Calibration for precision cosmology with the South Pole Telescope

Federica Guidi (IAP, Paris, guidi@iap.fr)
on behalf of the NEUCosmoS team
and the SPT-3G collaboration

CMB-Cal 2024 @ Bicocca
4 Nov 2024

Corpse and Mirror II | The Art Institute of Chicago

Outline

- South Pole Telescope (SPT) third generation camera (3G)

- SPT-3G cosmology: CMB primary anisotropies and lensing
  - Past: 2018 cosmological constraints
  - Present (upcoming): 2019+2020 survey
  - Future: wide survey and full depth

- Focus on:
  - Beams
  - Calibration
  - Systematics

The South Pole Telescope

Credit Kevin Zagorski, March 2024

The South Pole Telescope

- **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

The South Pole Telescope

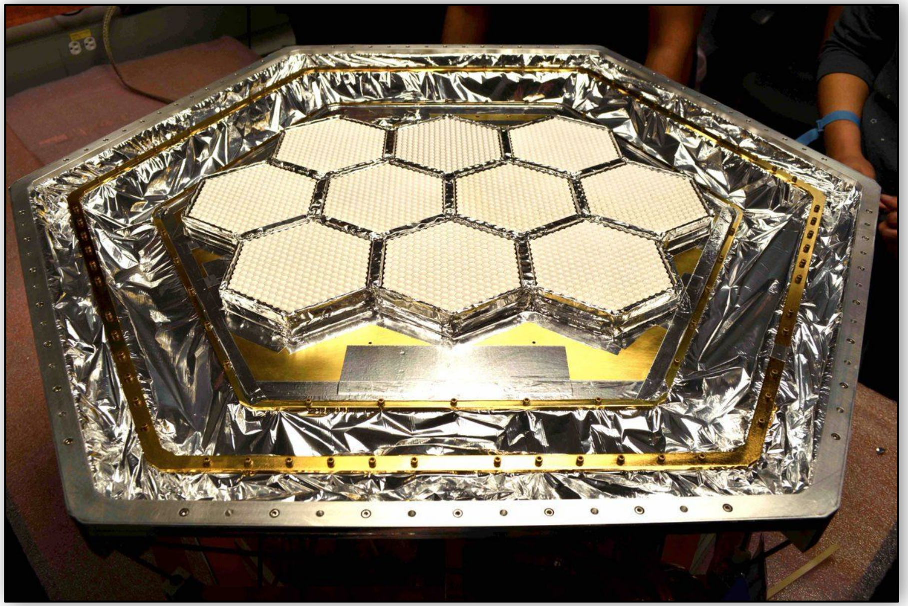
1. **SPT-SZ** (2007–2011)
    a. Temperature data
    b. 95, 150, 220 GHz
    c. 960 detectors
    d. 2500 deg2
    e. 18 μK-arcmin at 150 GHz

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

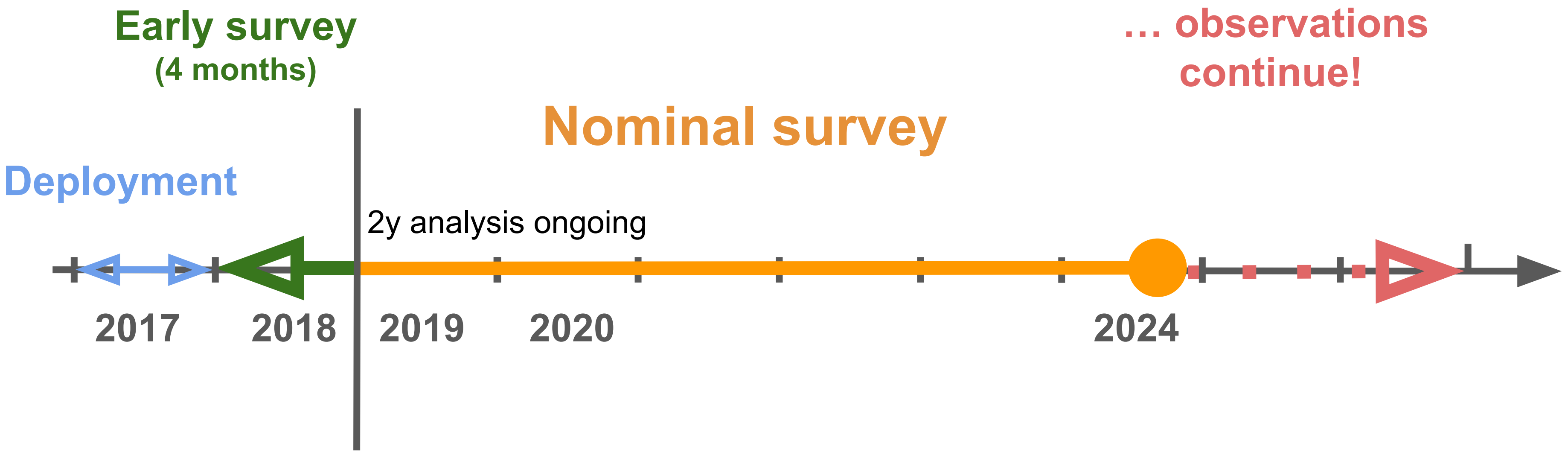
Third survey camera installed on SPT after SPT-SZ and SPT-pol



- 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 timeline

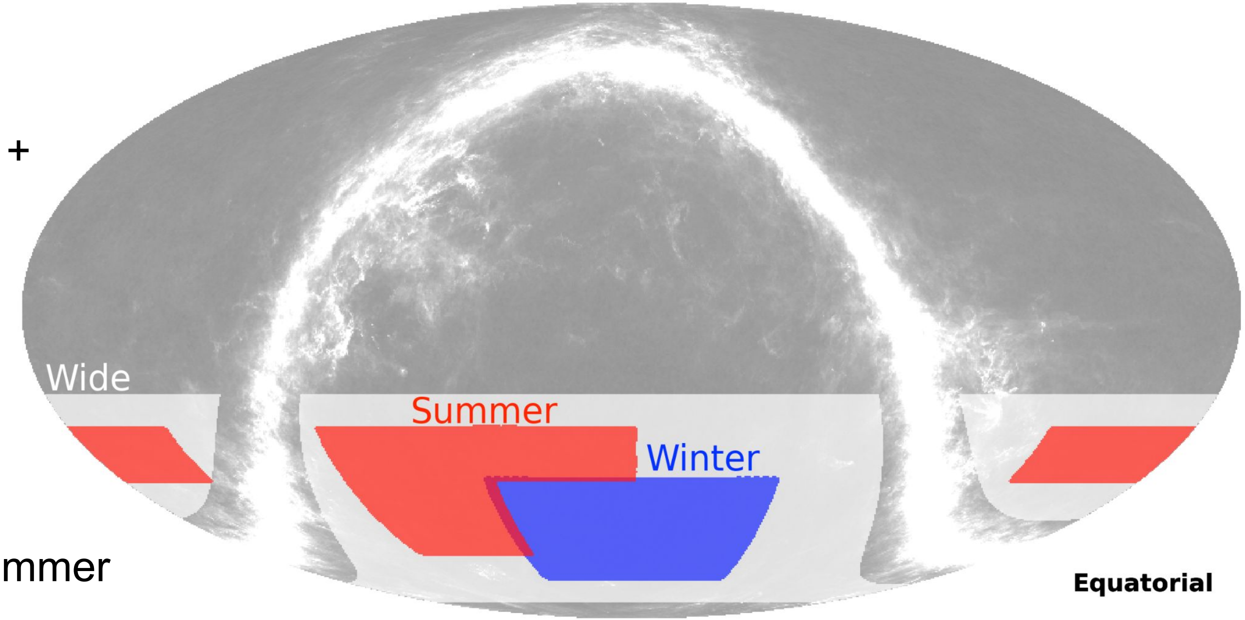


SPT-3G observations

Fields of observation:

- **Winter/Main**
  - 8 months/yr
  - 1 early survey (2018) + 5 nominal surveys + 2 more to come
  - perfect overlap with BK
- **Summer**
  - 4 months/yr
  - 4 nominal surveys
  - **Ext-4K** = Winter + Summer
- **Wide**
  - 1yr (2024)
  - **Ext-10K** = Winter + Summer + Wide

SPT-3G footprint and T Planck 353GHz



SPT Collaboration meeting June 2024

SPT-3G science

- ➔ **ΛCDM constraints** → **TT/TE/EE**, CMB lensing, galaxy clusters, …
- ➔ Inflation → Low-ℓ BB, CMB lensing, …
- ➔ Birefringence → E/B
- ➔ Structure formation → CMB lensing, tSZ, kSZ, …
- ➔ Epoch of Reionization → kSZ, High-ℓ TT, …
- ➔ Extragalactic foregrounds → High-ℓ TT, …
- ➔ ....
- ➔ High redshift astrophysics → mm-wave sources, galaxy clusters, …
- ➔ Solar system science → Asteroids, Planet9, …

Significant improvement to Planck coming from:

- Small angular scales
- Polarization
- Lensing

SPT-3G Cosmology

Past, Present (upcoming), Future

Credit Kevin Zagorski, March 2024

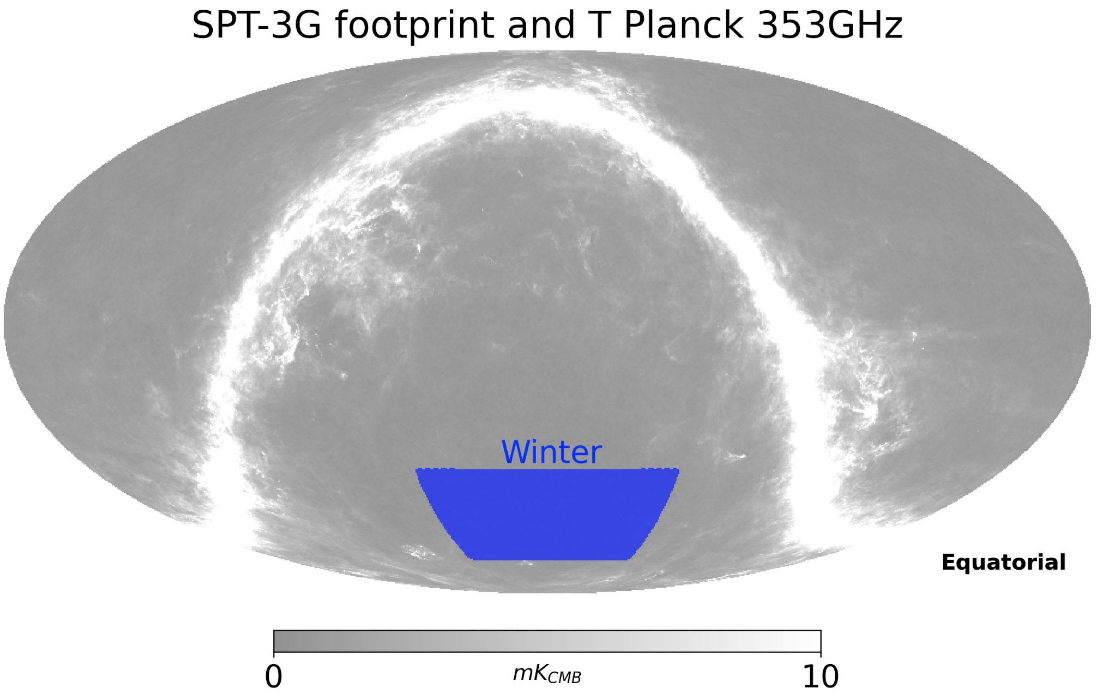
SPT-3G 2018

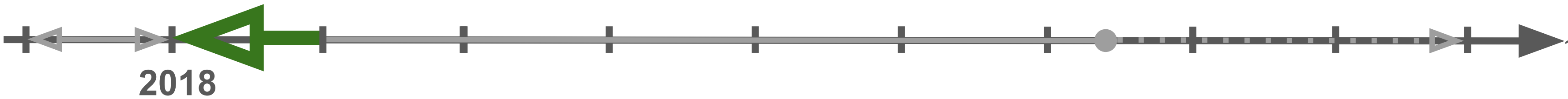
Field:
- **Winter**

Noise levels:
(at 90, 150, 220 GHz, T):
- **21, 15, 53** μK-arcmin

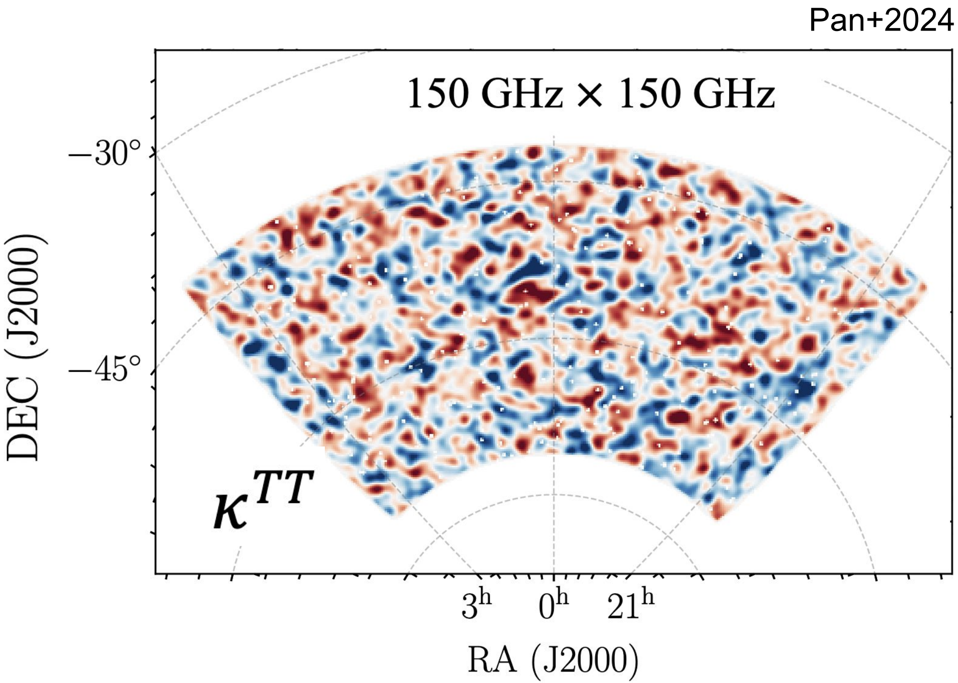
Covered sky fraction:
- **4%** (1500 deg2)

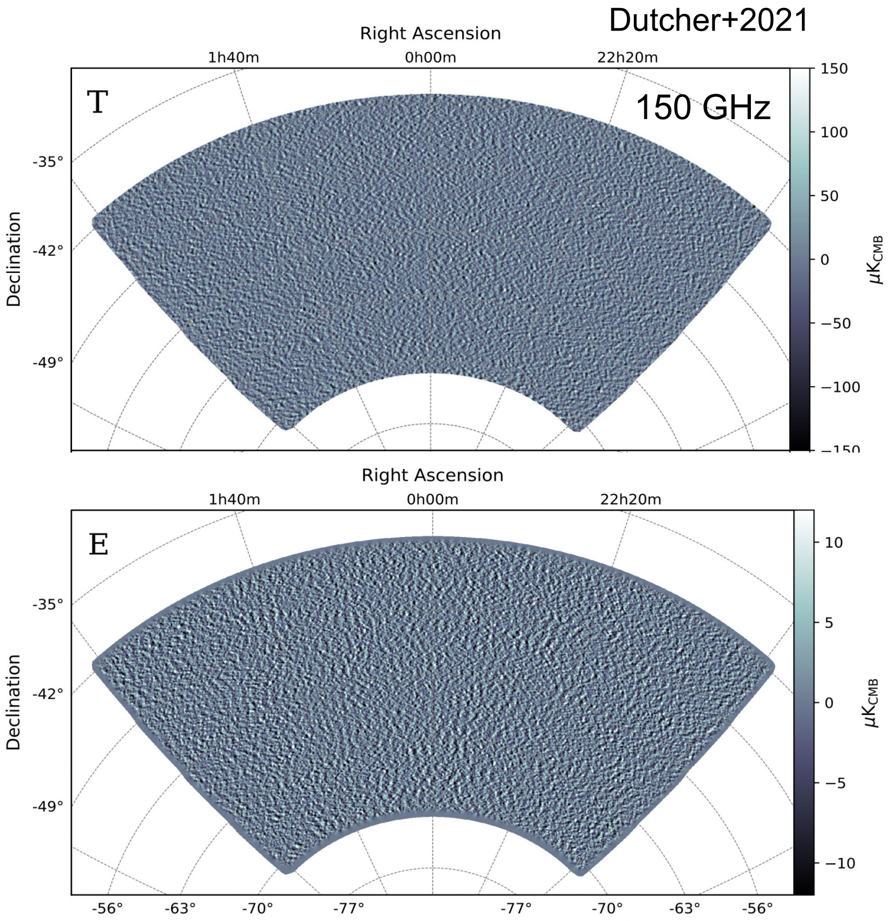
Results:
- Maps, TE/EE bandpowers, ΛCDM. Dutcher et al. 2021 (arXiv:2101.01684)
- ΛCDM Extensions from TE/EE, Balkenhol et al. 2021 (arXiv:2103.13618)
- Full TT/TE/EE release, Balkenhol et al. 2023 (arXiv:2212.05642)
- CMB lensing, Pan et al. 2024 (arXiv:2308.11608)

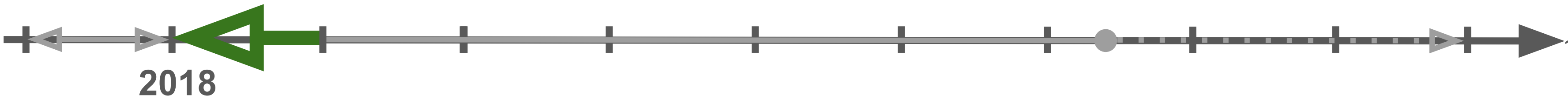




SPT-3G 2018


Pan+2024
150 GHz × 150 GHz
−30°
−45°
DEC (J2000)
κ^{TT}
3h 0h 21h
RA (J2000)

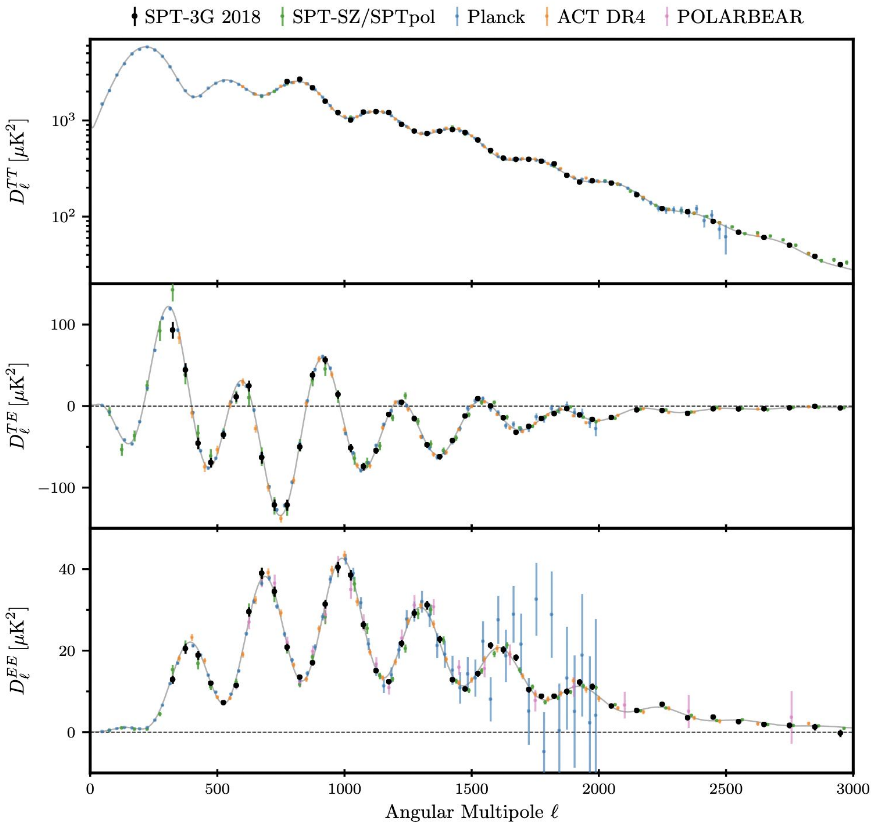

Dutcher+2021
Right Ascension
1h40m
0h00m
22h20m
T
150 GHz
-35°
-42°
-49°
Declination
150
100
50
0
−50
−100
μK_{CMB}
E
10
5
0
−5
−10
-56° -63° -70° -77° -77° -70° -63° -56°


2018

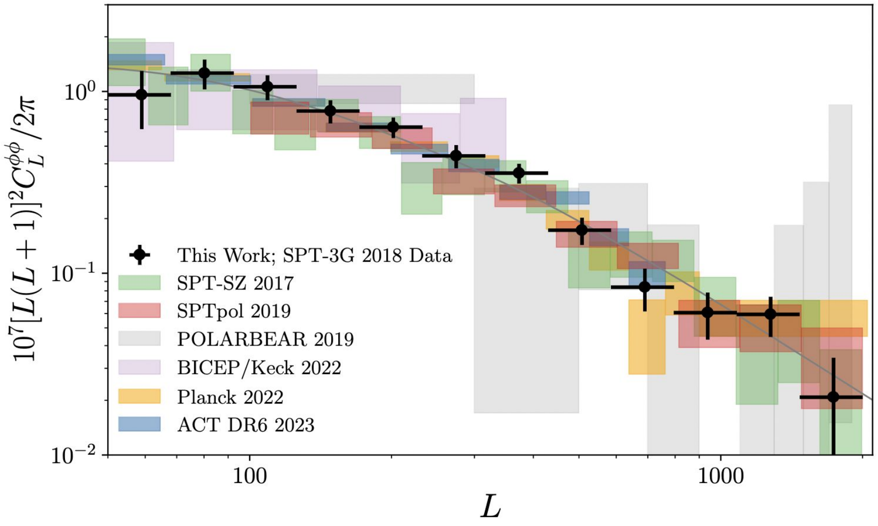
SPT-3G 2018

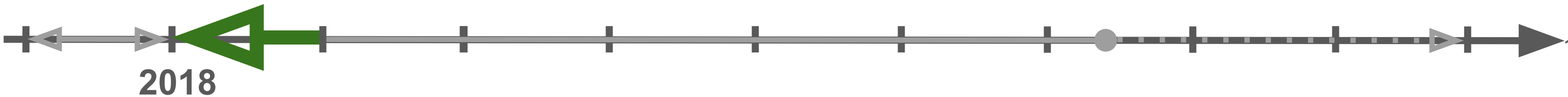
1. CMB primary TT/TE/EE
2. CMB lensing

Balkenhol+2023



Pan+2024





SPT-3G 2018 results

1. CMB primary TT/TE/EE
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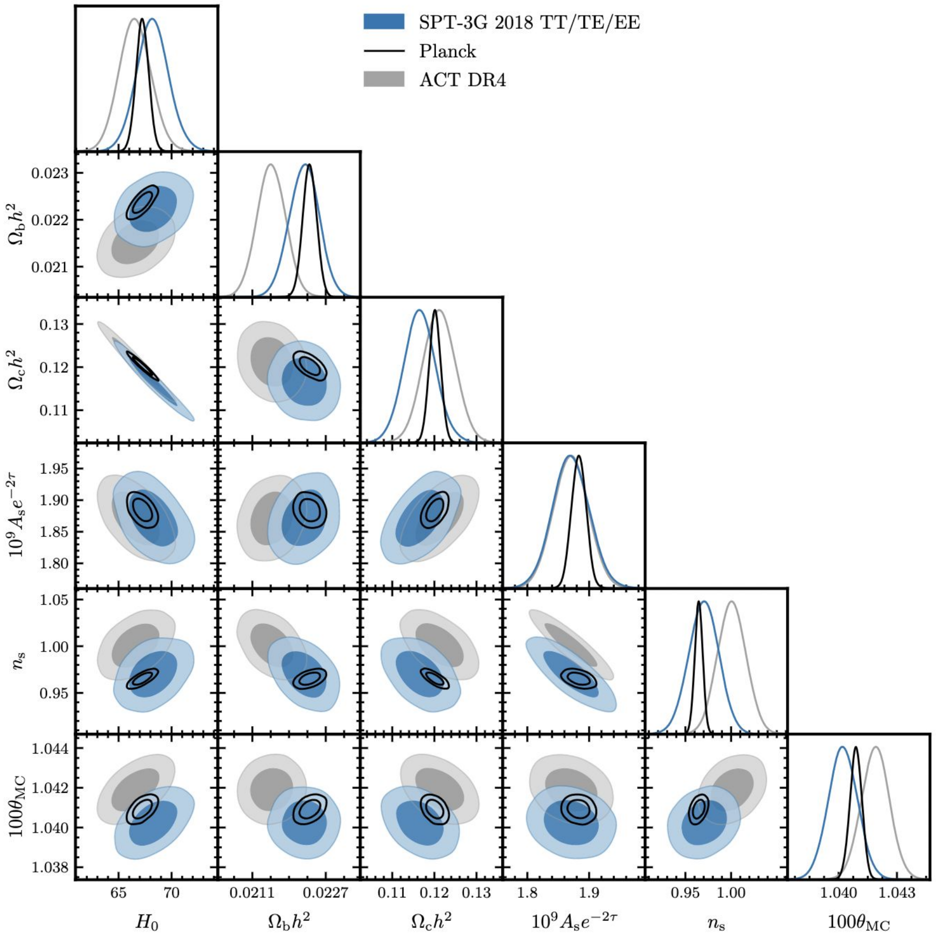
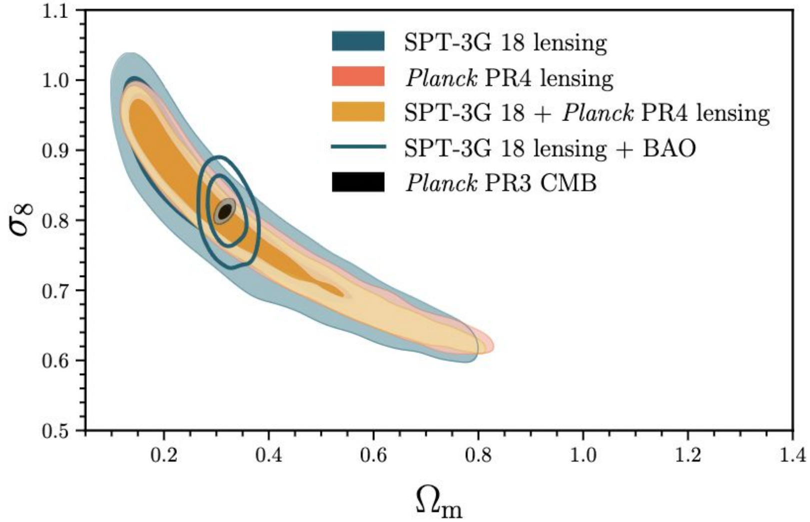
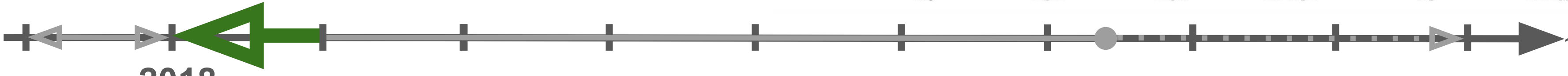


Pan+2024





SPT-3G Cosmology

Present (upcoming)

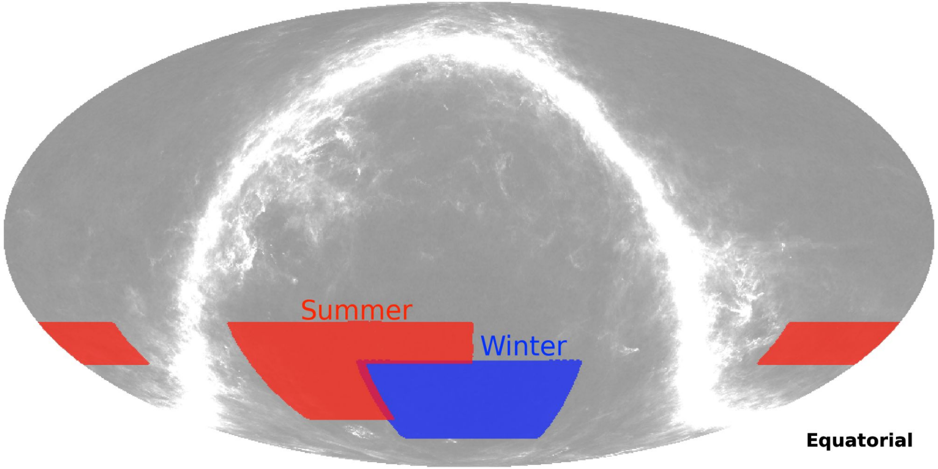
Credit Kevin Zagorski, March 2024

SPT-3G 2019/20

Fields:

- **Winter**: deep but small
  → very sensitive at intermediate & high-ℓ
- **Summer**: shallow but wide
  → gives access to large scales
  reducing sample variance
- **Ext-4k** = Winter+Summer
  → constraints nearing Planck's precision
  → powerful to test extended models

SPT-3G footprint and T Planck 353GHz

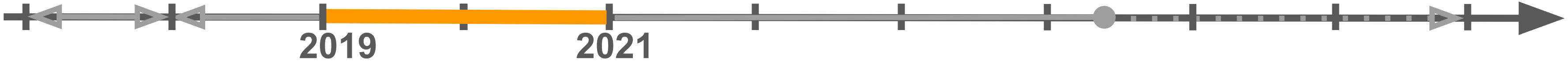


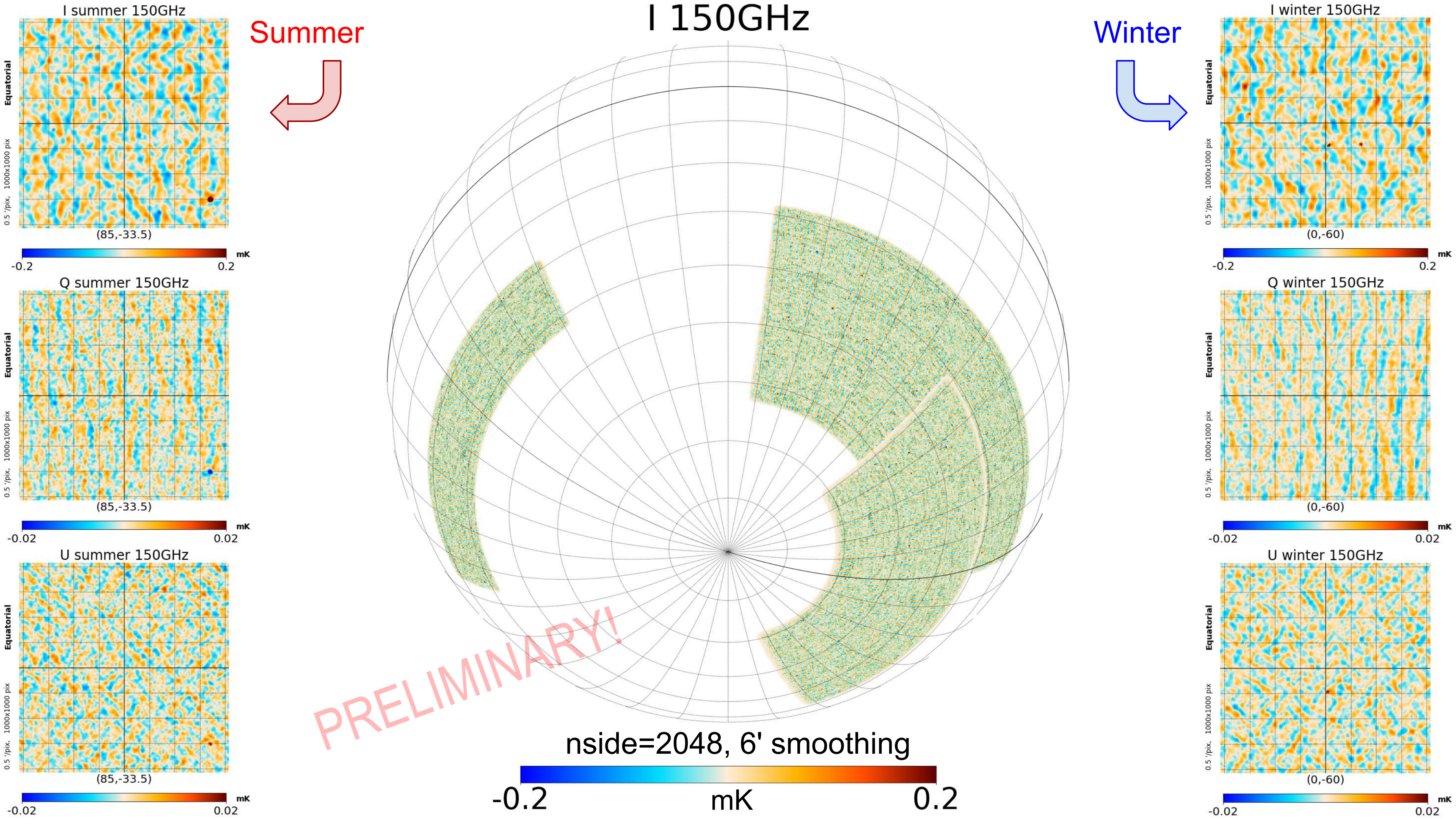
Noise levels (at 90, 150, 220 GHz):

- **6, 5, 16** μK-arcmin
- **14, 13, 42** μK-arcmin

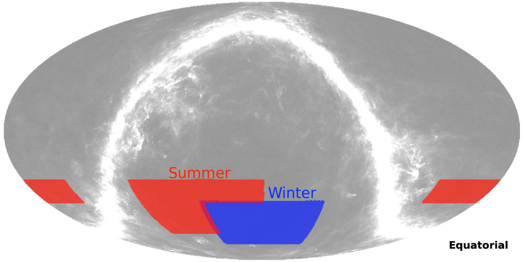
Sky fraction:

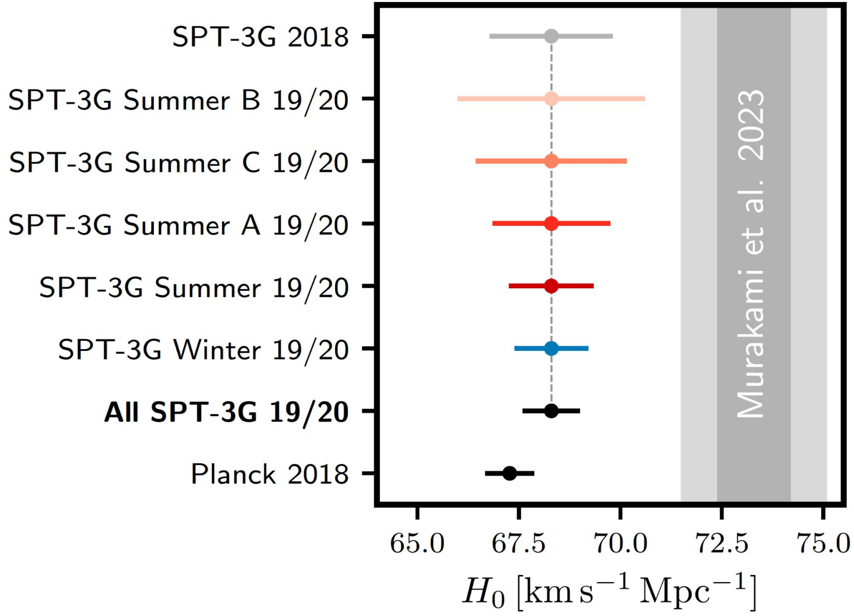
- **4%** (1650 deg2)
- **6.6%** (2800 deg2)




I 150GHz
Summer
Winter
I summer 150GHz
Q summer 150GHz
U summer 150GHz
I winter 150GHz
Q winter 150GHz
U winter 150GHz
Equatorial
0.5 '/pix, 1000x1000 pix
(85,-33.5)
(0,-60)
-0.2
0.2
-0.02
0.02
mK
PRELIMINARY!
nside=2048, 6' smoothing
-0.2
mK
0.2

SPT-3G 2019/20: ΛCDM forecasts



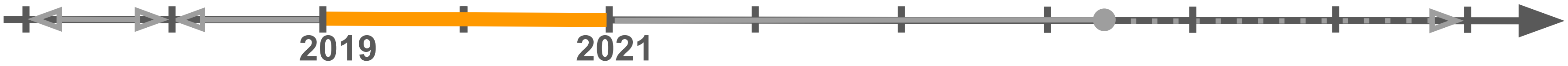


PRELIMINARY!

σ(H_0) [Km/s/Mpc] TT/TE/EE angular power spectra (ΛCDM)		
Planck	SPT-3G Winter	SPT-3G Summer
0.6	**0.9**	**1.0**
	0.7	
0.43		

Forecasts by L. Balkenhol and S.Raghunathan

Additional 30–40% improvement of the SPT-3G constraints when including the SPT-3G lensing information (TT/TE/EE+ϕϕ)



Many independent pipelines

Primary CMB TT/TE/EE

- Cross-bundles approach for unbiased power spectra
- **Analytic covariance** (Camphuis et al. arXiv:2204.13721)
- **Fast end-to-end simulations** (Quickmock) (Hivon et al., in preparation)
- **Inpainting** at the location of point sources and galaxy clusters (Camphuis, Benabed, et al. in prep.)
- **Differentiable likelihood** (`candl`, Balkenhol et al. arXiv:2401.13433) that allows us to:
    - Assess the impact on parameters of potential systematics
    - Perform lots of internal consistency test

(Winter: Camphuis, Quan et al in prep; Summer: Guidi et al in prep; Wide: Fichman, Vitrier et al in prep)

CMB Lensing

- Flat-sky QE (Daley et al. in prep)
- Curved-sky QE (Winter: Omori et al. in prep, Summer: Levy et al. in prep)

Primary and Lensing combined (MUSE bayesian approach, Millea and Seljak 2021, arXiv:2112.09354)

- EE+$\phi\phi$ (Ge et al in prep)
- +T (Doohan et al in prep)

SPT-3G Cosmology

Future

Credit Kevin Zagorski, March 2024

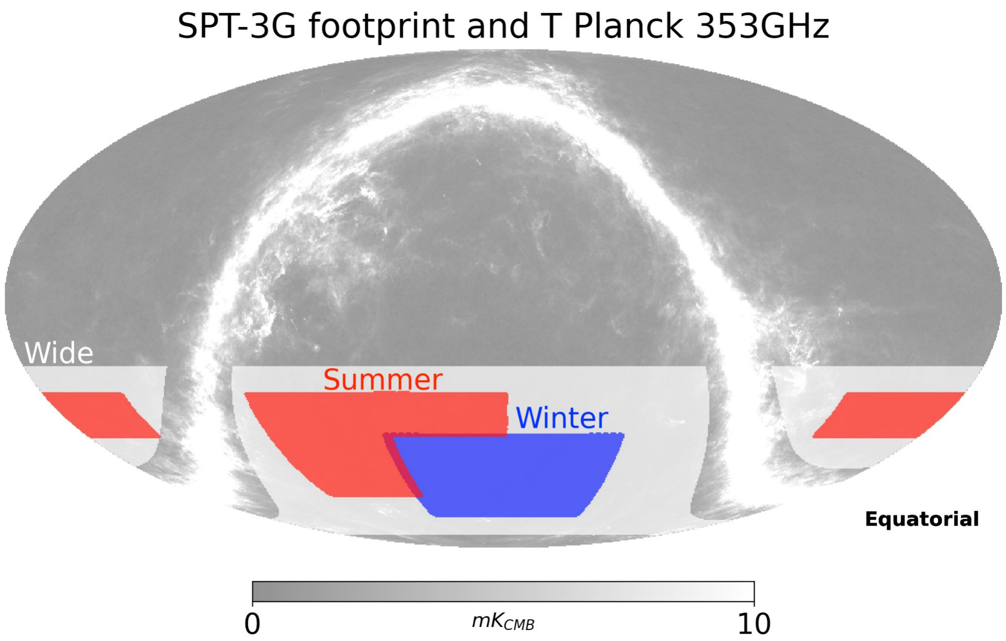
Final SPT-3G survey: Ext-10K

Ext-10K = Winter+Summer+Wide

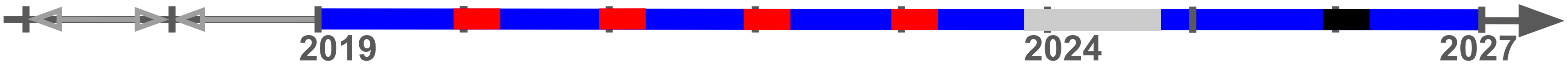
- Wide field **FINISHED**!
- -80°< declination < -20°
- Excluding Galaxy
- Total covered sky fraction ~25%

Target noise levels
(at 90, 150, 220 GHz):

- **2.5, 2.1, 7.6** μK-arcmin in 7 years
- **10, 9, 30** μK-arcmin in 4 years
- **14, 12, 42** μK-arcmin in 1 year



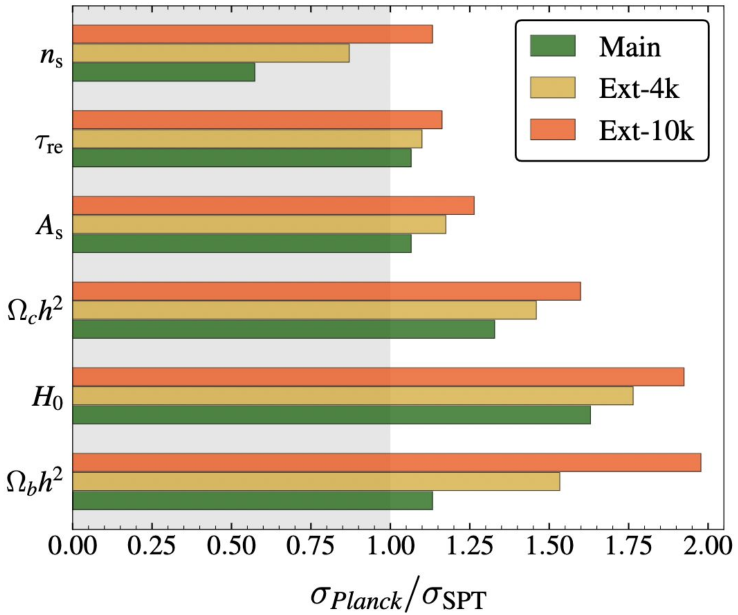
Low noise and low sample variance thanks to the increased f_{sky}



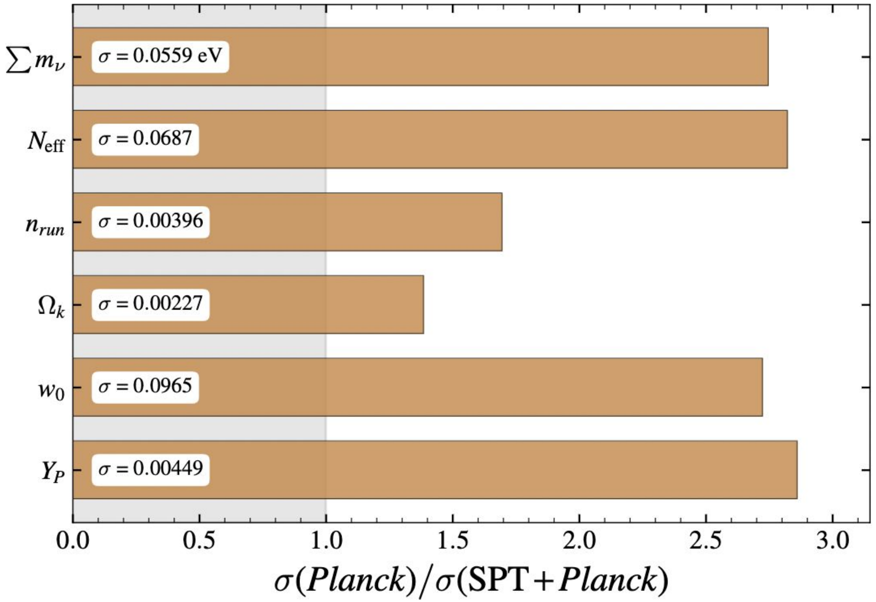
Prabhu et al., arXiv:2403.17925

Ext-10K forecasts: TT/TE/EE+ϕϕ

ΛCDM



Extension of ΛCDM

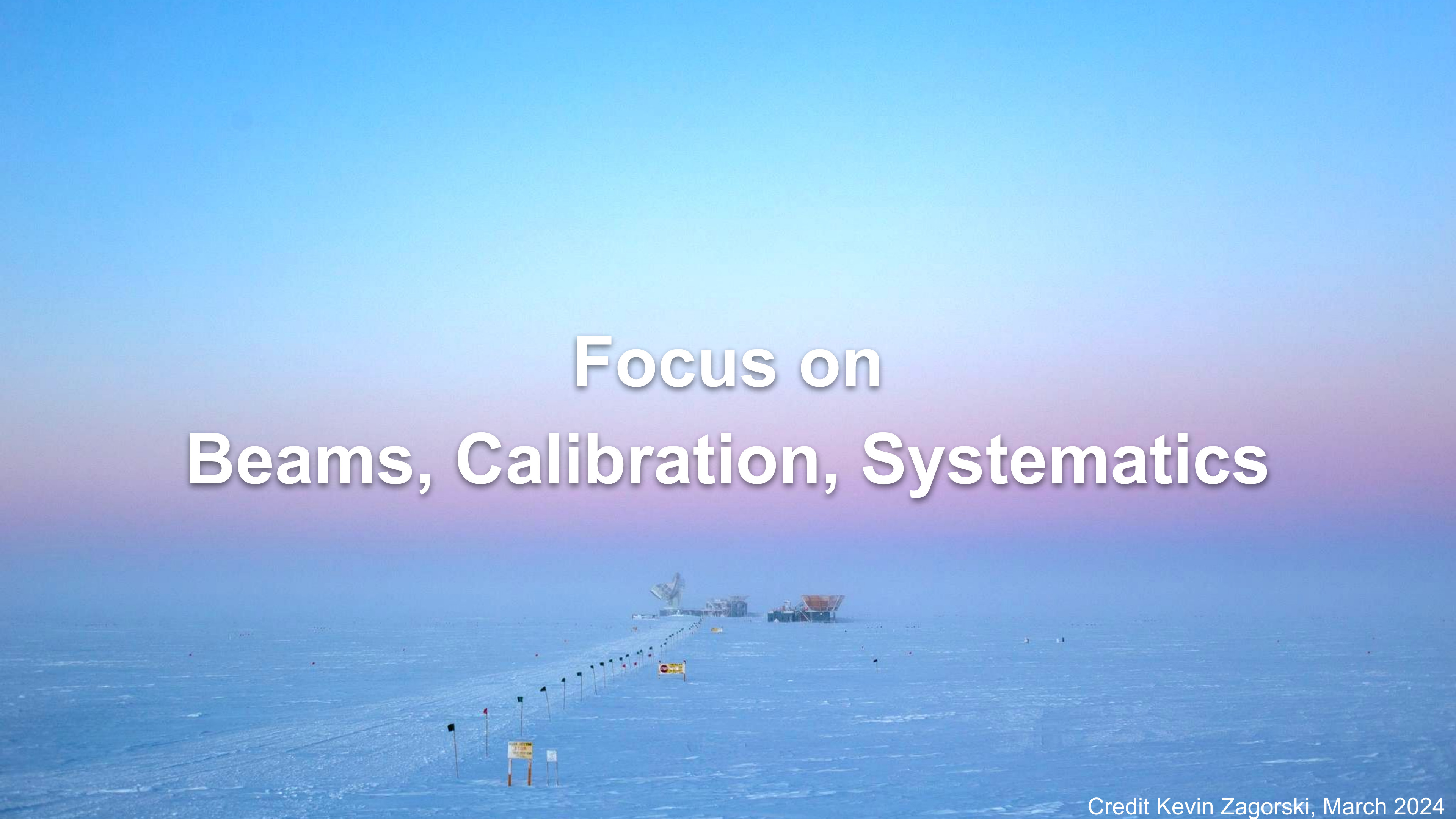


Gain in cosmological parameters constraints up to:

x2 in ΛCDM

x3 in extended ΛCDM

Focus on
Beams, Calibration, Systematics

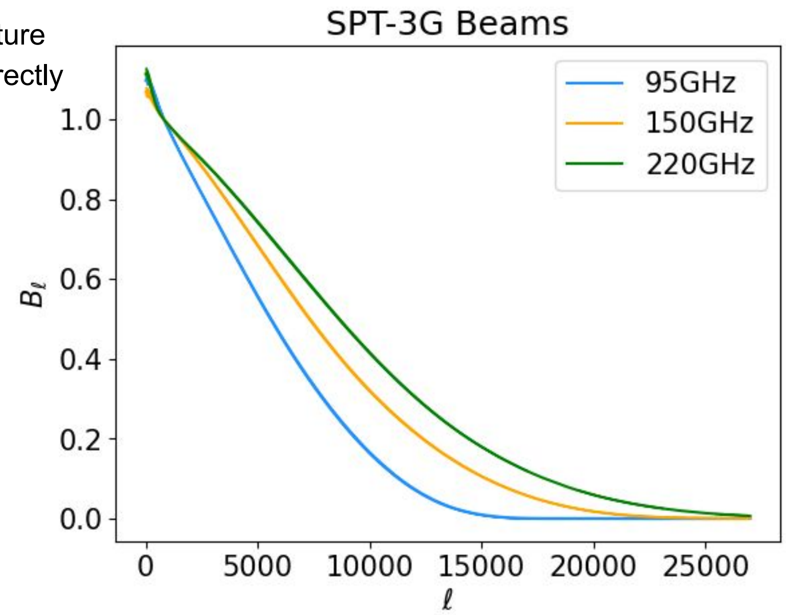


Credit Kevin Zagorski, March 2024

Huang et al., in prep

Beams: temperature

- Stitching observations of Saturn and bright point sources (AGNs)
  - Outer beam: Saturn observations
    - Pro: high signal-to-noise to resolve the extended beam structure
    - Cons: detectors non-linearity and saturation when pointed directly at the planet. Approaching-only scans used.
  - Inner beam: bright point sources in the CMB field
    - Pro: detectors in linear regime, not saturated
    - Cons: insufficient to resolve the extended beam structure
- Challenges:
  - Stitching radius
  - Time constants:
    - Different scan speed in Saturn and sources observations
    - Different in the various CMB fields
  - Astrophysical backgrounds in the AGN maps
  - Frequency dependence
    - Conversion of the AGN/planet beam to a beam appropriate for the CMB spectrum
- Beam normalization at ell 800 to decouple with absolute calibration
- Covariance matrix: cross spectrum estimation (as described in Lueker 2010) + systematics
- At likelihood level: beam eigenmodes free to vary within the covmat



Beams: polarization

- Lack of bright polarized sources observed deeply to map the polarized beams
- We expect some deviation from the temperature beam if the sidelobes are polarized differently from the main beam
    - polarization beams = 100% polarized main central beam +
      X(<100)% polarized diffuse beam sidelobe
      due to diffraction and scattering
- Fit the sidelobes amplitude parameter $\beta_{\rm pol}(\nu)$ at the likelihood level
    - β = 1 if 100% polarization of the sidelobe
    - 0< β < 1 sidelobes not fully polarized
- Thinking at how we can measure more directly our polarized beam

$$\mathbb{B}^{\nu}_{P}(\beta_i, \beta^{\nu}_{\rm pol}) = \mathbb{B}^{\nu}_{\rm main} + \beta^{\nu}_{\rm pol}(\mathbb{B}^{\nu}_{T}(\beta_i) - \mathbb{B}^{\nu}_{\rm main})$$

Central beam physical model fit at θ <0.75' (primary illumination, diffraction and frequency dependence)

\-

Measured T beam

=

Sidelobes

Calibration: raw data temperature calibration

- **Power to temperature conversion**
  - Long HII regions observations (1h20min, once per week) so that every detectors sees the source
    - RCW38, MAT5A, IRAS17258, SgrB2, W28A2
    - Fluxes based on Planck-calibrated SPT-SZ maps
- **Correction for changing atmospheric opacity**
  - Quick observation of the HII region (ten minutes, before and after the CMB scans)
- **Correction for changing detector responsivity**
  - Observations of the artificial "calibrator", with the telescope pointed at different elevations, chopped at a certain frequency, for about 1 min
    - "Calibrator" = thermal source (1000K) at the center of the secondary mirror
  - Remaining ~5% cal drift across the subfields

⟶ Relative calibration of subfields

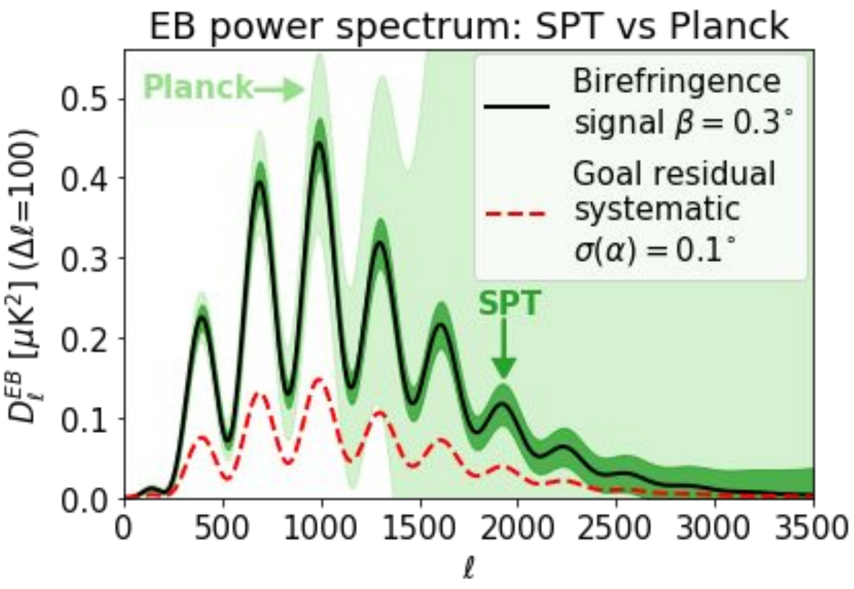
Calibration and systematics: CMB maps

- **Temperature calibration** (Tcal)
  - <u>External</u>: SPT150 vs Planck143
    - Subfield-based
    - ≲3% recalibration ~0.2% uncertainty
  - <u>Internal</u>: SPT90 and SPT220 vs SPT150
    - Subfield-based
    - ≲8(2)% recalibration ≲0.2(1.0)% uncertainty at 90(220)
- **Temperature-to-Polarization leakage correction**
  - Monopole
    - Field or subfield-based
    - Fit the amount of TT and T(Q/U) in QQ and UU
    - ~0.1% recalibration ~0.01%
  - Higher orders
    - At the likelihood level (currently under investigation)
- **Polarization angle: EB de-rotation**
  - 0.05°–0.10° uncertainty
- **Polarization efficiency** (Pcal)
  - <u>External</u> field-based: ~10% recalibration ~1% uncertainty
  - <u>Internal</u> field-based: ~0.1(10)% recalibration ~0.2(0.7)% uncertainty at 90(220)

- **At likelihood level:**
  - Tcal Pcal free to vary
  - Prior width accounts for:
    - SPT cal. uncertainties
    - Planck's 143 cal. uncertainty
      - Tcal:0.0025
      - Pcal:0.00509

Polarization angle calibration: future prospects

- See A. Foster talk on Tuesday 13:00!
- So far, we have applied EB de-rotation (0.05°–0.10° deg uncertainty)
- Calibration of polarization angle:
  a. Cross-calibration with BK?
     Target $\sigma(\alpha)$=0.1°, but maybe we can do even better! Let's see at the end of this week…
  b. Polarized atmosphere?
     Coerver+2024
  c. Galactic foregrounds?
     Minami+2020, Diego-Palazuelos+2022, …



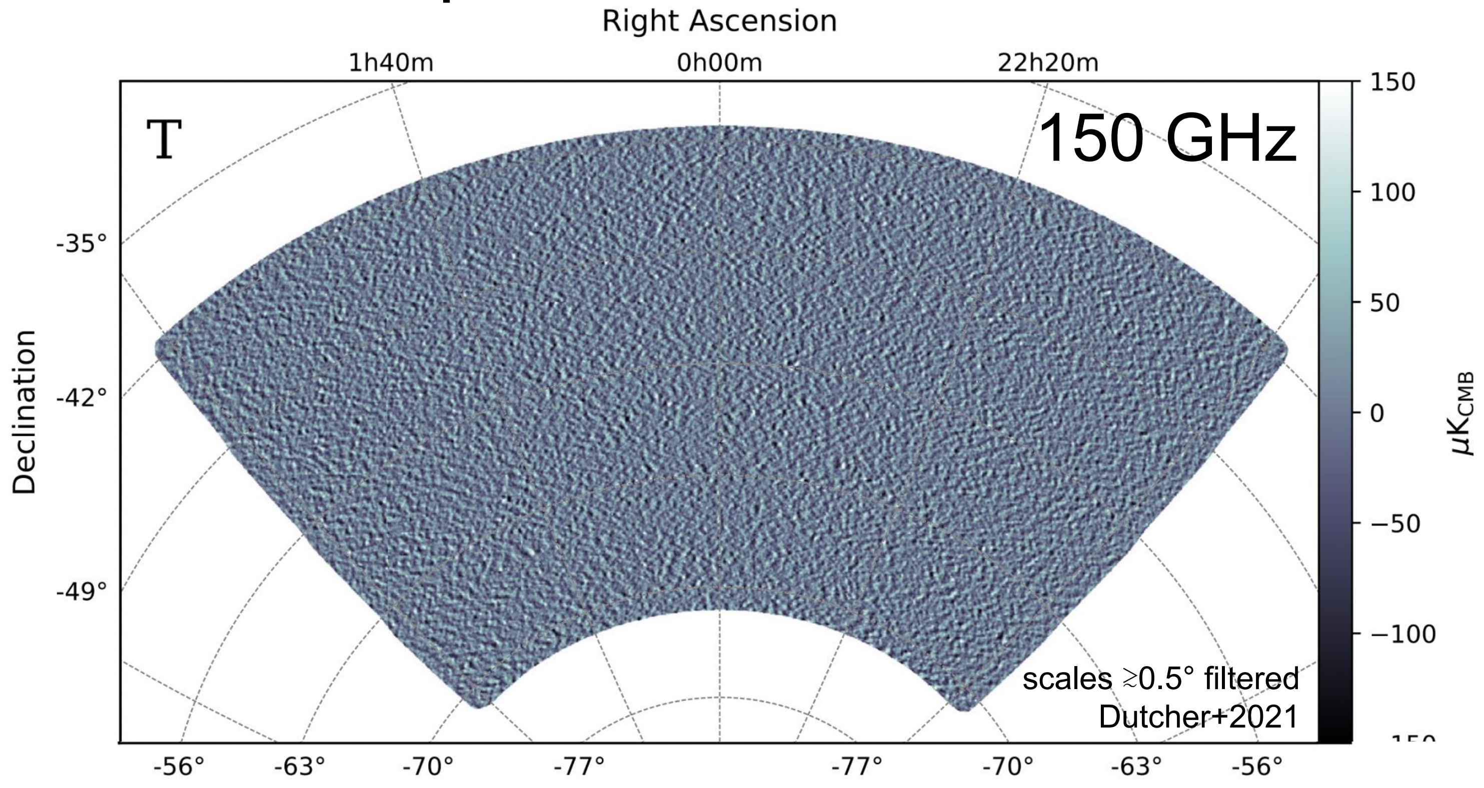
Conclusions

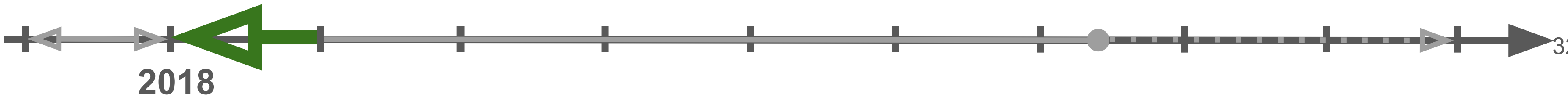
- SPT-3G is providing a **powerful dataset to test cosmology with the CMB**
  - Almost **independently from Planck,** in a **complementary** range of multipoles (low:Planck, intermediate–high: SPT)
  - Reaching Planck's constraining power very soon
  - Going **beyond Planck**'s constraining power by a factor~2 with Ext-10k
- We are **learning lots of lessons** to use the fantastic SPT-3G constraining power
  - Current main limitations: polarized beams, high order T2P leakage, …
- **Absolute calibration** still depends from Planck. Can we be more independent?
- Need to develop methodology to **calibrate the polarization angle** to have access to EB

Credit Josh Veitch-Michaelis, March 2024

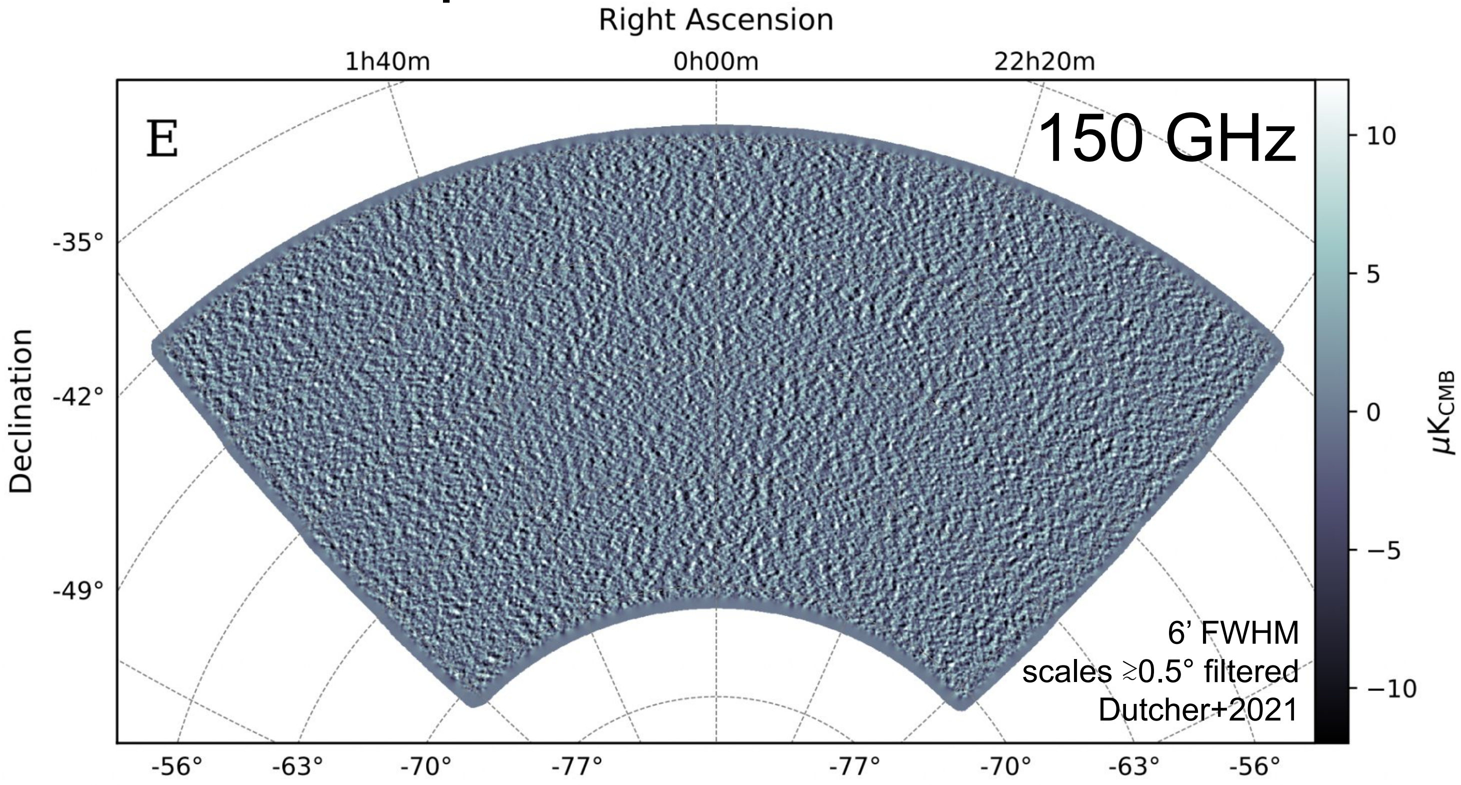
Backup

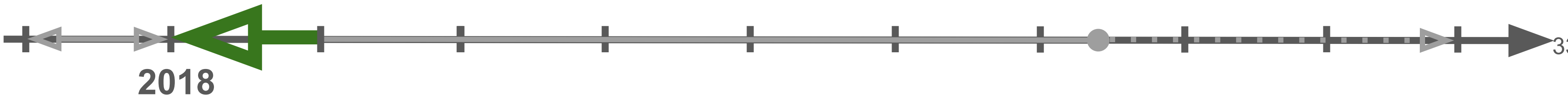
SPT-3G 2018 maps



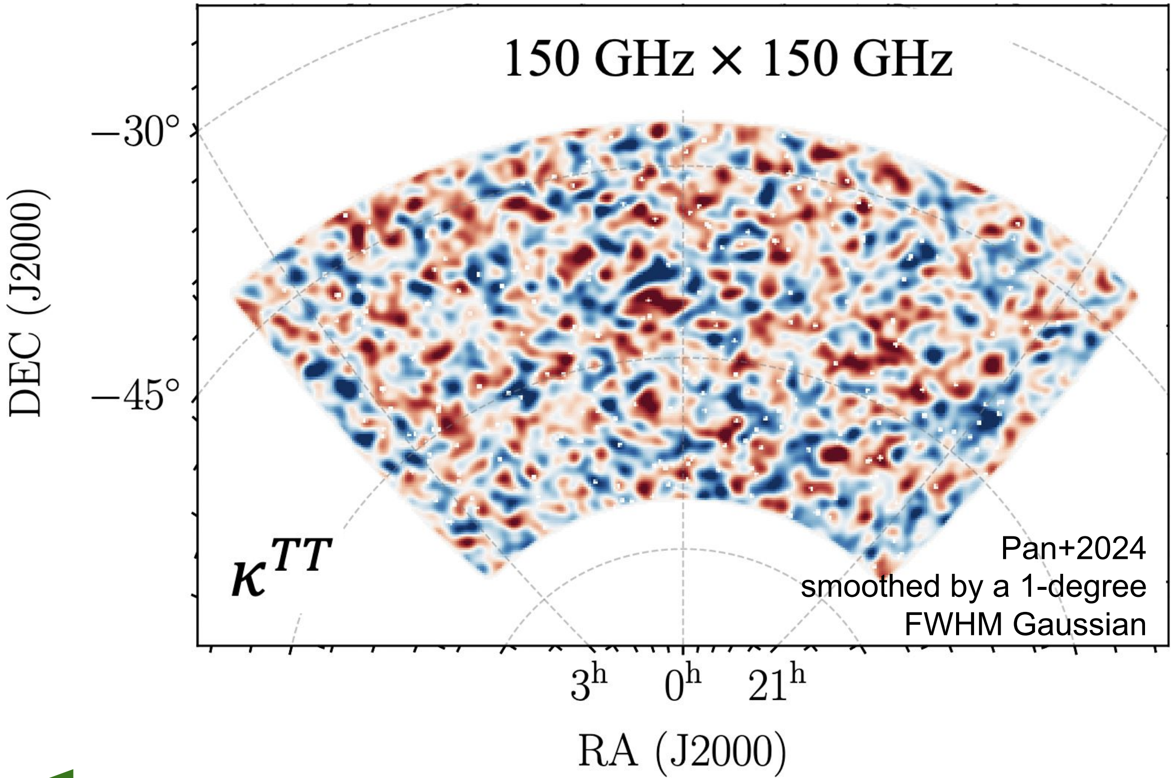


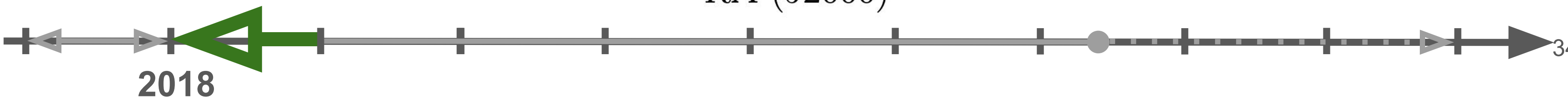
SPT-3G 2018 maps



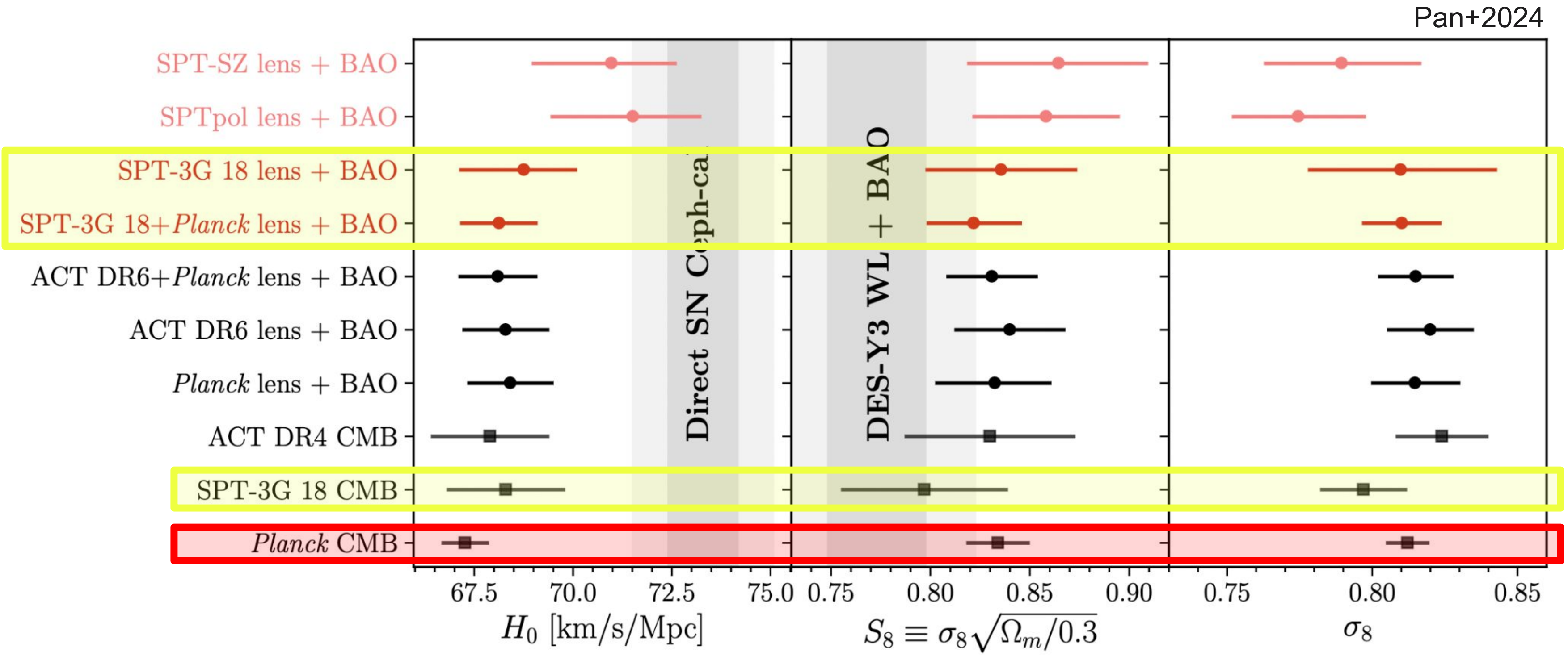


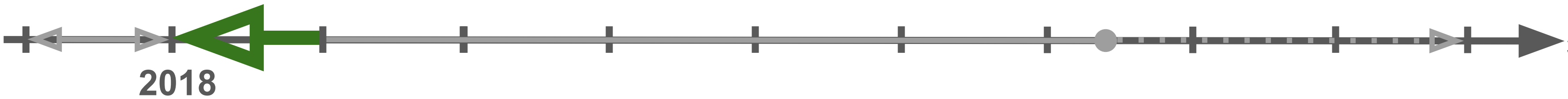
SPT-3G 2018 maps





SPT-3G 2018 results





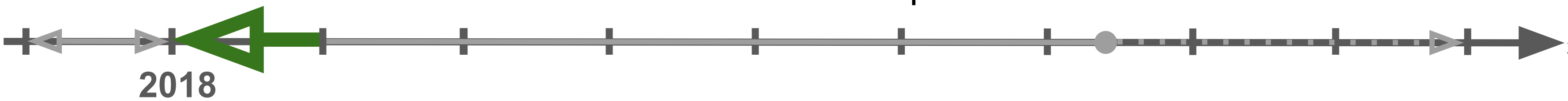
SPT-3G 2018 results

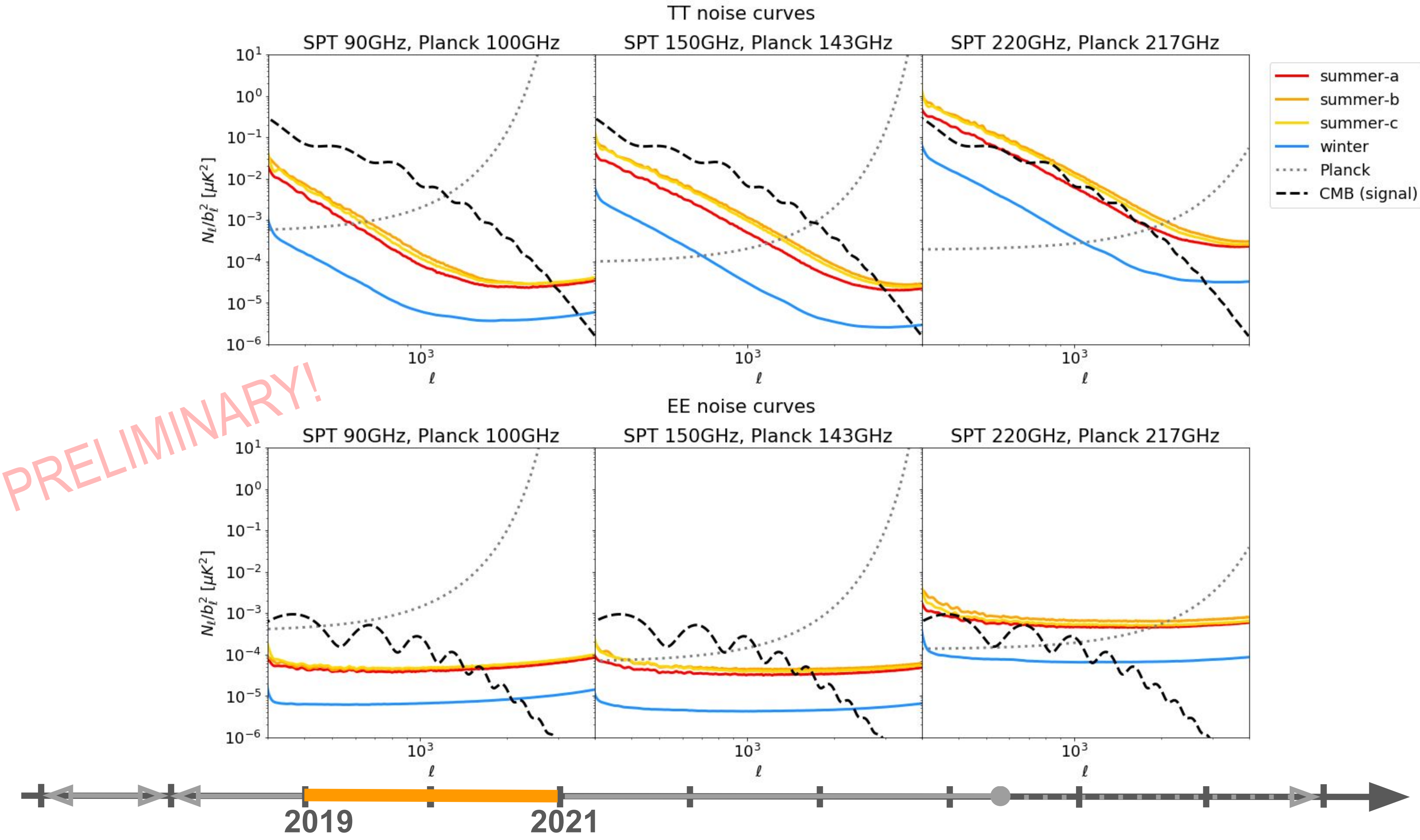
Lensing (arXiv:2308.11608)

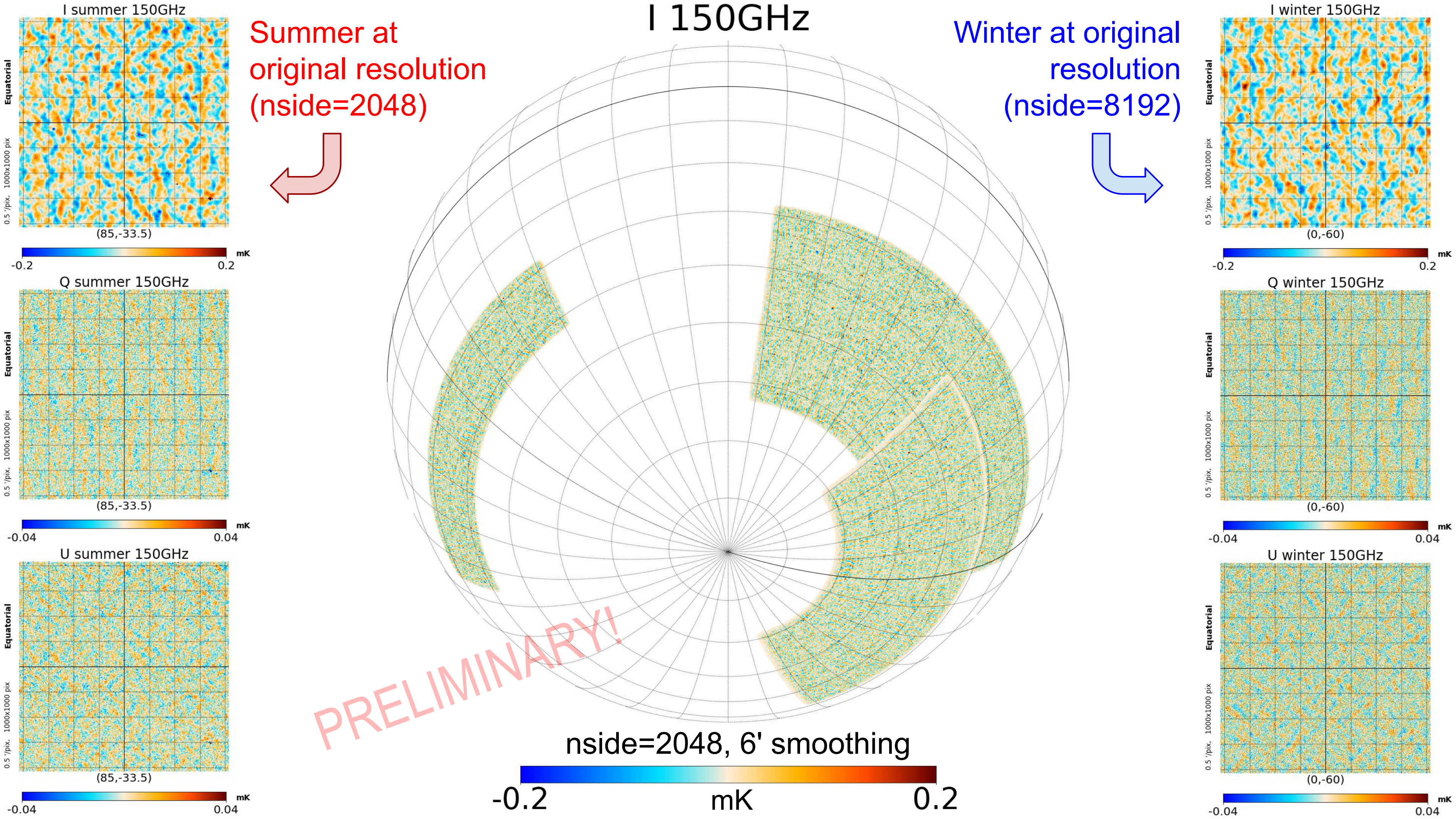
- Very good consistency with **ΛCDM**
- **Ω_m–σ_8** consistent with Planck
  - **$\sigma_8\Omega_m^{0.25}$** consistent with other CMB lensing measurements and with Planck 's primary CMB anisotropy
- **Lensing amplitude A_L**
  - consistent with 1
  - compatible with ACT and Planck
- **H_0 and S_8** consistent with the cosmology inferred from Planck primary CMB measurements

Primary CMB TT/TE/EE (arXiv:2212.05642)

- Very good consistency with
  - **ΛCDM** (deviations < 1σ)
  - **Planck,** although largely **independent**
  - **ACT** (DR4), with **similar constraining power**
- **Hubble constant (H_0)** is as low as other CMB measurements
  - ~5σ tension with cepheid-calibrated local distance ladder measurements (Khalife+2024, arxiv:2312.09814)
- **Structure growth parameter (S8)** compatible with both low-z data and Planck

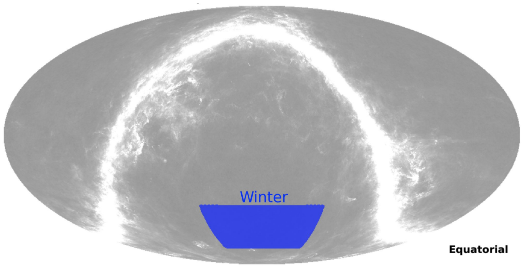


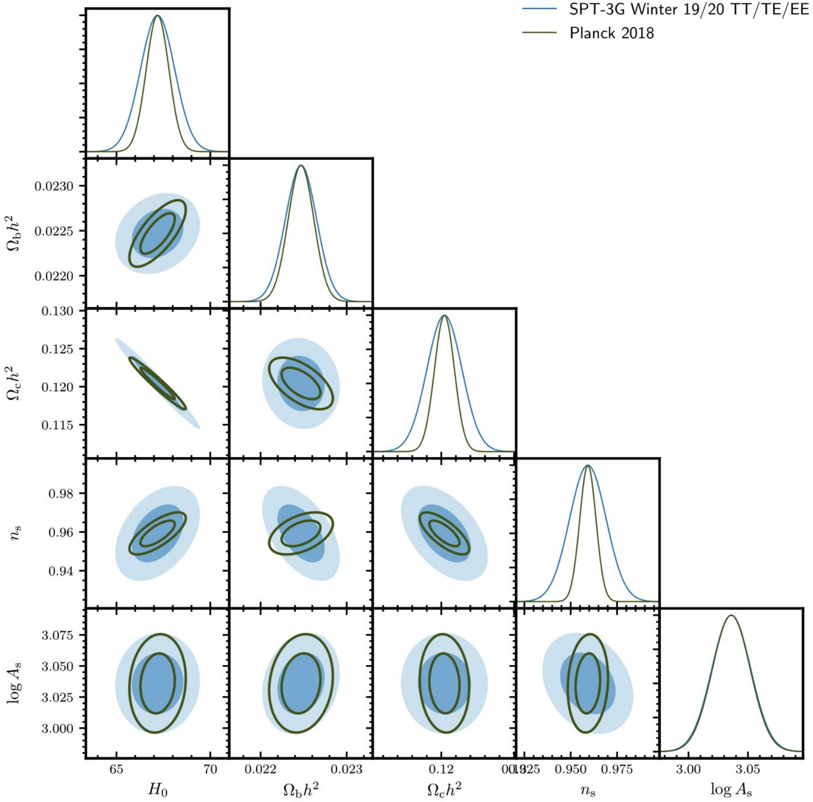

TT noise curves
SPT 90GHz, Planck 100GHz
SPT 150GHz, Planck 143GHz
SPT 220GHz, Planck 217GHz
N_ℓ/b_ℓ^2 [μK^2]
ℓ
summer-a
summer-b
summer-c
winter
Planck
CMB (signal)
PRELIMINARY!
EE noise curves
SPT 90GHz, Planck 100GHz
SPT 150GHz, Planck 143GHz
SPT 220GHz, Planck 217GHz
N_ℓ/b_ℓ^2 [μK^2]
ℓ
2019
2021



I 150GHz
Summer at original resolution (nside=2048)
Winter at original resolution (nside=8192)
I summer 150GHz
Equatorial
0.5 '/pix, 1000x1000 pix
(85,-33.5)
-0.2
0.2
mK
Q summer 150GHz
(85,-33.5)
-0.04
0.04
mK
U summer 150GHz
(85,-33.5)
-0.04
0.04
mK
I winter 150GHz
(0,-60)
-0.2
0.2
mK
Q winter 150GHz
(0,-60)
-0.04
0.04
mK
U winter 150GHz
(0,-60)
-0.04
0.04
mK
PRELIMINARY!
nside=2048, 6' smoothing
-0.2
mK
0.2

SPT-3G 2019/20: ΛCDM forecasts

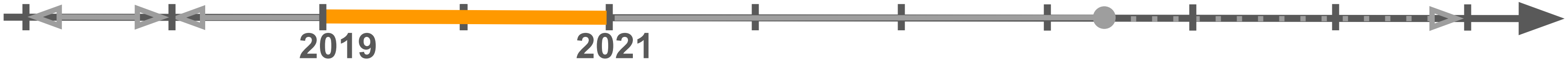




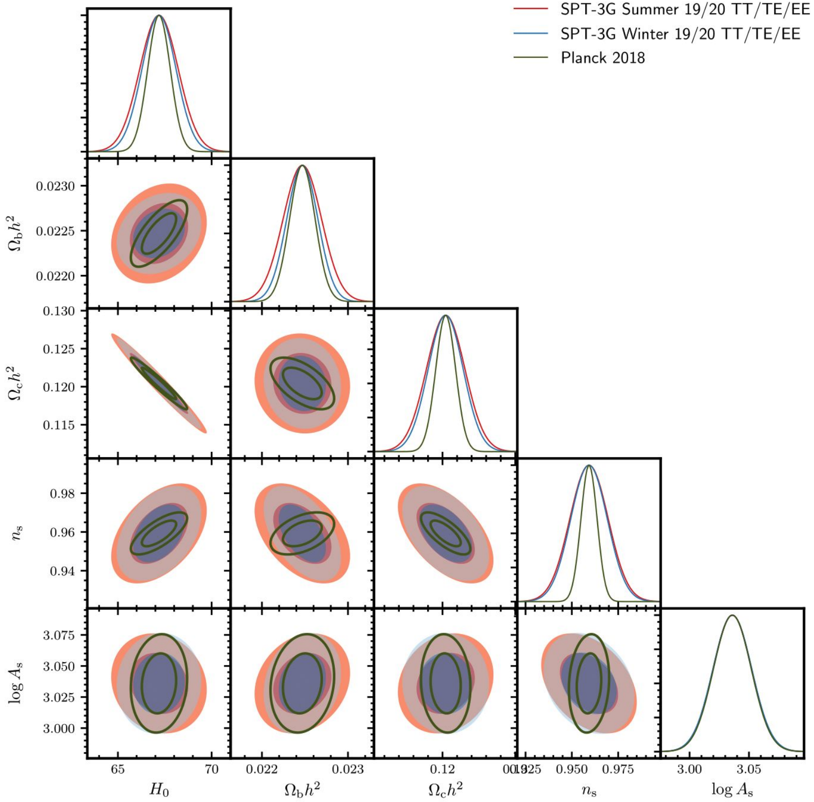
PRELIMINARY!

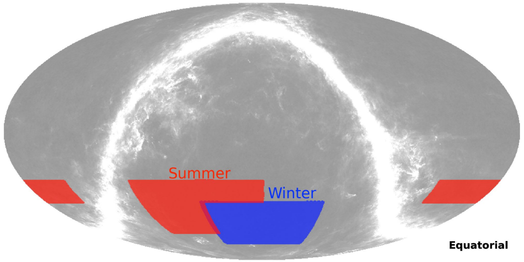
$\sigma(H_0)$ [Km/s/Mpc] TT/TE/EE angular power spectra (ΛCDM)		
Planck	SPT-3G Winter	SPT-3G Summer
0.6	**0.9**	

Forecasts by L. Balkenhol and S.Raghunathan



SPT-3G 2019/20: ΛCDM forecasts

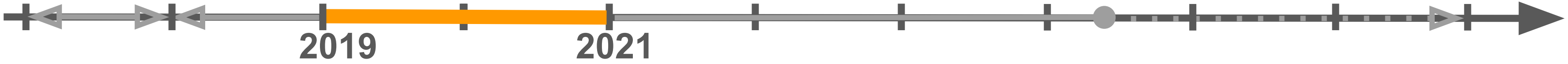




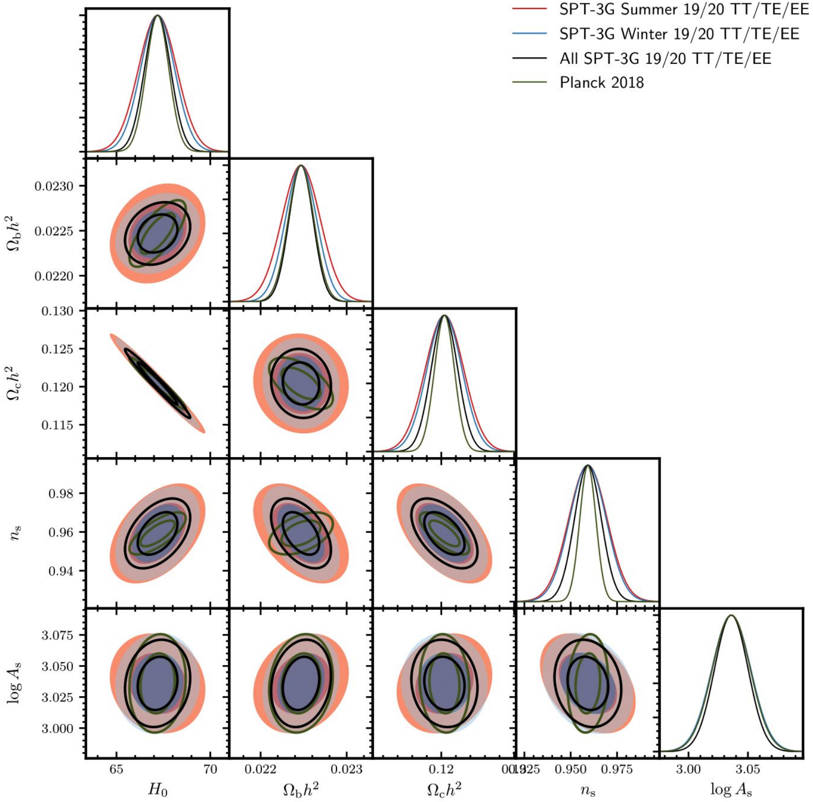
PRELIMINARY!

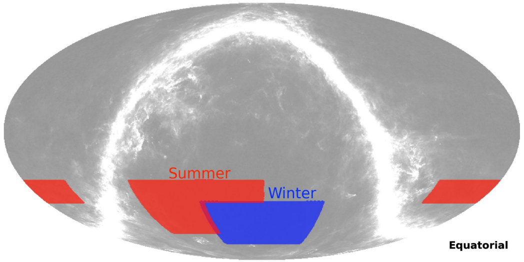
σ(H_0) [Km/s/Mpc] TT/TE/EE angular power spectra (ΛCDM)		
Planck	SPT-3G Winter	SPT-3G Summer
0.6	**0.9**	**1.0**

Forecasts by L. Balkenhol and S.Raghunathan



SPT-3G 2019/20: ΛCDM forecasts



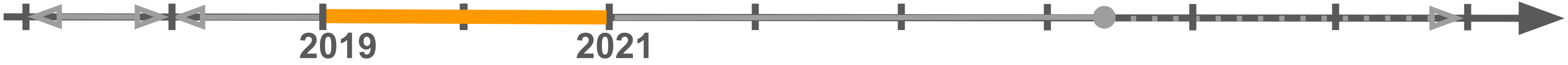


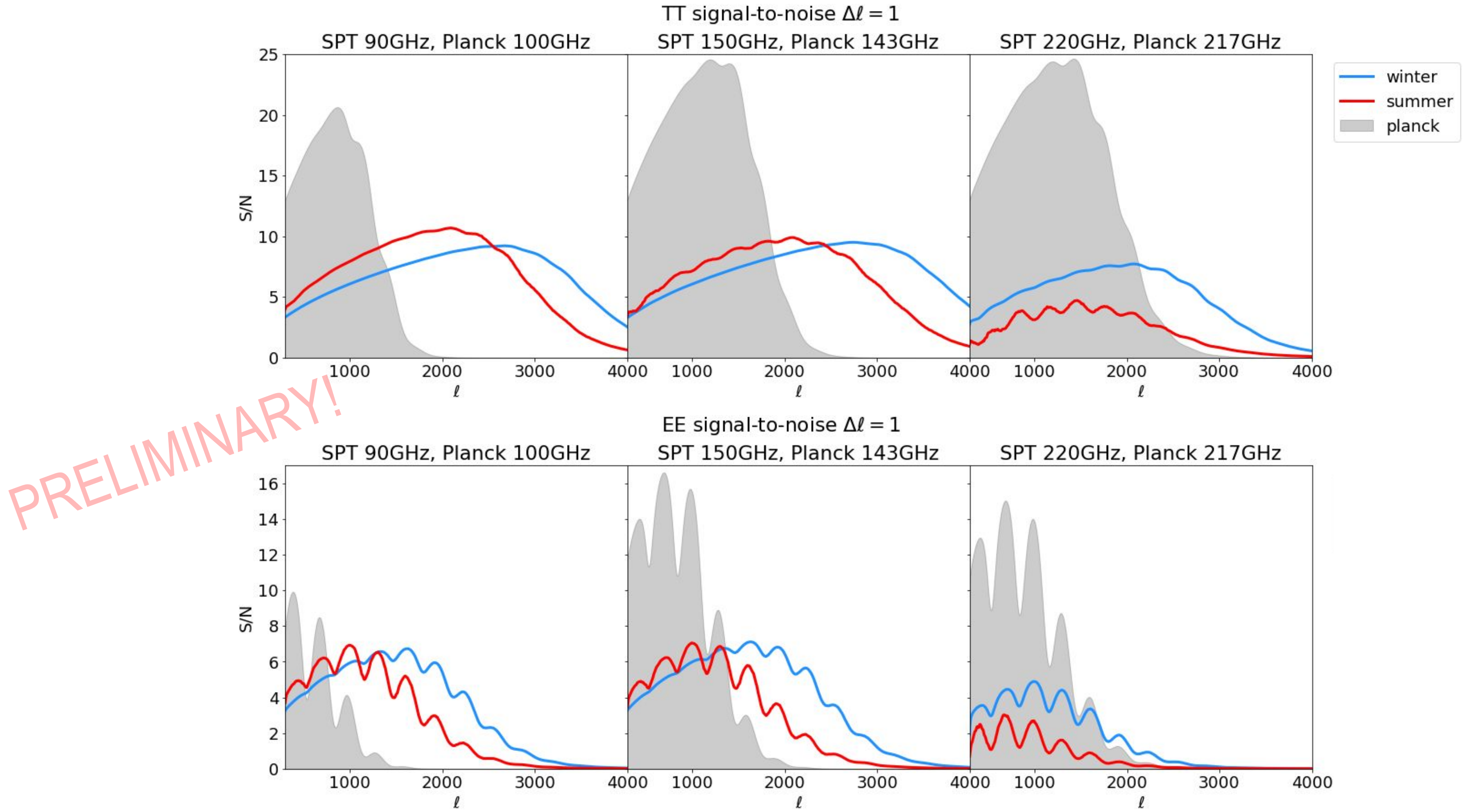
PRELIMINARY!

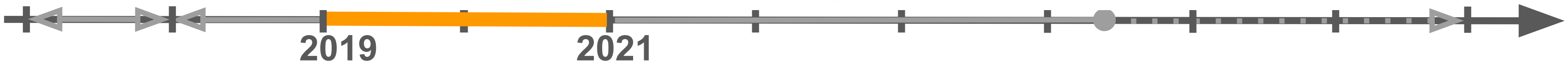
σ(H_0) [Km/s/Mpc] TT/TE/EE angular power spectra (ΛCDM)		
Planck	SPT-3G Winter	SPT-3G Summer
0.6	**0.9**	**1.0**
	0.7	
0.43		

Forecasts by L. Balkenhol and S.Raghunathan

Additional 30–40% improvement of the SPT-3G constraints when including the SPT-3G lensing information (TT/TE/EE+ϕϕ)




TT signal-to-noise $\Delta\ell = 1$
SPT 90GHz, Planck 100GHz
SPT 150GHz, Planck 143GHz
SPT 220GHz, Planck 217GHz
winter
summer
planck
S/N
ℓ
EE signal-to-noise $\Delta\ell = 1$
PRELIMINARY!

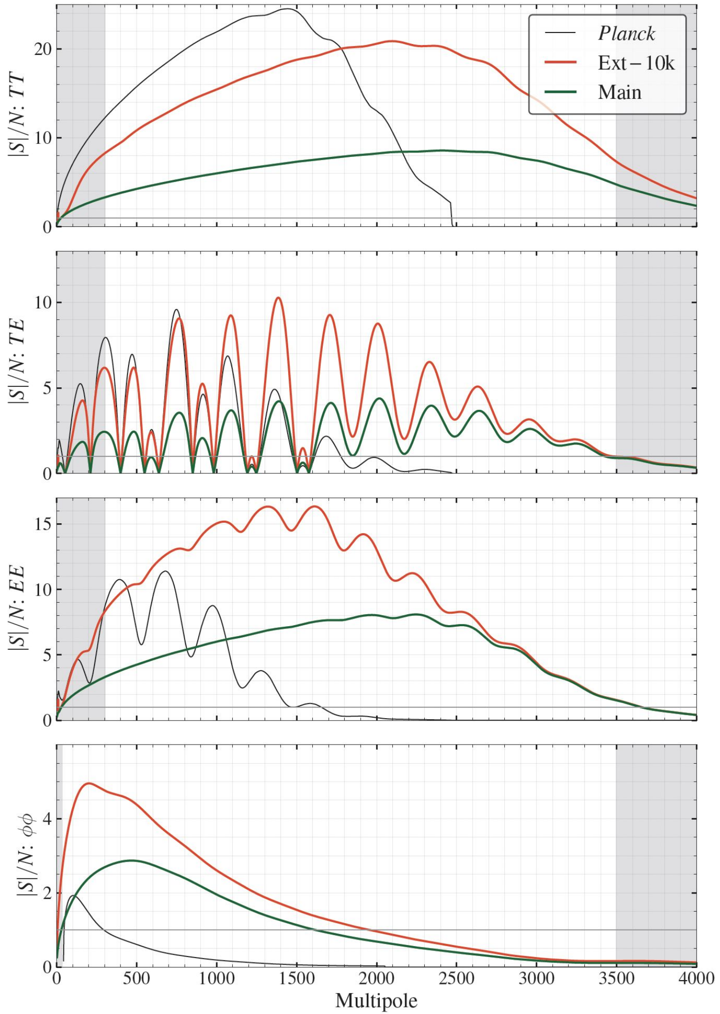

2019
2021

Prabhu et al., arXiv:2403.17925

Ext-10K forecasts

- Huge gain in S/N as compared to Planck
  - TT $\ell \gtrsim 1800$
  - TE $\ell \gtrsim 700$
  - EE $\ell \gtrsim 500$
  - $\phi\phi$ L $\gtrsim 30$

- Big overlap with other surveys
  - cross-correlations!



SPT-3G calibration

Calibration scheme of winter fields applied to summer as well

1 per week

- **Fast Point** : deep observations of the calibration source
  → fit the pointing and global pW/K conversion

Before/during/after each subfield

- **elnod**: calibrate the phase between current and voltage of TES
  → maximized signal timestream
  → characterization of the atmosphere
- **Very Fast Point**: quick observations of the calibration source
  → correct for changes in the sky transmission at different times of observation
- **Calibrator:** 1 min observations of thermal sources (300 and 1000 K) located at the center of the secondary mirror
  → correct for elevation and time dependent responsivity of the TES

$$C(El,t) = \frac{Peak\ RCW38\ pW}{Cal(El_{Rth}, t_{Rth})} \times Normal.Int. \times Bright.Ratio \times Cal(El,t) \times \frac{1}{K\ Integral}$$

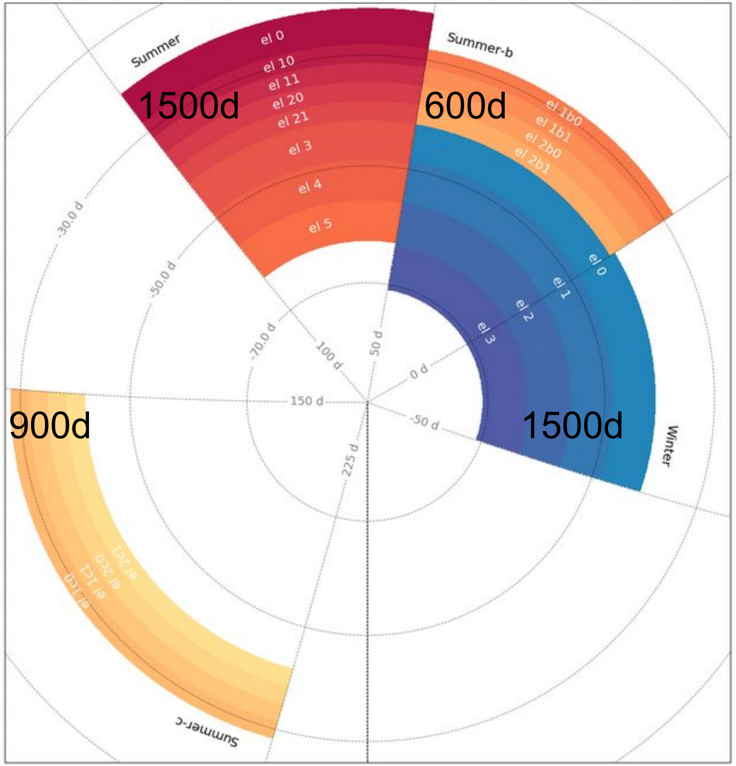
This ratio called `FluxCalibration`

Called `IntegralFlux`

Called `SkyTransmision`

Called `CalibratorResponse`

Hardcoded in the 3G software



Beams covariance