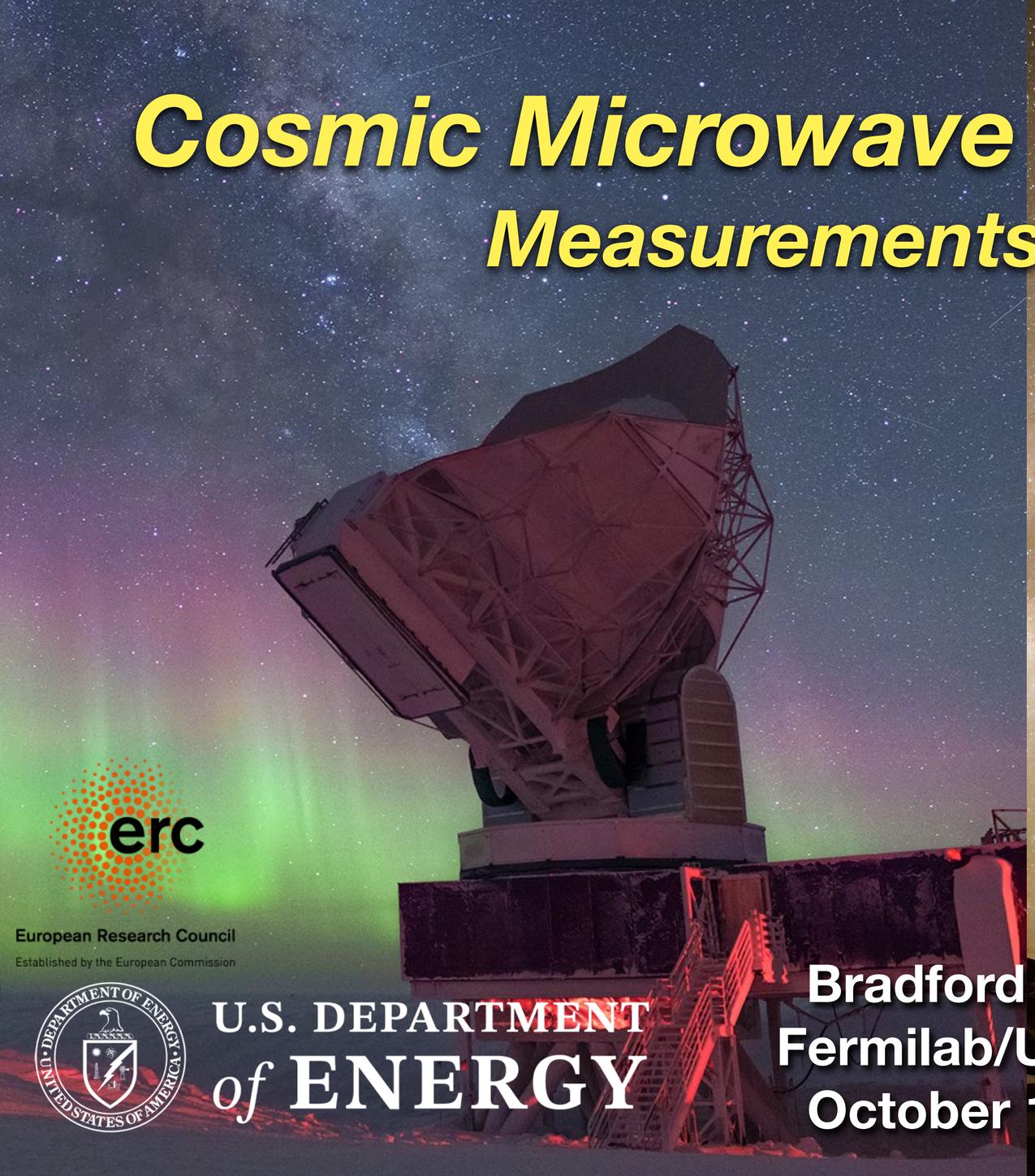
Cosmic Microwave Background (CMB):
Measurements and Prospects





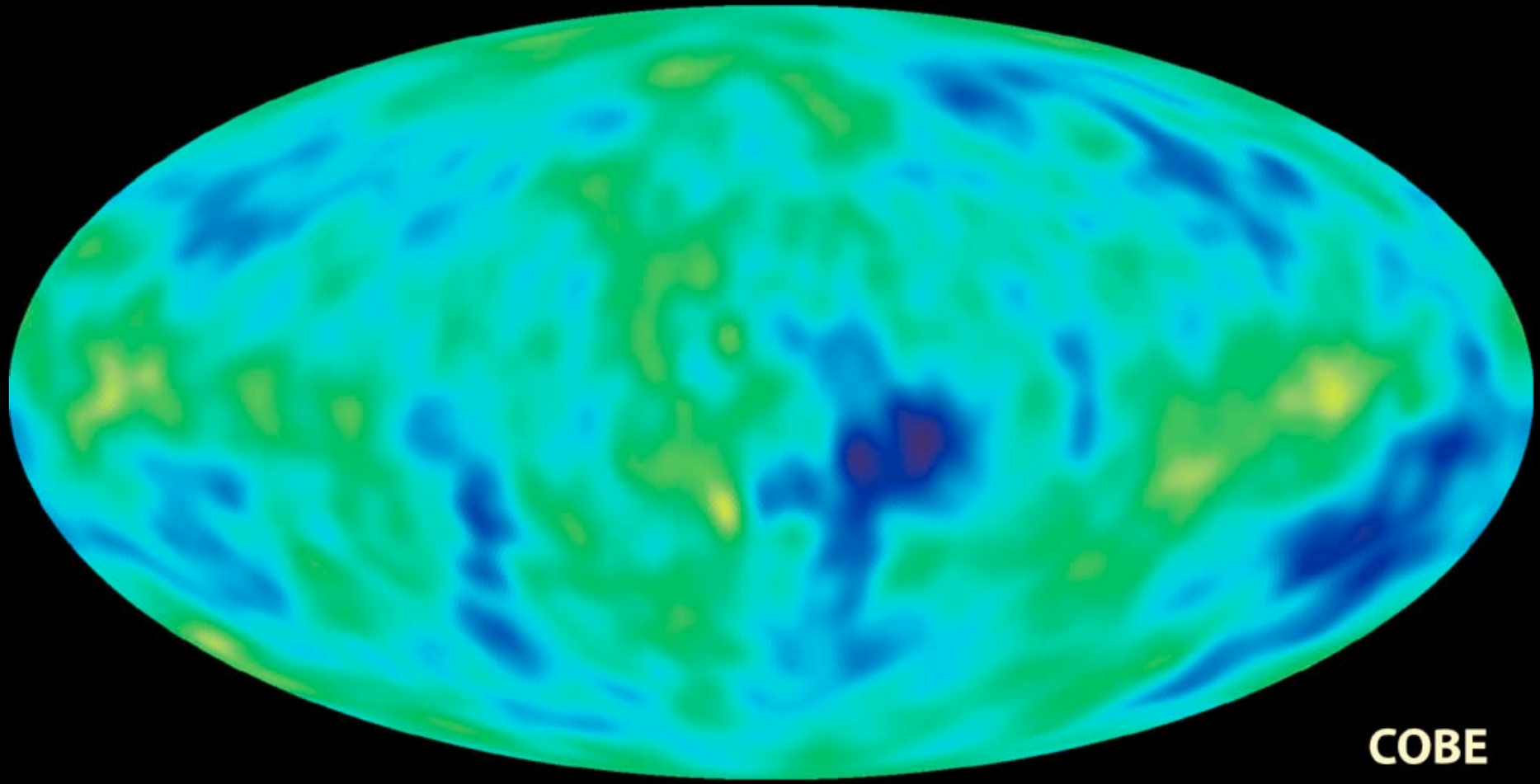
European Research Council
Established by the European Commission

U.S. DEPARTMENT of ENERGY

Bradford Benson
Fermilab/UChicago
October 15, 2026

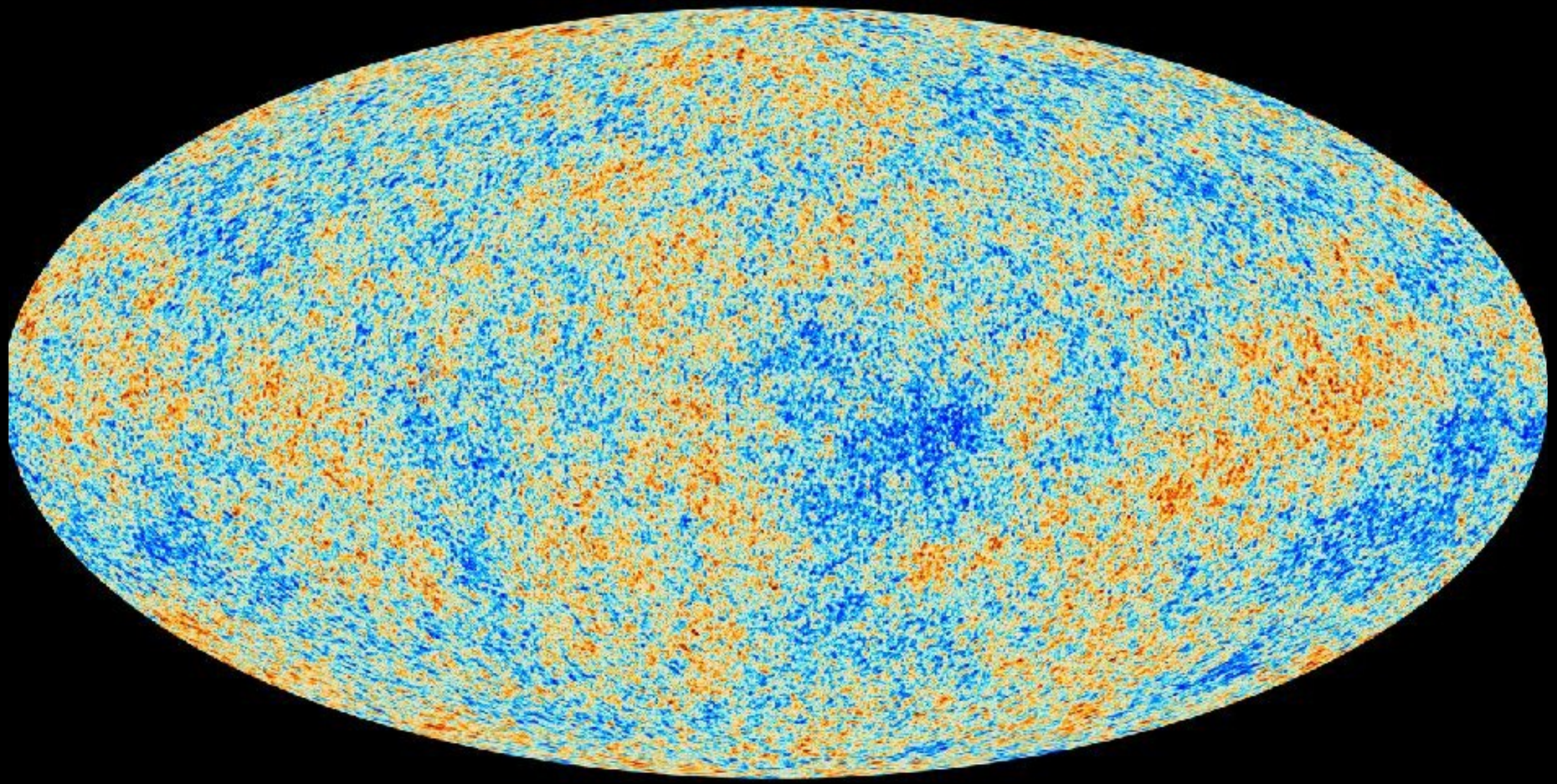
1992: COBE - First Detection of CMB Anisotropy

1/100,000 fluctuations on 3 Kelvin background



2013: Planck - Best All-sky CMB Measurements Today

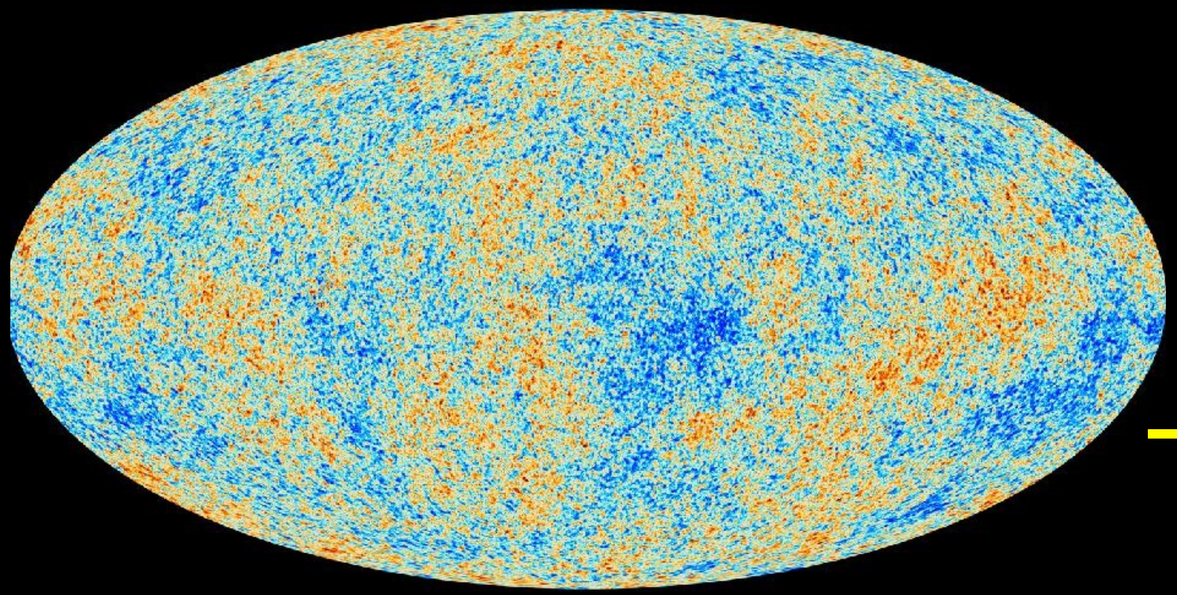
1/100,000 fluctuations on 3 Kelvin background

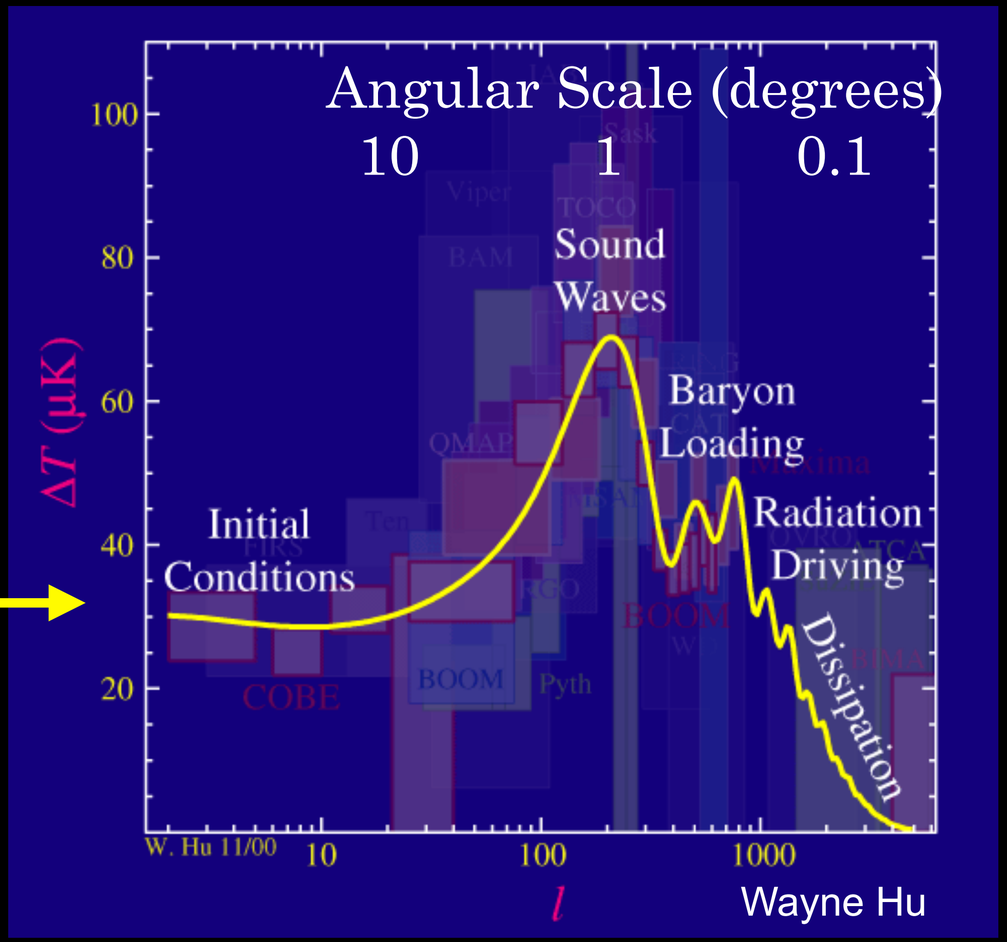


Credit: ESA (Planck)

What have we learned?

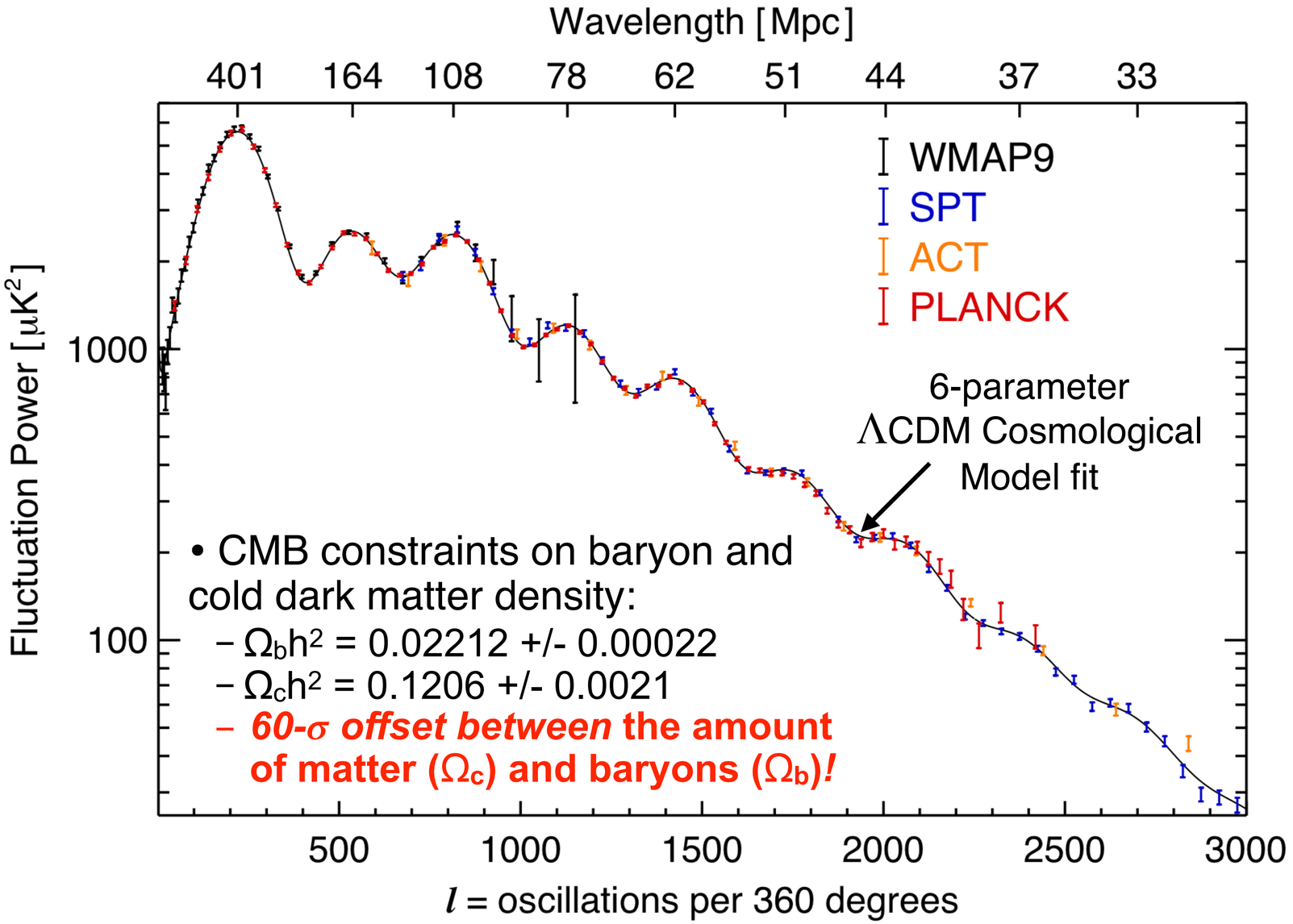
Encoded within the CMB is information regarding the Universe's **initial conditions**, its **geometry** (flat vs curved), and its **content** (ordinary matter, dark matter, dark energy)



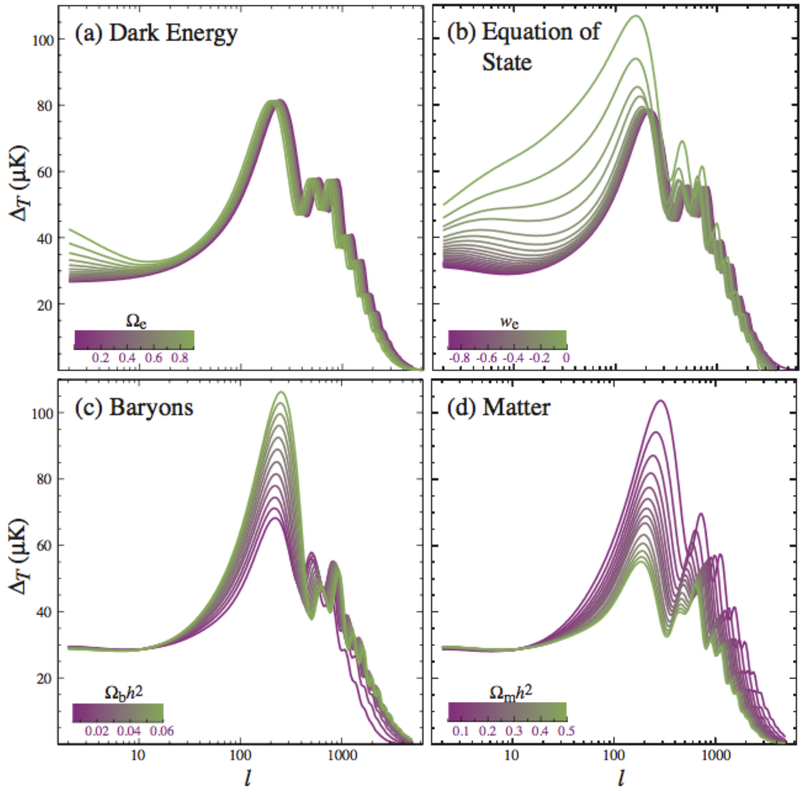


Cosmology predicts a distinct "spectrum" to the CMB with well-defined "harmonics"

The CMB Today: implies a Universe dominated by dark matter and dark energy (ΛCDM model)

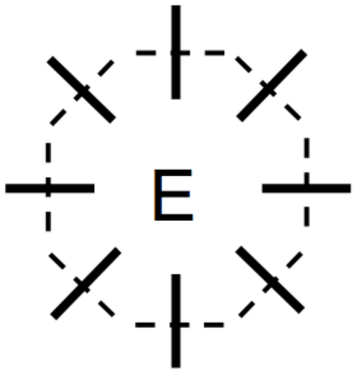


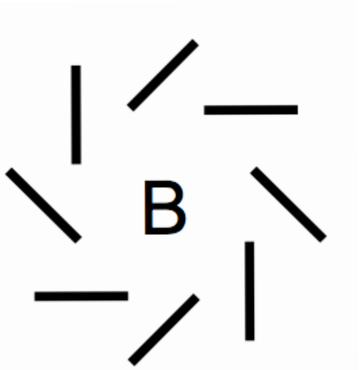
Planck Collaboration L06 (2018)

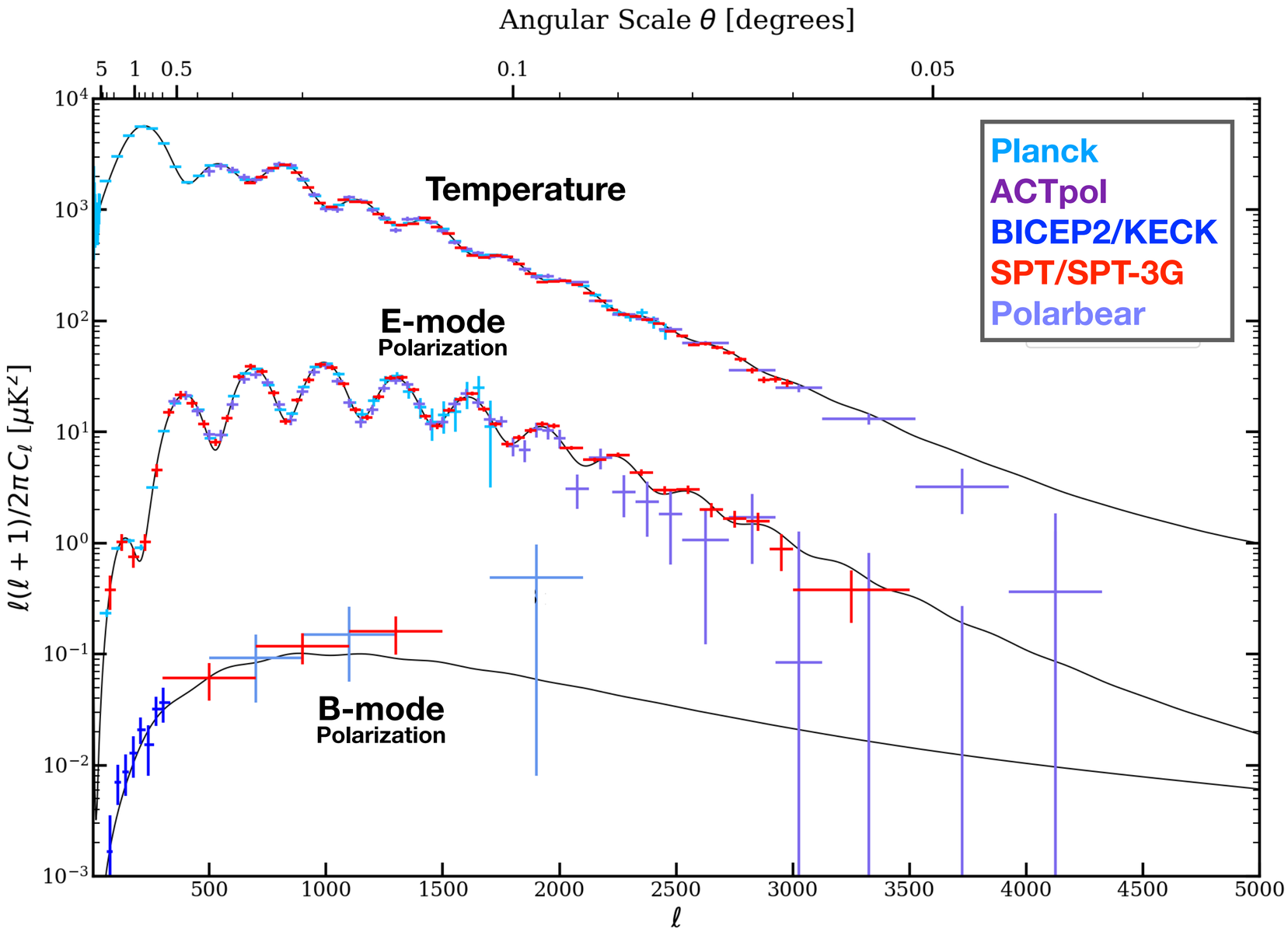


Hu (2008) arXiv: 0802.3688

The Next Frontier: CMB Polarization

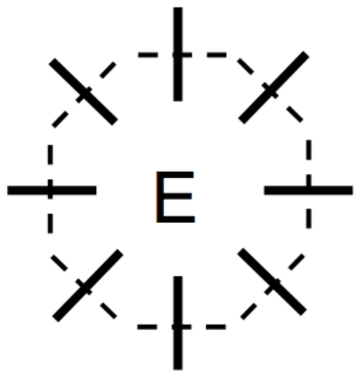


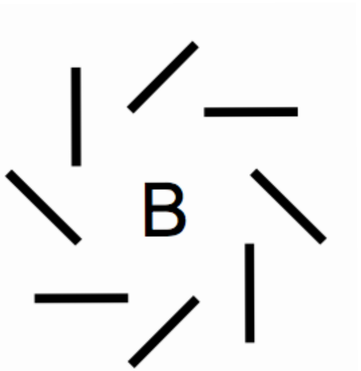


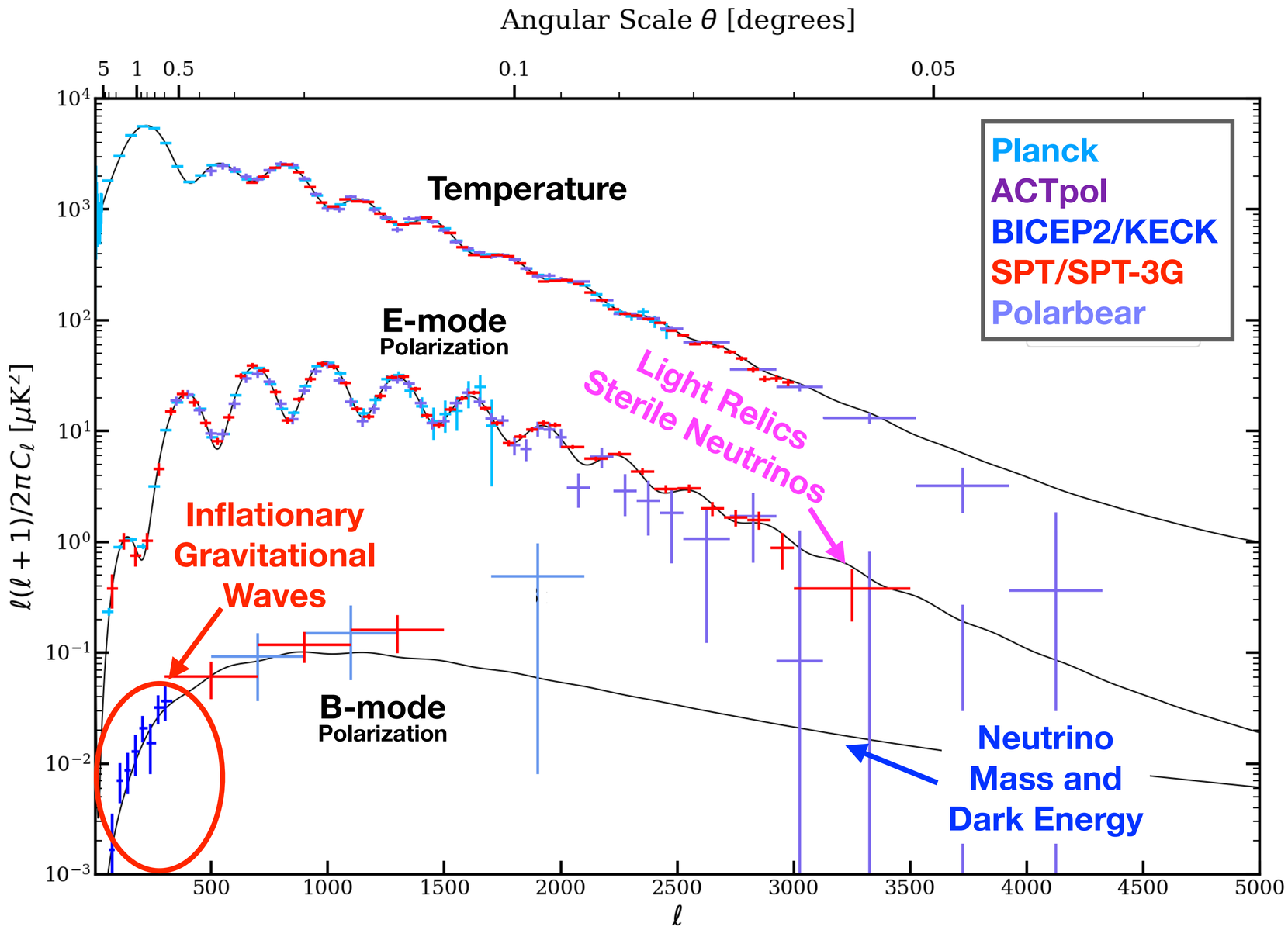


(SPT-3G) Dutcher et al. (2021)

The Next Frontier: CMB Polarization





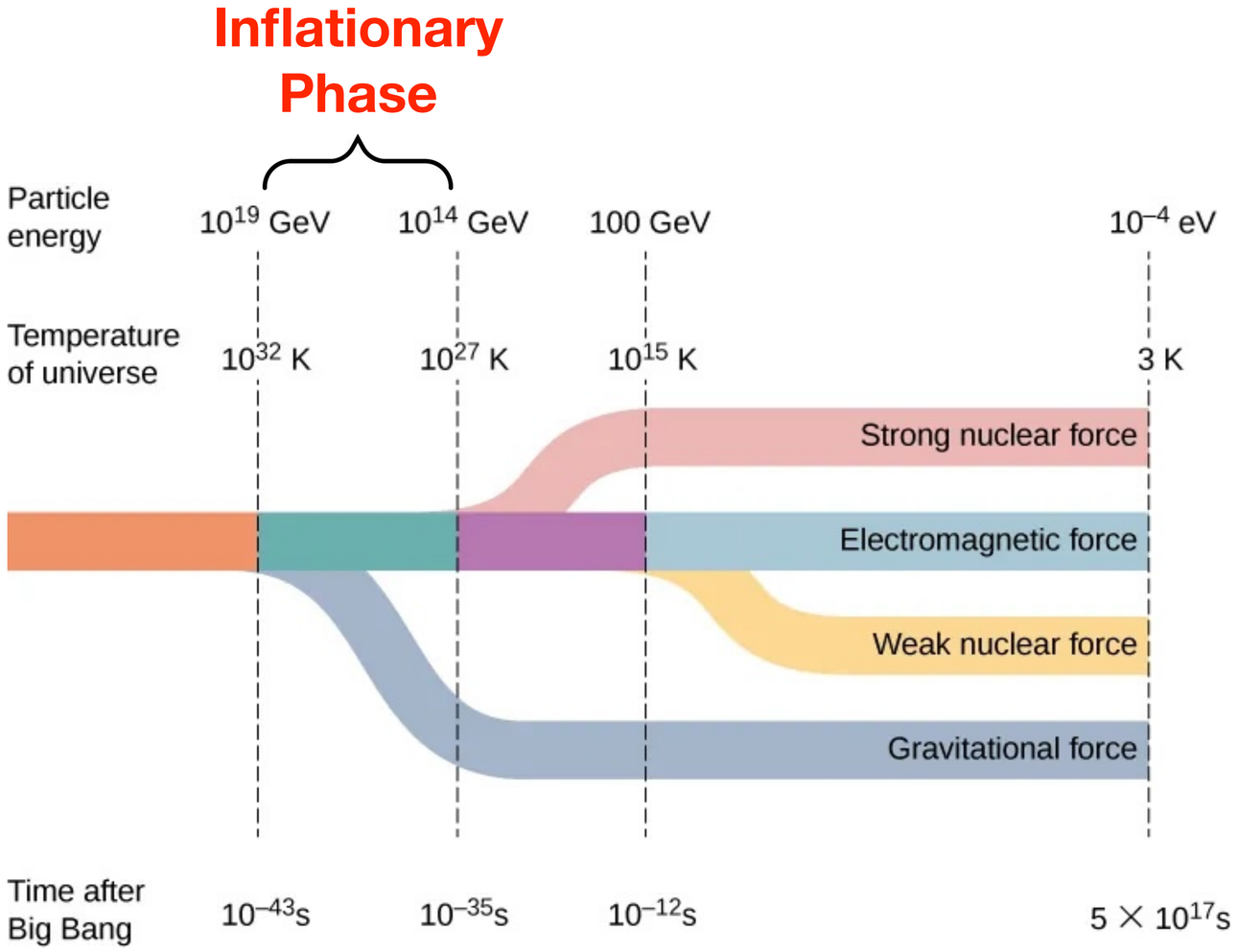


(SPT-3G) Dutcher et al. (2021)

Cosmic Inflation: Testing Physics at 10^{16} GeV

- Inflation proposes a period of exponential inflation in the first 10^{-35} seconds near GUT energy scale.
- Probes physics at 10^{16} GeV energy scales, a trillion times beyond the reach of the LHC.
- Inflation generates a background of gravitational waves that imprints B-mode polarization signal in the CMB, with an amplitude characterized by the **tensor-to-scalar ratio, r.**

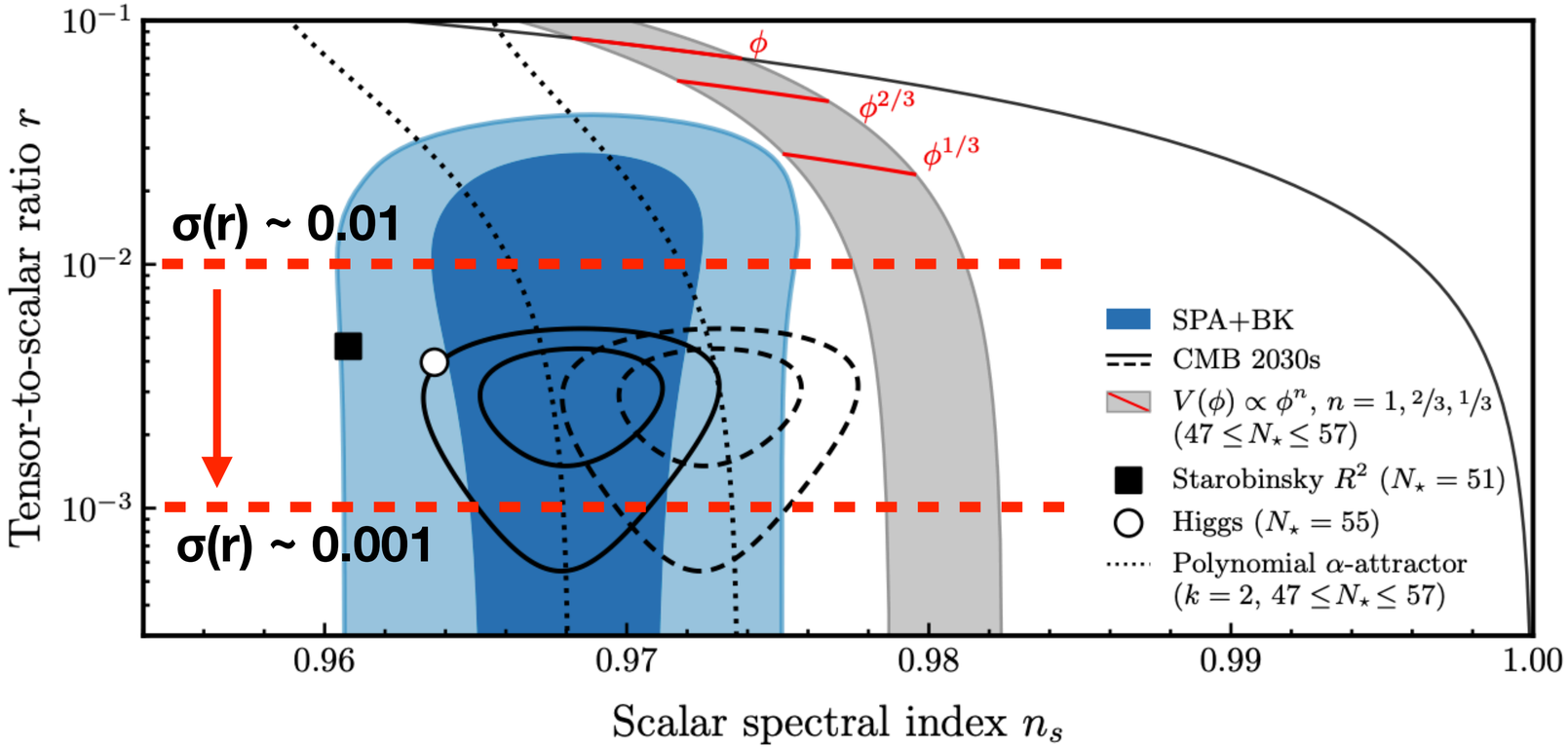
$$\text{energy} = 10^{16} \left(\frac{r}{0.01}\right)^{\frac{1}{4}} \text{GeV}$$



Ting et al. (2016)

Cosmic Inflation: Testing Physics at 10^{16} GeV

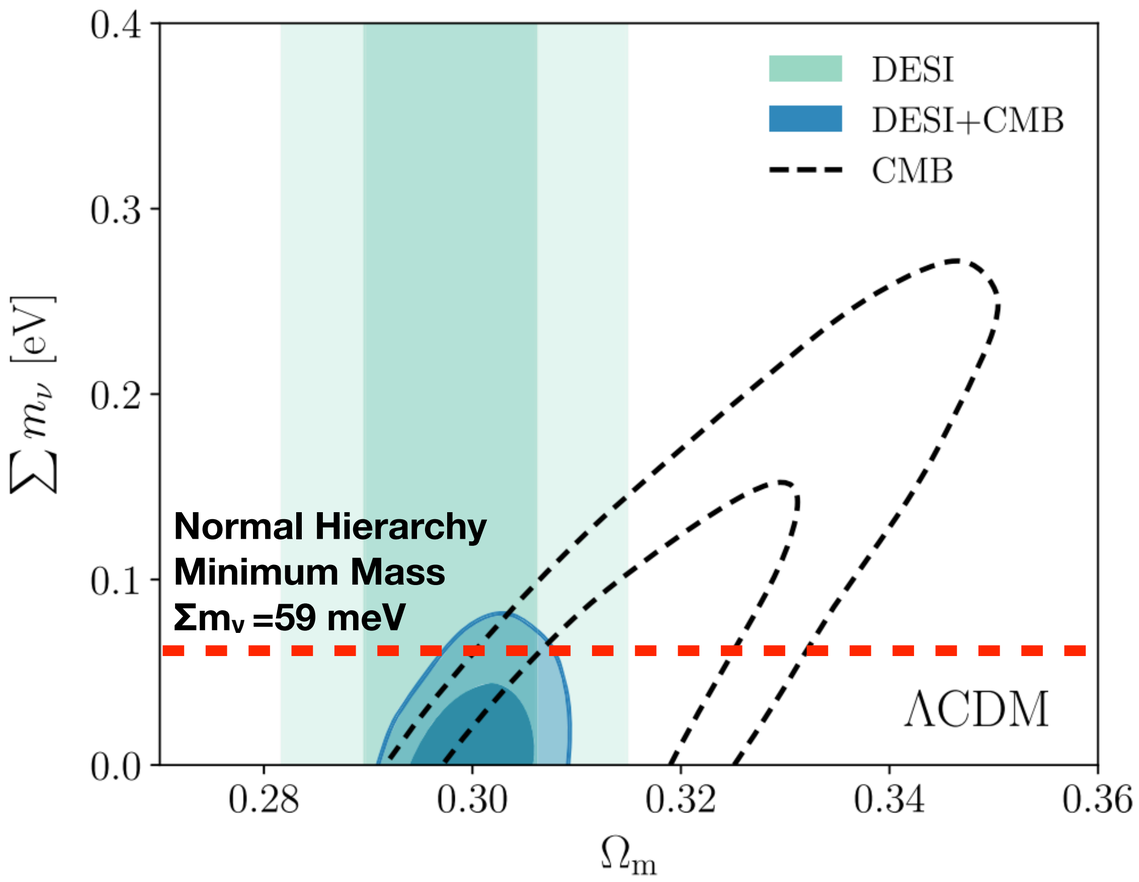
- Current best r-constraints are set by the BICEP experiment with σ(r) = 0.009 (BICEP collaboration 2021)
- ***Goal is to achieve σ(r) = 0.001 by 2035.***
- This threshold will either lead to a detection, a strong hint of *r*, or rule out leading inflationary models and motivate alternate models for the origin of the universe.



Balkenhol et al. (2025)

Tightening Constraints on Neutrino Mass

- Cosmological constraints are sensitive enough that we will soon need a “7th” parameter to fit the data:
  - ***Sum of neutrino masses (Σm_ν)***
- For past 20-years, 95% upper limits have been marching down:
  - 2008: $\Sigma m_\nu < 1.3$ eV (WMAP CMB)
  - 2013: $\Sigma m_\nu < 0.66$ eV (Planck CMB)
  - 2018: $\Sigma m_\nu < 0.27$ eV (Planck CMB)
  - 2018: $\Sigma m_\nu < 0.12$ eV (Planck+SDSS BAO)
- **Recent DESI BAO + CMB results constrains $\Sigma m_\nu < 0.064$ eV (95% CL)**
  - Results put pressure on lower bound of 0.059 eV from oscillation measurements assuming the normal hierarchy
  - However, constraints tighter than expected due to weak tension between CMB-BAO measurements.



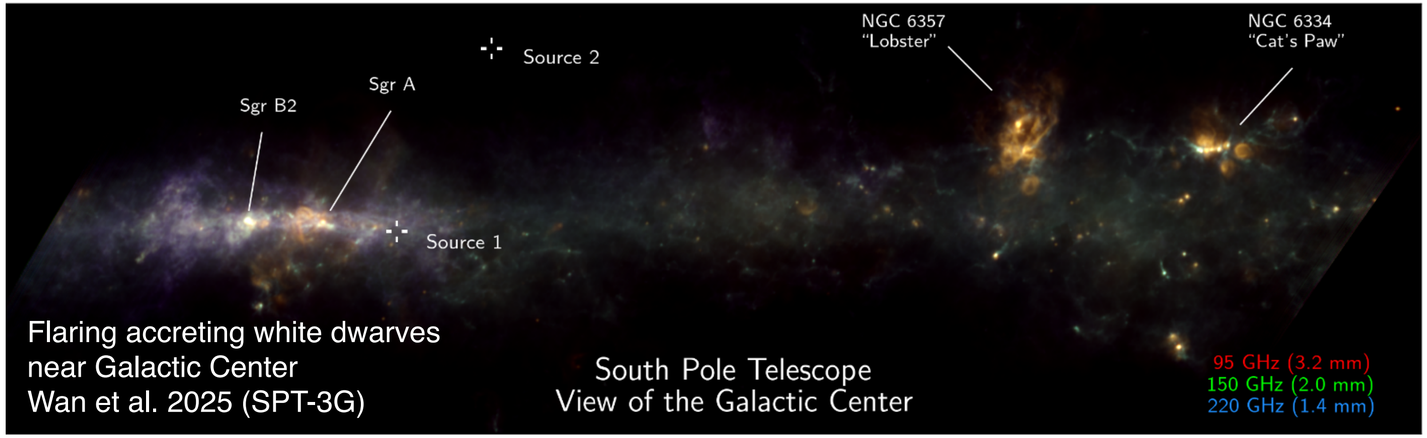
DESI Collaboration (2025)

Transients & the mm-wave Time-Variable Sky

CMB measurements are also opening a new window into the time-variable mm-wave sky;

- Guns et al. (2021): **First catalog of 15 events**, a combination of new stellar and extragalactic sources.
- Tandoi et al. (2024): **Catalog of 111** short-duration (<10-day) **events** from 4-years of SPT-3G data
- Recent results of mm-wave time-variable sky:
  - Asteroids; Low-Earth Orbit Satellites; AGN variability and flaring; Discovery of flaring white dwarves in Galactic plane, Constraints on Gamma Ray Bursts
- Transient alerts are produced internally within hours after SPT-3G observations.

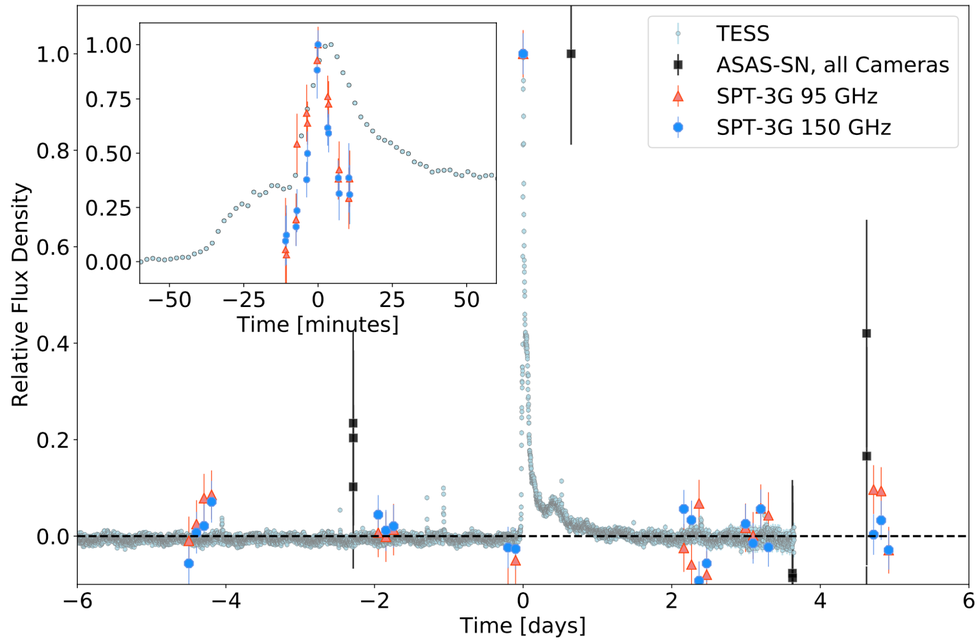
Astro2020: "*An important requirement for our strong endorsement is that the project broadly engage astronomers beyond the traditional CMB community… It is essential that CMB-S4 produce transient alerts…*".



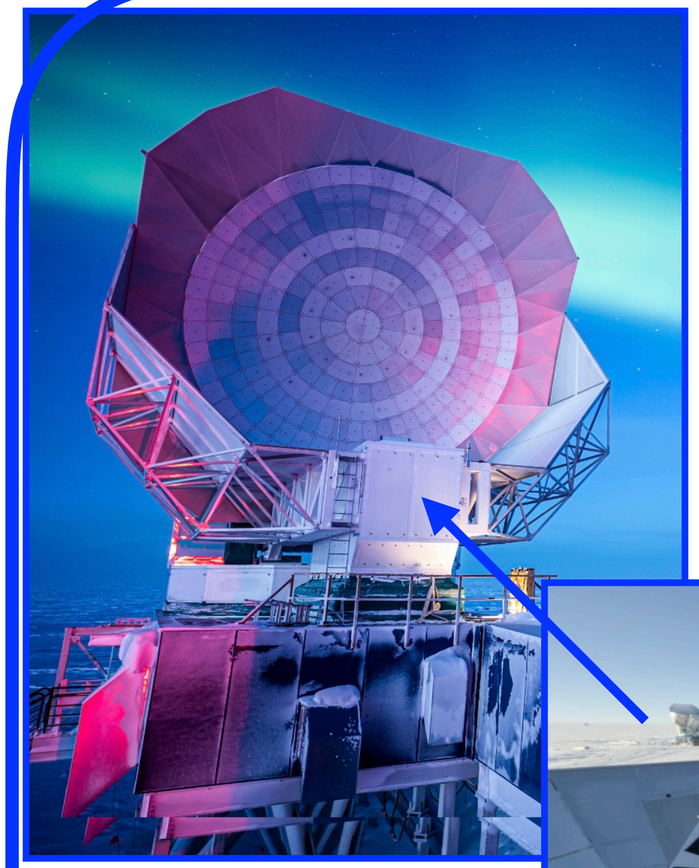
Flaring accreting white dwarves near Galactic Center
Wan et al. 2025 (SPT-3G)

South Pole Telescope
View of the Galactic Center

Stellar flare light-curves from Guns et al. 2021 (SPT-3G)

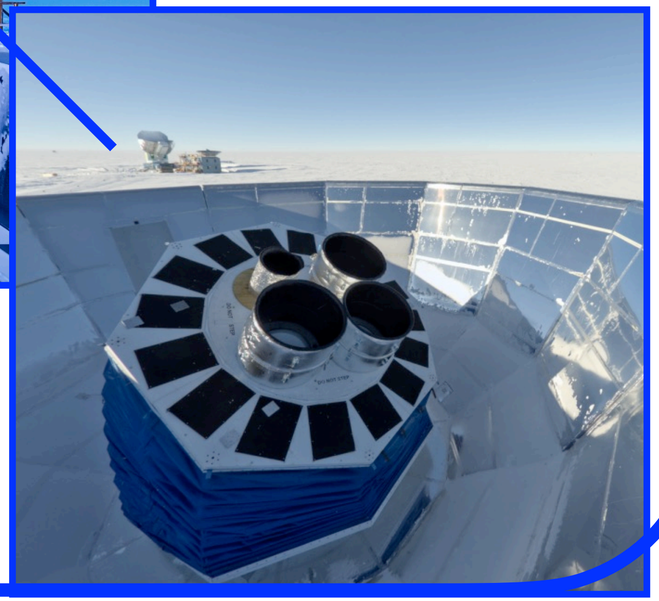


Ongoing & Upcoming CMB Surveys



South Pole

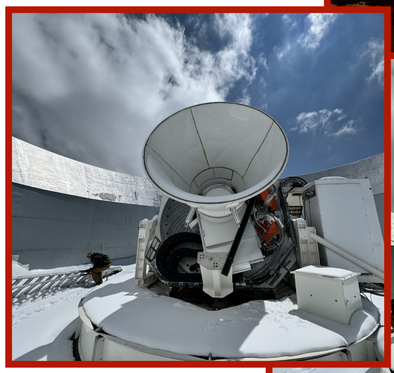
SPT & BICEP South Pole Observatory (SPO)



Chile

Simons Observatory (SO)







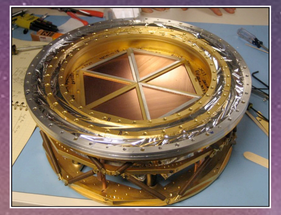


The South Pole Telescope (SPT)

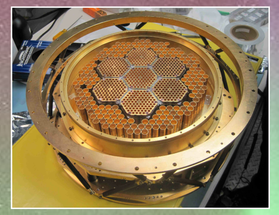
10-meter diameter telescope

95, **150**, **220** GHz frequency
1.6, **1.2**, **1.0** arcmin resolution

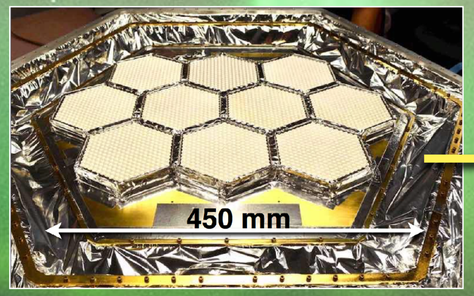
2007: SPT-SZ
960 detectors
100,150,220 GHz



2012: SPTpol
1600 detectors
100,150 GHz
+Polarization

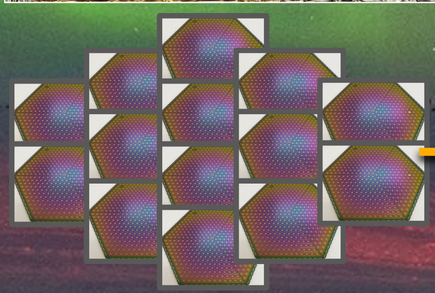


2017: SPT-3G
~16,200 detectors
100,150,220 GHz
+Polarization



SPT-3G has 7x larger mapping speed relative to Planck!

2029: SPT-3G+
~24,000 detectors
100,150 GHz
+Polarization

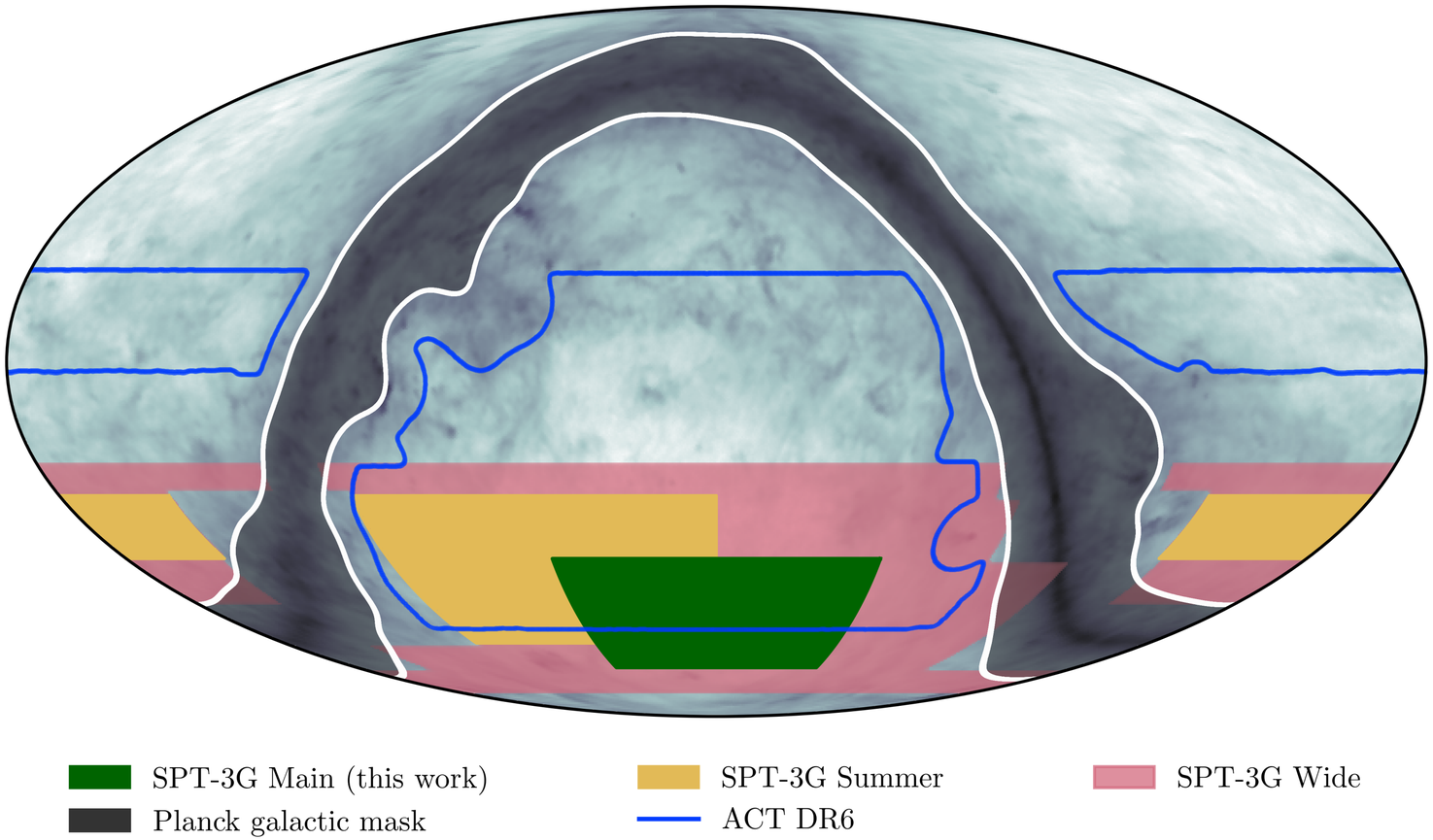


SPT-3G+ will increase this by another factor of 7



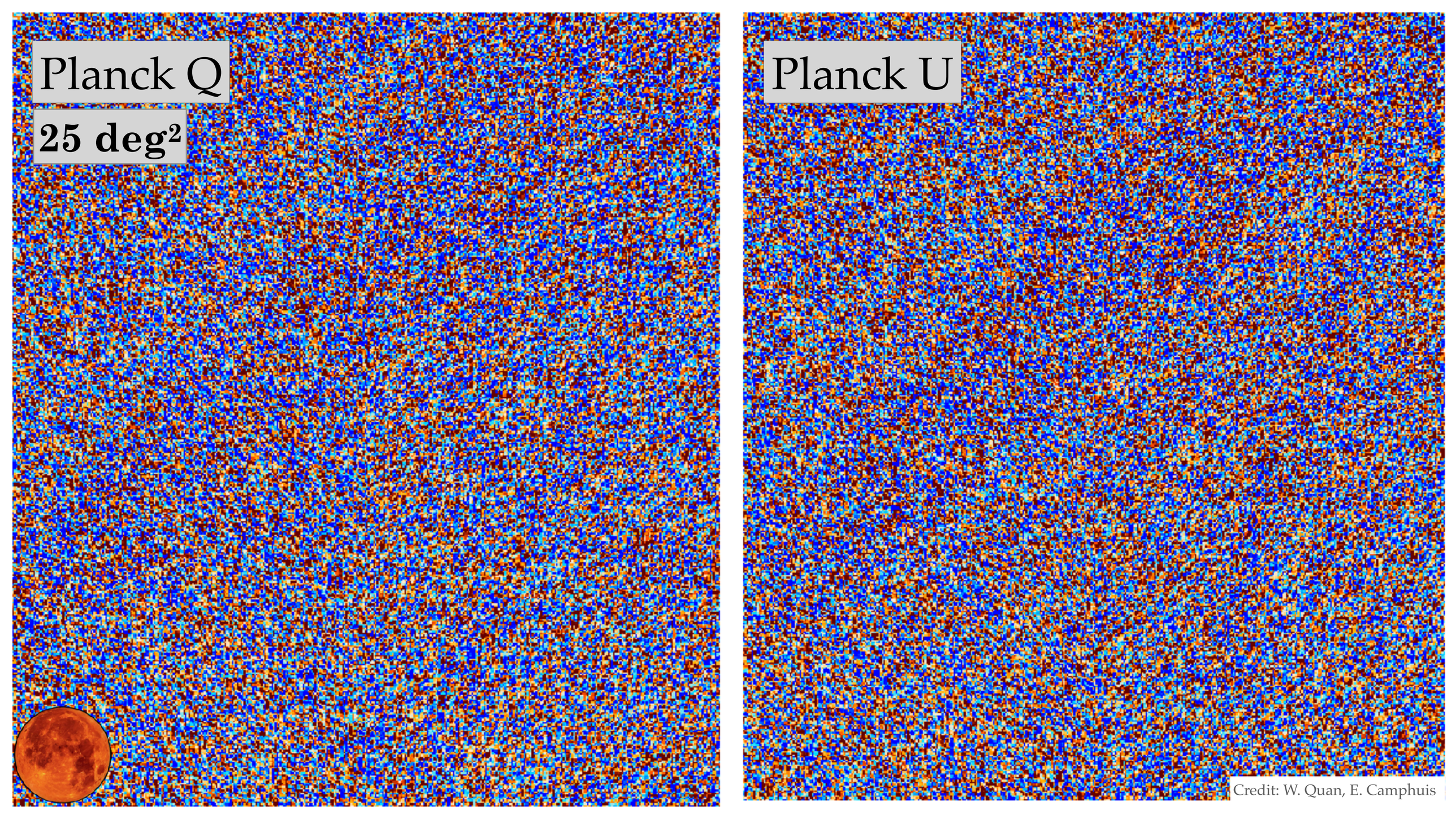
Funded by:
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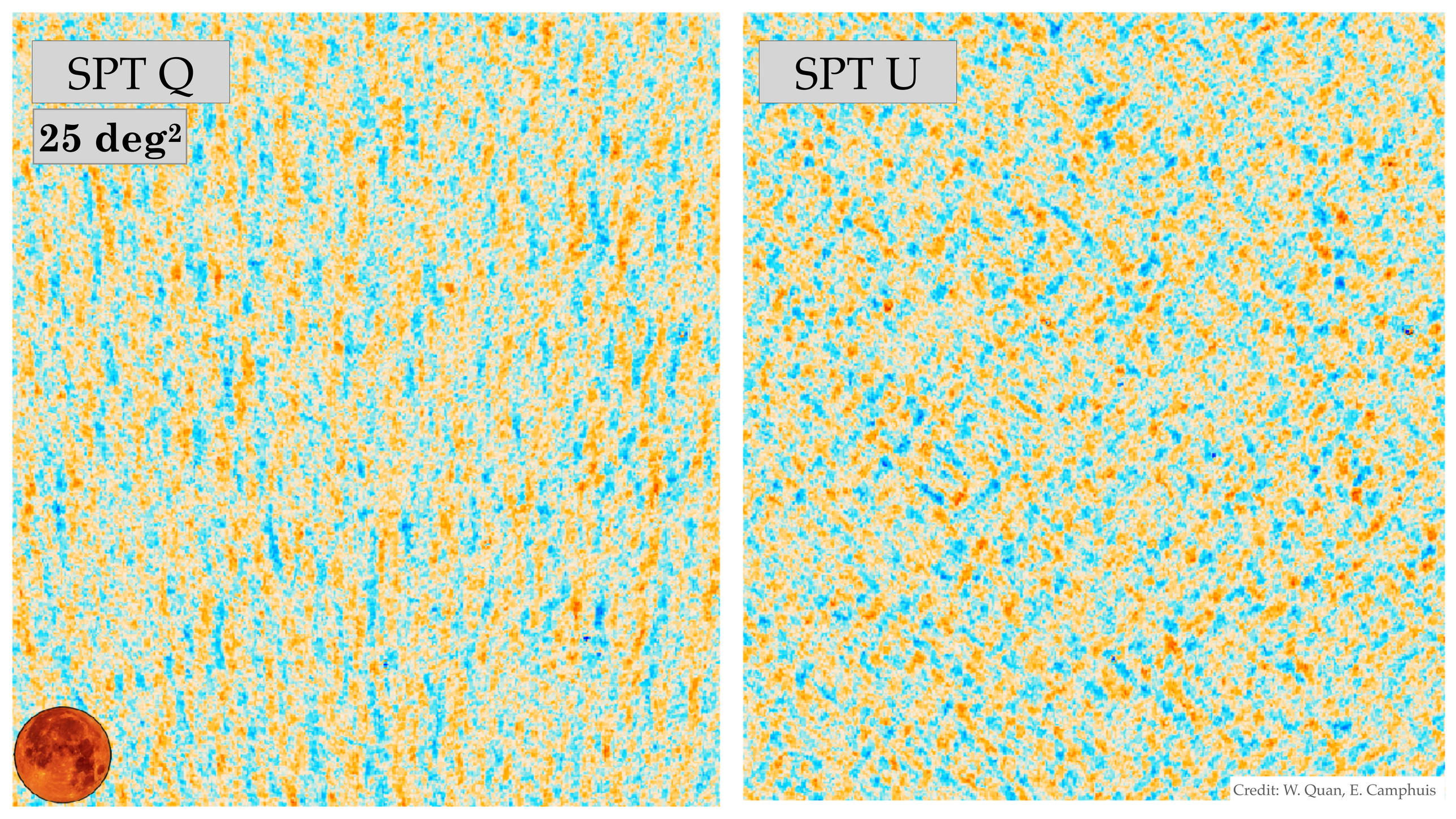
SPT-3G Surveys



- In 2019, SPT-3G started a **1500 deg² Main survey**, funded to continue observations thru 2028.
  - Most-sensitive measurement of gravitational lensing of CMB yet made (~20x deeper than Planck)
  - CMB primary and lensing results from first two years (2019-2020) of data recently released (**Camphuis et al. 2025, Omori et al. 2026)**
- SPT-3G also has **Summer** and **Wide surveys** totaling 10,000 deg² (~25% of the sky)
  - First results expected in early 2027, I will preview results at end of this talk

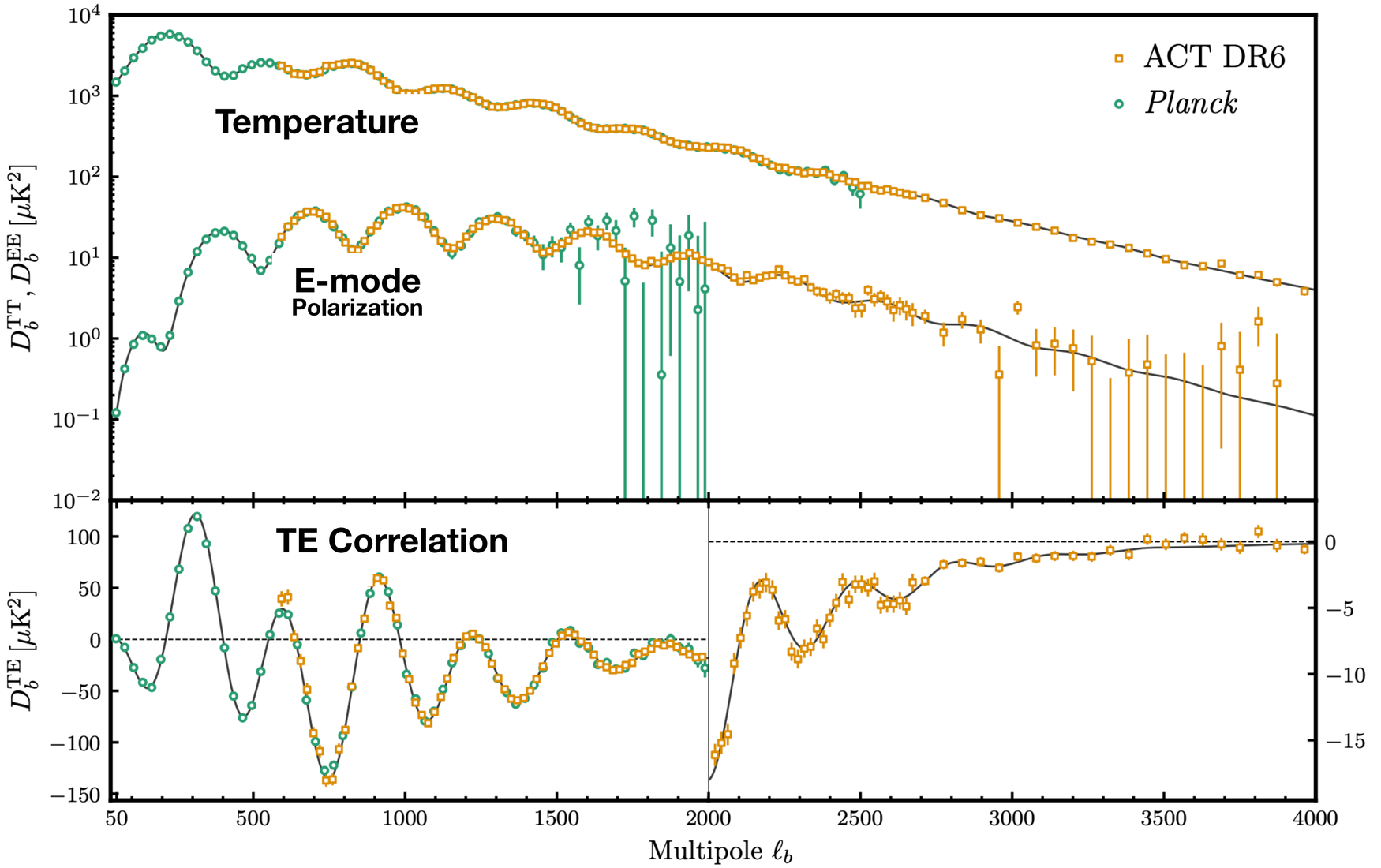
(SPT-3G) Camphuis et al. (2025), arXiv: 2506.20707
(SPT-3G) Omori et al. (2026), arXiv: 2608.31136


Planck Q
25 deg²
Planck U
Credit: W. Quan, E. Camphuis


SPT Q
25 deg²
SPT U
Credit: W. Quan, E. Camphuis

SPT-3G: CMB Power Spectra

No SPT-3G

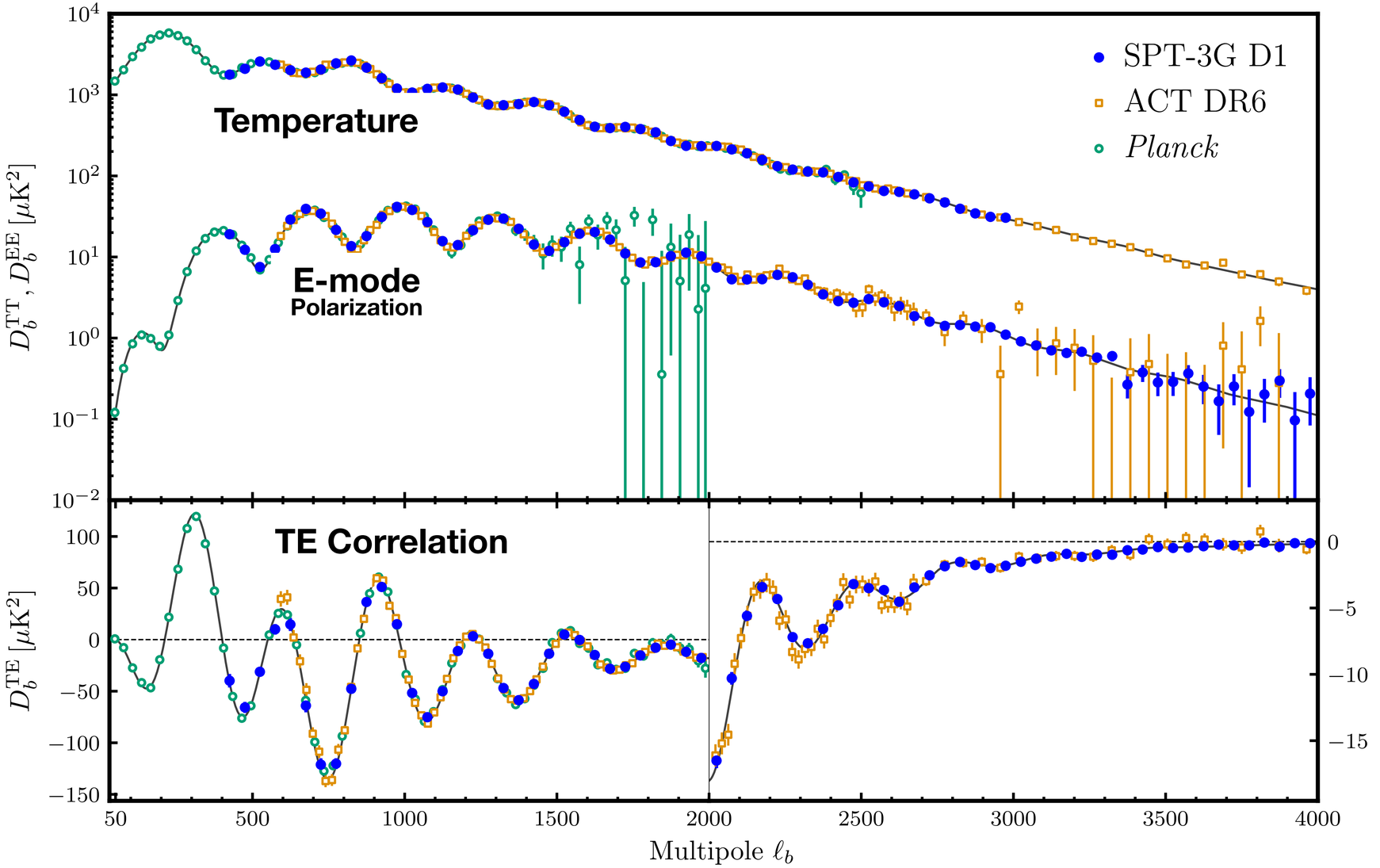


(SPT-3G) Camphuis et al. (2025), arXiv: 2506.20707

SPT-3G: CMB Power Spectra

With SPT-3G

- SPT-3G provides the most precise measurement of polarization power spectra at multipoles, $\ell > \sim 1800$



(SPT-3G) Camphuis et al. (2025), arXiv: 2506.20707

ΛCDM Cosmology fits to CMB Data

- For the first time, the combined constraining power of SPT & ACT ***exceeds*** the precision from the Planck satellite on many parameters
- For example, constraints on the Hubble constant (H_0):

Planck

$H_0 = 67.41 \pm 0.49$ km/s/Mpc

SPT-3G D1

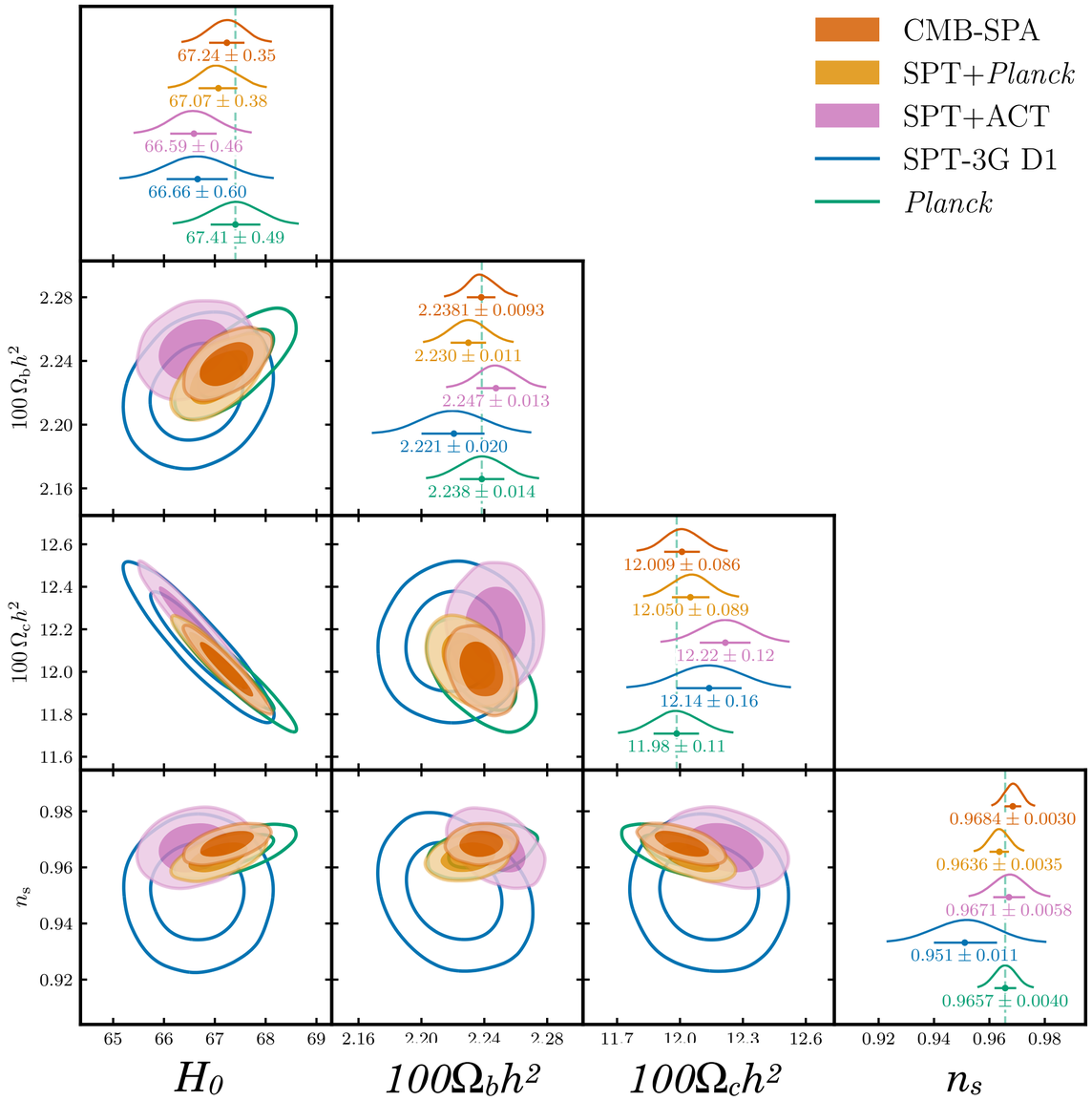
$H_0 = 66.66 \pm 0.60$ km/s/Mpc

SPT+ACT

$H_0 = 66.59 \pm 0.46$ km/s/Mpc

CMB-SPA

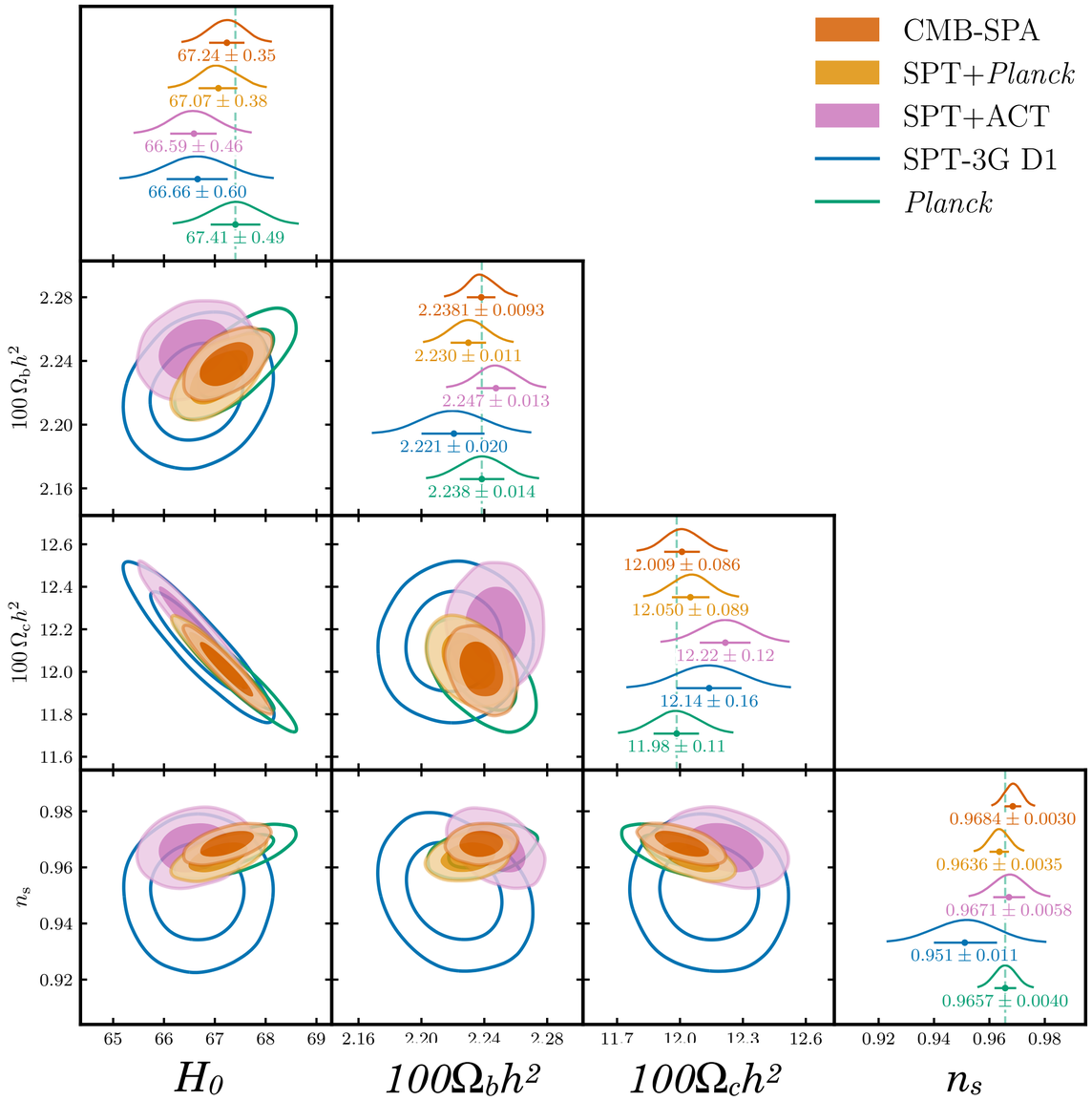
$H_0 = 67.24 \pm 0.35$ km/s/Mpc



(SPT-3G) Camphuis et al. (2025), arXiv: 2506.20707

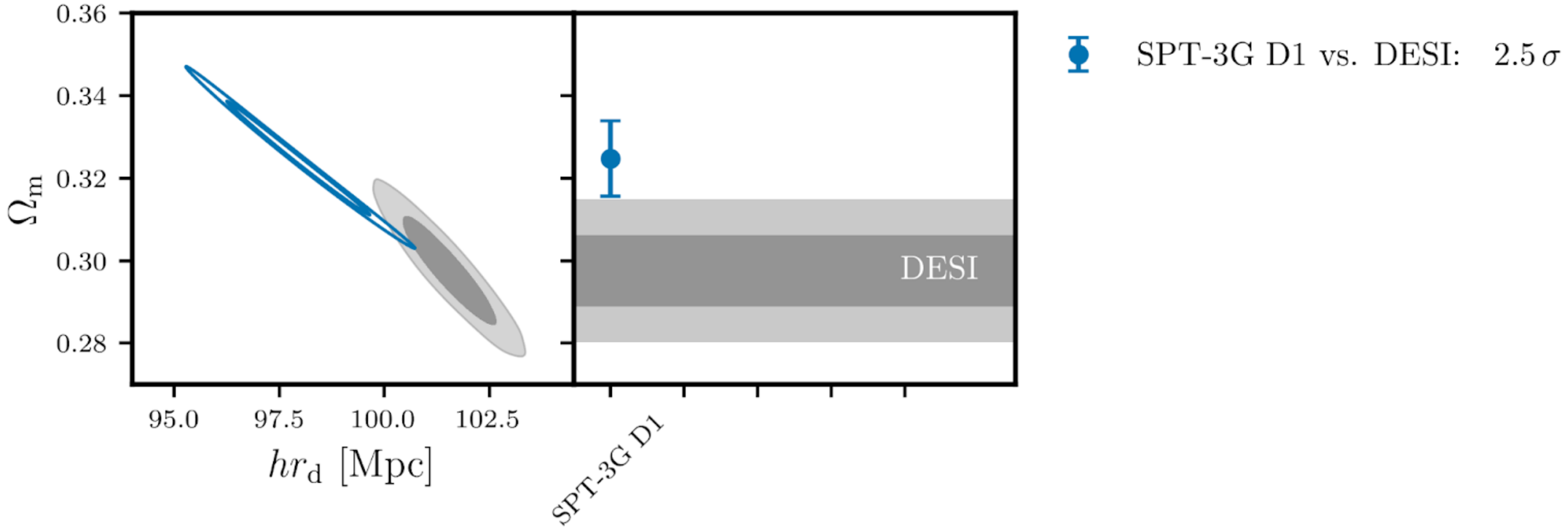
ΛCDM Cosmology fits to CMB Data

- The **SPT**, **Planck**, & **ACT** CMB measurements give statistically consistent constraints.
- The combination of SPT, Planck, & ACT (aka **CMB-SPA**) provides the most precise determination of ΛCDM cosmology parameter from CMB data.
- The data set is well-fit by ΛCDM model with a good probability to exceed (PTE=0.52)



(SPT-3G) Camphuis et al. (2025), arXiv: 2506.20707

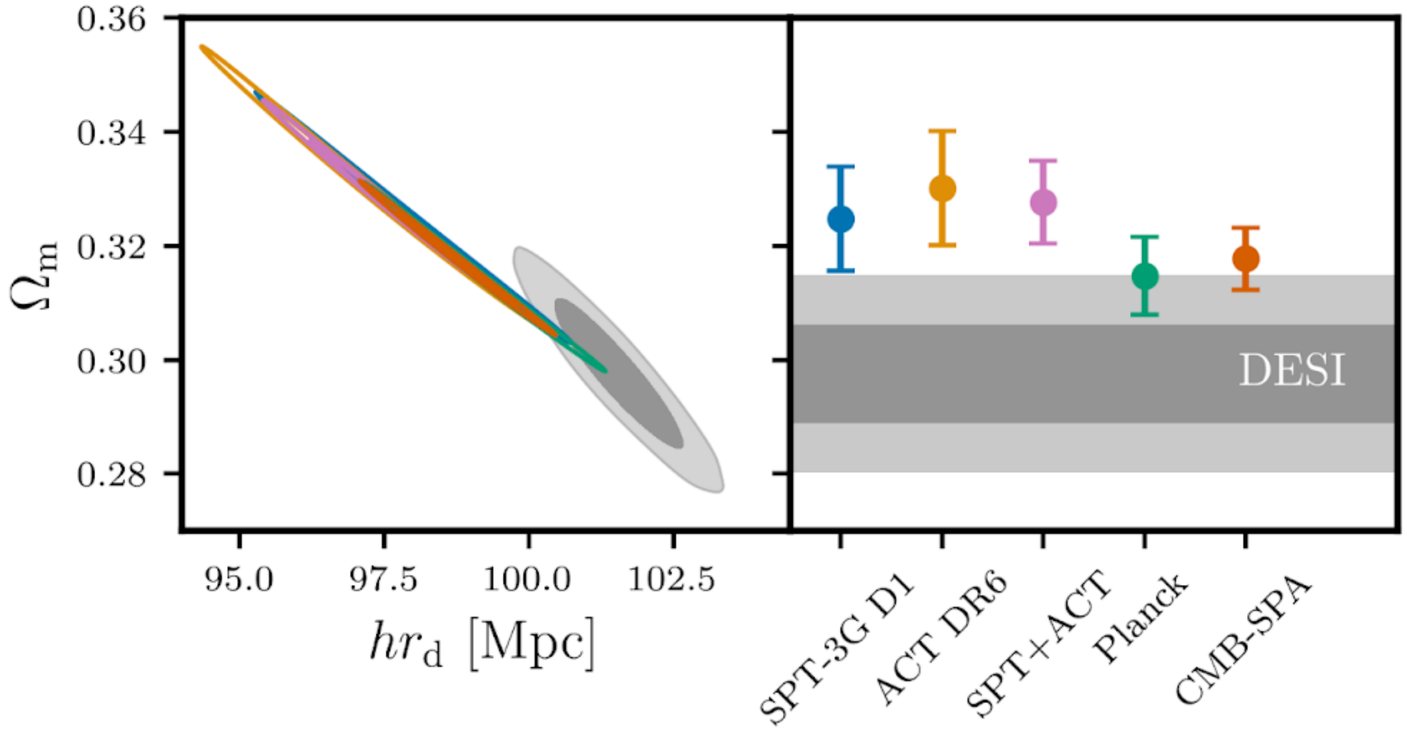
Evaluating the Consistency of CMB data with DESI DR2 BAO in ΛCDM model



- Growing tension between CMB & BAO data sets
- Consistent across SPT, Planck, & ACT CMB data sets compared to DESI
- Given differences, cosmological interpretation should be treated with caution

(SPT-3G) Camphuis et al. (2025), arXiv: 2506.20707

Evaluating the Consistency of CMB data with DESI DR2 BAO in ΛCDM model



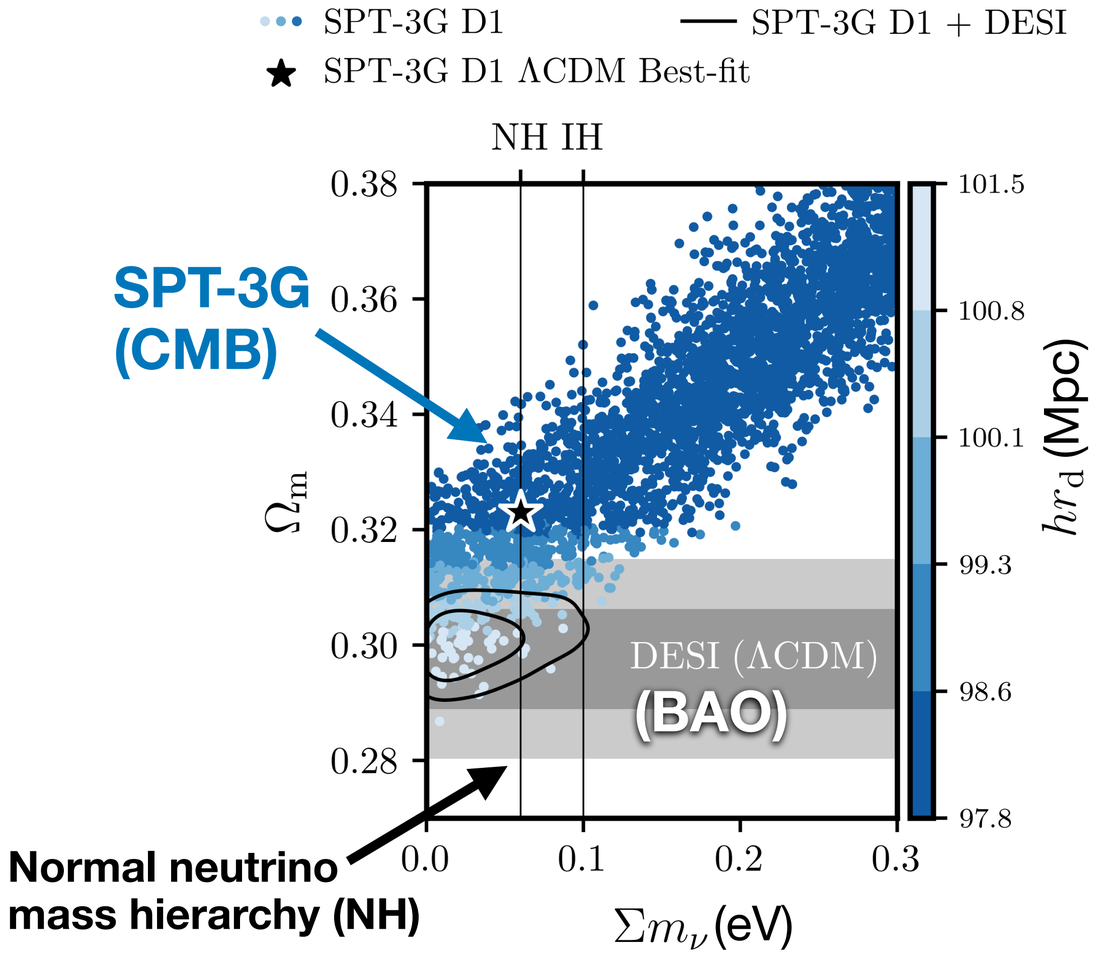
SPT-3G D1 vs. DESI:	$2.5\,\sigma$
ACT DR6 vs. DESI:	$3.1\,\sigma$
SPT+ACT vs. DESI:	$3.7\,\sigma$
Planck vs. DESI:	$2.0\,\sigma$
CMB-SPA vs. DESI:	$2.8\,\sigma$

- Growing tension between CMB & BAO data sets
- Consistent across SPT, Planck, & ACT CMB data sets compared to DESI
- Given differences, cosmological interpretation should be treated with caution

(SPT-3G) Camphuis et al. (2025), arXiv: 2506.20707

Evaluating Extensions of the ΛCDM model

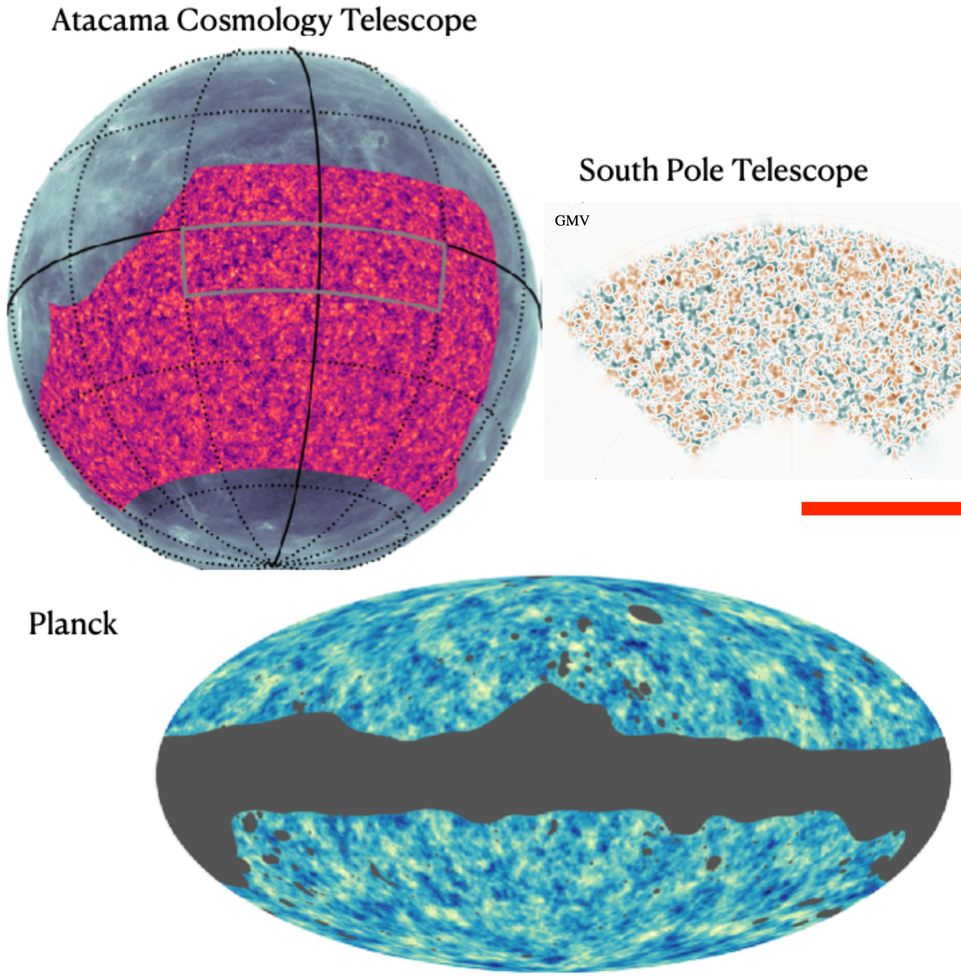
Model Class	Preference over ΛCDM
Rescaling of CMB lensing	3.1σ
Light relics (N_{eff})	<1.5σ
Modified recombination	2.0σ
Spatial curvature	2.5σ
Spatial curvature and electron mass	2.1σ
Neutrino mass	2.8σ
Dynamical dark energy	3.2σ

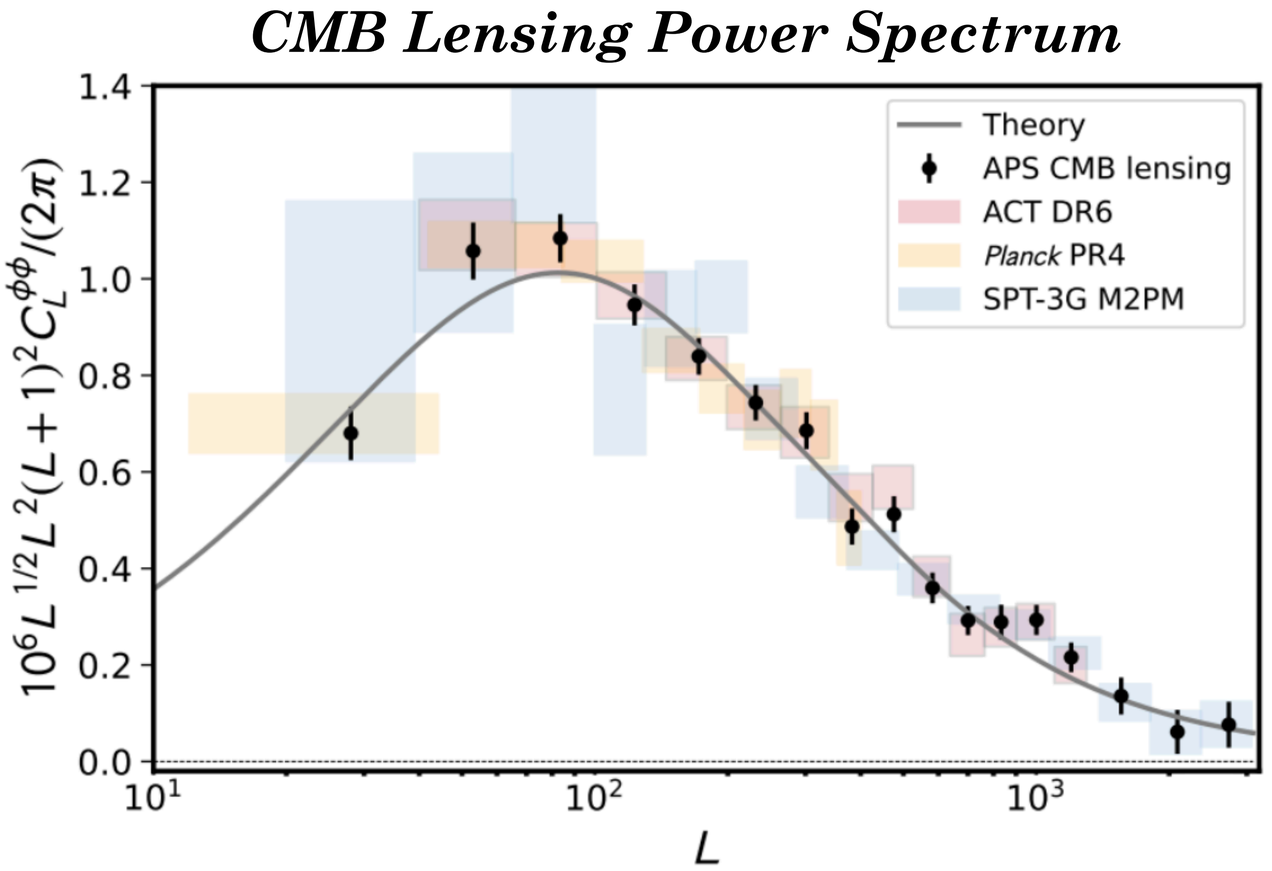


- Several different extensions to the ΛCDM model can relax tension between CMB & BAO data at 2-3σ level though none is strongly favored.

(SPT-3G) Camphuis et al. (2025), arXiv: 2506.20707

CMB Lensing Measures Integrated Cosmic Structure between Today and z~1100

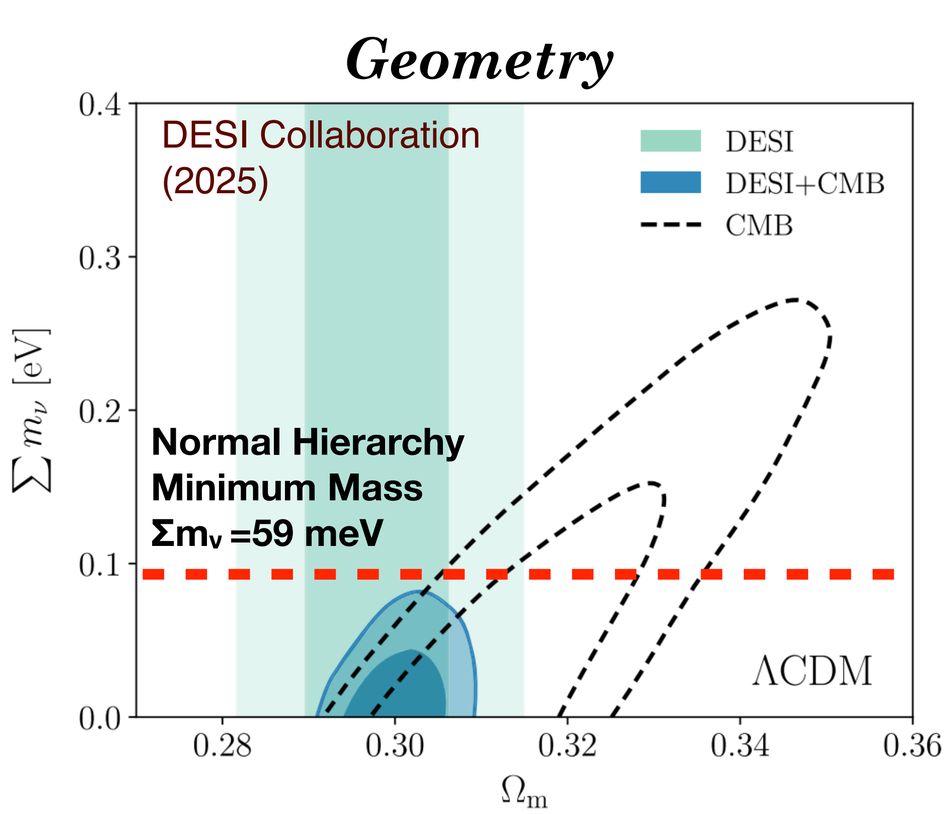


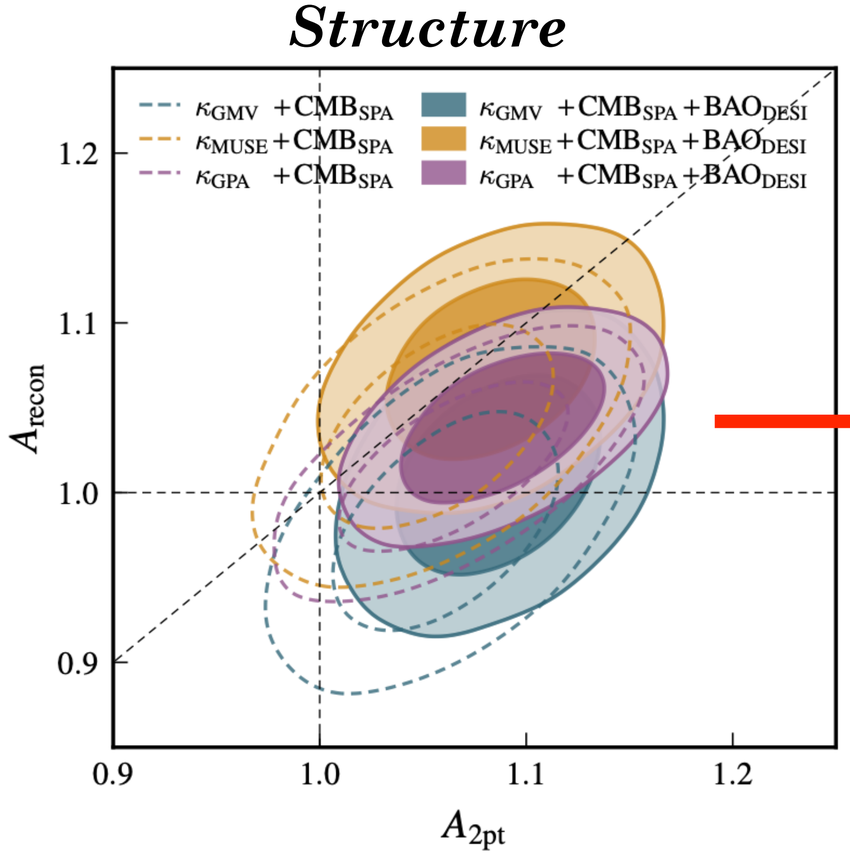


CMB Lensing Amplitude consistent with best-fit cosmology from CMB primary anisotropy

(ACT & SPT) Qu et al. (2025), arXiv: 2504.20038
(SPT-3G) Omori et al. (2026), arXiv: 2608.31136

Neutrino Mass (Σm_ν): Geometry vs Structure





Latest CMB lensing results combined with DESI constrains $\Sigma m_\nu < 0.072$ eV (95% CL)

Omori et al. 2026

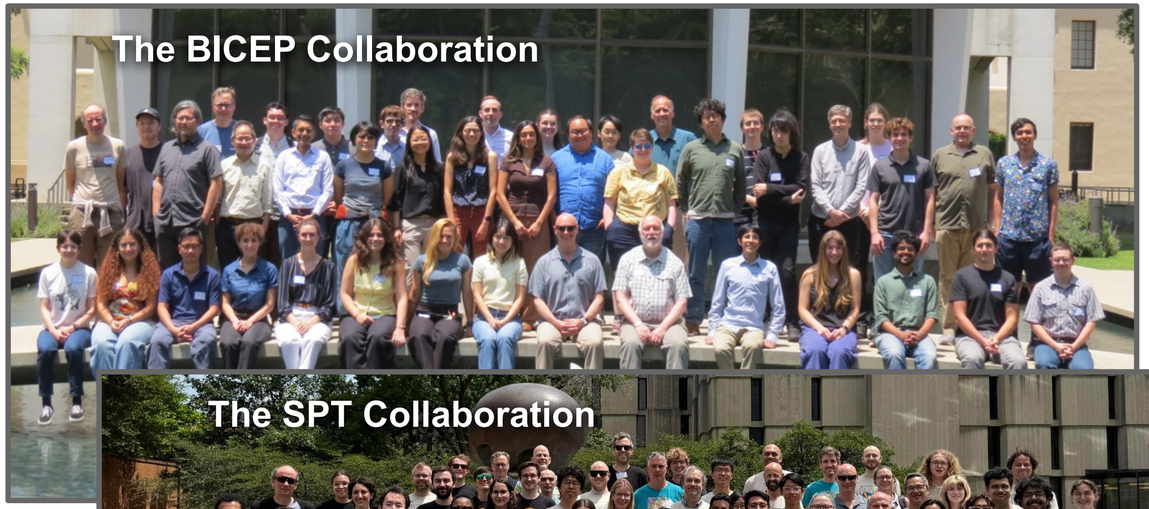
- CMB primary & BAO combined constrain neutrino mass via ***Geometry***, from the effect of neutrinos on expansion rate and the size of the sound horizon between z ~ 0 to z ~ 1100
- CMB primary & CMB lensing combined constrain neutrino mass via ***Structure***, from neutrinos not clustering like dark matter by comparing amplitude of structure at z ~ 2 to z ~ 1100

(ACT & SPT) Qu et al. (2025), arXiv: 2504.20038
(SPT-3G) Omori et al. (2026), arXiv: 2608.31136

The South Pole Observatory (SPO)



SPO collaboration consists of over 200 members across 25 institutions







Harvard · Stanford · Caltech · Minnesota · CEA · JPL · UBC · SLAC National Accelerator Laboratory · NIST · Cardiff University · Boston University · Cincinnati · The University of Chicago · Berkeley University of California · Argonne National Laboratory · Fermilab · IAP · University of Illinois · KICP · McGill · Case Western Reserve University · The University of Melbourne · Michigan State University · Colorado University of Colorado at Boulder · Center for Astrophysics Harvard & Smithsonian

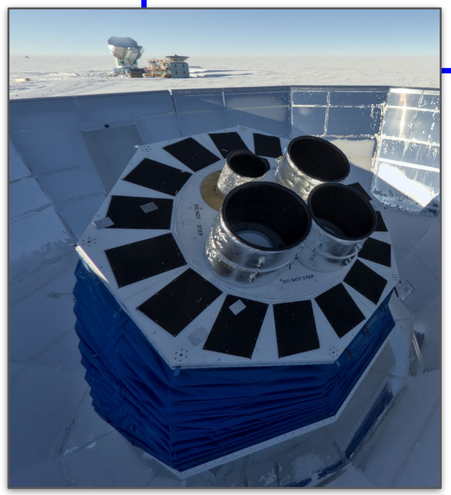
The South Pole Observatory (SPO)



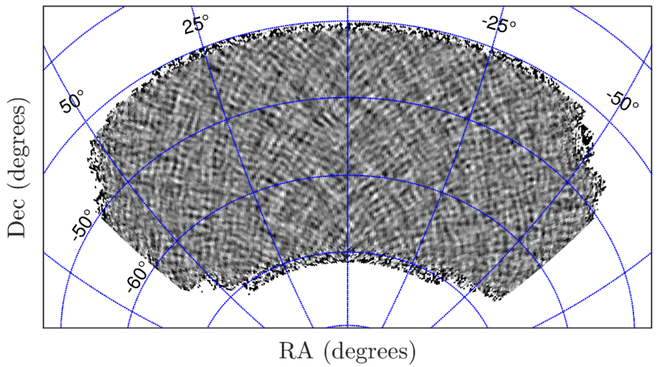
A **coordinated observing and analysis program** to probe Inflation by trying to measure *r,* to detect or rule out the most compelling models of single-field slow-roll inflation.

BICEP

Optimized to measure CMB B-modes at degree angular scales, where the Inflationary signal is predicted, with broad frequency coverage to mitigate Galactic foregrounds.



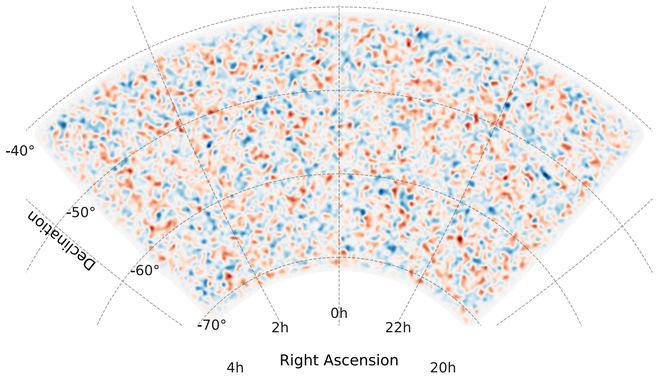
95 GHz polarization U map (BK24)

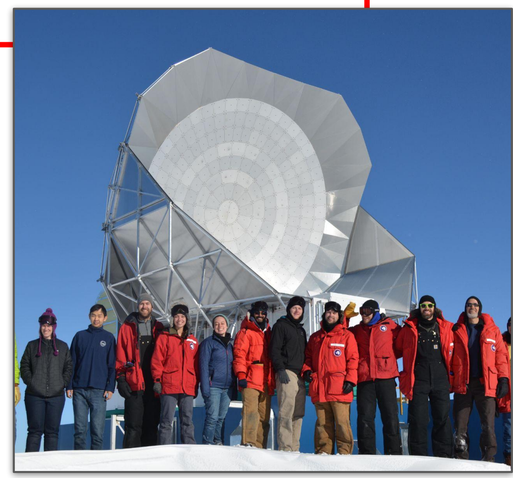


South Pole Telescope

Optimized to measure CMB polarization at arcminute angular scales to reconstruct the lensing B-modes, so they can be separated from the Inflationary B-modes, a process called “delensing”

Lensing template from SPT-3G (2-yr sim)





The Simons Observatory

15+ Countries
60+ Institutions
450+ Researchers



Adapted from Eve Vavagiakis

July 2026
U. Toronto

The Simons Observatory

Atacama Desert, Chile, 5200 m

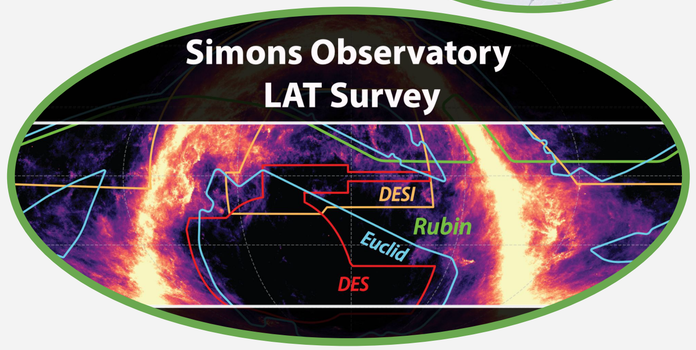
Wide, arcminute survey
with the Large Aperture Telescope (LAT)

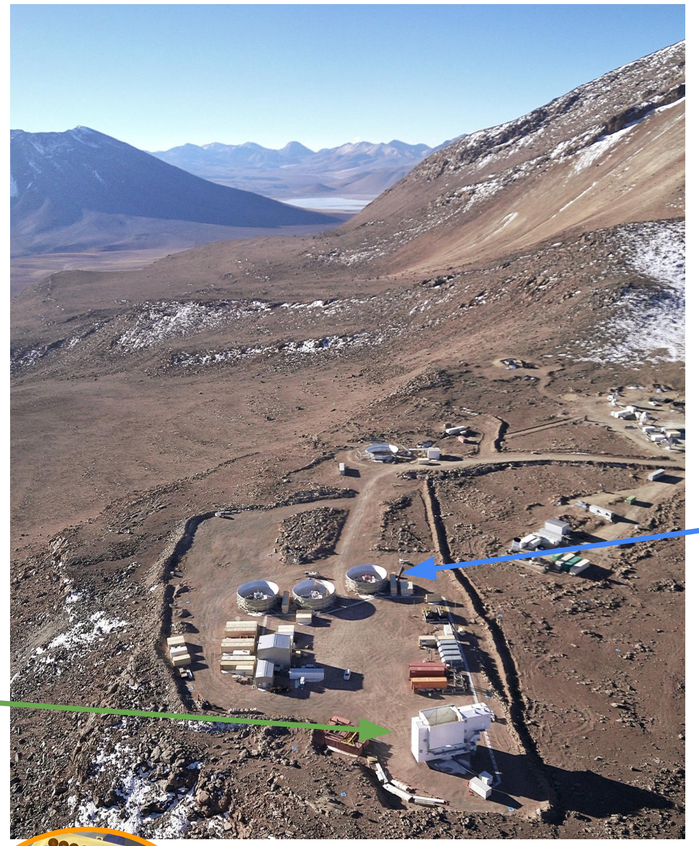
Observing at 30, 40, 90, 150, 220, and 280 GHz

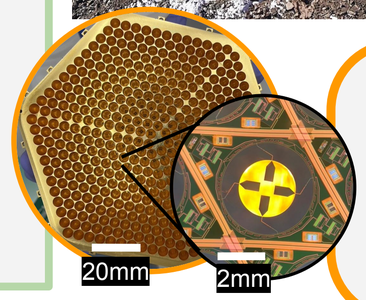
10x mapping speed of ACT

One 6 m telescope with ~63,000 detectors









~100,000 superconducting polarimeters at 100 mK

Deep, degree survey
with Small Aperture Telescopes (SATs)

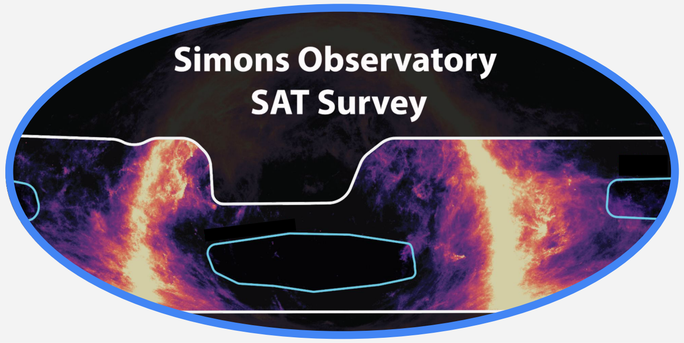
Observing at 90, 150, 220, and 280 GHz



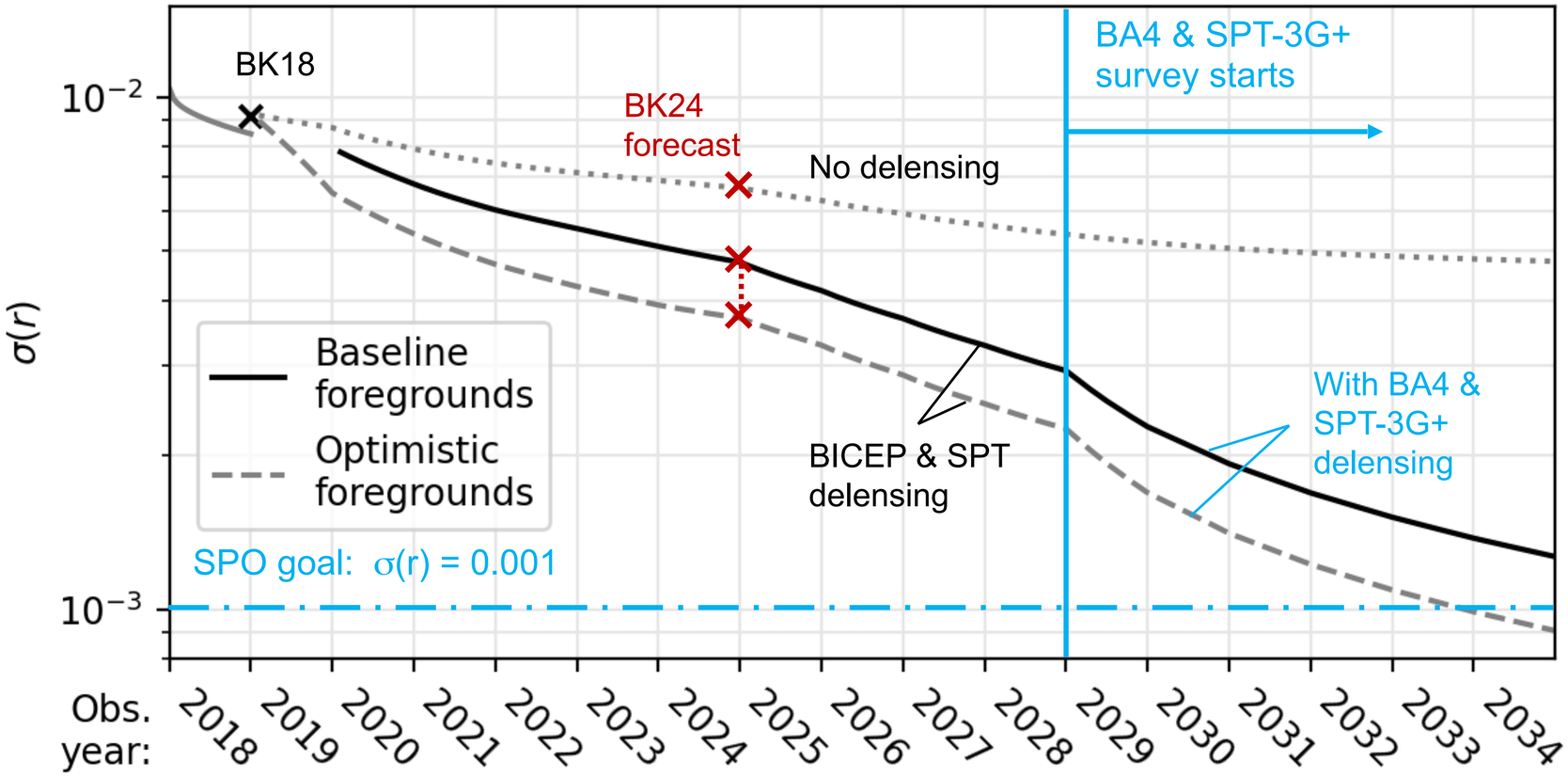
B-mode search from Chile

3x 0.5m telescopes with ~36,000 detectors

+3x from SO:UK and SO:Japan



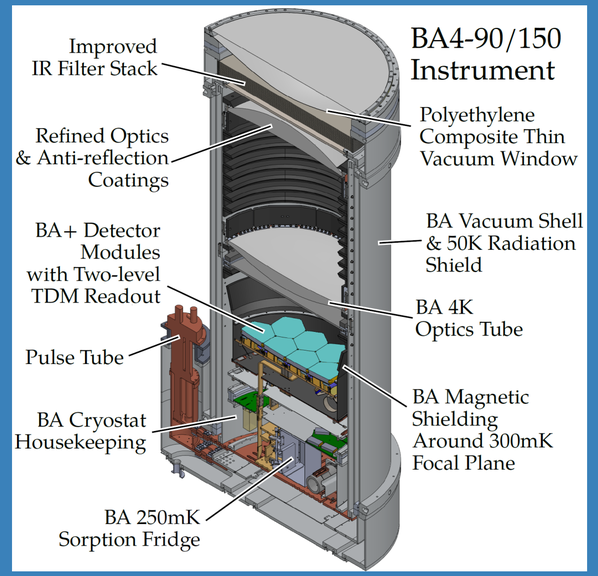
South Pole Observatory (SPO):
Future Constraints on Inflation (r)



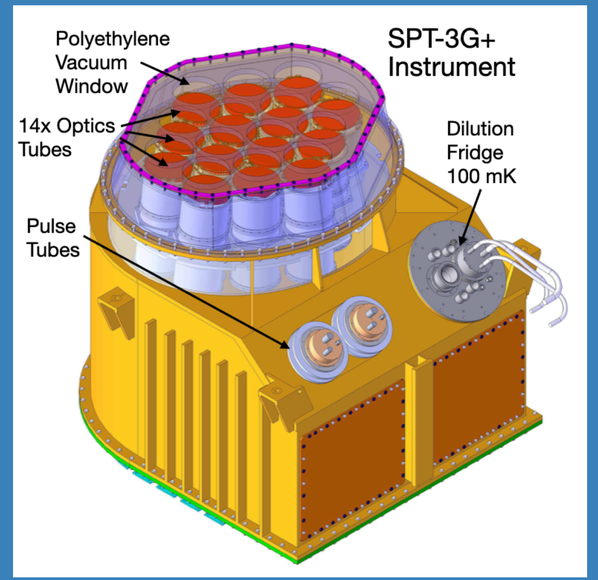


(SPT-3G+) Natoli et al. (2026)
(SPT-3G+) Athreya et al. (2026)
(BA+) Petroff et al. (2026)

Focal Plane Upgrades



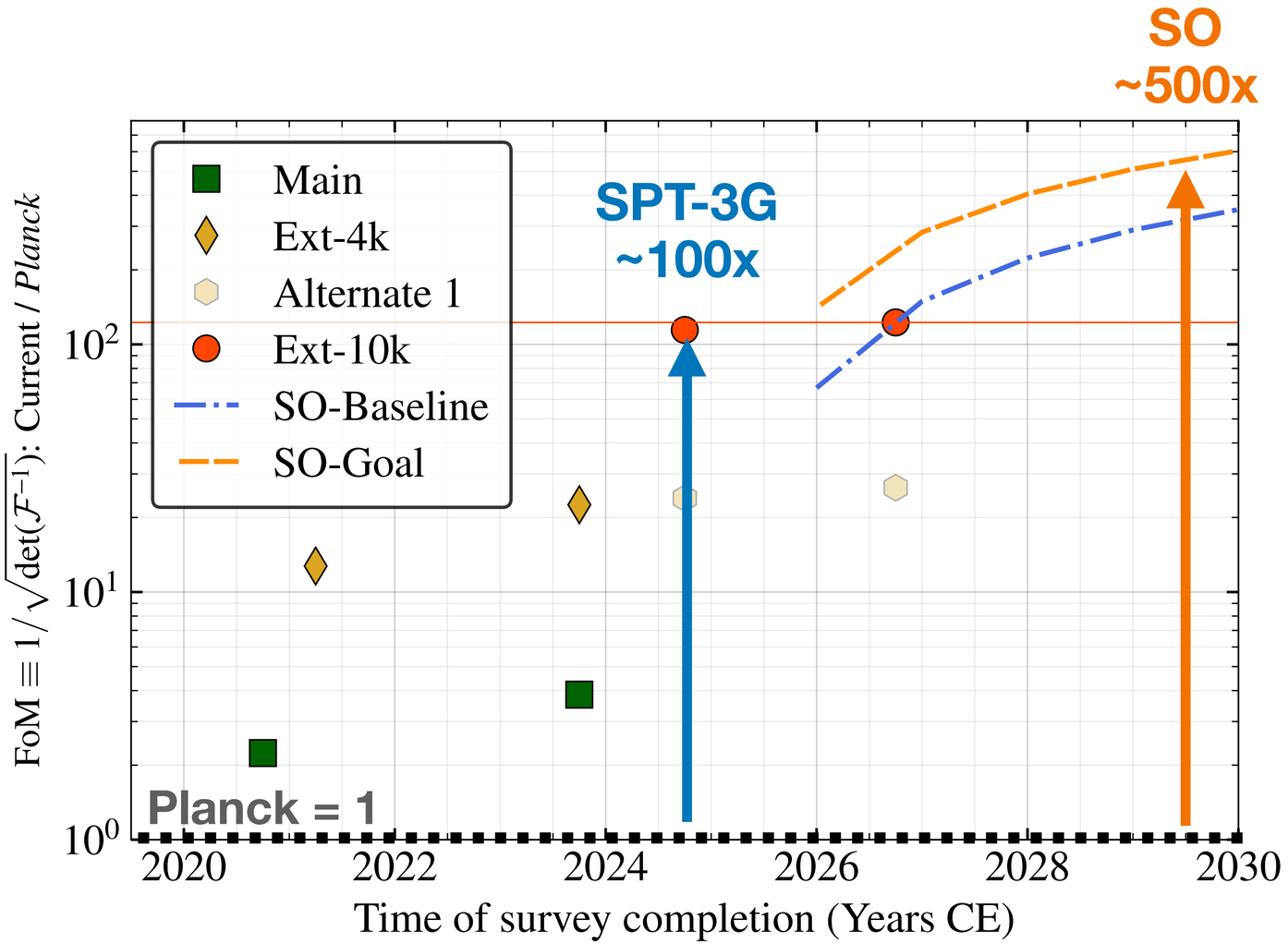
BA4 90/150 GHz Receiver



SPT-3G+ Receiver

Upcoming Cosmology Constraints: SPT-3G & SO

- Large area (25-50% of sky) surveys from **SPT-3G** and **Simons Observatory** (**SO**) will soon significantly improve cosmological constraints
- The "Figure-of-merit" (FOM) comparing allowed ΛCDM likelihood volume to Planck, SPT-3G and SO will improve by factors of ~100 and ~500, respectively
- If cosmic "tensions" are signs of new physics, new CMB measurements should make significant detections, with complementary experiments and survey strategies providing a powerful systematic check.



(SPT-3G) Prabhu et al. (2024), arXiv: 2403.17925

Summary

- New ground-based CMB measurements from the South Pole (SPT) and Chile (ACT, SO) have started to surpass the cosmological constraining power of Planck.
- In next several years, these measurements will lead to significantly improved cosmological constraints from the CMB, a factor >100 larger constraining power, with implications for understanding the neutrino mass hierarchy.
- Results will also improve constraints on Inflation by an order of magnitude, confirming or ruling out the most compelling Inflation models.
- CMB surveys are also opening new windows into the mm-wave sky, including astrophysical transients, high-redshift galaxies and galaxy clusters.



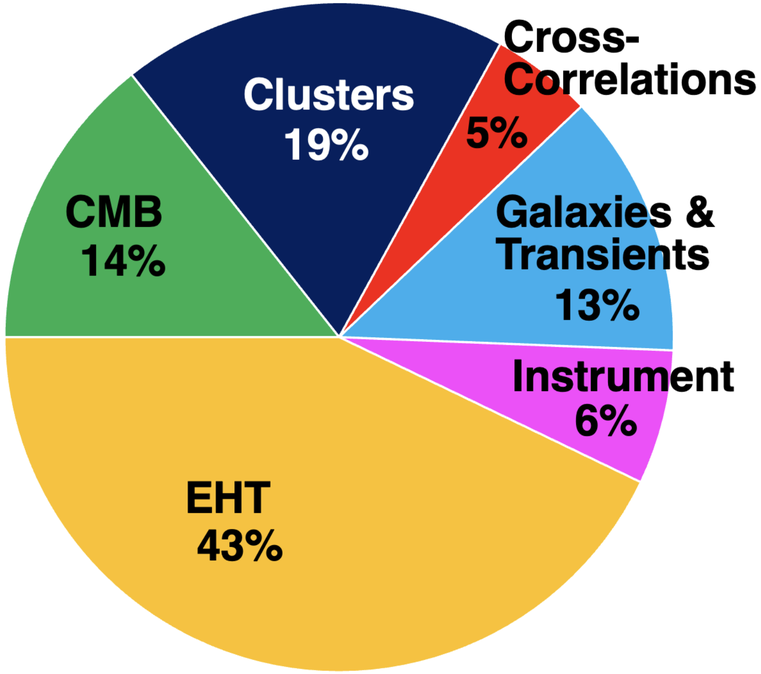
Extras

SPT's high angular resolution supports broad science program



- **SPT data serves a large community of scientists.**
  - SPT collaboration and working groups consists of approximately 200 scientists.
  - SPT is part of Event Horizon Telescope (EHT) network and collaboration, consisting of over 300 scientists.
  - Data releases serve the entire astronomical community

- **Broad science reach across cosmology, astronomy, and high-energy physics:**
  - Cosmic **Inflation** and the origin of the Universe (with BICEP)
  - Cosmological constraints, including on **growth of structure, dark energy**, **neutrinos**, and **reionization,** from CMB power spectra, CMB lensing, and SZ cluster surveys, and correlation with OIR surveys, e.g., DES, DESI, LSST, Euclid, SPHEREx.
  - Discovering the earliest formed **galaxies** and **galaxy clusters** in the Universe, and new classes of **astrophysical transients**.
  - Joint science and observations with many of the biggest facilities in Astronomy, e.g. JWST, Hubble, Chandra, ALMA.
  - Physics of **Black Holes** and general relativity (with **EHT**).

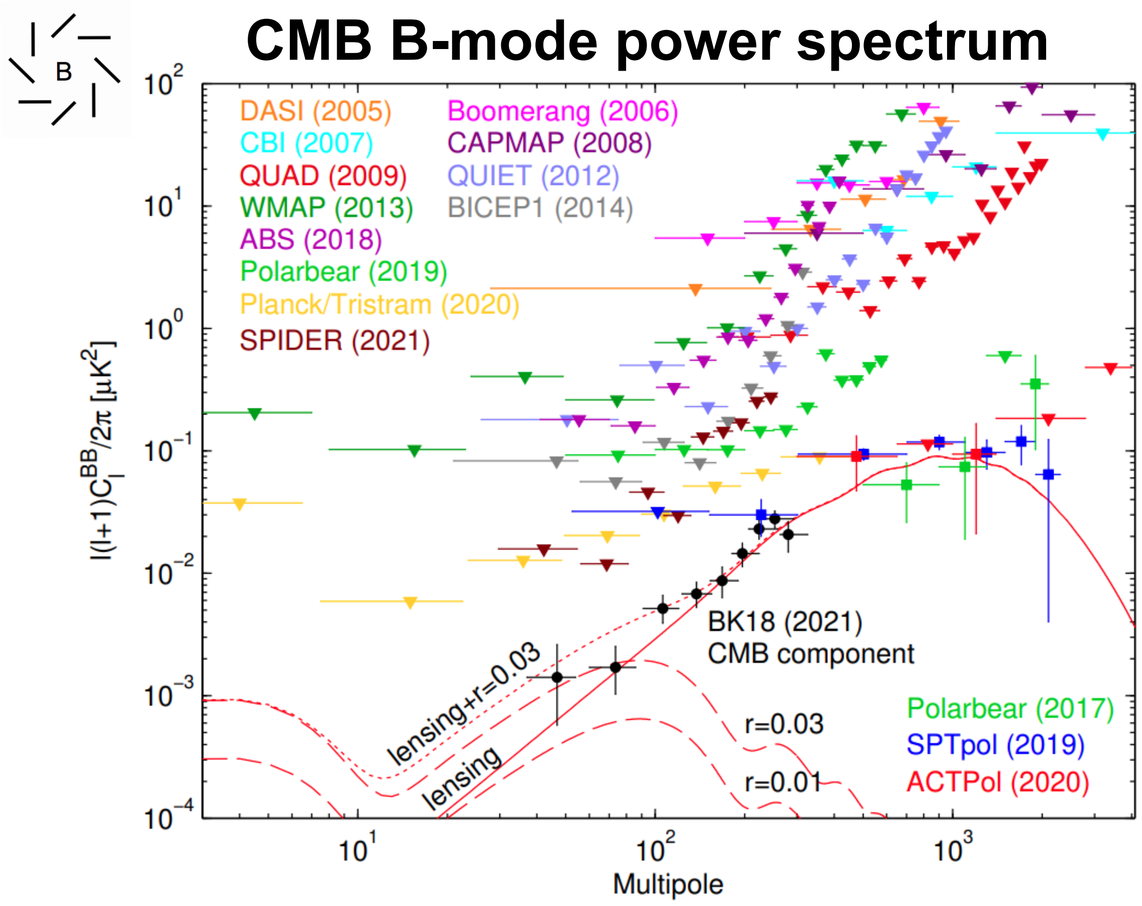


Citation fraction by topic
(over 37,500 total)

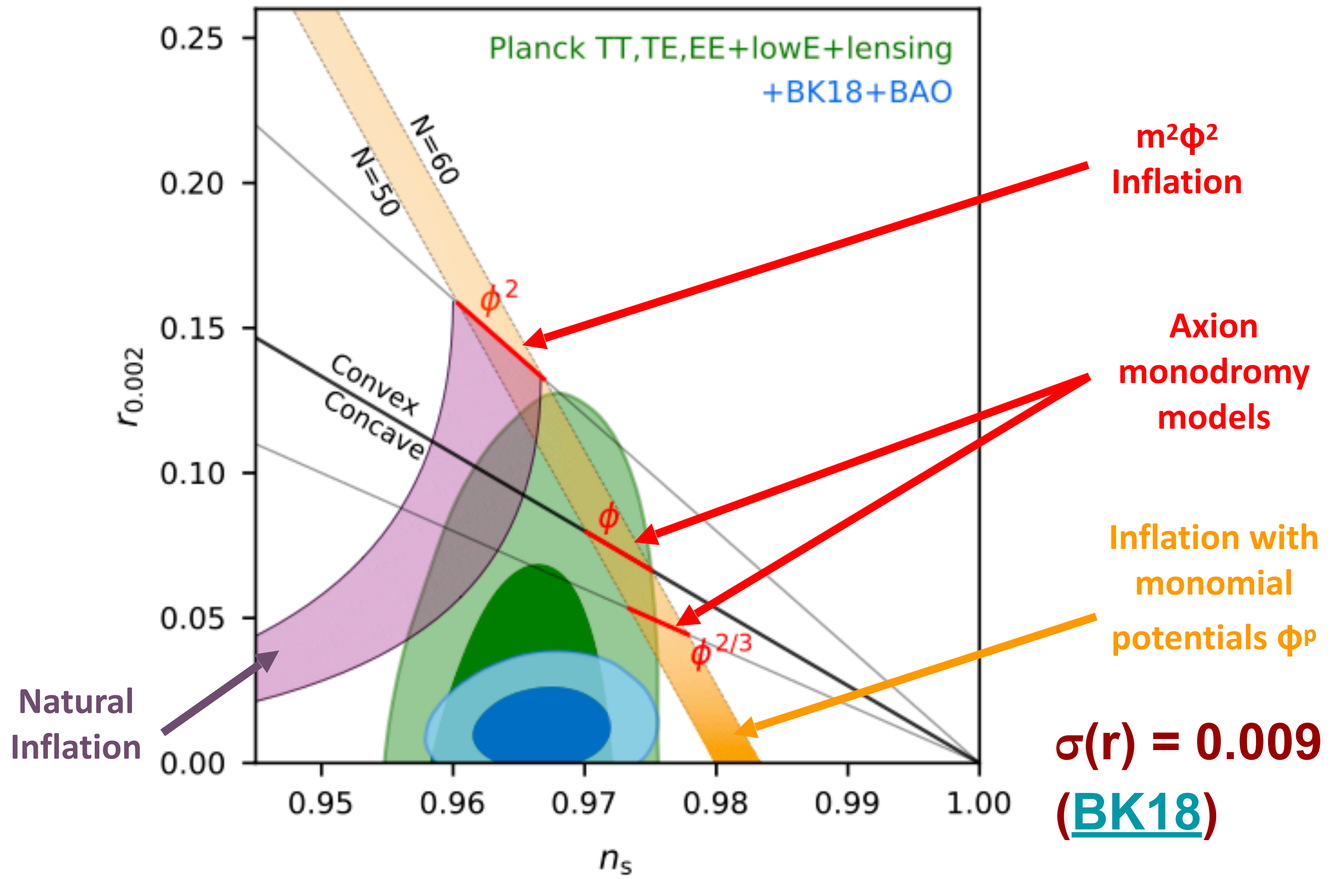
See backup slides for list of SPT papers over last 12 months. For full list see pole.uchicago.edu

Latest Inflation Constraints from BICEP (arXiv: 2110.00483)





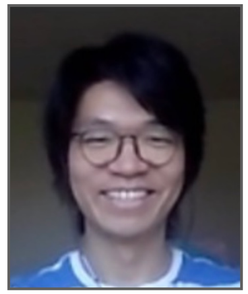
BICEP has made the most sensitive degree-scale B-mode power measurements (black points above), constraining *r*. (Fig 7 of BK18)



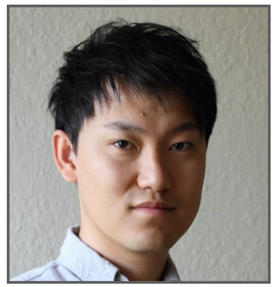
As a result, the inflation parameter space has been significantly constrained, ruling out model classes shown above. (Fig 5 of BK18)

Adapted from Jamie Bock

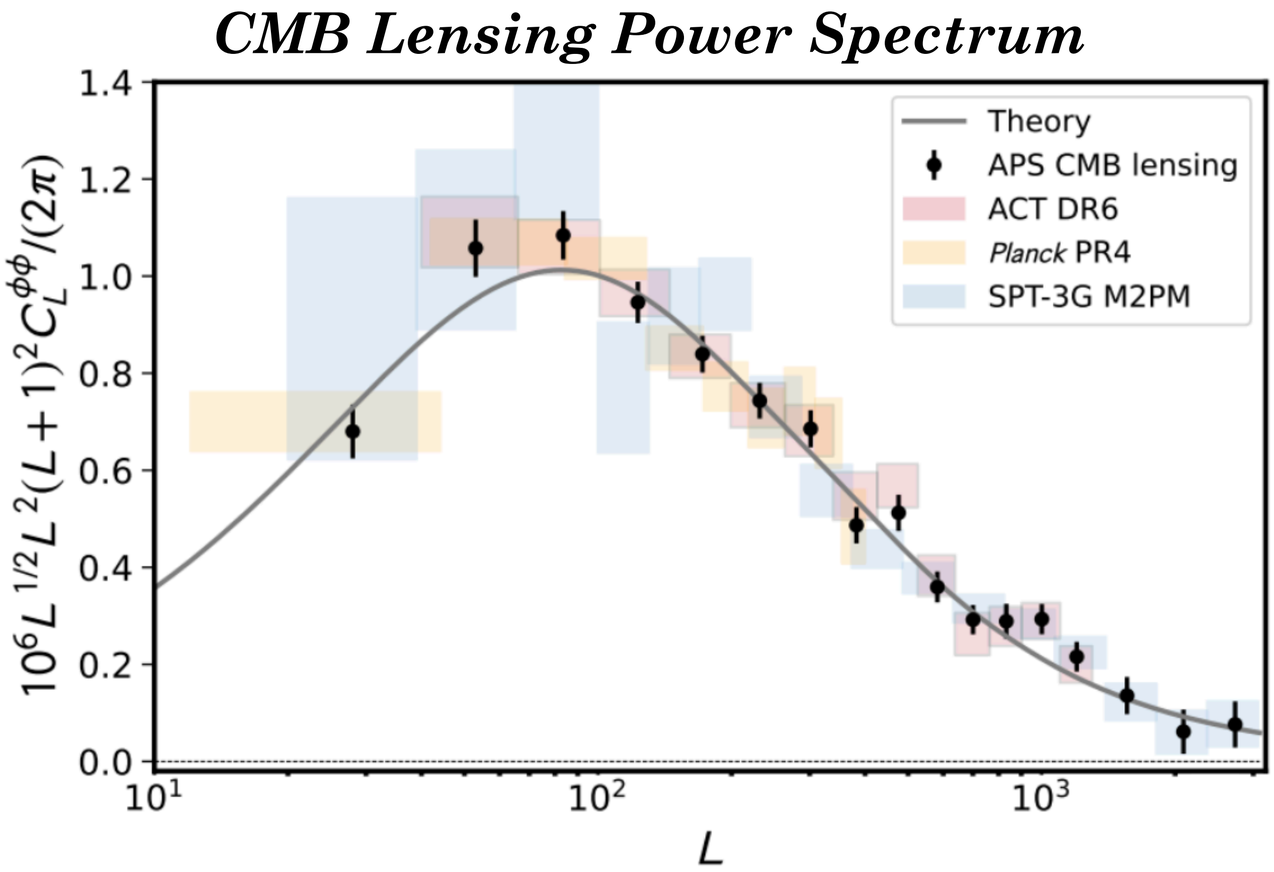
2019-2020 Main Survey: CMB Lensing



Fei Ge



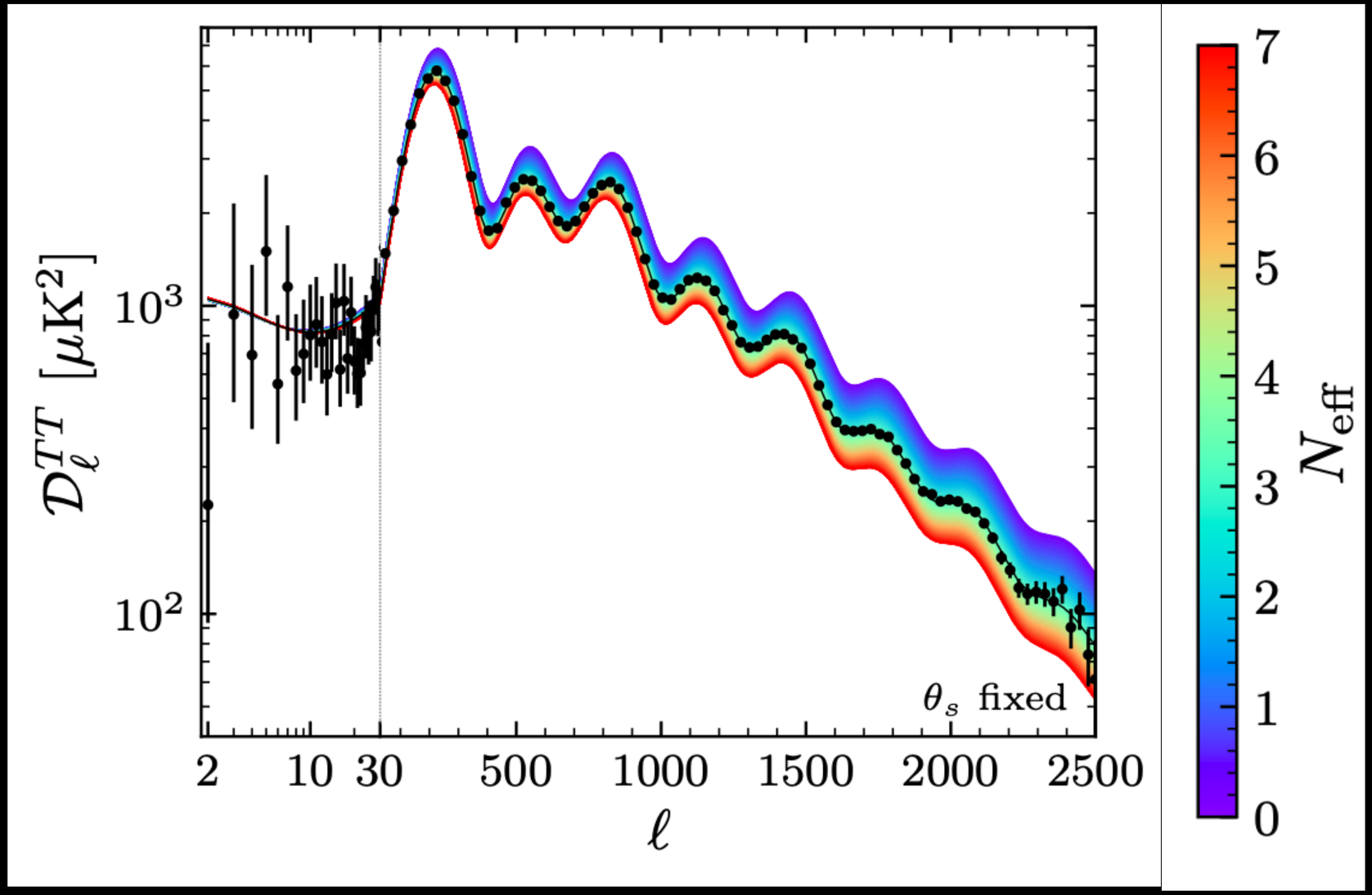
Yuuki Omori
UC Research Scientist



- CMB lensing map from polarization data alone (SPT-3G, Ge et al. 2024)
- 38-σ measurement of CMB lensing (2.6% constraint on lensing amplitude)
  - Similar constraining power between SPT-3G and Planck & ACT lensing data
  - SPT-3G highly complementary, providing more sensitivity from polarization and smaller (more non-linear) scales
- SPT+ACT+Planck lensing data combine for a 61-σ measurement
  - Alens = 1.025+/- 0.017, well fit by LCDM Planck cosmology

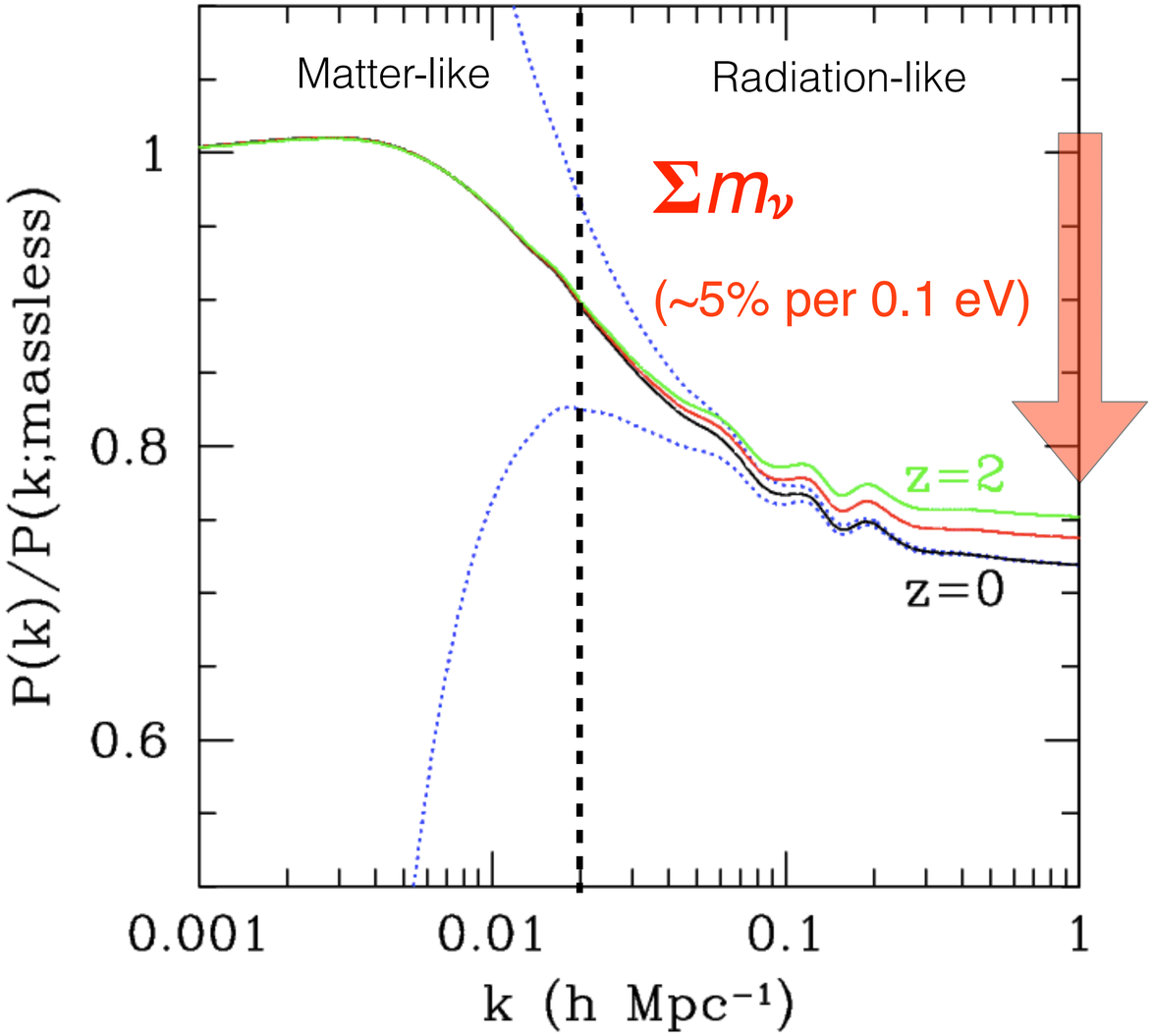
SPT-3G) Ge et al. (2024), arXiv: 2411.06000
(ACT & SPT) Qu et al. (2025), arXiv: 2504.20038

CMB Power Spectrum variation with Neff



Gerbino et al. (2022), arXiv: 2203.07377

Neutrino Mass Affects Structure Growth



- Neutrinos affect growth of large-scale structure in the Universe
- Sum of the neutrino mass species (Σm_ν) > 0.06 eV from oscillation experiments
  - ***Neutrinos ~> mass of all the stars in the Universe***
- Above free-streaming scale, neutrinos act like **matter**
- Below free-streaming scale, neutrinos act like **radiation**