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Data calibration for dust polarization and component separation

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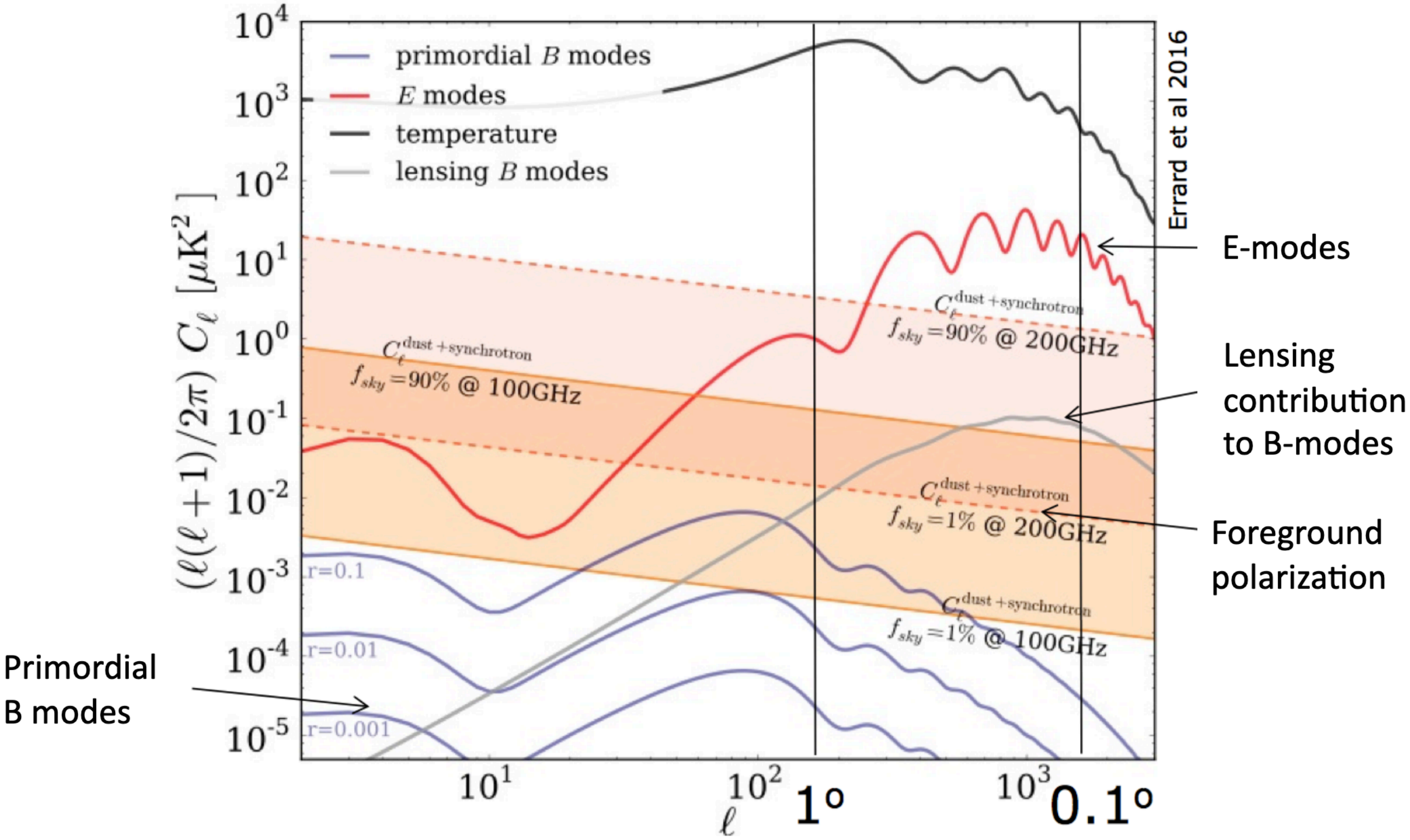
Towards primordial B-modes & cosmic bi-refringence

- Astrophysics of magnetized interstellar medium
- Component separation
- Data calibration

My aim is to convince you that these three challenges are closely linked



Dust polarization & CMB E-modes have similar power

But calibration requirements are easier to express for the CMB than for dust

Dust polarization maps

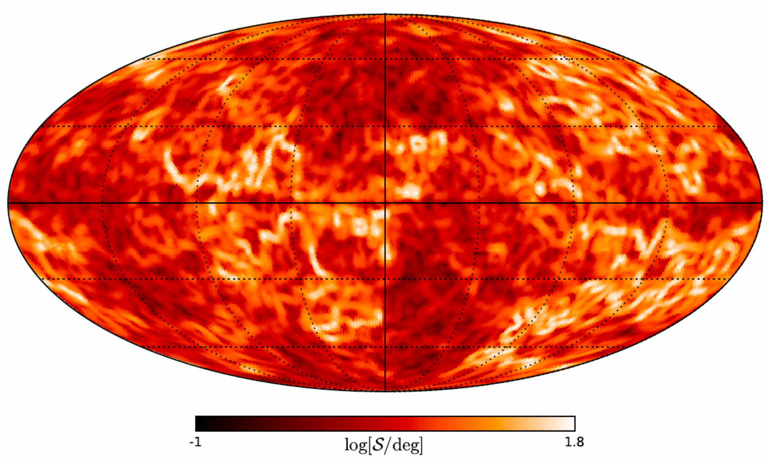
Key ingredients of phenomenological models

e.g. Vansyngel+ 17; Ghosh+ 17; Clark & Hensley 2019; Huffenberger+20; Hervías-Caimapo & Huffenberger 22 …

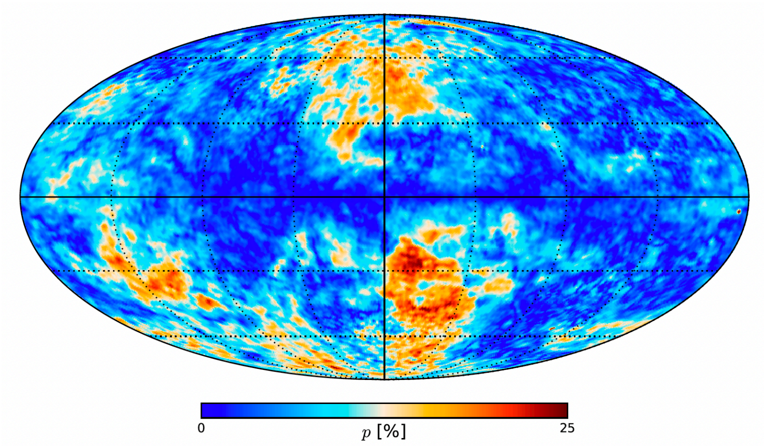
- Mean and random components of local Galactic magnetic field
- Statistical alignement between magnetic field and filamentary ISM structure to account for TE correlation & EE/BB ratio
- **Summing emission over a few emitting layers (ISM structure along the line of sight)** to account for anticorrelation between the polarization fraction and the dispersion of polarization angles

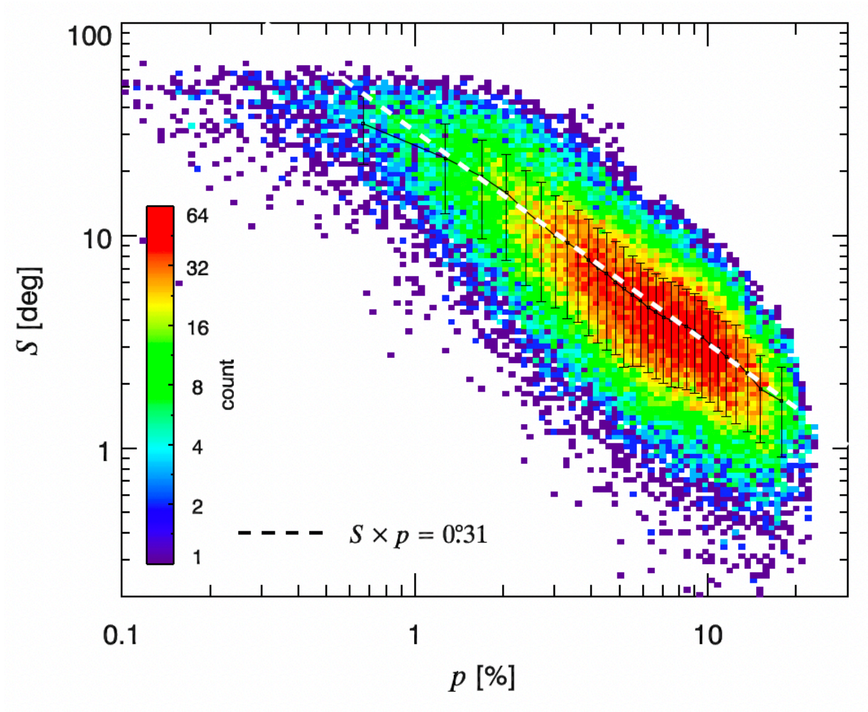
Dust polarization statistics

Dispersion of polarization angles



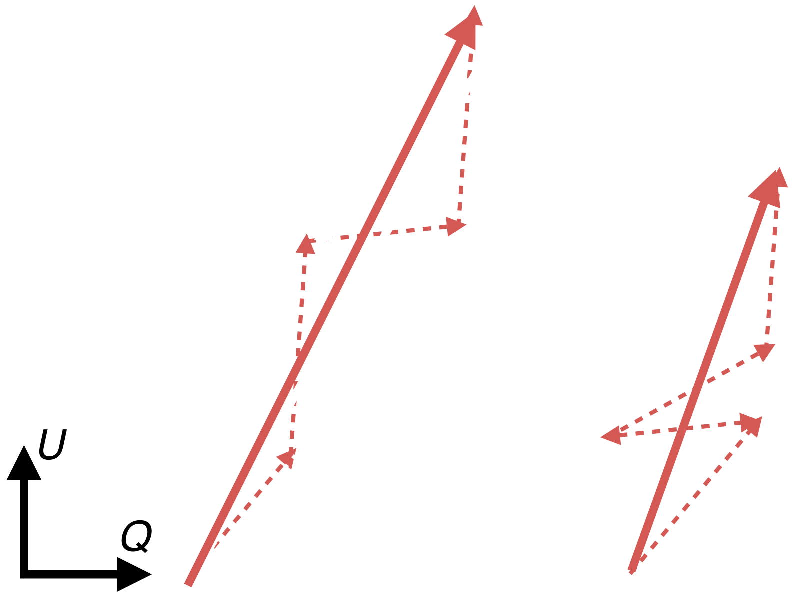
Polarization fraction





Planck Legacy XII (2018)

Line of sight depolarization



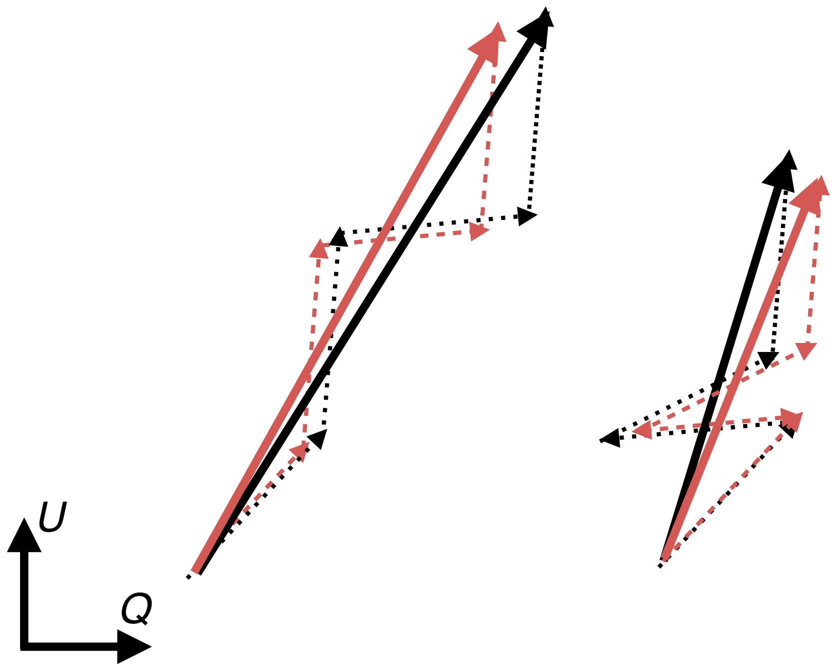
Two sky pixels same I_{dust} but different polarized intensities (vectors length)

Statistically, dust polarization may be understood as a random walk in the *Q,U* plane around a preferred orientation with a small number of steps

- The local orientation of the magnetic field sets the vector angle of each step about that of the mean magnetic field
- Dust polarized intensity sets the length of each step.

Planck intermediate results L (2017)

Frequency dependence of polarization angles



Frequencies ν_1 & ν_2

Planck intermediate results L (2017)

- Due to variations of dust properties along the line of sight, the length of the vectors depend on frequency

➡Polarization angles depend on frequency

Moving forward

Observational evidence

Dust polarization spectral dependence from *Planck* HFI data

Turning point for cosmic microwave background polarization-foreground modeling

Alessia Ritacco[1,2,3], François Boulanger[2], Vincent Guillet[3,4], Jean-Marc Delouis[5], Jean-Loup Puget[2,3], Jonathan Aumont[6], and Léo Vacher[6]

A&A 670, A163 (2023)

see also Pelgrims+ 21

How to model it?

Frequency dependence of the thermal dust *E*/*B* ratio and *EB* correlation: Insights from the spin-moment expansion

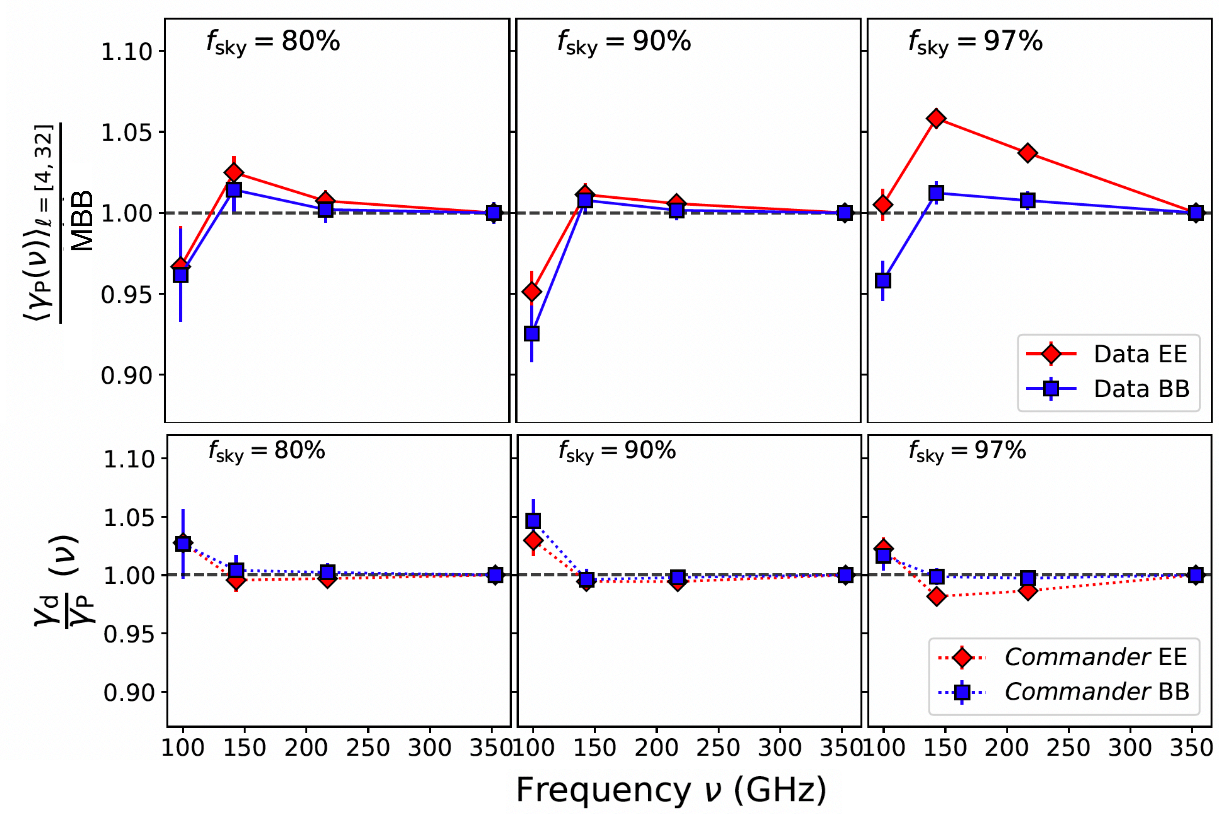
L. Vacher[1], J. Aumont[1], F. Boulanger[2], L. Montier[1], V. Guillet[3,4], A. Ritacco[5,2], and J. Chluba[6]

A&A 672, A146 (2023)

Spectral energy distribution

Dust polarization - Planck

Ritacco+ 23



- Mean dust polarization SED consistent with a Modified Black Body (MBB) function within few %
- SEDs for polarization and total intensity are remarkably close

Spatial variations of the polarization SED

- Residual maps from SED variations

$$R_Q(\nu) = Q_{\mathrm{d}}(\nu) - \gamma_{\mathrm{P}}(\nu) \cdot Q_{\mathrm{Planck}}(\nu_0)$$
$$R_U(\nu) = U_{\mathrm{d}}(\nu) - \gamma_{\mathrm{P}}(\nu) \cdot U_{\mathrm{Planck}}(\nu_0).$$

where $\gamma_P(\nu)$ is the mean polarization SED normalized at $\boldsymbol{\nu}_0$ = 353 GHz

- Residual maps from variations of polarization angles

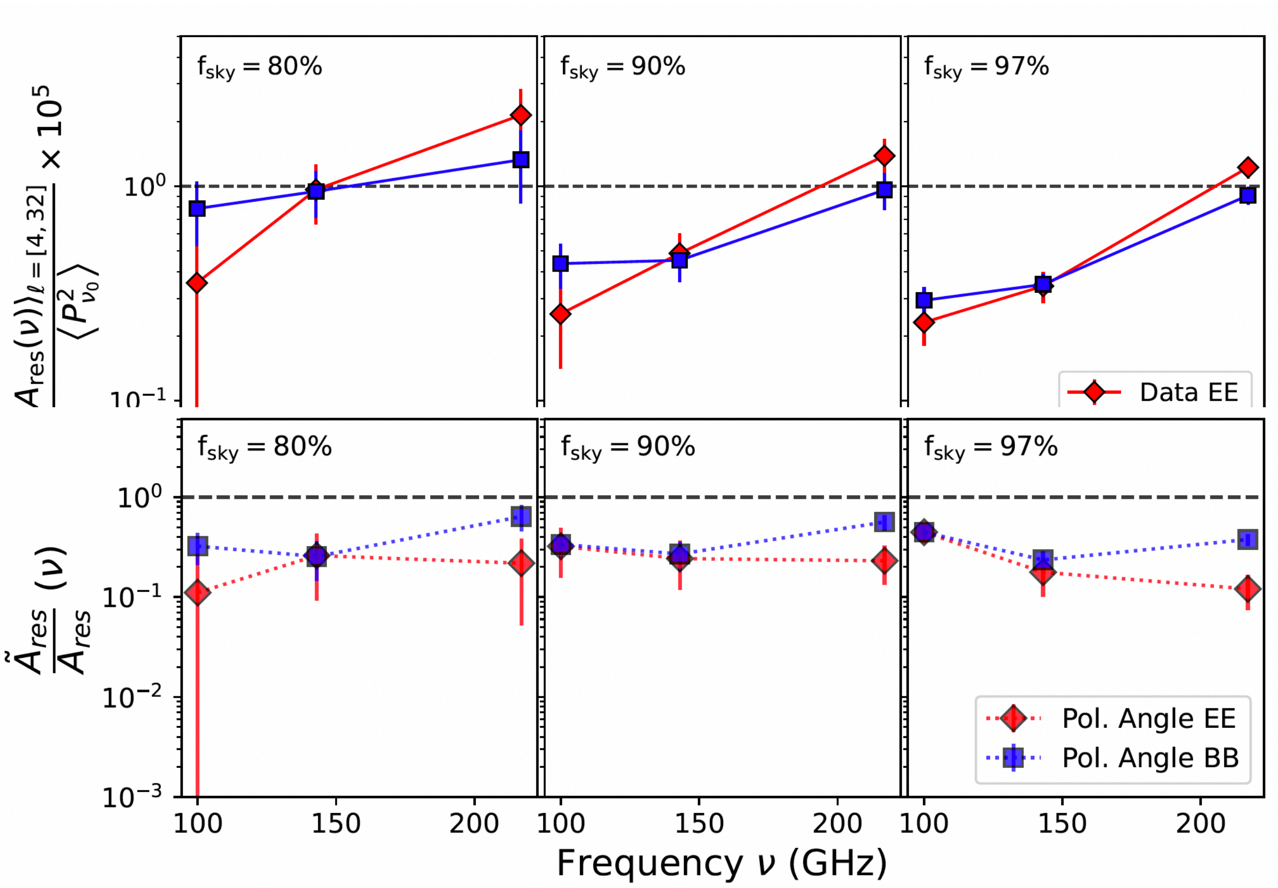
$$R_{\tilde{Q}}(\nu) = \tilde{Q}(\nu) - \gamma_P(\nu) \cdot \tilde{Q}(\nu_0)$$
$$R_{\tilde{U}}(\nu) = \tilde{U}(\nu) - \gamma_P(\nu) \cdot \tilde{U}(\nu_0)$$

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

Power spectra

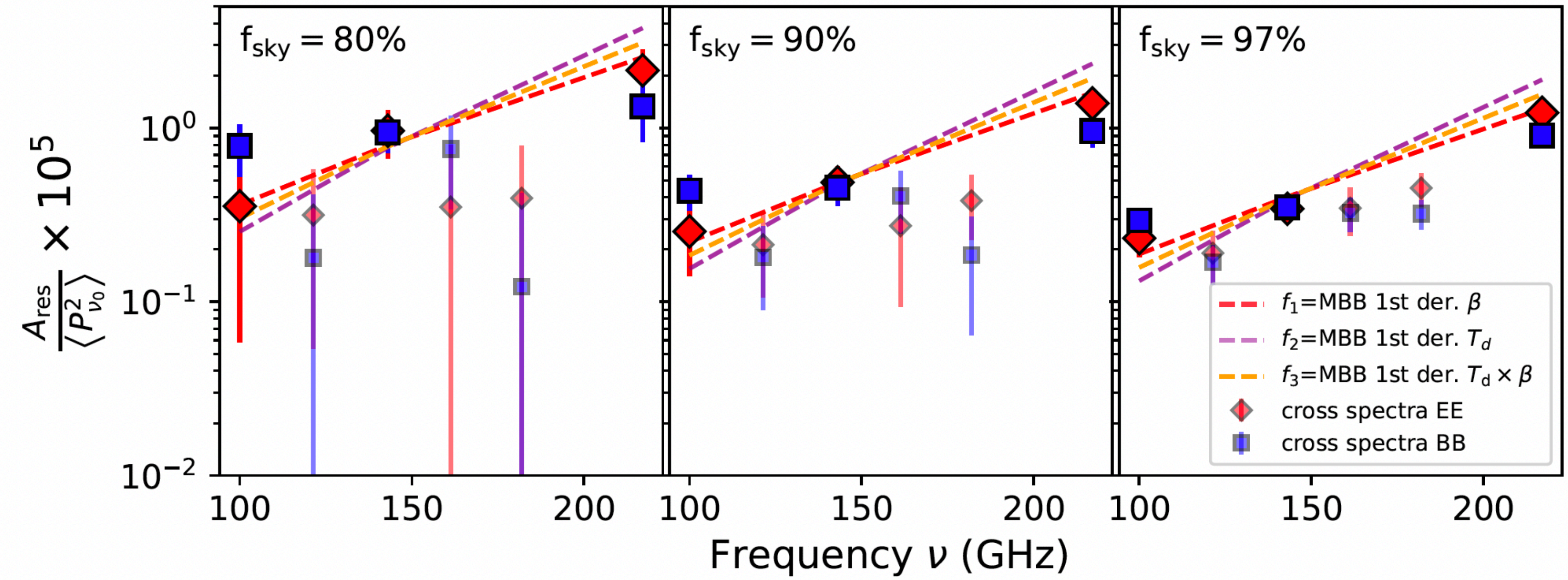
Total residuals

Contribution from polarization angles



- EE and BB residuals have comparable amplitude (no E/B asymmetry)
- We detect variations of polarization angles. This contribution is high.

Spectral dependence



- The BB & EE residuals have distinct SEDs
- The EE data points are consistent with first order expansion of MBB on β but not BB
- Cross-spectra between distinct frequencies point at frequency decorrelation

Modelling SED variations

- Taylor expansion of MBB with respect to β & T

$$\mathcal{P}_\nu \equiv Q_\nu + iU_\nu = A_1 \varepsilon_\nu^P(\beta_1, T_1) e^{2i\phi_1} + A_2 \varepsilon_\nu^P(\beta_2, T_2) e^{2i\phi_2} + \ldots$$

$$= \varepsilon_\nu(\bar{\beta}, \bar{T}) \left(\mathcal{W}_0 + \mathcal{W}_1^\beta \, ln \left(\frac{\nu}{\nu_0} \right) + \ldots \right)$$

- Moment maps

$$\mathcal{W}_0 = \sum_i A_i e^{2i\phi_i} \qquad \mathcal{W}_k^\beta = \sum_i A_i (\beta_i - \bar{\beta})^k e^{2i\phi_i} \qquad \mathcal{W}_k^T = \sum_i A_i (T_i - \bar{T})^k e^{2i\phi_i}$$

Vacher+22

- Moments are **spin-2 complex sky maps** that characterize the frequency dependence of both polarized intensity and polarization angle
- They depend on variations of dust polarization properties and their correlation with the structure of the magnetized ISM

Modelling E/B spectra

- Taylor expansion of E & B

$$\mathcal{S}_\nu \equiv E + iB = -\bar{\eth}^2 \mathcal{P}_\nu$$

$\bar{\eth}$ spin-rising operator

$$\langle \mathcal{S}_\nu(\boldsymbol{n}) \rangle = \varepsilon_\nu^P(\bar{\beta}, \bar{T}) \left(\mathbb{W}_0 + \mathbb{W}_1^\beta \ln\left(\frac{\nu}{\nu_0}\right) + \dots \right)$$

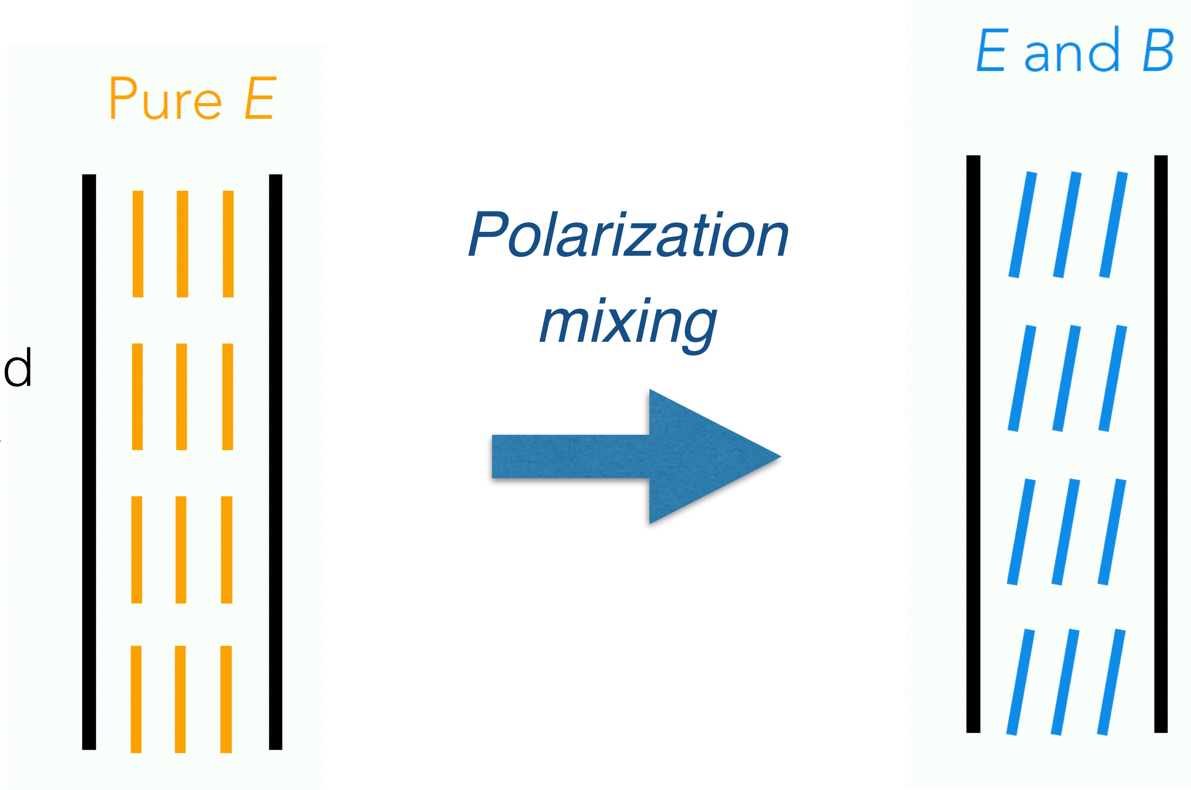
- E & B moment maps

$$\mathbb{W}_{k,E}^\beta = \mathrm{Re}(\mathbb{W}_k^\beta) = -\mathrm{Re}(\bar{\eth}^2(\mathcal{W}_k^\beta))$$
$$\mathbb{W}_{k,B}^\beta = \mathrm{Im}(\mathbb{W}_k^\beta) = -\mathrm{Im}(\bar{\eth}^2(\mathcal{W}_k^\beta))$$

Vacher+23

- Taylor expansion separates spatial and frequency dependence
- Distinct frequency dependence for E & B modes
- Correlation between moment maps may break the expected hierarchy of the expansion orders

Toy model



Filament aligned with magnetic field

No background

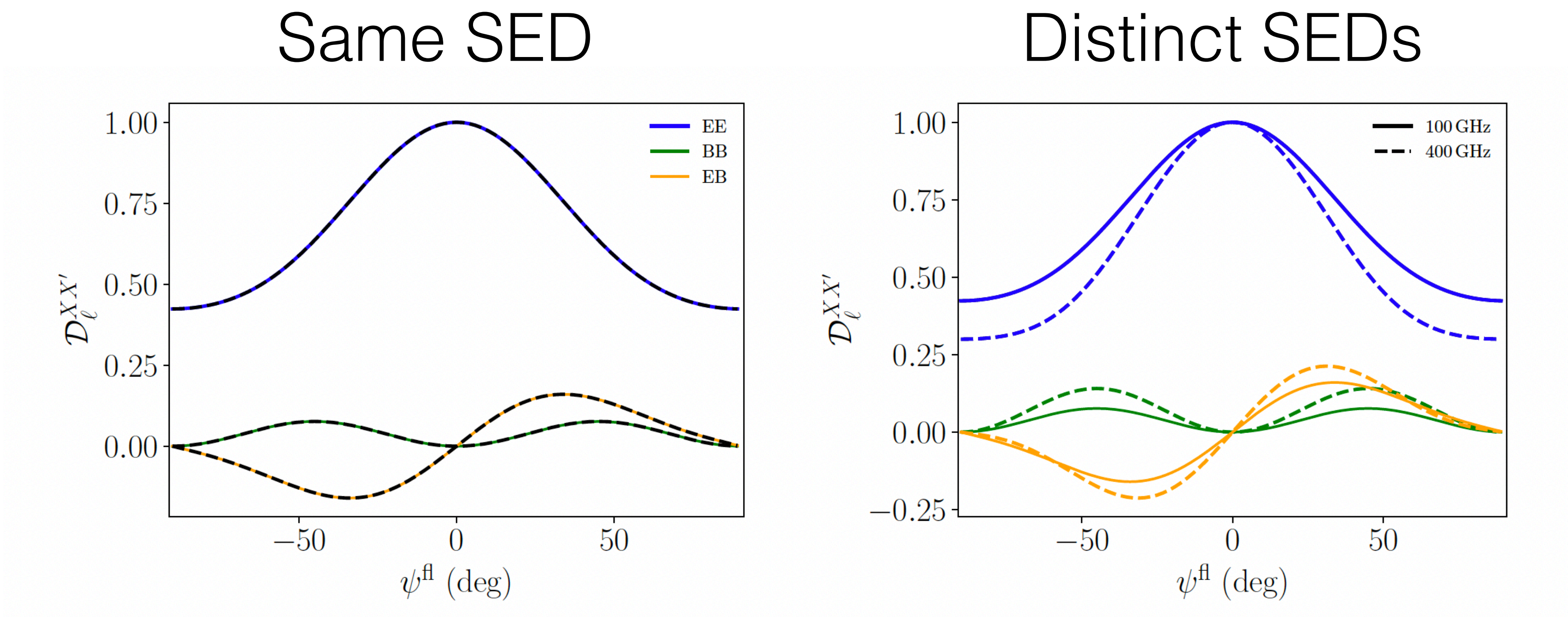
Non-zero background

Mis-alignment introduced by background

Background generates BB & EB power from EE and TB from TE

EE & EB from *polarization mixing*

Toy model with equal polarization intensity for background & filament



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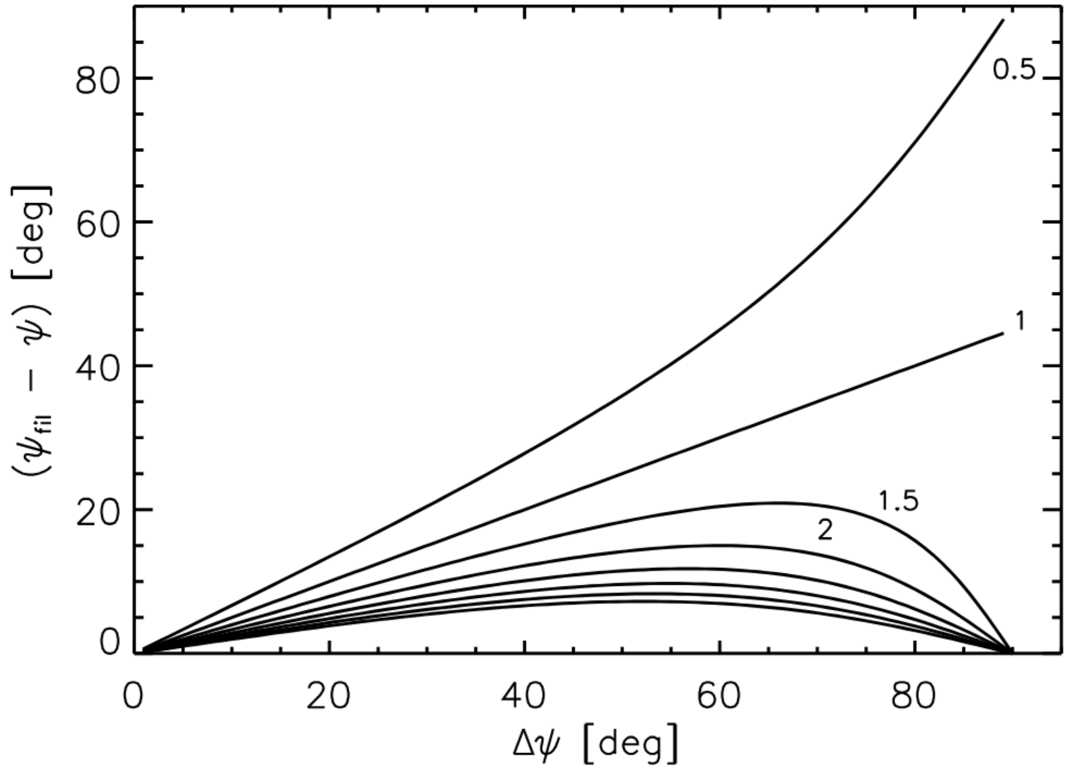
➡ EE, BB & EB spectra have distinct frequency dependence

Filaments in Taurus molecular cloud



$$\Delta\psi = |\psi_{fil} - \psi_{bg}|$$

$$Q = P_{bg}\,(f_d \cos 2\psi_{fil} + \cos 2\psi_{bg}),$$
$$U = P_{bg}\,(f_d \sin 2\psi_{fil} + \sin 2\psi_{bg}),$$

$$f_d = P_{fil}/P_{bg}$$

Toy model first used to characterize the relative alignment of filaments & magnetic field in Taurus molecular cloud

Planck Intermediate results XXXIII 2016

EE/BB for PySM models

Frequency dependence of EE/BB ratio

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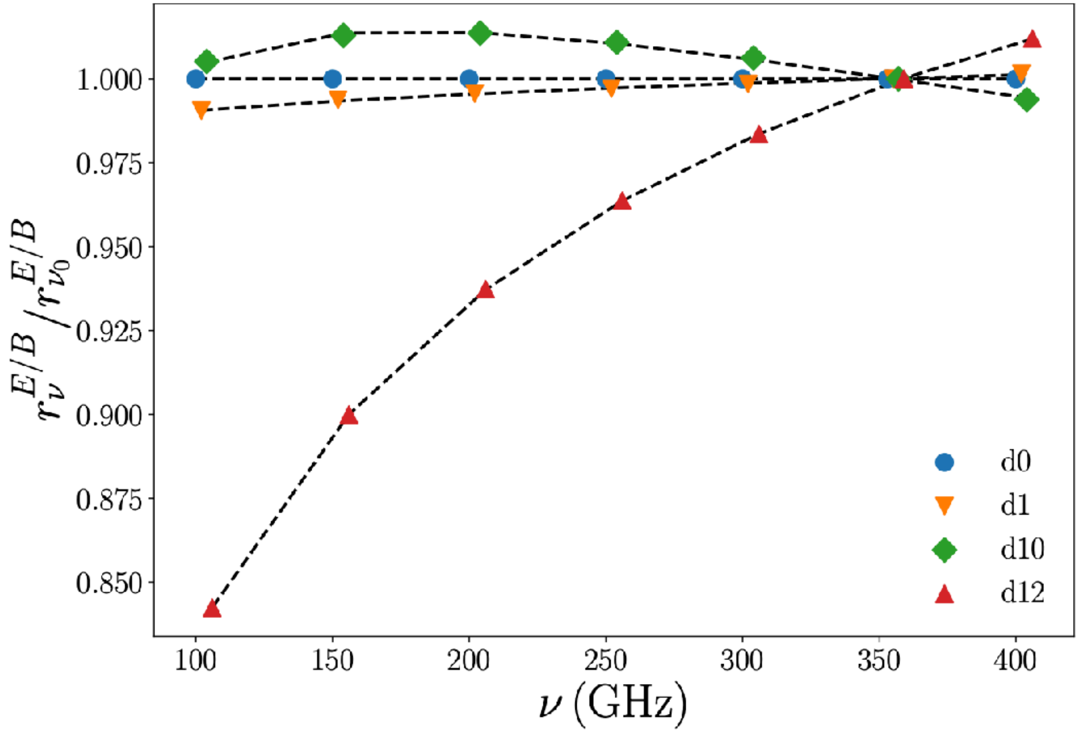


- d_0: single MBB with constant $\boldsymbol{\beta}$ and T over the sky
- d_1 : single MBB with varying $\boldsymbol{\beta}$ and T over the sky
- d_{10}: refined version of d1
- d_{12}: Six layers model with different maps of $\boldsymbol{\beta}$ and T
- Galactic mask f_{sky}=0.8 and a broad ell bin 2-200

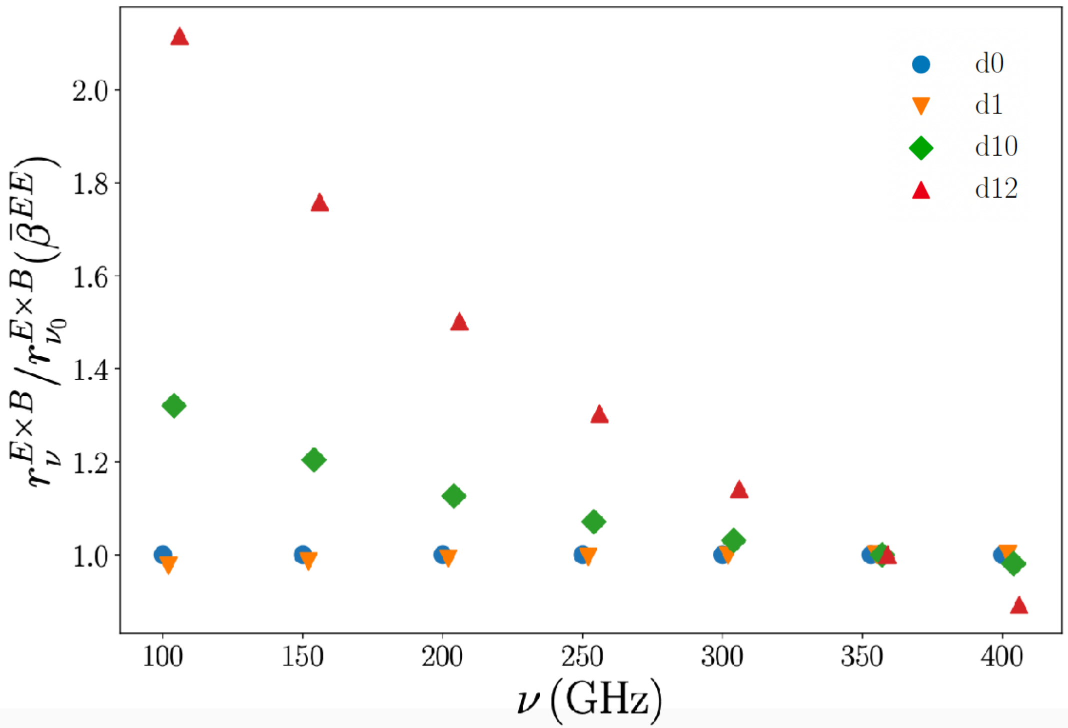
Frequency dependence observed in PySM models even in those that do not include line of sight integration

Spectral distortions from MBB

$$r_\nu^{E\times B} \equiv \frac{\mathcal{D}_\ell^{EB}}{\underbrace{\left(\varepsilon_\nu(\bar\beta,\bar T)\right)^2}_{\text{MBB}}}$$

$\bar\beta$ and $\bar T$

are fitted on EE spectra



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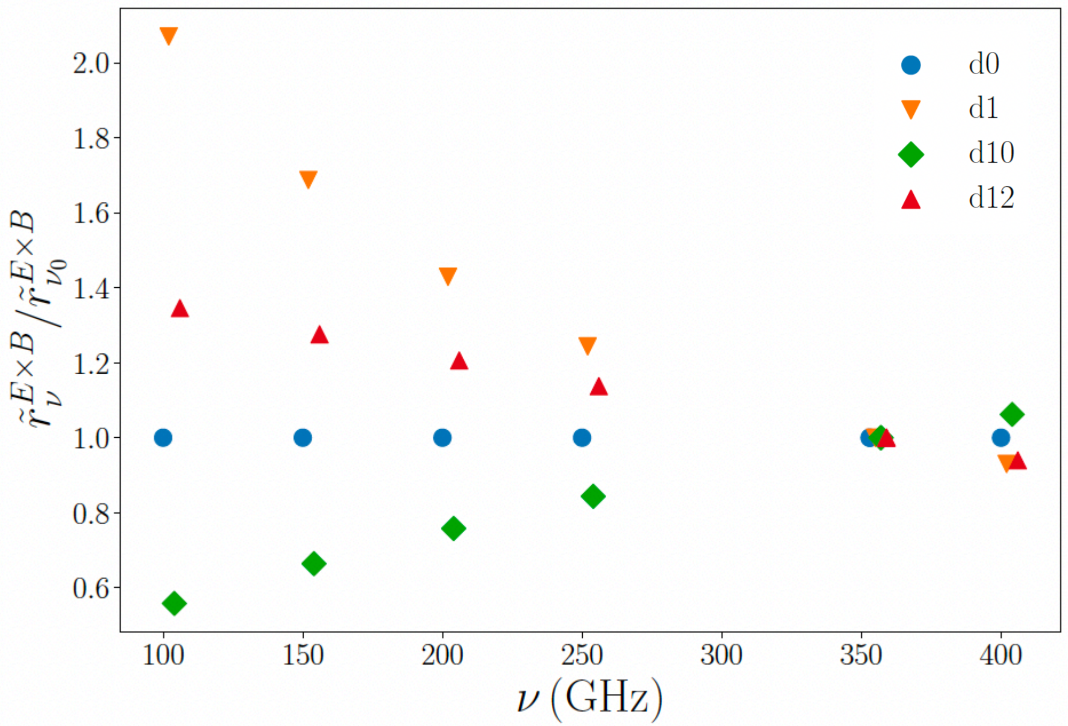
➡ Spectral dependence departs from MBB law

EB for PySM models

$$(\tilde{r}_\nu^{E\times B})_\ell = \frac{\mathcal{D}_\ell^{EB}}{\widetilde{\mathcal{D}}_\ell^{EB}}$$

$$\widetilde{\mathcal{D}}_\ell^{EB} \simeq A_\ell^{E\times B} \frac{\mathcal{D}_\ell^{EE}\mathcal{D}_\ell^{TB}}{\mathcal{D}_\ell^{TE}},$$

Clark+ 21
Diego-Palazuelos+ 22



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➡ EB dust spectrum may not be simply estimated from higher signal to noise spectra

Astrophysical questions

- Physical origin of TB signal ?
- How to estimate EB ?
- How to apply moments formalism to produce realistic models?
  - Do β or T moments dominate?
  - Do we need to consider both parameters with their interdependence?
  - How crucial are variations of dust properties between ISM phases?
- How to interpret moments analysis of observations?

Calibration requirements

- Variations of polarization angles should be correlated across frequency but we do not know a priori the frequency dependence
- We need to learn from observational data combining Planck 353 GHz maps with microwave data from ground-based experiments
- Calibration errors must be small enough to reveal the frequency coherence of dust polarization angles in the data
- Models quantifying plausible hypotheses, based on known astrophysical constraints, are needed to move forward with calibration requirements and guide/test component separation methods

Summary

- Planck data provide first evidence for frequency-dependence of polarization angles.
- These variations make EE, BB, EB, TE & TB spectra frequency-dependent in different ways.
- The moments expansion formalism provides an analytical framework to model these dependencies
- Calibration errors must be small enough to reveal the frequency coherence of dust polarization angles in observational data
- Models quantifying plausible hypotheses, based on astrophysical constraints, are needed to move forward and assess calibration requirements

Thank you