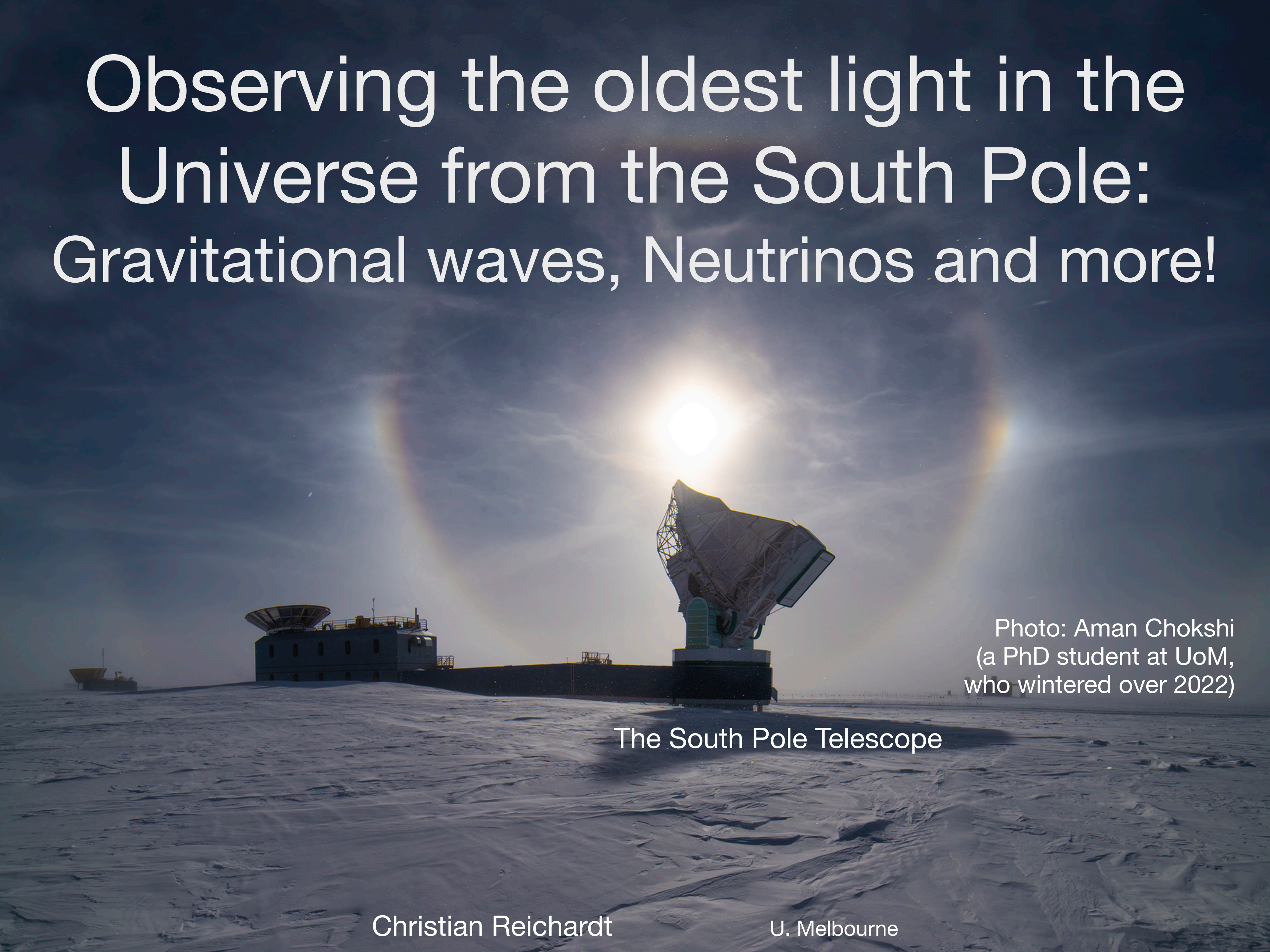
Observing the oldest light in the Universe from the South Pole:
Gravitational waves, Neutrinos and more!

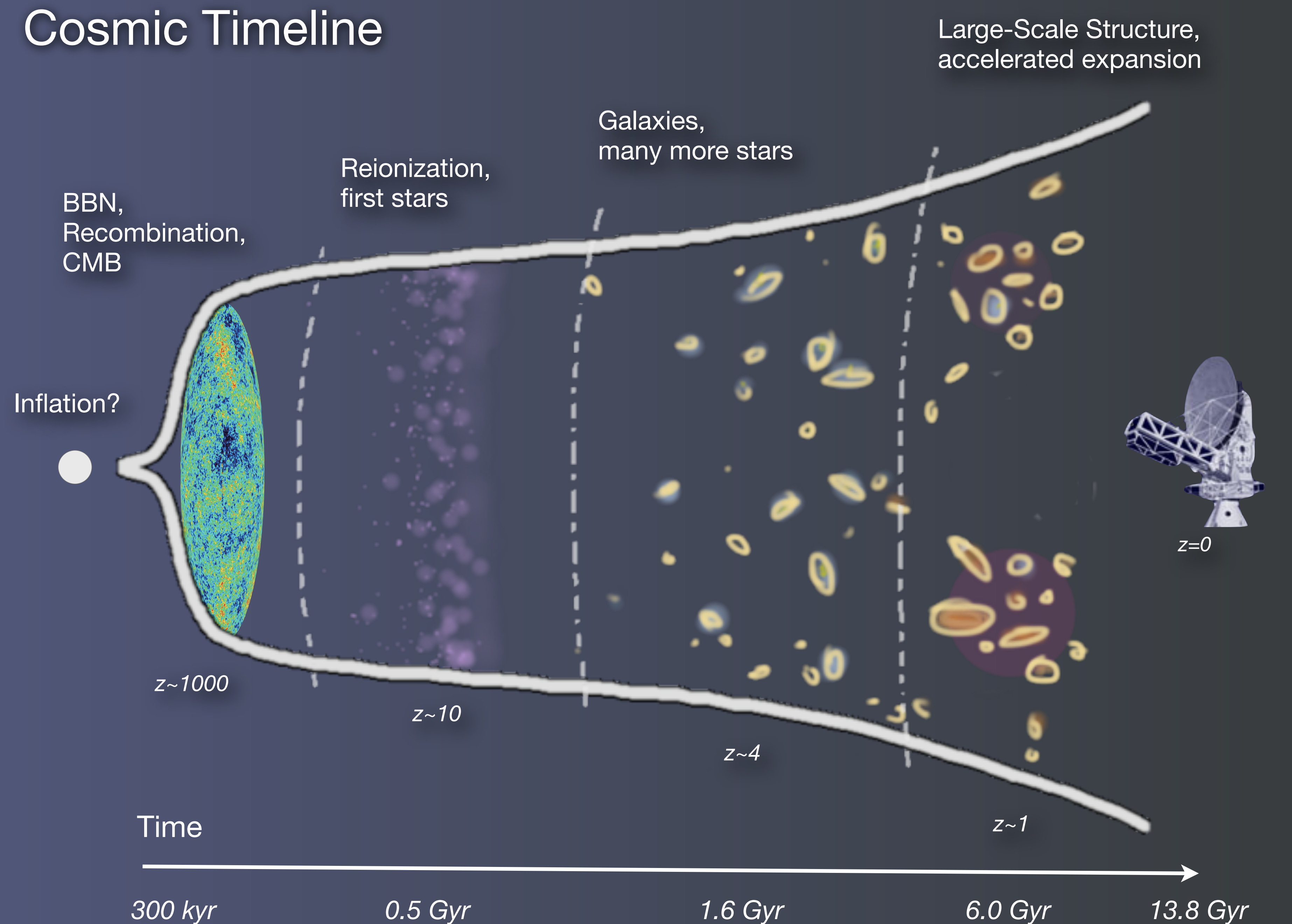


Christian Reichardt
U. Melbourne

Outline

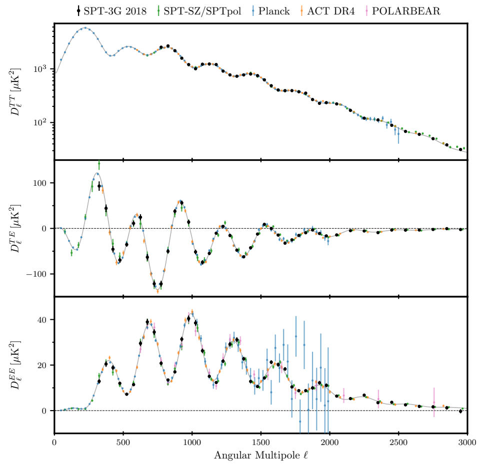
- A brief intro to cosmology and CMB Polarization
- The South Pole Telescope (SPT), a precursor to CMB-S4
- Power spectra from 1500 deg^2 of the SPT-3G survey

Cosmic Timeline

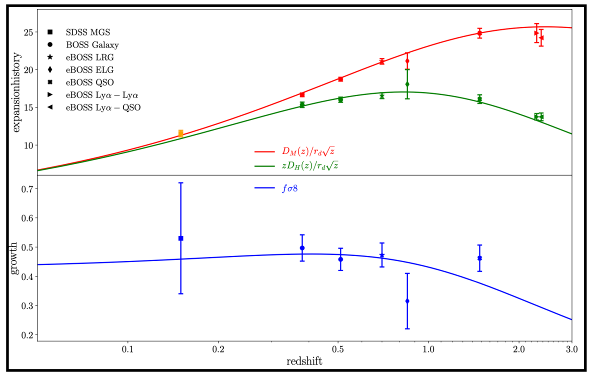


A host of observations point to ΛCDM

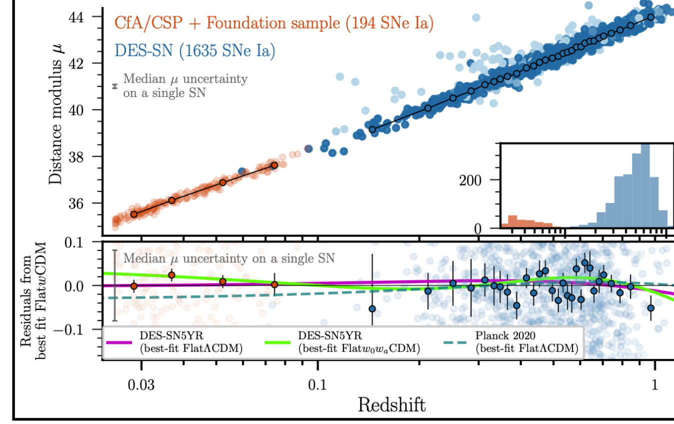
Balkenhol et al. 2023



Alam et al 2020

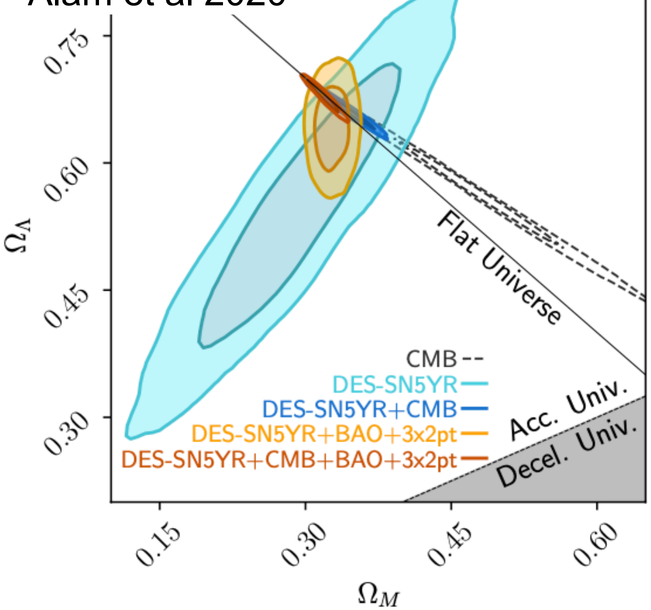


DES collab. 2024



Cosmic Microwave Background + Large Scale Structure + Supernovae

Alam et al 2020



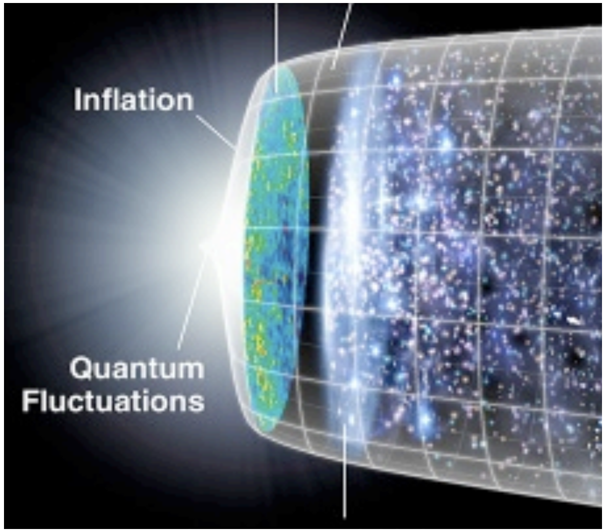
We live in a flat universe whose expansion is accelerating!

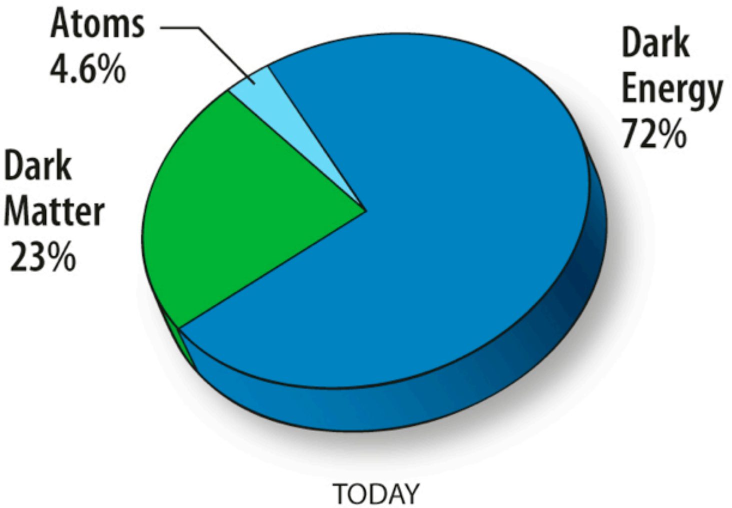
But this can't last…

1. What are dark matter and dark energy?

2. What caused inflation?

among others — such as the neutrino masses

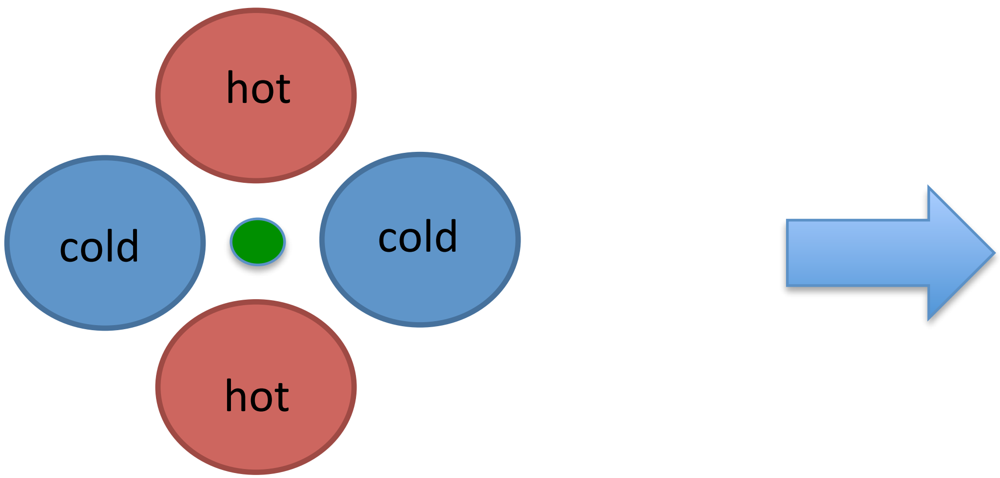


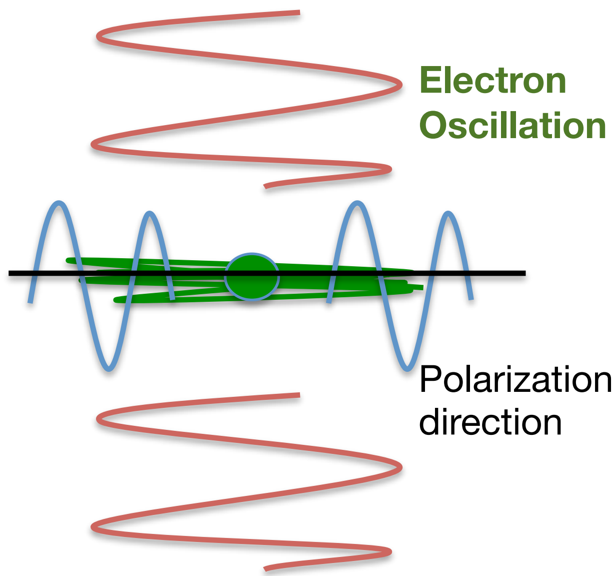


$$\Omega_\Lambda + \Omega_c = 0.9539 \pm 0.0015$$

The CMB is polarized (~10%)

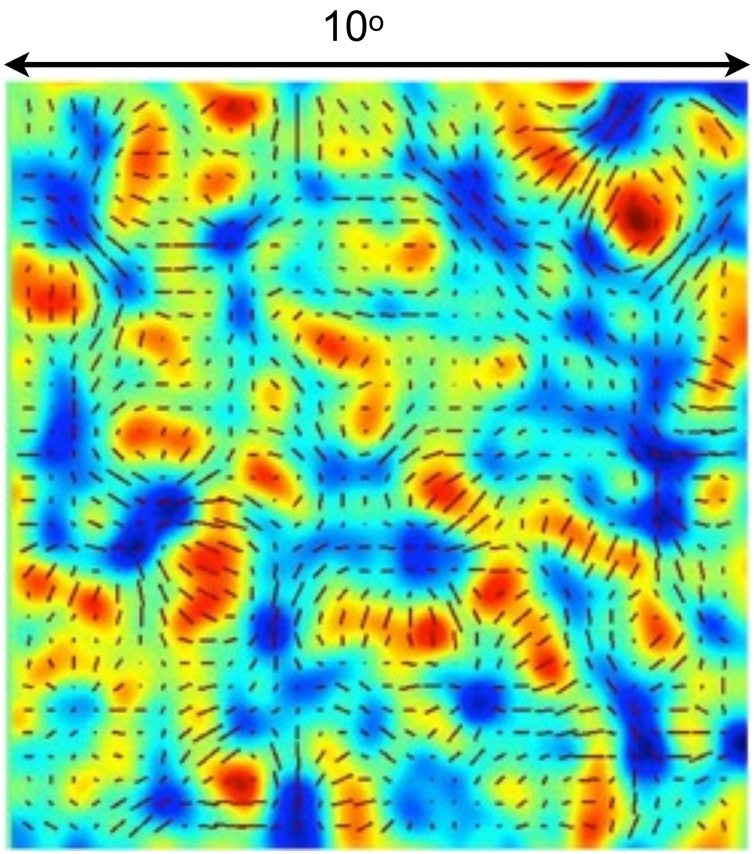
Photons/electrons Thompson scatter at last scattering surface
Local radiation quadrupole leads to a preferred direction





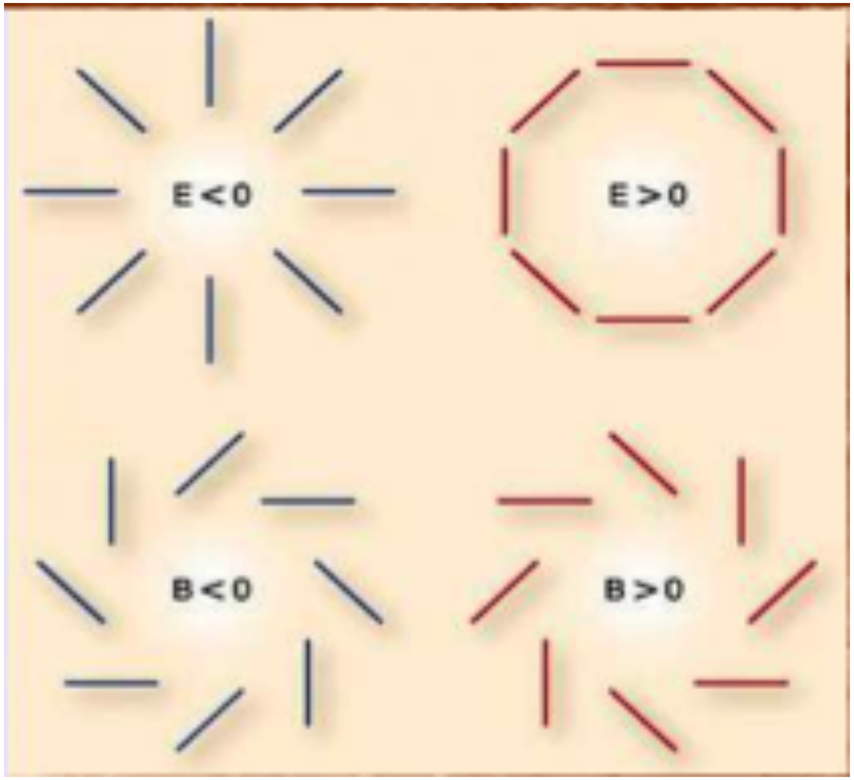
Net linear polarization!

The CMB is polarized (~10%)



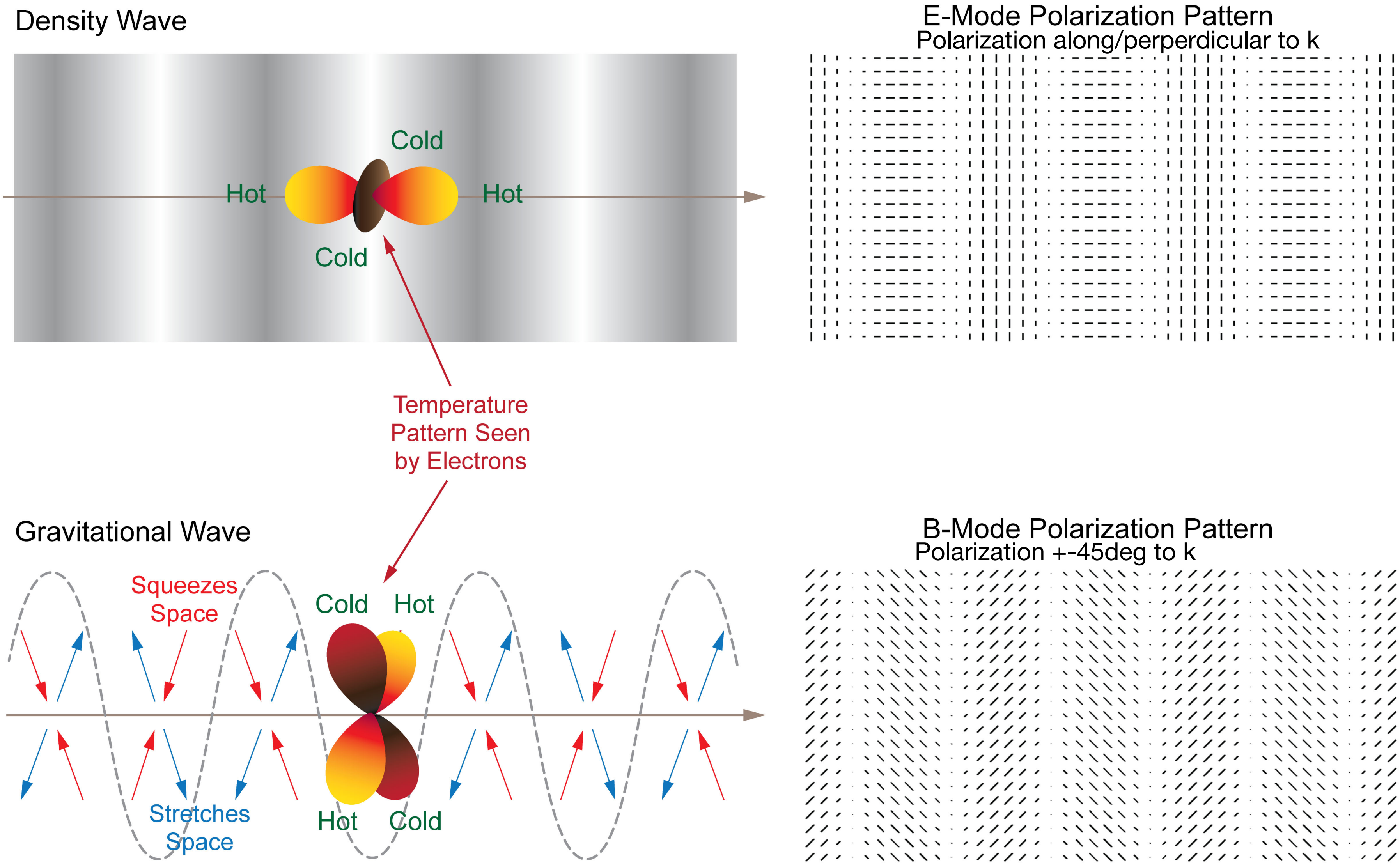
Smith et al 2008

- Any polarization pattern can be decomposed into "E" (grad) and "B" (curl) modes



Why use E&B?

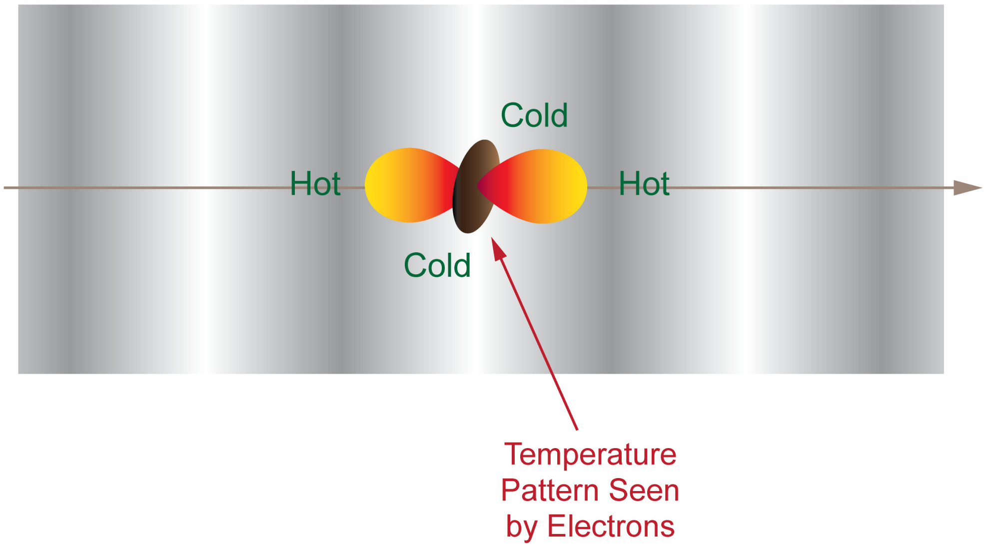
look at what produces each



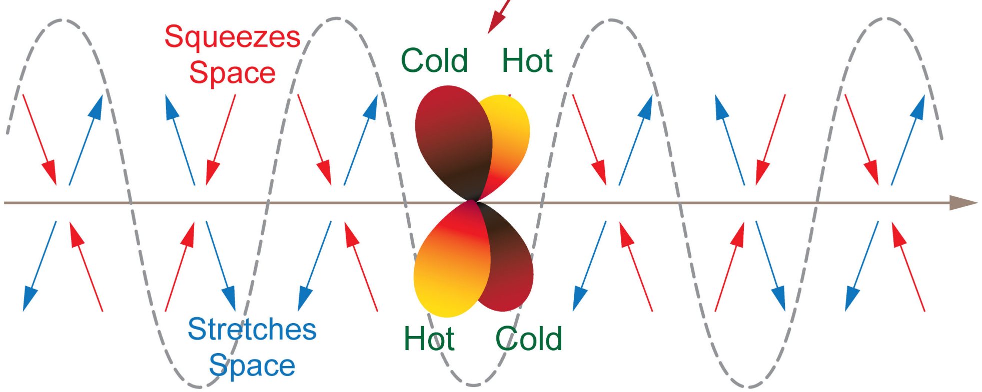
Why use E&B?

look at what produces each

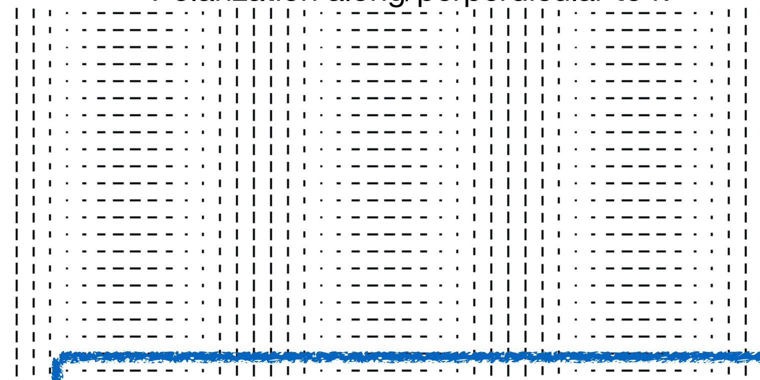
Density Wave



Gravitational Wave



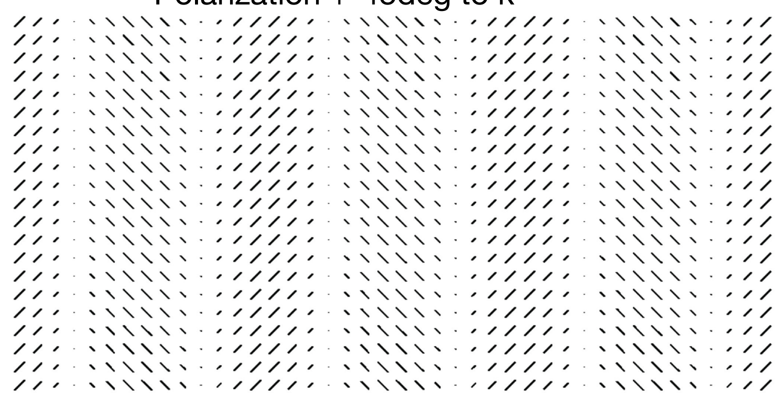
E-Mode Polarization Pattern
Polarization along/perperdicular to k



Density fluctuations at LSS do not produce “B” modes;

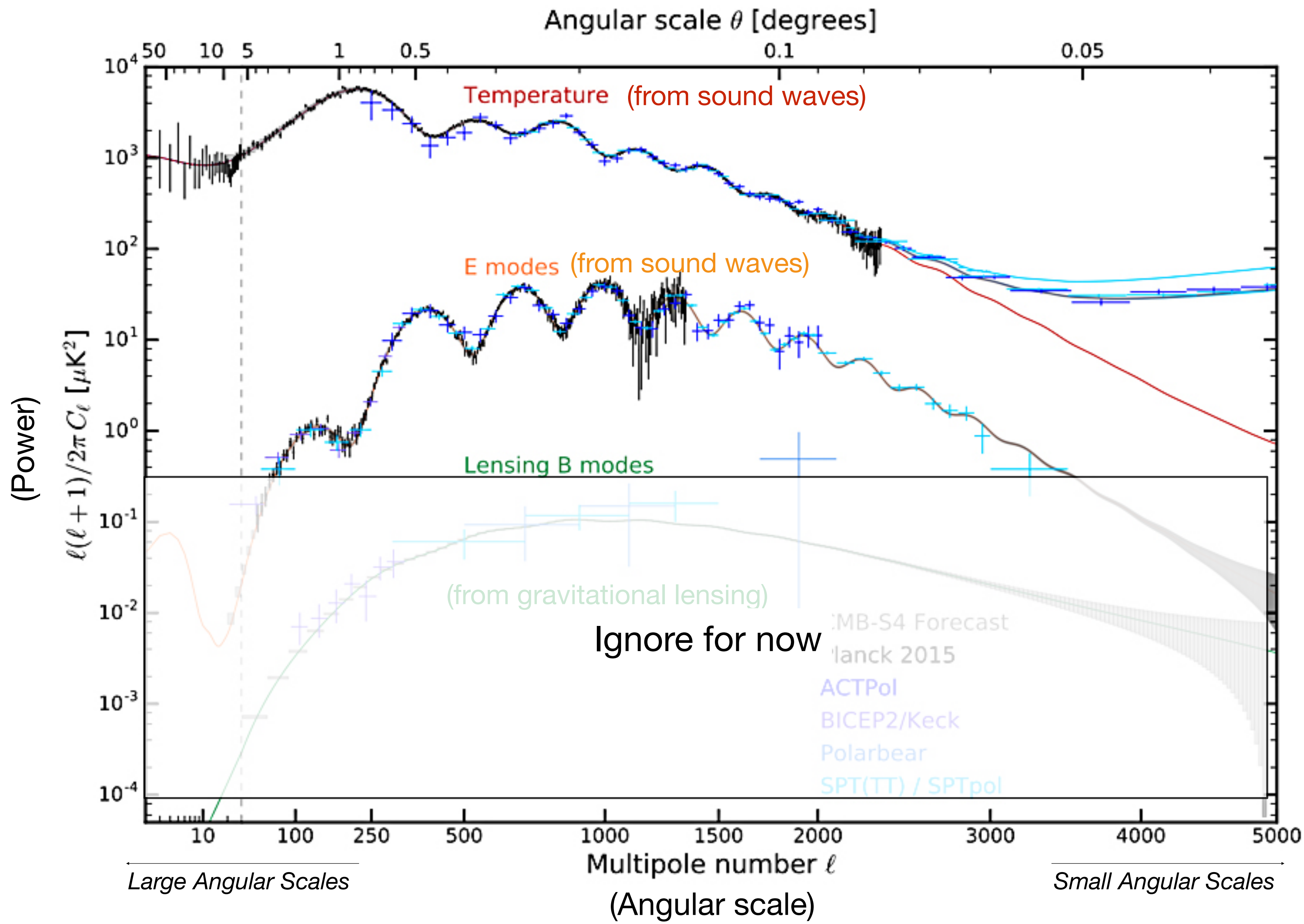
Gravitational waves do!

B-Mode Polarization Pattern
Polarization +-45deg to k



Measurements of CMB Power spectra

from CMB-S4 Science Book 2016



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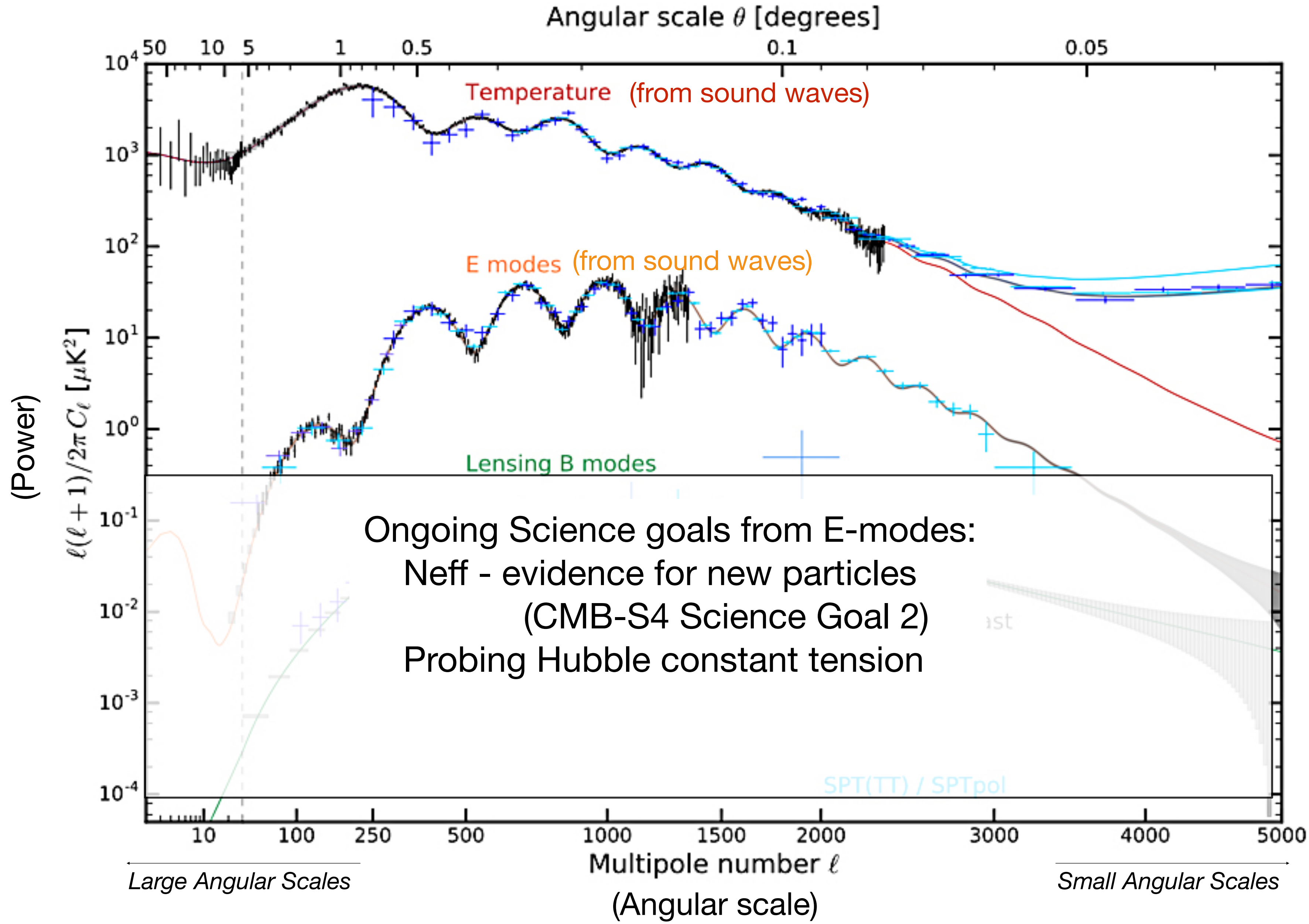
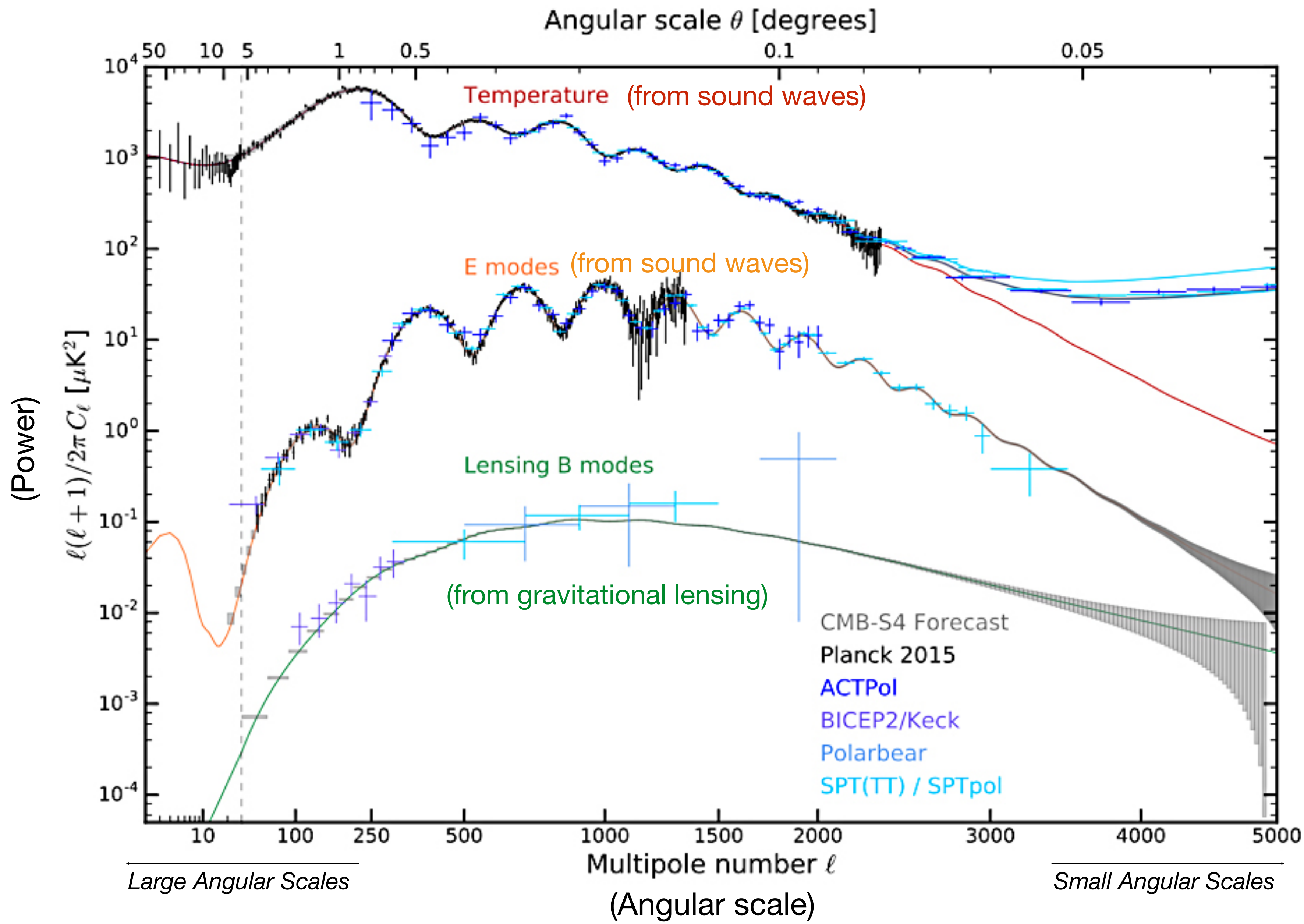


Ongoing Science goals from E-modes:
Neff - evidence for new particles
(CMB-S4 Science Goal 2)
Probing Hubble constant tension

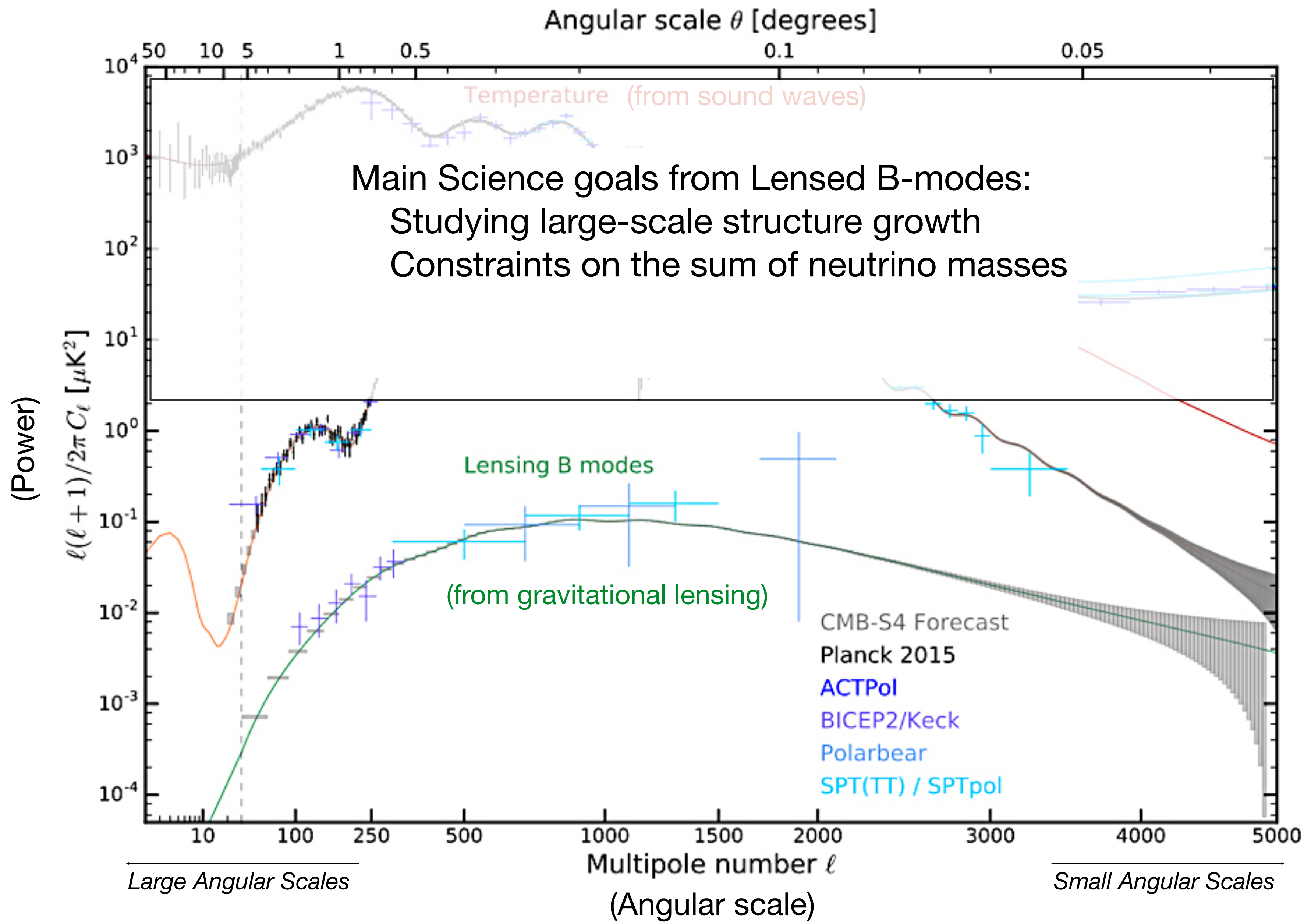
Measurements of CMB Power spectra

from CMB-S4 Science Book 2016



Measurements of CMB Power spectra

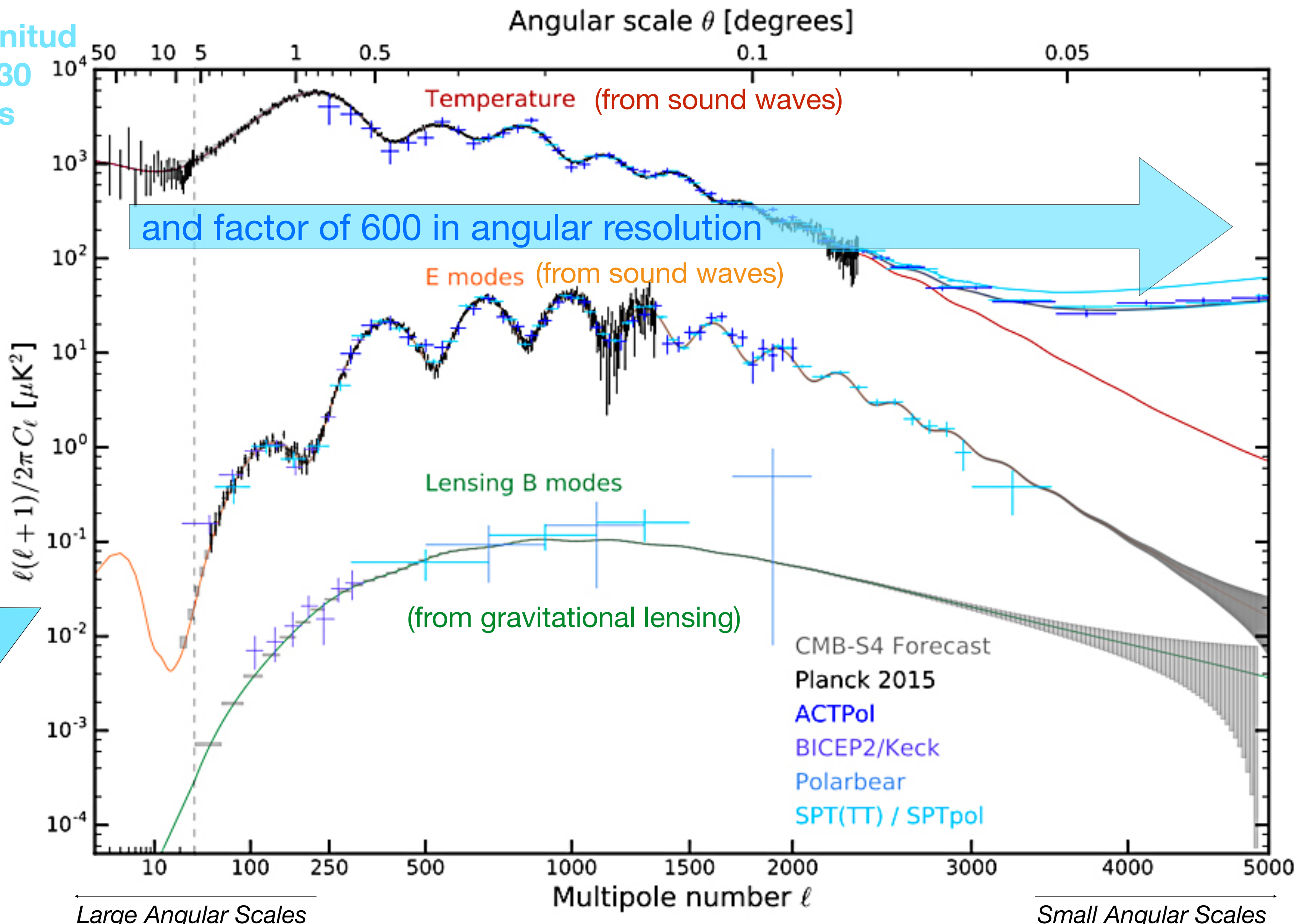
from CMB-S4
Science Book 2016



Measurements of CMB Power spectra

from CMB-S4 Science Book 2016

Six orders of magnitude in 30 years

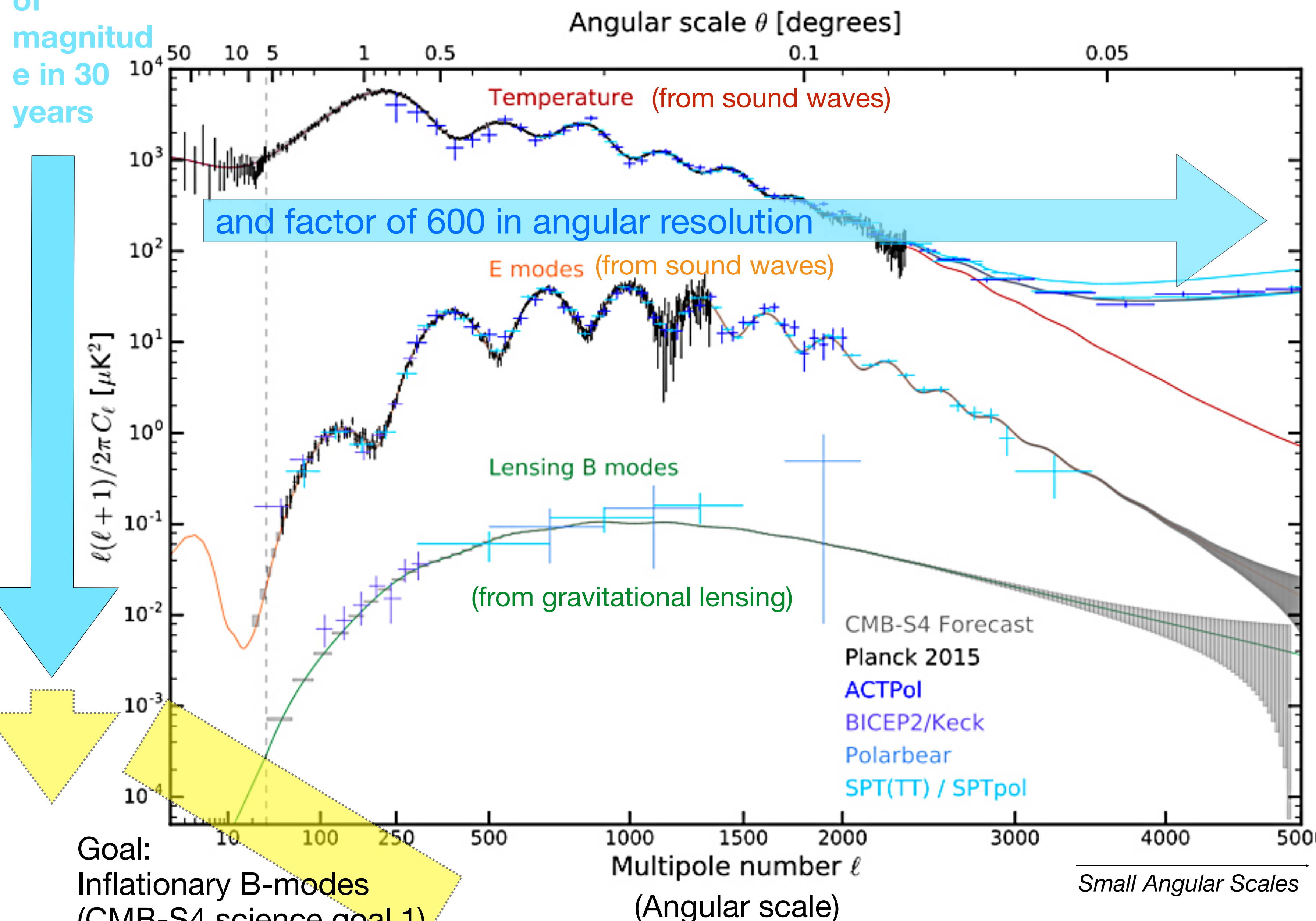


(Angular scale)

Measurements of CMB Power spectra

from CMB-S4 Science Book 2016

Six orders of magnitude in 30 years

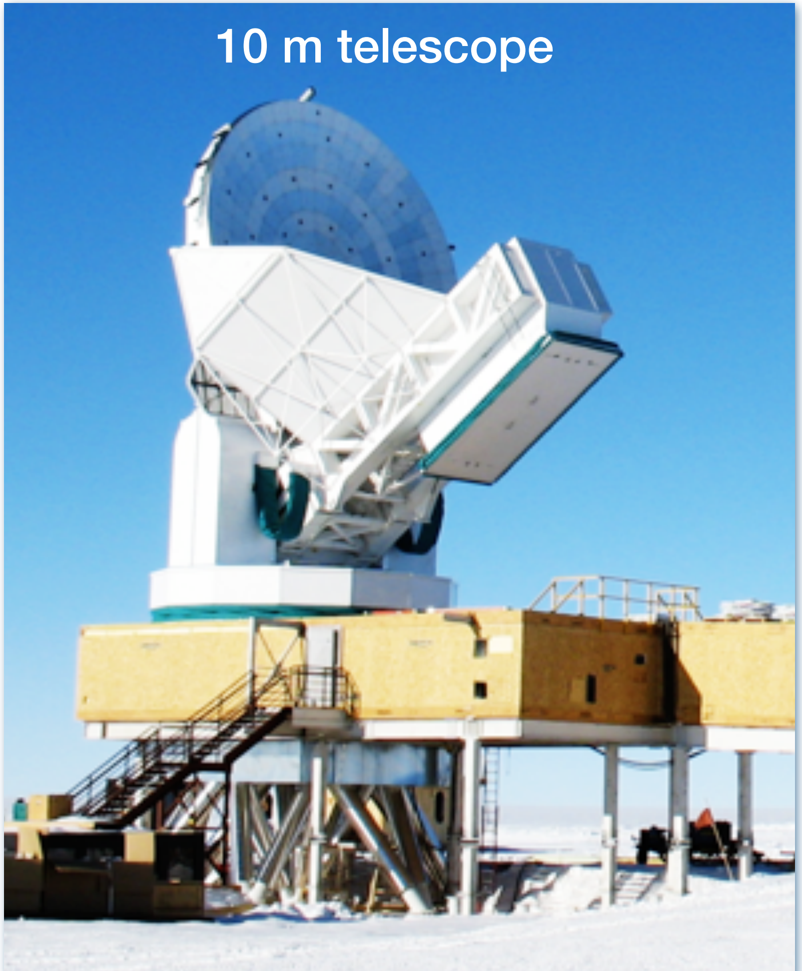


Goal:
Inflationary B-modes
(CMB-S4 science goal 1)

Outline

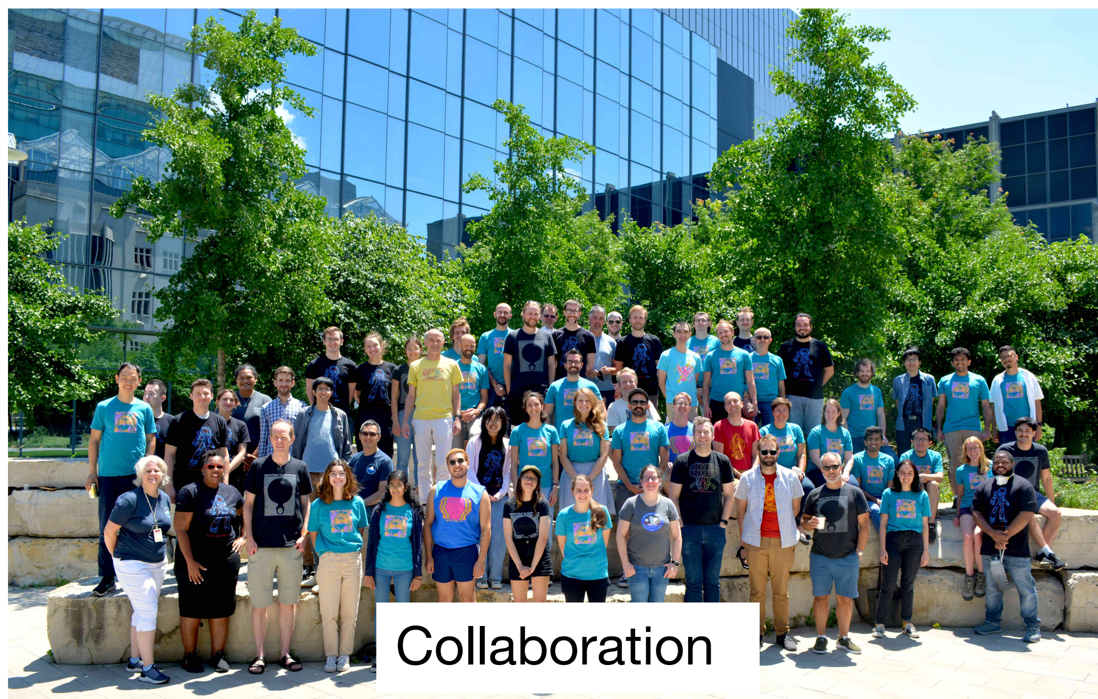
- ☑ A brief intro to cosmology and CMB Polarization
- **The South Pole Telescope (SPT), a precursor to CMB-S4**
- Power spectra from 1500 deg^2 of the SPT-3G survey

The South Pole Telescope (SPT)

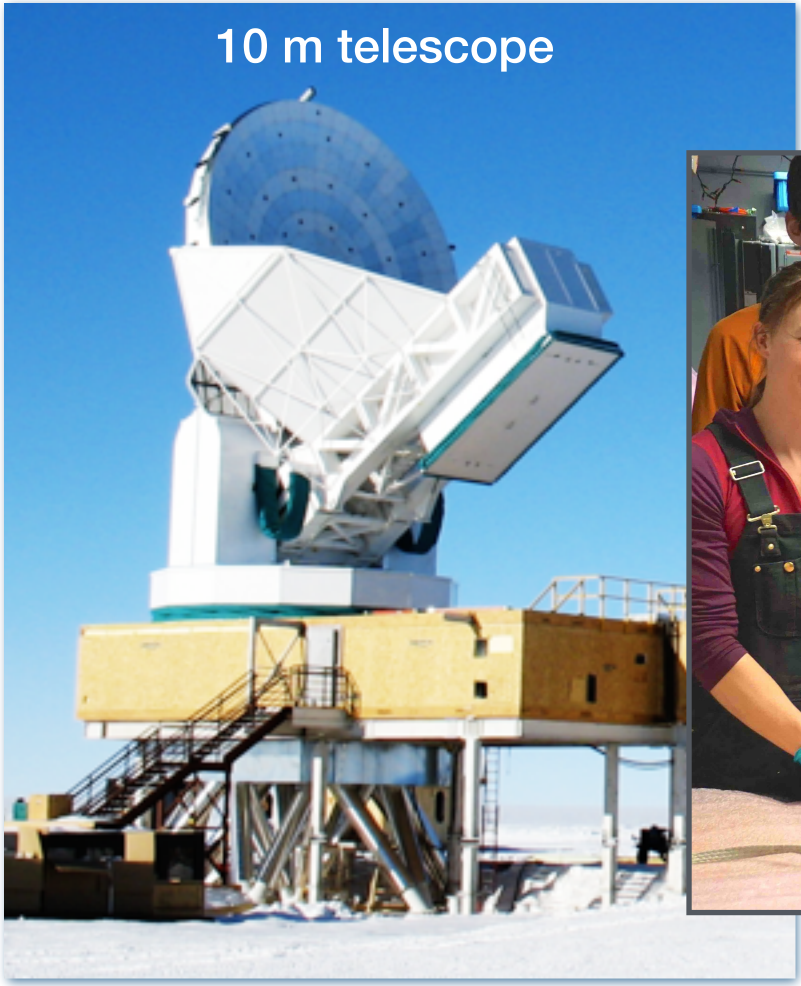


Sub-millimeter Wavelength Telescope:

- 10 meter telescope (1.1’ FWHM beam)
- Off-axis Gregorian optics design
- Fast scanning (up to 2 deg/sec in azimuth)
- 2” pointing accuracy



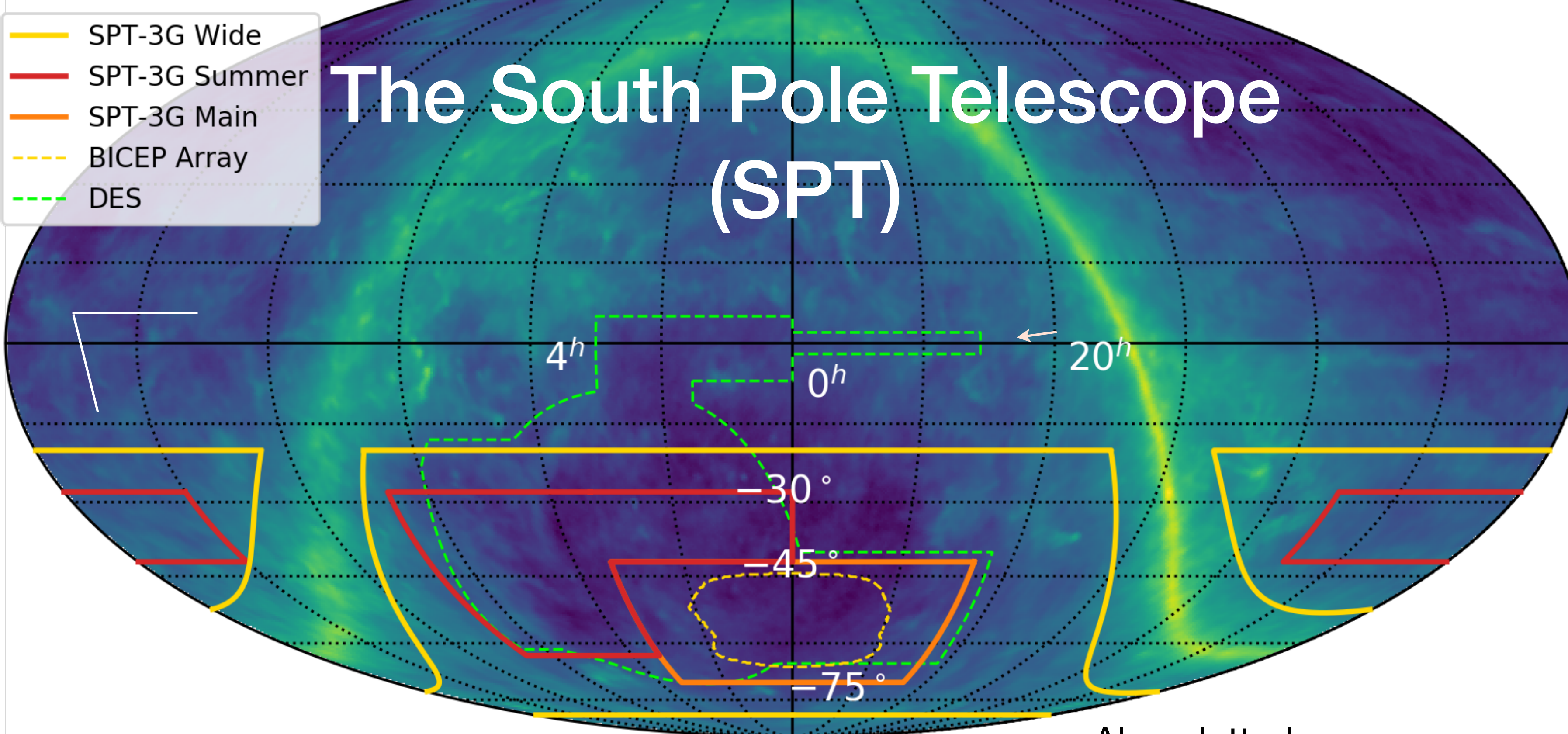
The South Pole Telescope (SPT)



SPT-3G - 3rd camera on SPT

- 16,200 bolometers in trichroic pixels
- Currently surveying 10,000 deg^2 at 95, 150, 220 GHz

The South Pole Telescope (SPT)



Also plotted:

- Dashed yellow: BICEP field (for gravitational waves and delensing)
- Dashed green: DES

Combined temperature noise levels:

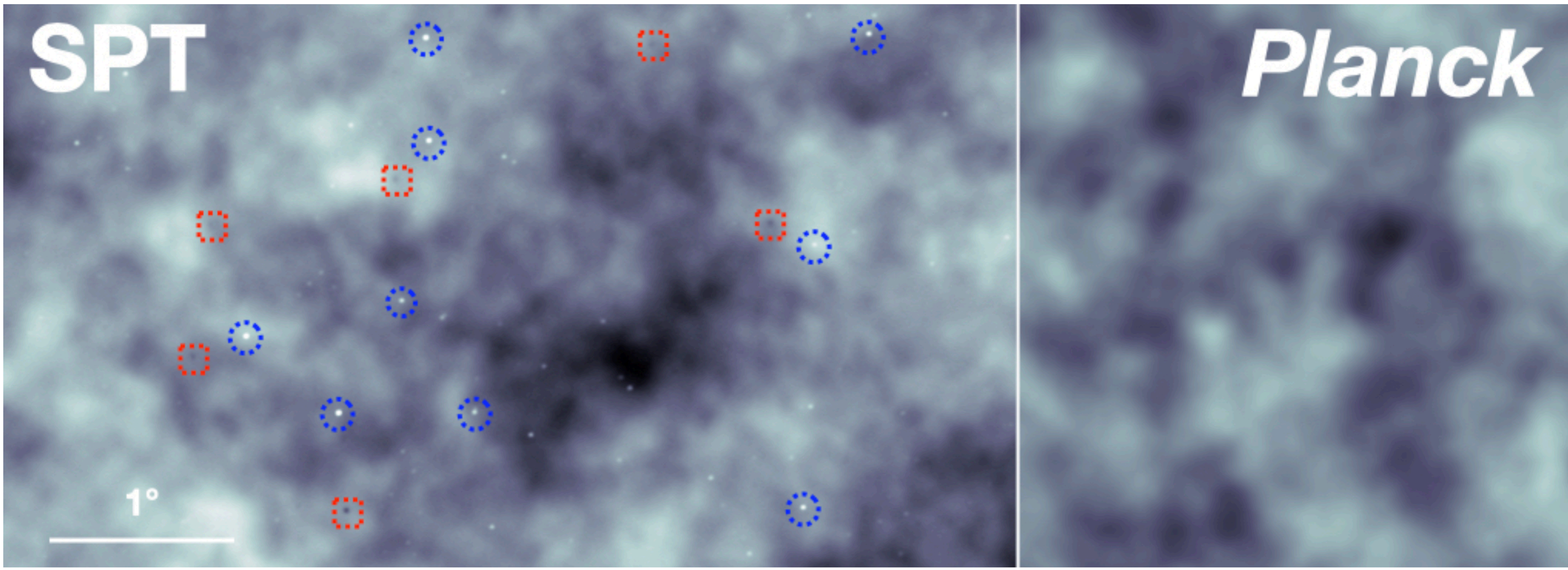
- **1500 deg²** Main field: **1.6 μK-arcmin** (orange)
- **2600 deg²** Summer field: **6.1 μK-arcmin** (red)
- **6000 deg²** Wide field: **8.8 μK-arcmin** (yellow)

Survey covers **10,100 deg² in total**

Planck noise level ~ 30 μK-arcmin

Comparing SPT-3G and Planck

Composite of SPT-3G and Planck over 30 deg^2 of sky



Dark dots (red) = Galaxy clusters (discovering clusters is CMB-S4's Science Goal 3)
White dots (blue) = Galaxies (AGN or lensed dusty galaxies)

SPT-3G brings much finer angular resolution and ~15x lower noise

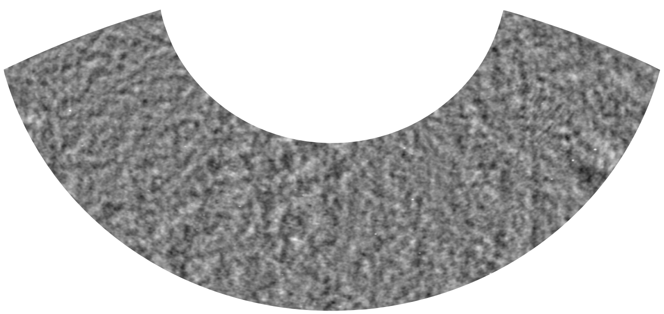
Outline

- ☑ A brief intro to cosmology and CMB Polarization
- ☑ The South Pole Telescope (SPT), a precursor to CMB-S4
- **Power spectra from 1500 deg^2 of the SPT-3G survey**

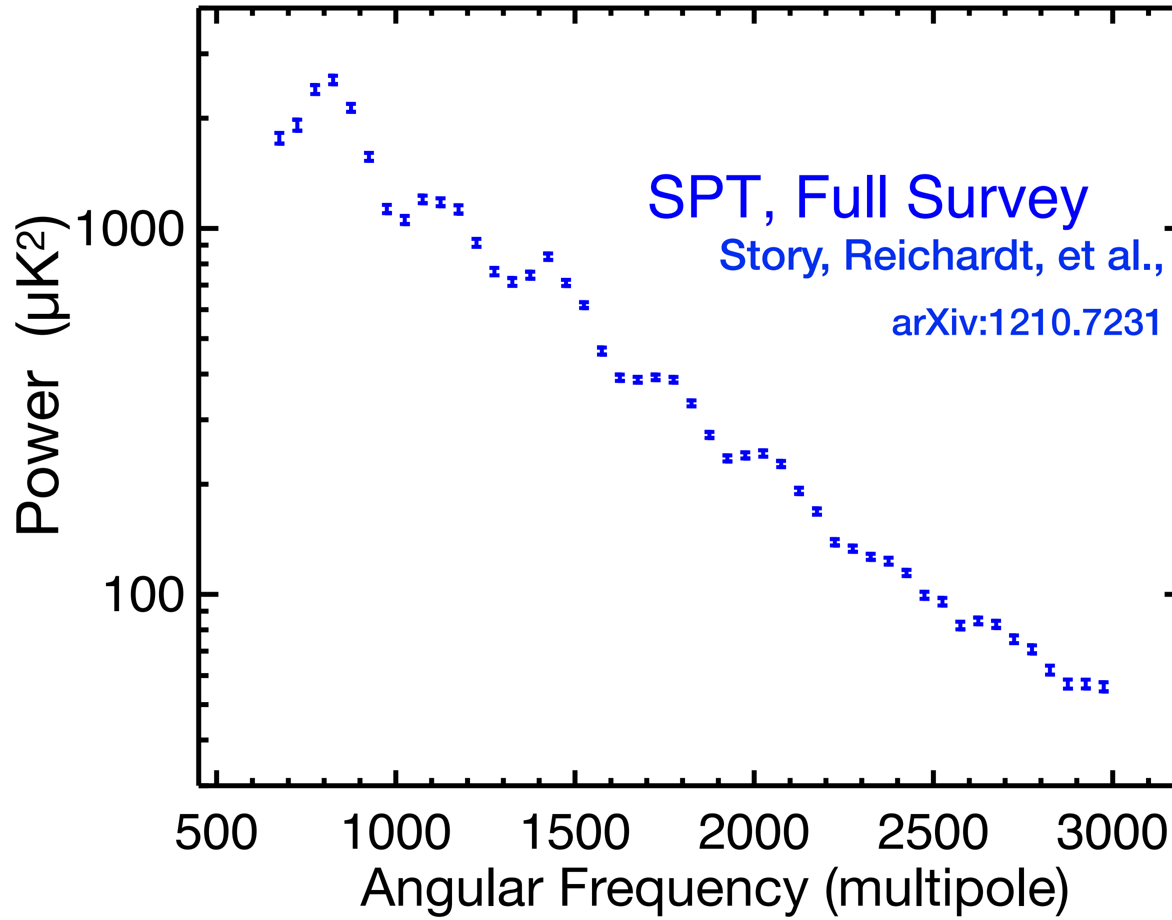
Cosmic Microwave Background (CMB) Power Spectra

Basic idea:

Fourier transform this

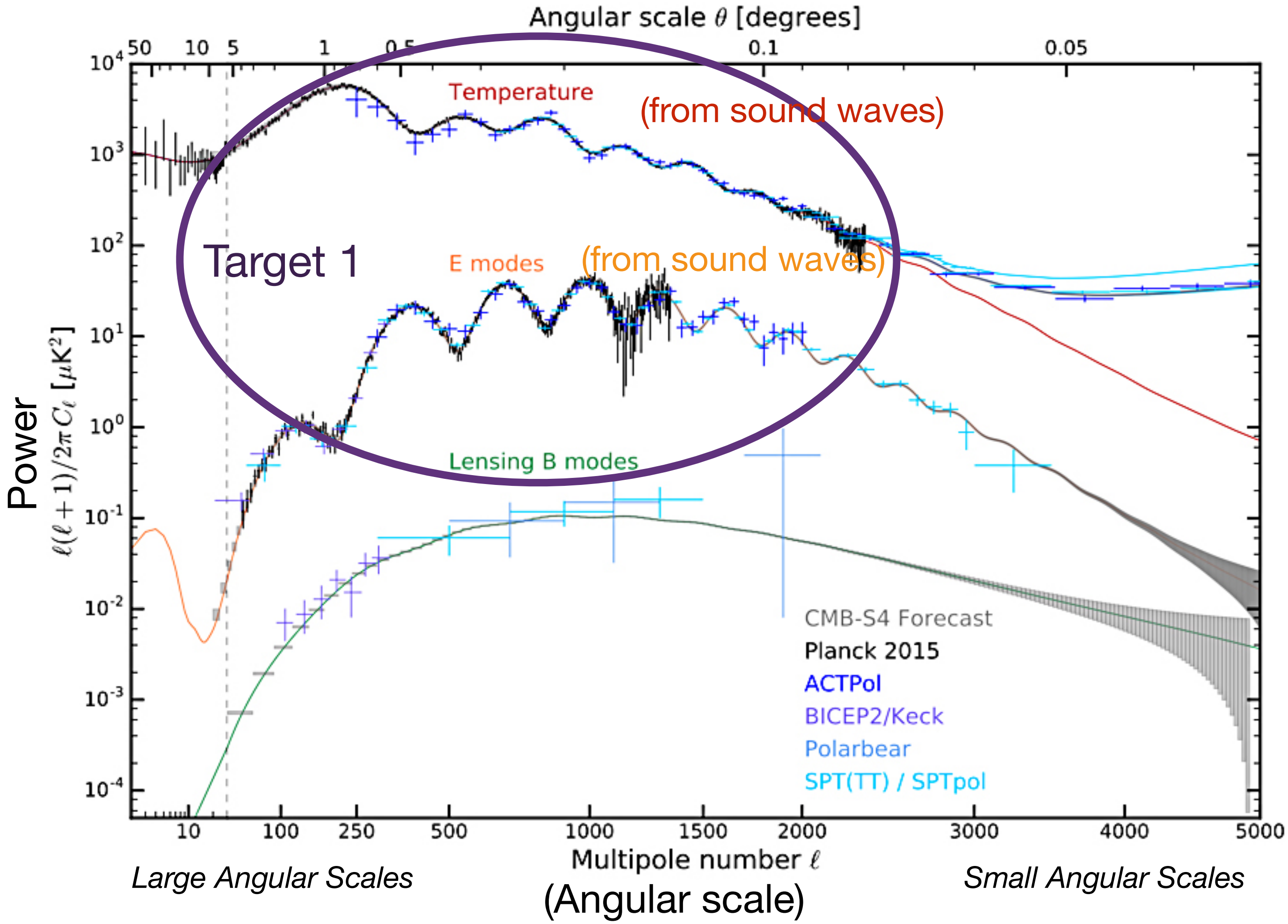


and you get....



Three Measurements of CMB Power spectra

from CMB-S4 Science Book 2016

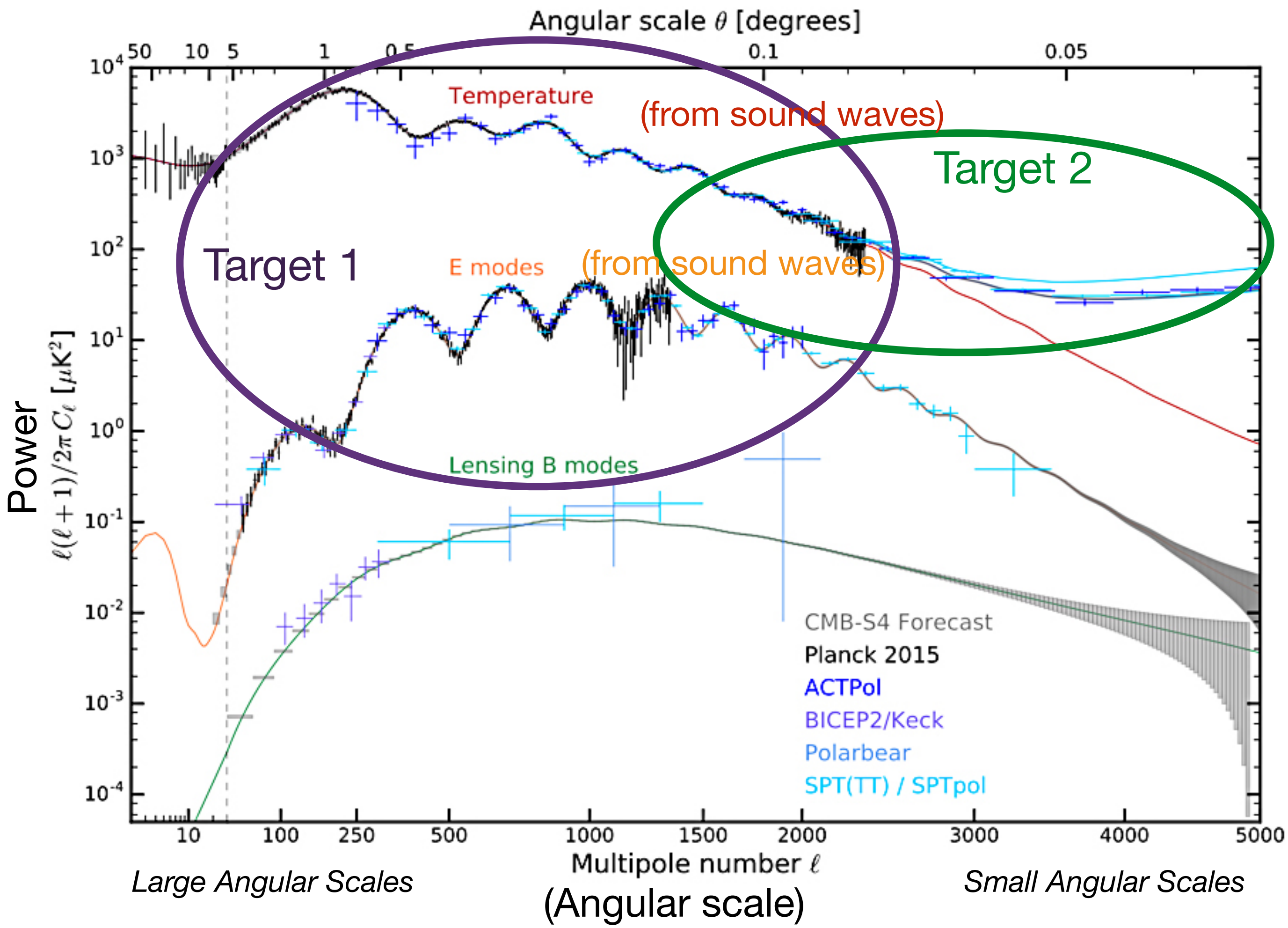


Target 1: Primary CMB anisotropy (temperature+polarization)

All 3 use SPT-3G data on the 1500 deg^2 Main field

Three Measurements of CMB Power spectra

from CMB-S4 Science Book 2016



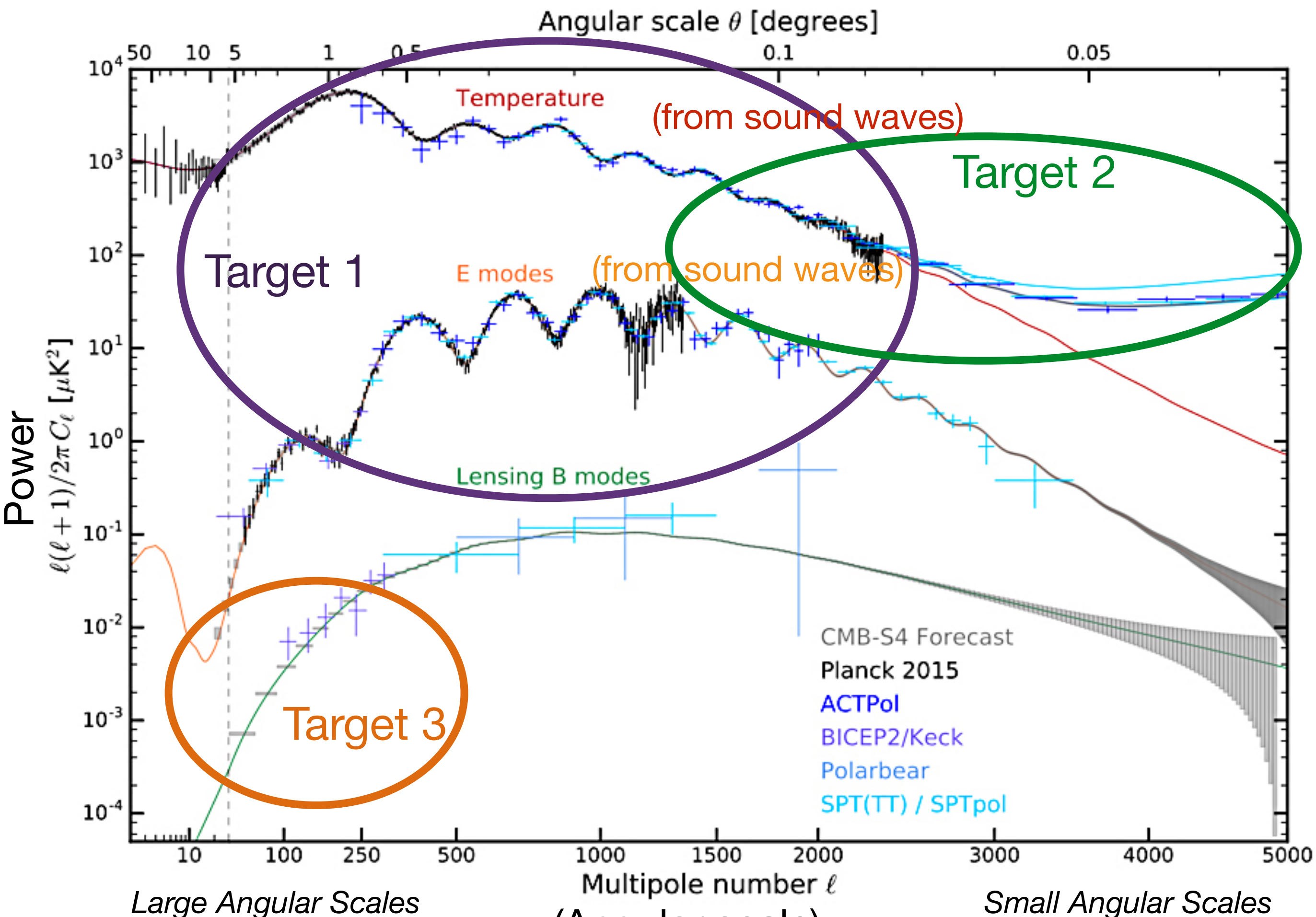
Target 1: Primary CMB anisotropy (temperature+polarization)

Target 2: Secondary anisotropy: interactions of CMB photons with large-scale structure (temperature)

All 3 use SPT-3G data on the 1500 deg^2 Main field

Three Measurements of CMB Power spectra

from CMB-S4 Science Book 2016



(Angular scale)

Target 1: Primary CMB anisotropy (temperature+polarization)

Target 2: Secondary anisotropy: interactions of CMB photons with large-scale structure (temperature)

Target 3: Inflationary gravitational waves (polarization)

I'll talk about current work on each of these science targets

Daniel Dutcher
(work done at Chicago, now Princeton)

SPT-3G Power Spectra

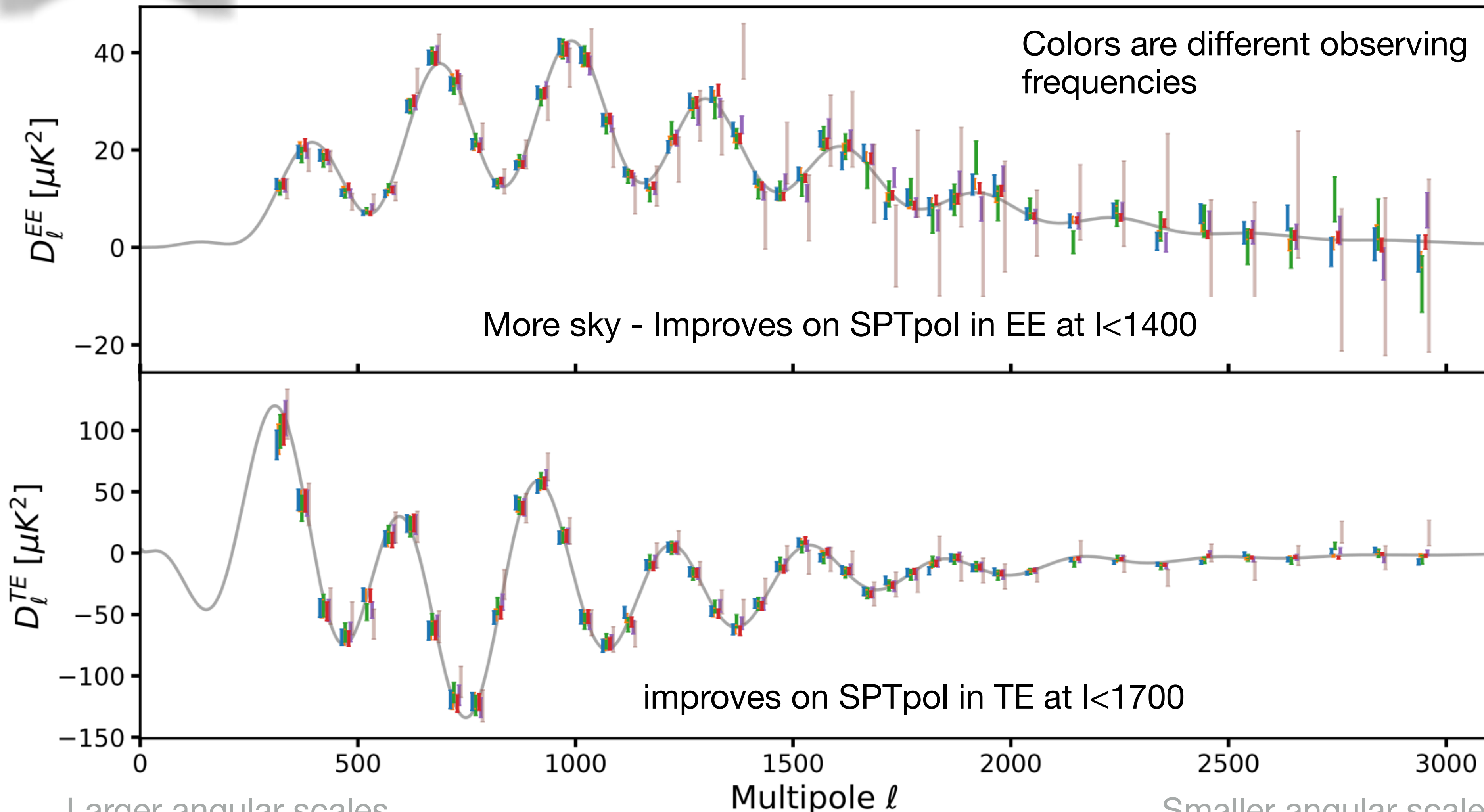
Target 1: Primary CMB anisotropy

Lennart Balkenhol
(work done at Melbourne, now IAP)

- I'll be showing results from 3 papers
  - D. Dutcher, L. Balkenhol, *et al.* (SPT-3G Collaboration) PRD 2021
  - L. Balkenhol, D. Dutcher, *et al.* (SPT-3G Collaboration) PRD 2021
  - L. Balkenhol, D. Dutcher, *et al.* (SPT-3G Collaboration) PRD 2023
- These were led by Daniel and Lennart as part of their PhD, with contributions from others

From
2018
data

Power spectra

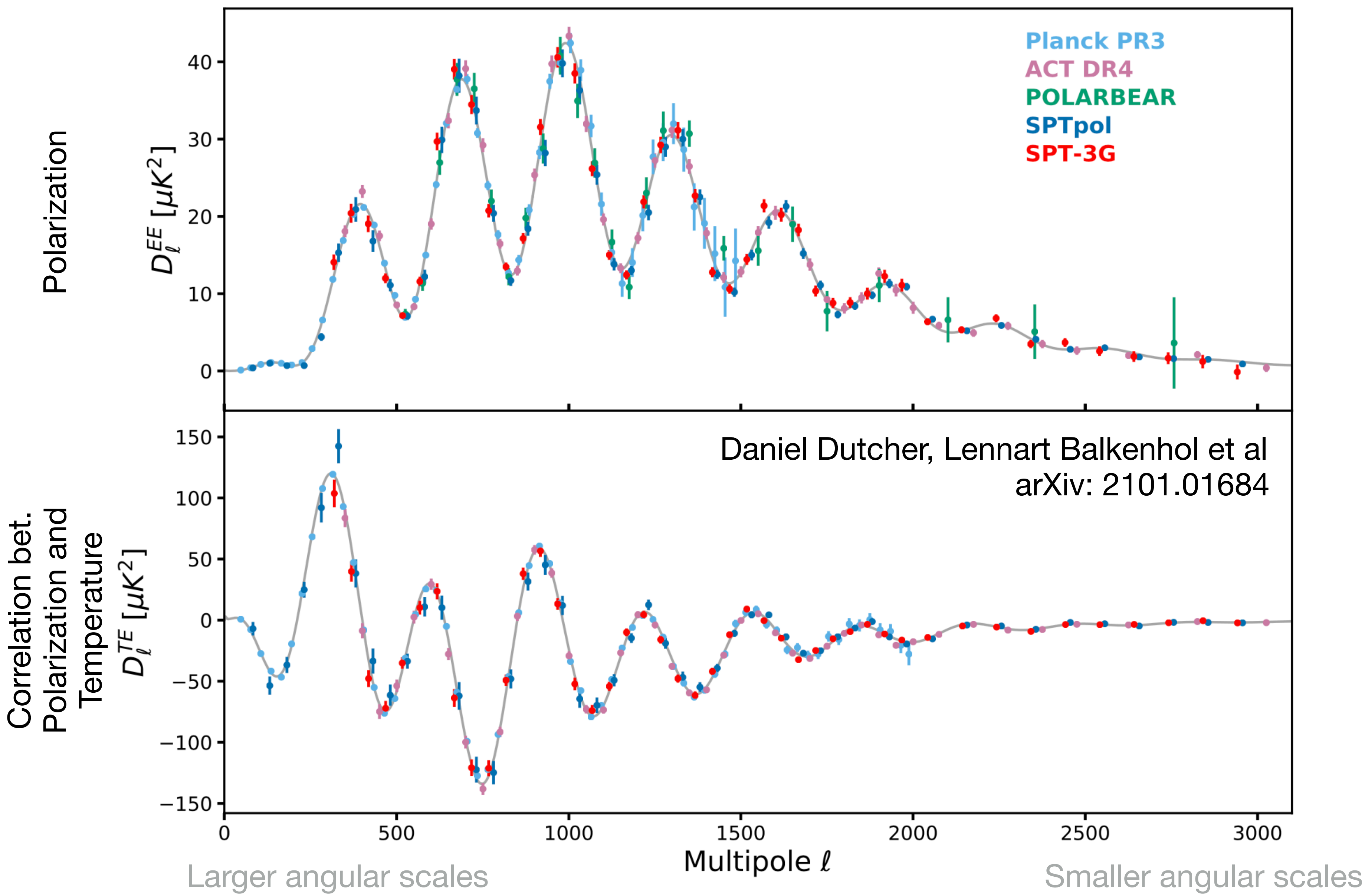


Larger angular scales

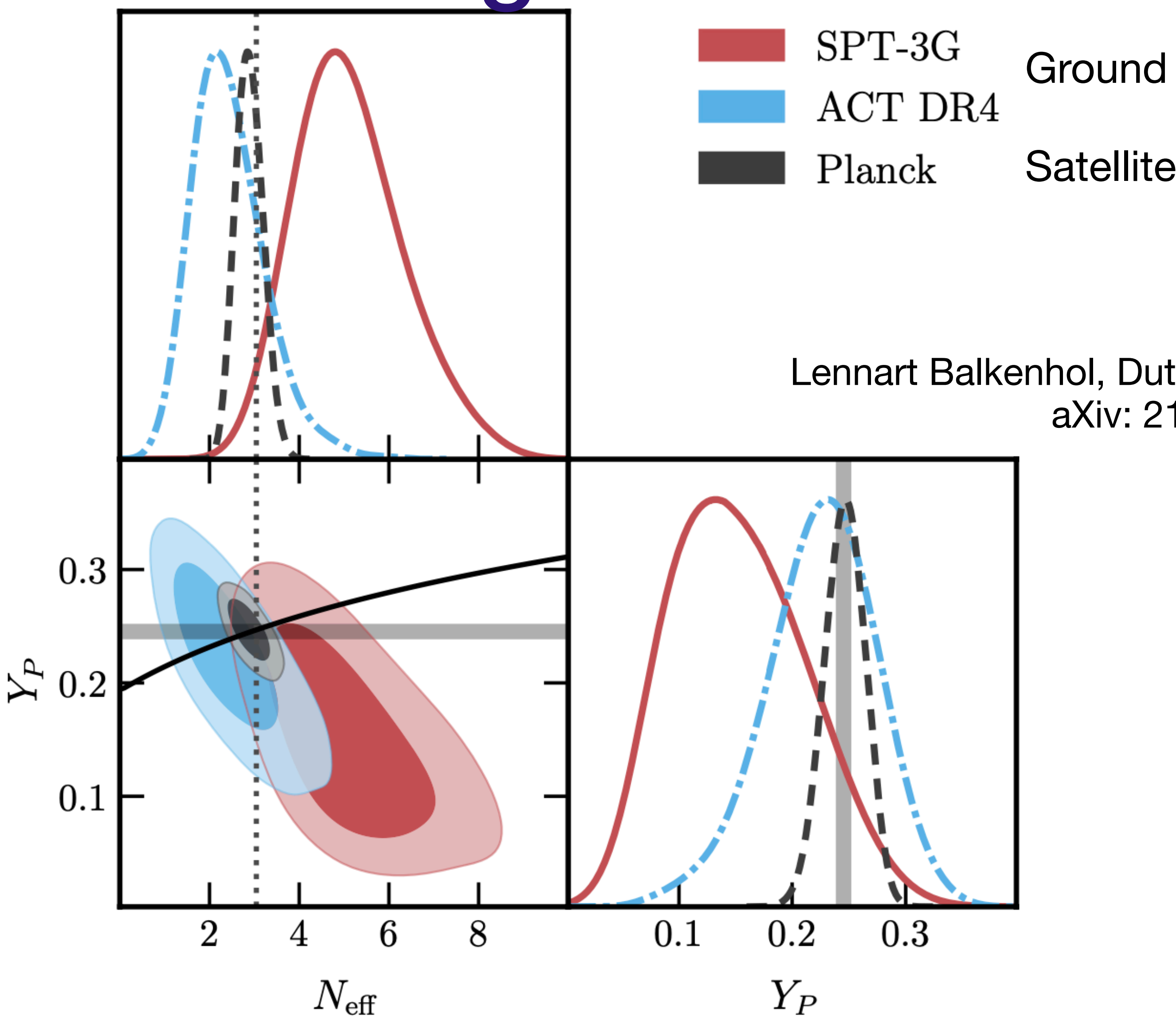
Smaller angular scales

Daniel Dutcher, Lennart Balkenhol et al
arXiv: 2101.01684

Comparing to other measurements

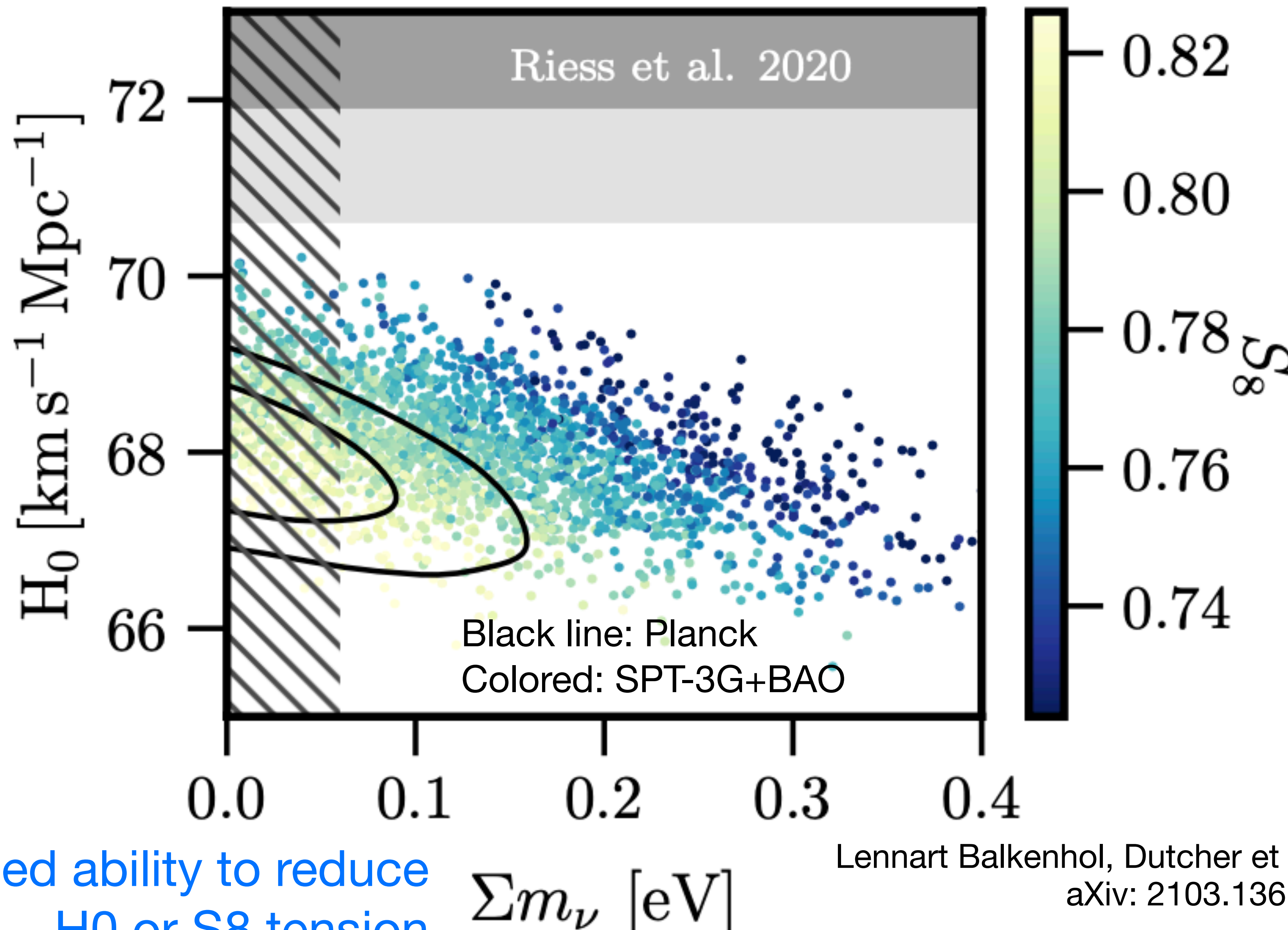


No evidence for extensions affecting BBN



Lennart Balkenhol, Dutcher et al.
aXiv: 2103.13618

Neutrino mass?

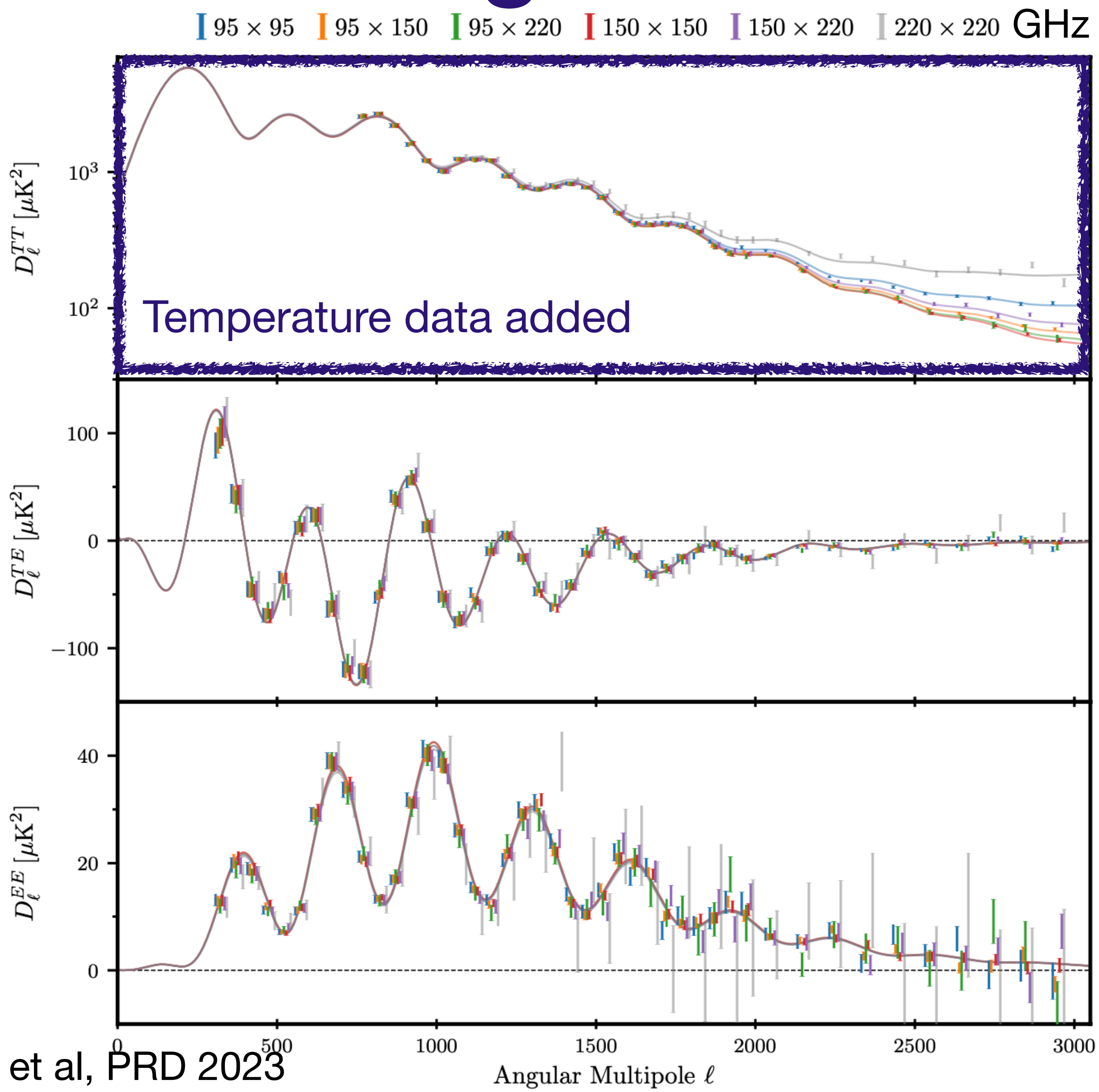


Limited ability to reduce H0 or S8 tension

Lennart Balkenhol, Dutcher et al.
aXiv: 2103.13618

From 2018 data

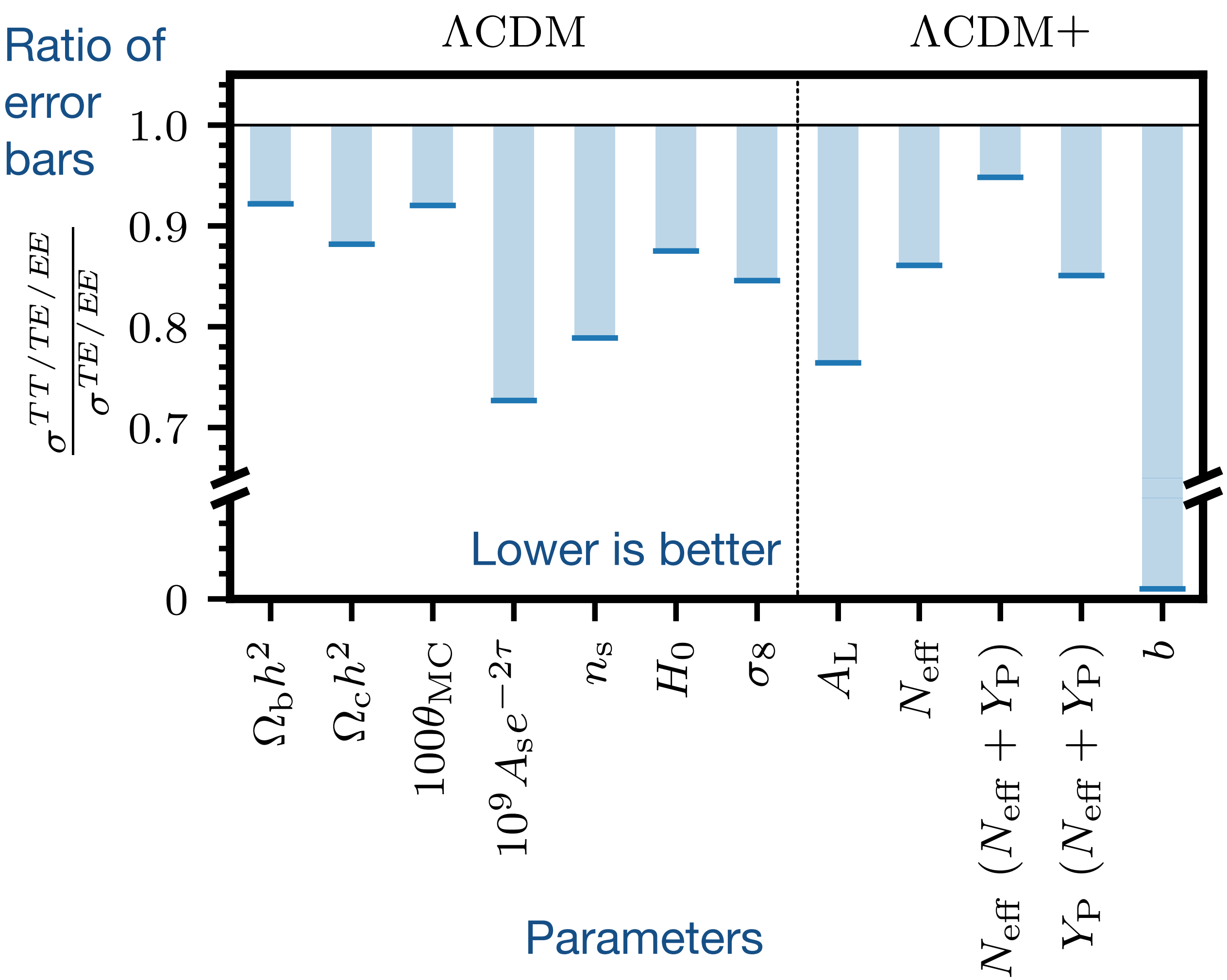
Adding temperature to break degeneracies



Lennart Balkenhol et al, PRD 2023

Lennart
PhD at Melbourne

Improvement from adding temperature (TT) power spectra

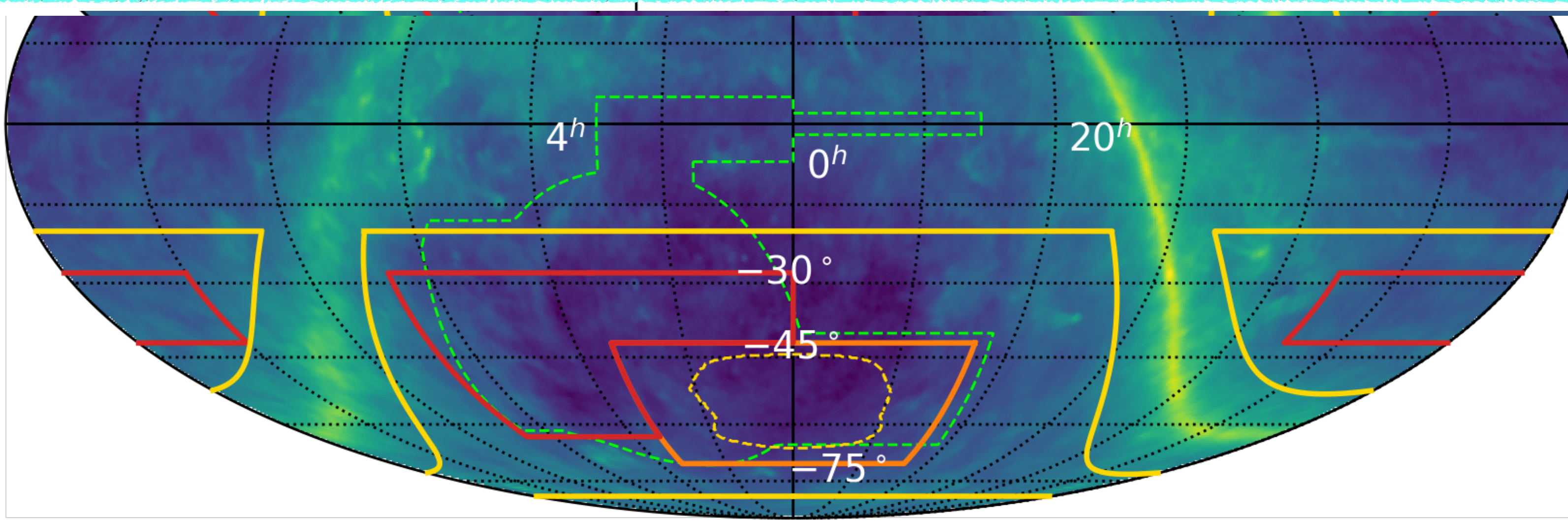


Adding TT tightens LCDM constraints by 8-27%

Similar improvement for most extensions

Future improvements

	ΛCDM					
	$\Omega_b h^2$	$\Omega_c h^2$	H_0	n_s	A_s	FoM
$\sigma(Planck)/\sigma(\text{Ext-10k})$	2.32	1.68	1.96	1.40	1.40	161
$\sigma(Planck)/\sigma(\text{Ext-10k+}Planck)$	2.72	2.15	2.44	1.83	1.67	283



- SPT-3G will continue till 2026, with full survey covering 25% of sky
- Will yield independent and tighter constraints than Planck on LCDM

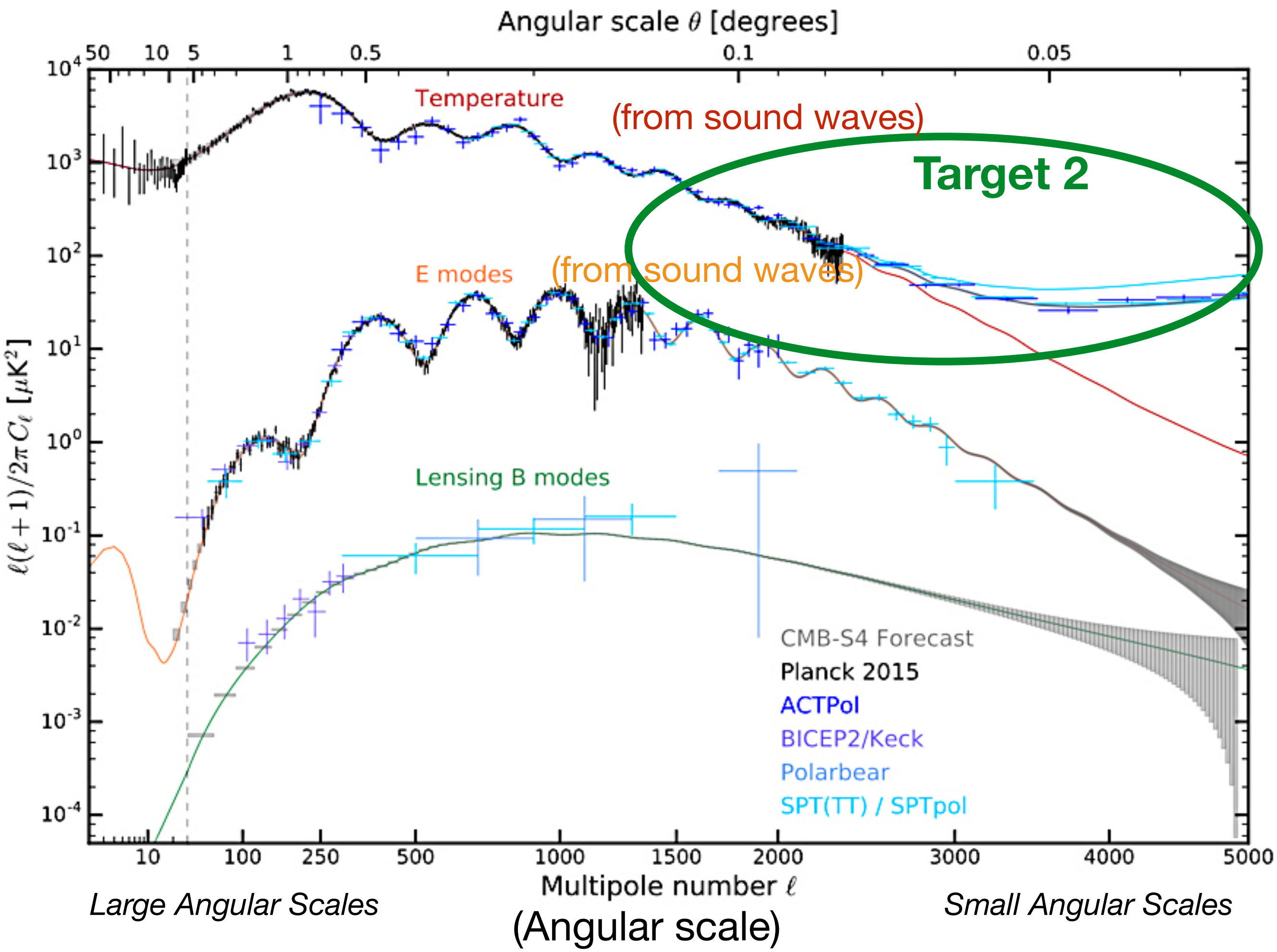
Takeaway 1:

SPT-3G is observing 25% of the sky, with great measurements of CMB temperature and polarization.

The SPT-3G power spectra are currently consistent with Planck & ΛCDM

Different Measurements of CMB Power spectra

from CMB-S4 Science Book 2016



Target 2: Secondary anisotropy: interactions of CMB photons with large-scale structure (temperature)

Next up: Secondary anisotropies

Prakrut Chaubal
(Melbourne)

SPT-3G Power Spectra

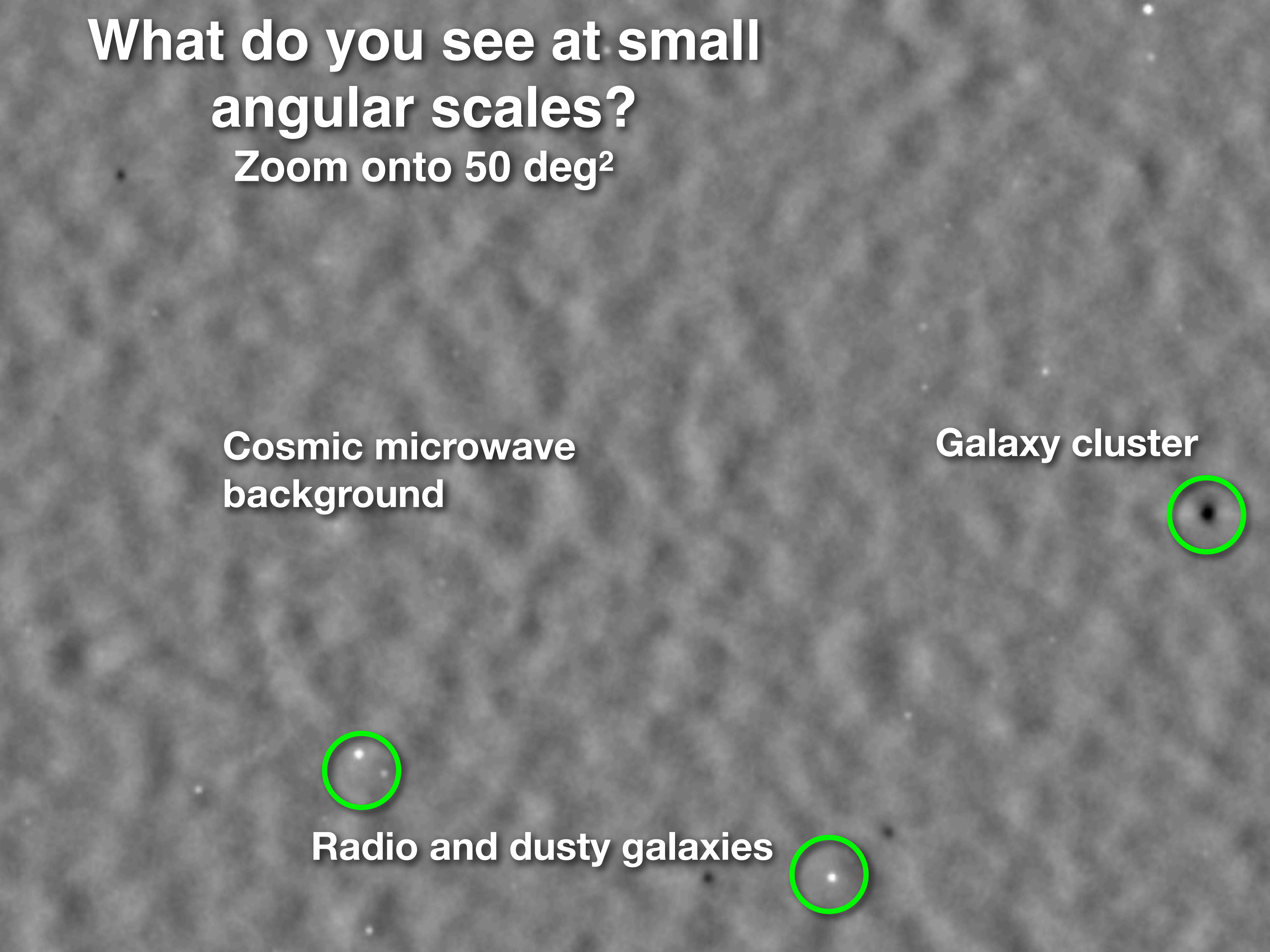
Target 2: Interactions between CMB photons and large scale structure

Nick Huang
(Berkeley)

- This is work in preparation, using the 2019+2020 SPT-3G data at 95, 150 and 220 GHz across 1500 deg^2
- Prakrut led the power spectrum estimation, while Nick is leading the modelling and interpretation

What do you see at small angular scales?

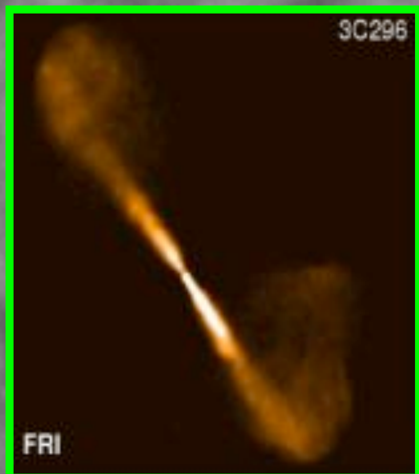
Zoom onto 50 deg^2



What do you see at small angular scales?

Zoom onto 50 deg²

Active galactic nuclei



Credit: https://www.jb.man.ac.uk/atlas/

Dusty, starforming galaxy

Radio and dusty galaxies show up as bright spots

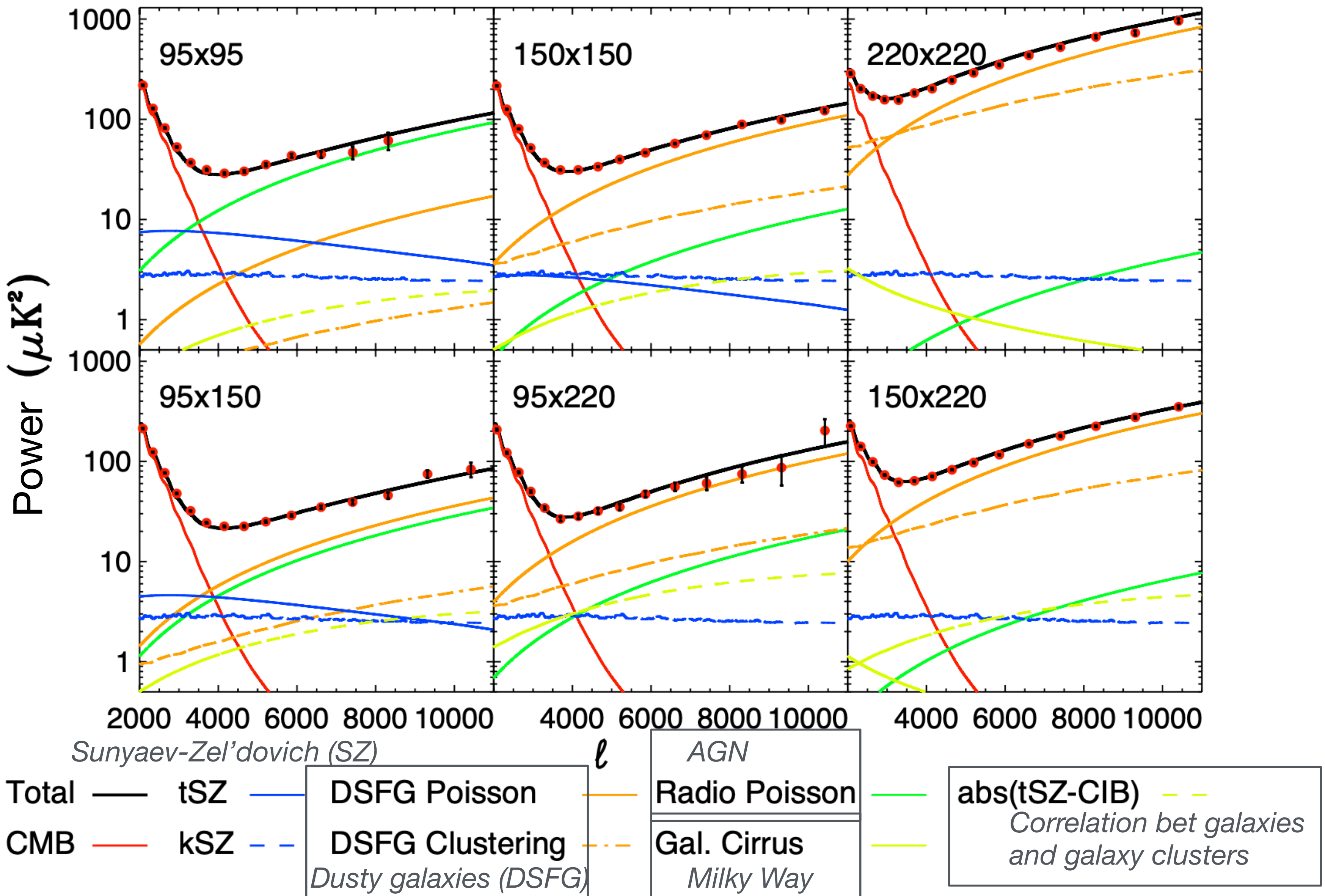
What do you see at small angular scales?

Zoom onto 50 deg^2

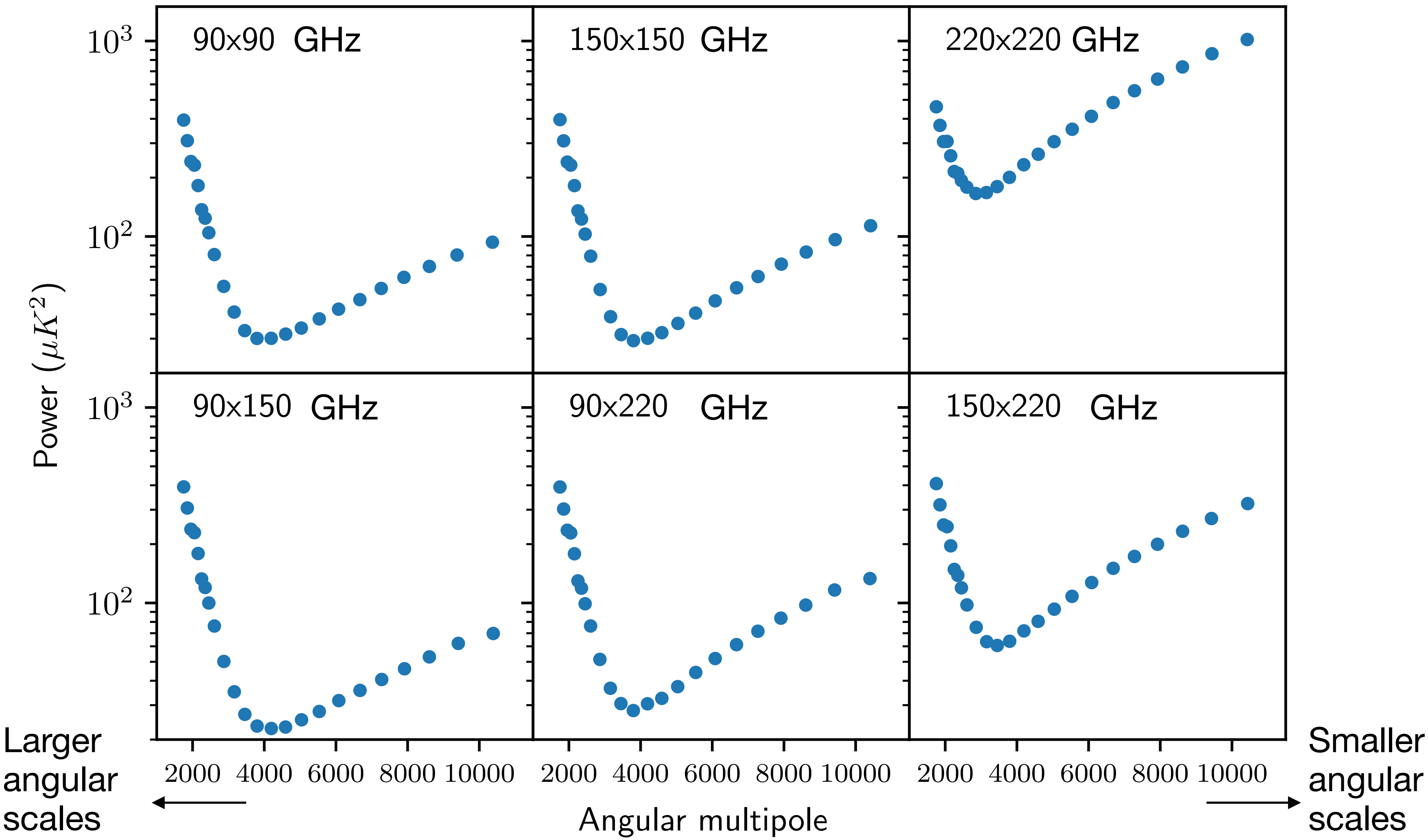
Thermal Sunyaev-Zel'dovich (SZ) - galaxy cluster create "shadows" in the CMB!

Model fit to previous SPT-SZ+SPTpol power spectra (from Reichardt et al 2021)

Expected Sky signals

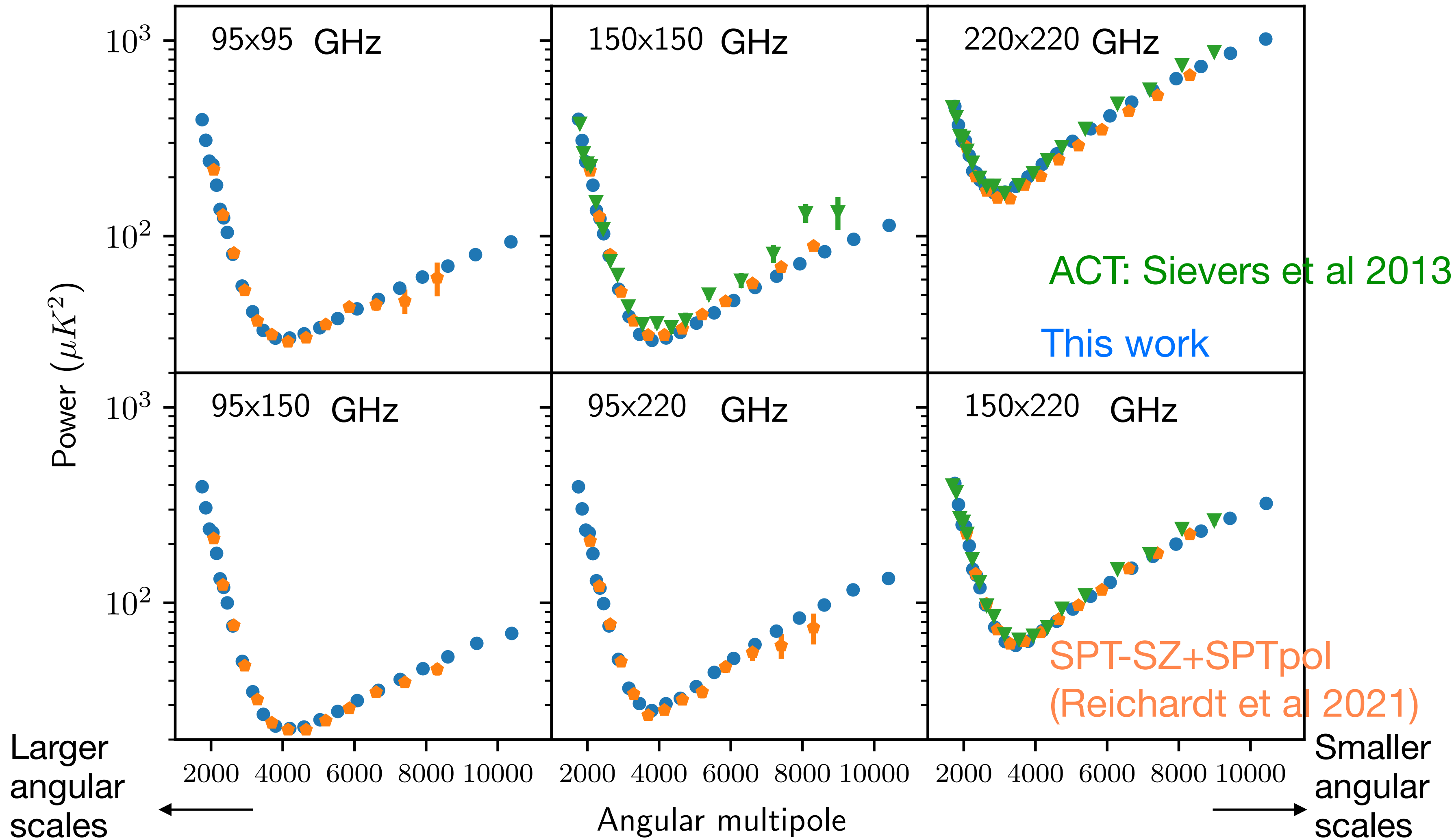


SPT-3G bandpowers!



Error bars smaller than symbols!

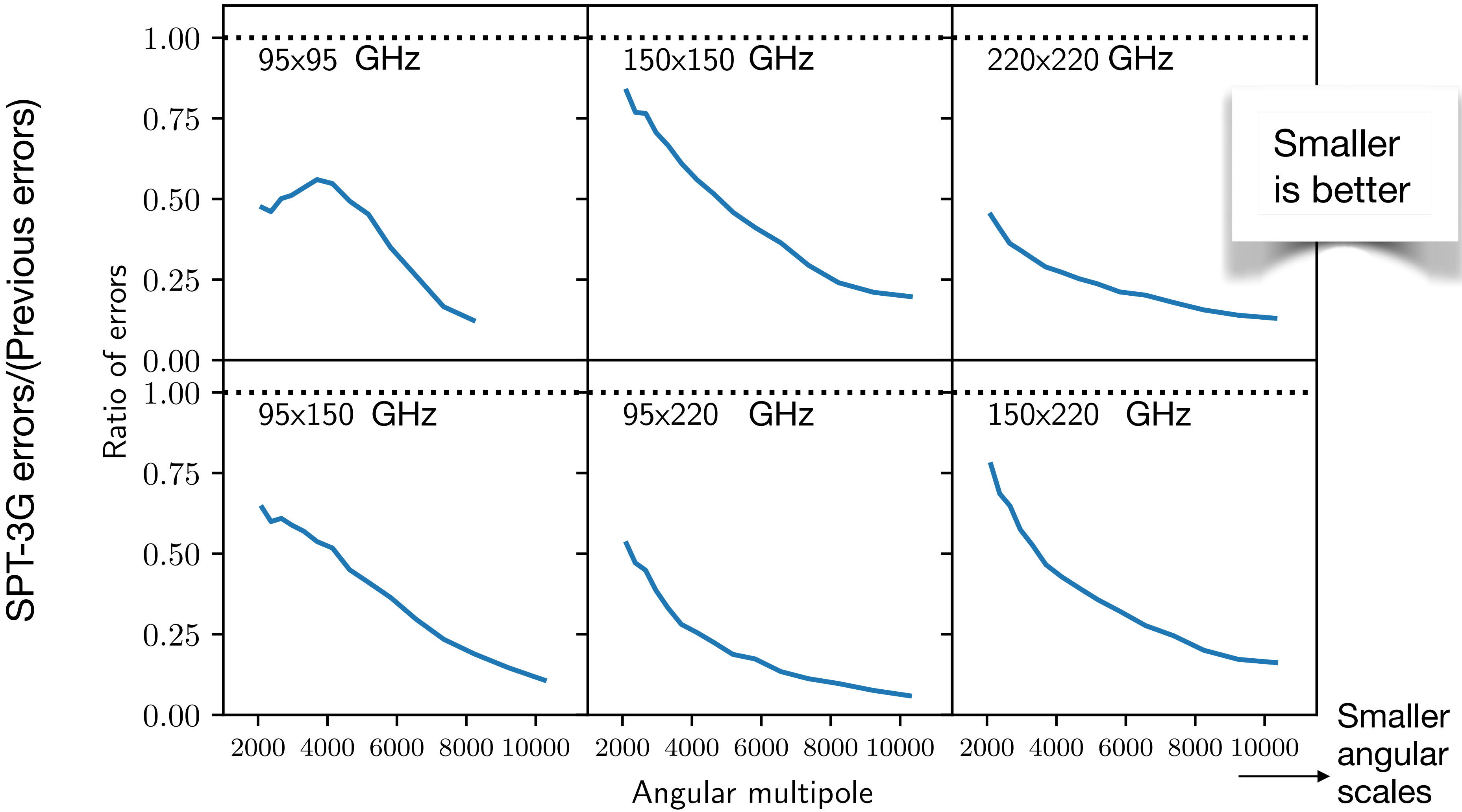
Compared to previous work



Note: Each experiment has **slightly different** frequencies and source masking

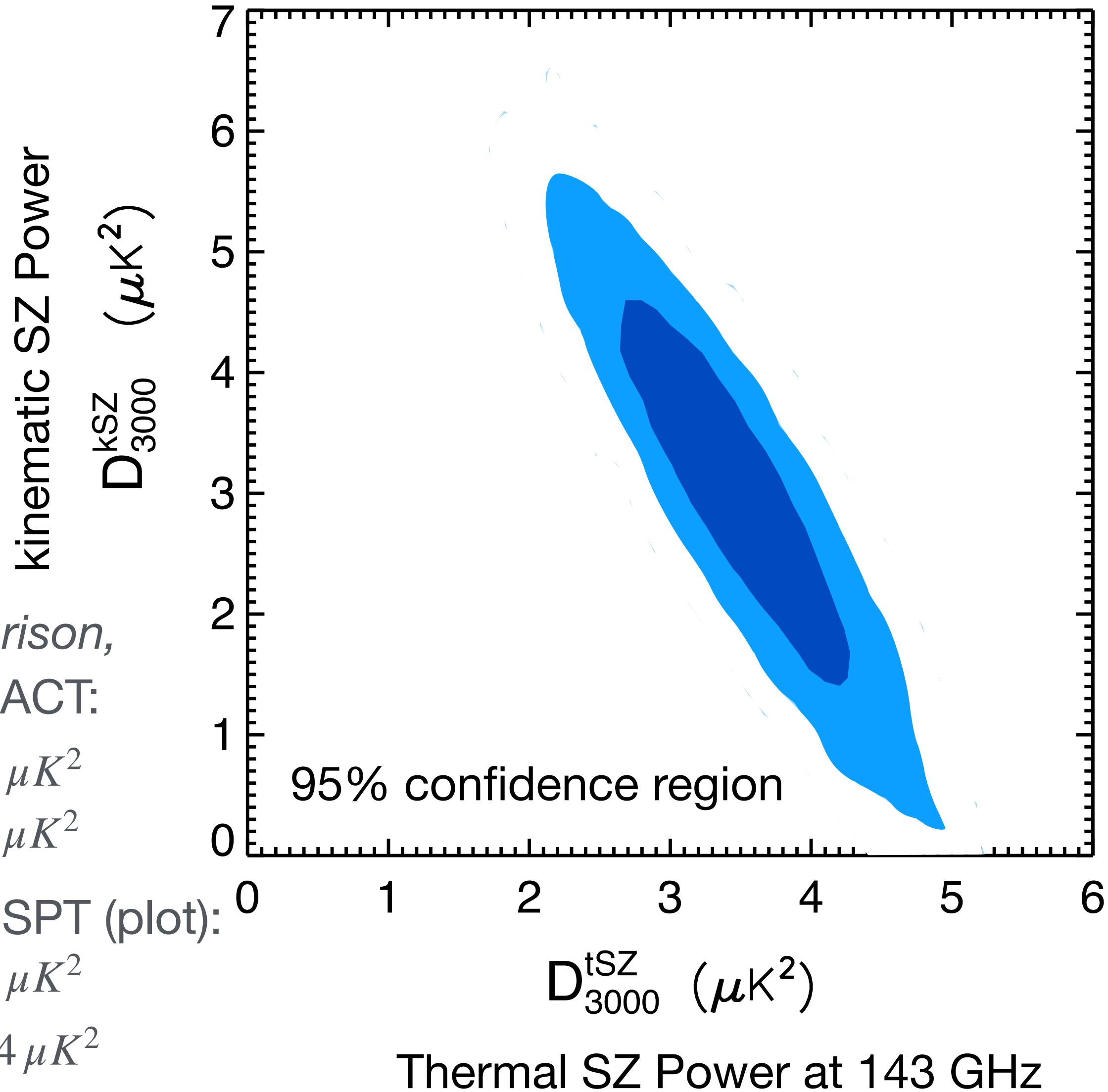
Significant improvements

in all frequency bands, especially at small angular scales



Much smaller error bars than previous measurement
with SPT-SZ+SPTpol in Reichardt et al. 2021

Tighter constraints on kinematic SZ and thermal SZ power



Previous best SPT-SZ+SPTpol (Reichardt et al 2021)

In comparison,
Previous ACT:

$\sigma_{kSZ} \sim 4.3\,\mu K^2$

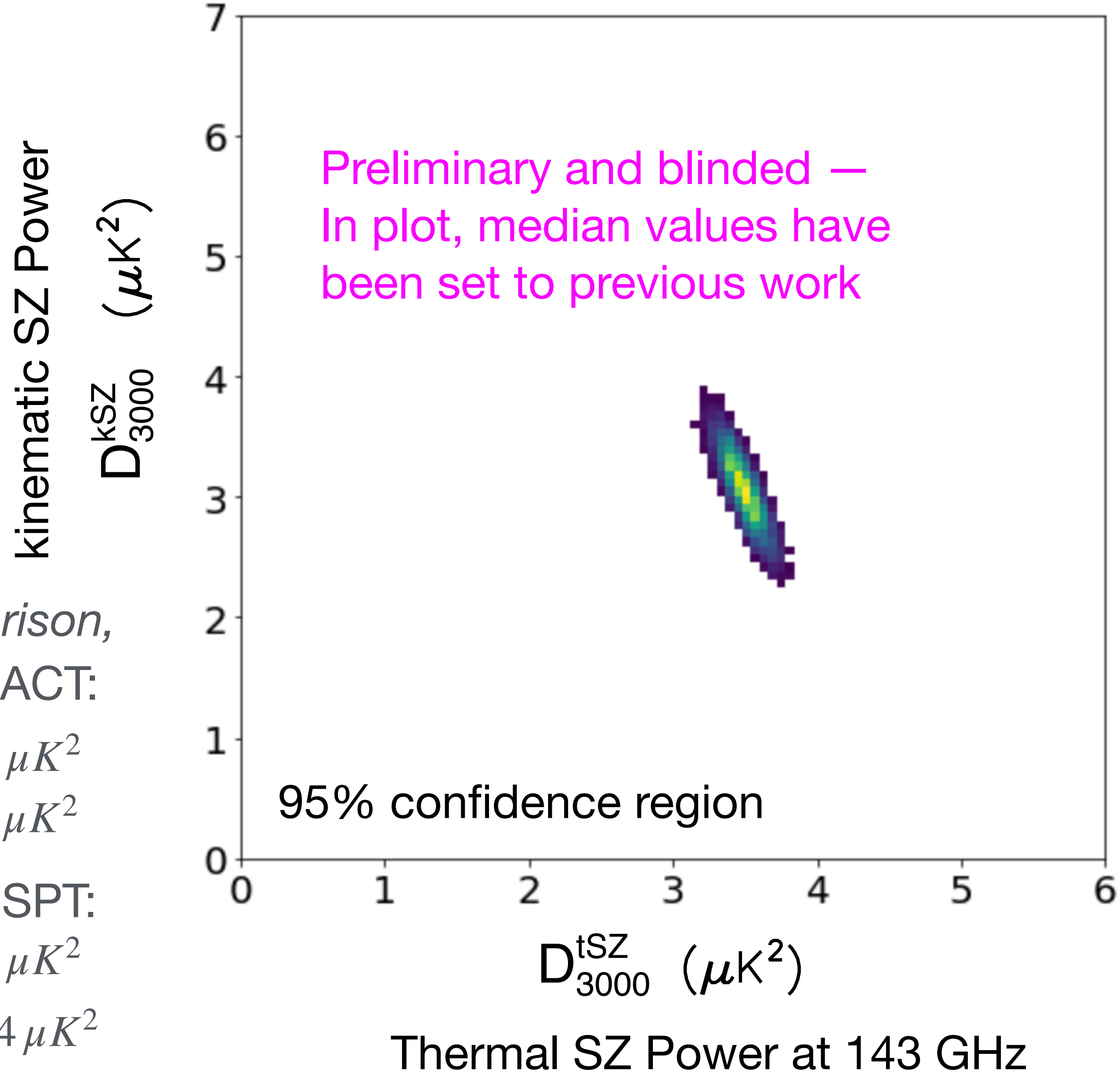
$\sigma_{tSZ} = 1.4\,\mu K^2$

Previous SPT (plot):

$\sigma_{kSZ} = 1.0\,\mu K^2$

$\sigma_{tSZ} = 0.54\,\mu K^2$

Tighter constraints on kinematic SZ and thermal SZ power



This work

Same model, with new SPT-3G data

Modelling may change for final results

Central values ***will change***

$$\sigma_{kSZ} = 0.33\,\mu K^2$$
$$\sigma_{tSZ} = 0.13\,\mu K^2$$

In comparison,

Previous ACT:

$\sigma_{kSZ} \sim 4.3\,\mu K^2$

$\sigma_{tSZ} = 1.4\,\mu K^2$

Previous SPT:

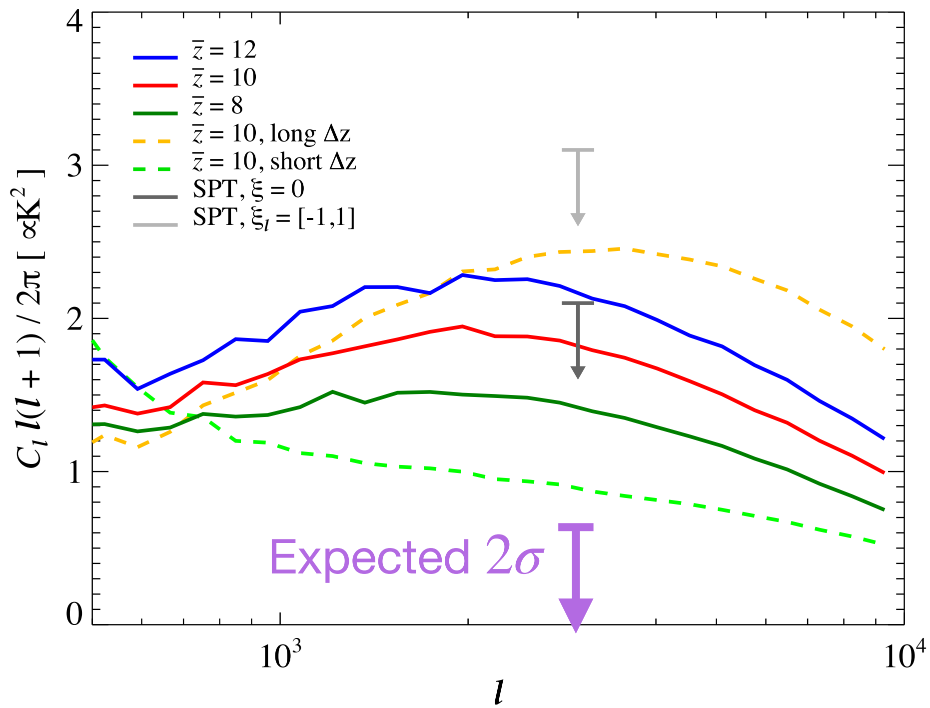
$\sigma_{kSZ} = 1.0\,\mu K^2$

$\sigma_{tSZ} = 0.54\,\mu K^2$

What might be learned?

Better understanding of astrophysics and the epoch of reionization:

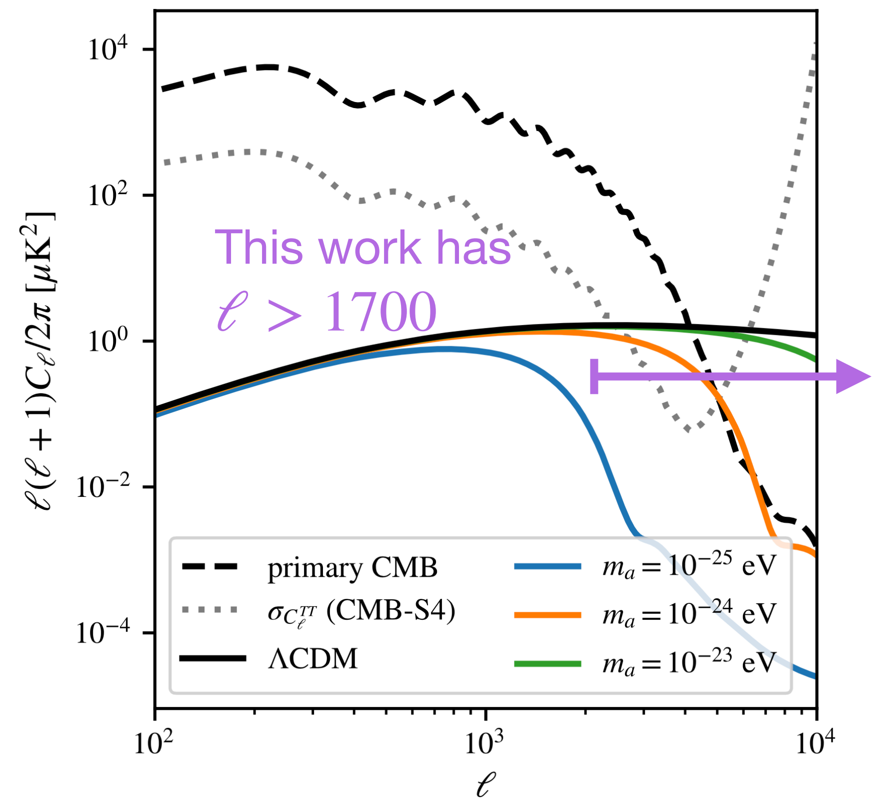
Battaglia et al 2013



kinematic SZ signal from reionization depends on EoR's timing and duration (more power if reionization is longer or happens earlier)

And maybe also limits on BSM physics:

Farren et al 2022



Ultra-light axions (for some masses) suppress small-scale haloes and the resulting Ostriker-Vishniac effect

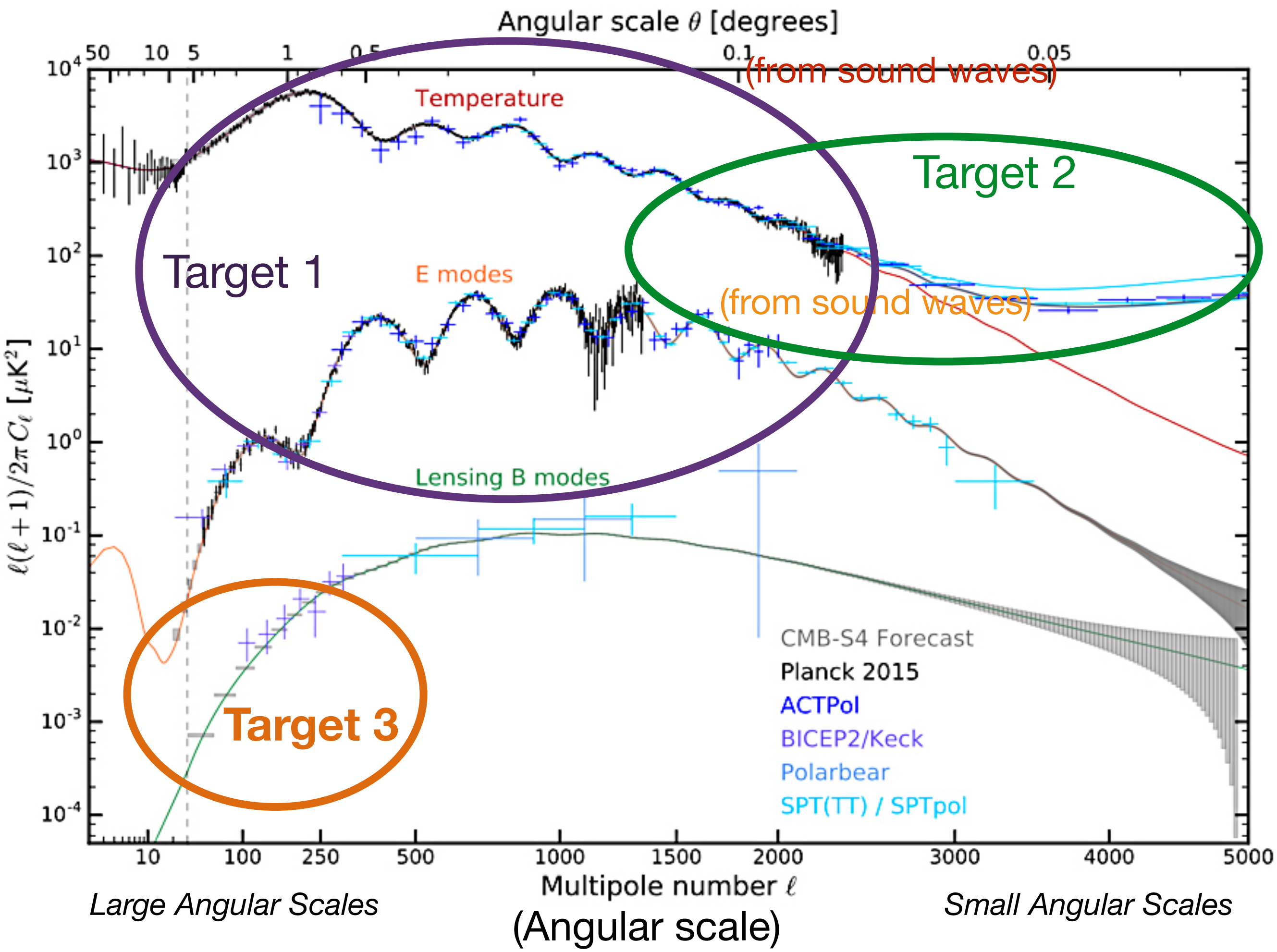
Takeaway 2:

SPT-3G data will yield superb constraints on the thermal and kinematic SZ power spectra, as well as other sources of power on small angular scales.

The measurements will help constrain the Epoch of Reionization and *potentially* BSM physics.

Different Measurements of CMB Power spectra

from CMB-S4 Science Book 2016



Target 1: Primary CMB anisotropy (temperature+polarization)

Target 2: Secondary anisotropy: interactions of CMB photons with large-scale structure (temperature)

Target 3: Inflationary gravitational waves (polarization)

Next up: Inflationary gravitational waves

Jessica Avva Zebrowski (work done at Berkeley and Chicago)

SPT-3G Power Spectra

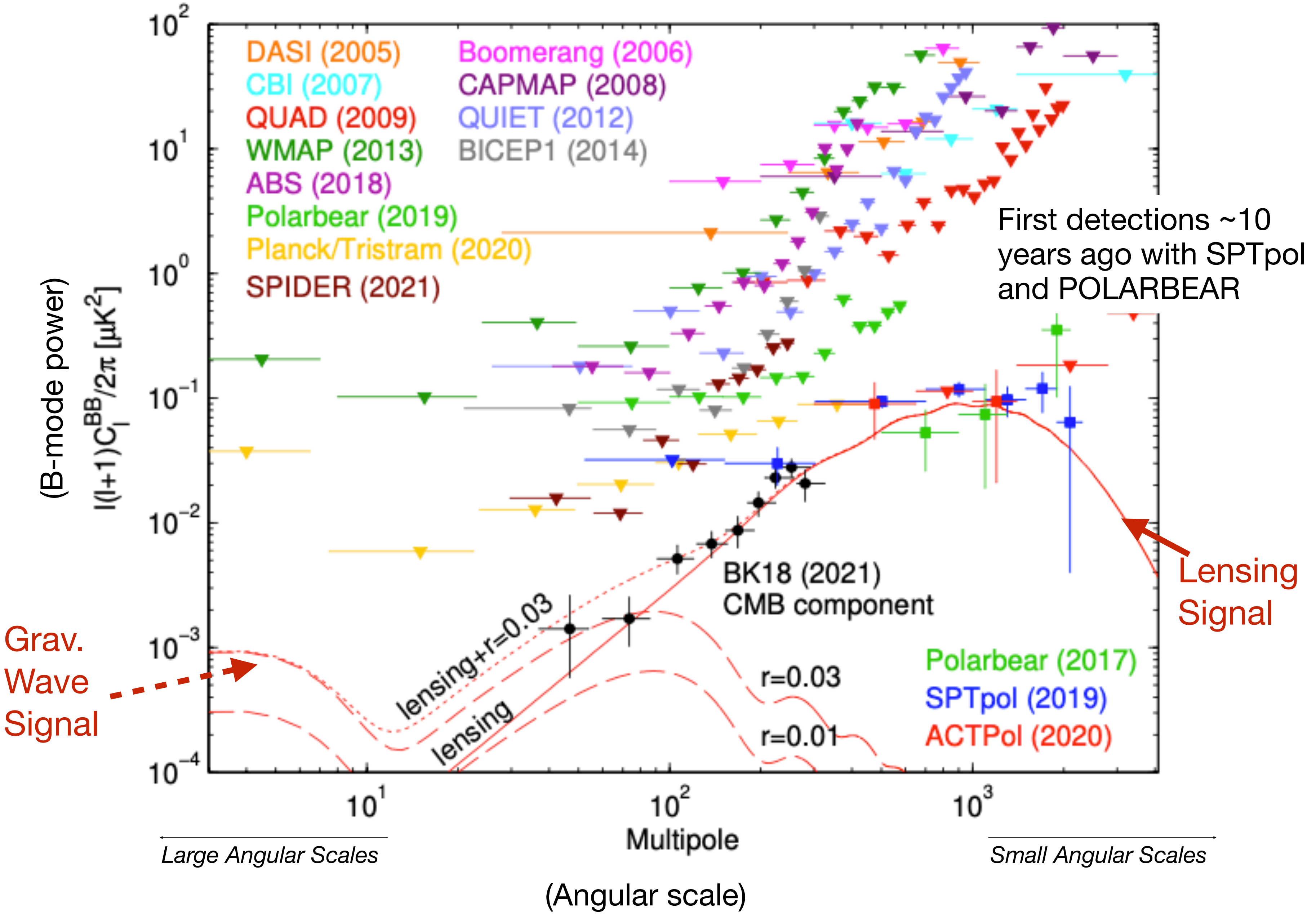
Target 3: Inflationary Gravitational Waves

Mahsa Rahimi (Melbourne)

- This is work in preparation, using the 2019+2020 SPT-3G data
- Jessica has been the driving force behind this measurement (especially in quantifying and removing sources of low-frequency noise), with more recent contributions from Mahsa and myself

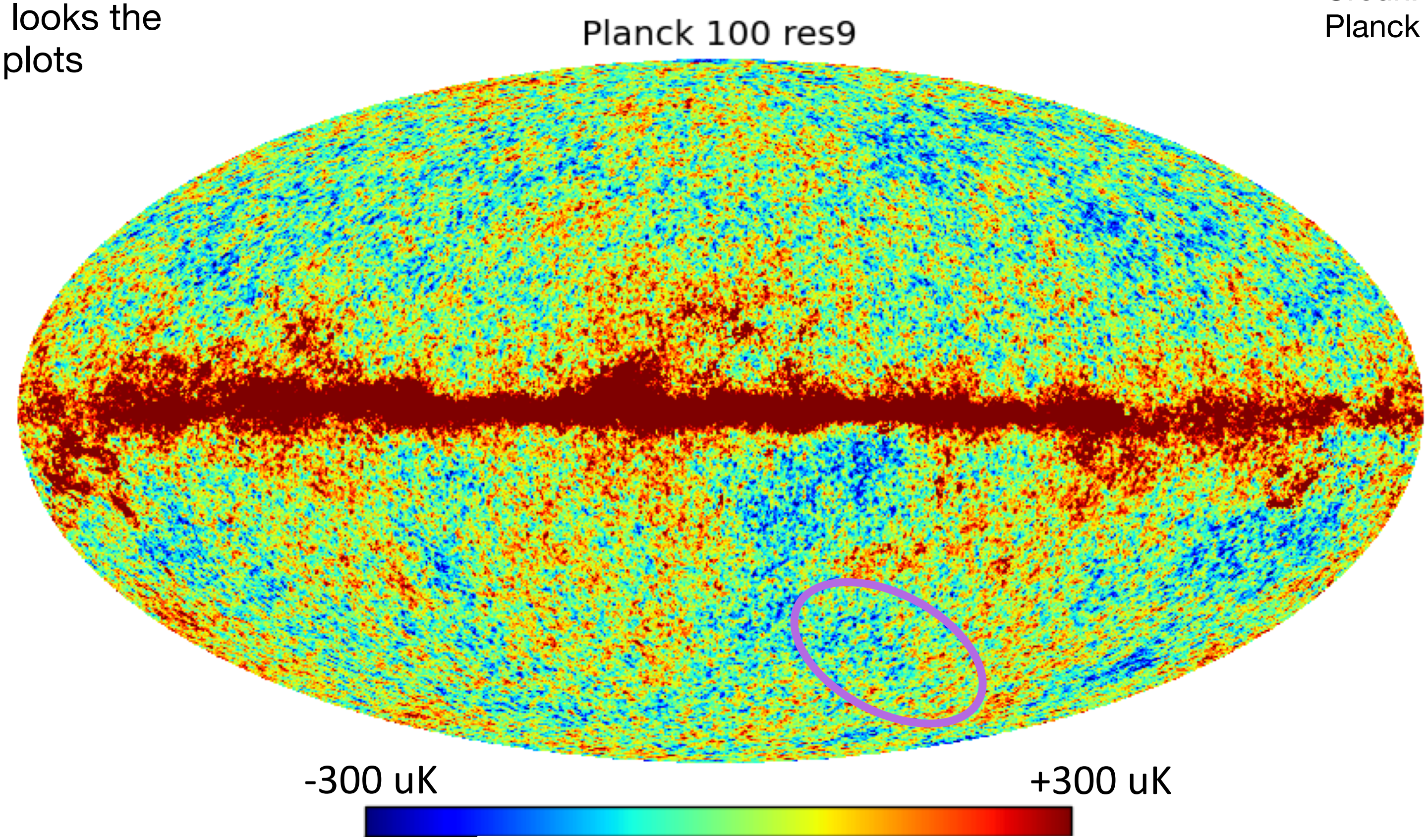
Figure from Bicep/Keck XIII

Current state of B-mode power spectra

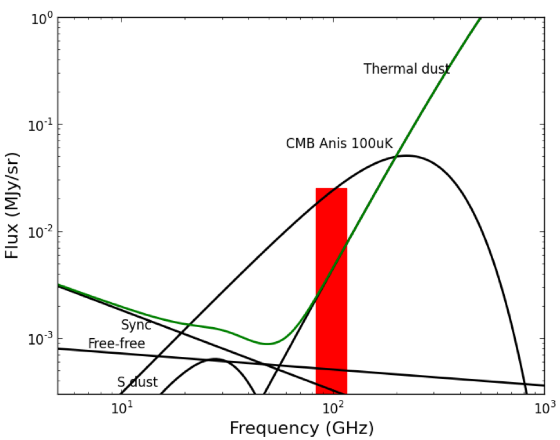


Note: CMB looks the same in all plots

Credit: S. Ferrara & Planck



Very Approx area with SPT-3G 100 GHz data

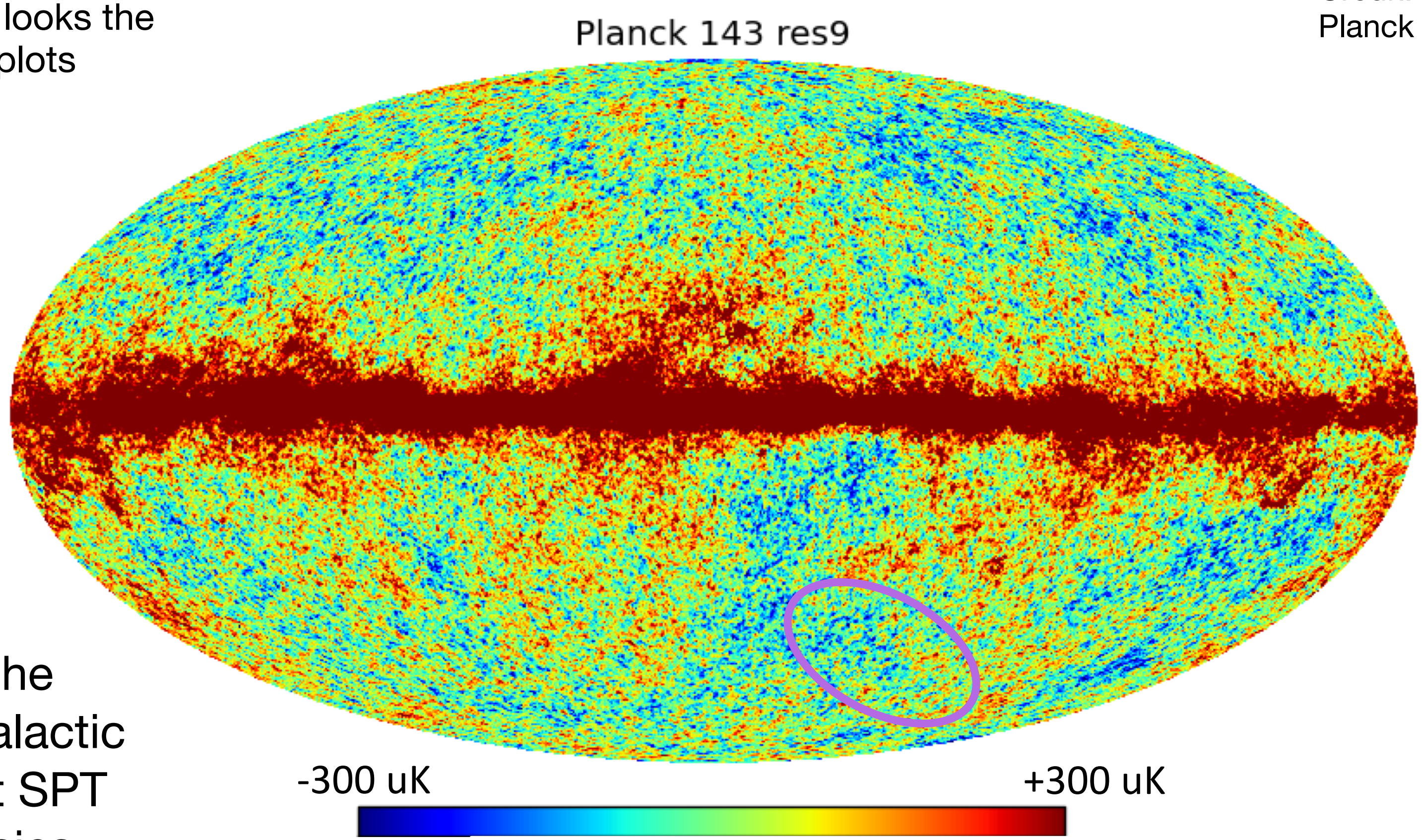


Separating the CMB and Milky Way: A trip from low to high frequencies

Multiple frequency bands can distinguish CMB from the dust and synchrotron emission of the Milky Way

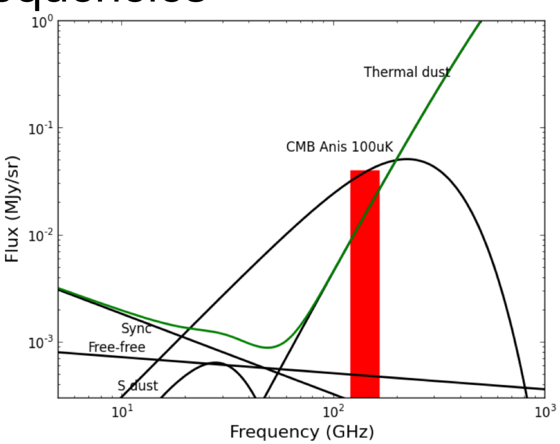
Note: CMB looks the same in all plots

Credit: S. Ferrara & Planck



Very Approx area with SPT-3G 150 GHz data

Dust is the major galactic signal at SPT frequencies



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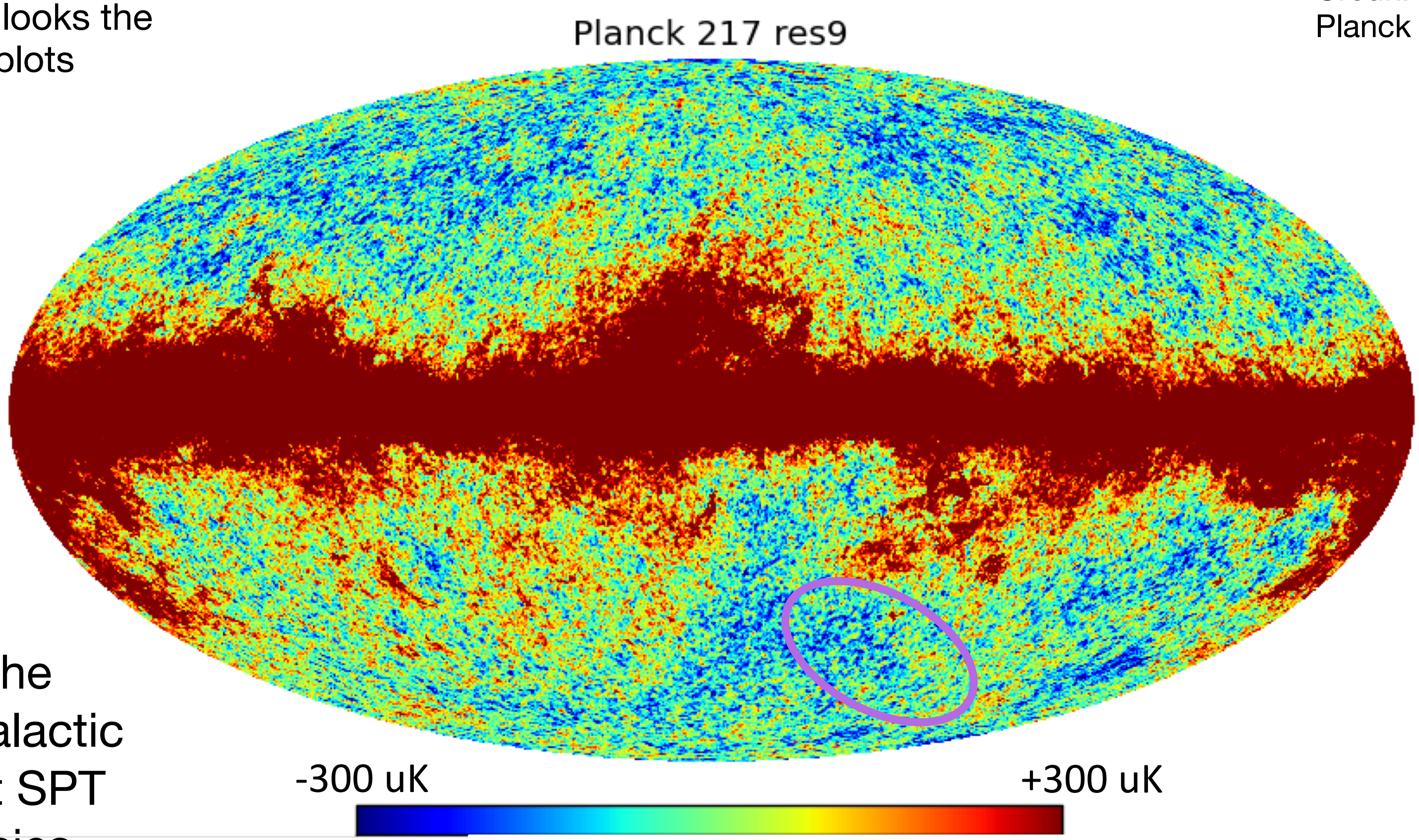
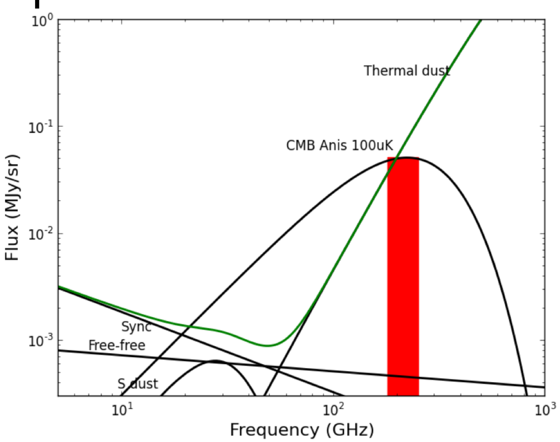


Very Approx area with SPT-3G 220 GHz data

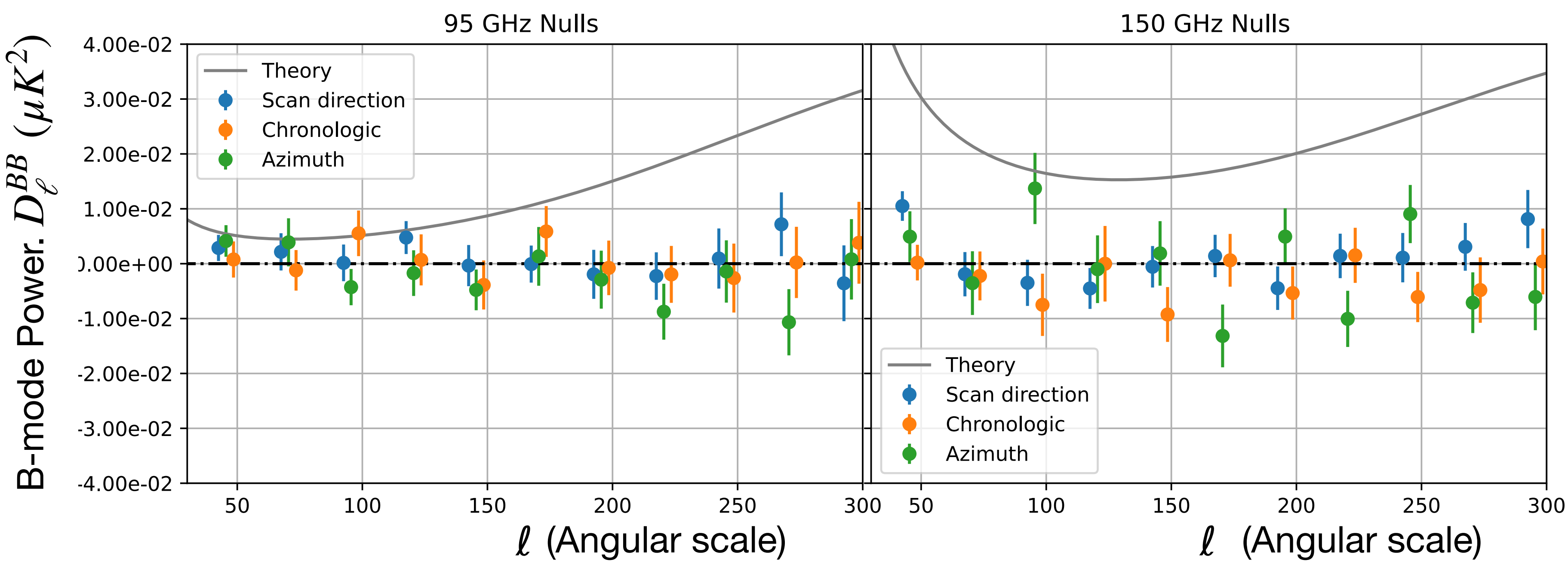
Dust is the major galactic signal at SPT frequencies



Separating the CMB and Milky Way: A trip from low to high frequencies

Multiple frequency bands can distinguish CMB from the dust and synchrotron emission of the Milky Way

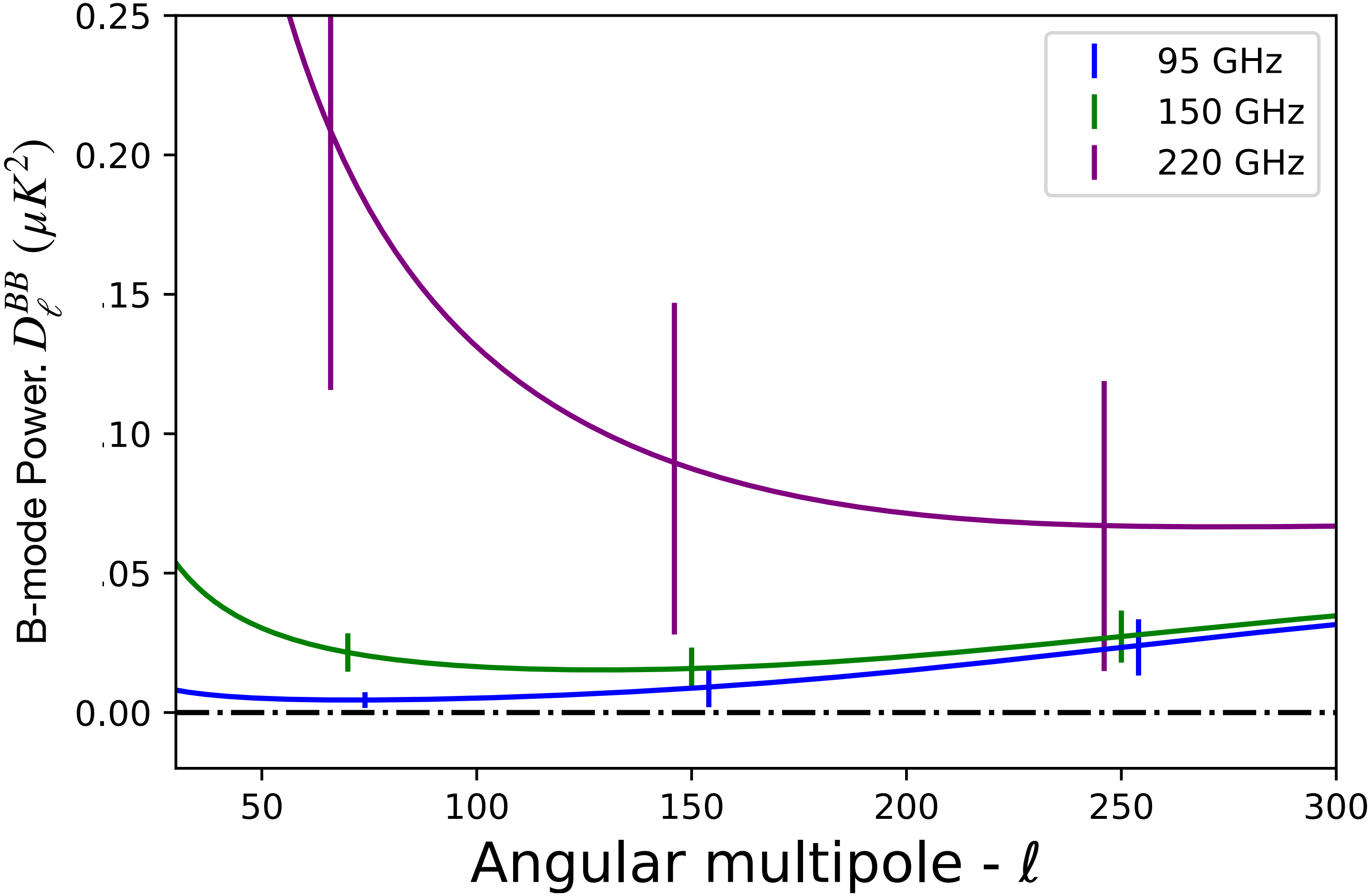
No evidence for systematics



Null tests are consistent with zero: Chronologic, Scan direction, Azimuth,

Also (not shown): Moon up/down & Sun up/down, and 220 GHz nulls

Expected Performance



Independent cross-check of BICEP/ Keck limits

Bandpower uncertainties (centered at zero) compared to the expected signals at 95, 150 and 220 GHz

Takeaway 3:

SPT-3G will yield competitive constraints on inflationary gravitational waves.

In conclusion

- SPT-3G has made high S/N measurements of the CMB polarisation spectra
    - Precision constraints on the standard cosmological model
    - No resolution yet to Hubble tension
- More than halfway through SPT-3G survey

    Plans for SPT3G+ at higher frequencies
- Experimental sensitivities are improving rapidly with diverse technology base
    - CMB-S4 is being built for 2032
    - Improve sensitivity by ~O(x50) over 2020 state