Component Separation and Cosmological Parameter Estimation from NPIPE Simulations

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Challenge at the CMB Frontier

Introduction

About me :

- M1 Student at ENS - PSL (Physics Dept.)
- 4 months internship at Kavli IPMU with Baptiste Jost
- Going into a Astroparticle - Cosmology M2 next year

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About the Internship :

MEGATOP

- Adapting the MEGATOP pipeline (created for SO) to the NPIPE simulations (but the final goal is to work on the real maps)
- Goal : infer the **tensor-to-scalar ratio** r and the **cosmic birefringence** β from polarized maps.

Probing New Physics

Tensor-to-scalar ratio

- ΛCDM model works but doesn't explain everything
- Cosmic Inflation $\Rightarrow$ solves some issues and predicts **primordial GW** and tensorial perturbations

$\hookrightarrow$ Those are related to the generation of **primordial B-modes**

- One way to characterize their **amplitude** is with $r = \frac{A_t}{A_s}$ (current upper bound: $r < 0.032$ (M. Tristram et al. 2022))

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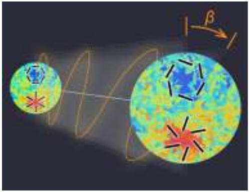
Cosmic Birefringence

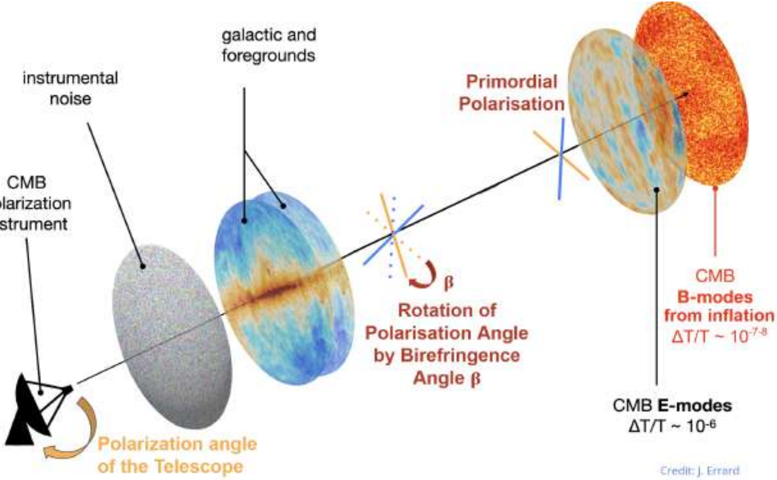
- E-modes are parity **even** and B-modes are parity **odd** $\Rightarrow C_\ell^{EB} = 0$ (Standard Cosmology)
- New physics beyond the SM can induce parity violation which can be detected via non-zero EB component
- Axionlike field ϕ (CS coupling to EM field) $\Rightarrow$ Birefringent Universe

$\hookrightarrow$ Rotation of the polarization plane by $\beta = \frac{\alpha}{2f}(\phi_{\mathrm{obs}} - \phi_{\mathrm{em}})$



Credits : Y. Minami

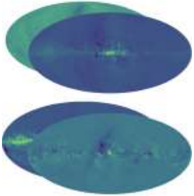
Components and Systematics Effects



Data Model

An observed pixel can be written as:

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



$$\begin{pmatrix} Q_1 \\ U_1 \\ \vdots \\ Q_{n_f} \\ U_{n_f} \end{pmatrix} \qquad \begin{pmatrix} Q^{CMB} \\ U^{CMB} \\ Q^d \\ U^d \\ Q^s \\ U^s \end{pmatrix}$$

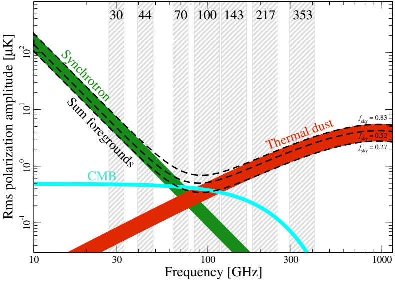
Data Model

$\mathbf{A}_p$ is the mixing matrix :

$$\mathbf{A}_p = \underbrace{\begin{bmatrix} 1 & A_1^d & A_1^s \\ \vdots & \vdots & \vdots \\ 1 & A_{n_f}^d & A_{n_f}^s \end{bmatrix}}_{\text{3 sky components}} \left.\vphantom{\begin{bmatrix} 1 \\ \vdots \\ 1 \end{bmatrix}}\right\} n_f : \text{number of frequencies}$$

It encodes the frequency dependance of each component:

$$\begin{cases} \text{Dust : Modified Black Body} \quad (\beta_d, T_d) \\ \text{Synchrotron : Power Law} \quad (\beta_s) \end{cases}$$



Source : Planck Collaboration 2018

Spectral Likelihood

To estimate, $\{\beta_d, T_d, \beta_s\} = \{\theta_i\}$, we use the **spectral likelihood** $\mathcal{L}_{\rm spec}$ (Stompor et al. 2009) given by:

$$-2\ln\mathcal{L}_{\rm spec}(\{\theta_i\}) = -\left(\mathbf{A}^T\mathbf{N}^{-1}\mathbf{d}\right)^T\left(\mathbf{A}^T\mathbf{N}^{-1}\mathbf{A}\right)^{-1}\mathbf{A}^T\mathbf{N}^{-1}\mathbf{d} + cst$$

Leading to an estimation $\{\hat{\theta}_i\}$:

$$\begin{cases} \hat{\mathbf{A}}_p & = \mathbf{A}_p(\{\hat{\theta}_i\}) \\ \hat{\mathbf{s}}_p & = (\hat{\mathbf{A}}^T\mathbf{N}^{-1}\hat{\mathbf{A}})^{-1}\hat{\mathbf{A}}^T\mathbf{N}^{-1}\mathbf{d} \end{cases}$$

CMB Spectra

From our cleaned maps, we can recover the spectra:

$$\mathbf{C}_\ell^{obs} = \begin{pmatrix} C_\ell^{EE,o} & C_\ell^{EB,o} \\ C_\ell^{EB,o} & C_\ell^{BB,o} \end{pmatrix}$$

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and we can model the angular power spectra of the CMB with $\{r, \beta, A_{lens}\}$ as:

$$\mathbf{C}_l^{CMB,th} \equiv \mathcal{R}(\beta) \begin{pmatrix} C_l^{EE,prim} & 0 \\ 0 & r\, C_l^{BB,prim} + A_{lens}\, C_l^{BB,lens} \end{pmatrix} \mathcal{R}^{-1}(\beta)$$

where $\mathcal{R}(\beta)$ is a 2x2 rotation matrix.

Cosmological Likelihood

By implementing the recovered noise spectra, we have:

$$\mathbf{C}_l^{model} = \mathbf{C}_l^{CMB,th} + \mathbf{N}_l$$

And this equation can be extended considering some residual components:

$$\boxed{\mathbf{C}_l^{model} = \mathbf{C}_l^{CMB,th} + \mathbf{N}_l + A_{dust}\mathbf{C}_l^{dust} + A_{synch}\mathbf{C}_l^{synch}}$$

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We can infer the cosmological parameters via the **cosmological likelihood**:

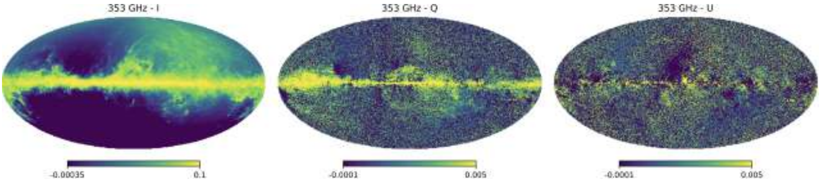
$$-2\ln\mathcal{L}_{\rm cosmo}(r, \beta, A_{lens}) = \sum_l (2l+1) f_{sky} \left((\mathbf{C}_l^{model})^{-1}\mathbf{C}_l^{obs} + \ln(det(\mathbf{C}_l^{model})) \right)$$

NPIPE Simulations

Type of Data used

- 600 sets of polzarized maps for each frequencies (Sky and Residual Noise maps)
- Maps with nside = 256 or 1024/2048
- 7 frequency channels used : 30, 44, 70, 100, 143, 217 and 353 GHz
- Effective beams:

Frequency [GHz]	30	44	70	100	143	217	353
FWHM [arcmin]	32.3	27	13.3	9.7	7.2	5	4.8



One set of NPIPE simulations at 353 GHz.

Pre-processing

- **Beams:** All the maps will be put to a common beam (chosen at 35 arcmin) , so we can get rid of the frequency-dependent beam $\mathbf{B}_\nu$.

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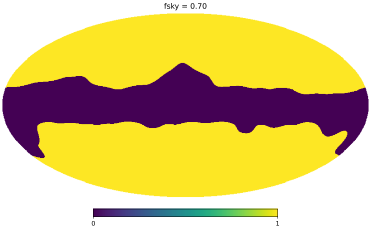
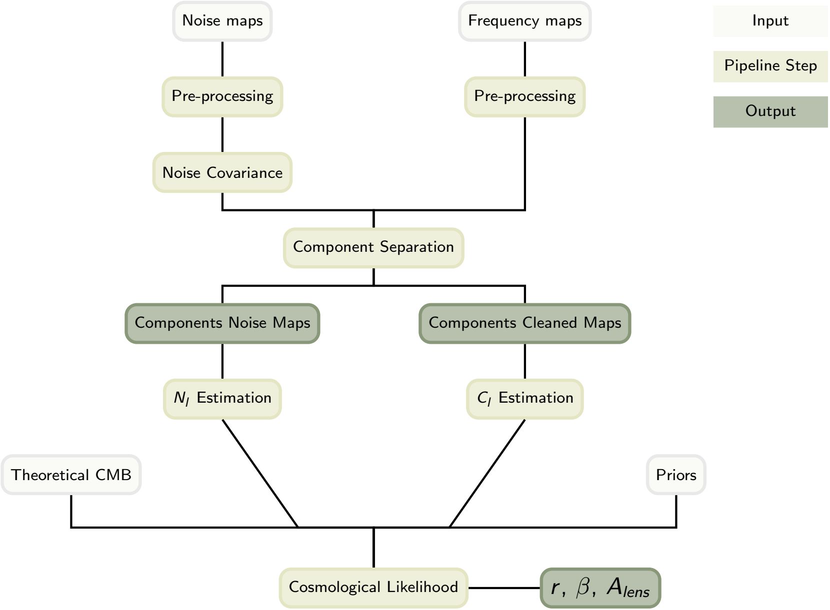
- **Masking:** Removing the galactic emission with a galactic mask:



Pipeline


Noise maps
Frequency maps
Input
Pipeline Step
Output
Pre-processing
Pre-processing
Noise Covariance
Component Separation
Components Noise Maps
Components Cleaned Maps
N_l Estimation
C_l Estimation
Theoretical CMB
Priors
Cosmological Likelihood
r, β, A_{lens}

Type of config used

Config 1/2

- PySM sky realization ("d0s0" and "d1s1")
- White Noise maps (noise level estimated from NPIPE residual noise maps)

Config 3

- PySM sky realization ("d0s0")
- NPIPE residual noise maps

Config 4/5

- NPIPE sky simulations
- NPIPE residual noise maps
- nside = 256 or 1024

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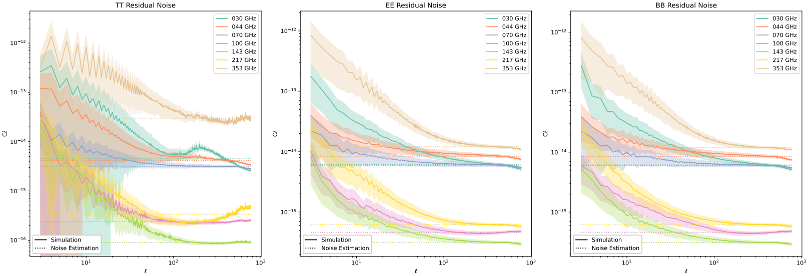
For the **Config 1**:



Config 1 - White Noise + d0s0

Config :

- 100 "d0s0" sky realization: $\boxed{\beta_d = 1.54, \quad T_d = 20\,K, \quad \beta_s = -3}$
- 2000 white noise maps

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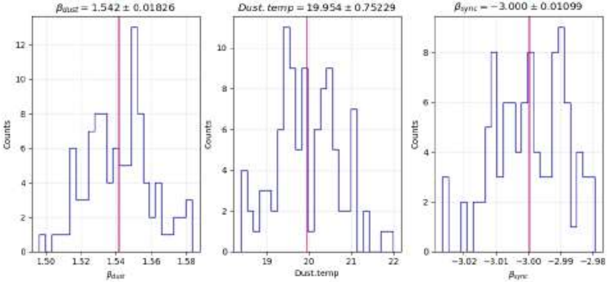
Spectral indices:



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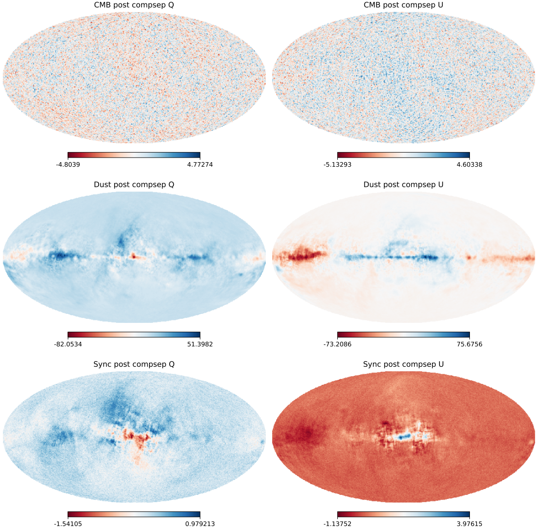
Components Maps:



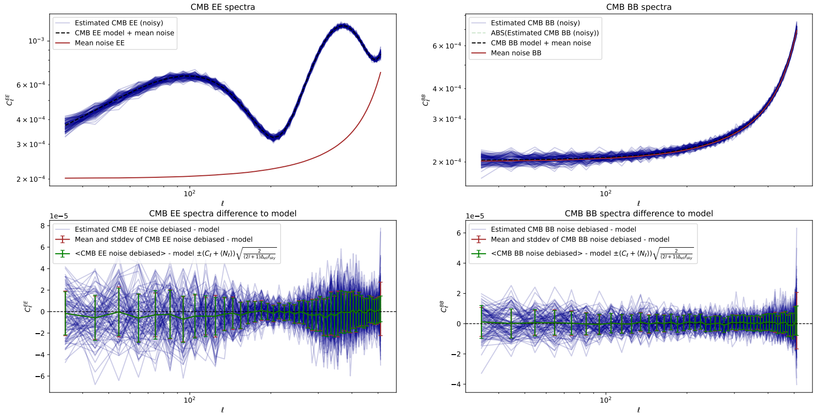
CMB

Dust

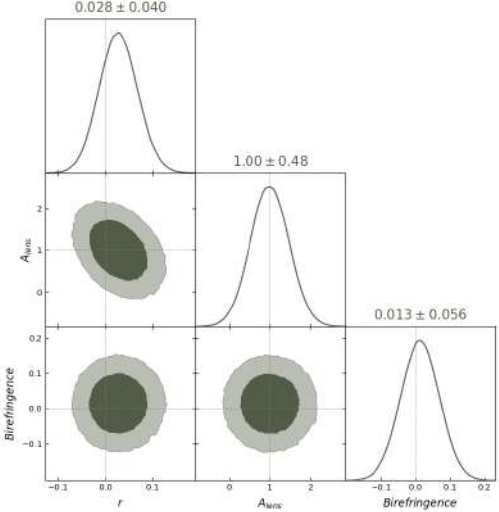
Synchrotron

Config 1 - White Noise + d0s0

Spectra:



mcmc results:

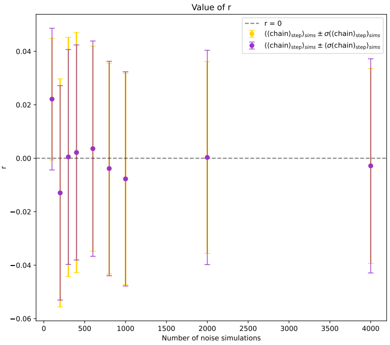


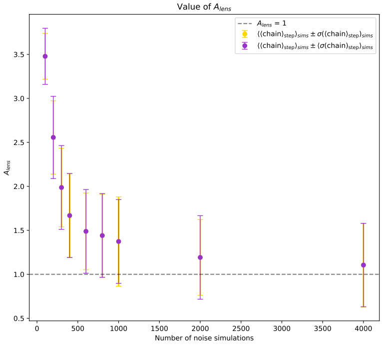
Final estimation:

$$\begin{cases} r = 0.0003 \pm 0.0359 \\ A_{lens} = 1.1918 \pm 0.4302 \\ \beta = 0.0040 \pm 0.0564 \end{cases}$$

Impact of the number of (white) noise simulations

Done with a fix number (100) of "d0s0" sky realization





Config 2 - White noise + d1s1

Config:

- 100 "d1s1" sky realization
- 600 white noise maps
- Galactic mask

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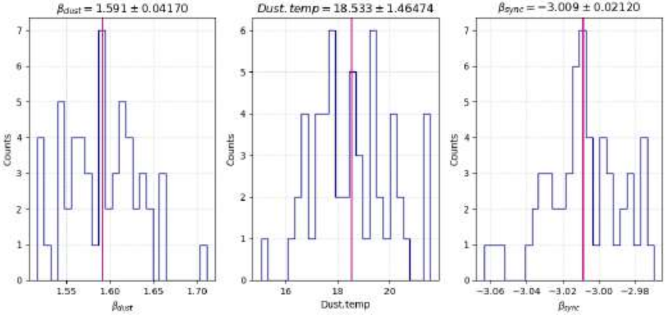
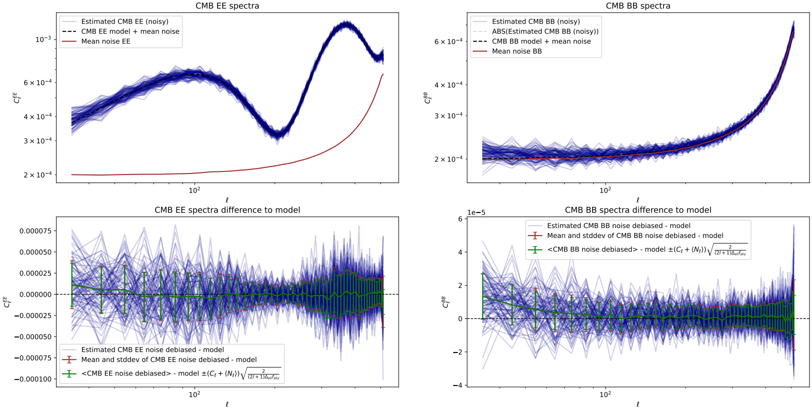


Config 2 - White Noise + d1s1

Spectra:



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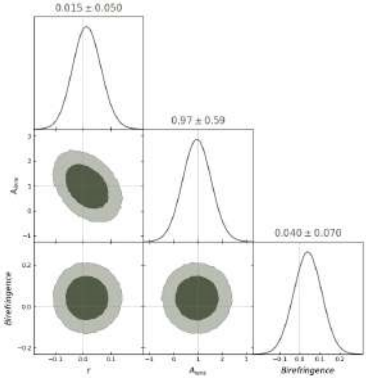
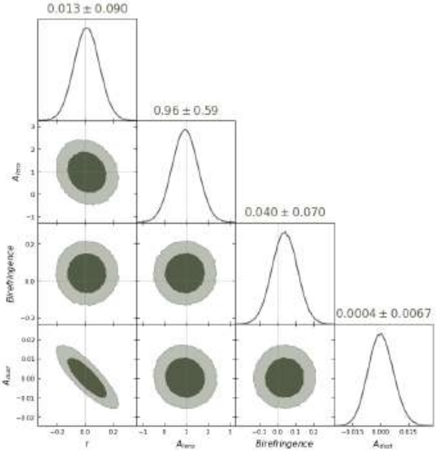


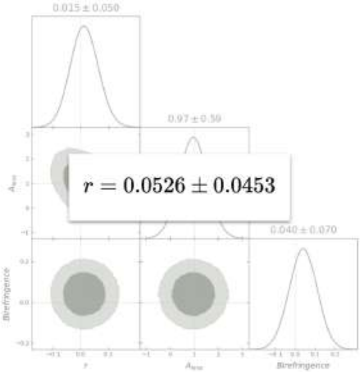
Without Dust Marginalization



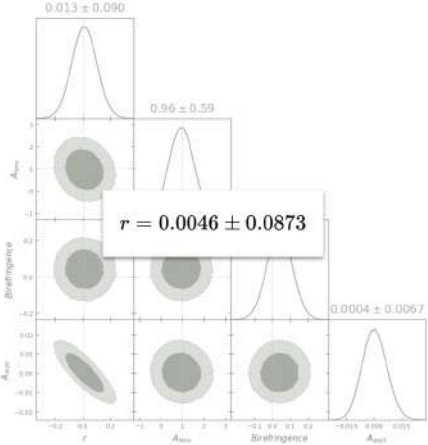
With Dust Marginalization

Config 2 - White Noise + d1s1

mcmc results:



Without Dust Marginalization



With Dust Marginalization

Config 3 - NPIPE noise + d0s0

Config:

- 100 "d0s0" sky realization: $\boxed{\beta_d = 1.54, \quad T_d = 20\,K, \quad \beta_s = -3}$
- 100 NPIPE residual noise maps
- Galactic mask : fsky = 0.7

Config 3 - NPIPE noise + d0s0

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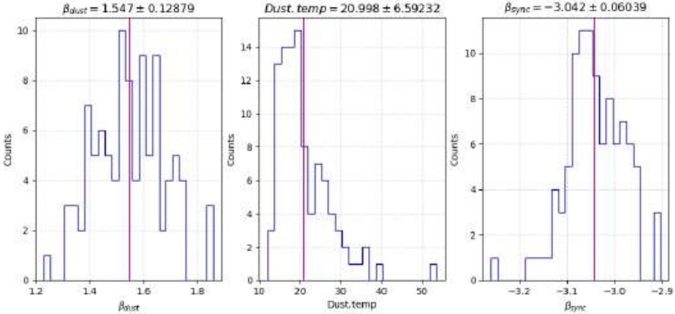
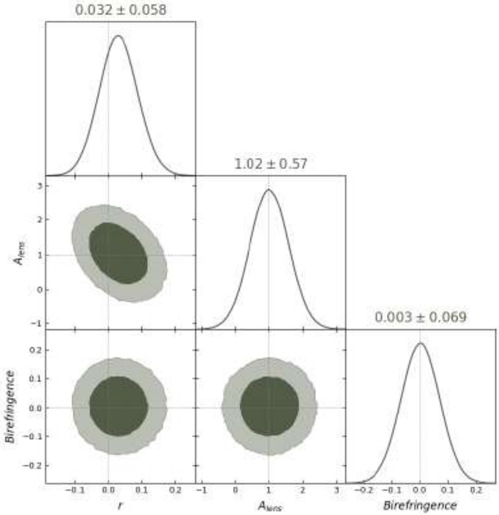
Spectral indices:



mcmc results:

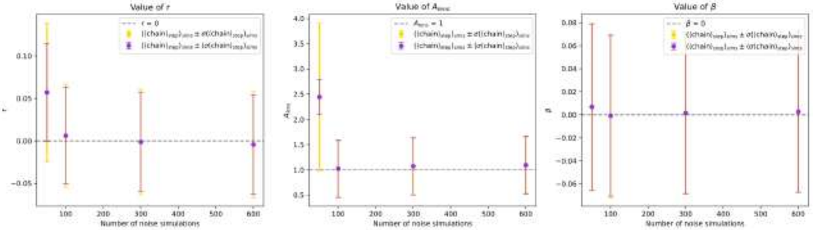


Final estimation:

$$\begin{cases} r = 0.0062 \pm 0.0607 \\ A_{lens} = 1.0216 \pm 0.5419 \\ \beta = -0.0009 \pm 0.0711 \end{cases}$$

Impact of the number of noise simulations

Done with a fix number (100) of "d0s0" sky realization



Config 4 - downgraded NPIPE

Config :

- 100 NPIPE simulations (nside 256)
- 100 NPIPE residual noise maps (nside 256)
- Galactic mask : fsky = 0.7

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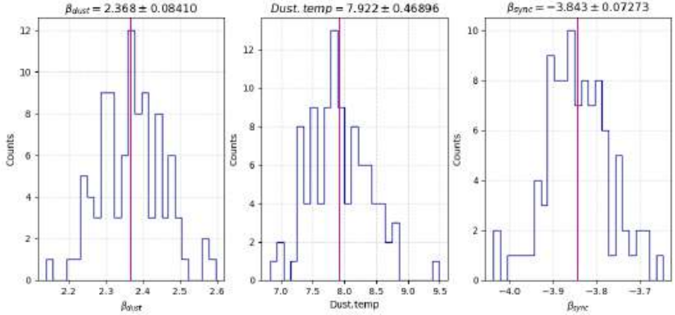
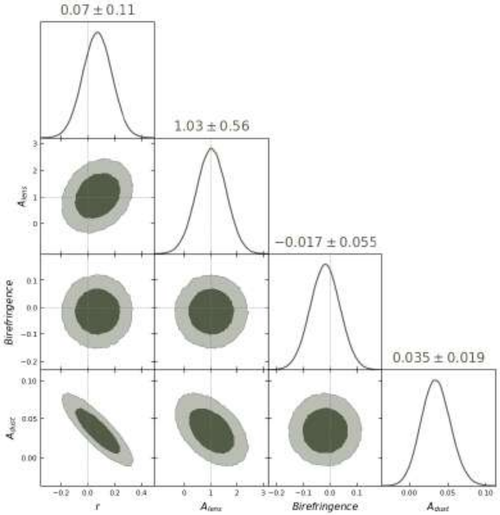
Spectral indices:



Config 4 - downgraded NPIPE

mcmc results:



Final estimation:

$$
\begin{cases}
r = 0.0203 \pm 0.1023 \\
A_{lens} = 0.7011 \pm 0.5115 \\
\beta = -0.0275 \pm 0.0525 \\
A_{dust} = 0.0331 \pm 0.0192
\end{cases}
$$

Config 5 - Full resolution NPIPE

Config :

- 100 NPIPE simulations (nside 1024)
- 100 NPIPE residual noise maps (nside 1024)
- Galactic mask : fsky = 0.7

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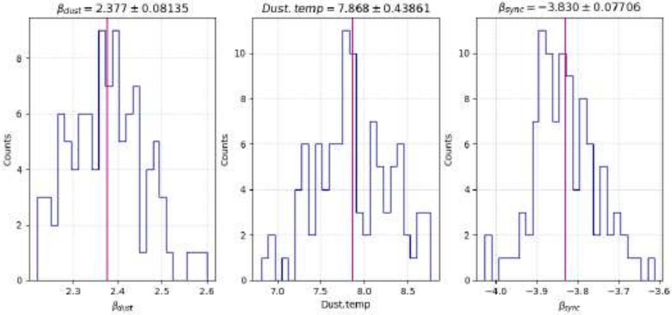
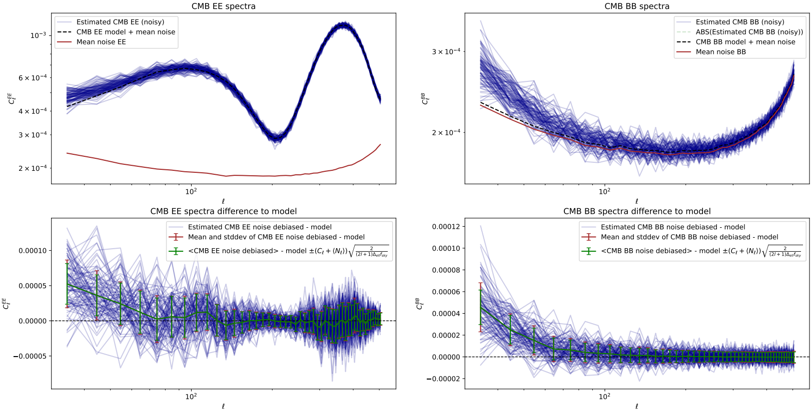
Spectral indices:



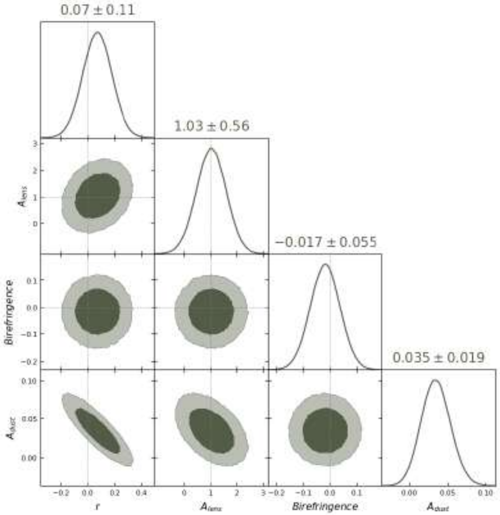
Config 5 - Full resolution NPIPE

Spectra:



Config 5 - Full resolution NPIPE

<u>mcmc results:</u>



Final estimation:

$$\begin{cases} r = 0.0831 \pm 0.0822 \\ A_{lens} = 0.6901 \pm 0.3863 \\ \beta = -0.0224 \pm 0.0509 \\ A_{dust} = 0.0122 \pm 0.0179 \end{cases}$$

Conclusion and Future Implementations

What we achieved:

- Successful application of FGBuster (parametric component separation) on NPIPE simulations.
- Estimation of r and β consistent with zero

Next Steps:

- Implementation of the polarization angle for each frequency channel at the component separation step (Jost et al. 2023)
- Exploration of the multi-patches version of FGBuster
- Using the detector-set splits A and B to get rid of the noise bias

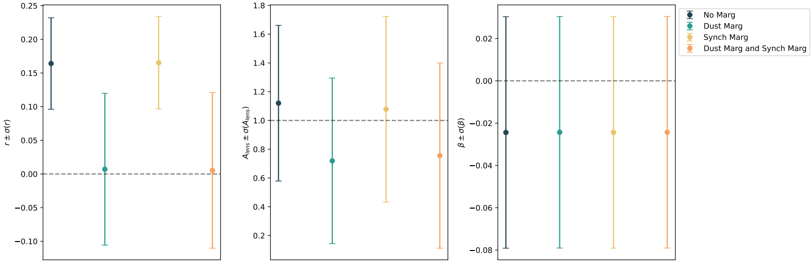
$\hookrightarrow$ Adapting the pipeline to the real Planck maps

Thank you for your attention !

Backup slide: dust or sync marg

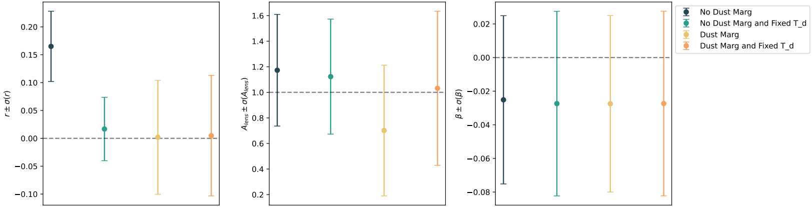
Config :

- 600 NPIPE simulations (nside 256)
- 600 NPIPE residual noise maps (nside 256)
- Galactic mask : fsky = 0.7

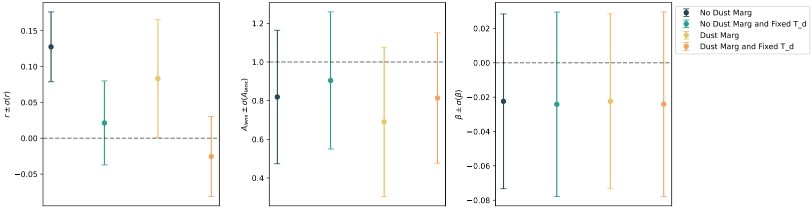


Backup slide: config 4 and 5 tests

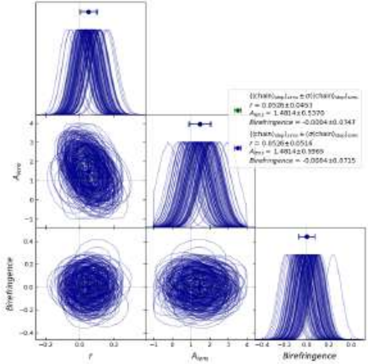
nside = 256



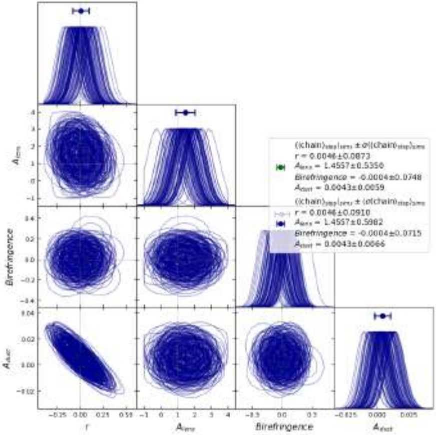
nside = 1024



Backup slide: config 2 full mcmc results



Without Dust Marginalization



With Dust Marginalization

Backup slide: config 5 full mcmc results