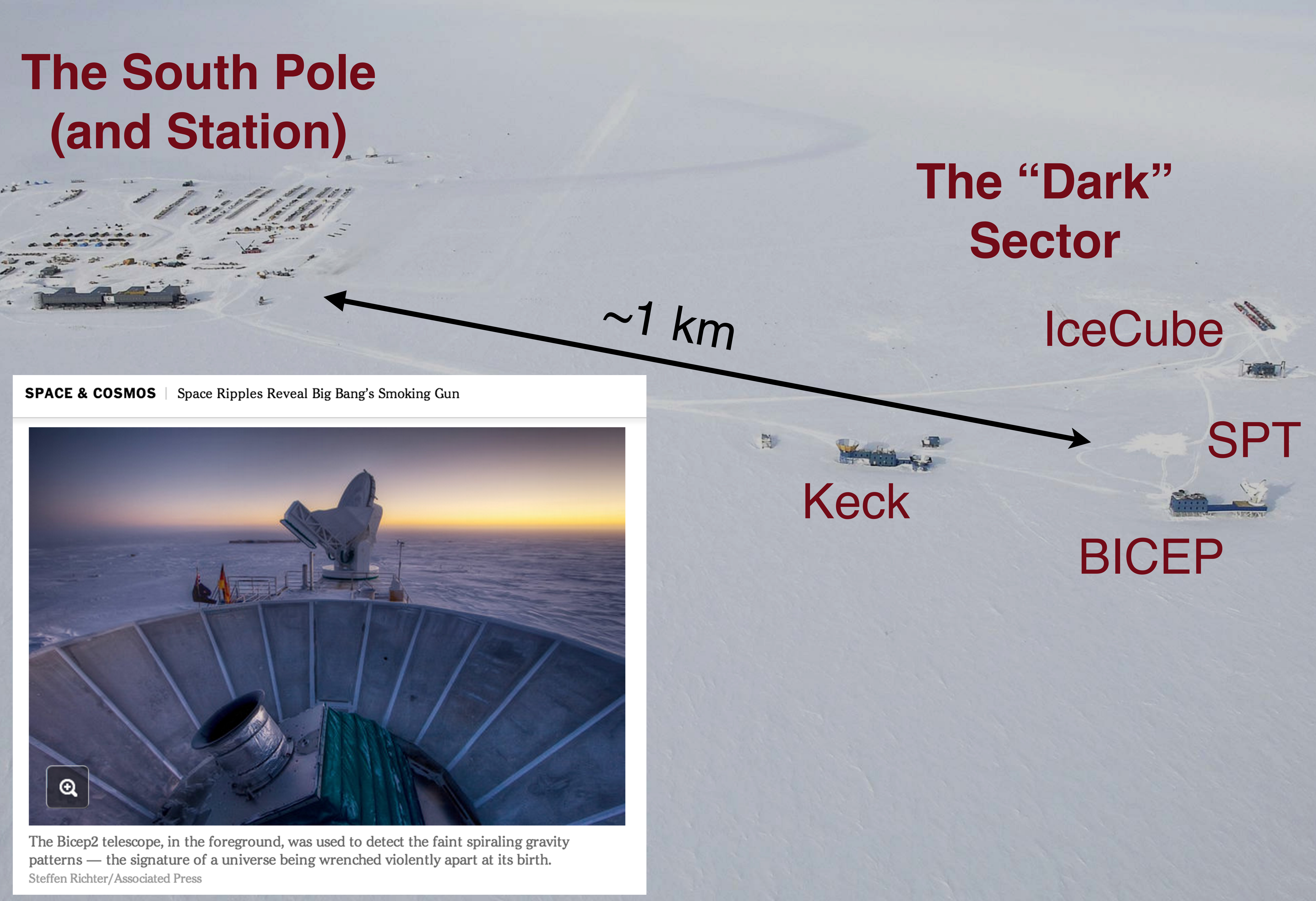




# The South Pole

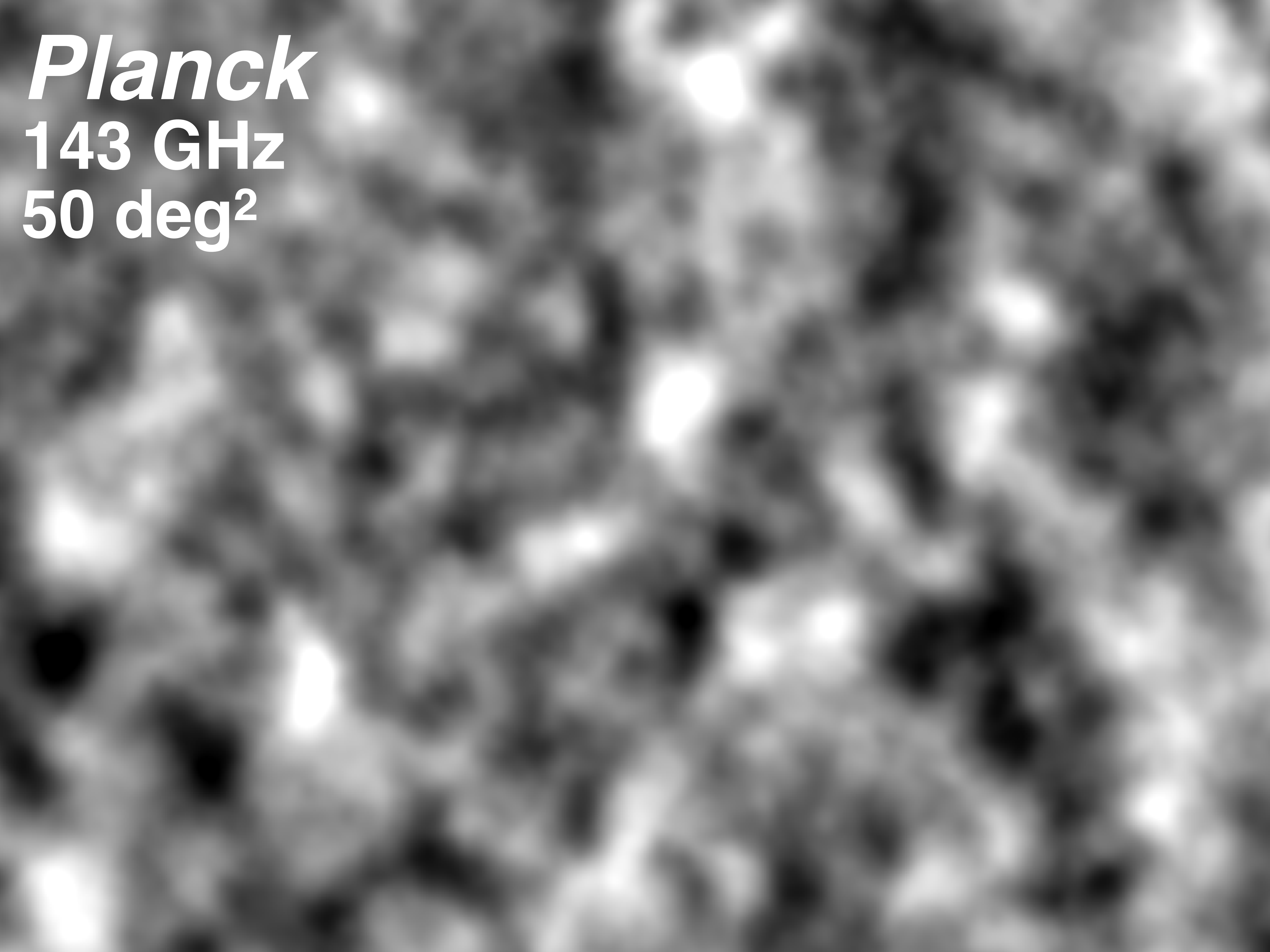


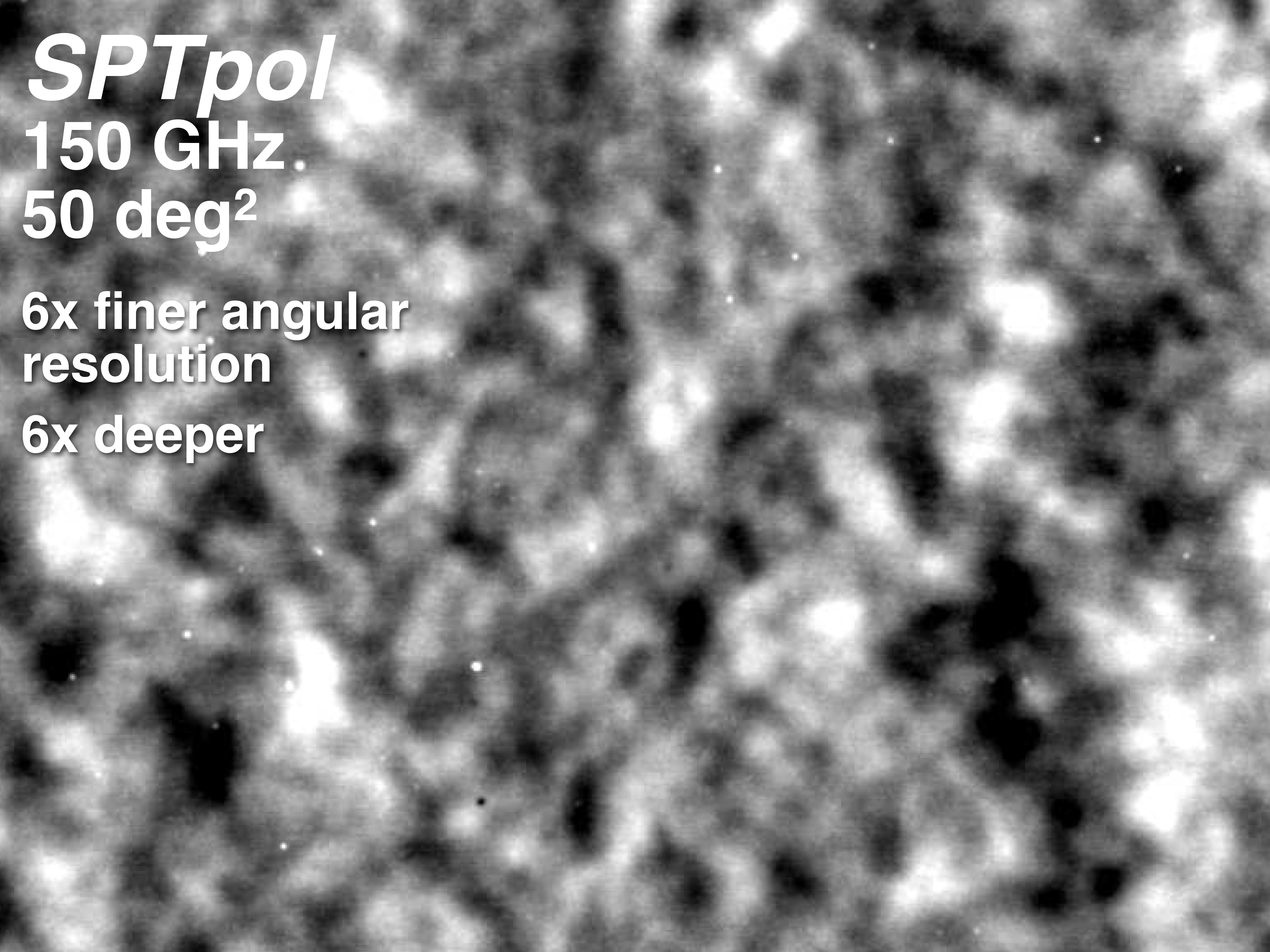
# The South Pole

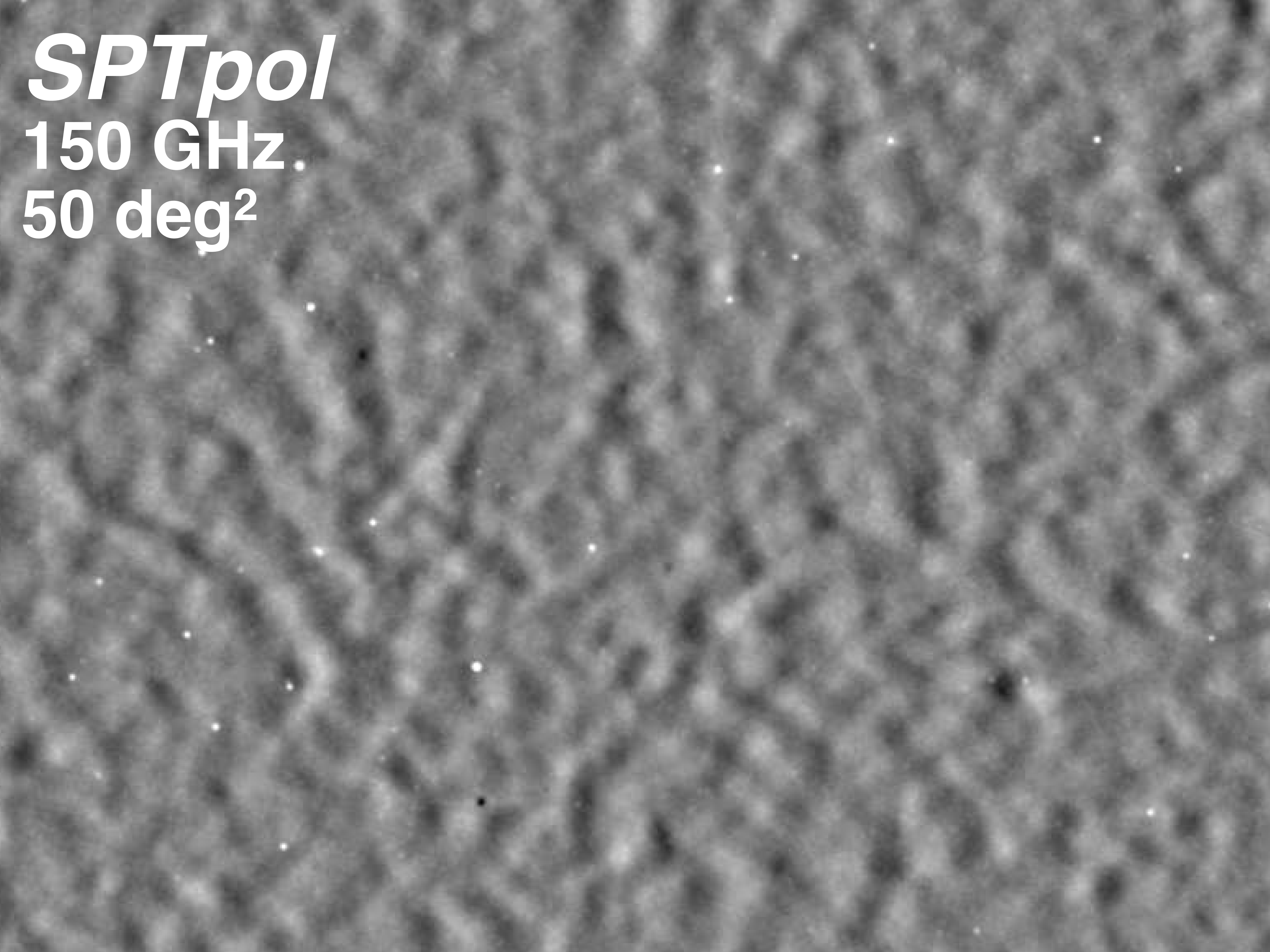


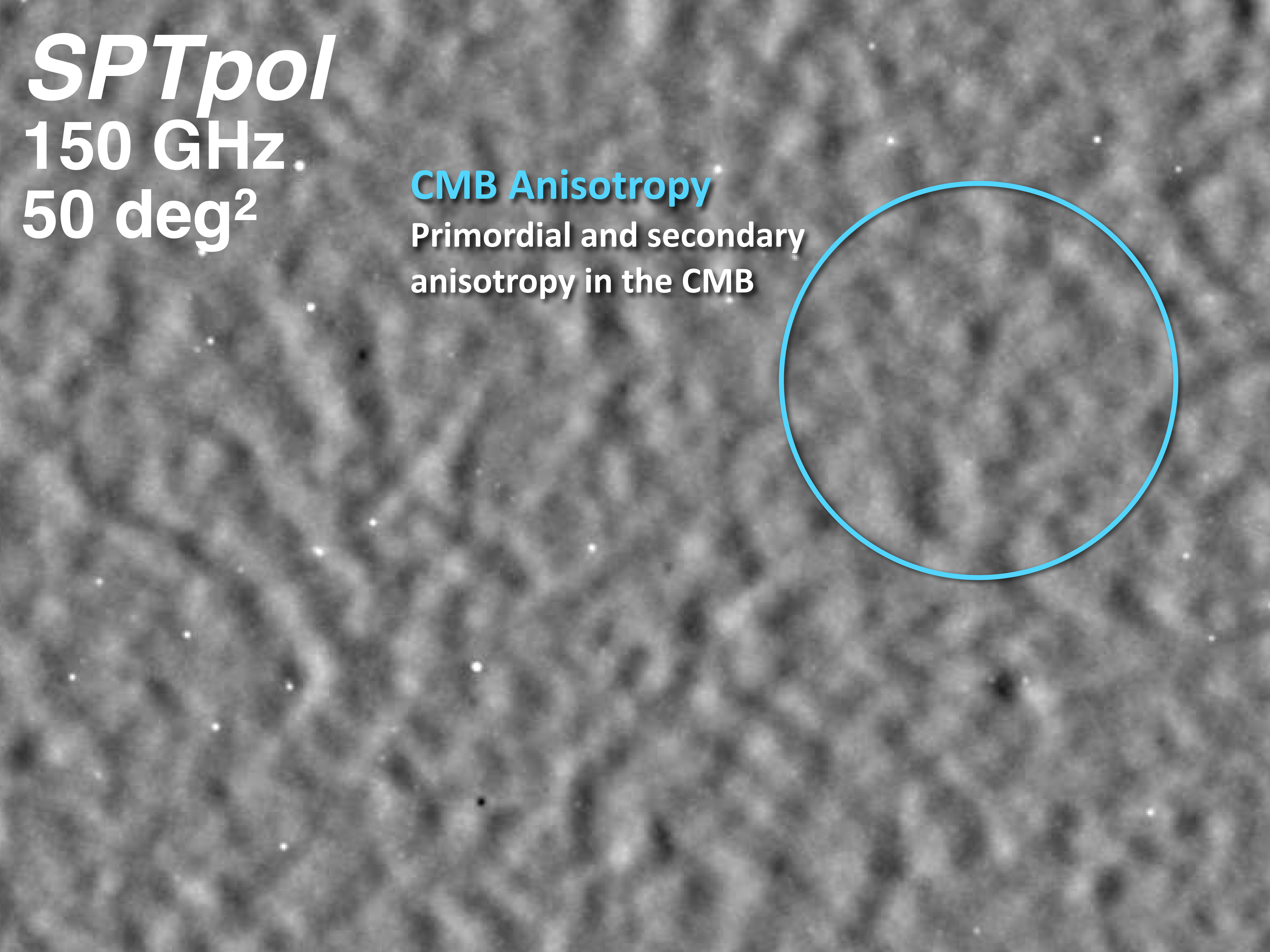

**SPACE & COSMOS** | Space Ripples Reveal Big Bang's Smoking Gun

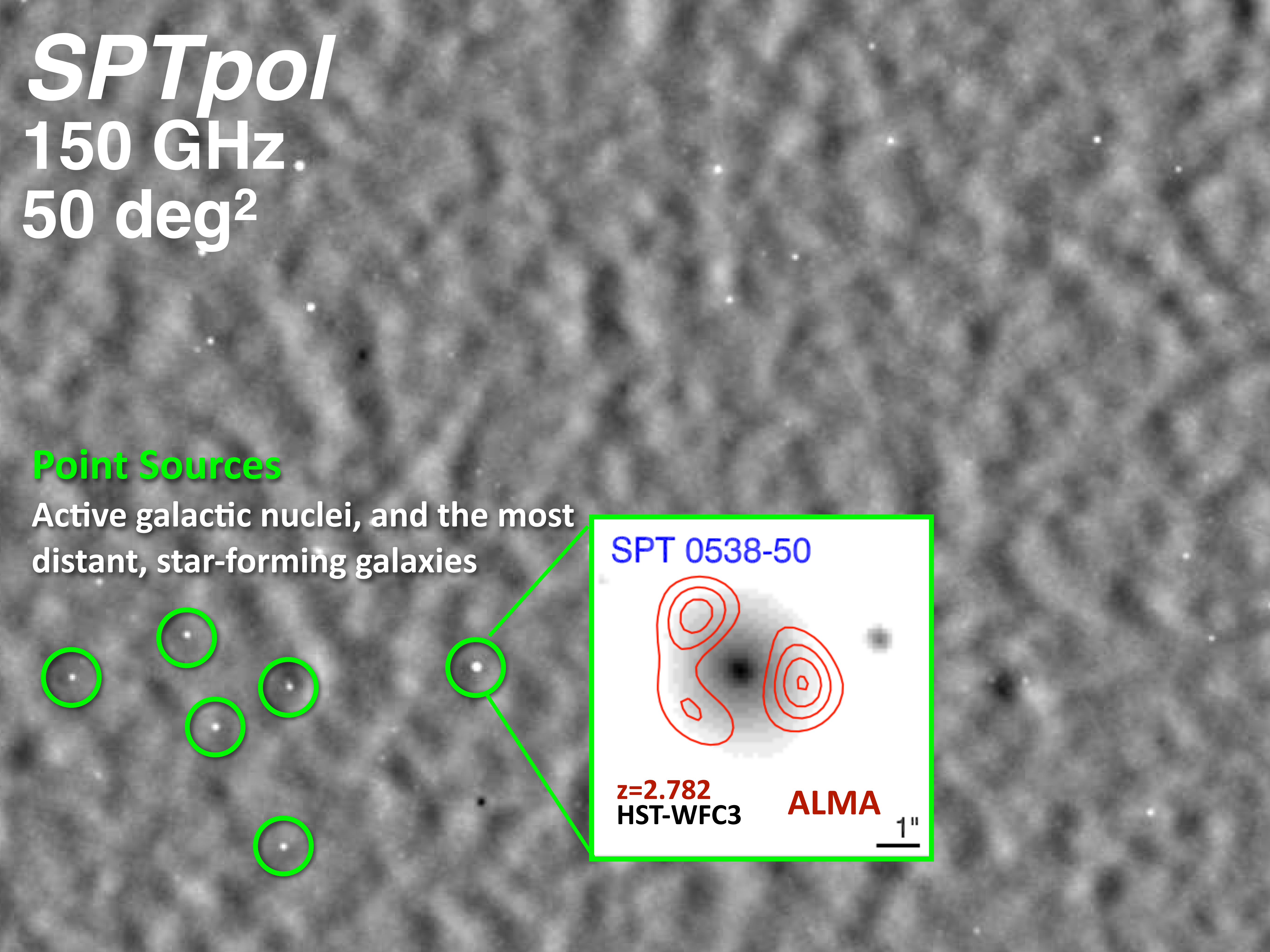
The Bicep2 telescope, in the foreground, was used to detect the faint spiraling gravity patterns — the signature of a universe being wrenched violently apart at its birth.
Steffen Richter/Associated Press

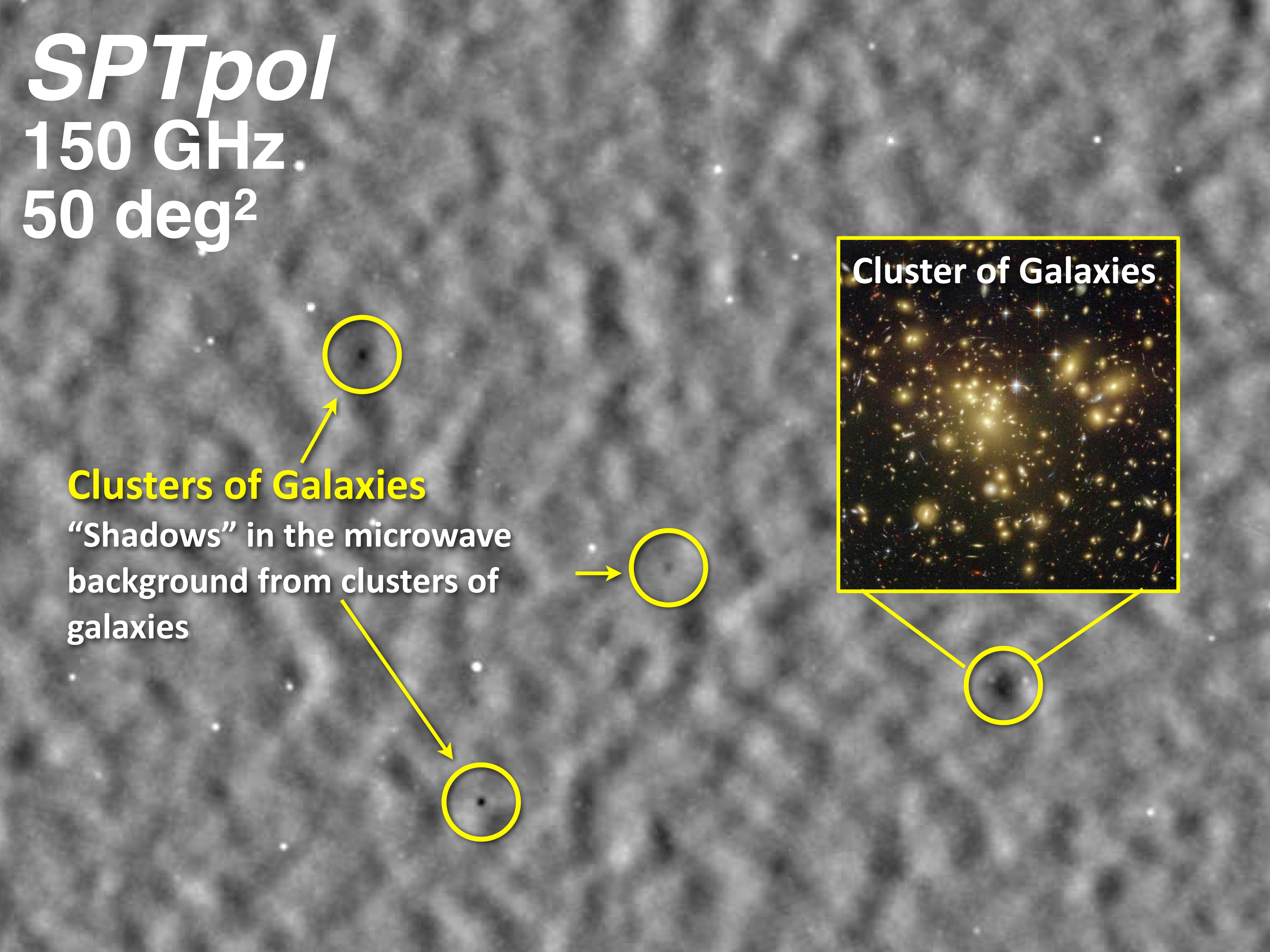

Planck
143 GHz
50 deg²


*SPTpol*
150 GHz
50 deg$^2$
6x finer angular resolution
6x deeper

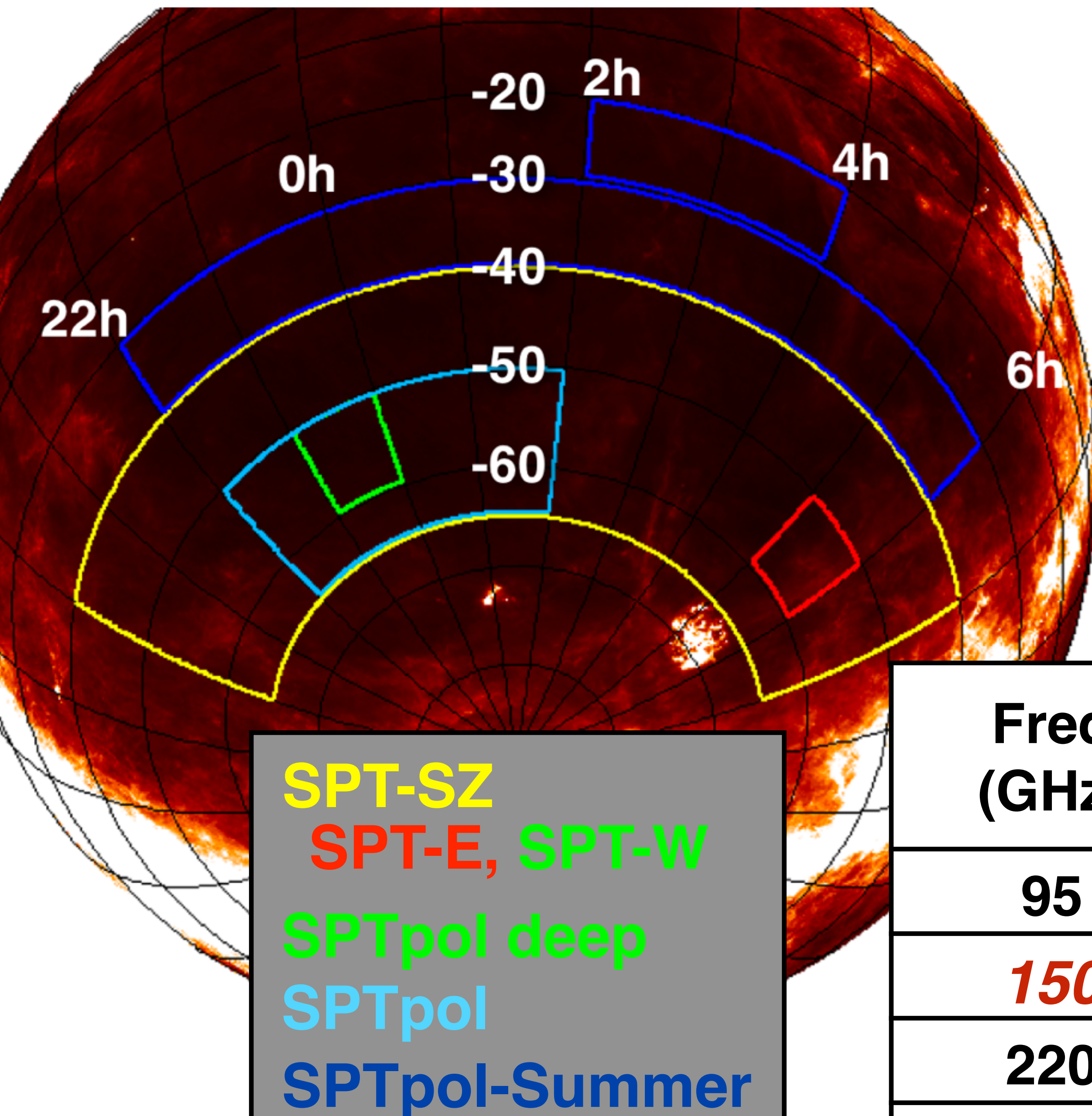

SPTpol
150 GHz
50 deg²

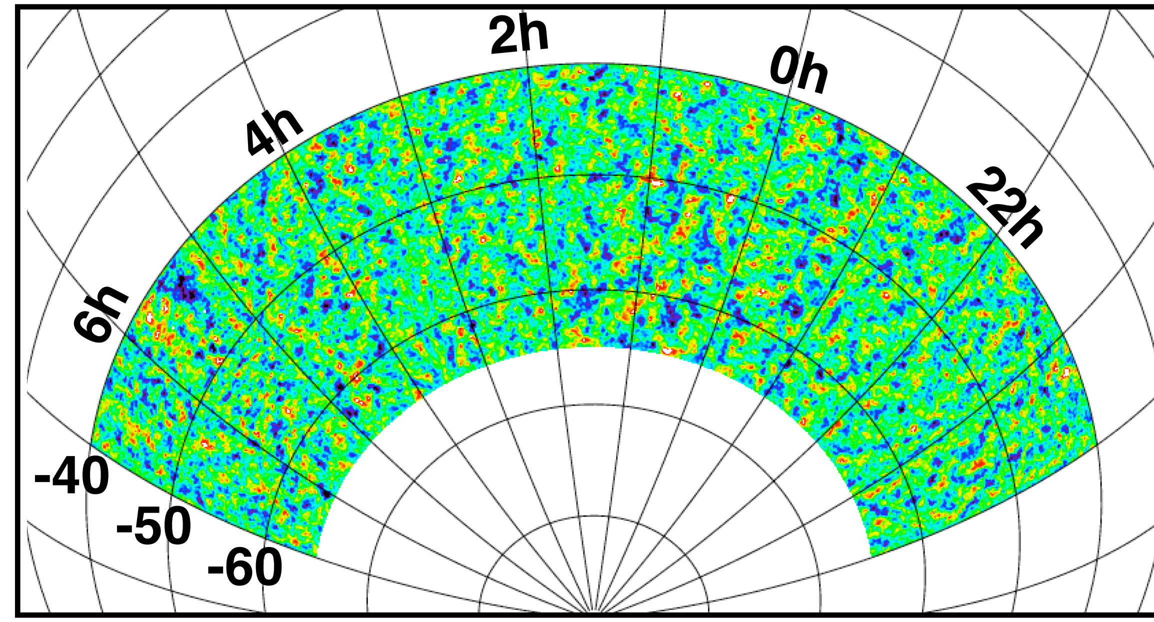

SPTpol
150 GHz
50 deg2
CMB Anisotropy
Primordial and secondary
anisotropy in the CMB


SPTpol
150 GHz
50 deg²
Point Sources
Active galactic nuclei, and the most distant, star-forming galaxies
SPT 0538-50
z=2.782
HST-WFC3
ALMA
1"


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

# The SPT Surveys




Depth (μK-arcmin)

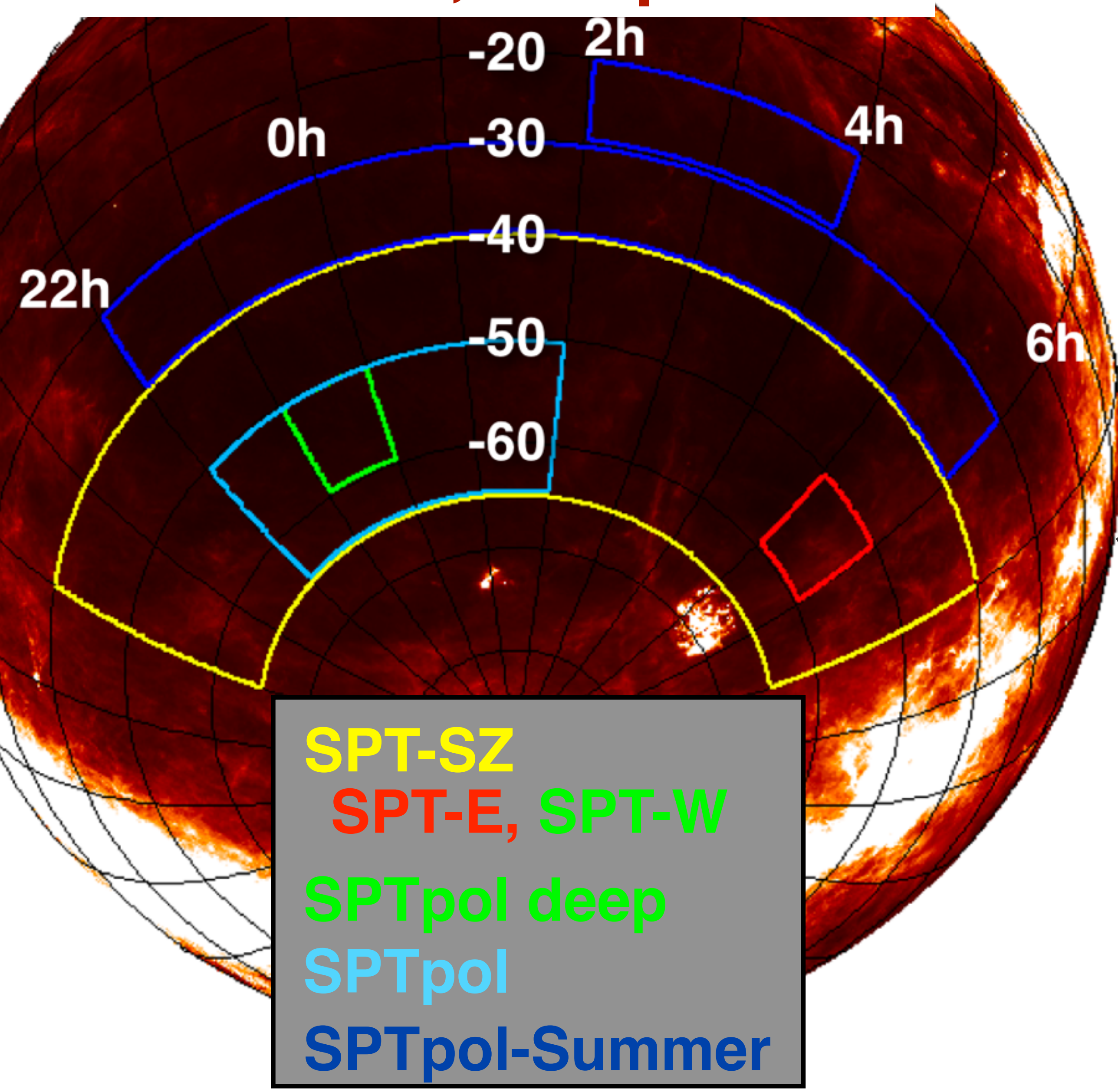
| Freq (GHz) | SPT-SZ | SPTpol Deep | SPTpol Summer | SPTpol Main |
|---|---|---|---|---|
| **95** | 40 | 15 | 70 | 15 |
| ***150*** | ***17*** | ***6*** | ***30*** | ***6*** |
| **220** | 80 | - | - | |
| **Area ($deg^2$)** | 2500 | 100 | 1250 | 500 |
| **Status** | *Complete* | *Complete* | *Complete* | *In Progress* |

***3750 $deg^2$ surveyed in total by SPT-SZ and SPTpol***

***- 150 GHz NET depths between 6-30 μK-arcmin***

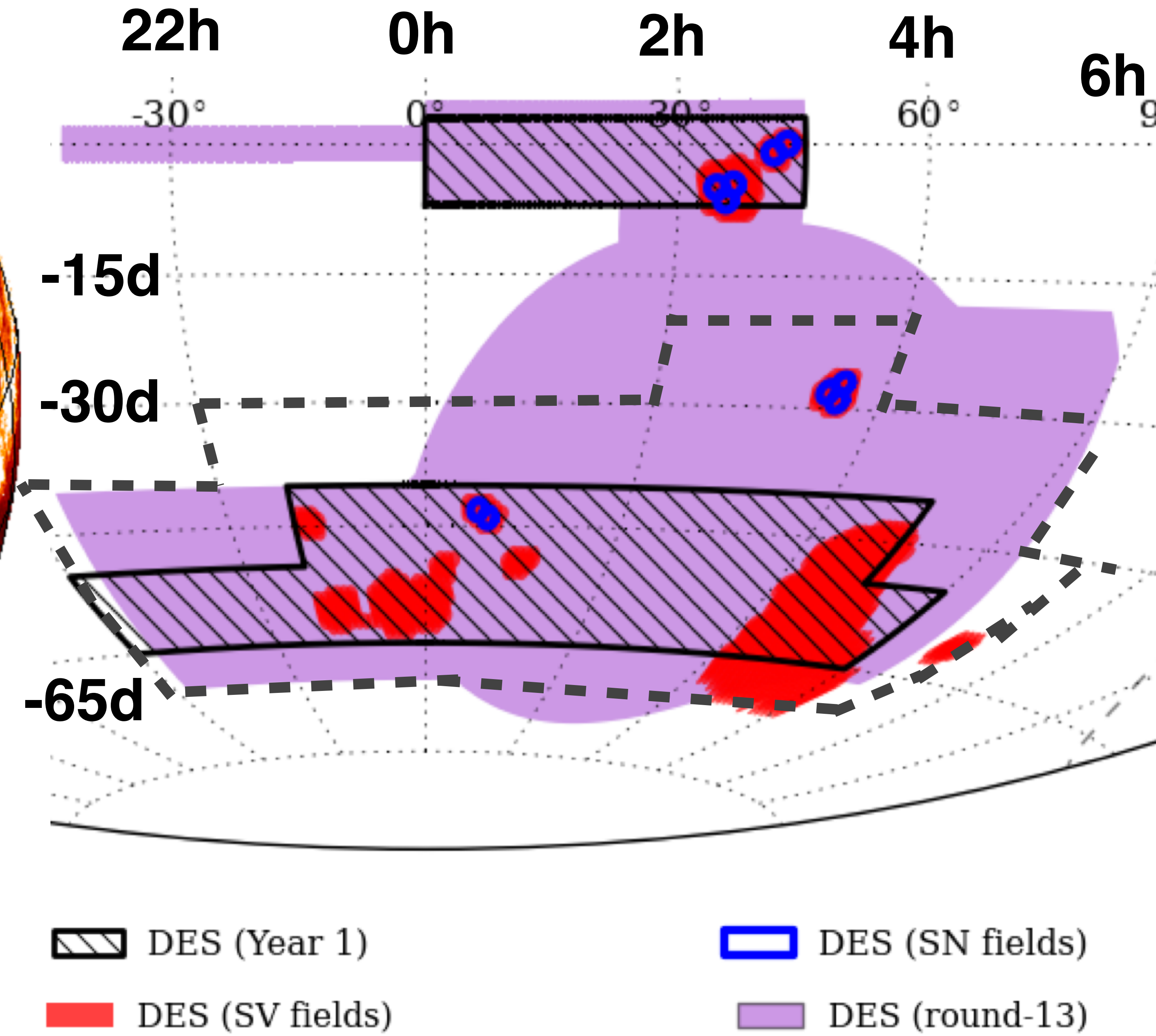
# SPT Footprints

## 3750 deg² between SPT-SZ, SPTpol




# DES Footprint

# SPT Footprint

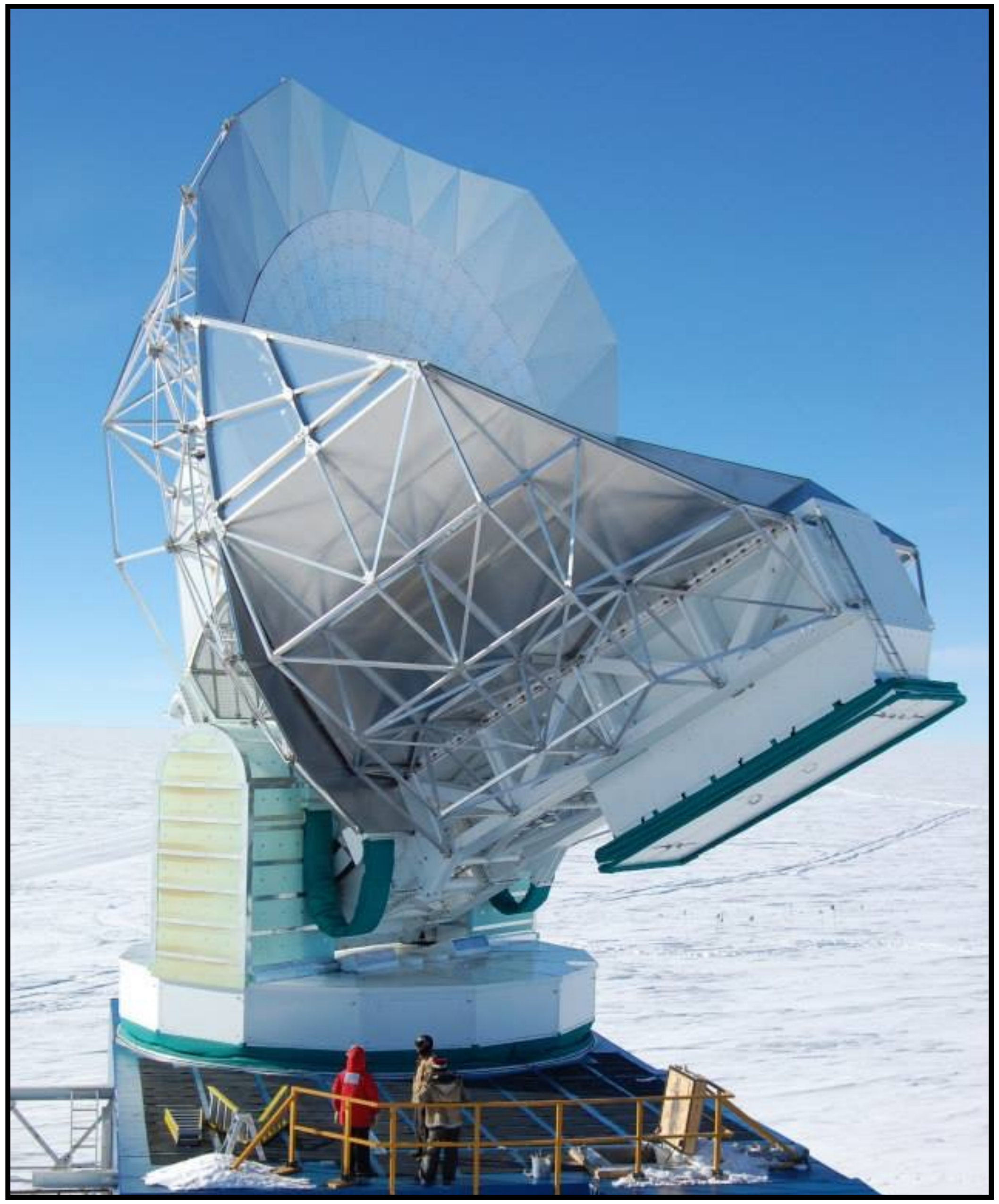


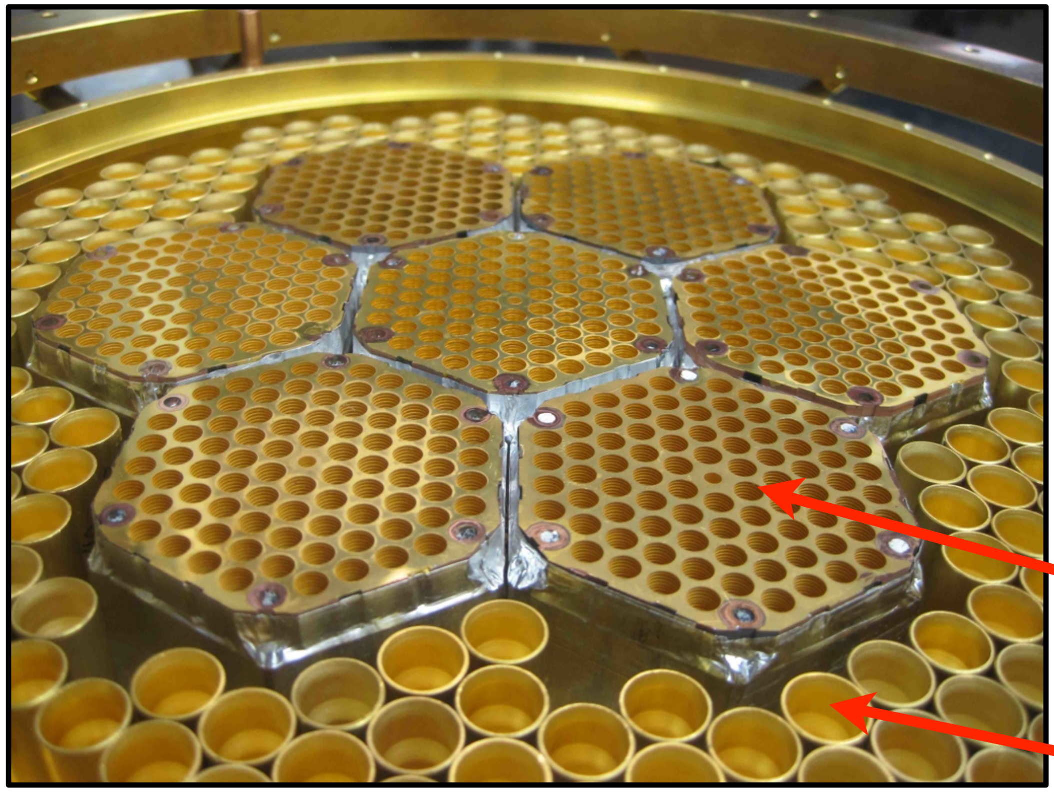

*3200 deg² overlap with Dark Energy Survey*

# ***SPTpol*: *A polarization-sensitive receiver on SPT***

## Status:

- First light Jan. 26, 2012
- 95 and 150 GHz receiver
- ***3 years into 4 year survey***
  - **2012-13:** 100 deg$^2$ deep field
  - **2013-15:** 500 deg$^2$ main survey field (overlaps BICEP2)

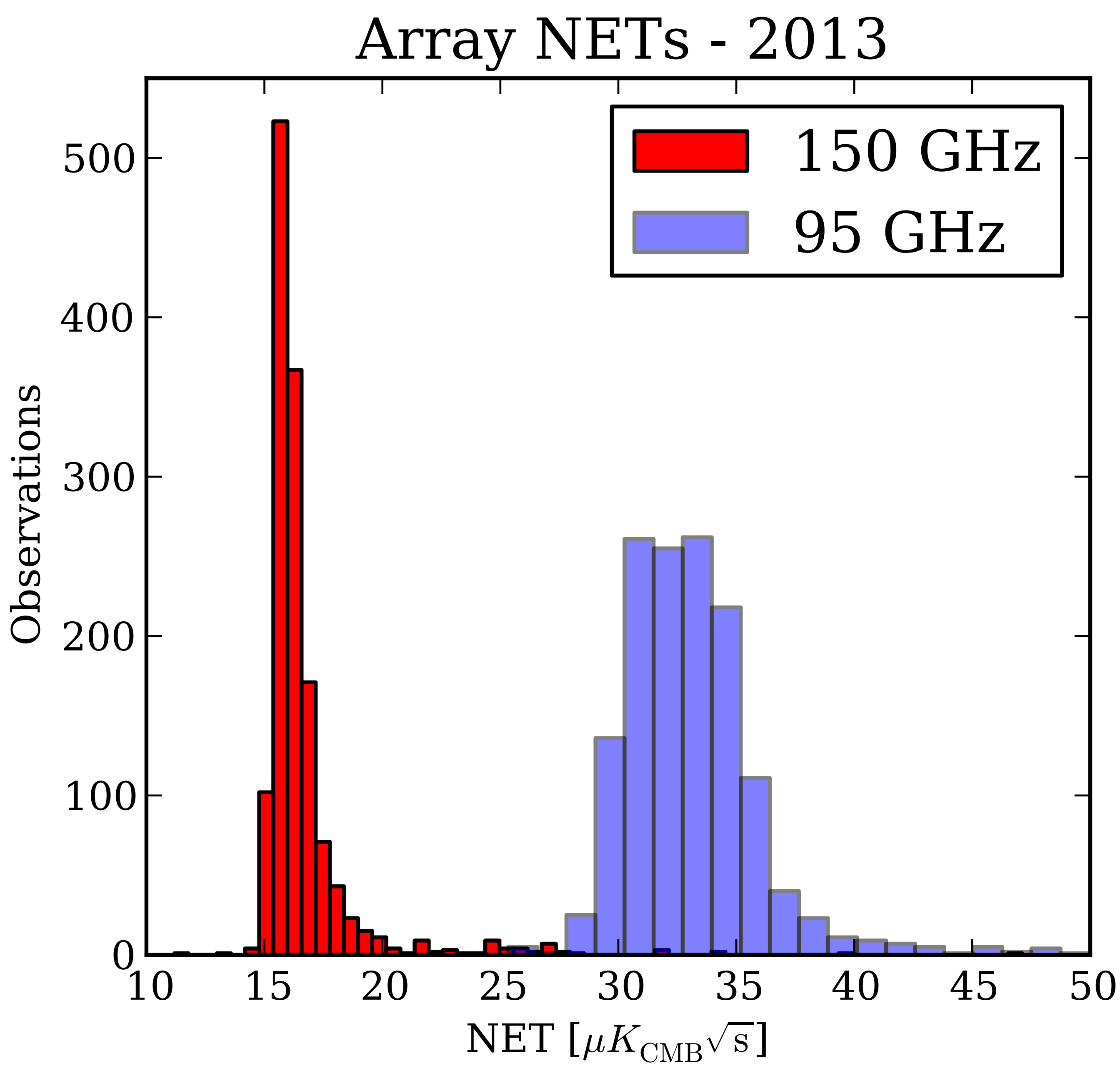




(1176x TES) **150 GHz** detectors (NIST)

(360x TES) **95 GHz** detectors, (Argonne National Labs)

# SPTpol Array Performance




- Histogram of the SPTpol array sensitivity in units of Noise Equivalent CMB Temperature (NET) for the 2013 observing season.
- **Mode array NET of:**
  - **15.5 $\mu$K s$^{1/2}$ at 150 GHz**
  - **32.5 $\mu$K s$^{1/2}$ at 95 GHz**
- Width represents the variation of the array NET over ~1500 survey field observations.

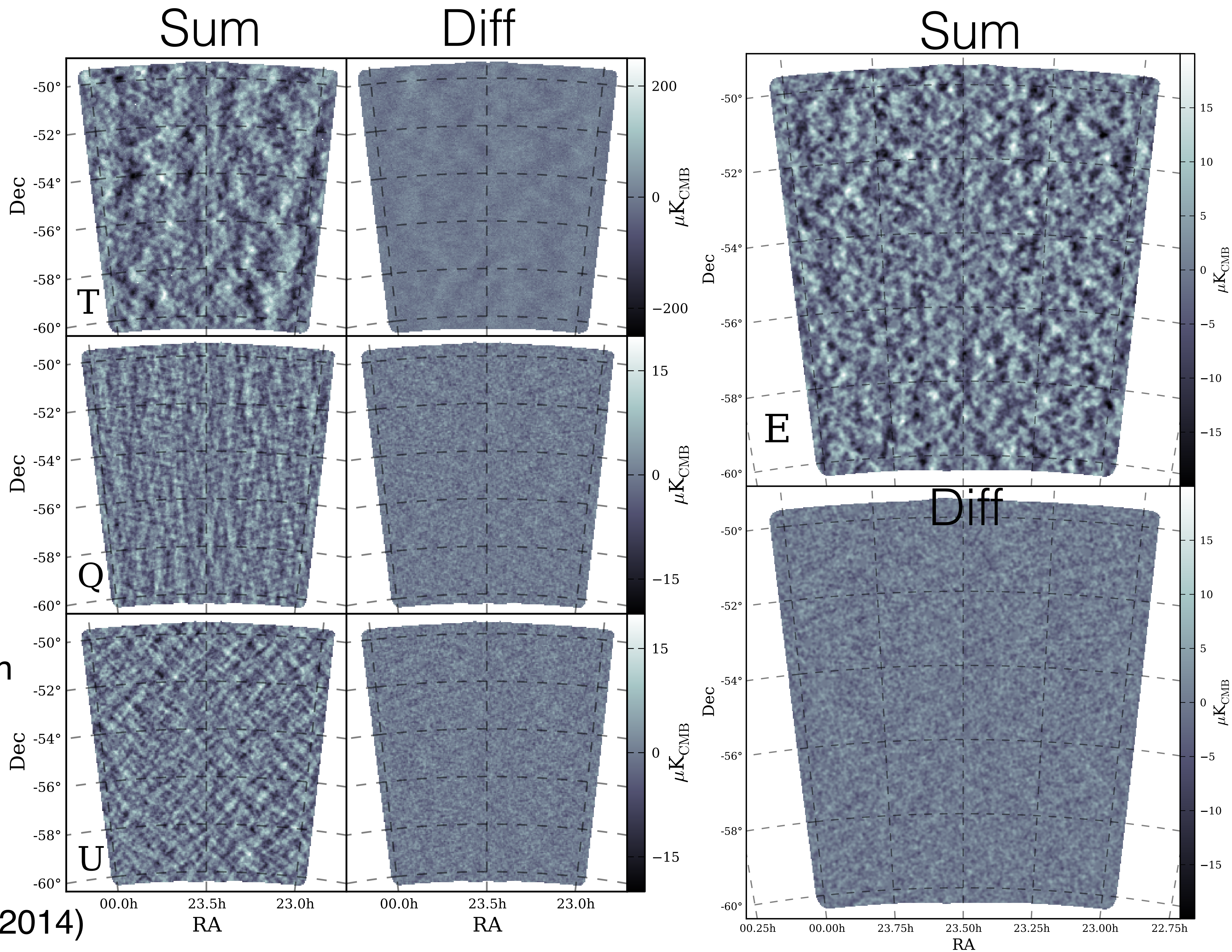
# SPTpol (2012): 100 deg² "Deep" Field

**T-depth:**

7 $\mu$K-arcmin

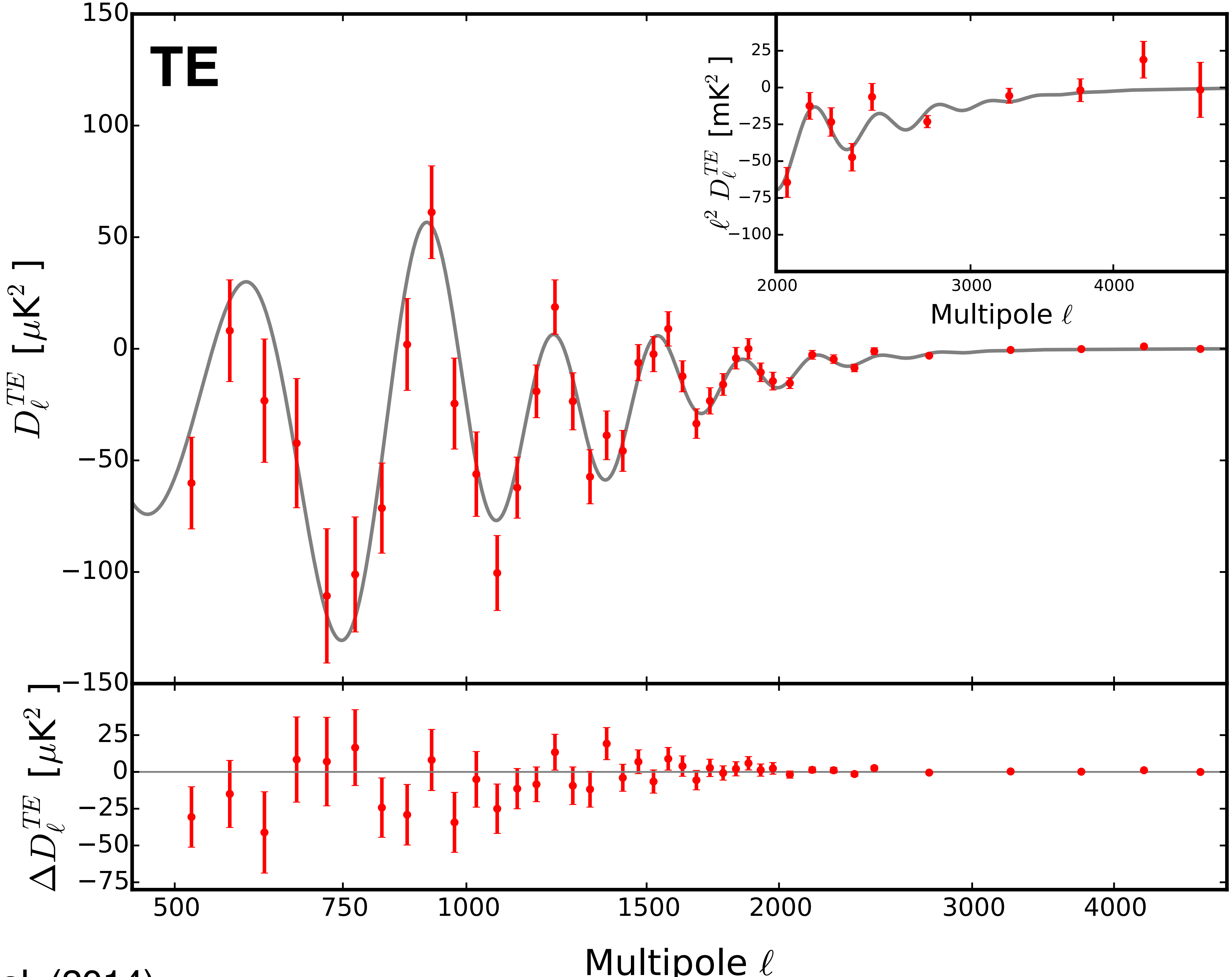
**P-depth:**

10 $\mu$K-arcmin



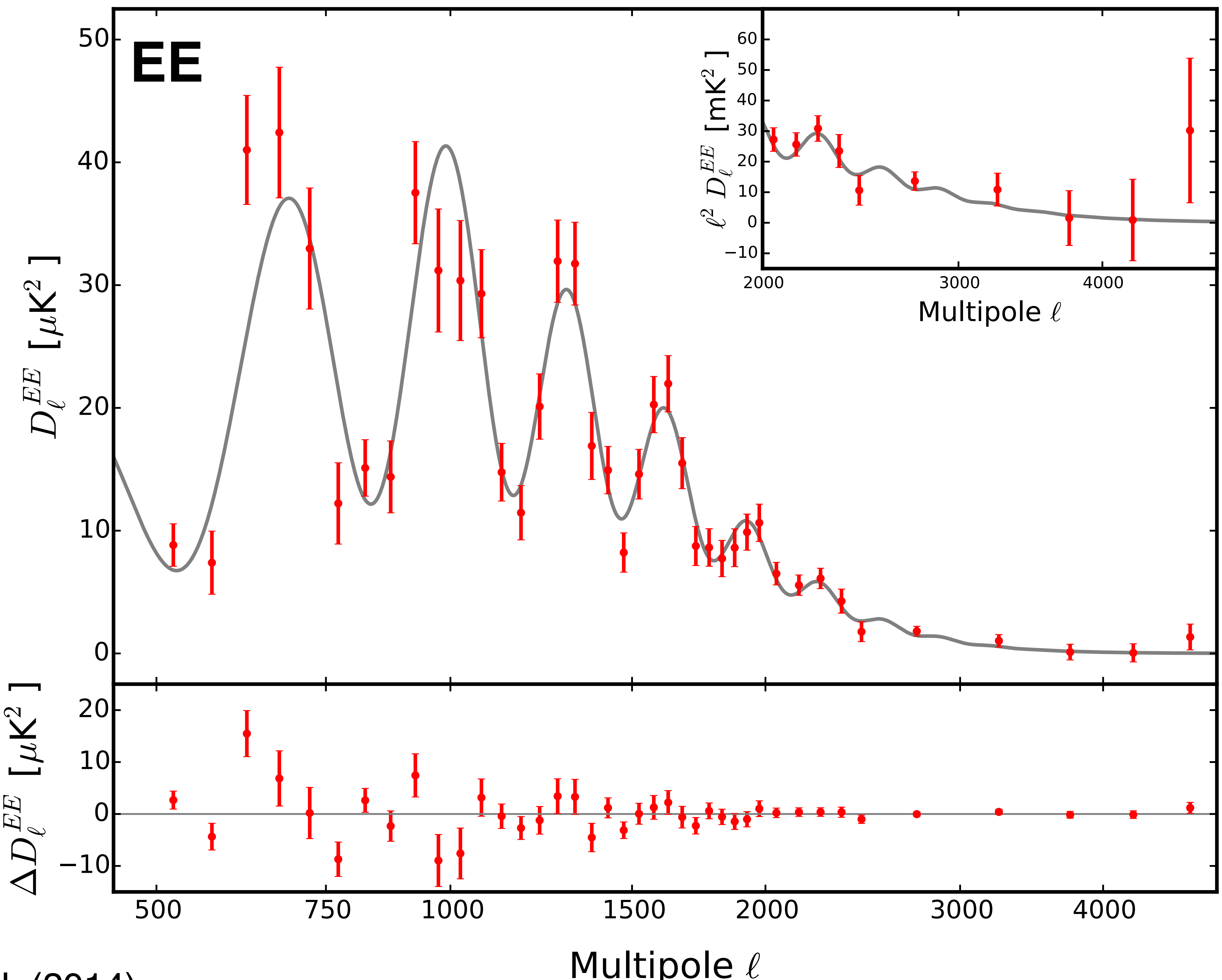

Crites et al. (2014)

# SPTpol (2012): 100 deg² "Deep" Field



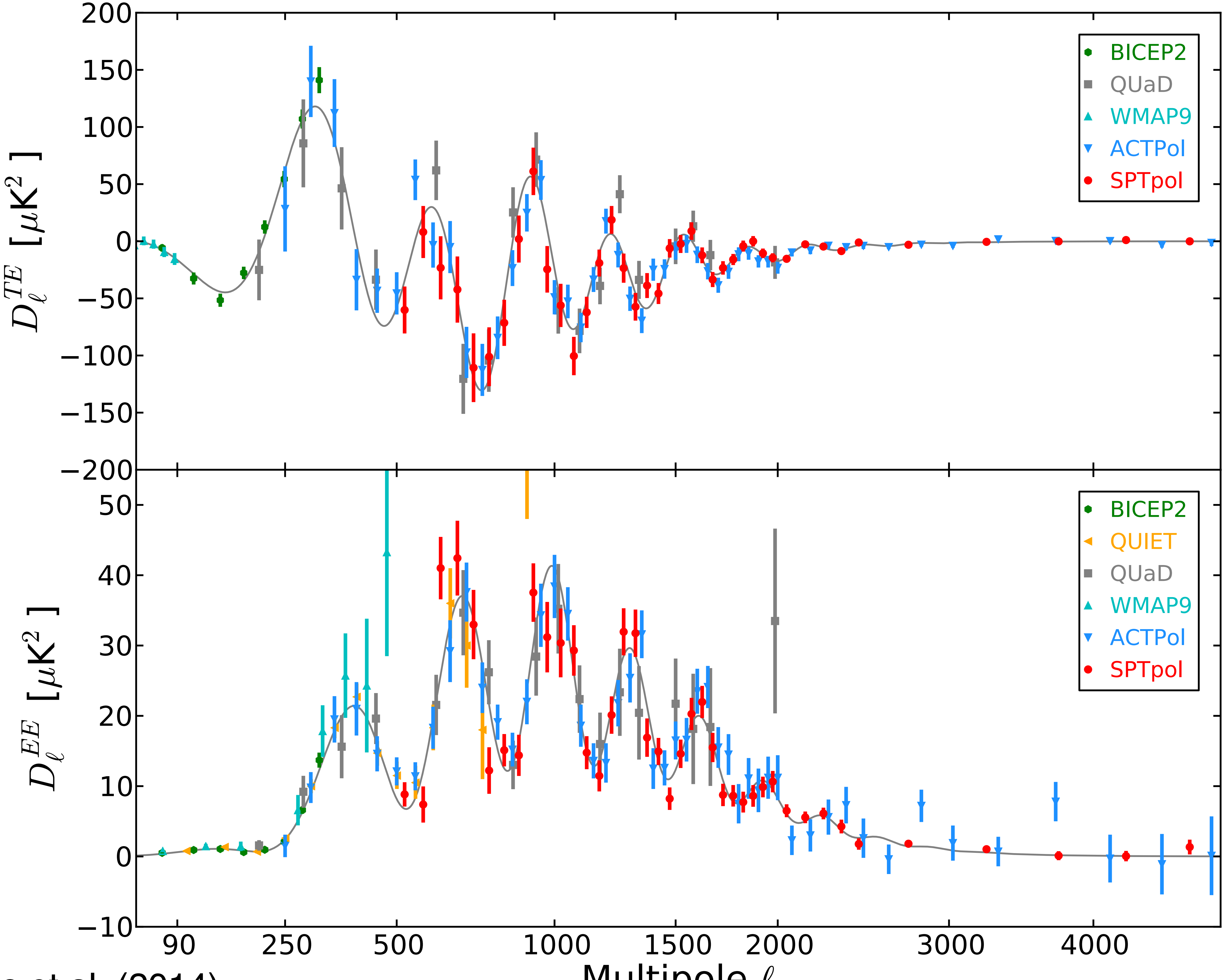

Crites et al. (2014)

# SPTpol (2012): 100 deg² "Deep" Field



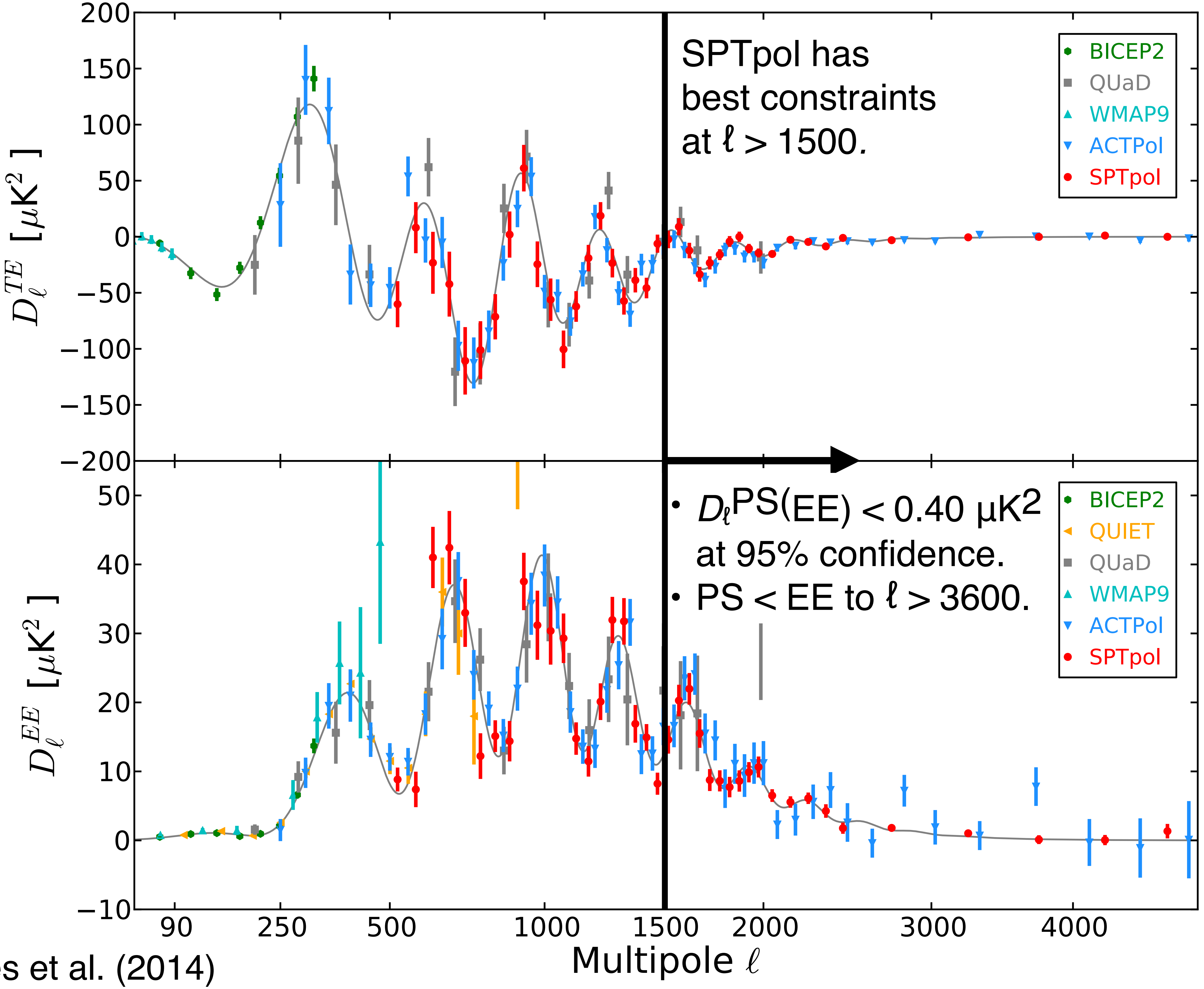

Crites et al. (2014)

# TE, EE Compilation Power Spectrum



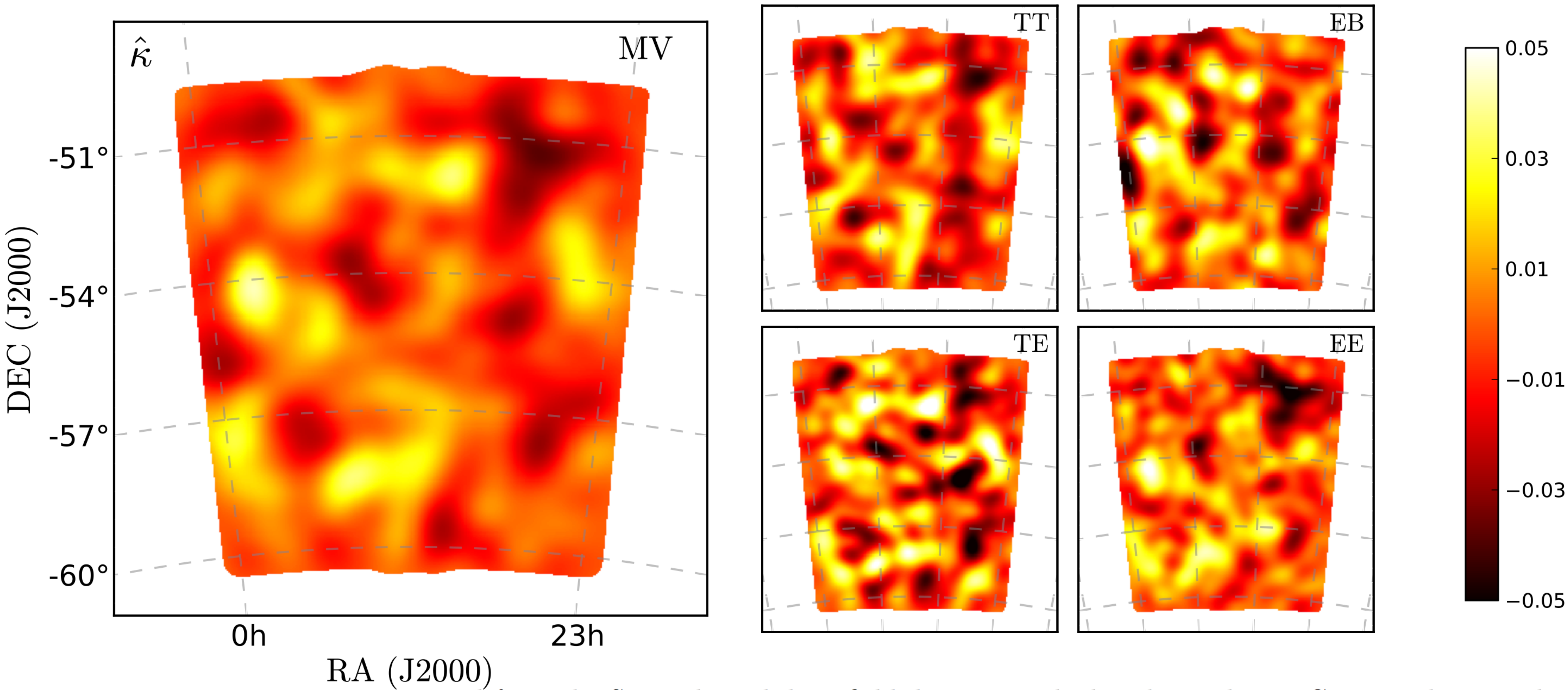

Crites et al. (2014)

# TE, EE Compilation Power Spectrum




Crites et al. (2014)

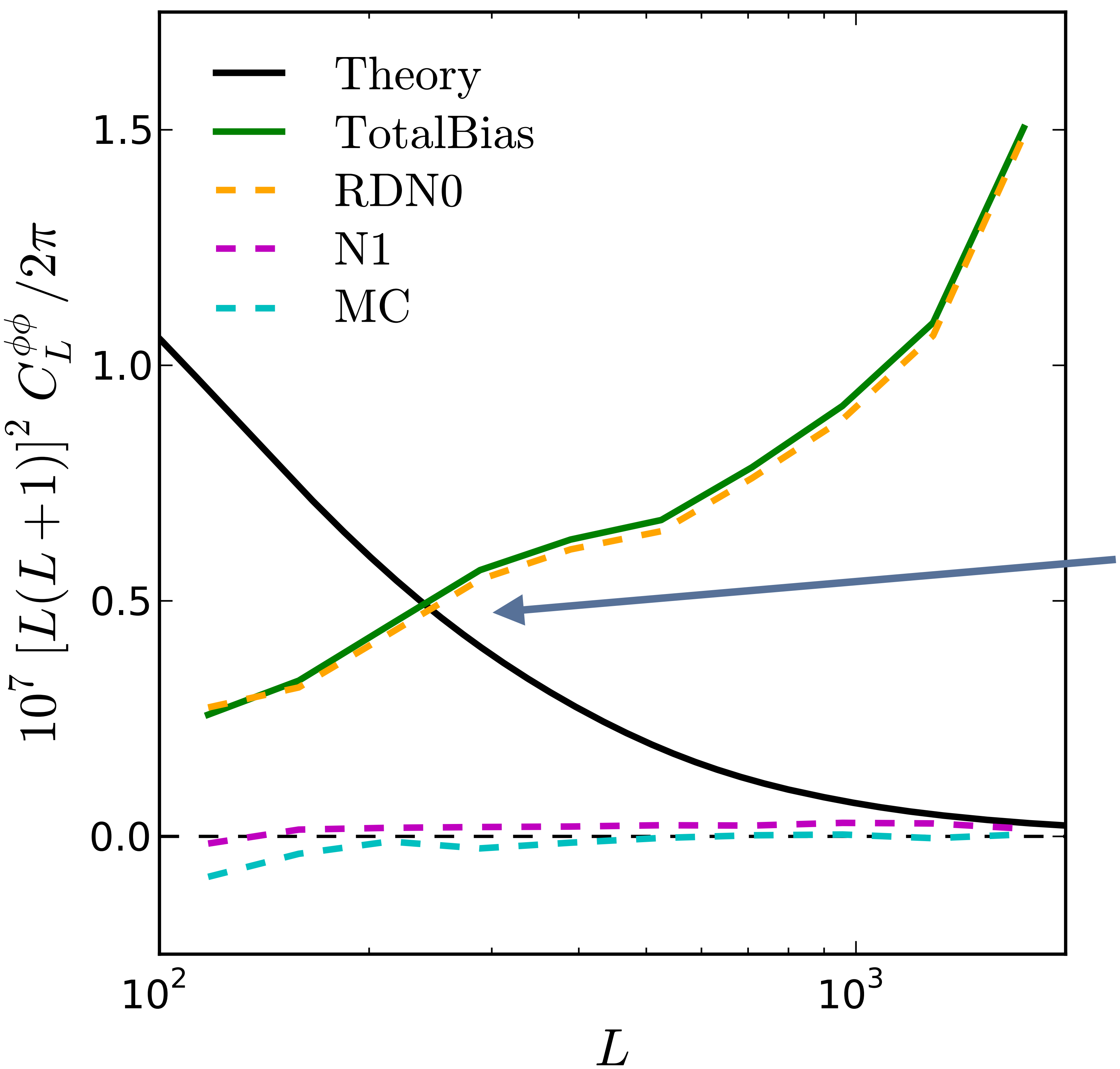
# CMB lensing: ΦΦ




MV =
(TT, TE, EE, EB, TB)

Story et al. (2014)

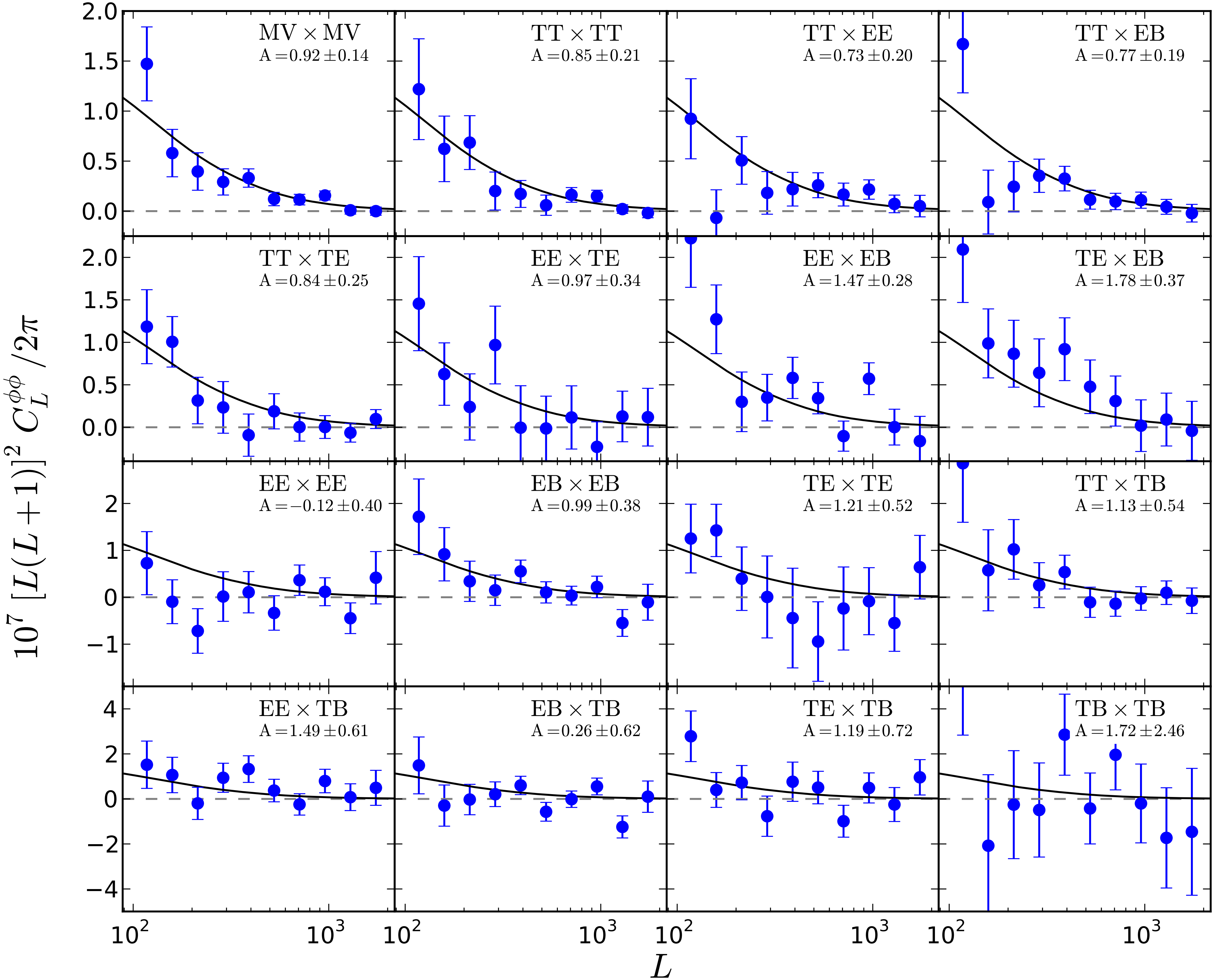
# Φ Noise Bias




"Imaging"
L < ~250
Φ modes.

Story et al. (2014)

# Lensing Power Spectra: 15 estimators




Story et al. (2014)

# CMB Lensing: ΦΦ

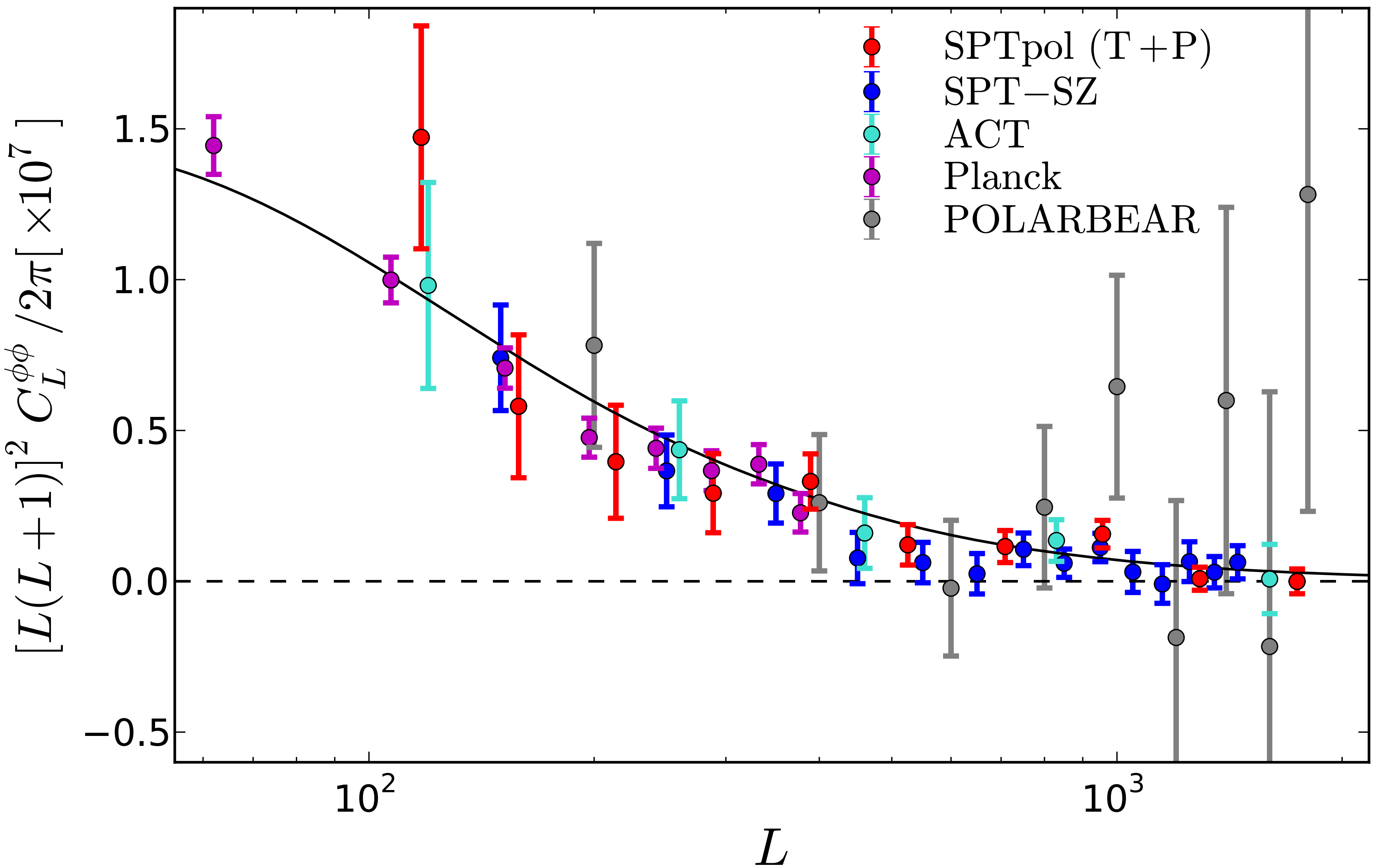



Fig. 6.— Lensing potential power spectrum bandpowers estimated from SPTpol, as well as those previously reported for temperature by SPT-SZ (van Engelen et al. 2012), ACT (Das et al. 2014), *Planck* (Planck Collaboration XVII 2013), and for polarization by POLARBEAR (POLARBEAR Collaboration). The black solid line shows the Planck+Lens+WP+highL best-fit ΛCDM model.

**SPTpol gives:**

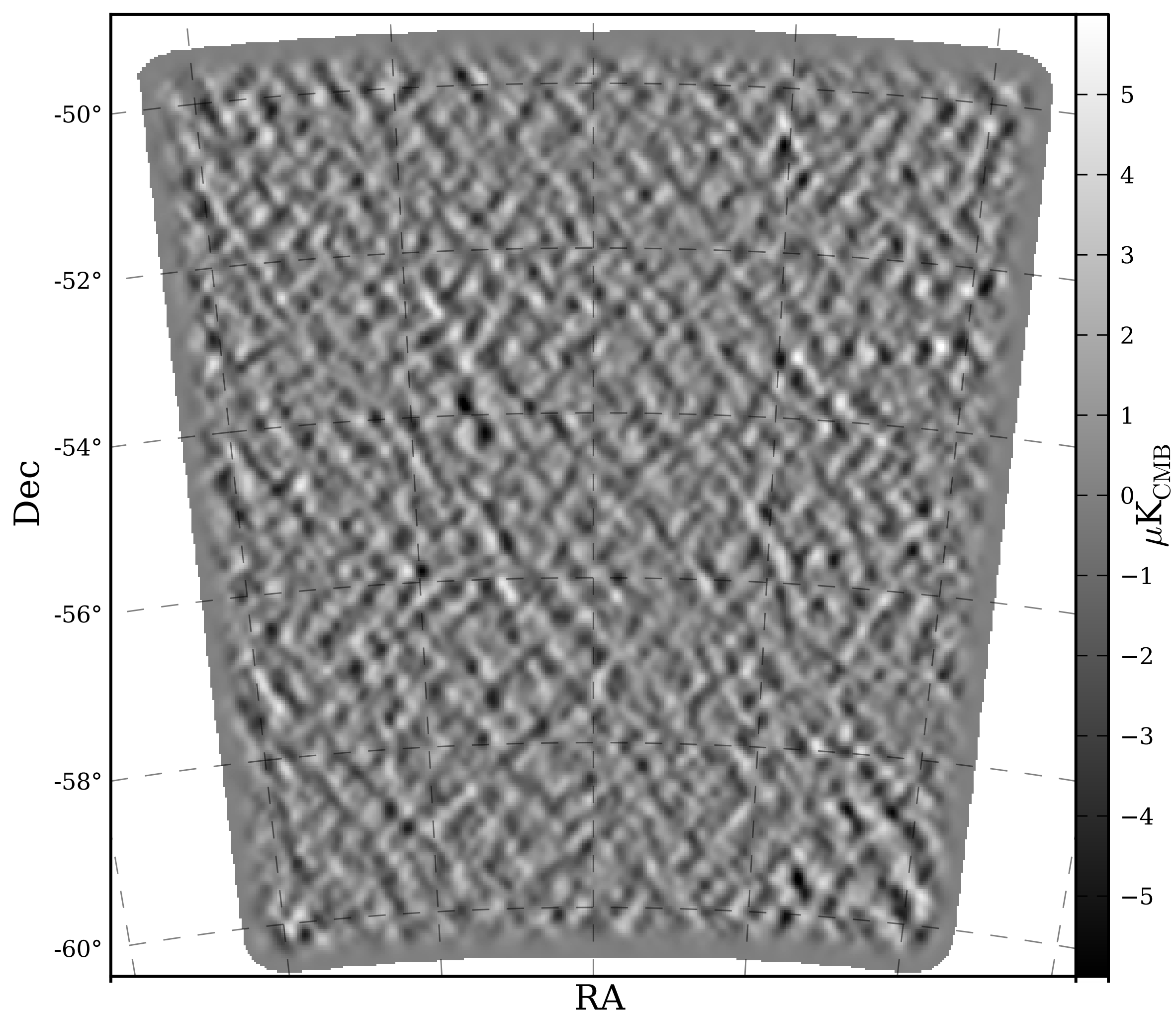
- 14σ no-lensing.
  - 5.8σ using POL only (EE+EB)
- 18% constraint on lensing amplitude (sample variance limited).

Story et al. (2014)

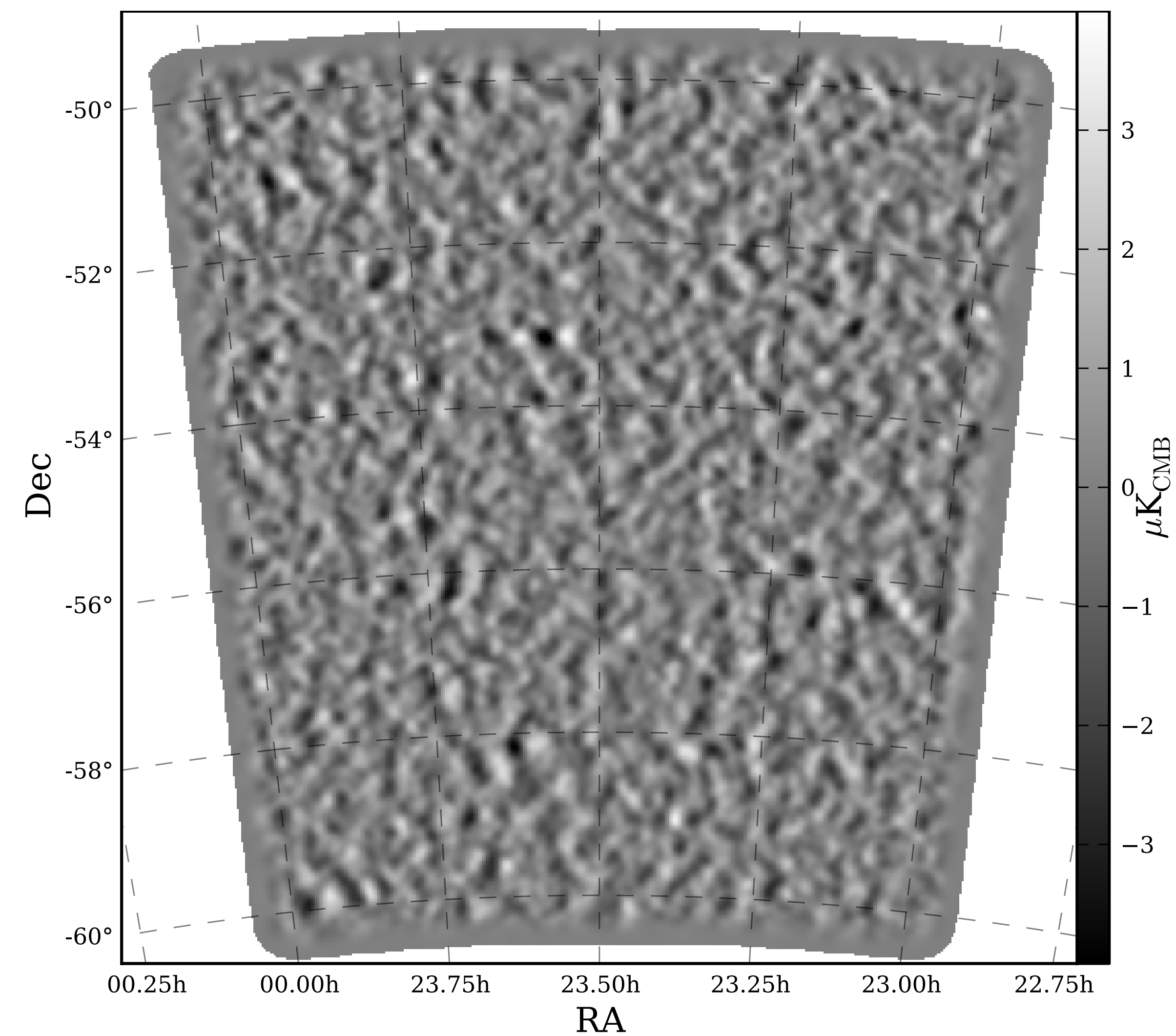
Preliminary

# BB Maps: Direct

## 95 GHz




## 150 GHz

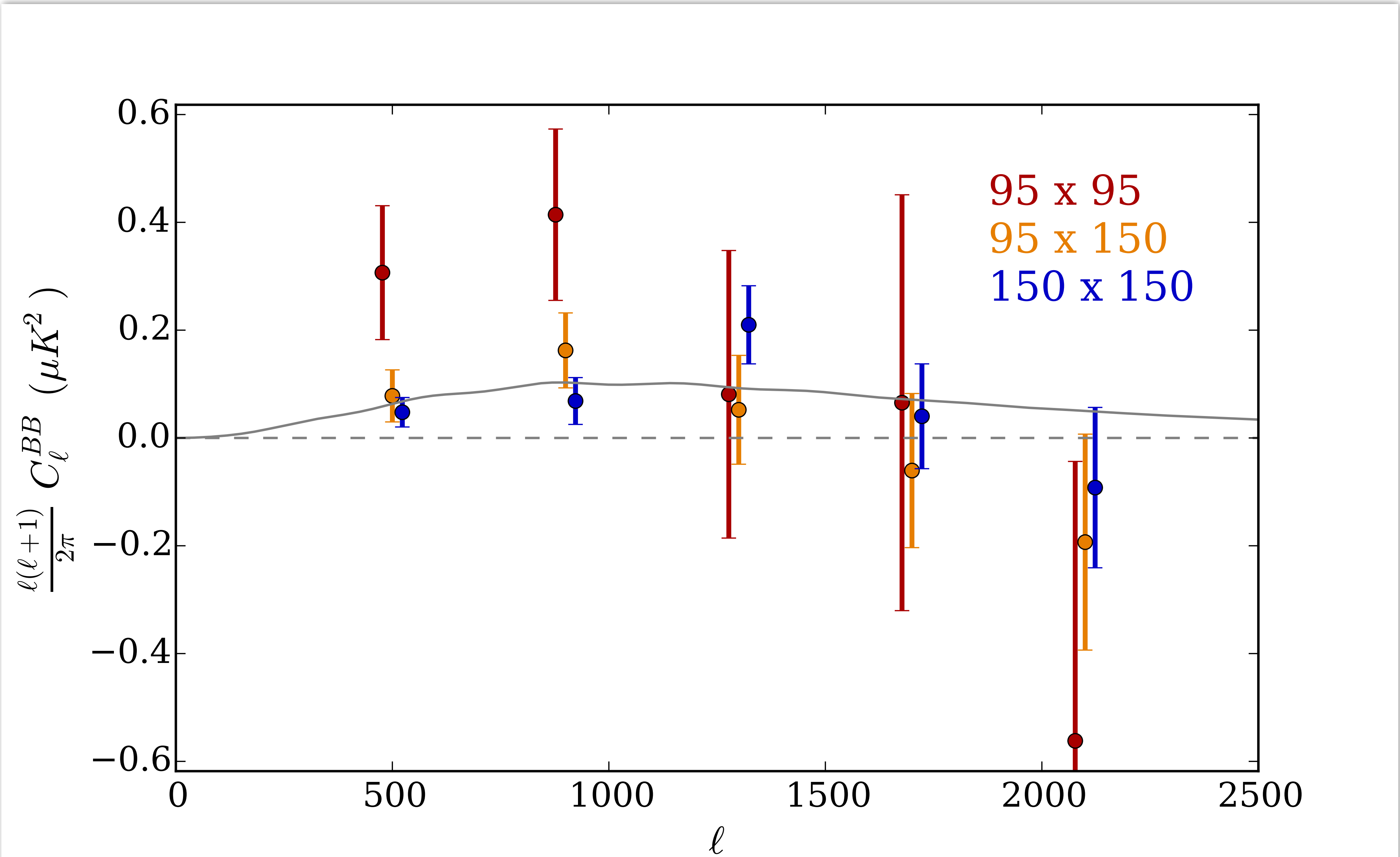



- "Chi B" estimator (Smith & Zaldarriaga 2007)
- We analyze only 300 < L < 2300 (low sensitivity to tensor power).

led by R. Keisler, N. Harrington, J. Henning, S. Hoover

Preliminary

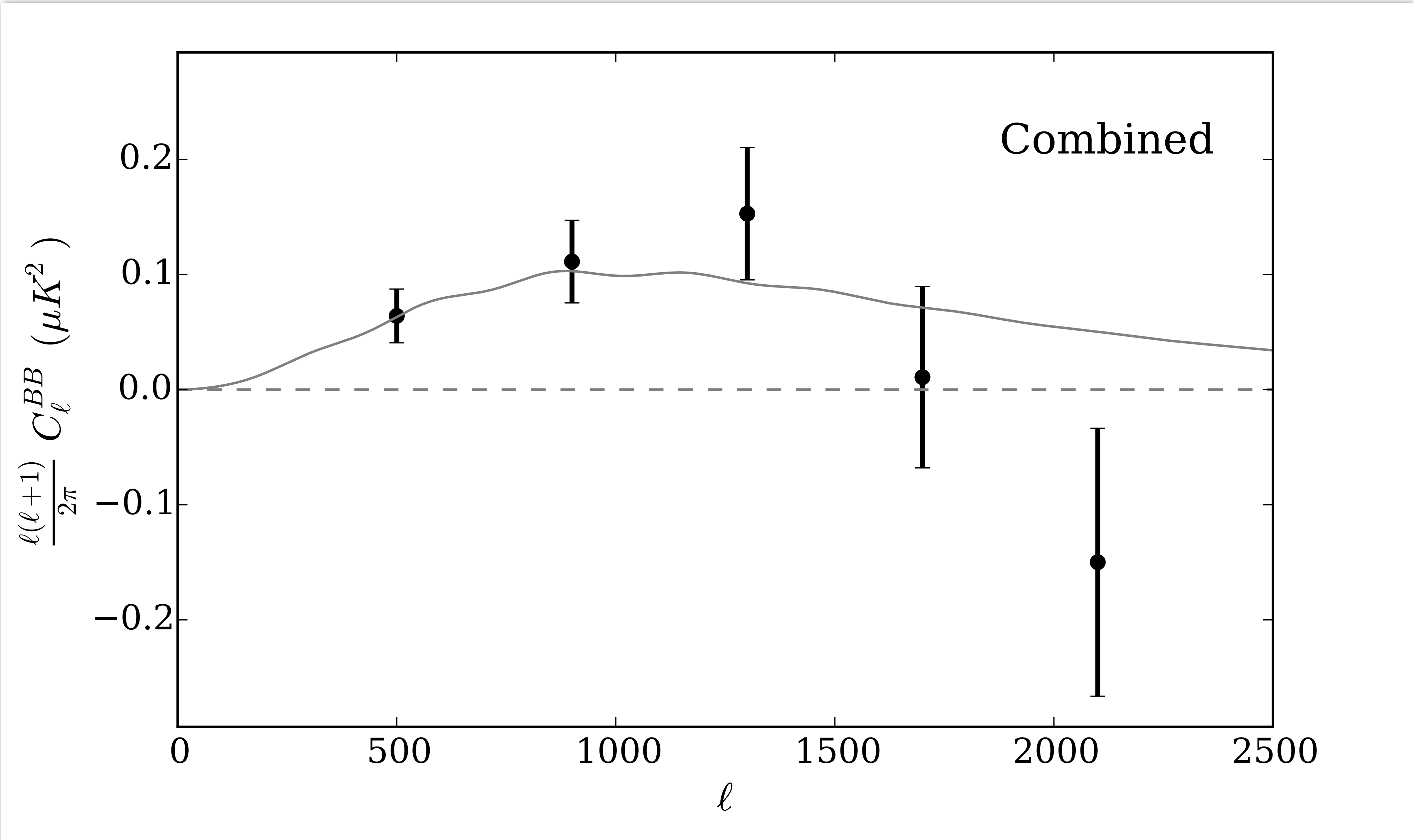
# BB Spectra: 95x95, 95x150, 150x150




led by R. Keisler, N. Harrington, J. Henning, S. Hoover

Preliminary

# BB Combined Spectrum




LCDM BB provides a good fit.

~5σ detection of A_lensBB>0, assuming no foregrounds.

led by R. Keisler, N. Harrington, J. Henning, S. Hoover

# BB Compilation (c. 2014)

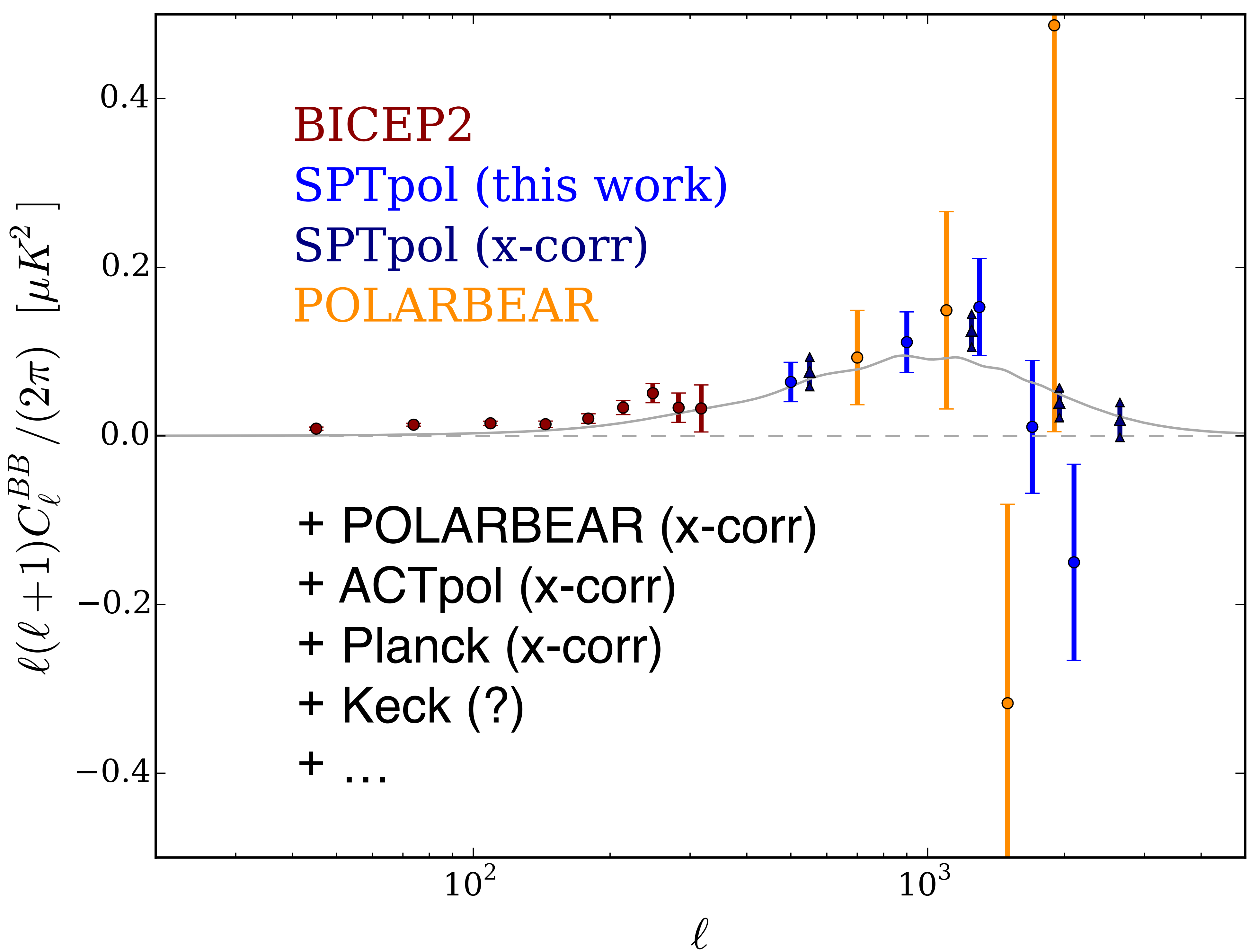



FIG. 4.— *BB* bandpower measurements from this work (**blue circles**), BICEP2 auto-spectrum measurements (**magenta circles**, BICEP2 Collaboration 2014), POLARBEAR auto-spectrum measurements (**orange circles**, POLARBEAR Collaboration 2014a), and SPTpol cross-correlation with the CIB (**black triangles**, H13).

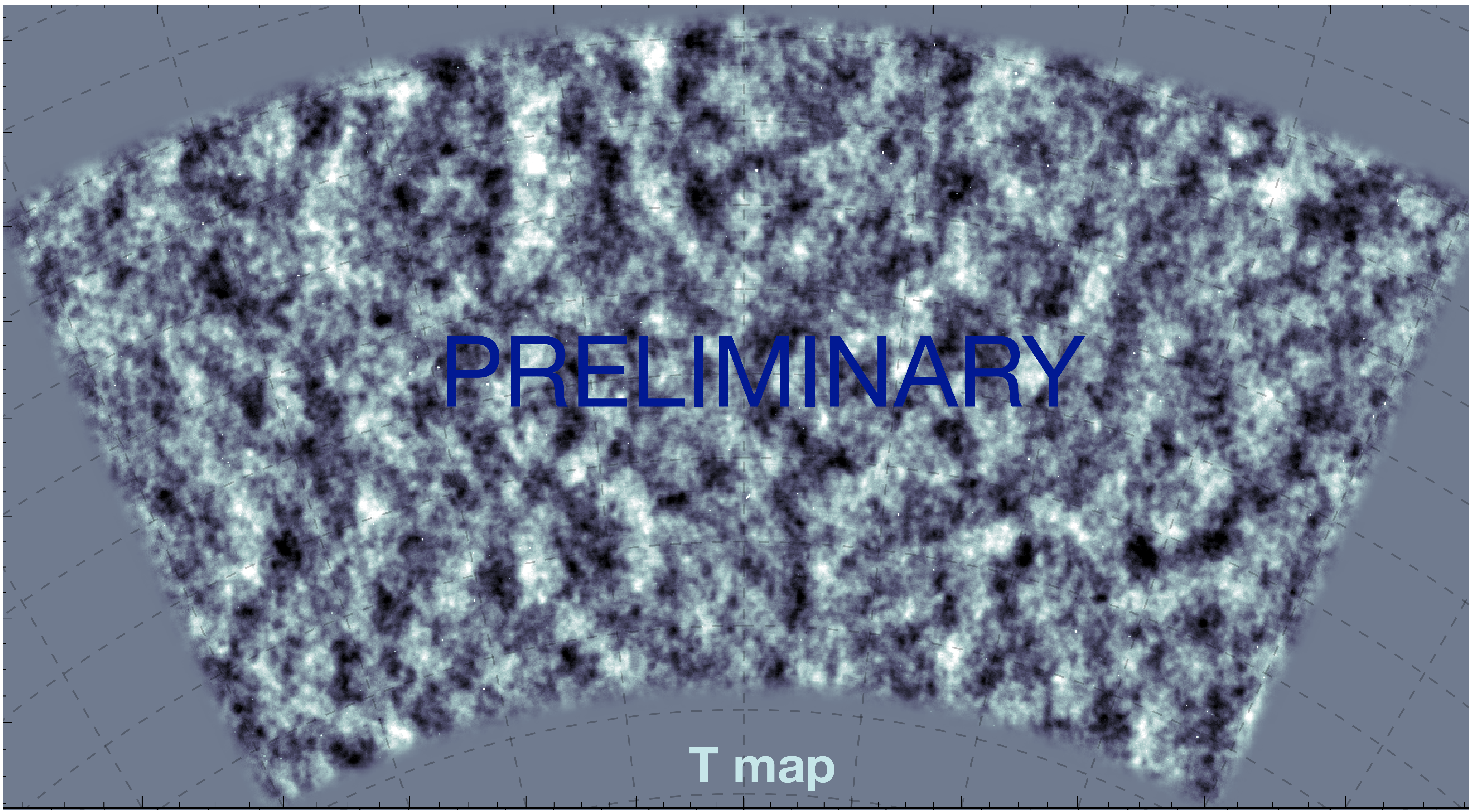
# *SPTpol (2013-15): 500 deg² Field*

**As of July 2014:**

30 uK-arcmin-P @ 95 GHz
14 uK-arcmin-P @ 150 GHz

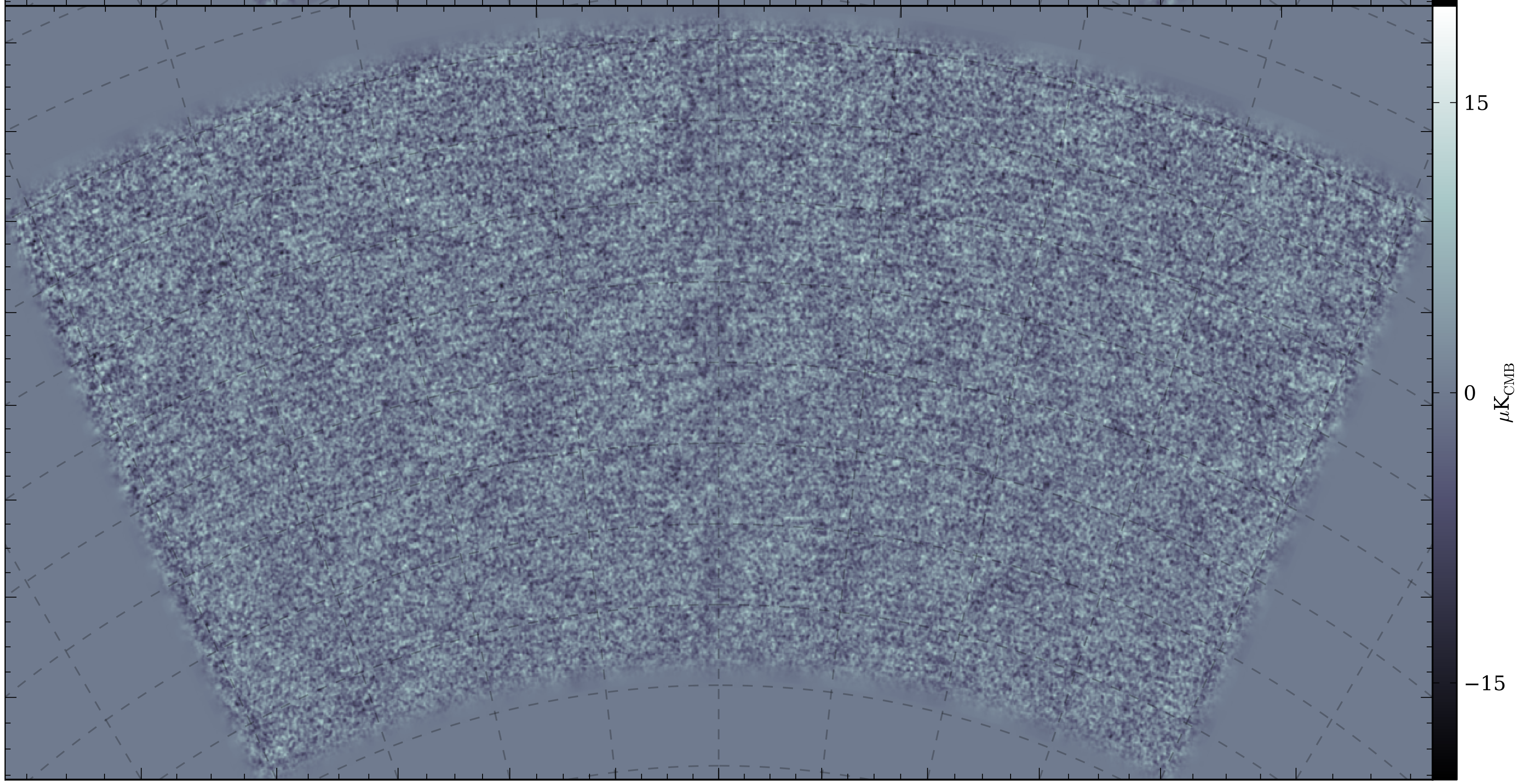
**End of 2015 (projected):**

20 uK-arcmin-P @ 95 GHz
9 uK-arcmin-P @ 150 GHz



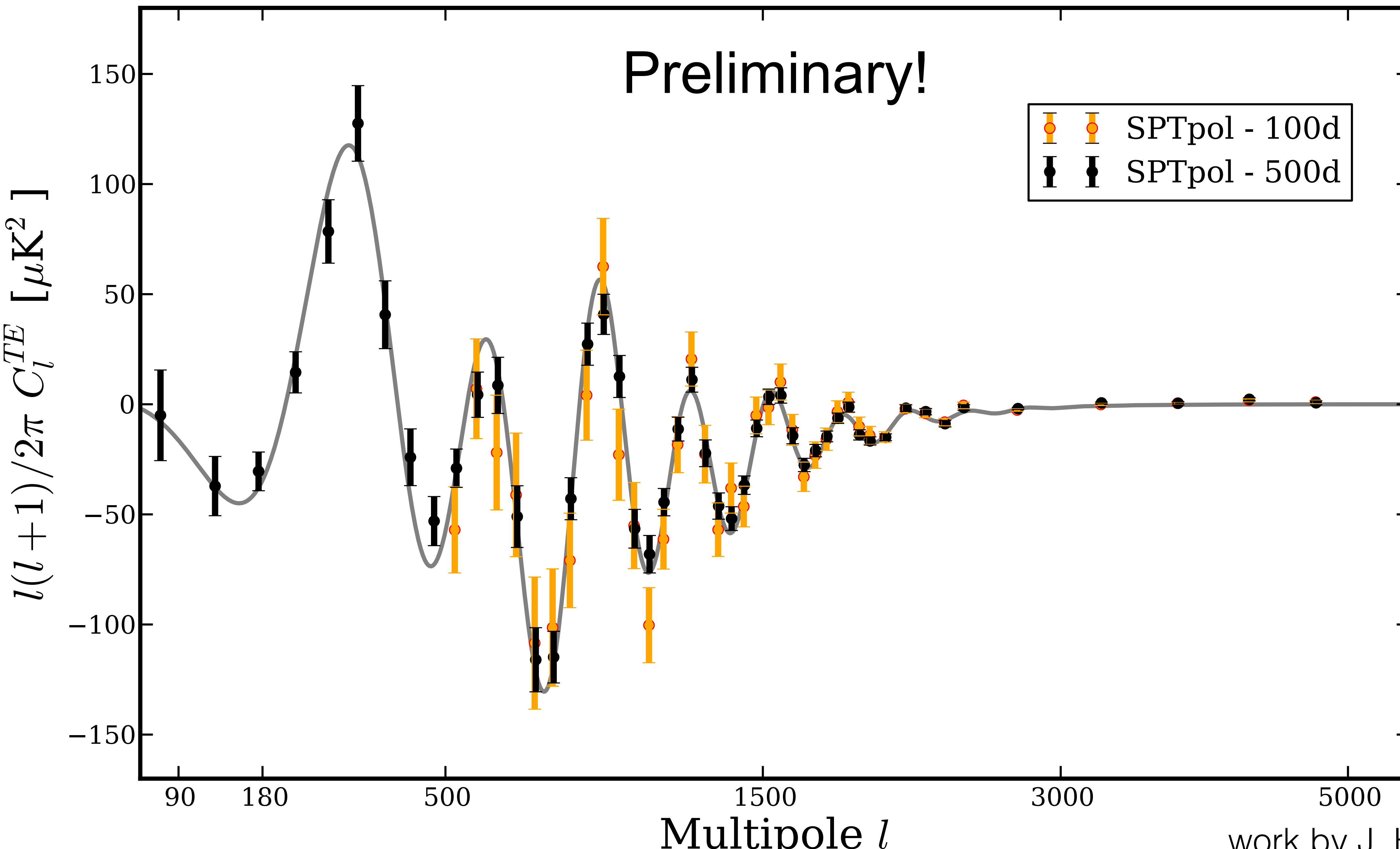
# E map
(signal+noise)


# E map
(noise)



# *SPTpol (2013-15): 500 deg² Field*

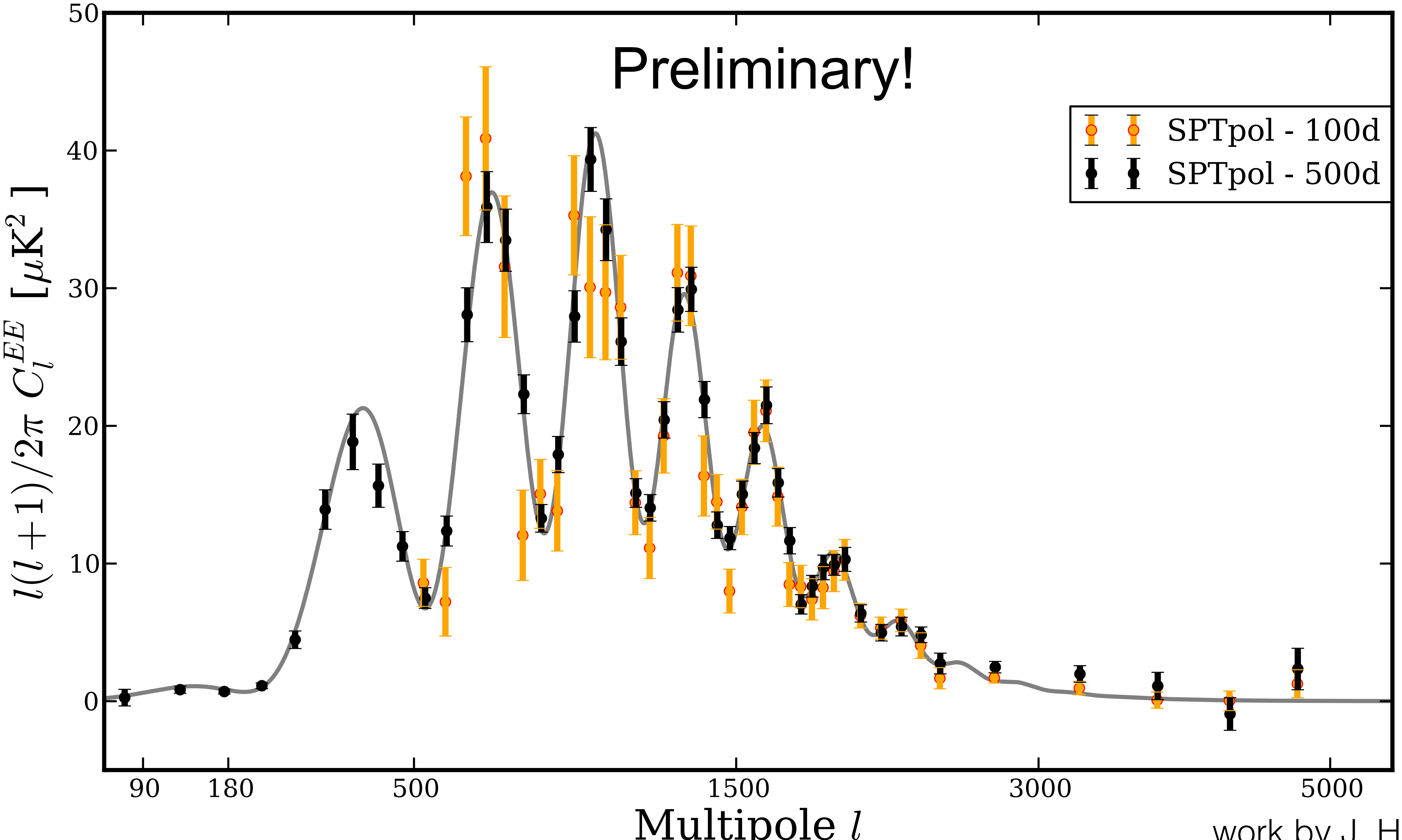
- **TE Power Spectrum (150x150)**. (Filter transfer function has not been removed).
- Errors include sample and noise variance.




work by J. Henning

# SPTpol (2013-15): 500 deg² Field

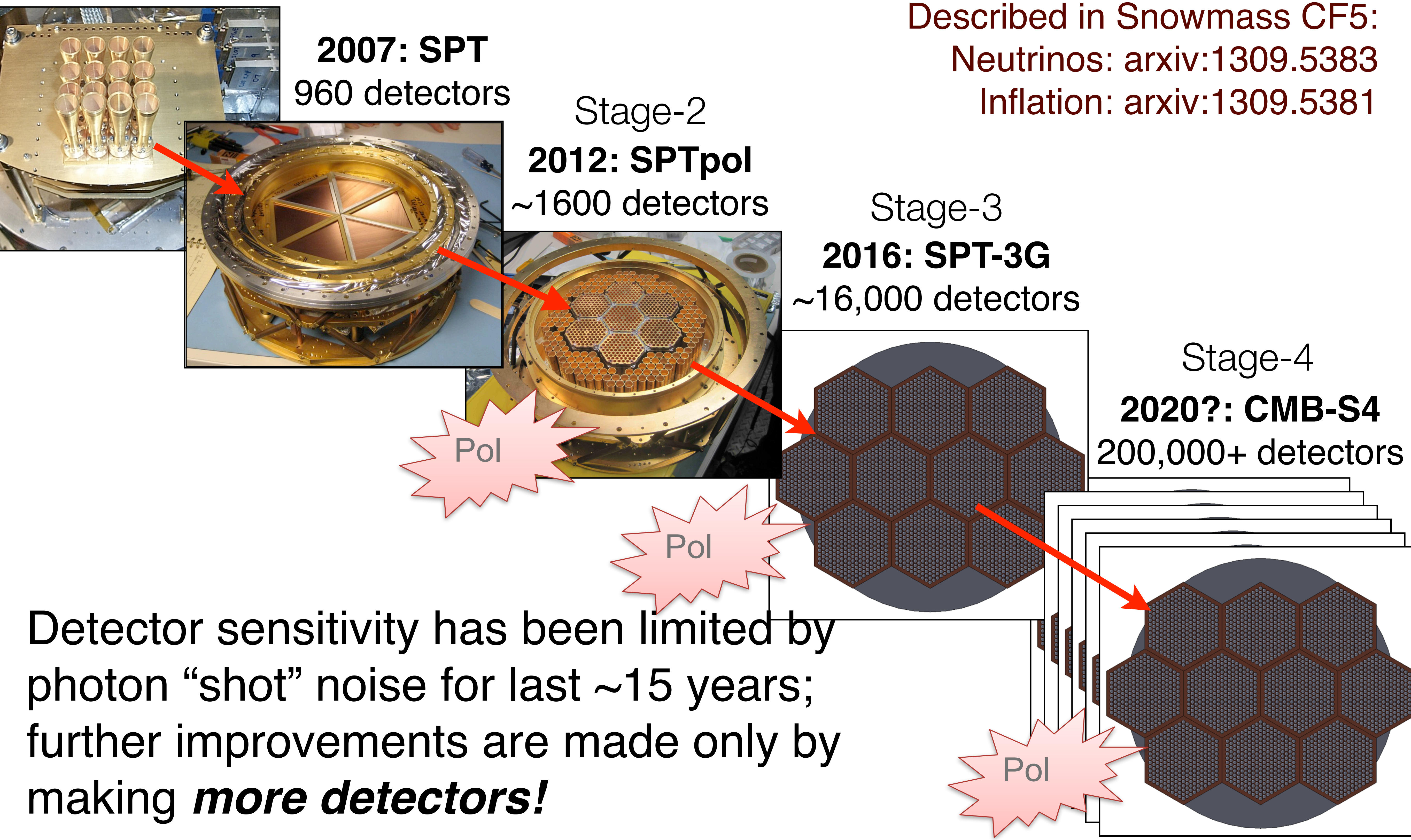
- **EE Power Spectrum (150x150).** (Filter transfer function has not been removed).
- Errors include sample and noise variance.




work by J. Henning

# Evolution of CMB Focal Planes

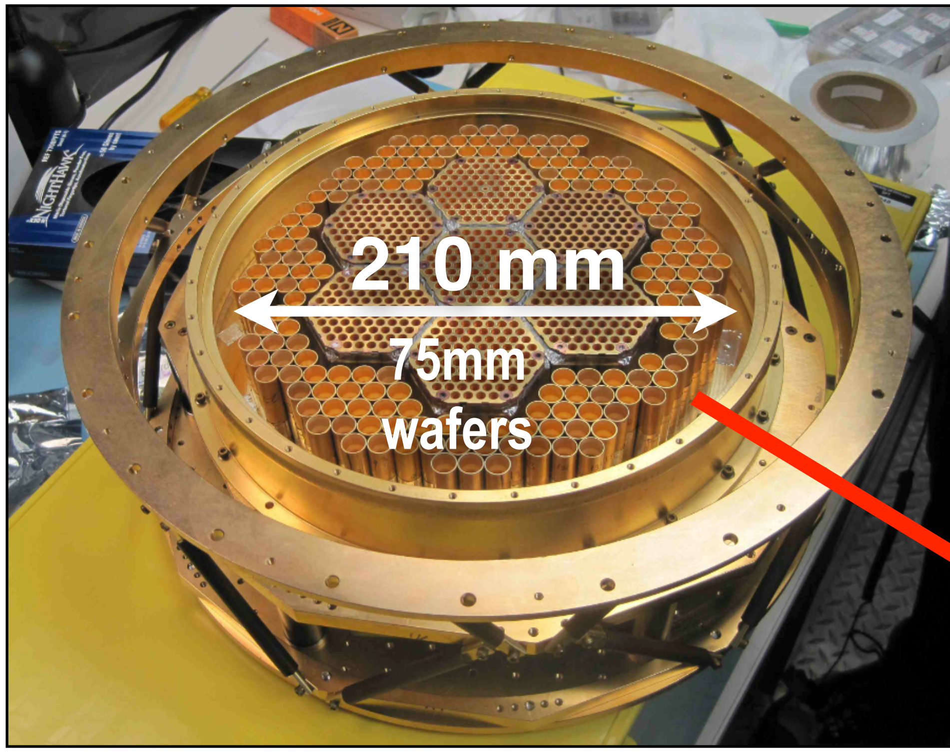
**CMB Stage-4 Experiment**
Described in Snowmass CF5:
Neutrinos: arxiv:1309.5383
Inflation: arxiv:1309.5381



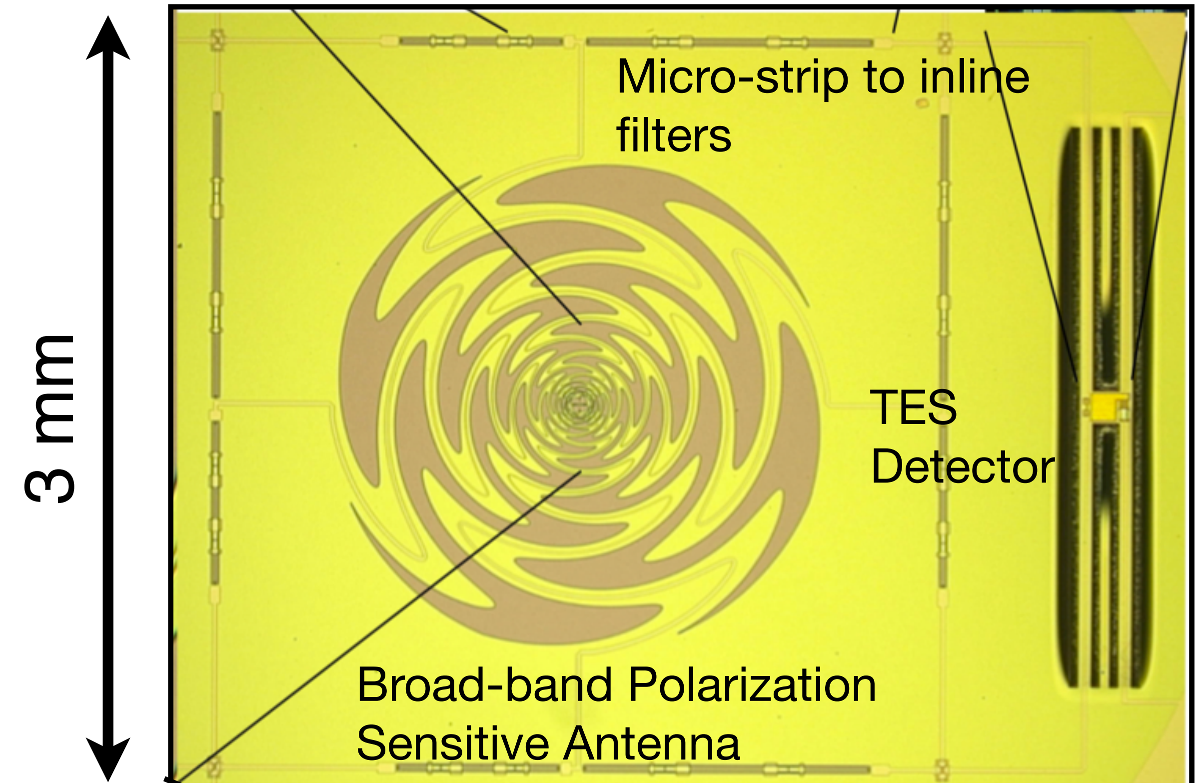

Detector sensitivity has been limited by photon "shot" noise for last ~15 years; further improvements are made only by making ***more detectors!***

# SPTpol to SPT-3G

**2012: SPTpol Stage II**
1600 detectors (ANL/NIST)

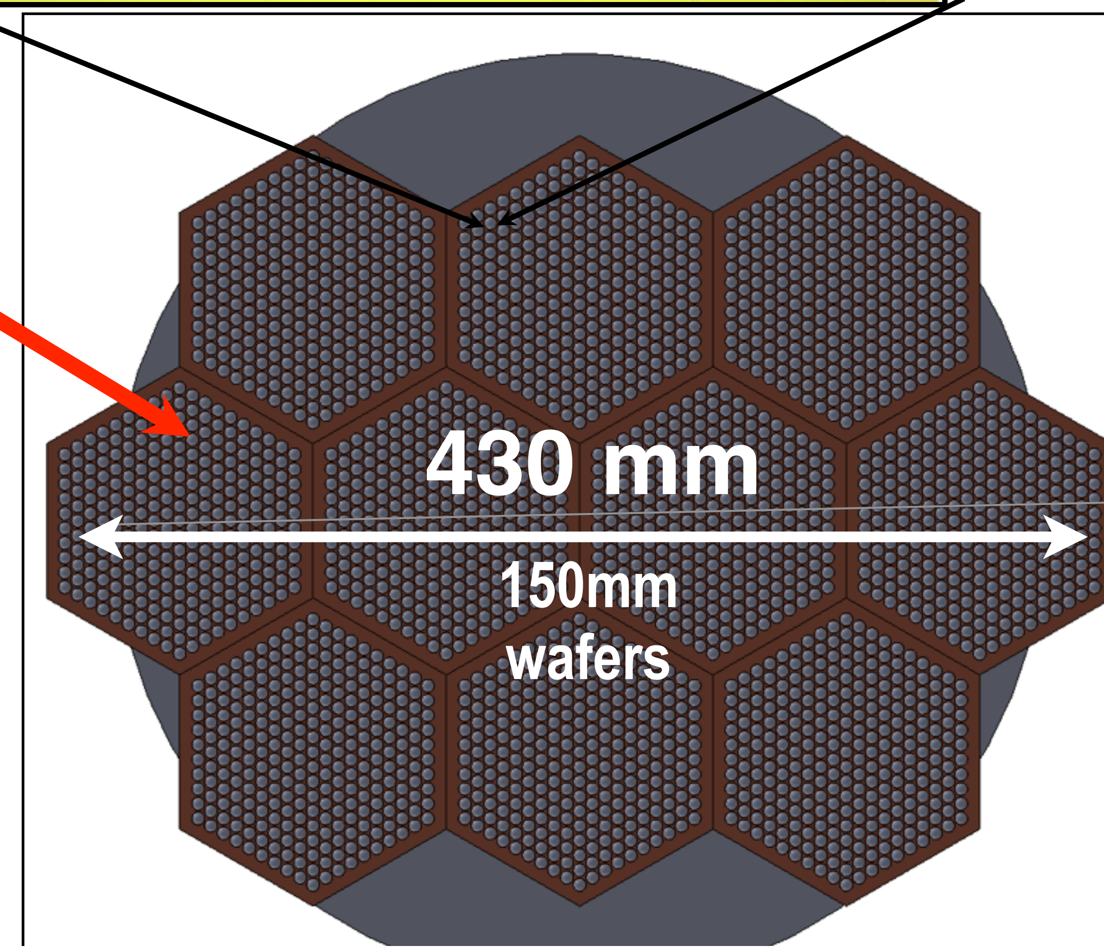



UC Berkeley prototype pixel



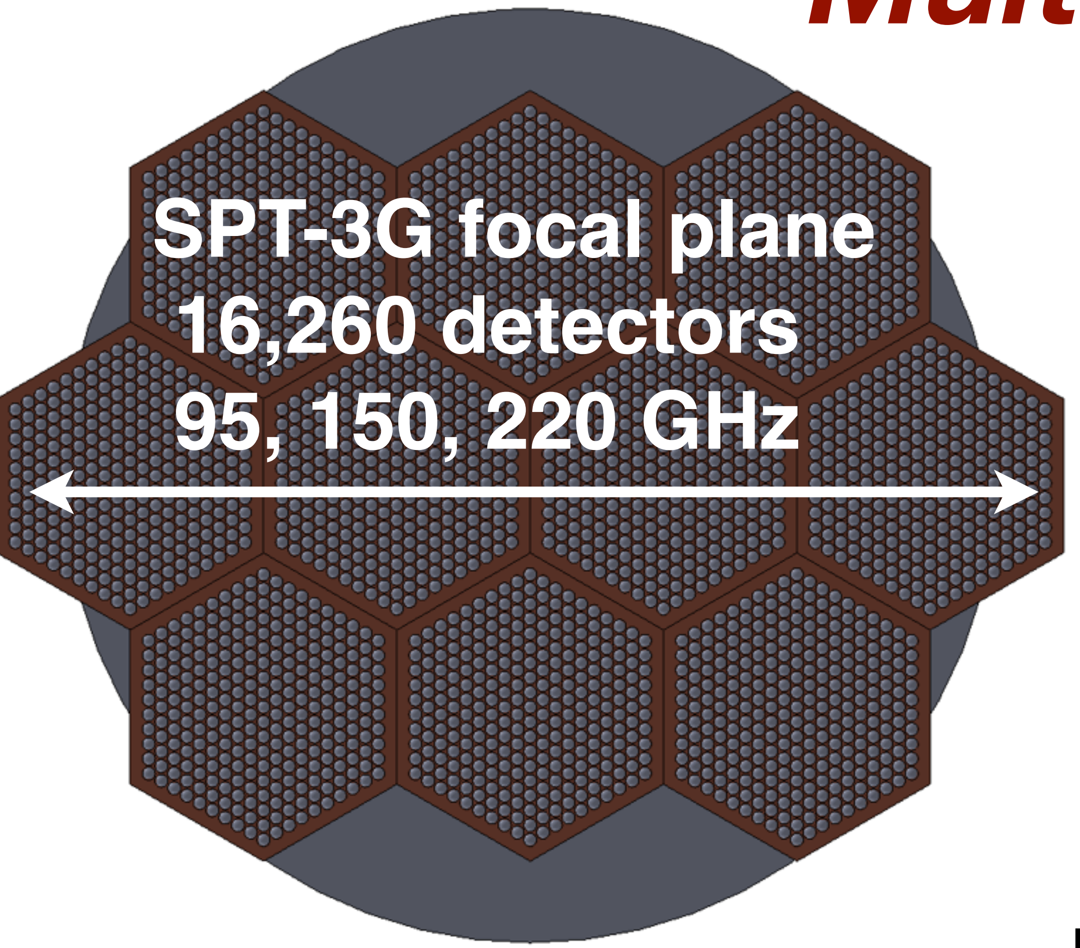

**DOE Labs (ANL, LBNL, SLAC, FNAL) working on developing Stage II to Stage III detector based on 3-band, dual polarization pixel.**

- Background limited performance per detector
- Uniform properties with high-fab-throughput
- Consistent fabrication on 6” wafers



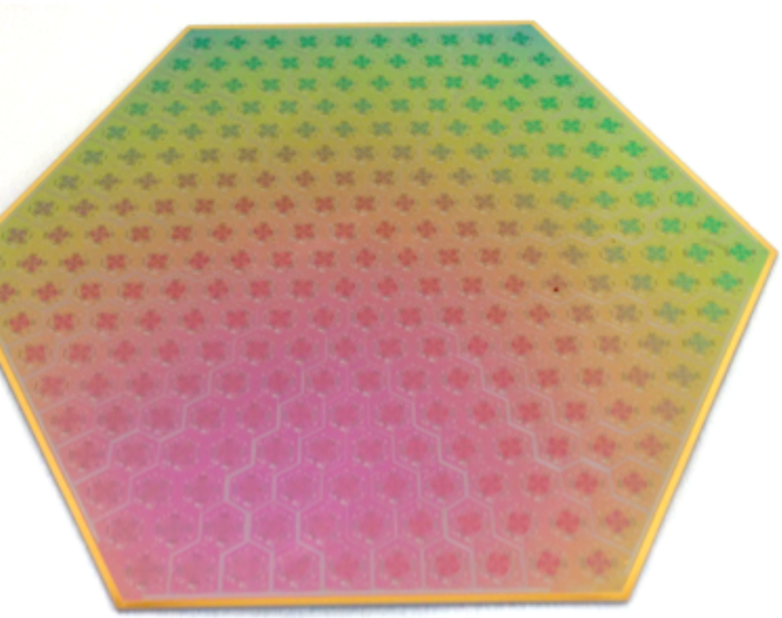

**2016: SPT-3G Stage III** 4x larger area
**16,260** detectors at T = 250mK

# *Multi-chroic Pixels*

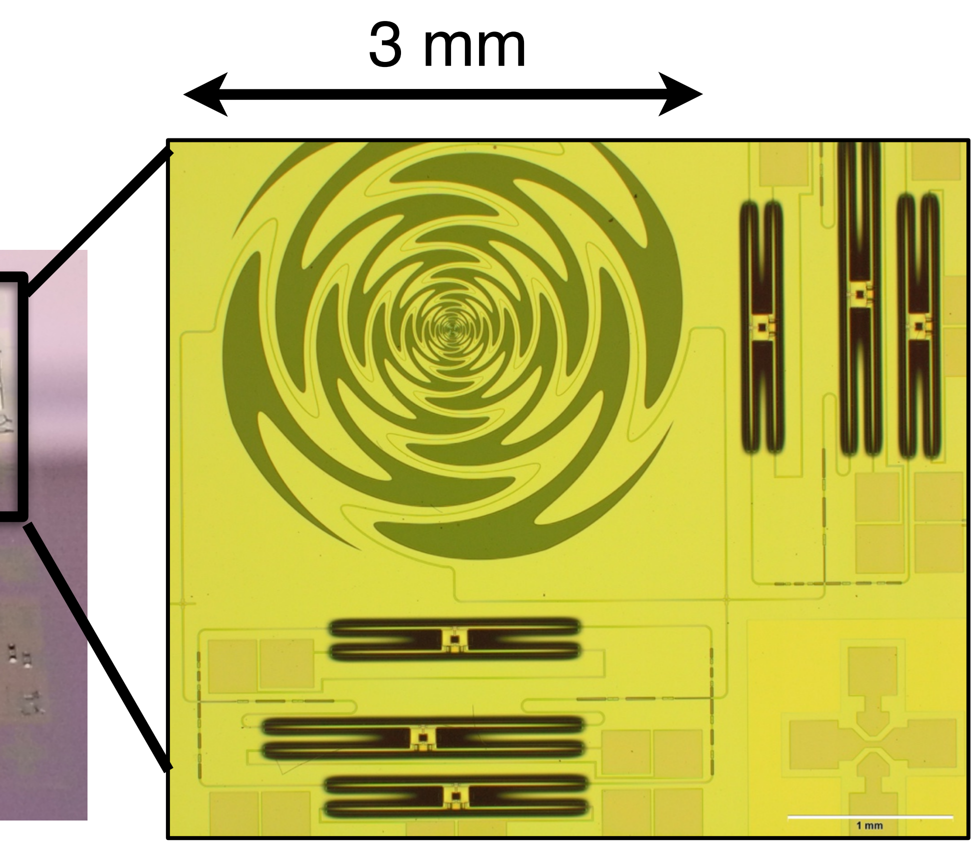



- Using lenslet coupled, 3-band sinuous detector design (Suzuki et al, 1210.8256)
- Detector fabrication at Argonne National Labs on 6” silicon wafers
- 68x frequency multiplexed SQUID readout (McGill), using SSA’s from NIST-Boulder

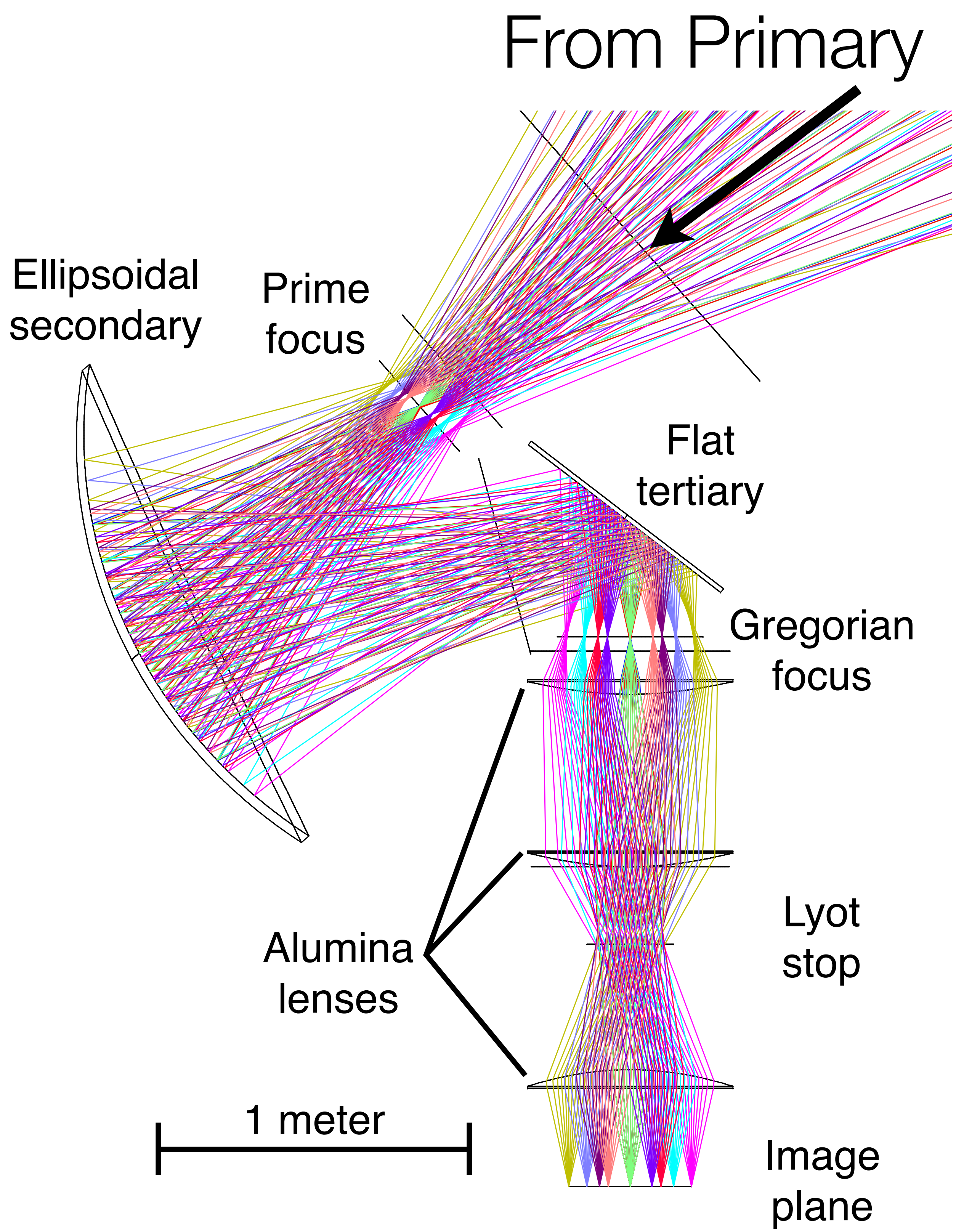
**Prototype 2-band 6” detector wafer (UC-Berkeley)**



**Prototype 3-band detectors (ANL)**



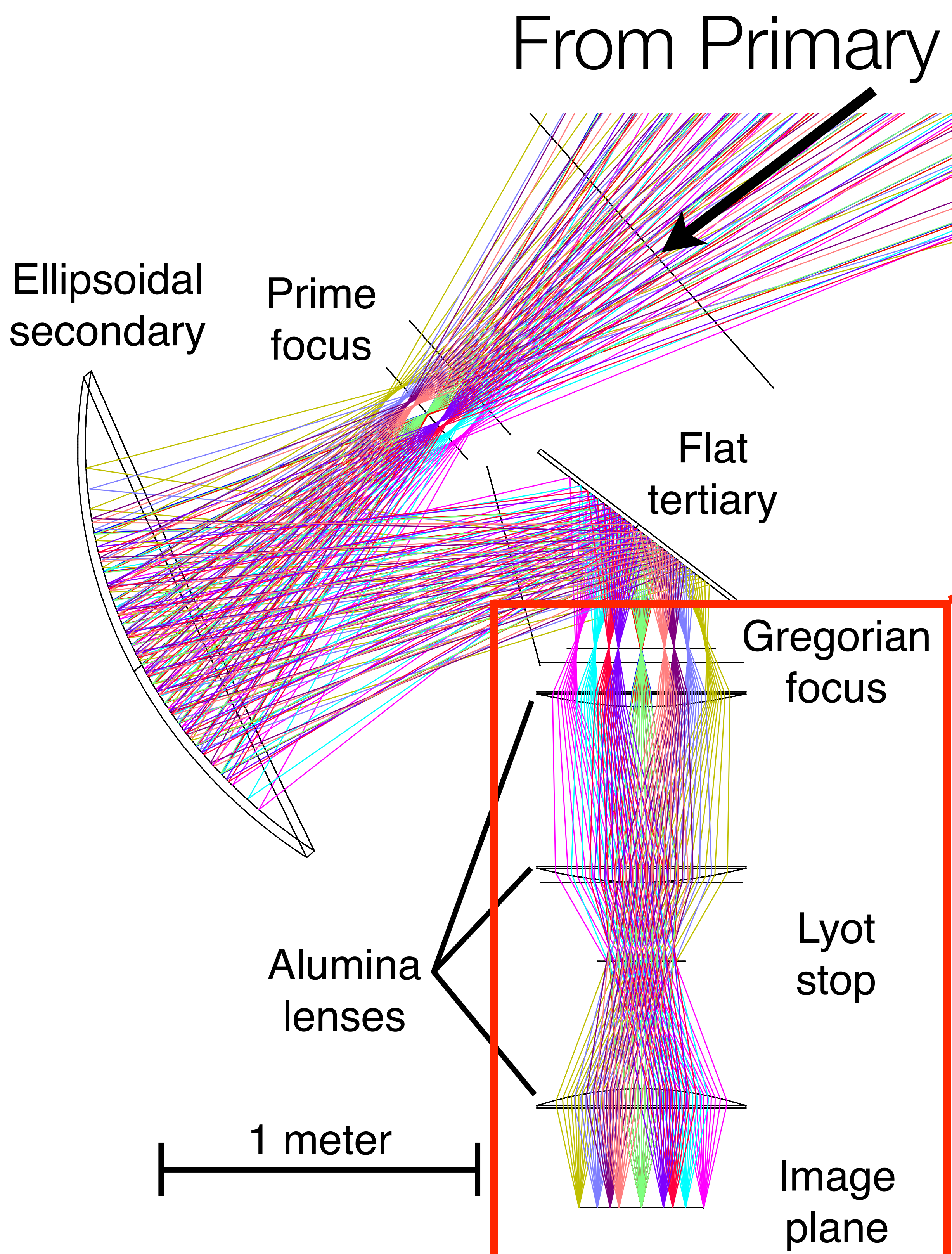
# SPT-3G Optics & Receiver

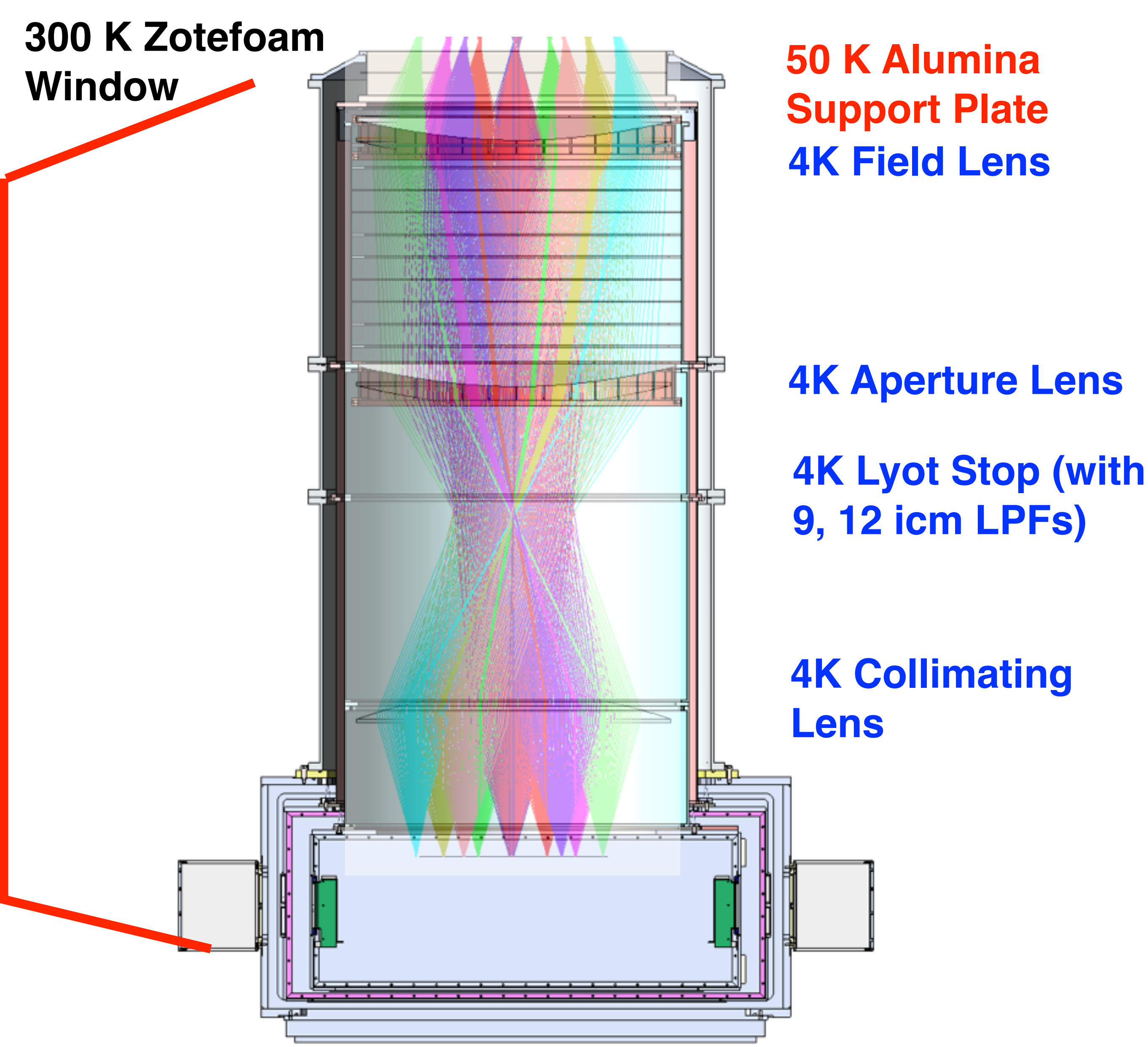



- **Warm secondary, with three cold 4K alumina lenses, and 4K Lyot stop**
- ***1.9 deg diameter (2.8 deg$^2$) field of view (FOV)***
    - Strehl ratios > 0.98 in all three bands within 430 mm focal plane

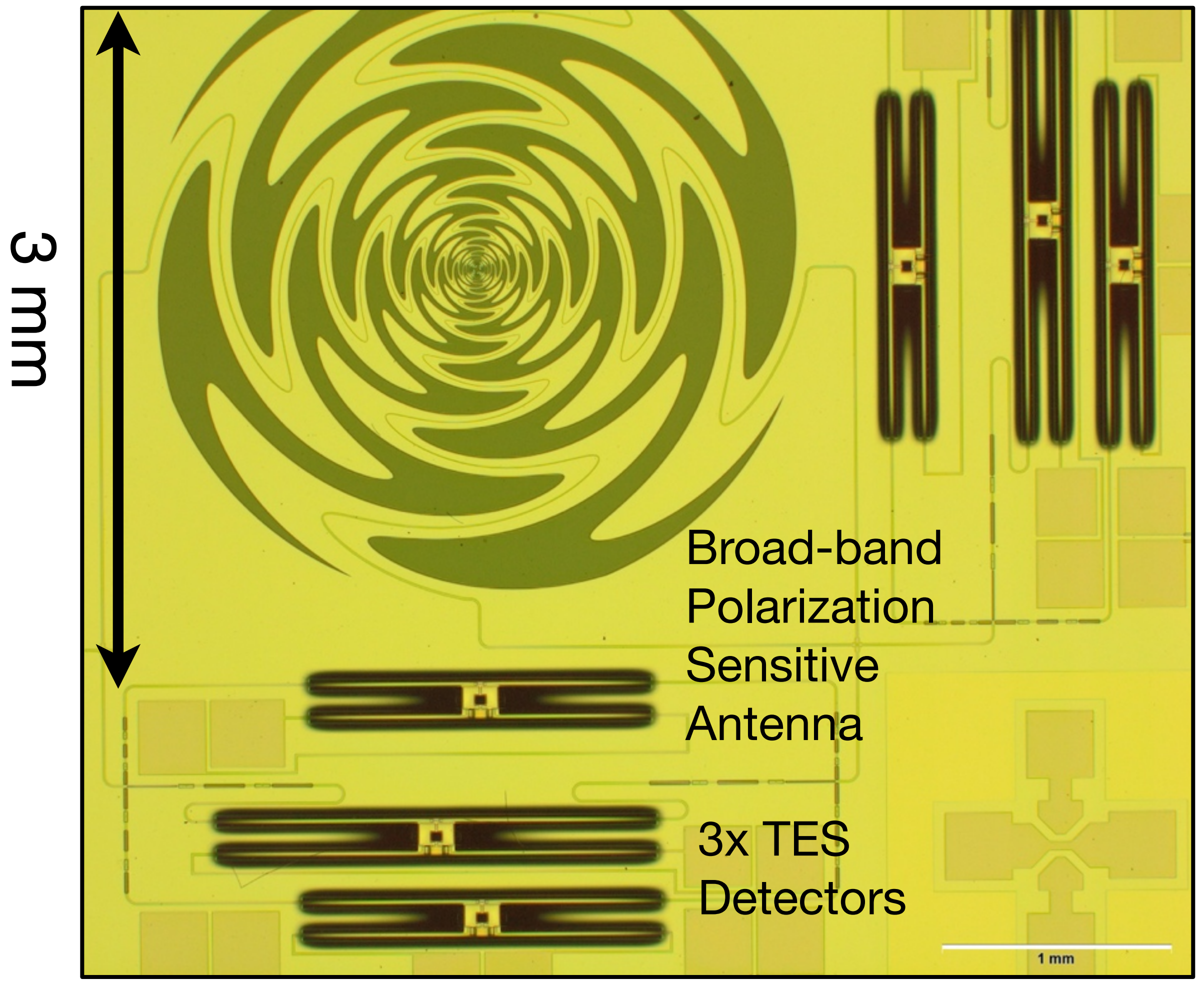
# SPT-3G Optics & Receiver

- **700 mm diameter zotefoam window supported by 50 K alumina plate**
- **Three 4 K alumina lenses, each 720 mm diameter and 50-65 mm thick**
- **300 mm diameter 4 K Lyot stop**



# SPT-3G Mapping Speed



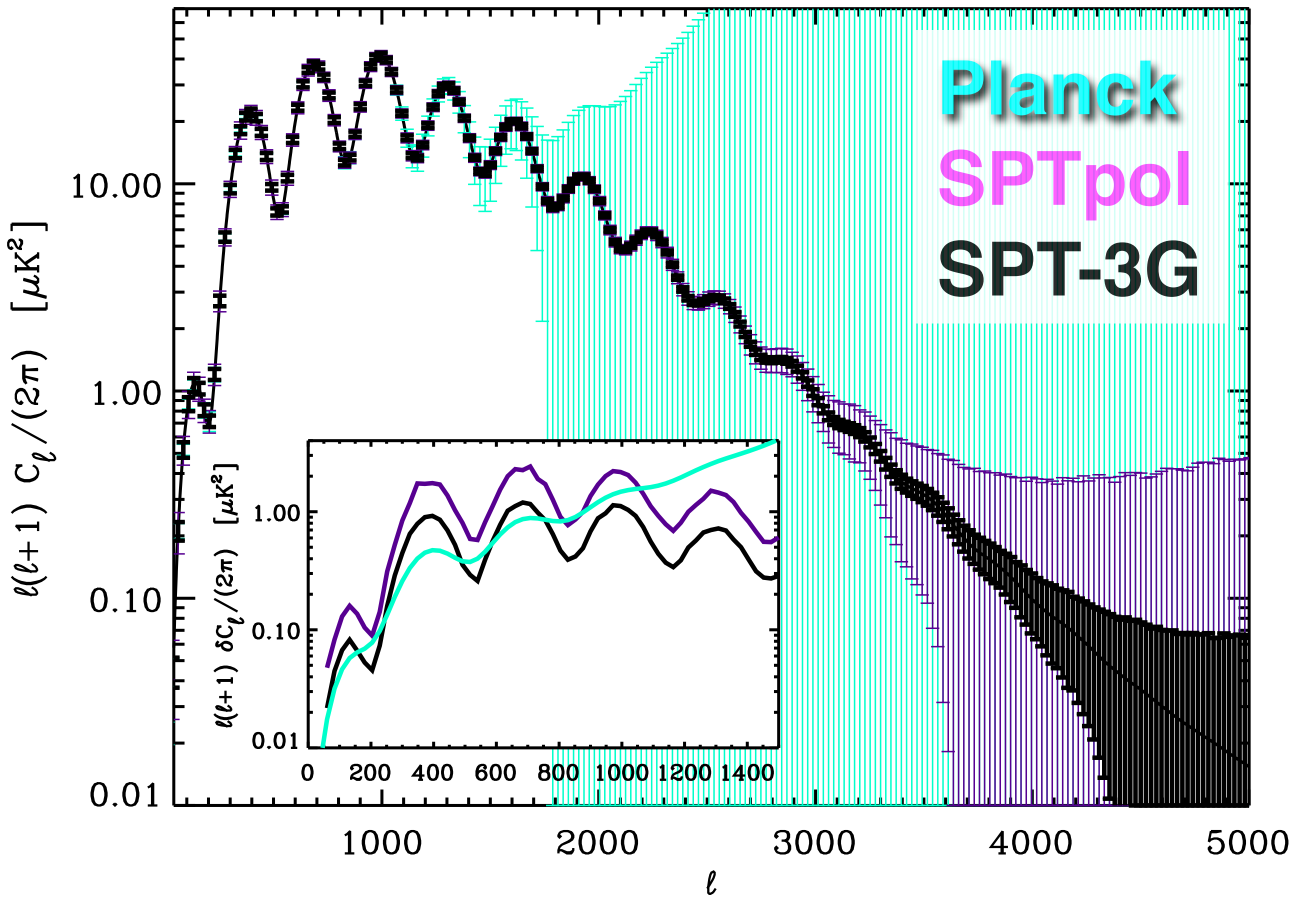

## ~20x Increase in Mapping Speed Relative to SPTpol:

1) ***Multi-chroic pixels***
   - 3-bands: 95, 150, 220 GHz
2) ***Increased field of view***
   - 3x increase in area (2.8 $deg^2$)
   - use large aperture (720 mm diameter), low-loss alumina lenses
3) ***Reduce internal loading***
   - Reduce from 30 K to 10 K
   - Zotefoam window supported by ~50 K alumina lens

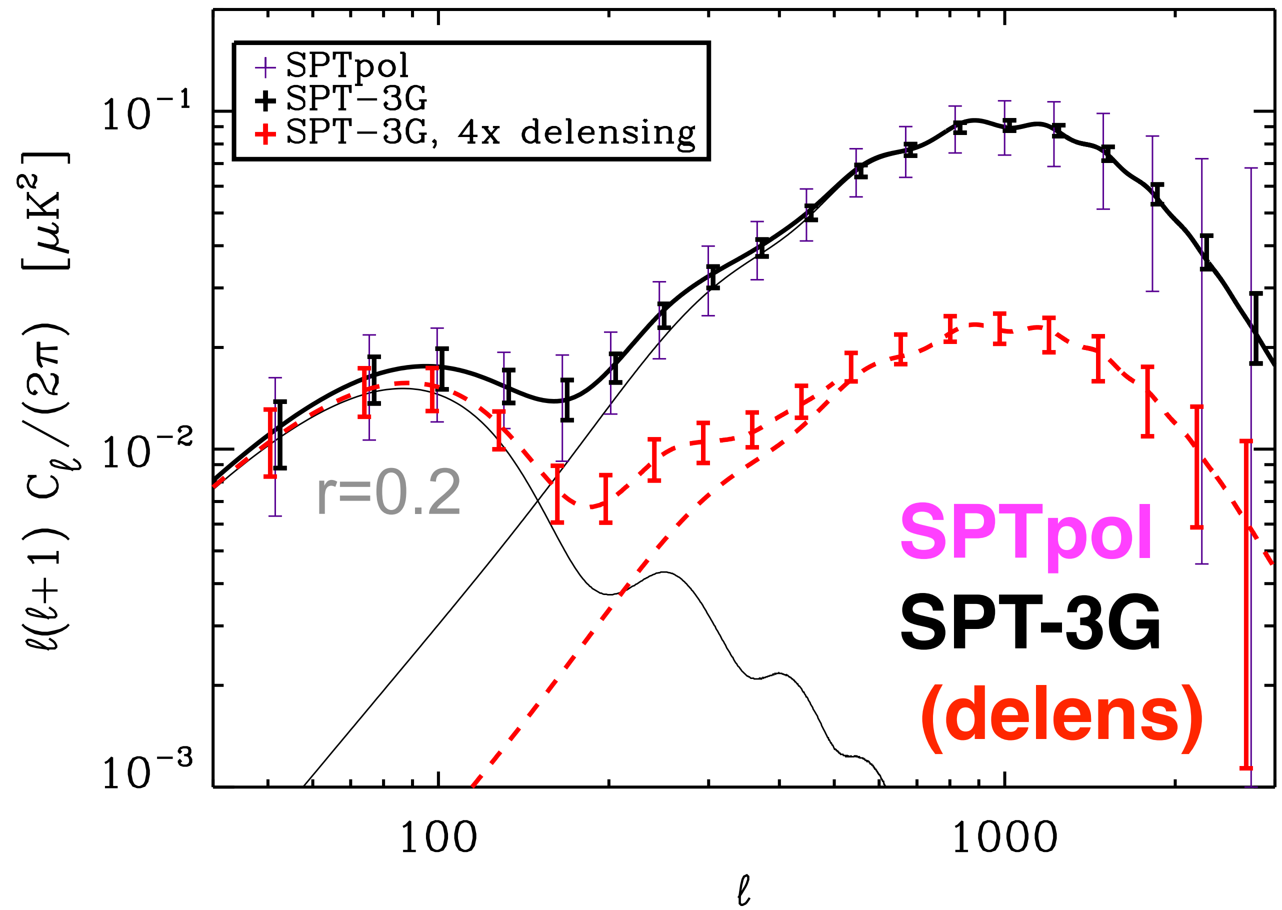
| Experiment | $N_{bolo}$ | $NET_T$ ($\mu K\sqrt{s}$) | $Speed_T$ | $NET_P$ ($\mu K\sqrt{s}$) | $Speed_P$ |
|---|---|---|---|---|---|
| SPT-SZ | 960 | 22 | 1.0 | - | - |
| SPT-POL | 1,536 | 14 | 2.5 | 20 | 1.0 |
| SPT-3G | 16,260 | **3.4** | **43** | **4.8** | **17** |

# SPT-3G, SPTpol (Projected) Polarization Power Spectra

## EE-Spectrum

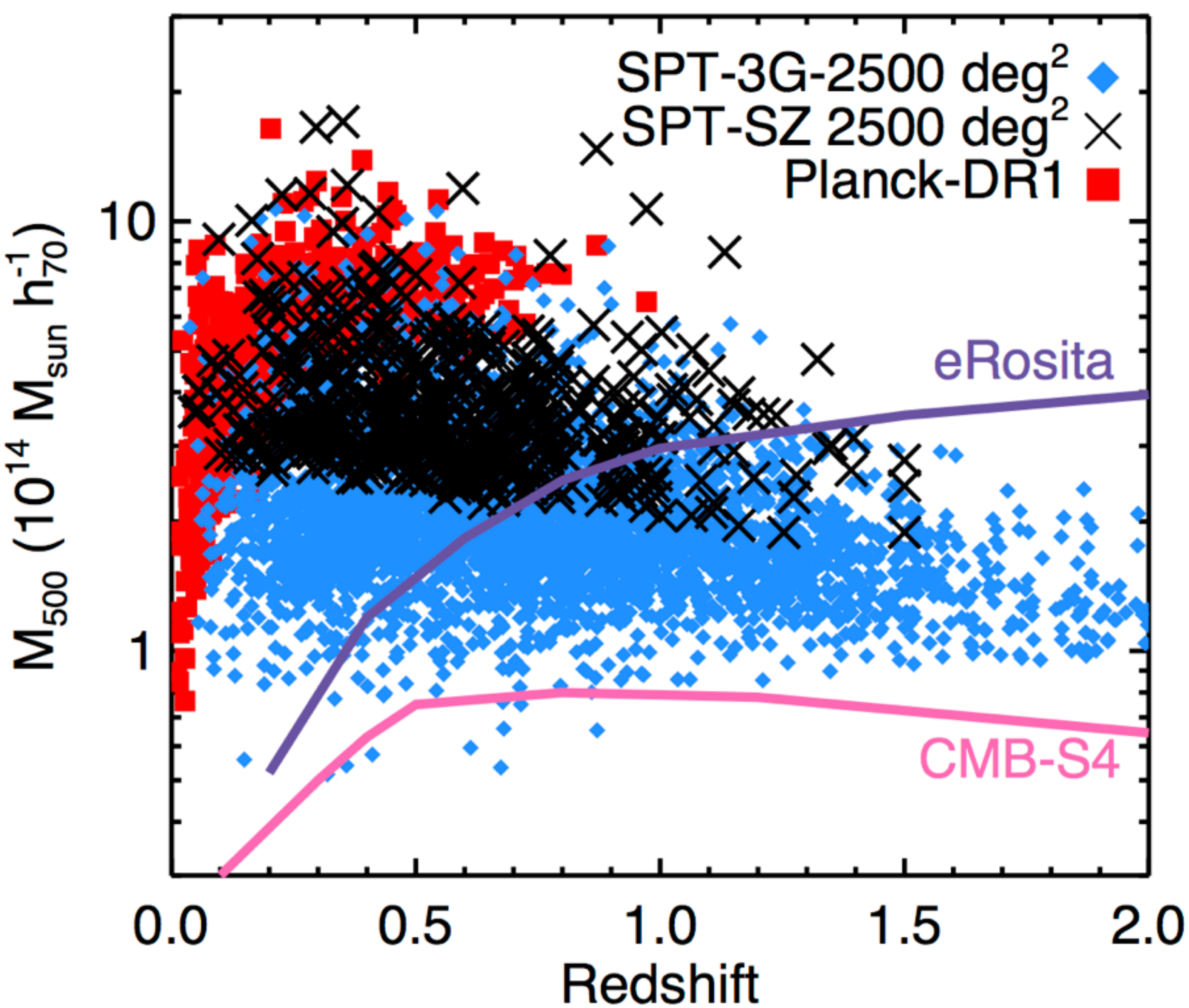



## BB-Spectrum




- Expected ~150-$\sigma$ detection of CMB Lensing
  - ***20 meV neutrino mass -> 1% shift in lensing spectrum***
- With Planck priors, **SPT-3G will constrain:**
  - ***Effective number of relativistic species $\sigma(N_{\text{eff}})$=0.06***
  - ***Tensor-to-scalar ratio to $\sigma(r)$=0.01***

# SPT-3G SZ Cluster Survey




SZ cluster counts will increase by orders of magnitude with future surveys:

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

Deep CMB data enables CMB cluster lensing as a mass calibration tool for cluster cosmology (Baxter et al. 2014):

***SPT-3G: σ(M) ~ 3%***
***CMB-S4: σ(M) < ~0.1%***

Especially promising for cluster masses at $z > 1$


TT
TE/EE
BB
clusters
ΦΦ
Thanks!