CMB at the South Pole

John Carlstrom

South Pole CMB efforts started in 1980's

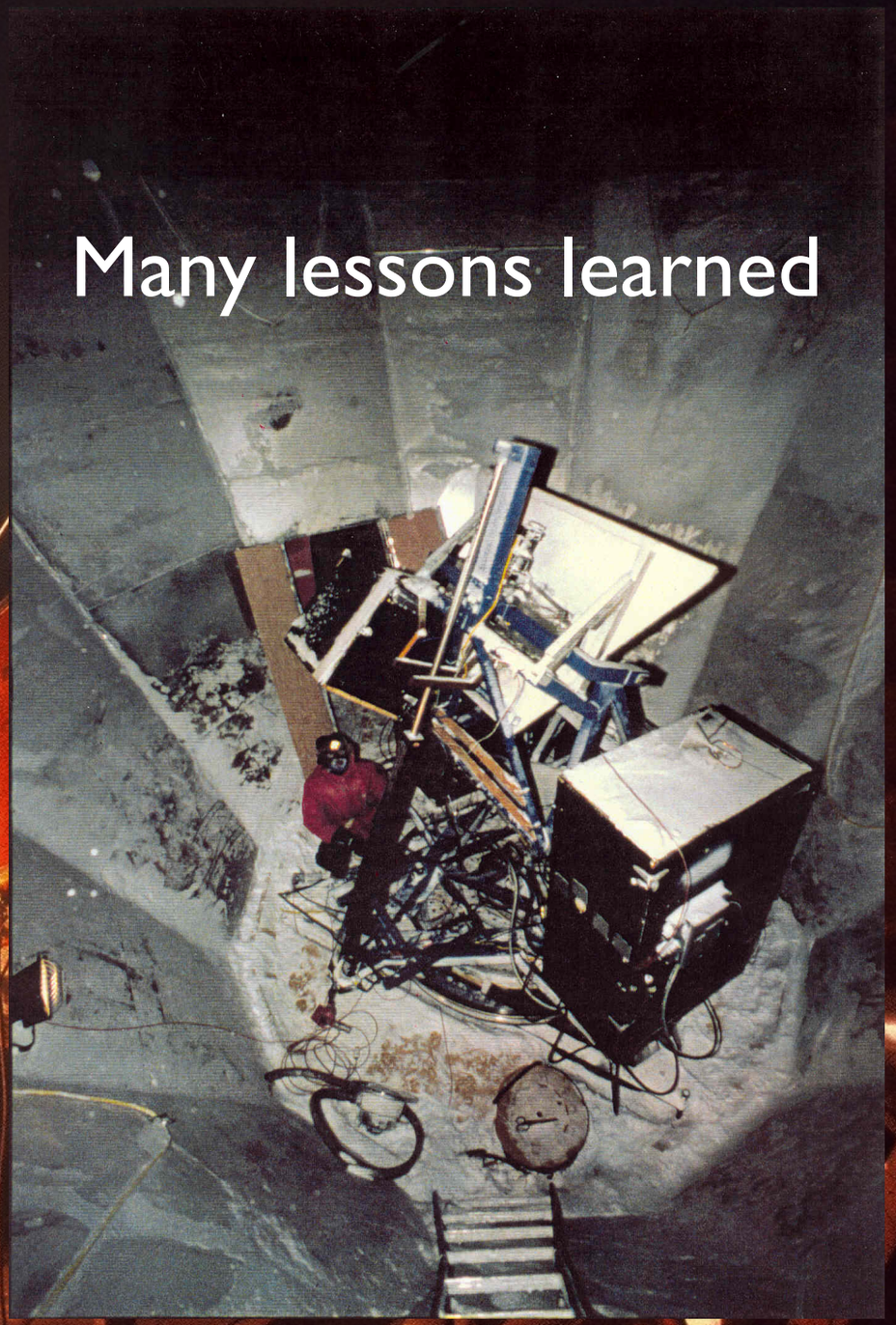
Python CMB Telescope

1994 Winter-over
John Kovac

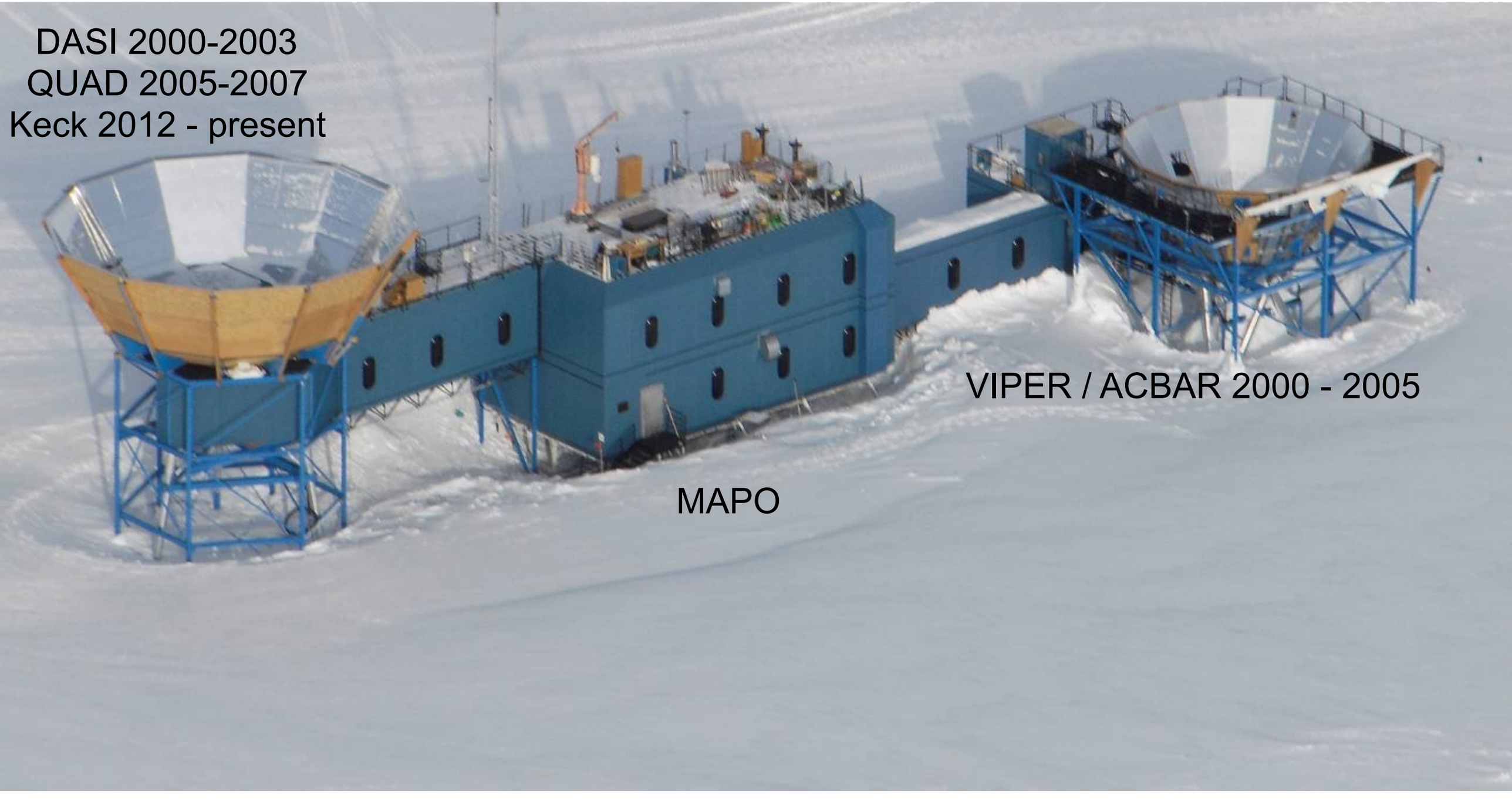
South Pole CMB efforts started in 1980's

1994 Winter-over
John Kovac

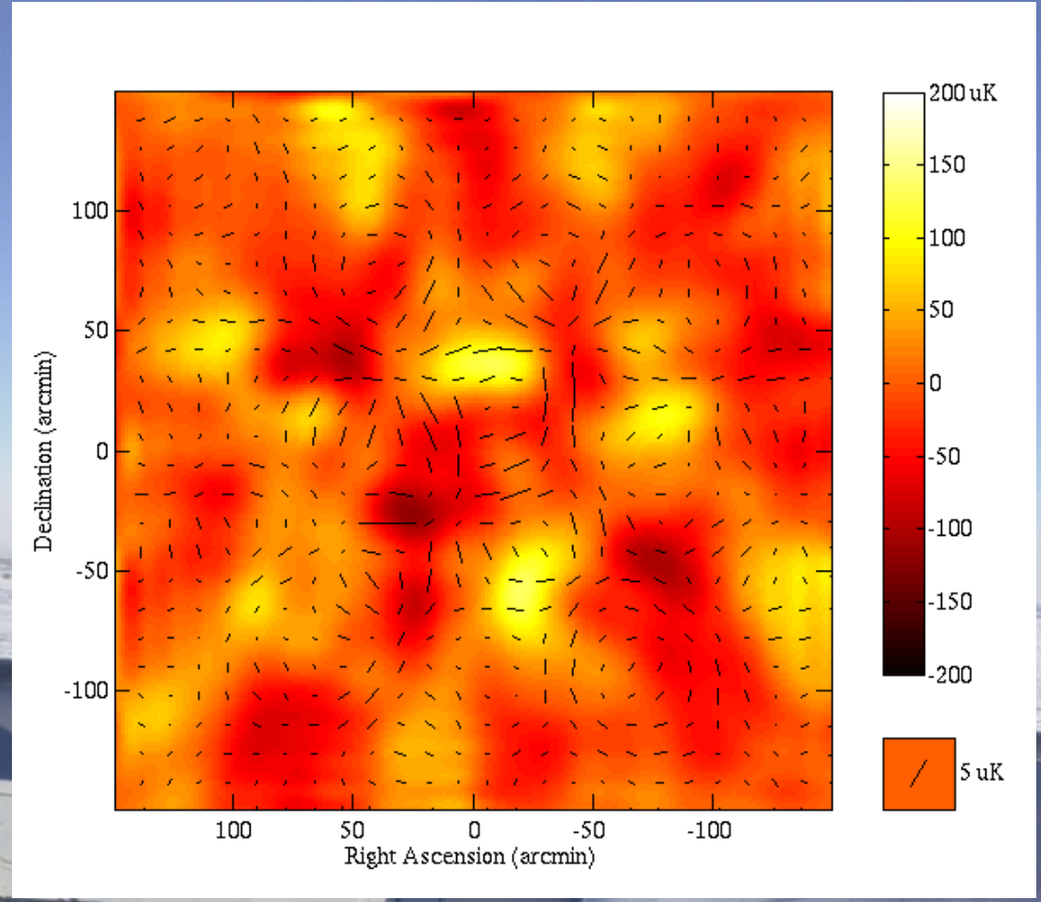
Many lessons learned



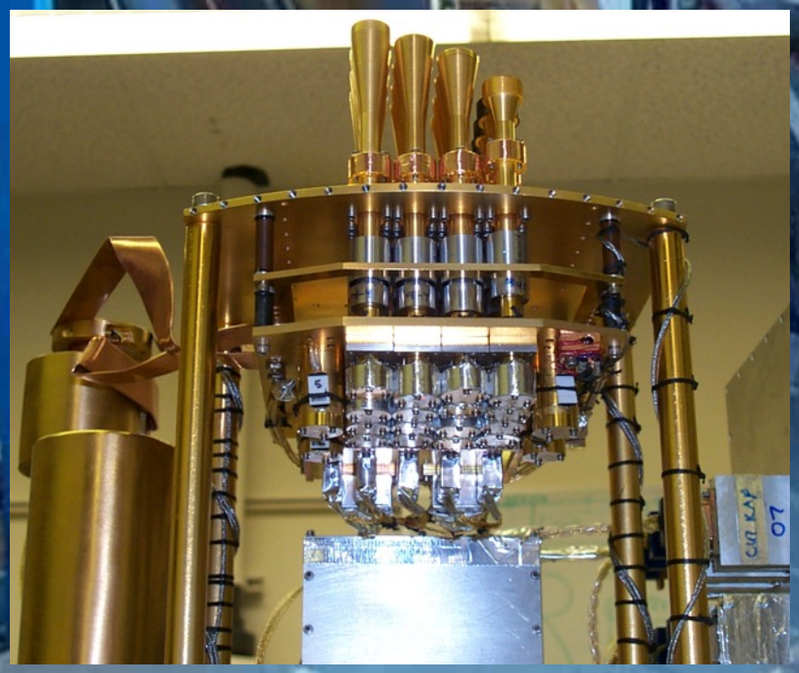
Martin A. Pomerantz Observatory (MAPO)



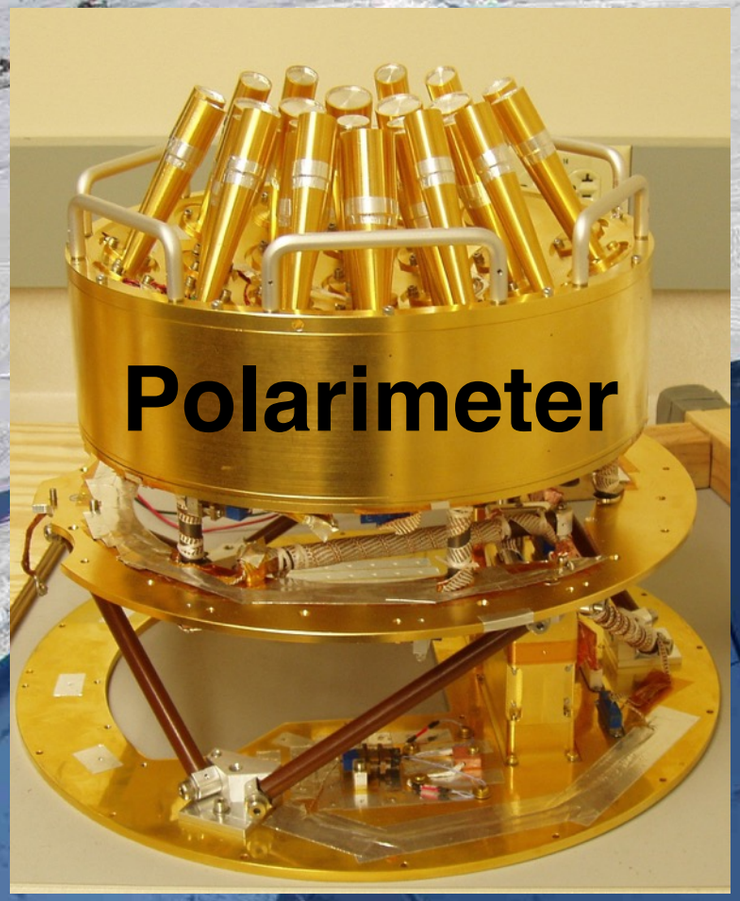
CMB polarization first detected in 2002, at South Pole

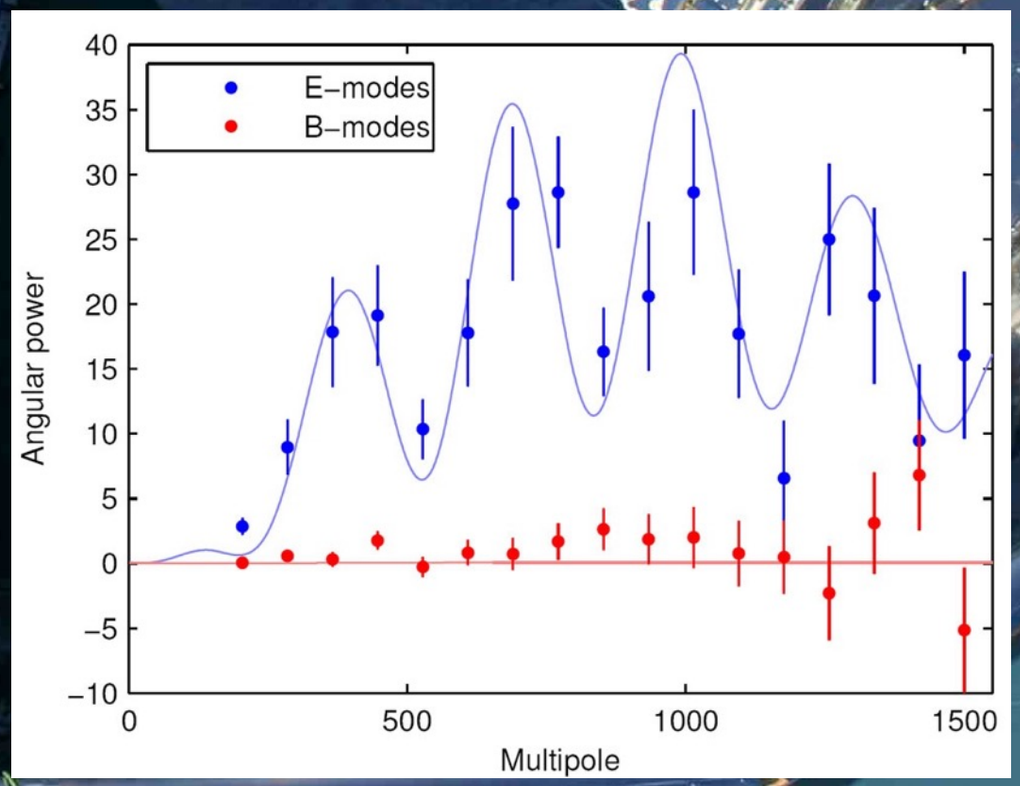


ACBAR

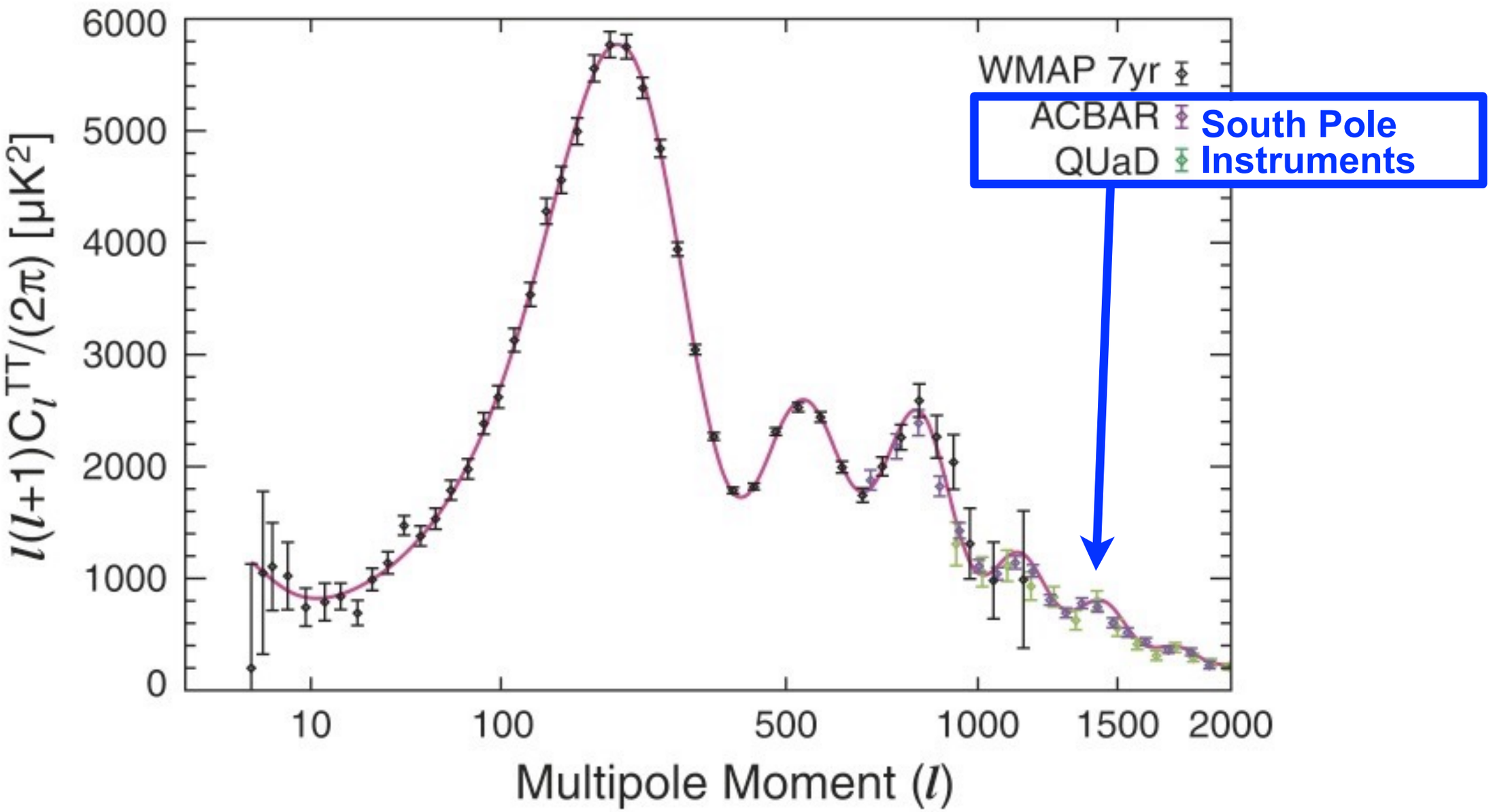


QUaD - an example of a 50/50 split US-European Collaboration





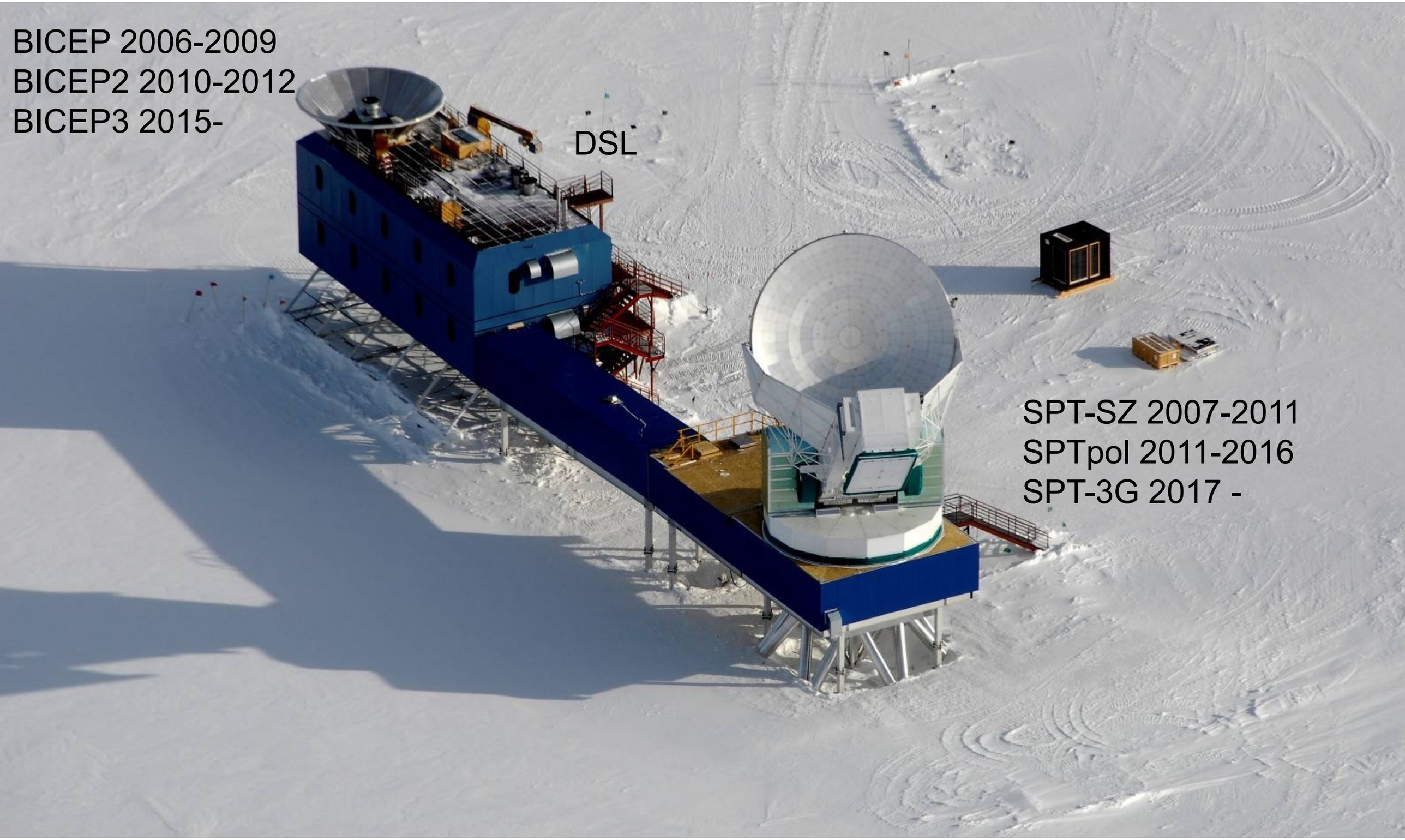
WMAP ext



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)



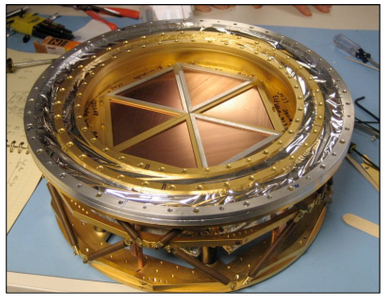
The South Pole Telescope (SPT)

10-meter
submm wave telescope

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

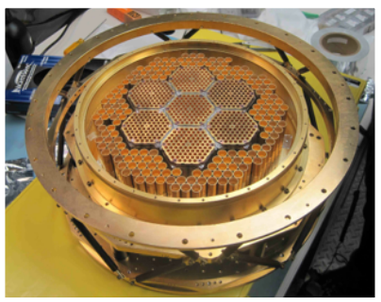
2007: SPT-SZ

960 detectors (UCB)
100,150,220 GHz



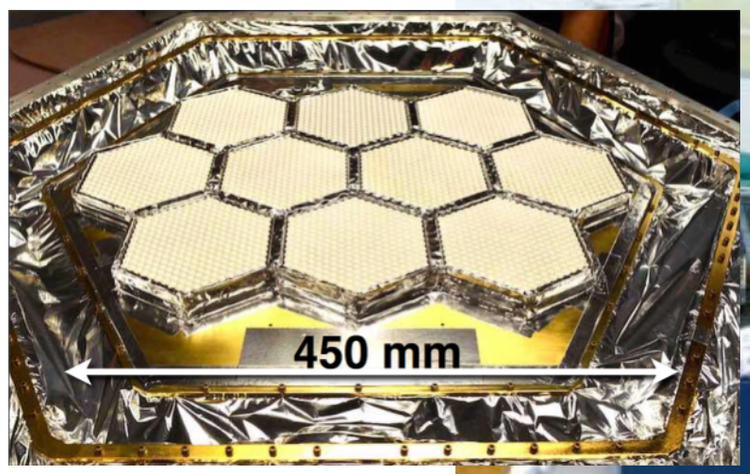
2012: SPTpol

1600 detectors
100,150 GHz
+Polarization



2016: 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

UCDAVIS
UNIVERSITY OF CALIFORNIA

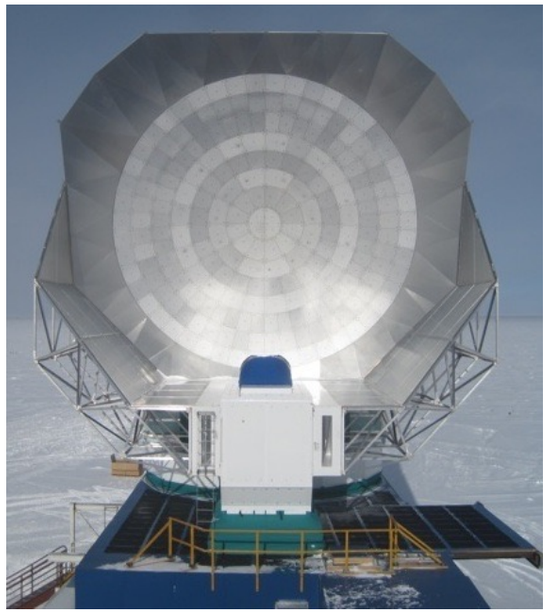
Fermilab

KAVLI

GORDON AND BETTY MOORE FOUNDATION

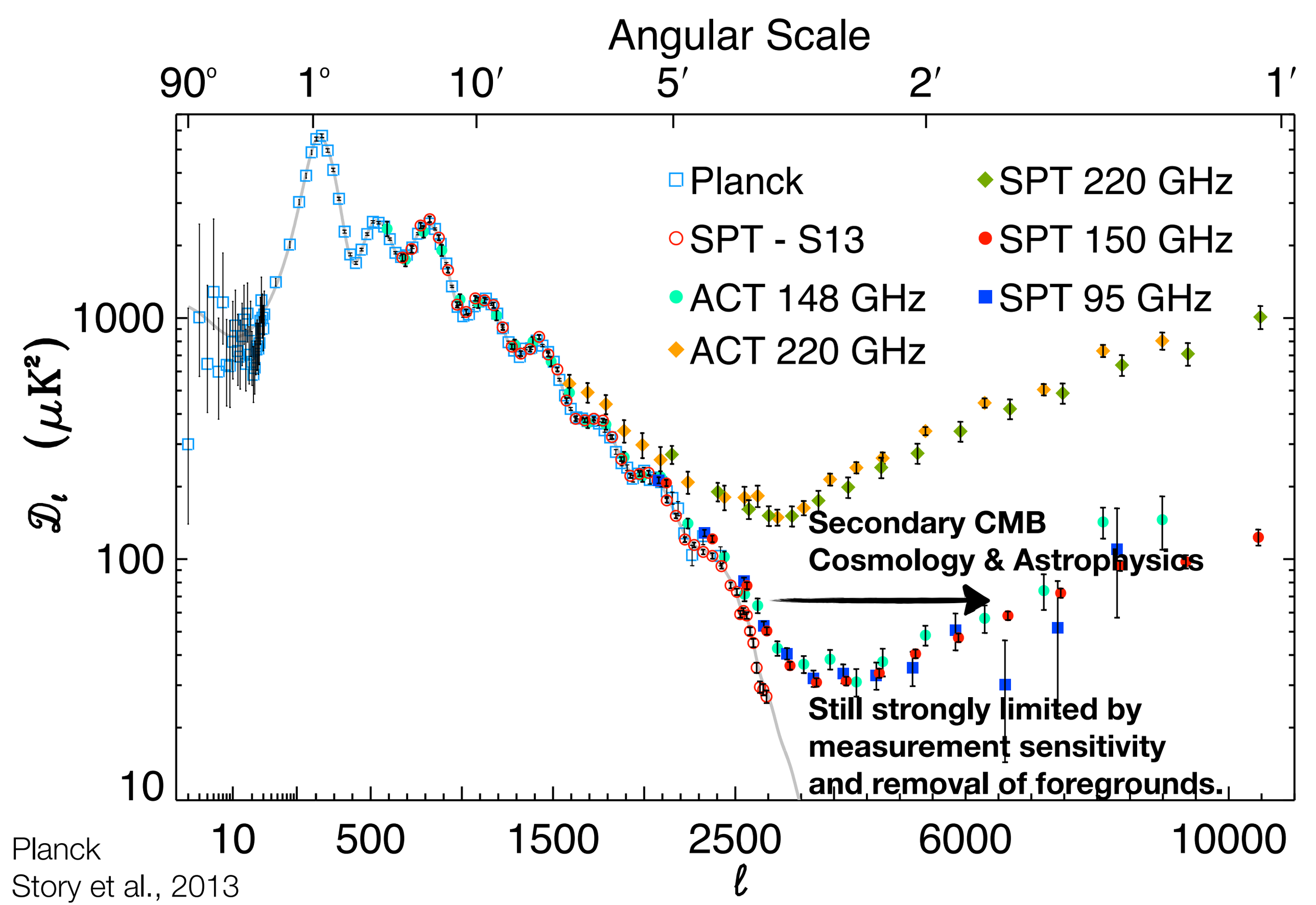
Overview of SPT results

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



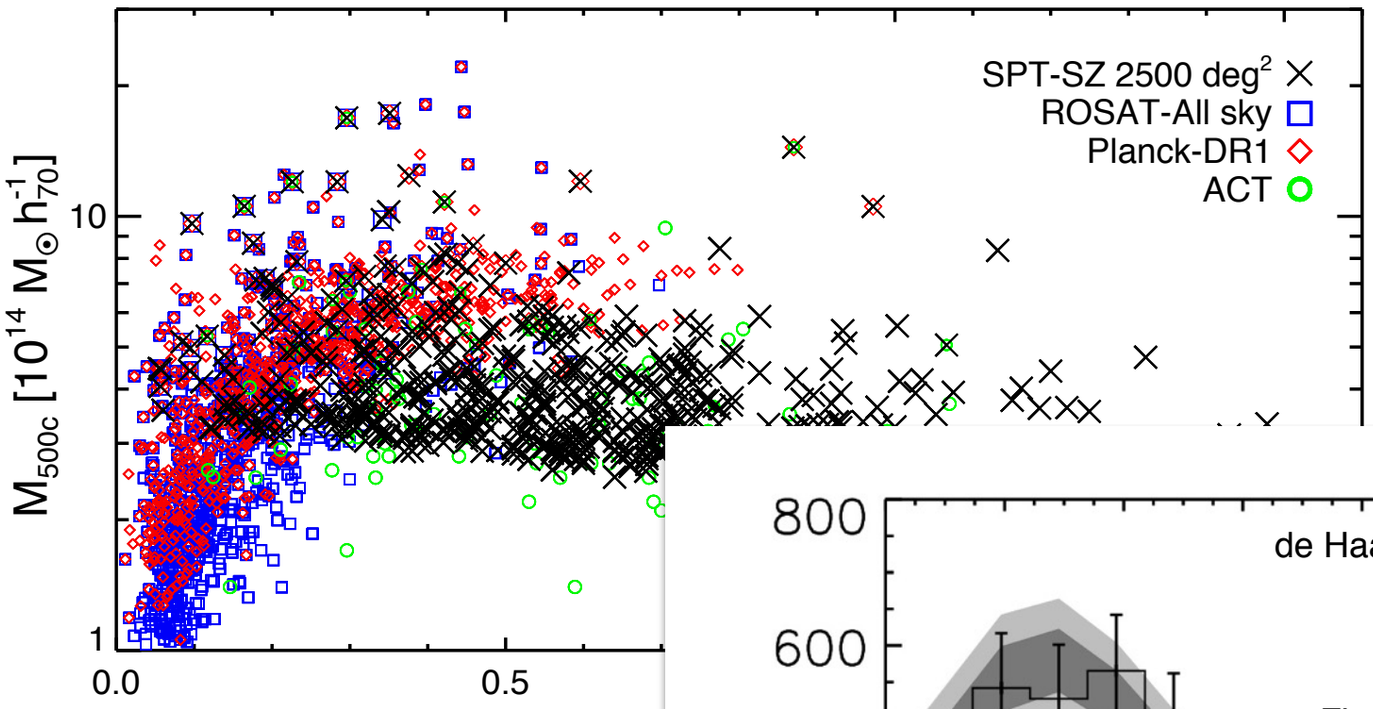
- Two primary surveys completed:
  - 2500 deg^2 SPT-SZ survey:
    Temperature only, three bands (90, 150, 220 GHz) at ≲ 18 μK-arcmin
    (additional shallower 2500 deg^2 for extended SZ cluster catalog)
  - 500 deg^2 SPTpol survey
    Temperature and polarization, two bands (90/150) at ≲ 6 μK-arcmin

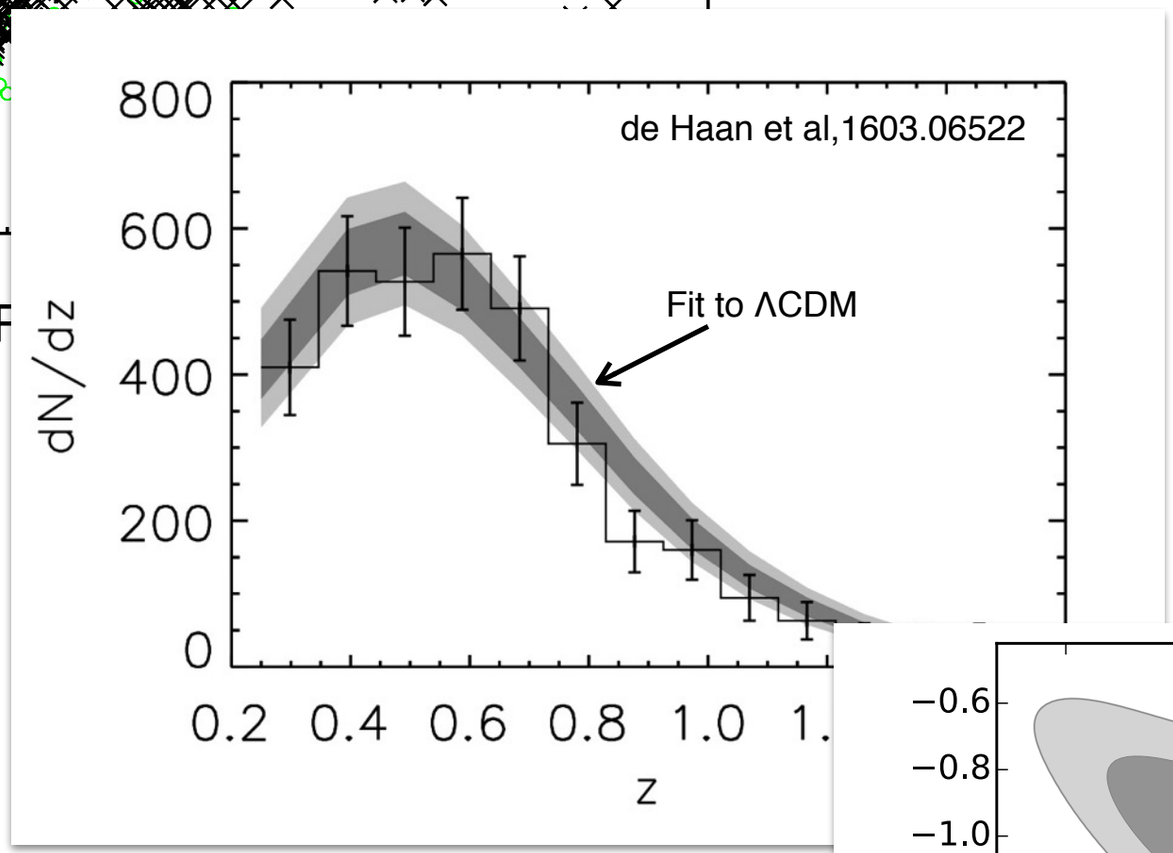
- Results (~100 science publications)
  - Temperature and Polarization power spectra and cosmological parameters
  - First SZ discovery of Galaxy Clusters, SZ cluster catalog and cosmology
  - Diffuse kinematic and thermal SZ effect constraints
  - CMB lensing: power spectra and cross-correlations; Cluster lensing mass calibration
  - First detection of lensing B-mode polarization
  - many more…

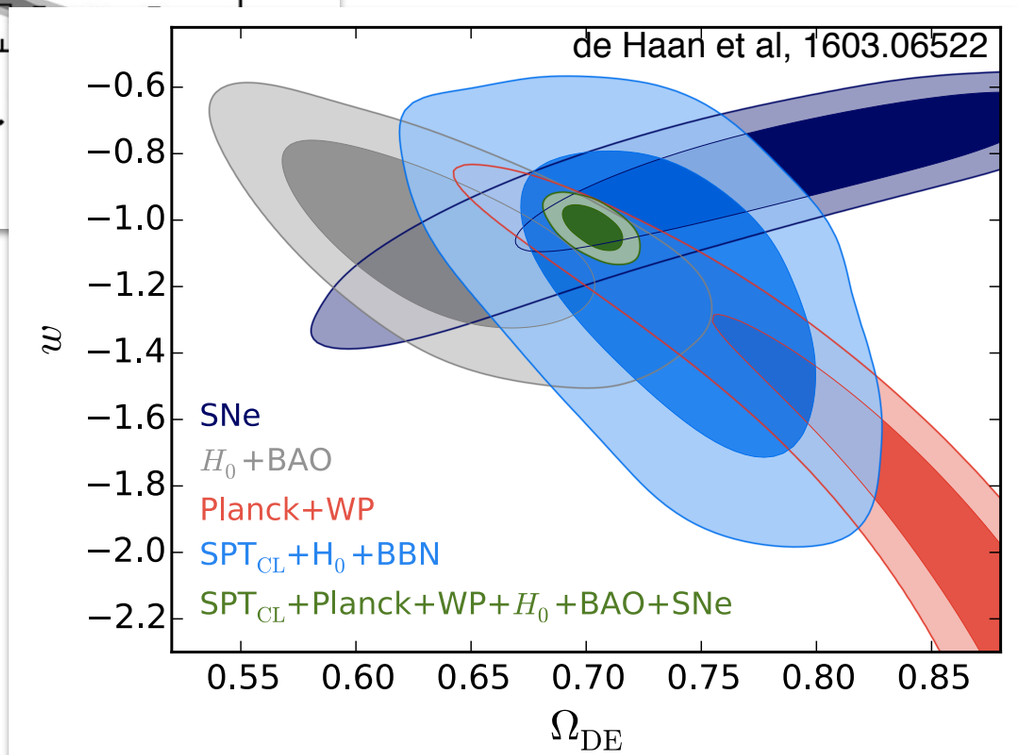


Planck
Story et al., 2013
George et al., 2014
Das et al., 2014

Recent SPT results: Cosmology with SZ clusters



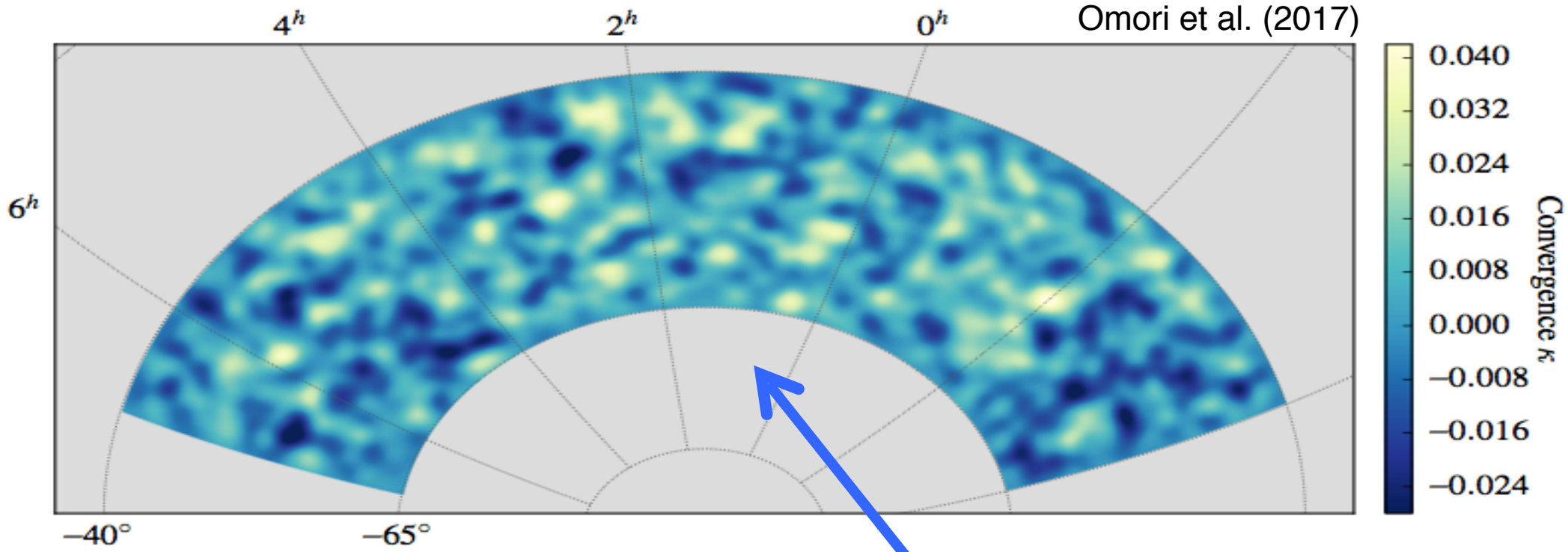


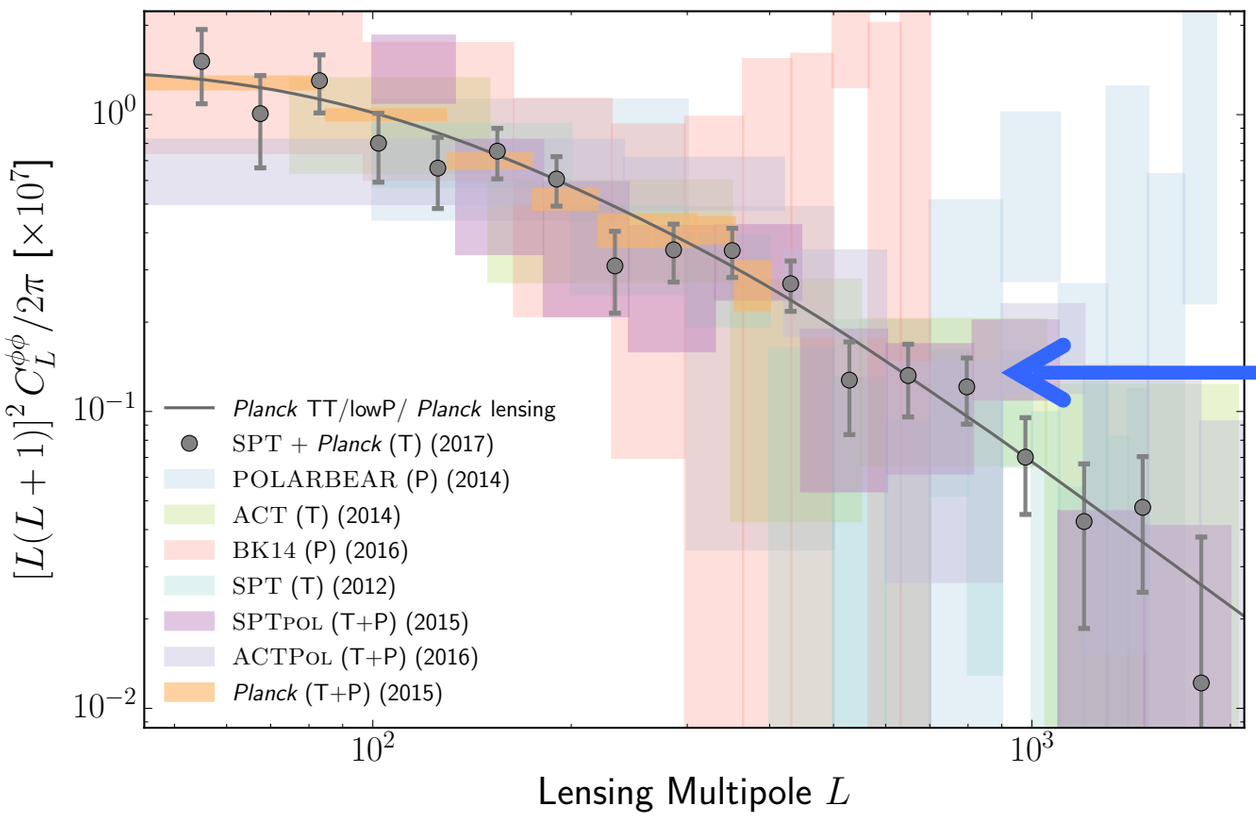


Tracing the growth of structure with evolution of massive galaxy clusters.

<u>Results limited by mass calibration.</u>

Recent SPT results: gravitational lensing



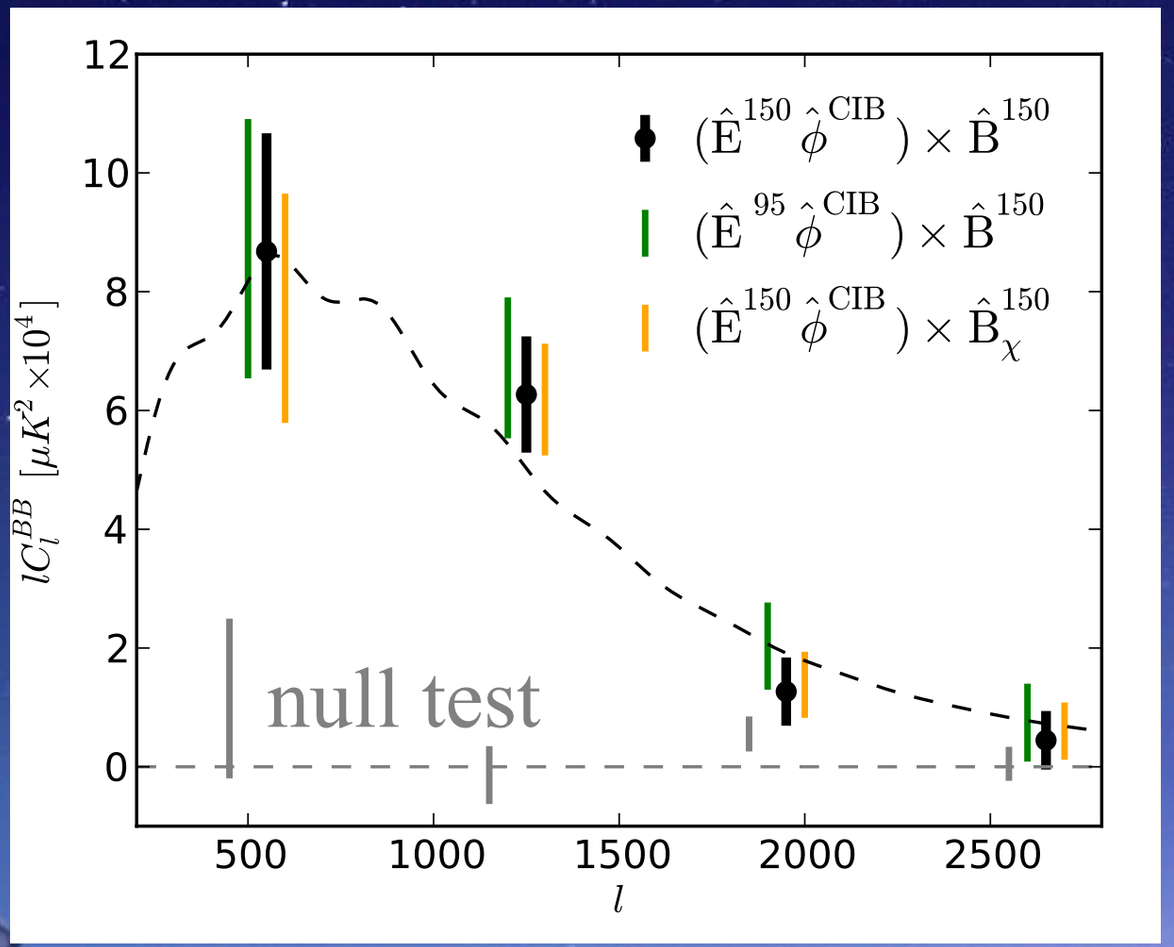


SPT SZ + Planck map of all the mass between us and T = 1eV (6% of the sky)

Power spectrum of that map

Not yet sensitive enough to measure sum of neutrino masses, but soon.

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:

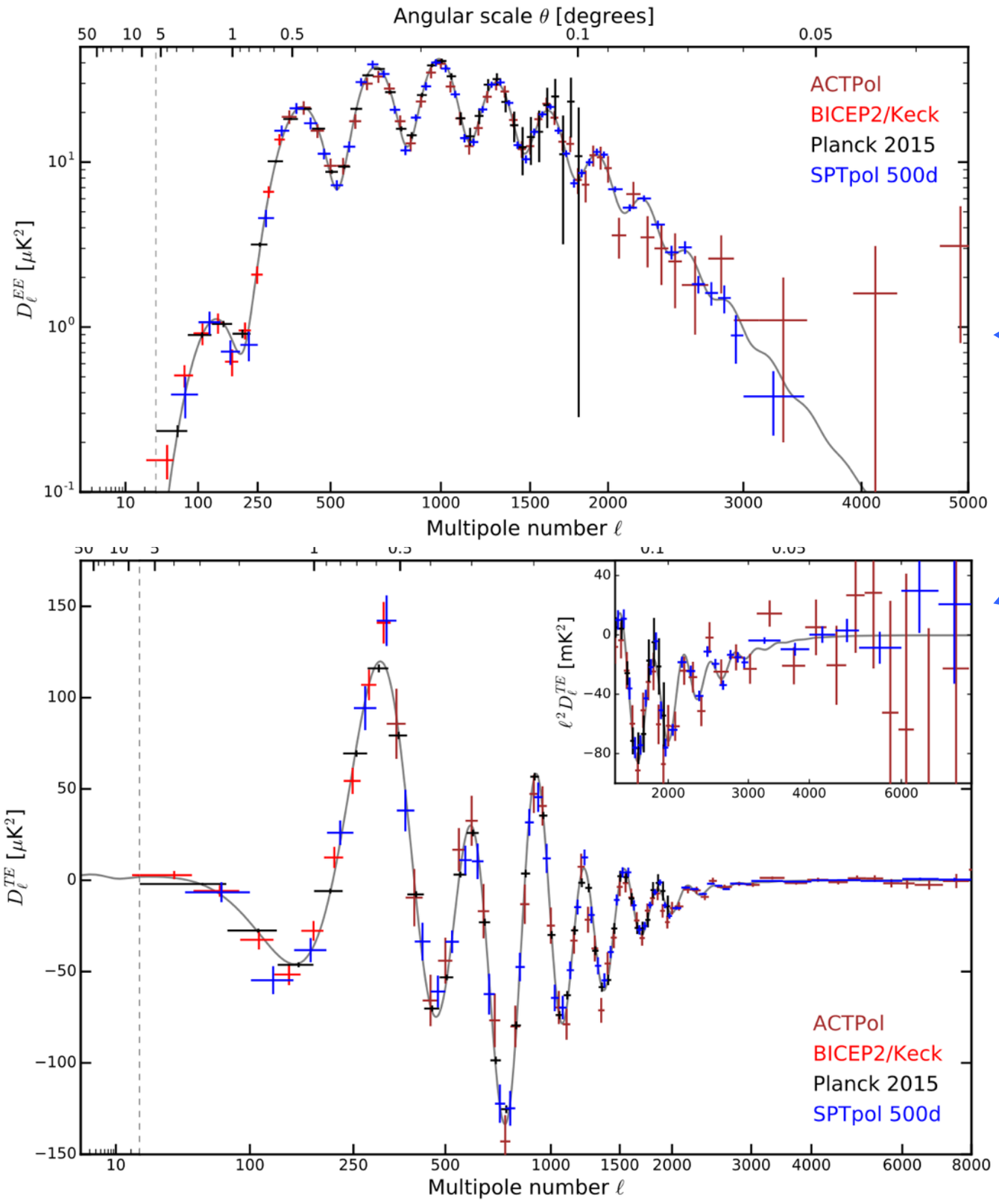
- Fundamental importance of research
- Significant advance in knowledge
- Strong connection between theory and experiment
- General interest to all physicists

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

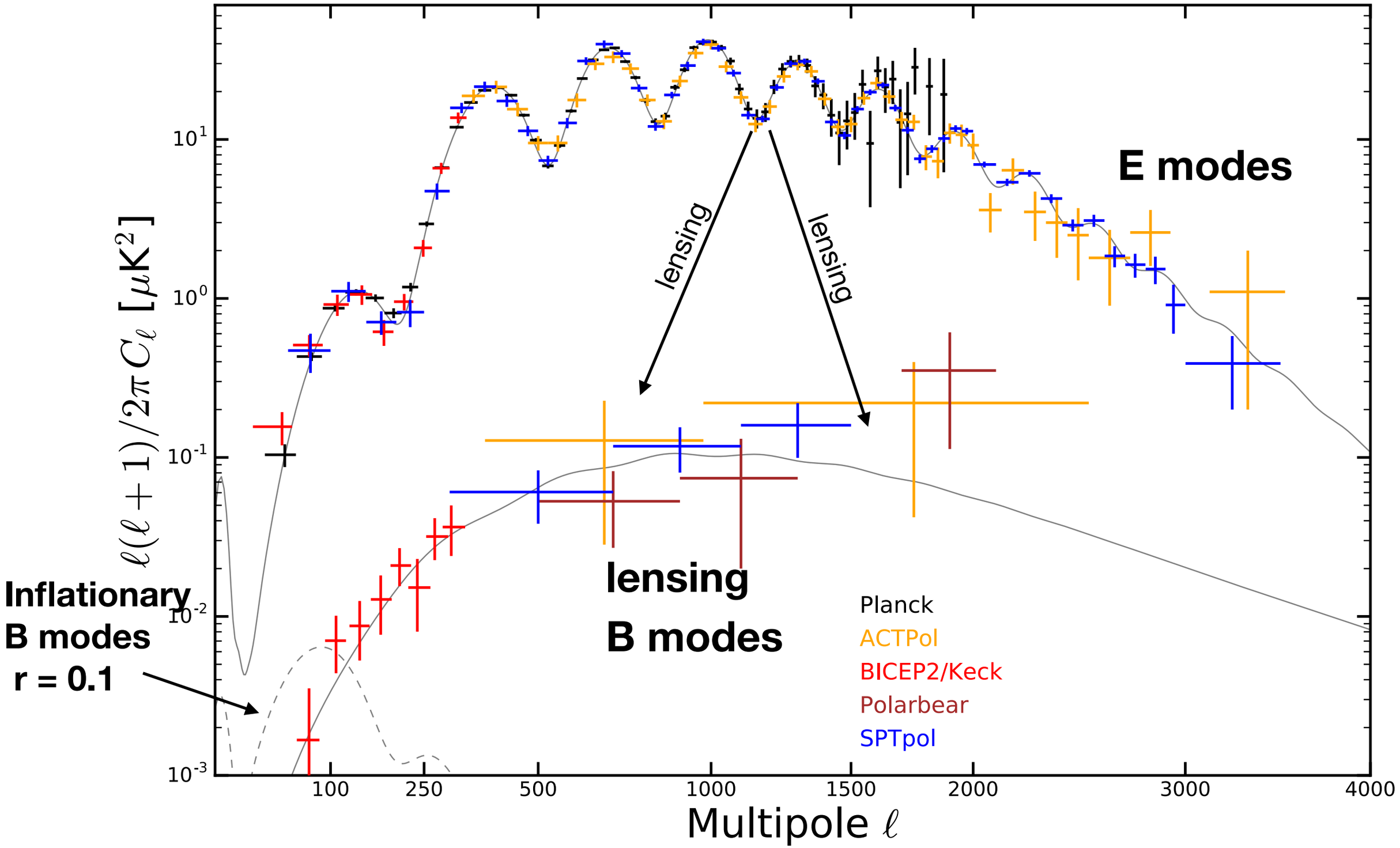
Recent SPT polarization results



- Most sensitive measurement of E-mode polarization power spectrum (EE) and temperature-E-mode correlation spectrum (TE) at multipoles l ≳ 1000.
- 2.4x reduction in parameter volume for N_{eff} & primordial Helium abundance.

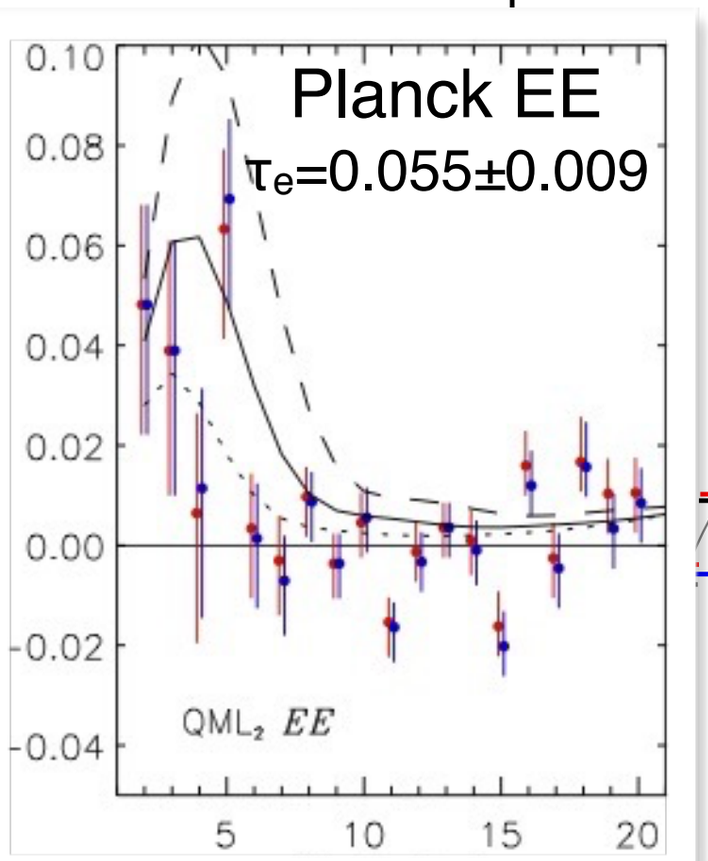
Henning et al. arXiv:1707.09353

Overall status of CMB polarization measurements



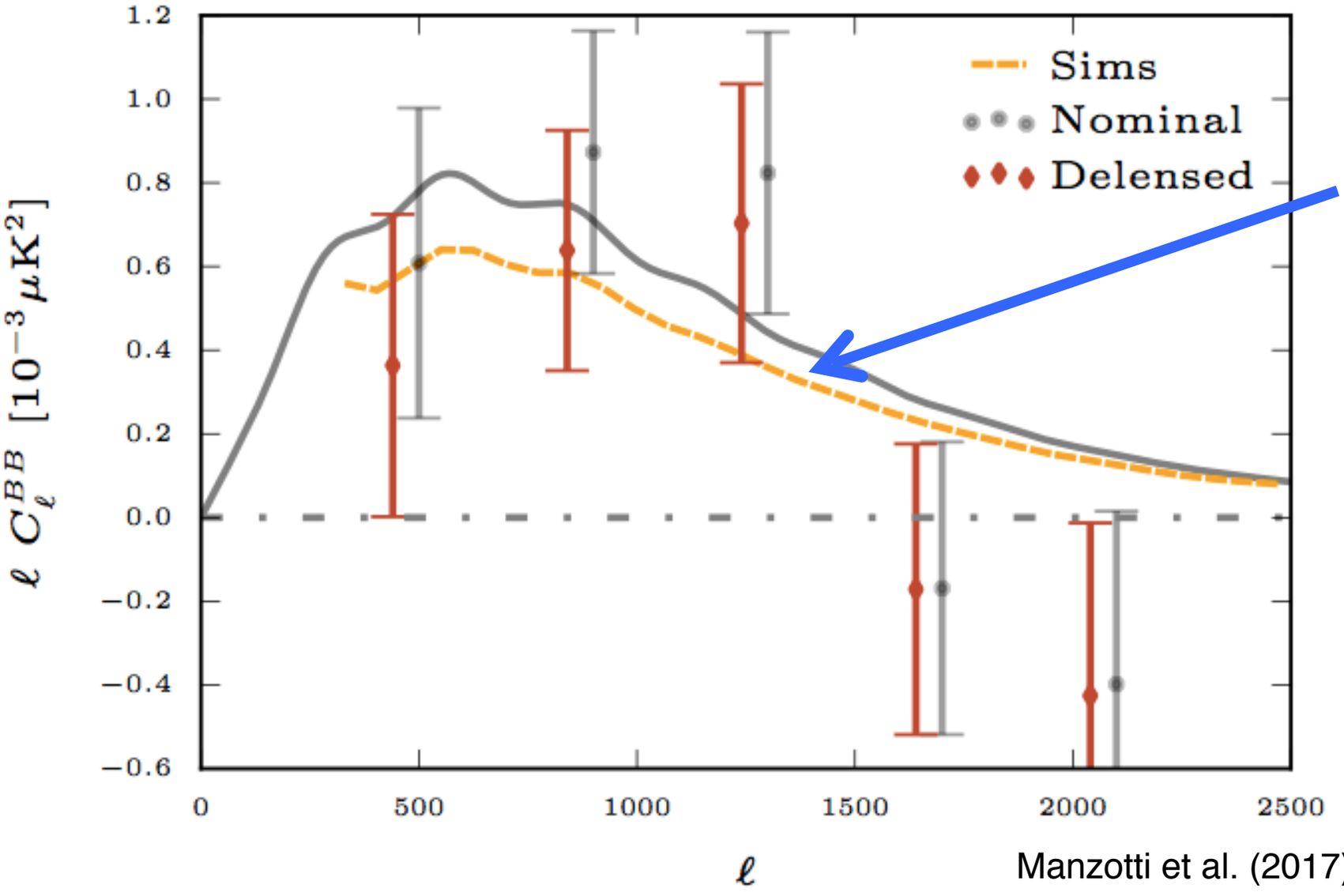
Rapid progress. All within last few years.

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.

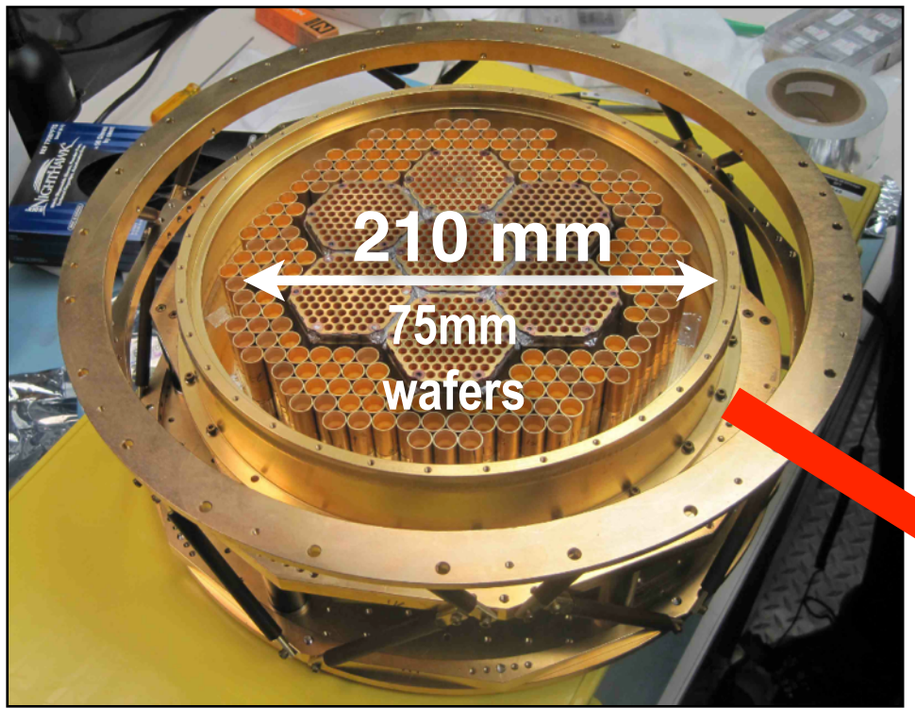
6.9σ proof of concept

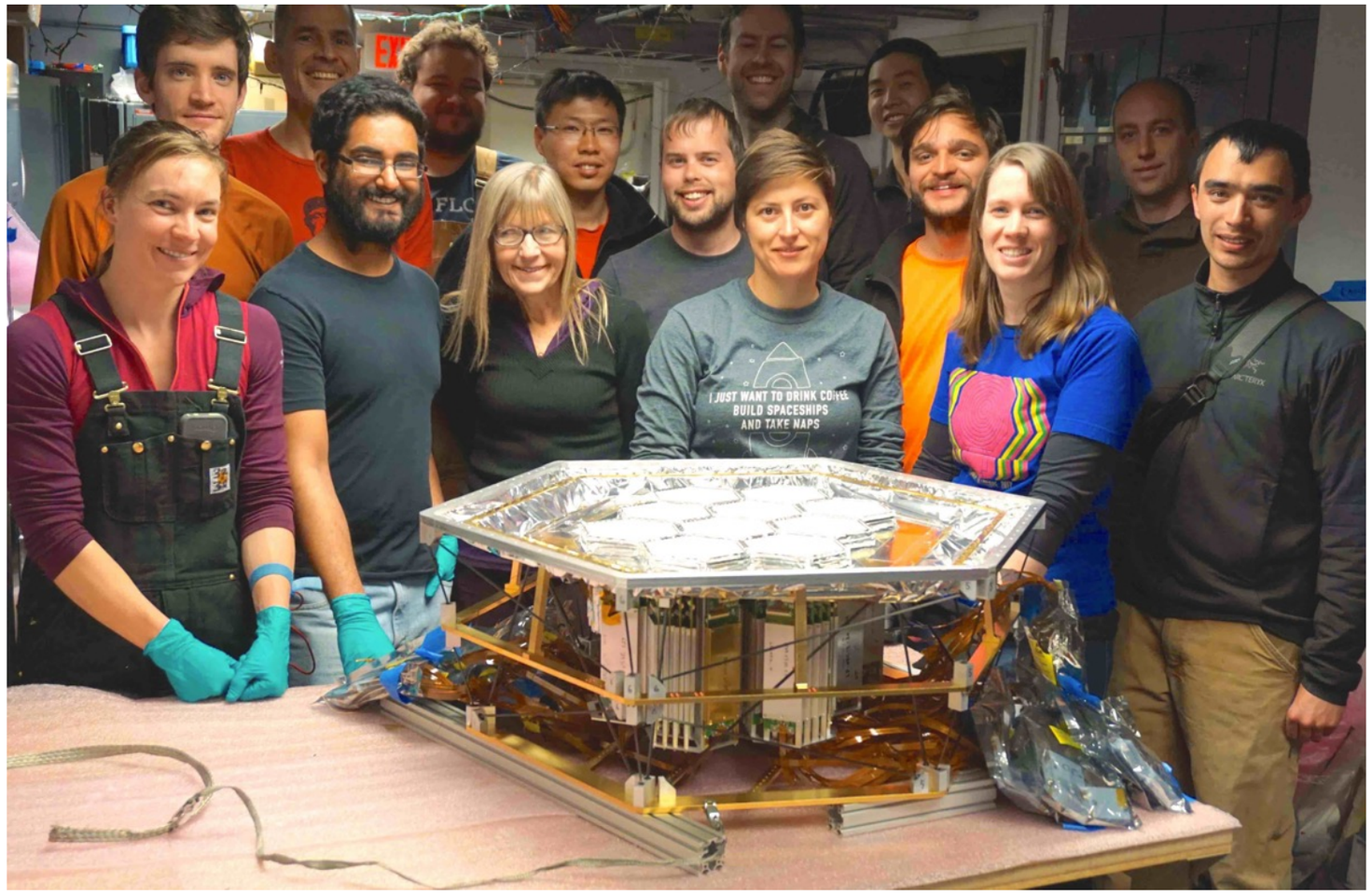
Manzotti et al. (2017)

- 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"

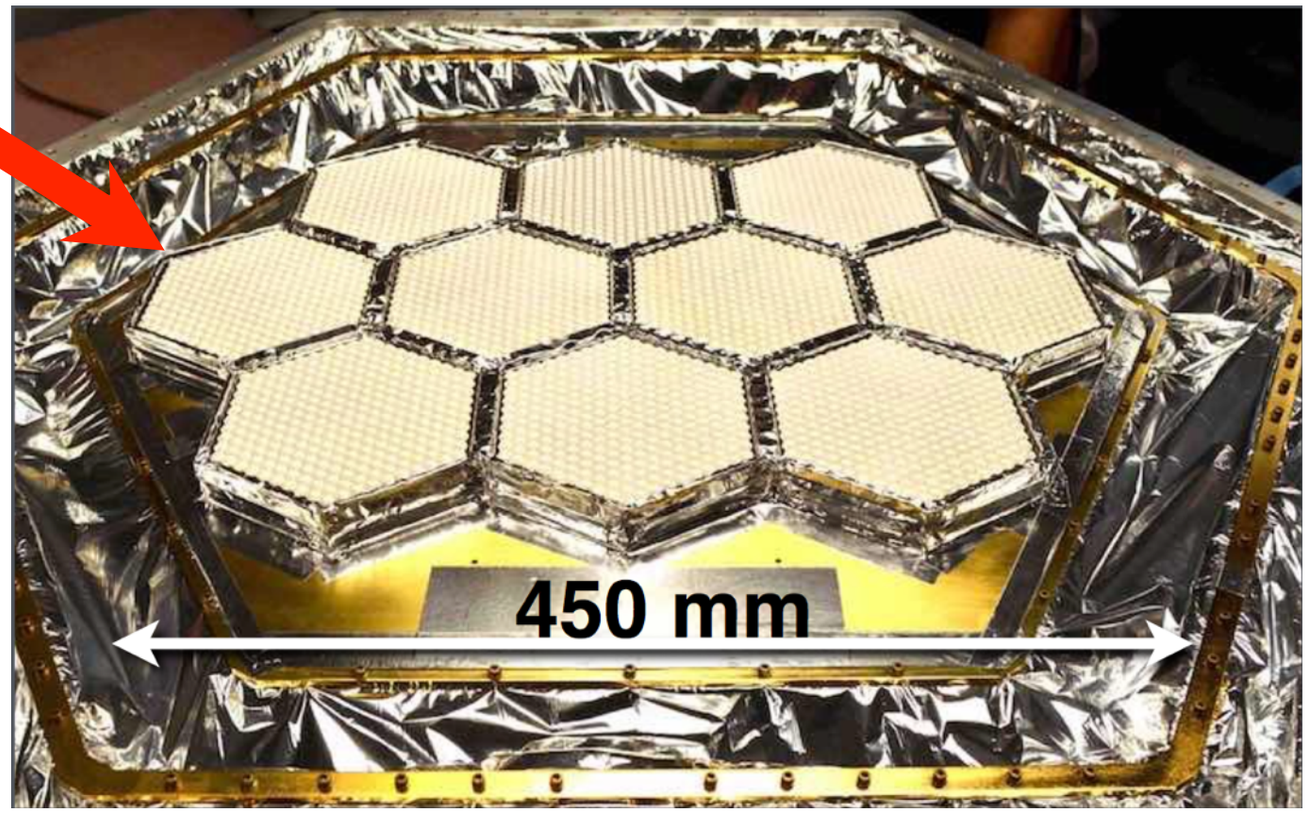
SPTpol → SPT-3G

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

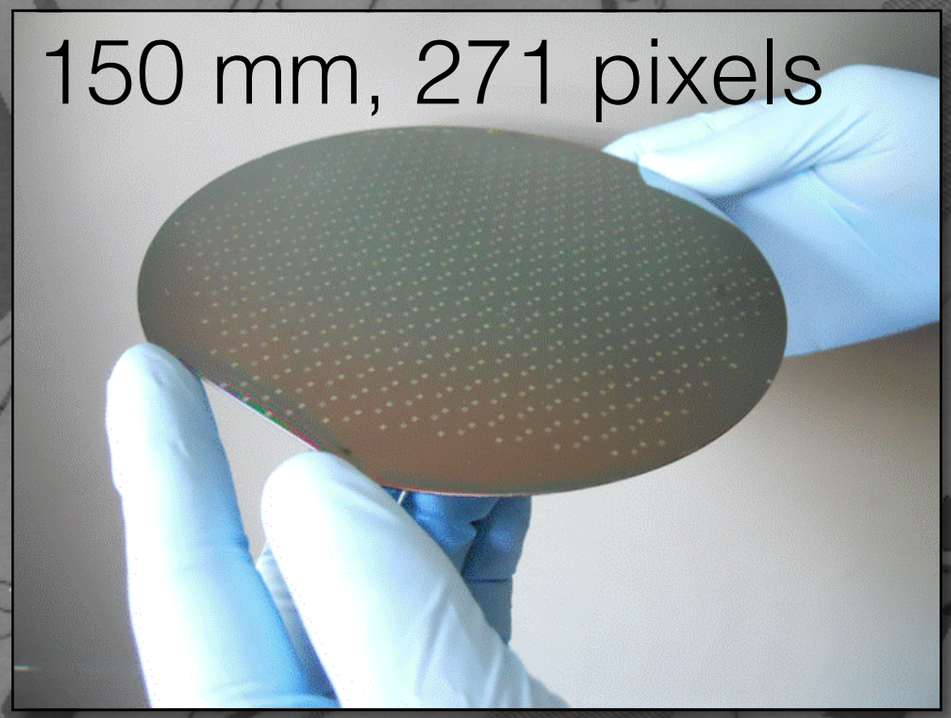




2017: SPT-3G Stage 3 4x larger area
16,000 detectors at T = 250mK
First light January 2017



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



3-color, dual polarization, pixel

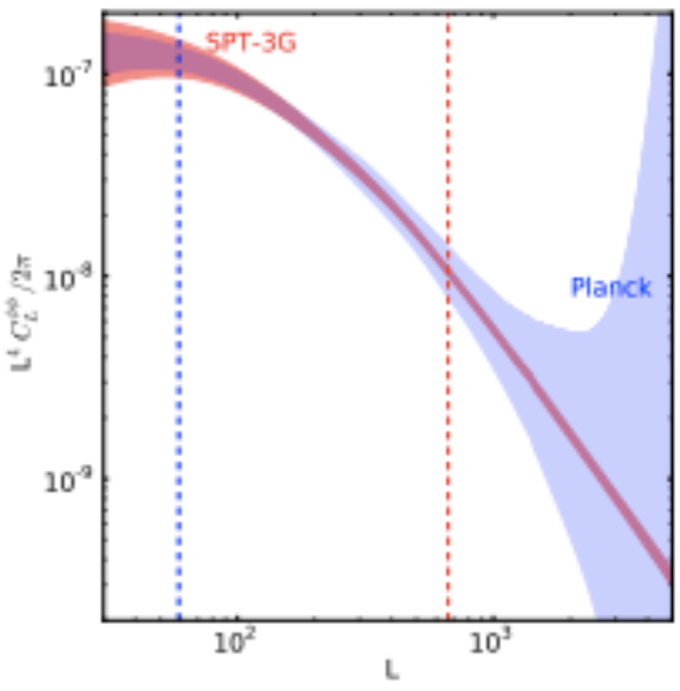
Based on UCB design O'Brient R et al 2013 Appl. Phys. Lett. 102 063506 & Suzuki et al 2014 J. Low Temp. Phys. 176 650

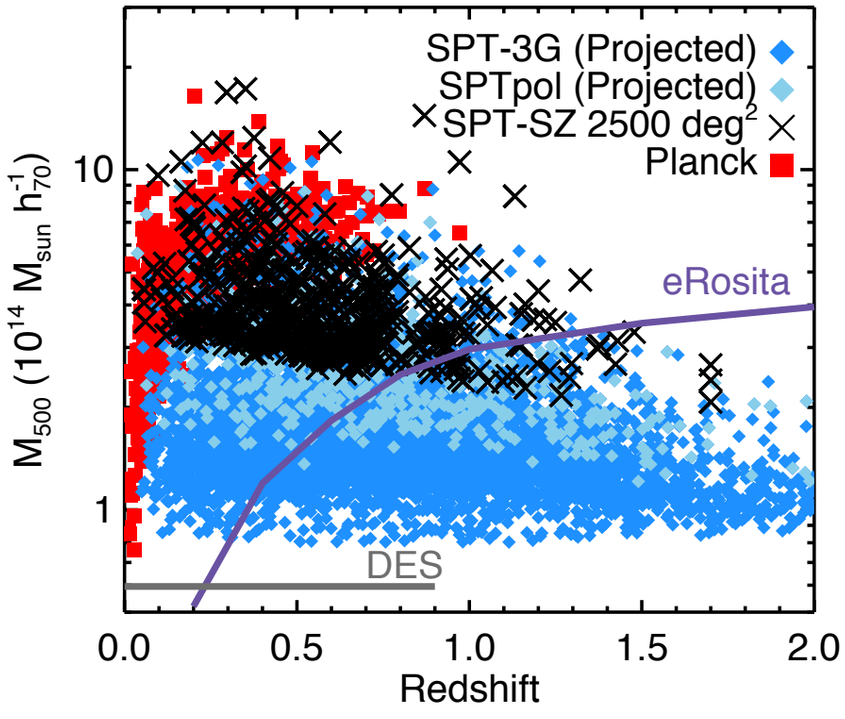
SPT-3G will improve on all the above

Benson et al. (2014)

Dataset	Cosmological parameter constraints								
	$\sigma(\Omega_b h^2)$ $\times 10^4$	$\sigma(\Omega_c h^2)$ $\times 10^3$	$\sigma(A_s)$ $\times 10^{11}$	$\sigma(n_s)$ $\times 10^3$	$\sigma(h)$ $\times 10^2$	$\sigma(\tau)$ $\times 10^3$	$\sigma(N_{\rm eff})$ $\times 10^1$	$\sigma(\Sigma m_\nu)$ [meV]	$\sigma(r)$ $\times 10^2$
Planck	1.93	2.02	5.36	7.07	1.88	4.96	1.39	117	5.72
+ SPT-POL	1.64	1.71	4.92	6.19	1.58	4.95	1.17	96	**2.75**
+ SPT-3G	**1.02**	**1.25**	**4.18**	**4.61**	**1.14**	4.94	**0.76**	**74**	**1.05**
Planck + BOSS	1.34	1.21	4.01	4.54	1.21	4.92	0.74	88	5.72
+ SPT-3G	**0.85**	**0.95**	3.71	3.91	**0.94**	4.90	**0.58**	**61**	**1.05**

Table 2. Expected $1\,\sigma$ constraints on cosmological parameters using SPT-3G power spectrum and lensing reconstruction data, assuming a 9-parameter ΛCDM+$N_{\rm eff}$+Σm_ν+tensor model. Parameters for which adding SPT-3G improves the constraint by at least a factor of 1.5 over the *Planck* or *Planck*+BOSS constraint are marked in **blue**, while those for which the constraints improve by at least a factor of 1.25 are marked in **orange**.



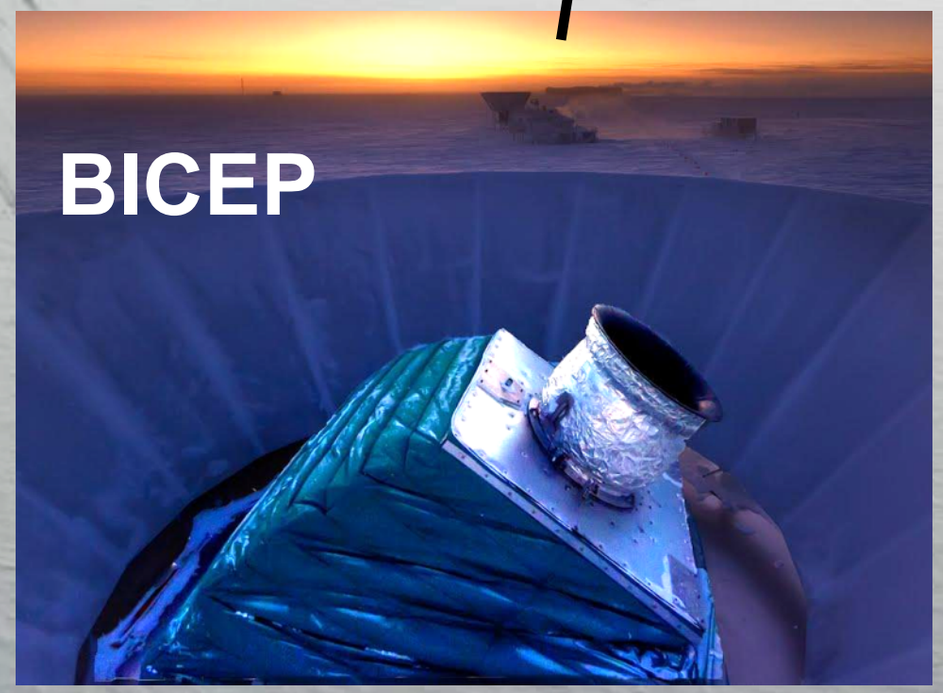


and will de-lens B-modes from BICEP & SPT

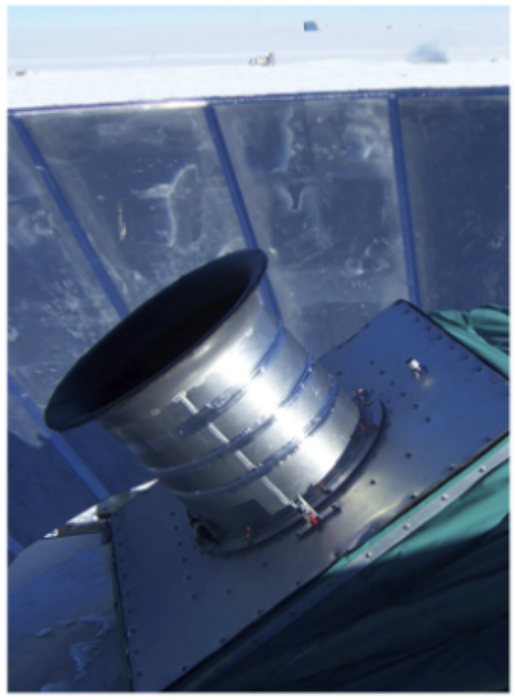
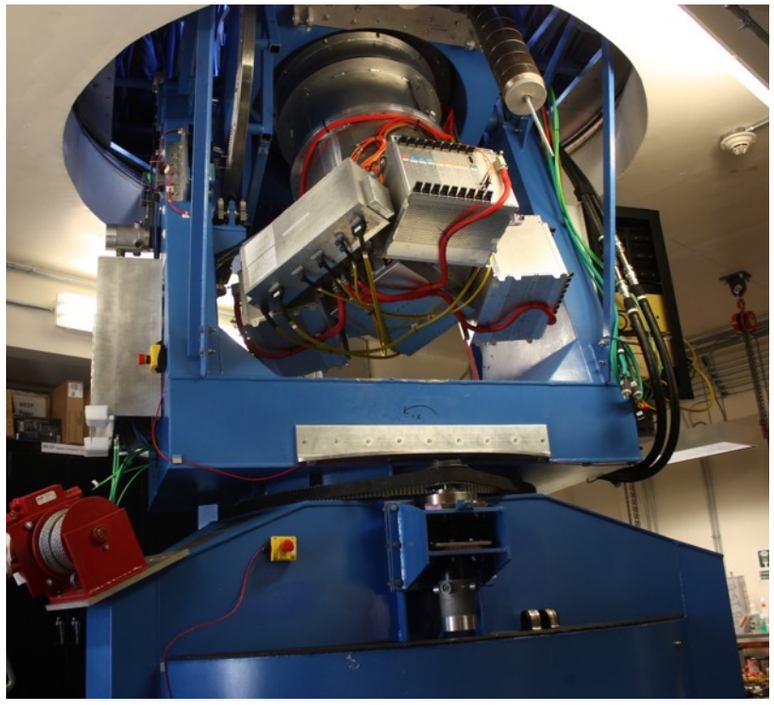
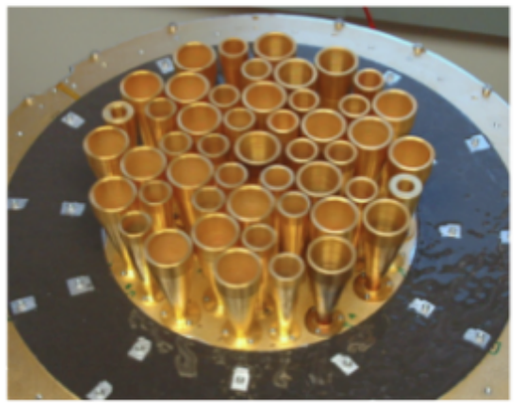
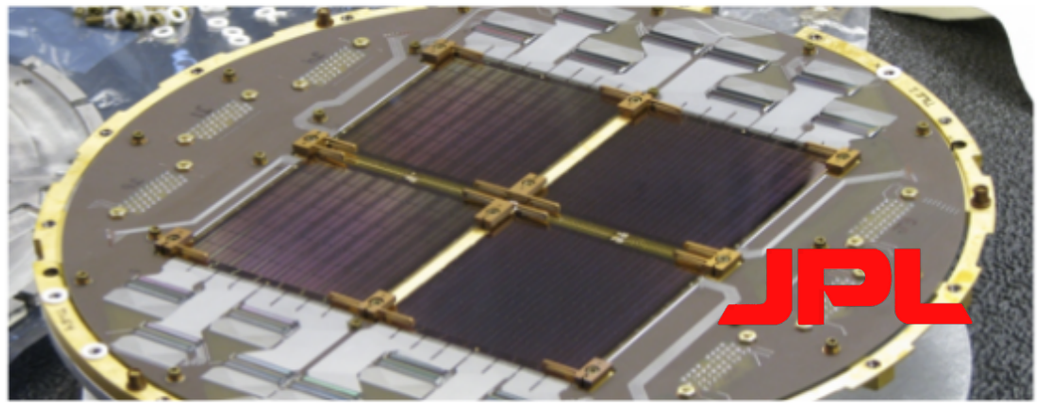
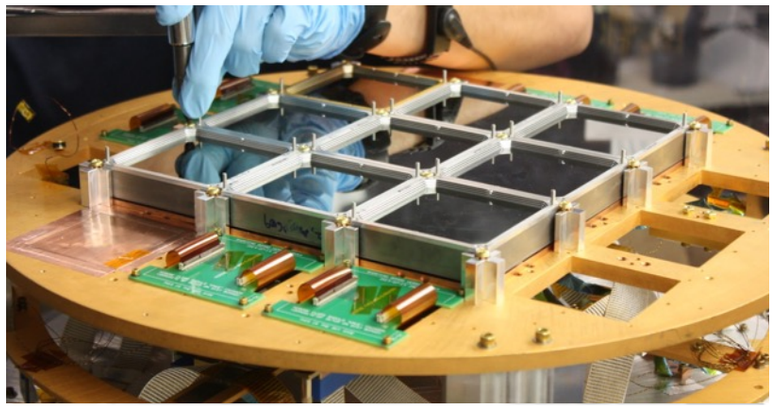
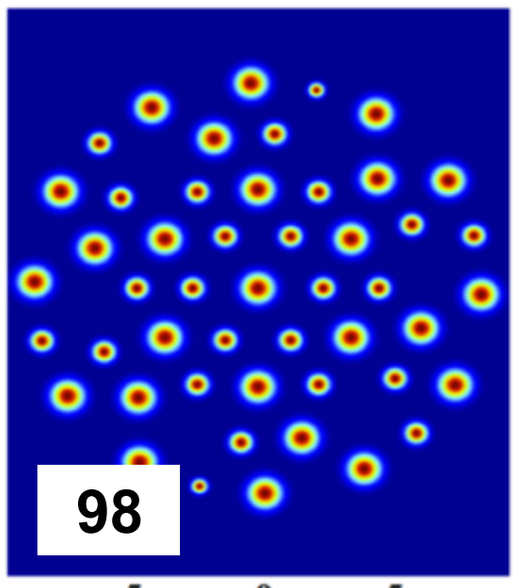
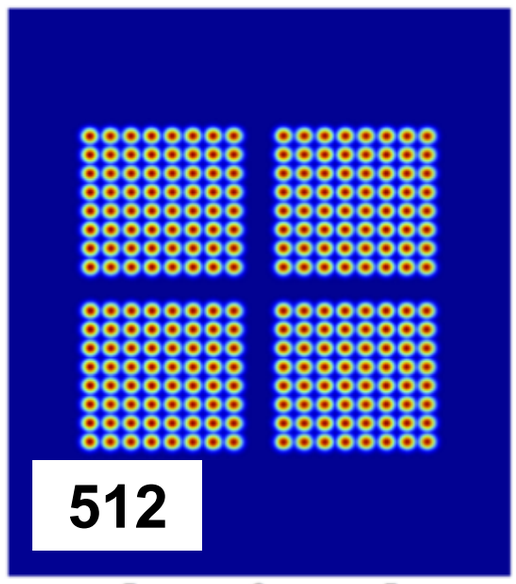
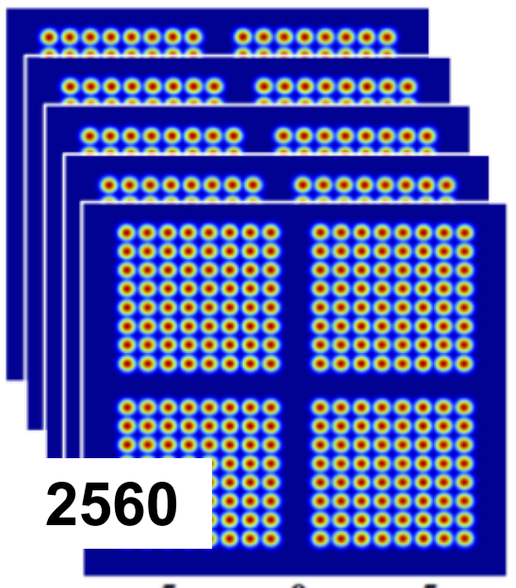
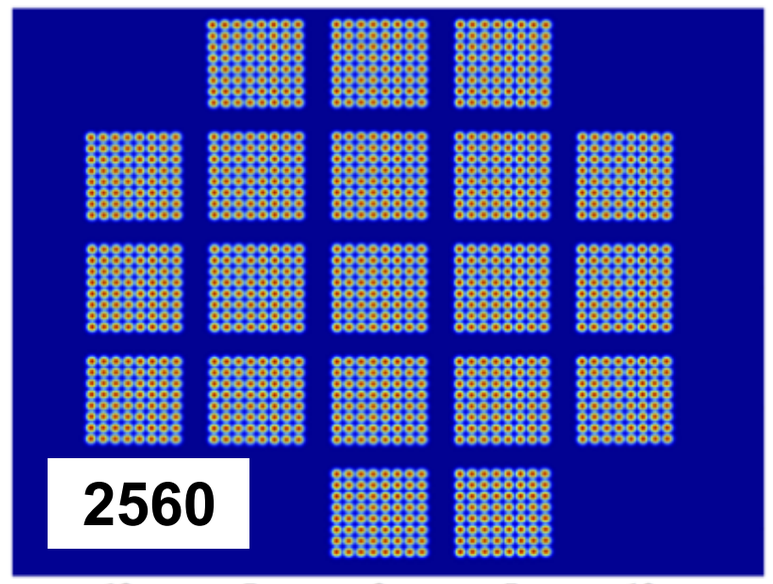
BICEP / Keck CMB Program

Using small refracting telescopes to control beam systematics.

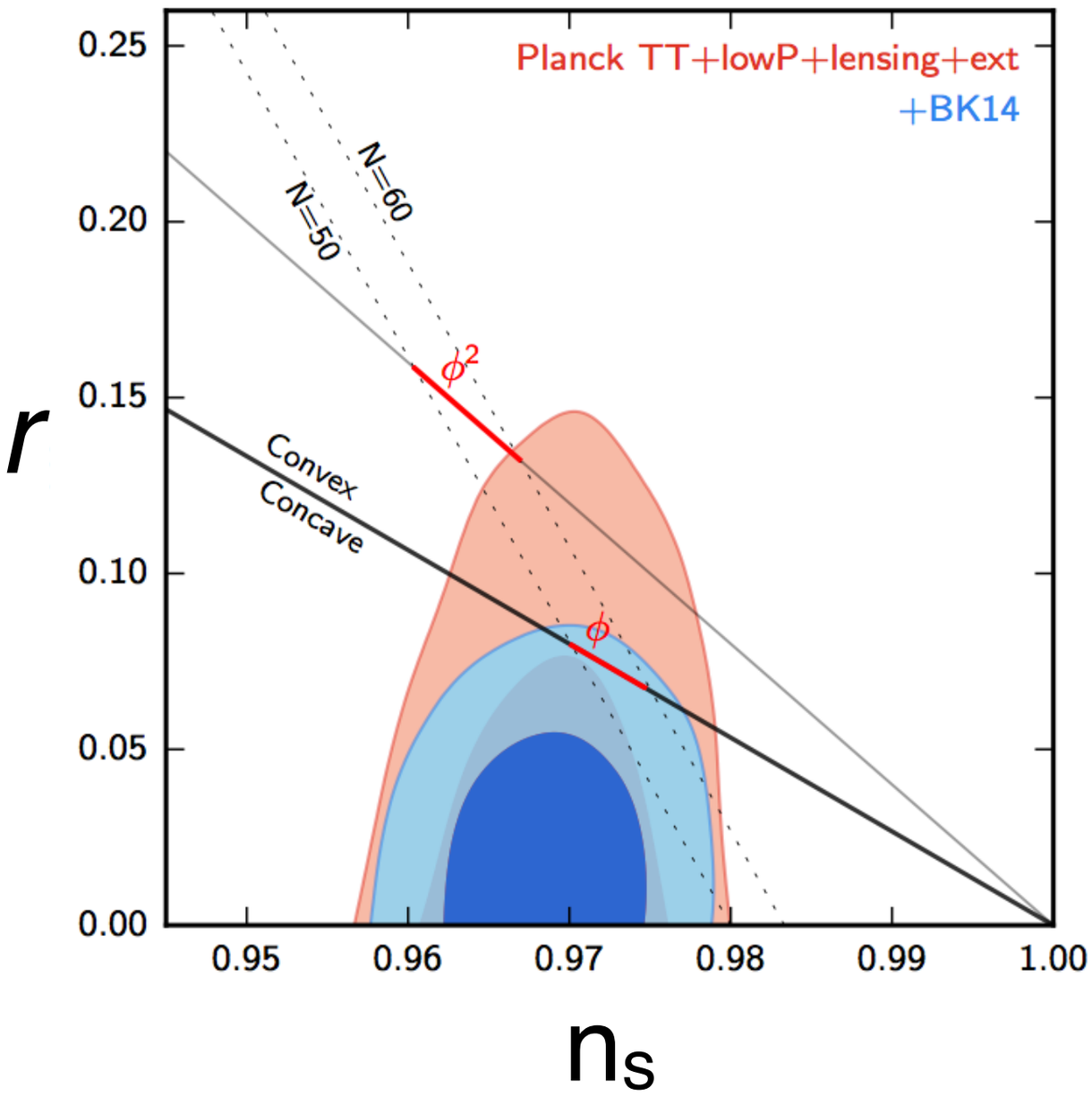
Modular frequency coverage for foregrounds mitigation.



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

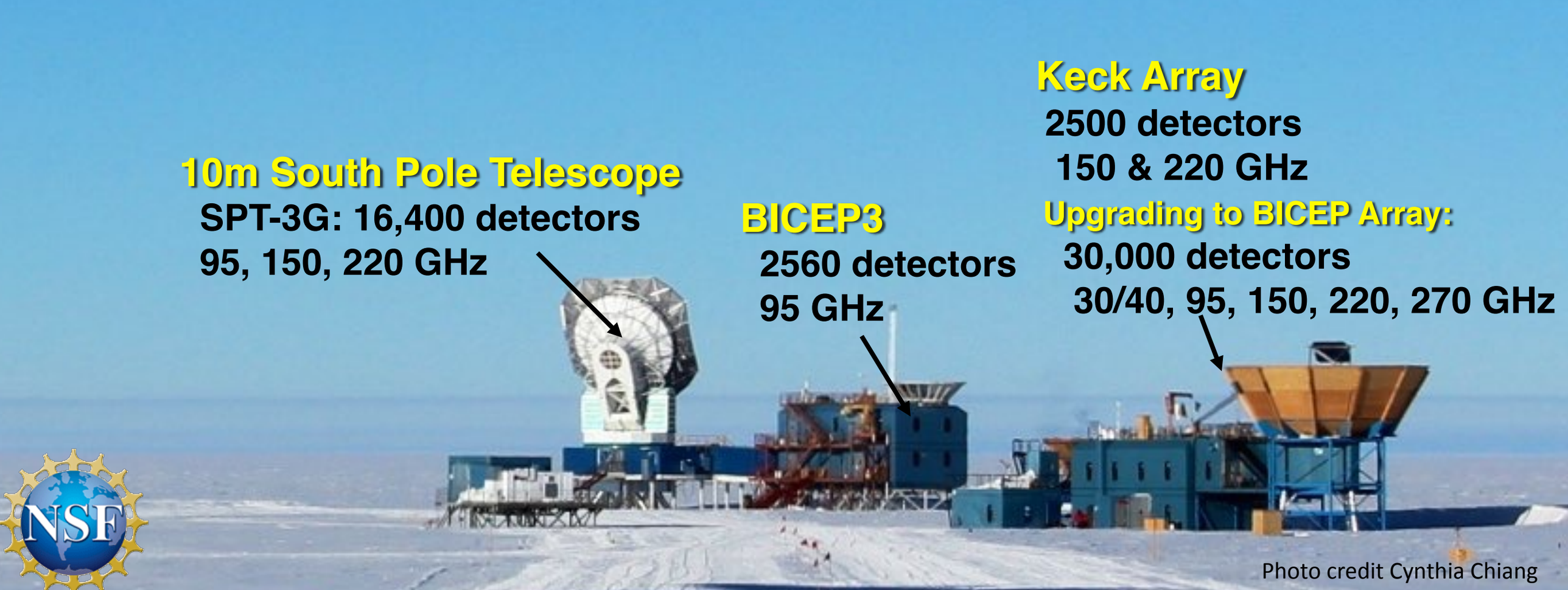
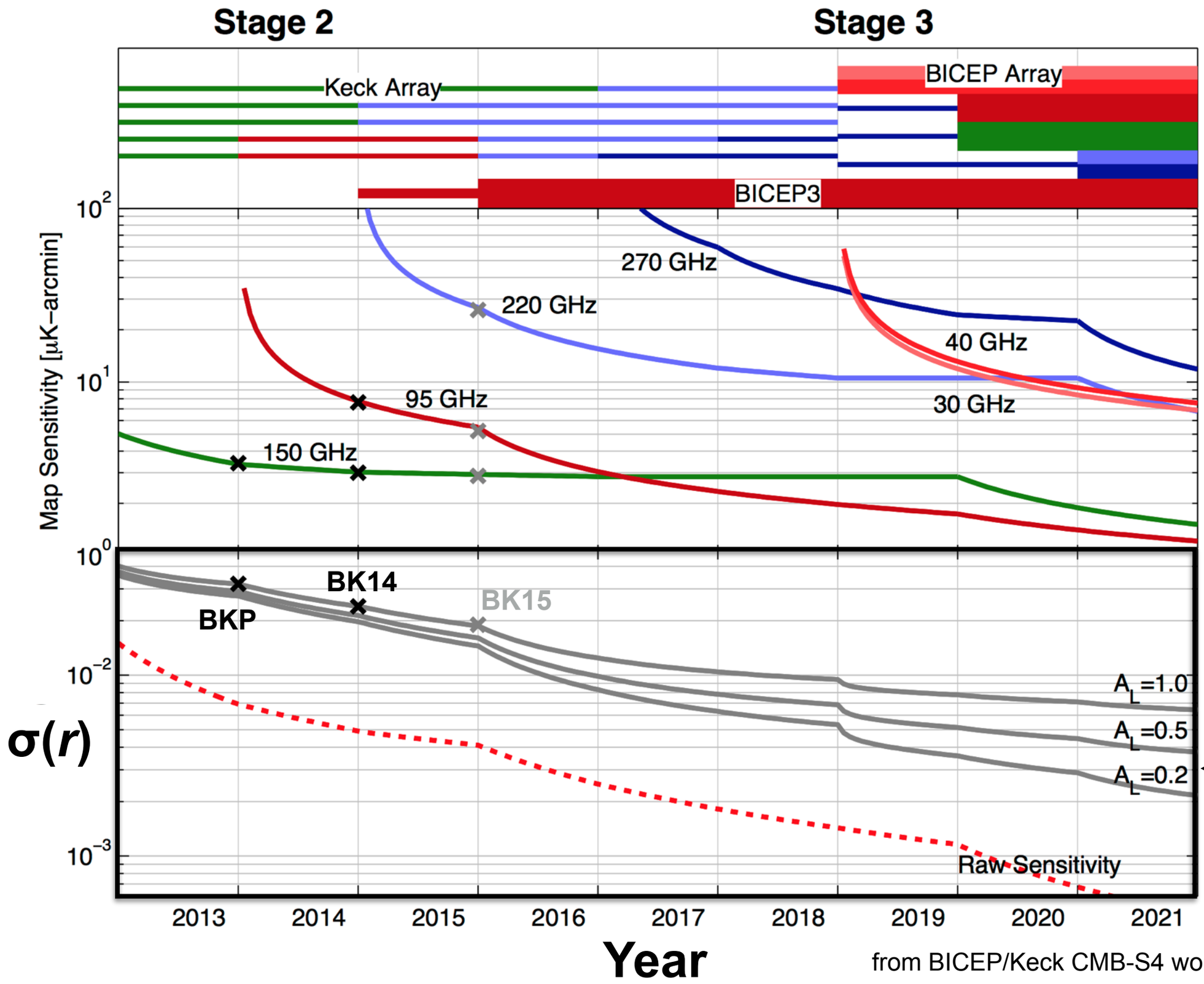


Photo credit Cynthia Chiang



with SPT-3G de-lensing **σ(r)~0.003**

from BICEP/Keck CMB-S4 workshop

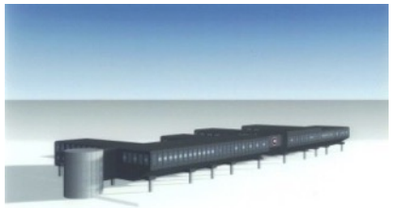
Photo credit Cynthia Chiang

Why Does South Pole work so well for CMB?

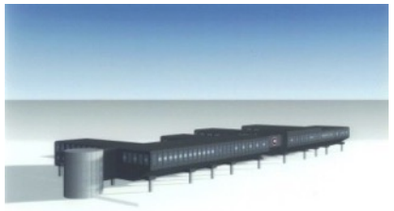
- **<u>Extremely dry *& stable*[1] atmosphere</u>**.
- High altitude ~ 10,500 feet.
- Sun below horizon for 6 months.
- Unique geographical location:
  Relentless observing through low-foreground path of Galaxy 24/7, actually 24/7/52
- Excellent support from National Science Foundation research station
- Steady investment by NSF in South Pole CMB

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

[1]South Pole sky noise power at least 30x less than Atacama at mm-wavelengths.
Bussmann et al. ApJ 622 1343 (2005); Lay & Halverson ApJ 543, 787 (2000)



Amundsen-Scott South Pole Research Station



Station Features

Kitchen

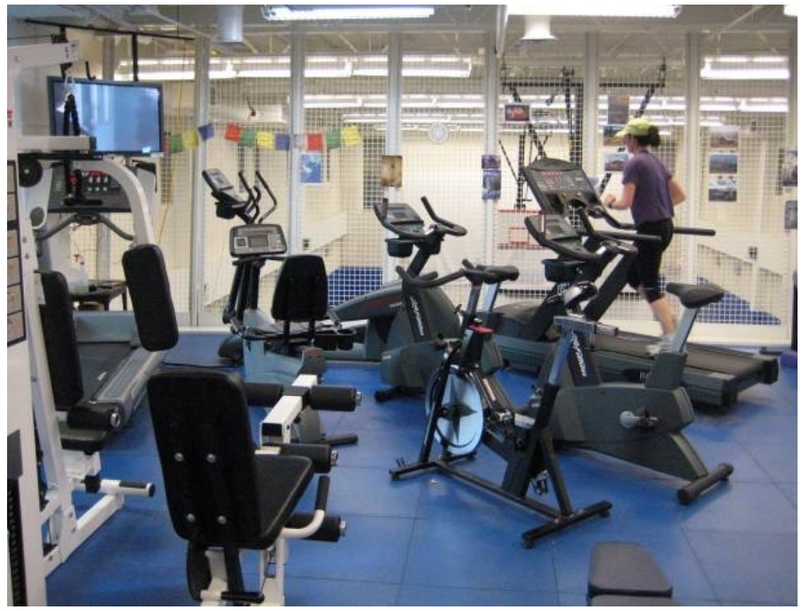
Communications

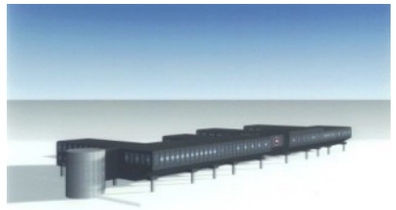
Berthing

Dining Area

Medical

Recreation





Power Plant

1 Megawatt Power Capacity

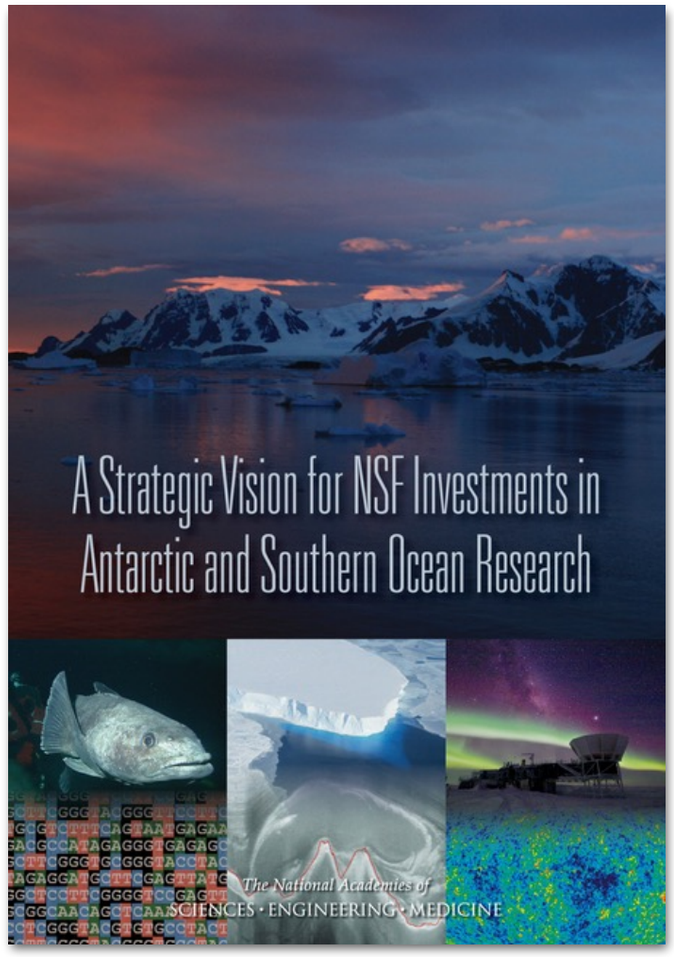
next steps for CMB from South Pole

- 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 science collaboration.

- SPT open to expanding science collaboration now

- Now is time to plan (start!) next phase at S. Pole
  - Start CMB-S4? Timing depends on many factors at the U.S. Agencies
  - Partner to install high throughput large telescope and/or more BICEP-like telescopes, to eventually be part of CMB-S4?
  - Establish South Pole CMB Observatory, with additional partners? With other stations → e.g., Antarctic CMB Consortium?



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