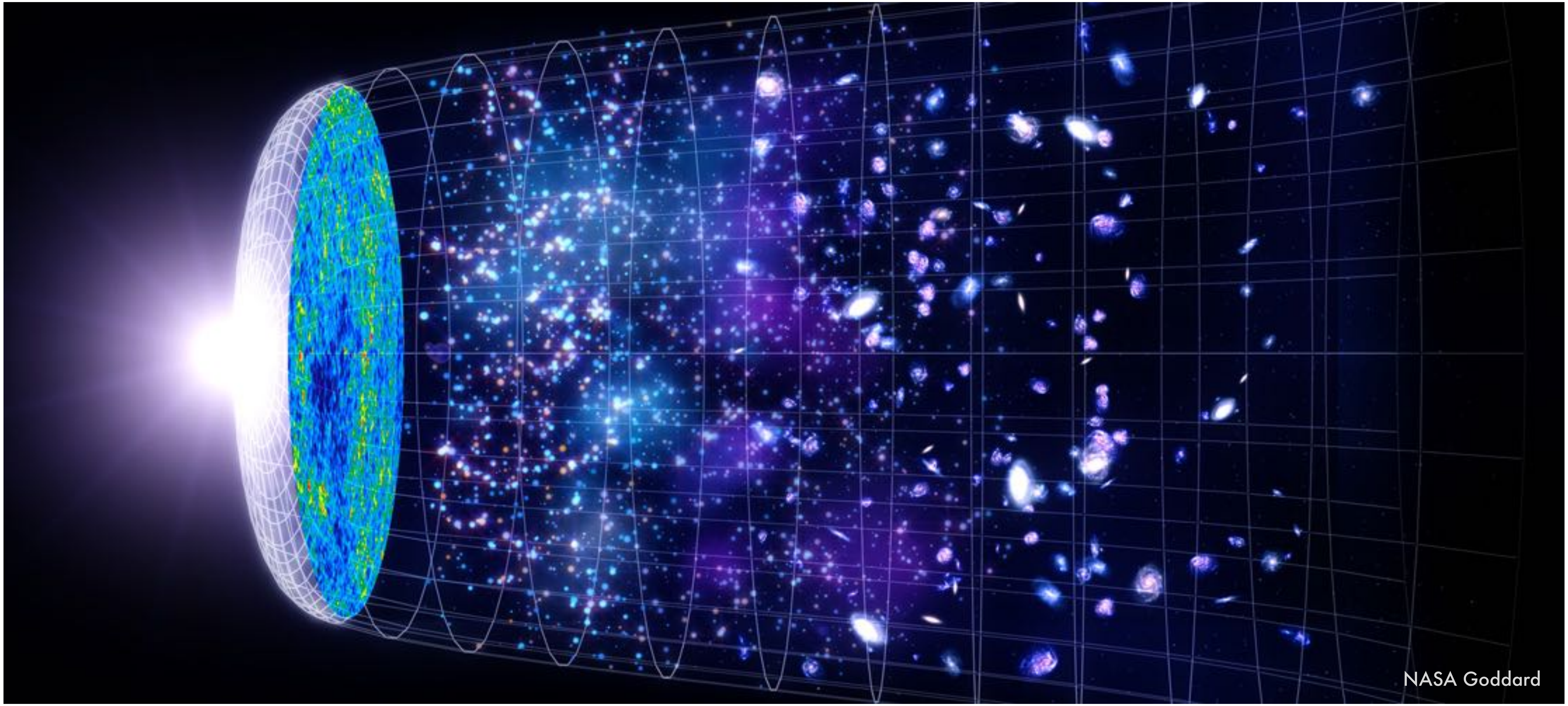
A new era for cosmology

with current and next-generation CMB experiments

Clara Vergès – Center for Astrophysics | Harvard & Smithsonian

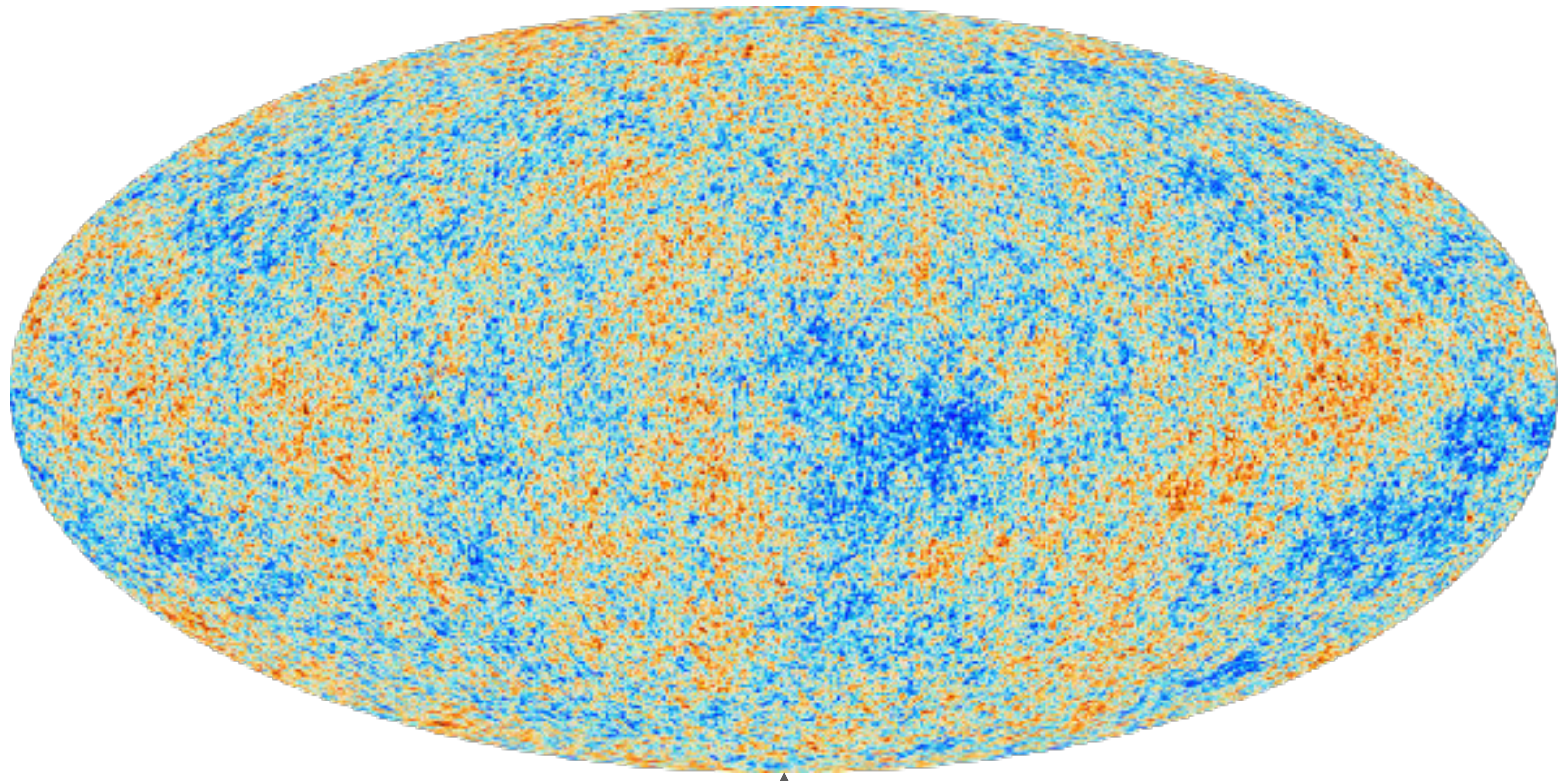
Lawrence Berkeley National Laboratory– February 20th, 2024

13.8 billions years to explore!



Early Universe   Particle physics   Matter distribution & evolution   Milky Way

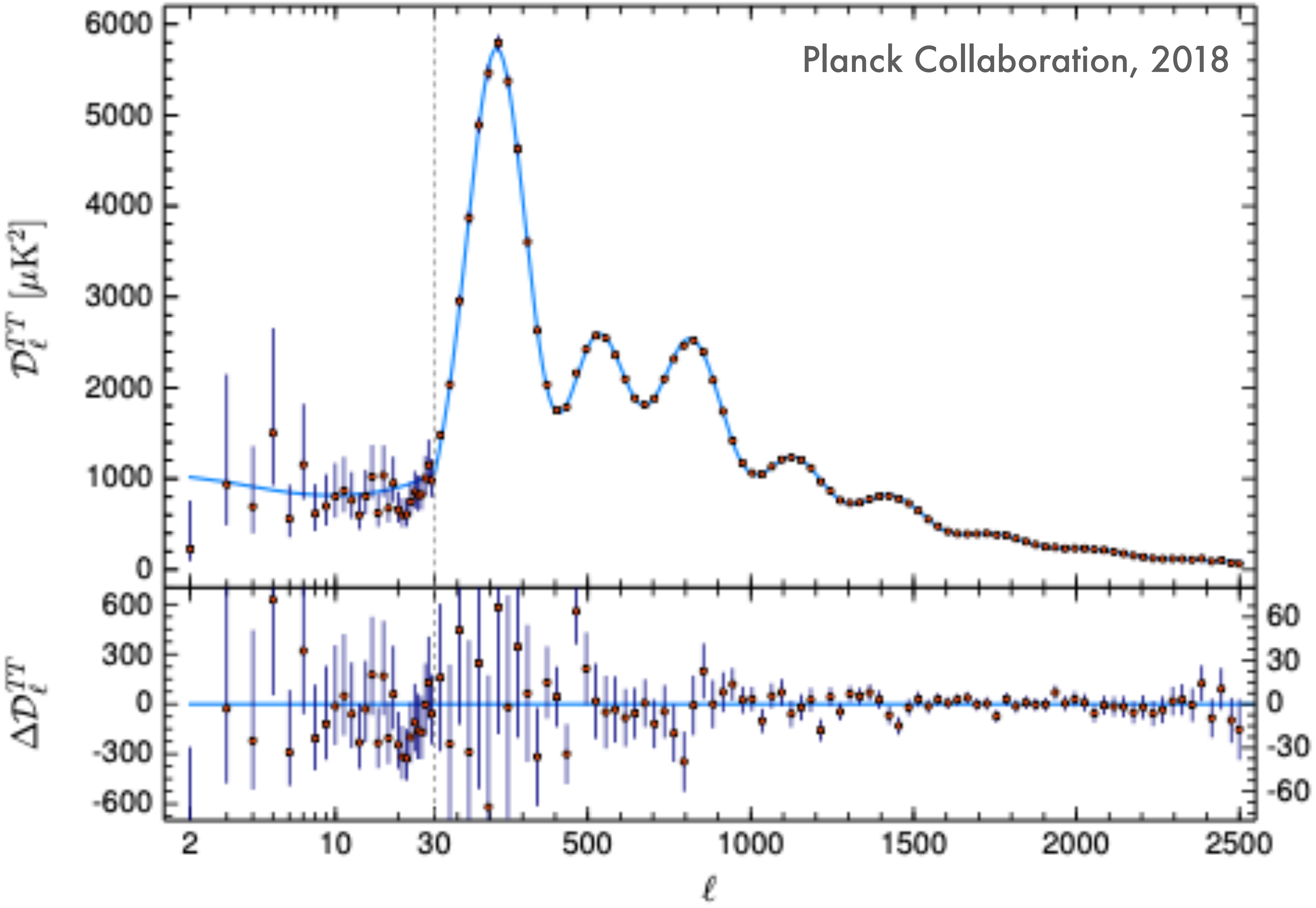
Standard cosmological model



ΛCDM model

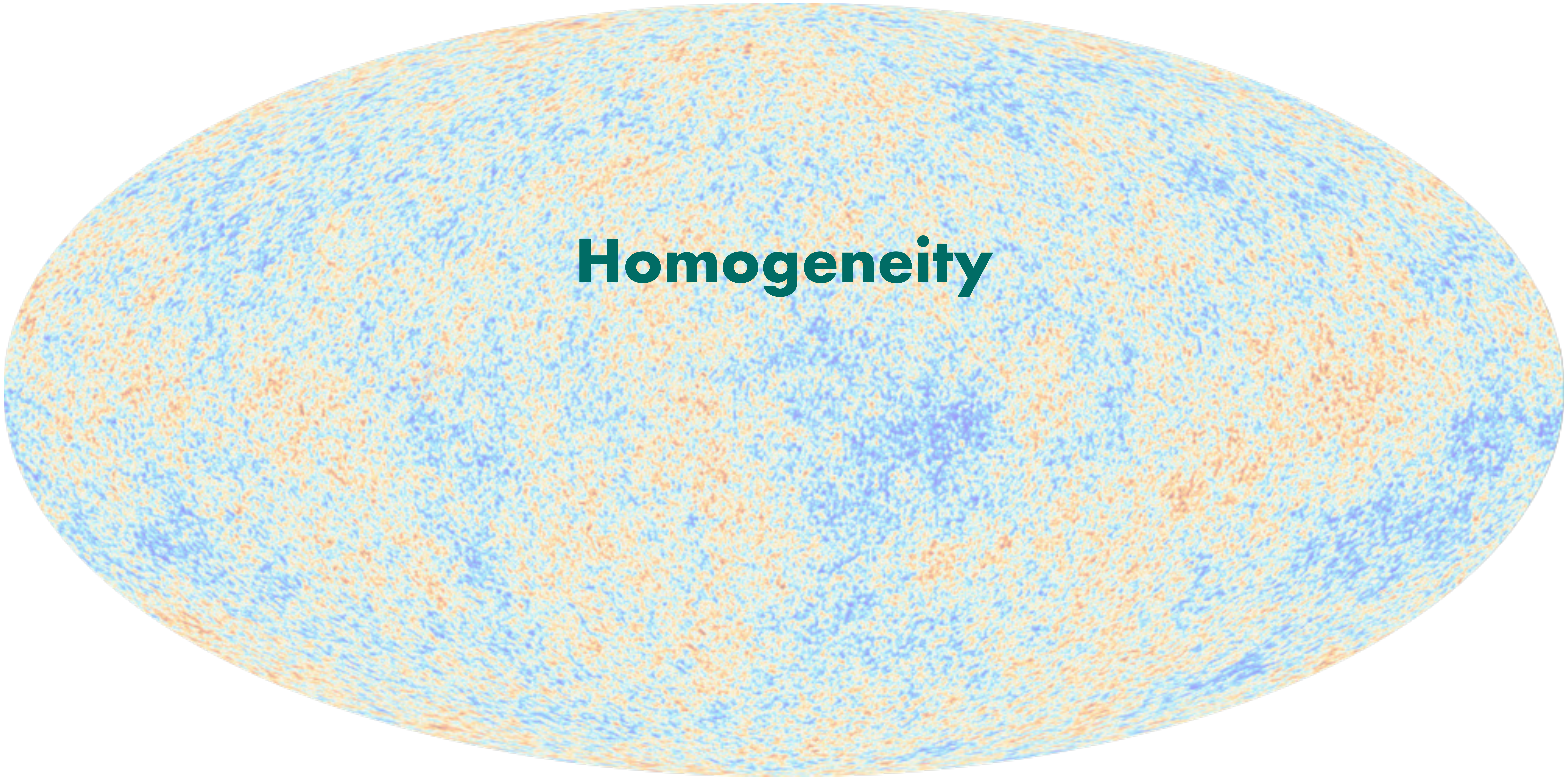
Content & Evolution of the Universe

Power



Angular scale

Initial conditions puzzles



Initial conditions puzzles

Homogeneity

T = 2.7K

Distance > age of the Universe x speed of light

Initial conditions puzzles

Homogeneity

Flatness

k < 0 **k = 0** k > 0

Initial conditions puzzles

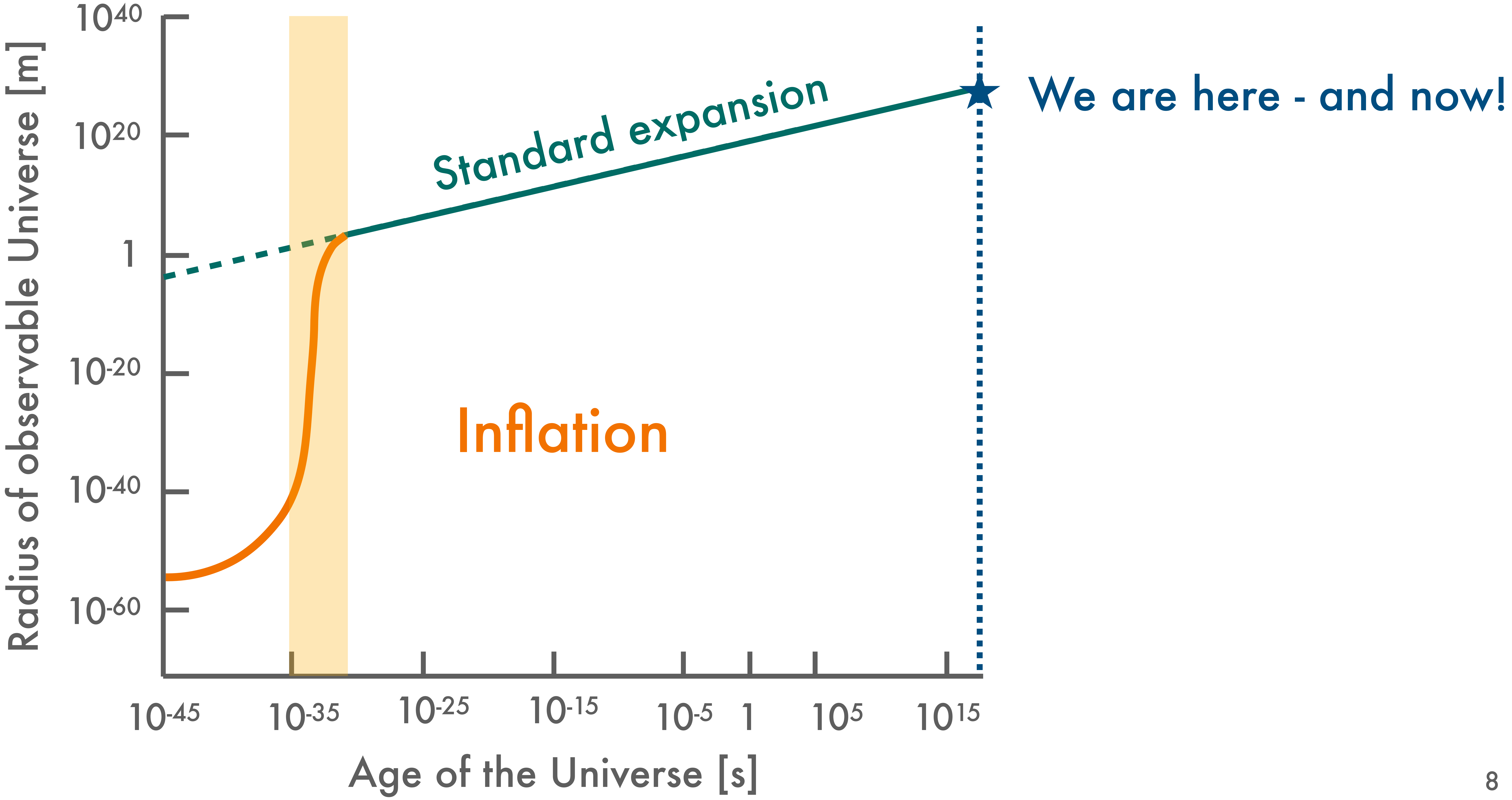
Homogeneity

Flatness

Fluctuations

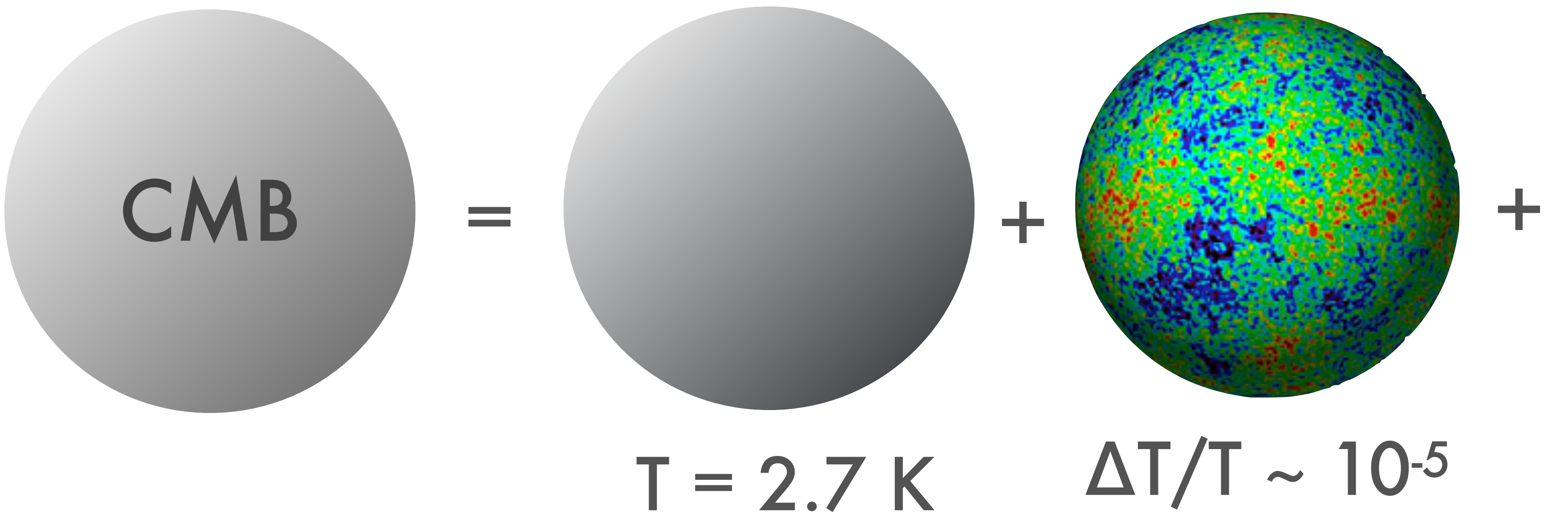
Scale?

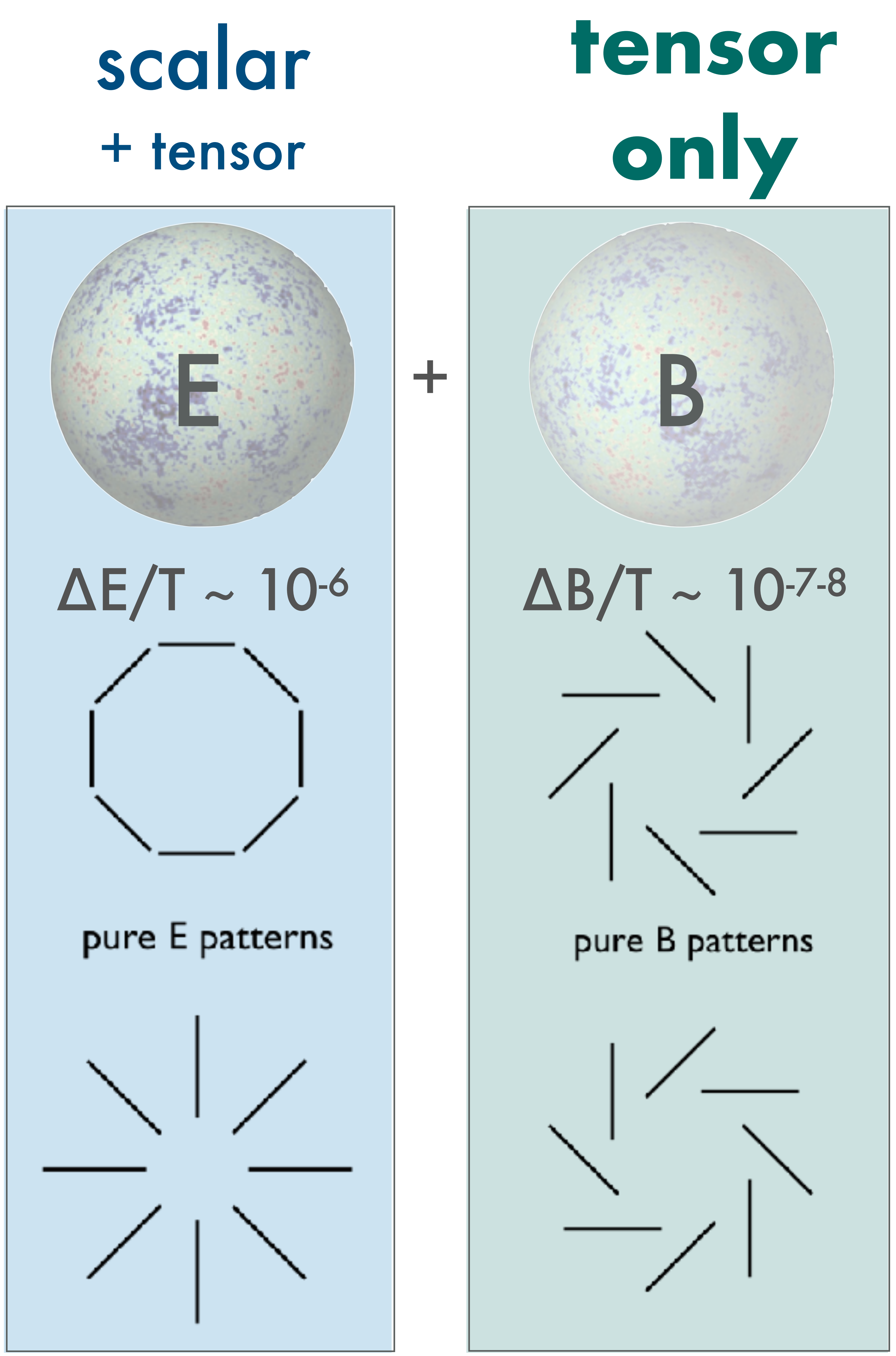
Inflation



Radius of observable Universe [m]
10^{40}
10^{20}
1
10^{-20}
10^{-40}
10^{-60}
Standard expansion
We are here - and now!
Inflation
10^{-45}
10^{-35}
10^{-25}
10^{-15}
10^{-5}
1
10^{5}
10^{15}
Age of the Universe [s]

CMB light — a breakdown



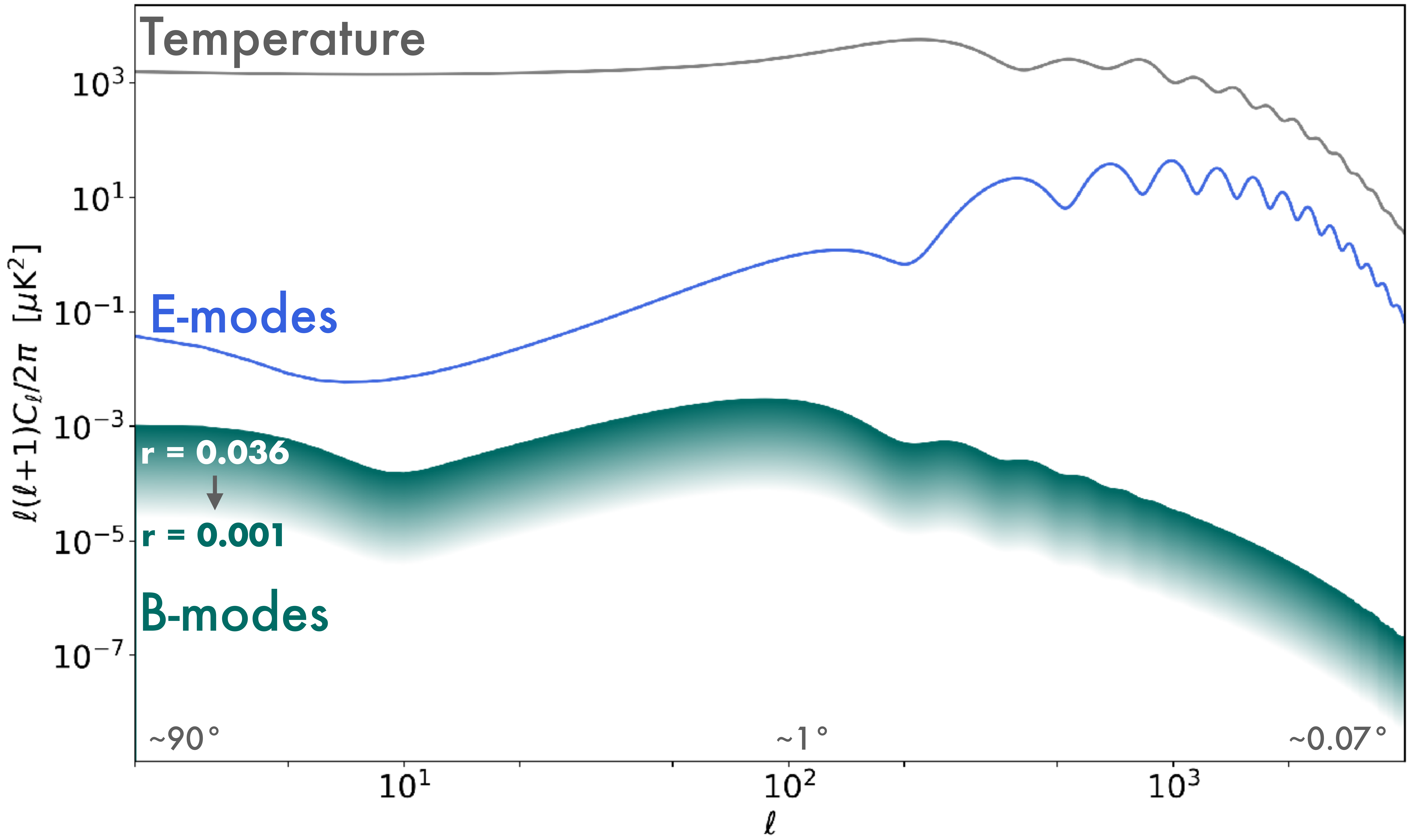


B-modes are sourced by tensor fluctuations predicted by inflation models and parametrised by the

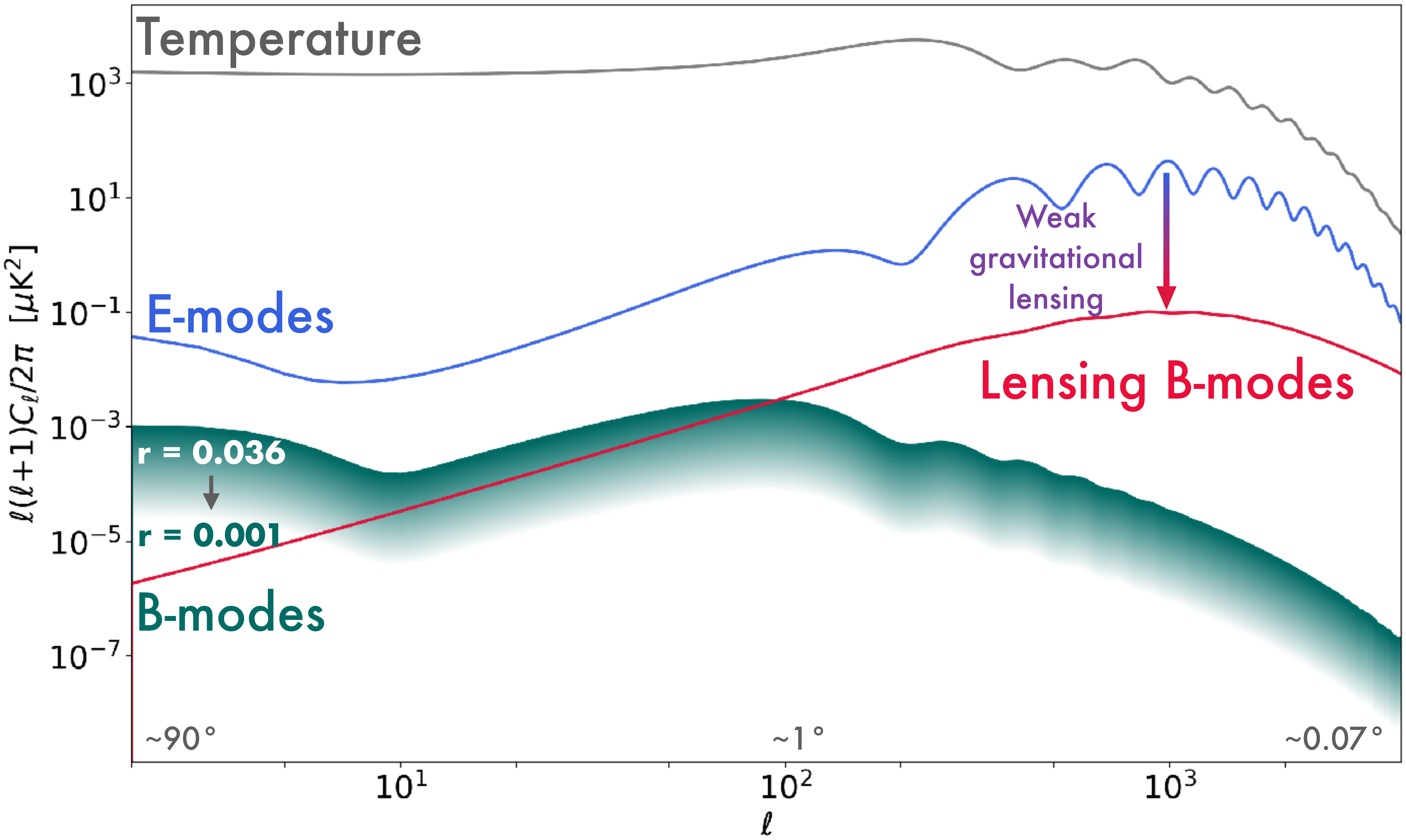
tensor-to-scalar ratio r

Differential Thompson scattering

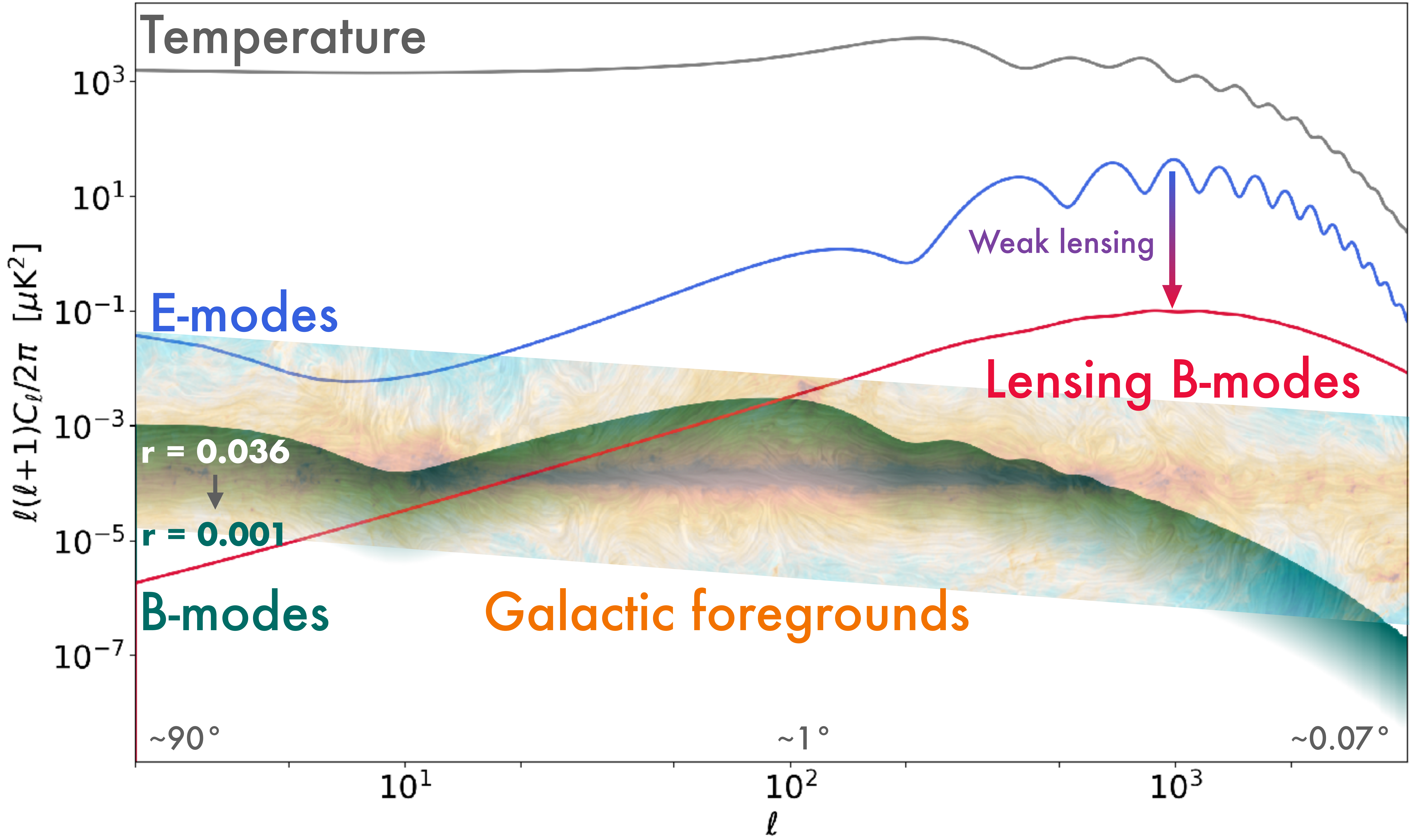
CMB power spectrum



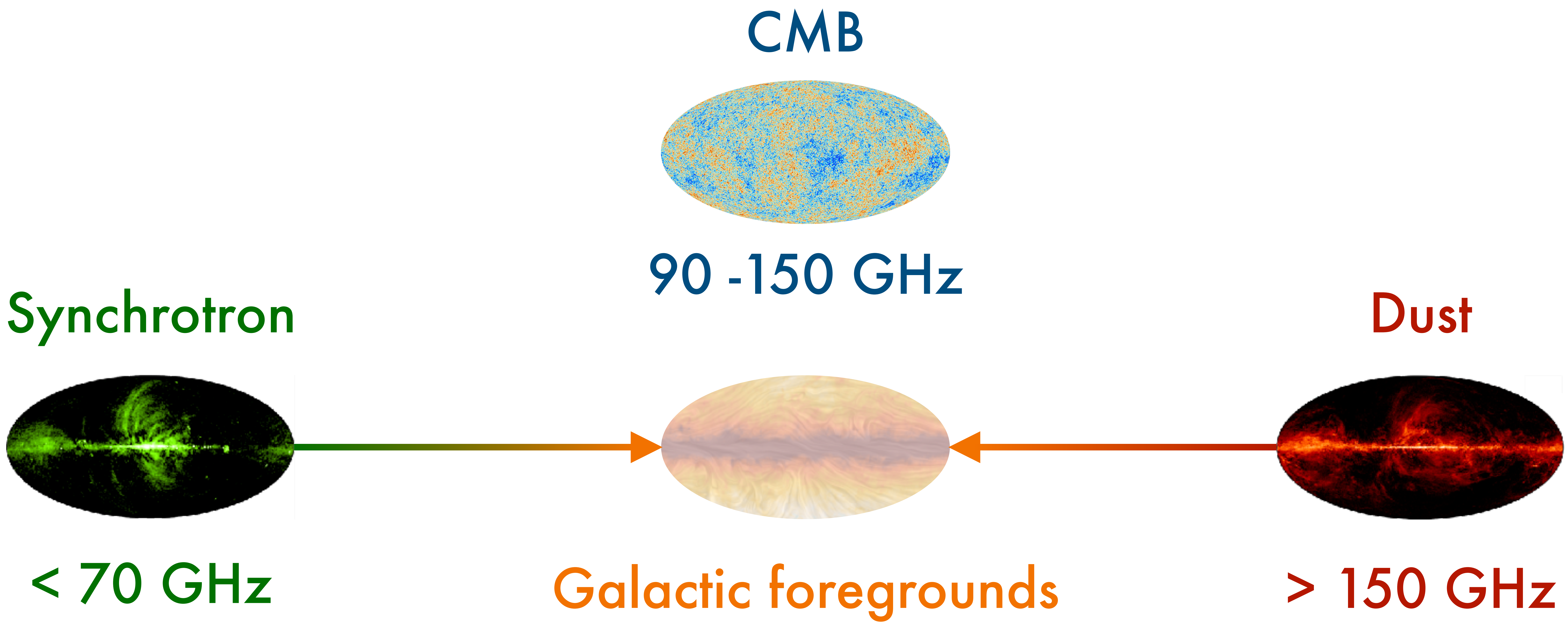
CMB power spectrum



CMB power spectrum



Component separation



Detecting primordial B-modes

Very faint signal

Weak gravitational lensing

Galactic emission

→

High sensitivity, multi-resolution, multi-frequency experiment

South Pole Observatory: BICEP/*Keck* + SPT

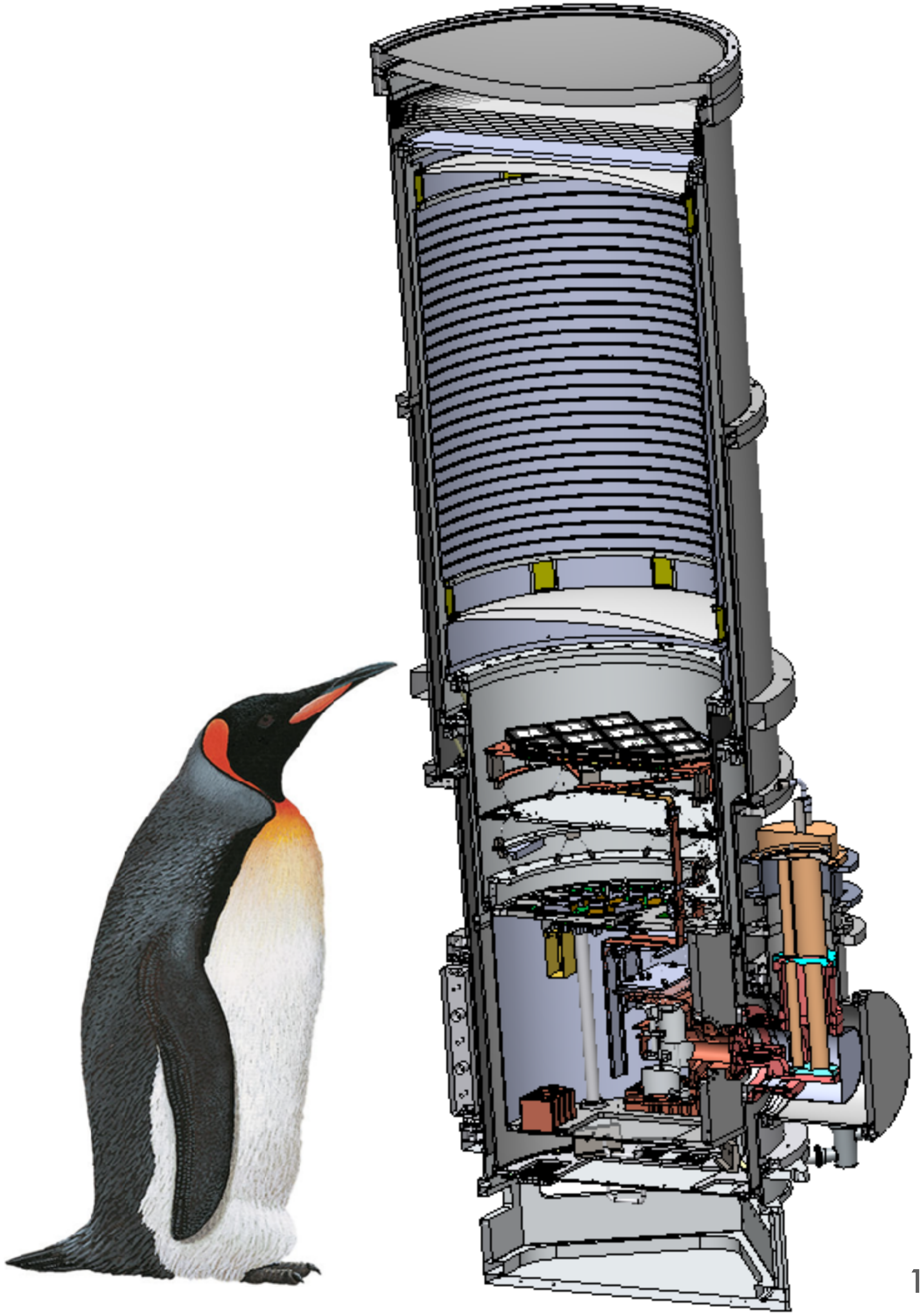
25,000+ polarised detectors
Six frequency bands
Two aperture sizes

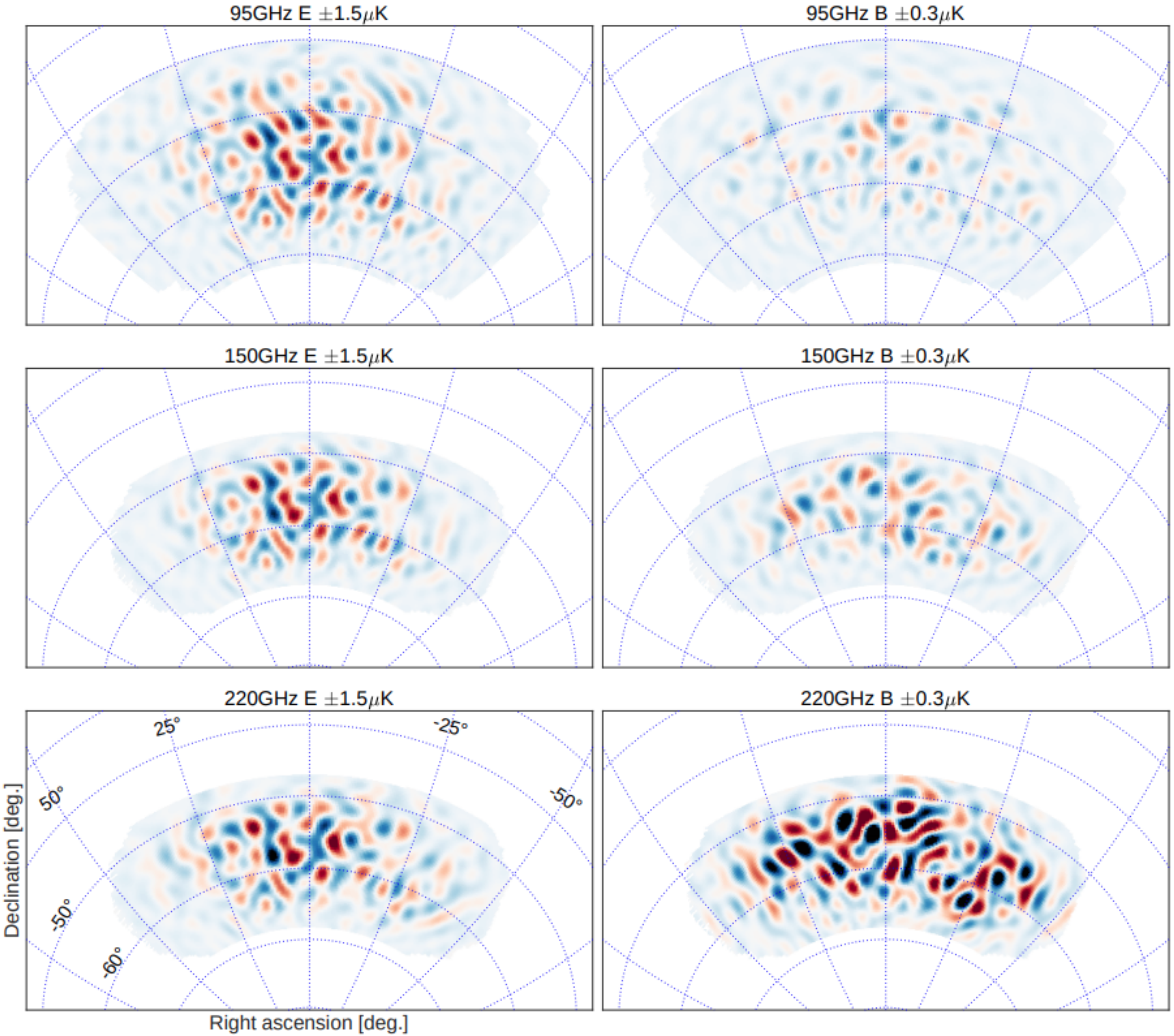
BK receivers

Small Aperture Telescopes (SAT)

Compact, on-axis optics design

Targets a small and deep sky patch





BK Collaboration

Multicomponent likelihood analysis

Observed data

Parametric likelihood

lensed ΛCDM + tensor-to-scalar ratio r + foreground model

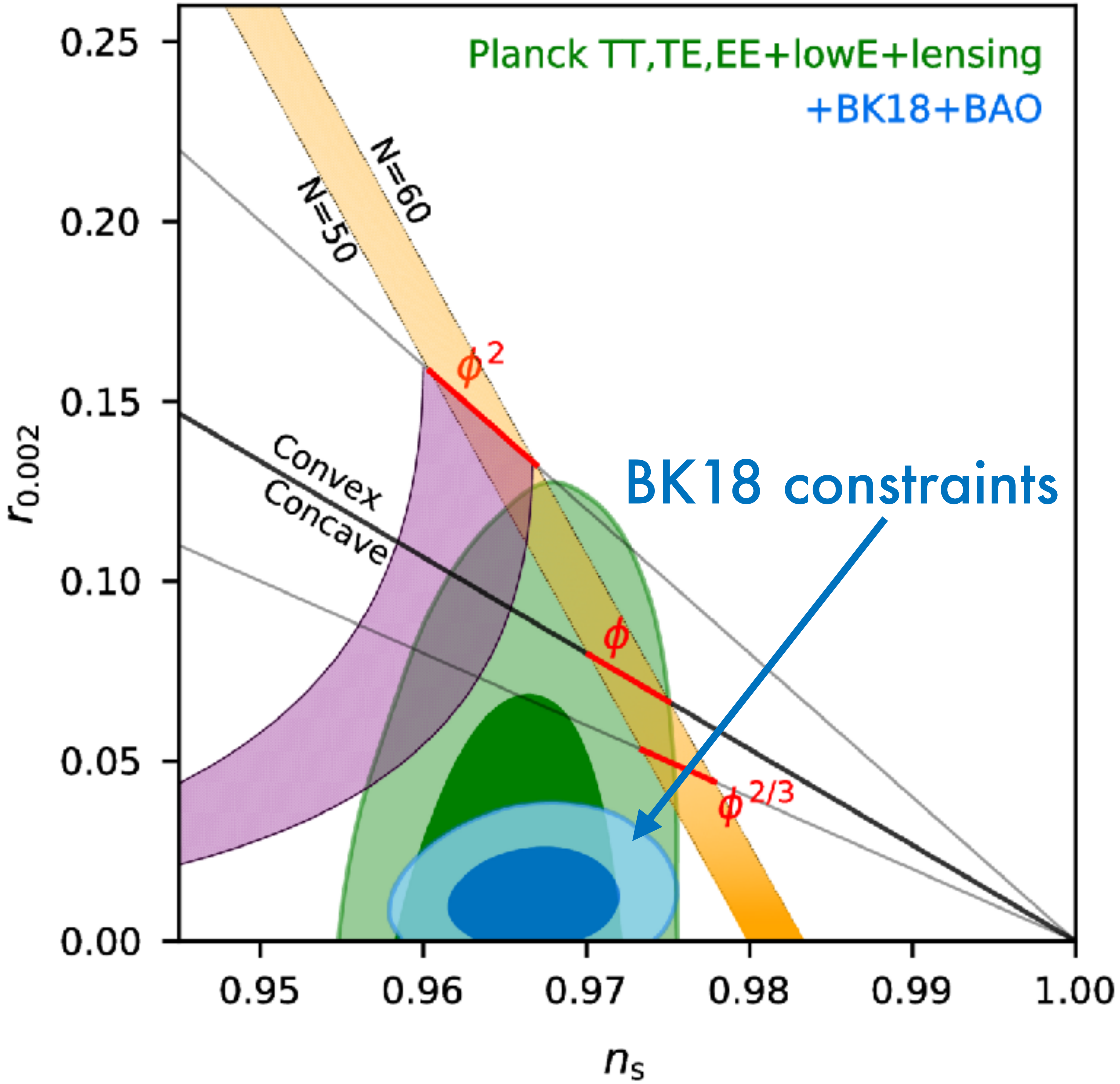
Expectation values

Model

Parameters

r + foregrounds

Where we *r*



Most recent BK results (aka BK18)

BK Collaboration, PRL 2021

r < 0.036 (95% C.L.)

Statistical uncertainty

σ(r = 0) = 0.009

Pushing the limits on *r*

SPO→ **σ**(r = 0) ~ 0.003 by 2027

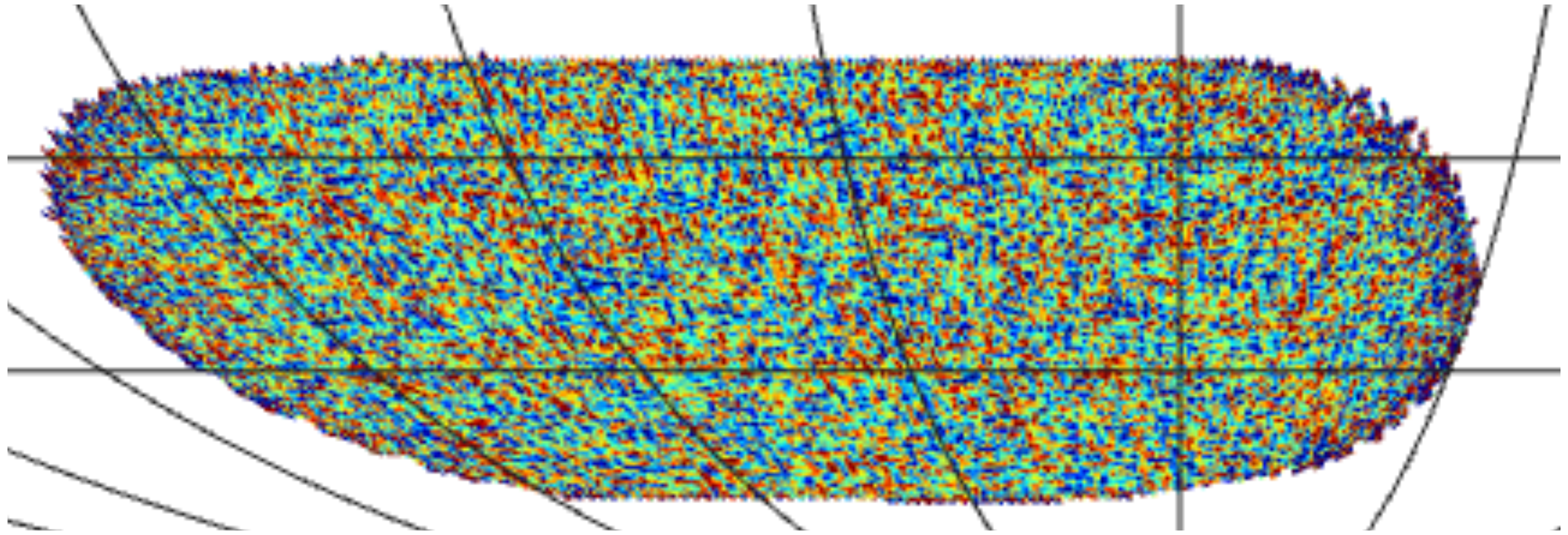
CMB-S4 - next-generation ground-based CMB experiment!

Ultra-deep survey
Inflation: $\sigma(r = 0) = 0.0005$
Limit $r < 0.001$

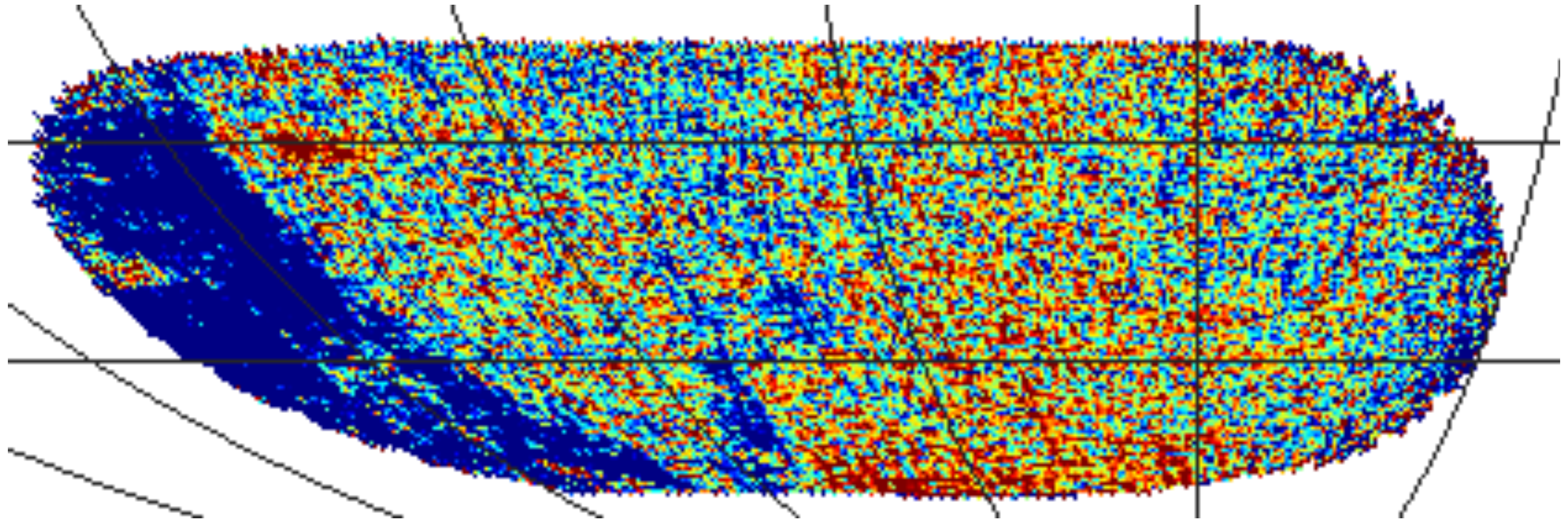
Deep-wide survey
Neutrinos & Light relics
Matter distribution
Transient alerts

Foreground complexity

Gaussian dust



More complex dust model



Very recent and preliminary work!

No bias on r
in the parametric
likelihood framework

Bias on r at the level of ~2σ
How can we improve the robustness
of our component separation frameworks?

Instrumental systematics & where to find them

Systematics analysis

Effects that can be well **modelled**
→ subtract or deproject in the analysis, include in the data model

Extended component separation framework

Standard likelihood
Sky data model only

→

Generalised likelihood
Sky + **instrument** data model

Joint estimation of instrumental and astrophysical parameters
Transfer of calibration information between frequency channels

Framework for analysis of next generation, polarised CMB data sets in the presence of galactic foregrounds and systematic effects
C. Vergès, J. Errard and R. Stompor – PRD 2020

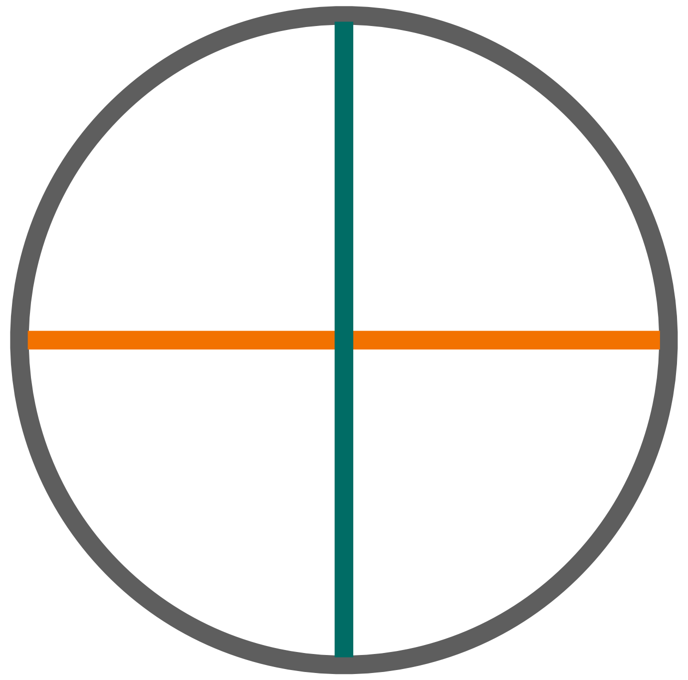
Systematics analysis

Effects that can be well **modelled**
→ subtract or deproject in the analysis, include in the data model

Effects hard to model a priori but that you can **measure**
→ calibrate & evaluate the impact

Main beam mismatch

A detector

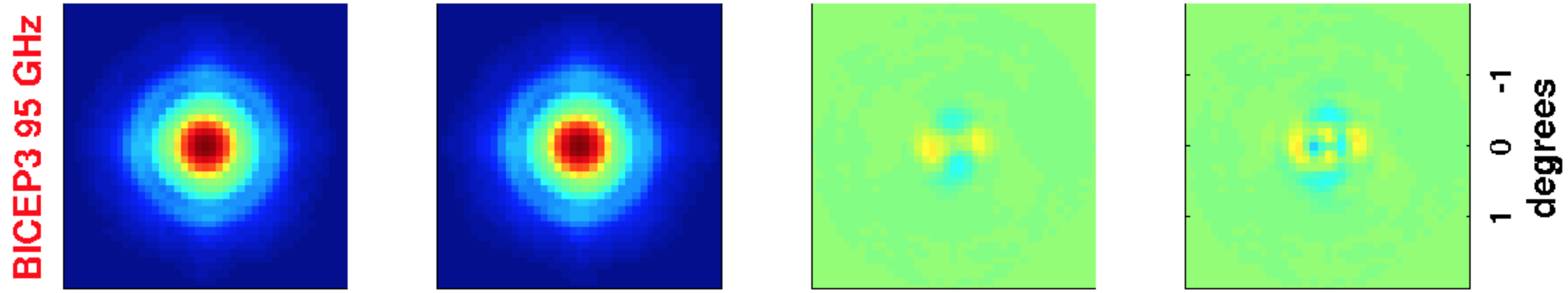


B detector

Results in temperature-to-polarisation leakage

Polarised signal = (A-B)/2

A | B | Difference | Residual

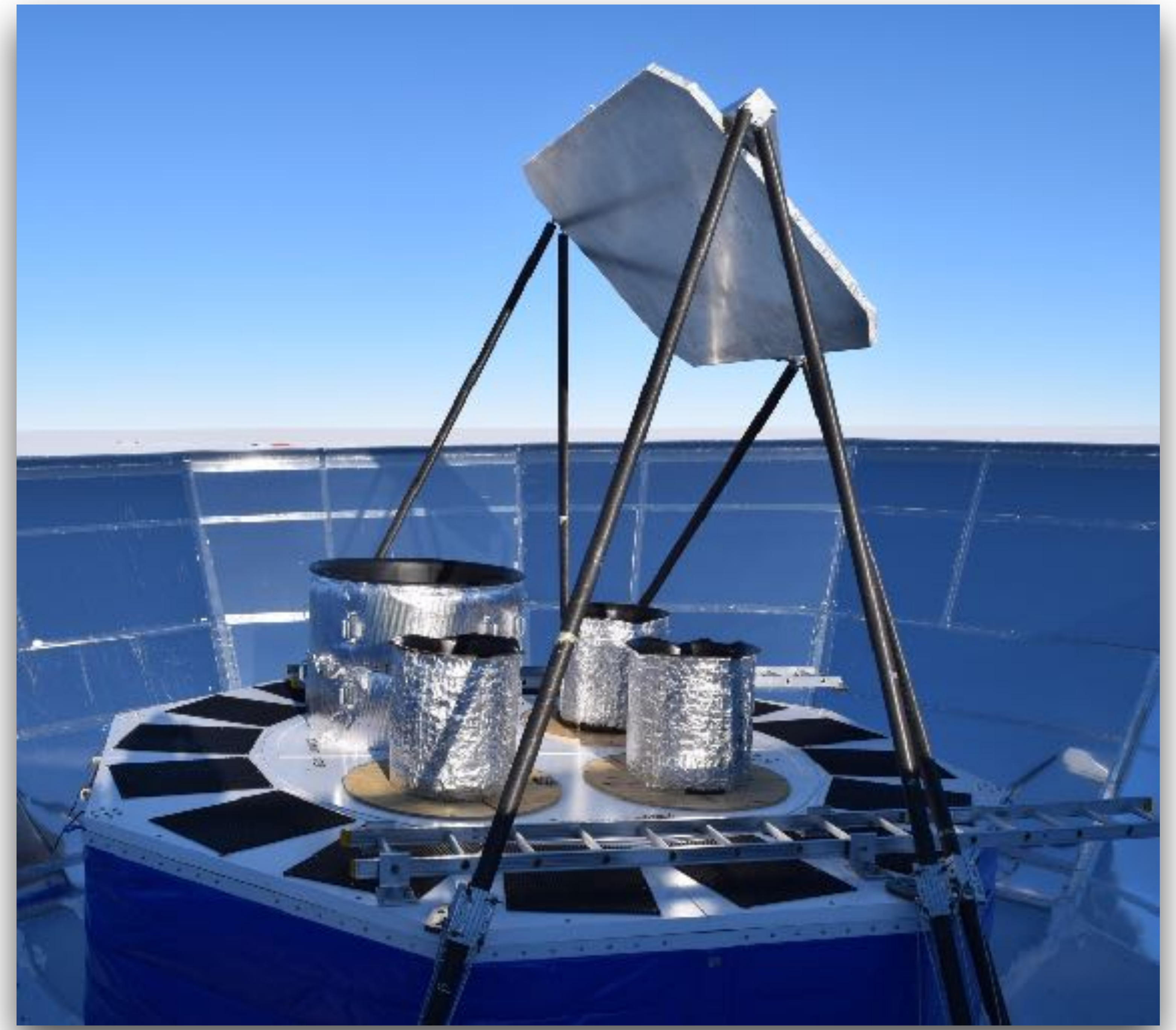


Peak normalised

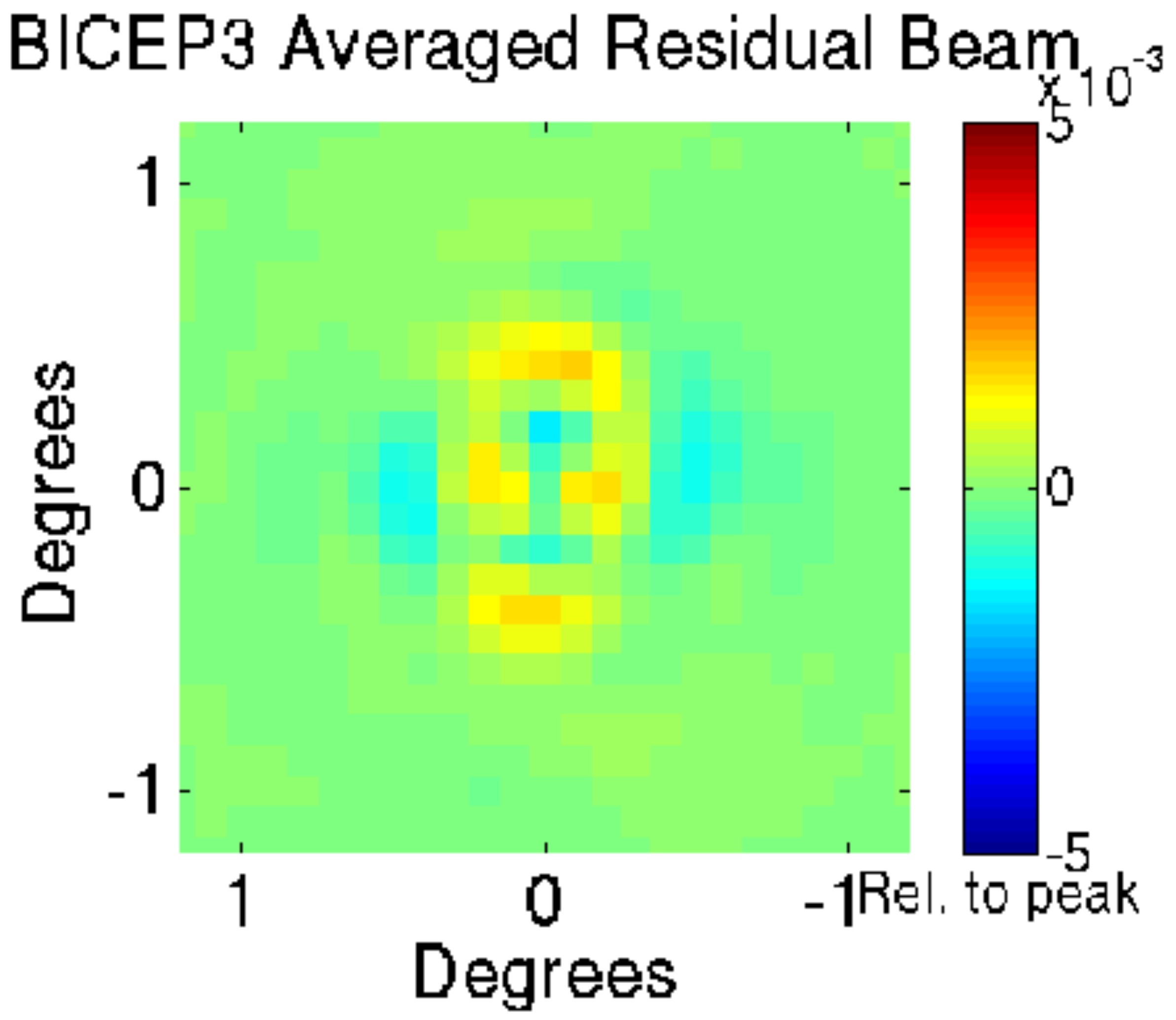
~1or 2% of main beam

<0.5% of main beam

Calibration

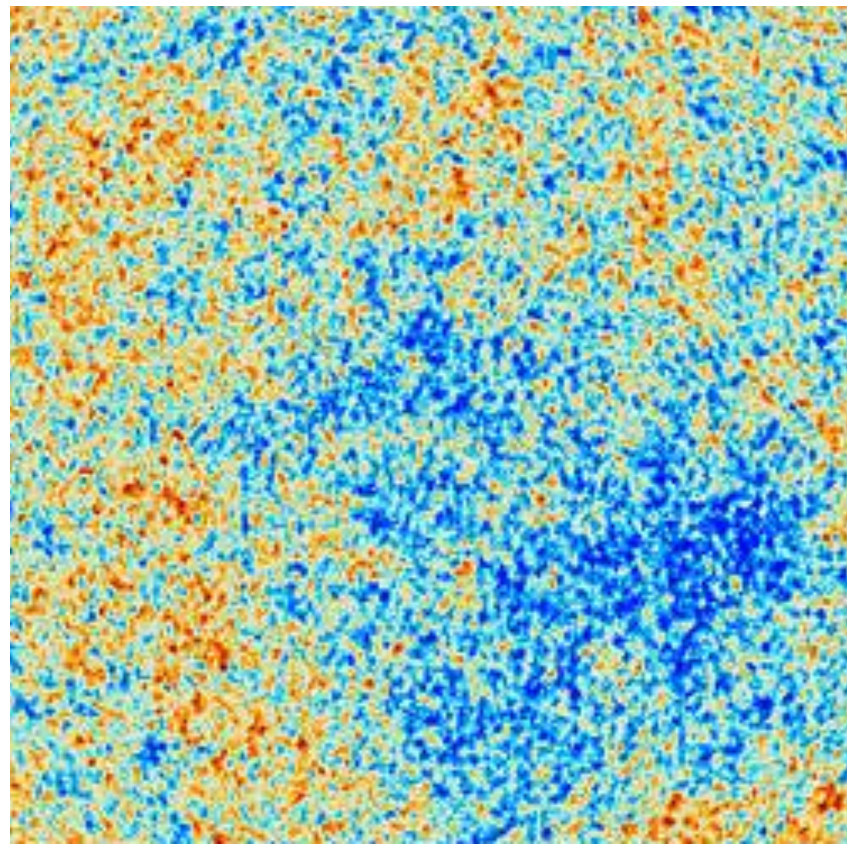


Systematics template

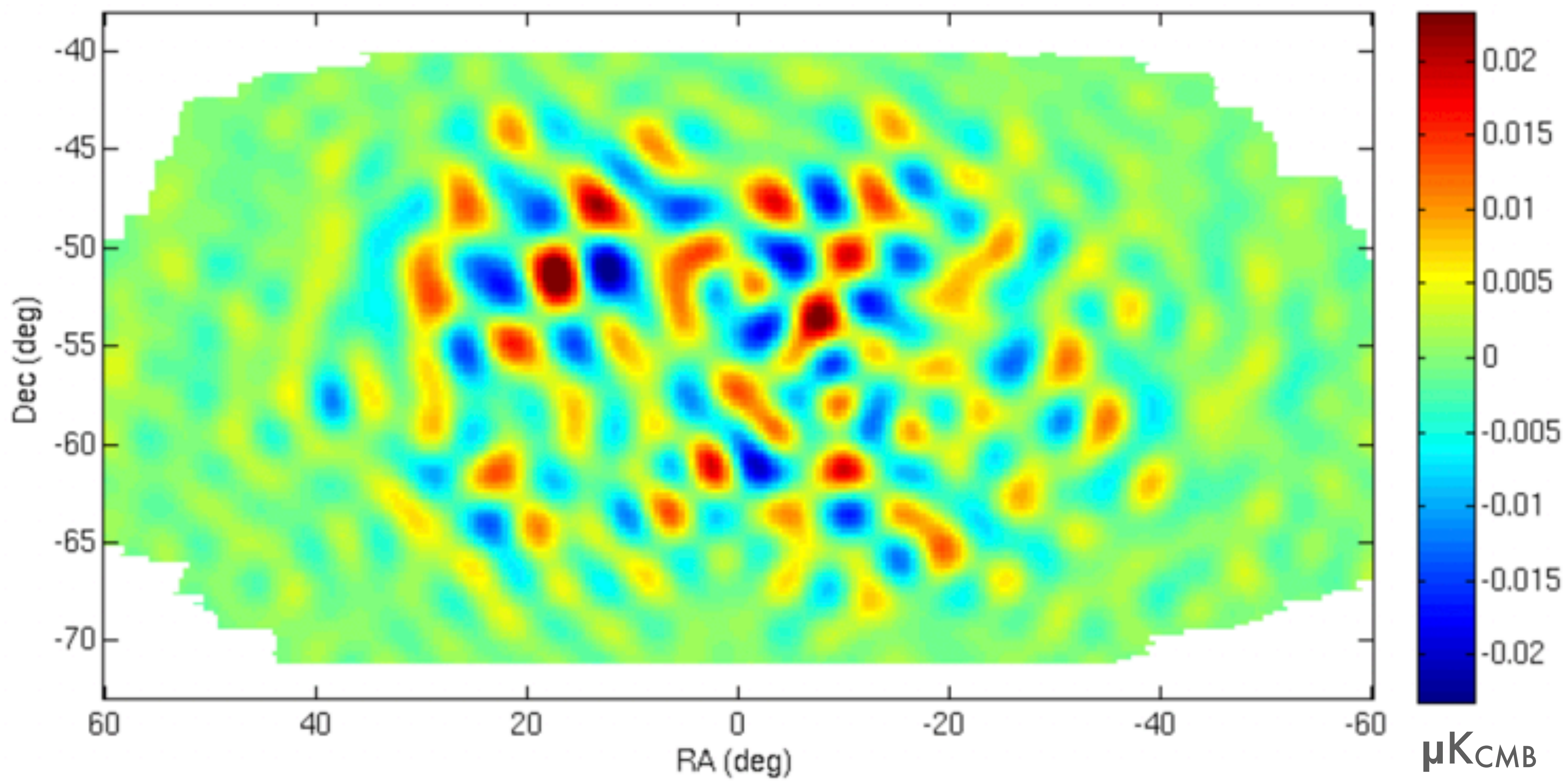


Residual differential beam

$\star$

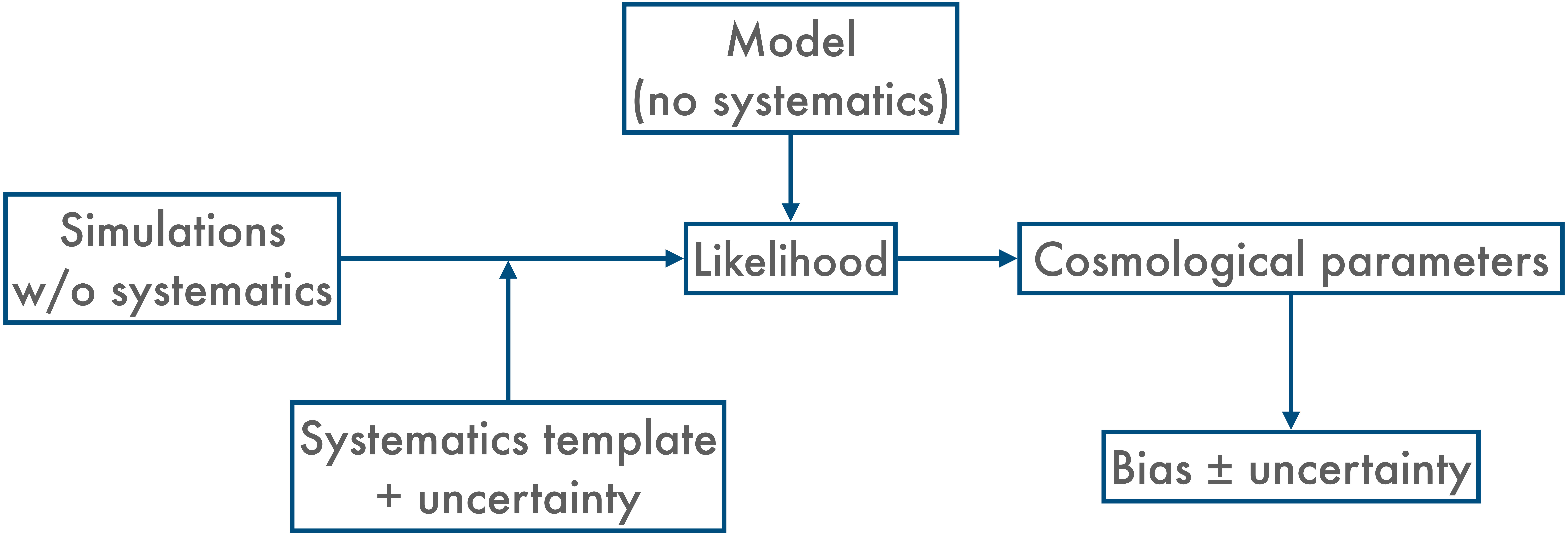


CMB T only map



T→P leakage template map

Likelihood analysis



Path forward – from BK to CMB-S4

CMB-S4: $\sigma(r = 0) = 0.0005$

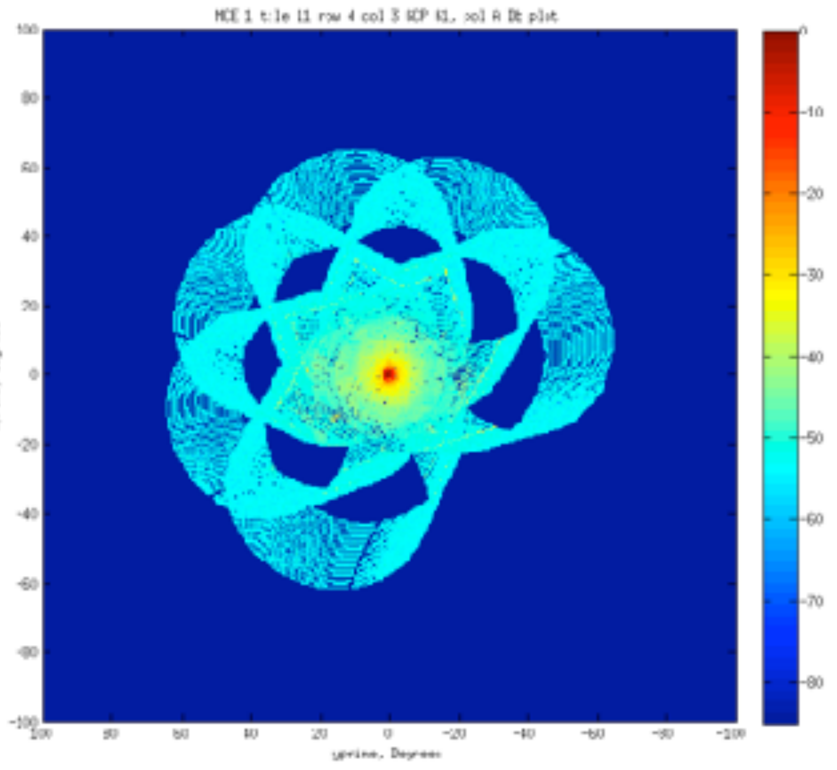
Main beam mismatch
$\Delta(r) = 0.0015 \pm 0.0011$
Bandpass uncertainty
$\Delta(r) < 0.00084$
Polarisation angle uncertainty
$\Delta(r) < 0.00004$

1. Improved control at the instrument level
   → **design requirement**
2. Improved calibration measurements
   → **calibration requirement**
3. Improved treatment in the analysis
   → **demonstration on current data**

Appendix F of BK18, PRL 2021 – led by **C. Vergès**
BK Systematics project – **C. Vergès** w/ J. Cornelison, B. Elwood, C. Giannakopoulos

Calibration data

In-depth analysis of existing calibration data

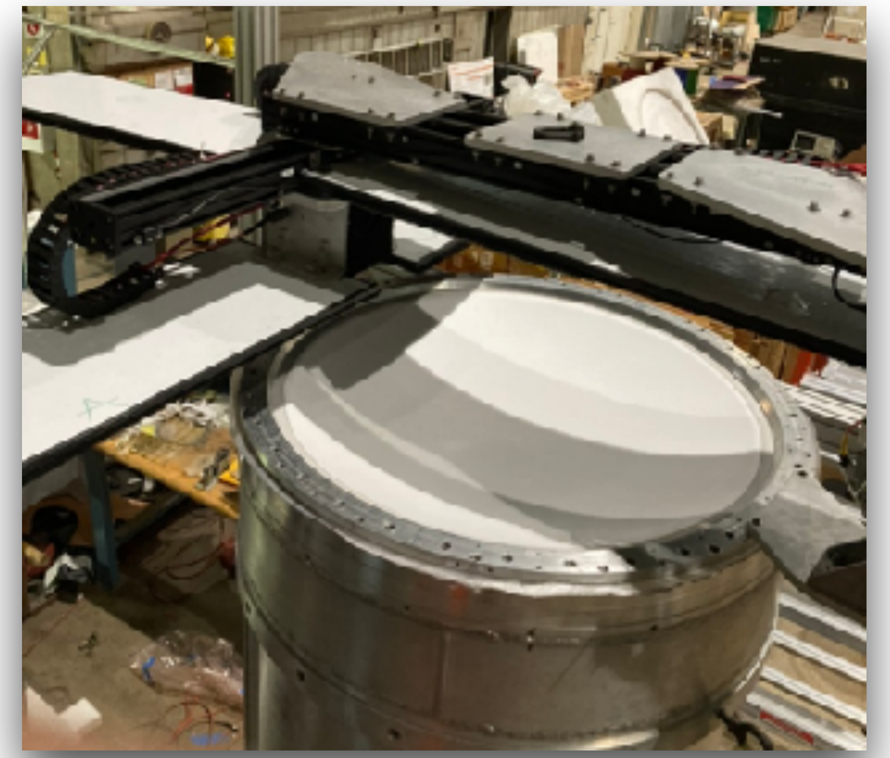


BICEP3 extended beam response
C. Giannakopoulos

Calibration measurement systematics

→ *New algorithms for characterizing the beams of next-generation CMB experiments*, W. Golay & **C. Vergès**, AAS Winter Meeting 2023

Calibration equipment prototyping



New near field beam mapper for BA receivers
B. Elwood

CMB-S4: SAT systematics forecasting project

Goal: setting calibration & design requirements
to mitigate instrumental systematics for CMB-S4 SATs

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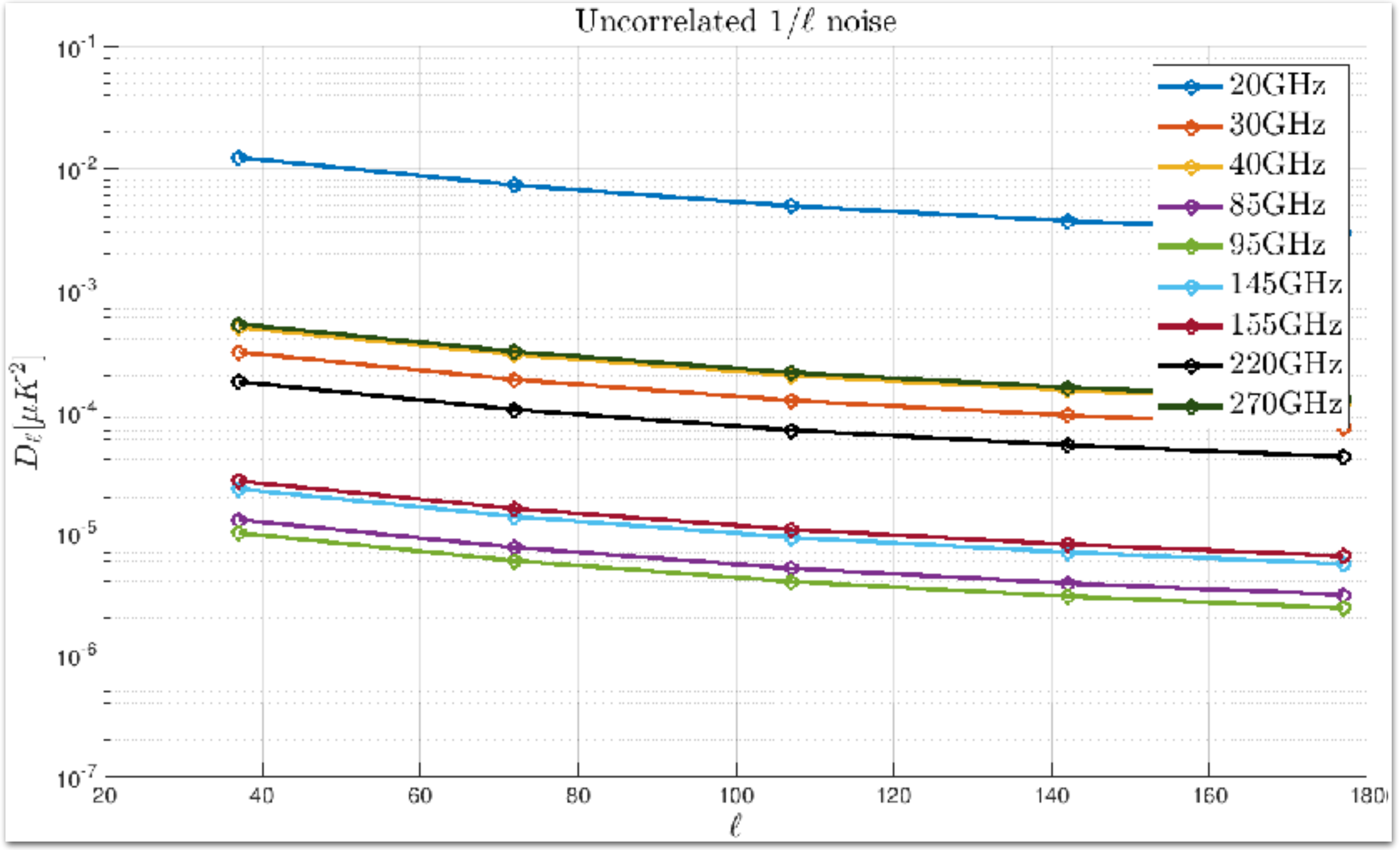
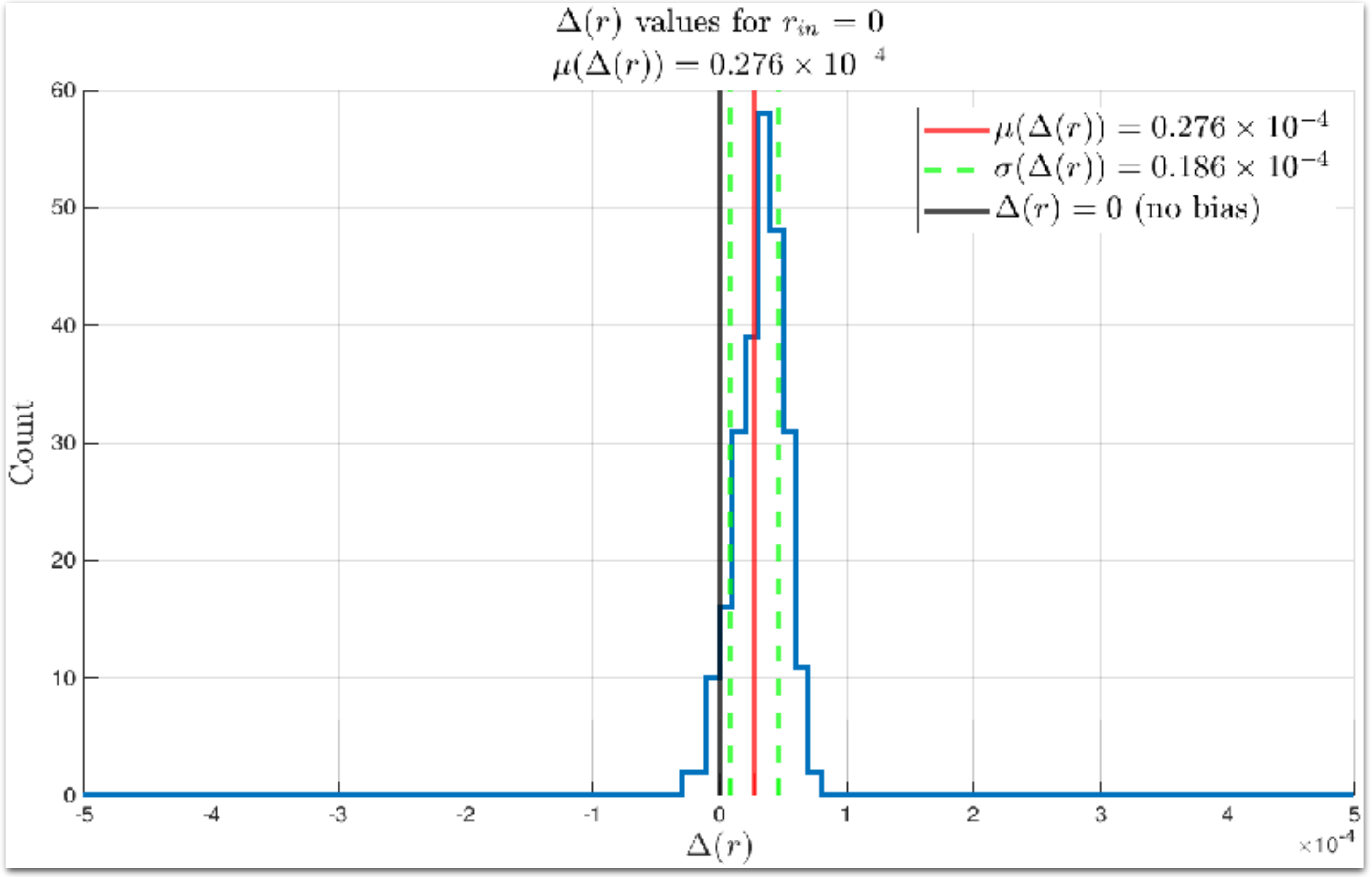




Instrumental effects

Cosmic birefringence

Parity-violating field interacting with the electromagnetic field
Primordial magnetic fields
→ **polarisation rotation angle α**
aka "cosmic birefringence"

Effect integrates over the line-of-sight
→ **the CMB is the best place to look for the signal!**

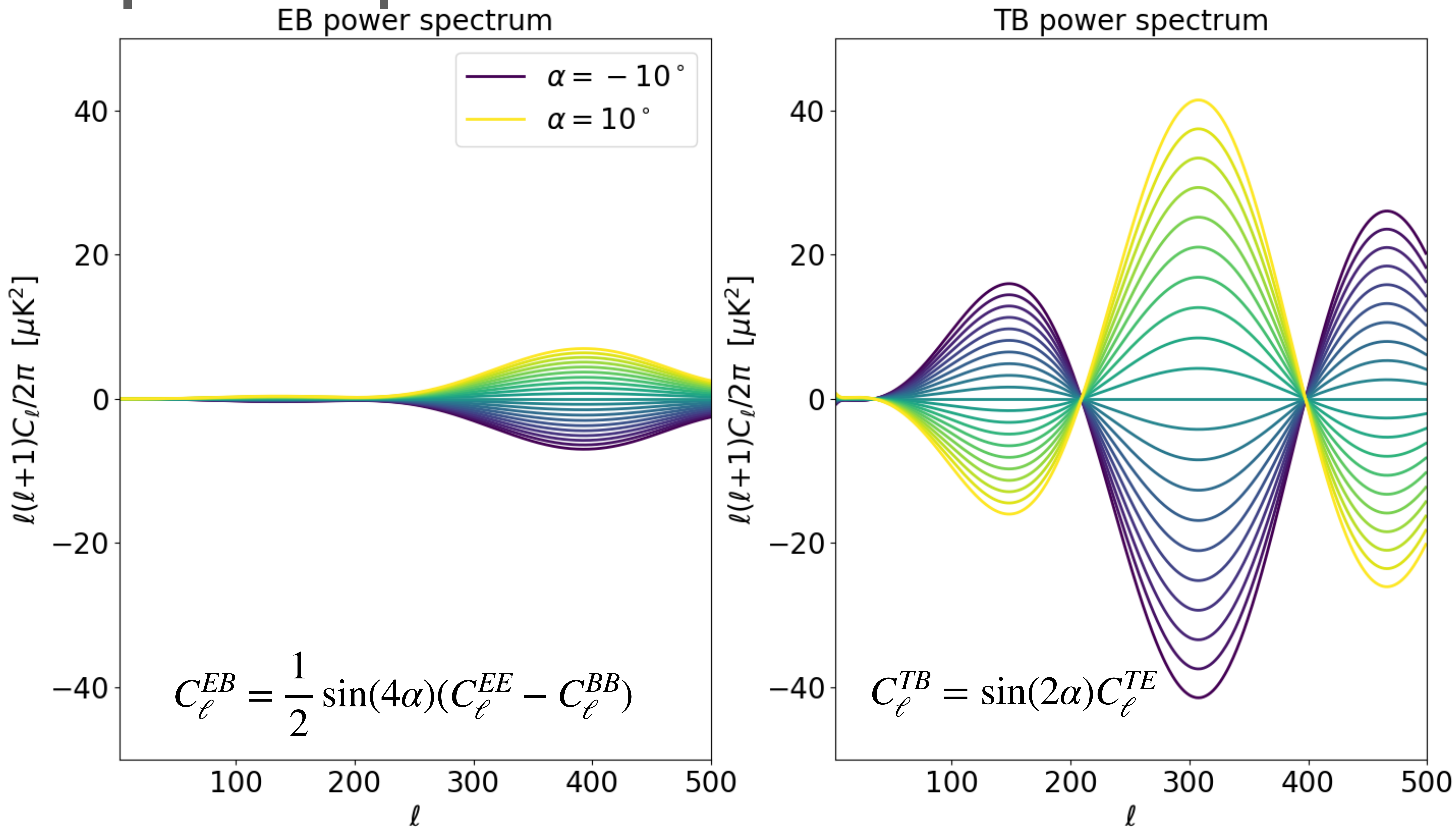
Impact on the CMB

E-modes

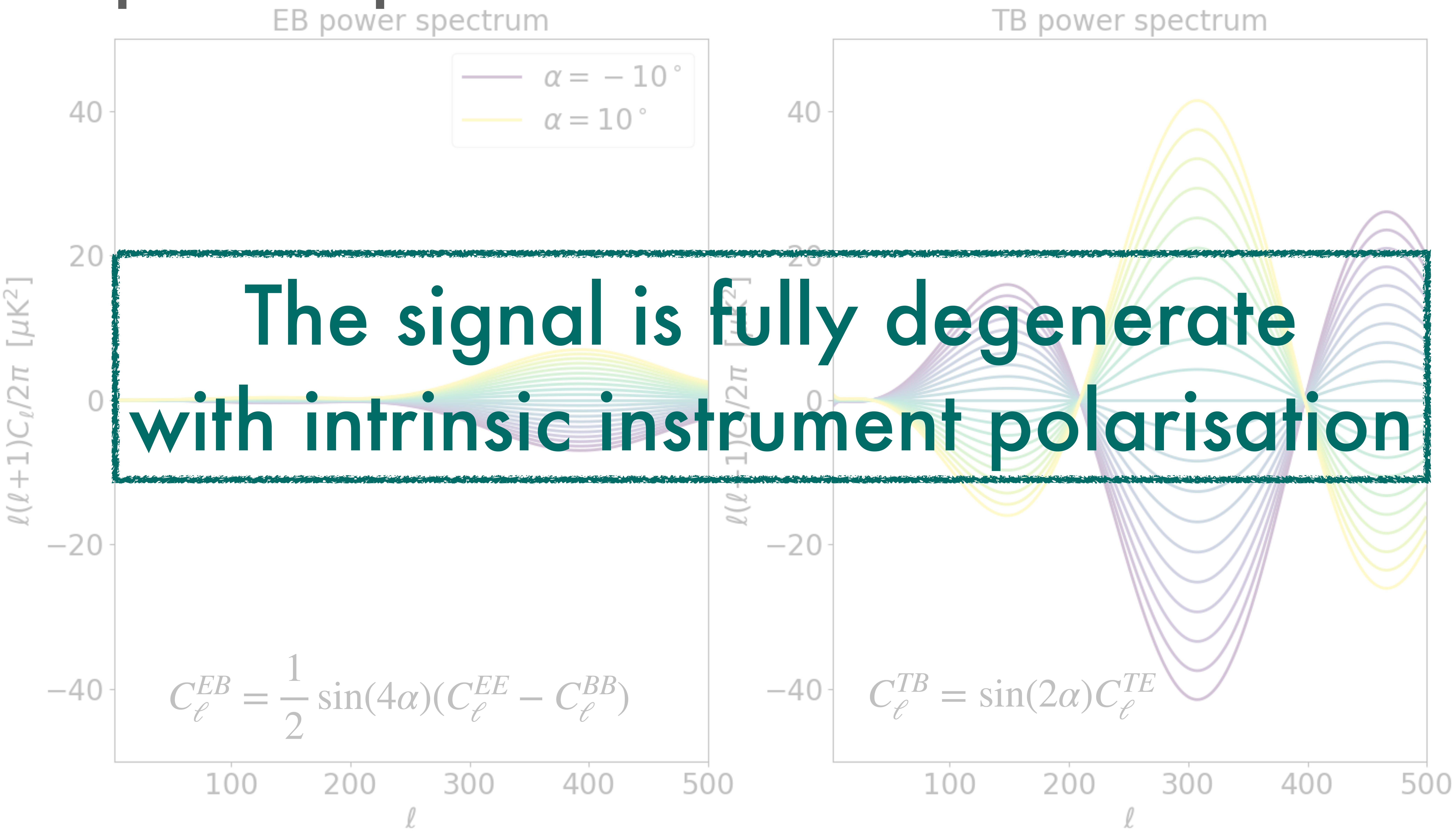
Angle α → **EB & TB signals**

B-modes

CMB power spectrum



CMB power spectrum



The signal is fully degenerate with intrinsic instrument polarisation

State of the art

ACTPol (2020): - 0.07° ± 0.09°
Celestial sources + pointing model – systematic uncertainty unconstrained

Planck/WMAP data (2021/2022): ~ 0.3° ± 0.1°
Assumes model for foreground emission

Our goal: $\sigma(\alpha)$ < 0.1°
Absolute angle calibration, careful systematics mitigation

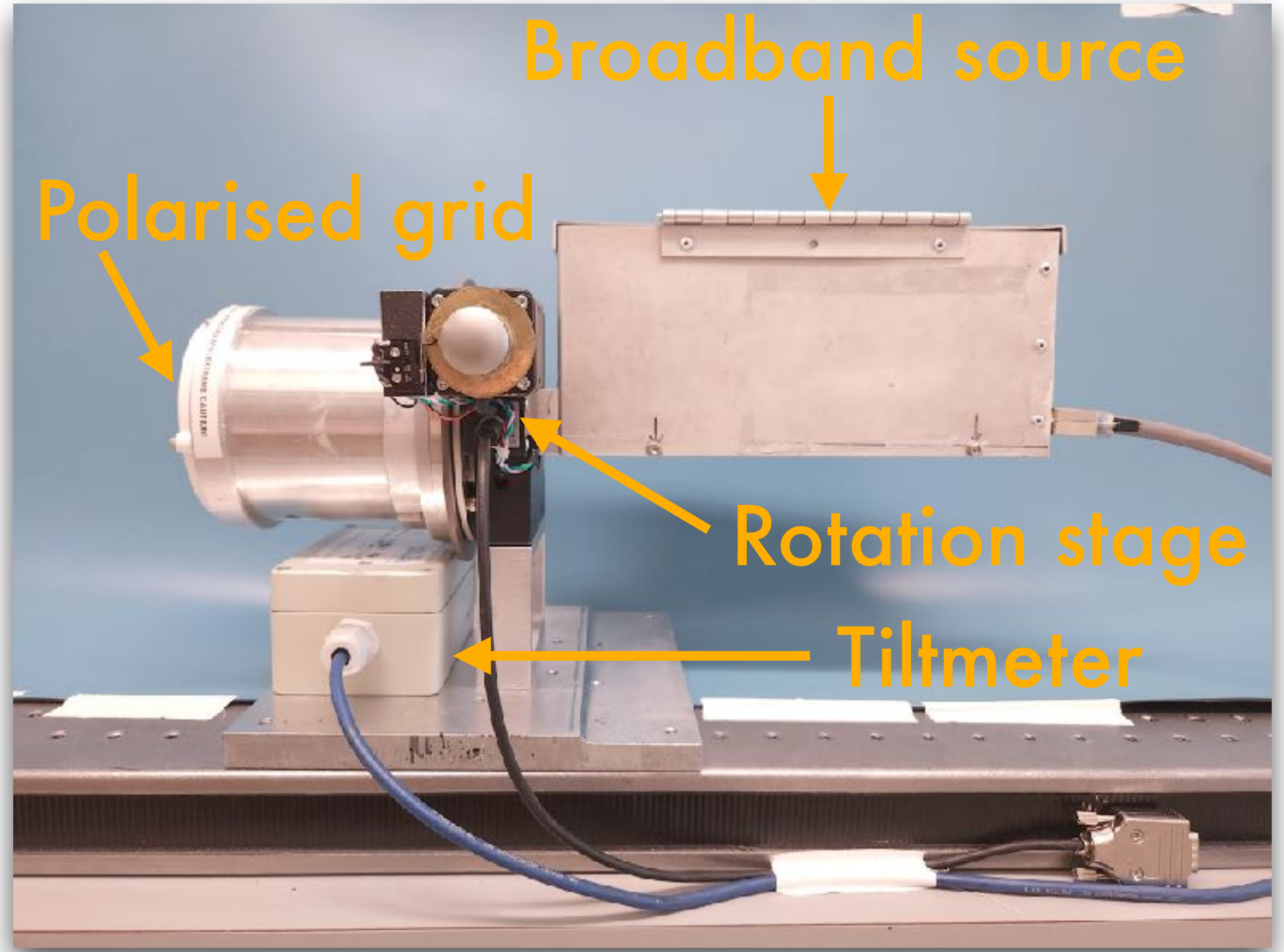
Overview

1. Measure **individual detector polarisation angles** of BICEP3
2. Use these angles in real data + sims to create **data products** that include information about the **telescope intrinsic polarisation**
3. **Fit an angle** to the real data and sims power spectra
4. Compare real data to sims given **error budget $\sigma(\alpha)$**
   → Instrumental calibration (statistical and systematic uncertainties)
   → CMB data (noise, lensing, dust, instrumental systematics)

We remain blinded to real data

Calibrating BICEP3

Rotating Polarised Source (RPS)

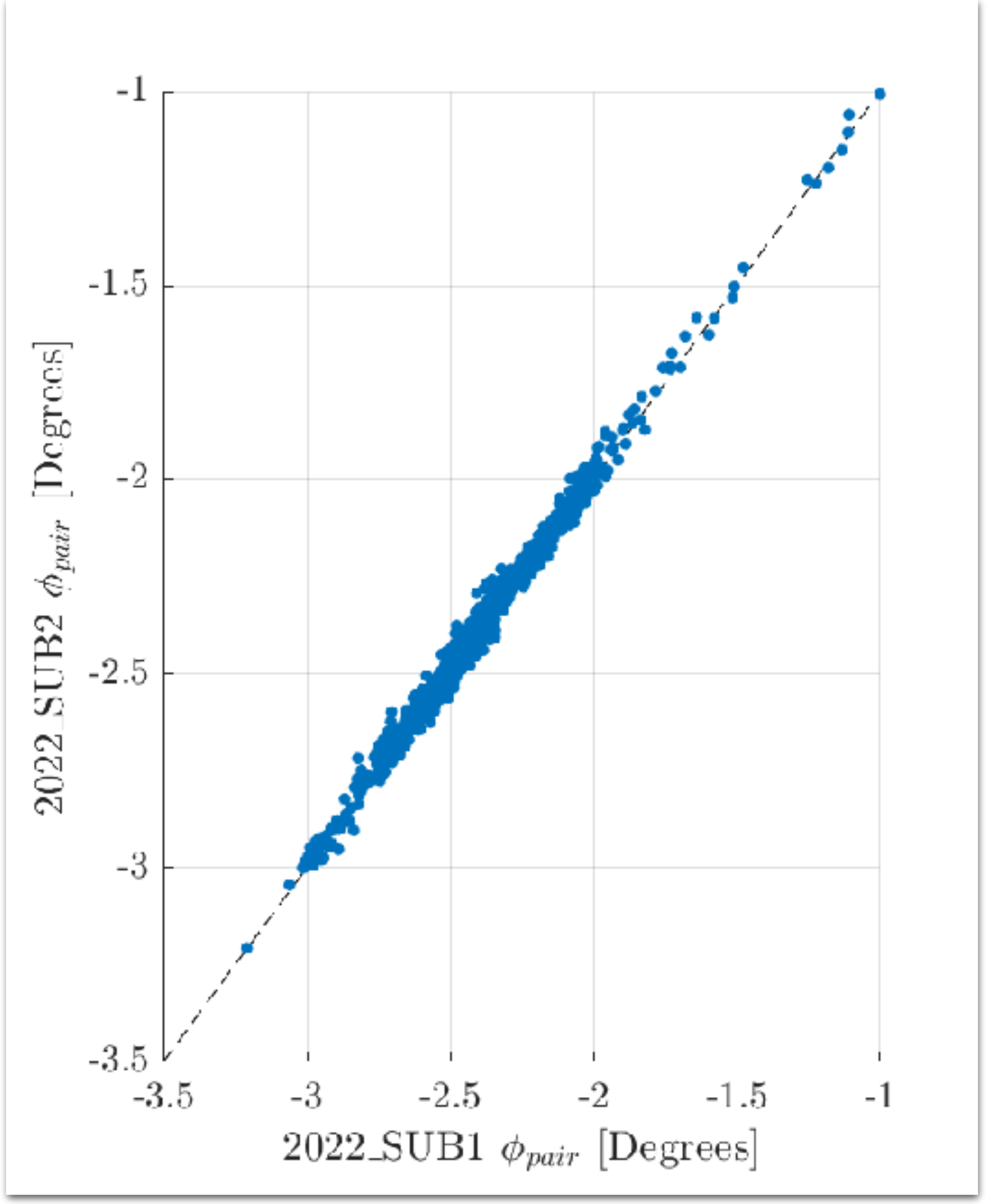


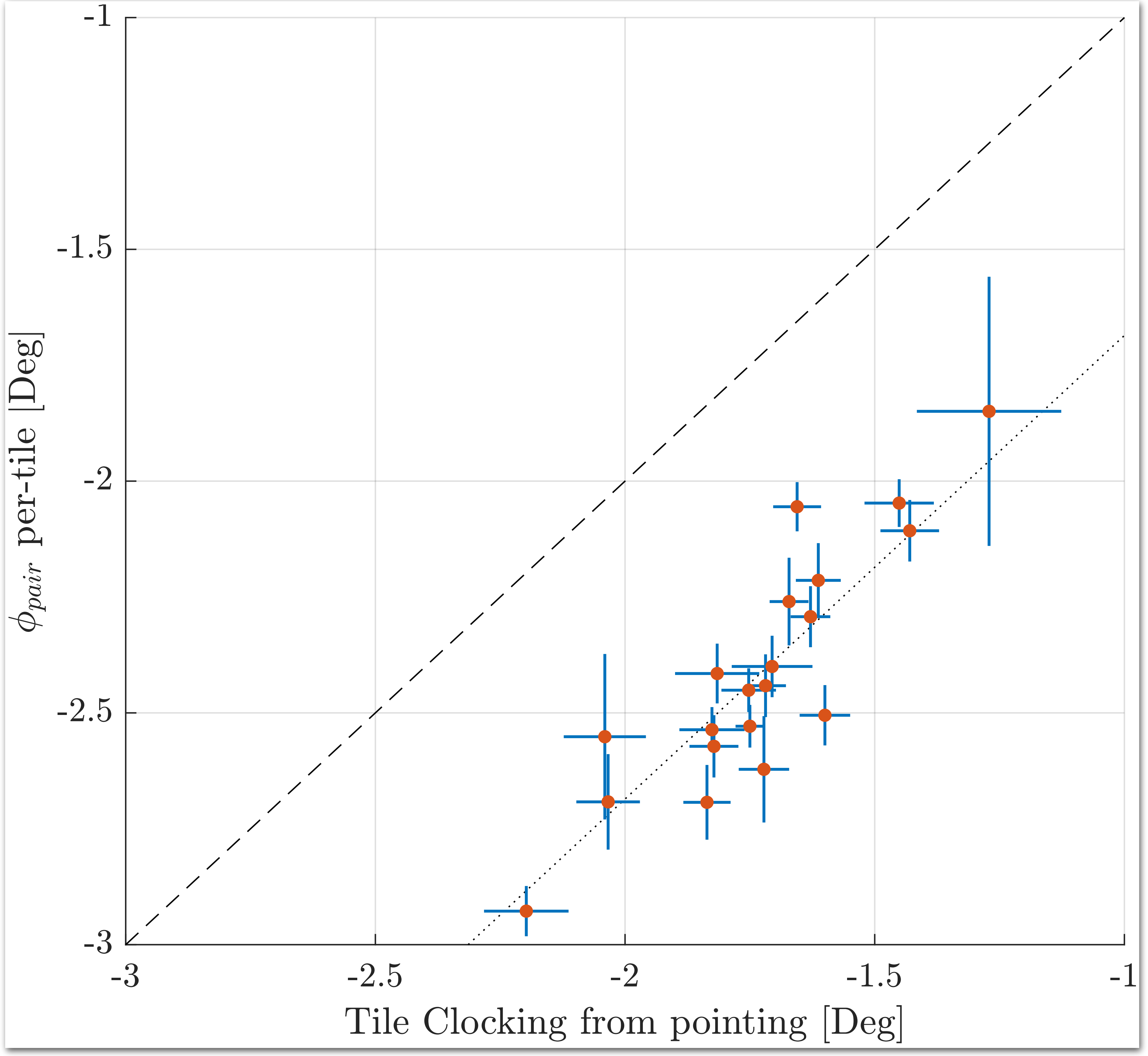
2022 RPS calibration campaign

1-month campaign
390hrs of calibration observation
+ 240hrs of cross-checks & Moon obs.
9 different telescope orientations

BK Collaboration/J. Cornelison

Polarisation angle measurements





Statistical uncertainty
σ(α) = 0.02°

Consistency with
per-tile pointing

Improved Polarization Calibration of the BICEP3 CMB Polarimeter at the South Pole
J. Cornelison, **C. Vergès** & BK collaboration – SPIE 2022

Polarisation angle measurements

Systematic uncertainty: **σ(α) > 0.1 ° :(**

On-going lab investigations with A. Polish, K. Sjöberg

Constraining power of the BICEP3 data set

Sims that contain...

→ only noise: **σ(α)** = 0.061°

→ only lensed-ΛCDM: **σ(α)** = 0.035° (vs unlensed-ΛCDM **σ(α)** = 0.004°)

→ **lensed-ΛCDM + noise + Gaussian dust: σ(α) = 0.078°**

→ additional **σ(α)** = 0.02° to account for non-Gaussian dust contribution

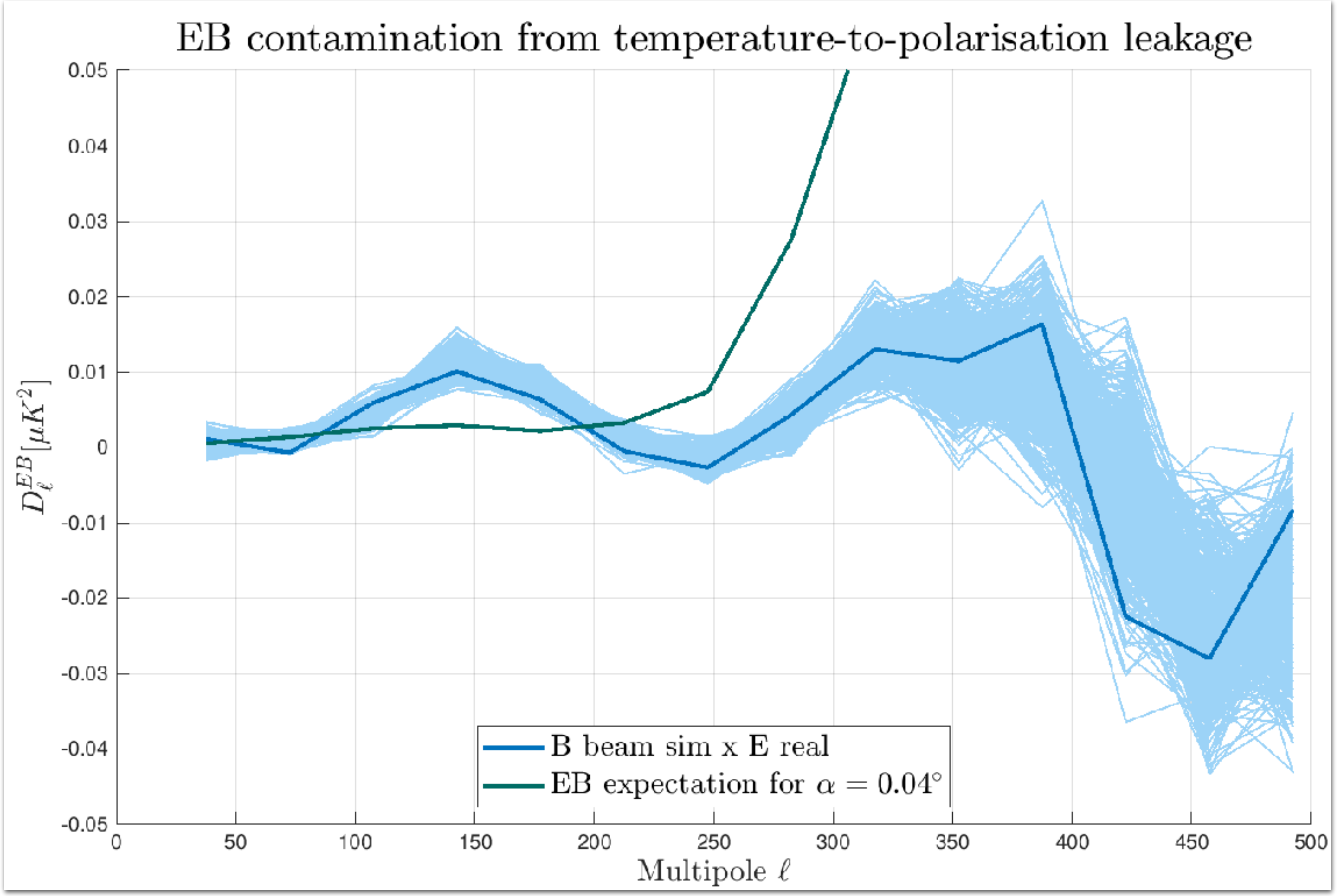
Real BK dust map – no EB contribution expected above Gaussian dust

Instrumental systematics

TP leakage from main beam mismatch

σ(α) ~ 0.04°

Due to T-to-B leakage correlating with TE in the CMB



Cosmic birefringence quest summary

	Calibration	CMB data
Statistical uncertainty	0.02 °	**0.078 °**
Systematic uncertainty	**> 0.1 °**	0.04°

How to address the biggest contributions in the error budget?

1. Improve & better characterise hardware performance
2. Use more data, delens

Measurement of BICEP3 polarisation angles and consequences for constraining cosmic birefringence and inflation
C. Vergès, J Cornelison & BK collaboration (in prep.)
Improved RPS calibration for the BICEP3 telescope – K. Sjöberg et al., AAS Winter Meeting - January 2024

Contributions

→ Expertise in analysis that ties calibration data to cosmological results

→ **BK**: leading role in *Calibration* & *Systematics* & contributions to published science results

→ **CMB-S4**: *Low-ℓ BB working group* co-coordinator & *SAT Systematics* project leader

Plans

Ensure the success of the CMB-S4 inflation survey

- → Calibration & Systematics control
- → Foreground cleaning
- → Delensing

Advance our comprehension of fundamental physics using CMB data

Let's continue to unravel the mysteries of the Universe!