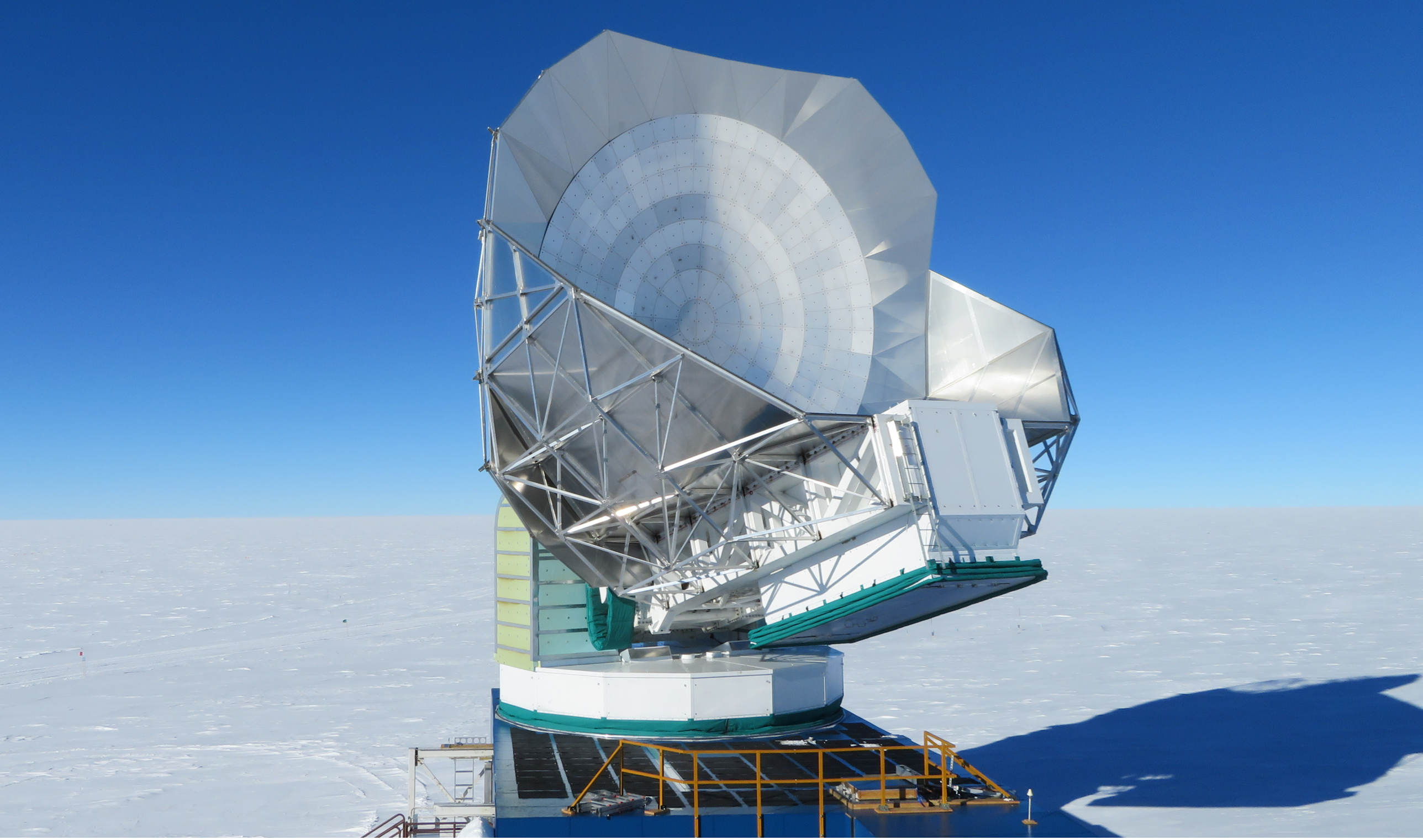
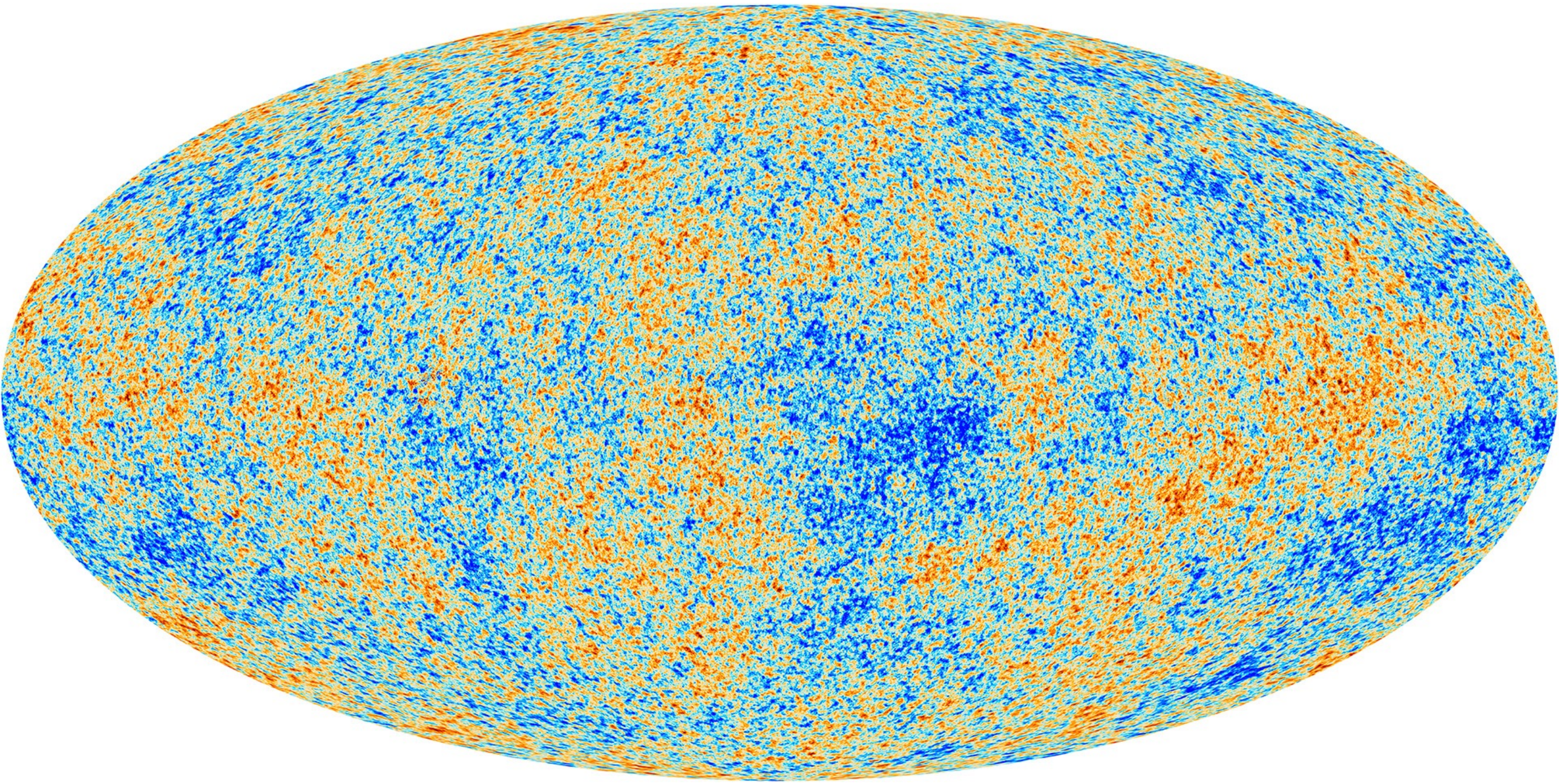


SPT-3G and Recent Results from the South Pole Telescope

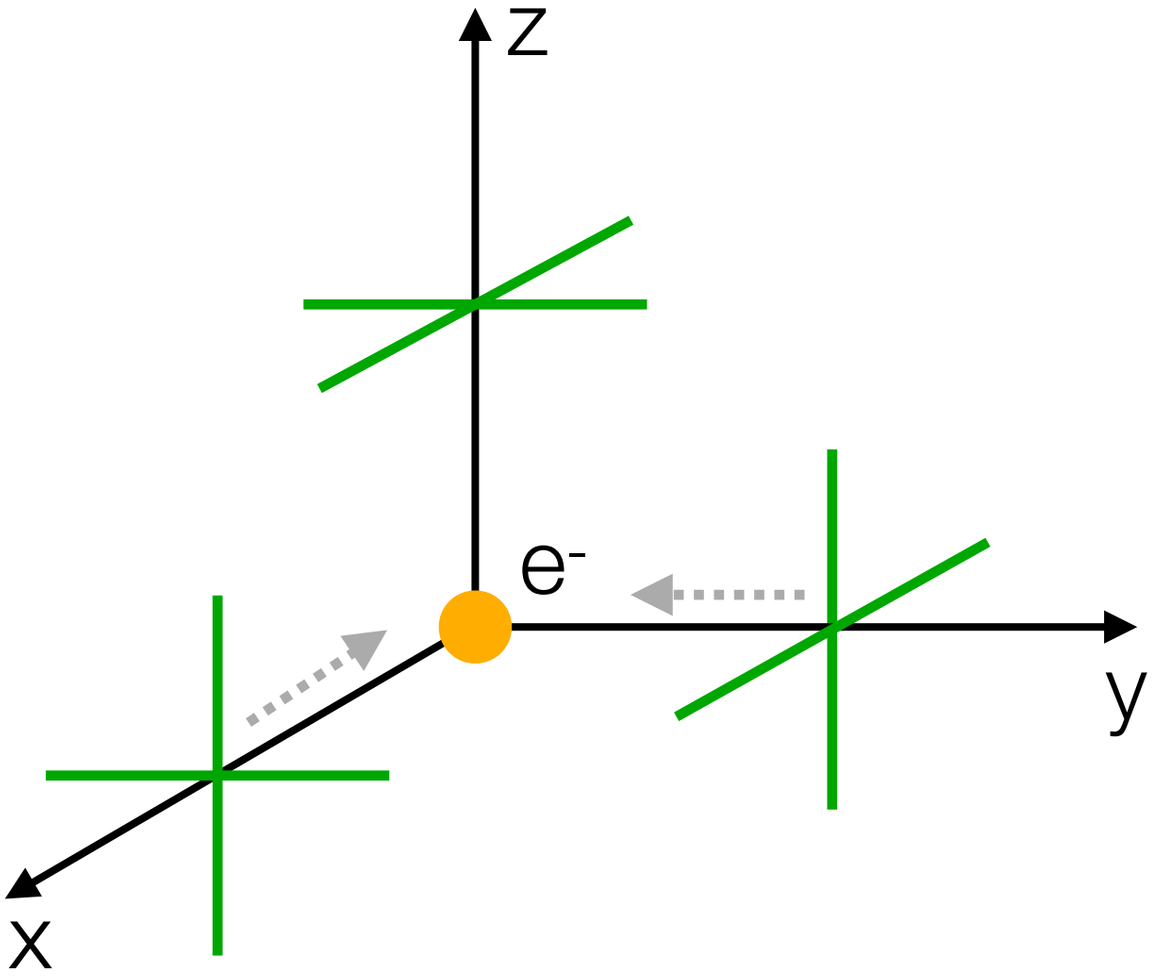
Adam Anderson
Fermilab / University of Chicago
6 June 2018
Rencontres de Blois

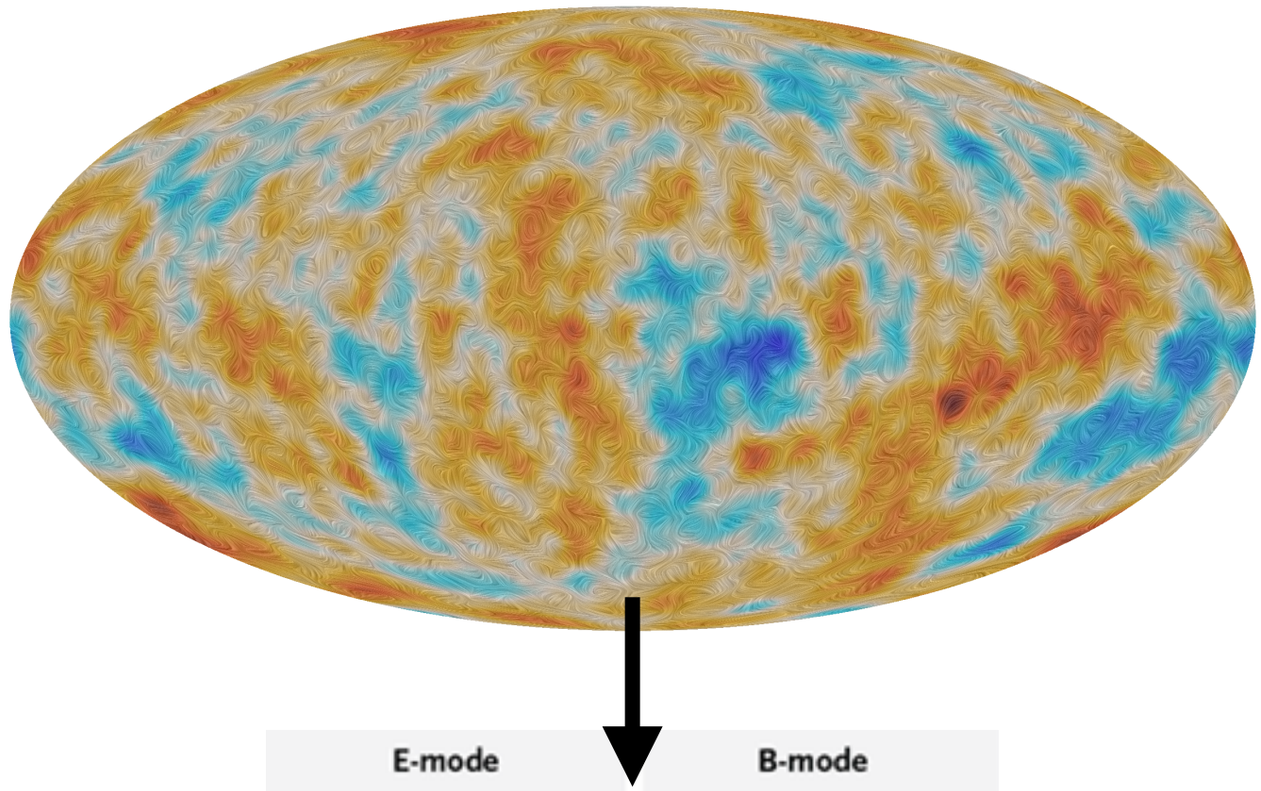
Temperature Anisotropy from Planck

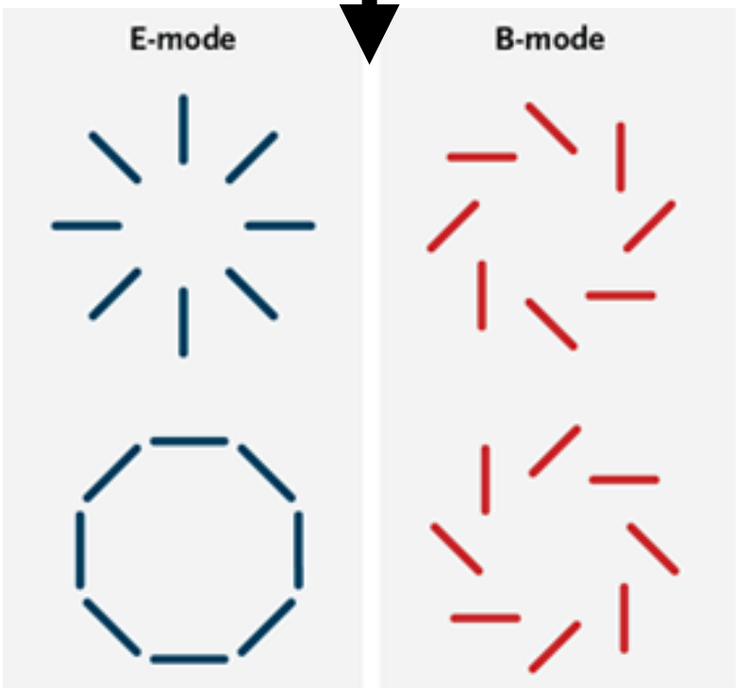


What is left to do?

CMB Polarization

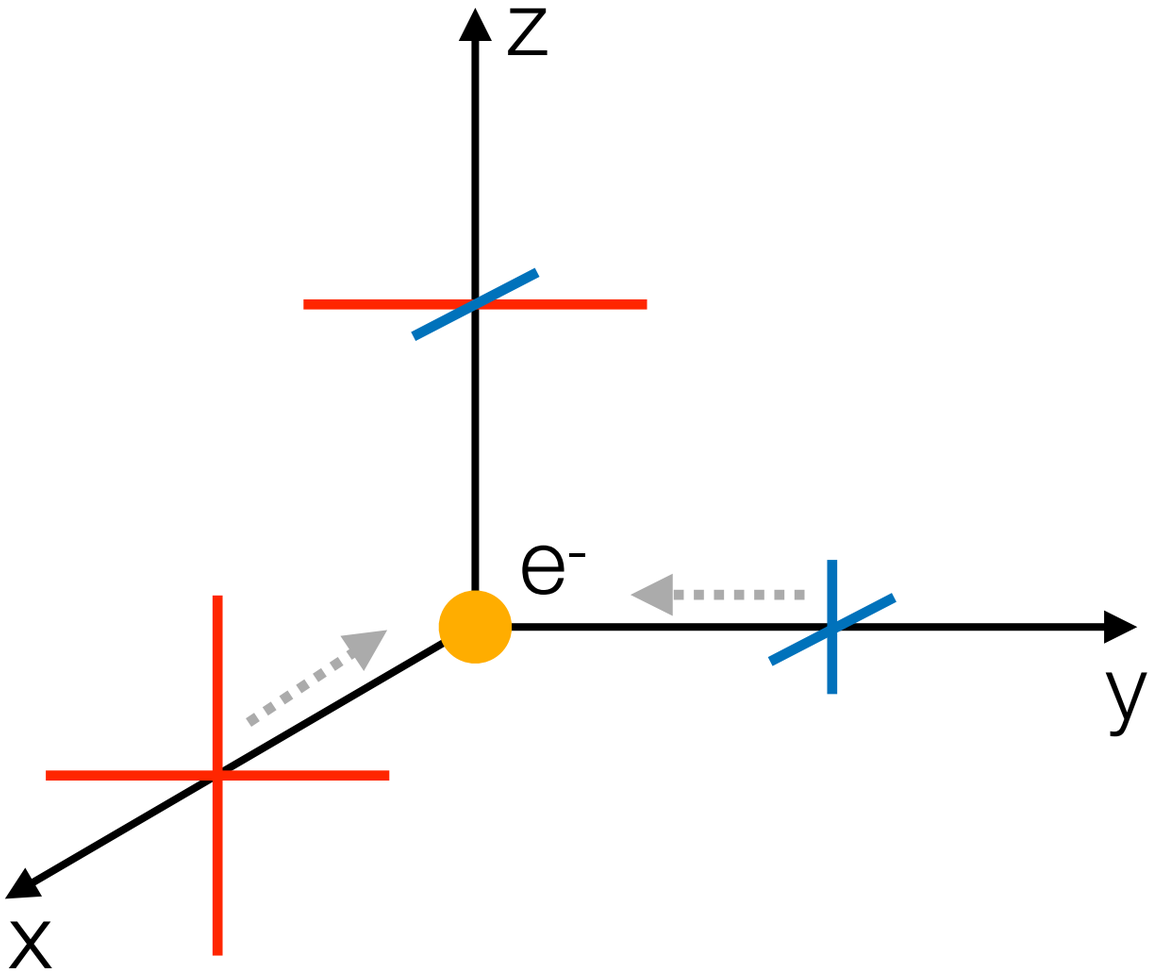


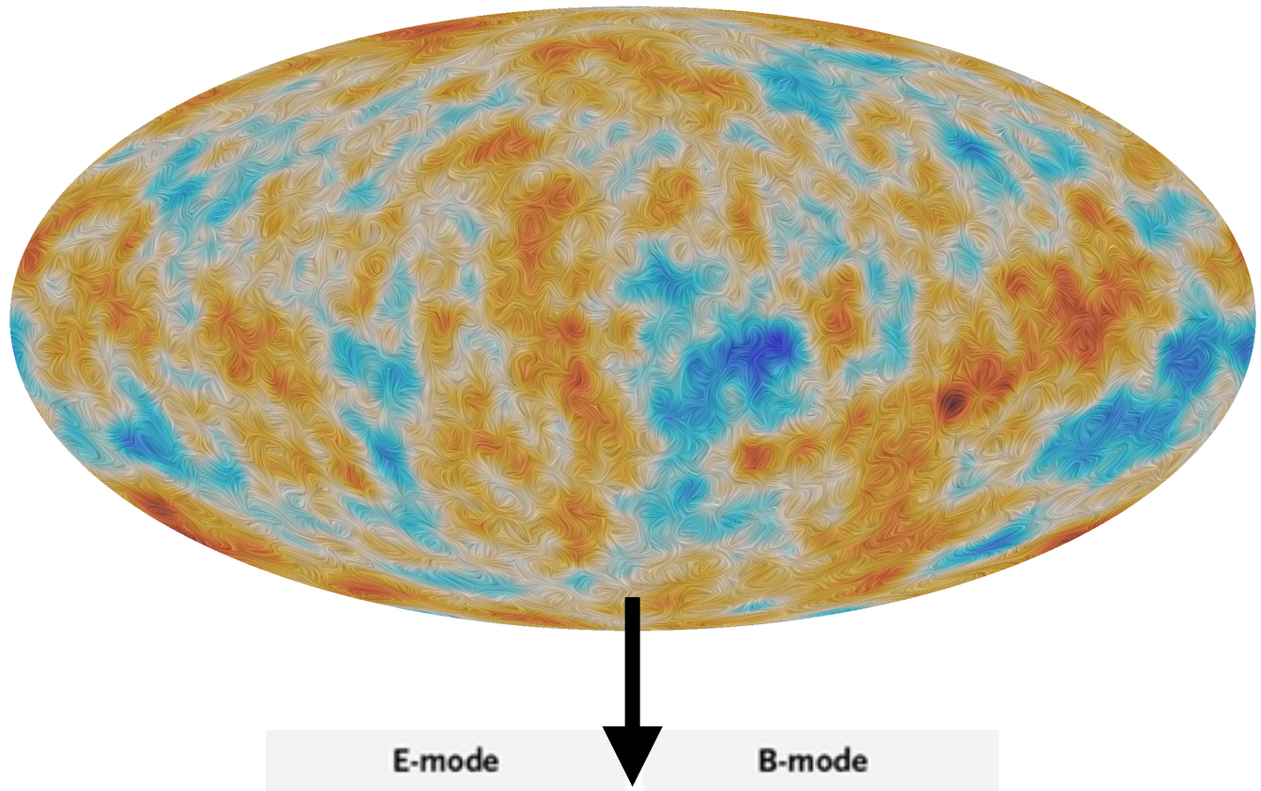


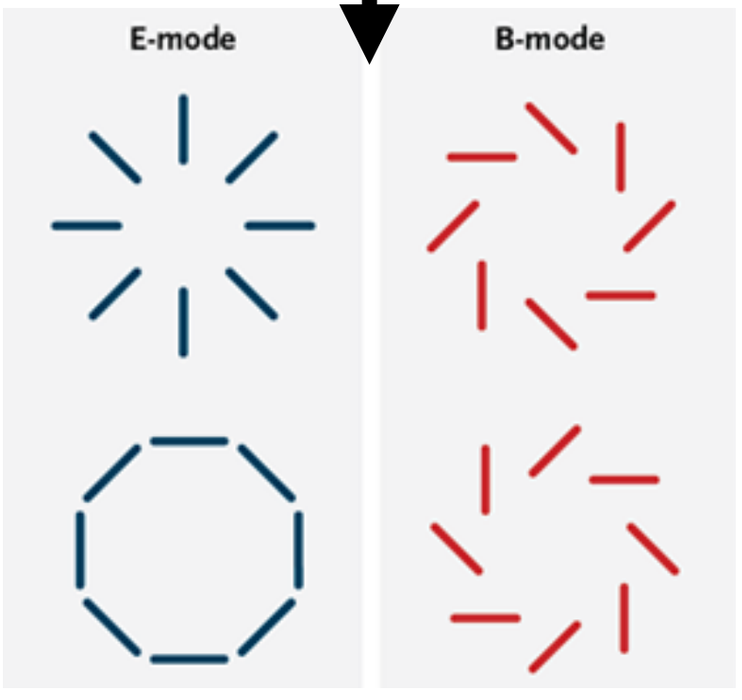


- Thomson scattering in with quadrupole anisotropy
- **E-modes:** sourced by scalar (density) perturbations
- **B-modes:** sourced by gravitational lensing of E-modes + tensor fluctuations due to inflationary gravitational waves

CMB Polarization







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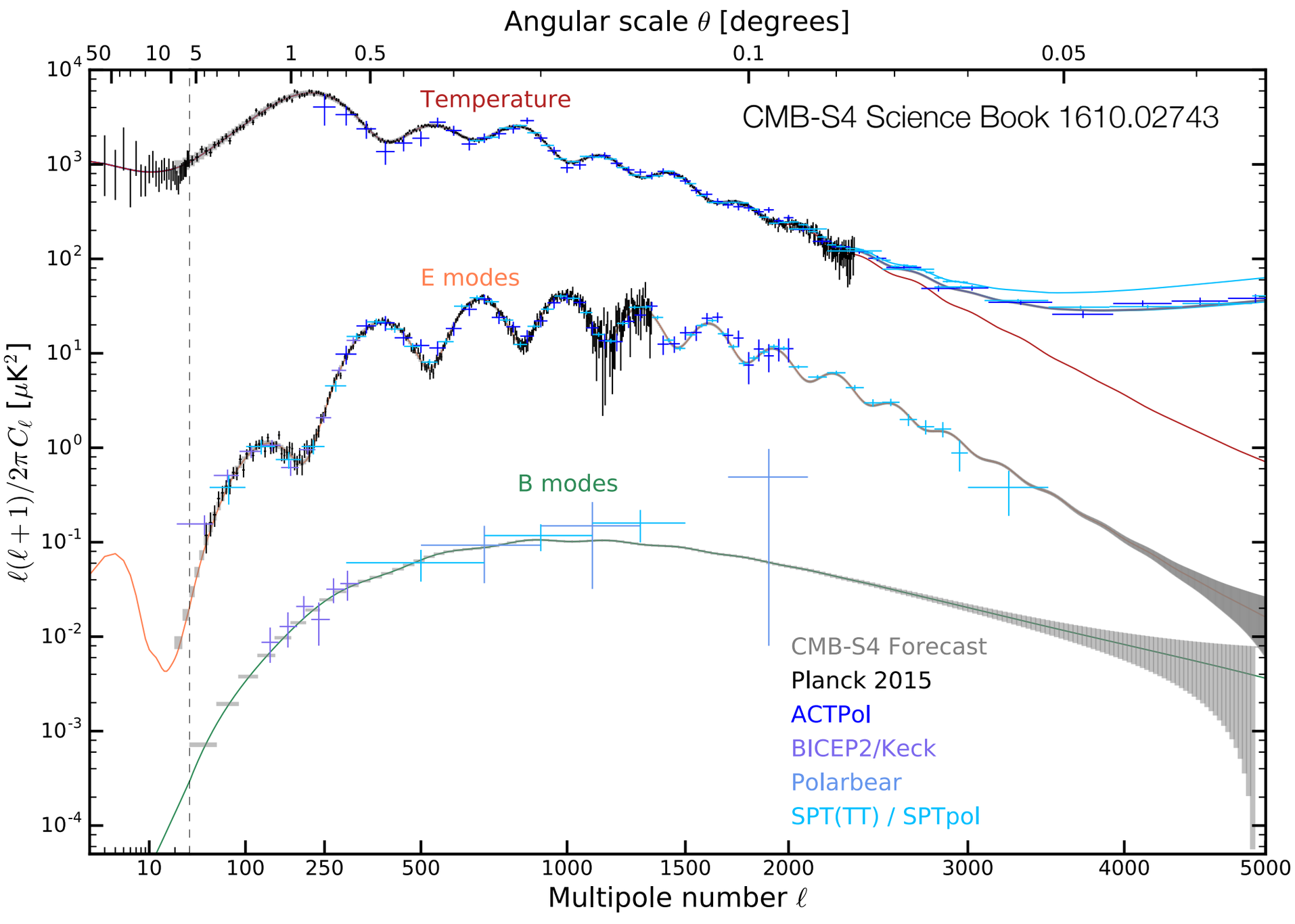
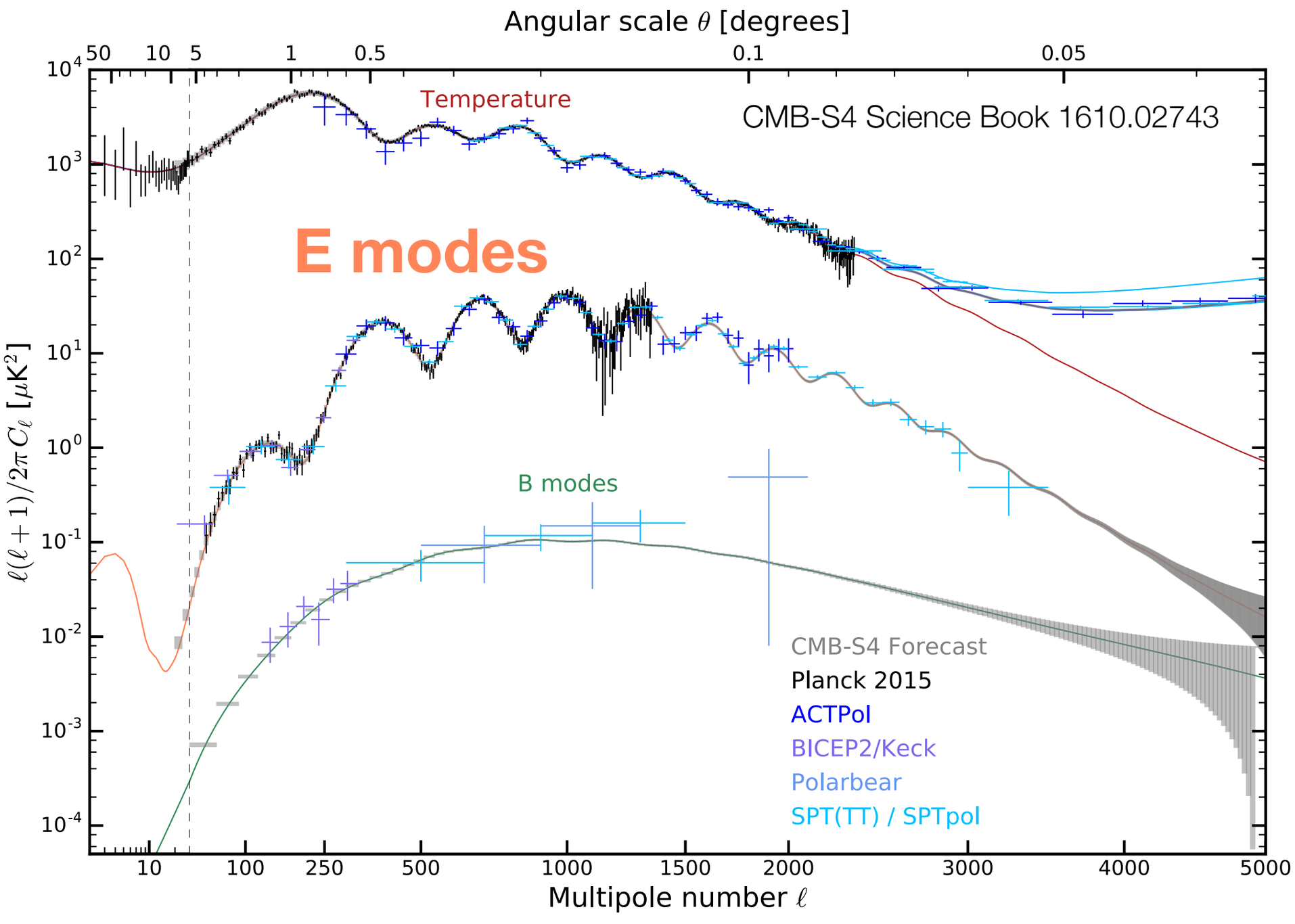

Angular scale θ [degrees]
50
10
5
1
0.5
0.1
0.05
Temperature
CMB-S4 Science Book 1610.02743
E modes
B modes
$\ell(\ell+1)/2\pi C_\ell$ [μK^2]
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
CMB-S4 Forecast
Planck 2015
ACTPol
BICEP2/Keck
Polarbear
SPT(TT) / SPTpol
10
100
250
500
1000
1500
2000
3000
4000
5000
Multipole number ℓ

Motivation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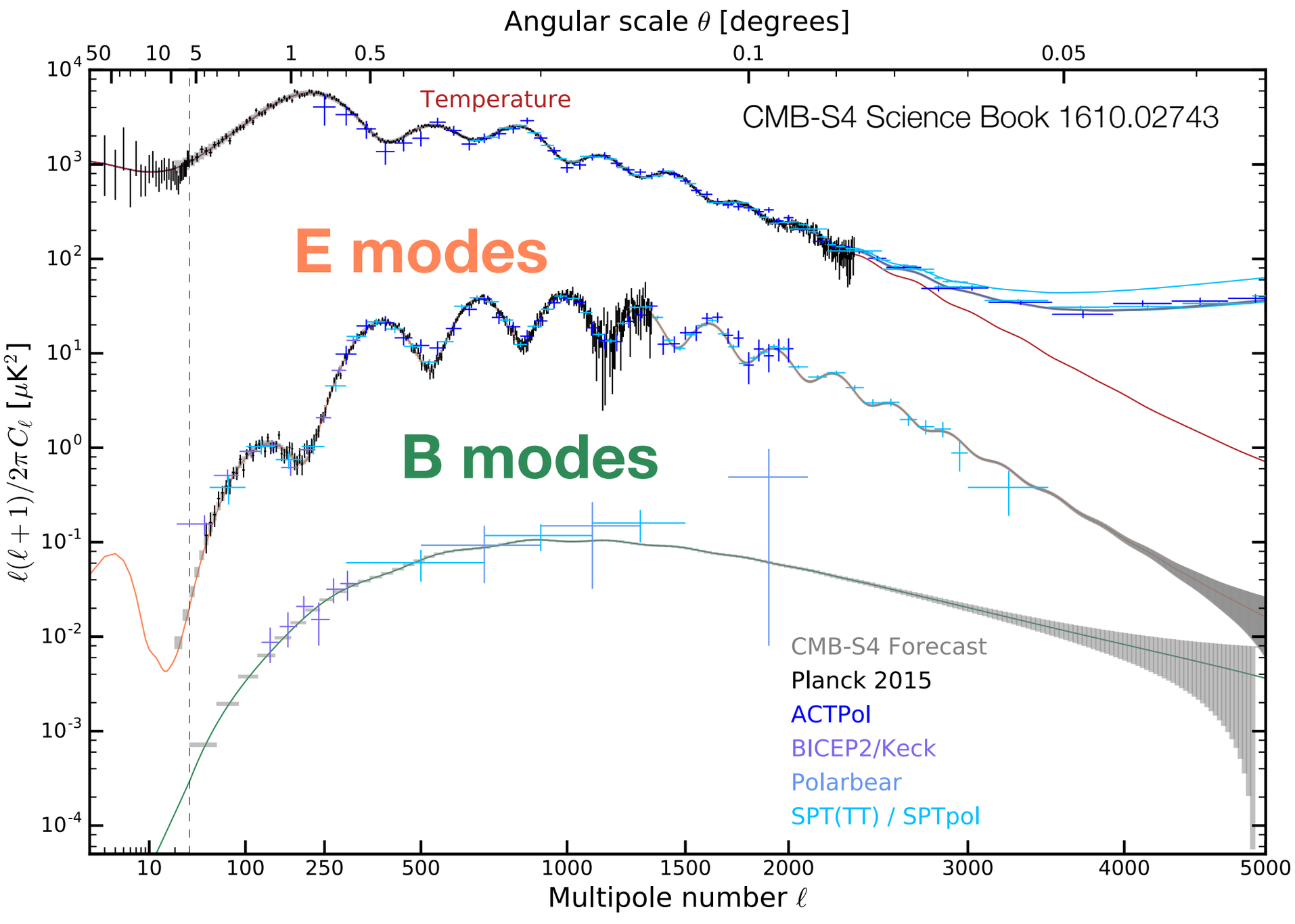
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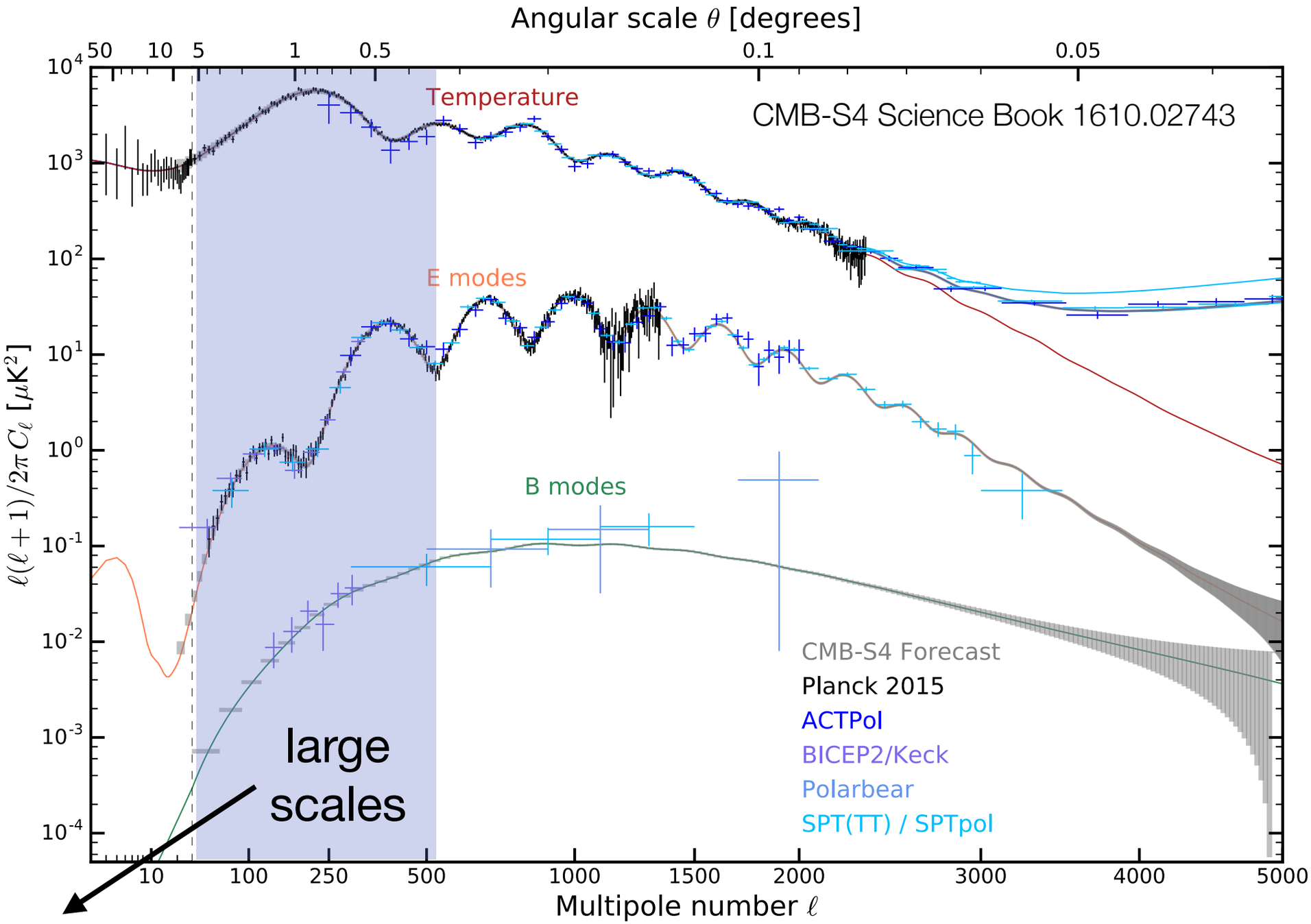
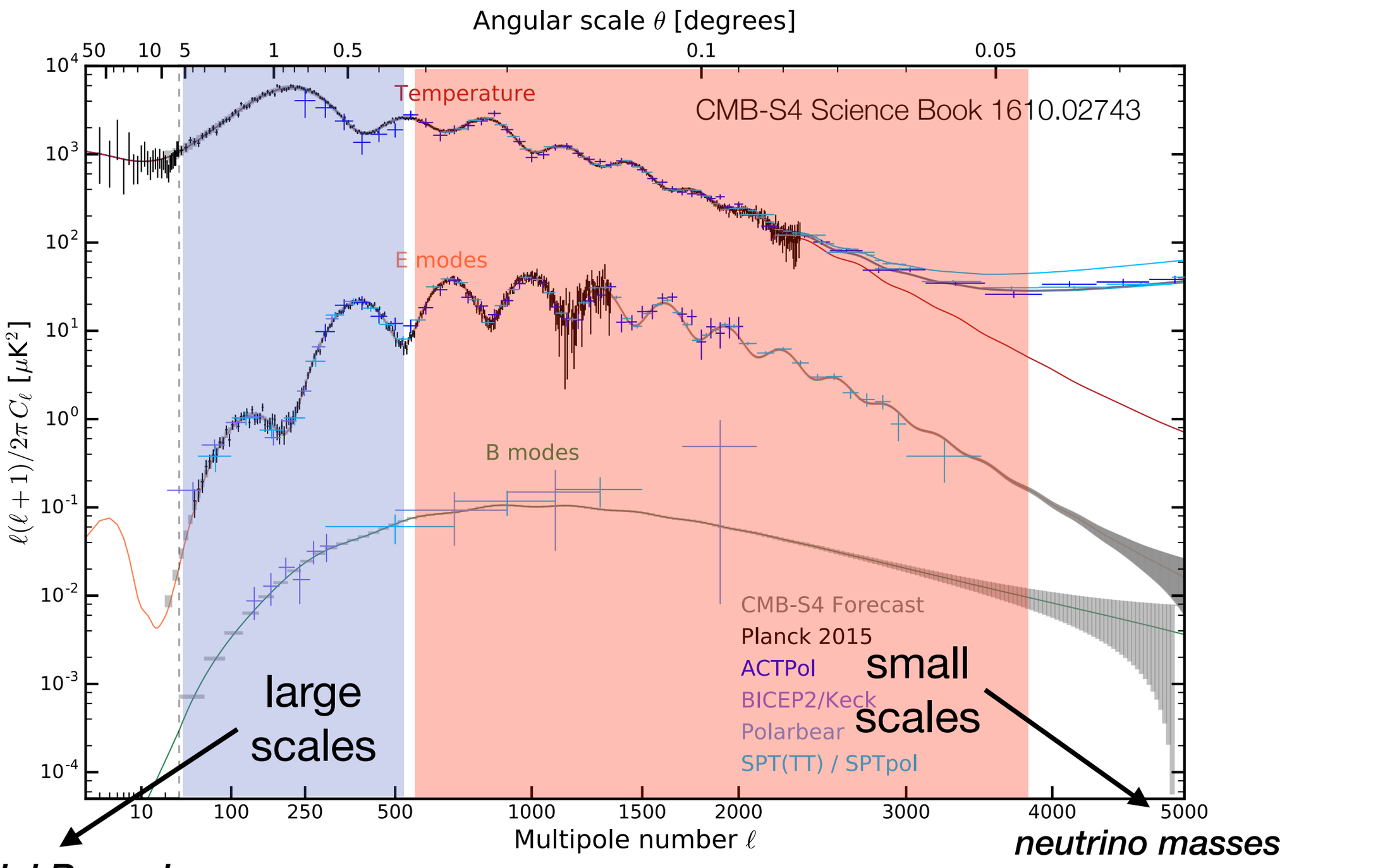


primordial B-modes inflation

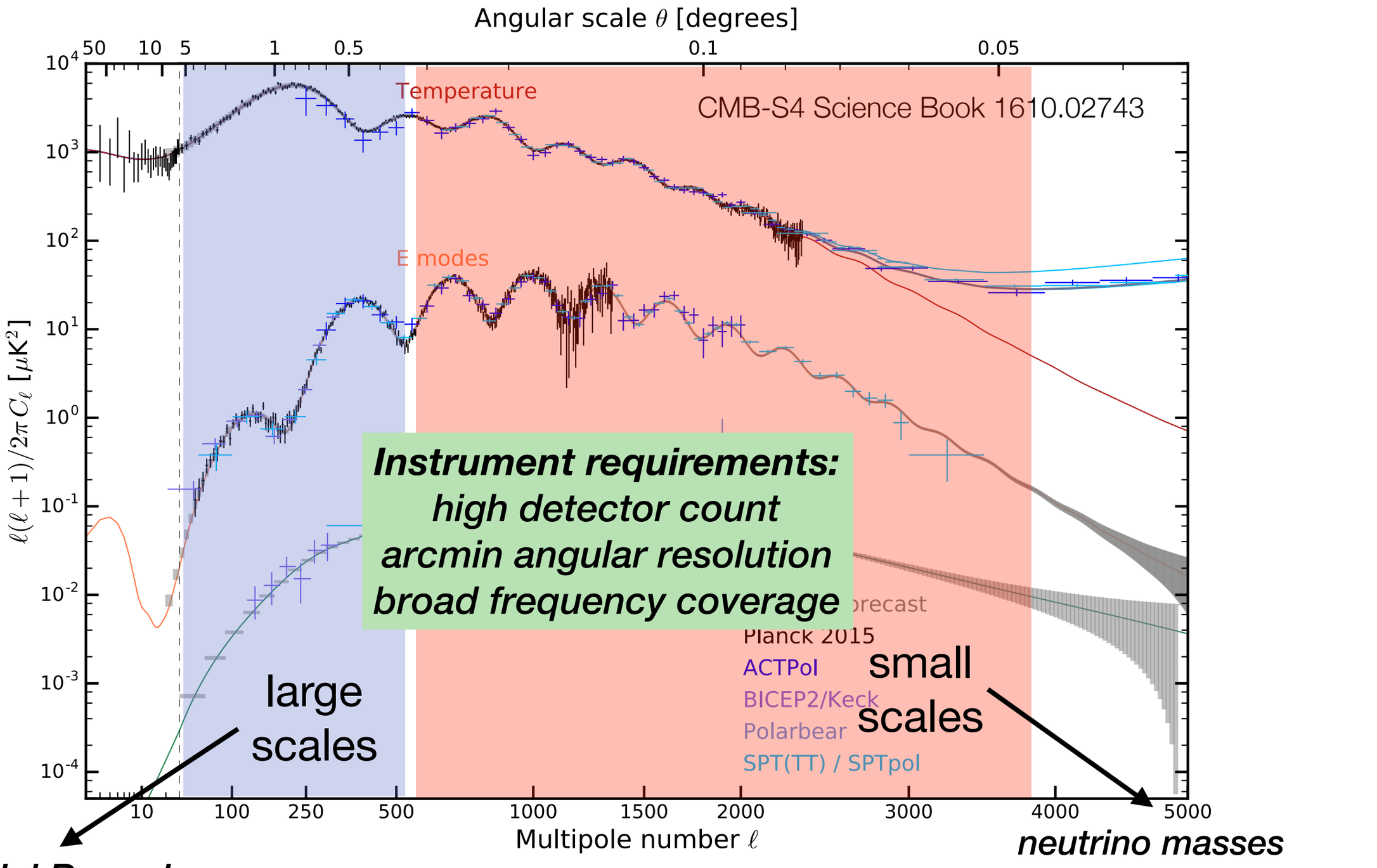
Motivation



primordial B-modes
inflation

neutrino masses
light relics (N_{eff})
galaxy clusters, SZ effect

Motivation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0.05
Temperature
CMB-S4 Science Book 1610.02743
E modes
$\ell(\ell+1)/2\pi C_\ell$ [μK^2]
Instrument requirements:
high detector count
arcmin angular resolution
broad frequency coverage
Planck 2015
ACTPol
BICEP2/Keck
Polarbear
SPT(TT) / SPTpol
large scales
small scales
Multipole number ℓ
primordial B-modes
inflation
neutrino masses
light relics (N_{eff})
galaxy clusters, SZ effect

photo credit: Jason Gallicchio

South Pole Telescope

- 10 m primary mirror
- 1.3 arcmin angular resolution at 150 GHz, highest resolution CMB maps
- South Pole is excellent site for CMB observations: high altitude, dry, extremely stable atmosphere

Planck
143 GHz
50 deg²

The moon
(for scale)

SPT

150 GHz

50 deg^2

finer angular resolution

deeper on a fraction of the sky

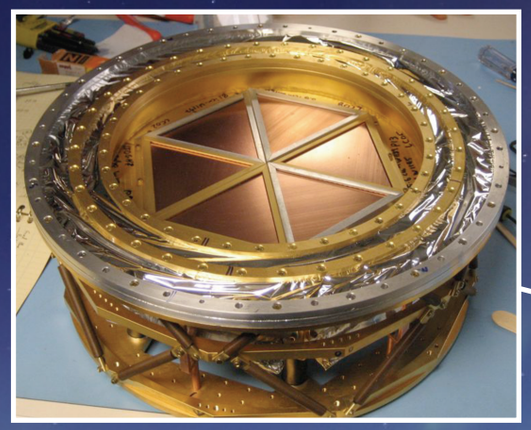
The moon (for scale)

photo credit: Jason Gallicchio

South Pole Telescope

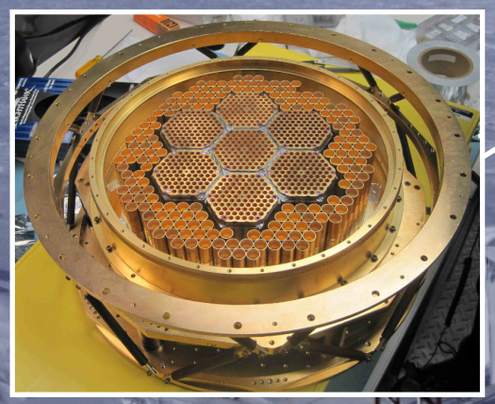
- 10 m primary mirror
- ~1 arcmin angular resolution, highest resolution CMB maps
- South Pole is excellent site for CMB observations: high altitude, dry, extremely stable atmosphere

SPT-SZ (2007)



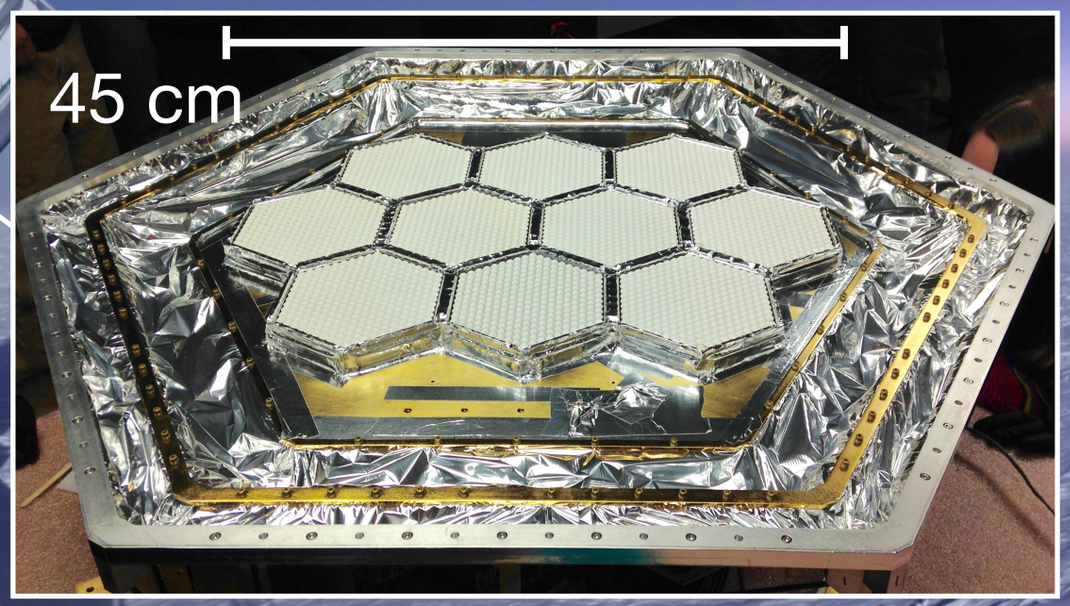
960 detectors at 95, 150, 220 GHz

SPTpol (2012)



1500 detectors at 90, 150 GHz w/polarization

SPT-3G (2017)



15,000 detectors at 90, 150, 220 GHz w/polarization

photo credit: Jason Gallicchio

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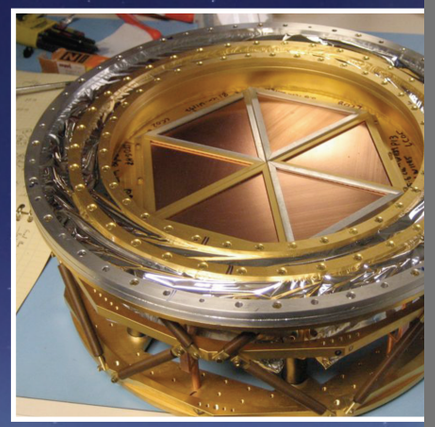
SPT-SZ (200

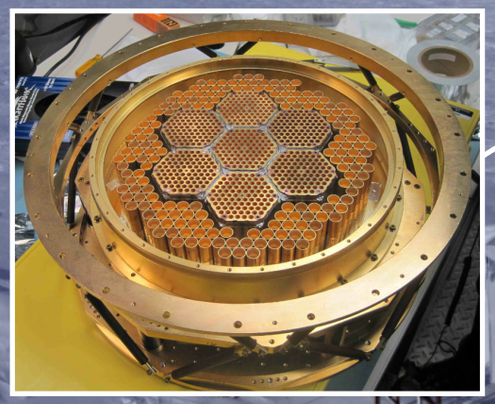


960 detectors at 95, 150,

complete redesign of everything except primary structure:

- secondary optics
- detectors
- readout electronics
- software

SPTpol (2012)



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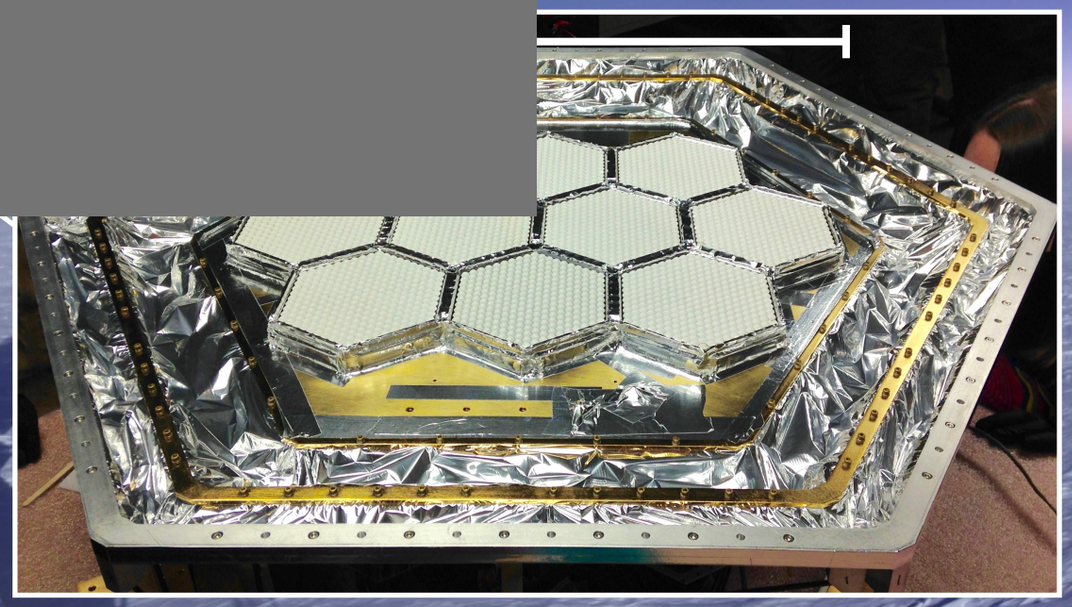
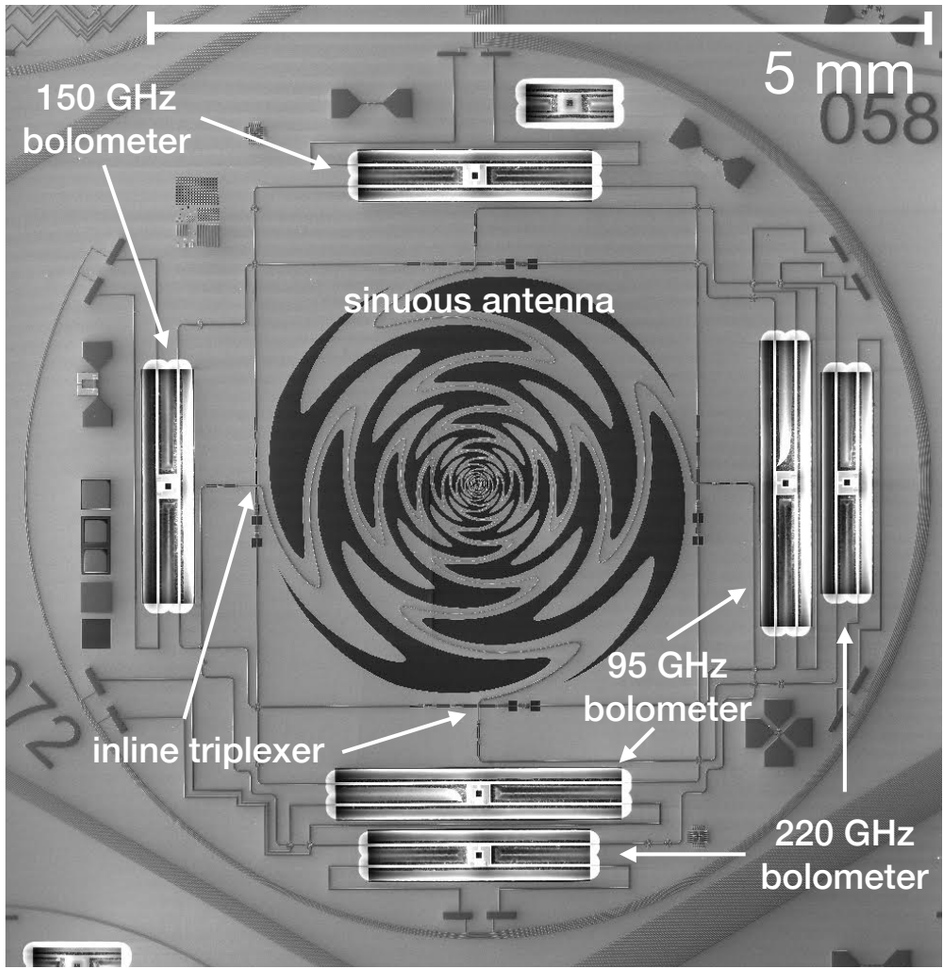
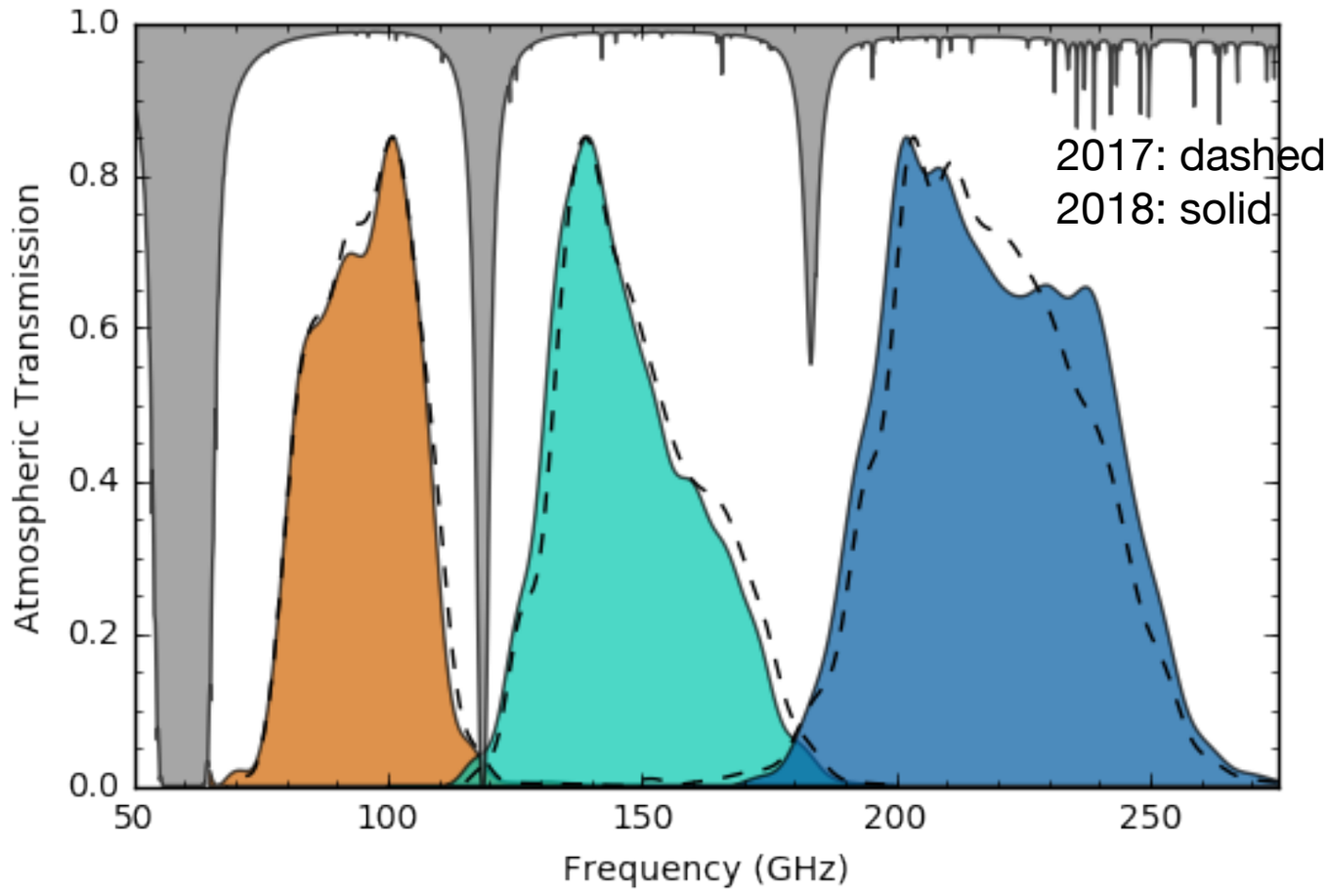


15,000 detectors at 90, 150, 220 GHz w/polarization

SPT-3G: Multichroic Pixels





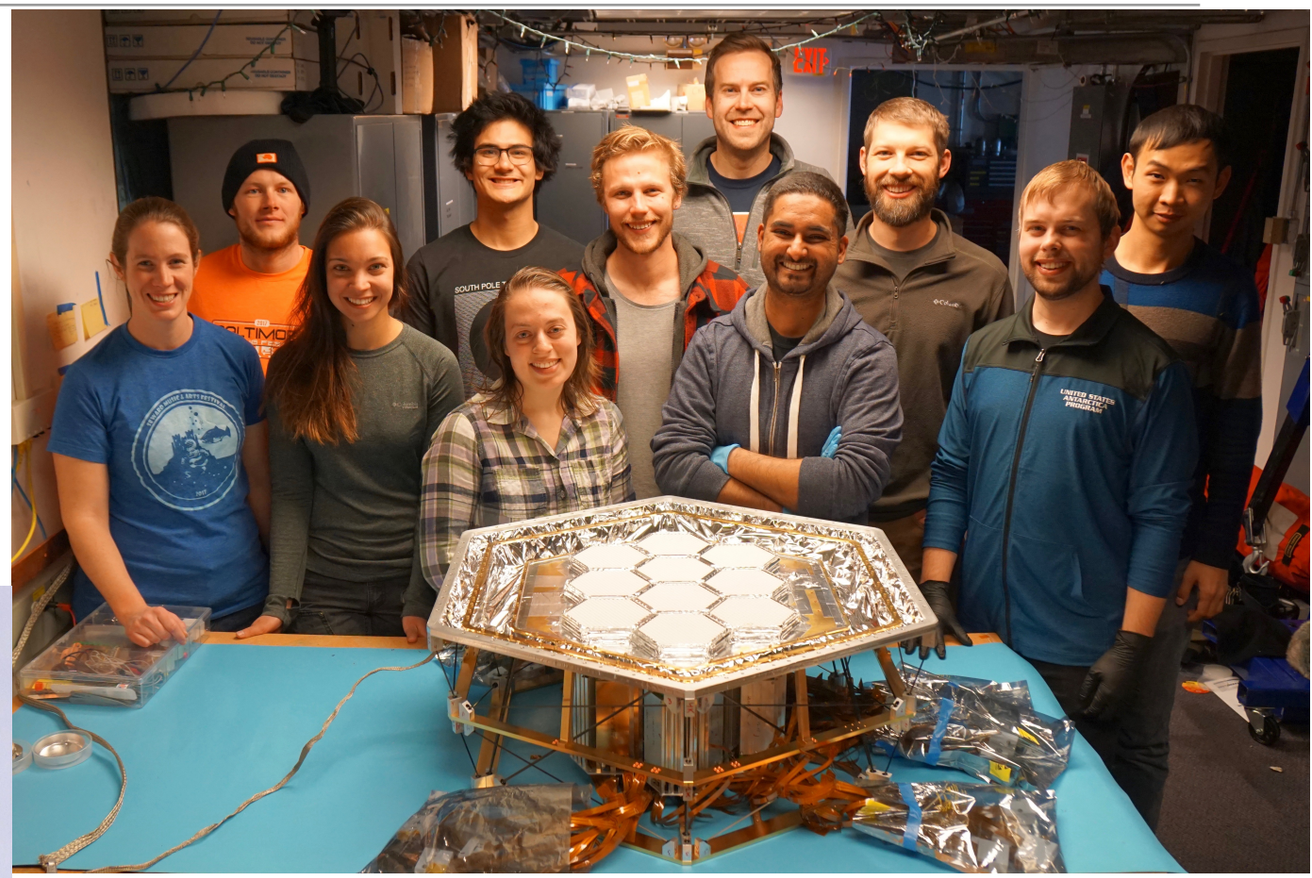
- ***3 frequency bands per pixel:*** enables higher detector packing density within focal plane

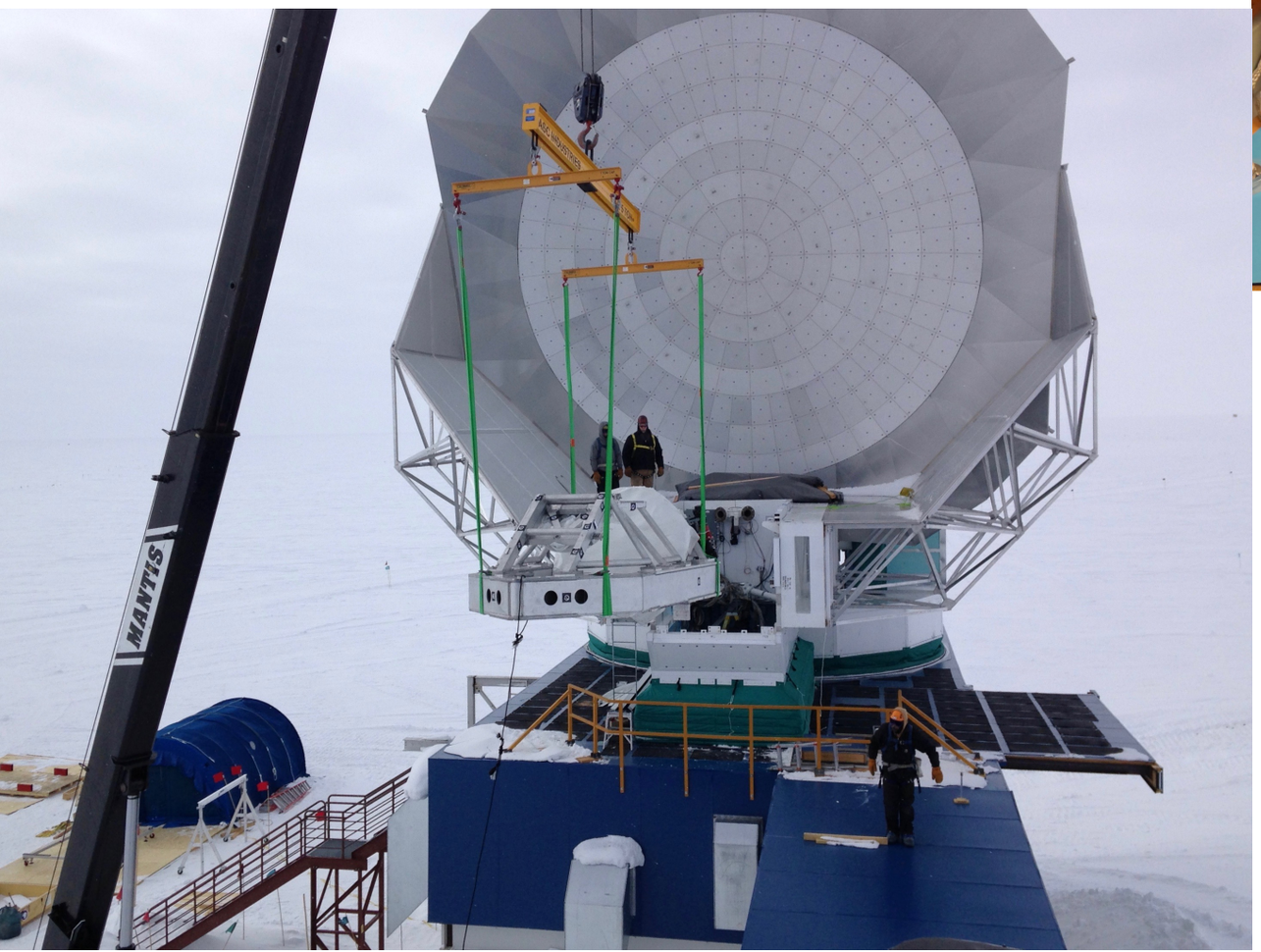
- Bands at **95, 150, 220 GHz** help mitigate foregrounds from dust, enable SZ cluster science

Deployment and 2018 Upgrades

- First deployed in early 2017
- Major upgrades in early 2018:

    1. ***More sensitive detectors:*** new detectors with lower saturation power



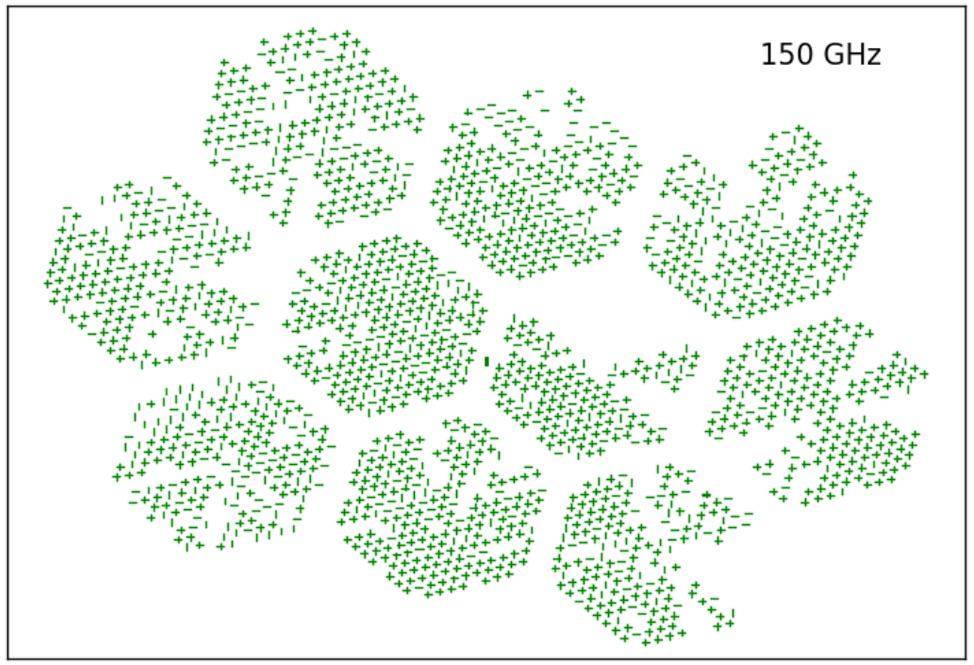


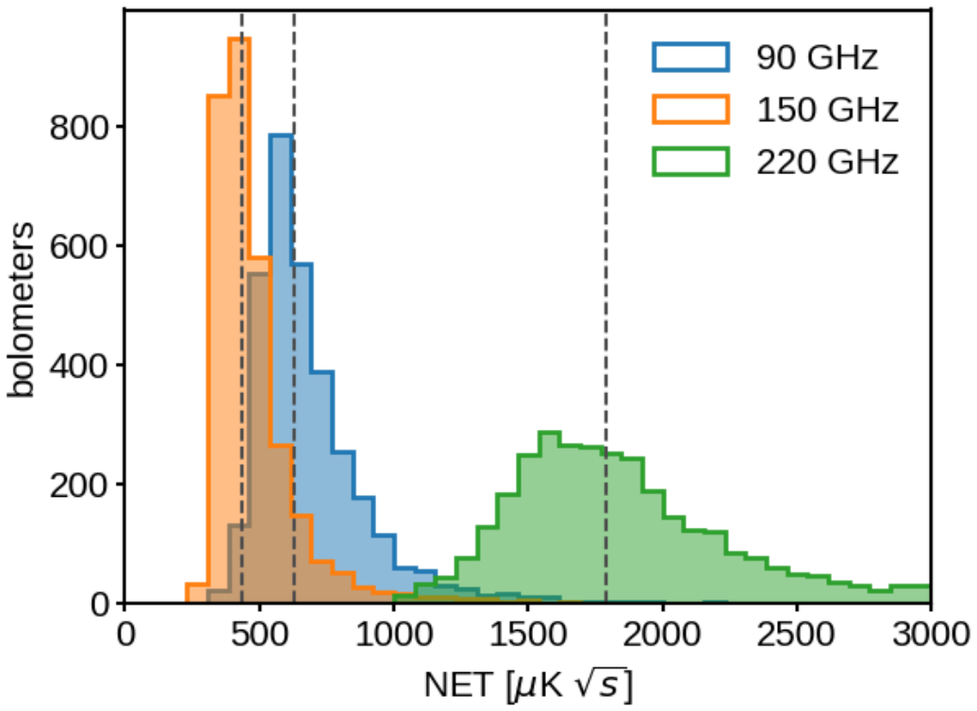
2. ***Improved optical efficiency:*** Replaced AR coatings of lenses (efficiency now ~40-45% at 150 GHz)
3. ***Reduced readout noise:*** Replaced SQUID amplifiers and modified electronics to match detector impedance

2018 Performance

- 11,000 operational detectors (~75% yield)
- Photon-noise-dominated performance at 90, 150, 220 GHz, consistent with expectations
- 220 GHz NET is 1.5x expected, believed due to poor transmission in AR coatings of alumina surfaces

band	NET (array) [uK rtsec]	mapping speed (x SPTpol)
95 GHz	10	11 x
150 GHz	8	5 x
220 GHz	30	inf. x

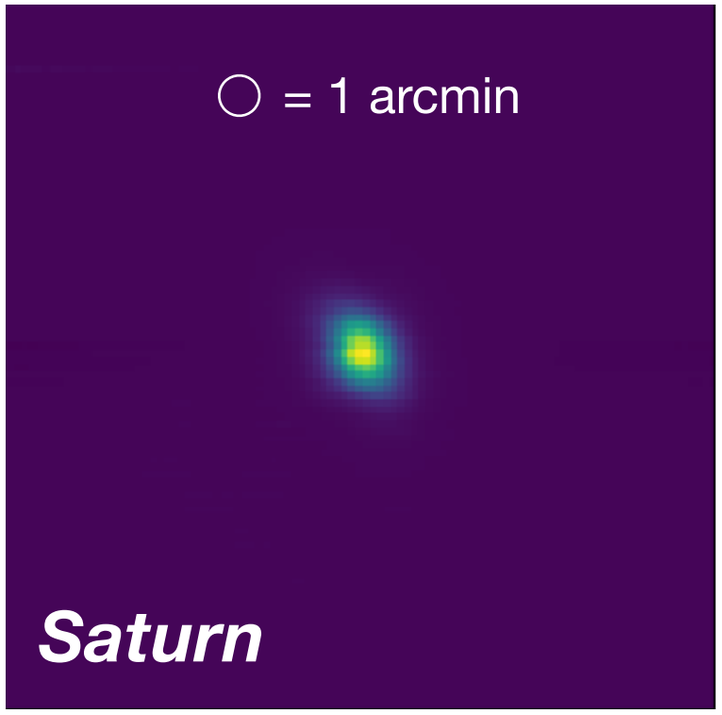


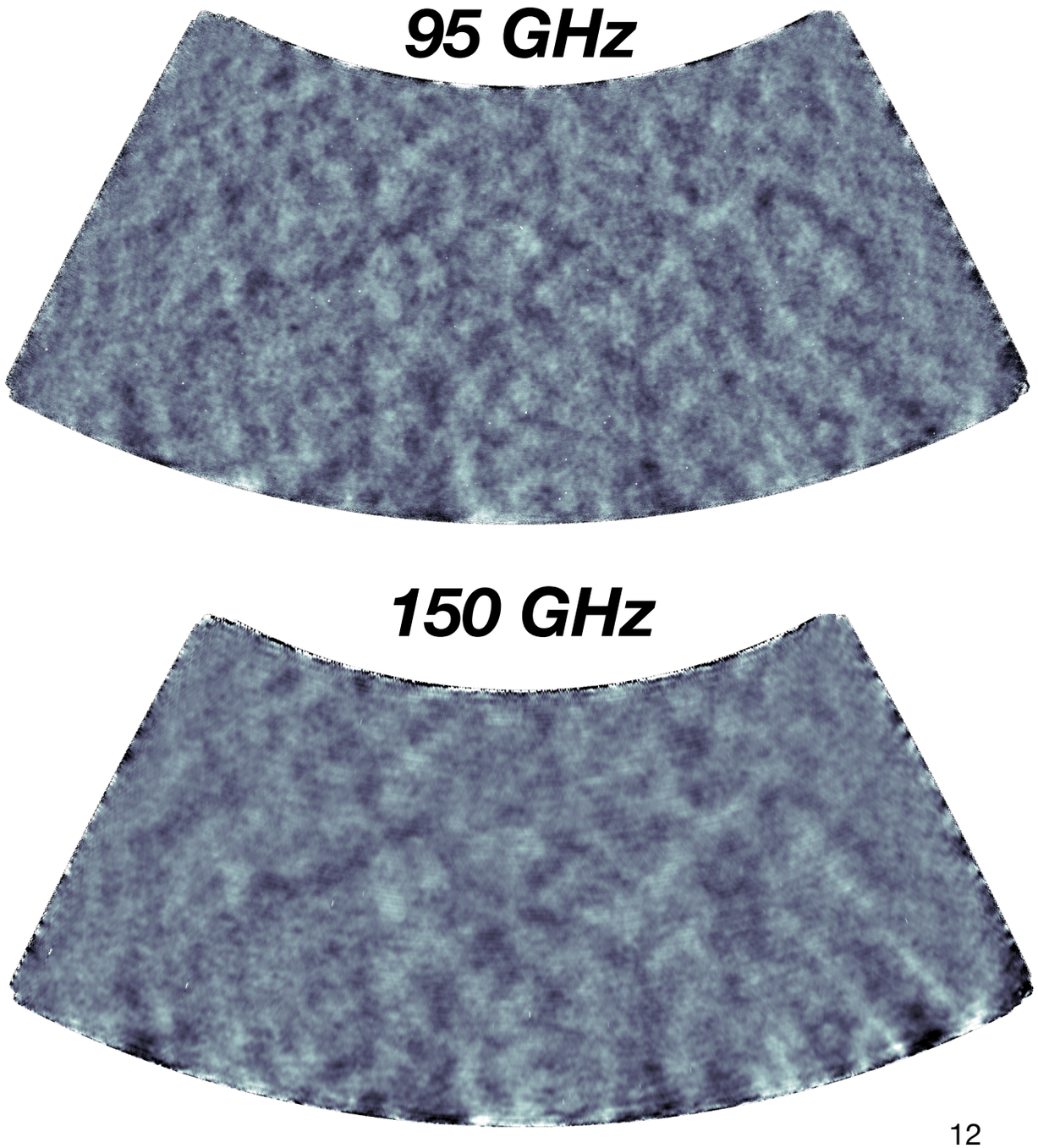


500d Validation Maps

- 500d field observed early in 2018 to validate detector performance

- Common structures and point sources visible in all three bands





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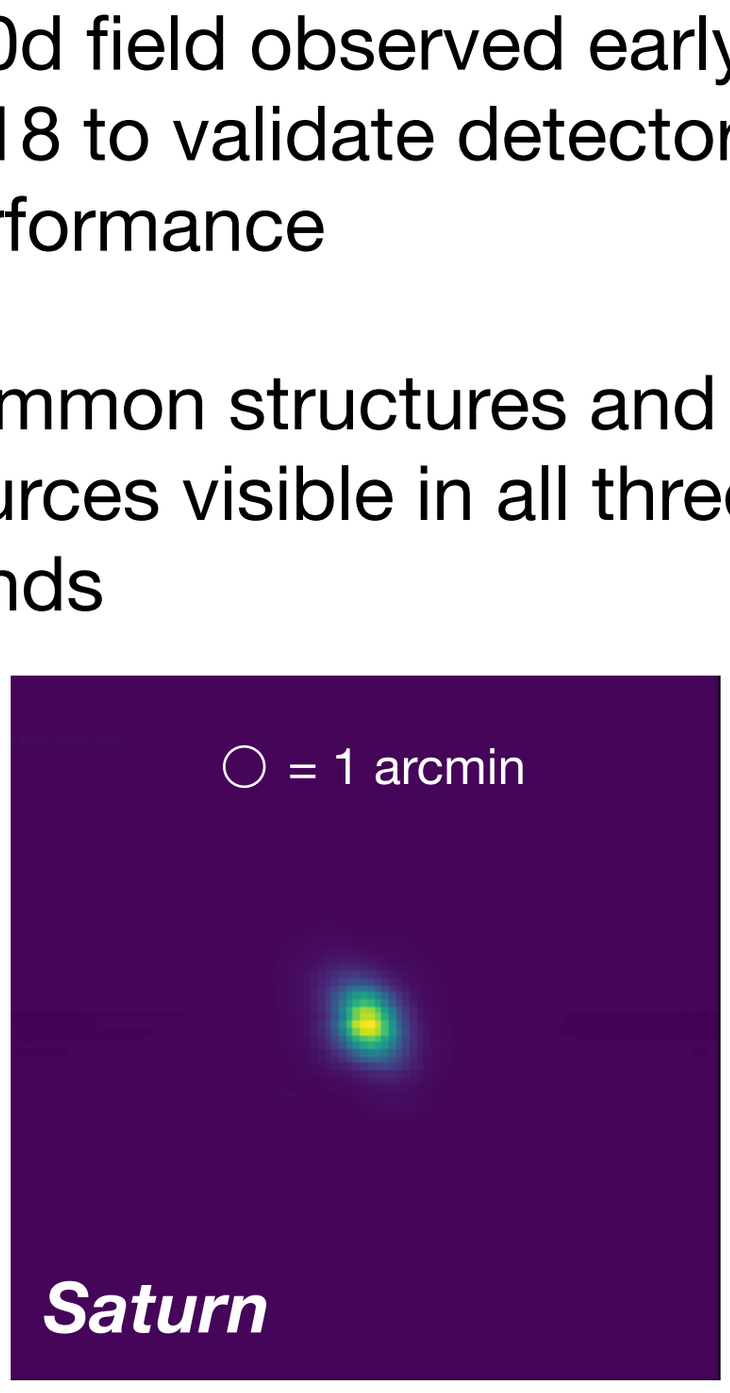
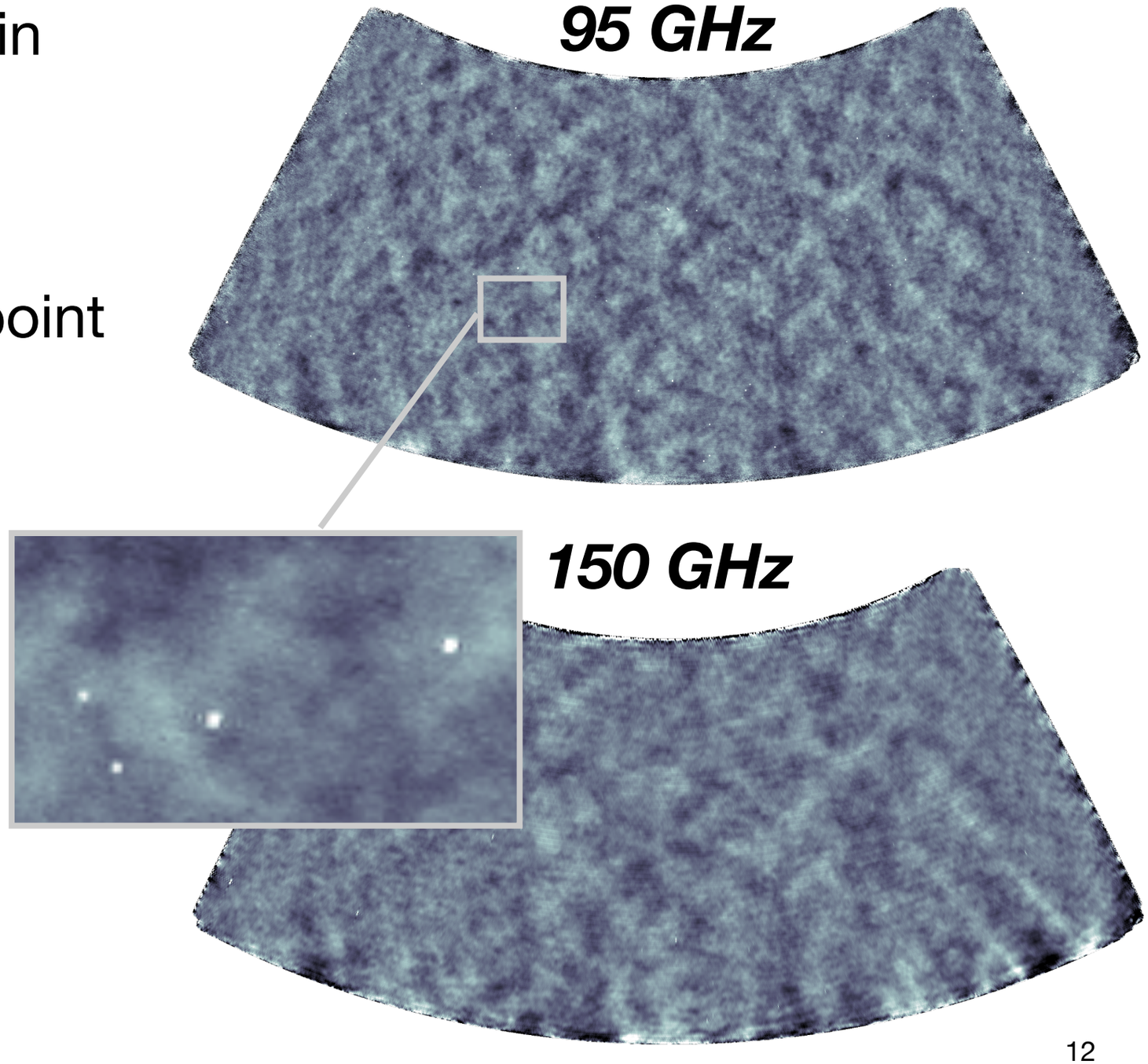
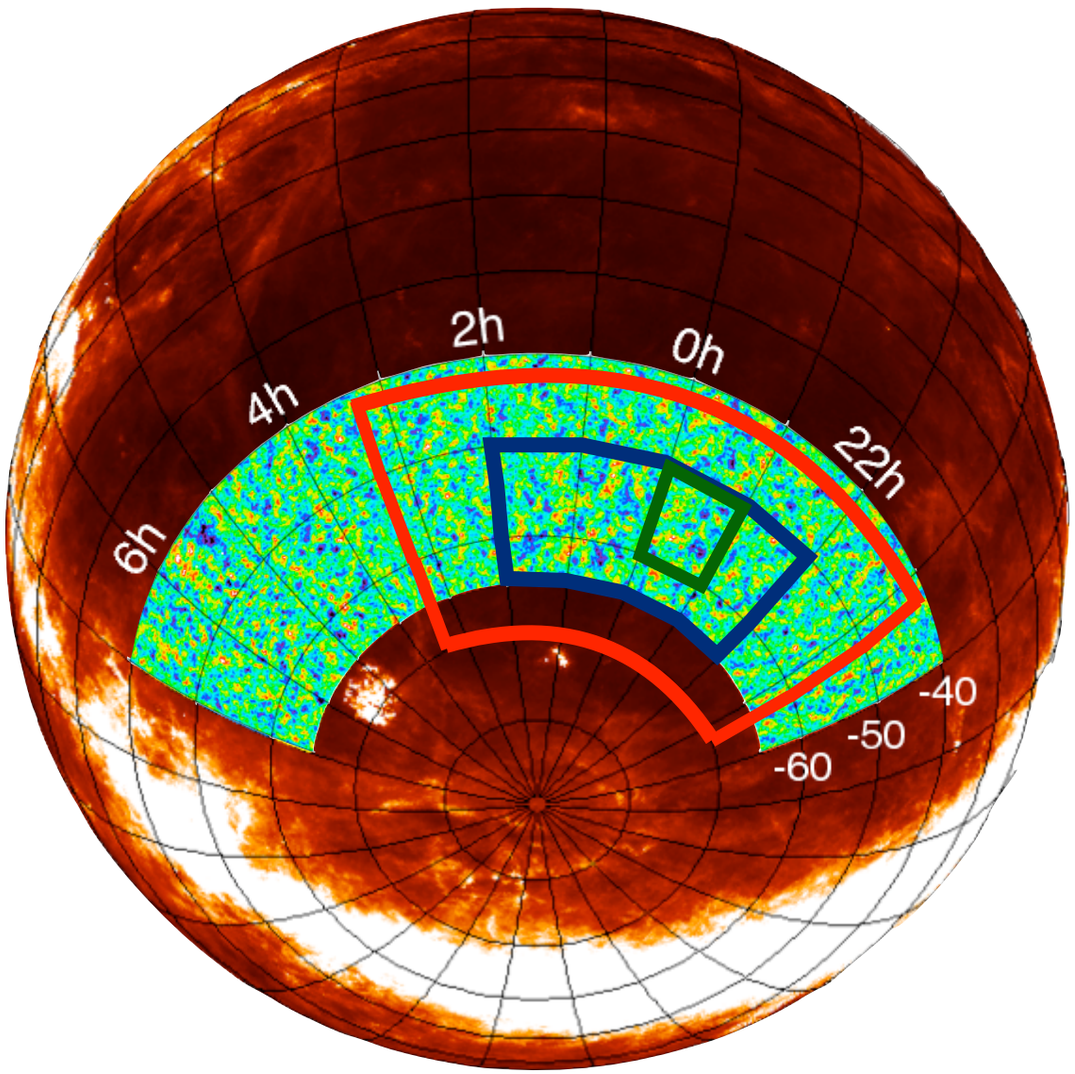




Survey and Projected Depth

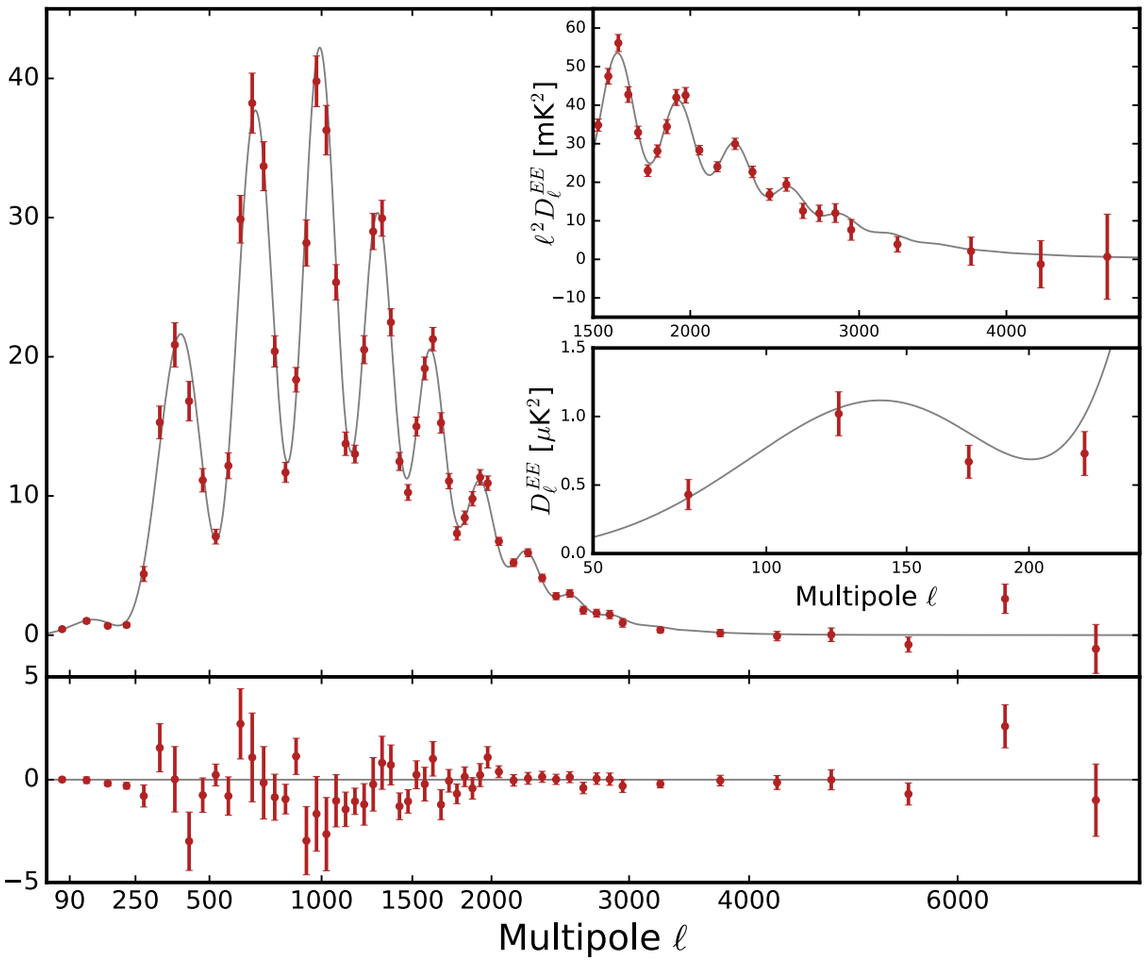


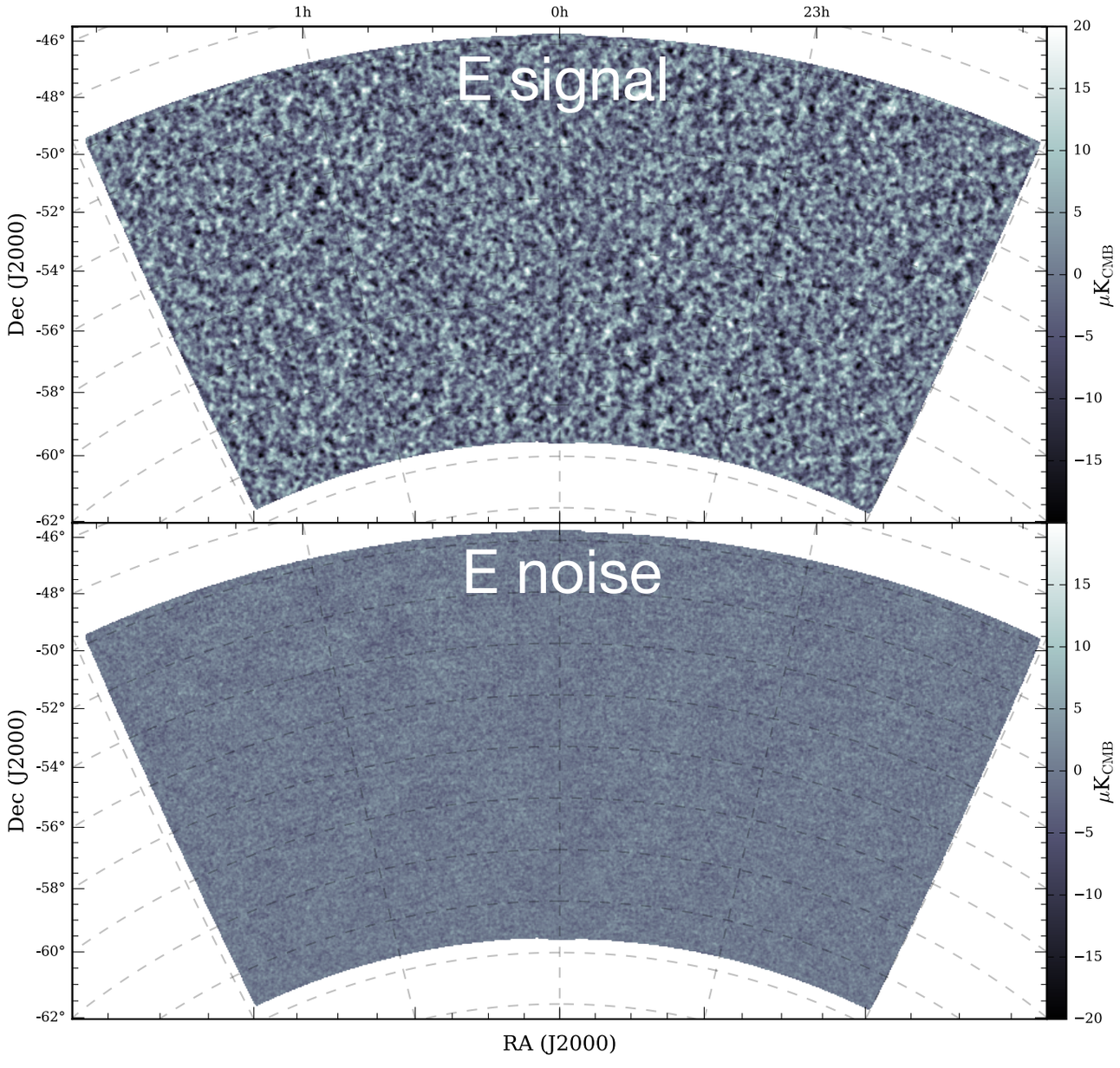
	Obs. Years	Area (deg2)	95 GHz (uK-arcmin)	150 (uK-arcmin)	220 (uK-arcmin)
SPT-SZ	2007-11	2500	40	17	80
SPTpol-Main	2012-16	500	13	5	-
SPTpol-Deep	2012-16	100	10	3.5	-
SPT-3G ***projected***	***2018-22***	***1500***	***3.3***	***2.5***	***9.8***

- Started observing 1500d field in March of 2018
- Overlaps with BICEP/Keck patch of sky. Good for ***delensing***.
- Overlaps with DES survey. Good for ***cross-correlation*** studies.

E-modes with SPTpol 500d

- Detect first 9 acoustic peaks in EE
- Measured over 50 < l < 8000, most sensitive measurement to-date for l>1050
- N_{eff} = 3.18 ± 0.28 (SPTpol+PlanckTT)





Henning, et al. 1707.09353

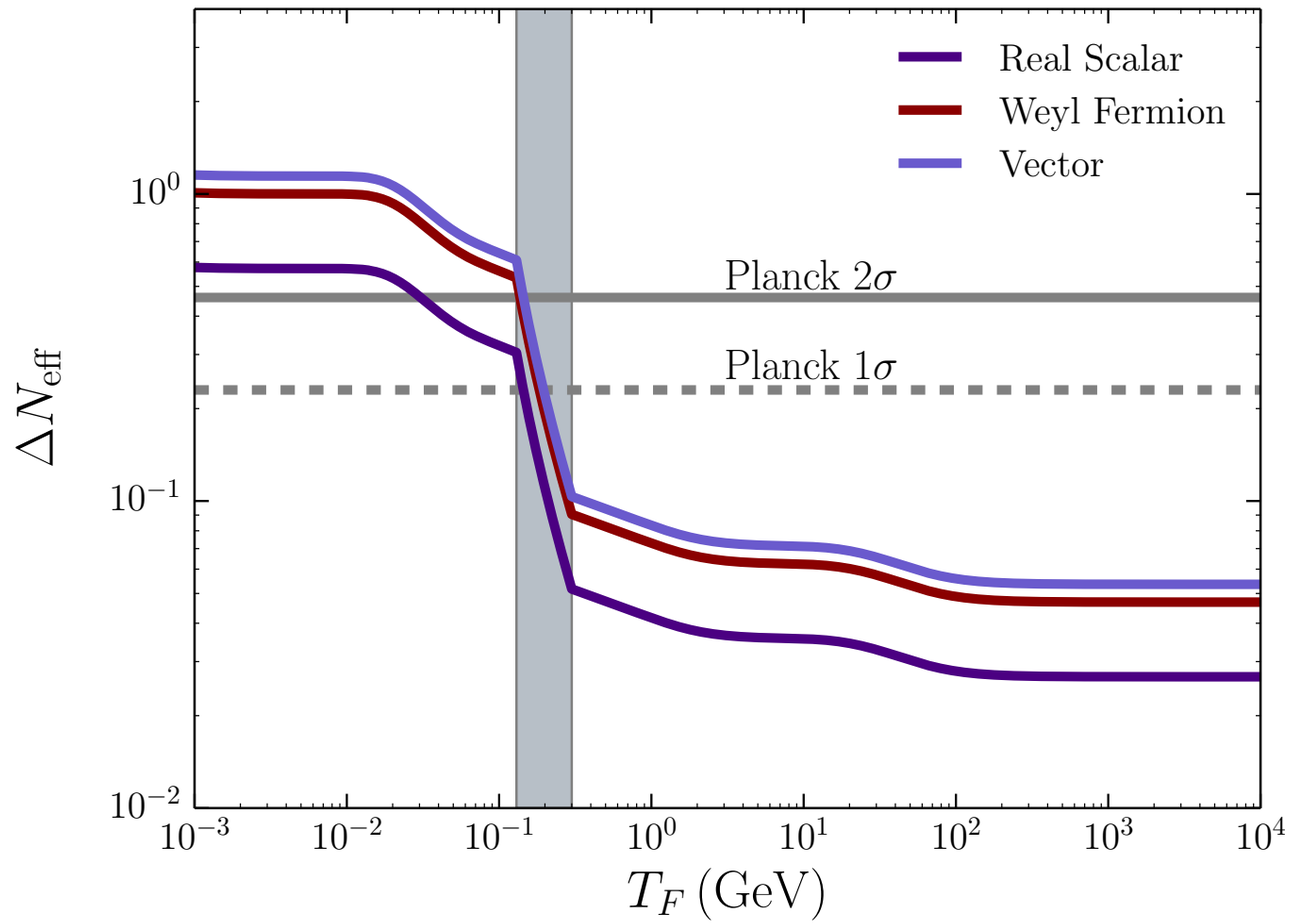
Light Relics: N_{eff}

- N_{eff} parameter measures number of relativistic degrees of freedom at recombination

- Most constrained by phase of acoustic peaks in E-mode power spectrum

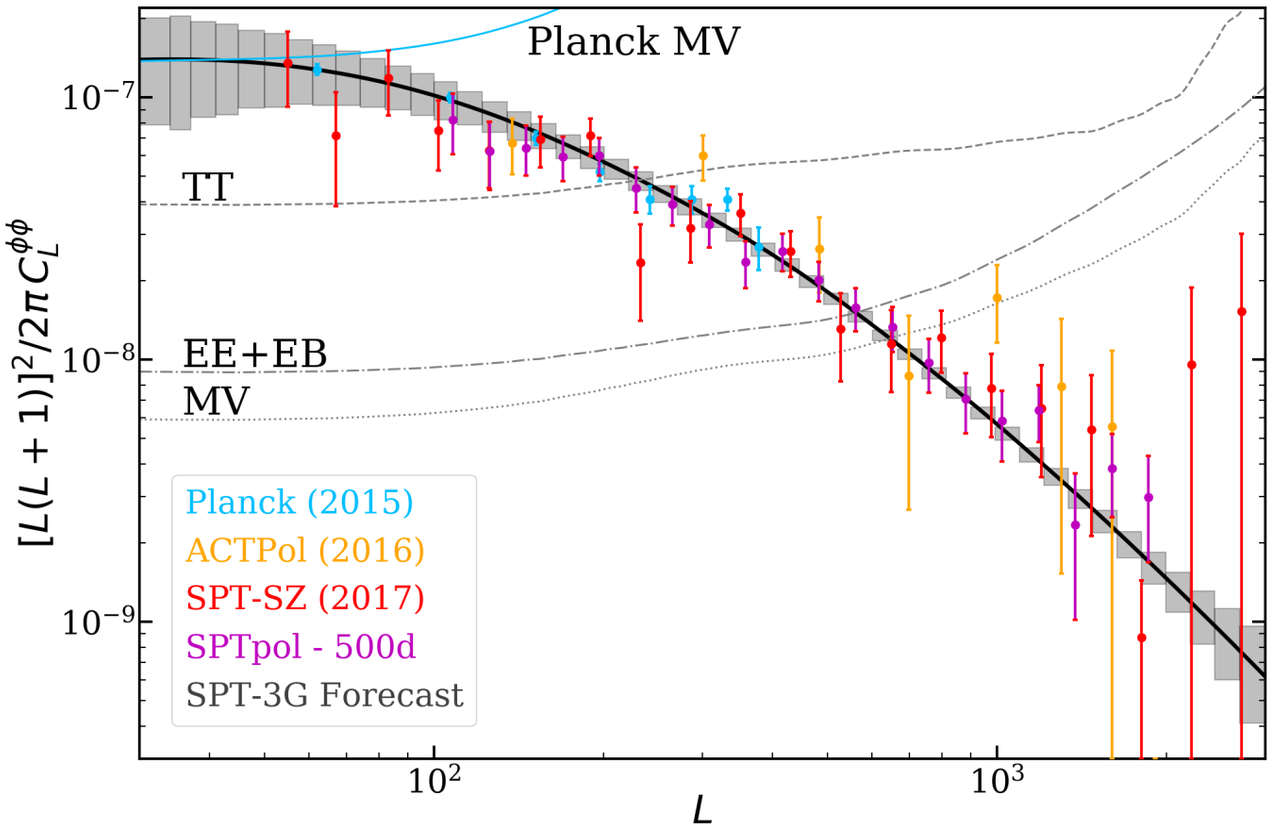
- Light thermal relics contribute a *minimum* of $\Delta N_{eff} > 0.027$, corresponding to decoupling above the top mass (assuming no heavier states)

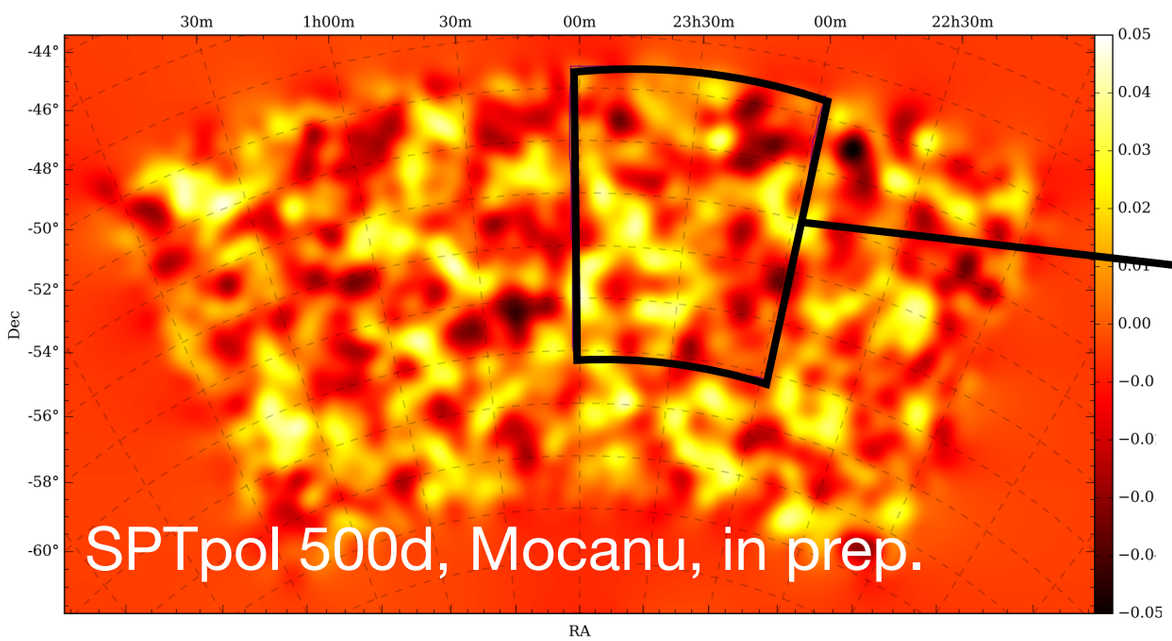
- Very generic probe of BSM physics: axions, gravitinos, other light relics…

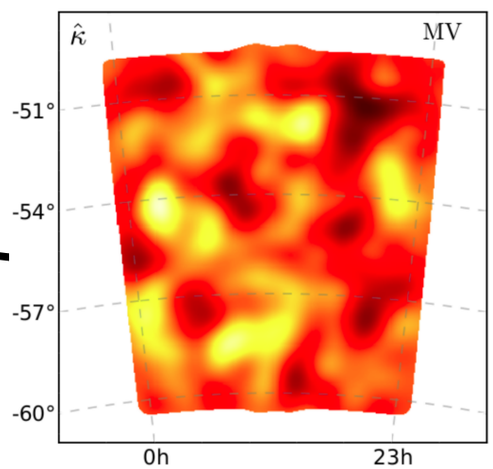


CMB Lensing with SPTpol & SPT-3G

- Gravitational lensing of CMB photons deflects paths by ~2 arcmin
- Mixes E-modes into B-modes
- Combination of T and P information used to reconstruct lensing potential between us and the surface of last scattering
- SPT-3G will significantly improve existing lensing measurements

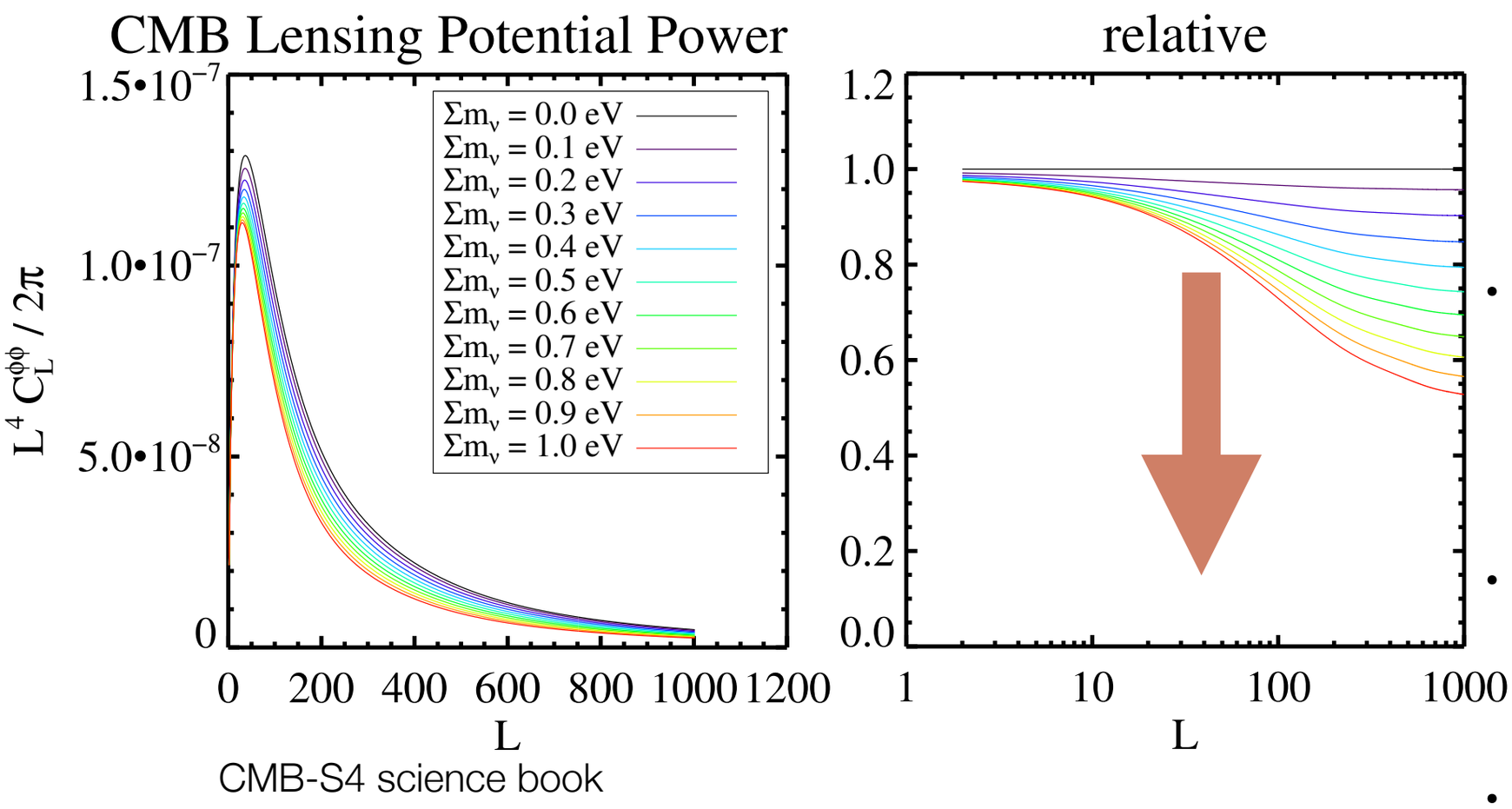






SPTpol 100d, Story 1412.4760

Neutrino Mass



CMB-S4 science book

- ***Neutrino masses suppress growth of structure at small scales***
- CMB lensing power spectrum can be used to measure neutrino mass
- ~5% suppression per 0.1eV in total mass
- ***Lower*** limit from oscillations:

$$\sum m_\nu > 0.06\text{eV}$$

oscillations depend on mass differences
not absolute mass scale

Delensing

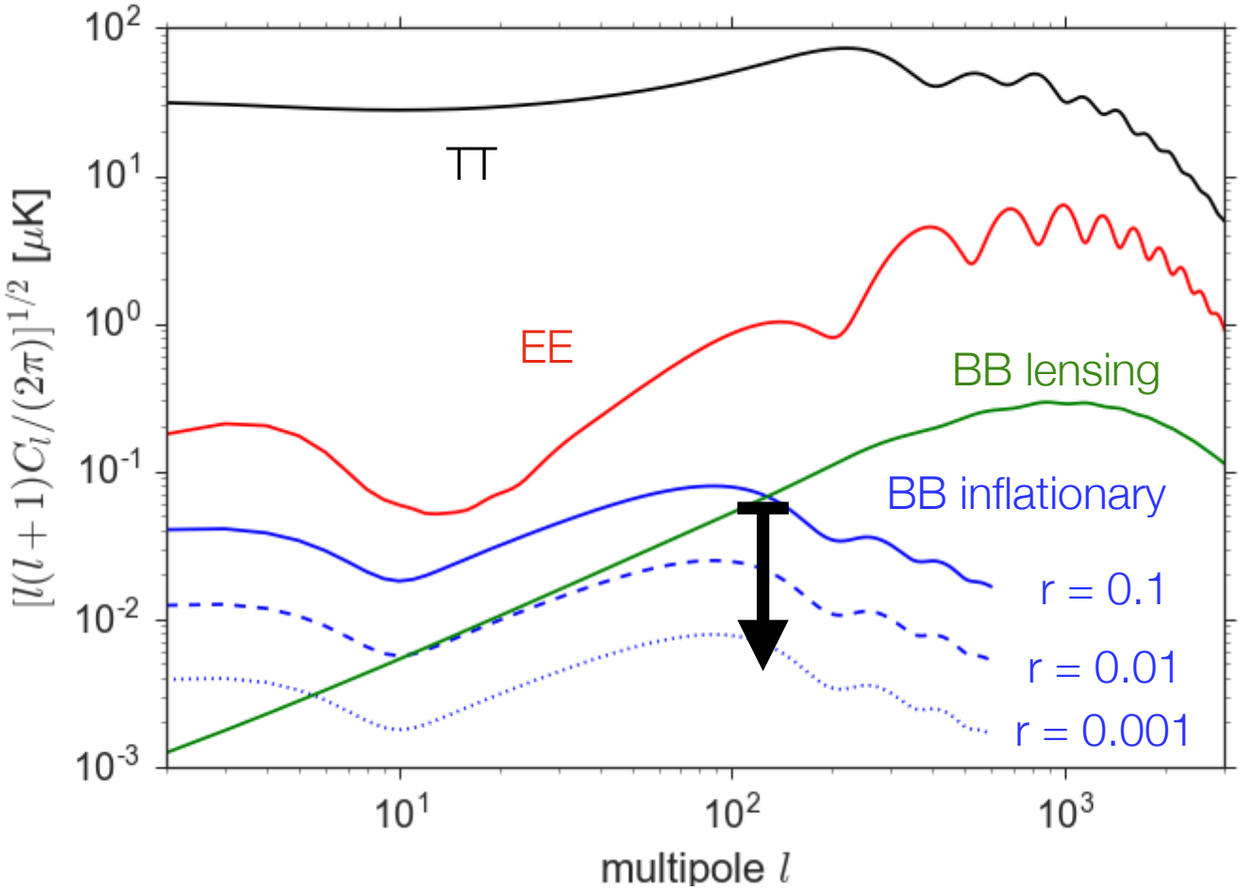
- Inflationary B-modes are contaminated by lensing signal at small scales

- Can “subtract away” using high-resolution E-mode measurement and lensing potential to estimate B-modes. Method called ***delensing***.

- Can apply data from high resolution experiment to low-resolution experiment

- E.g. SPT is ideal delensing machine for BICEP/Keck!

- SPT can also delens itself internally



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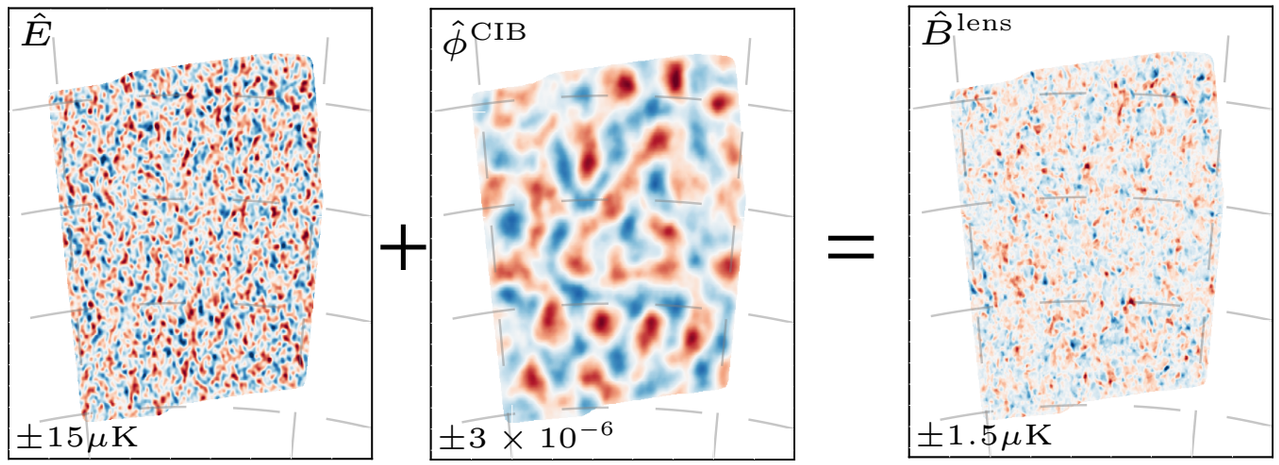
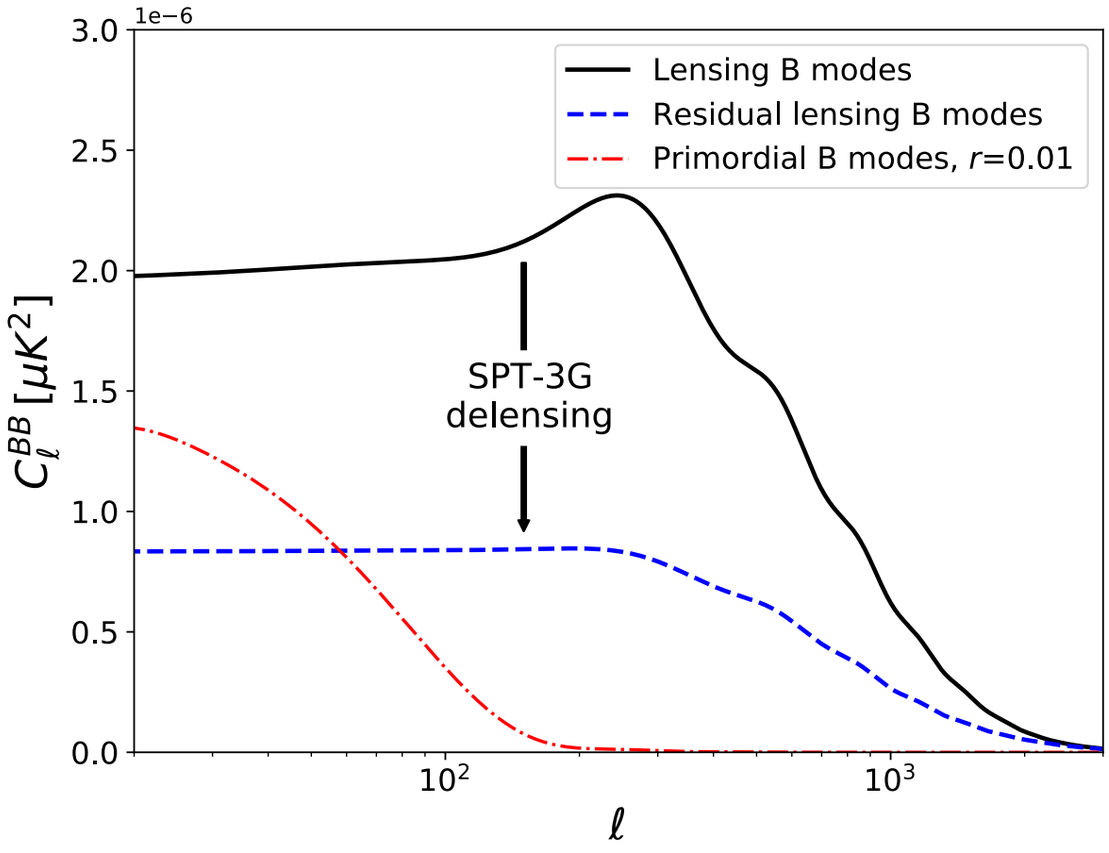
Delensing demonstration with SPTpol, Herschel data:



Manzotti, et al. 1701.04396



The CMB-S4 Experiment

- Endorsed by DOE/NSF P5 report, NRC/NSF Antarctic Science report, Concept Definition Taskforce (CDT) report accepted by AAAC panel
- **Concept:**
  - **400,000 detectors** split between 3x 6m-aperture, 14x 0.5m-aperture telescopes
  - **Two sites:** Split between South Pole and Atacama in Chile
  - **Two surveys:** Deep survey on 3-8% of sky for inflationary B-modes, wide survey on 40% of sky for neutrinos and cross-correlation science

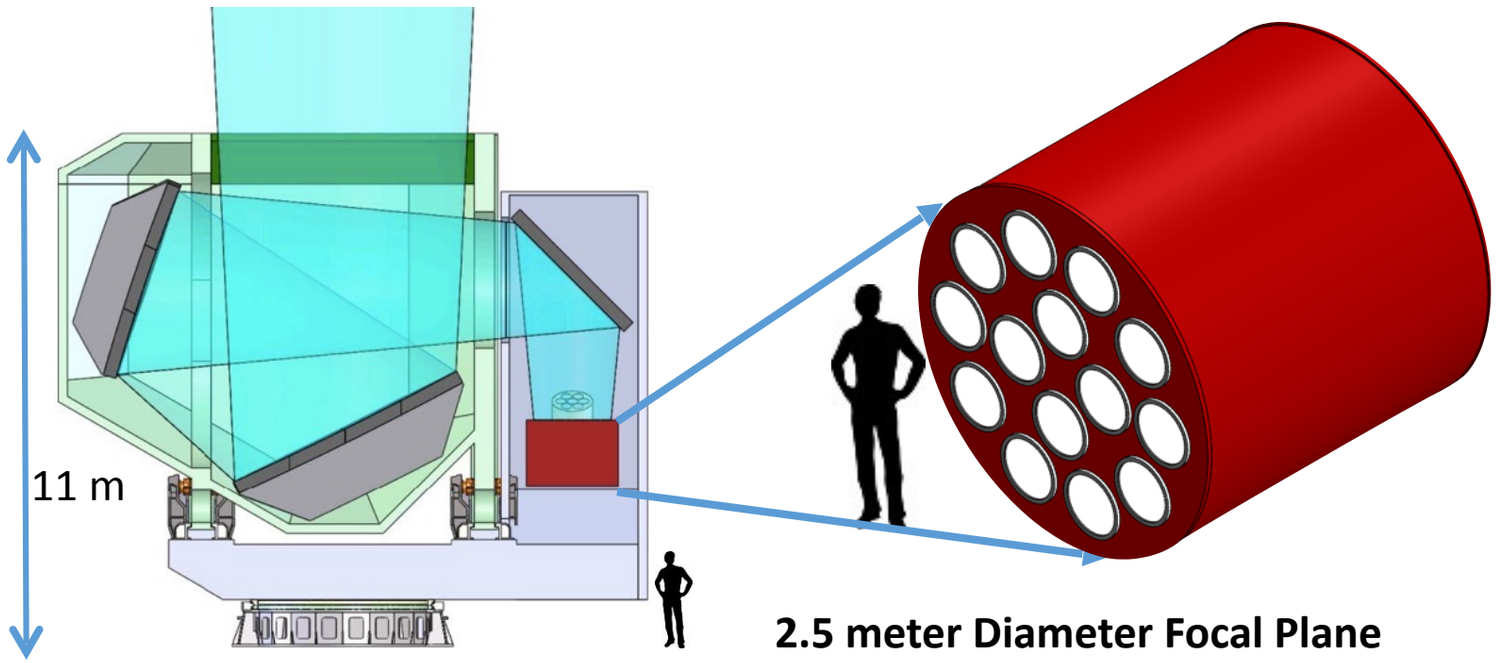


Figure: Mark Devlin / Mike Niemack

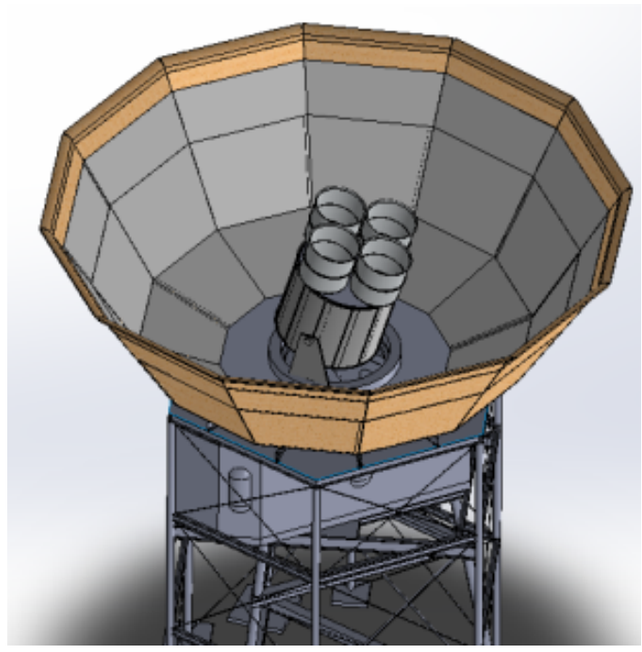


Figure: BICEP Array

Conclusions and Outlook

- Successful deployment of upgrades at Pole in 2017 and 2018
- Started 1500d survey in early 2018, low-level analysis ongoing
- Interesting physics opportunities for neutrinos, light relics, inflation, and astrophysics
- Pathfinder instrument for ultimate ground-based CMB experiment: CMB-S4

	$\sigma(r)$	$\sigma(N_{eff})$	$\sigma(\Sigma m_\nu)$
Current CMB	0.05	0.3	0.17 eV
SPT-3G	0.01	0.10	0.10 eV
Stage 4: CMB-S4	***0.001***	***0.027***	***0.015 eV***

SPT-3G Collaboration

Argonne NATIONAL LABORATORY

BERKELEY LAB

NIST

Fermilab

Case CASE WESTERN RESERVE UNIVERSITY

McGill

Colorado University of Colorado at Boulder

UC DAVIS UNIVERSITY OF CALIFORNIA

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

M

I

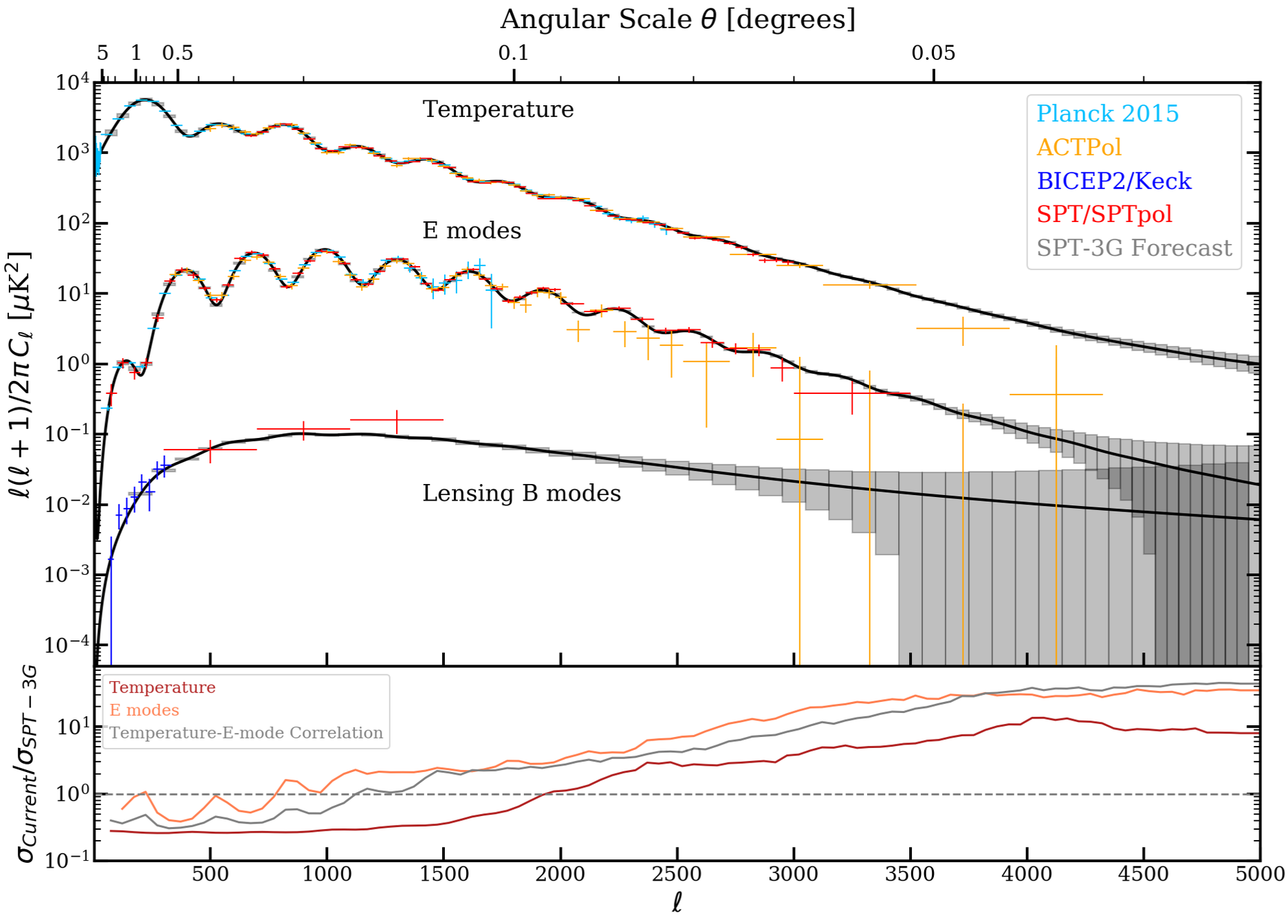
SLAC

NATIONAL SCIENCE FOUNDATION

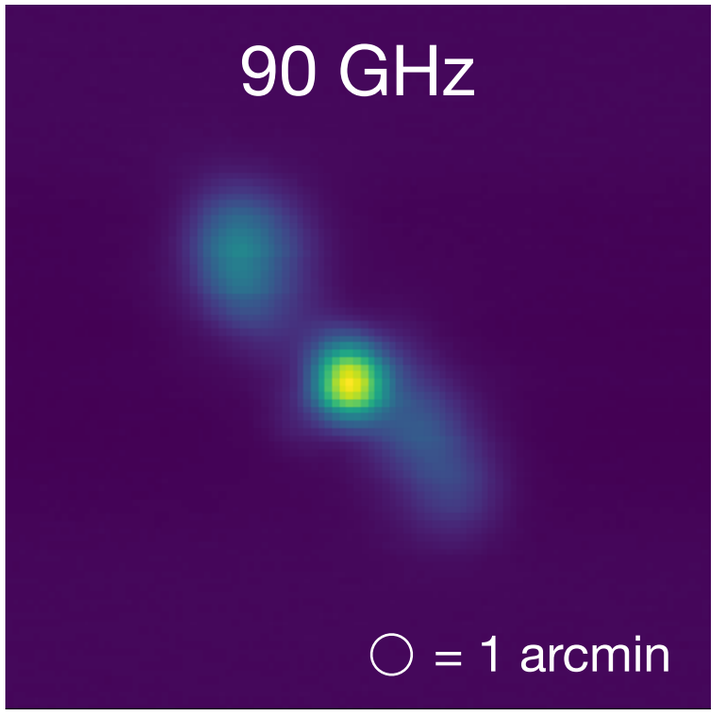
U.S. DEPARTMENT OF ENERGY

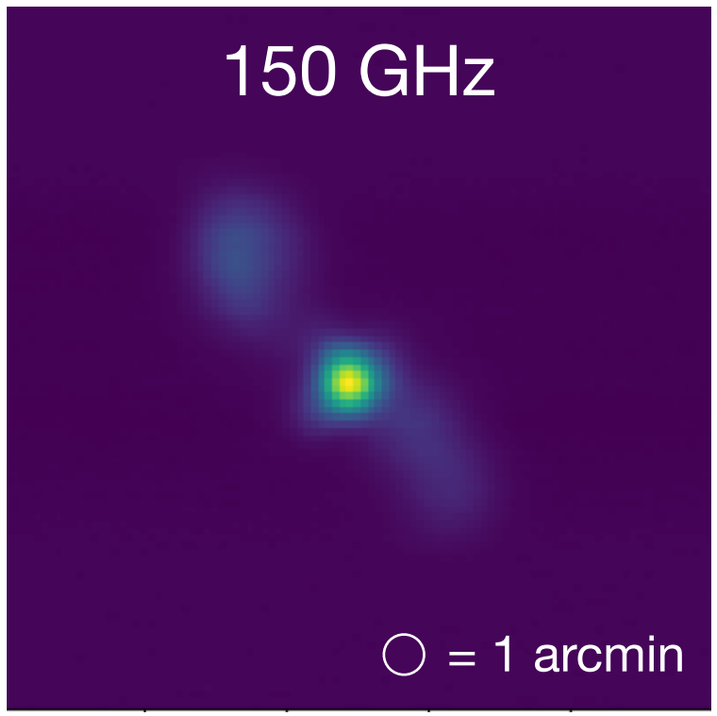
Backup

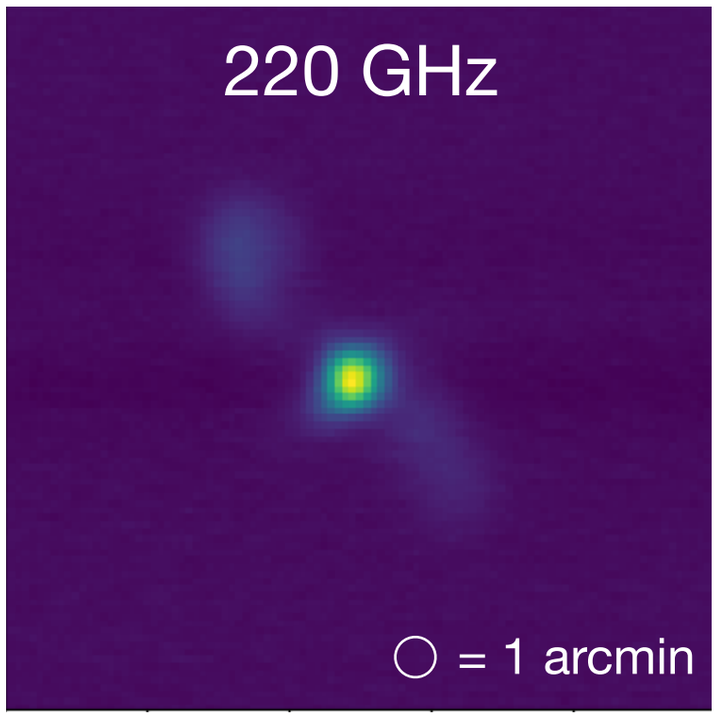
E- & B-modes with SPT-3G

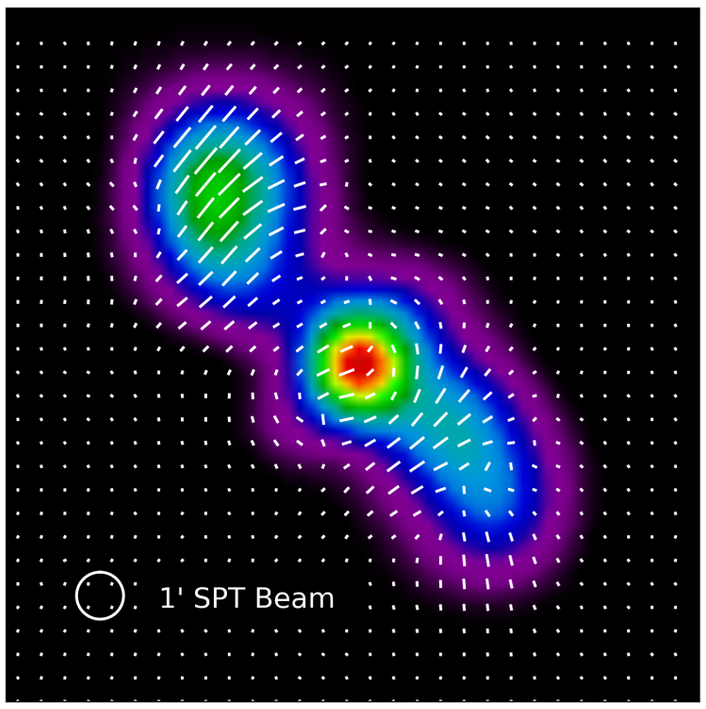


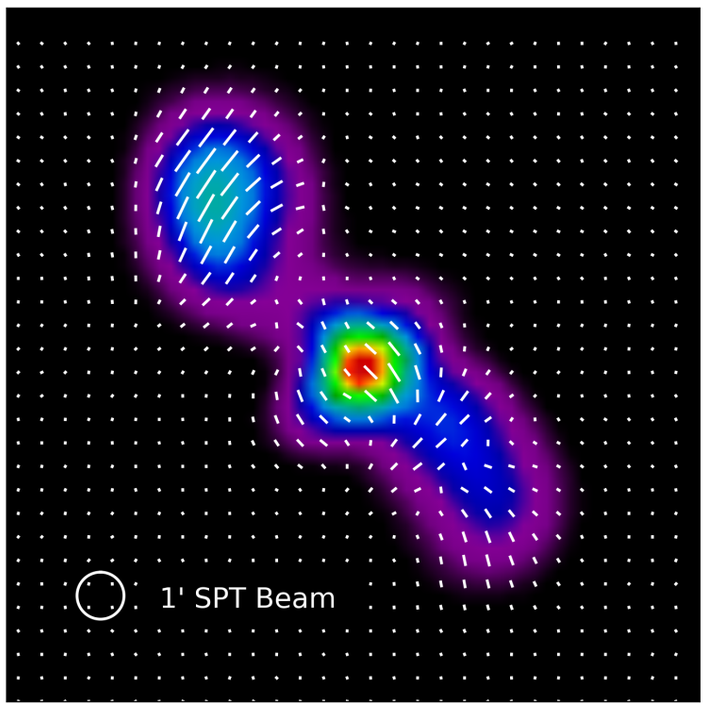
Calibrations: CenA

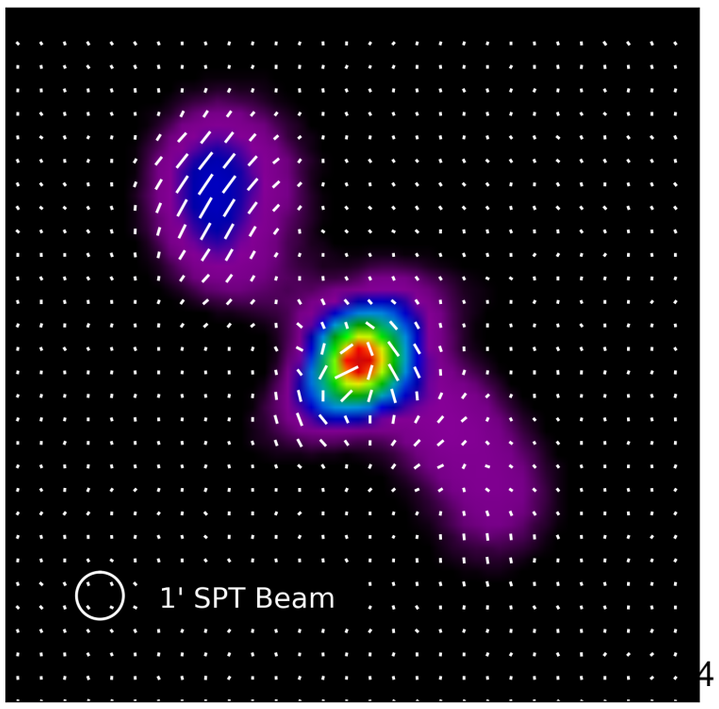




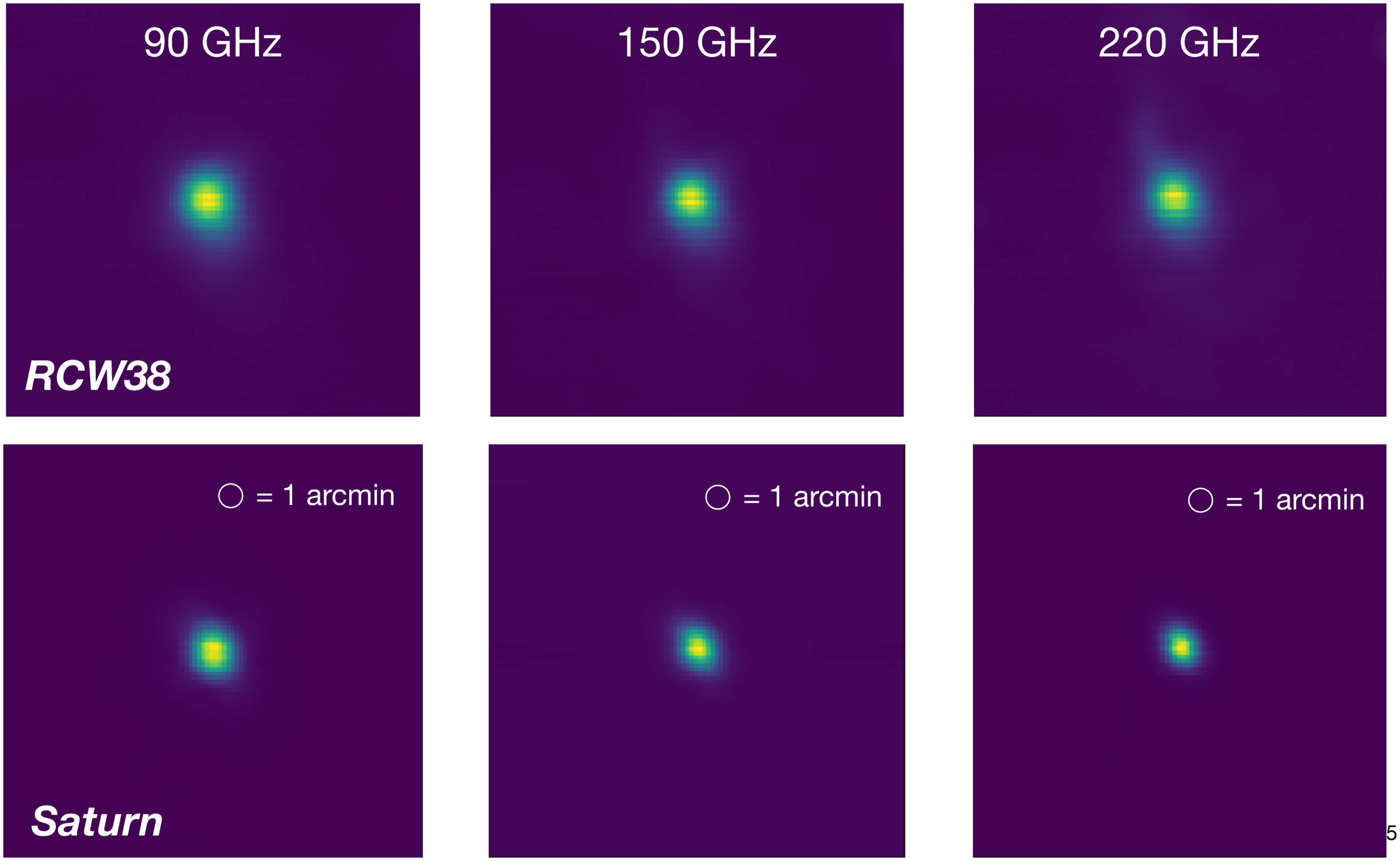








Calibrations: RCW38 & Saturn



SPT-3G: Optics

- Completely redesigned optics provides larger 1.9deg diameter FOV
- Large focal plane area achieved with 75 cm diameter alumina lenses
- 3 observing bands requires broadband AR coatings: use 3-layer plastic laminates, thermally stable to 4K. Challenging engineering problem!