CMB at the South Pole

John Carlstrom

South Pole CMB efforts started in 1980's

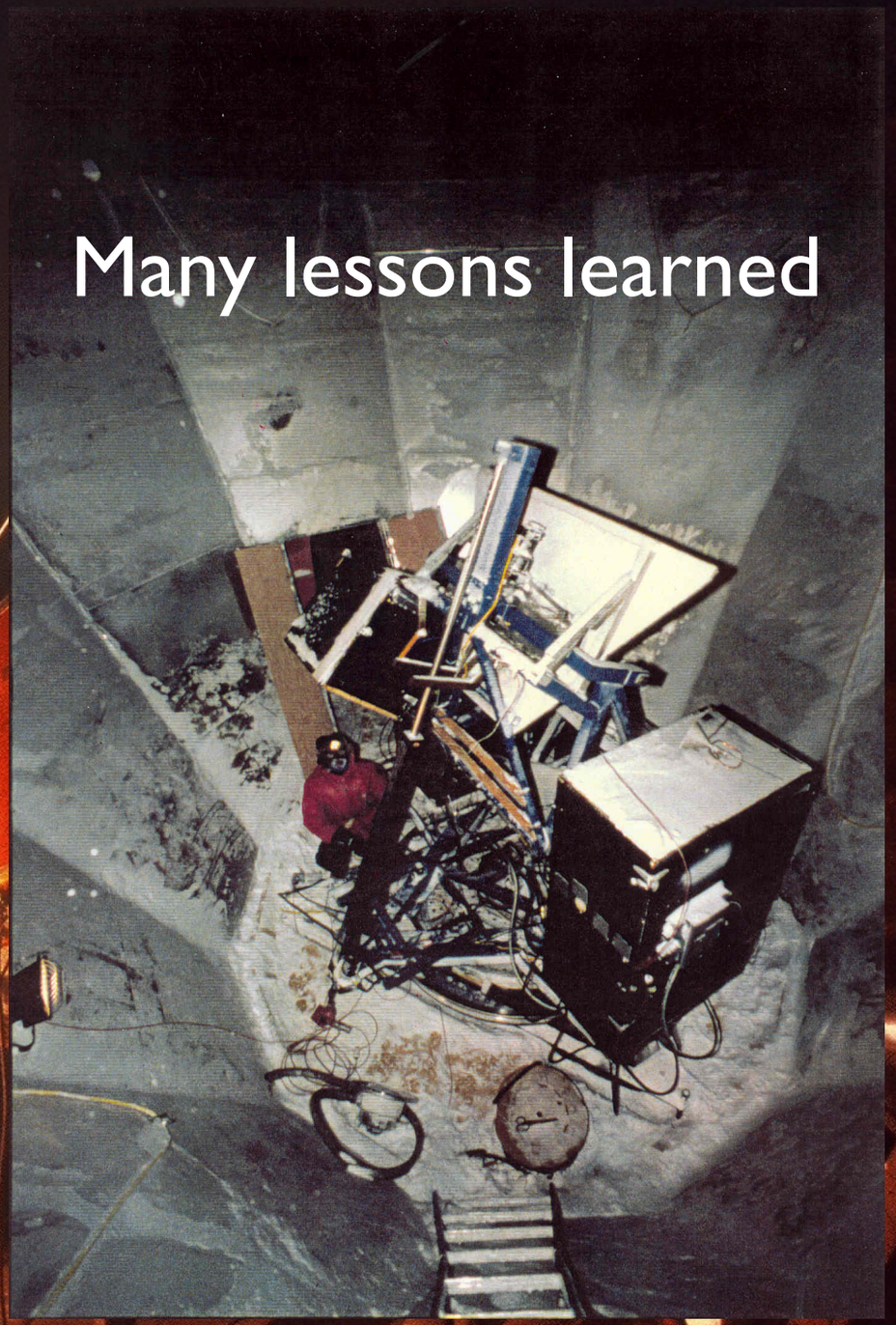
Python CMB Telescope

1994 Winter-over
John Kovac

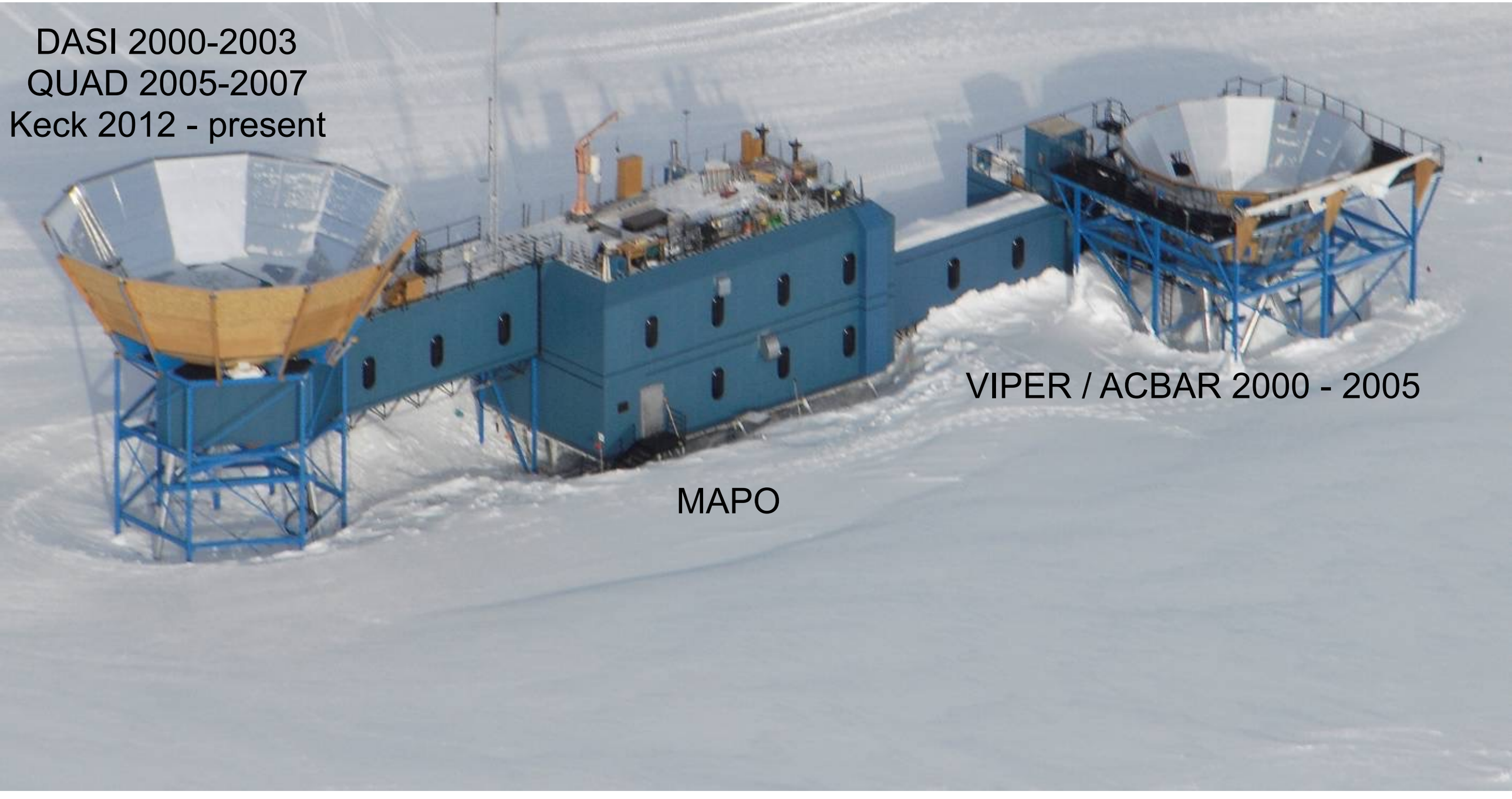
South Pole CMB efforts started in 1980's

1994 Winter-over
John Kovac

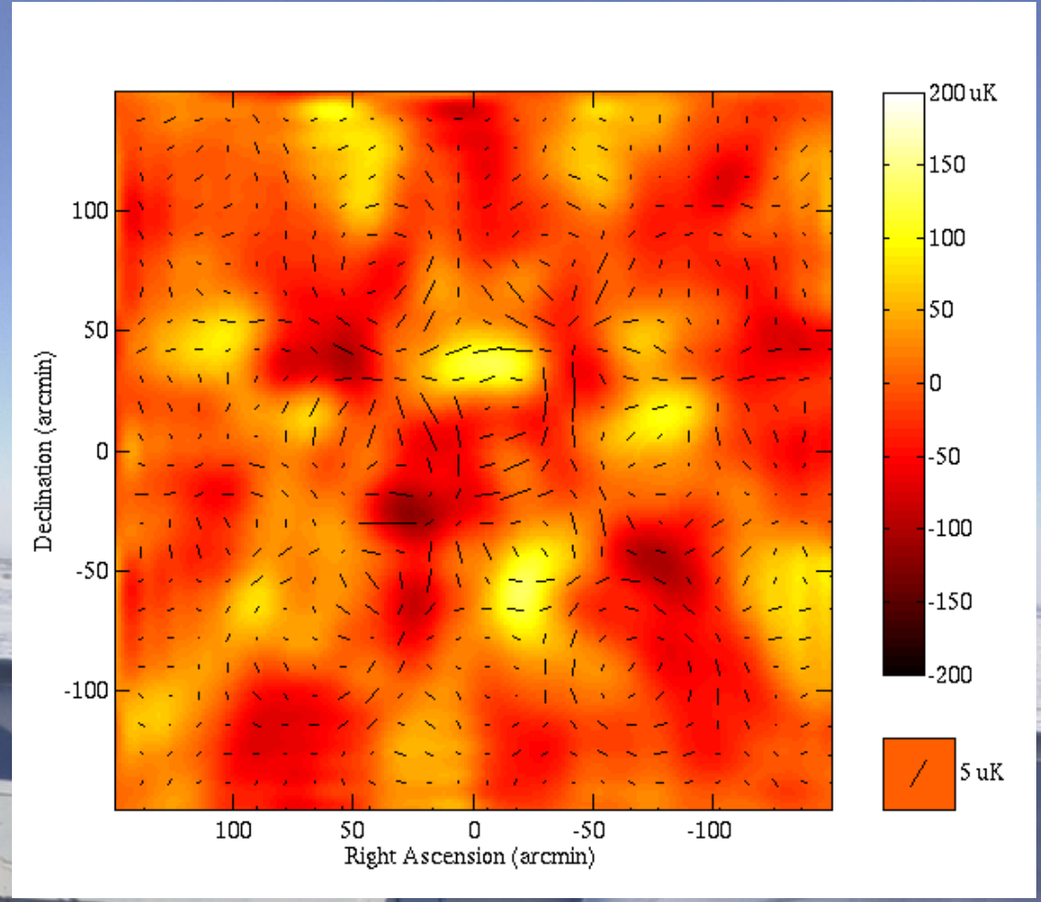
Many lessons learned



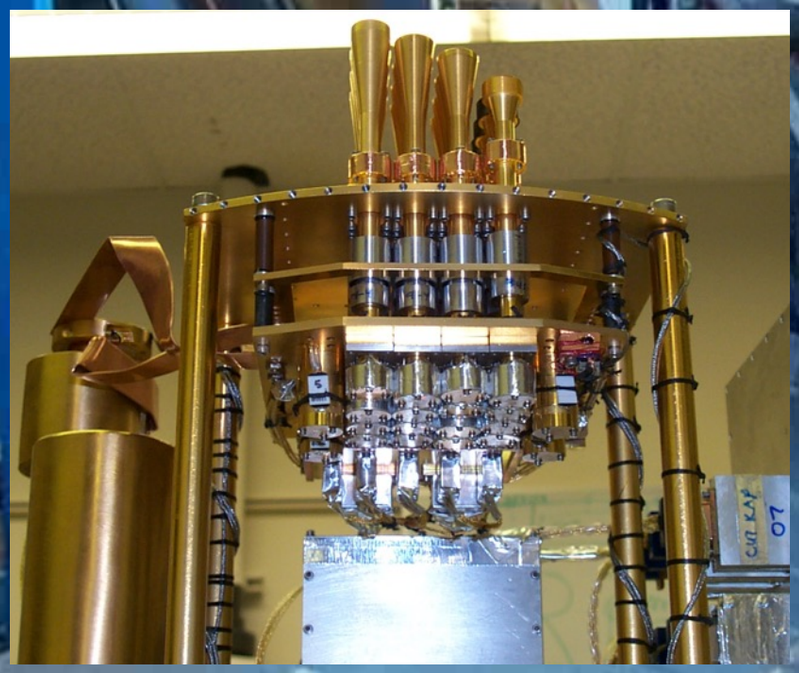
Martin A. Pomerantz Observatory (MAPO)



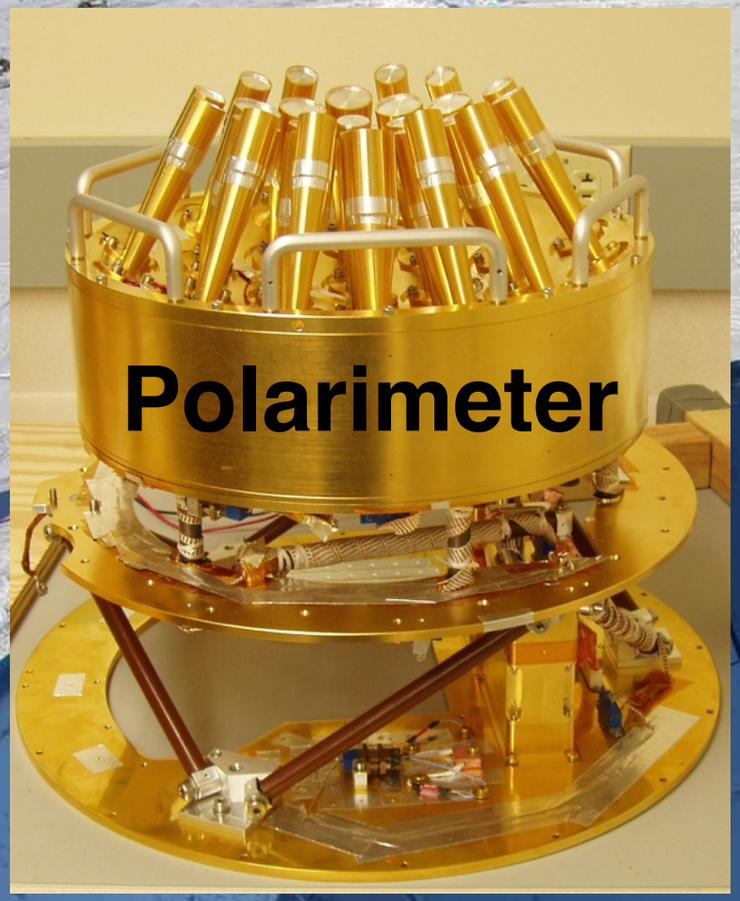
CMB polarization first detected in 2002, at South Pole

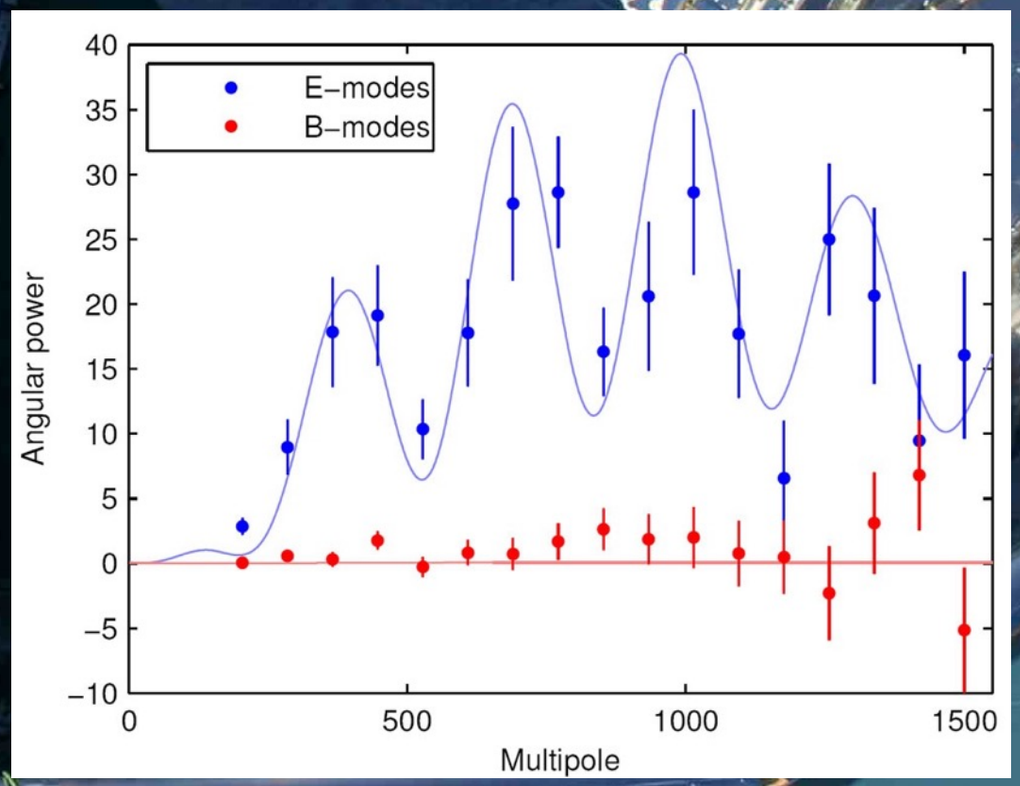


ACBAR

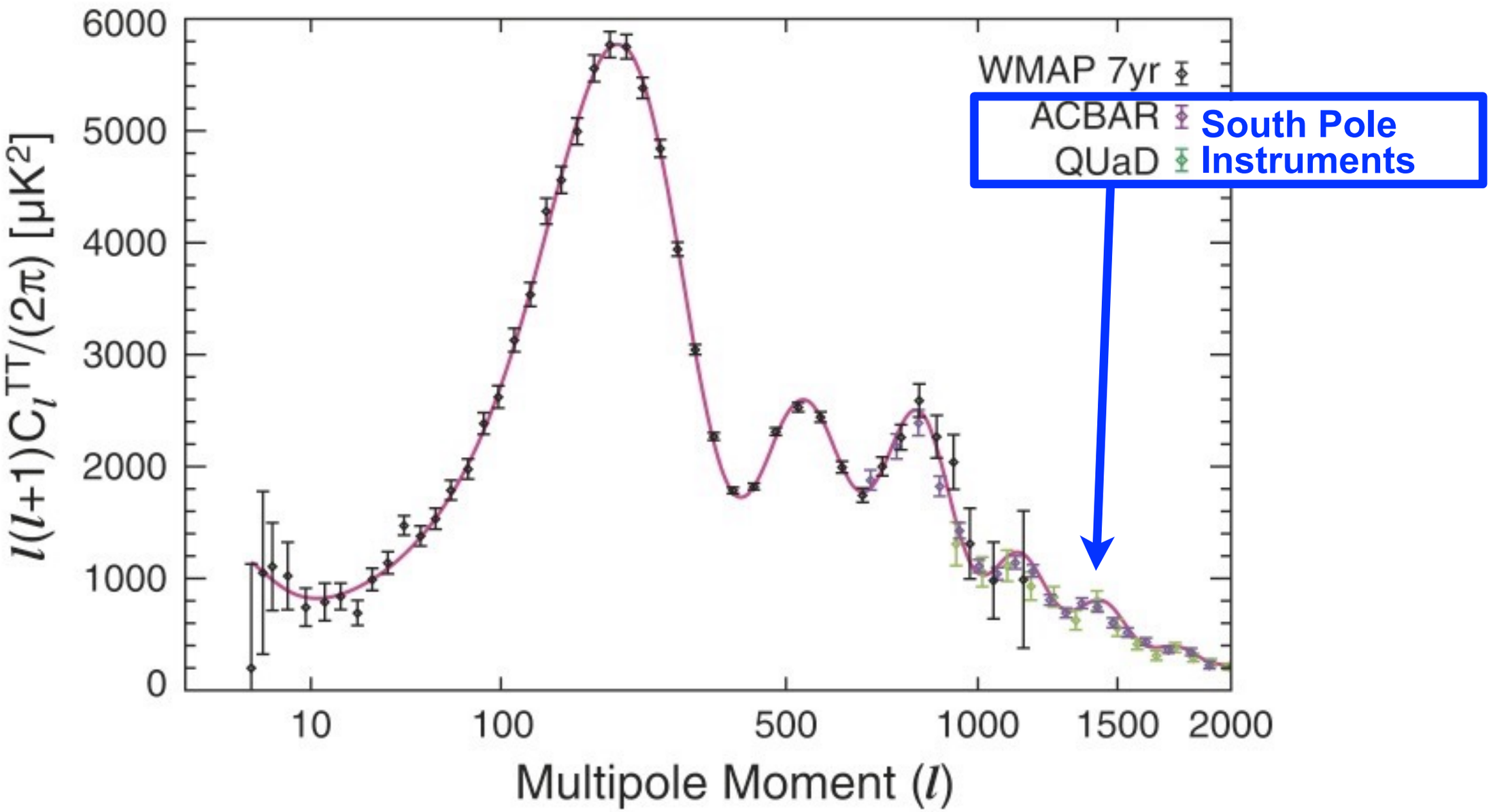


QUaD - an example of a 50/50 split US-European Collaboration





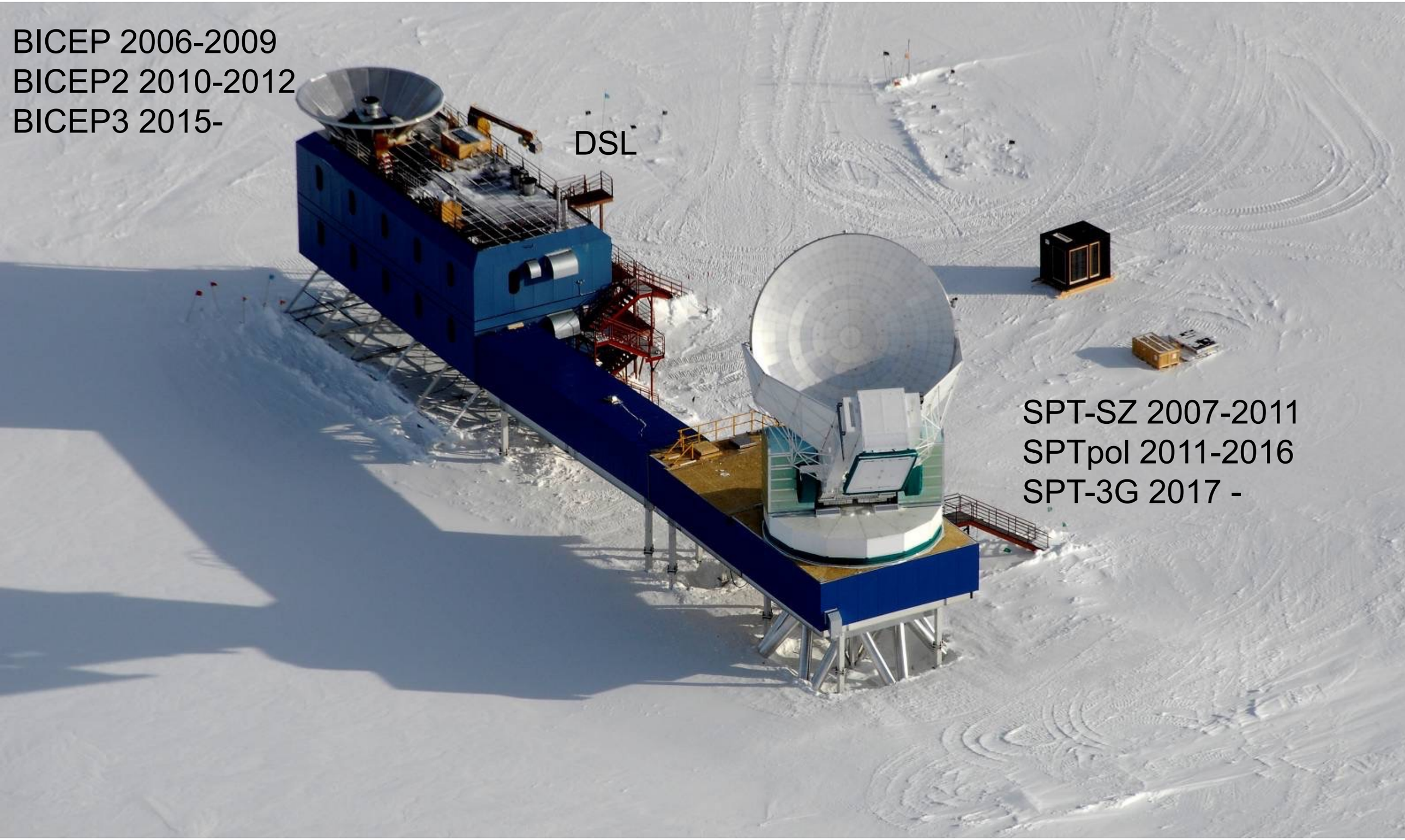
WMAP ext



Fit to ΛCDM cosmological model with just six parameters

Komatsu et al., arXiv:1001:4538
Larson et al., arXiv:1001.4635

Dark Sector Laboratory (DSL)



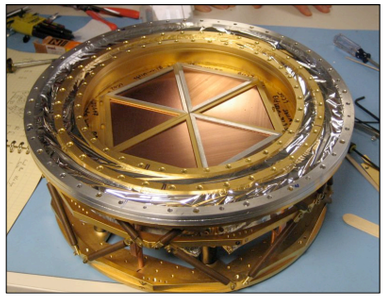
The South Pole Telescope (SPT)

10-meter
submm wave telescope

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

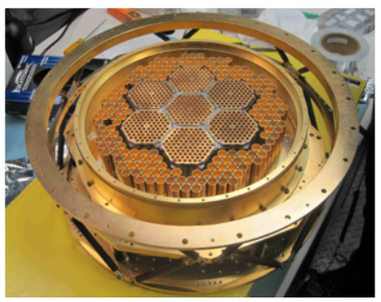
2007: SPT-SZ

960 detectors (UCB)
100,150,220 GHz



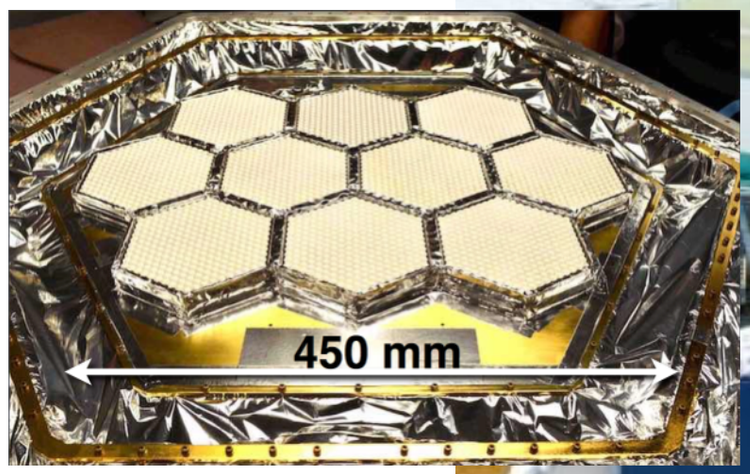
2012: SPTpol

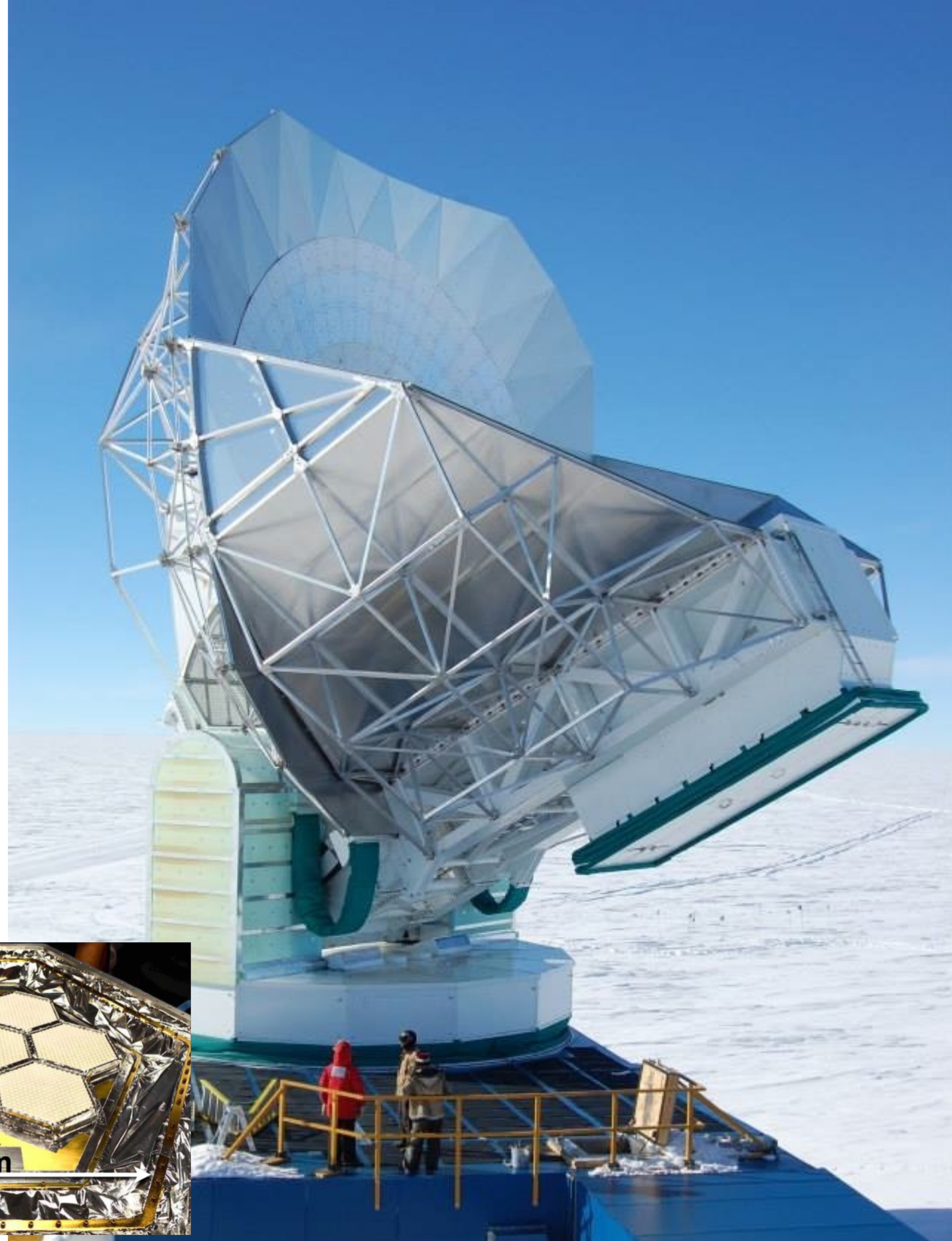
1600 detectors
100,150 GHz
+Polarization



2017: SPT-3G

16,000 detectors
100,150, 220 GHz
+Polarization





The South Pole Telescope Collaboration

funding:

NSF

U.S. DEPARTMENT OF ENERGY

Argonne NATIONAL LABORATORY

BERKELEY LAB

CARDIFF UNIVERSITY / PRIFYSGOL CAERDYDD

NIST

MIT

SLAC

McGill

Colorado
University of Colorado at Boulder

Case
CASE WESTERN RESERVE UNIVERSITY

STANFORD UNIVERSITY

KICP
Kavli Institute for Cosmological Physics
AT THE UNIVERSITY OF CHICAGO

Berkeley
University of California

THE UNIVERSITY OF CHICAGO

LMU
LUDWIG-MAXIMILIANS-UNIVERSITÄT MÜNCHEN

Harvard-Smithsonian Center for Astrophysics

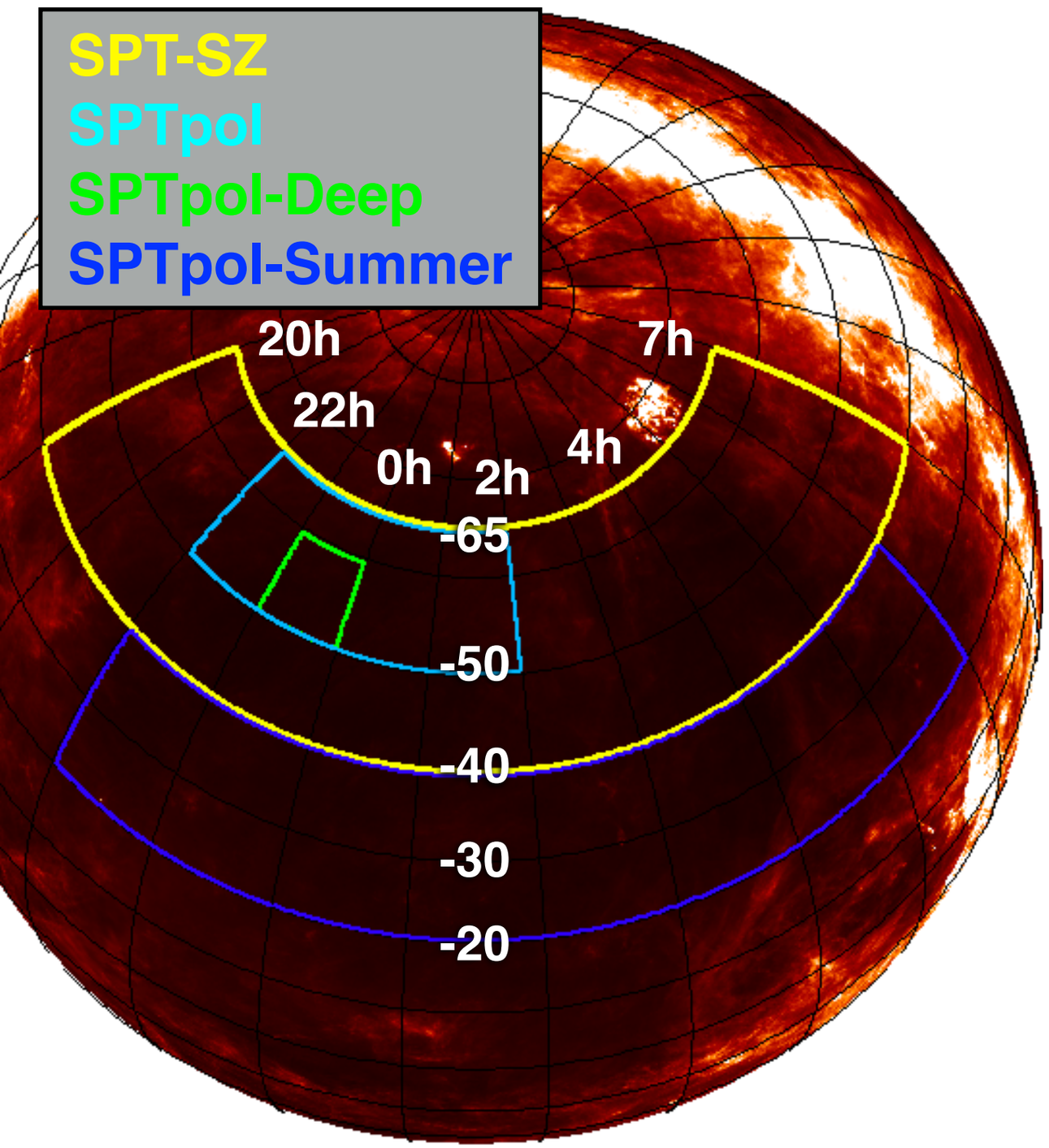
UC DAVIS
UNIVERSITY OF CALIFORNIA

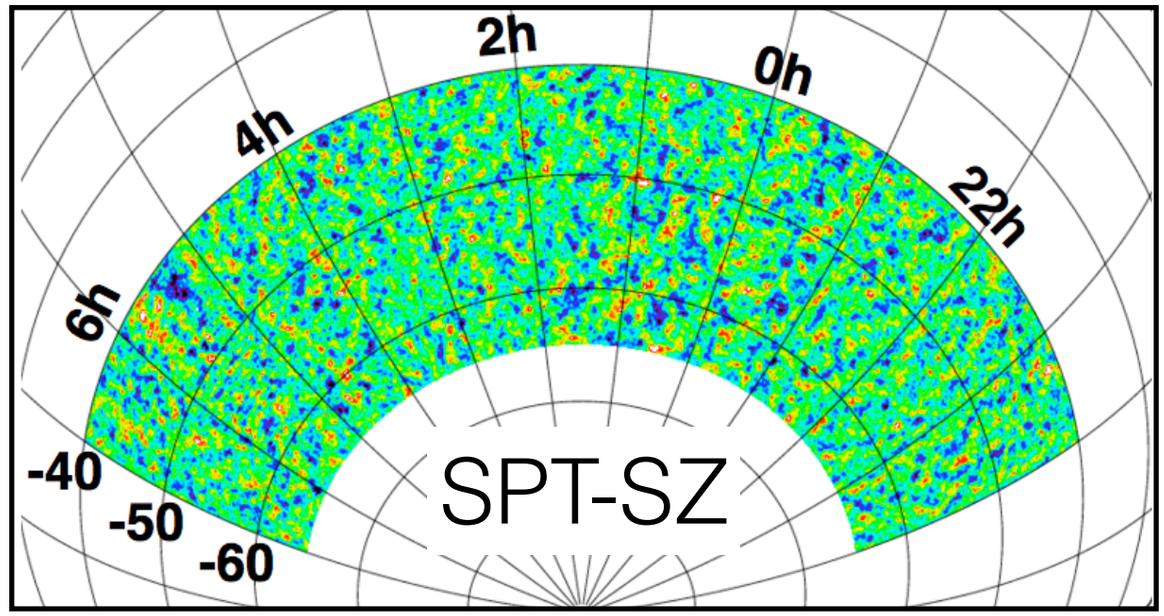
Fermilab

KAVLI

GORDON AND BETTY MOORE FOUNDATION

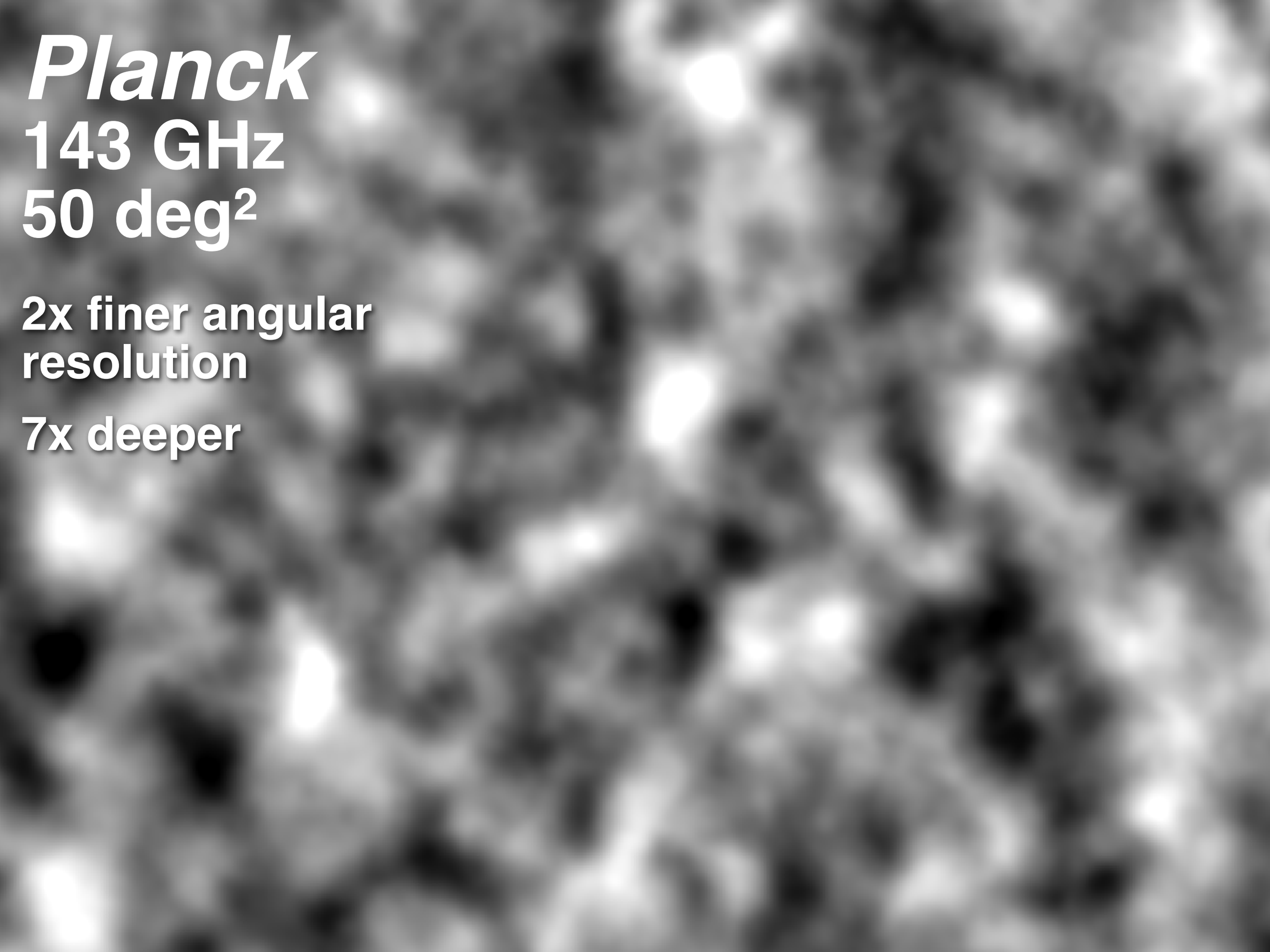
The SPT Surveys
5000 deg²





	Obs. Years	Area (deg²)	95 GHz (uK-arcmin)	150 (uK-arcmin)	220 (uK-arcmin)
SPT-SZ	2007-11	2500	40	17	80
SPTpol-Main	2012-16	500	13	5	-
SPTpol-Deep	2012-16	100	10	3.5	-
SPTpol-Summer	2012-16	2500	47	28	-
SPT-3G *(projected)*	2018-21	1500	2.8	2.6	6.6

WMAP
94 GHz
50 deg^2


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

SPT

150 GHz

50 deg^2

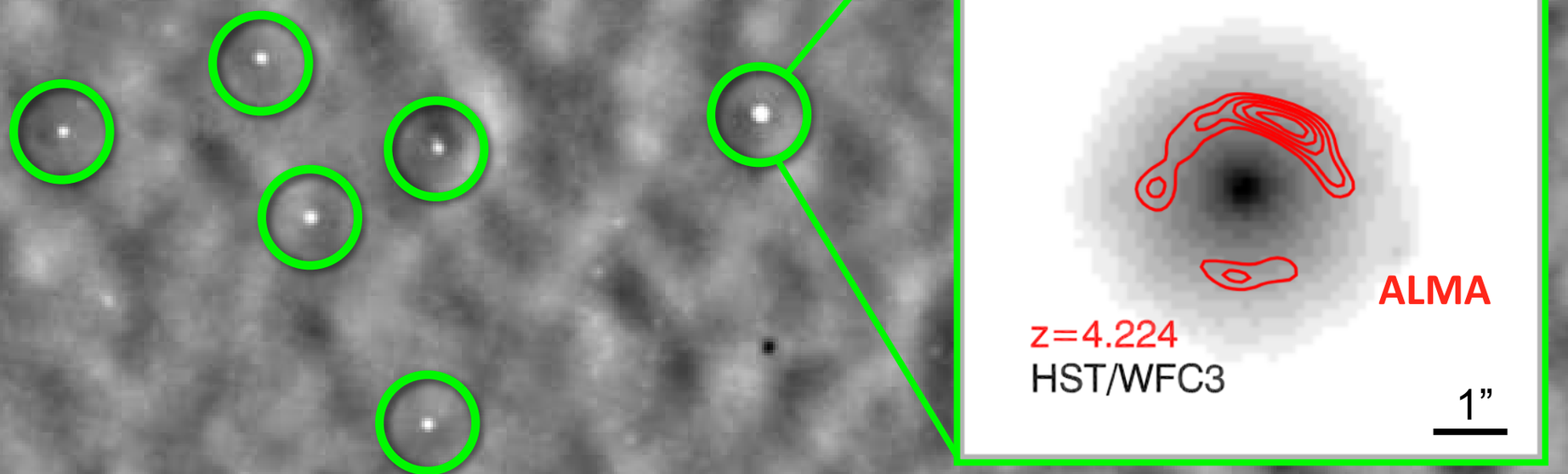
13x finer angular resolution

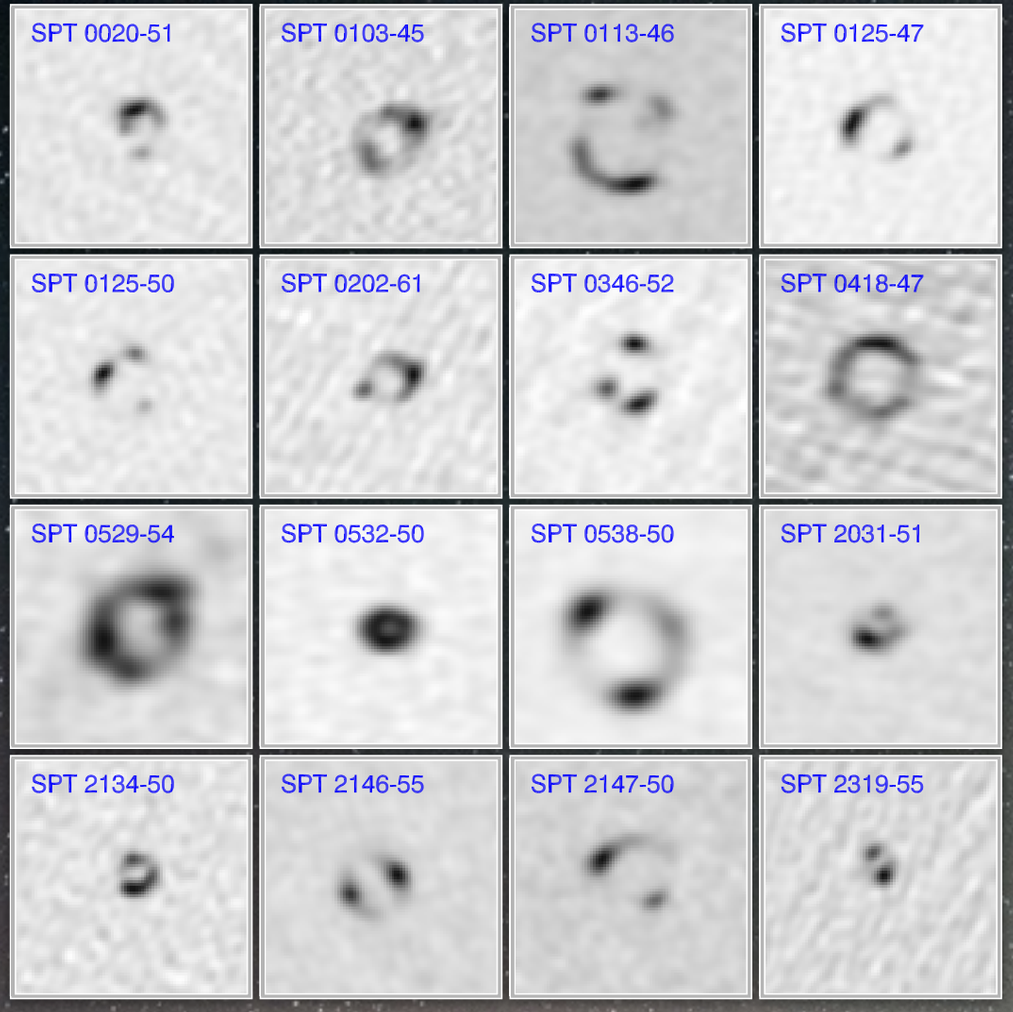
50x deeper

SPT
150 GHz
50 deg^2

Point Sources

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





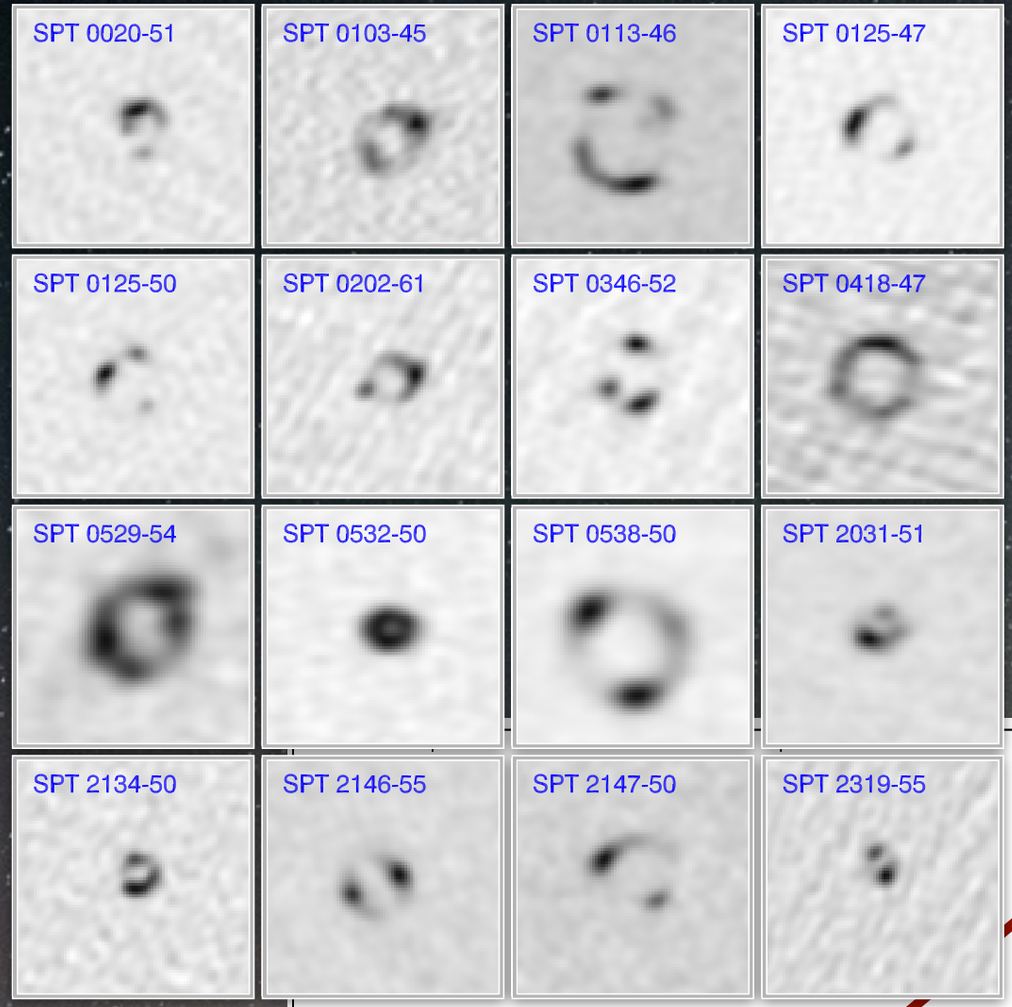
ALMA Cycle 0

Imaging

Band 7 350 GHz
~0.5" resolution
8"x8" thumbnails
2 minute snapshots

ALMA can probe the
Dark Matter substructure
of the lenses. *Hezevah et al. 1601.01388*

Vieira et al. 2013, Hezevah et al. 2013



ALMA Cycle 0

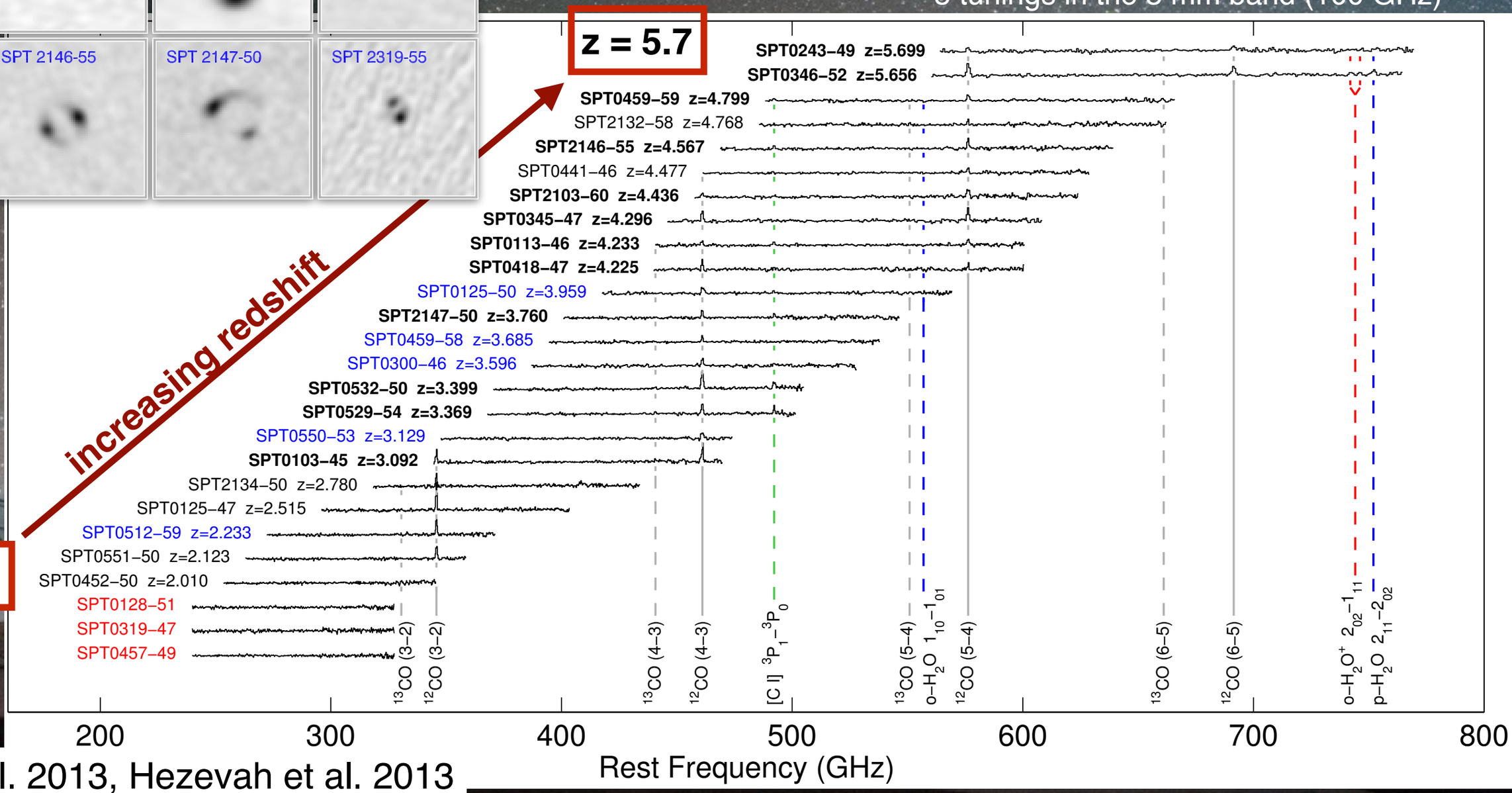
Imaging

Band 7 350 GHz
~0.5" resolution
8"x8" thumbnails
2 minute snapshots

ALMA can probe the Dark Matter substructure of the lenses. *Hezevah et al. 1601.01388*

Spectroscopic redshift survey

5 tunings in the 3 mm band (100 GHz)

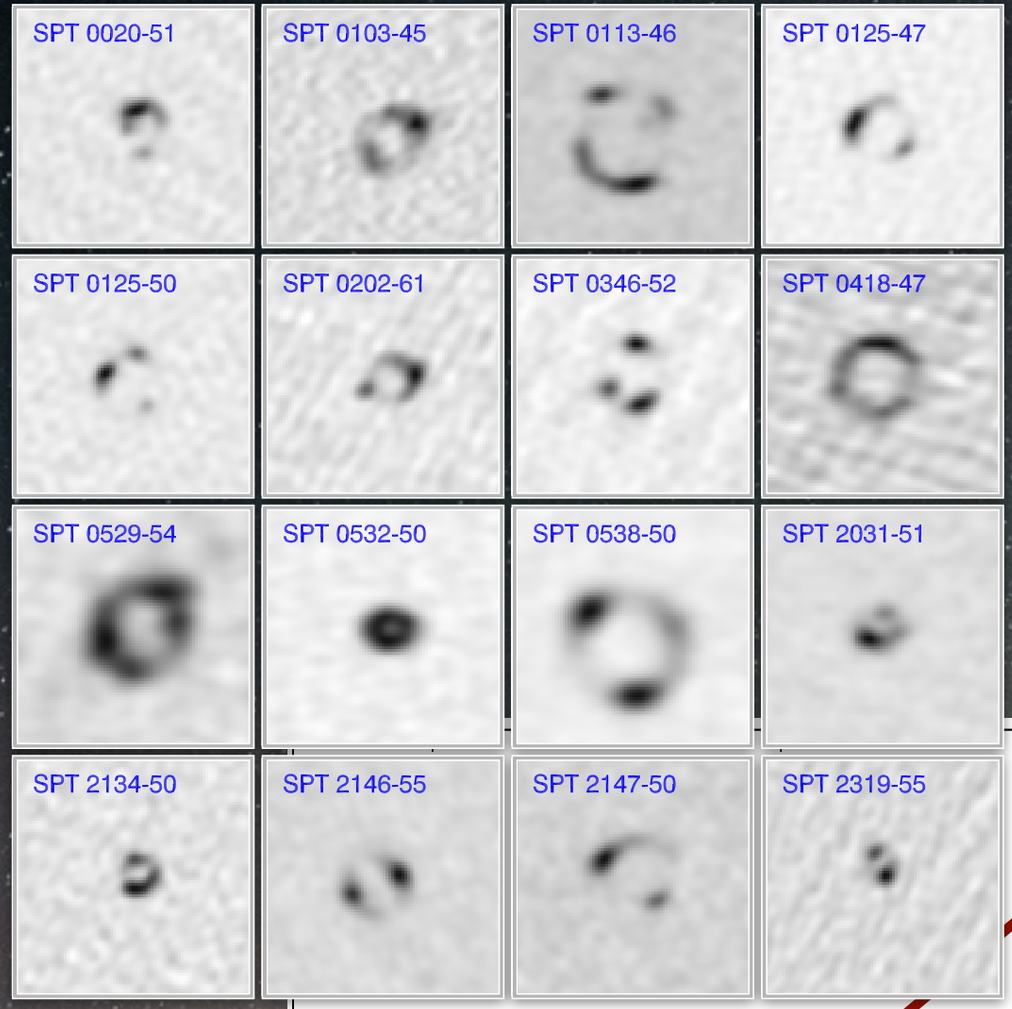


Vieira et al. 2013, Hezevah et al. 2013

ALMA Cycle 0

Imaging

Band 7 350 GHz
~0.5" resolution
8"x8" thumbnails
2 minute snapshots



ALMA can probe the
Dark Matter substructure
of the lenses. *Hezevah et al. 1601.01388*

Spectroscopic redshift survey

5 tunings in the 3 mm band (100 GHz)

z = 2.0

z = 5.7

increasing redshift

SPT0243–49 z=5.699
SPT0346–52 z=5.656
SPT0459–59 z=4.799
SPT2132–58 z=4.768
SPT2146–55 z=4.567
SPT0441–46 z=4.477
SPT2103–60 z=4.436
SPT0345–47 z=4.296
SPT0113–46 z=4.233
SPT0418–47 z=4.225
SPT0125–50 z=3.959
SPT2147–50 z=3.760
SPT0459–58 z=3.685
SPT0300–46 z=3.596
SPT0532–50 z=3.399
SPT0529–54 z=3.369
SPT0550–53 z=3.129
SPT0103–45 z=3.092
SPT2134–50 z=2.780
SPT0125–47 z=2.515
SPT0512–59 z=2.233
SPT0551–50 z=2.123
SPT0452–50 z=2.010
SPT0128–51
SPT0319–47
SPT0457–49

^{13}CO (3–2)
^{12}CO (3–2)
^{13}CO (4–3)
^{12}CO (4–3)
[C I] $^3P_1$–$^3P_0$
^{13}CO (5–4)
o–H_2O 1_{10}–1_{01}
^{12}CO (5–4)
^{13}CO (6–5)
^{12}CO (6–5)
o–H_2O^+ 2_{02}–1_{11}
p–H_2O 2_{11}–2_{02}

200 300 400 500 600 700 800
Rest Frequency (GHz)

Highest redshift so far z = 6.9
Two massive galaxies colliding
800 Myr after the big bang
(Marrone et al Nature 2017)

Vieira et al. 2013, Hezevah et al. 2013

SPT
150 GHz
50 deg²

Clusters of Galaxies

"Shadows" in the microwave background from clusters of galaxies

Angular Scale

90° 1° 10′ 5′ 2′ 1′

Planck
SPT - S13
ACT 148 GHz
ACT 220 GHz
SPT 220 GHz
SPT 150 GHz
SPT 95 GHz

$\mathcal{D}_\ell$ (μK^2)

1000
100
10

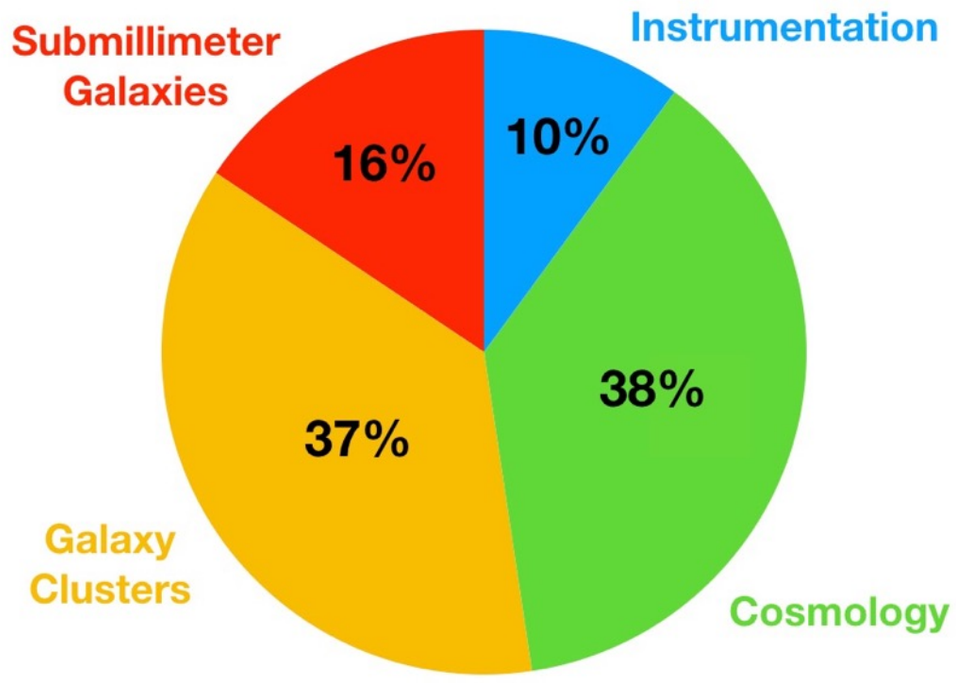
10 500 1500 2500 6000 10000

ℓ

Planck
Story et al., 2013
George et al., 2014
Das et al., 2014

Overview of SPT results

https://pole.uchicago.edu/public/publications.html



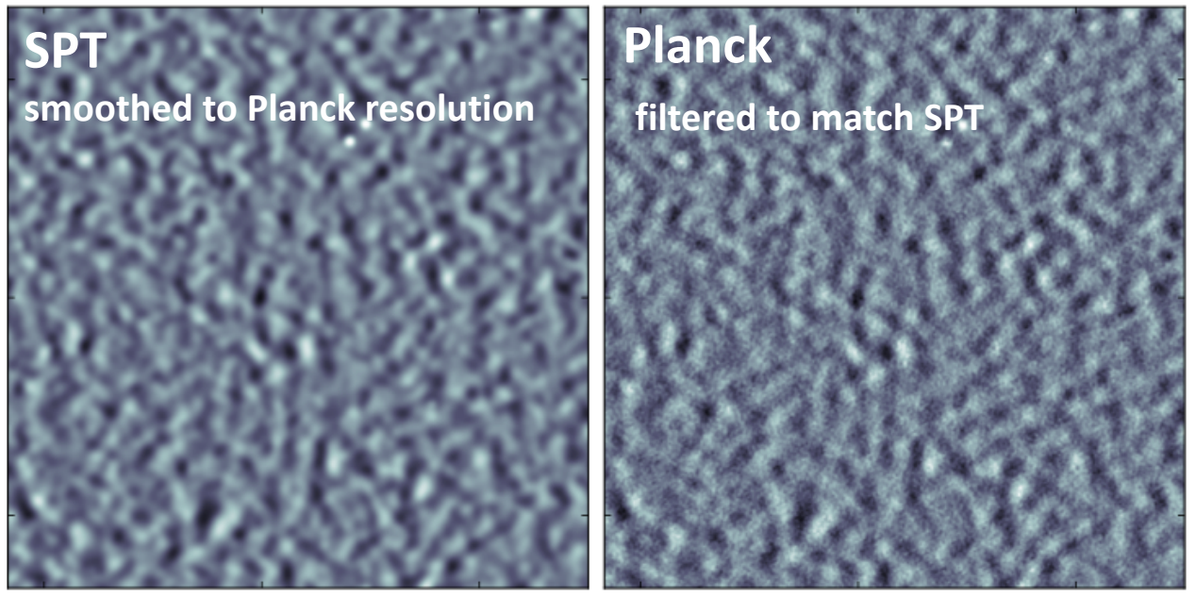
Results (>100 science publications)

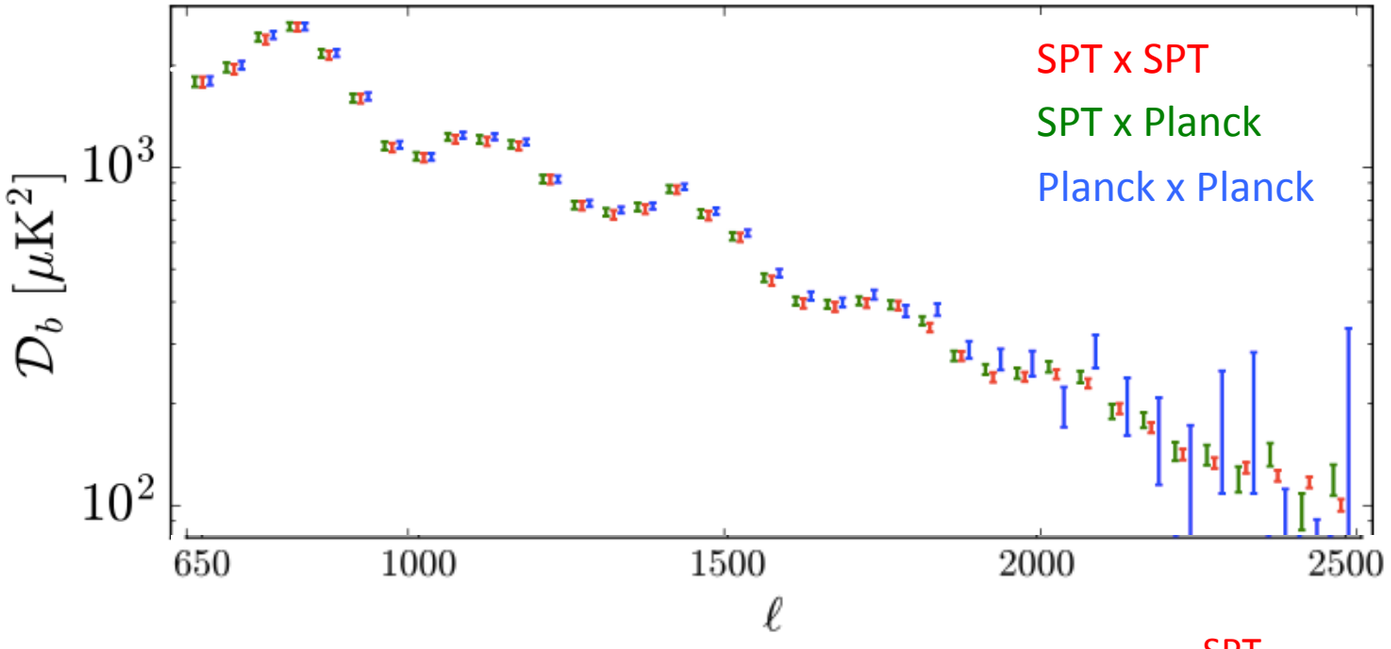
- Temperature and Polarization power spectra and cosmological parameters
- Diffuse kinematic and thermal SZ effect constraints, bi-spectrum, pairwise kSZ
- CMB lensing: power spectra; cross-correlations; cluster CMB lensing mass calibration
- First SZ discovery of Galaxy Clusters, SZ cluster catalog and cosmology
- Discovered population of high redshift lensed dusty star forming galaxies
- First detection of lensing B-mode polarization; demonstrating of de-lensing
- many many more…

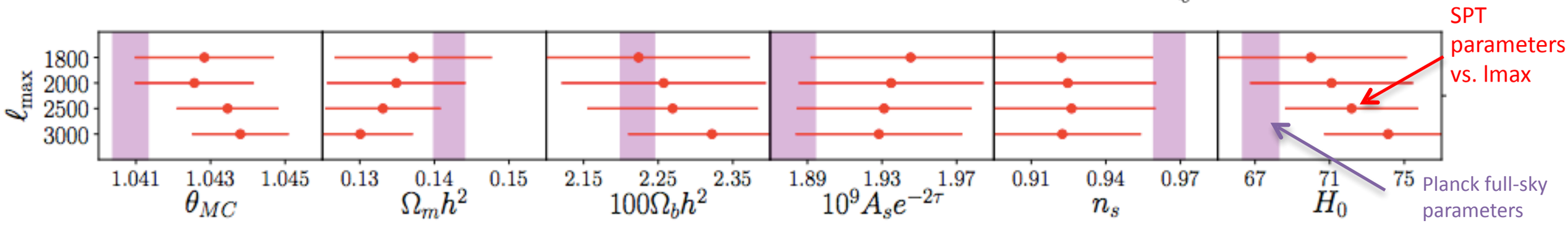
Recent SPT result: Comparison with Planck

Comparison of SPT and Planck data at the map, power-spectrum, and cosmological-parameter level

- Maps and power spectra on SPT sky region fully consistent (PTE=0.3) from 650 < l < 2500.
- Cosmological parameters on SPT sky region fully consistent between SPT and Planck (PTE=0.7).
- Cosmological parameters on SPT sky region using 650 < l < 2000 consistent with Planck full-sky parameters (PTE=0.2).
- Interesting trends in parameters (particularly H_0) when SPT data at l > 2000 added back in.
- Hou et al., ApJ, in press, arXiv:1701.04396; Aylor et al., ApJ 850 (2017) 101, arXiv: 1706.10286

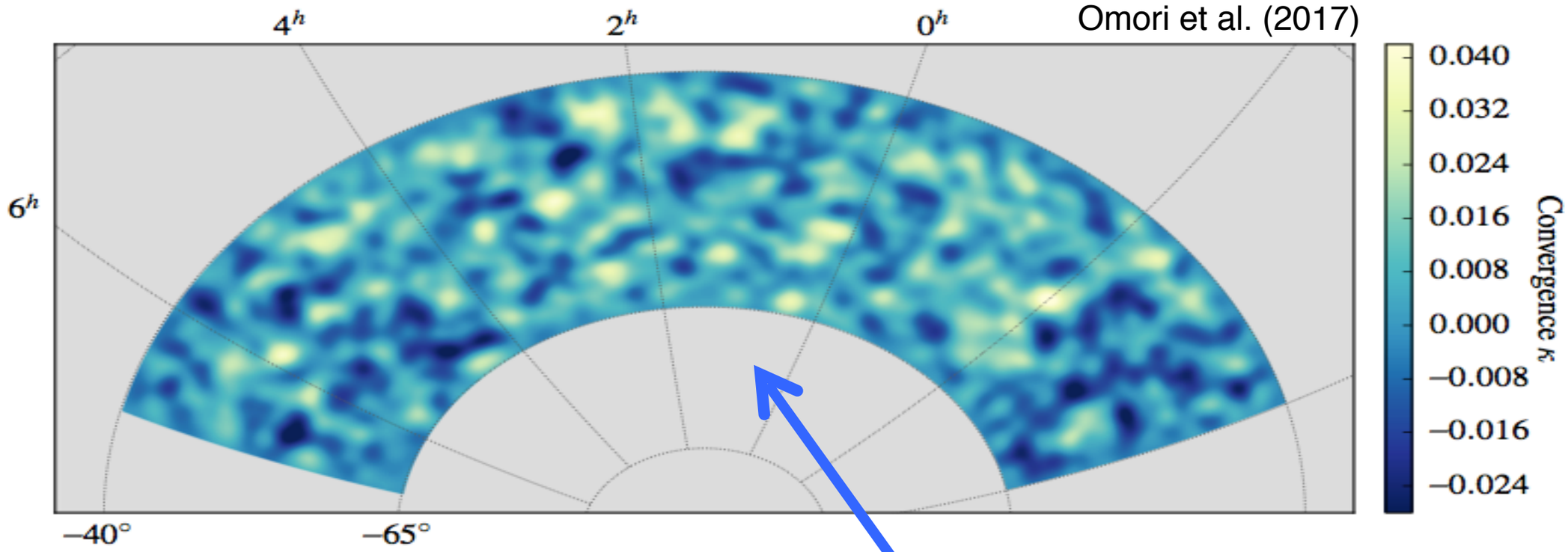


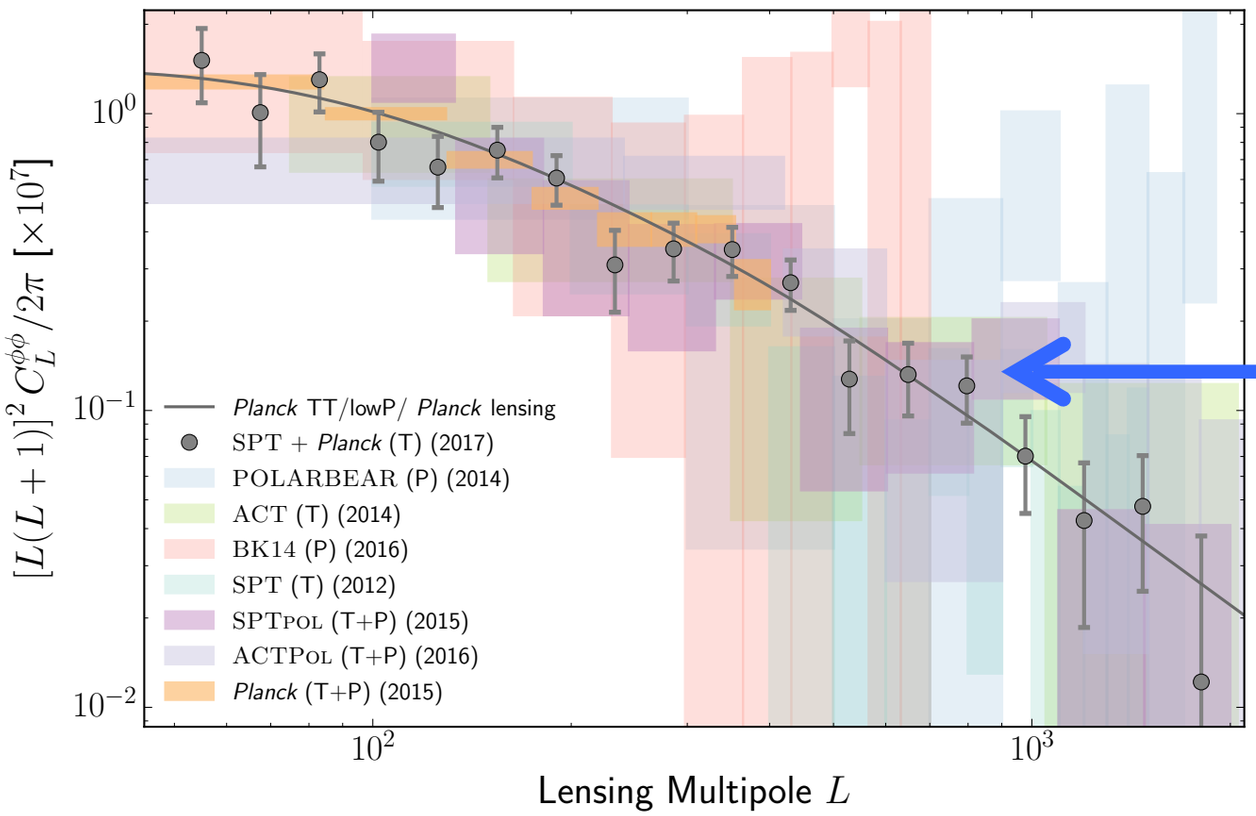




Recent SPT results: gravitational lensing

Omori et al. (2017)

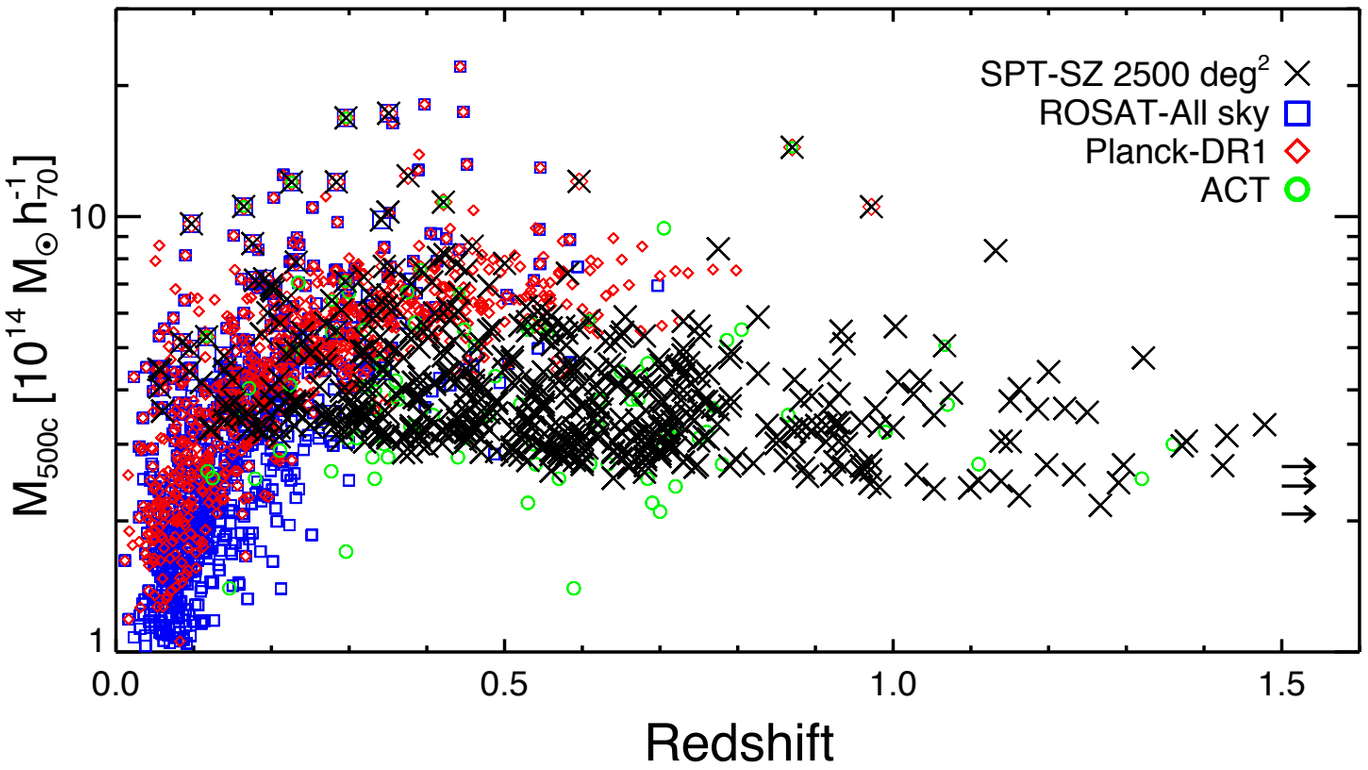


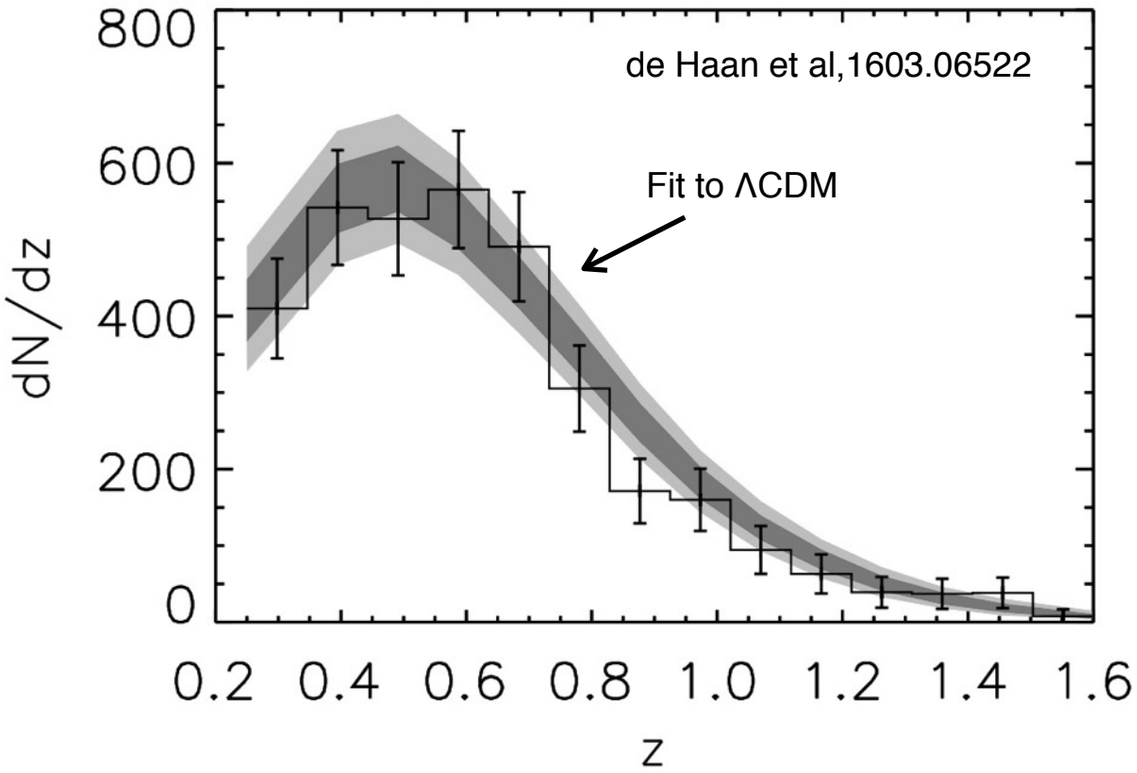


SPT SZ + Planck CMB lensing map (6% of the sky)

Power spectrum

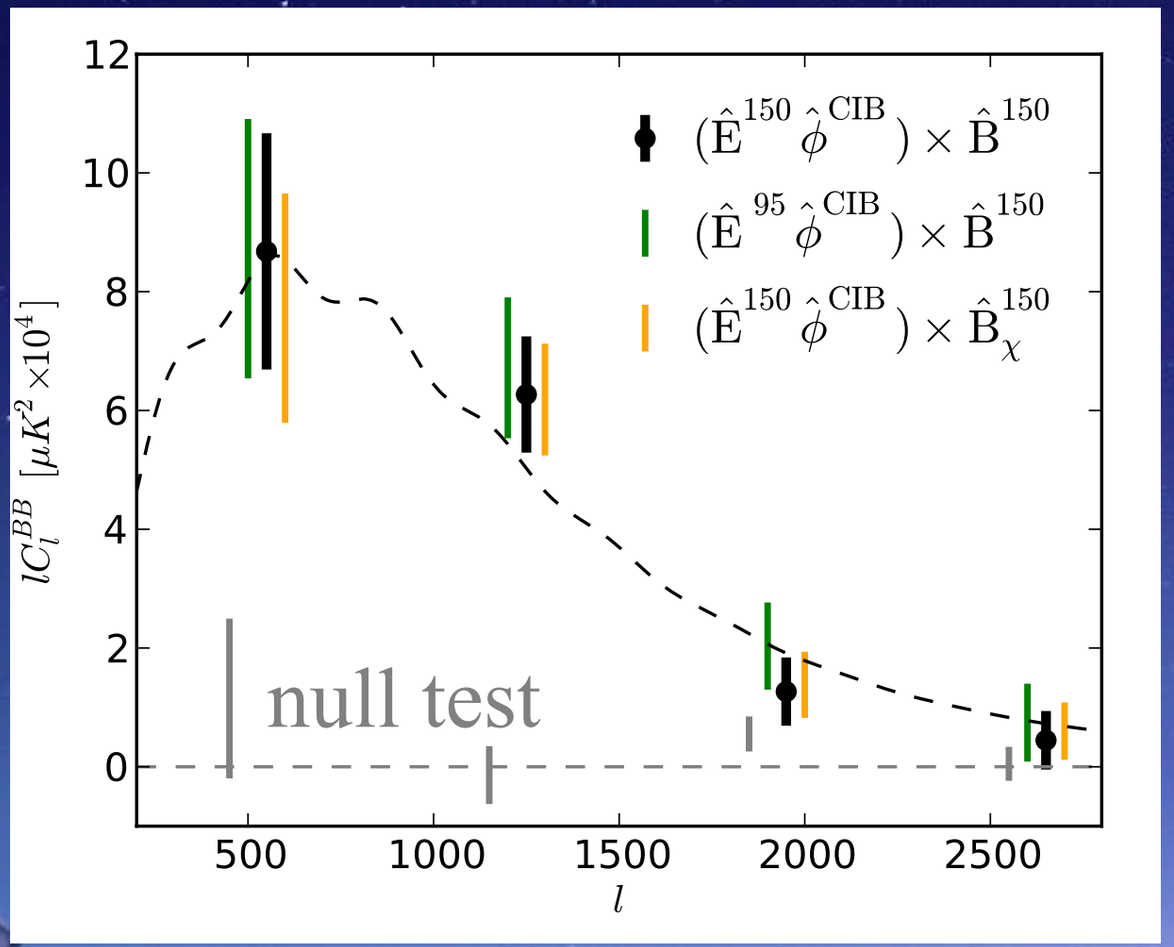
Recent SPT results: Cosmology with SZ clusters





Tracing the growth of structure with evolution of massive galaxy clusters. Results limited by mass calibration. (See Sebastian's presentation)

CMB B-mode Polarization first detected in 2013, at South Pole




physicsworld
TOP 10 BREAKTHROUGH 2013

Physics World
Breakthrough of the Year 2013

A *Physics World* Top 10 Breakthrough of the Year is awarded for physics research published in 2013 and the decision is based on the following criteria:

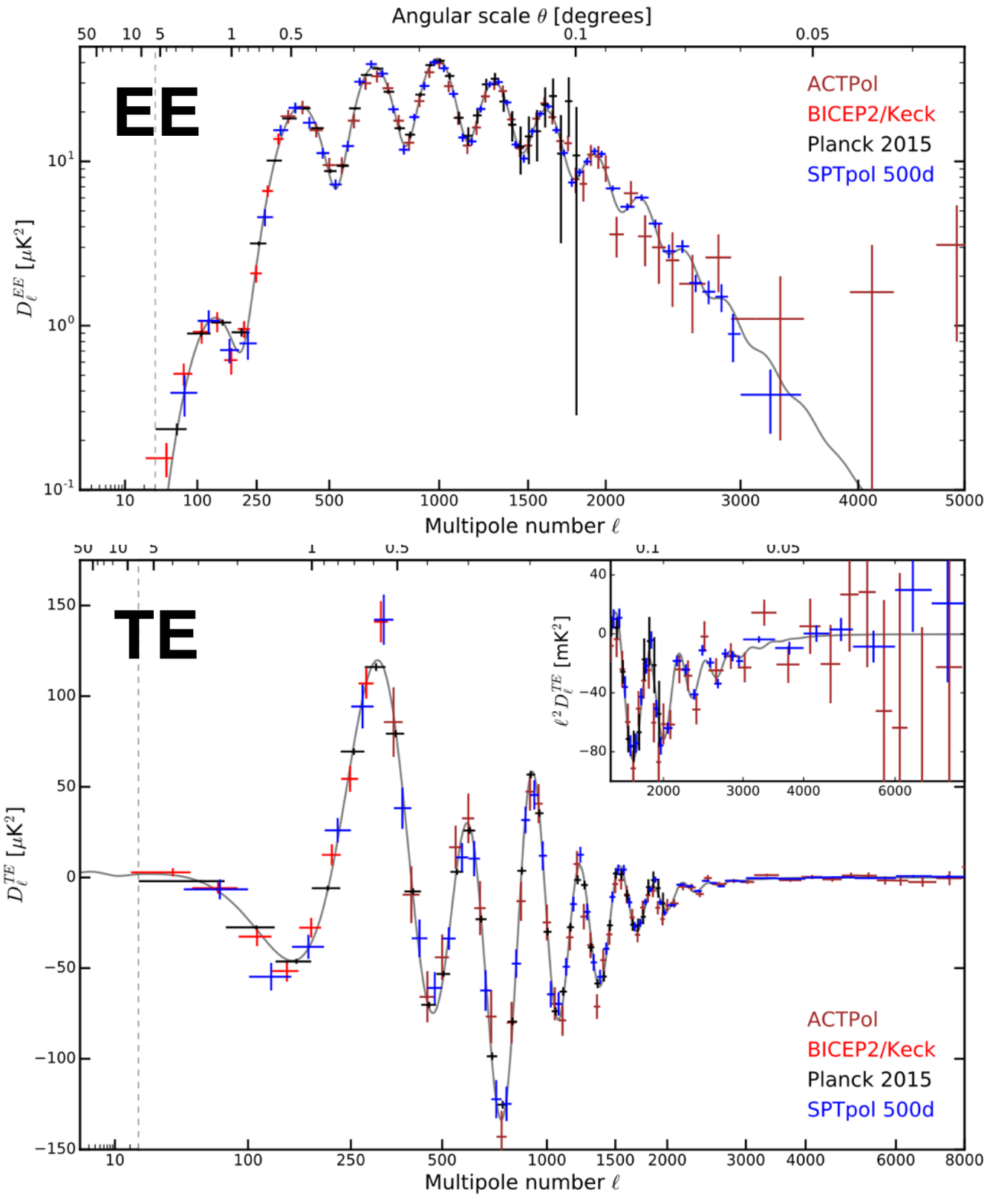
- Fundamental importance of research
- Significant advance in knowledge
- Strong connection between theory and experiment
- General interest to all physicists

This is to certify that a *Physics World* Top 10 Breakthrough of the Year has been given to

The astronomers working on the South Pole Telescope

for being the first to measure B-mode polarization in the cosmic

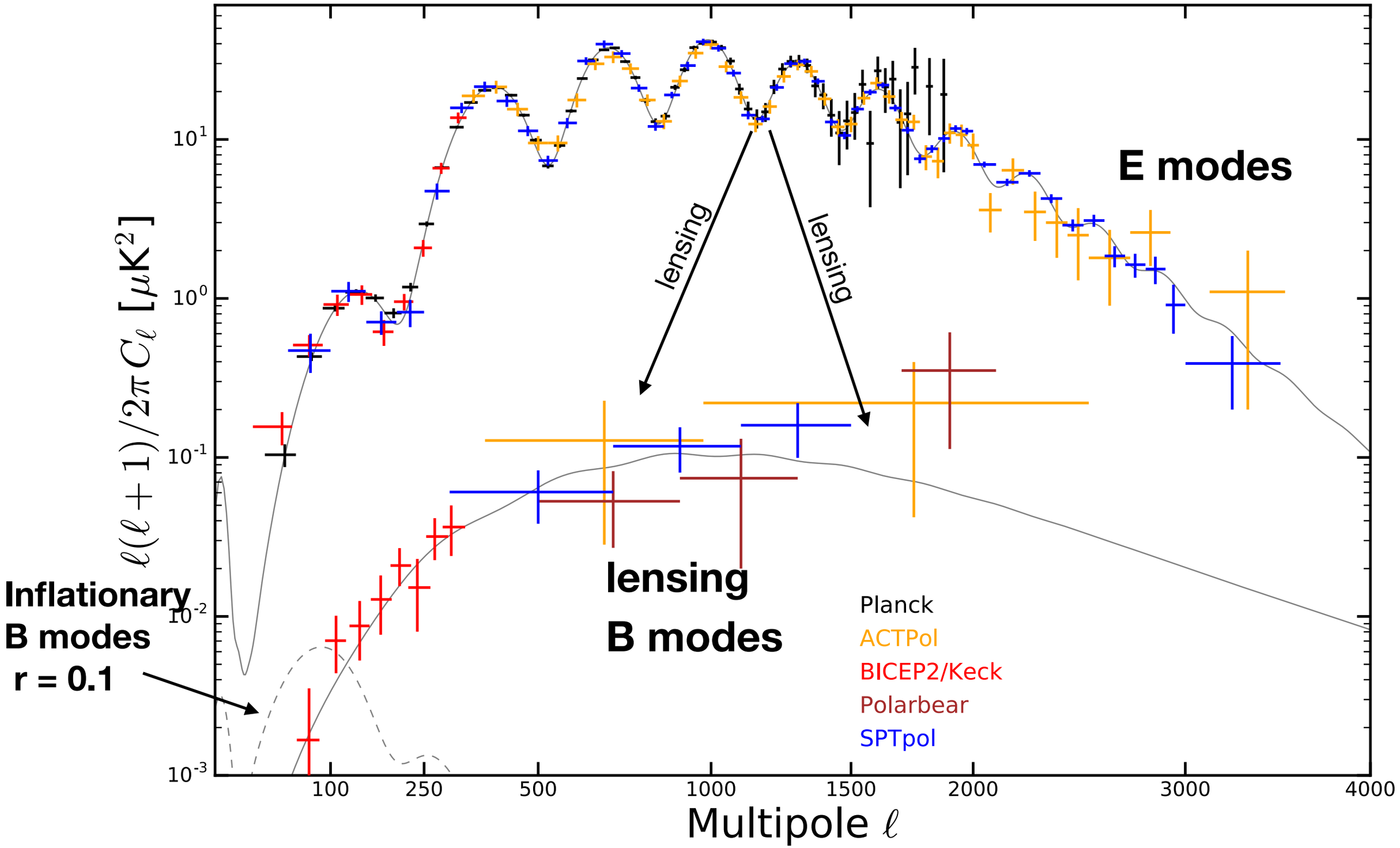
Recent SPT polarization results



- Most sensitive measurement of E-mode polarization power spectrum (EE) and temperature-E-mode correlation spectrum (TE) at multipoles l ≳ 1000.
- Similar behavior of cosmological parameters (esp. H0) with multipole, similar to those seen in Aylor et al. SPT-Planck comparison.

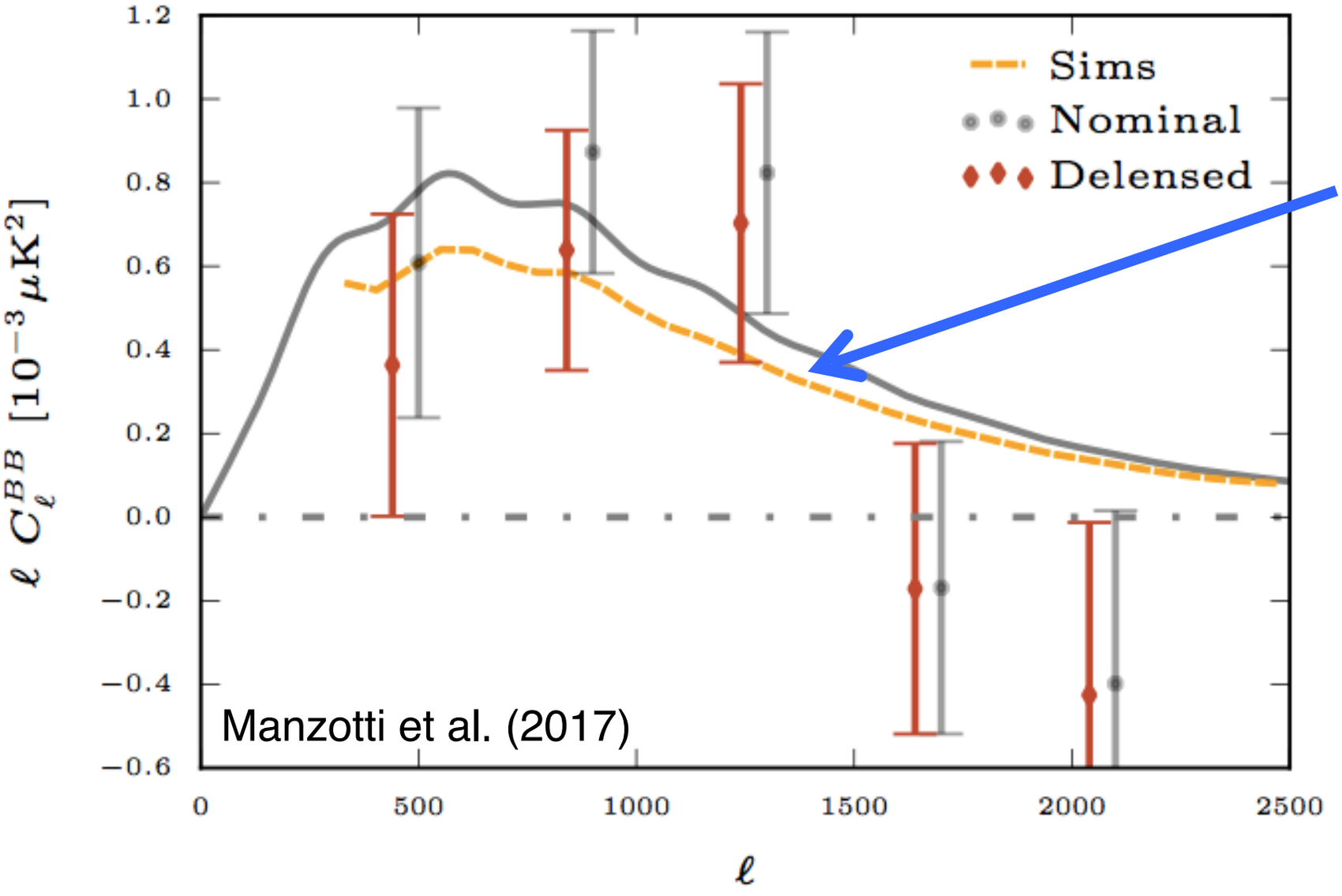
Henning et al. arXiv:1707.09353

Overall status of CMB polarization measurements



Rapid progress. All within last few years.

Recent SPT results: de-lensing



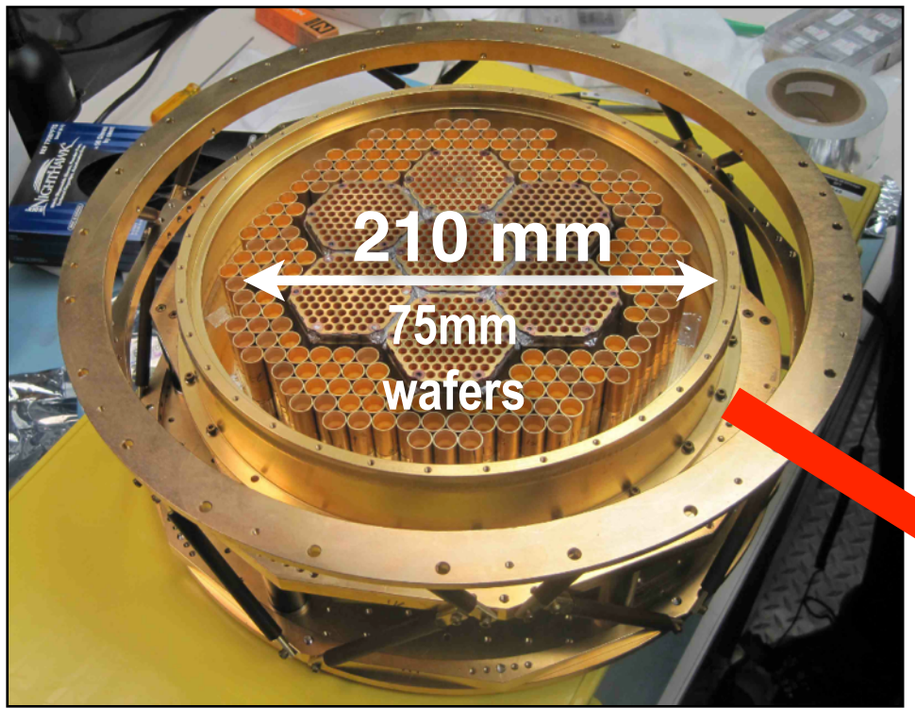
Demonstration of delensing on high-S/N B-mode data.

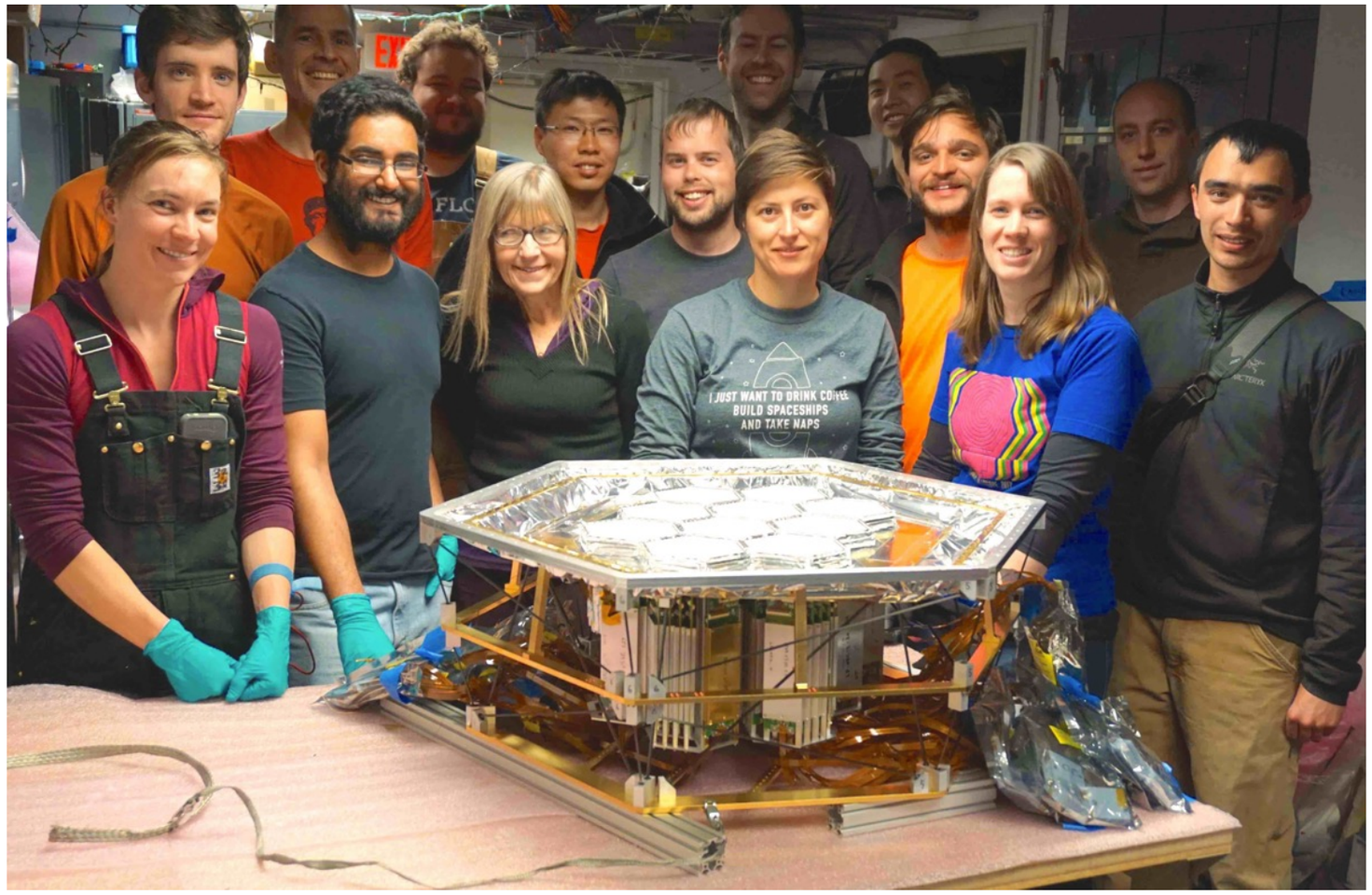
6.9σ proof of concept

- B modes from gravitationally lensed E modes: Largest foreground that can't be spectrally separated from IGW signal.
- Solution: use measured E modes and estimate of gravitational potential to create estimate of lensed B modes, subtract from IGW signal: "delensing"

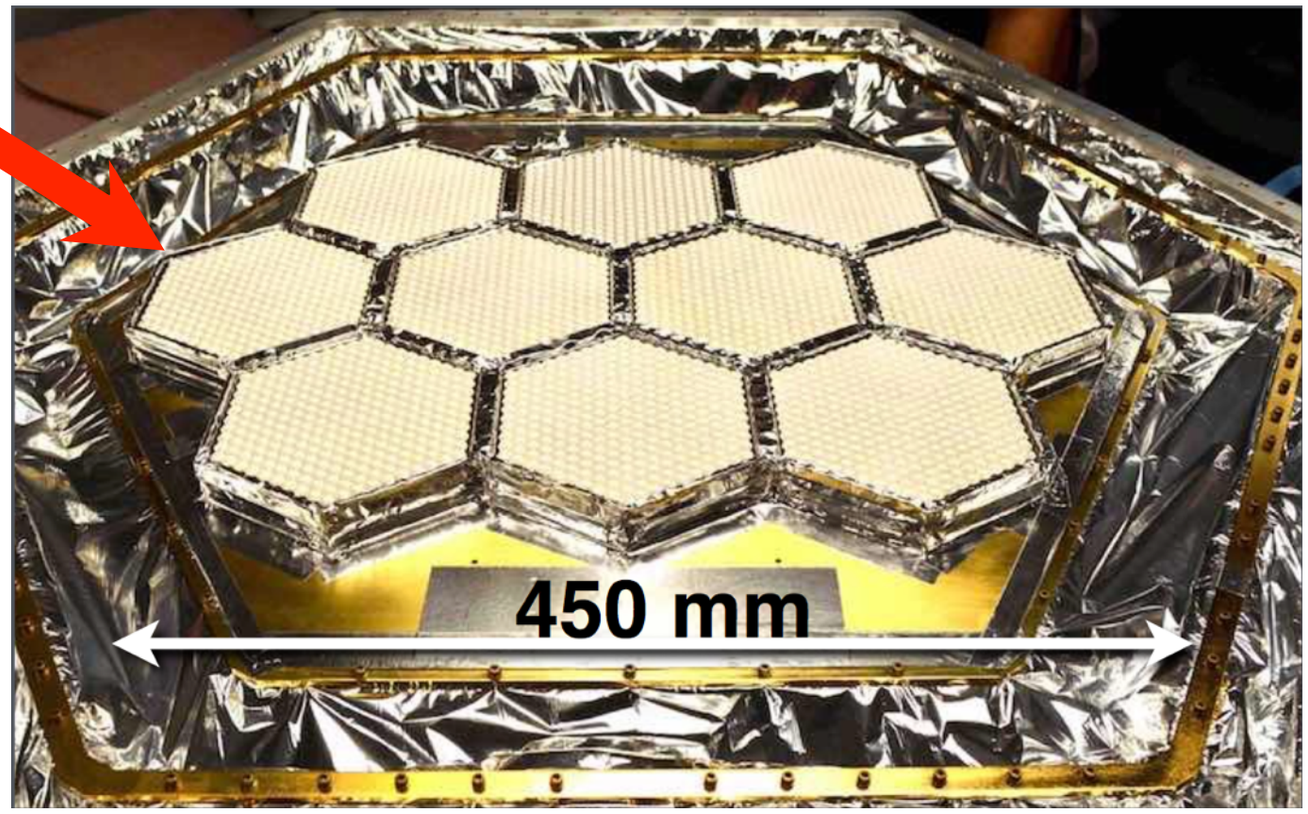
SPTpol → SPT-3G

2012: SPTpol Stage 2
1600 detectors (ANL/NIST)

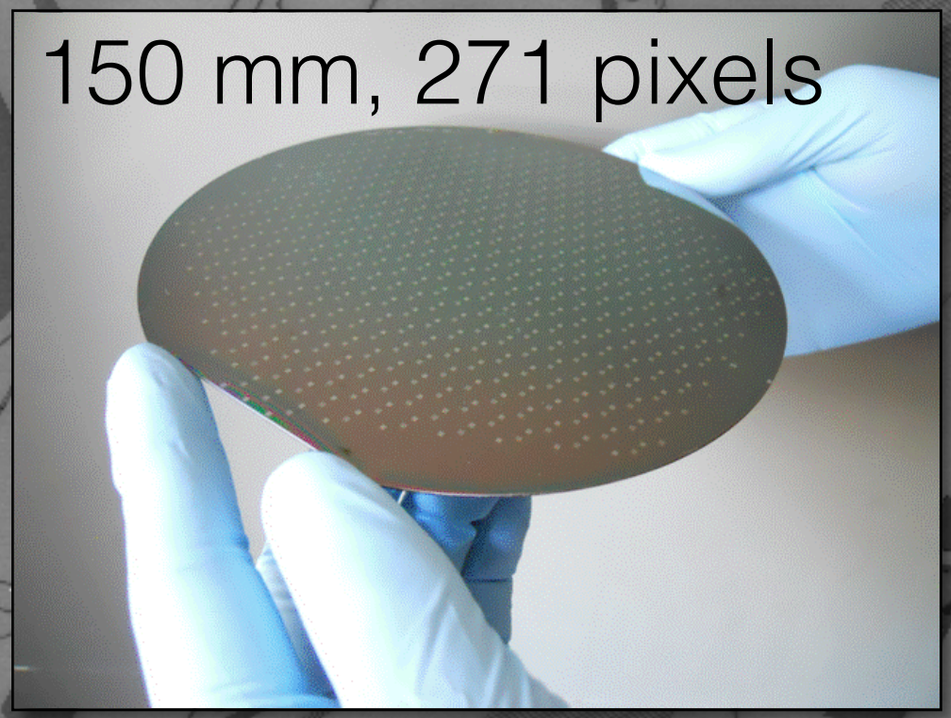




2017: SPT-3G Stage 3 4x larger area
16,000 detectors at T = 250mK



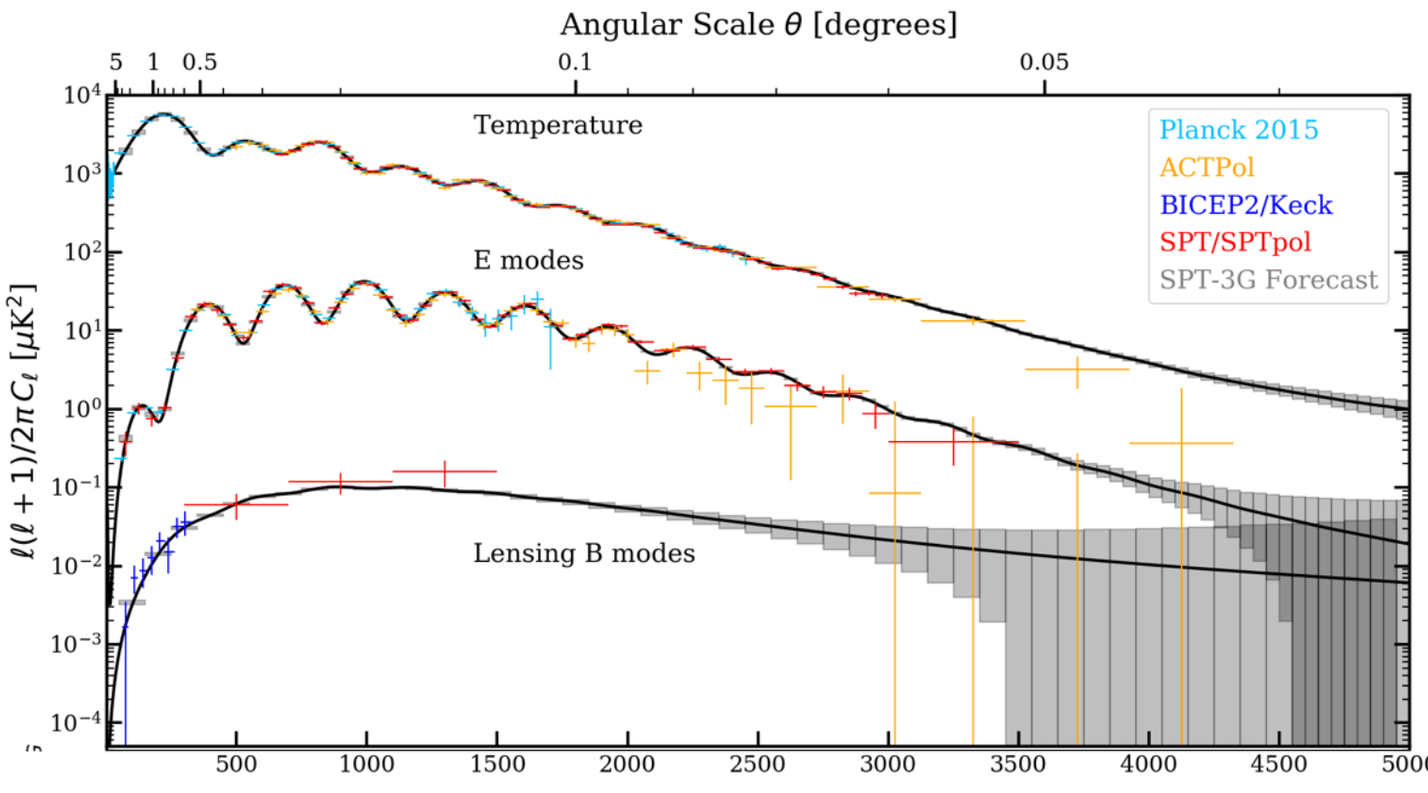
NSF U.S. DEPARTMENT OF ENERGY KAVLI GORDON AND BETTY MOORE FOUNDATION

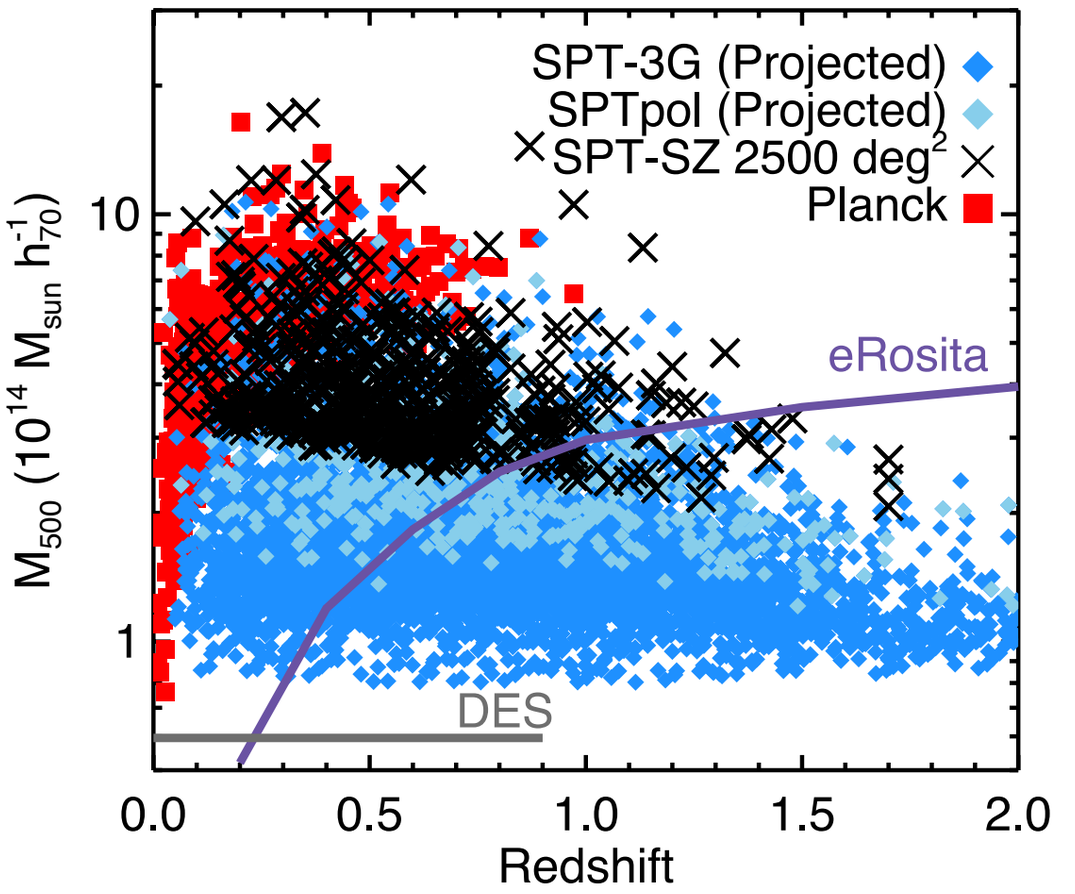


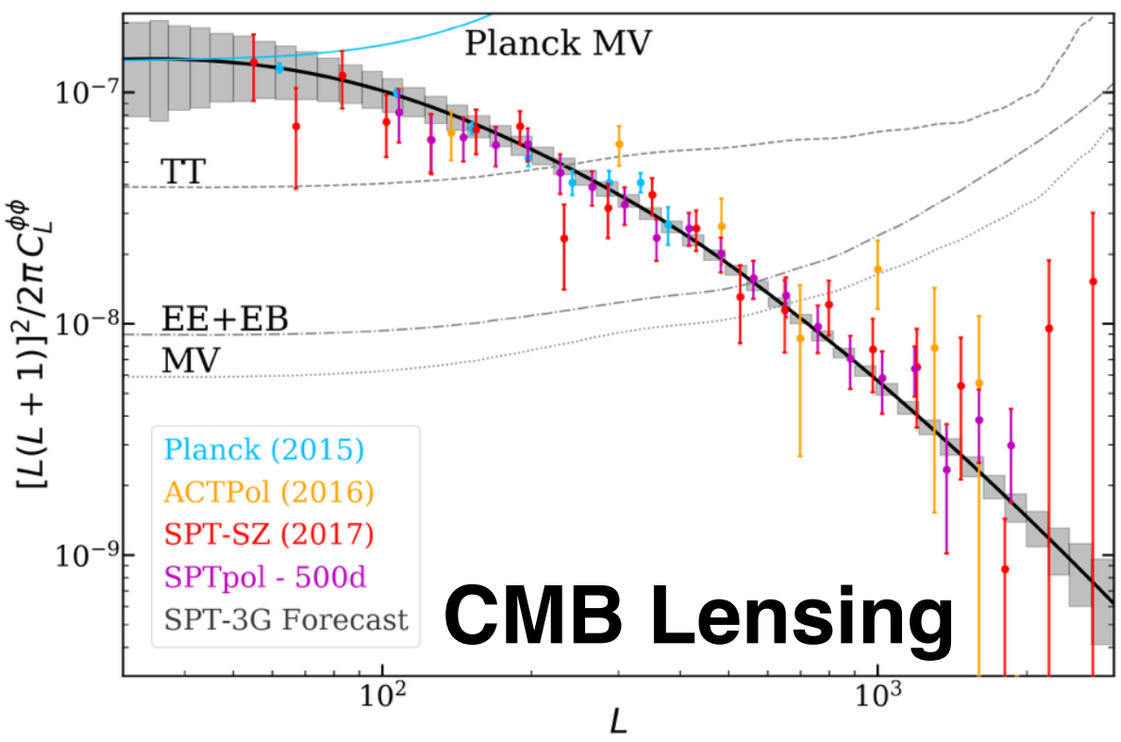
3-color, dual polarization, pixel

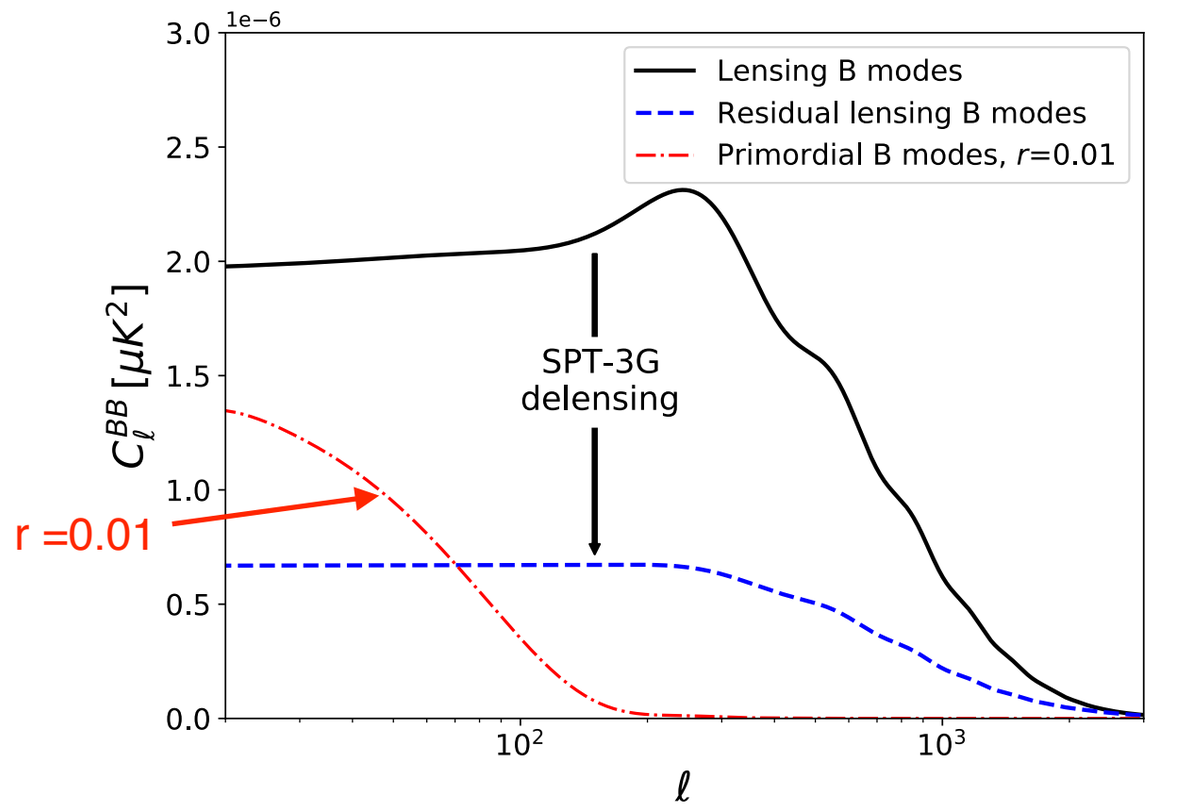
Based on UCB design O'Brient R et al 2013 Appl. Phys. Lett. 102 063506 & Suzuki et al 2014 J. Low Temp. Phys. 176 650

SPT-3G will improve on all the above





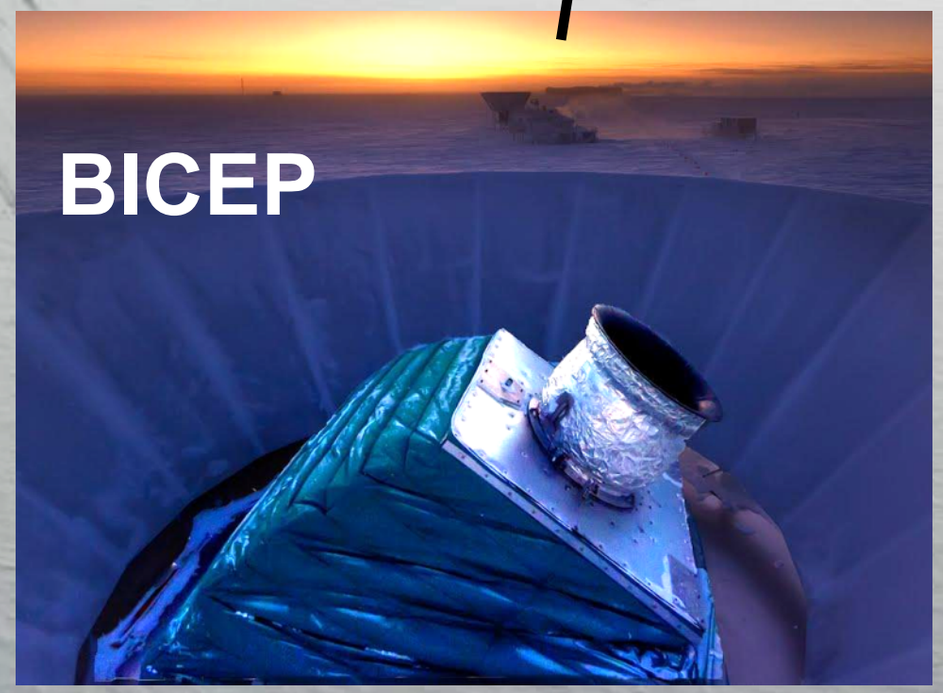




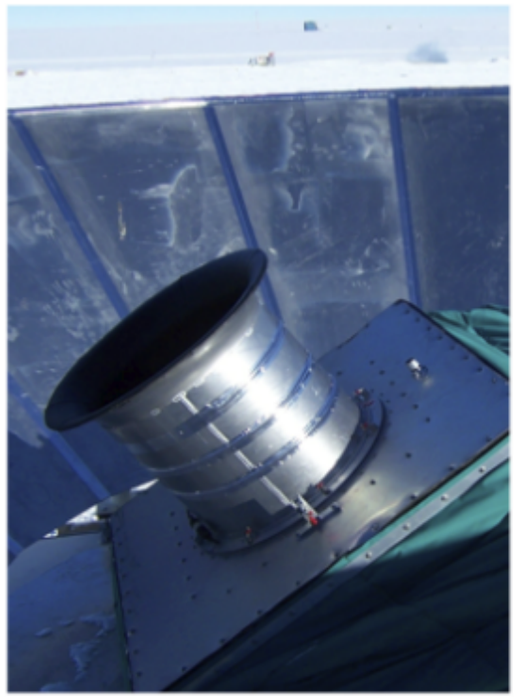
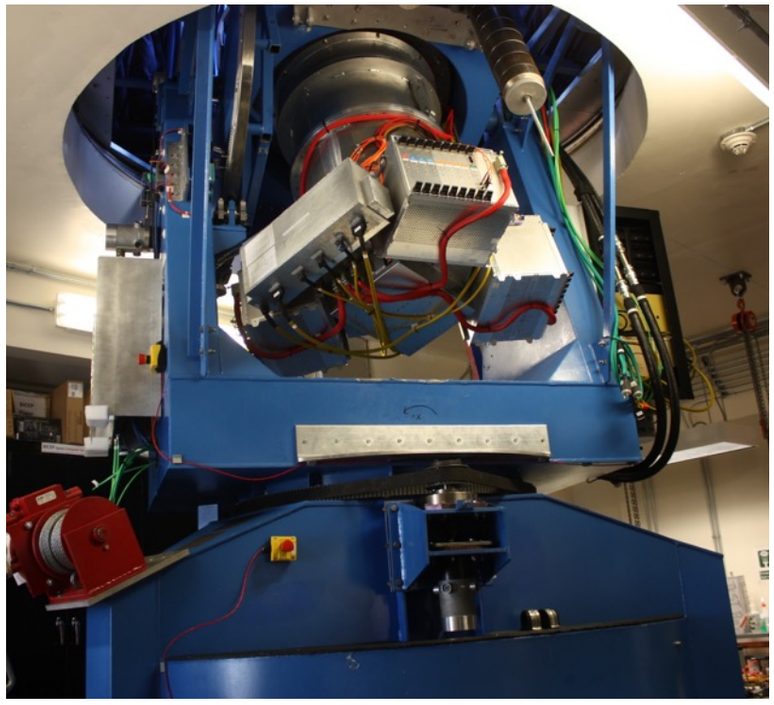
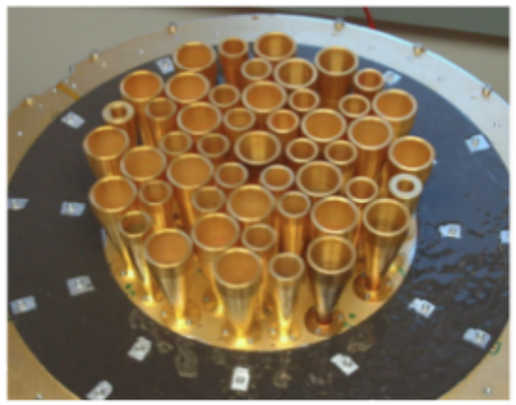
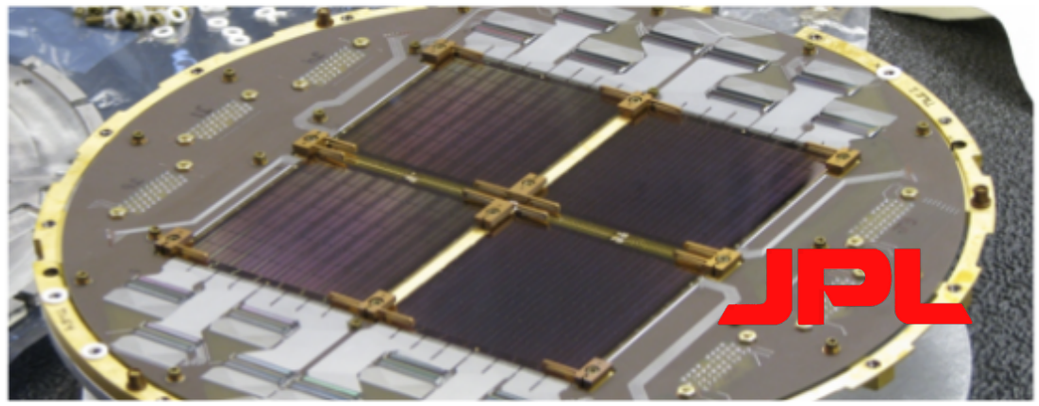
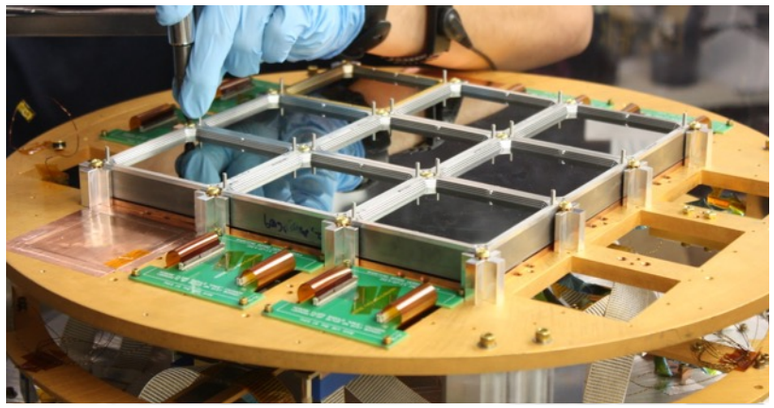
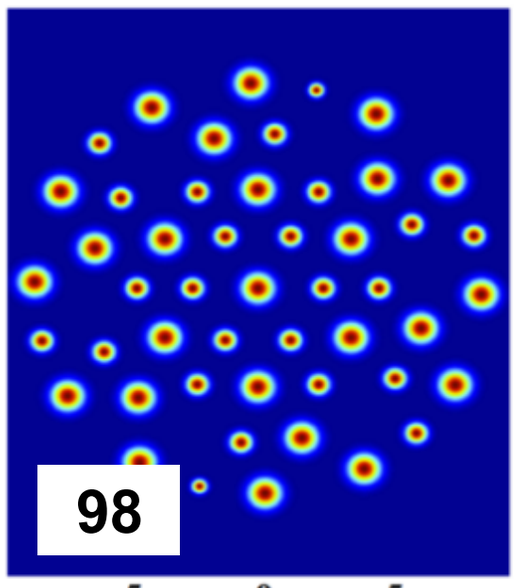
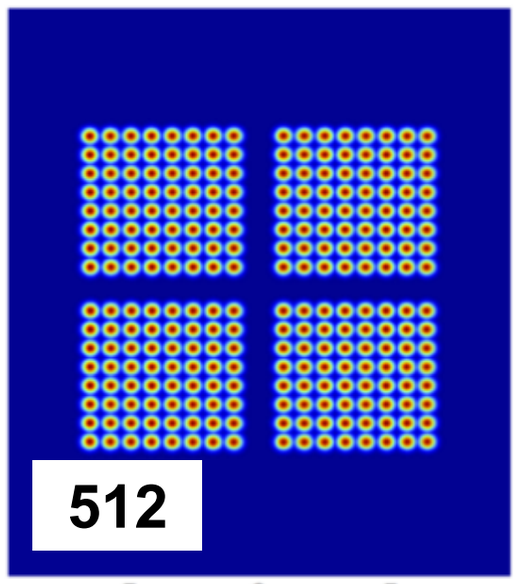
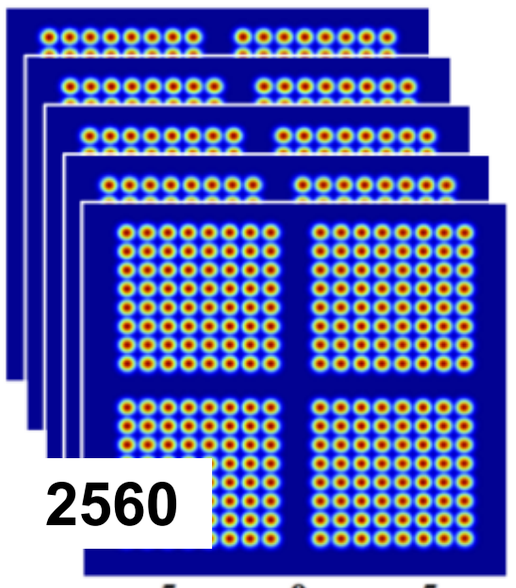
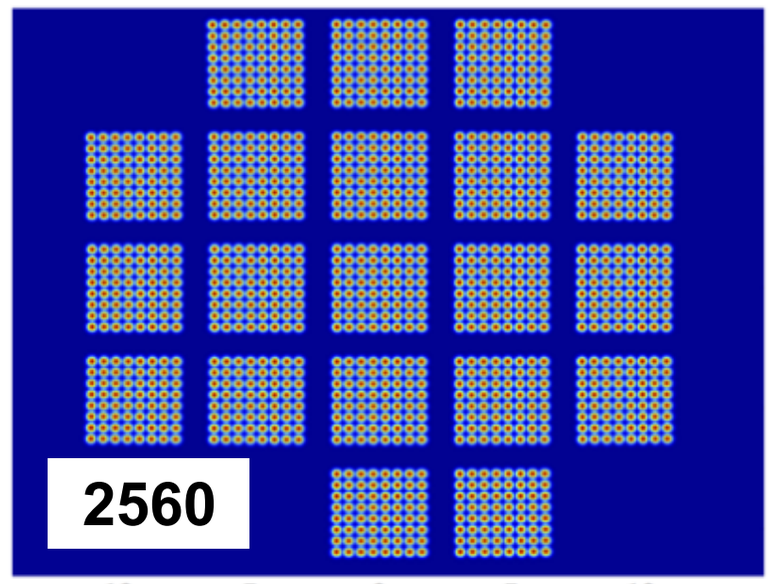
BICEP / Keck CMB Program

Using small refracting telescopes to control beam systematics.

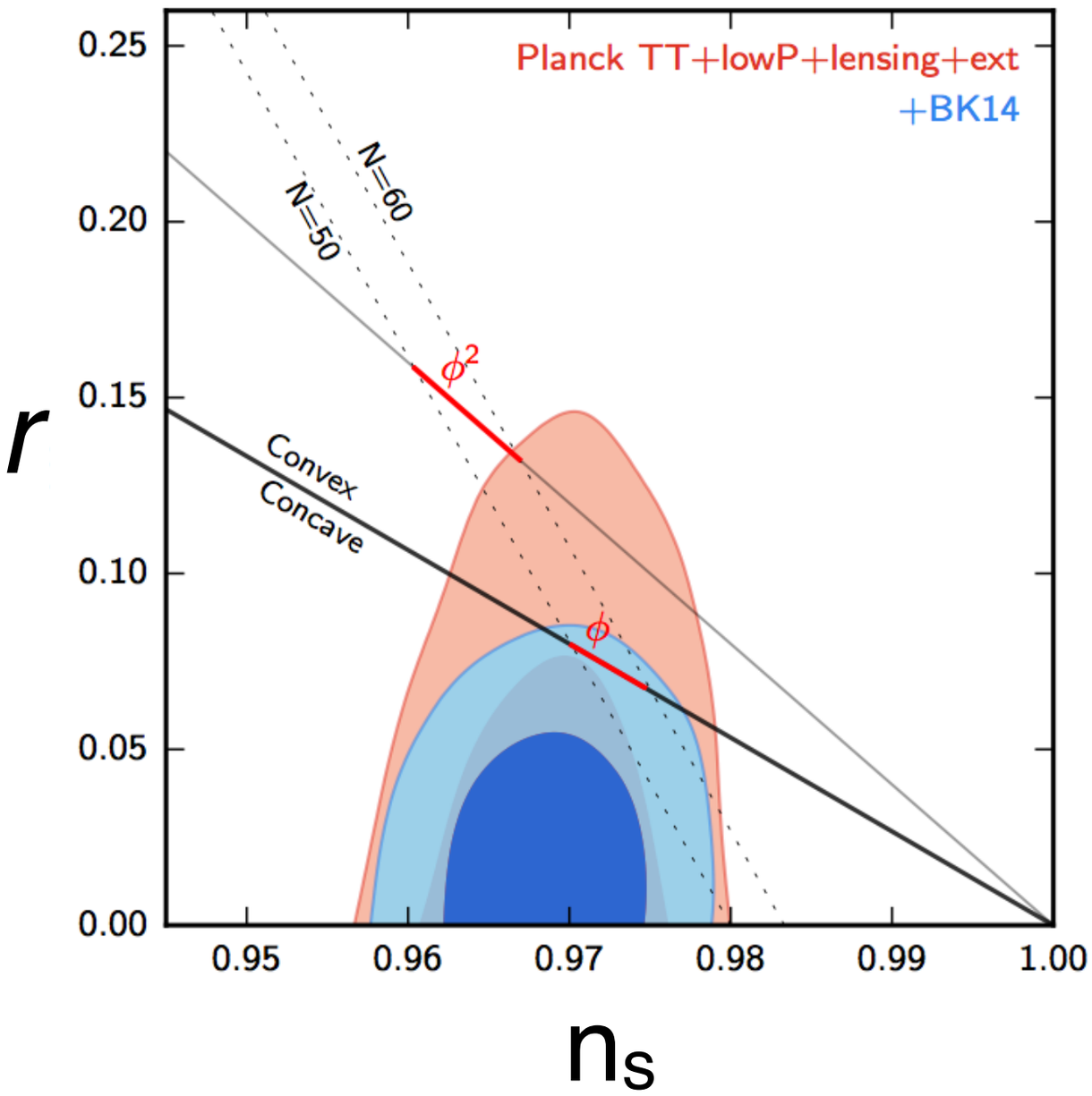
Modular frequency coverage for foregrounds mitigation.



The BICEP / Keck Collaboration

	BICEP1 (2006 - 8)	BICEP2 (2010 - 12)	Keck Array (2011 -)	BICEP3 (2015-)
Telescope and Mount				
Focal Plane				
Beams on Sky				

arXiv:1510.09217



The tensor to scalar ratio, r, is now constrained by B-mode polarization measurements

BICEP/Keck & Planck result:

$r < 0.07$ at 95% C.L.

Raw sensitivity σ(r) = 0.006

→ *limited by foreground component separation and soon by gravitational lensing distortions of the CMB*

SPT + BICEP is prototype of the CMB-S4 concept to use small (degree resolution) and large (arc minute resolution) telescopes for B-mode + de-lensing

10m South Pole Telescope
SPT-3G: 16,400 detectors
95, 150, 220 GHz

BICEP3
2560 detectors
95 GHz

Keck Array
2500 detectors
150 & 220 GHz

Upgrading to BICEP Array:
30,000 detectors
30/40, 95, 150, 220, 270 GHz

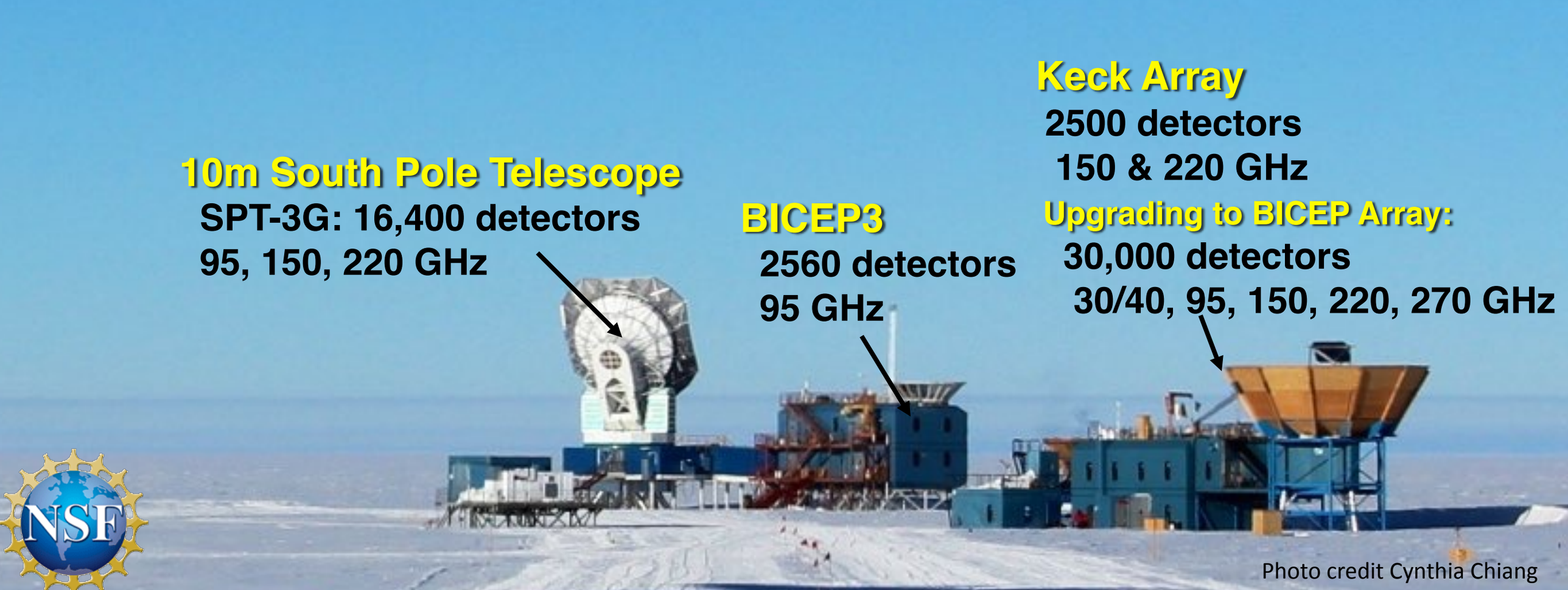
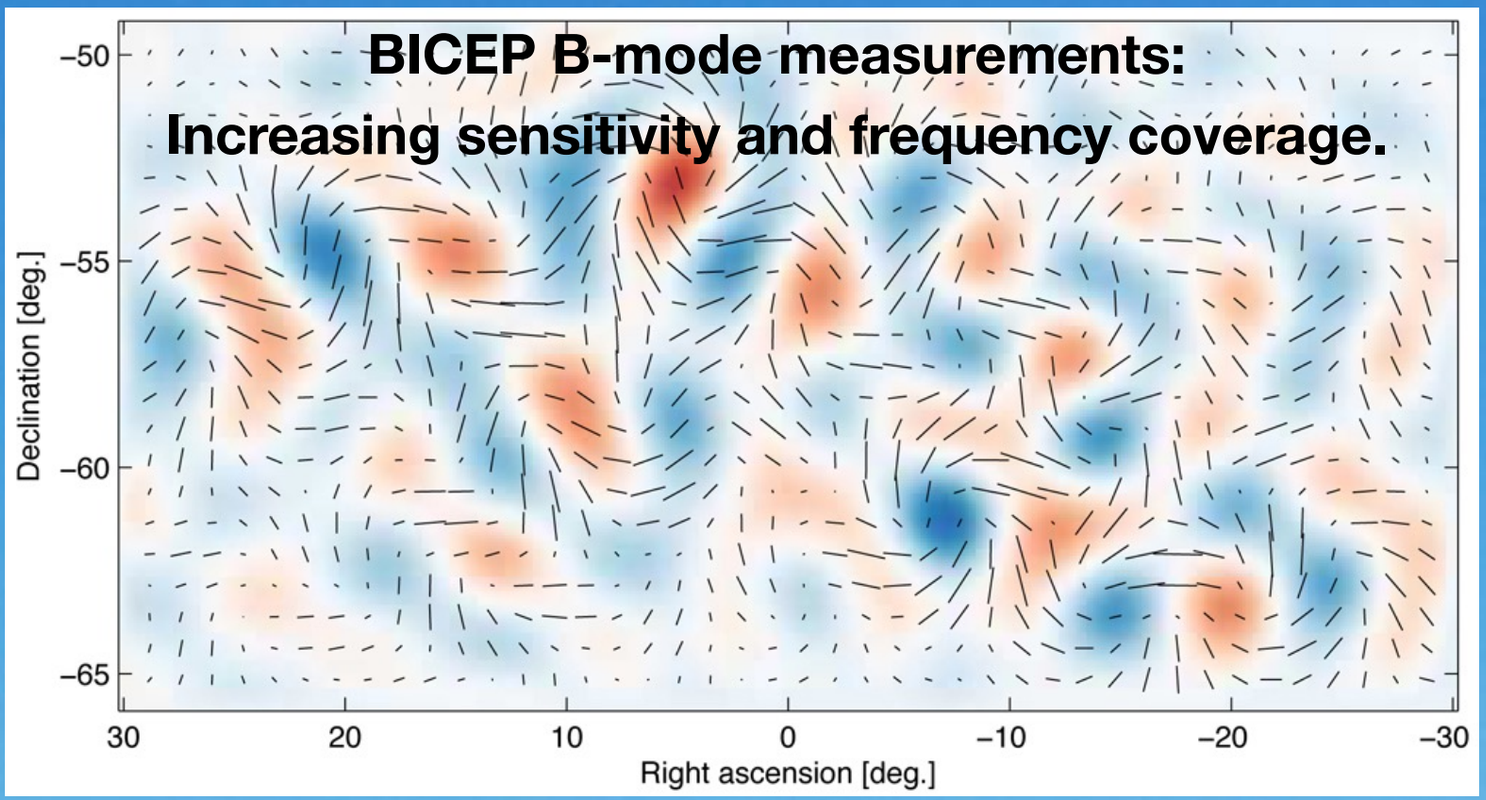


Photo credit Cynthia Chiang

BICEP B-mode measurements:
Increasing sensitivity and frequency coverage.



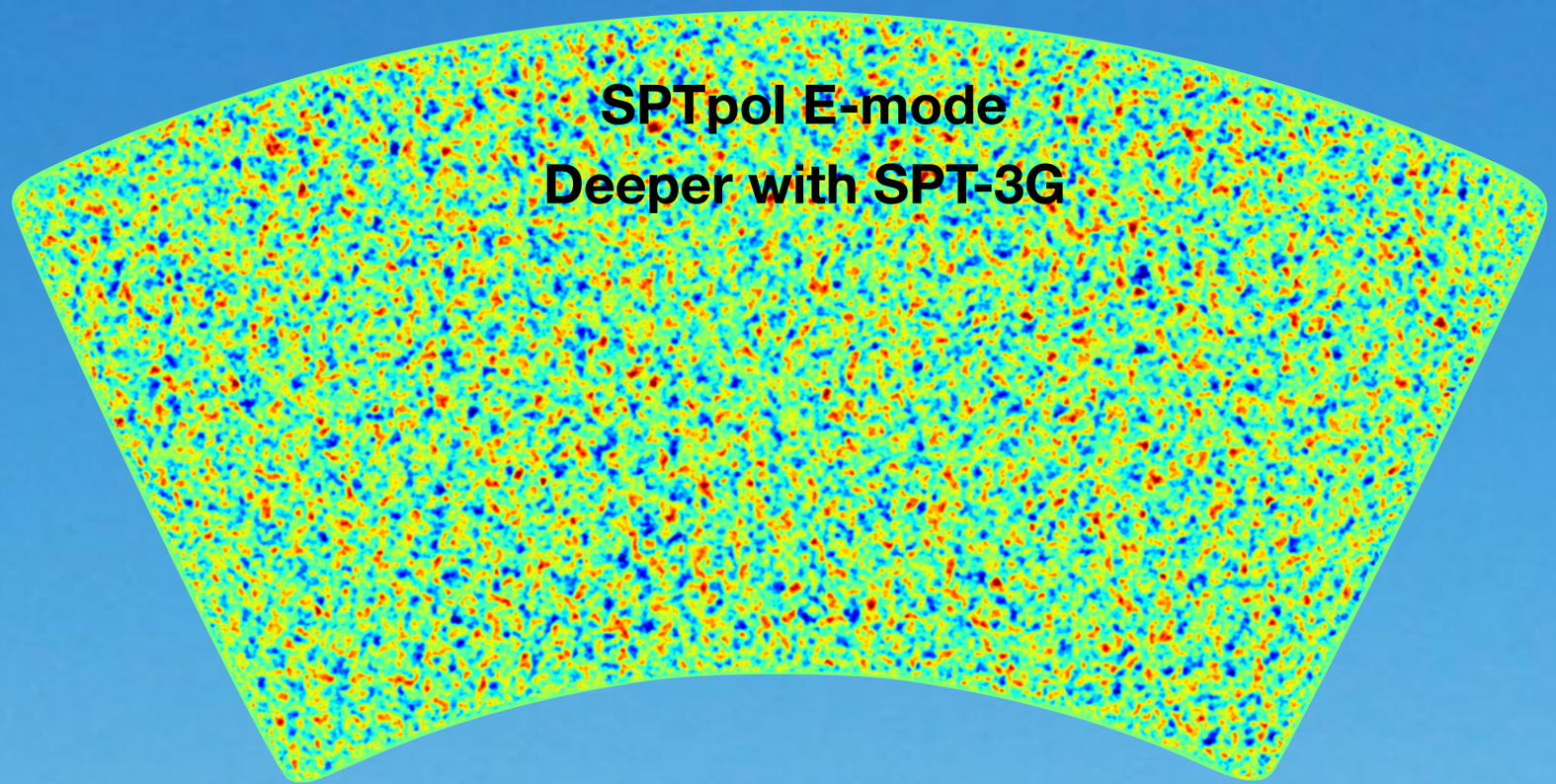
10m South Pole Telescope
SPT-3G: 16,400 detectors
95, 150, 220 GHz

BICEP3
2560 detectors
95 GHz

Keck Array
2500 detectors
150 & 220 GHz

Upgrading to BICEP Array:
30,000 detectors
35, 95, 150, 220, 270 GHz

Photo credit Cynthia Chiang



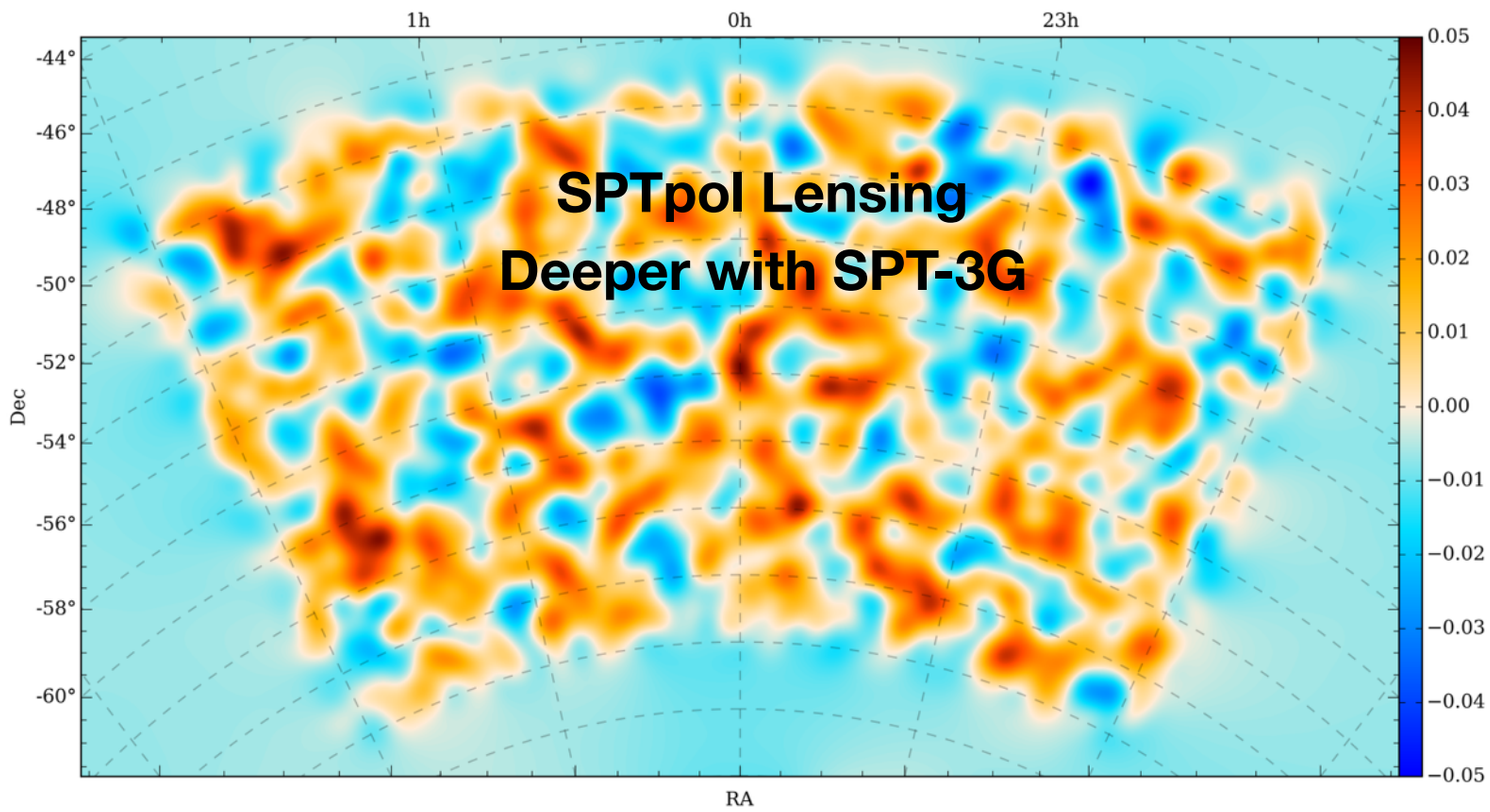
10m South Pole Telescope
SPT-3G: 16,400 detectors
95, 150, 220 GHz

BICEP3
2560 detectors
95 GHz

Keck Array
2500 detectors
150 & 220 GHz

Upgrading to BICEP Array:
30,000 detectors
35, 95, 150, 220, 270 GHz

Photo credit Cynthia Chiang



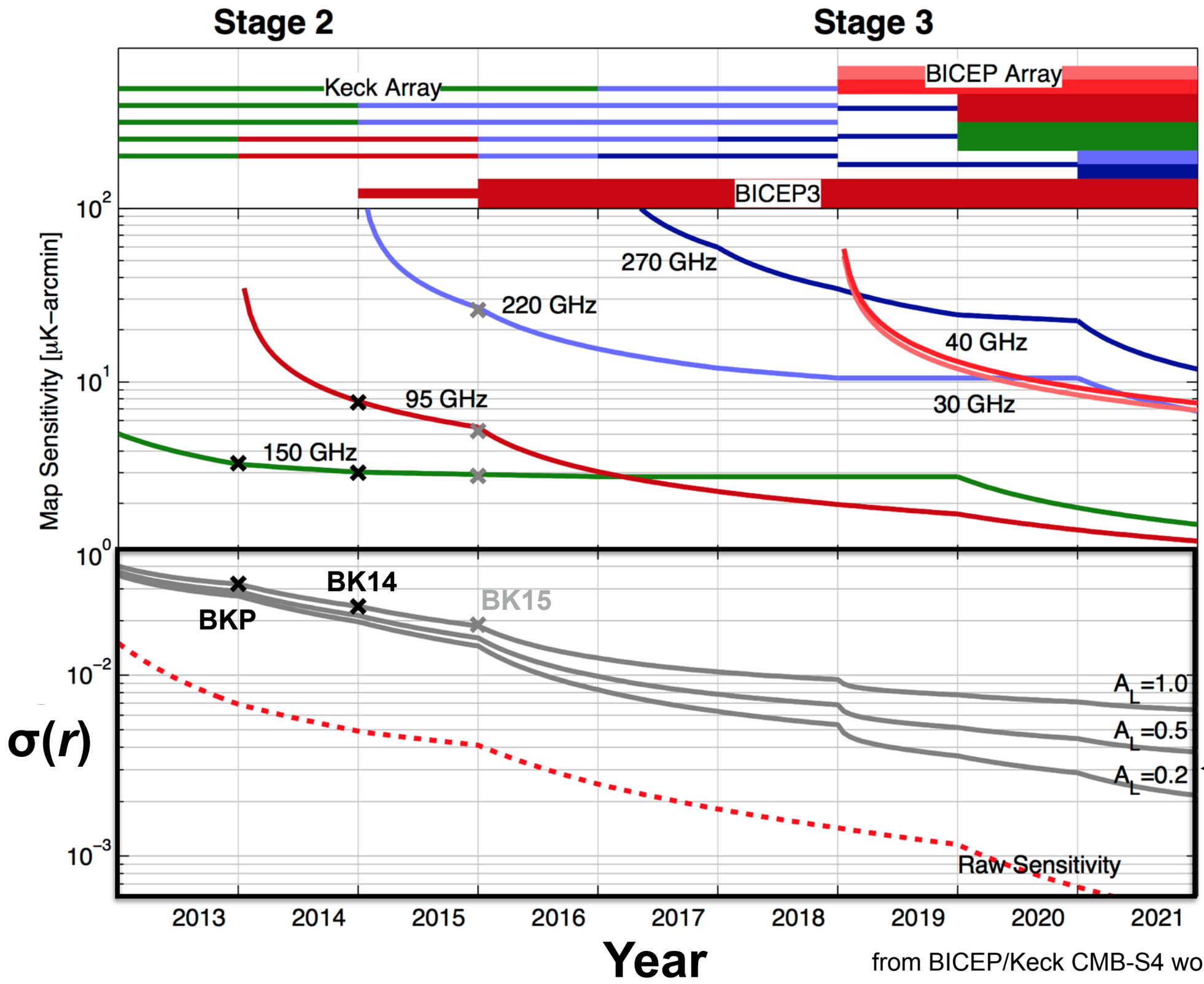
10m South Pole Telescope
SPT-3G: 16,400 detectors
95, 150, 220 GHz

BICEP3
2560 detectors
95 GHz

Keck Array
2500 detectors
150 & 220 GHz

Upgrading to BICEP Array:
30,000 detectors
35, 95, 150, 220, 270 GHz

Photo credit Cynthia Chiang



with SPT-3G de-lensing **σ(r)~0.003**

from BICEP/Keck CMB-S4 workshop

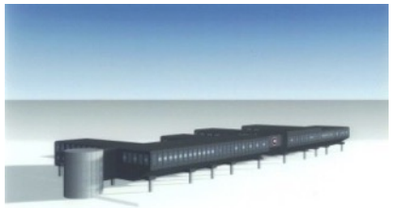
Photo credit Cynthia Chiang

Why Does South Pole work so well for CMB?

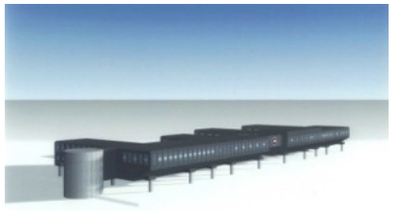
- **<u>Extremely dry *& stable* atmosphere</u>**.
- High altitude ~ 10,500 feet.
- Sun below horizon for 6 months.
- Unique geographical location:
  Relentless observing through low-foreground path of Galaxy 24/7, actually 24/7/52
- Excellent support from National Science Foundation research station
- Steady investment by NSF in South Pole CMB

→ ***Best developed ground based site for ultra-sensitive CMB measurements***

[1]South Pole sky noise power is much less than Atacama at mm-wavelengths.
Bussmann et al. ApJ 622 1343 (2005); Lay & Halverson ApJ 543, 787 (2000), Kuo arXiv 1707.08400



Amundsen-Scott South Pole Research Station



Station Features

Kitchen

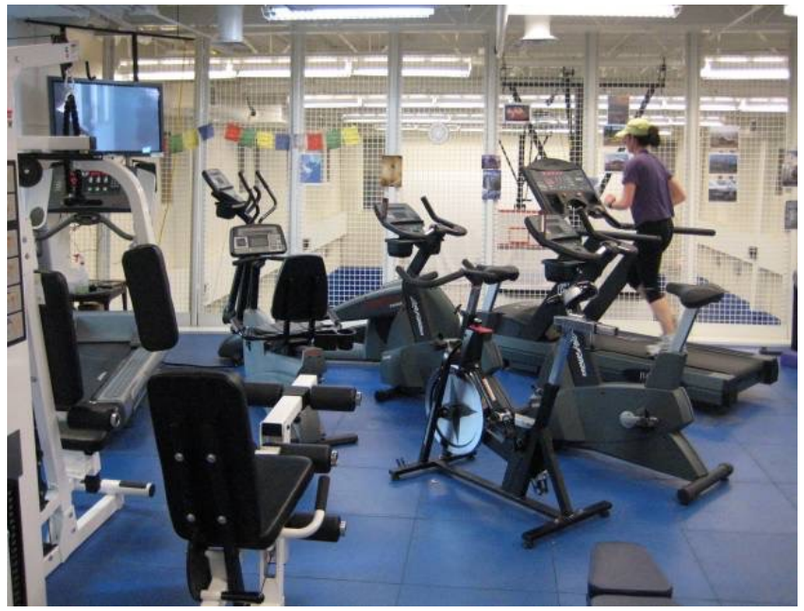
Communications

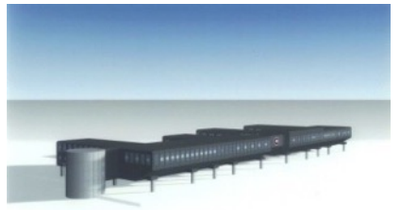
Berthing

Dining Area

Medical

Recreation



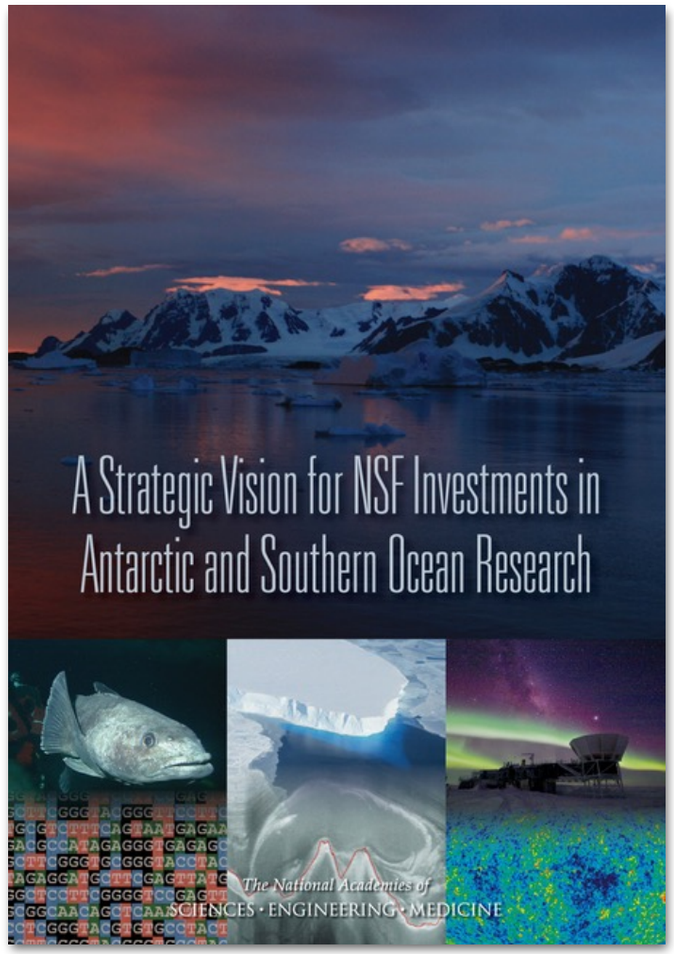


Power Plant

1 Megawatt Power Capacity

Summary

- Strong program of CMB measurements with SPT-3G and BICEP Array through 2021
- SPT & BICEP collaborations working together on gravitational wave B-mode search with de-lensing, discussing broader collaboration.
- SPT open to expanding science collaboration
- Now is time to plan (start!) next phase at South Pole:
  - Partner to install high throughput large telescope and/or more BICEP-like telescopes, which later become part of CMB-S4?
  - Establish “South Pole CMB Observatory,” with additional partners?



NAS/NRC report (2015) recommended CMB as one of 3 strategic priorities, specifically called out role of South Pole in CMB-S4.