PROBING THE EARLY OF THE UNIVERSE with the SIMONS OBSERVATORY

Preliminary Analysis from the SATs and the Road to Detecting Primordial Gravitational Waves

11 Feb 2025
UC Berkeley
BCCP Seminar

Susanna Azzoni
sazzoni@princeton.edu

Photo credit: Hironobu Nakata

Outline

- Overview

  Testing the initial conditions of the Universe with the CMB

- The Simons Observatory

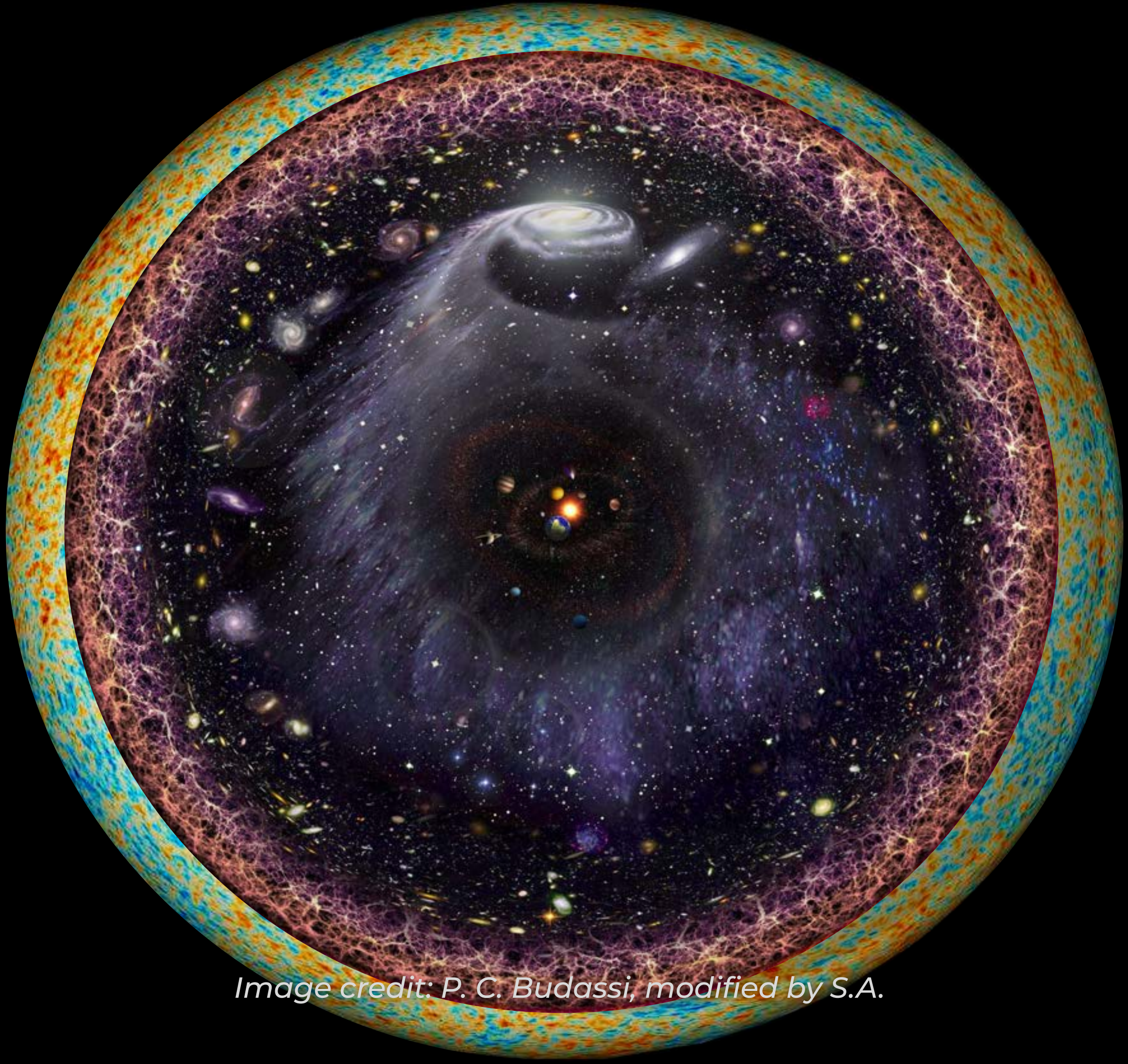
  Small Aperture Telescopes

- Early Analysis

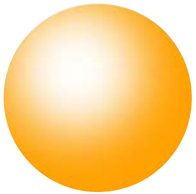
  Preliminary Results

  The road to PGW

- More open questions

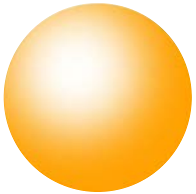


The Cosmic Microwave Background (CMB)

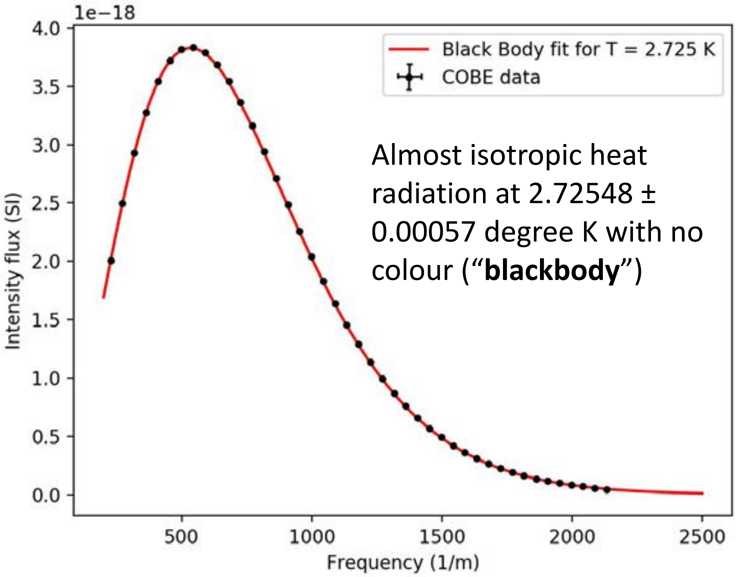


Holmdel Horn Antenna	COBE-FIRAS	Toco, MAXIMA, Boomerang	DASI, WMAP	SPT, ACT, POLARBEAR, BICEP	Planck
1965	1992	2001	2002	2014	2015

The Cosmic Microwave Background (CMB)



T = 2.7 K

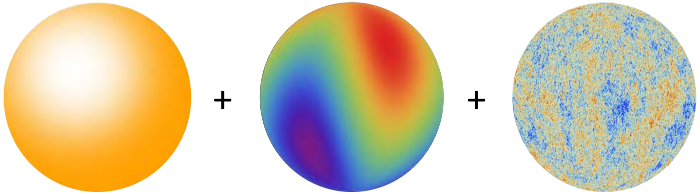


Almost isotropic heat radiation at 2.72548 ± 0.00057 degree K with no colour ("**blackbody**")

1965	1992	2001	2002	2014	2015
Holmdel Horn Antenna	COBE-FIRAS	Toco, MAXIMA, Boomerang	DASI, WMAP	SPT, ACT, POLARBEAR, BICEP	Planck

The Cosmic Microwave Background (CMB)

non polarized



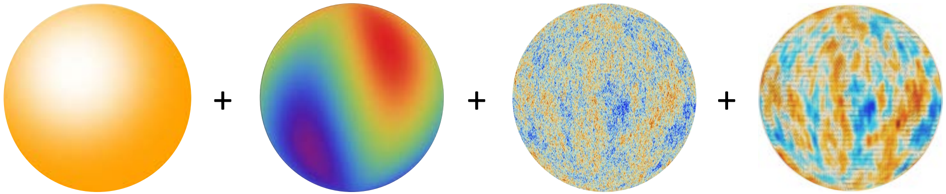
$T = 2.7$ K + $\Delta T/T \sim 10^{-3}$ + $\Delta T/T \sim 10^{-5}$

1965	1992	2001	2002	2014	2015
Holmdel Horn Antenna	COBE-FIRAS	Toco, MAXIMA, Boomerang	DASI, WMAP	SPT, ACT, POLARBEAR, BICEP	Planck

The Cosmic Microwave Background (CMB)

non polarized

polarized



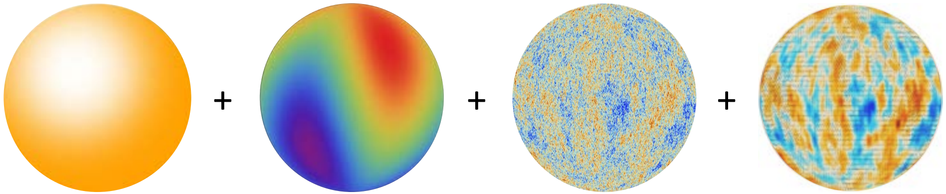
$T = 2.7\ K$ | $\Delta T/T \sim 10^{-3}$ | $\Delta T/T \sim 10^{-5}$ | $\Delta P/T \sim 10^{-6}$

1965	1992	2001	2002	2014	2015
Holmdel Horn Antenna	COBE-FIRAS	Toco, MAXIMA, Boomerang	DASI, WMAP	SPT, ACT, POLARBEAR, BICEP	Planck

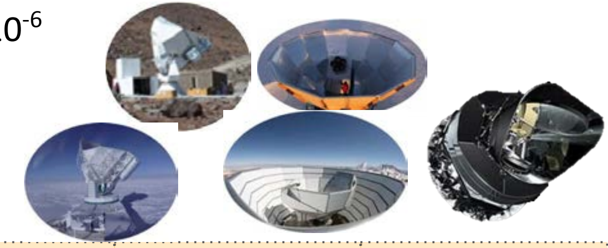
The Cosmic Microwave Background (CMB)

non polarized

polarized

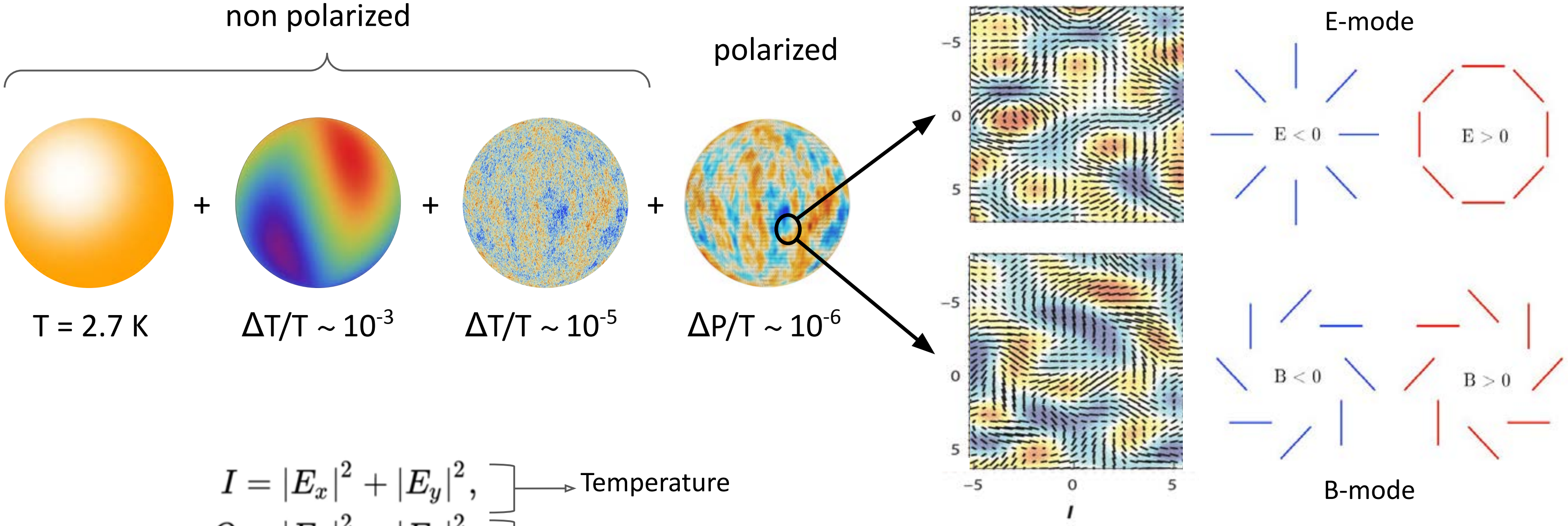


$T = 2.7$ K + $\Delta T/T \sim 10^{-3}$ + $\Delta T/T \sim 10^{-5}$ + $\Delta P/T \sim 10^{-6}$



1965	Holmdel Horn Antenna
1992	COBE-FIRAS
2001	Toco, MAXIMA, Boomerang
2002	DASI, WMAP
2014	SPT, ACT, POLARBEAR, BICEP
2015	Planck

The CMB polarization

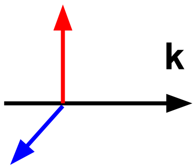


Stokes parameters

$$I = |E_x|^2 + |E_y|^2,$$ → Temperature

$$Q = |E_x|^2 - |E_y|^2,$$
$$U = 2\mathrm{Re}(E_x E_y^*),$$
$$V = -2\mathrm{Im}(E_x E_y^*),$$

$$\mathcal{P}_{ab} = \frac{1}{\sqrt{2}} \begin{pmatrix} Q(\boldsymbol{\theta}) & U(\boldsymbol{\theta}) \\ U(\boldsymbol{\theta}) & -Q(\boldsymbol{\theta}) \end{pmatrix} \quad \nabla^2 E = \partial_a \partial_b \mathcal{P}_{ab}, \quad \nabla^2 B = \epsilon_{ac} \partial_b \partial_c \mathcal{P}_{ab}$$

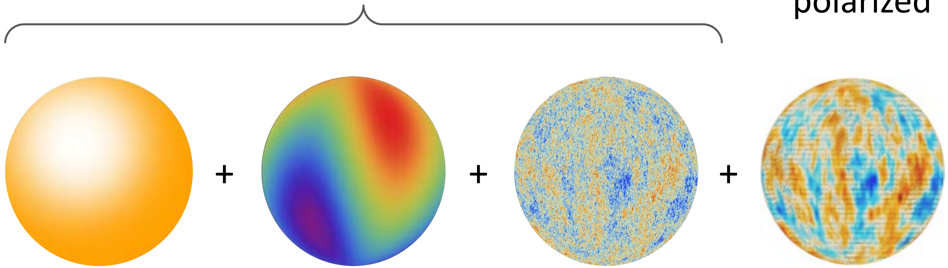


Kamionkowski et al. 9609132
Selijak & Zaldarriaga 9609169

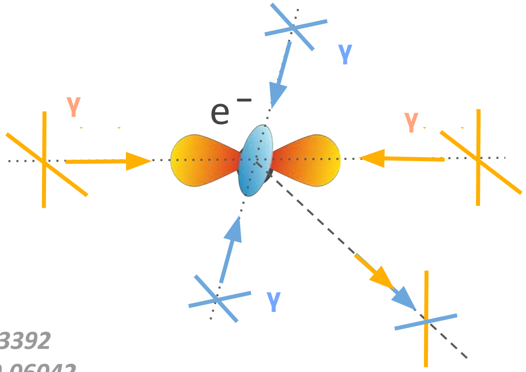
The CMB polarization

non polarized

polarized



T = 2.7 K — $\Delta T/T \sim 10^{-3}$ — $\Delta T/T \sim 10^{-5}$ — $\Delta P/T \sim 10^{-6}$

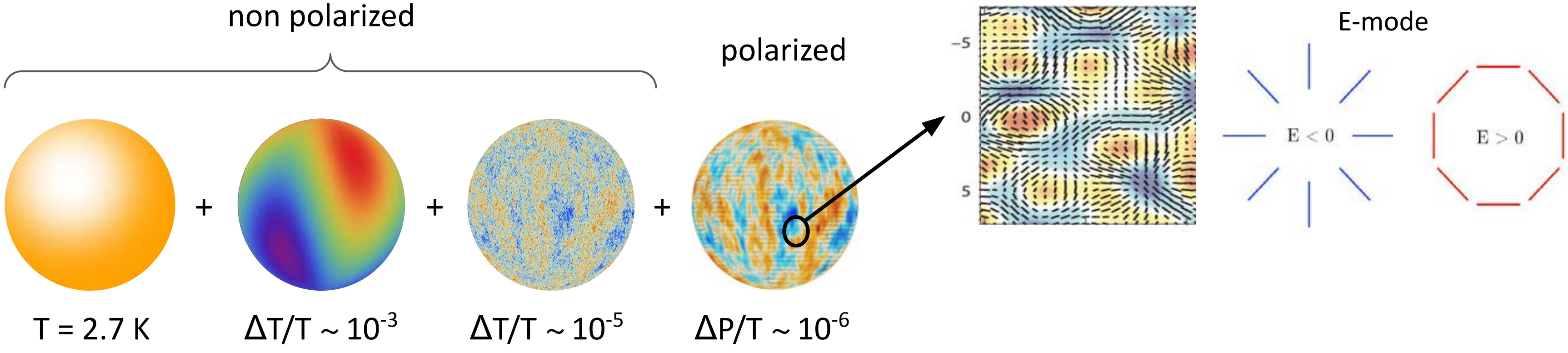


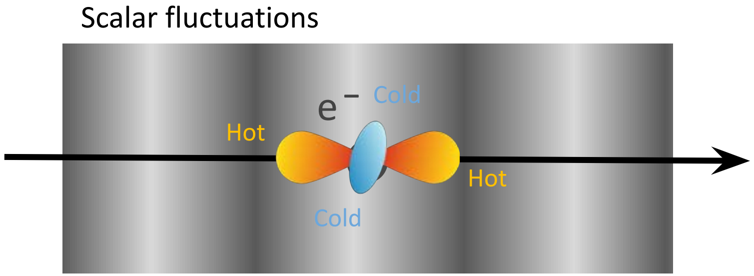
Thomson scattering generates polarization:

- Photons have electric and magnetic fields
- electrons accelerates, emit photons
- when e- sees **quadrupole temperature pattern:** hot ***γ*** accelerates them more
- emitted light is polarized

Kosowski 9501045
Cabella & Kamionkowski 0403392
Kamionkowski & Kovetz 1510.06042

The CMB polarization

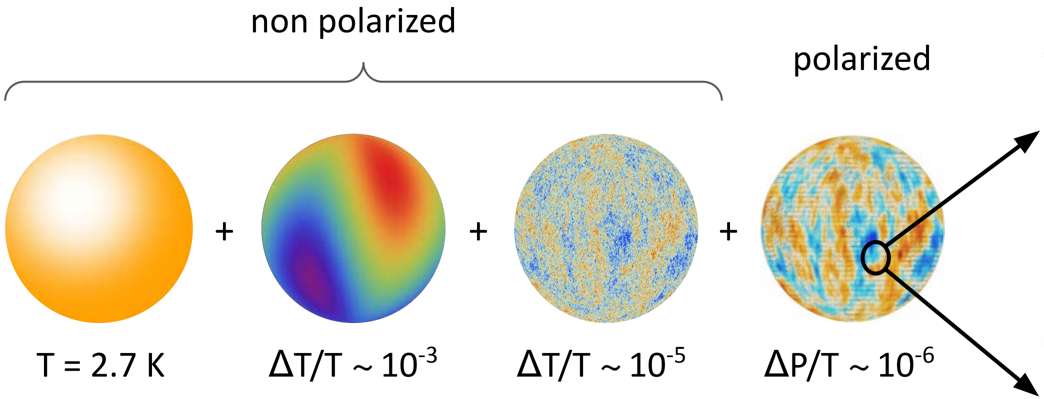


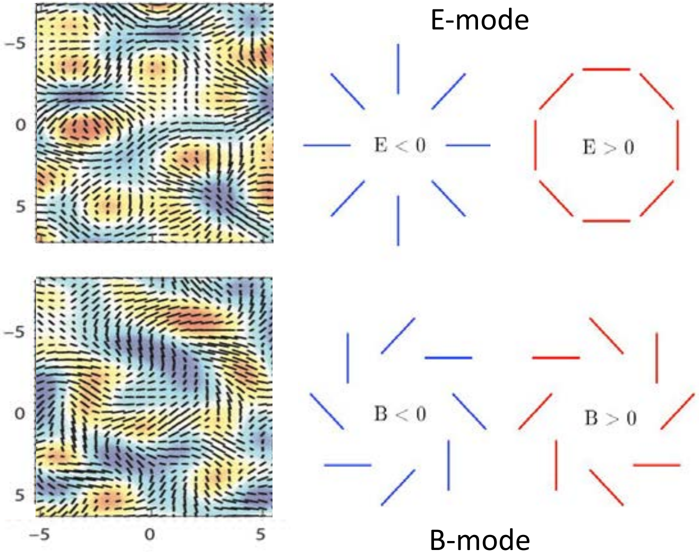


Thomson scattering + anisotropic background: density fluct. generate **CMB E-modes**

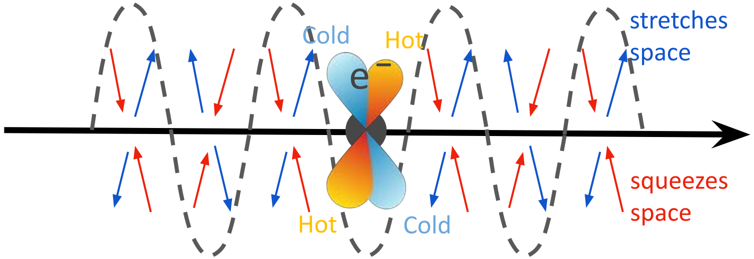
Kosowski 9501045
Cabella & Kamionkowski 0403392
Kamionkowski & Kovetz 1510.06042

The CMB polarization





Tensor fluctuations

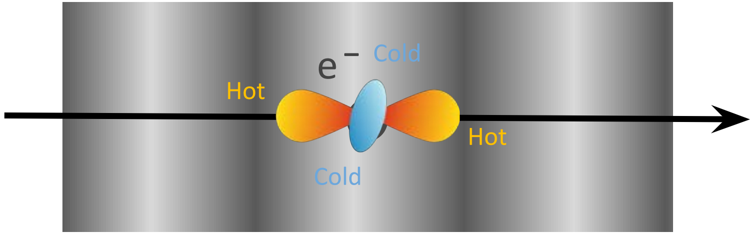


Thomson scattering + anisotropic background:
PGW can generate **CMB E-modes + B-modes**

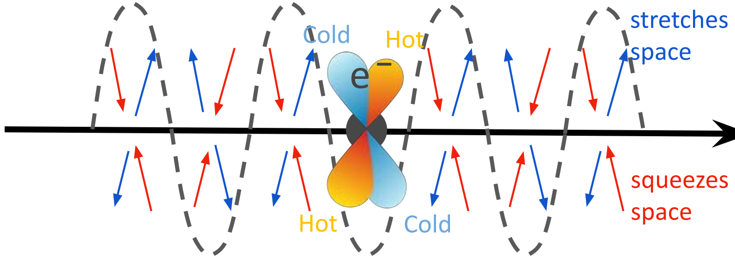
Kosowski 9501045
Cabella & Kamionkowski 0403392
Kamionkowski & Kovetz 1510.06042

Inflation theory

Scalar fluctuations



Tensor fluctuations



Inflation: quantum vacuum fluctuations excite cosmological scalar and tensor perturbations, **seen today in the CMB** and matter distribution

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

scalar mode ("curvature perturbation")

tensor mode ("gravitational waves")

$$\mathcal{P}_\zeta(k) = \left(\frac{H}{2\pi}\right)^2 \left(\frac{H}{\dot{\phi}}\right)^2 = \frac{1}{8\pi^2} \frac{H^4}{M_{\rm Pl}^2 |\dot{H}|}\bigg|_{k=aH} \approx A_s \left(\frac{k}{k_*}\right)^{n_s - 1}$$

$$\mathcal{P}_h(k) = \frac{8}{M_{\rm Pl}^2} \left(\frac{H}{2\pi}\right)^2 \underset{k=aH}{\simeq} A_t \left(\frac{k}{k_*}\right)^{n_t}$$

Not Yet Observed!!

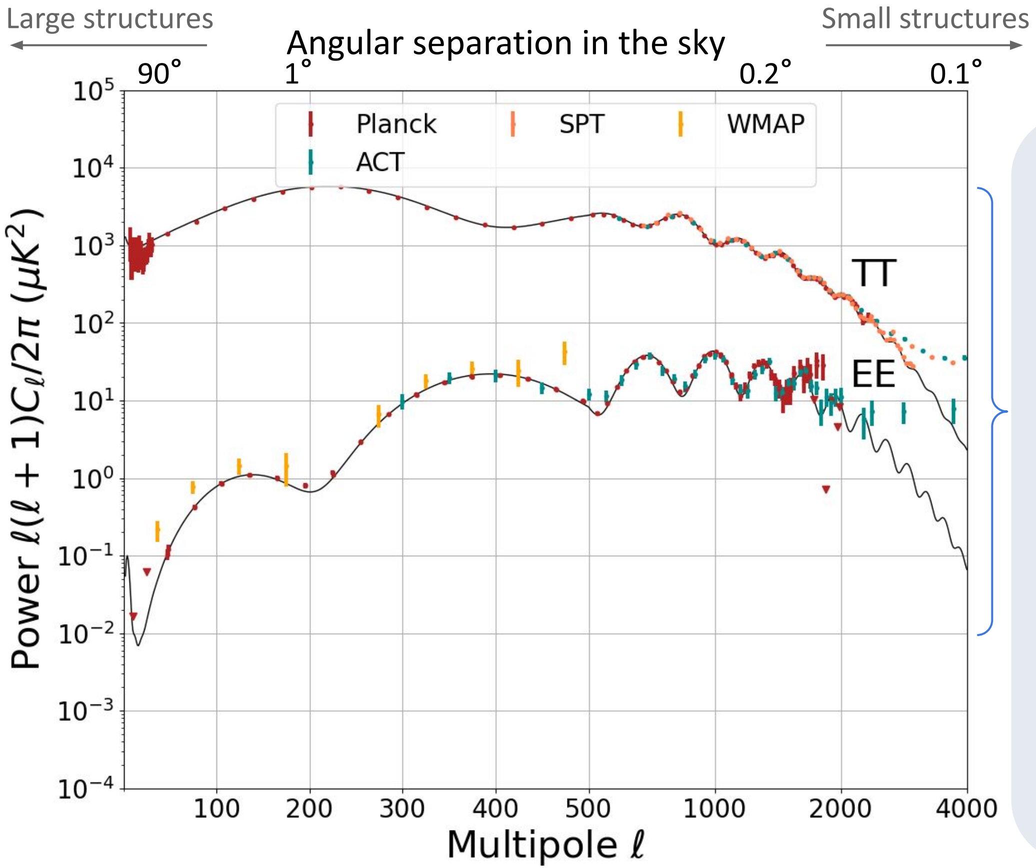
Tensor-to-scalar ratio $r = \frac{A_t}{A_s} = 16 \frac{|\dot{H}|}{H^2}$

Characterizes amplitude of PGW, direct probe of energy scale associated with inflation

Guth & Pi (1982) || Mukhanov & Chibisov (1981) Hawking (1982) ||Starobinsky (1982) Bardeen || Steinhardt & Turner (1983)

Grishchuk (1974) Starobinsky (1979)

Testing Early-Universe Models with the CMB



CMB field highly gaussian ⟶
power spectra encode statistics:

Scalar fluctuations: generate T / E modes

Measurements compatible with single-field inflation:

- *power law* (dn/dlnk = -0.005 ± 0.007)
- *adiabatic fluctuations* (Variance < 2%)
- *gaussian* initial fluctuations ($f_{NL\text{-}local}$ = -1 ± 5)

Consistent with ΛCDM

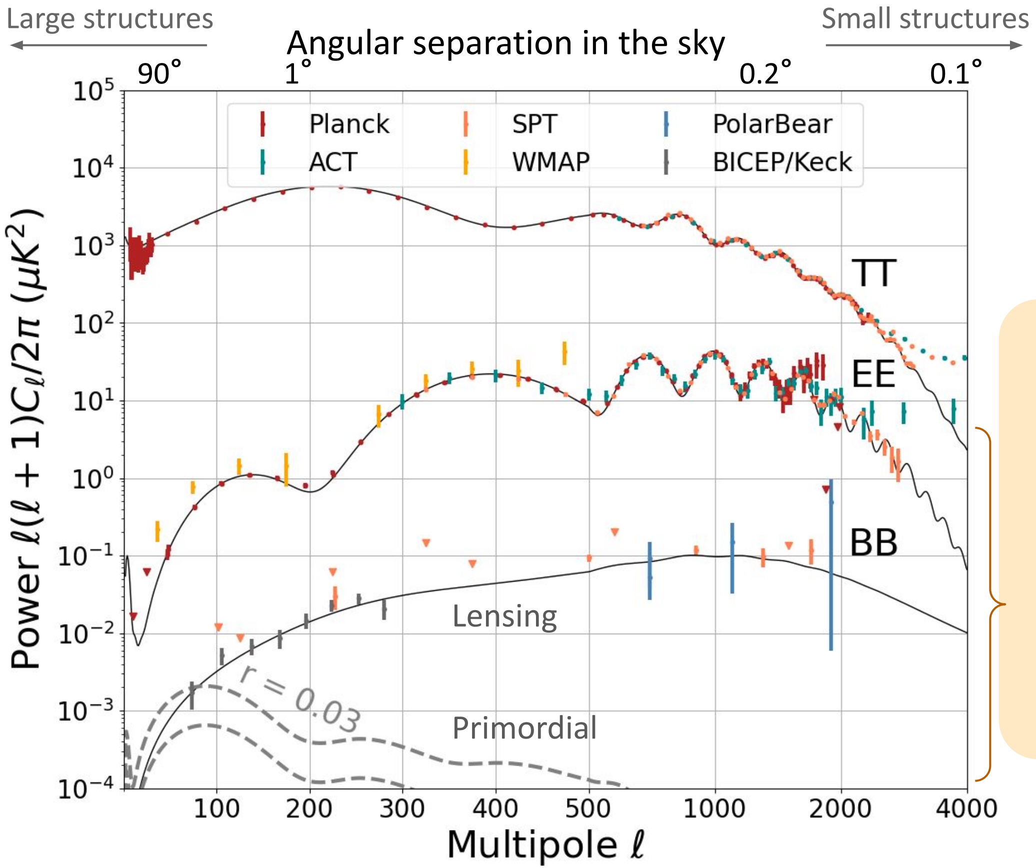
- No sign of extra-light particles: N_{eff} = 3 ± 0.2
- No non-zero neutrino mass: Σm_ν < 0.12 eV
- No departure from flatness: Ω_k = 0.001 ± 0.002
- No departure from cosmo constant: ω_0 = -0.98 ± 0.03

from Planck Collab. 2018, X and IX

Probes of initial conditions:

- anisotropies at small scales
- spectral distortions
- non-Gaussianity

Testing Early-Universe Models with the CMB



CMB field highly gaussian →
power spectra encode statistics:

Tensor fluctuations: generate E / B modes:

Still no detection of PGW

- current constraints from BICEP/Keck 2022:
  PGW ∝ r < 0.032 (95% C.L.)

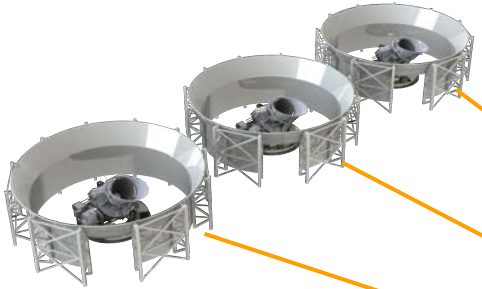
Probes of initial conditions:

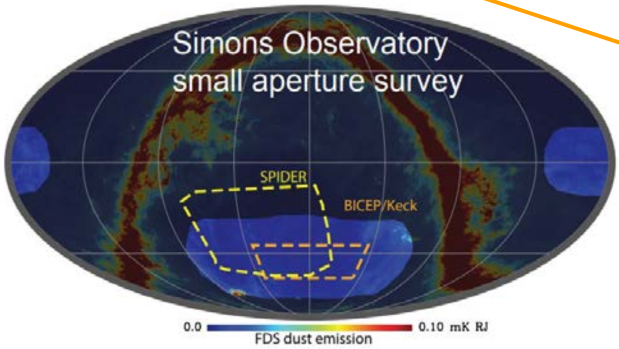
- CMB polarization
  E-modes: photon-baryon plasma velocity
  B-modes rule out many inflationary and non-inflationary models

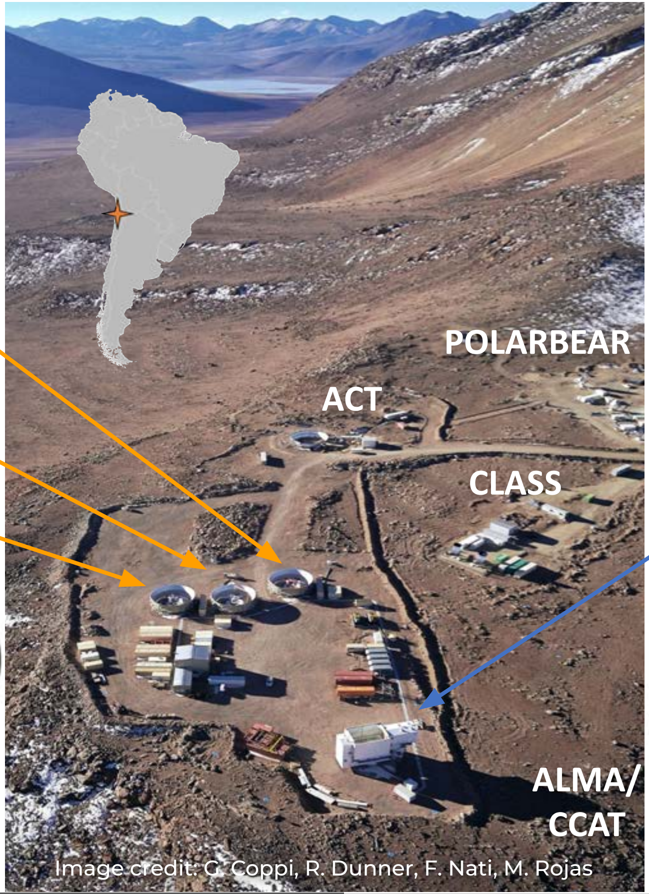
The Simons Observatory: SAT and LAT

Small Aperture Telescopes (SATs)

- Focusing on Larger Angular Scales (low ℓ)
- 0.4m on smaller sky fraction (10%)
- Deep maps with low angular resolution

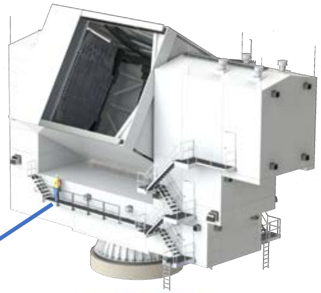


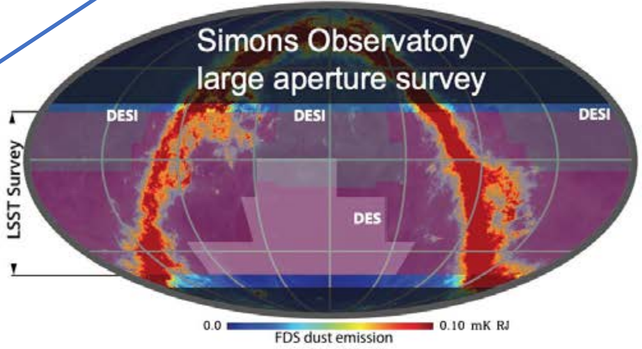




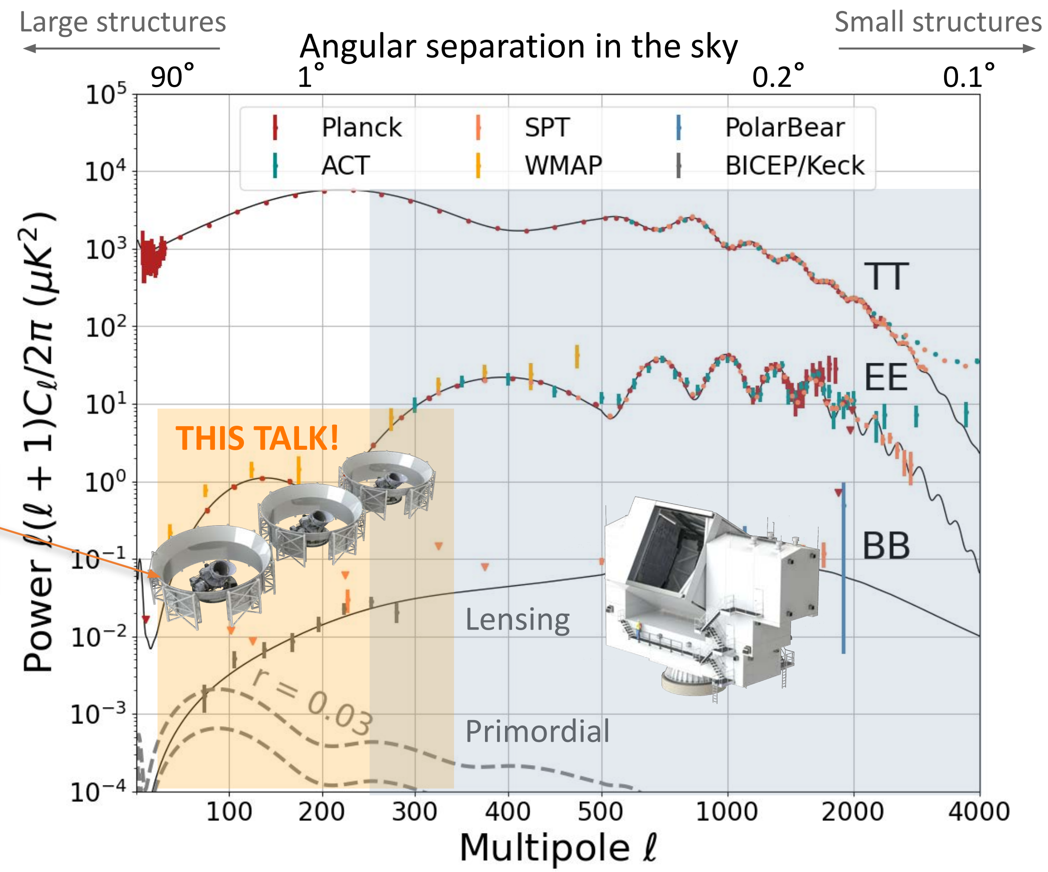
Large Aperture Telescopes (LAT)

- Focusing on Smaller Angular Scales (high ℓ)
- 6m on larger sky fraction (40%)
- Wide maps with high angular resolution





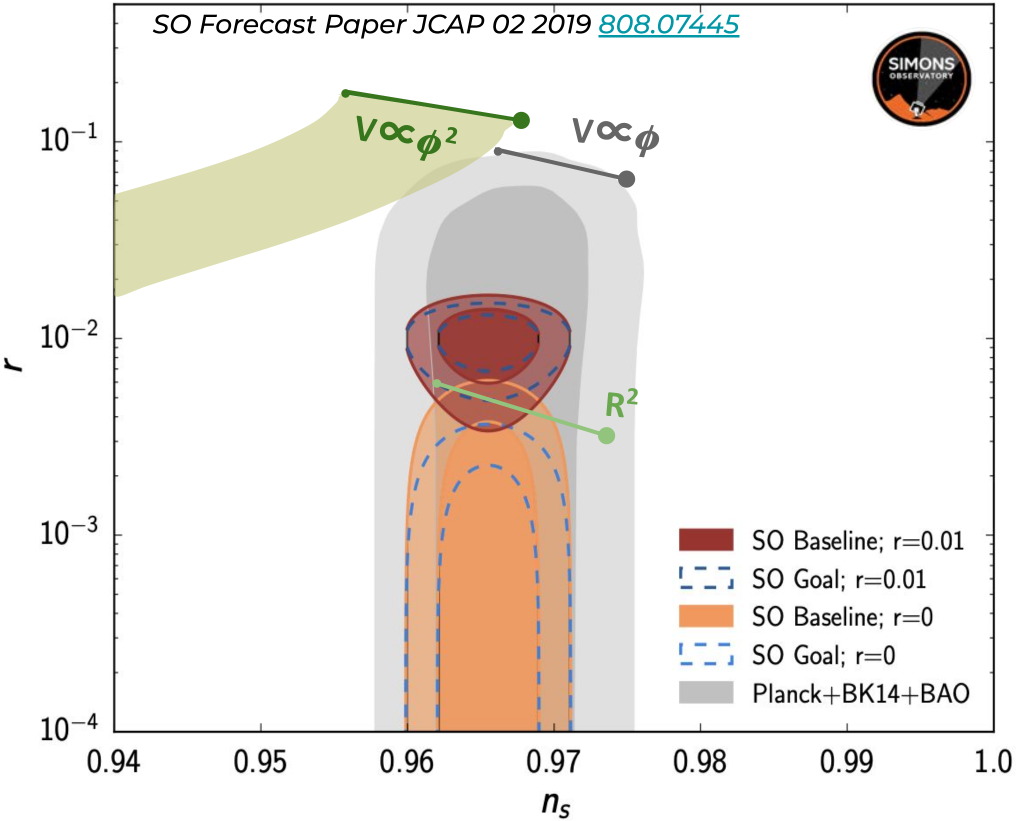
The Simons Observatory: SAT and LAT



One of the SATs was built here at Berkeley (Adrian Lee ++)

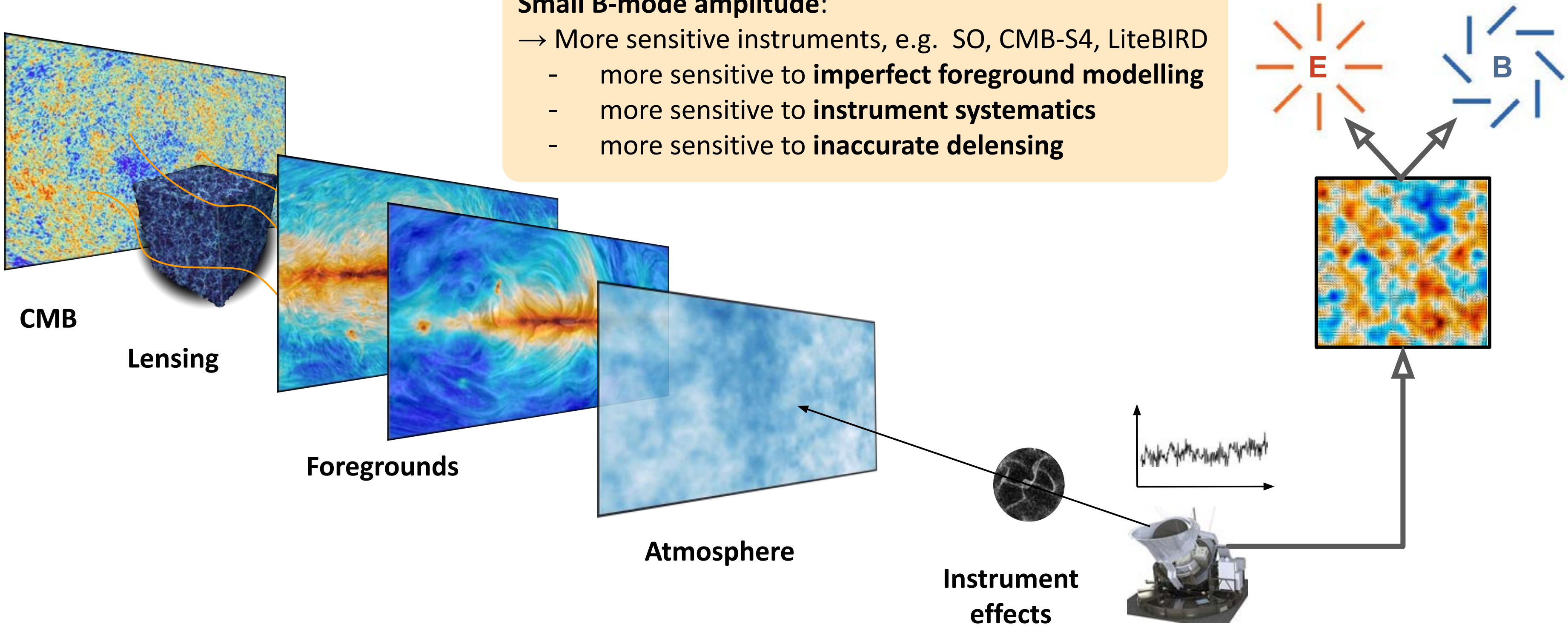
Probing the beginning with the SATs

Goal: **σ(r) < 0.002-0.003**
i.e. provide direct evidence for the quantization of gravity or rule out R^2 inflation.



Observational challenges

Small B-mode amplitude:
⟶ More sensitive instruments, e.g. SO, CMB-S4, LiteBIRD
- more sensitive to **imperfect foreground modelling**
- more sensitive to **instrument systematics**
- more sensitive to **inaccurate delensing**

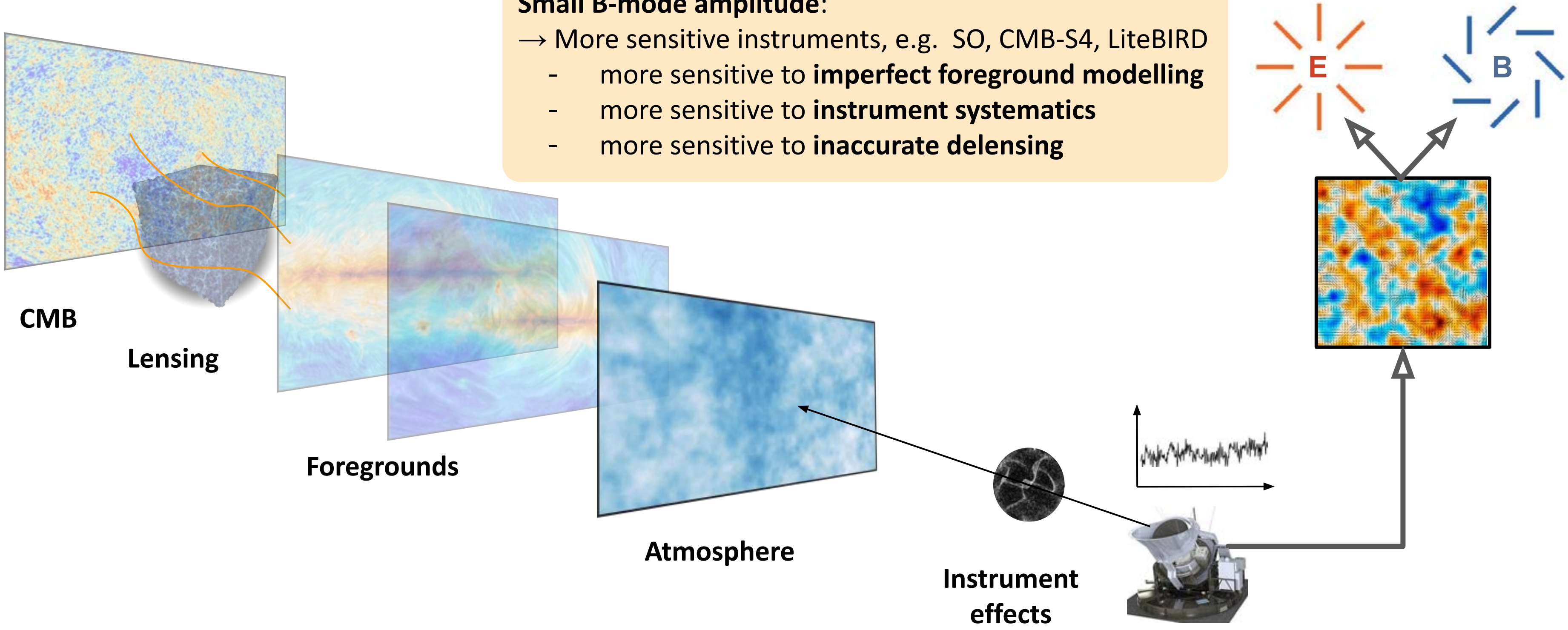


Observational challenges

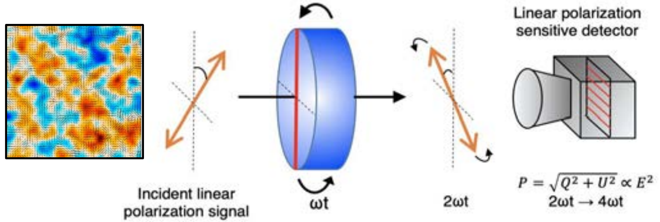
Small B-mode amplitude:

⟶ More sensitive instruments, e.g. SO, CMB-S4, LiteBIRD

- more sensitive to **imperfect foreground modelling**
- more sensitive to **instrument systematics**
- more sensitive to **inaccurate delensing**



Polarization and Half Wave Plate (HWP)



Input signal:

$$[I_{\rm in} + Q_{\rm in} \pm U_{\rm in}](t) = [I_{\rm in} + Q_{\rm in} \pm U_{\rm in}] \exp(i\omega_{\rm sig}\, t)$$

Data model:

$\theta(t) = 2\pi f_{\rm HWP}\, t = \omega_{\rm HWP}\, t$

$$d_{\rm m}(t) = I_{\rm in}(t) + {\rm Re}\{[Q_{\rm in}(t) \pm iU_{\rm in}(t)] \exp[\mp i4\theta(t)]\}$$

Unpolarised Stokes component

HWP-modulated polarized sky signal

Time domain

Fourier transform

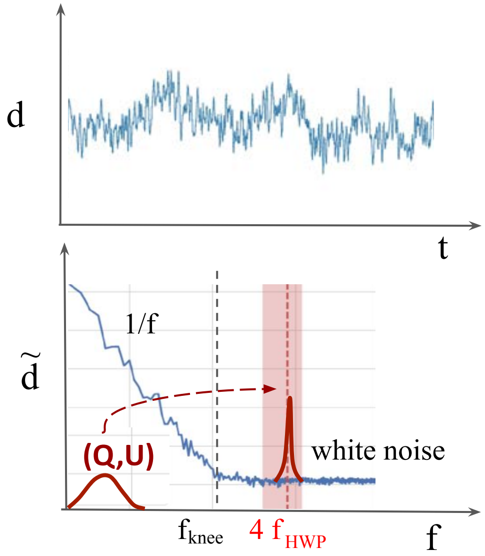
Fourier domain

$$d_{\rm m}(\omega_{\rm sig}) = I(\omega_{\rm sig}) + \frac{1}{2}[Q_{\rm in} \pm iU_{\rm in}](4\omega_{\rm HWP} \pm \omega_{\rm sig})$$

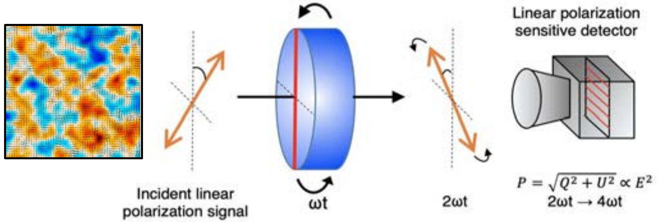
Polarization signal uplifted above $f_{\rm knee}$

CHWP paper: Yamada K. et al. Rev. Sci. Instrum. 95, 024504 (2024)
10.1063/5.0178066

Rotating HWP:
- suppresses long time scales effects (1/f noise)
- mitigates differential systematic uncertainties (beam)



Polarization and Half Wave Plate (HWP)



Input signal:

$$[I_{\rm in} + Q_{\rm in} \pm U_{\rm in}](t) = [I_{\rm in} + Q_{\rm in} \pm U_{\rm in}] \exp(i\omega_{\rm sig}\, t)$$

Data model:

$\theta(t) = 2\pi\, f_{\rm HWP}\, t = \omega_{\rm HWP}\, t$

$$d_{\rm m}(t) = I_{\rm in}(t) + {\rm Re}\{[Q_{\rm in}(t) \pm iU_{\rm in}(t)] \exp[\mp i4\theta(t)]\}$$

Unpolarised Stokes component

HWP-modulated polarized sky signal

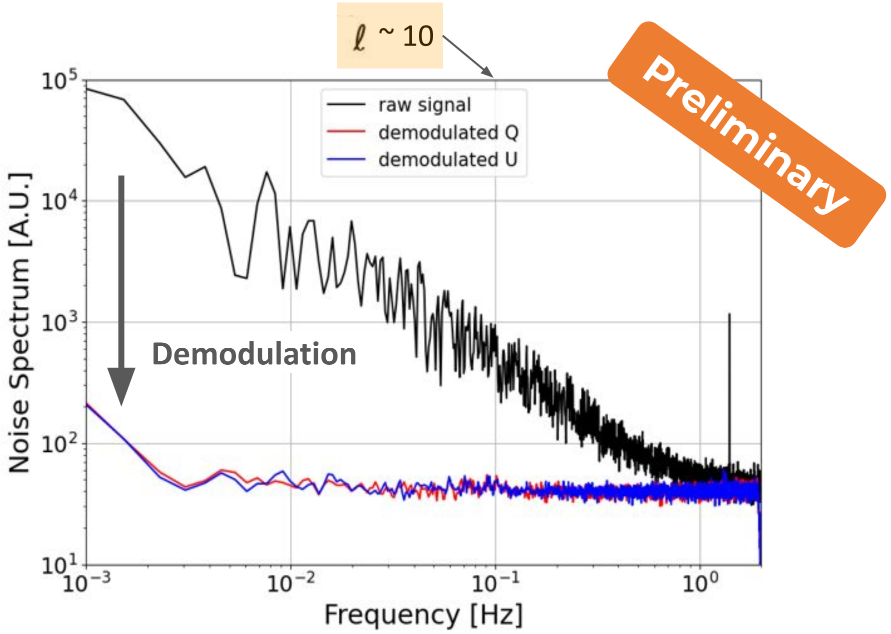
Time domain

Fourier transform

Fourier domain

$$d_{\rm m}(\omega_{\rm sig}) = I(\omega_{\rm sig}) + \frac{1}{2}[Q_{\rm in} \pm iU_{\rm in}](4\omega_{\rm HWP} \pm \omega_{\rm sig})$$

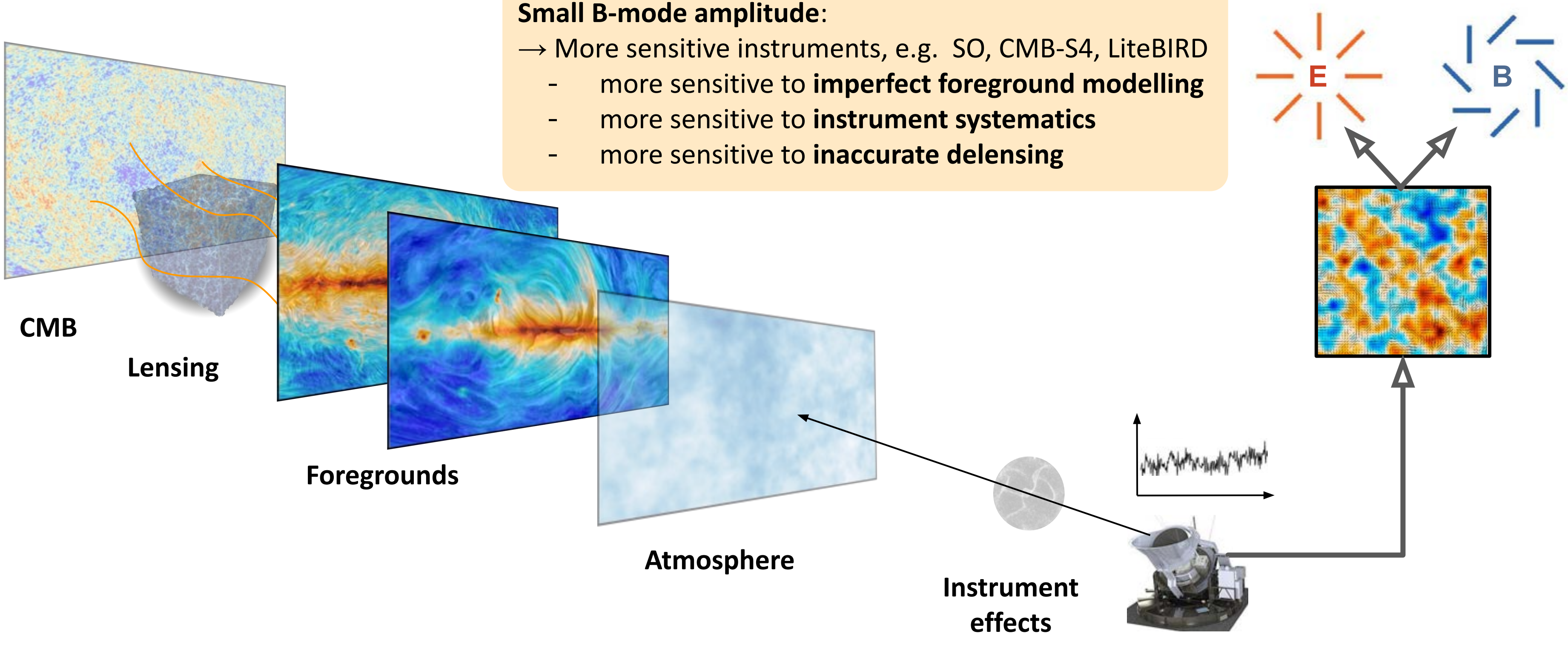
Polarization signal uplifted above $f_{\rm knee}$



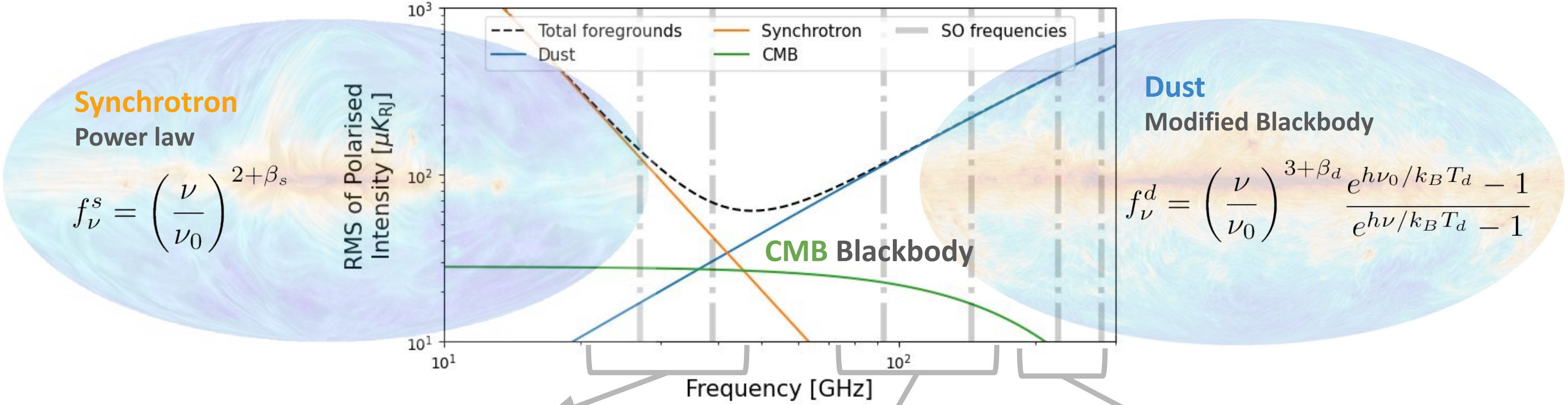
Noise spectra from ~100 detectors with no additional filtering post-demodulation. Spectrum is white until very low frequencies (i.e. very low ℓ)

Observational challenges

Small B-mode amplitude:
→ More sensitive instruments, e.g. SO, CMB-S4, LiteBIRD
- more sensitive to **imperfect foreground modelling**
- more sensitive to **instrument systematics**
- more sensitive to **inaccurate delensing**



SAT Bandpasses (and Foregrounds)



$$f_\nu^s = \left(\frac{\nu}{\nu_0}\right)^{2+\beta_s}$$

$$f_\nu^d = \left(\frac{\nu}{\nu_0}\right)^{3+\beta_d} \frac{e^{h\nu_0/k_B T_d} - 1}{e^{h\nu/k_B T_d} - 1}$$

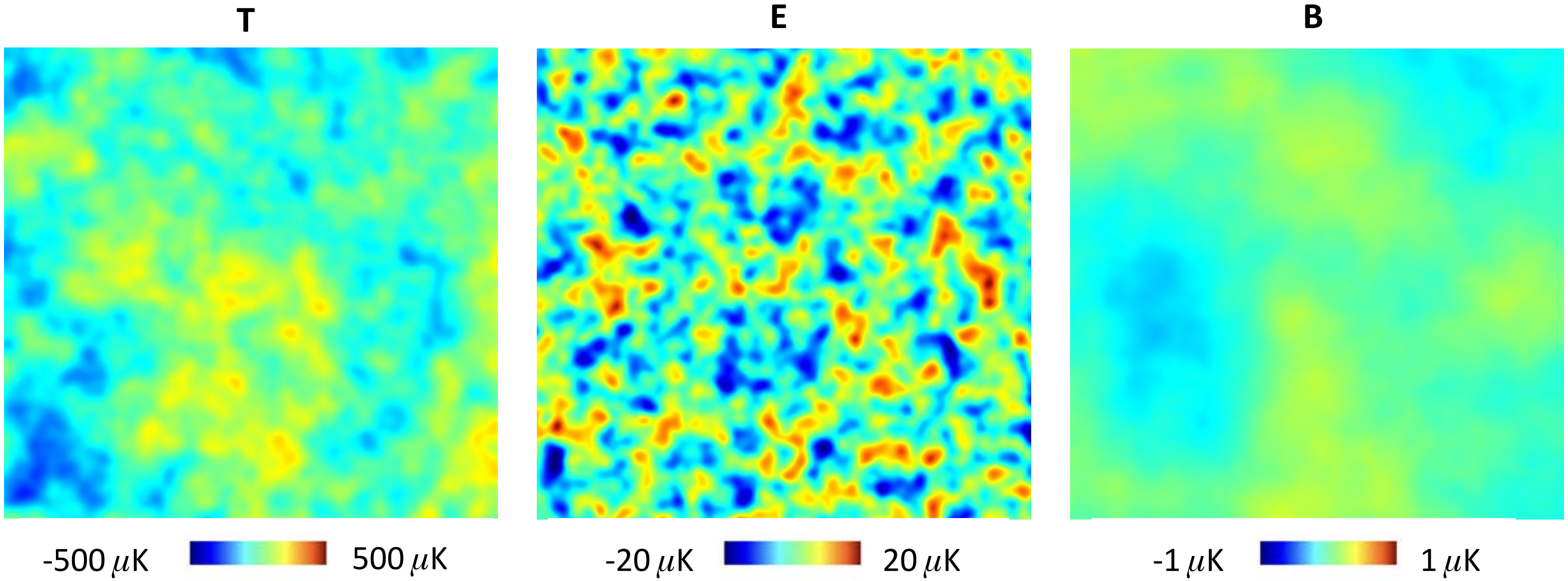
30/40 GHz (LF)
under development

Galactic foregrounds have different spectra wrt the CMB black body.

SO observes at **6 different frequencies** to separate these components.

From CMB to actual data

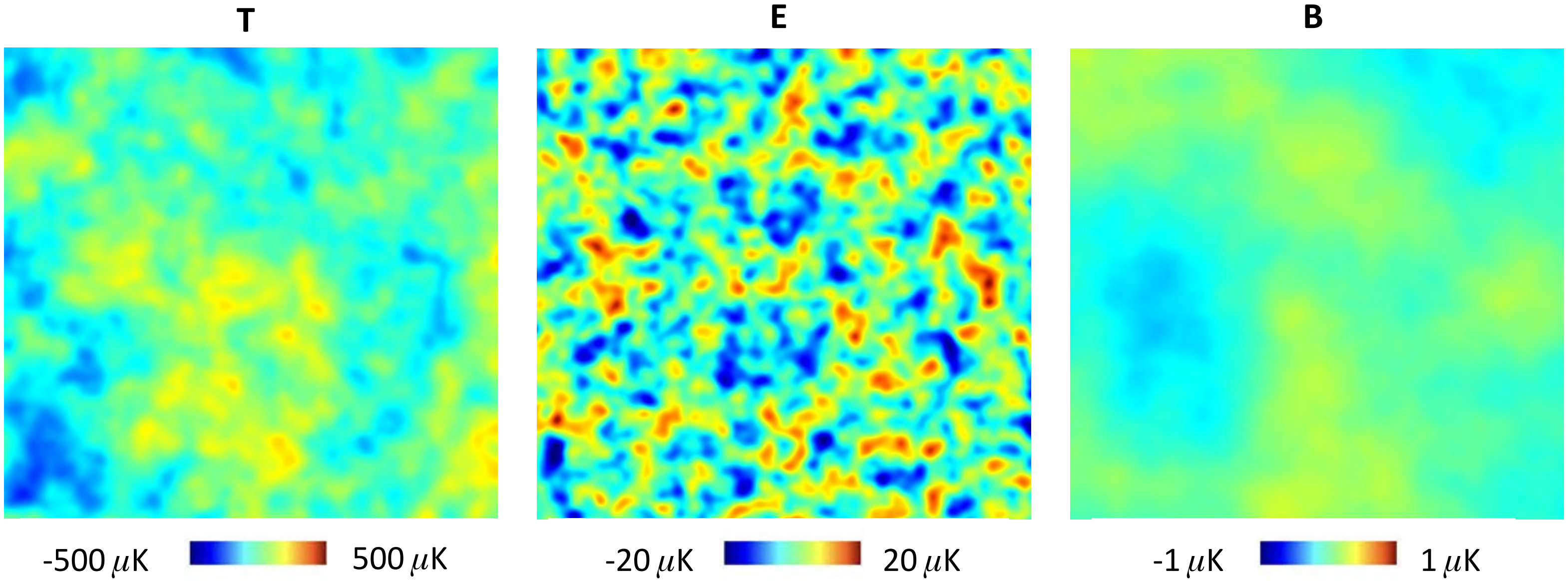
At the surface of last scattering



From CMB to actual data

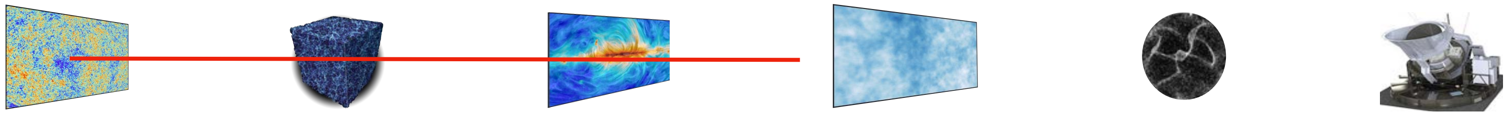
amaurea

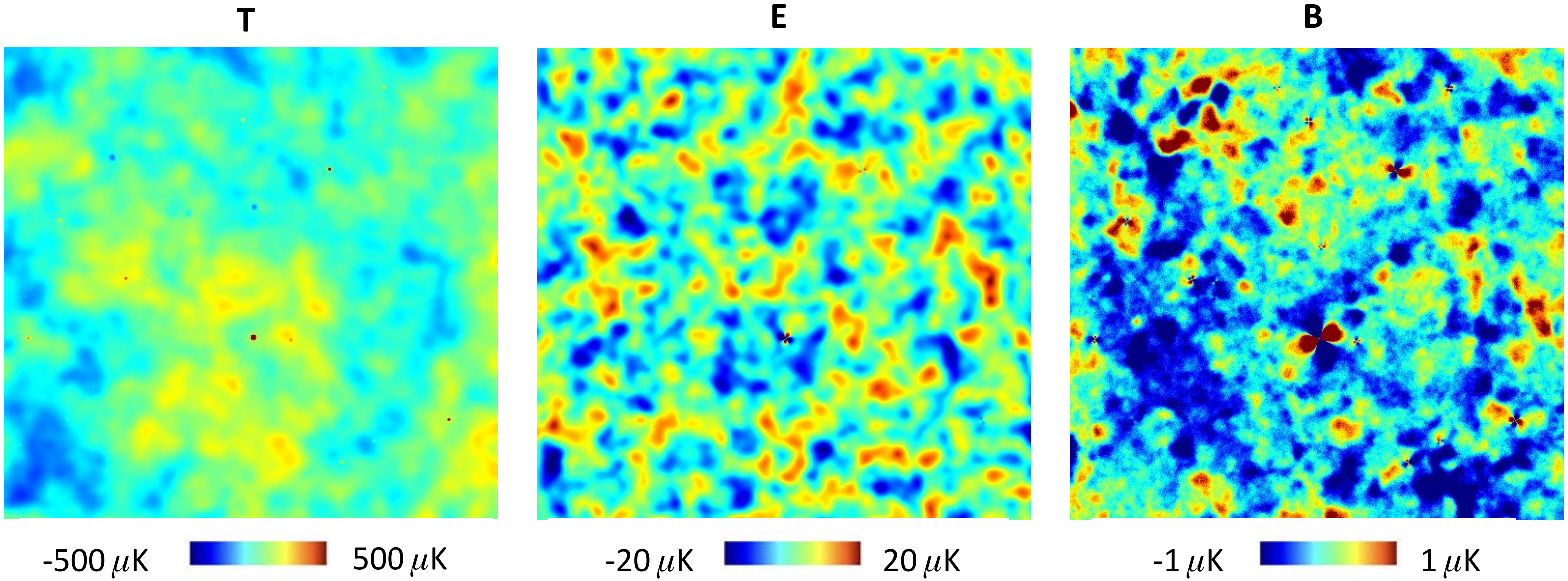
Lensing by Large Scale Structure



From CMB to actual data

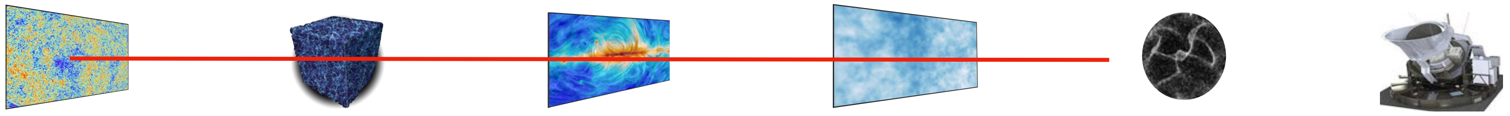
Foregrounds

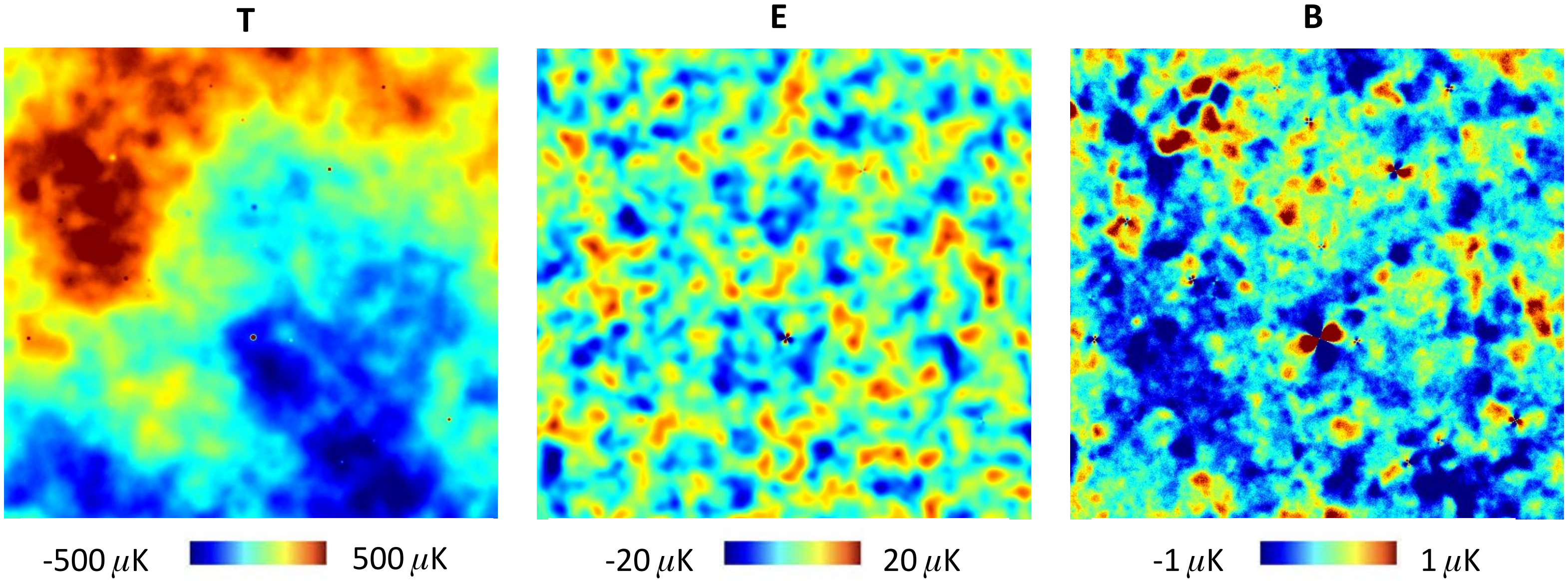




From CMB to actual data

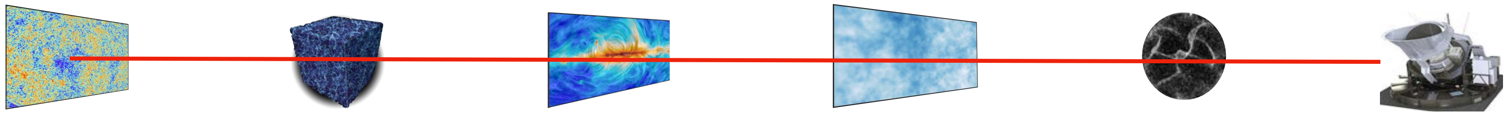
Atmospheric emission

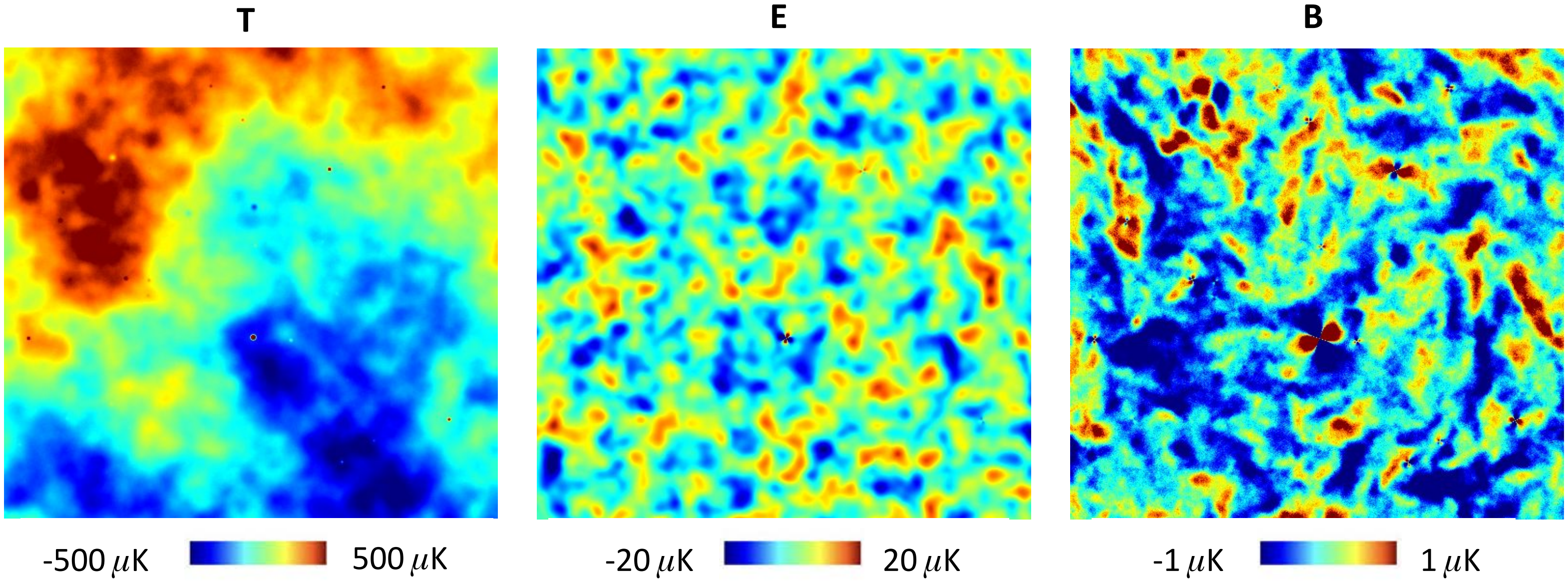




From CMB to actual data

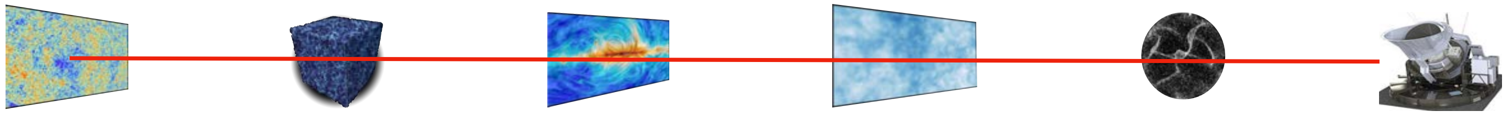
Absolute polarization angle offset

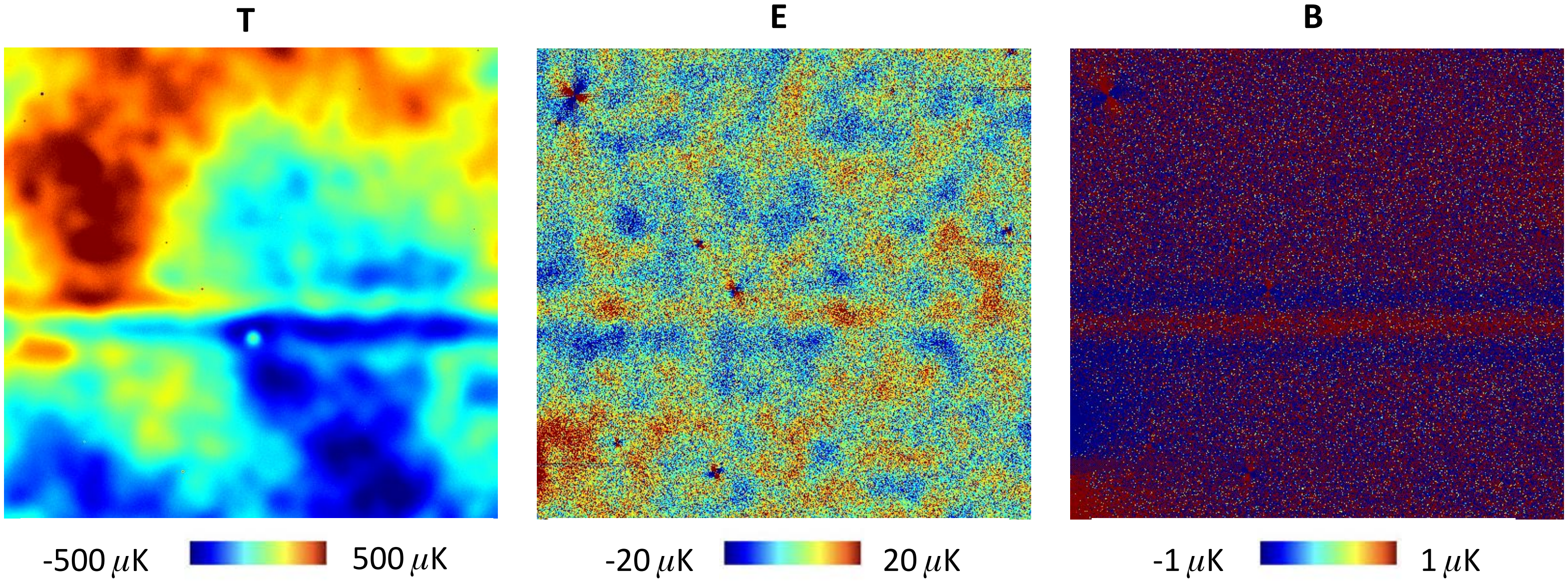




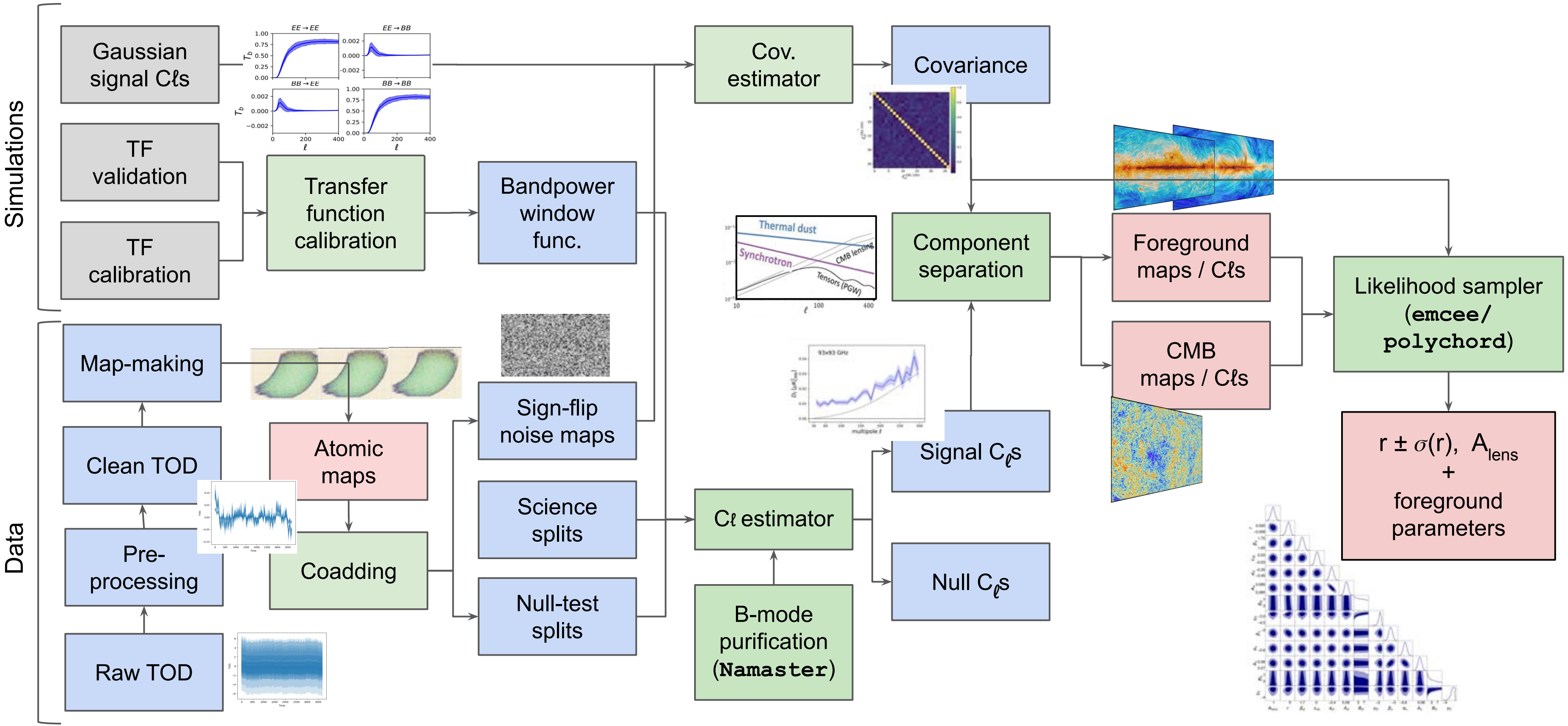
From CMB to actual data

Optics + detector noise + glitches





From data to cosmology

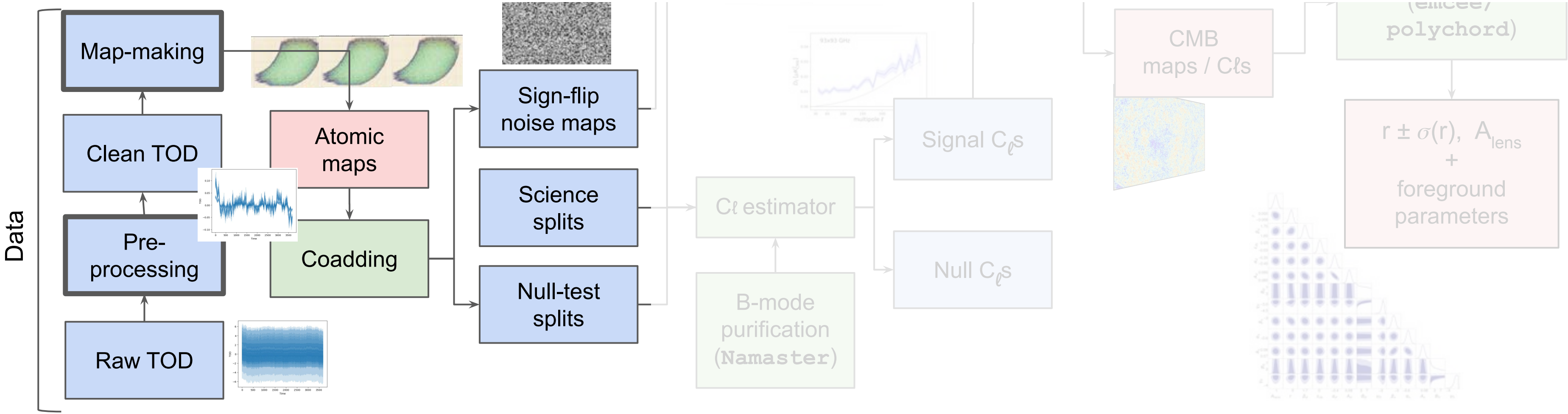


From data to cosmology

From Time-Ordered-Data (TOD) to maps: simonsobs/sotodlib

Pre-processing
$O(10^{12} - 10^{14})$

Map-making
$O(10^{7})$

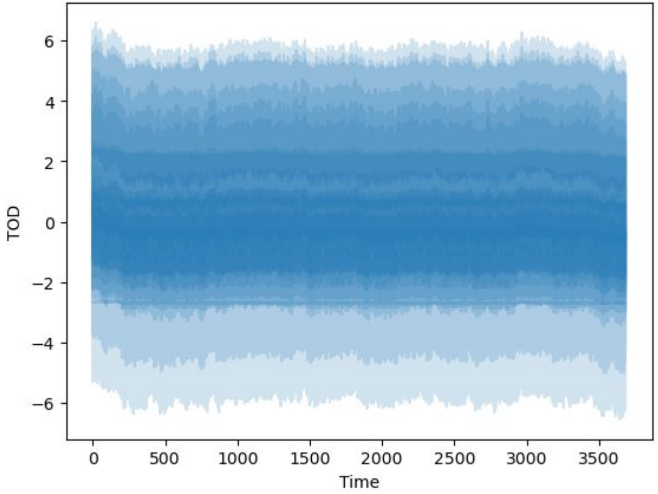


From Time-Ordered-Data (TOD) to maps

Data model:

$$\underbrace{d_{dt}}_{\text{TOD}} = \underbrace{s_{dt}}_{\text{signal}} + \underbrace{n_{dt}}_{\text{noise}} = P_{tp} m_{dp} + n_{dt}$$

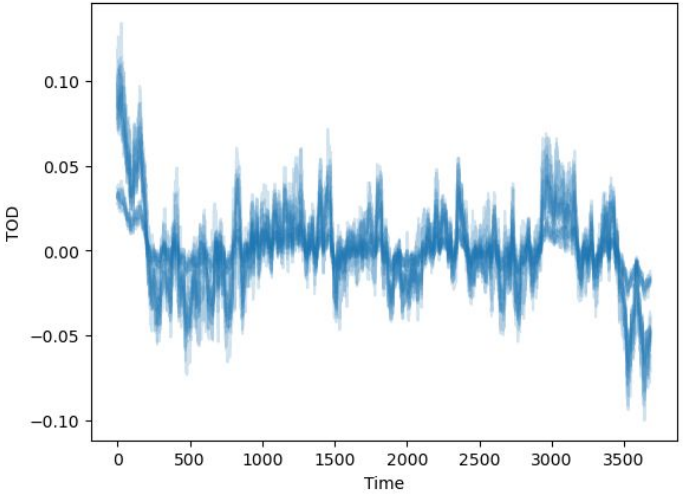
In reality: $d = P\,(signal + \underbrace{galaxy + point\ sources + \ldots}_{\text{sky systematics}}) + n + \underbrace{optics + glitches + \ldots}_{\text{instrument systematics}}$



From Time-Ordered-Data (TOD) to maps

Data model: $\underbrace{d_{dt}}_{\text{TOD}} = \underbrace{s_{dt}}_{\text{signal}} + \underbrace{n_{dt}}_{\text{noise}} = P_{tp} m_{dp} + n_{dt}$

In reality: $d = P\,(\underbrace{signal + galaxy + point\ sources + \ldots}_{\text{sky systematics}}) + n + \underbrace{optics + glitches + \ldots}_{\text{instrument systematics}}$

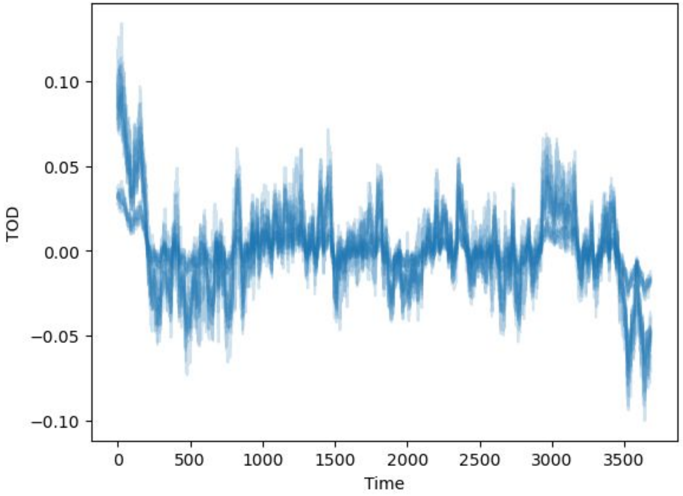


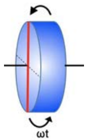
< 0.5% is useful signal,
the rest is **noise**!

From Time-Ordered-Data (TOD) to maps

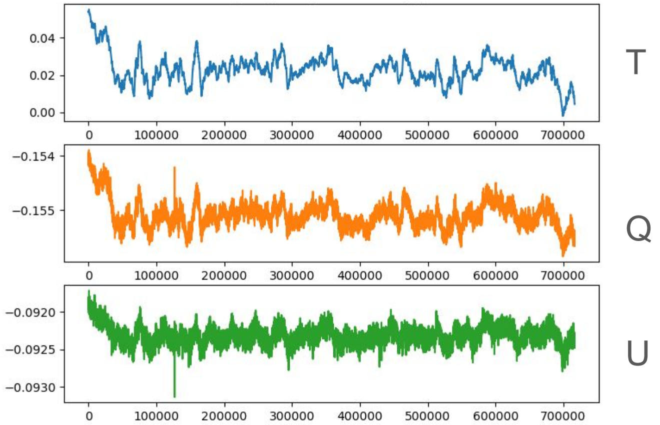
Data model: $\underbrace{d_{dt}}_{\text{TOD}} = \underbrace{s_{dt}}_{\text{signal}} + \underbrace{n_{dt}}_{\text{noise}} = P_{tp} m_{dp} + n_{dt}$

In reality: $d = P\,(\underbrace{signal + galaxy + point\ sources + \ldots}_{\text{sky systematics}}) + n + \underbrace{optics + glitches + \ldots}_{\text{instrument systematics}}$





Demodulate HWP



From Time-Ordered-Data (TOD) to maps

Data model:

$$\underbrace{d_{dt}}_{\text{TOD}} = \underbrace{s_{dt}}_{\text{signal}} + \underbrace{n_{dt}}_{\text{noise}} = P_{tp} m_{dp} + n_{dt}$$

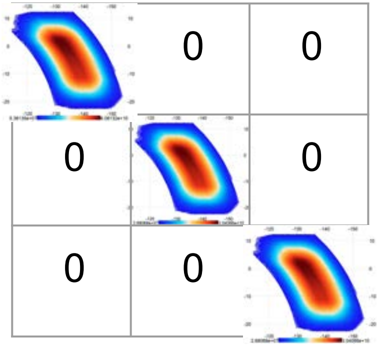
P_{tp}: pointing matrix; m_{dp}: map of the sky

We see Intensity and each detector is sensitive to polarization depending on its angle wrt the sky

$$\vec{d} = \mathbf{P}[\vec{I} + \vec{Q}\cos(2\gamma) + \vec{U}\sin(2\gamma)] + \vec{n}$$

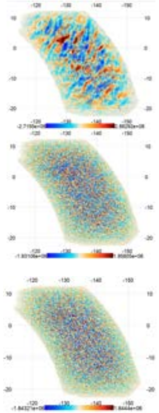
Mapmaking equation → linear and unbiased, **N = <n n^T>** is the noise covariance matrix

$$(\mathbf{P}^T\mathbf{N}^{-1}\mathbf{P})\mathbf{m} = \mathbf{P}^T\mathbf{N}^{-1}\mathbf{d}$$



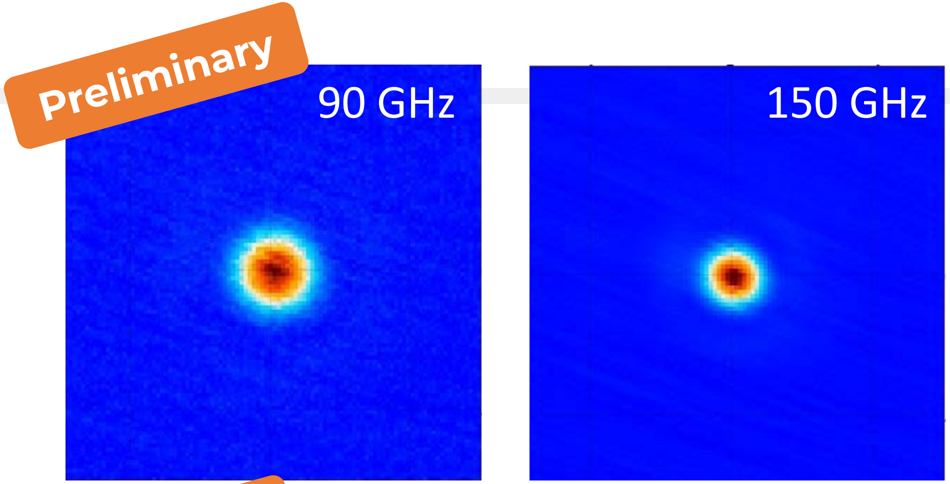
weights
(a "matrix")

weighted map
(a "vector")

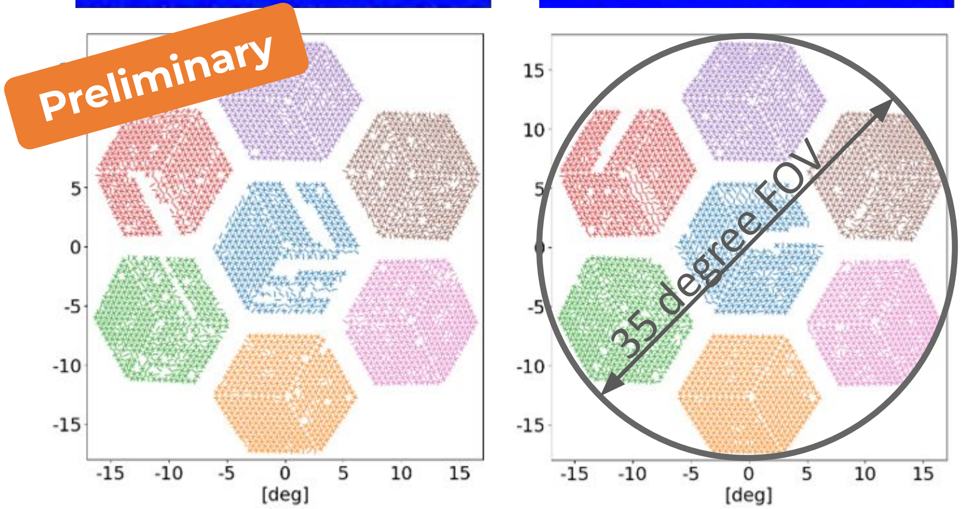


Preliminary results

First Light of **Jupiter**.
Observations show expected beam shapes

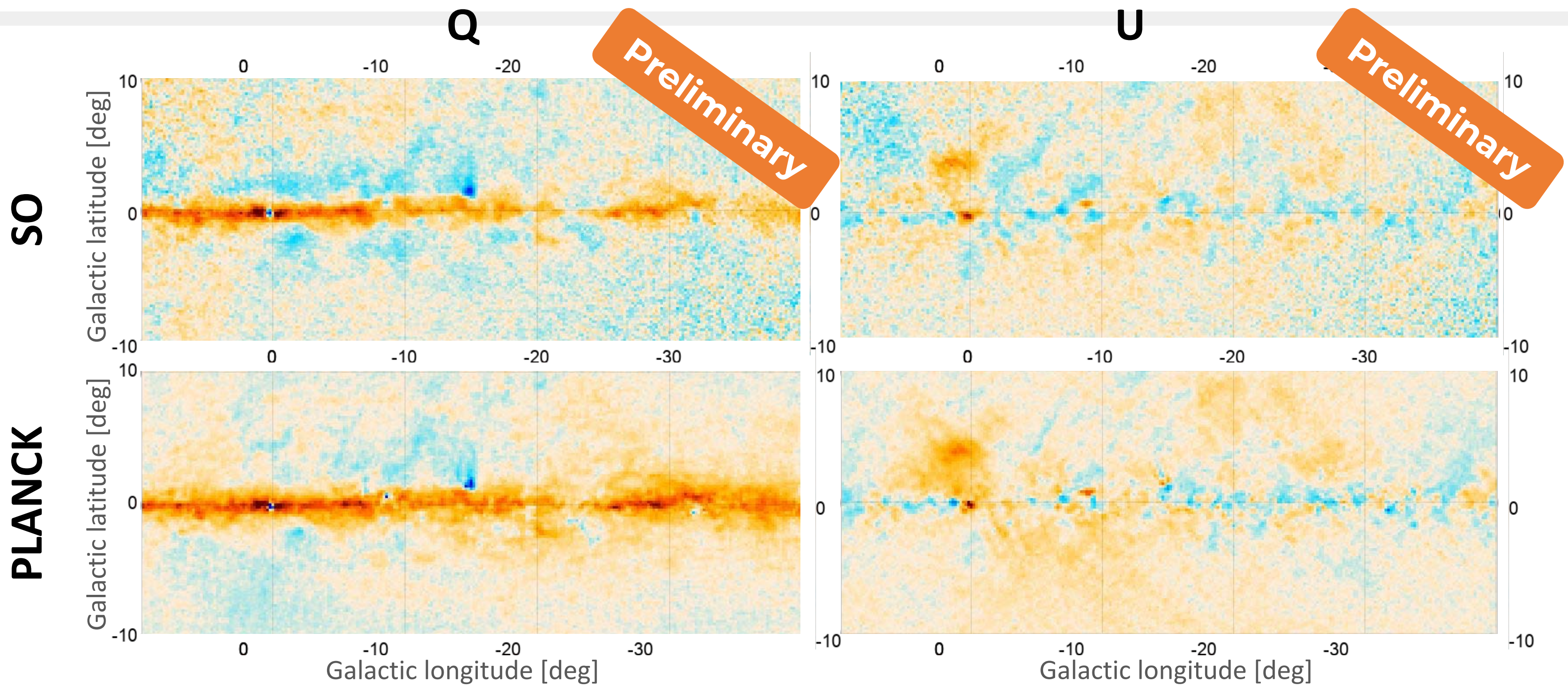


Per-detector **pointing** developed from Moon and Jupiter observations.



Day-Weiss et al. (inc. SA), in preparation

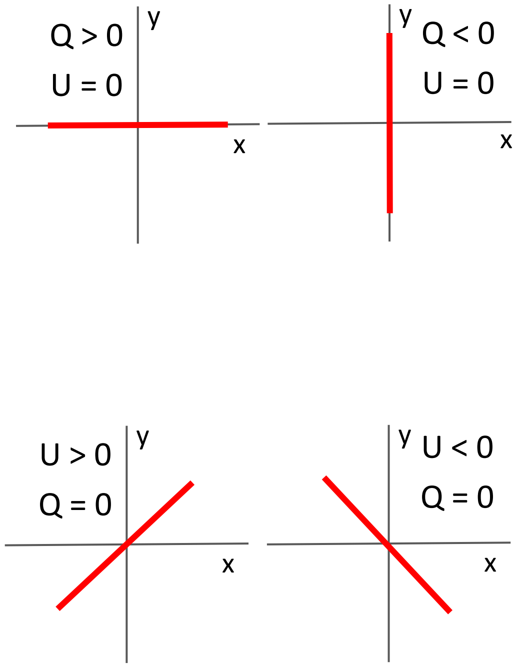
Preliminary results

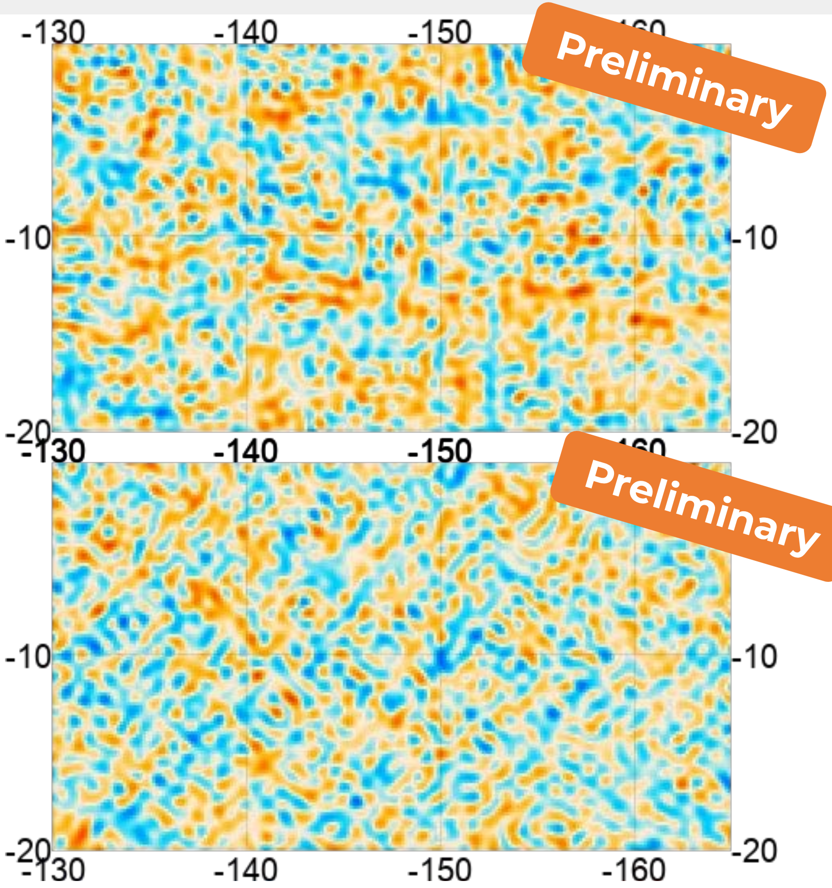


Galaxy center maps in comparison with Planck demonstrate instrument performance and larger scale recovery.

SA et al., in prep.

Preliminary results





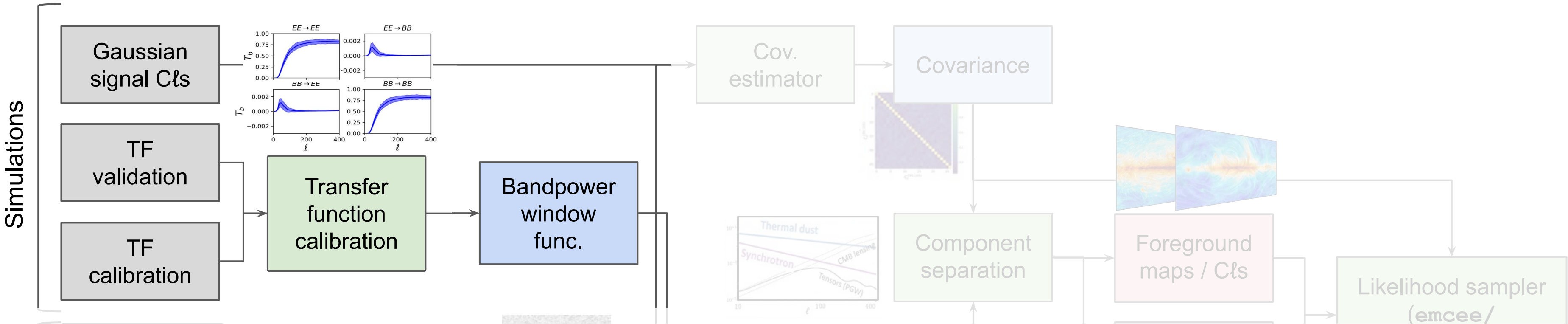
Started mapping the sky with two MF SATs.

Applied low-pass filter to maps. → **Zoom-in**

Q/U polarization patterns start being visible in the targeted SAT regions.

SA et al., in prep.

From data to cosmology

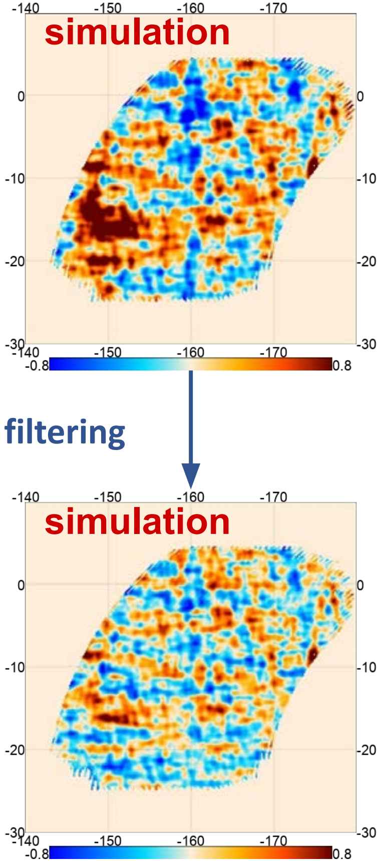


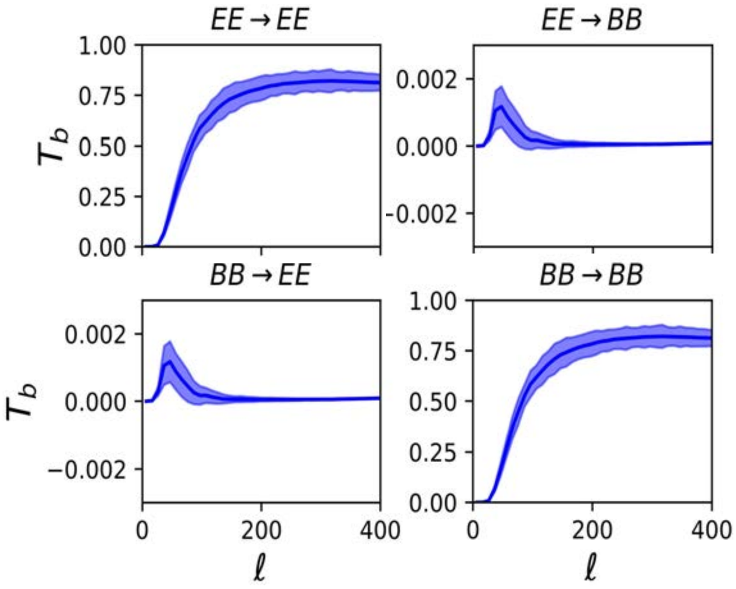
Unbiasing the spectra with Transfer Functions (TF)

simonsobs/SOOPERCOOL

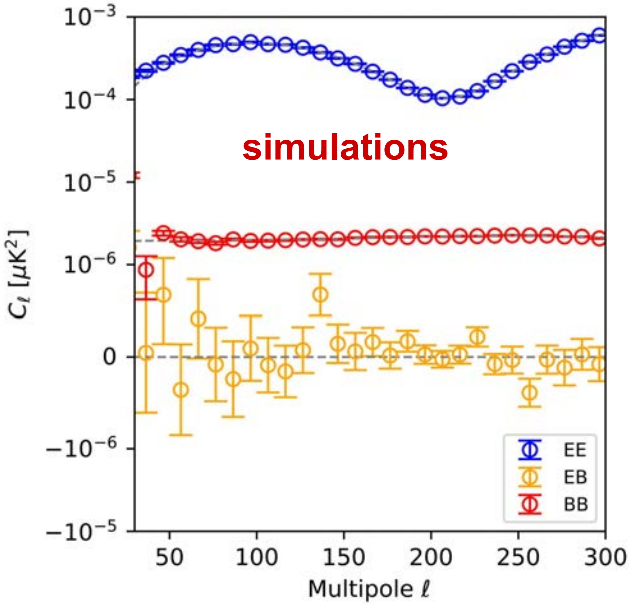
Unbiasing the spectra with Transfer Functions (TF)

Hérvias, Wolz, La Posta, **Azzoni** et al. 2025, [2502.00946]





simulations with aggressive filtering



$$\tilde{C}_b^{\alpha\beta} = \sum_{\alpha'\beta'} T_b^{\alpha'\beta' \to \alpha\beta} C_b^{\alpha'\beta'}$$

From data to cosmology

From maps to (component separated) spectra

Map-making
$O(10^7)$

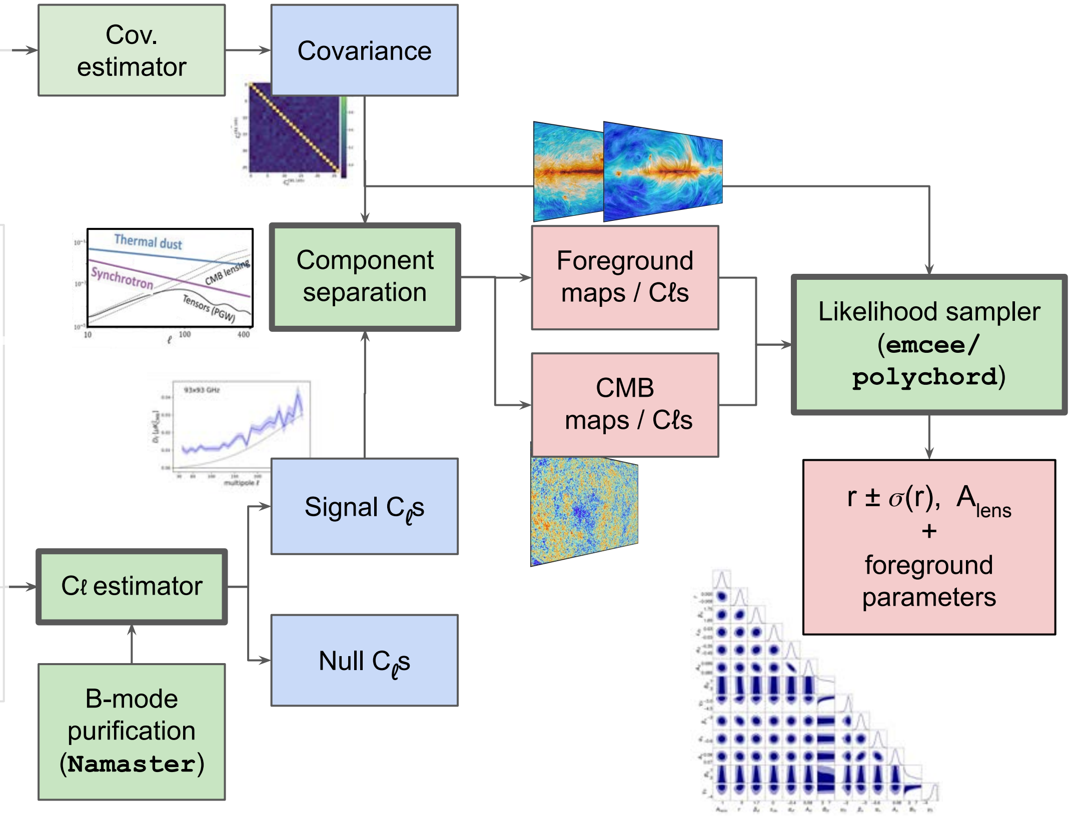
Spectrum estimation
$O(10^3)$

...to cosmological parameters

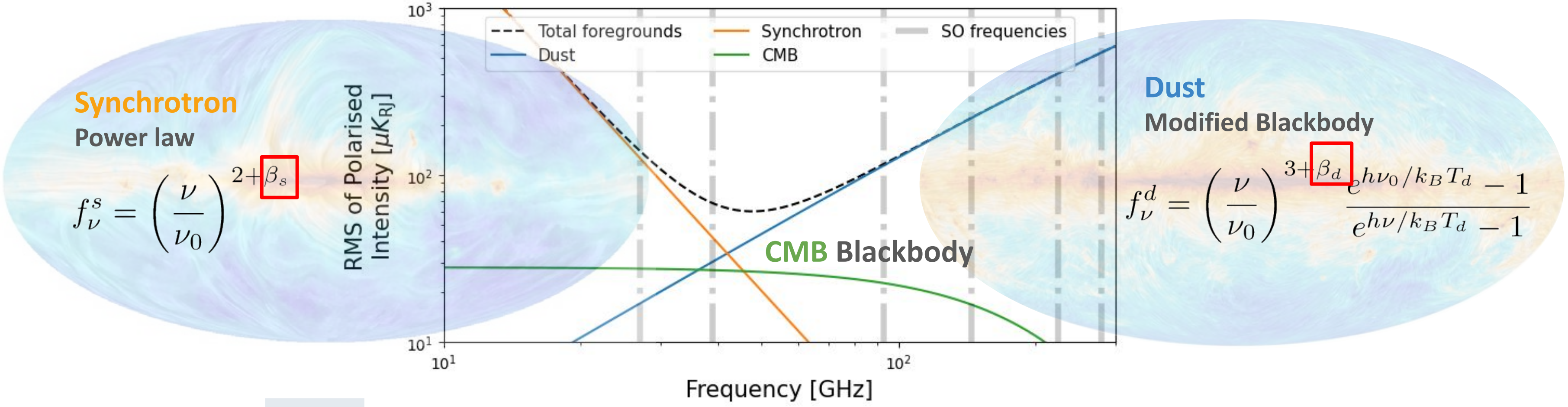
Parameters estimation
$O(10)$

[simonsobs/BBPipe](#)
[simonsobs/BBPower](#)

Azzoni et al. 2021
Abitbol et al. (inc. **SA**) 2021
Azzoni et al. 2023



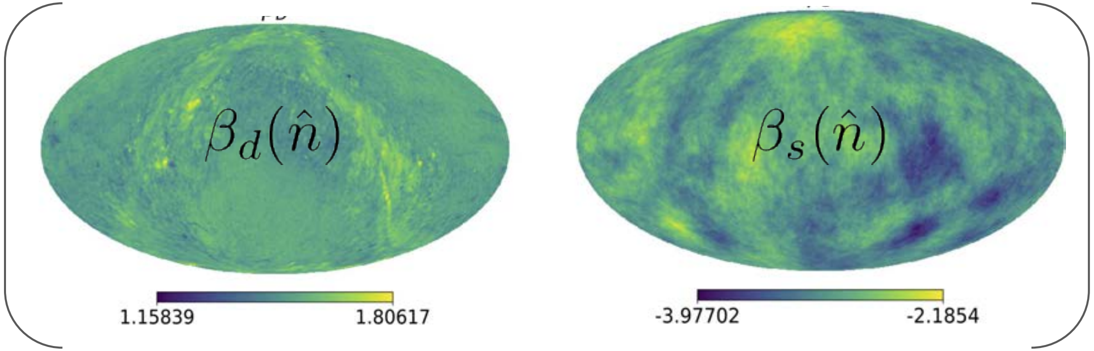
Foreground cleaning methods



$$m_\nu(\hat{n}) = \sum_c \underbrace{S^c_\nu(\vec{\beta}(\hat{n}))}_{\text{SED}} \cdot \underbrace{T^c(\hat{n})}_{\text{Amplitude}}$$

Challenge: Galactic foregrounds (i.e. their spectral parameters) vary across the sky!

$$\vec{\beta}(\hat{n}) =$$



Foreground cleaning methods

Map-based: model the contribution of each component at each pixel and at each frequency (*real space*)

- Exact likelihood function in real space
- *BUT* Expensive computational cost for ℓ_{max} > few hundreds

C_ℓ -based: compute all spectra between different frequencies (*harmonic space)*

- Easier to account for systematics effects in harmonic space
- *BUT* Harder to account for spatial variations

moments method:

- can we devise a method that models variations without introducing too many parameters (i.e. too much uncertainty)?

hybrid method

- can we combine advantages of map and C_ℓ methods?

"Minimal" moment expansion (method 1)

See *Azzoni et al. 2021 (2011.11575)*

- Assume **small spatial variation** $\beta(\hat{\eta}) = \beta_0 + \delta\beta(\hat{\eta})$

- Based on existing "**moment expansion**'" methods
  Taylor expand SEDs, additional parameters

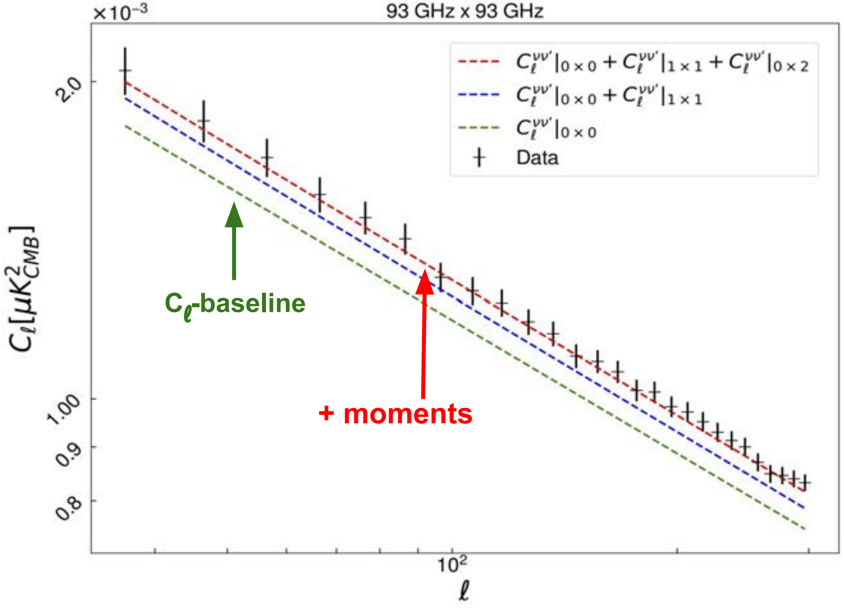
$$S_\nu^c(\beta(\hat{\eta})) = S_\nu^c(\beta_0) + \delta\beta(\hat{\eta}) \frac{\partial S_\nu^c}{\partial \beta}\bigg|_{\beta_0} + \frac{1}{2!}[\delta\beta(\hat{\eta})]^2 \frac{\partial^2 S_\nu^c}{\partial \beta^2}\bigg|_{\beta_0} + \ldots$$

- **Propagate moments into the power spectrum**
  - Parameterize the C_l of the moment parameters
  - Model amplitudes & spectral index as power law

$$C_\ell^{cc} = \langle T^c T^c \rangle_\ell = A_c \left(\frac{\ell}{80}\right)^{\alpha_c} \quad C_\ell^{\beta_c\beta_c} = \langle \beta_c \beta_c \rangle_\ell = A_{\beta_c} \left(\frac{\ell}{80}\right)^{\gamma_c}$$

- Full C_l model:

$$C_\ell = C_\ell^{\mathrm{CMB}}(r, A_{\mathrm{lens}}) + C_\ell^{\mathrm{FG}}(7\ \mathrm{dust} + \mathrm{synch\ params}) + \beta\ \mathrm{model}\ (4\ \mathrm{params})$$



"Minimal" moment expansion (method 1)

See ***Azzoni et al. 2021 (2011.11575)***

In practice…

$$C_\ell^{\nu\nu'} = C_\ell^{\nu\nu'}|_{0\times0} + C_\ell^{\nu\nu'}|_{0\times1} + C_\ell^{\nu\nu'}|_{1\times1} + C_\ell^{\nu\nu'}|_{0\times2},$$

***"Minimal"* assumptions:**

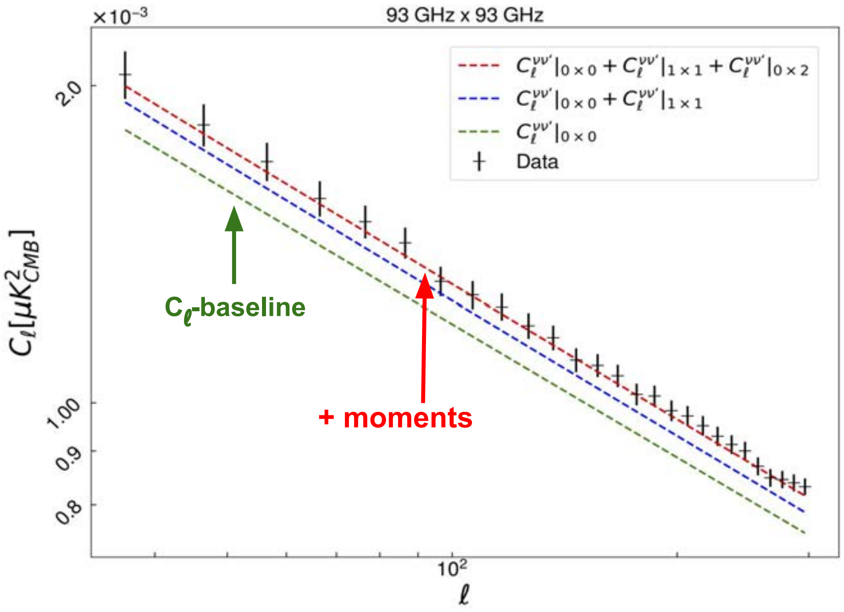
1. $\vec{\beta}_c(\hat{n})$ are Gaussianly distributed
2. FG amplitudes and $\vec{\beta}_c(\hat{n})$ are uncorrelated
3. $\vec{\beta}_c(\hat{n})$ of different FGs are uncorrelated

$$C_\ell^{\nu\nu'} = C_\ell^{\nu\nu'}|_{0\times0} + C_\ell^{\nu\nu'}|_{1\times1} + C_\ell^{\nu\nu'}|_{0\times2}$$

$$C_\ell^{\nu\nu'}|_{0\times0} = \bar{S}^{\rm D}_\nu \bar{S}^{\rm D}_{\nu'} C_\ell^{\rm DD} + \bar{S}^{\rm S}_\nu \bar{S}^{\rm S}_{\nu'} C_\ell^{\rm SS} + (\bar{S}^{\rm D}_\nu \bar{S}^{\rm S}_{\nu'} + \bar{S}^{\rm S}_\nu \bar{S}^{\rm D}_{\nu'}) C_\ell^{\rm SD},$$

$$C_\ell^{\nu\nu'}|_{1\times1} = \sum_{c\in\{\rm D,S\}} \partial_\beta \bar{S}^c_\nu \, \partial_\beta \bar{S}^c_{\nu'} \sum_{\ell_1\ell_2} \frac{(2\ell_1+1)(2\ell_2+1)}{4\pi} \begin{pmatrix} \ell & \ell_1 & \ell_2 \\ 0 & 0 & 0 \end{pmatrix}^2 C^{cc}_{\ell_1} C^{\beta_c}_{\ell_2}$$

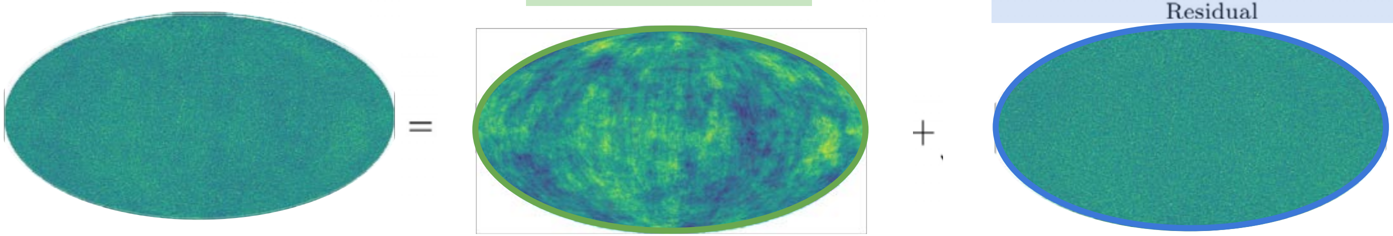
$$C_\ell^{\nu\nu'}|_{0\times2} = \sum_{c\in\{\rm D,S\}} \frac{1}{2} \left[\bar{S}^c_\nu \, \partial^2_\beta \bar{S}^c_{\nu'} + \bar{S}^c_{\nu'} \, \partial^2_\beta \bar{S}^c_\nu\right] C^{cc}_\ell \sigma^2_{\beta_c}.$$



Hybrid map-C_ℓ (method 2)

See *Azzoni et al. 2022 (2210.14838)*

$$m_\nu(\hat{\mathbf{n}}) = \overbrace{\bar{S}_\nu T(\hat{\mathbf{n}})}^{\text{Foregrounds (const. SED)}} + \underbrace{\overbrace{\Delta S(\hat{\mathbf{n}})_\nu T(\hat{\mathbf{n}})}^{\text{Foregrounds (var SED)}} + \overbrace{S_\nu(\hat{\mathbf{n}}) T(\hat{\mathbf{n}})}^{\text{CMB}}}_{\text{Residual}}$$



Sequential map-domain, power-spectrum domain cleaning

1) Clean out FG spatially-constant part at map level

$$\mathbf{m} = \mathsf{S}\,\mathbf{T} + \mathbf{n}$$

$\Delta\mathsf{S} + \bar{\mathsf{S}}$

Best guess of the mean spectra of all components

$$\mathbf{T}_{\rm BF} = \left(\bar{\mathsf{S}}^T \mathsf{N}^{-1} \bar{\mathsf{S}}\right)^{-1} \bar{\mathsf{S}}^T \mathsf{N}^{-1} \mathbf{m}$$

Fit for spectral parameters, solve **m** as a least-squared problem to get best-fit **T**

$$\Rightarrow \quad \mathbf{m}^{\rm FG}_{\rm BF} = \bar{\mathsf{S}}\mathsf{P}\mathbf{T}_{\rm BF}$$

Best estimate of foreground contribution (spatially constant)

2) Model the residuals at power-spectrum level

$$\mathbf{r} \equiv \mathbf{m} - \mathbf{m}^{\rm FG}_{\rm BF} = \mathsf{Q}\mathbf{m}$$

Q is a filtering matrix, $\mathsf{Q}\bar{\mathsf{S}} = \bar{\mathsf{S}}(\mathbb{1} - \mathsf{P})$

sky model $(\bar{\mathsf{S}}\mathbf{T} + \Delta\mathsf{S}\mathbf{T} + \mathbf{n})$

expand: $\Delta S^c_\nu(\hat{\mathbf{n}}) = \partial_{\beta_c} \bar{S}^c_\nu \, \delta\beta_c(\hat{\mathbf{n}})$

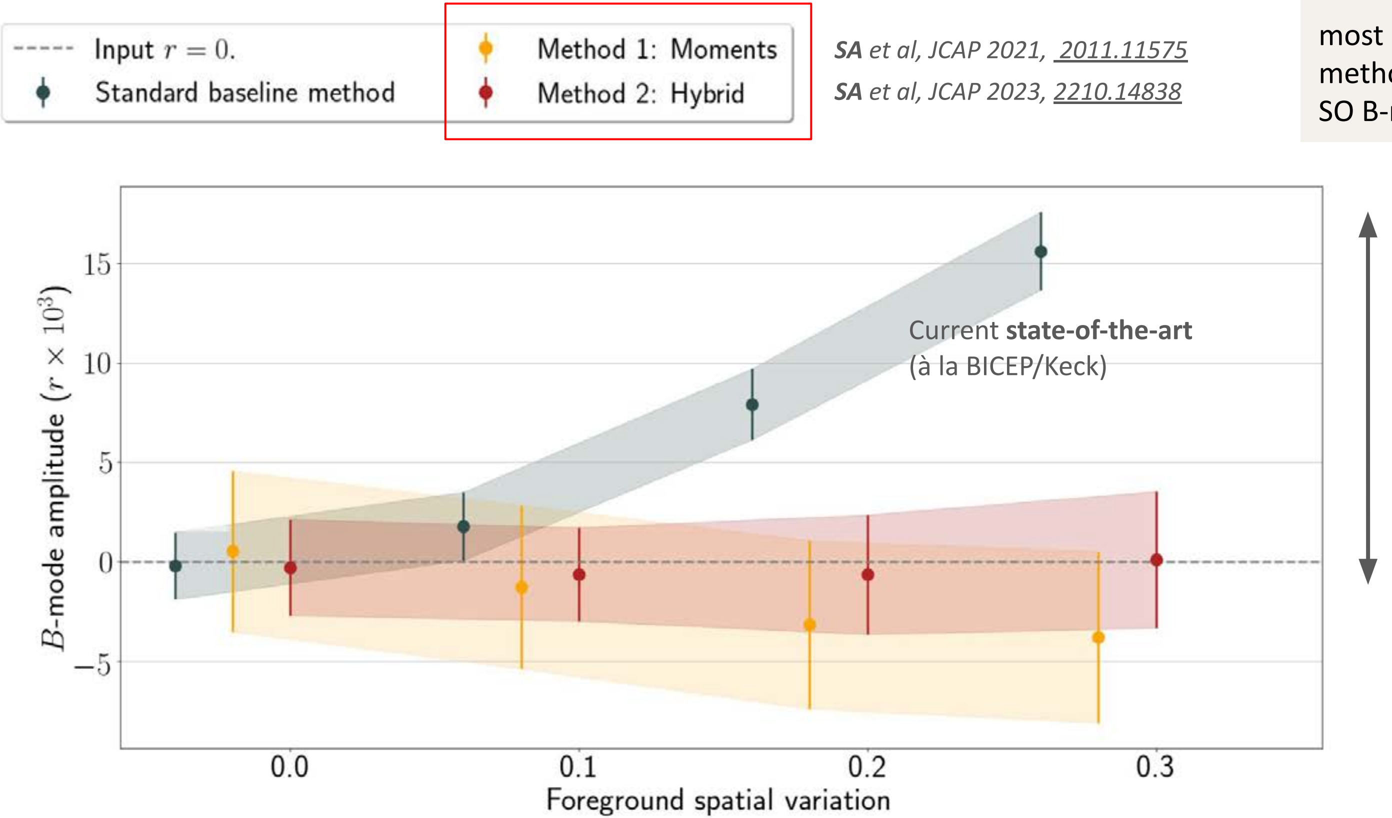
$$\Rightarrow \quad r_\nu(\hat{\mathbf{n}}) = S^{\rm CMB}_\nu T_{\rm CMB}(\hat{\mathbf{n}}) + \underbrace{\tilde{S}^c_\nu \tilde{T}_c(\hat{\mathbf{n}})}\ + \tilde{n}_\nu(\hat{\mathbf{n}})$$

Small, i.e. $\tilde{S}^c_\nu \equiv Q^{\nu'}_\nu \, \partial_{\beta_c} \bar{S}^c_{\nu'}, \ \tilde{T}_c(\hat{\mathbf{n}}) \equiv \delta\beta_c(\hat{\mathbf{n}}) T_c(\hat{\mathbf{n}})$

Expand to C_ℓ, assume **power-law** for residual amplitudes

$$C^{cc}_\ell = \langle \tilde{T}^c \tilde{T}^c \rangle_\ell = A_c \left(\frac{\ell}{\ell_0}\right)^{\alpha_c}$$

Complex foregrounds and cosmology



SA *et al, JCAP 2021, 2011.11575*

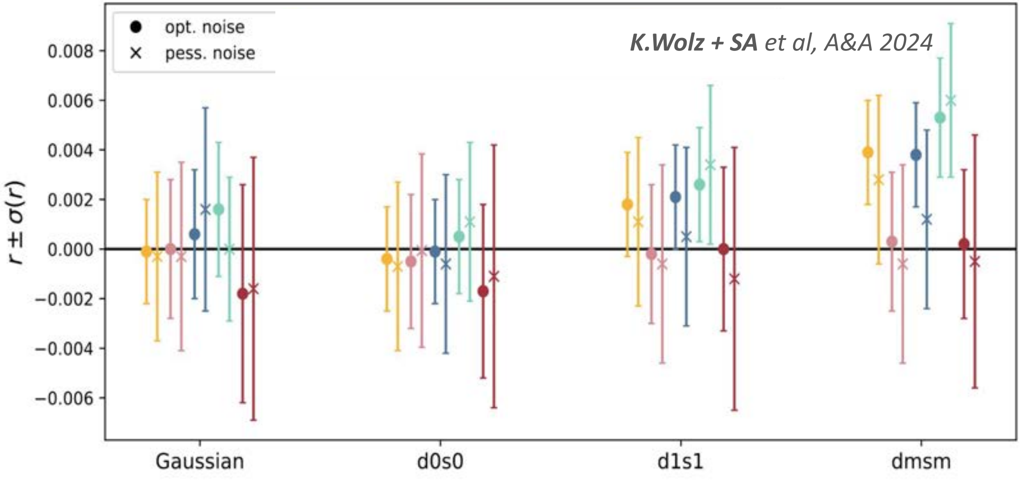
SA *et al, JCAP 2023, 2210.14838*

most robust separation methods currently for SO B-mode analysis

biases are corrected, relatively small penalty in uncertainty

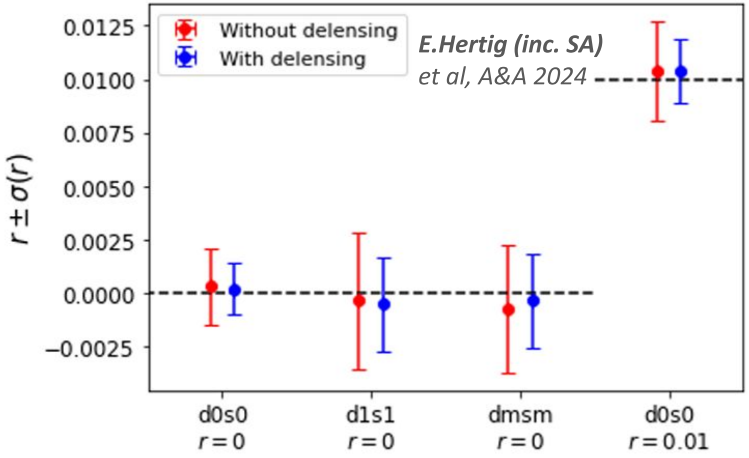
Complex foregrounds and cosmology

Comparison of three different component-separation pipelines
Cl-based, + moments, map-based, + marginalization on dust, NILC



Simulations with increasing foregrounds complexity

Moments + delensing

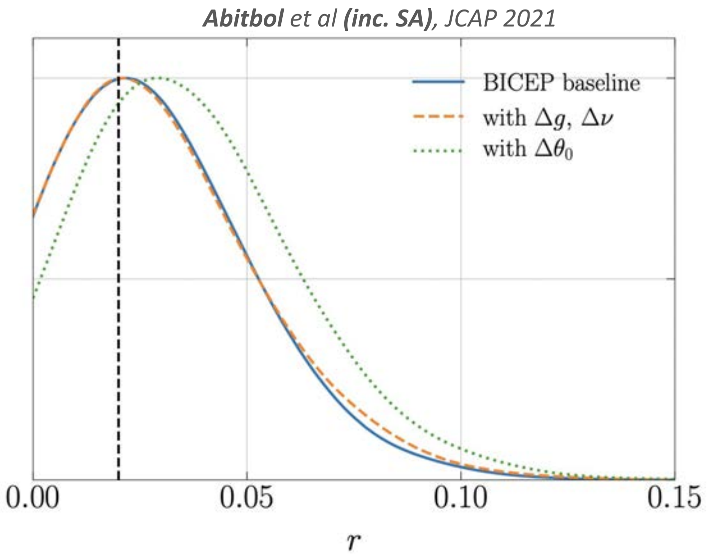


Simulations with increasing foregrounds complexity

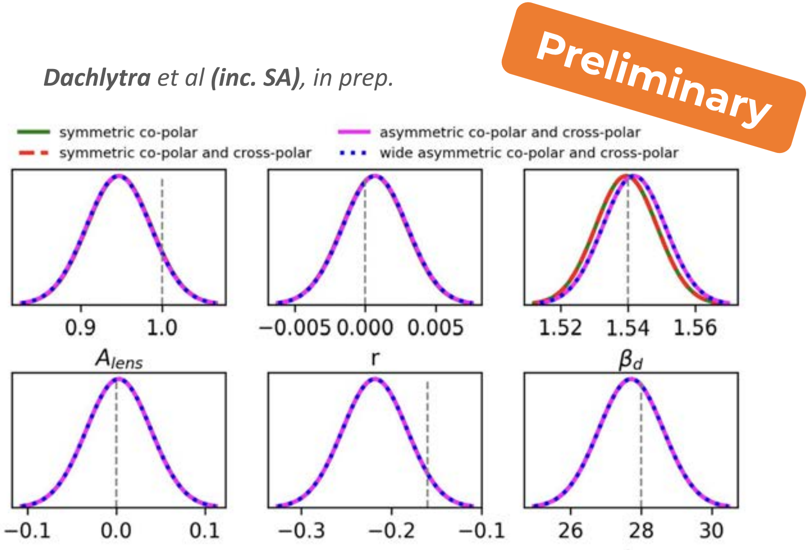
To recover unbiased cosmology with realistic foregrounds, we need more complex component separation techniques (e.g. moments method)

Robust delensing pipeline implemented, no additional bias, error bars reduced by ~30-40%

Instrument systematics: looking ahead

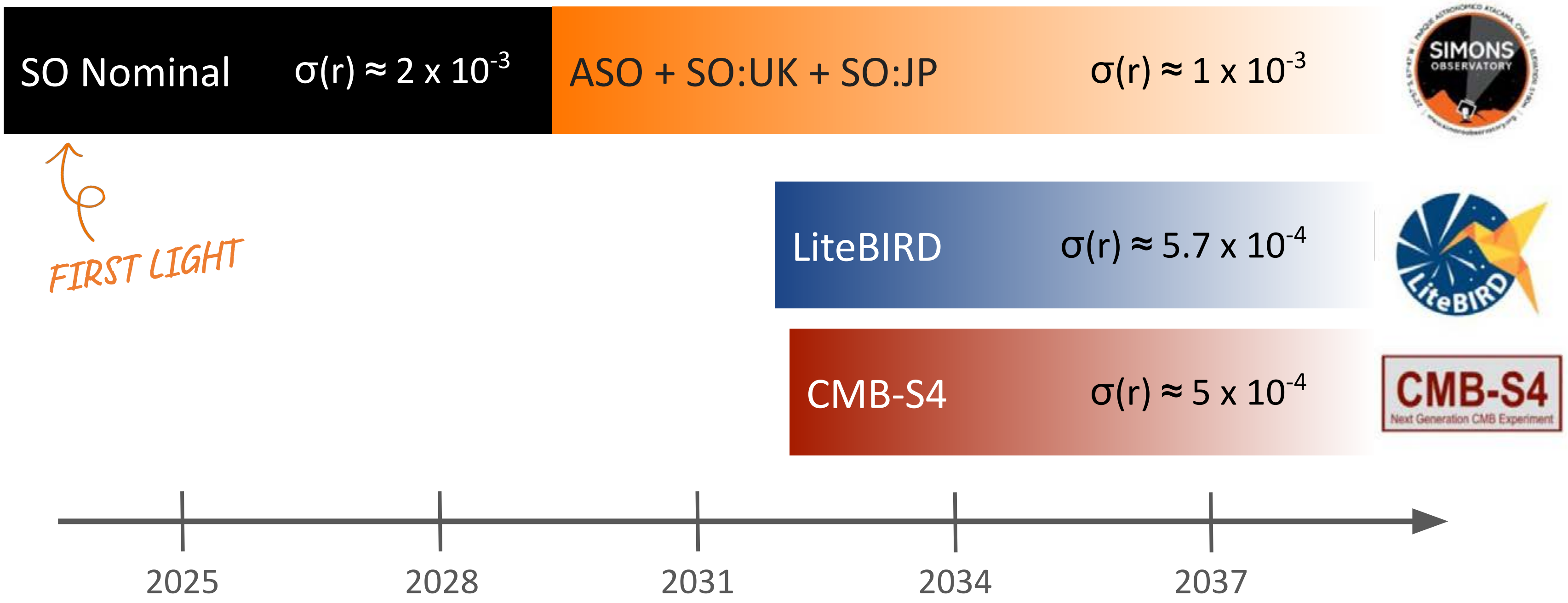


We are able to model and marginalize over gain calibration factors, bandpass frequency shifts, polarization angle rotations, and frequency dependent polarization angles with minimal degradation of sigma_r.

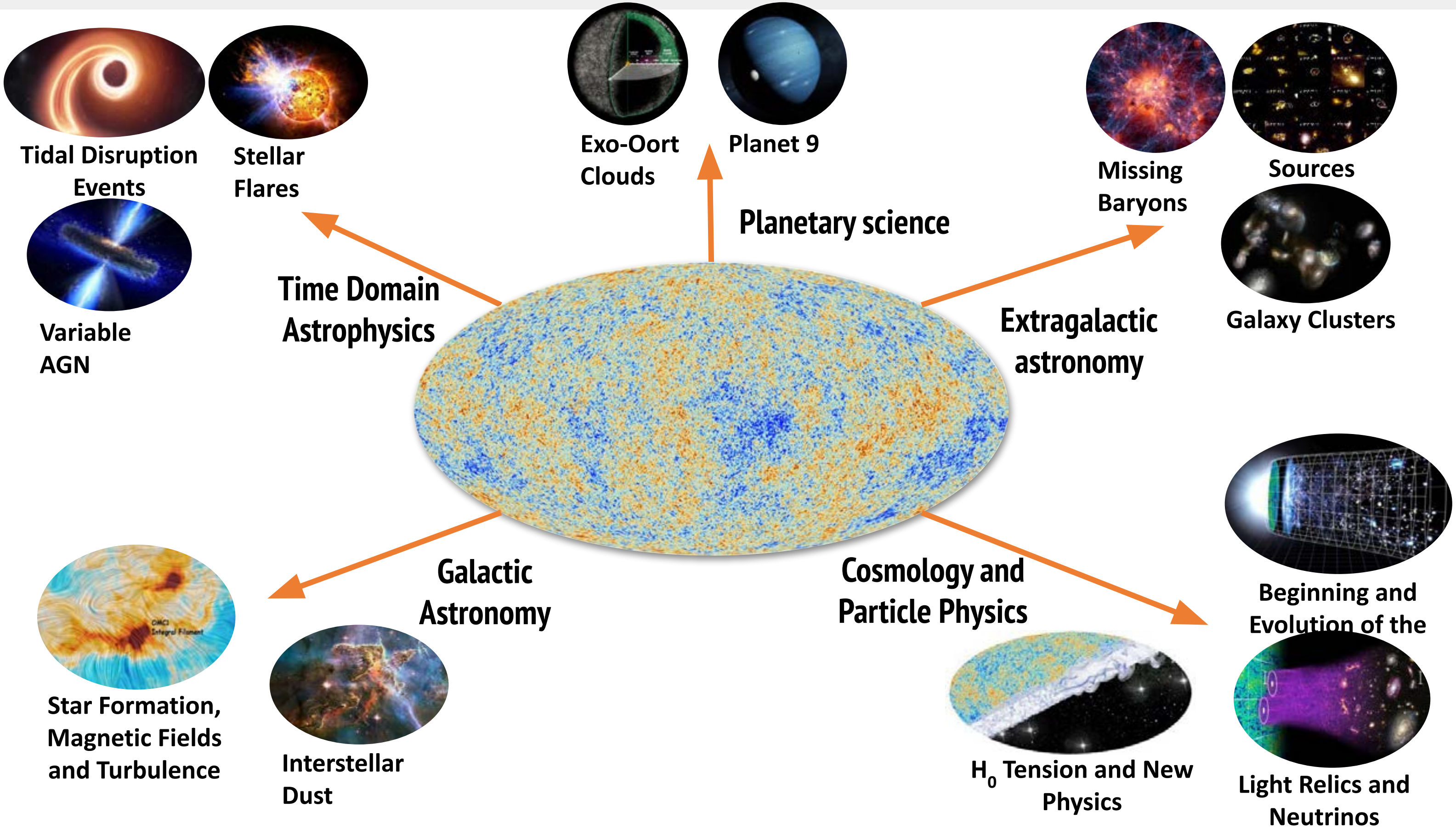


Interplay of beam chromaticity and intrinsic foreground frequency scaling: negligible effect on sigma_r

Looking ahead



Looking ahead



ΛCDM still best model of the Universe:
flat, made of baryonic ("regular") matter and dark matter, with simple initial conditions.

Some assumptions need further testing:
Dark matter? Dark energy? Neutrinos/ other light particles? Inflation?

The CMB is a powerful probe.
CMB primordial B-modes would unlock the secrets to the origin of our Universe.
But detection is challenging and requires careful analysis!

Thank you!

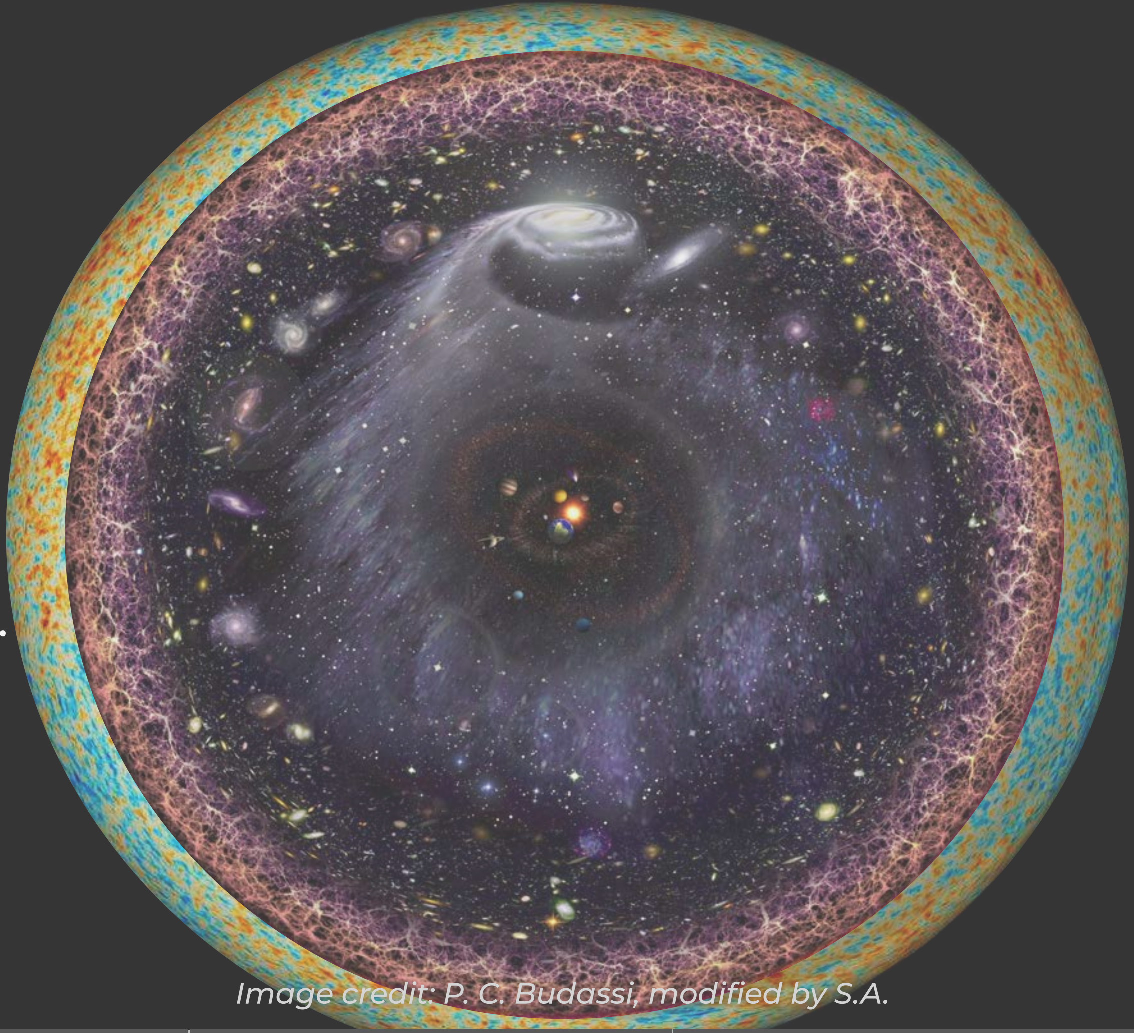


Image credit: P. C. Budassi, modified by S.A.

The Simons Observatory (SO) collaboration

15+ Countries, 60+ Institutions, 375+ Researchers