Cosmology from the South Pole Telescope

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on behalf of the NEUCosmoS team
and the SPT-3G collaboration

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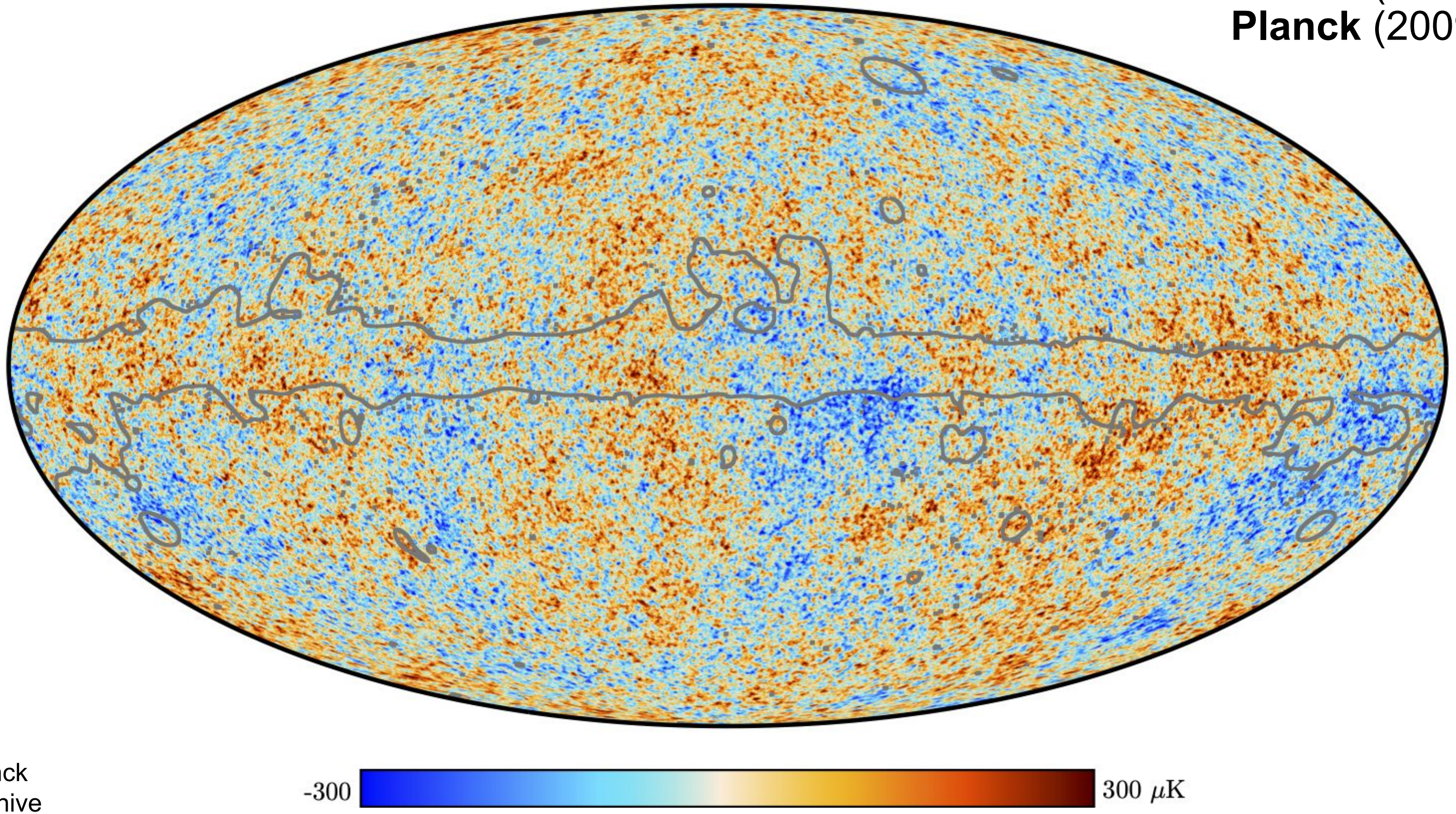
Corpse and Mirror II | The Art Institute of Chicago

Outline

- Introduction
  - State of the art of CMB experiments
- South Pole Telescope (SPT)
- SPT-3G early results
  - 2018 EE/TE Cosmology
- SPT-3G future prospects
  - 2018 TT/EE/TE
  - 2019+2020 TT/EE/TE
  - Extended survey

The Planck mission: temperature anisotropies

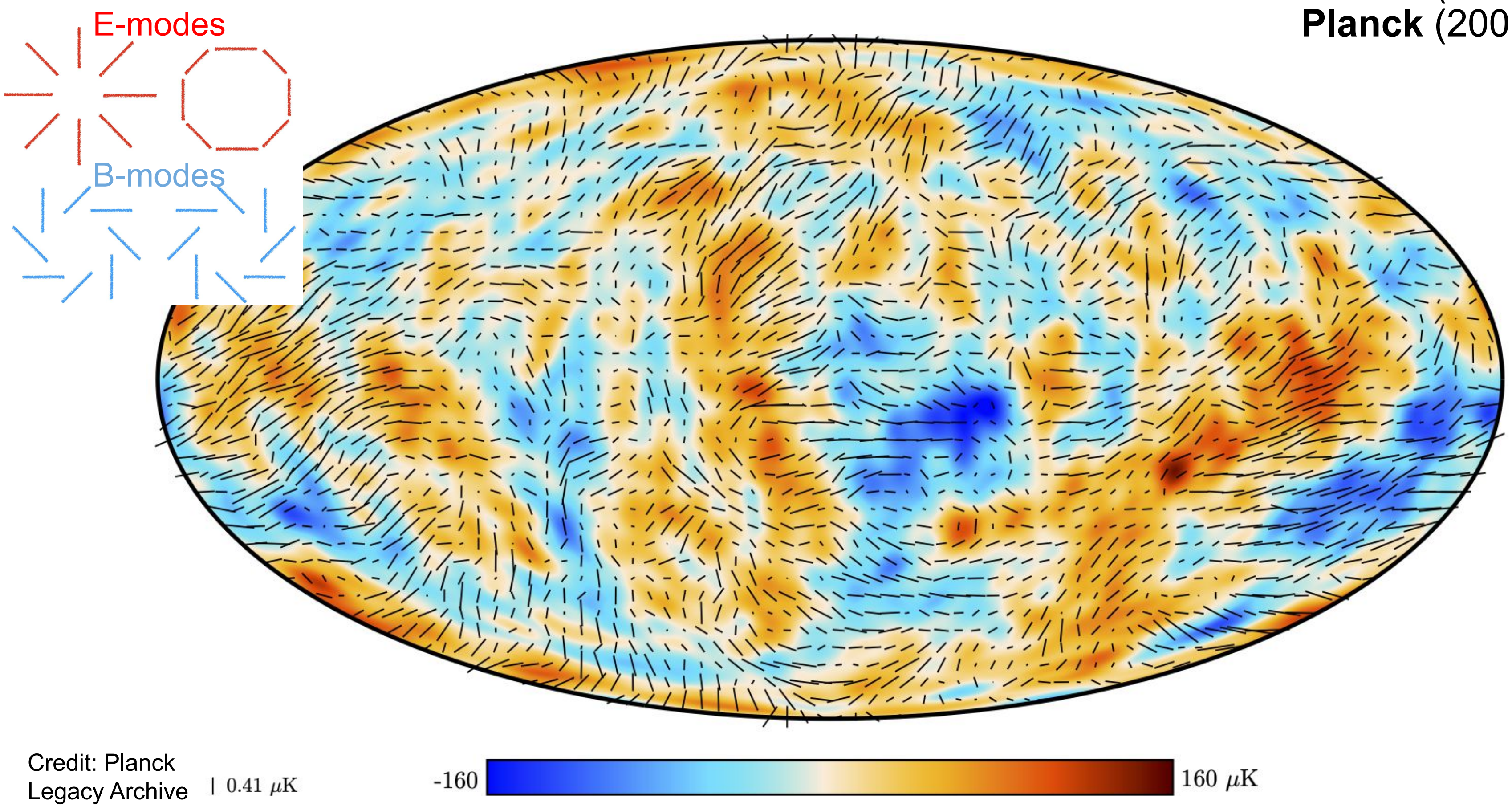
<u>Space missions:</u>
COBE(1989-1993)
WMAP (2001-2012)
Planck (2009-2013)



Credit: Planck Legacy Archive

The Planck mission: polarization anisotropies

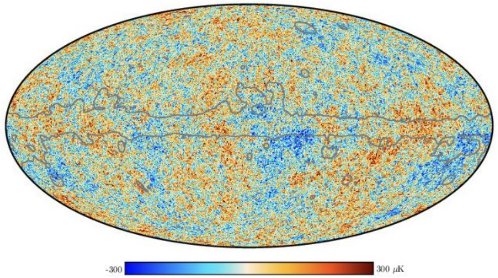
Space missions:
WMAP (2001-2012)
Planck (2009-2013)



Credit: Planck Legacy Archive

Planck angular power spectra

T



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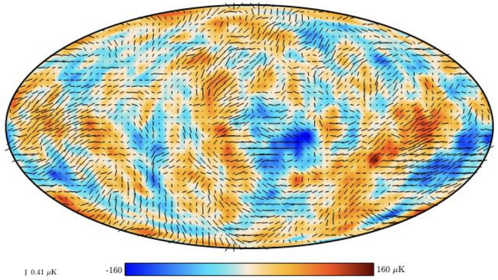

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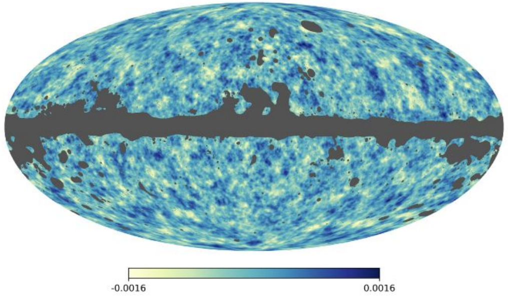
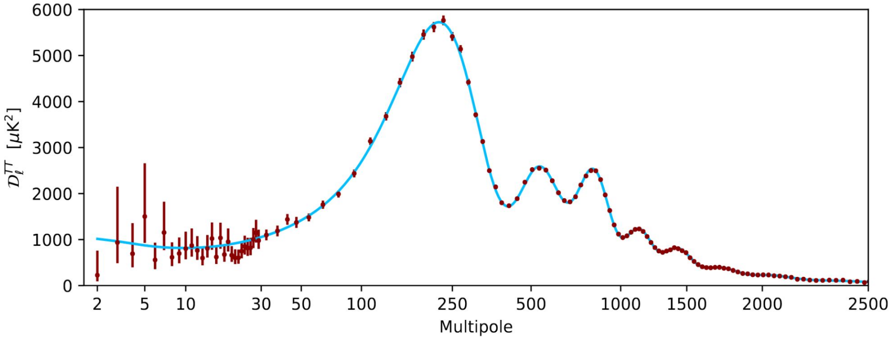
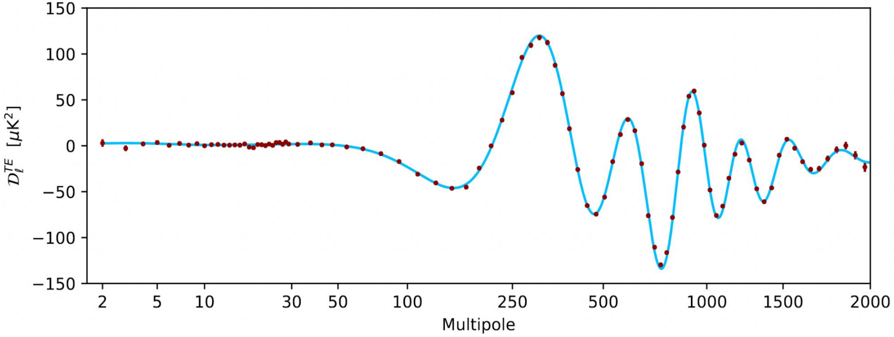
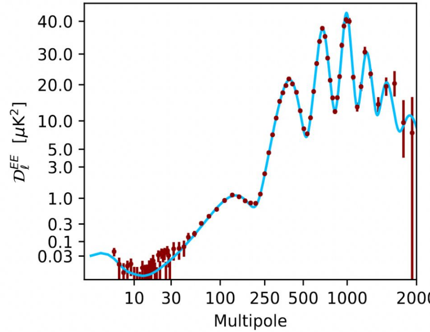
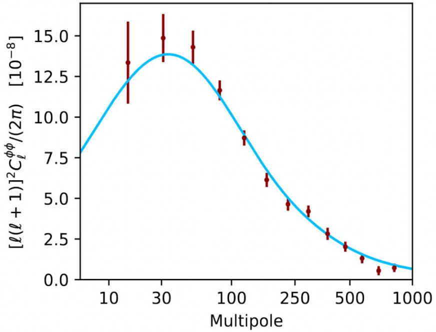










Planck and beyond

- Planck is the current reference in cosmology, it is still the most powerful dataset
- Planck allowed us to test the cosmological model with sub-percent level precision
- Very good consistency with the standard model of cosmology (ΛCDM)
- However… some tensions with other cosmological probes appeared → new physics? systematics?
  - Hubble constant: H_0
  - Growth of structure: σ_8 or S_8
  - Lensing amplitude: A_ℓ

J. Lesgourgue's talk!

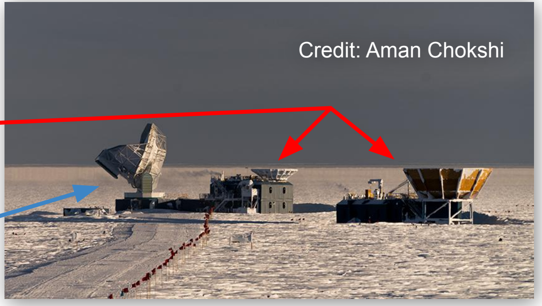
- Goals after Planck
  - Understand tensions
  - Continue to improve cosmological constraints (independently as much as possible)
  - Detect primordial gravitational waves (B-modes)

Parameter	*Planck* alone	*Planck* + BAO
$\Omega_b h^2$	0.022383	0.022447
$\Omega_c h^2$	0.12011	0.11923
$100\theta_{MC}$	1.040909	1.041010
τ	0.0543	0.0568
$\ln(10^{10} A_s)$	3.0448	3.0480
n_s	0.96605	0.96824
H_0 [km s^{-1}Mpc^{-1}] . .	67.32	67.70
Ω_Λ	0.6842	0.6894
Ω_m	0.3158	0.3106
$\Omega_m h^2$	0.1431	0.1424
$\Omega_m h^3$	0.0964	0.0964
σ_8	0.8120	0.8110
$\sigma_8(\Omega_m/0.3)^{0.5}$	0.8331	0.8253
z_{re}	7.68	7.90
Age [Gyr]	13.7971	13.7839

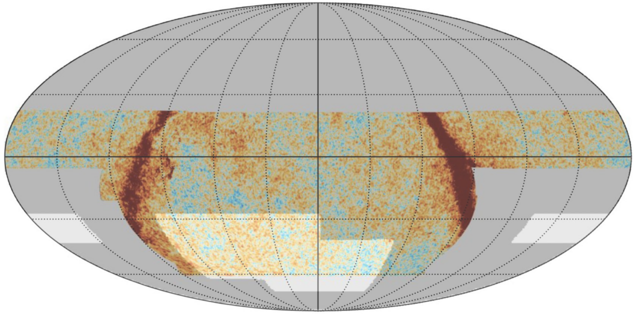
Planck 2018 results. I

State of the art CMB experiments

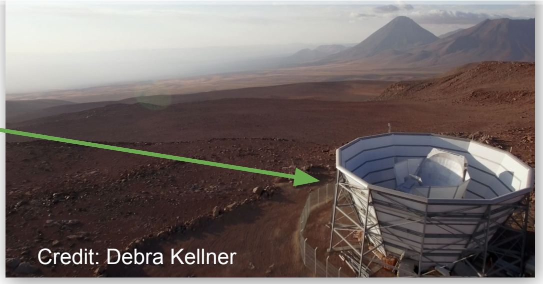
- BICEP/Keck (from the South Pole)
  - Targets the detection of primordial B-modes at large angular scales (low multipoles)
  - Very deep observations on a small sky patch
  - BICEP/Keck Collaboration, 2021: r<0.036



- South Pole Telescope (SPT)
  - BICEP/Keck delensing to contribute to the detection of primordial B-modes
  - Intermediate-high multipoles cosmology
  - Very deep observations on a small sky fraction
  - High constraining power from the small scales of CMB polarization



- Atacama Cosmology Telescope (ACT)
  - Intermediate-high multipoles cosmology
  - Deep observations on a large sky fraction
  - High constraining power from the small scales of CMB temperature (mostly) and polarization

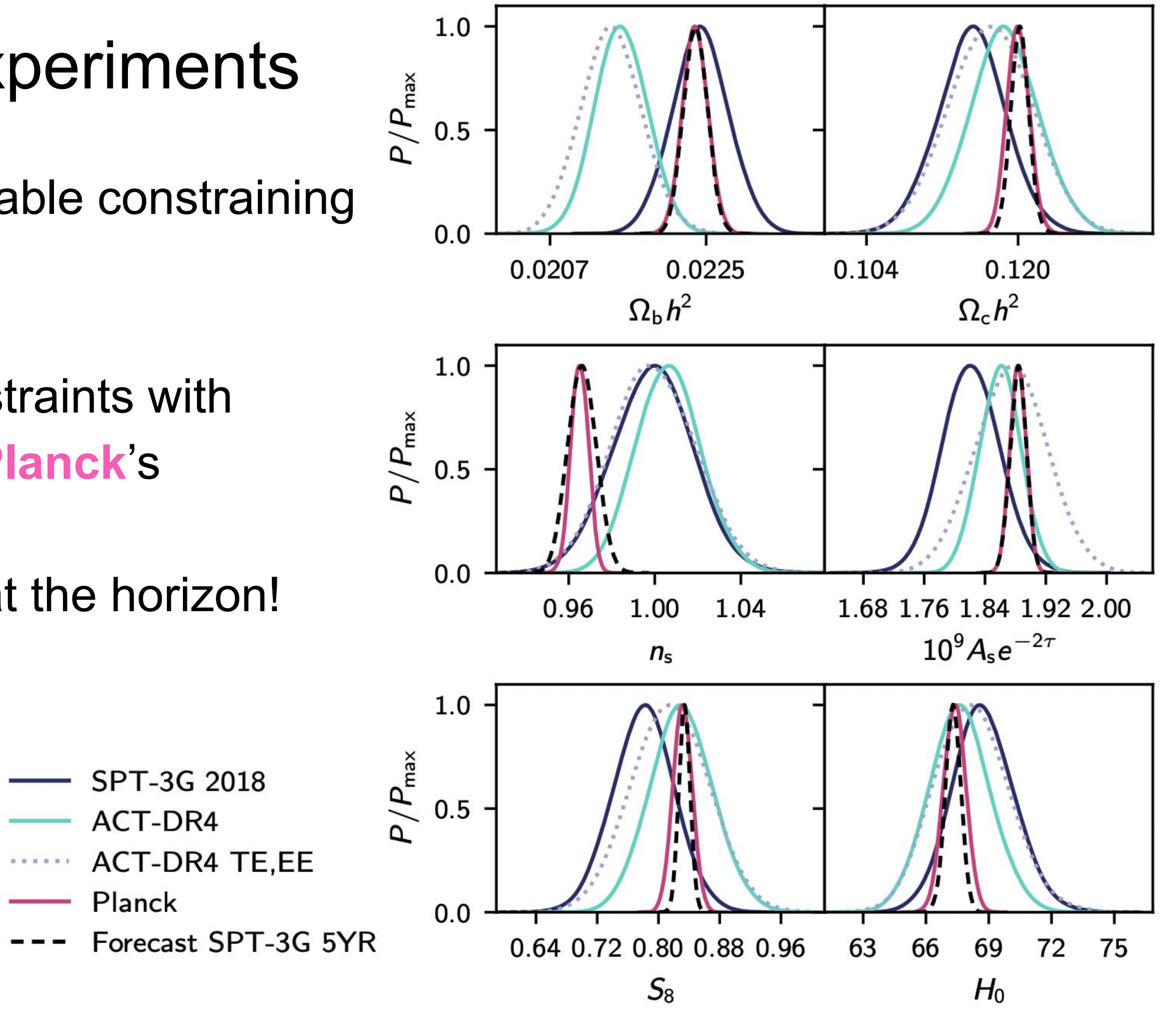


- Future experiments: CMB-S4 and Simons Observatory from the ground, LiteBIRD from space

Credit: Silvia Galli

State of the art CMB experiments

- **ACT** and **SPT** have comparable constraining power
- They expect to provide constraints with precision comparable with **Planck**'s
- Lots of funny comparisons at the horizon!



The South Pole Telescope

The South Pole Telescope (SPT)

- **10 m** primary mirror telescope
- Off-axis Gregorian optics design
- Location:
  Amundsen-Scott station,
  South Pole
- Dedicated to CMB observations with high angular resolution (~1 arcmin)
- Funded by

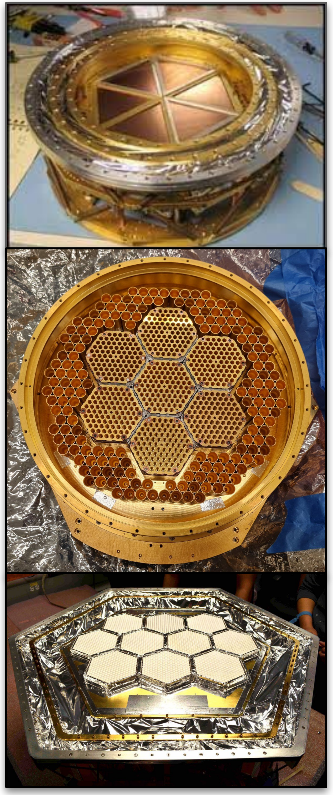
Credit Aman Chokshi, May 2022

The South Pole Telescope (SPT)

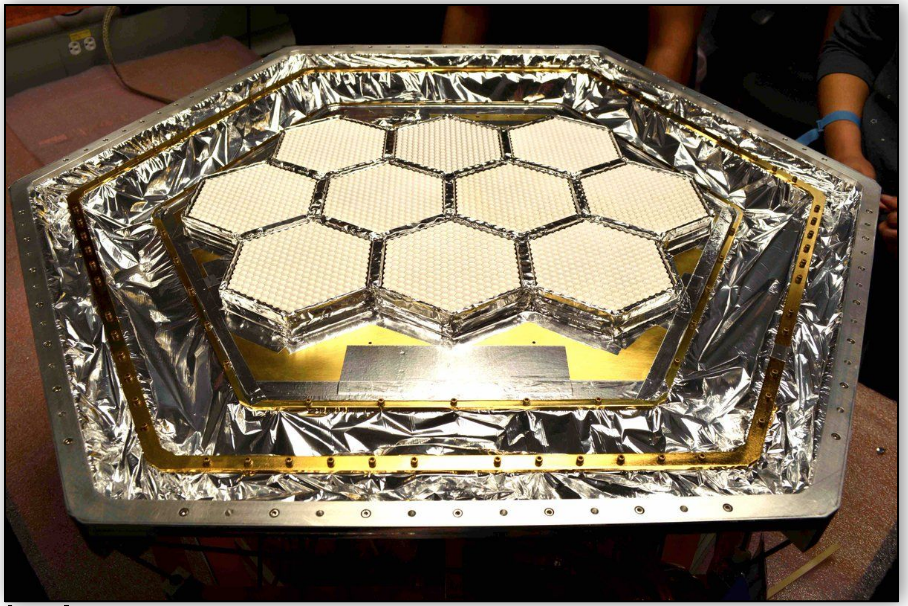
1. **SPT-SZ** (2007–2011)
    a. Temperature data
    b. 95, 150, 220 GHz
    c. 960 detectors
    d. 2500 deg2
    e. 18 μK-arcmin at 150 GHz

2. **SPTpol** (2012–2016)
    a. Temperature and Pol.
    b. 95, 150 GHz
    c. 1600 detectors
    d. ~500 deg2
    e. 5.5 (T) 7.7 (pol) μK-arcmin at 150 GHz

3. **SPT-3G** (2017–present)



SPT-3G



Third survey camera installed on SPT after SPT-SZ and SPT-pol

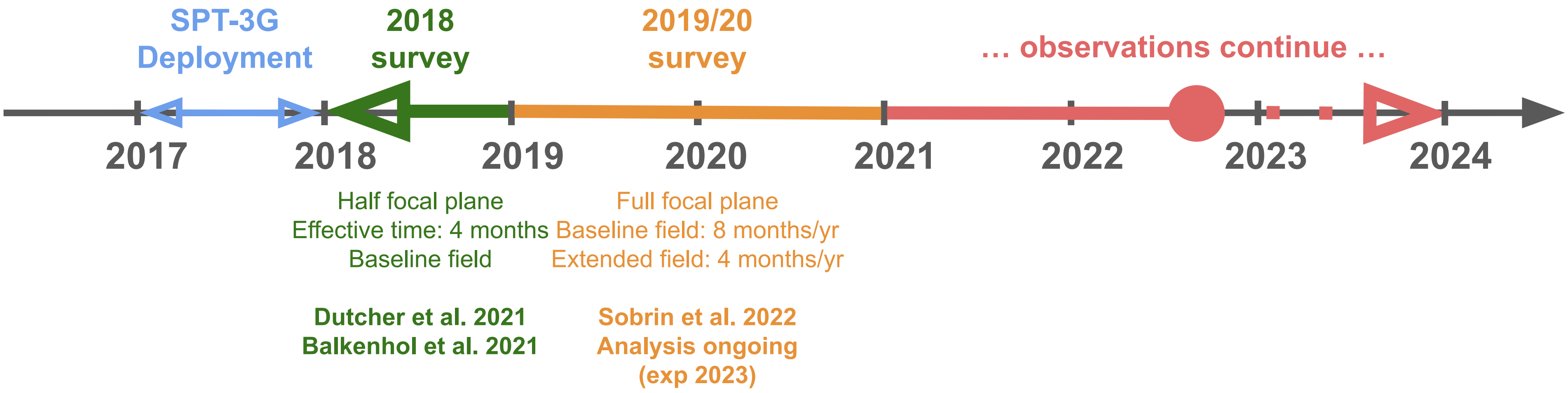
- Deployed in early **2017**
- Field of view **2.8 deg2**
- Diameter of the focal plane **0.43 m** (**3.5** larger area than before)
- ~**16 000** transition-edge sensor (**TES**) bolometers
  - Fabricated on **10** monolithic 150 mm silicon **wafers**
  - Operating at **300 mK**.
- Frequency bands: **95, 150, 220 GHz**, FWHM : **1.6, 1.2, 1.0 arcmin**

Sobrin et al. 2022 (arXiv:2106.11202, design and performance)

SPT-3G science

- **Cosmological constraints**
- Delensing in the BICEP/Keck field
- High-ℓ TT
- Low-ℓ BB
- DES x SPT
- tSZ kSZ
- Spatially varying cosmic birefringence
- Axions
- Galaxy clusters
- Pont sources, transients, asteroids, planet 9
- …

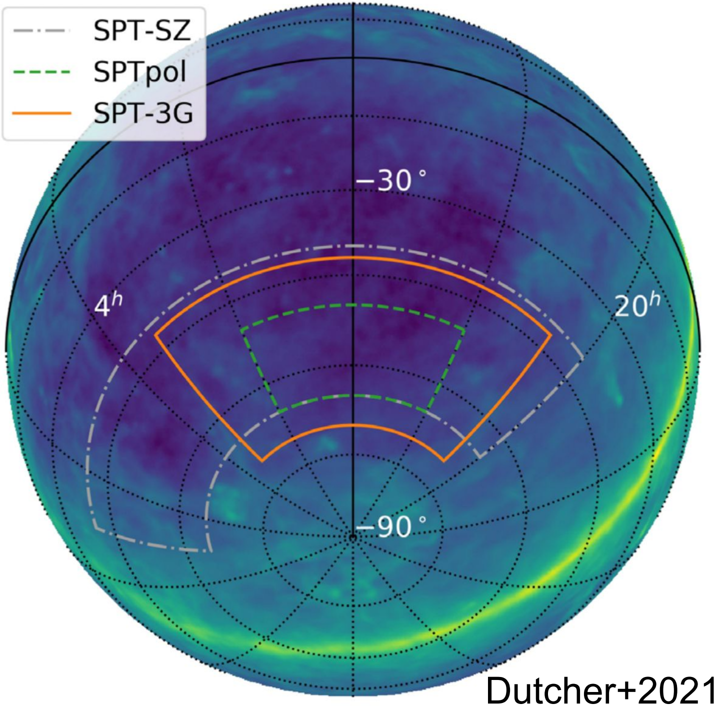
SPT-3G observations timeline



SPT-3G 2018

First survey with ~ half of the focal plane during 2018

- **Four months** during the winter season (April–November)
- **6600** active detectors in average
- Baseline (winter) field:
  ~1500 deg2 (fsky~4%)
  covered with stepping constant elevation rasters (1 deg/s, ~100 s per scan)
  - −42° to −70° declination and from
  - 20h 40m to 3h 20m right ascension
  - Overlap with the BICEP/Keck field

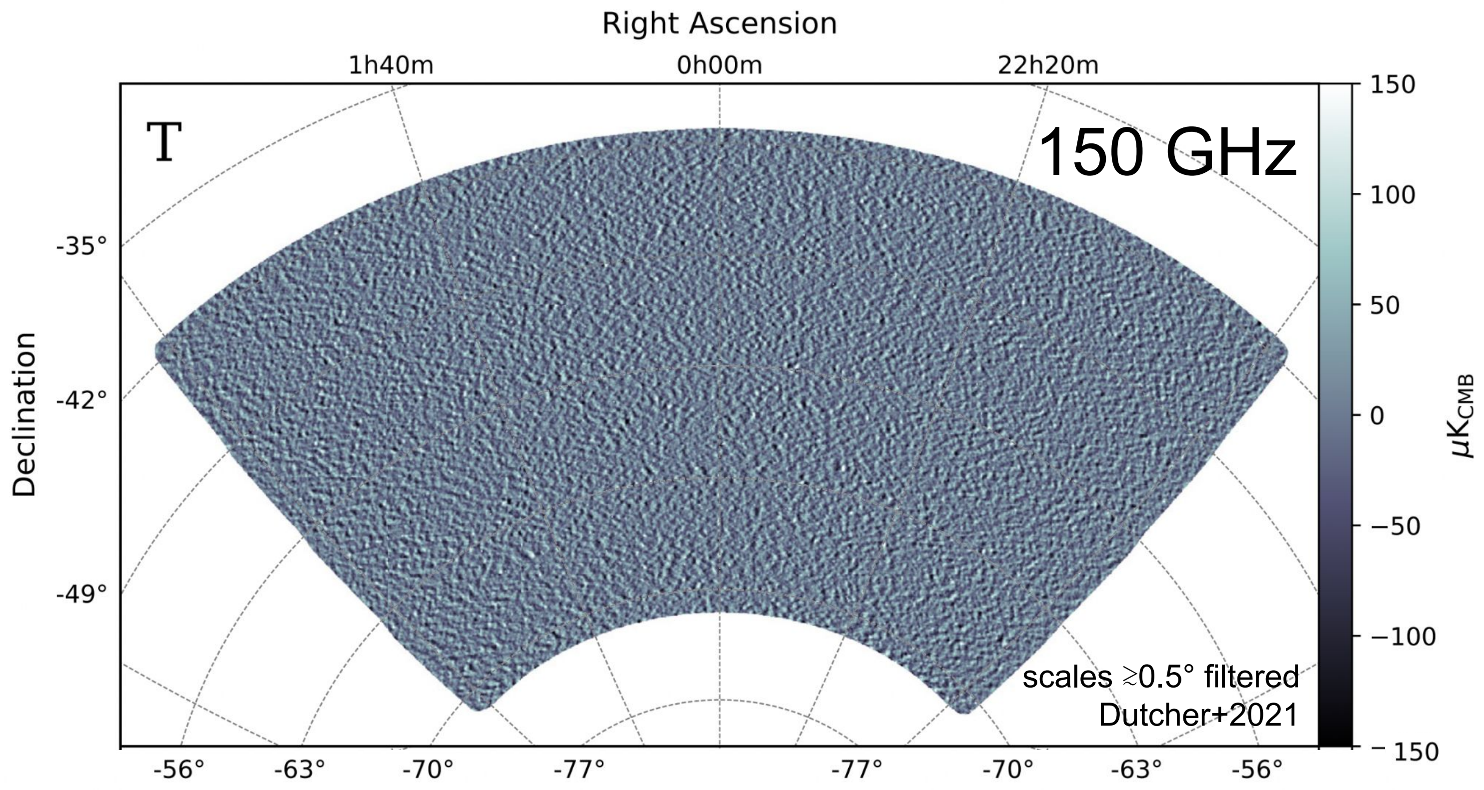


Dutcher+2021

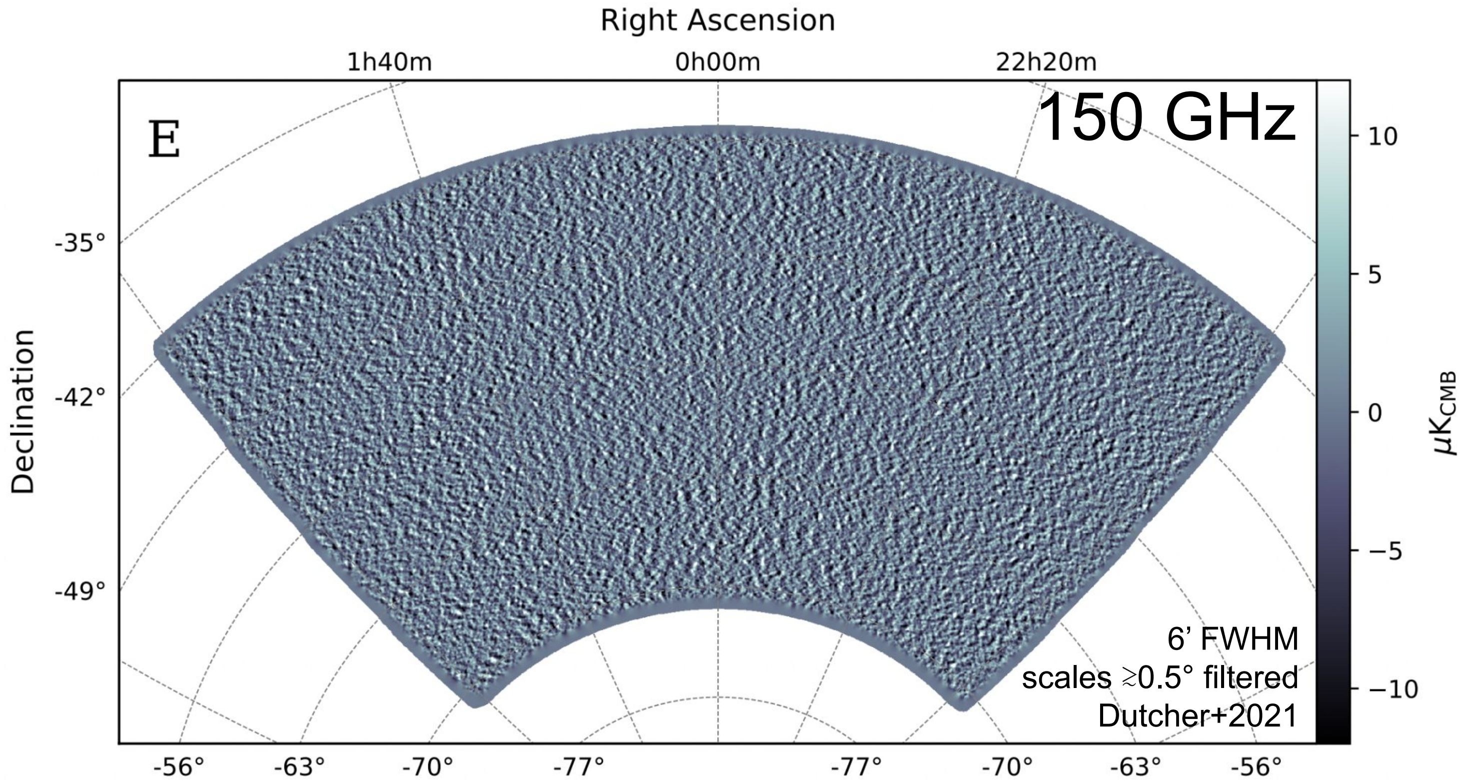
➔ Dutcher et al. 2021 (arXiv:2101.01684, maps, bandpowers, ΛCDM)

➔ Balkenhol et al. 2021 (arXiv:2103.13618, ΛCDM Extensions)

SPT-3G 2018 Maps

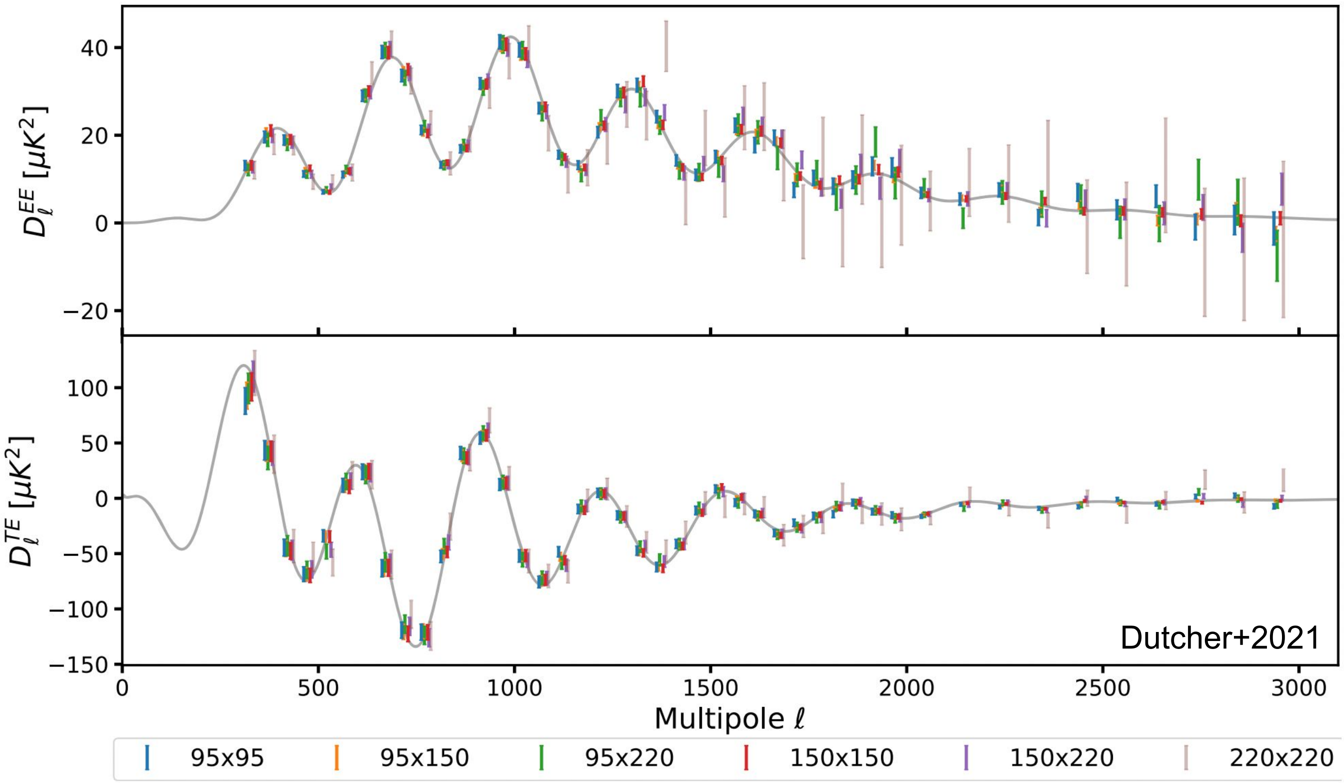


SPT-3G 2018 Maps



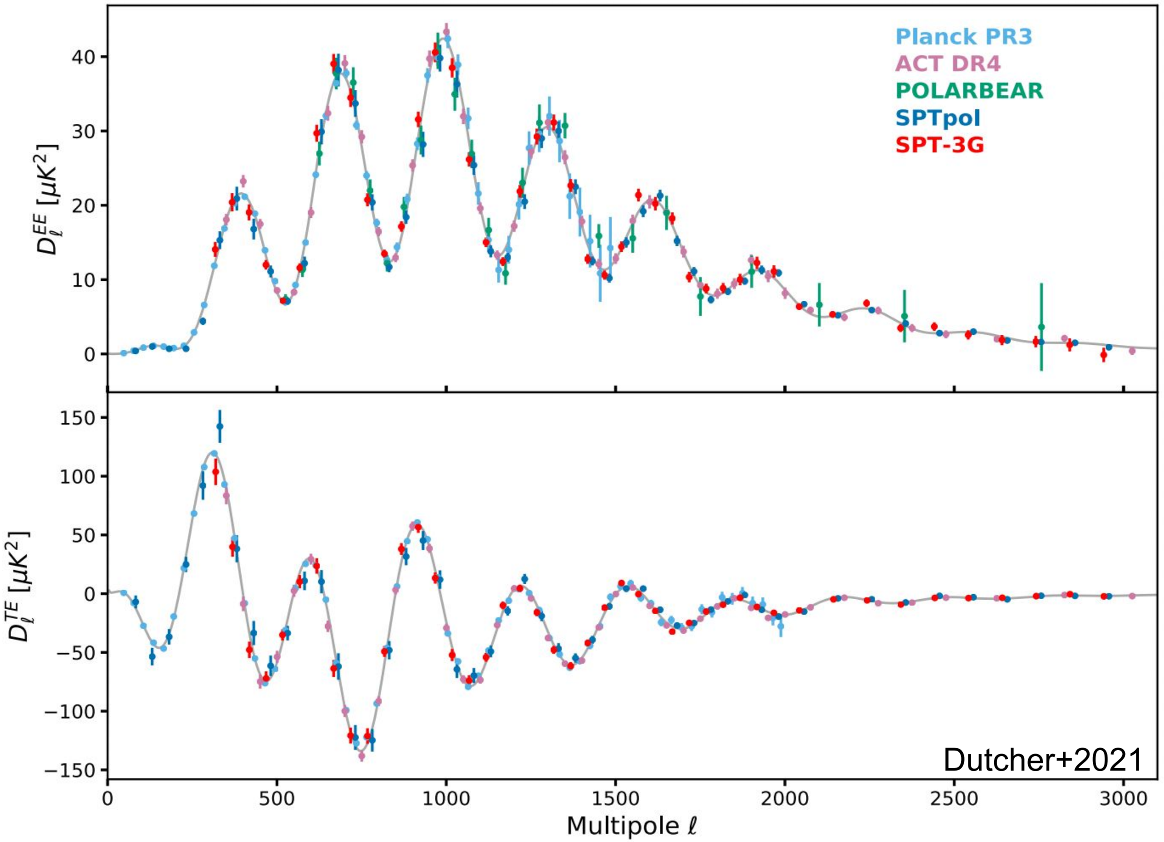
Polarized map depths: **29.6, 21.2, and 75 μK−arcmin** at 1000 < l < 2000
(at 95, 150, 220 GHz)

SPT-3G 2018 Power Spectra



SPT-3G 2018 Power Spectra

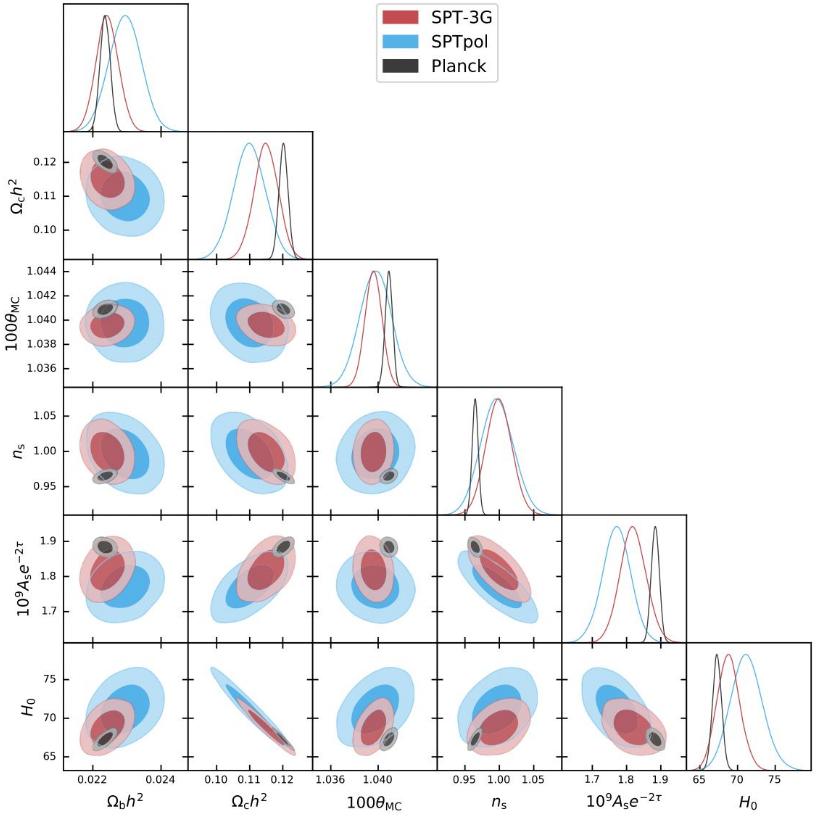
- SPT best measurements of the polarised CMB at intermediate angular scales (EE: 300 ≤ l ≤ 1400, TE: 300 ≤ l ≤ 1700)
- Already very constraining despite coming from only 4 months of observations and half of the focal plane
- Lead to SPT's tightest cosmological constraints from EE/TE data



SPT-3G 2018 ΛCDM constraints

Dutcher+2021

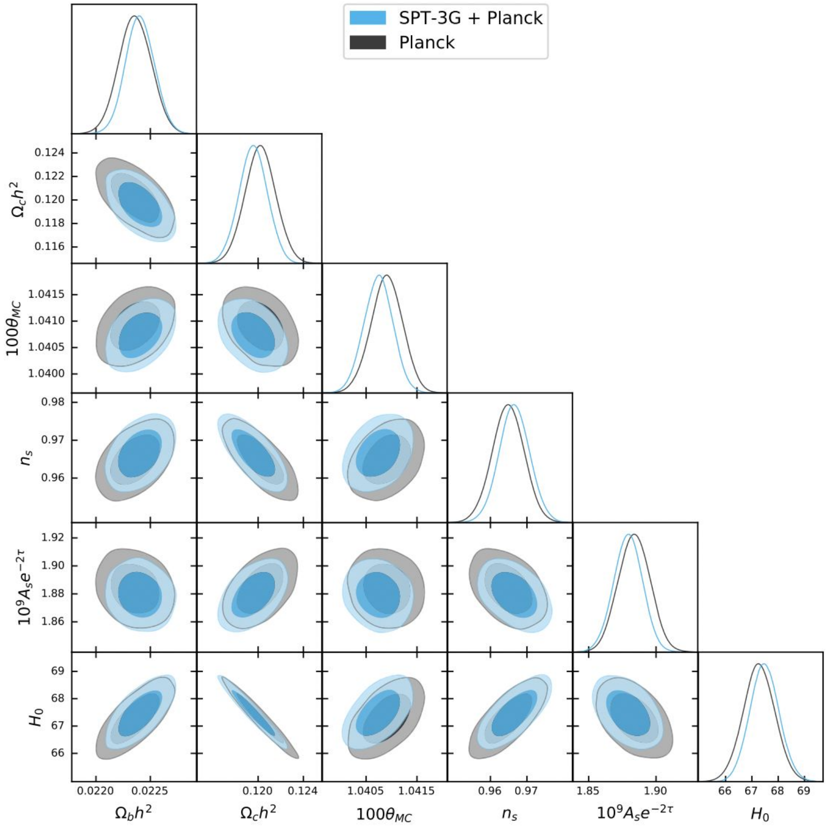
- More constraining than SPTpol, and consistent with it
- Consistent with Planck although they are largely independent
  - SPT-3G 2018 sensitive to intermediate and small angular scales of EE/TE, while Planck uses mostly larger scales TT/TE/EE, with large constraining power coming from TT
  - A small area is shared by the two surveys
  - Only a global re-calibration of SPT-3G relies on Planck



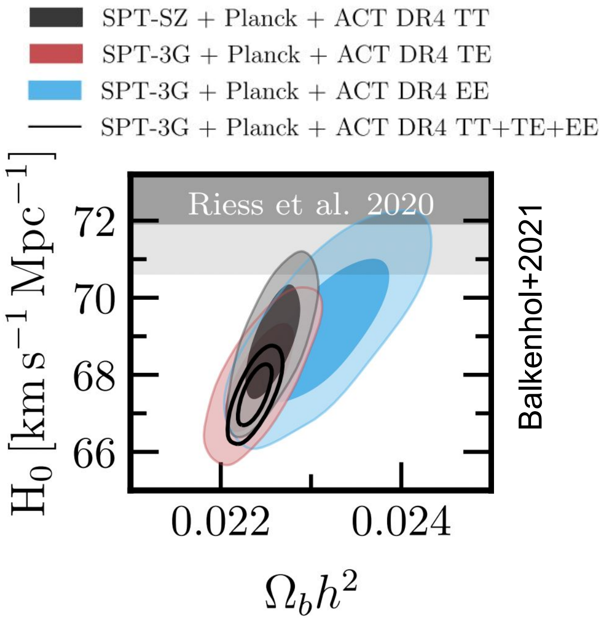
SPT-3G 2018 ΛCDM constraints

Dutcher+2021

- More constraining than SPTpol, and consistent with it
- Consistent with Planck although they are largely independent
- Even with this little amount of data, SPT-3G 2018+Planck slightly improves the Planck-only constraints



SPT-3G 2018 ΛCDM constraints



- Very good **consistency with ΛCDM**
  (χ^2 = 513.0 for 528 band powers, PTE = 0.61)

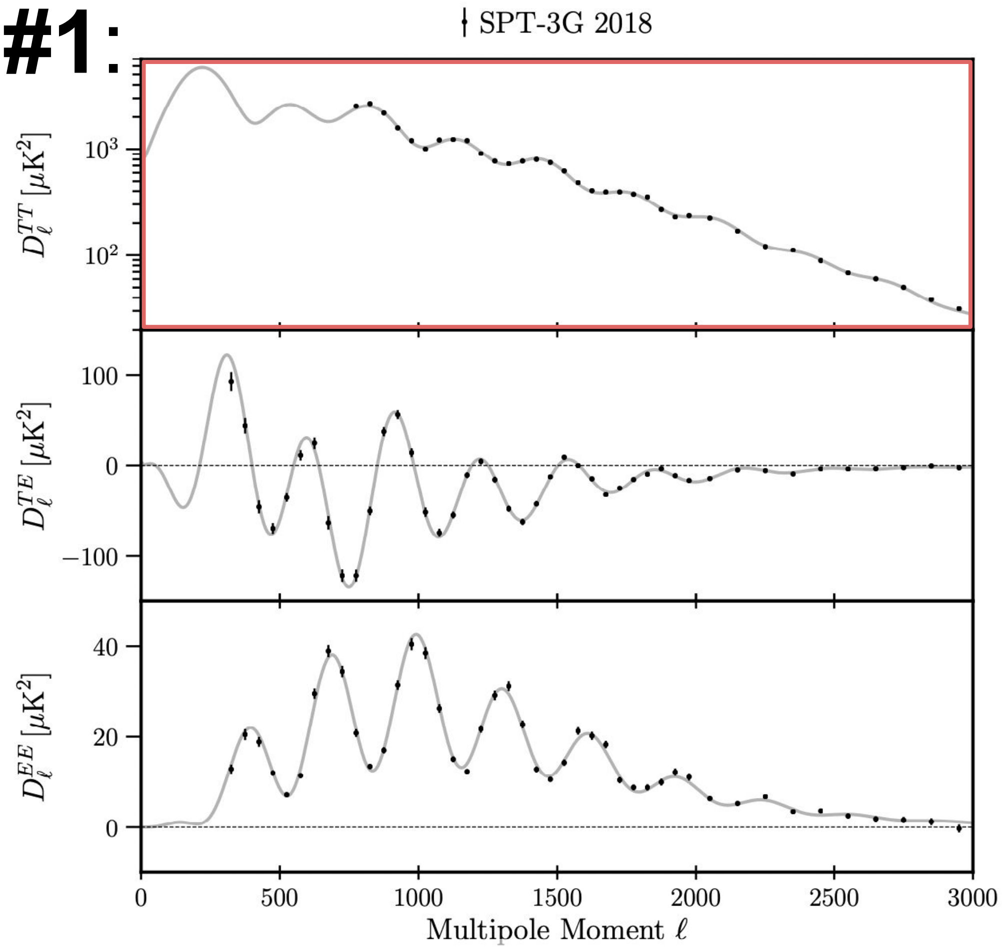
- Balkenhol et al. (2021) and Dutcher er al. (2021) constrained a bunch of **ΛCDM extensions**, with **no significant improvement over ΛCDM**

- SPT-3G constraint on $\mathbf{H_0}$ is as low as Planck's
  - H_0 = 67.49 ± 0.53 km/s/Mpc, obtained combining SPT-3G 2018, Planck, ACT DR4 temperature and polarization spectra (Balkenhol et al., 2021)
  - 4.8σ tension with Riess et al., (2022).
- The central value of $\boldsymbol{\sigma_8}$ aligns more with low-z data, though at current sensitivity the confidence region also overlaps with Planck's
  (σ_8 = 0.8084±0.0069 from SPT-3G+Planck, Dutcher et al., 2021)

Near future prospects **#1**: 2018 TT+EE/TE

Include 2018 **TT** to the EE/TE analysis (Balkenhol et al, in prep.)

- Breaks degeneracies and improve constraints of ΛCDM by ~10–30%.
- Helps testing extensions of ΛCDM

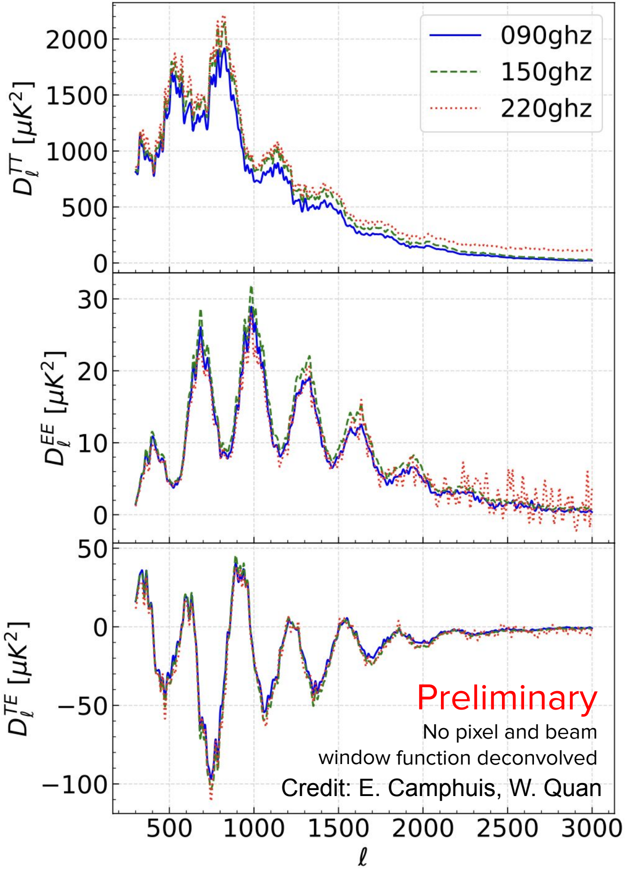


Near future prospects **#2**: 2019+2020 TT/EE/TE

- The analysis of the 2019+2020 winter survey (2x8 months) is ongoing
    - Full focal plane operative
    - Factor ~ 3.8 lower noise than in 2018
    - Map depth:
        - ~ 5/4/15 μK-arcmin at 95/150/220 GHz (T)
        - ~ 7/6/21 μK-arcmin at 95/150/220 GHz (pol)

see E. Camphuis talk tomorrow!

- Works ongoing to build a very robust analysis pipeline
(K. Benabed, E. Camphuis, T. Crawford, A. Doussot, S. Galli, E. Hivon, W. Quan, …)



Forecasts

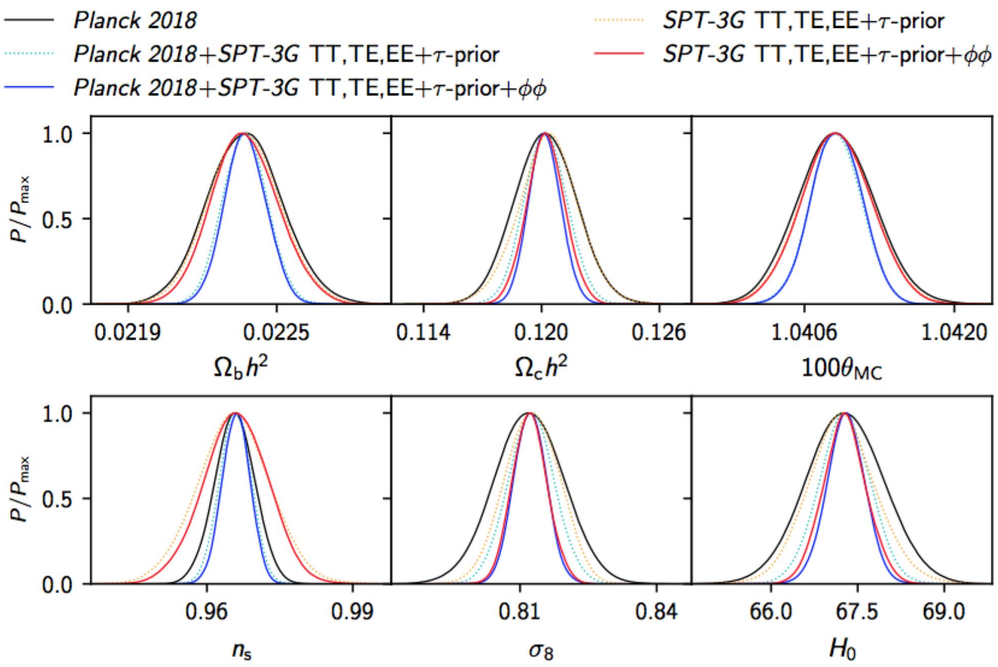
Observations will continue through at least 2023 (total of 5 years)

➔ Goal noise levels:
2.8, 2.6, 6.6 μK-arcmin (T)

➔ **ΛCDM constraints from SPT-3G TT/EE/TE winter alone comparable with Planck !**

➔ **SPT-3G TT/EE/TE + Planck will improve (most of the) parameters by a factor 2 !**

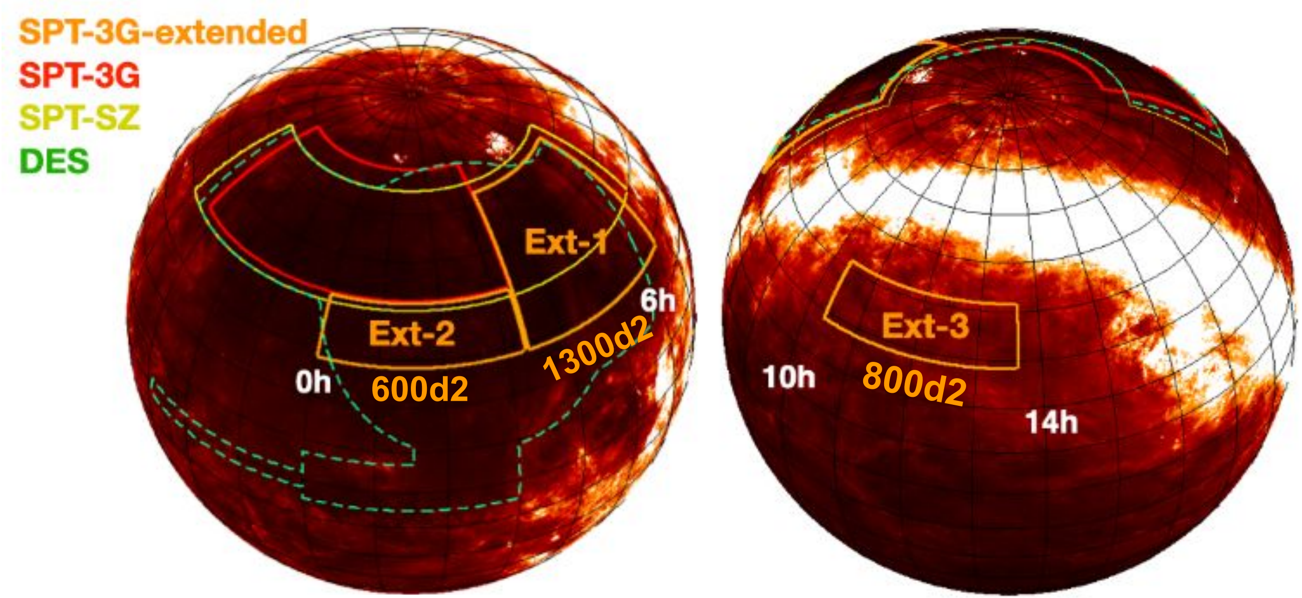
➔ Most of the constraining power is reached just with 2 years of data. Additional ~10% improvement by adding 2021/22/23.



Preliminary
Credit: Silvia Galli

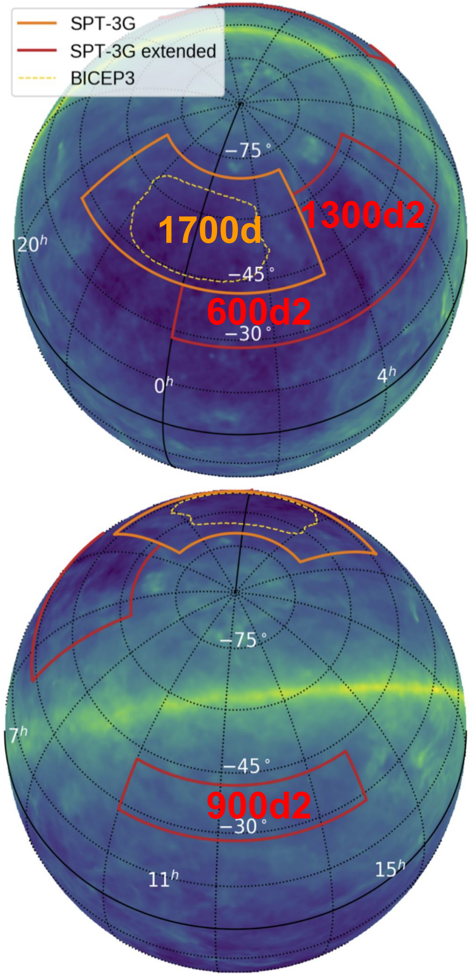
Near future prospects **#3**: extended survey or “summer fields”

- 3 extra patches in addition to the (baseline) winter fields:
  2800 deg2 (6.6%) = 1300 (3.1%) + 600 (1.4%) + 900 (2.1%)
- Observed during ~**4 months** per year (December–March)



SPT-3G Summer fields

- The analysis of the first two summer surveys is ongoing (19/20 + 20/21)
- Noise levels at 95/150/220 GHz:
  ~ **12, 12, 43** μK-arcmin (T)
  ~ **17, 17, 58** μK-arcmin (pol)
- White noise summer (2 years) ~ 3 times larger than white noise winter (2019+20)
- Summer+Winter ~ 3 times larger sky fraction than the winter fields → reduce sample variance

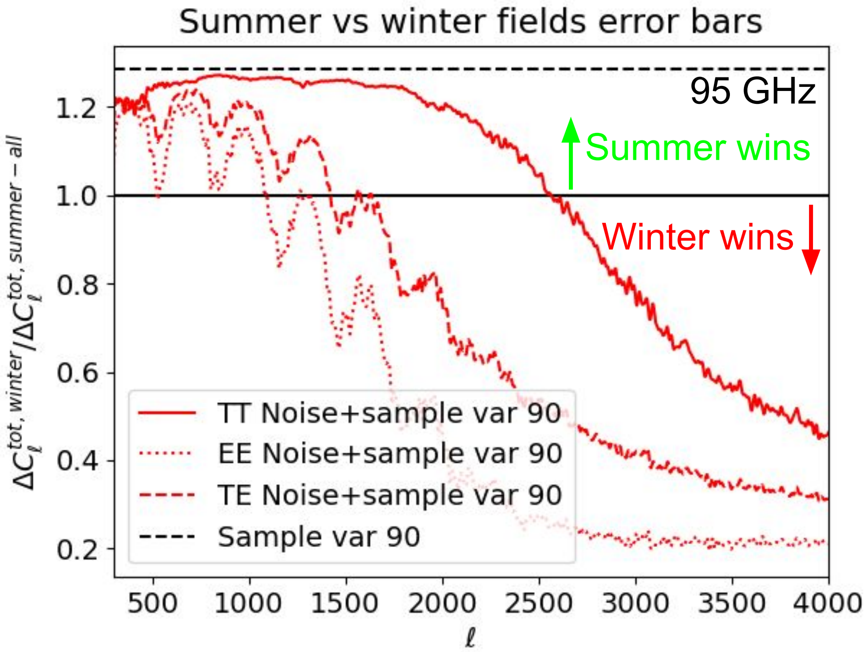


Impact of the summer fields

- Comparison of expected error bars of the summer (2y) and winter (19+20) angular power spectra

$$\Delta C_\ell^{XX} = \sqrt{\frac{2}{(2\ell+1)\Delta\ell \frac{w_2^2}{w_4} f_{sky}}} \left(C_\ell^{sky,XX} + N_\ell^{XX} \right)$$

  - Sample variance (fsky)
  - Noise variance (N_ℓ)



- Above 1: information added by the summer fields
  - Improvement in the sample variance limited regime of the SPT-3G spectra: at $\ell \lesssim$ 2600/1500/1100 in TT/TE/EE (at 95 GHz)

Forecasts including SPT-3G summer fields

1. **ΛCDM** constraints with SPT-3G TT/TE/EE* improve by **~15–20%** when including summer:
   - **σ(H_0)** = 0.66 (winter) → 0.52 (winter+summer, ~16%)
   - **σ(S_8)** = 0.018 (winter) → 0.015 (winter+summer, ~20%)

2. Summer fields will help to test extensions:
   ΛCDM+N_{eff} constraints with SPT-3G TT/TE/EE are expected to improve by up to **~40%** when including summer

(To be checked the impact of summer fields including CMB lensing)

Preliminary

Credit: Silvia Galli

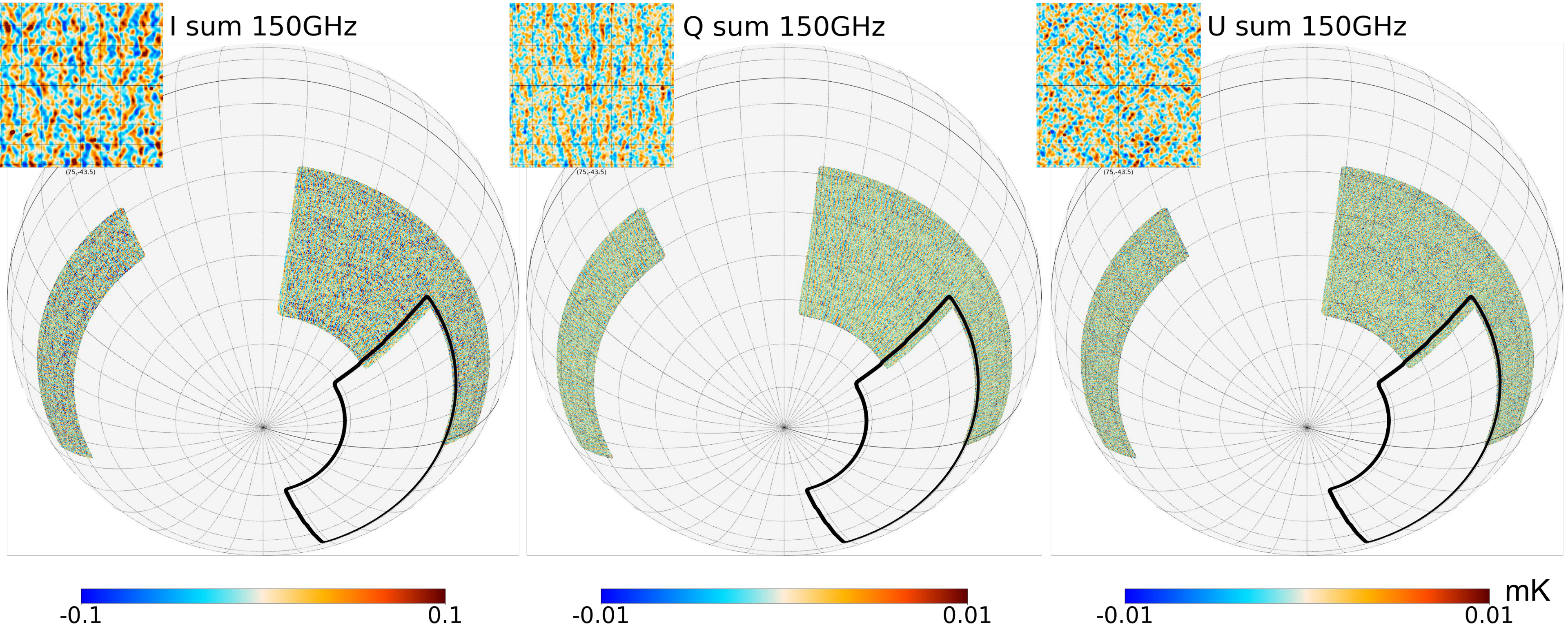
*For a 3100 deg2 summer fields and 5 years of integration on the winter fields.

SPT-3G Summer Maps

Only 2 summer seasons, 2 more to come

Preliminary

Gaussian smoothed
6 arcmin

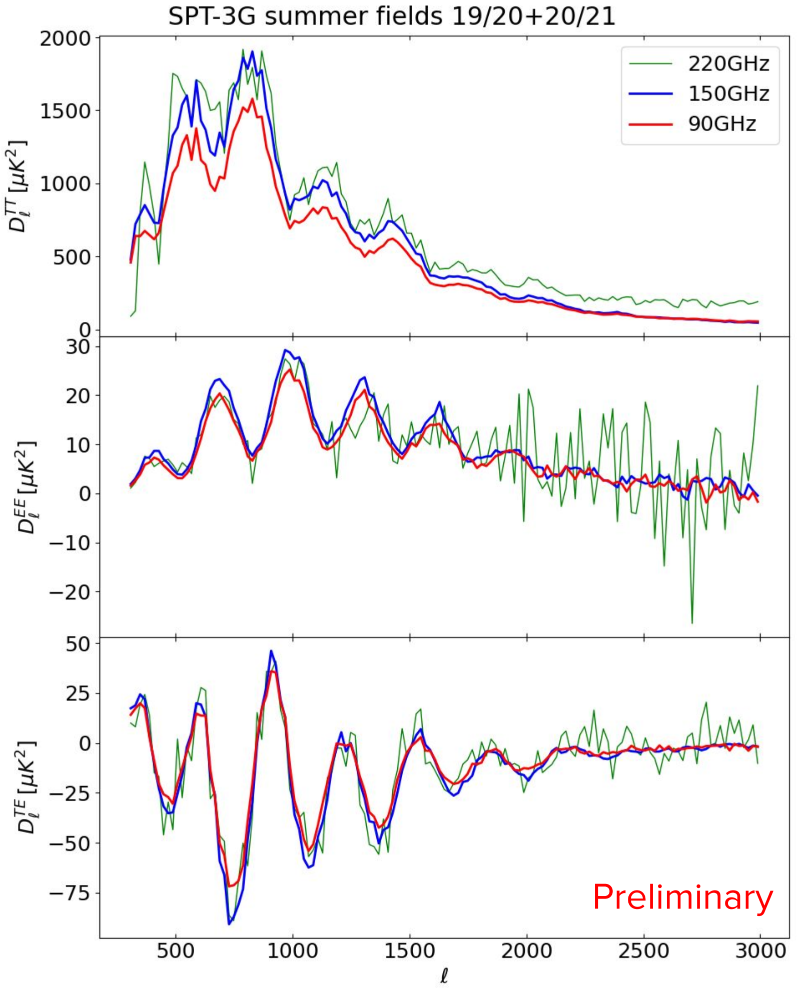


SPT-3G Summer angular power spectra

- Left-cross-Right-going spectra
  - Uncorrected data stream filtering (no transfer function correction)
  - Uncorrected by global re-calibration
  - Beam and pixel window function corrected

- High signal to noise at 95 and 150 GHz at $300 \lesssim \ell \lesssim 1500$ (EE) or larger ℓ for TT and TE

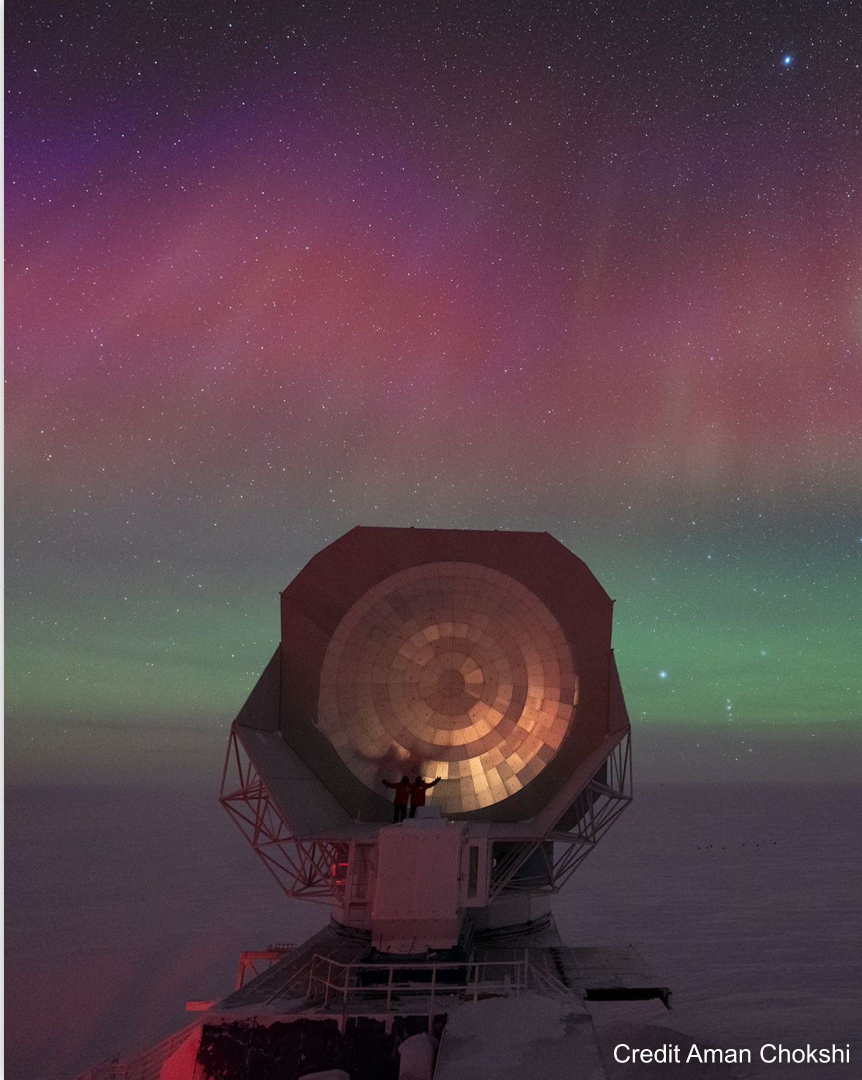
- This is from only 2 summer seasons (19/20+20/21)
  - 2 more to come, of which:
    - one already on disk (21/22)
    - and the last one planned for 22/23



Conclusions

- Planck is the current reference in cosmology, and it is still the most powerful dataset
- SPT-3G and ACT approaching Planck's cosmological containing power
- SPT-3G is providing a powerful dataset to test cosmology almost independently from Planck
  - Testing a complementary range of multipoles (low:Planck, intermediate–high: SPT)
  - Small region of the sky
- Winter fields of SPT will constrain ΛCDM as good as Planck
- The combination of SPT and Planck will be a factor 2 more constraining than Planck
- Summer fields will further improve the SPT-3G constraints, and will help to test ΛCDM extensions

Thank you!


Credit Aman Chokshi