Probing the Early Universe with Simons Observatory

Status and updates from ~one year of observations

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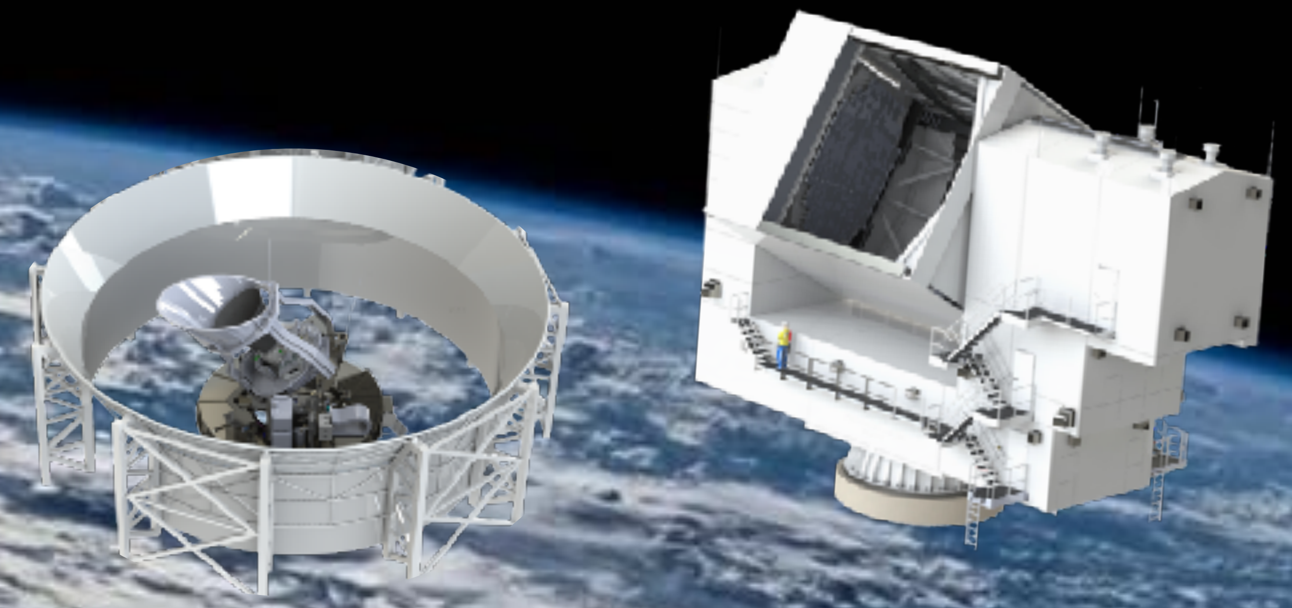
Postdoc @ APC-CNRS
February, 2nd 2026

LPNHE seminar



SciPol
Science from the large scale cosmic microwave background polarization structure

Outline

- The Cosmic Microwave Background (CMB)
- The Simons Observatory
- Status and (couple of) science goals.
- Modelling of extragalactic foregrounds : the ACT-DR6 example
- Component separation for SO-SATs

Cosmic Microwave Background

Cosmic Microwave Background

Inflation

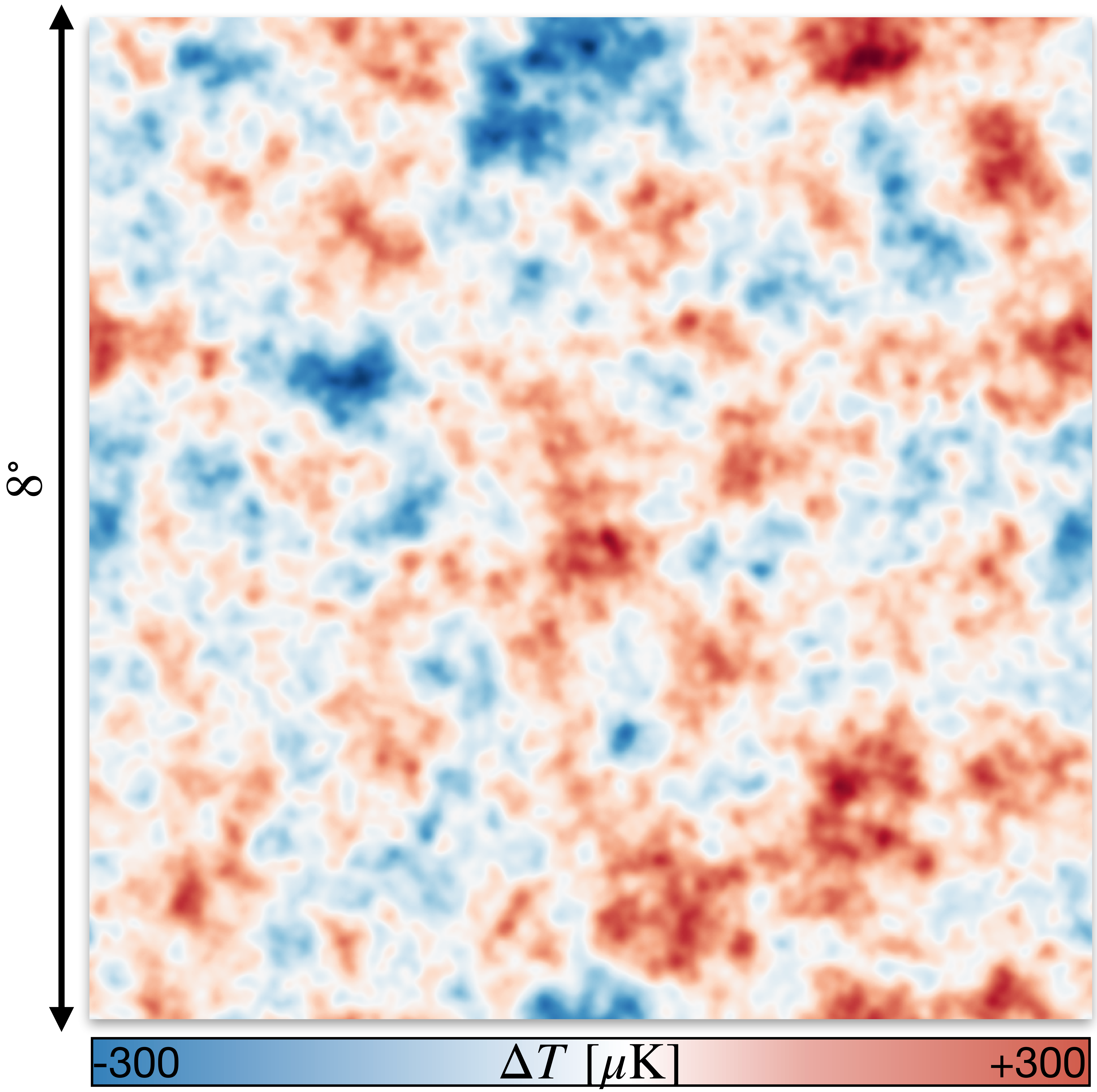
Radiation dominated expansion

CMB photons decoupling

Dark Ages

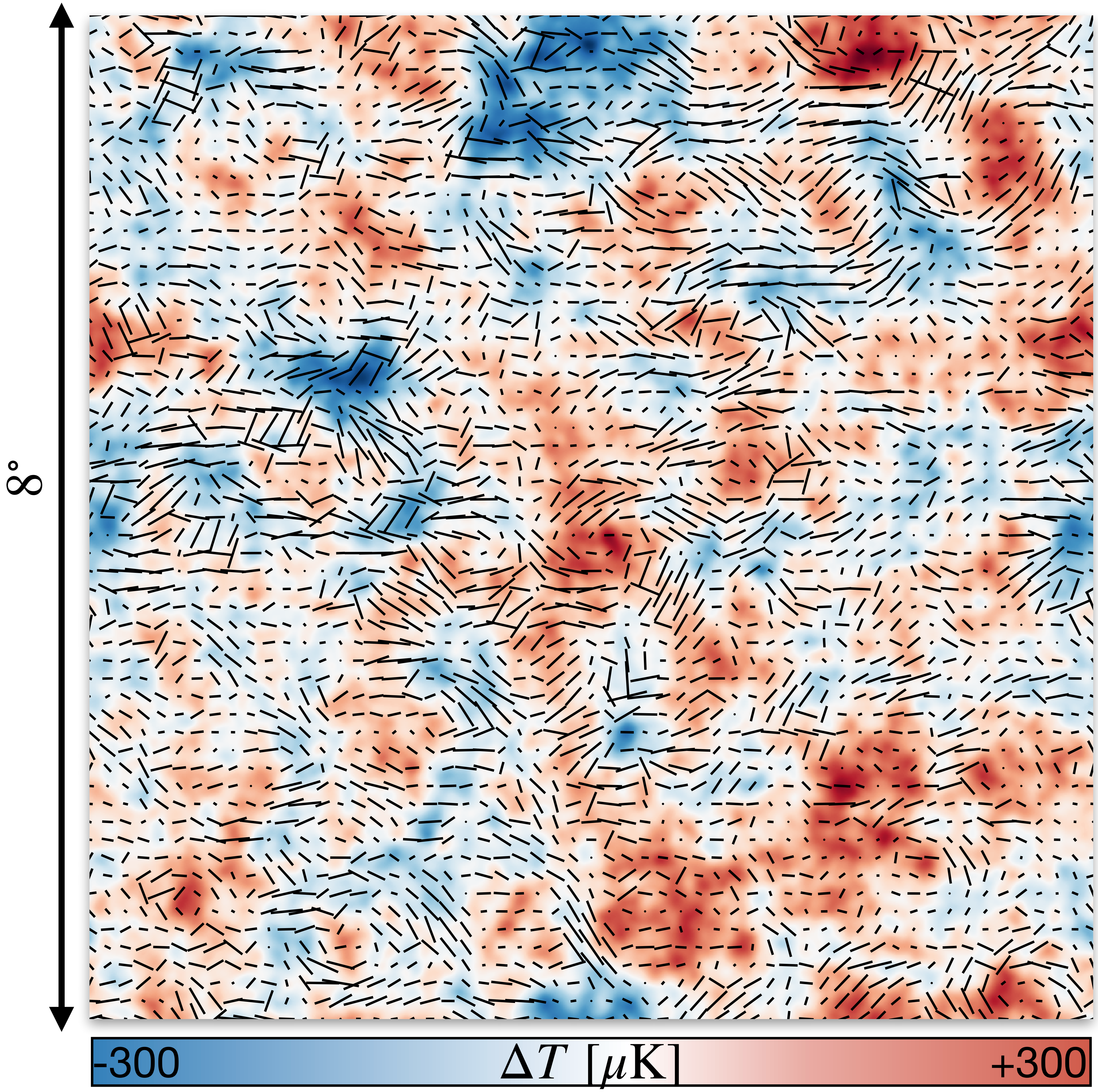
Structure formation and galaxy evolution

Cosmic Microwave Background



- ***Temperature anisotropies:*** caused by inhomogeneities of the primordial plasma (through Thomson scattering).

Cosmic Microwave Background



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- ***Polarisation anisotropies***: caused by local quadrupolar patterns in the inhomogeneities.

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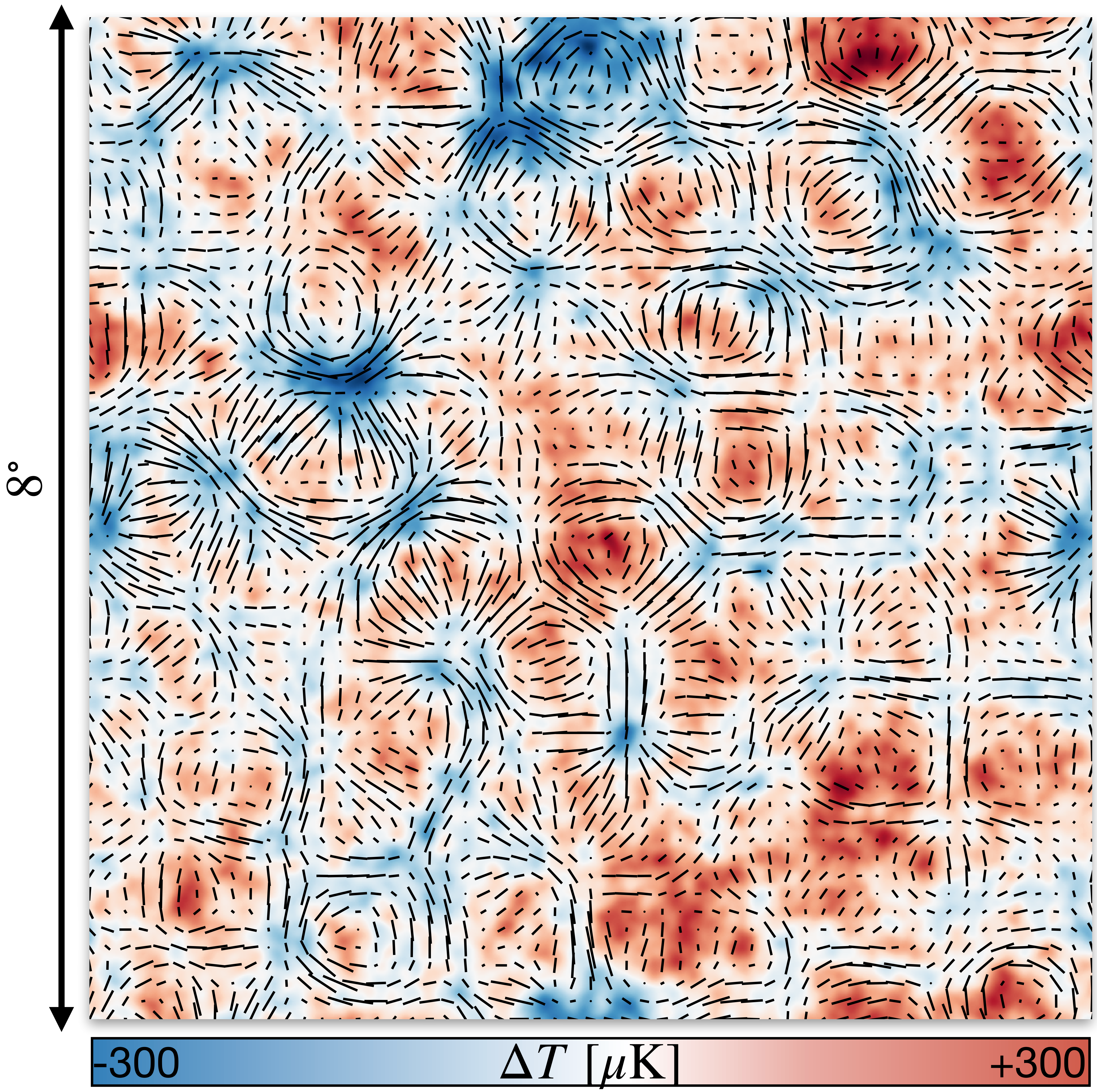

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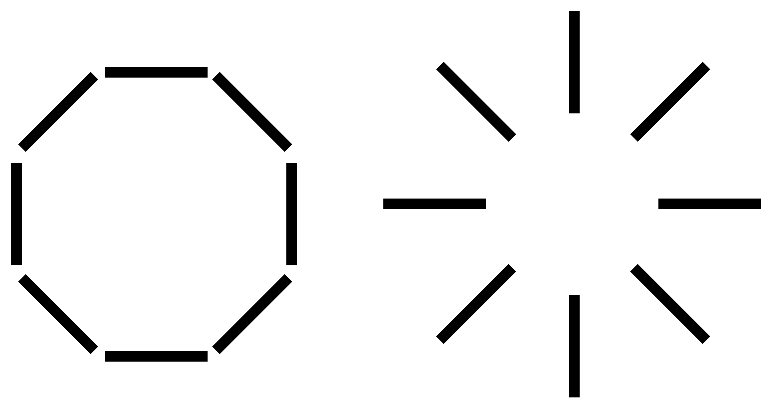
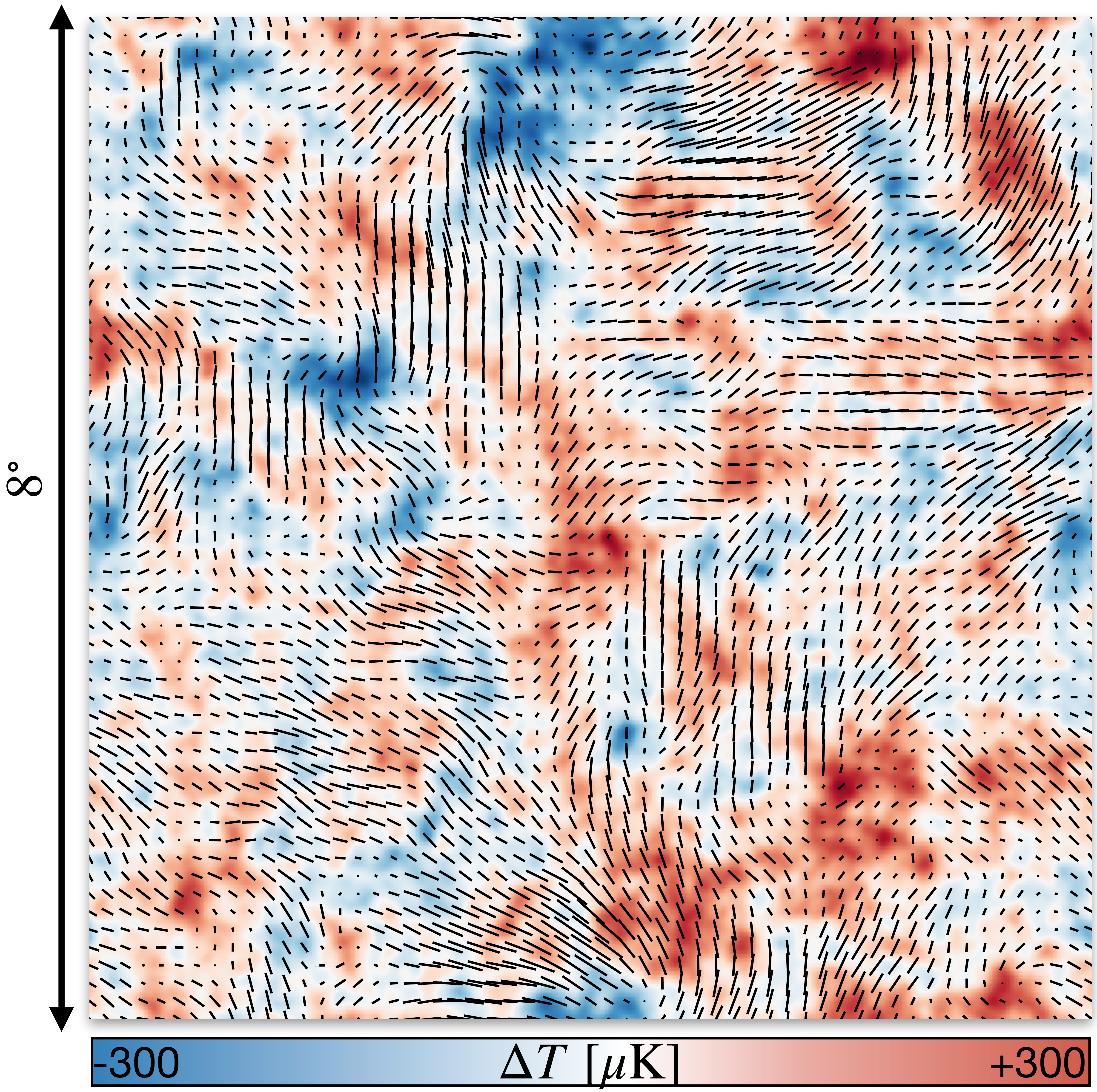
Modes E



Cosmic Microwave Background



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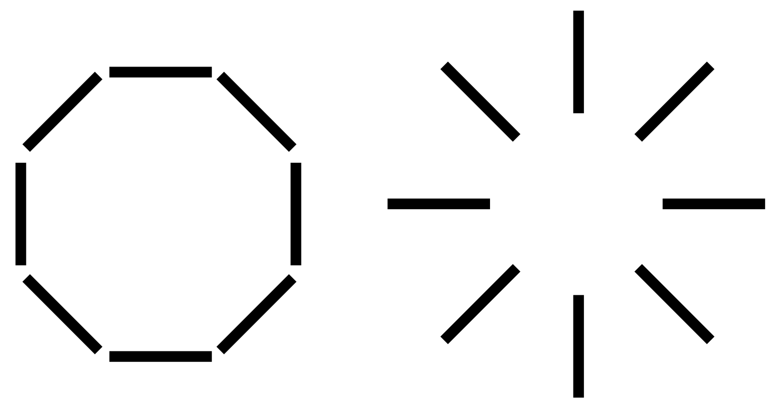
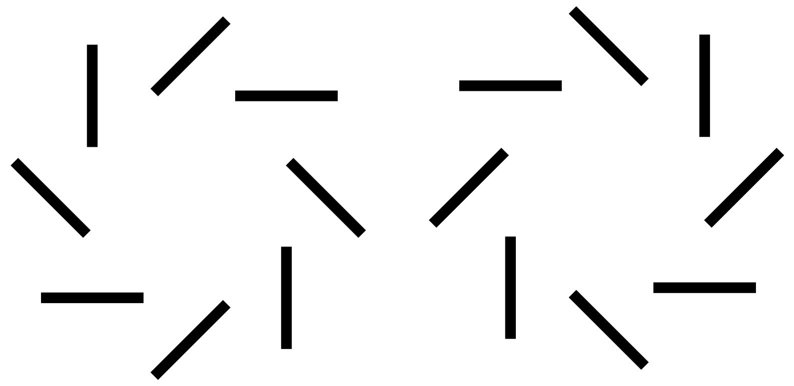
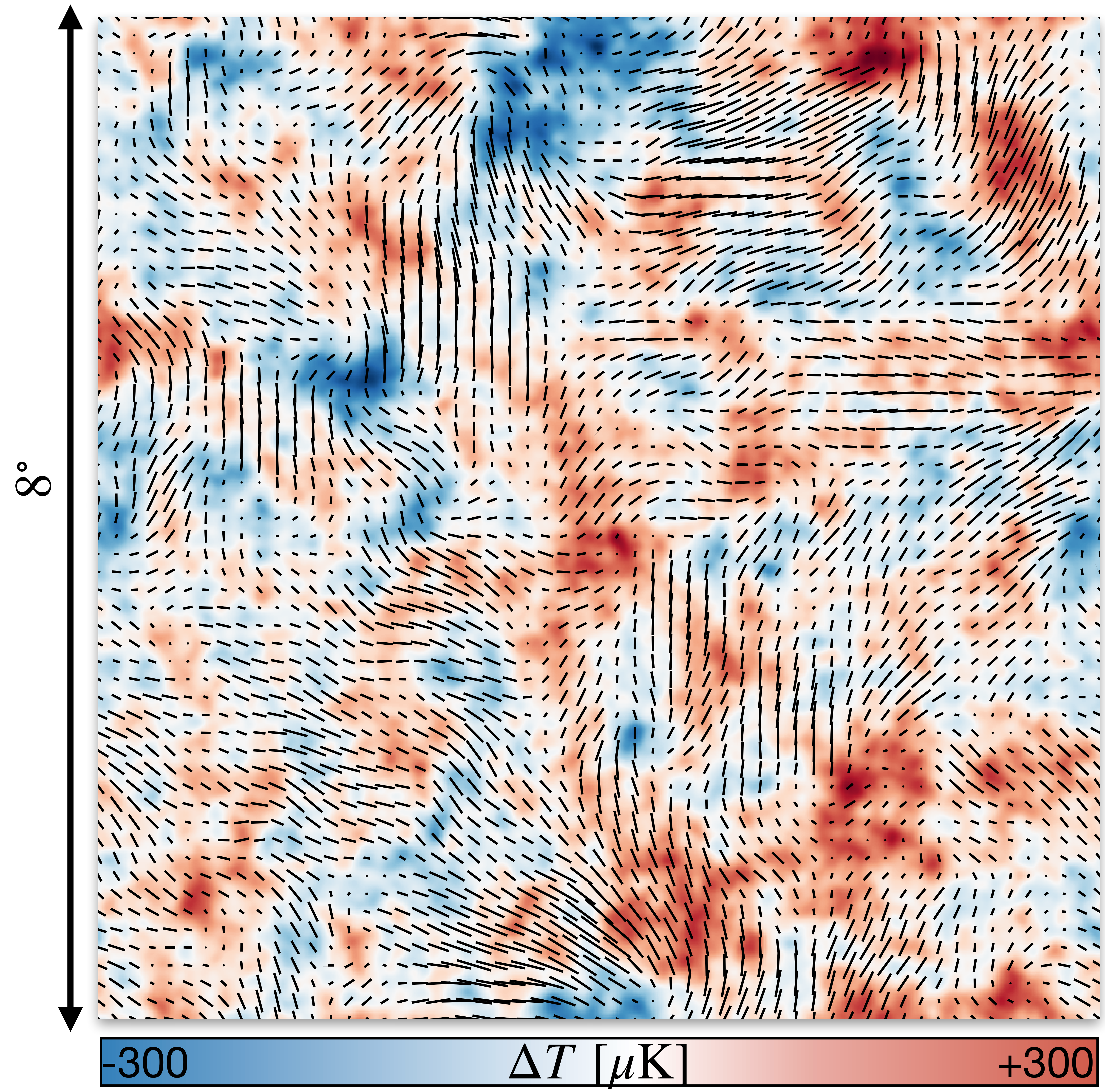


Modes B



Cosmic Microwave Background



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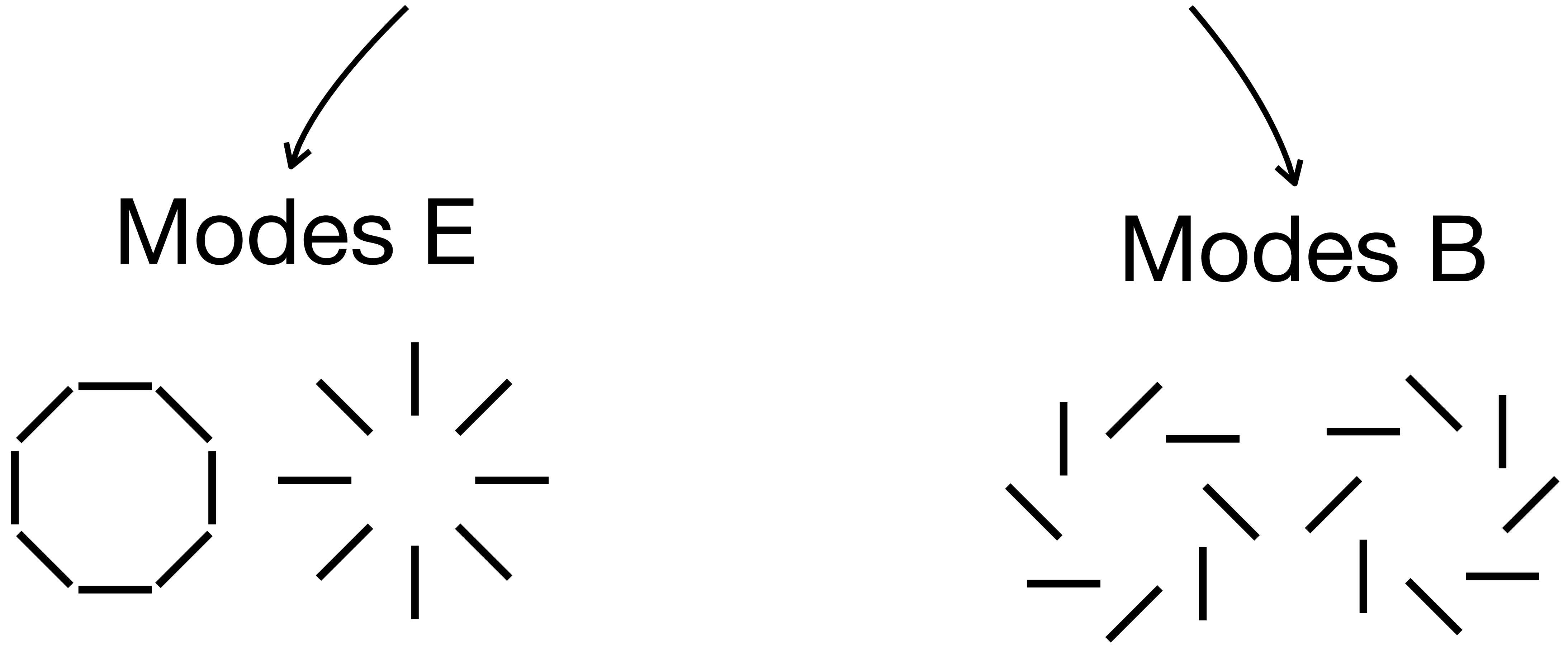
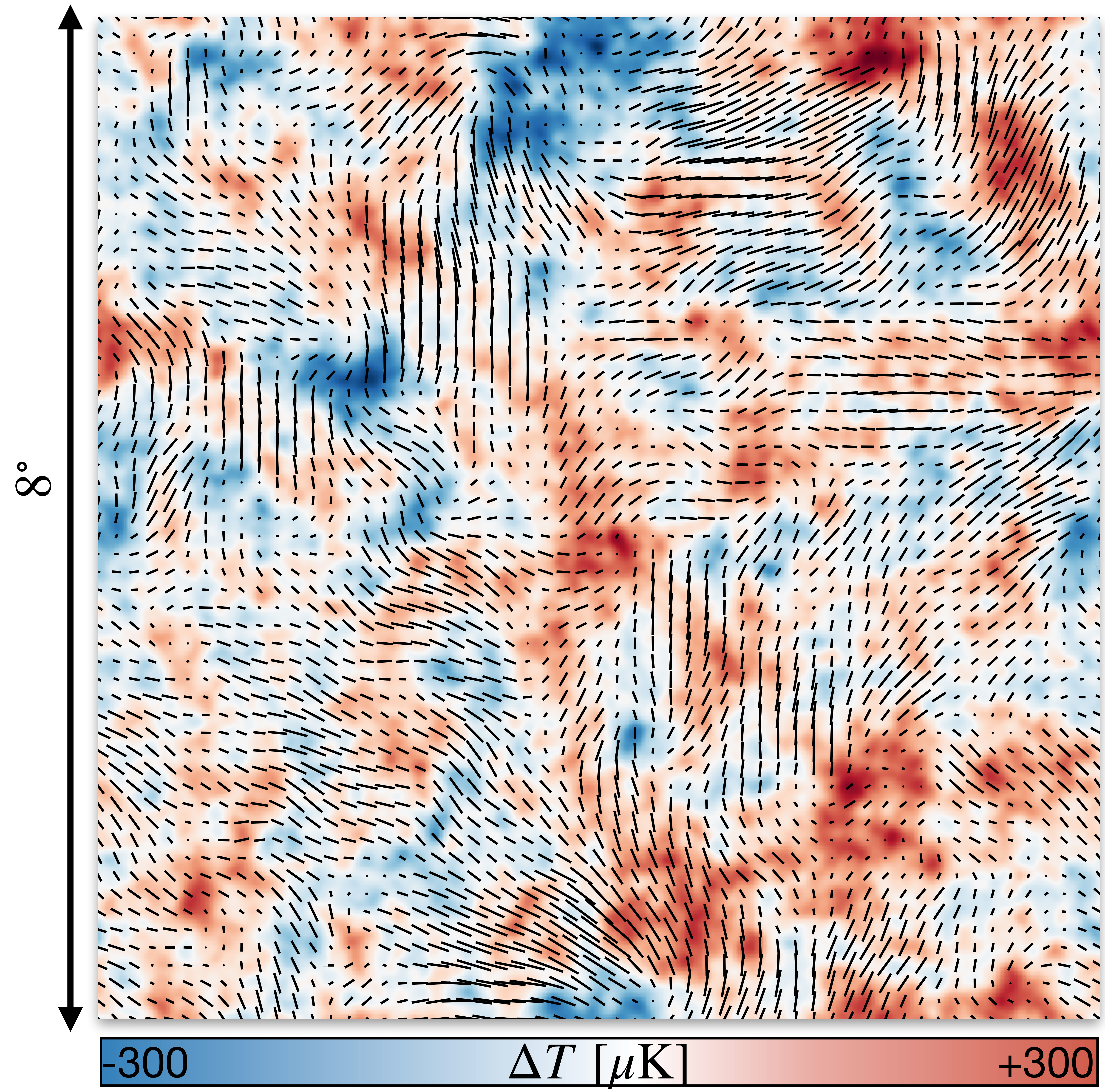


$$dl^2 = a^2(t)\left[1 + 2\zeta(\mathbf{x}, t)\right]\left[\delta_{ij} + h_{ij}(\mathbf{x}, t)\right] dx^i dx^j$$

Cosmic Microwave Background



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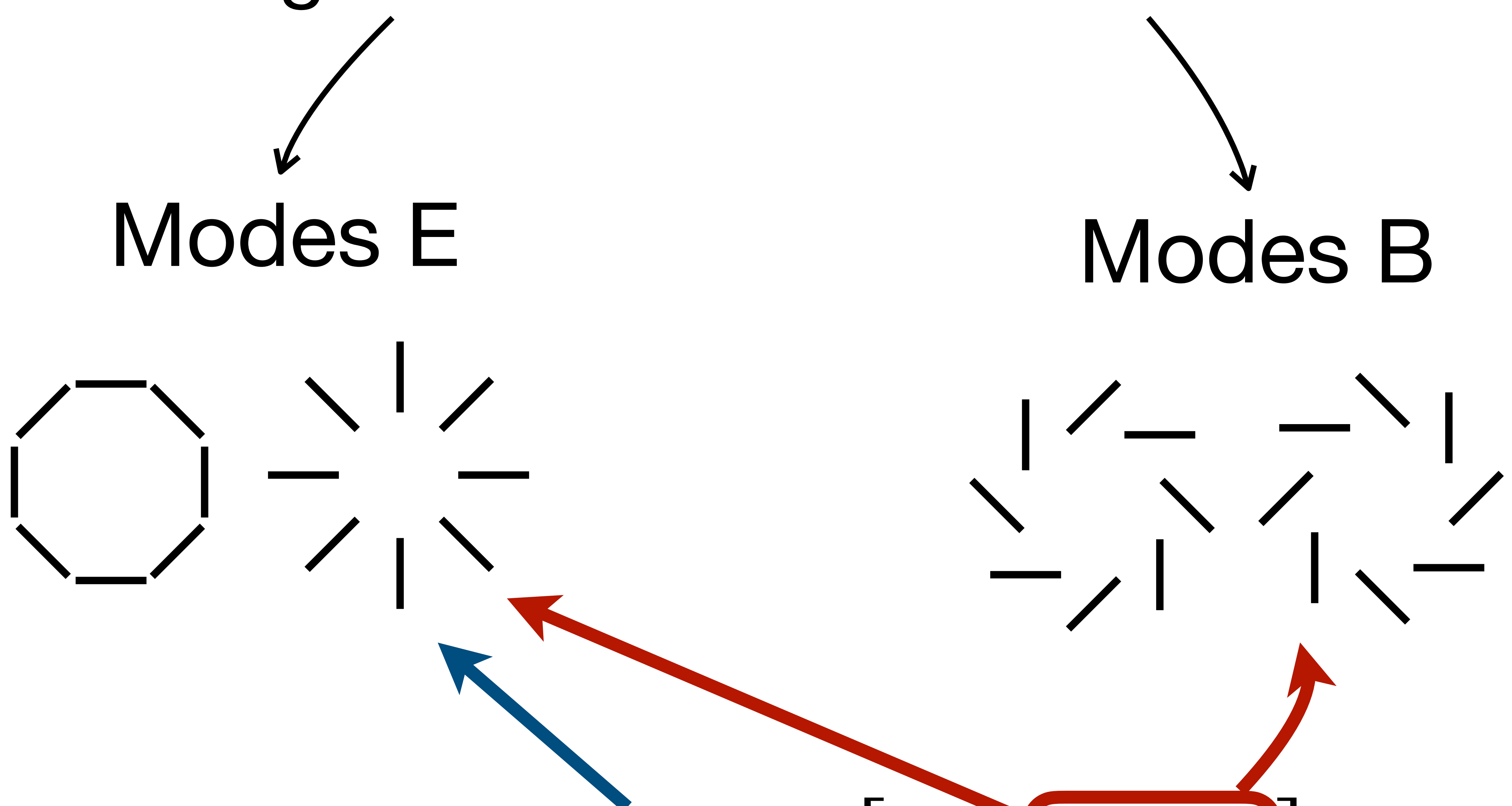

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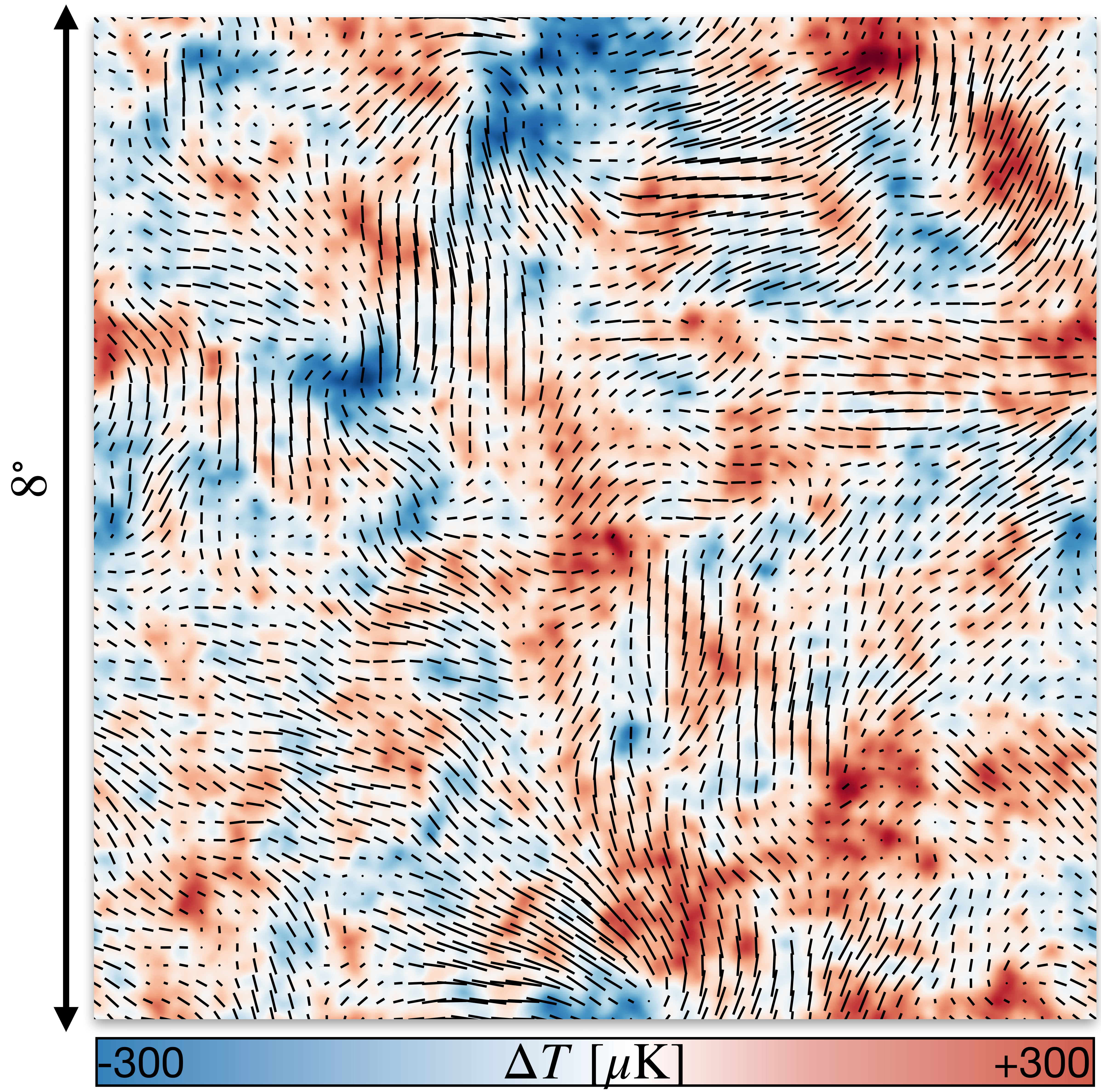

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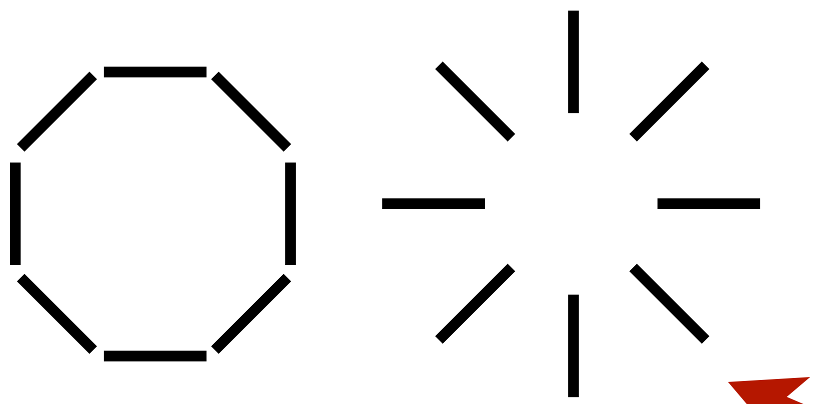
Modes E

Modes B



$$r \propto E^4$$
$$r < 0.032 \ (2\sigma)$$

[Tristam et al. (2023)]

$$dl^2 = a^2(t)\left[1 + 2\zeta(\mathbf{x}, t)\right]\left[\delta_{ij} + h_{ij}(\mathbf{x}, t)\right] dx^i dx^j$$

Cosmic Microwave Background

Inflation

- Large scale B-modes
- Primordial power spectrum (via TT,TE,EE)
- Primordial bispectrum

Radiation dominated expansion

- Y_p and $N_{\rm eff}$ (via damping tail)

CMB photons decoupling

- Imprints of ΛCDM

Dark Ages

Properties of reionisation:
- Duration (via kSZ)
- Mean free path of photons (via kSZ)

Structure formation and galaxy evolution

- Σm_ν (via lensing potential)
- Galaxy evolution
  - cluster properties (via tSZ)
  - feedback efficiency (via tSZ)
- Properties of Dark energy:
  - σ_8 (via lensing and tSZ)

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- Component separation for SO-SATs

How to build a sensitive CMB experiment ?

Noise per detector

Fraction of the sky observed

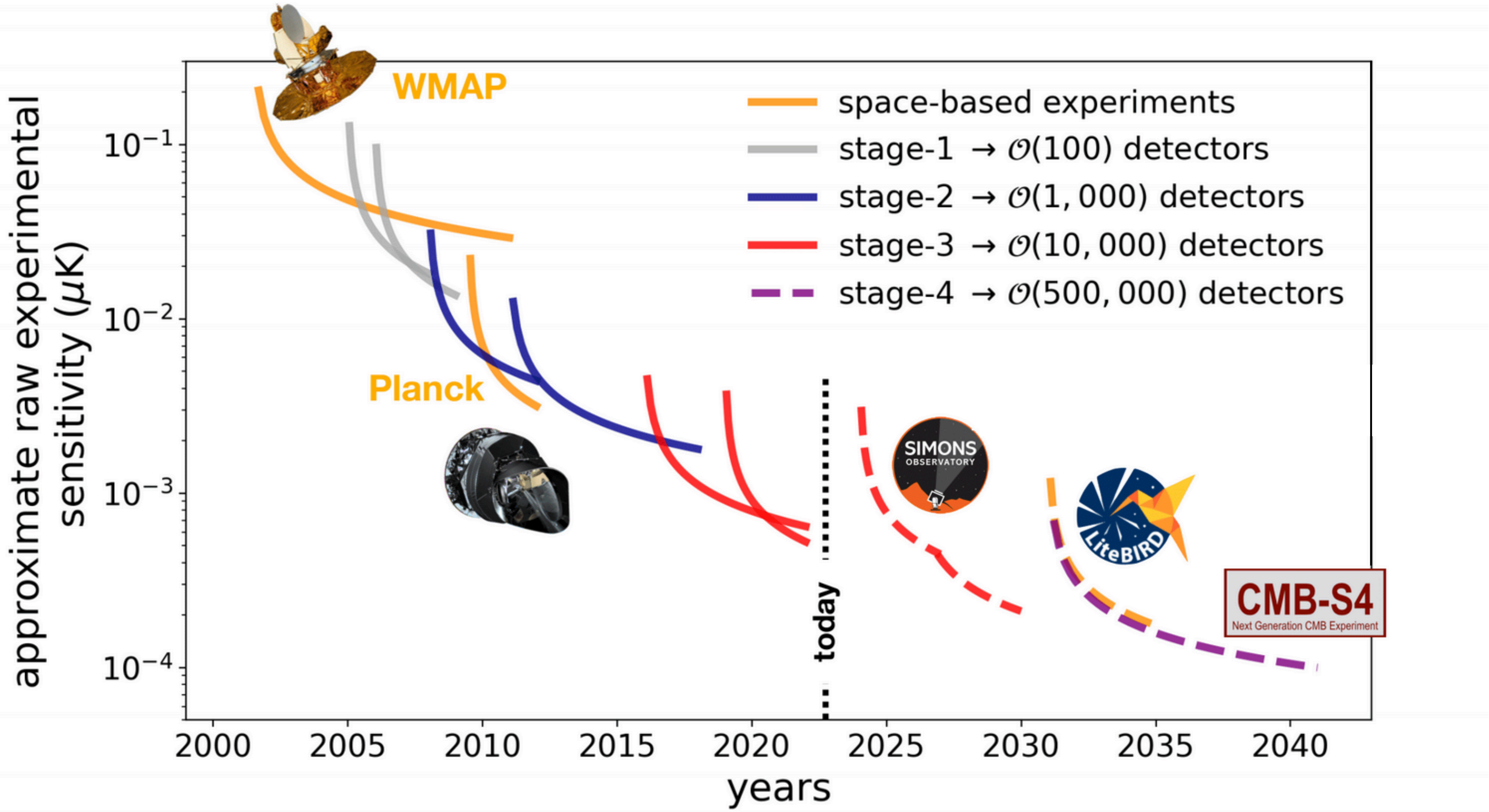
$$s[\mu\mathrm{K}\,.\,\mathrm{arcmin}] = \frac{\mathrm{NET}[\mu\mathrm{K}\,.\,\sqrt{\mathrm{s}}] \times \sqrt{f_{sky}[\mathrm{arcmin}^2]}}{\sqrt{N_{\mathrm{det}} \times Y \times \Delta t[s]}}$$

Number of detectors

Efficiency

Integration time

Noise improvements

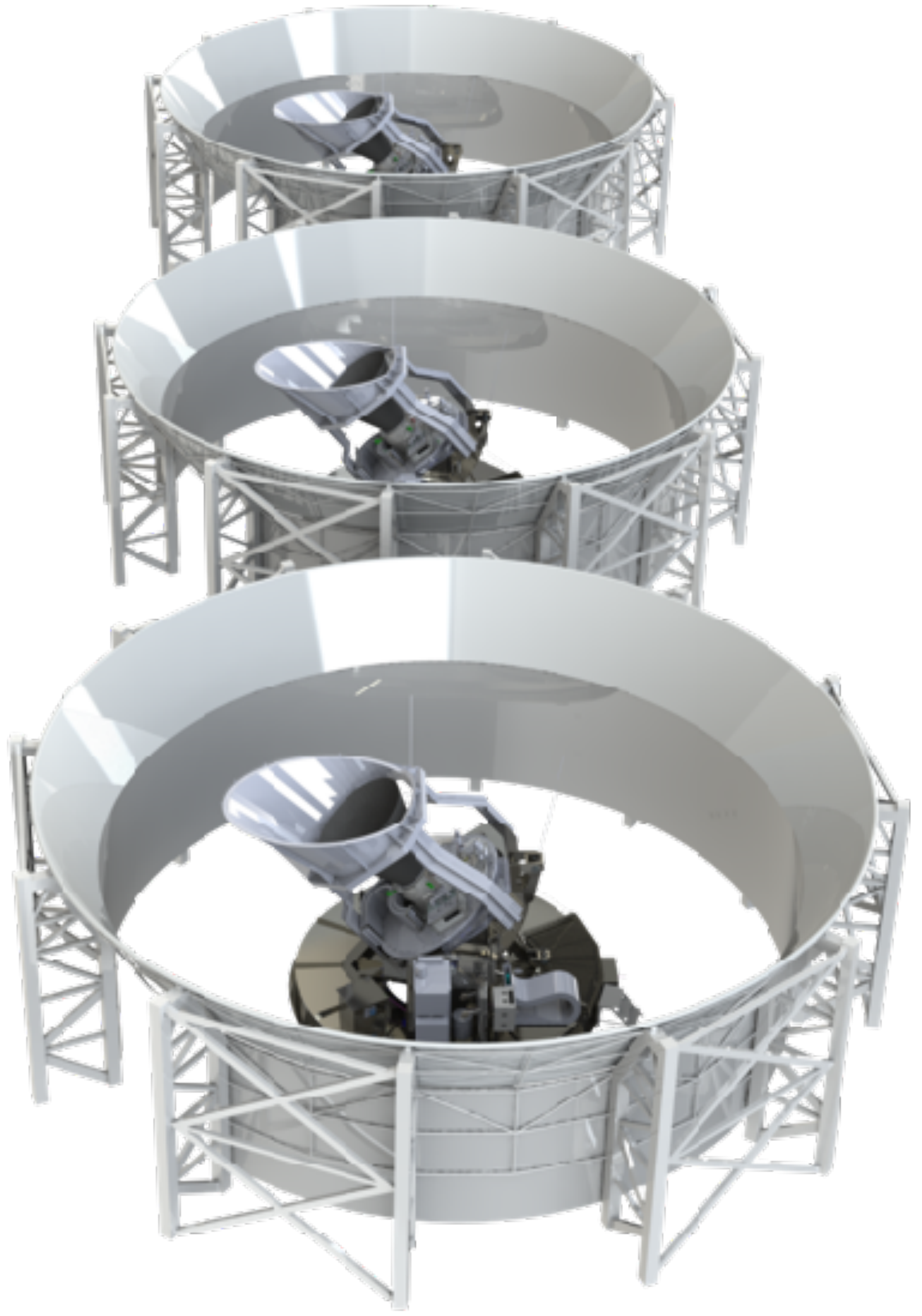


[Credit : J. Errard]

Simons Observatory

SO Small Aperture Telescopes (SATs)

- Nominally 3 telescopes
- **30.000** TES detectors
- **6 frequency** bands
- Focusing on **large scale polarisation modes**



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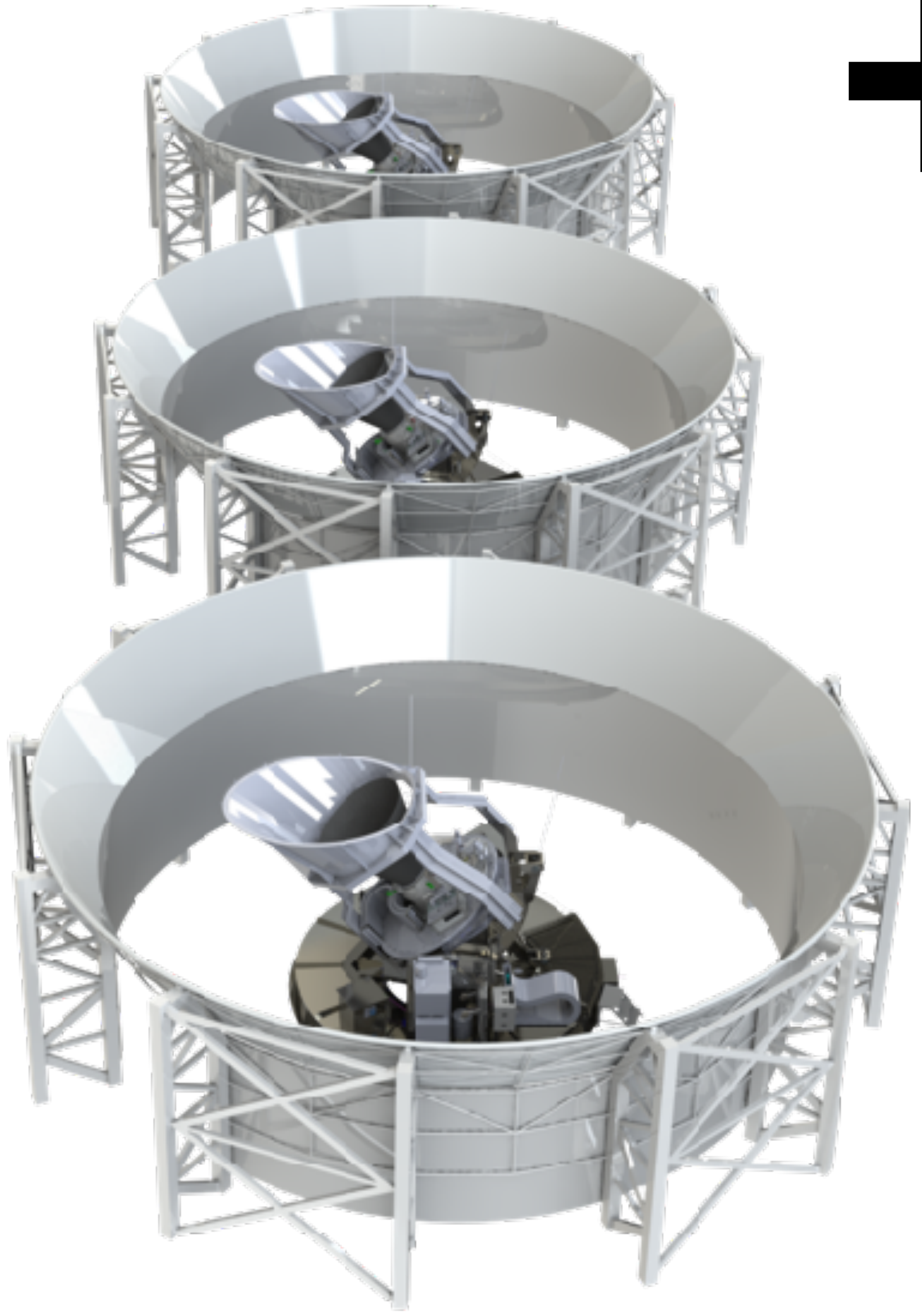

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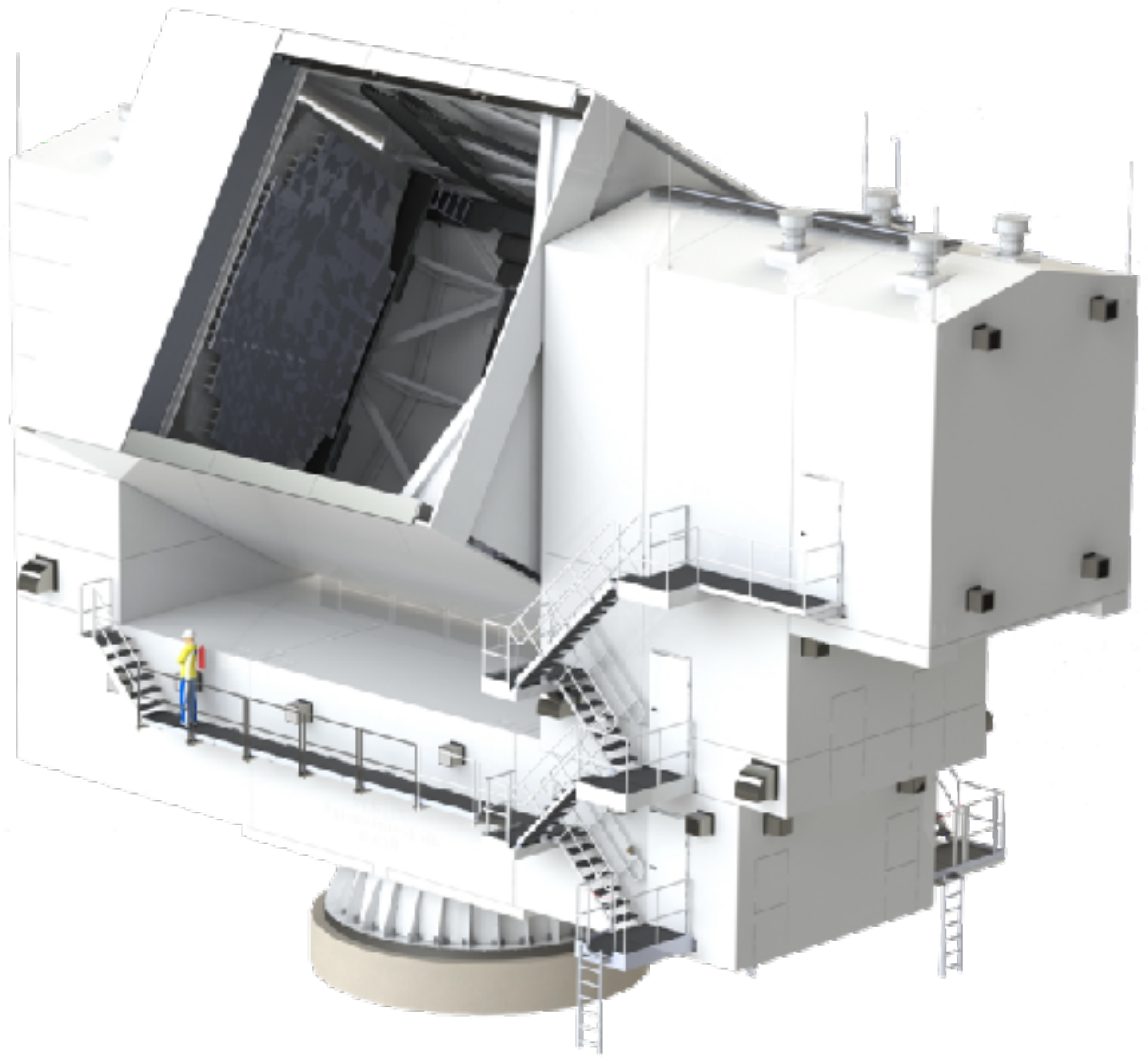

SO Large Aperture Telescope (LAT)

- **6m cross-Dragone** telescope
- **30.000** TES detectors
- **6 frequency** bands
- Observing **small scale anisotropies** over a large fraction of the sky

Simons Observatory

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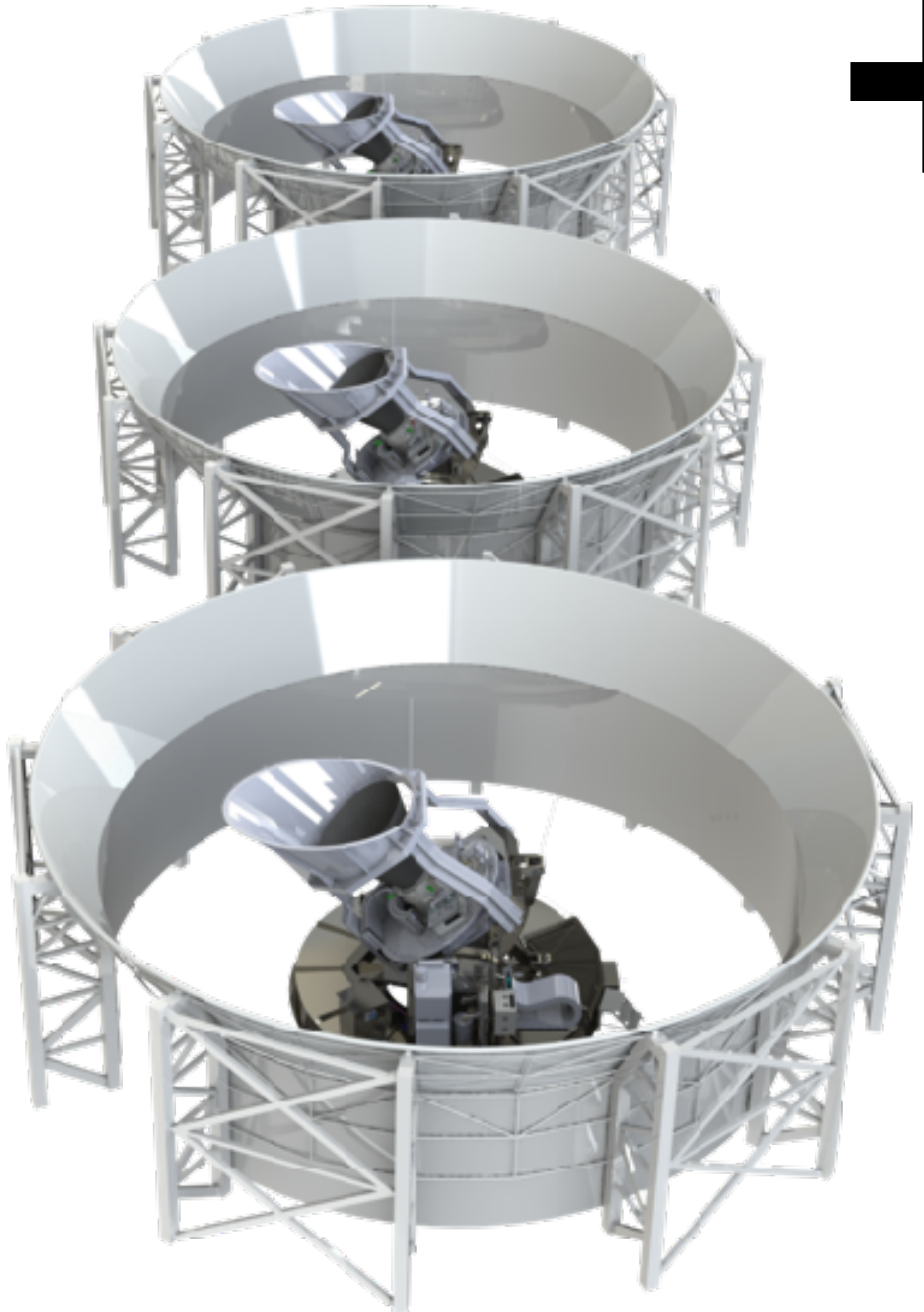
SO:UK + SO:JP

- 3 additional telescopes
- **30.000** TES detectors
- **Extended frequency range to LF**



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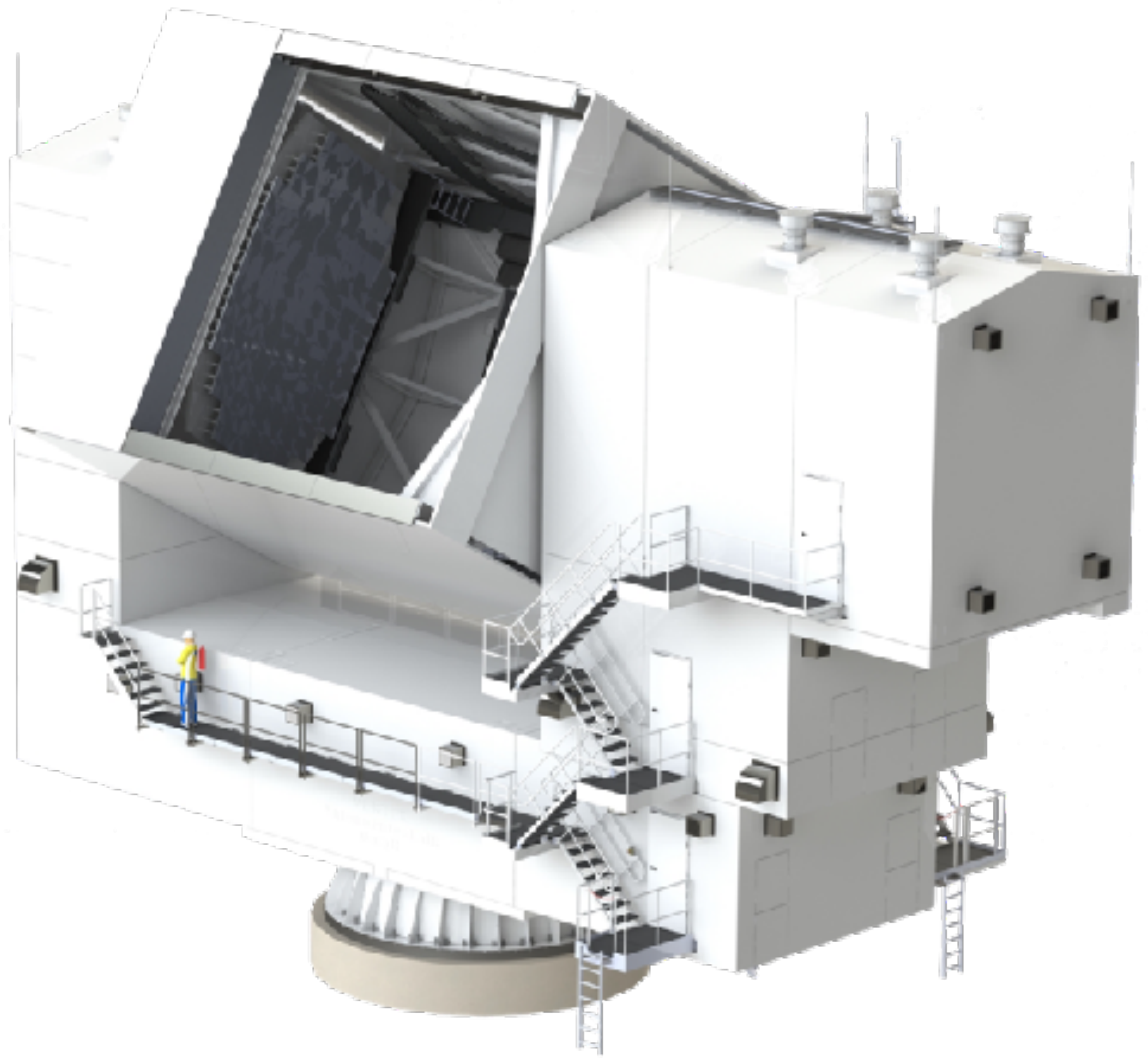

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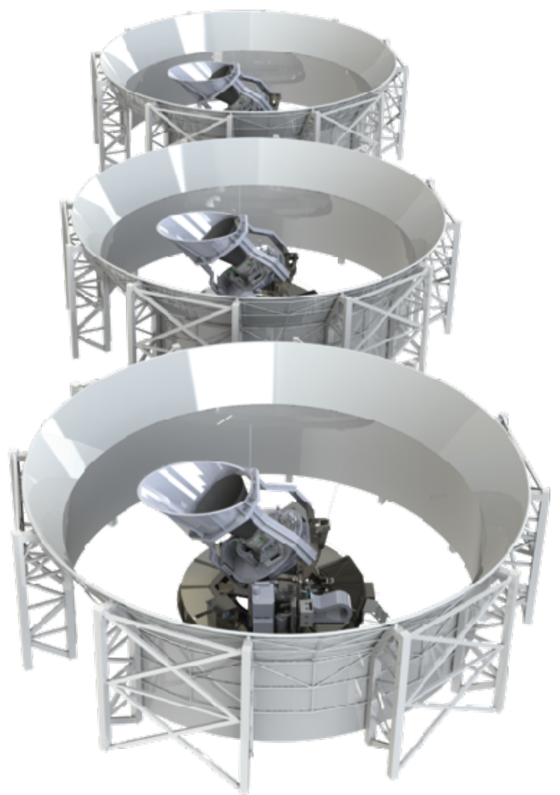

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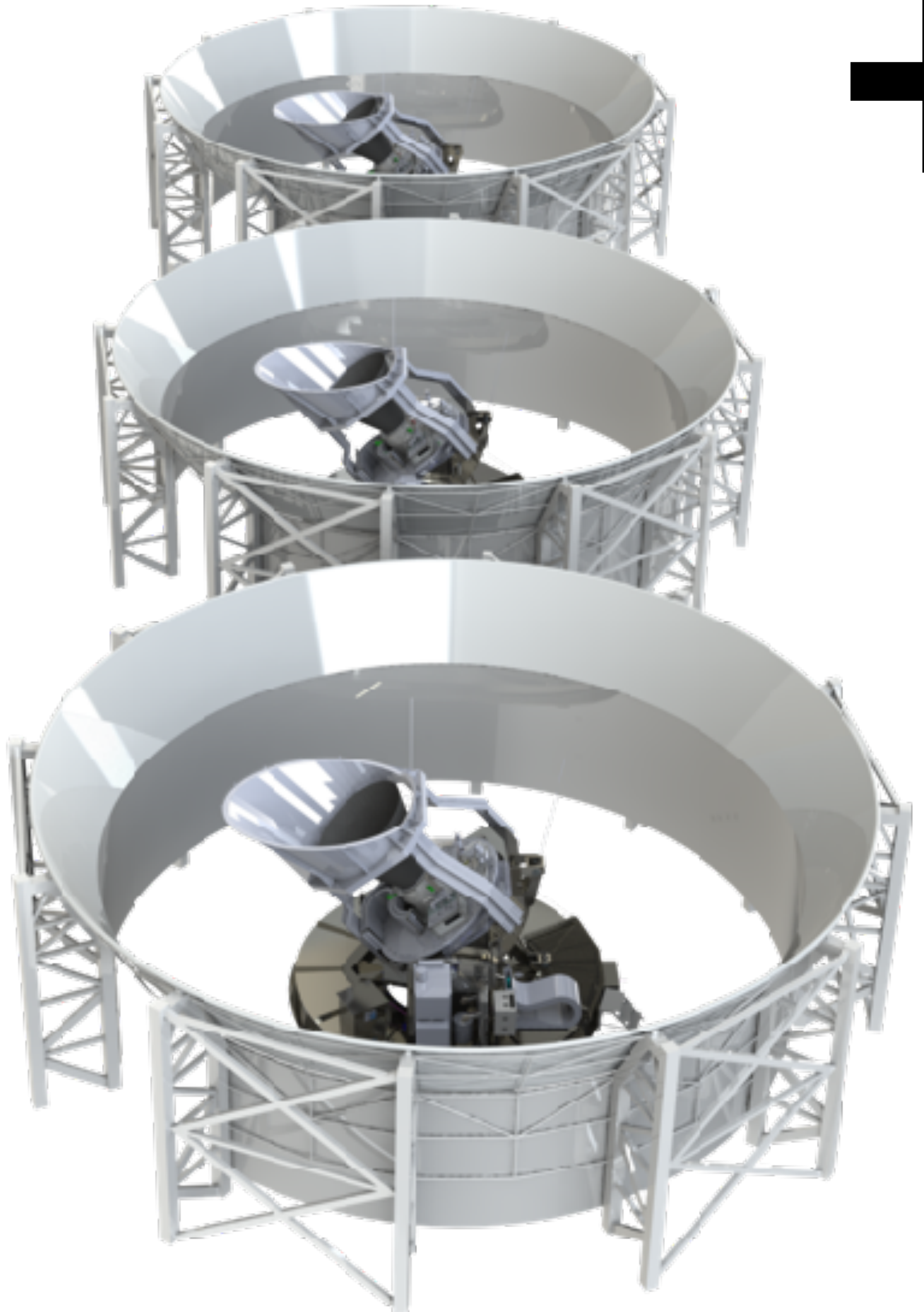
SO:UK + SO:JP + KAIROS (?)

- 3 additional telescopes
- **30.000** TES detectors
- **Extended frequency range to LF and UHF**



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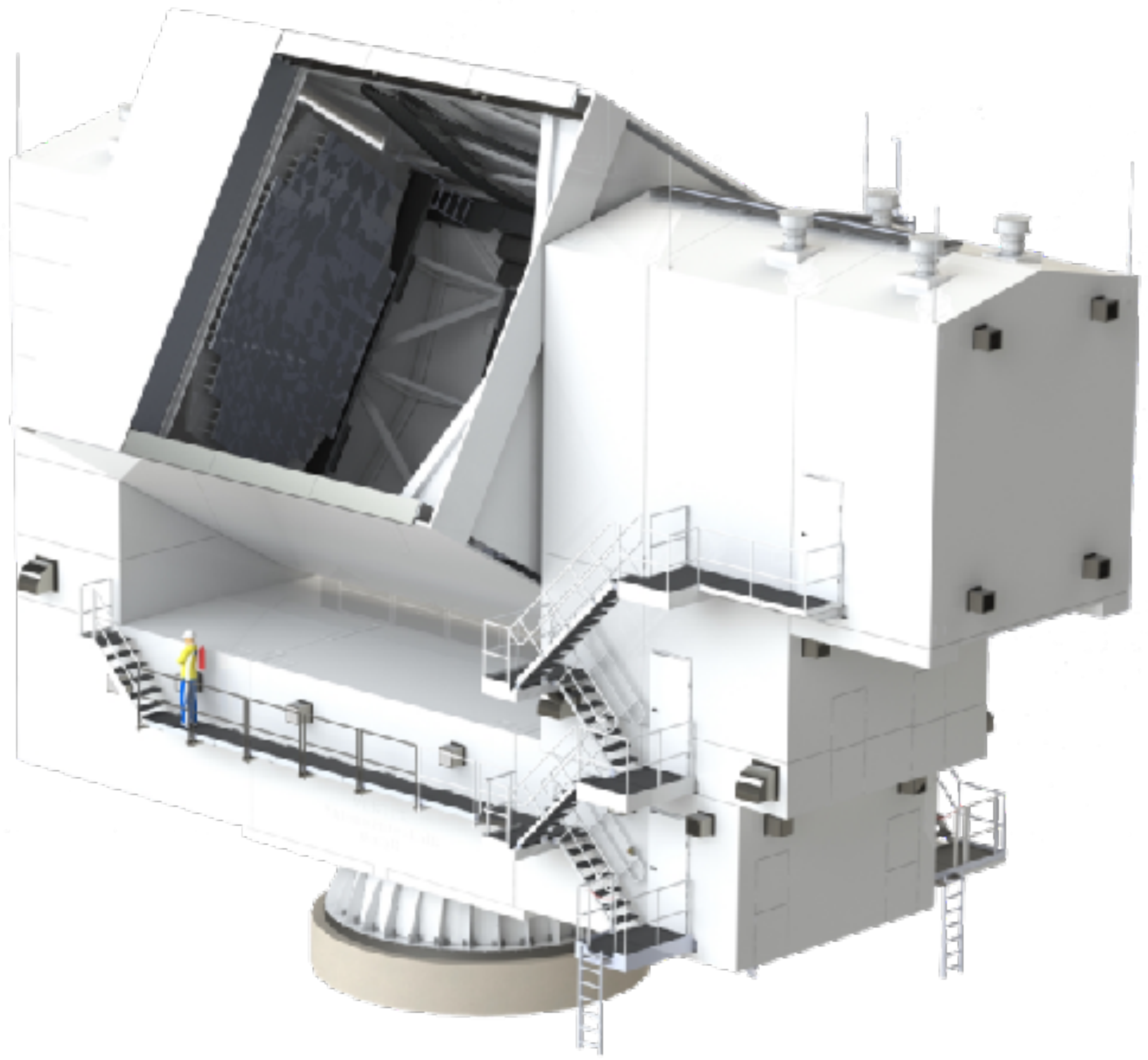

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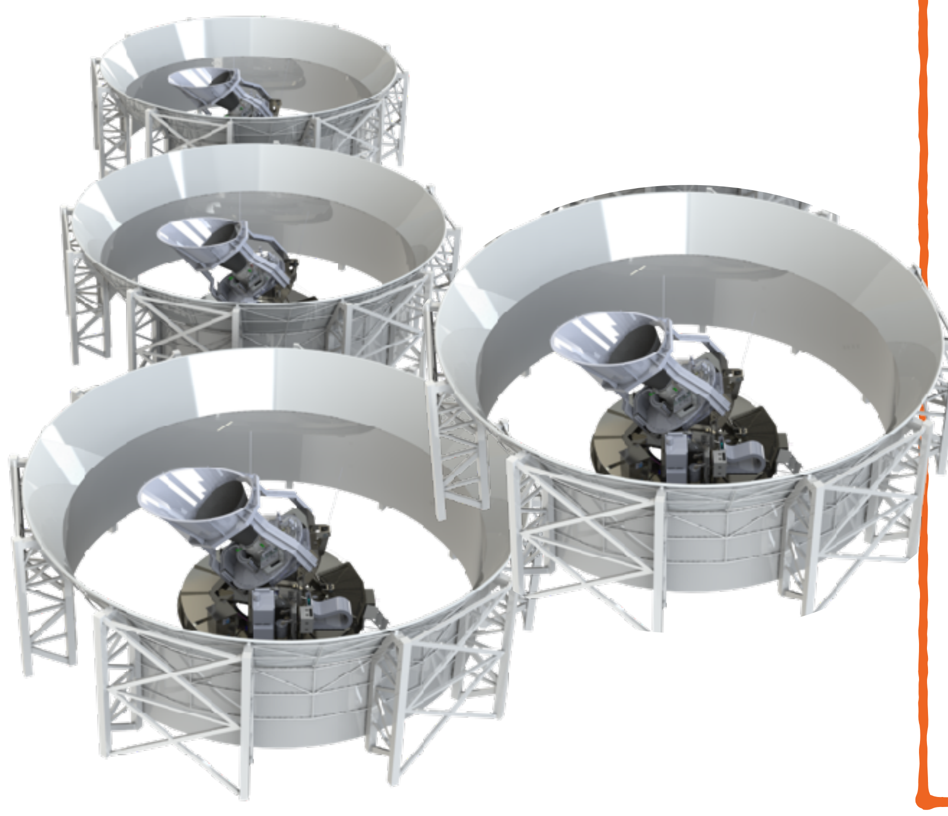

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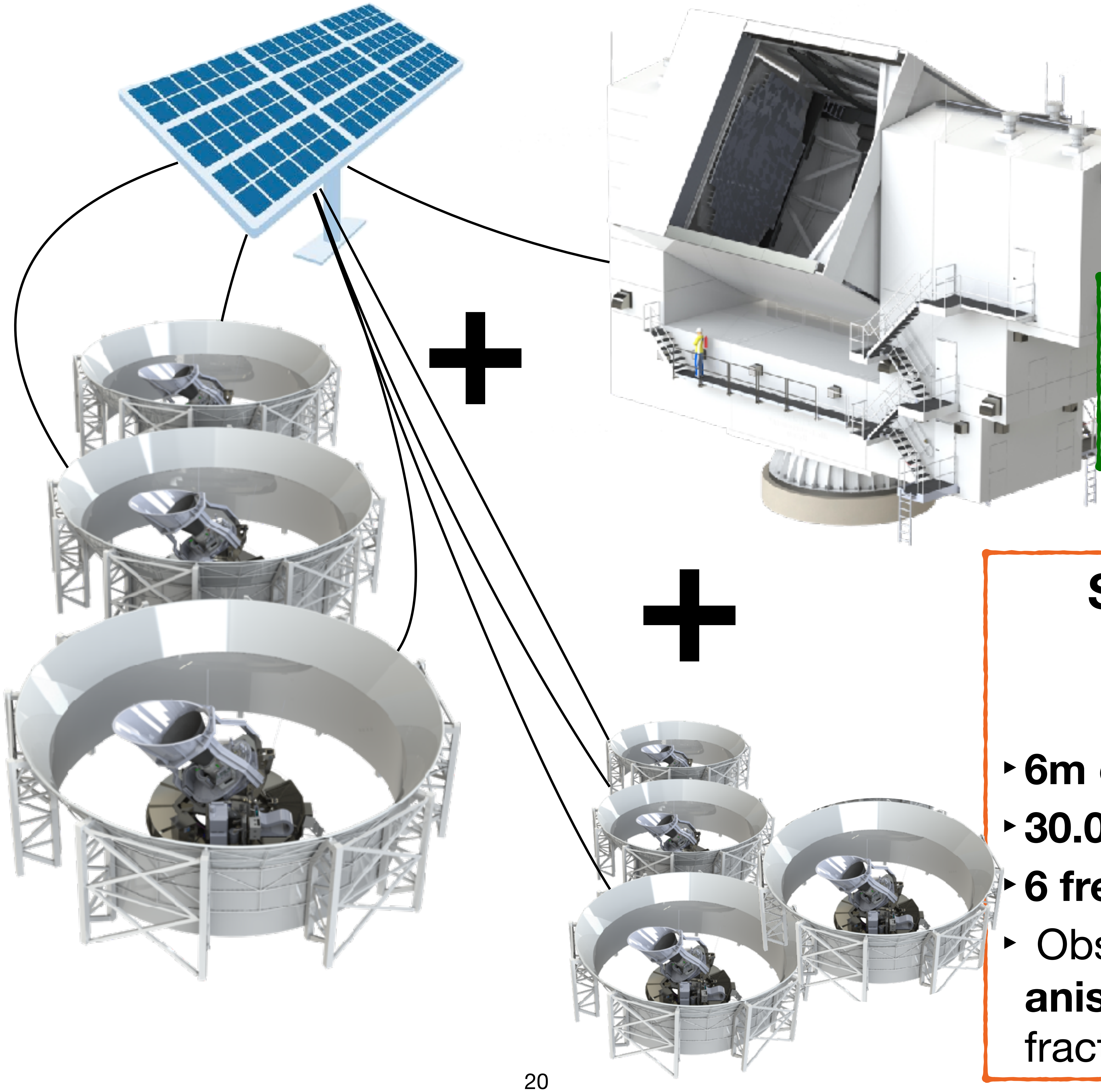

SO PV array

- **-70% diesel consumption**
- **+9% efficiency**

SO Large Aperture Telescope (LAT)

- **6m cross-Dragone** telescope
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Simons Observatory

Simons Observatory

- More than 450 collaborators worldwide
- Unique partnership between private and public funding.

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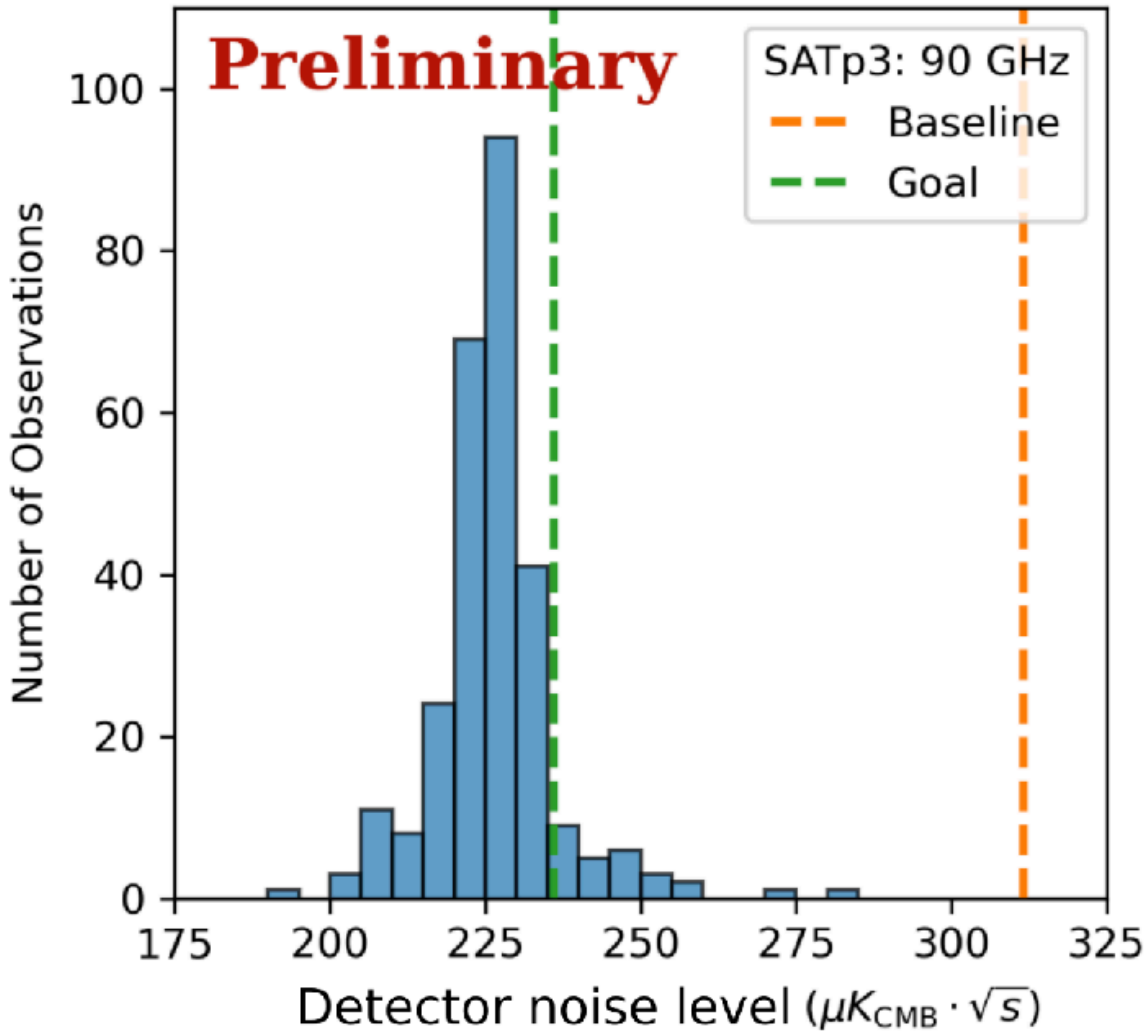
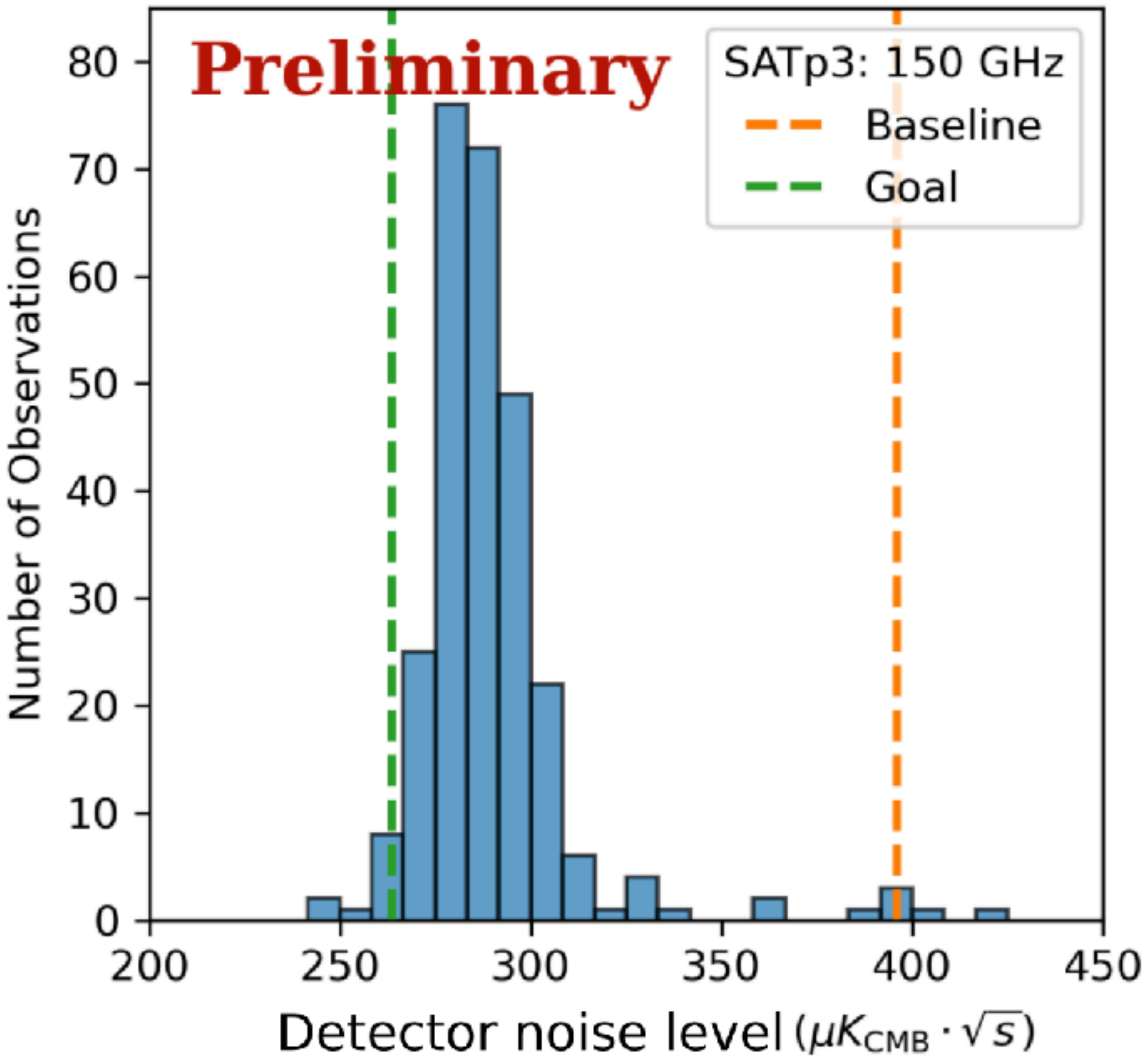
SAT Status

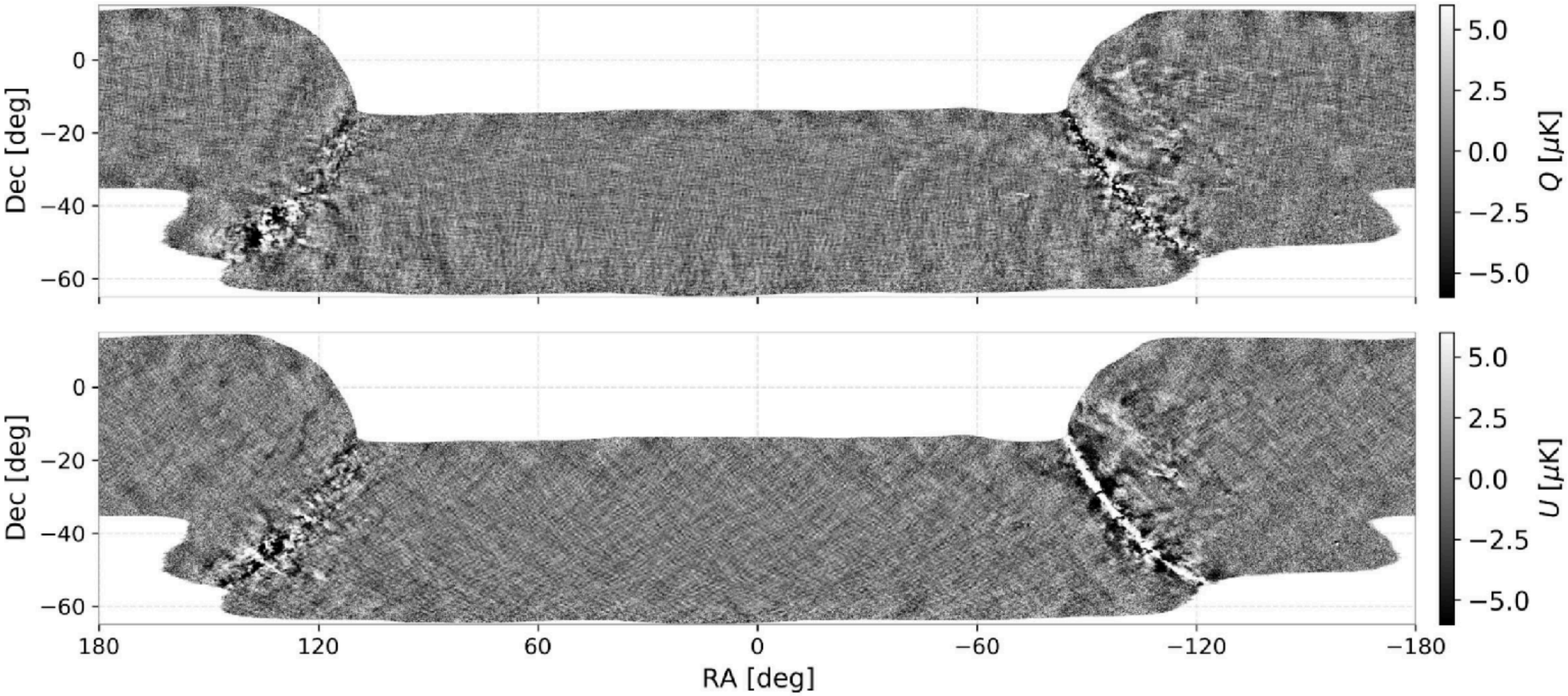


Preliminary
SATp3: 90 GHz
Baseline
Goal
Number of Observations
Detector noise level ($\mu K_{CMB} \cdot \sqrt{s}$)
100
80
60
40
20
0
175
200
225
250
275
300
325

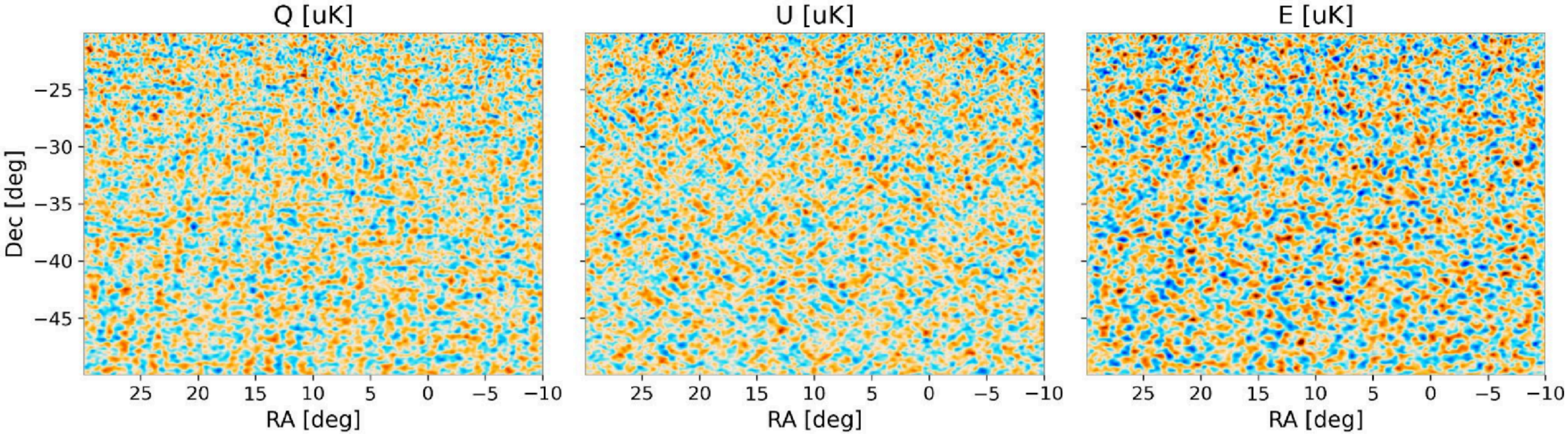


Preliminary
SATp3: 150 GHz
Baseline
Goal
Number of Observations
Detector noise level ($\mu K_{CMB} \cdot \sqrt{s}$)
80
70
60
50
40
30
20
10
0
200
250
300
350
400
450

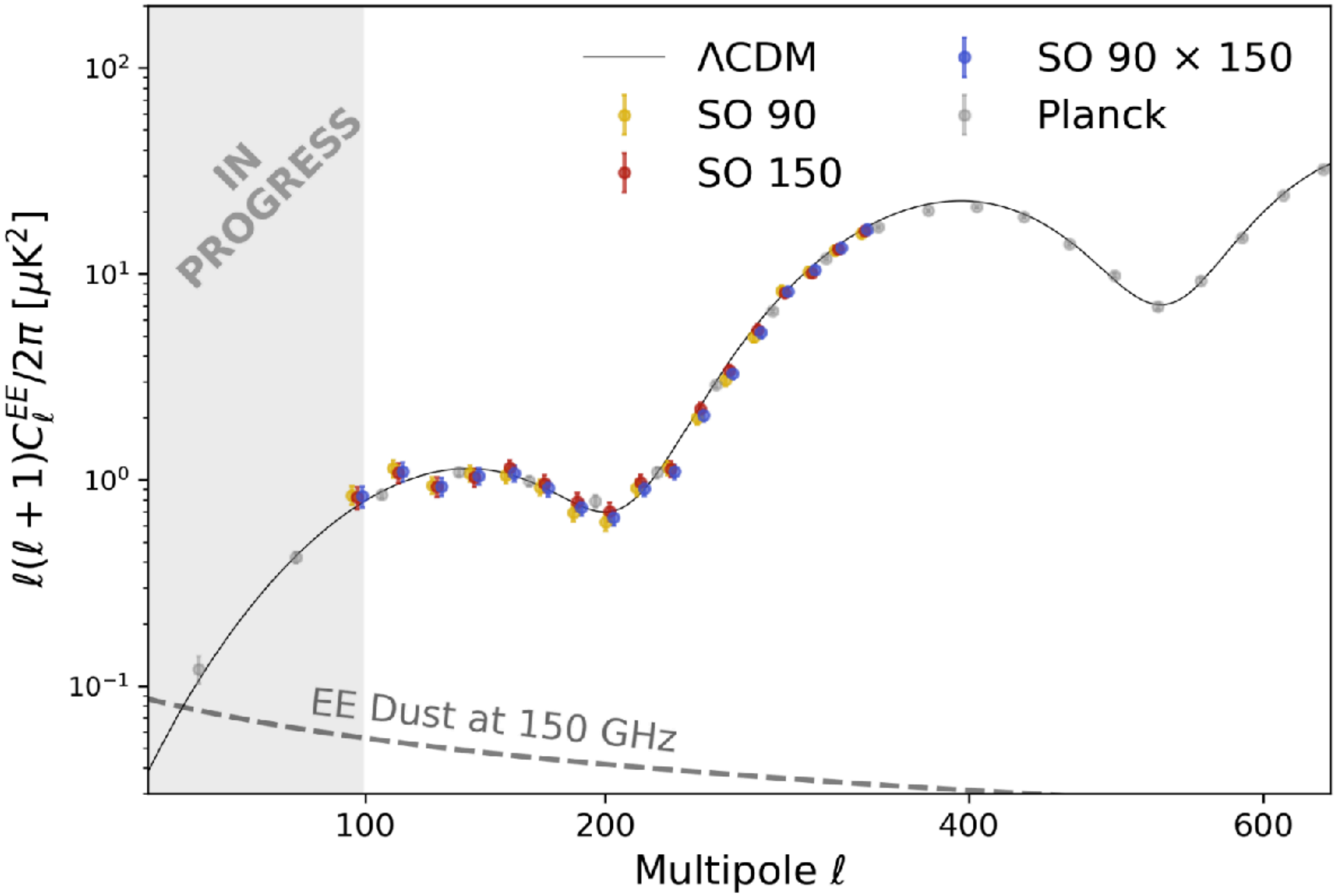
SAT Status


Dec [deg]
0
−20
−40
−60
5.0
2.5
0.0
−2.5
−5.0
Q [μK]
Dec [deg]
0
−20
−40
−60
5.0
2.5
0.0
−2.5
−5.0
U [μK]
180
120
60
0
−60
−120
−180
RA [deg]

SAT Status

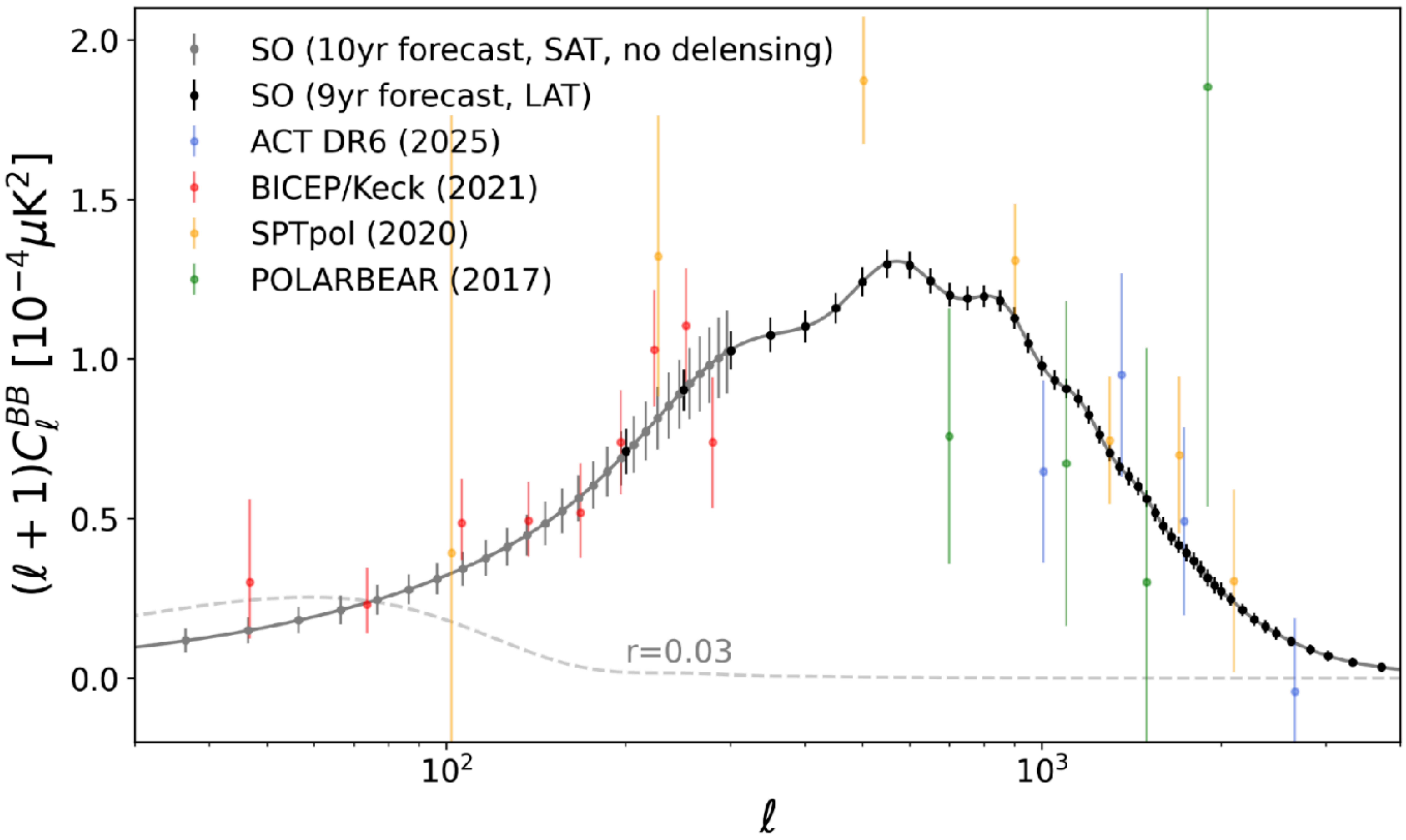


SAT Status



IN PROGRESS
ΛCDM
SO 90
SO 150
SO 90 × 150
Planck
EE Dust at 150 GHz
10^{2}
10^{1}
10^{0}
10^{-1}
$\ell(\ell+1)C_\ell^{EE}/2\pi\ [\mu K^2]$
100
200
400
600
Multipole ℓ

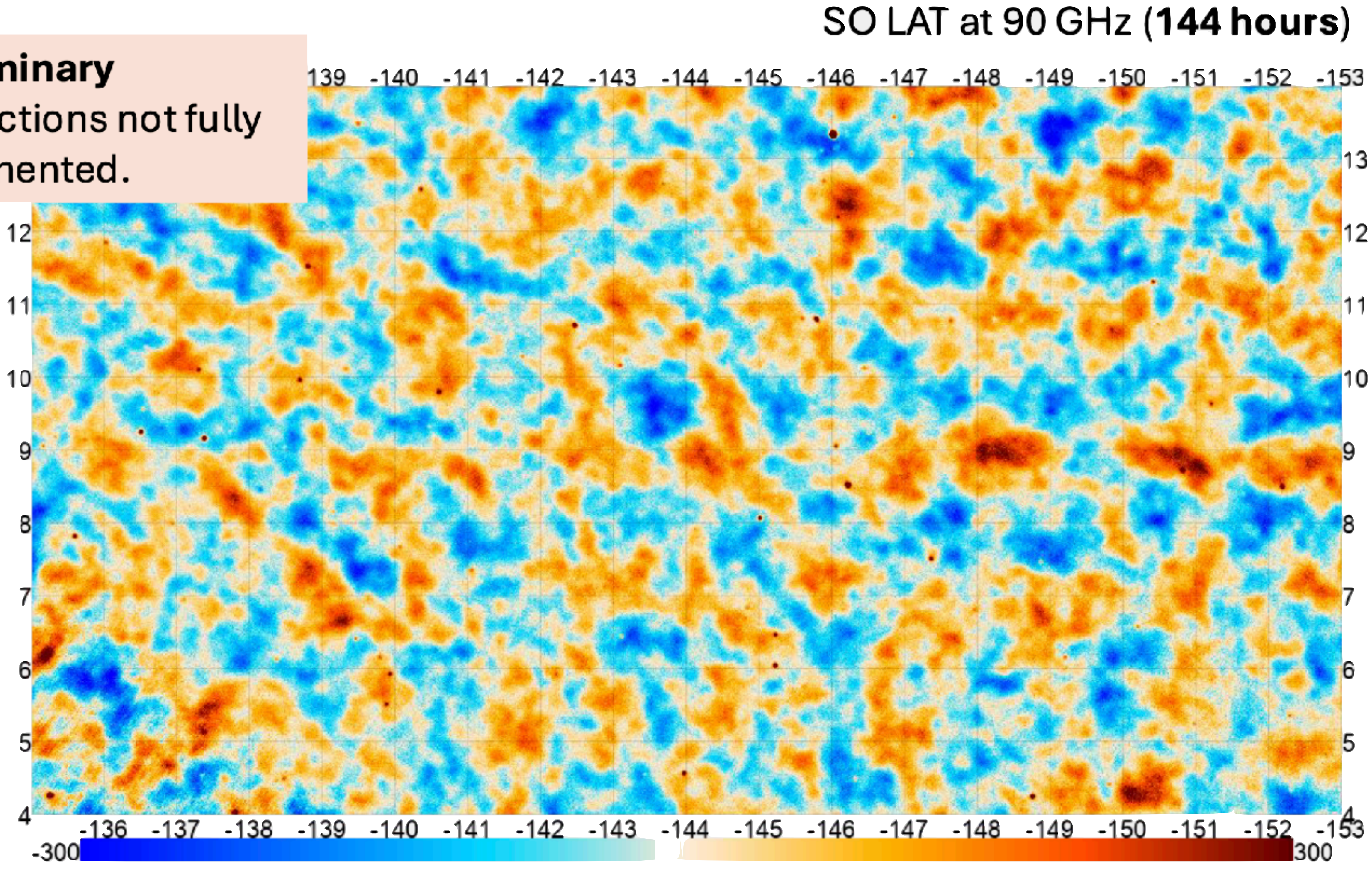
SAT Status



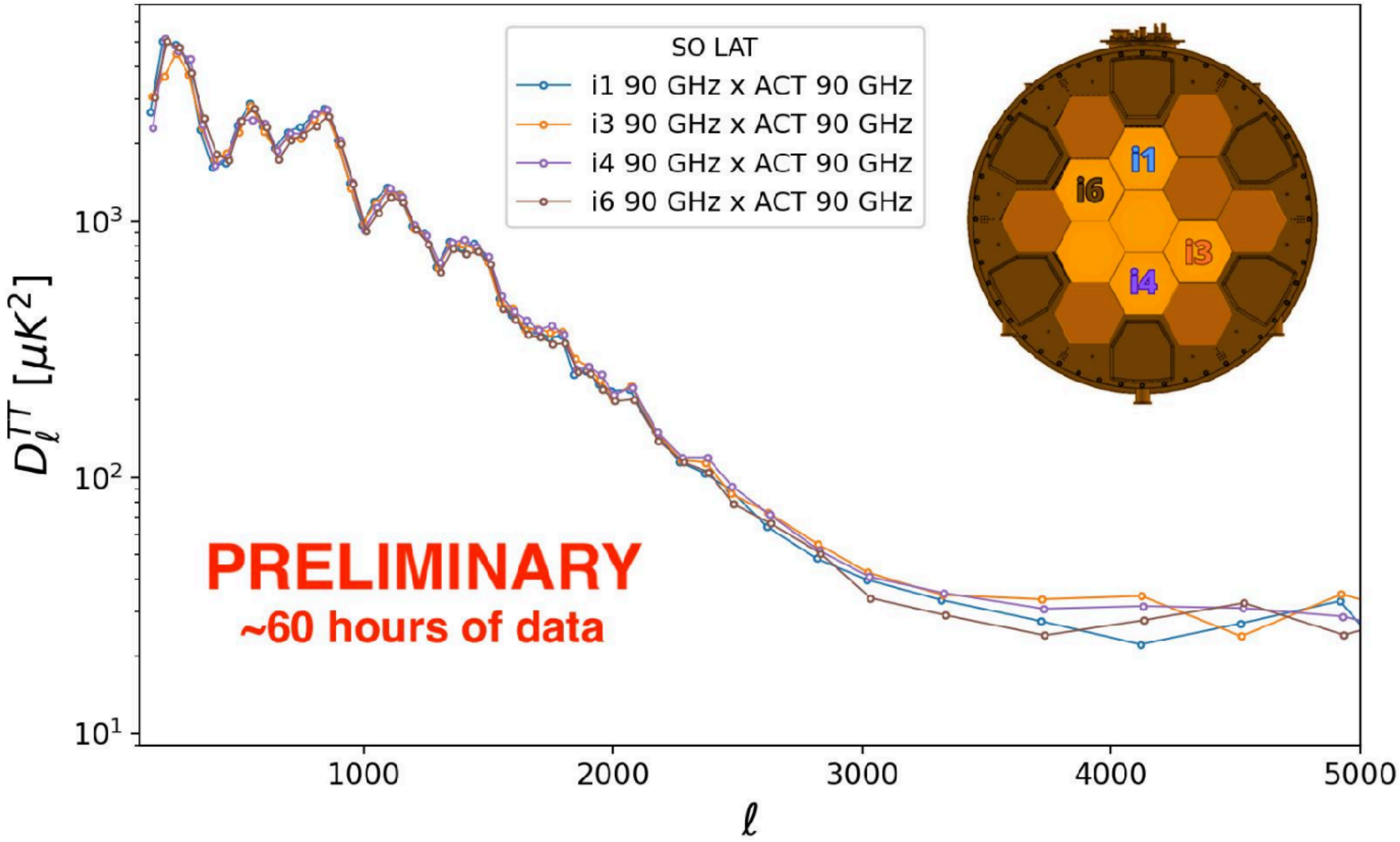
SO (10yr forecast, SAT, no delensing)
SO (9yr forecast, LAT)
ACT DR6 (2025)
BICEP/Keck (2021)
SPTpol (2020)
POLARBEAR (2017)
r=0.03
$(\ell+1)C_\ell^{BB}\ [10^{-4}\mu K^2]$
2.0
1.5
1.0
0.5
0.0
10^2
10^3
ℓ

LAT Status

Preliminary
Pointing corrections not fully implemented.

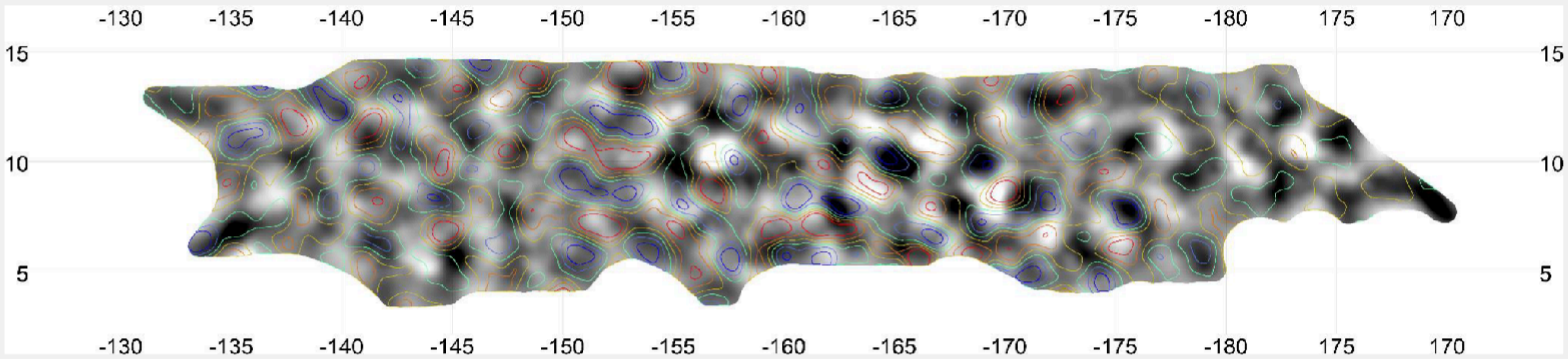


LAT Status



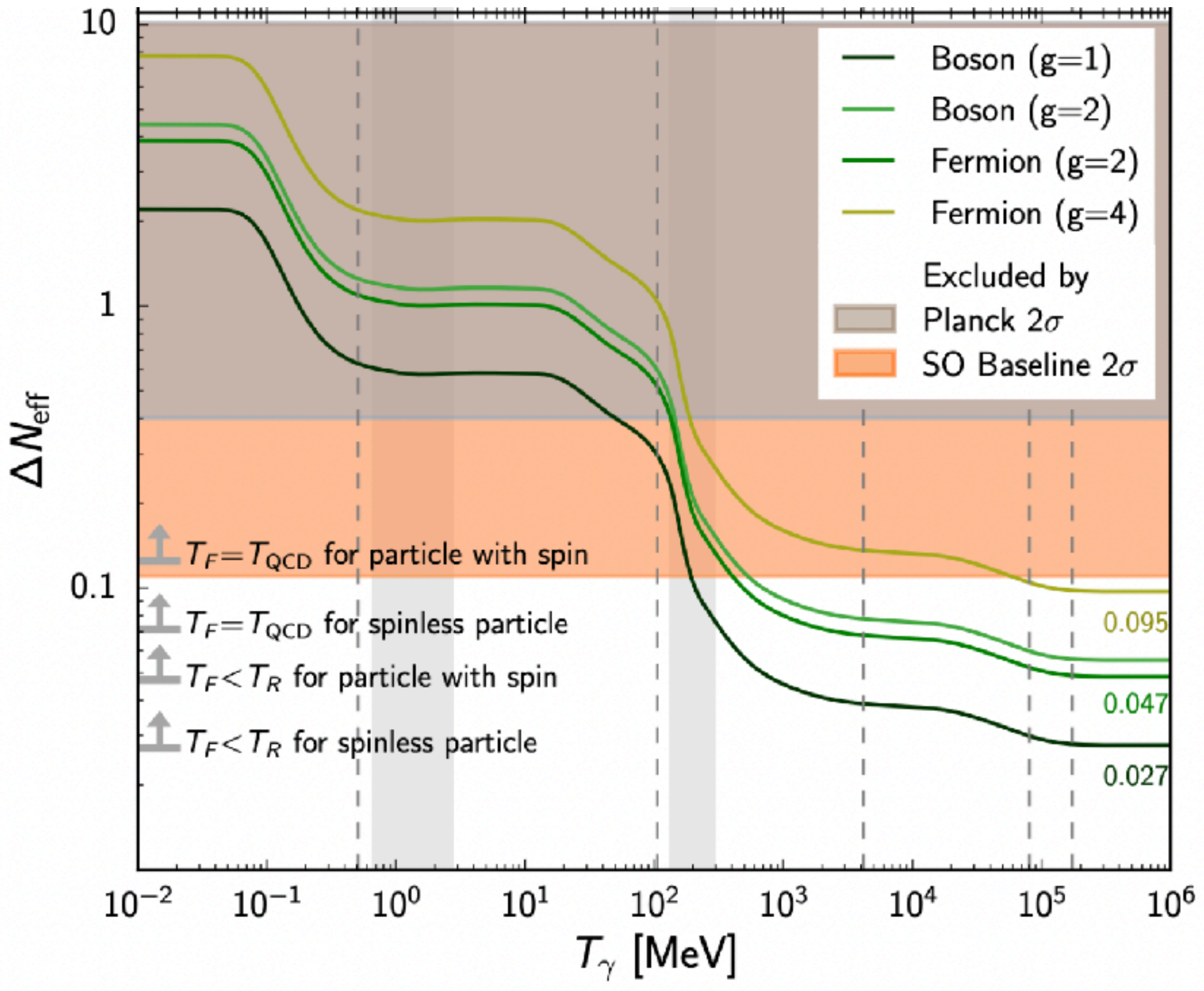
SO LAT
i1 90 GHz x ACT 90 GHz
i3 90 GHz x ACT 90 GHz
i4 90 GHz x ACT 90 GHz
i6 90 GHz x ACT 90 GHz
i1
i6
i3
i4
PRELIMINARY
~60 hours of data
D_ℓ^{TT} [μK^2]
10^3
10^2
10^1
1000
2000
3000
4000
5000
ℓ

LAT Status



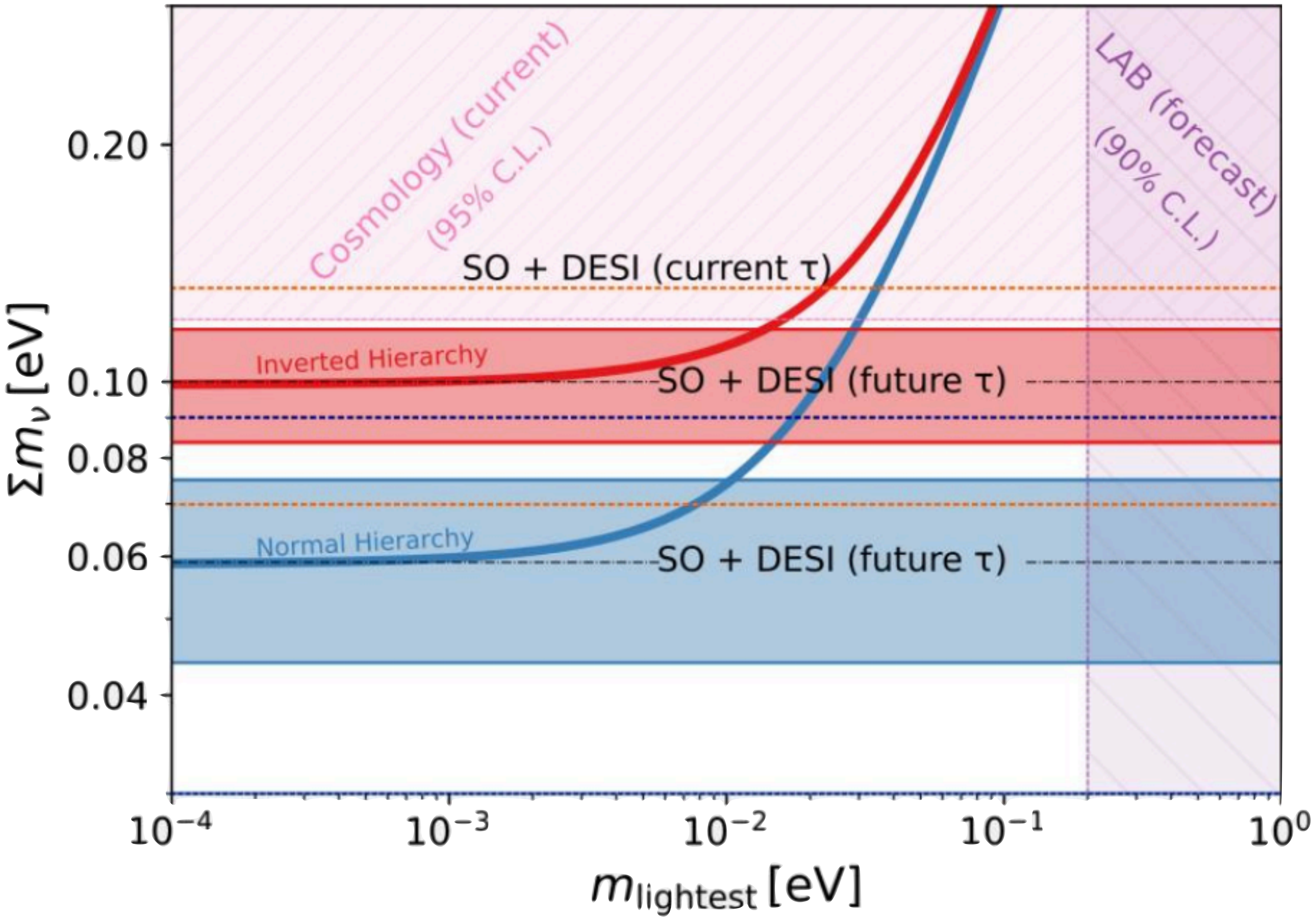
CMB lensing map from 144hrs of observations, CIB overlaid

LAT Status



- Light relativistic species affect the phase and amplitude of small scale CMB (temperature and polarisation).
- SO will rule out any particle with spin 3/2 back to reheating.

LAT Status



- Neutrino mass affect expansion rate and delay growth of structure. This leaves an imprint in the lensing signal.
- $\sigma(\Sigma m_\nu) \sim 30 \text{ meV}$ for SO + DESI.


B-modes
E-modes
Intensity anisotropies
Dipole
Monopole
CMB
Gravitational lensing
Galactic and extra-galactic foregrounds
Atmosphere
Systematics
Ground emissions
Noise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E-modes
Intensity anisotropies
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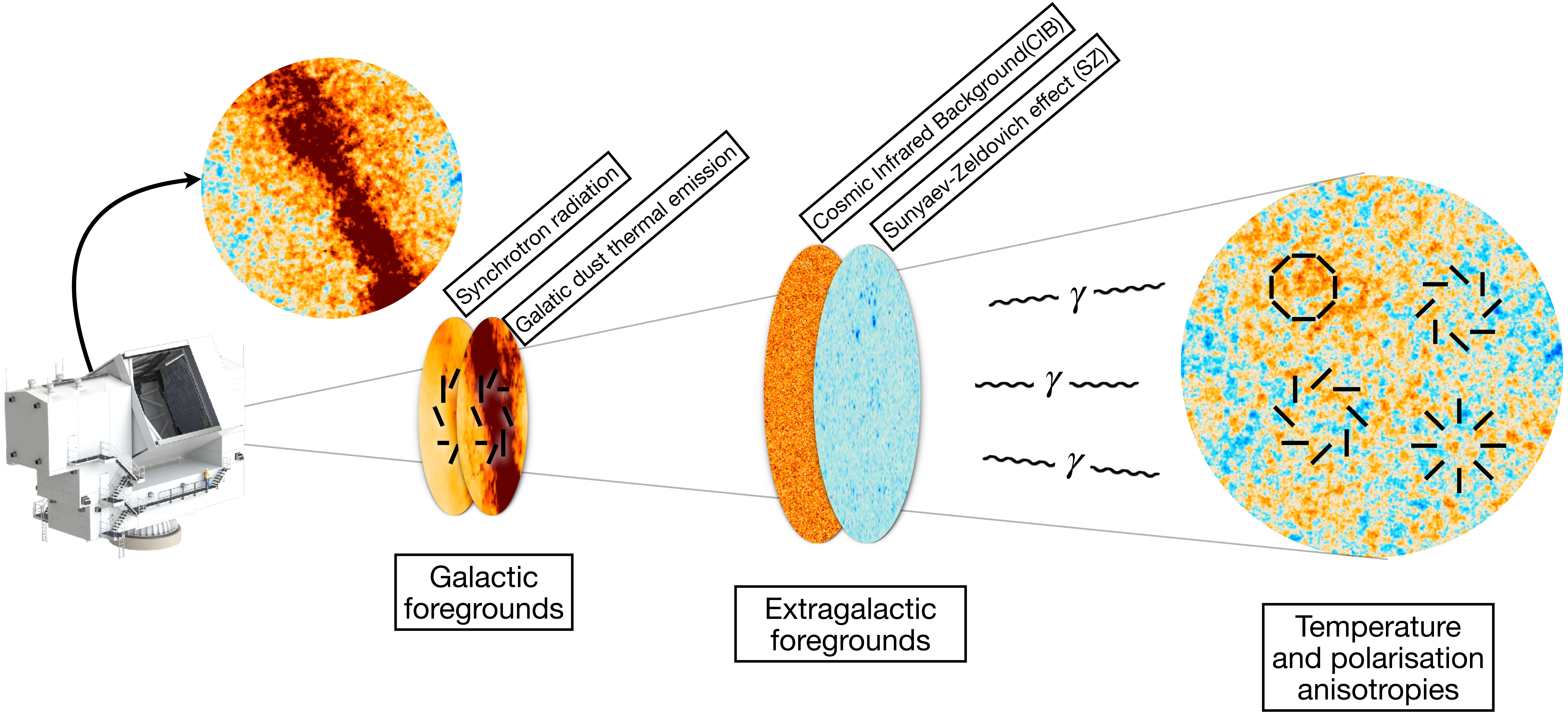
Component separation



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ACT-DR6 foreground modelling

$\hat{\mathscr{D}}_\ell^{90\times220}$ $\hat{\mathscr{D}}_\ell^{150\times220}$

$\hat{\mathscr{D}}_\ell^{90\times90}$ $\hat{\mathscr{D}}_\ell^{90\times150}$

$\hat{\mathscr{D}}_\ell^{150\times150}$

$$\hat{\mathscr{D}}_\ell^{\text{obs.}}$$

$$-2\ln L = ({\mathscr{D}_\ell}^{\text{th.}} - {\mathscr{D}_\ell}^{\text{obs.}})^T \Sigma^{-1} ({\mathscr{D}_\ell}^{\text{th.}} - {\mathscr{D}_\ell}^{\text{obs.}})$$

$$\Sigma_{\ell\ell'}$$

$$\mathscr{D}_\ell^{\text{th.}}$$

ACT-DR6 foreground modelling

$$\mathcal{D}_\ell^{\text{th.}} = \mathcal{D}_\ell^{\text{CMB}} + \mathcal{D}_\ell^{\text{foregrounds}}$$

ACT-DR6 foreground modelling

$$\mathscr{D}_\ell^{\rm fgs.,TT} = \mathscr{D}_\ell^{\rm tSZ} + \mathscr{D}_\ell^{\rm kSZ} + \mathscr{D}_\ell^{\rm CIB-c} + \mathscr{D}_\ell^{\rm CIB-p} + \mathscr{D}_\ell^{\rm tSZ\times CIB} + \mathscr{D}_\ell^{\rm radio,TT} + \mathscr{D}_\ell^{\rm dust,TT}$$

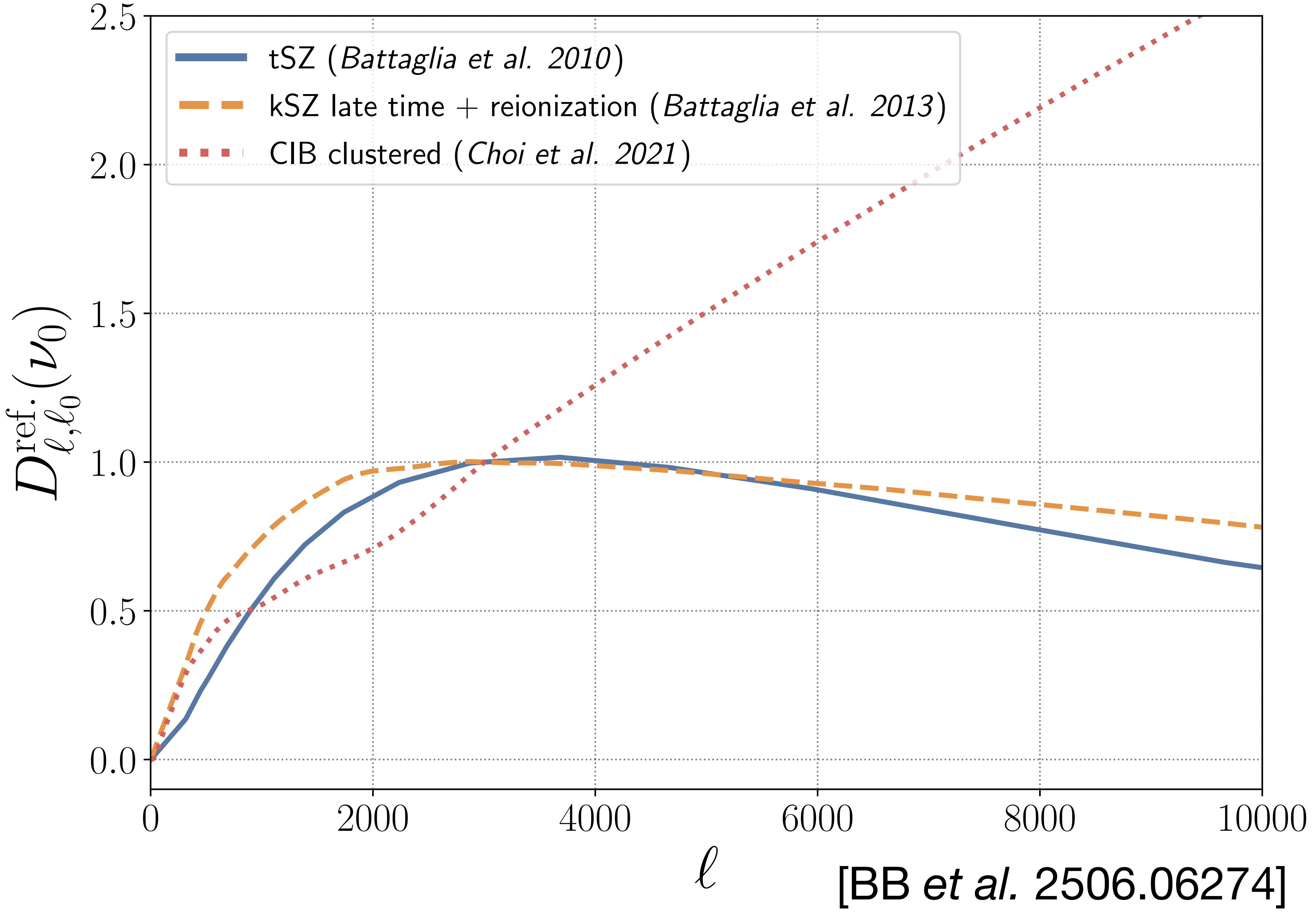
ACT-DR6 foreground modelling

$$\mathscr{D}_\ell^{\mathrm{fgs.,TT}} = \mathscr{D}_\ell^{\mathrm{tSZ}} + \mathscr{D}_\ell^{\mathrm{kSZ}} + \mathscr{D}_\ell^{\mathrm{CIB-c}} + \mathscr{D}_\ell^{\mathrm{CIB-p}} + \mathscr{D}_\ell^{\mathrm{tSZ\times CIB}} + \mathscr{D}_\ell^{\mathrm{radio,TT}} + \mathscr{D}_\ell^{\mathrm{dust,TT}}$$

Thermal Sunyaev-Zel'dovich effect

- Inverse Compton Scattering of CMB photons by hot electrons in clusters

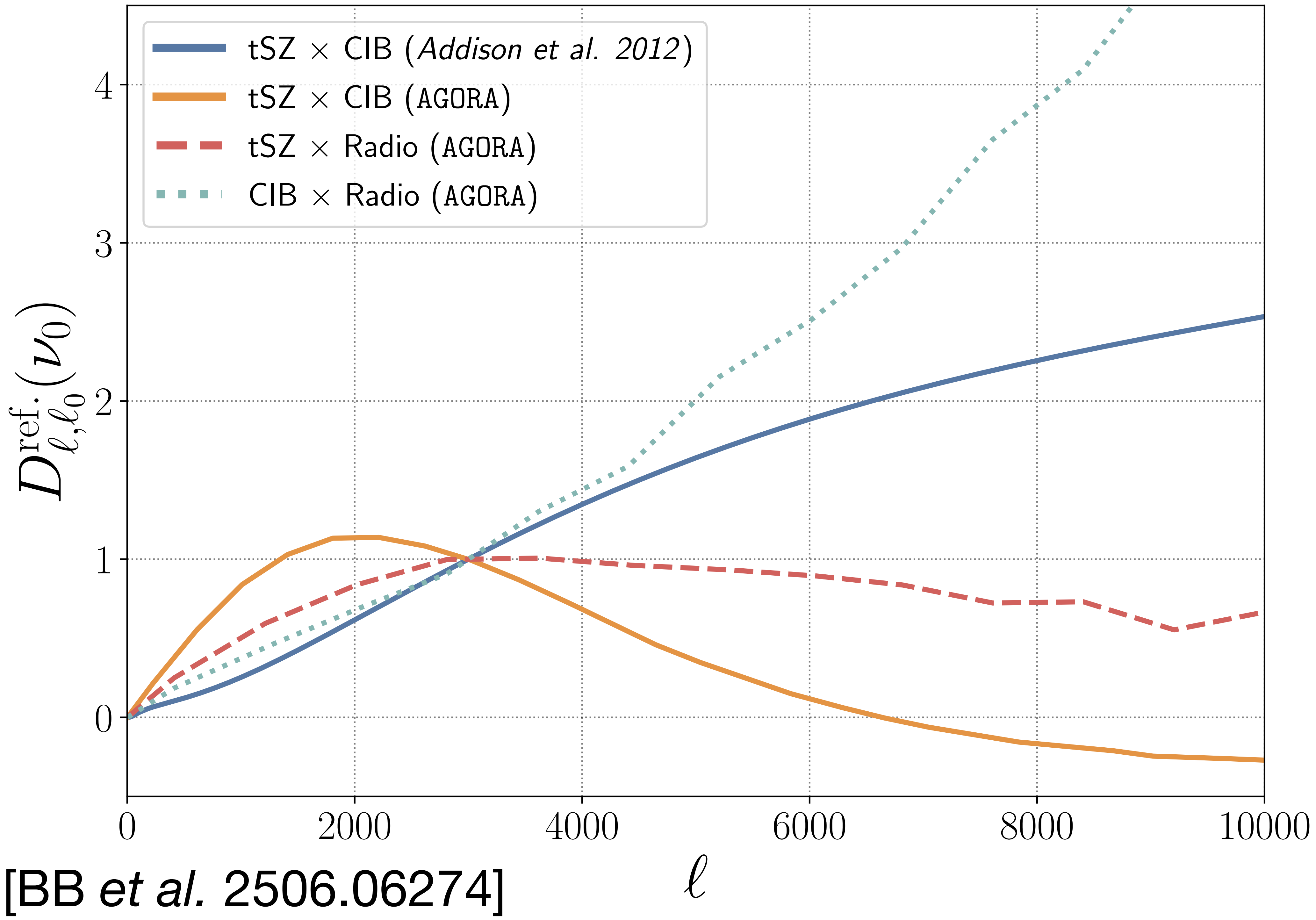
$$\mathscr{D}^{T_iT_j}_{\ell,\mathrm{tSZ}} = a_{\mathrm{tSZ}}\mathscr{D}^{\mathrm{tSZ}}_{\ell,\ell_0}\left[\frac{\ell}{\ell_0}\right]^{\alpha_{\mathrm{tSZ}}}\frac{f_{\mathrm{tSZ}}(\nu_i)f_{\mathrm{tSZ}}(\nu_j)}{f^2_{\mathrm{tSZ}}(\nu_0)}$$



[BB *et al.* 2506.06274]

ACT-DR6 foreground modelling

$$\mathscr{D}_\ell^{\mathrm{fgs.,TT}} = \mathscr{D}_\ell^{\mathrm{tSZ}} + \mathscr{D}_\ell^{\mathrm{kSZ}} + \mathscr{D}_\ell^{\mathrm{CIB-c}} + \mathscr{D}_\ell^{\mathrm{CIB-p}} + \mathscr{D}_\ell^{\mathrm{tSZ\times CIB}} + \mathscr{D}_\ell^{\mathrm{radio,TT}} + \mathscr{D}_\ell^{\mathrm{dust,TT}}$$



[BB *et al.* 2506.06274]

CIBxtSZ correlation

- tSZ and clustered CIB are sourced by the same clusters

$$\mathscr{D}^{T_iT_j}_{\ell,\mathrm{tSZ\times CIB}} = -\,\xi_{yc}\sqrt{a_c a_{\mathrm{tSZ}}}\,\mathscr{D}^{\mathrm{tSZ\times CIB}}_{\ell,\ell_0} \times \left(\frac{f_{\mathrm{tSZ}}(\nu_i)\mu(\nu_j;\beta_c,T_d) + f_{\mathrm{tSZ}}(\nu_j)\mu(\nu_i;\beta_c,T_d)}{f_{\mathrm{tSZ}}(\nu_0)\mu(\nu_0;\beta_c,T_d)}\right)$$

ACT-DR6 foreground modelling

$$\mathscr{D}_\ell^{\mathrm{fgs.,TT}} = \mathscr{D}_\ell^{\mathrm{tSZ}} + \mathscr{D}_\ell^{\mathrm{kSZ}} + \mathscr{D}_\ell^{\mathrm{CIB-c}} + \mathscr{D}_\ell^{\mathrm{CIB-p}} + \mathscr{D}_\ell^{\mathrm{tSZ\times CIB}} + \mathscr{D}_\ell^{\mathrm{radio,TT}} + \mathscr{D}_\ell^{\mathrm{dust,TT}}$$

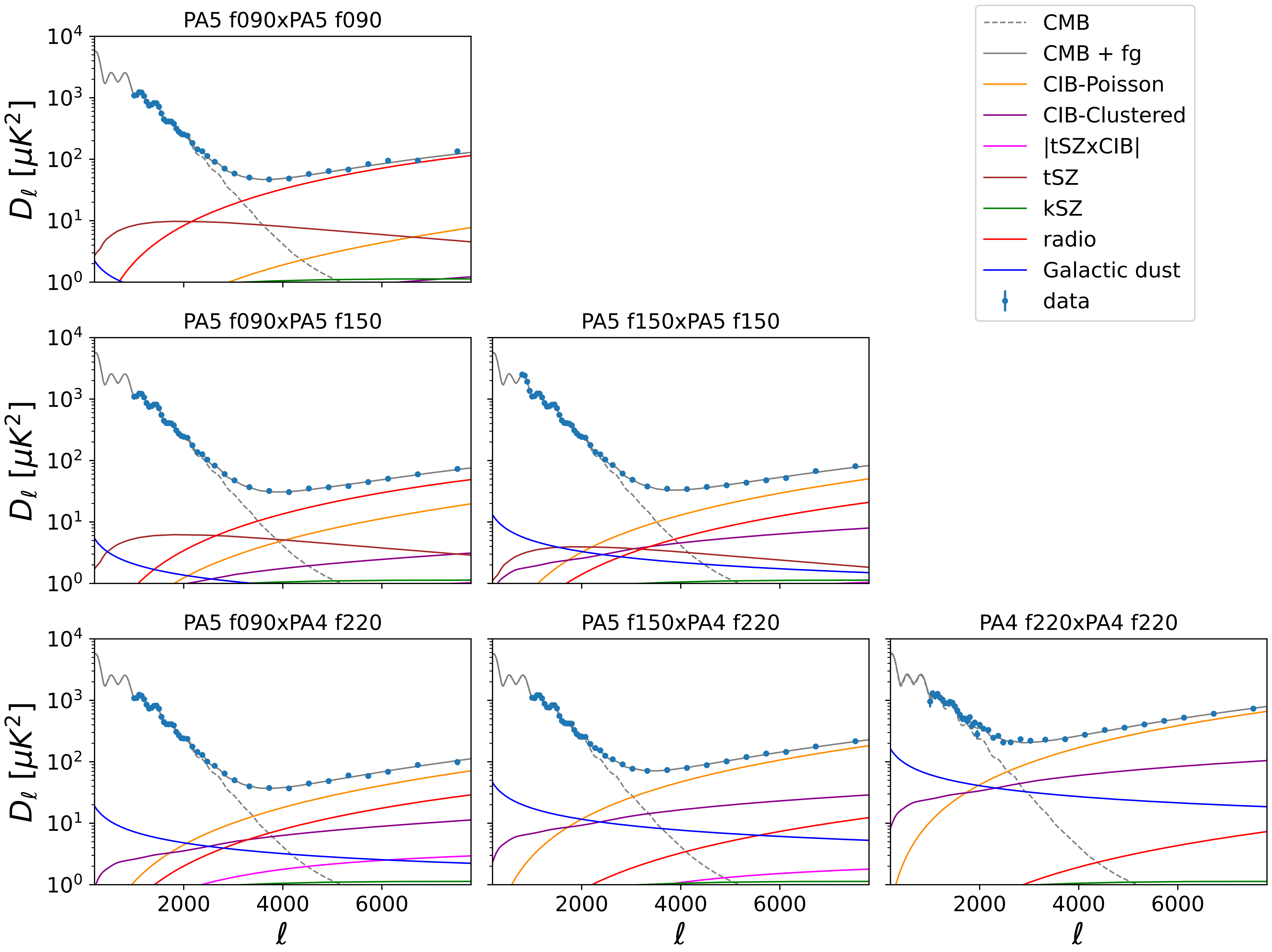
$$\mathscr{D}_\ell^{\mathrm{fgs.,EE}} = \mathscr{D}_\ell^{\mathrm{radio,EE}} + \mathscr{D}_\ell^{\mathrm{dust,EE}}$$

$$\mathscr{D}_\ell^{\mathrm{fgs.,TE}} = \mathscr{D}_\ell^{\mathrm{radio,TE}} + \mathscr{D}_\ell^{\mathrm{dust,TE}}$$

14 parameters

[BB *et al.* 2506.06274]

ACT-DR6 foreground modelling



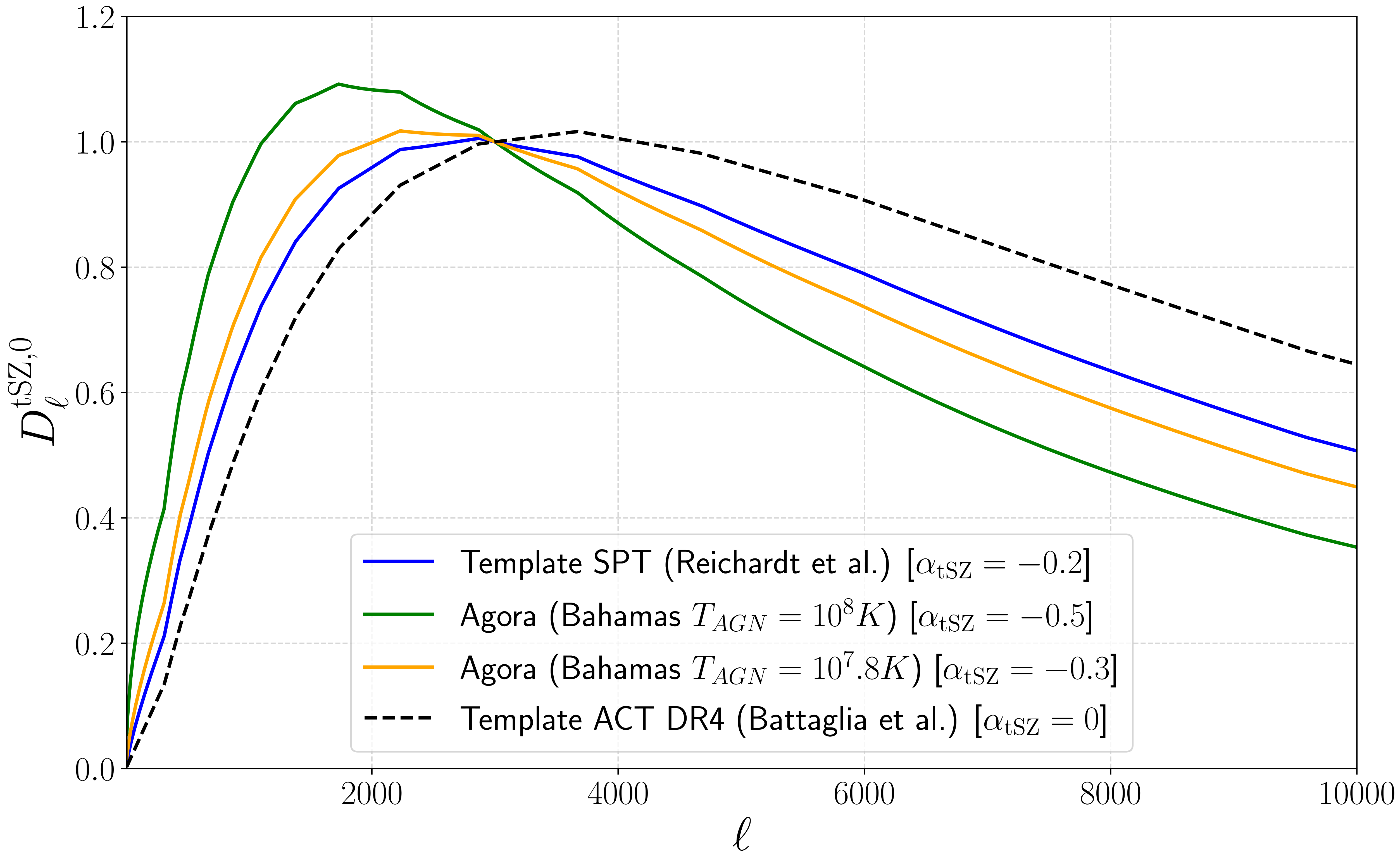
[ACT-DR6 : *Louis et al.* 2503.14452]

ACT-DR6 foreground modelling

$$\mathscr{D}^{T_iT_j}_{\ell,\mathrm{tSZ}} = a_{\mathrm{tSZ}} \mathscr{D}^{\mathrm{tSZ}}_{\ell,\ell_0} \left[\frac{\ell}{\ell_0}\right]^{\alpha_{\mathrm{tSZ}}} \frac{f_{\mathrm{tSZ}}(\nu_i) f_{\mathrm{tSZ}}(\nu_j)}{f^2_{\mathrm{tSZ}}(\nu_0)}$$

- Introduced new parameter : α_{tSZ} that empirically captures the scale dependence of the tSZ signal.

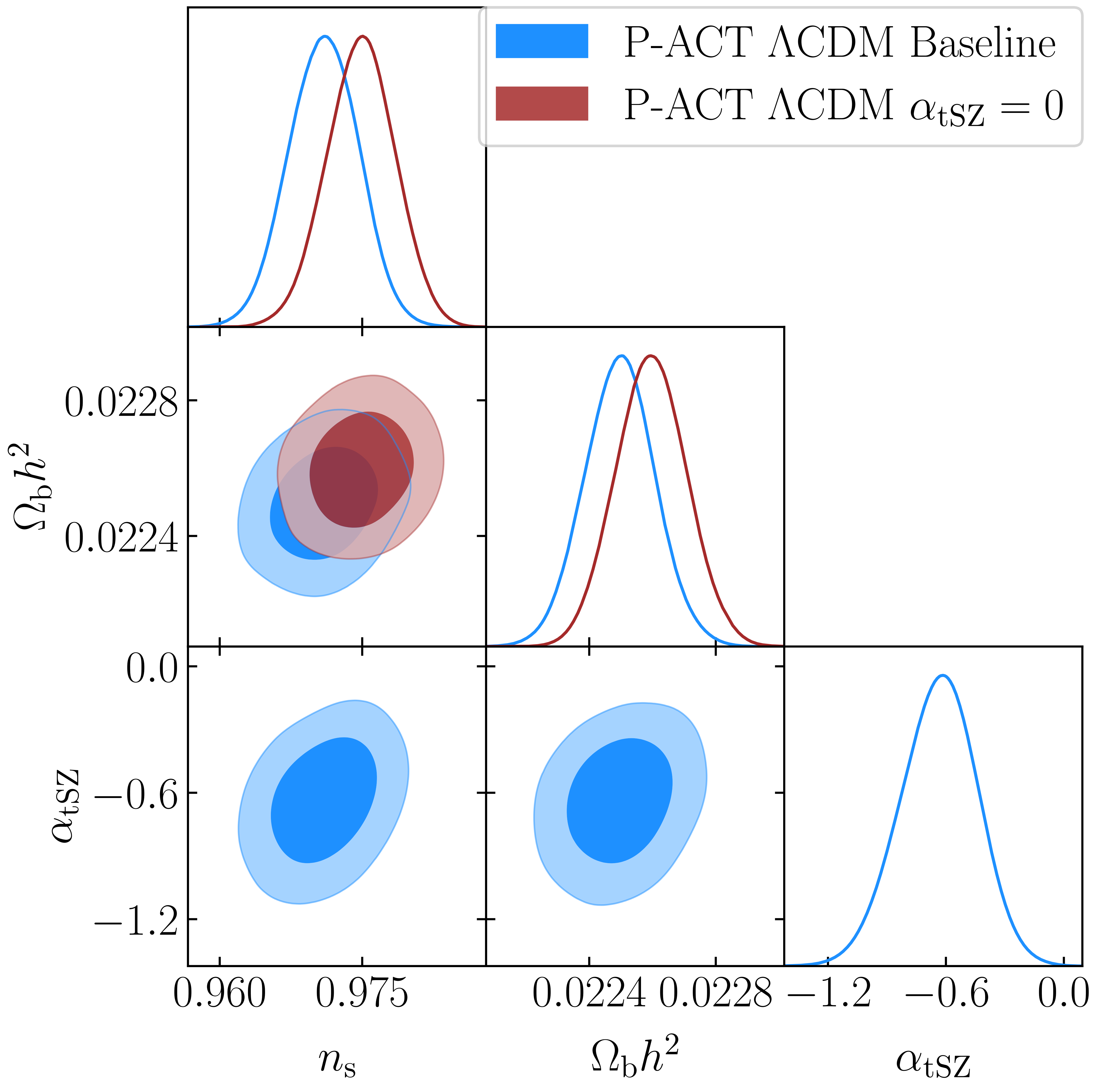
- Proxy for AGN temperature (in AGORA simulations). [Omori 2023].



ACT-DR6 foreground modelling

- $> 0.5\sigma$ shift in cosmological parameters when $\alpha_{\rm tSZ} = 0$.

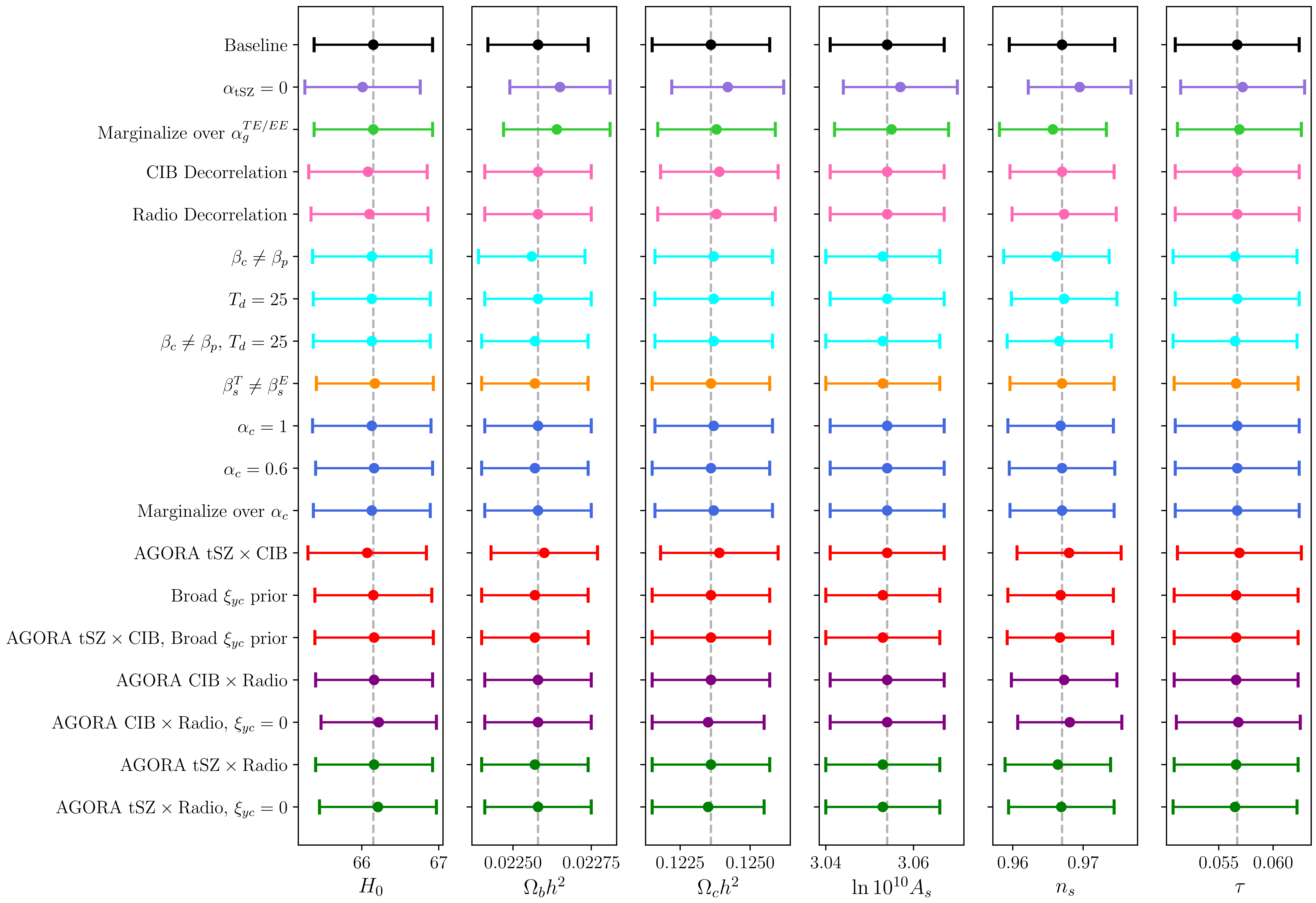
Parameter	ACT ΛCDM	ACT ΛCDM + $N_{\rm eff}$	P-ACT ΛCDM	P-ACT ΛCDM + $N_{\rm eff}$
H_0	−0.1	−0.3	0.3	−0.4
$\Omega_b h^2$	0.3	0.0	0.6	−0.2
$\Omega_c h^2$	0.2	−0.3	−0.2	−0.5
$\ln 10^{10} A_s$	0.2	0.0	0.3	−0.1
n_s	0.2	−0.2	0.8	−0.2
τ	0.1	0.2	0.3	0.1
$N_{\rm eff}$	–	−0.3	–	−0.5



[BB *et al.* 2506.06274]

ACT-DR6 foreground modelling

- Tested ~20 fg model extensions and assessed the impact on cosmological parameters.
- All changes below 0.1σ.
- No preference for any other model with ACT-DR6 data.

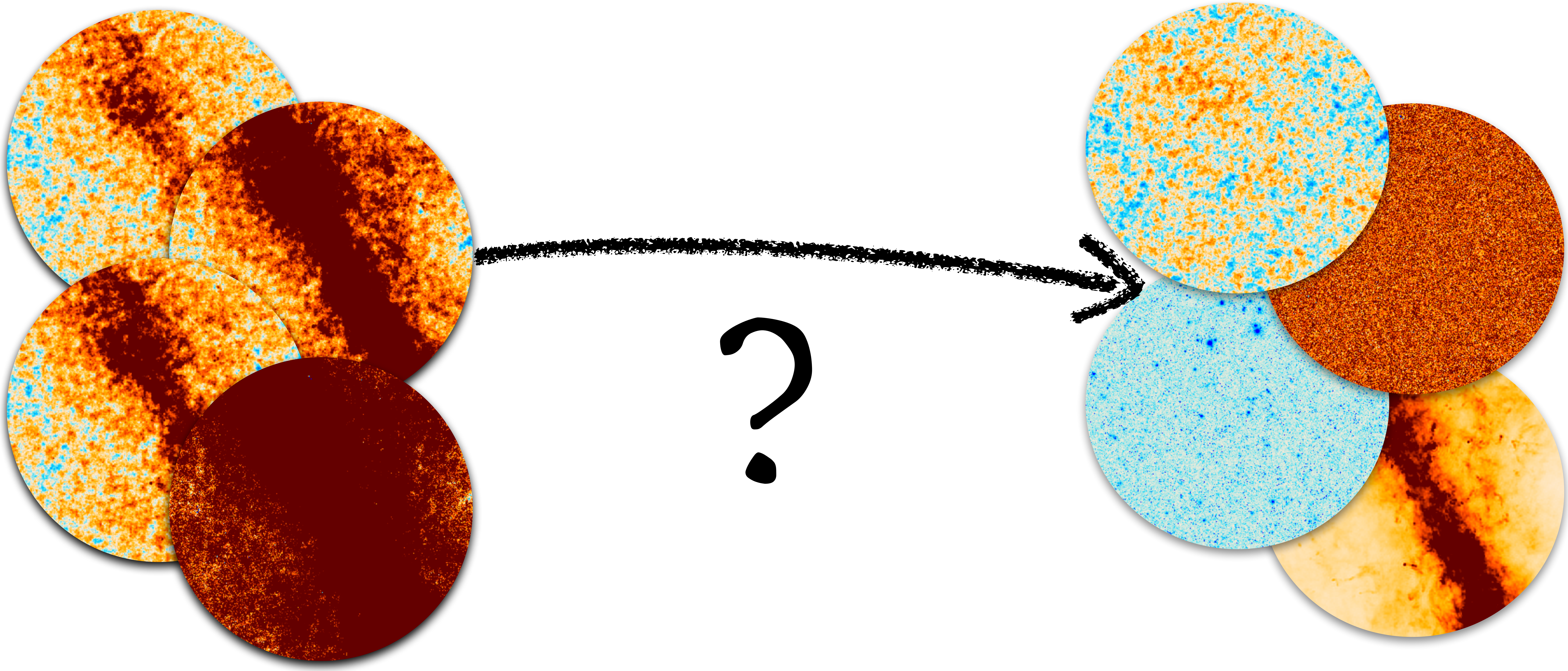


[BB *et al.* 2506.06274]

Outline

- The Cosmic Microwave Background (CMB)
- The Simons Observatory
- Status and (couple of) science goals.
- Modelling of extragalactic foregrounds : the ACT-DR6 example
- Component separation for SO-SATs

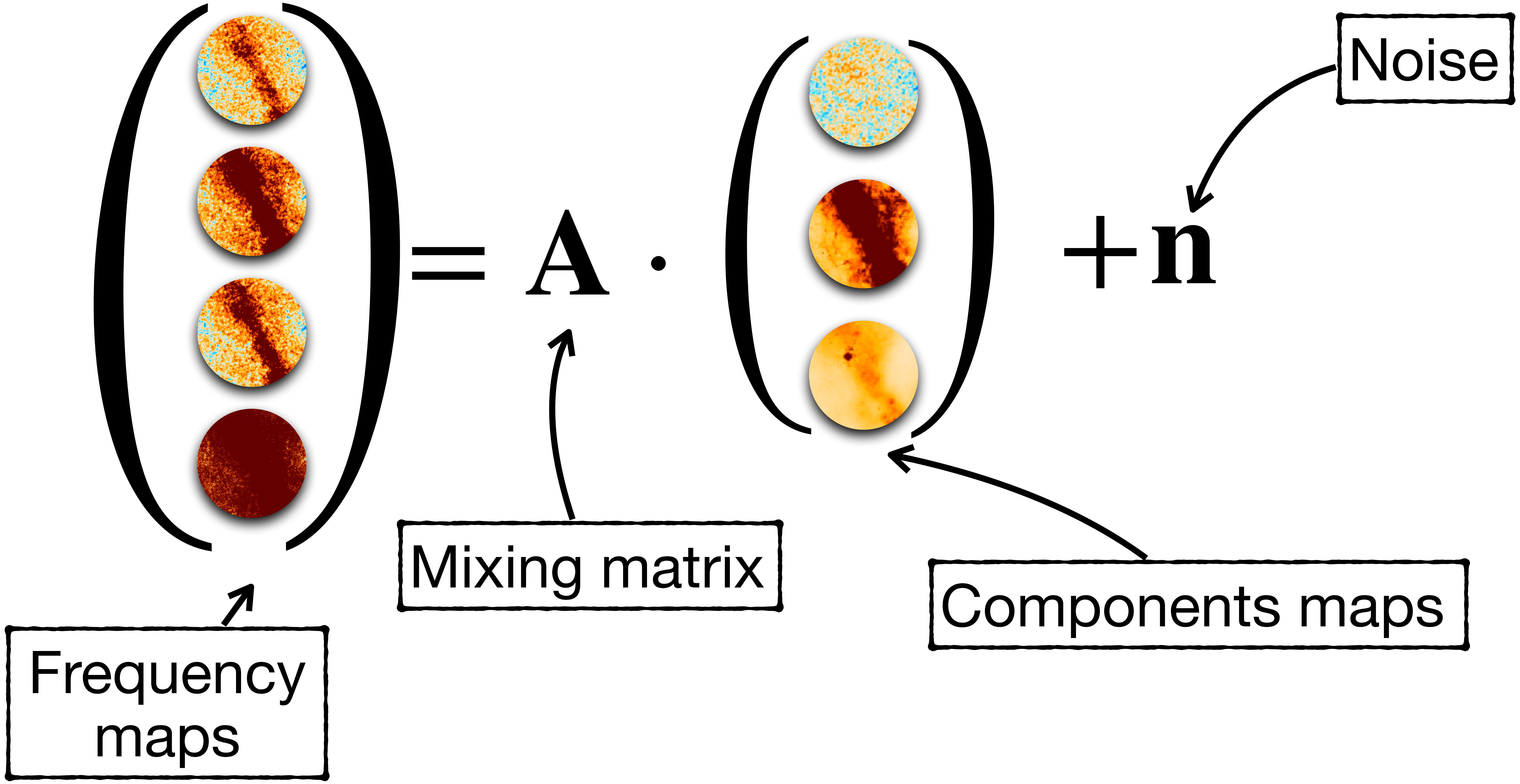
Component separation for SO-SATs



Component separation

$$\mathbf{d} = \mathbf{A} \cdot \mathbf{s} + \mathbf{n}$$

Component separation



Component separation Parametric component separation in pixel space

$$\mathbf{d} = \mathbf{A} \cdot \mathbf{s} + \mathbf{n}$$

Component separation Parametric component separation in pixel space

$$\mathbf{d} = \mathbf{A} \cdot \mathbf{s} + \mathbf{n}$$

$$\mathbf{d_p} = \mathbf{A}(\theta) \cdot \mathbf{s_p} + \mathbf{n_p}$$

Component separation Parametric component separation in pixel space

Full data likelihood:

$$-2\ln\mathscr{L}_{\rm data}(\mathbf{s},\theta) = {\rm cst} - (\mathbf{d} - \mathbf{A}\mathbf{s})^{\mathbf{T}}\mathbf{N}^{-\mathbf{1}}(\mathbf{d} - \mathbf{A}\mathbf{s})$$

Component separation Parametric component separation in pixel space

Full data likelihood:

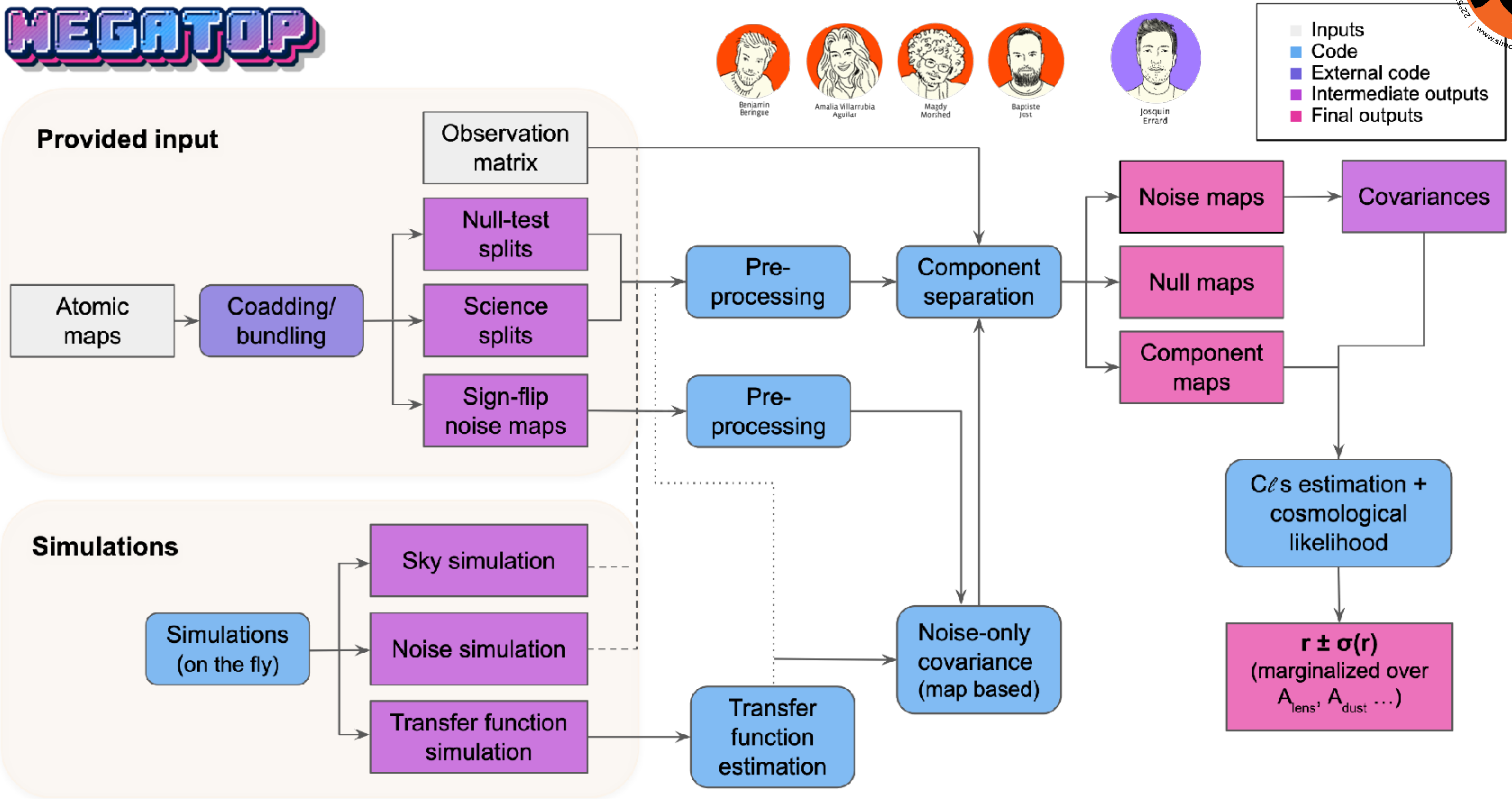
$$-2\ln\mathscr{L}_{\text{data}}(\mathbf{s},\theta) = \text{cst} - (\mathbf{d}-\mathbf{As})^{\mathbf{T}}\mathbf{N}^{-\mathbf{1}}(\mathbf{d}-\mathbf{As})$$

"Spectral" or ridge likelihood

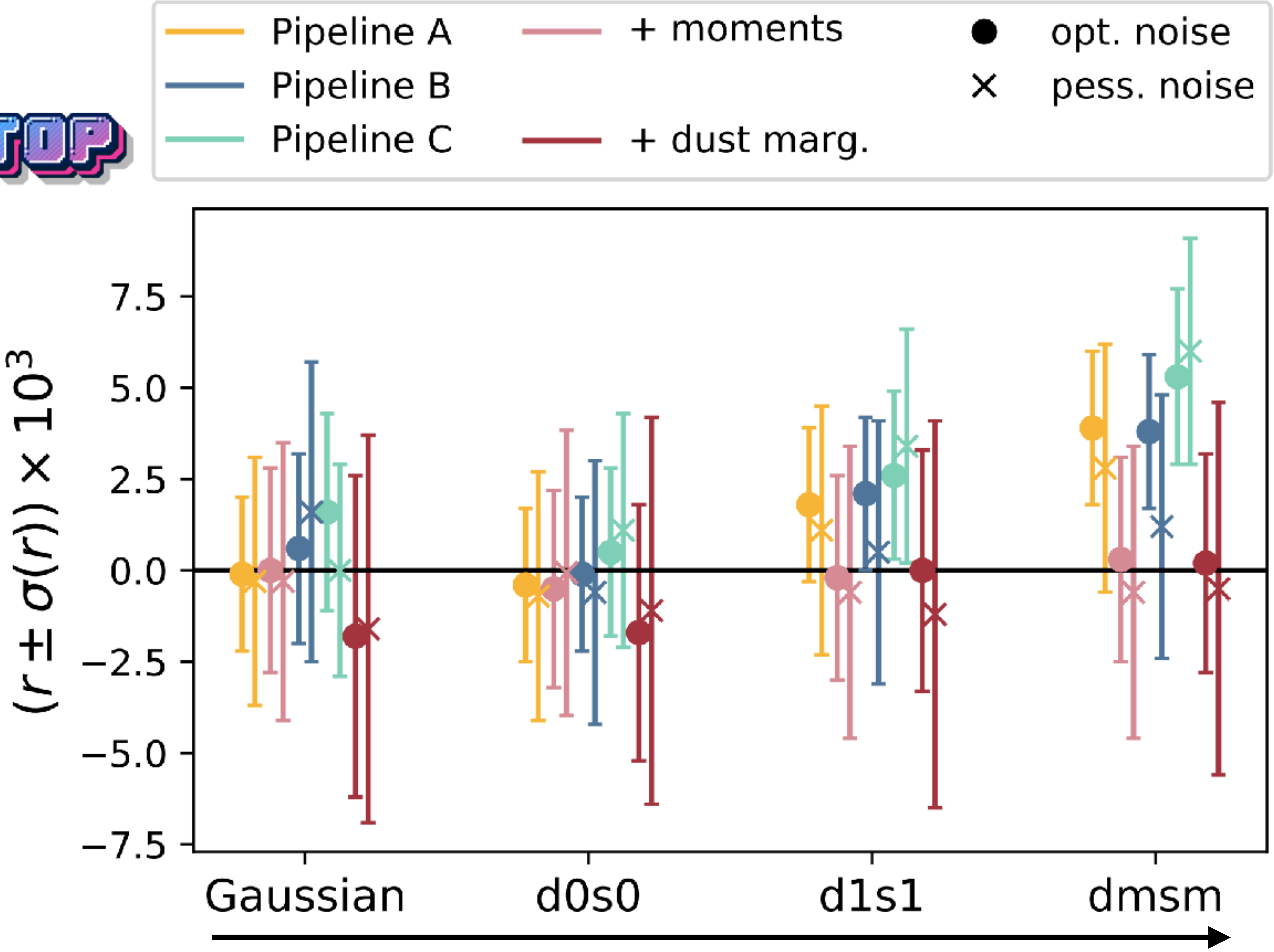
$$-2\ln\mathscr{L}_{\text{spec}}(\theta) = \text{cst} - (\mathbf{A}^{\mathbf{T}}\mathbf{N}^{-\mathbf{1}}\mathbf{d})^{\mathbf{T}}(\mathbf{A}^{\mathbf{T}}\mathbf{N}^{-\mathbf{1}}\mathbf{A})^{-\mathbf{1}}(\mathbf{A}^{\mathbf{T}}\mathbf{N}^{-\mathbf{1}}\mathbf{d})$$

Does not depend on sky signal !!

Component separation Parametric component separation in pixel space



Component separation
Parametric component separation in pixel space



Wolz et al. 2023

Component separation Parametric component separation in pixel space

<u>*Real-life issue*</u>: ground-based data are **filtered** ! Baseline (filter+bin) map-making produce **biased** frequency maps.

Filtering can be represented by a **linear operator** in pixel space.

$$\mathbf{d}^{\text{filt.}} = \mathcal{O}\mathbf{d}^{\text{raw}} = \mathcal{O}\mathbf{A}\cdot\mathbf{s} + \mathbf{n}$$

Component separation Parametric component separation in pixel space

Real-life issue: ground-based data are **filtered** ! Baseline (filter+bin) map-making produce **biased** frequency maps.

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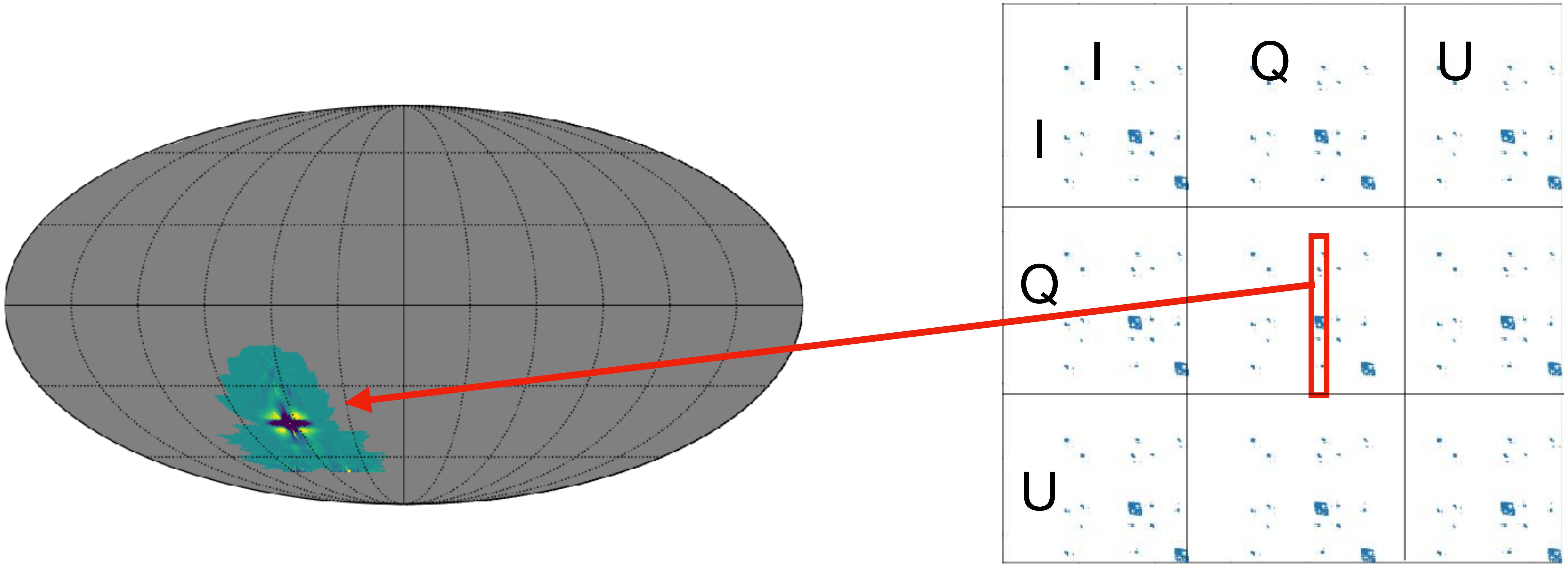


- **Very** large (600000x600000) pixels, but **very** sparse (0.4%).
- Can be efficiently constructed from **instrument model** and **preprocessing scheme.**

Component separation

Parametric component separation in pixel space

$$-2\ln\mathscr{L}_{\rm spec}(\theta) = \text{cst} - (\mathbf{A}^{\mathbf{T}}\mathcal{O}^{\mathbf{T}}\mathbf{N}^{-1}\mathbf{d})^{\mathbf{T}}\boxed{(\mathbf{A}^{\mathbf{T}}\mathcal{O}^{\mathbf{T}}\mathbf{N}^{-1}\mathcal{O}\mathbf{A})^{-1}}(\mathbf{A}^{\mathbf{T}}\mathcal{O}^{\mathbf{T}}\mathbf{N}^{-1}\mathbf{d})$$

Solved through **preconditioned gradient descent** (PCG):

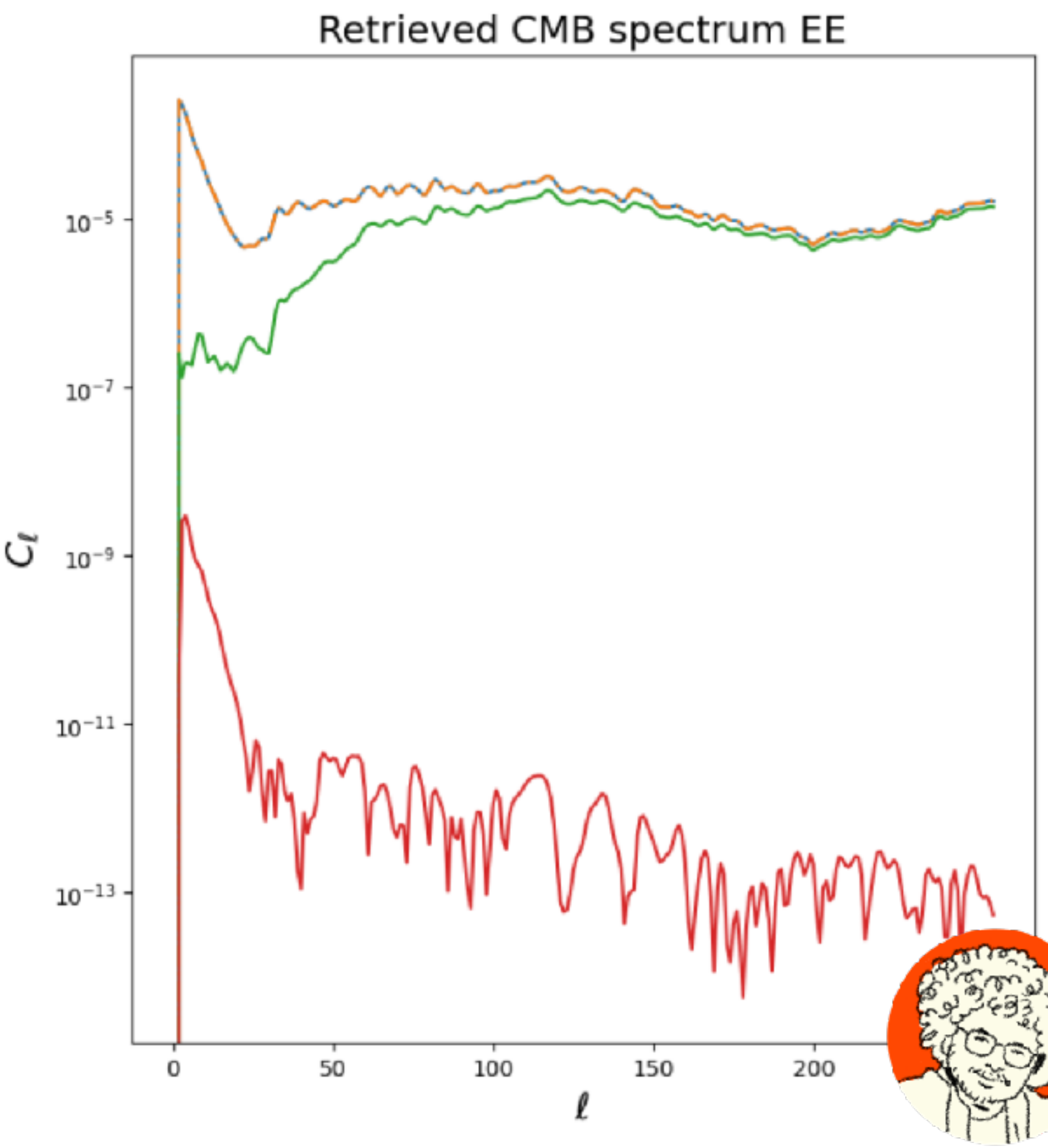
- Pre-conditioner from the SVD of mixing matrix **A**
- Pre-computation of the inner term (θ independent)

Magdy Morshed

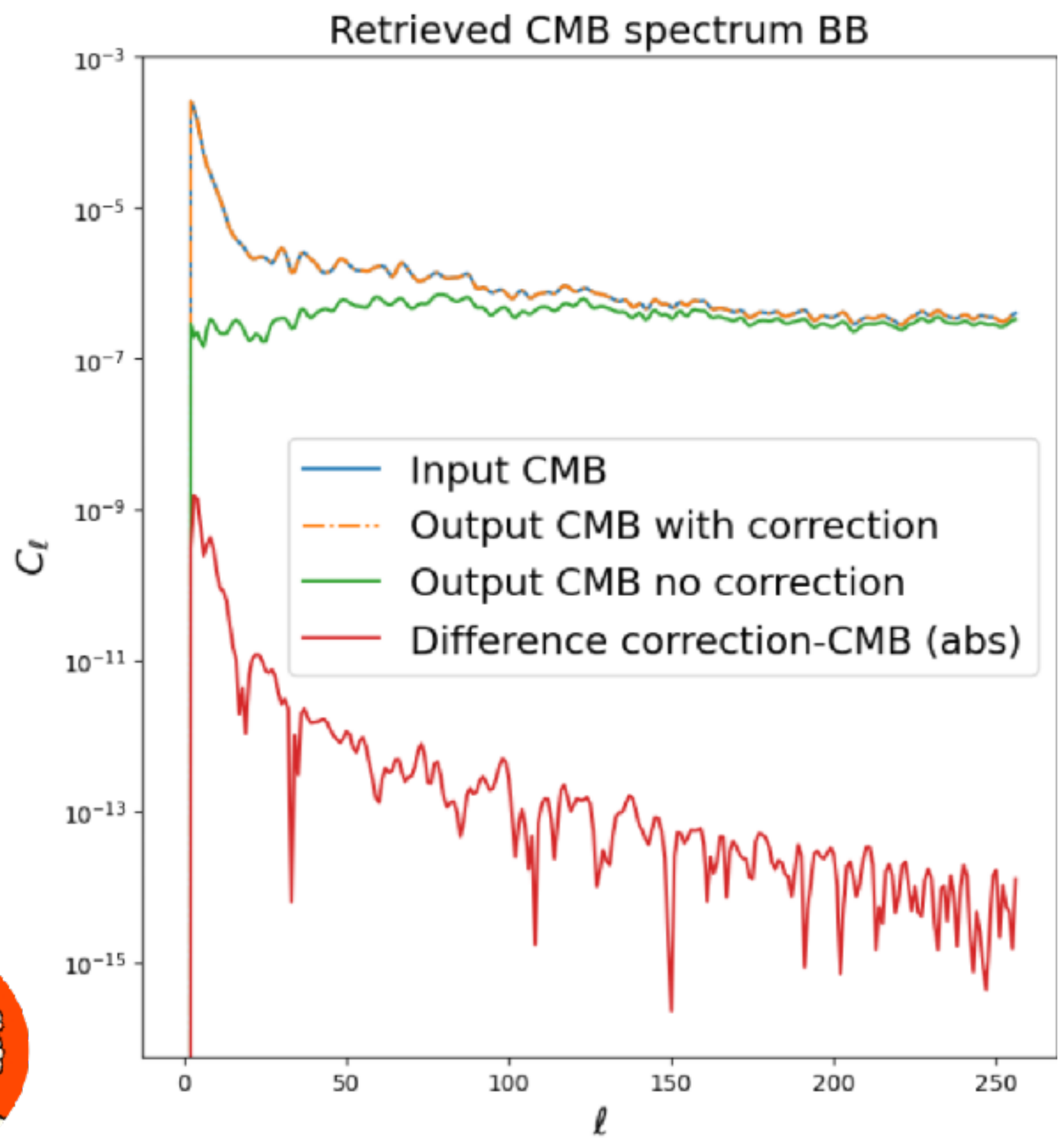
Component separation

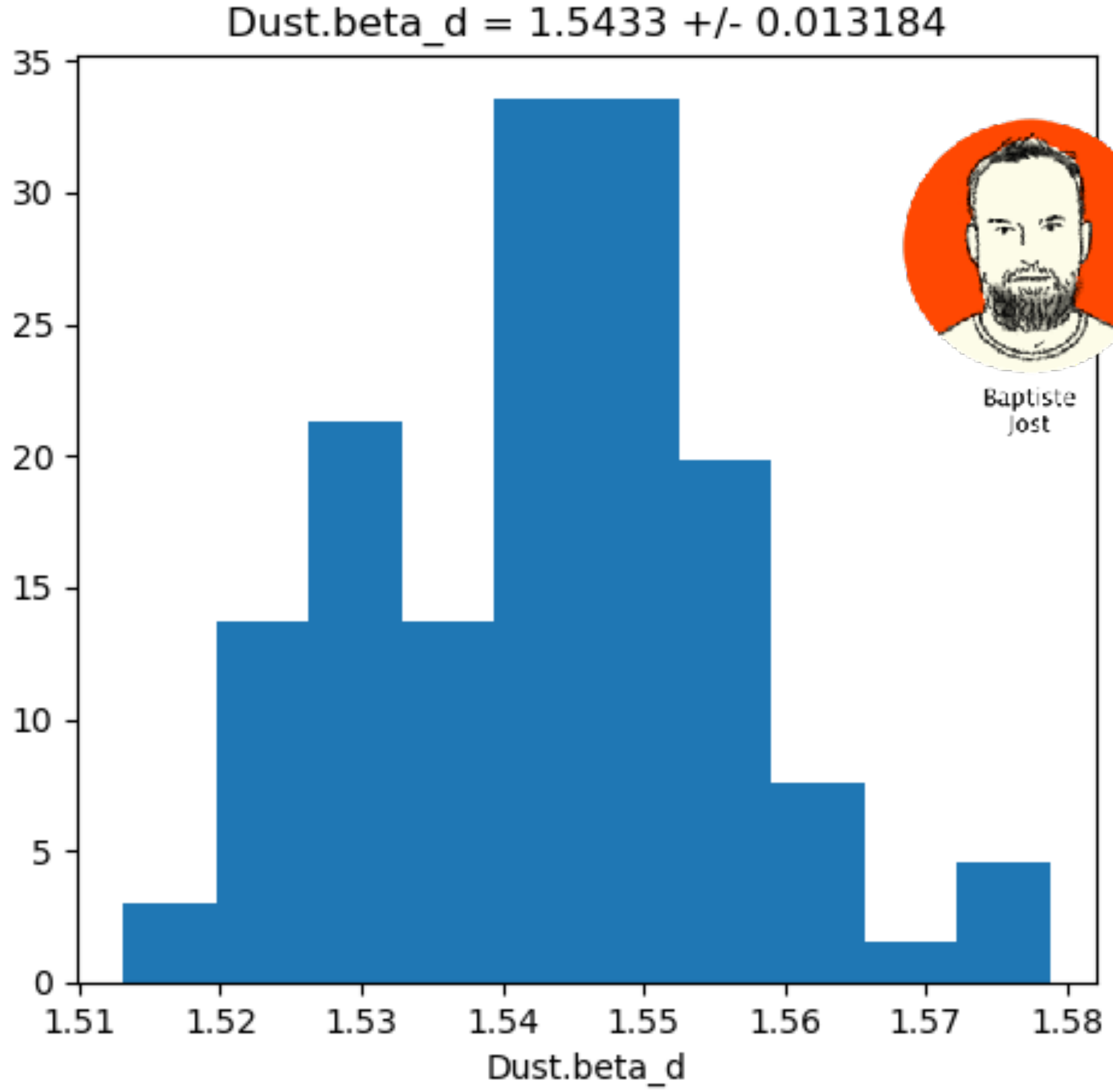
Parametric component separation in pixel space

$$-2\ln\mathscr{L}_{\mathrm{spec}}(\theta) = \mathrm{cst} - (\mathbf{A}^{\mathrm{T}}\mathscr{O}^{\mathrm{T}}\mathbf{N}^{-1}\mathbf{d})^{\mathrm{T}}(\mathbf{A}^{\mathrm{T}}\mathscr{O}^{\mathrm{T}}\mathbf{N}^{-1}\mathscr{O}\mathbf{A})^{-1}(\mathbf{A}^{\mathrm{T}}\mathscr{O}^{\mathrm{T}}\mathbf{N}^{-1}\mathbf{d})$$



Magdy Morshed

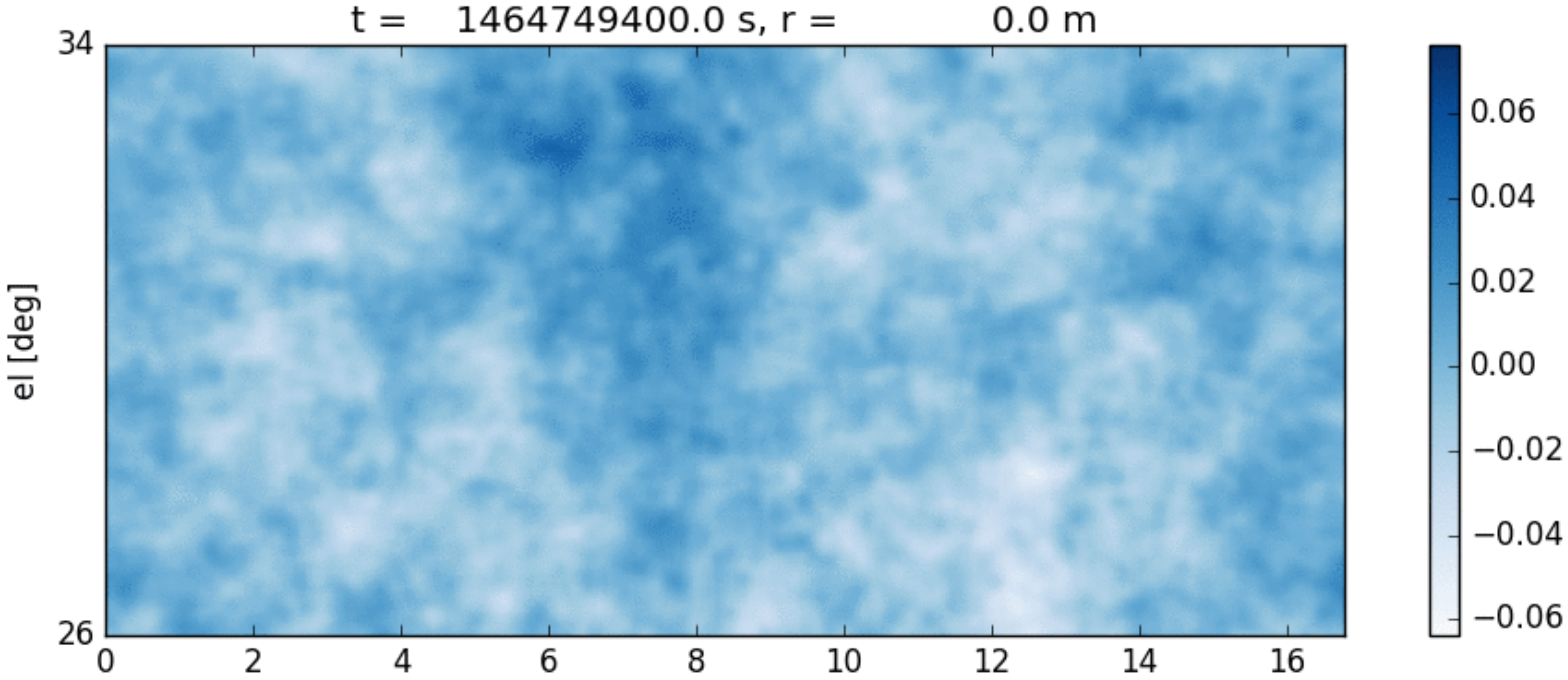




Baptiste Jost


B-modes
E-modes
Intensity anisotropies
Dipole
Monopole
CMB
Gravitational lensing
Galactic and extra-galactic foregrounds
Atmosphere
Systematics
Ground emissions
Noise

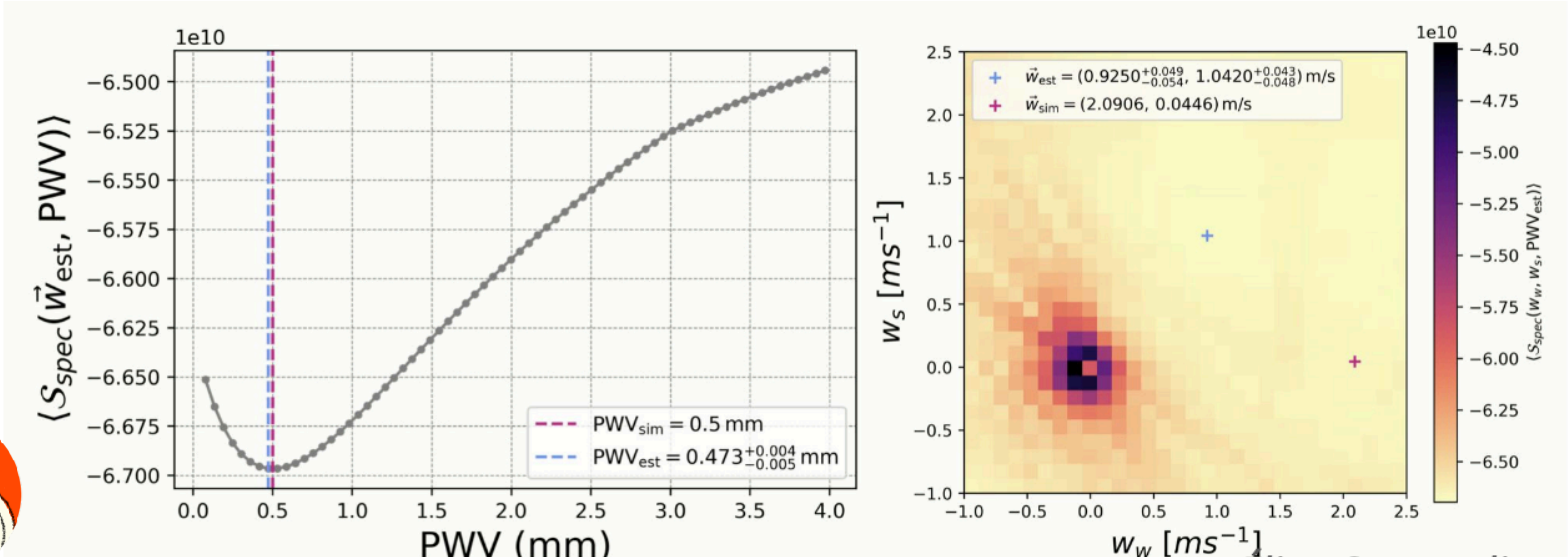
Component separation Separation of atmosphere signal in time domain



Atmosphere simulation. Credit: R. Keskitalo & J. Borrill

Component separation
Separation of atmosphere signal in time domain

$$\mathbf{d}_t = \mathbf{A}(\mathrm{PWV}) \cdot \mathbf{P}_{tp}(\mathrm{v_x}, \mathrm{v_y}) \cdot \mathbf{s}_p + \mathbf{n}_p$$



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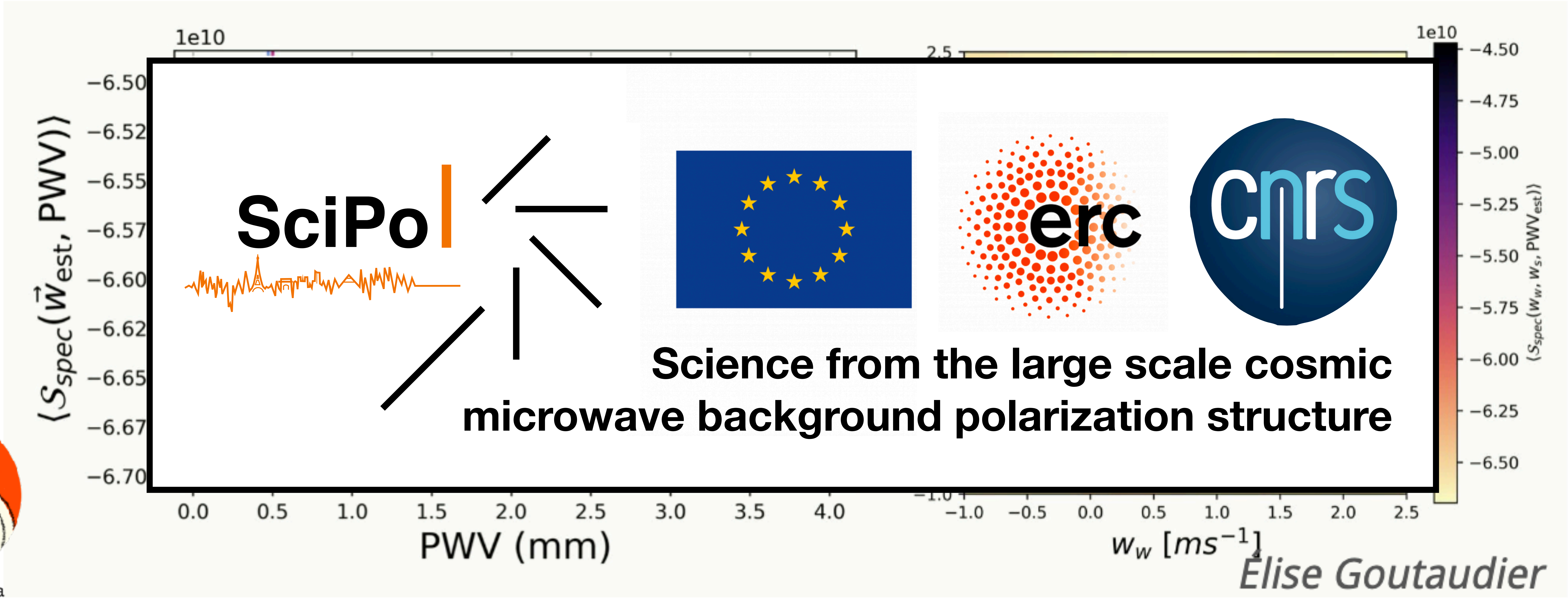

Amalia Villarrubia Aguilar

Outline

- Two SATs have ~1 year of early science data and continue to take data with sensitivity better than baseline.
- LAT is taking early science data and already reaching ACT sensitivities on small patches.
- 3 more SATs in construction: observing 2027
- LAT detector count nearly doubled now, filling the focal plane
- Active preparation of science pipelines !!

Credit : ESA and the *Planck* Collaboration

Thanks a lot !

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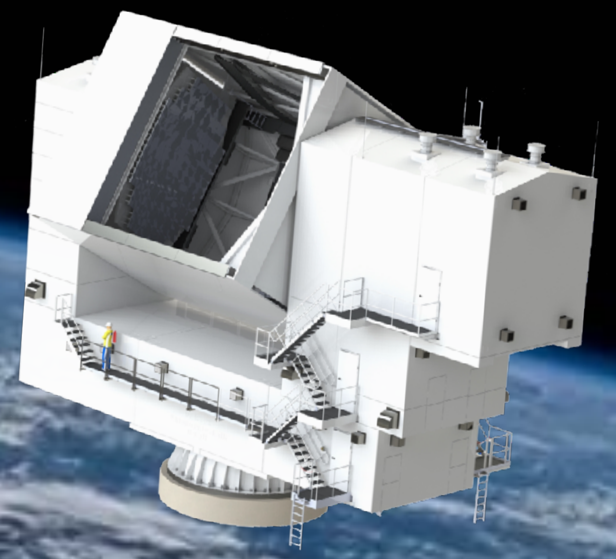
beringueb

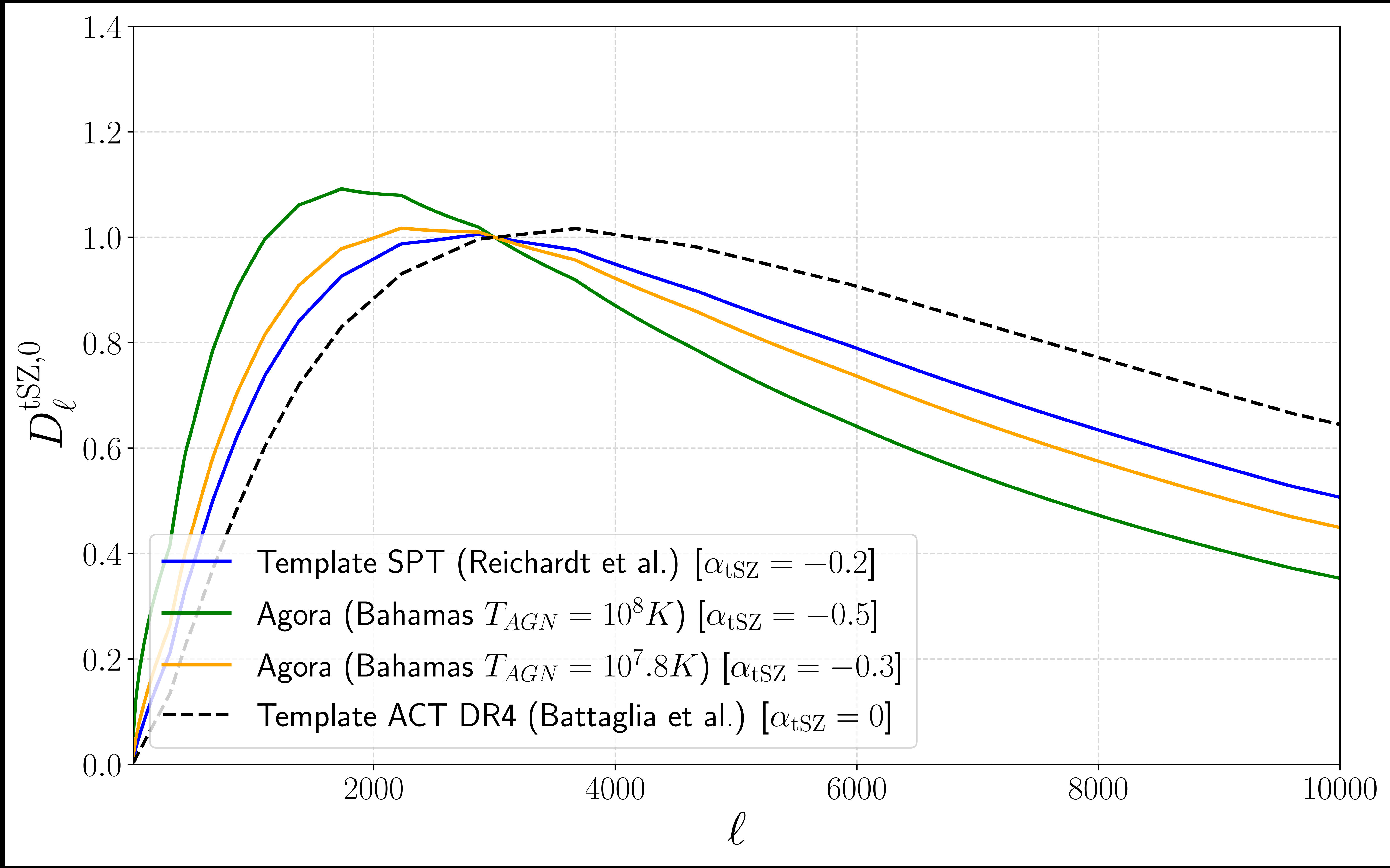


SciPol

Science from the large scale cosmic microwave background polarization structure

Constraints on tSZ spectrum

- $\alpha_{\rm tSZ}$ detected at 3σ in P-ACT: $\alpha_{\rm tSZ} = -0.6 \pm 0.2$.
- Higher AGN temperature than expected from AGORA/BAHAMAS simulations.
- Show sensitivity of multi-frequencies CMB data to tSZ modelling.



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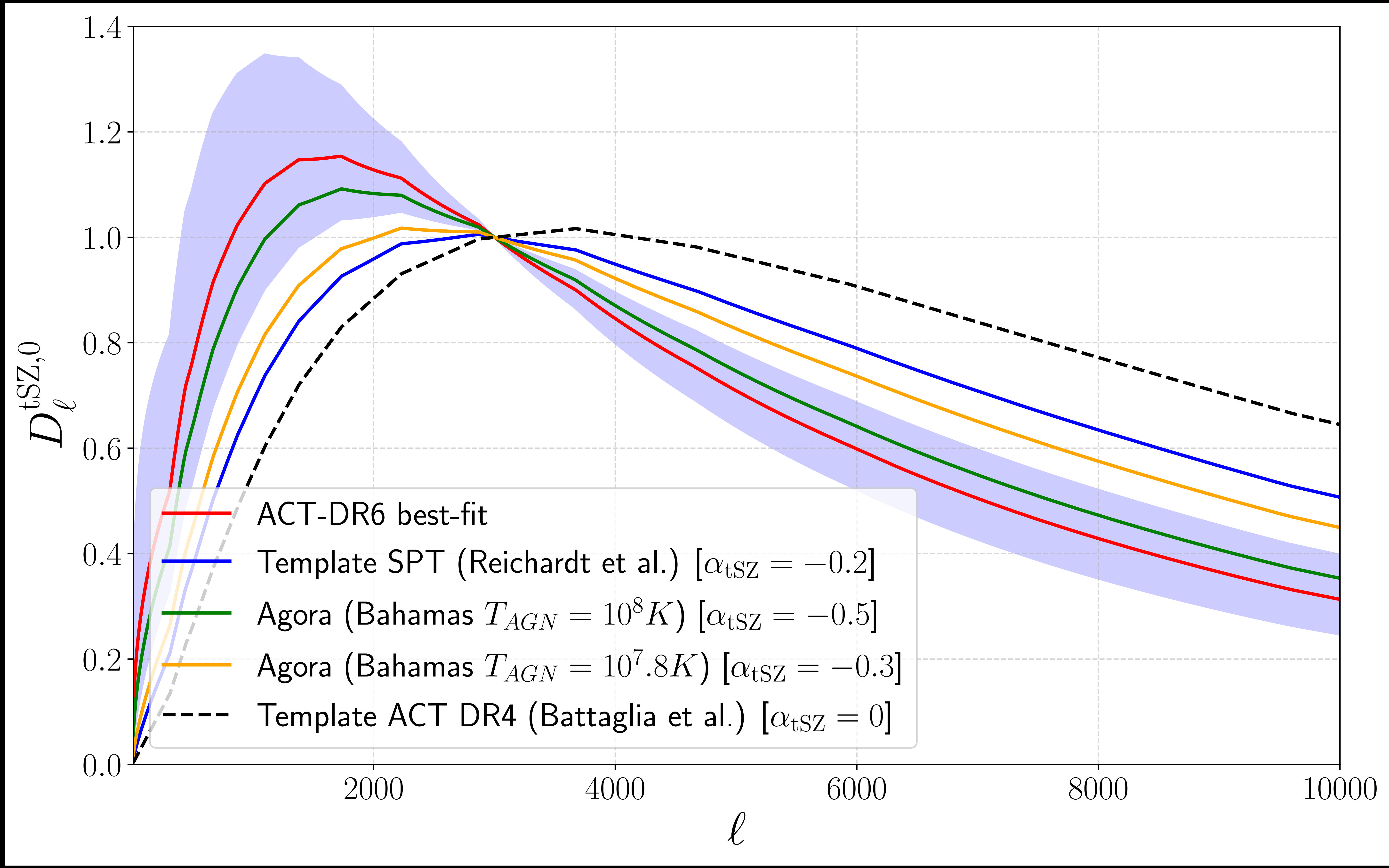


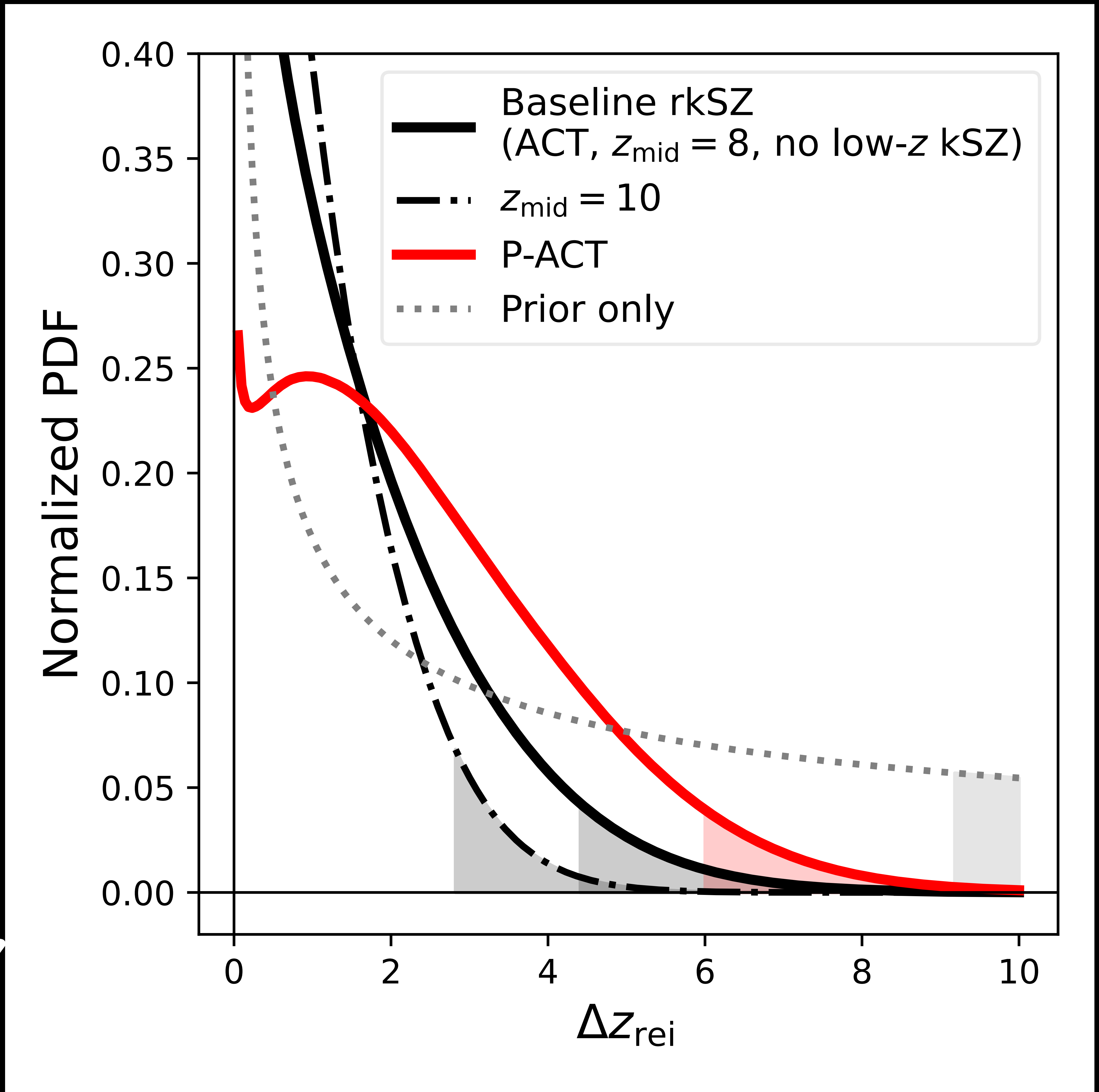
Benjamin BERINGUE, APC
October 13th 2025

Constraints on reionisation

$$a_{\mathrm{kSZ}} = 1.48^{+0.71}_{-1.10}\ \mu\mathrm{K}^2$$

$$a_{\mathrm{kSZ}} = 2.03\left[\frac{1+z_{\mathrm{mid}}}{11} - 0.12\right]\left(\frac{\Delta z_{\mathrm{rei}}}{1.05}\right)^{0.51}$$

[Battaglia et al. 2013]



[BB *et al.* 2506.06274]

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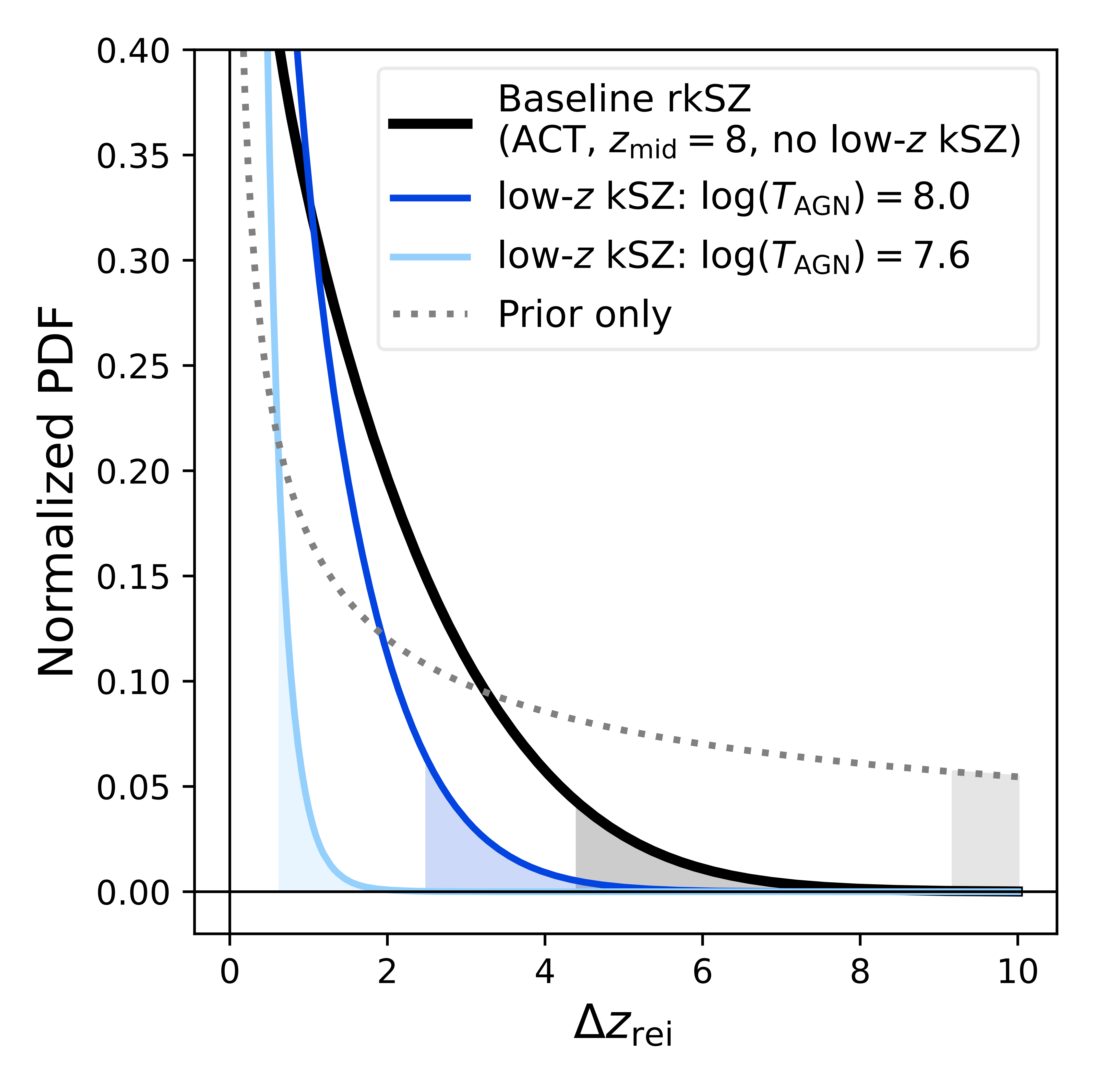
[Battaglia et al. 2013]



[BB *et al.* 2506.06274]

Constraints on reionisation

- Constraints on duration of reionisation for two different scaling relations.

Model	95% Upper Limit
Baseline rkSZ (ACT, B13 param., $z_{\rm mid} = 8$, no low-z kSZ)	$\Delta z_{\rm rei} < 4.4$
$z_{\rm mid} = 10$	$\Delta z_{\rm rei} < 2.9$
P-ACT	$\Delta z_{\rm rei} < 6.0$
low-z kSZ: $\log(T_{\rm AGN}) = 8.0$	$\Delta z_{\rm rei} < 2.5$
low-z kSZ: $\log(T_{\rm AGN}) = 7.6$	$\Delta z_{\rm rei} < 0.7$
Prior only	$\Delta z_{\rm rei} < 9.1$
AMBER param.	$\Delta z_{\rm rei,90} < 7.7$
AMBER param., $z_{\rm mid} = 10$	$\Delta z_{\rm rei,90} < 5.2$

[BB *et al.* 2506.06274]