# Dust polarization spectral dependence from Planck HFI data

## Turning point on CMB polarization foreground modelling

*Submitted to A&A* e-print: arXiv:2206.07671v1

Alessia Ritacco (OAC - INAF, LPENS)

and Francois Boulanger, Vincent Guillet, Jean-Marc Delouis, Jean-Loup Puget, Jonathan Aumont, Léo Vacher

LPENS
LABORATOIRE DE PHYSIQUE
DE L'ÉCOLE NORMALE SUPÉRIEURE

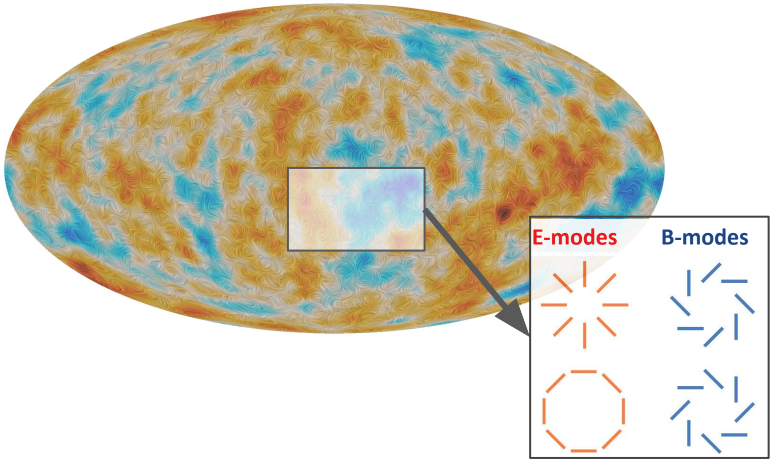
# Outline

- Scientific context
- Constraints on CMB polarization detection accuracy
- **CMB dust polarization foreground**
  - **Power spectra analysis of a recent release of Planck HFI data**
  - **Dust mean SED in polarization at very low multipoles**
  - **Spatial variations**
  - **Frequency dependence**
- **Conclusions and perspectives**

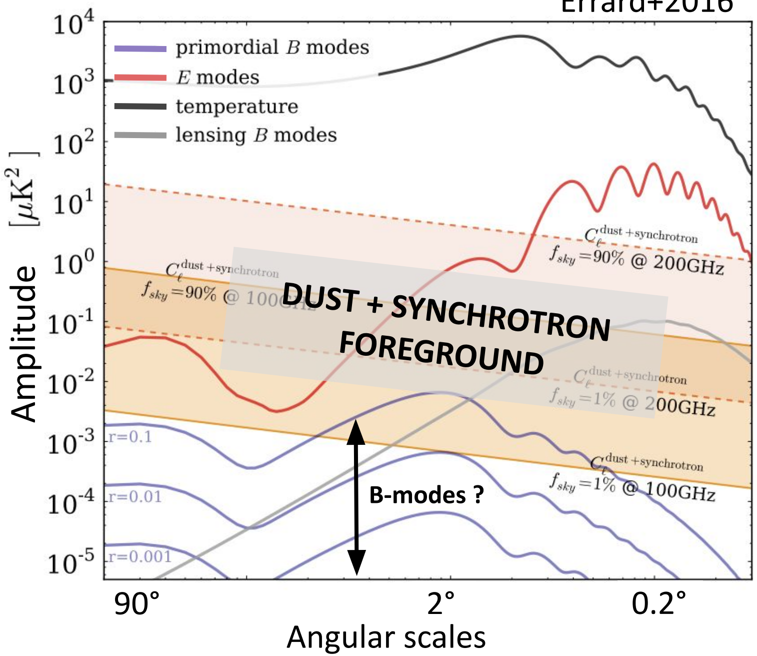
# **C**osmic **M**icrowave **B**ackground polarization

provides a unique insight on the primordial Universe

Credits: ESA and Planck collaboration




Errard+2016




**Sensitivity target**
**r parameter ~$10^{-3}$**

LiteBIRD (space)
CMB-S4 (ground)
and others

# CMB *B*-modes detection as probe of the inflation

## Technical
### Challenges

- ★ High sensitivity
  (LiteBIRD satellite, CMB-S4 *under development*)
- ★ Systematic effects control
- ★ Precise absolute calibration of the polarization angle
- ★ Foreground emission subtraction

# **CMB** *B*-modes detection as probe of the inflation

## Technical
### Challenges

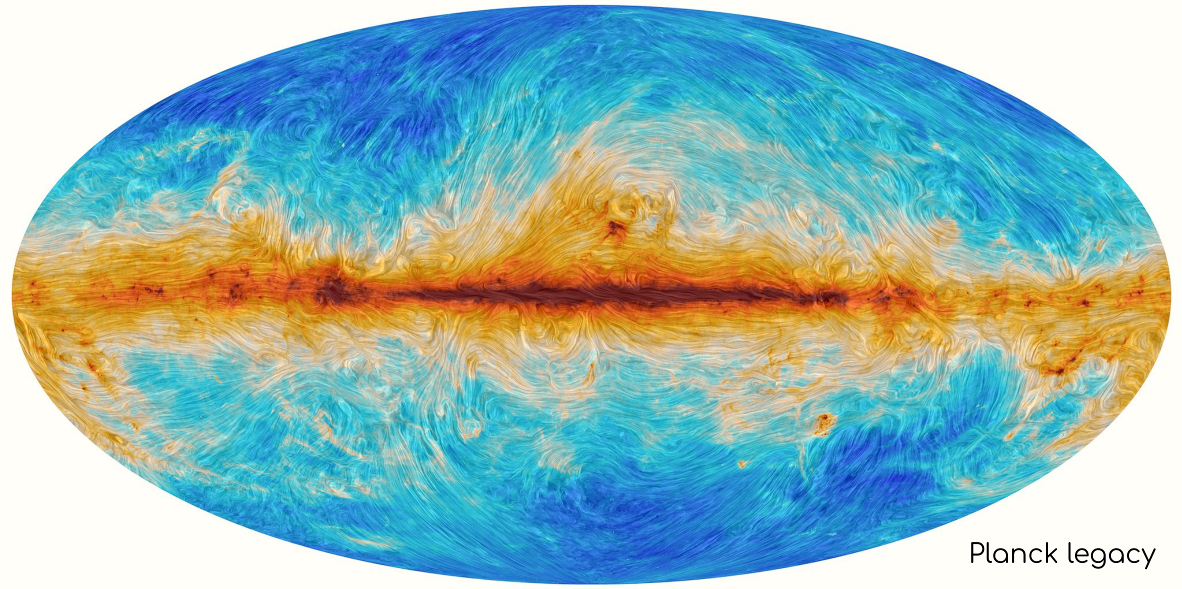
★ High sensitivity
(LiteBIRD satellite, CMB-S4 *under development*)

★ Systematic effects control

★ Precise absolute calibration of the polarization angle

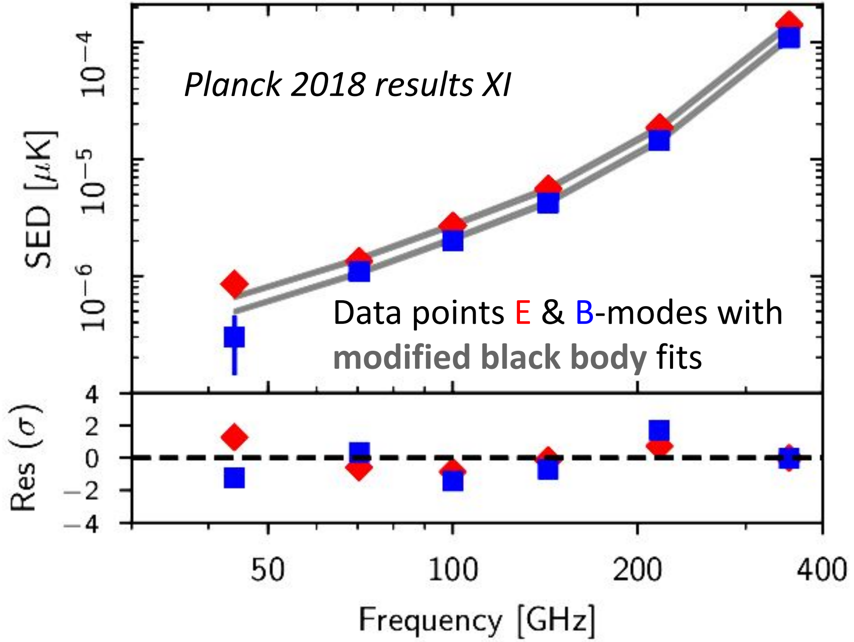
★ Foreground emission subtraction

# Polarized **dust** emission




To subtract the sky dust **polarization** we need to have a full-sky modelling
→ So we need to understand how dust polarization behaves

# Dust Spectral Energy Distribution




The dust SED in polarization from Planck 2018 results is remarkably well fit by a **single temperature modified black-body emission law** from 353 GHz to 44 GHz.

**This brought a significant advance in constraining dust models in astrophysics & for CMB foreground dust component separation methods.**

**⇒ Characterize spatial variations of polarization SEDs, i.e. the local frequency dependence of polarized intensity and angles)**

# Dust polarization low-$\ell$ SED spatial variation

# Planck HFI maps

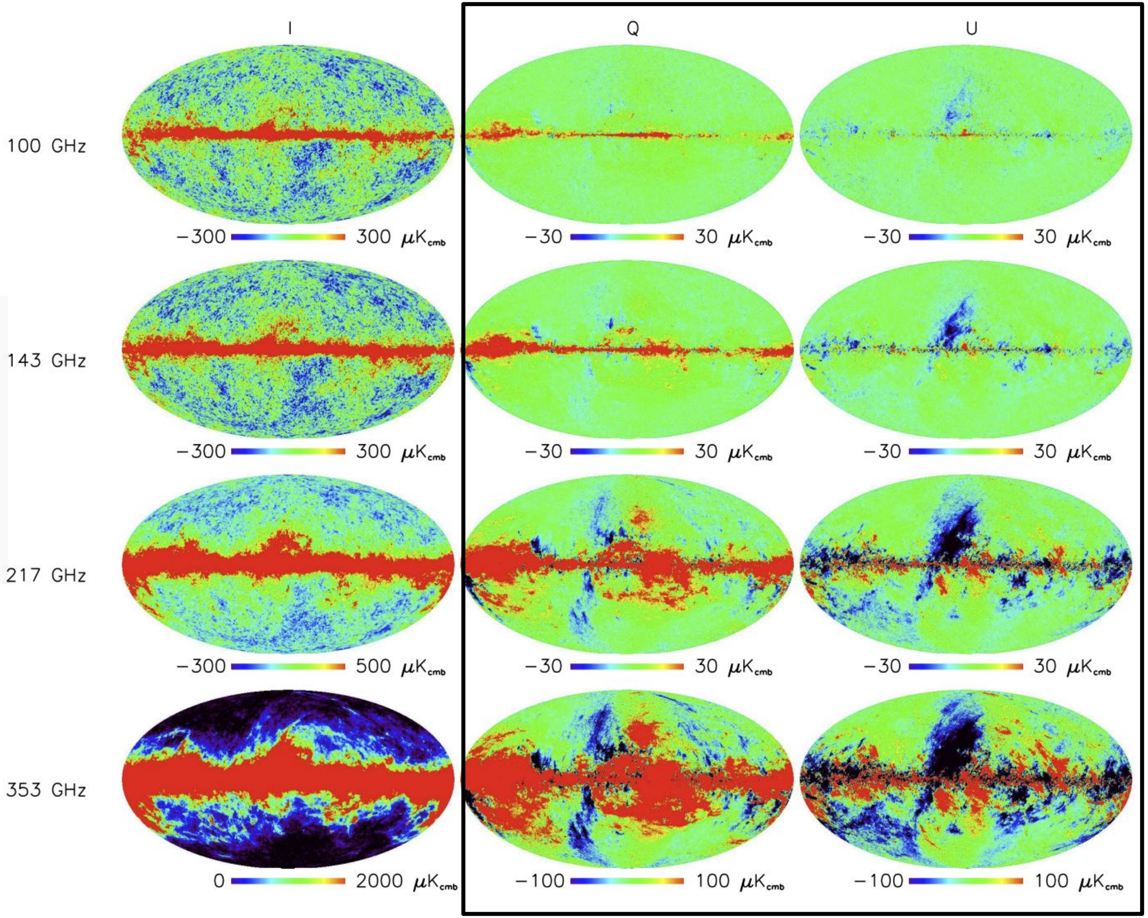
## SRoll2 release

http://sroll20.ias.u-psud.fr/sroll20_data.html

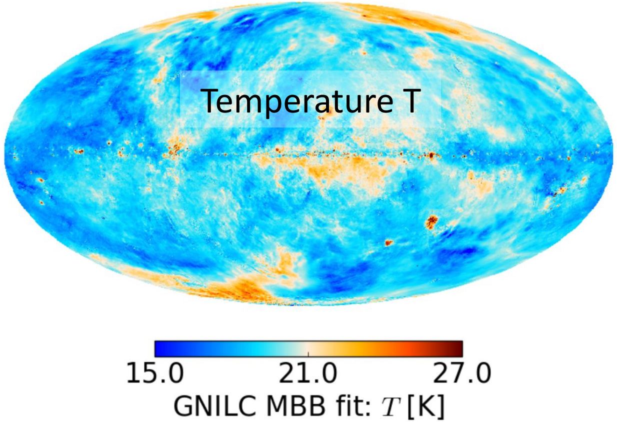
### Improved polarization maps w.r.t PR3

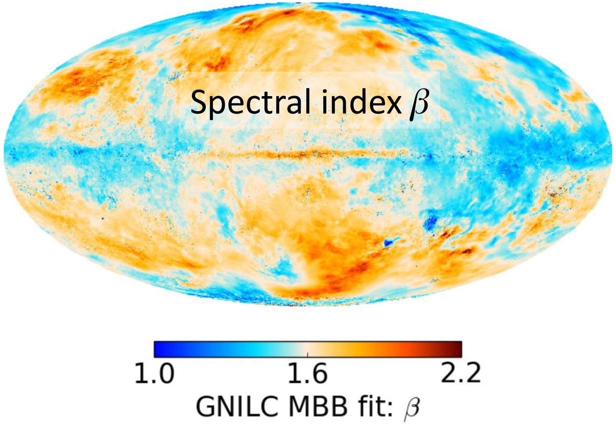
Check out *Delouis et al. A&A 629, A38 (2019)* for technical details

Polarization maps used



# A **synthetic model** based on total intensity spatial SED variations




**Modified Black Body function**

$$I_d(\nu) = \tau_{353} \times B(T,\nu) \times \left(\frac{\nu}{353\ \mathrm{GHz}}\right)^{\beta}$$

$\nu_0$ = 353 GHz

**Extrapolation to polarization**

$$Q_{\mathrm{model}}(\nu) = \frac{I_d(\nu)}{I_d(\nu_0)} \cdot (Q_{\mathrm{Planck}}(\nu_0) - Q_{\mathrm{Planck}}(\mathrm{CMB}))$$

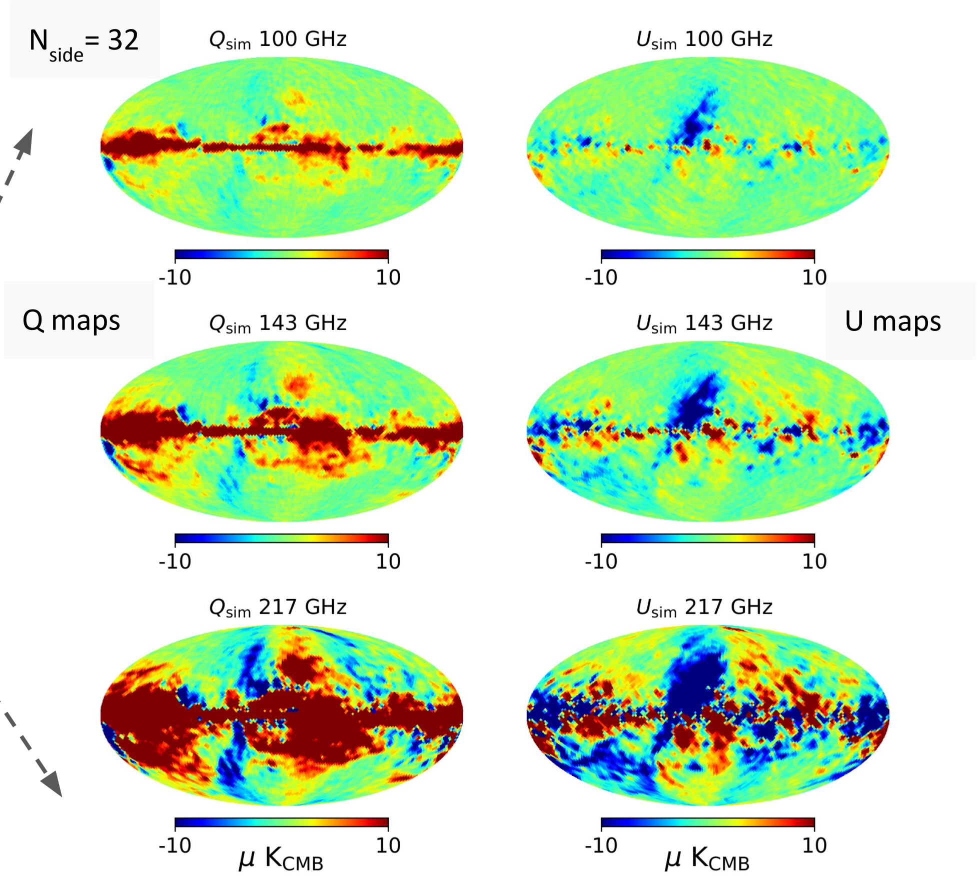
$$U_{\mathrm{model}}(\nu) = \frac{I_d(\nu)}{I_d(\nu_0)} \cdot (U_{\mathrm{Planck}}(\nu_0) - U_{\mathrm{Planck}}(\mathrm{CMB})),$$

**We use T, $\beta$ maps from Commander & GNILC**
**⇒ Dust polarization models commonly used by CMB community (models d1 & d11 of PySM)**

# A **synthetic model** based on total intensity spatial SED variations

**Including instrumental systematics + noise and CMB**

$$
\begin{aligned}
Q_{\rm sim}(\nu) &= Q_{\rm model}(\nu) + Q_{\rm noise}(\nu) + Q_{\rm CMB} \\
U_{\rm sim}(\nu) &= U_{\rm model}(\nu) + U_{\rm noise}(\nu) + U_{\rm CMB},
\end{aligned}
$$




Two total intensity model considered:

- *Commander* *(Planck Collaboration et al. 2016a)*
- *GNILC* *(Remazeilles+2011)*

# Dust **polarized mean** SED for low multipoles $\ell_{min}, \ell_{max}$=[4,32]

**SED computed** for **100, 143, 217** GHz w.r.t $\nu_0$= 353 GHz

**CROSS POWER SPECTRA ANALYSIS**

$$\gamma_{\rm P}^{\rm XX}(\nu) = \rho \left\langle \frac{\mathcal{D}_\ell^{\rm XX}(\nu \times \nu_0) - \mathcal{D}_\ell^{\rm XX}(\rm CMB)}{\mathcal{D}_\ell^{\rm XX}(\nu_0 \times \nu_0) - \mathcal{D}_\ell^{\rm XX}(\rm CMB)} \right\rangle_{\ell_{\rm min}, \ell_{\rm max}}$$

**SED**

**Polarization efficiency**

***Planck Coll. et al. 2020b***

**SPECTRA**

***XX*=EE, BB**

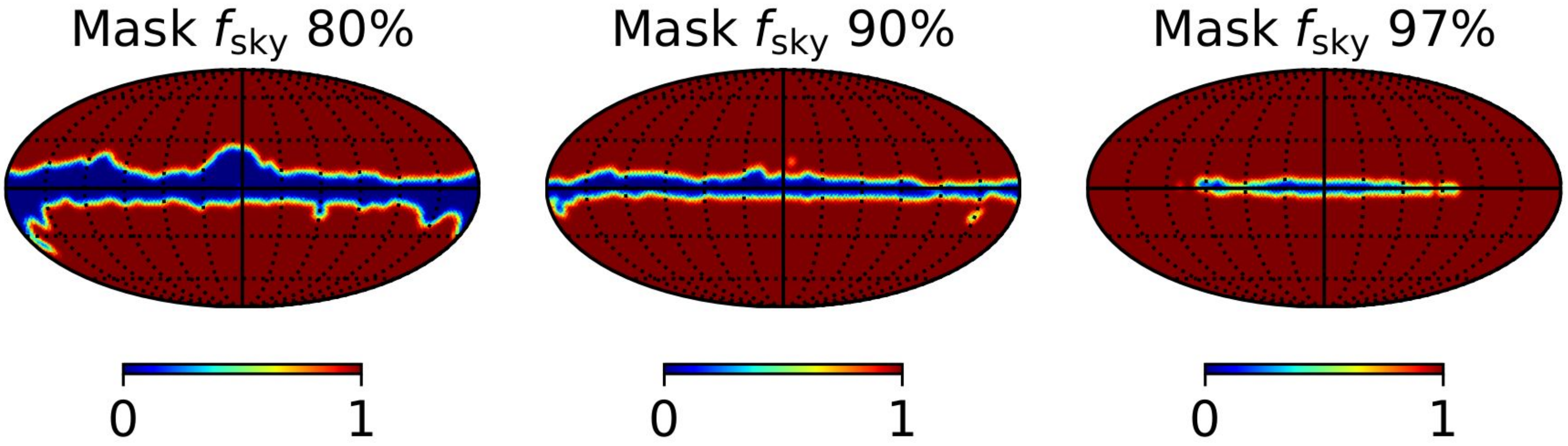
$\gamma_P$ is computed for:

- ***Planck SRoll2* data**

or

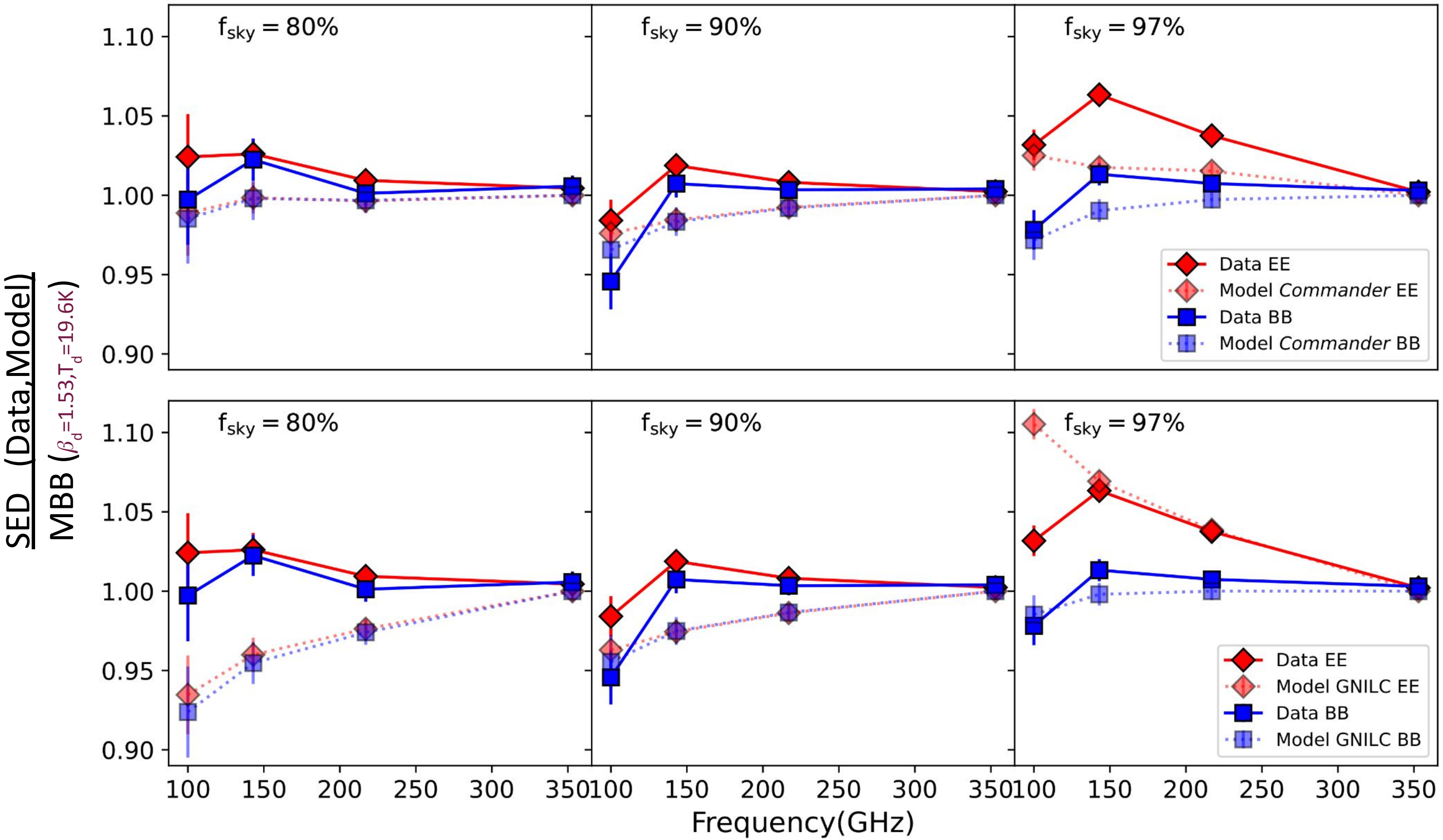
- ***Commander,* GNILC models**

# Galactic masks used for the power spectra data analysis

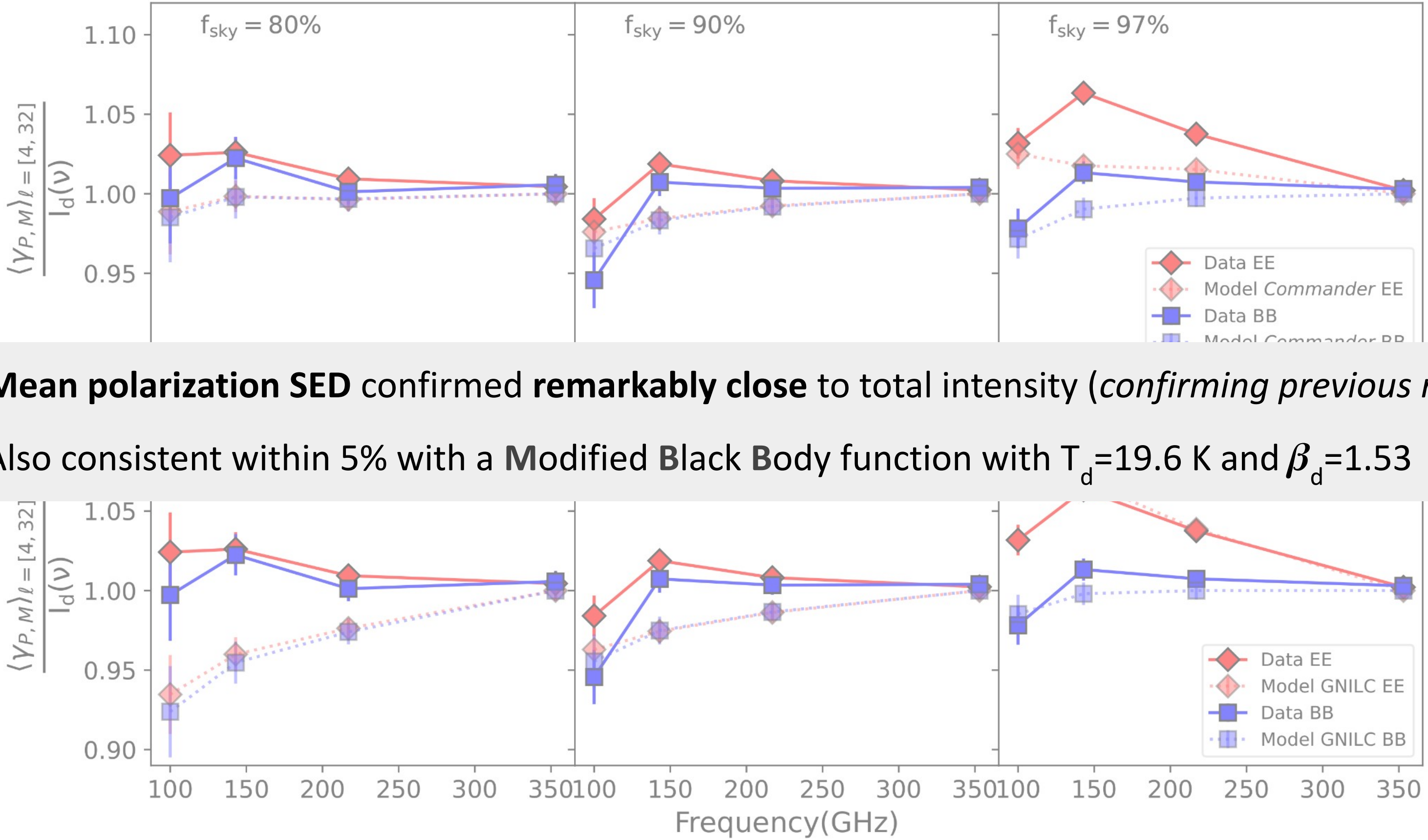



⇒ **We extend earlier studies to brighter Galactic sky emission to gain signal-to-noise ratio**

# Dust **polarized mean** SED for low multipoles $\ell_{min}, \ell_{max}$=[4,32]



# Dust **polarized mean** SED for low multipoles $\ell_{min}, \ell_{max}$=[4,32]




- **Mean polarization SED** confirmed **remarkably close** to total intensity (*confirming previous results*)
- Also consistent within 5% with a **M**odified **B**lack **B**ody function with $T_d$=19.6 K and $\beta_d$=1.53

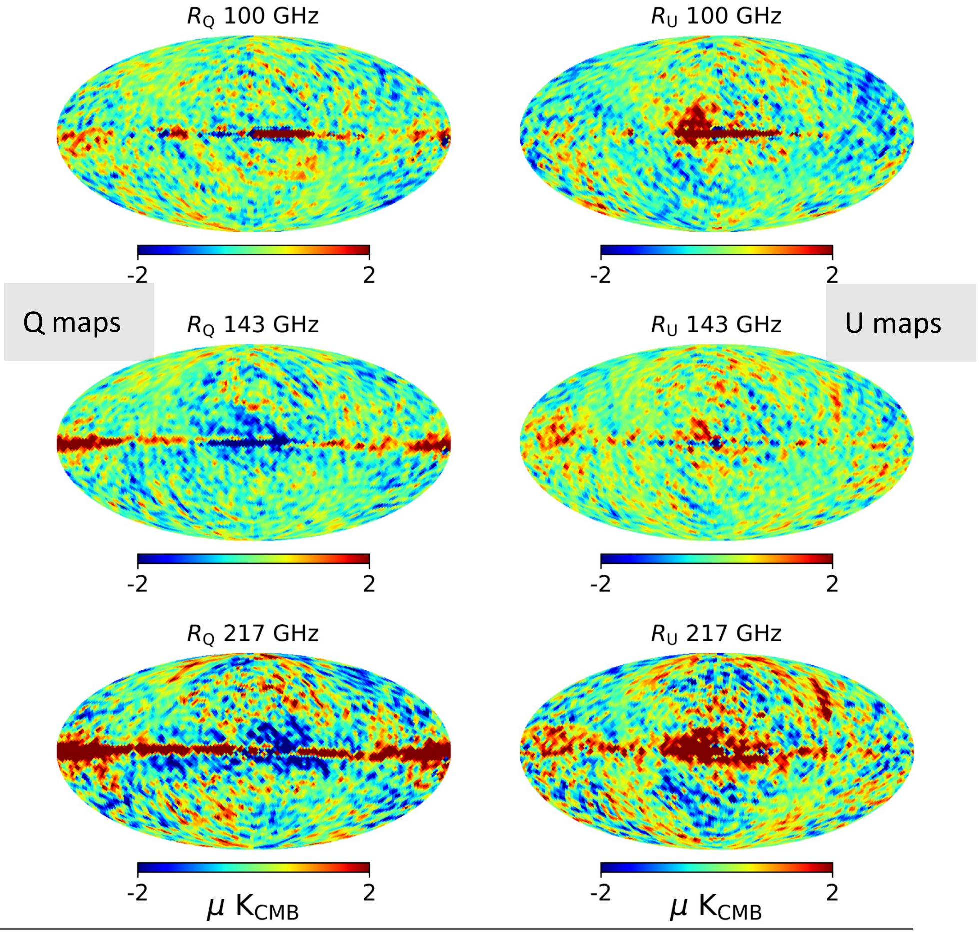
# Spatial SED variation of the dust polarization

## Residual maps

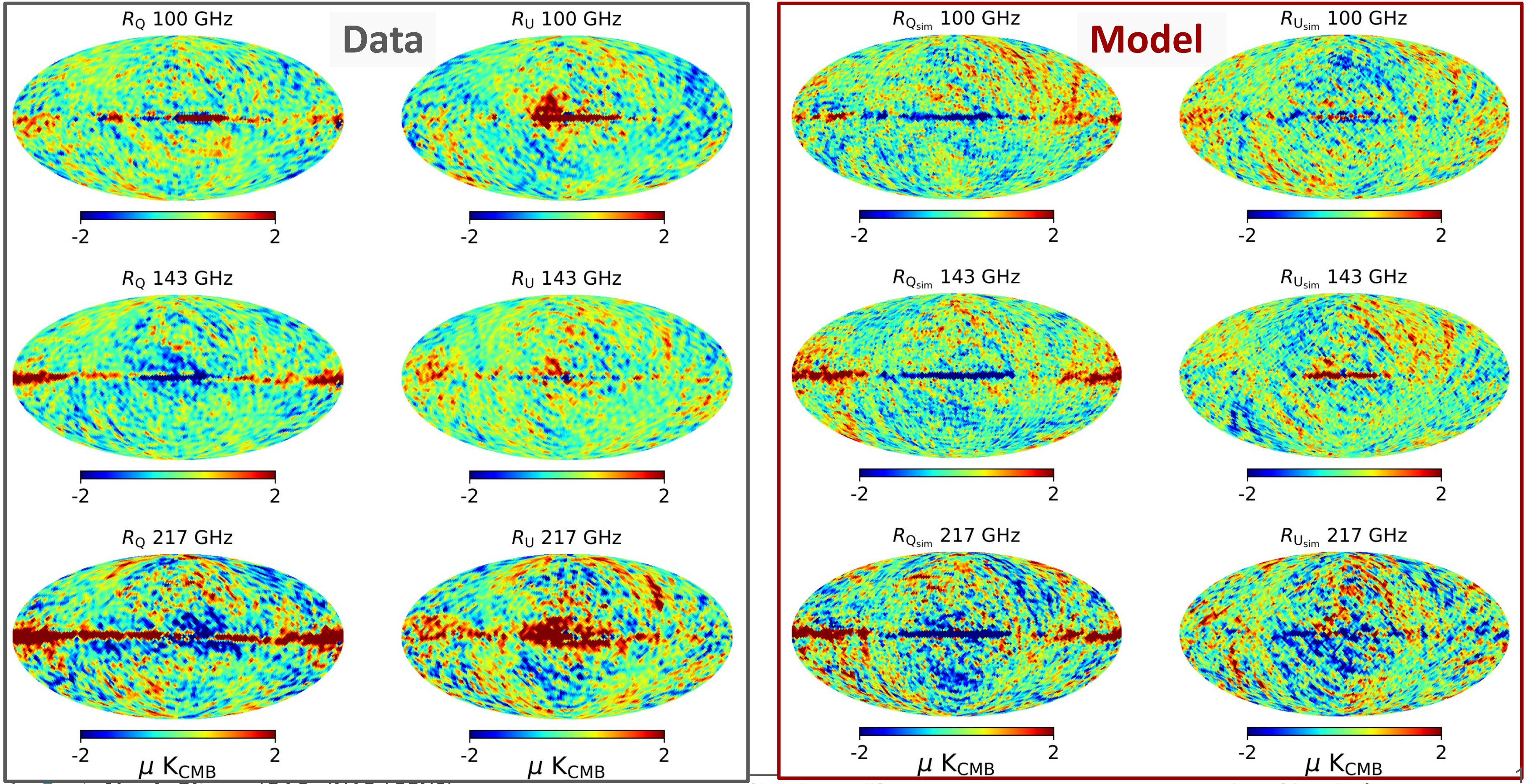
$$R_Q(\nu) = Q_d(\nu) - \gamma_P(\nu) \cdot Q_{Planck}(\nu_0)$$
$$R_U(\nu) = U_d(\nu) - \gamma_P(\nu) \cdot U_{Planck}(\nu_0).$$

**Mean SED**

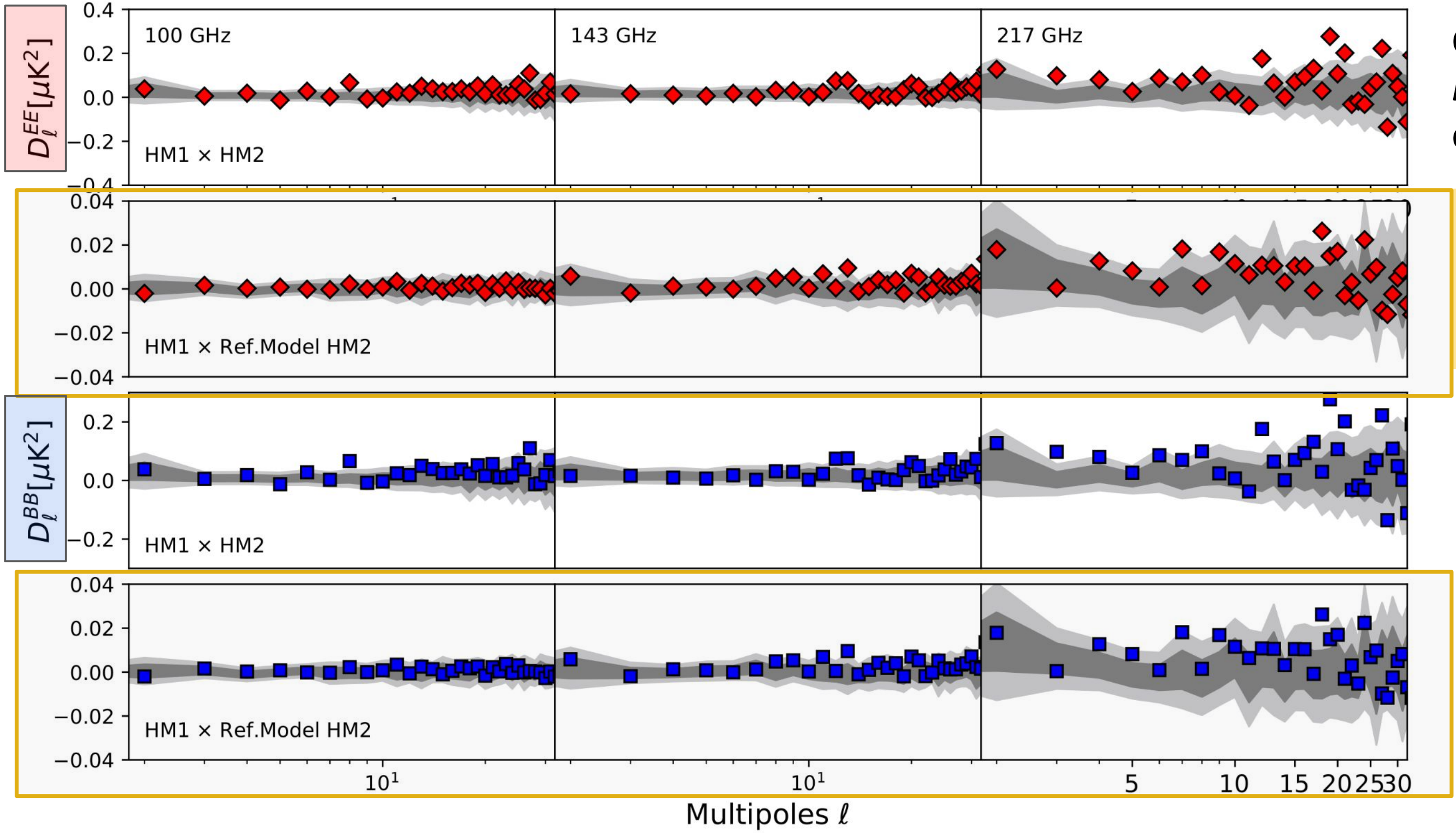
Corrected for synchrotron at 100,143 GHz



# Residual polarization maps



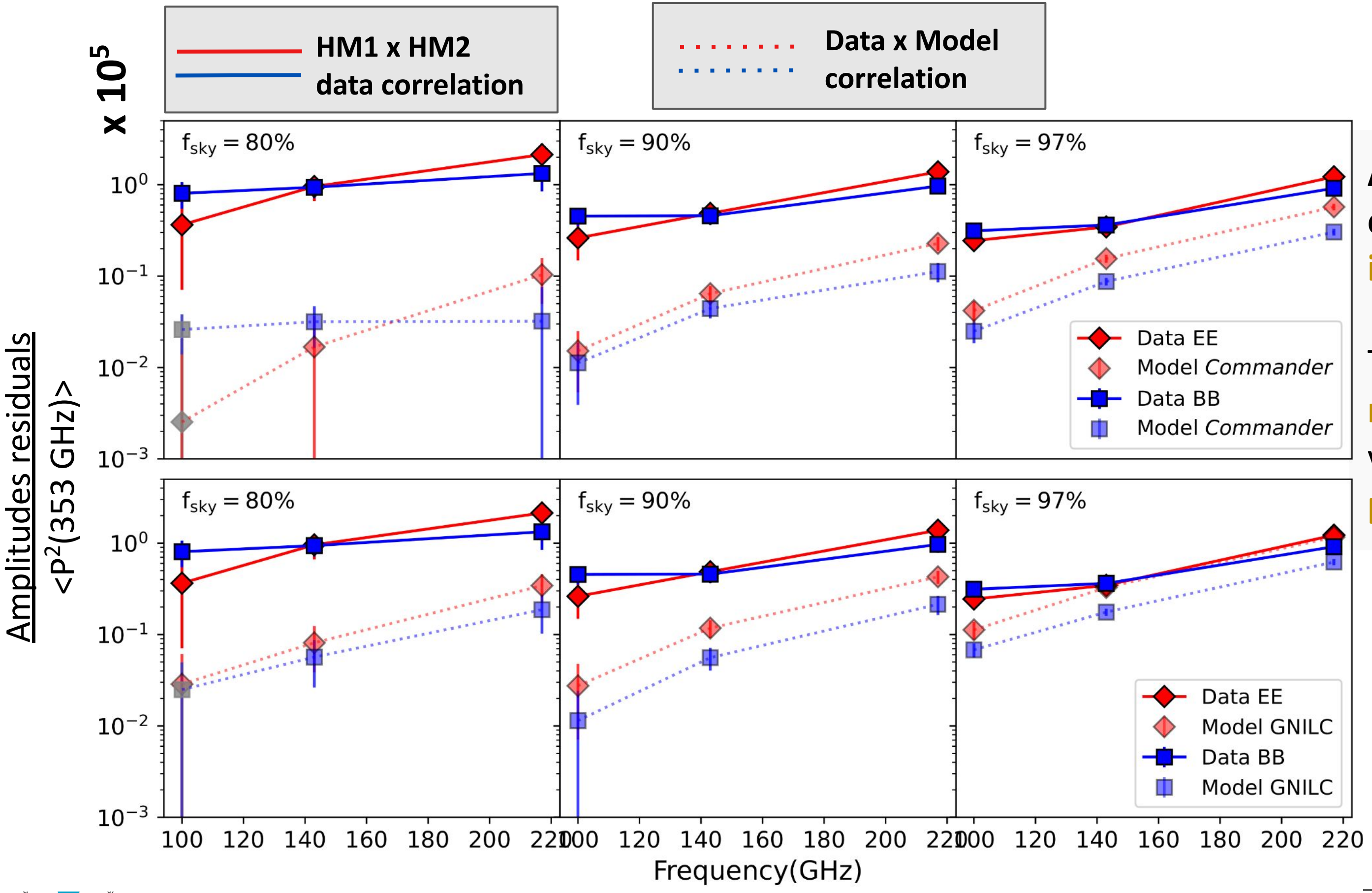
# Cross power spectra analysis of residual maps




Correlation between *Planck half-mission* data sets

Correlation between data and the *Commander* model

# Averaged cross-correlation between multipoles ℓ=[4,32]

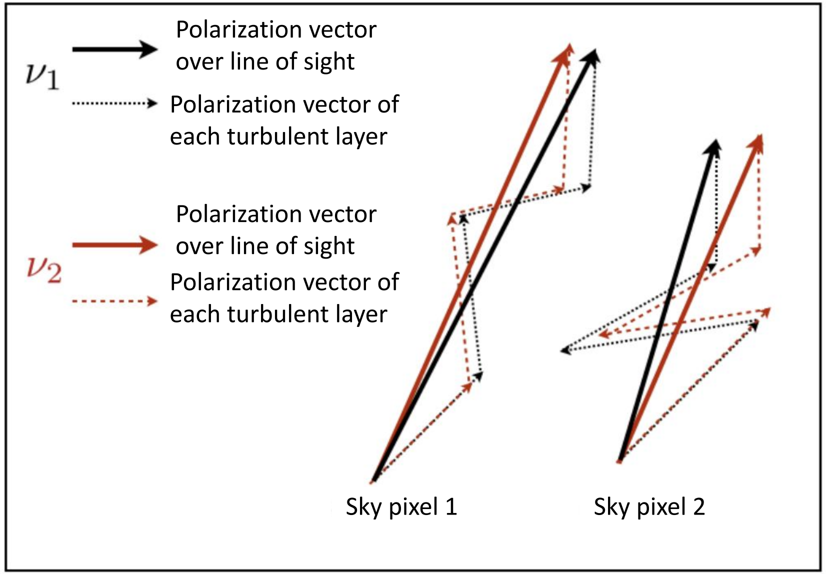



**At high latitudes→less $f_{sky}$ correlation with total intensity models** is low

These models **do not reproduce** spatial SED variations detected in **polarization data**

# Contribution from **polarization angles**

*Planck* intermediate results L. 2017




Decomposition of the LOS complex **polarization vector** into a random walk process through different *coherent cells* for two pixels at two frequencies, $\mathbf{v_1}$ and $\mathbf{v_2}$.

Frequency dependence of polarization angles introduced by the interplay between dust emission properties and the structure of the magnetized ISM

**⇒ Decorrelation of the polarization pattern with frequency**

# Isolating polarization angle variation effect

We build **synthetic Stokes Q and U** parameters which depend on the polarization angle

**SED**

**Synthetic maps Q & U**

$$\tilde{Q}(\nu) = \gamma_P(\nu) \cdot P(\nu_0) \times \cos 2\psi(\nu)$$
$$\tilde{U}(\nu) = \gamma_P(\nu) \cdot P(\nu_0) \times \sin 2\psi(\nu)$$

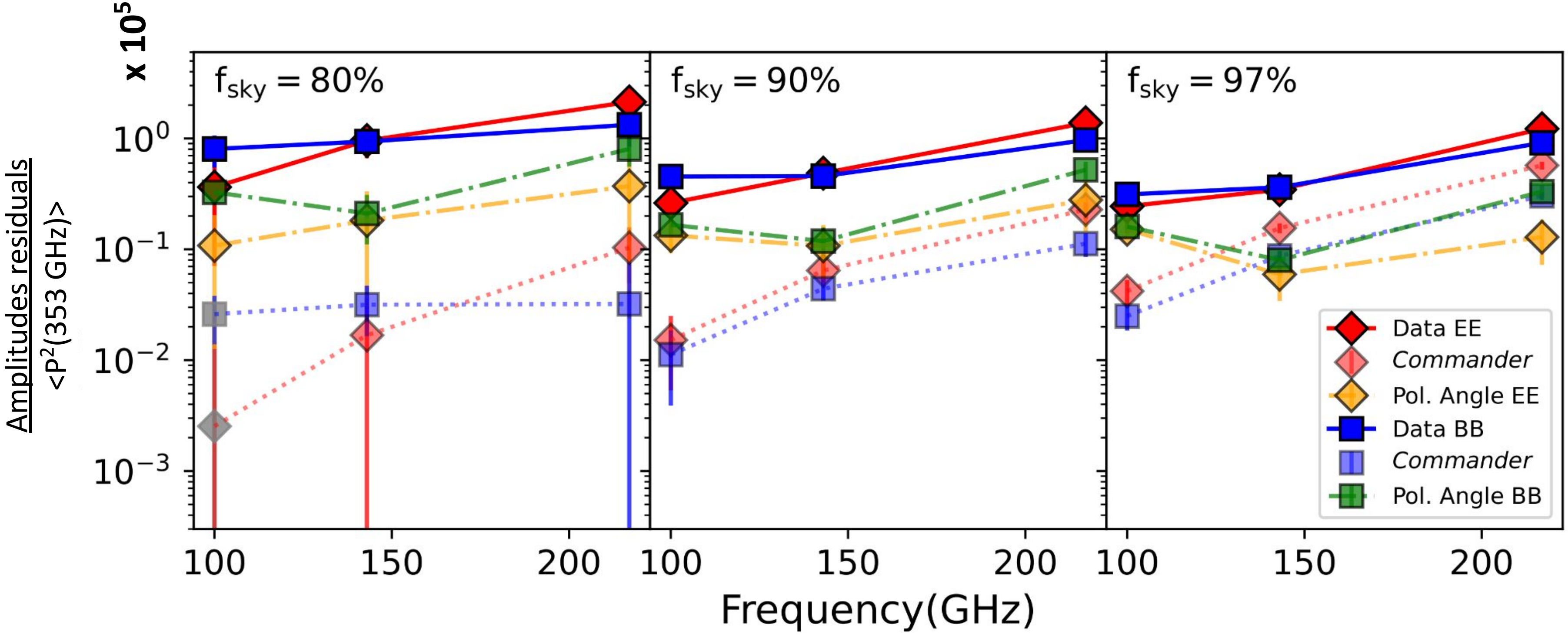
→ polarization angle maps:
$\psi_\nu$ = 0.5 x atan(U/Q)

↓

**Residual maps**

$$R_{\tilde{Q}}(\nu) = \tilde{Q}(\nu) - \gamma_P(\nu) \cdot \tilde{Q}(\nu_0)$$
$$R_{\tilde{U}}(\nu) = \tilde{U}(\nu) - \gamma_P(\nu) \cdot \tilde{U}(\nu_0)$$

# Isolating polarization angle variation effect




**Amplitudes of residuals due to polarization angle spatial variation**

# Isolating polarization angle variation effect

Converting the residual amplitudes due to variations of the polarization angle to **effective angle variation $\delta\psi$**

$$\sin \delta_{\psi}(\nu) = 0.5 \cdot (\tilde{A}^{EE}_{\rm res}(\nu) + \tilde{A}^{BB}_{\rm res}(\nu))^{0.5} \cdot (\gamma_{\rm P}(\nu) \cdot P(\nu_0))^{-1}$$

| | 100 GHz | 143 GHz | 217 GHz |
|---|---|---|---|
| $f_{sky}$ 80% | **3.1**° ± 0.4° | 1.4°± 0.2° | 0.8° ± 0.2° |
| $f_{sky}$ 90% | **2.7**° ± 0.3° | 1.1°± 0.1° | 0.6° ± 0.1° |
| $f_{sky}$ 97% | **2.6**° ± 0.2° | 0.8° ± 0.1° | 0.5° ± 0.1° |

**Decorrelation due to polarization angle variation along LOS**

This effect must be accounted for in future CMB dust foreground modelling

*Uncertainty on* **absolute angle calibration < 1°**
(*Rosset et al. 2010*)

# Frequency dependance

## Taylor expansion of the MBB emission law

Introduced by *Chluba et al. 2017*, *Mangilli et al. 2021*, *Azzoni et al. 2021*, *Vacher et al. 2022a*

$$\mathcal{D}_\ell(\nu) = \gamma_P(\nu)^2 \cdot \Big\{$$

$$1^{\text{st}} \text{ order } \beta \; \Big\{ \quad +\mathcal{D}_\ell^{\omega_1^\beta \times \omega_1^\beta} \ln\left(\frac{\nu}{\nu_0}\right)^2$$

$$1^{\text{st}} \text{ order } T \; \Big\{ \quad +\mathcal{D}_\ell^{\omega_1^T \times \omega_1^T} \left(\Theta_\nu(T_{\text{d}}) - \Theta_{\nu_0}(T_{\text{d}})\right)^2 \qquad (18)$$

$$1^{\text{st}} \text{ order } T\text{x}\beta \; \Big\{ \quad +2\mathcal{D}_\ell^{\omega_1^\beta \times \omega_1^T} \ln\left(\frac{\nu}{\nu_0}\right) \cdot \left(\Theta_\nu(T_{\text{d}}) - \Theta_{\nu_0}(T_{\text{d}})\right)\Big\},$$

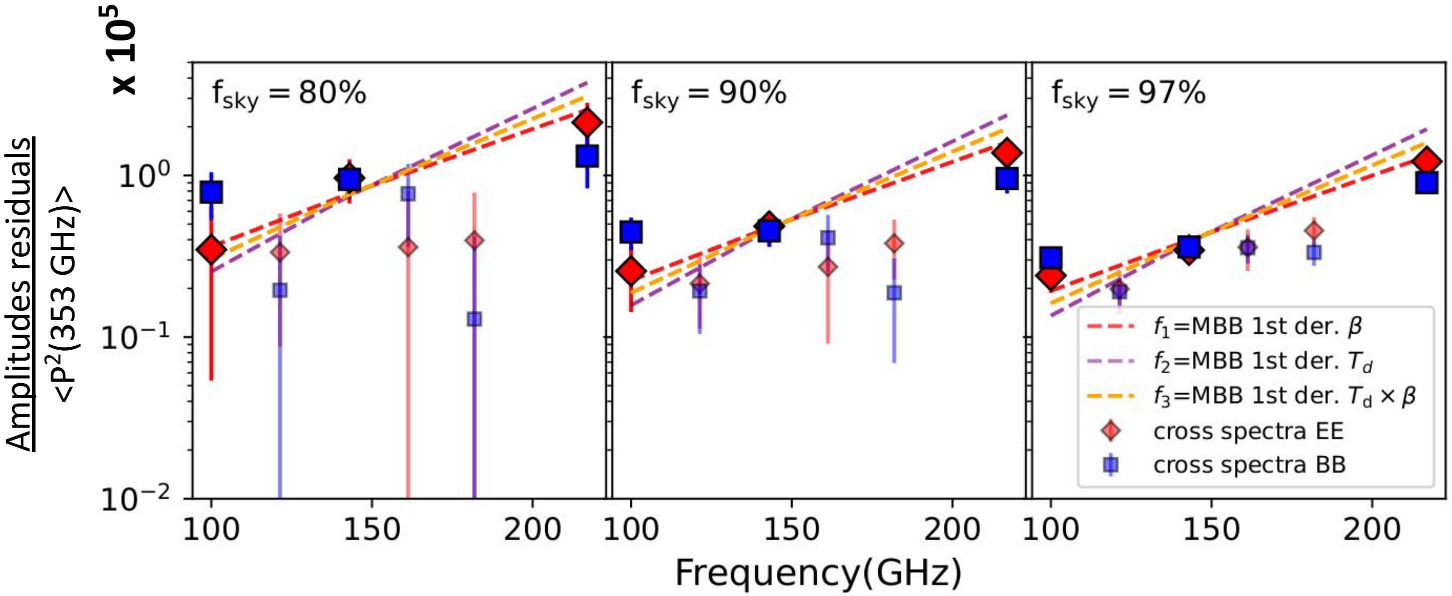
# Frequency dependance

## Taylor expansion of the MBB emission law

**MBB 1st order deriv. $\beta$**

**MBB 1st order deriv. T**

**MBB T-$\beta$ cross term**




- Dust polarization ***EE*** SED variation well described by MBB deriv. in $\beta$
- ***BB*** SED tends to flat towards high angular latitudes
- Residual maps between the three frequencies are not fully correlated

# Conclusions and Perspectives

## Power spectra to characterise spatial variations of polarized dust SED for $\ell$=[4,32]

– **Mean polarization SED** confirmed **Planck 2018 results**.

– **Residual maps** at **100, 143 and 217 GHz quantifies spatial variations** of the **dust polarization**.

– Residual maps correlated with **reference models** account for  **fraction** of the **total SED variation.**

# Conclusions and Perspectives

– We detect **variations in the polarization angle**.
They dominate variations of polarized intensity for $f_{sky}$ = 80% and 90%

**⇒ It is essential to consider in simulations of Galactic foregrounds and component separation**

– ***EE*** power of residuals is well fit by MBB 1st order $\beta$-derivative of MBB.

**⇒ It suggests SED variations follow from small variations of MBB parameters within the beam**

– This conclusion is challenged by **BB** results, in particular for $f_{sky}$ = 80%, and by cross-spectra that show that the residuals maps at the three frequencies are not fully correlated.

*Ritacco et al. 2022 A&A submitted* e-print: arXiv:2206.07671v1

**This work sets new requirements for CMB dust polarized foreground modelling**