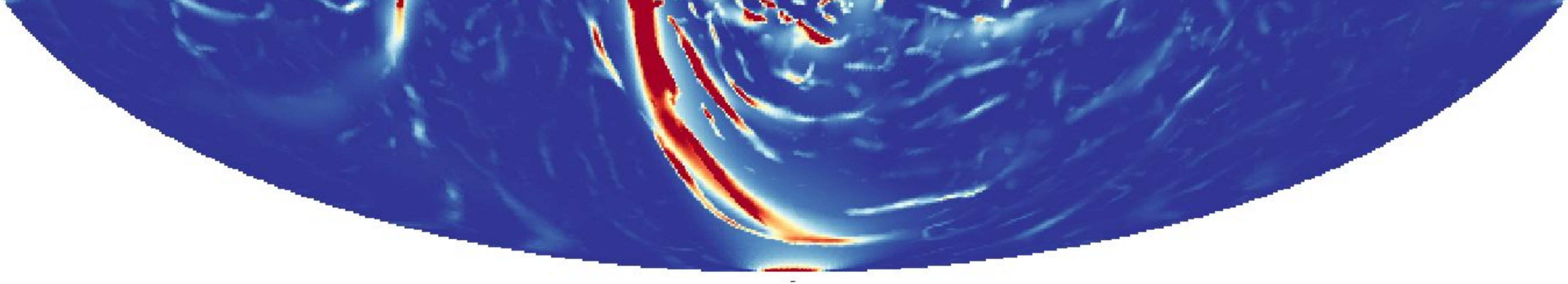


Interpreting map-based *E*/*B* spectral properties of CMB foregrounds

Applied on pol. synchrotron models (no data). First paper of a series.

arXiv:2603.02177

… & more

Gilles Weymann-Despres[1⋆], Léo Vacher[2,3], Michael E. Jones[1], Angela C. Taylor[1], Carlo Baccigalupi[2], A.J. Banday[4], Richard D.P. Grumitt[5], Nicoletta Krachmalnicoff[2].

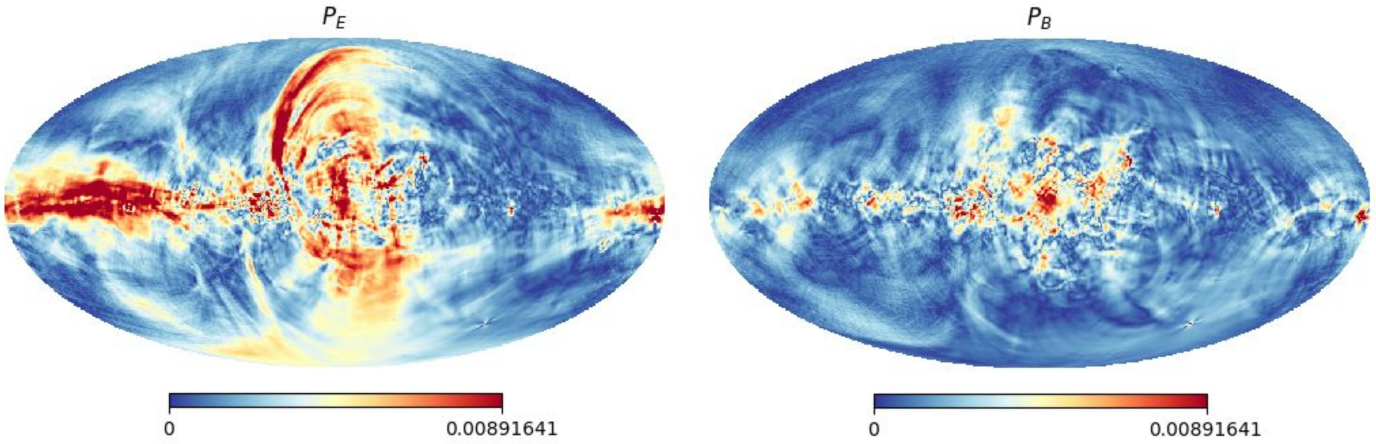
Gilles Weymann-Despres

01/04/2026

C-BASS

RADIO FOREGROUNDS+

Context & first results



For both **Galactic Science** and **CMB science**, we need analyses and modelling:

- in **map-space**,

  dust & synchrotron: *large-scale non-Gaussian* signatures,

- at **several frequencies**,

  in order to distinguish different physical origins,

- distinguishing between ***E*** ( ) and ***B*** ( ) patterns

  In "optimal analyses", *B* modes should be *the* contaminant for *r* seaches,
  E and *B* patterns are expected from different physical sources.

How to combine all those?

[log & LIC](P)

Pol. synchrotron by C-BASS & S-PASS

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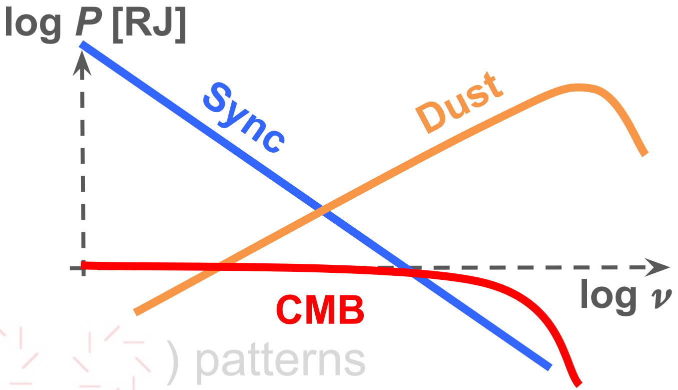

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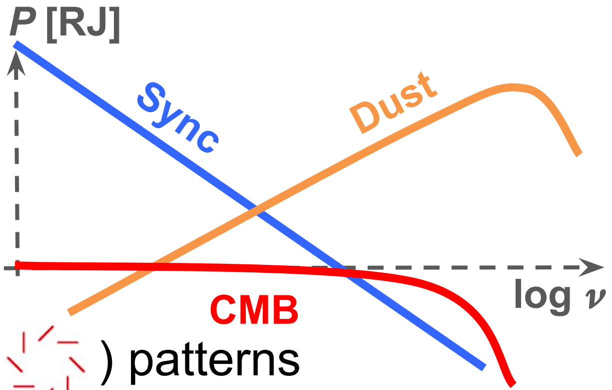

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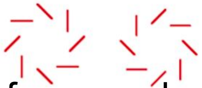
- distinguishing between ***E*** () and ***B*** () patterns
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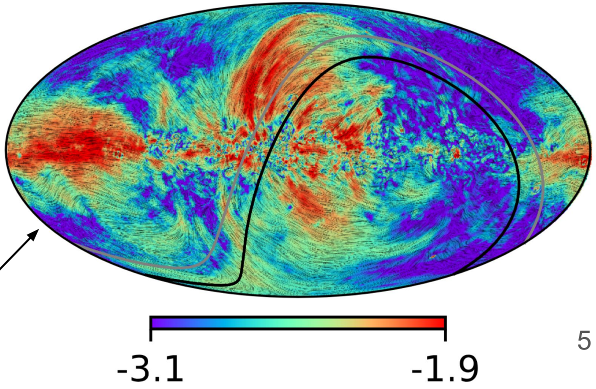

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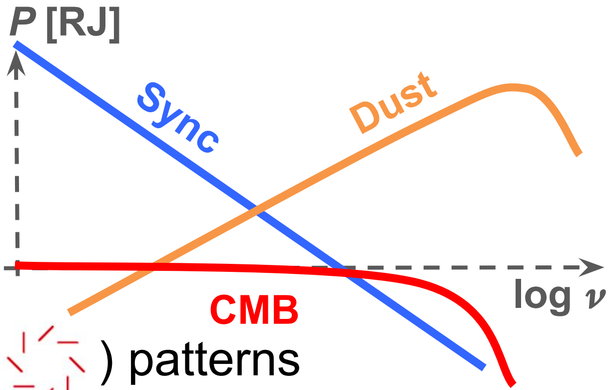

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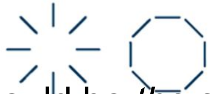
- distinguishing between ***E*** () and ***B*** () patterns

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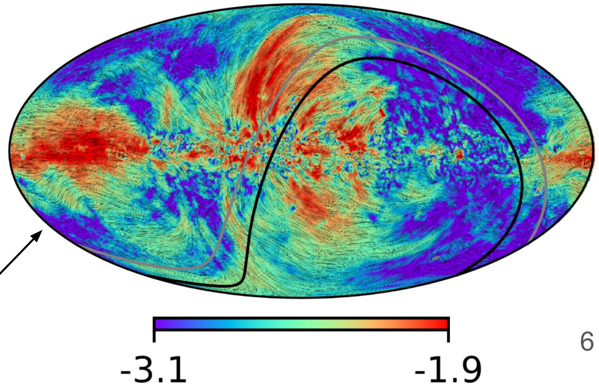

Pol. synchrotron by C-BASS & S-PASS

Spin-2 polarization field:

$$\mathcal{P}_{ab}(\mathbf{n}) = \frac{1}{\sqrt{2}}\begin{pmatrix} Q & U \\ U & -Q \end{pmatrix}(\mathbf{n}) = \frac{P(\mathbf{n})}{\sqrt{2}}\begin{pmatrix} \cos 2\psi & \sin 2\psi \\ \sin 2\psi & -\cos 2\psi \end{pmatrix}(\mathbf{n})$$

Ways to decompose it into ***E*** **and** ***B*** **modes**: into **spin-0** or **spin-2 fields**.

Concrete implementation:

$$\{I, Q, U\} \xrightarrow{\text{map2alm}} \{a^I_{\ell m}, a^E_{\ell m}, a^B_{\ell m}\},$$

$$\{E, Q_E, U_E\} \xleftarrow{\text{alm2map}} \{a^E_{\ell m}, a^E_{\ell m}, 0\},$$

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Spin-2 decompositions:

1) Easy to **interpret** and **manipulate in ℂ**:

$$P_E = \sqrt{Q_E^2 + U_E^2}$$

$$P_B = \sqrt{Q_B^2 + U_B^2}$$

$$\psi_E = \tfrac{1}{2}\arctan(U_E/Q_E)$$

$$\psi_B = \tfrac{1}{2}\arctan(U_B/Q_B)$$

$$\underline{P} \equiv Q + i\,U$$

$$\underline{S} \equiv E + i\,B$$

2) **Nice properties**: $\underline{L_E}$ and $\underline{L_B}$ are ***linear projectors*** that are ***orthogonal***.

In particular,

$$\mathcal{P}_{ab}(\mathbf{n}) = \mathcal{P}^{(E)}_{ab}(\mathbf{n}) + \mathcal{P}^{(B)}_{ab}(\mathbf{n})$$

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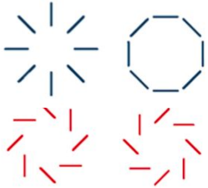

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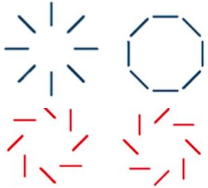

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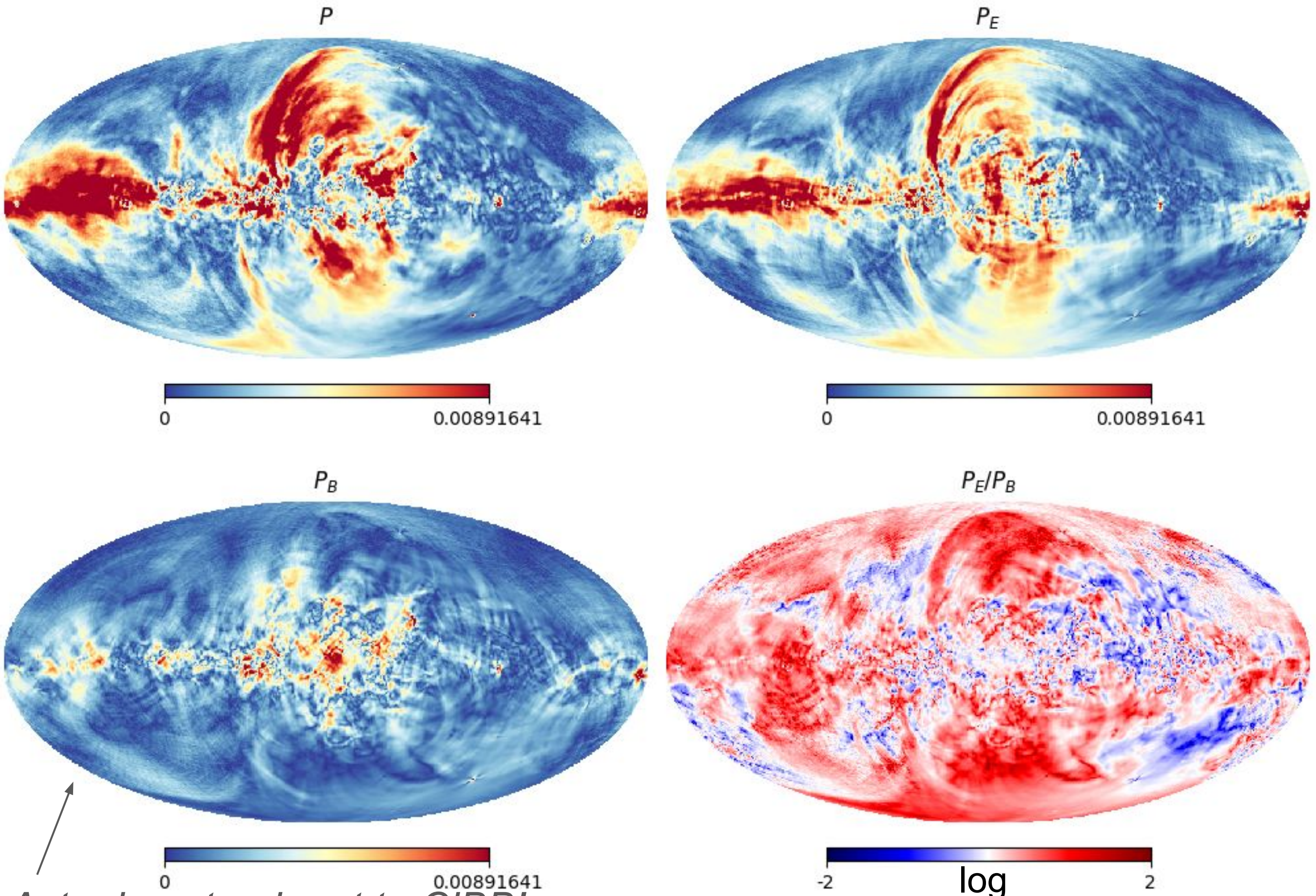
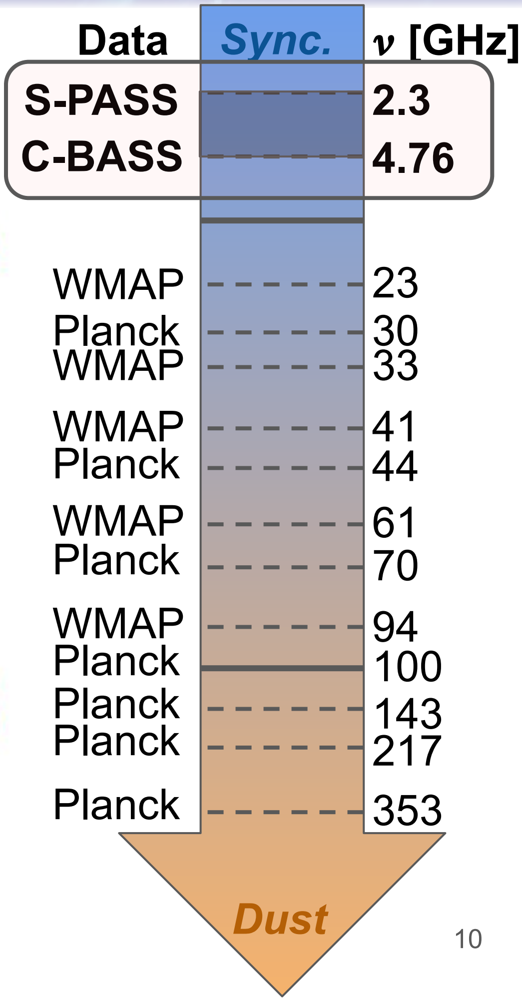


Actual contaminant to CIBB!



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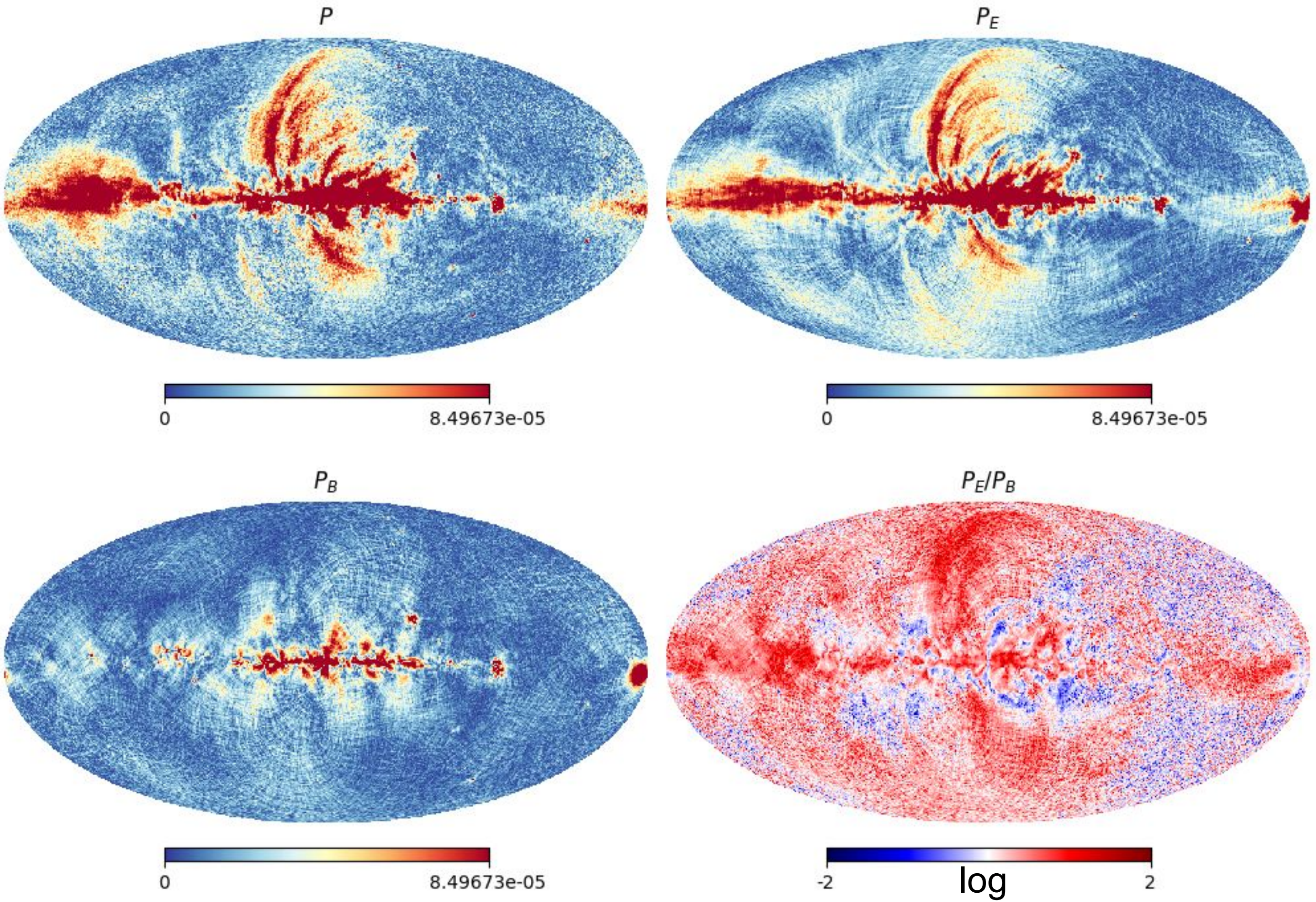

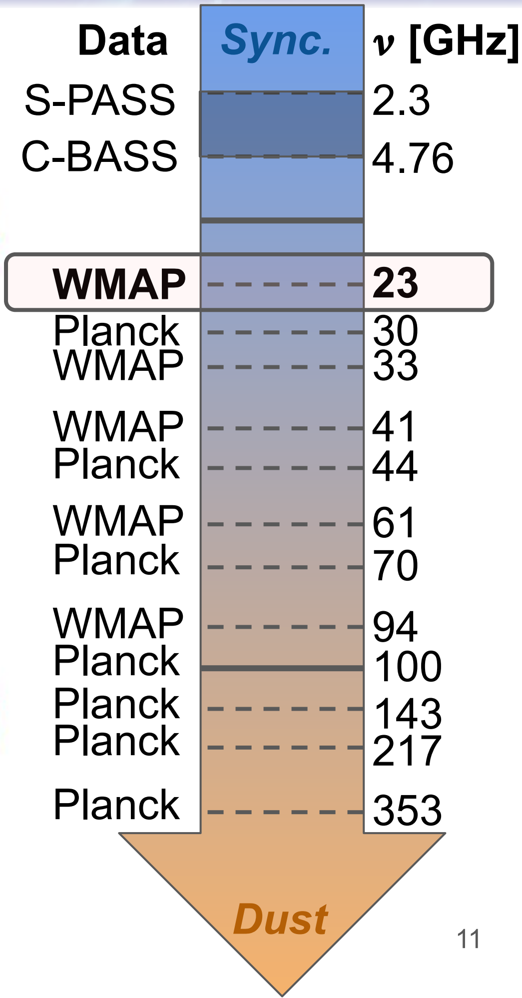

Context

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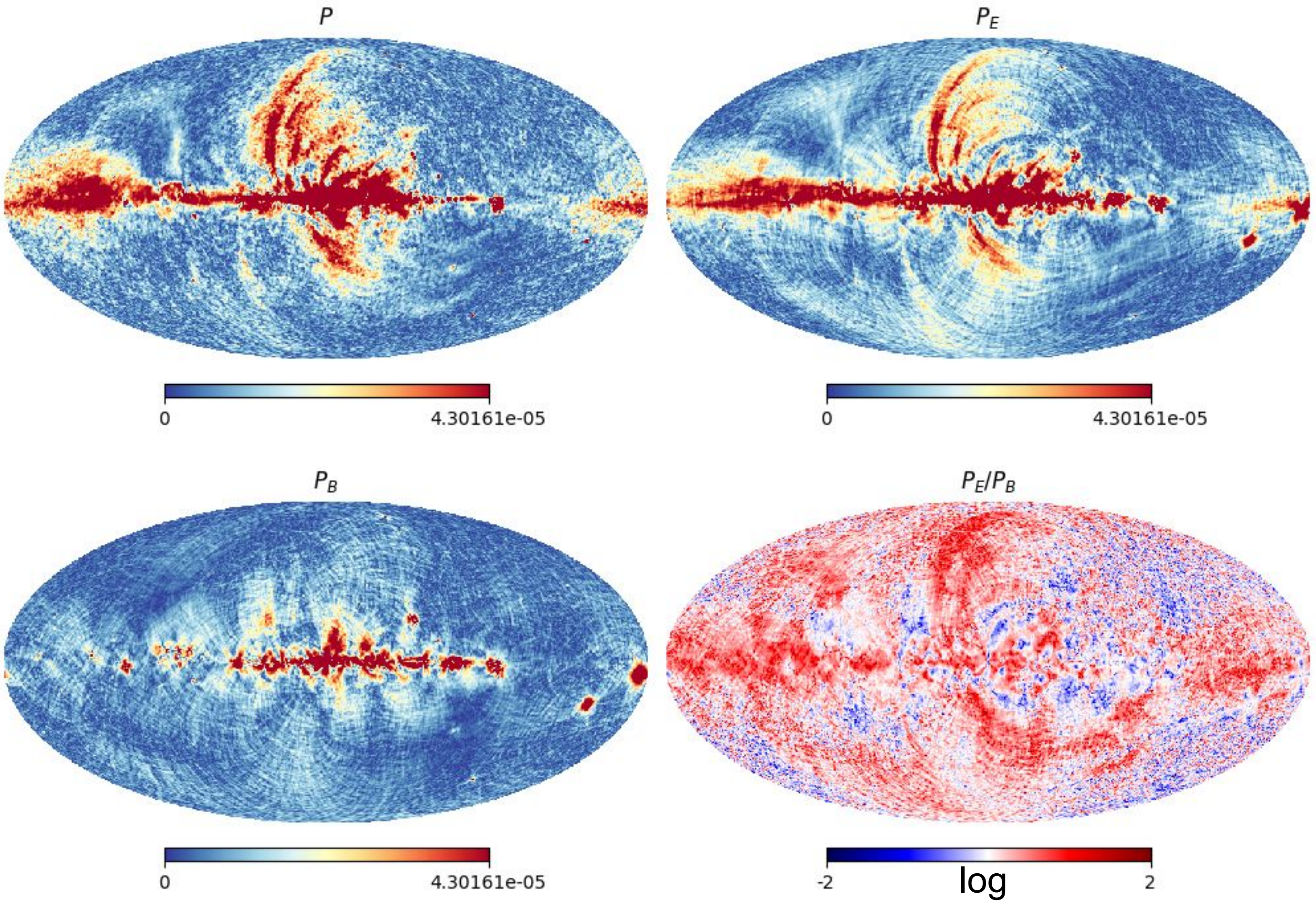

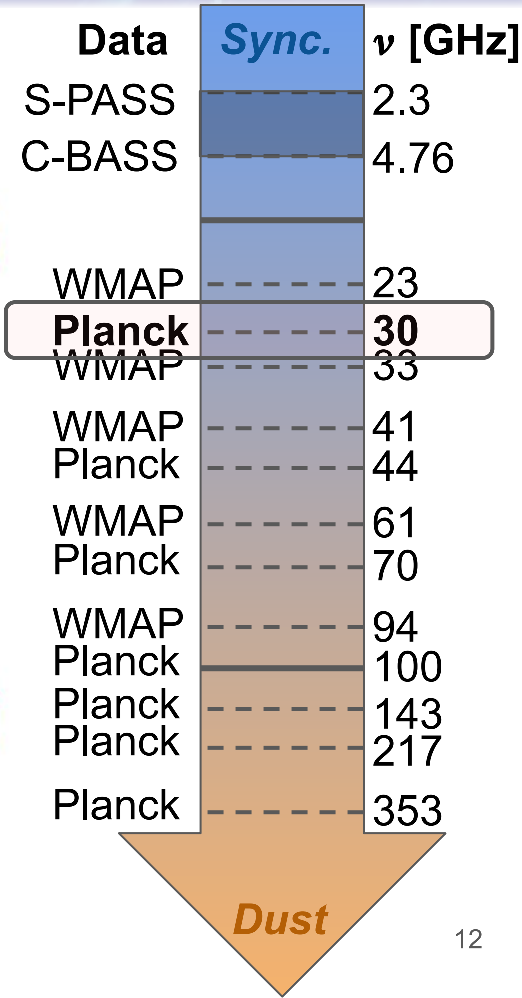

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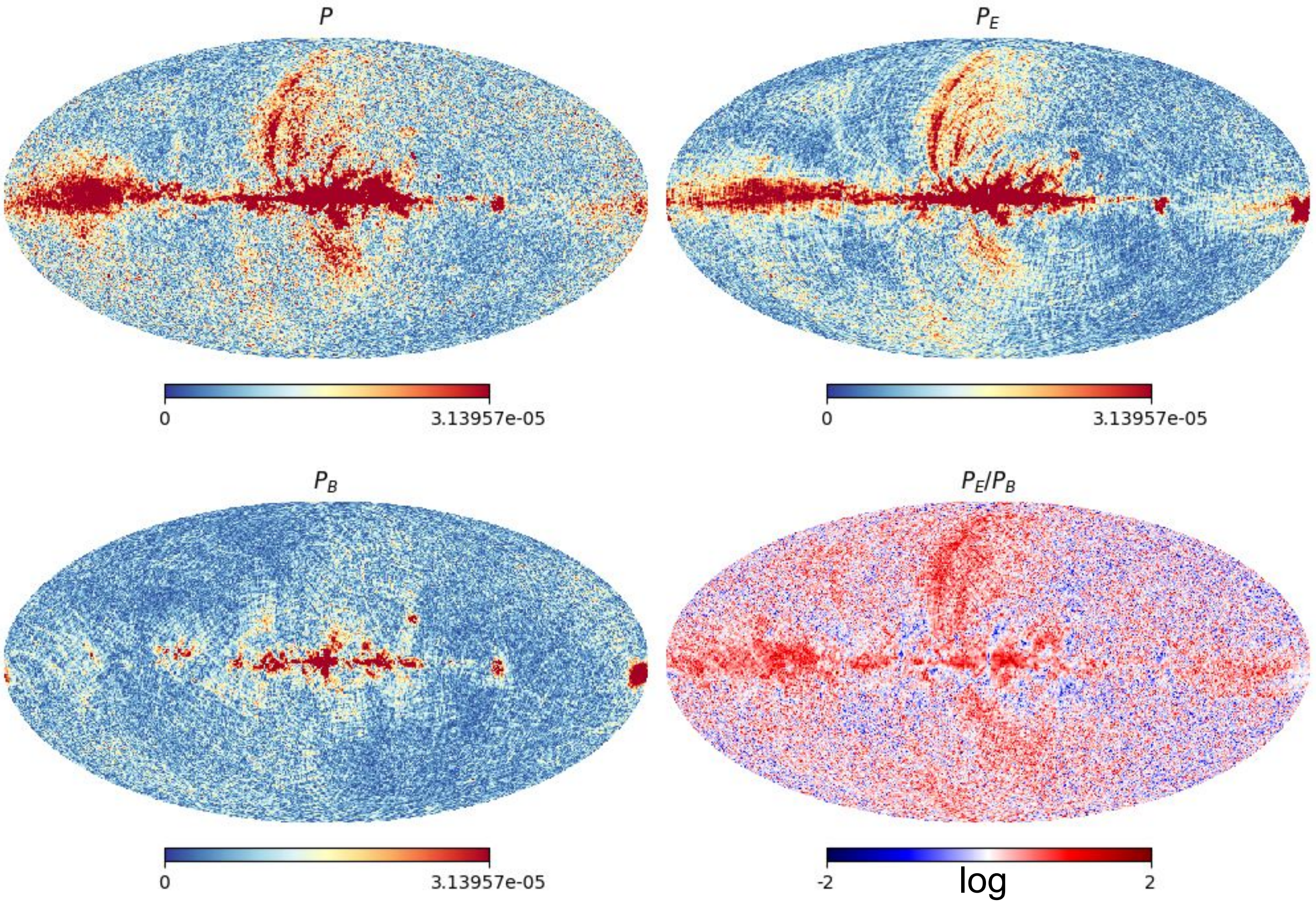

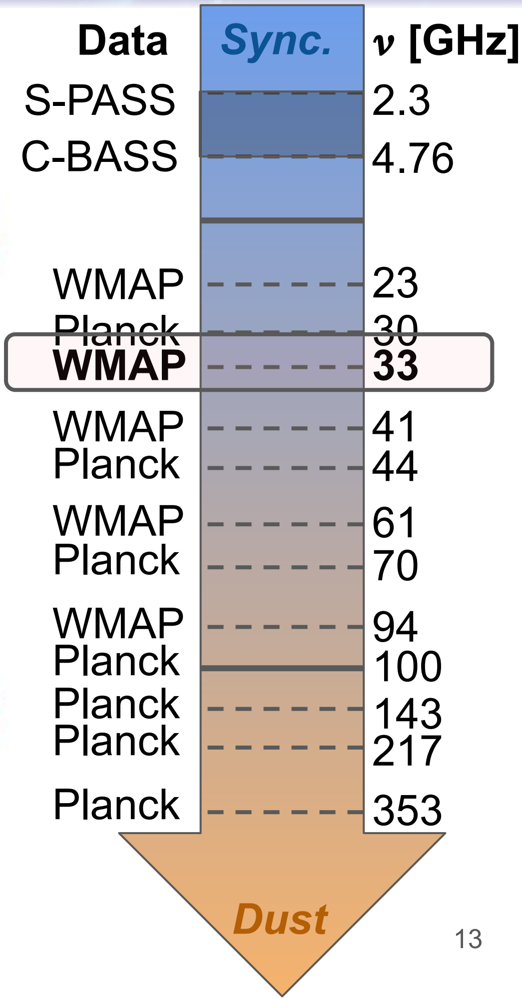

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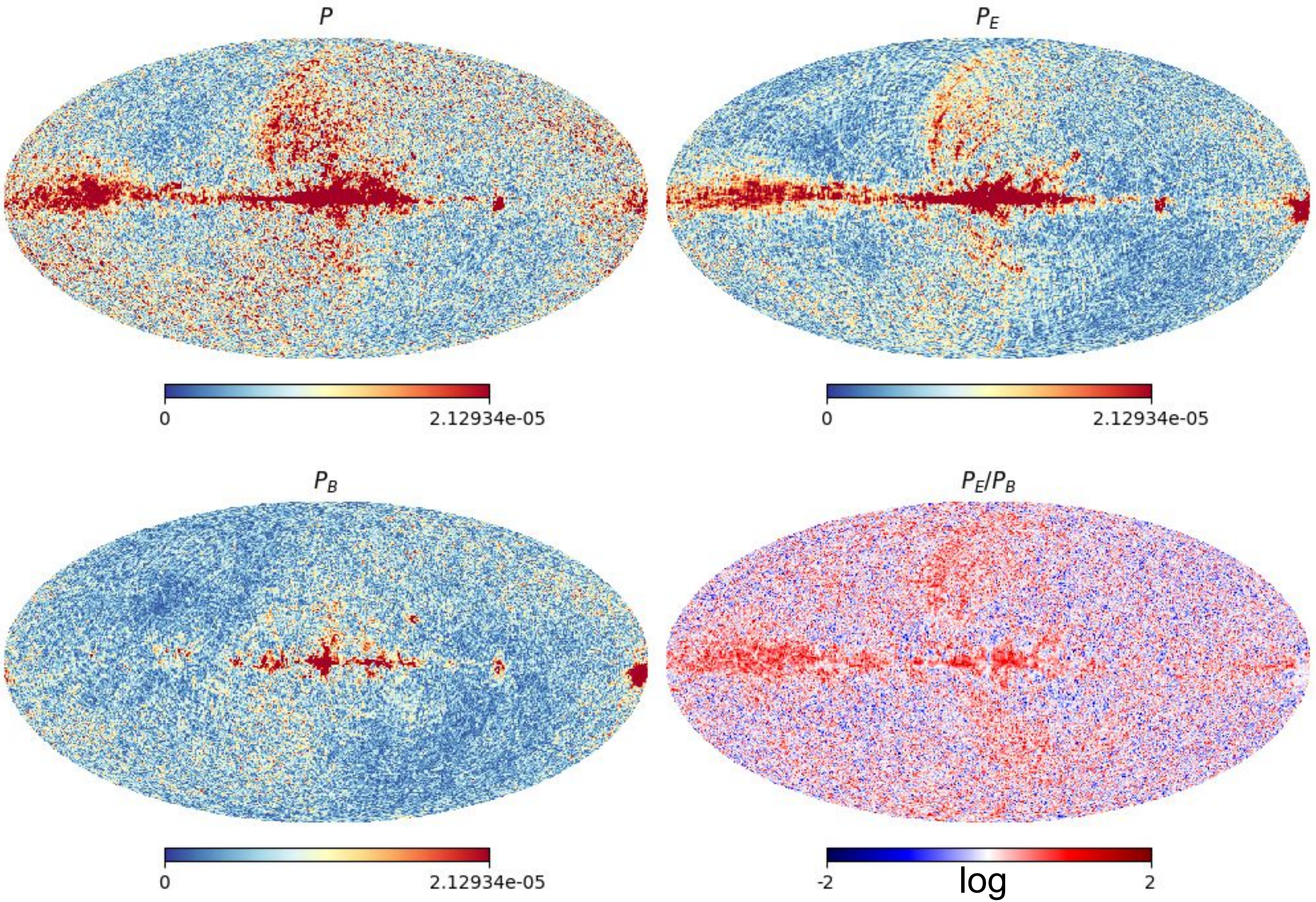

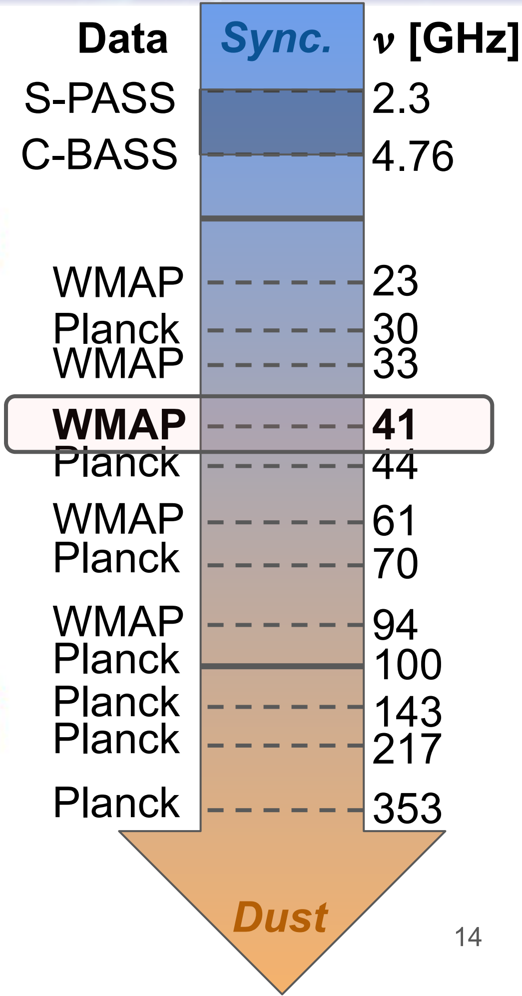

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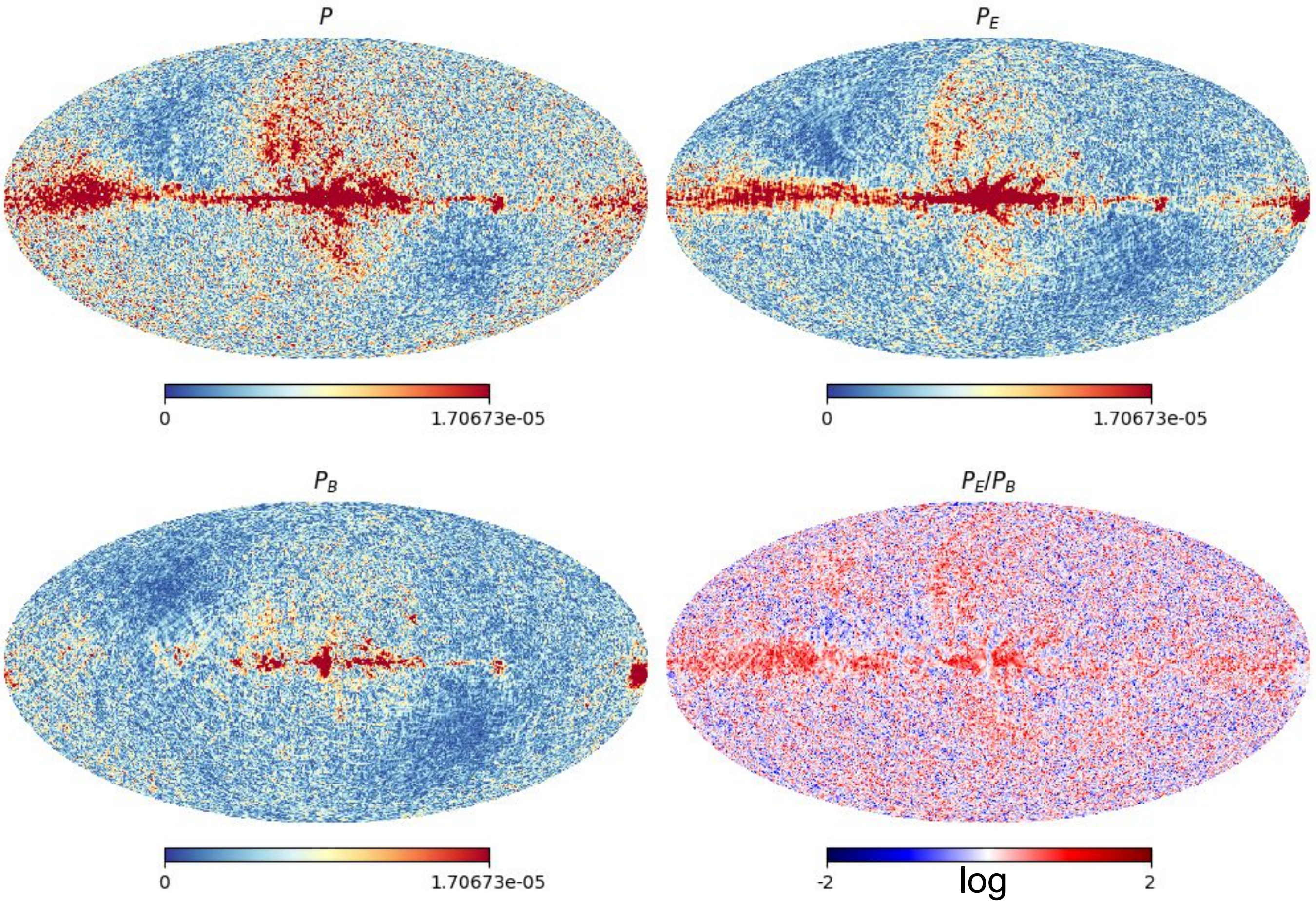

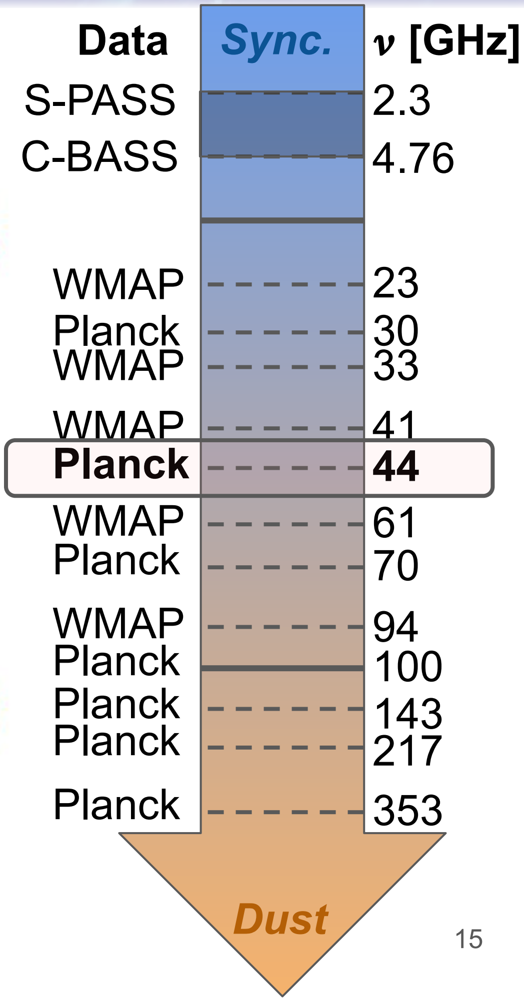

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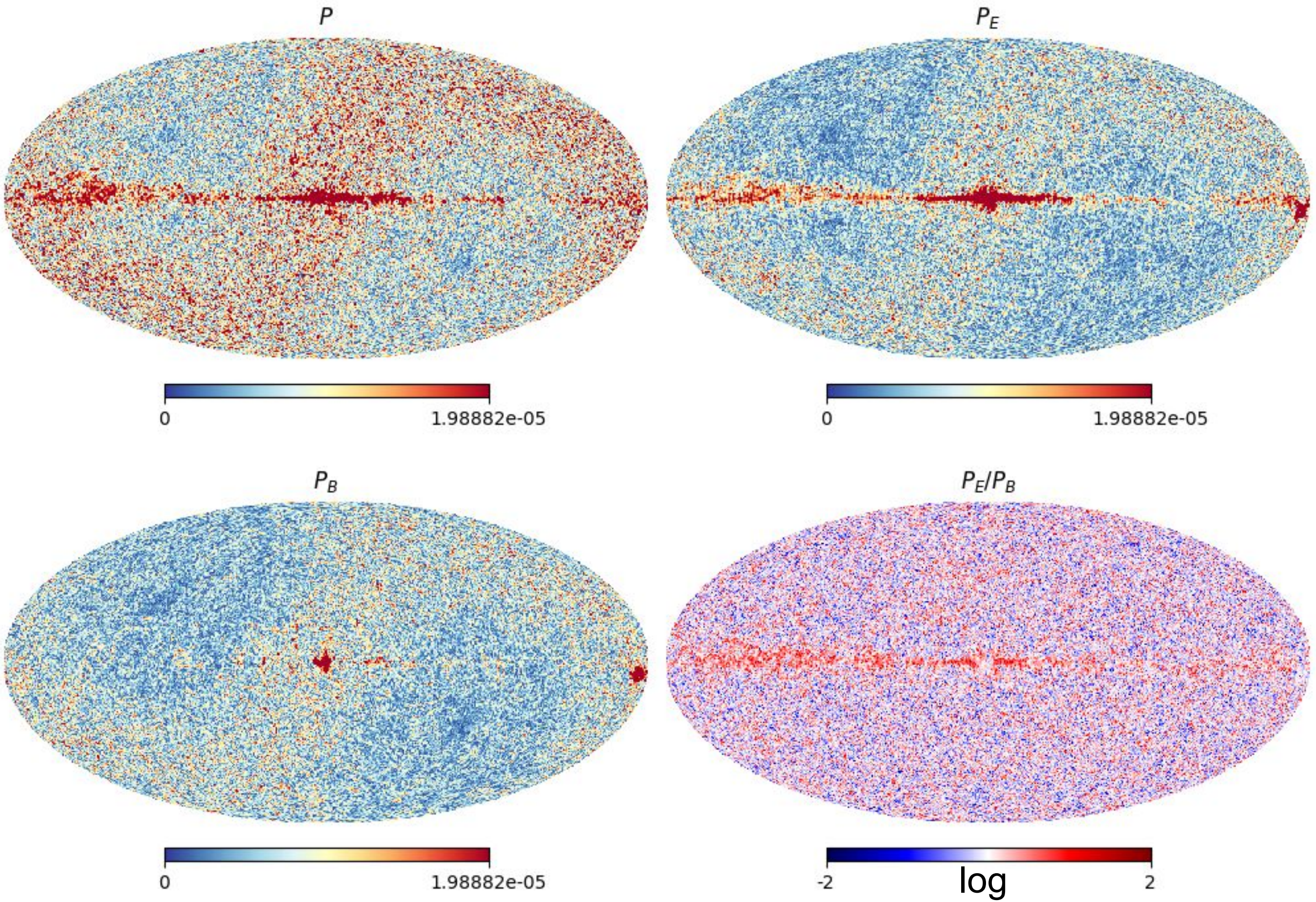

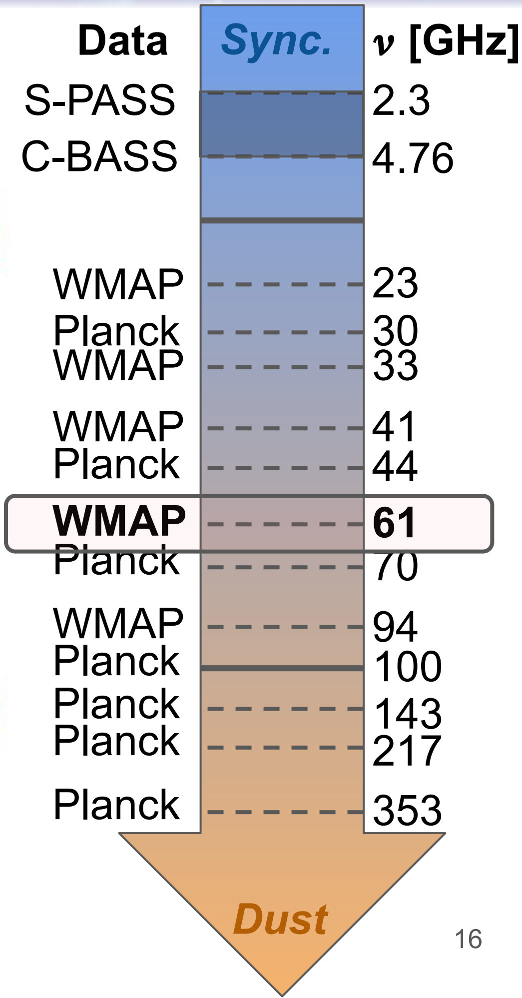

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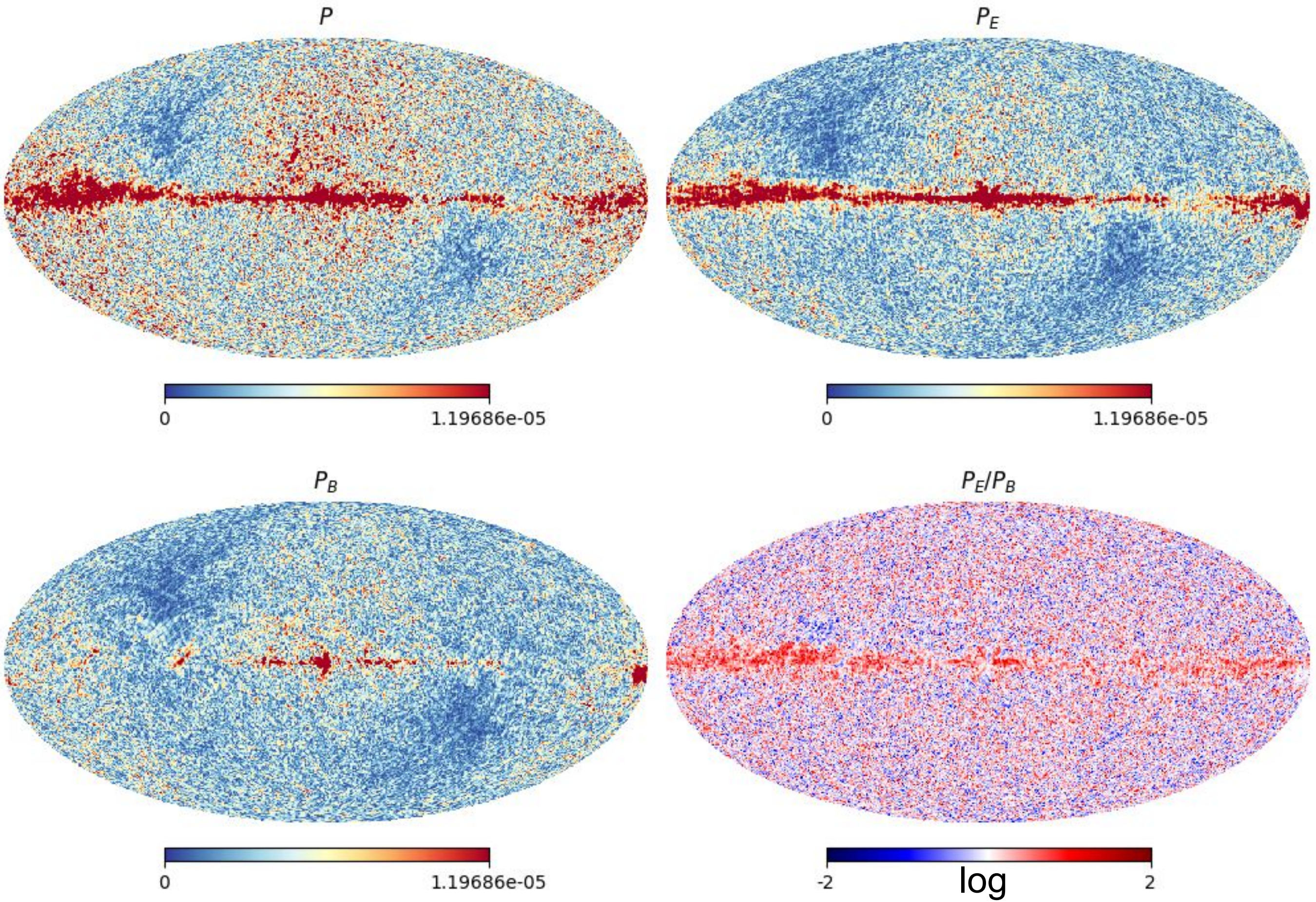

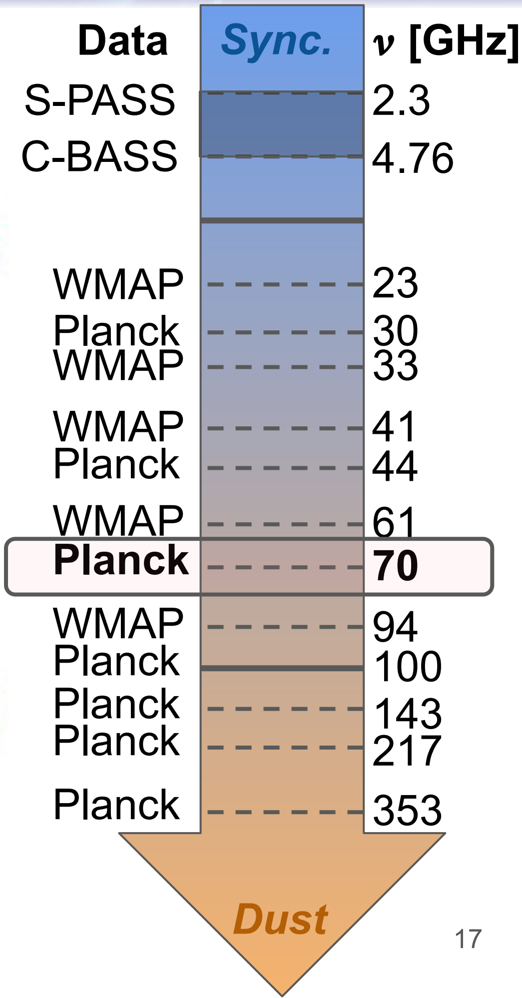

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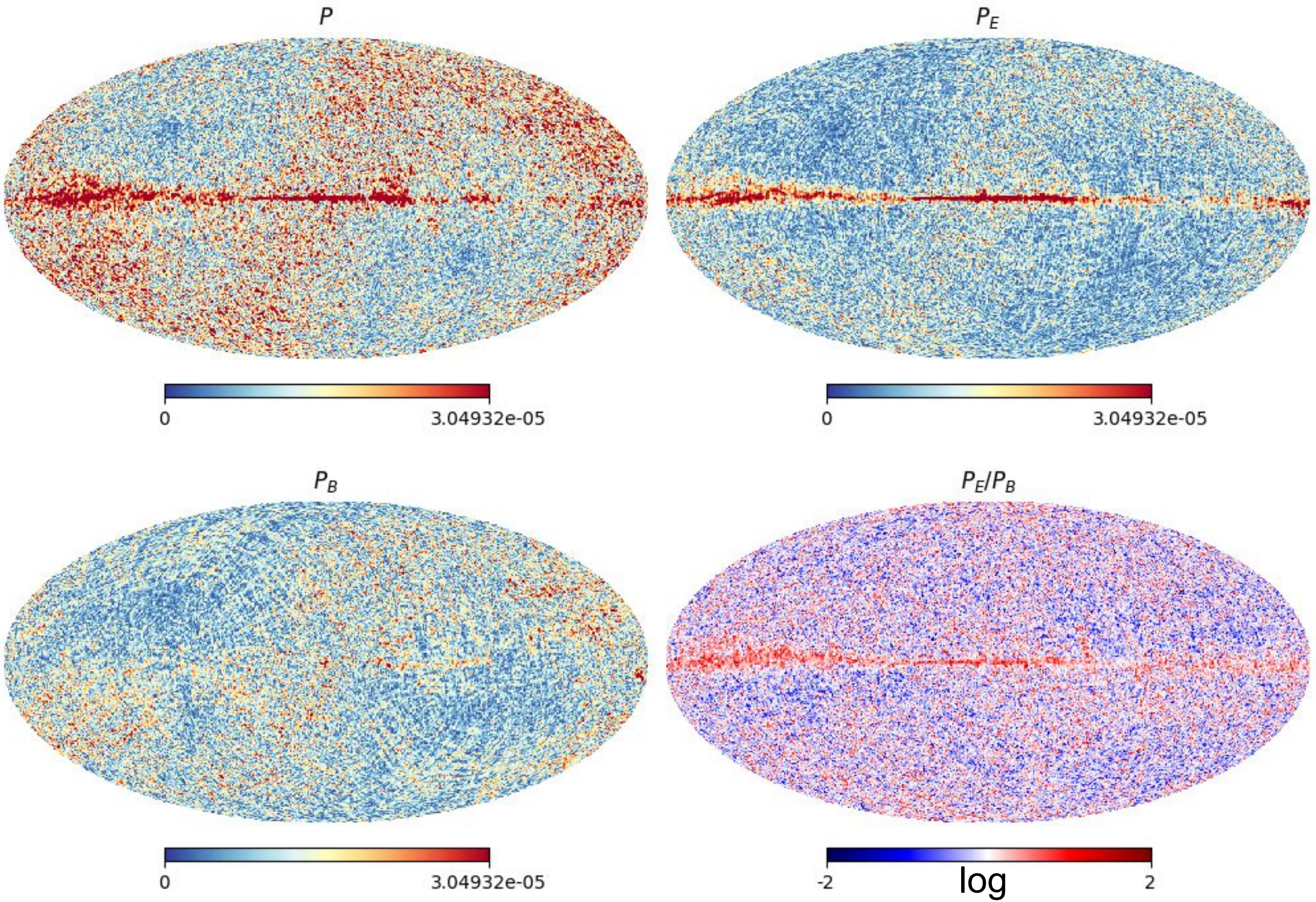

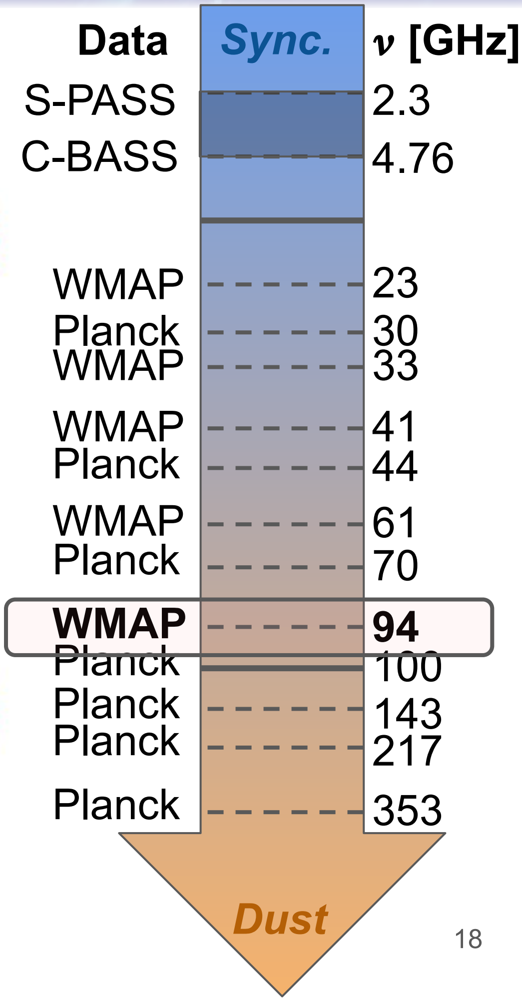

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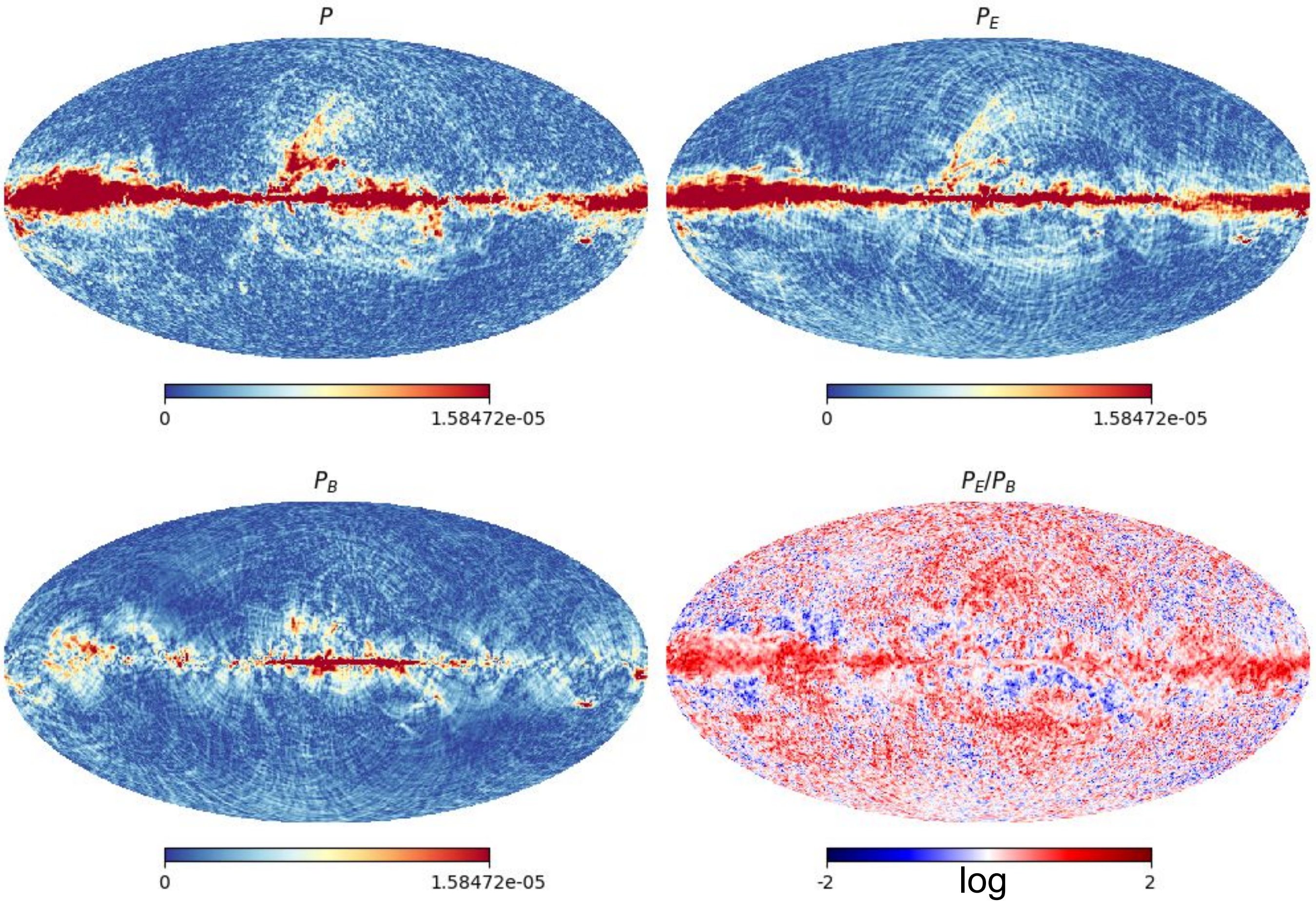

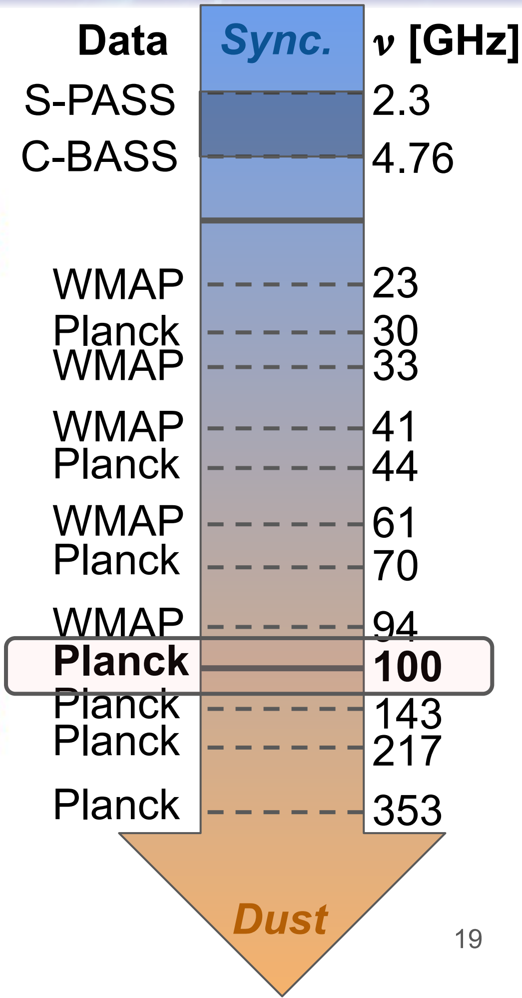

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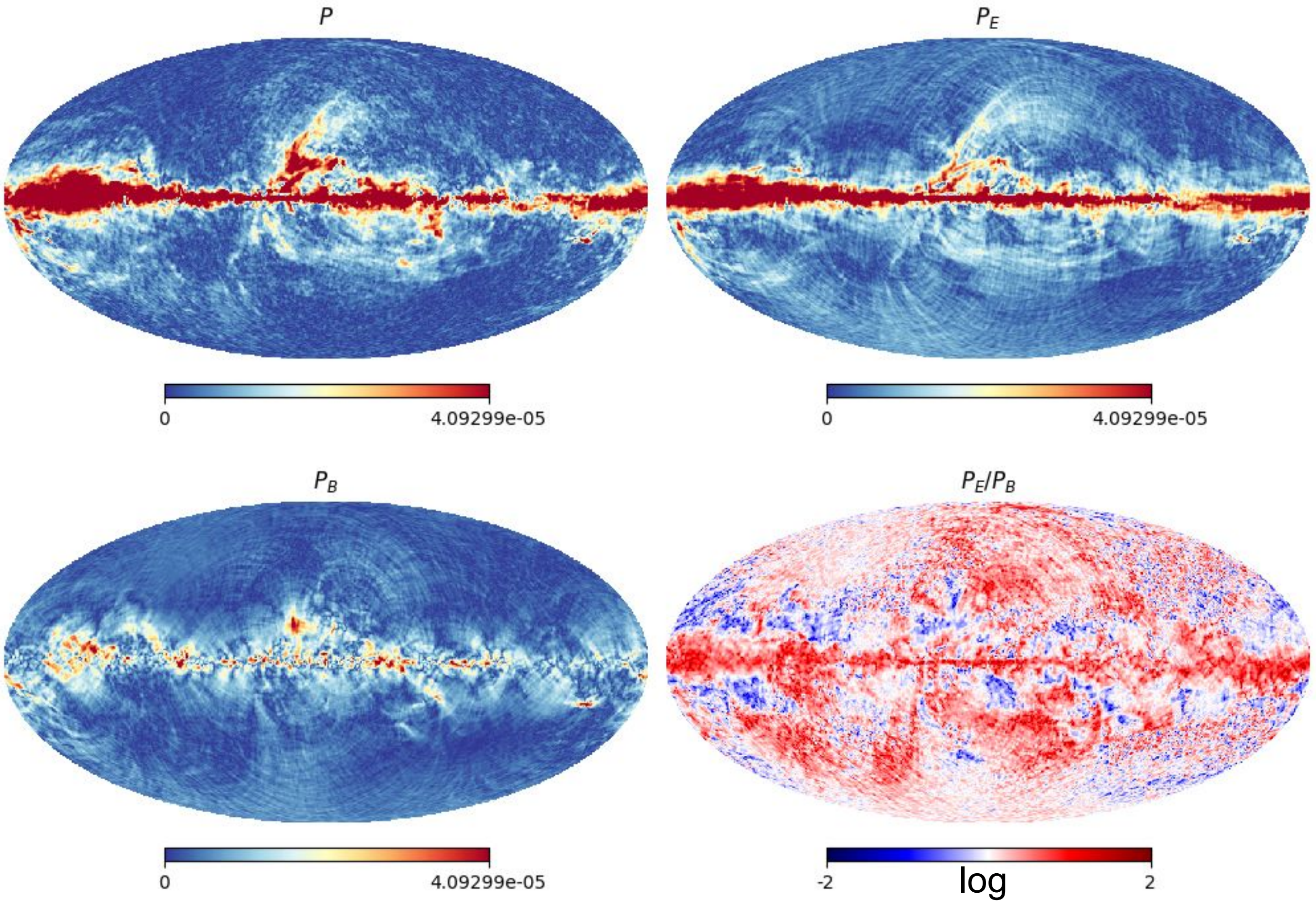

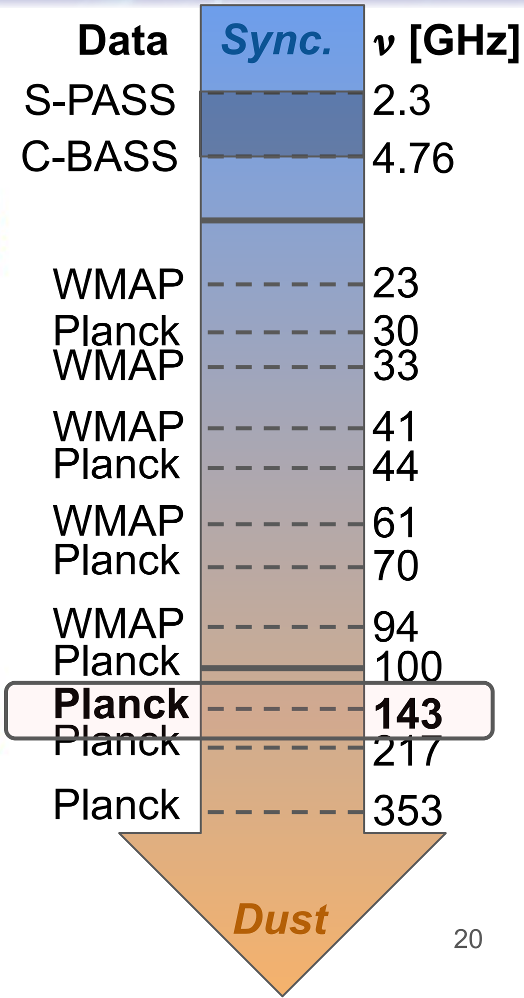

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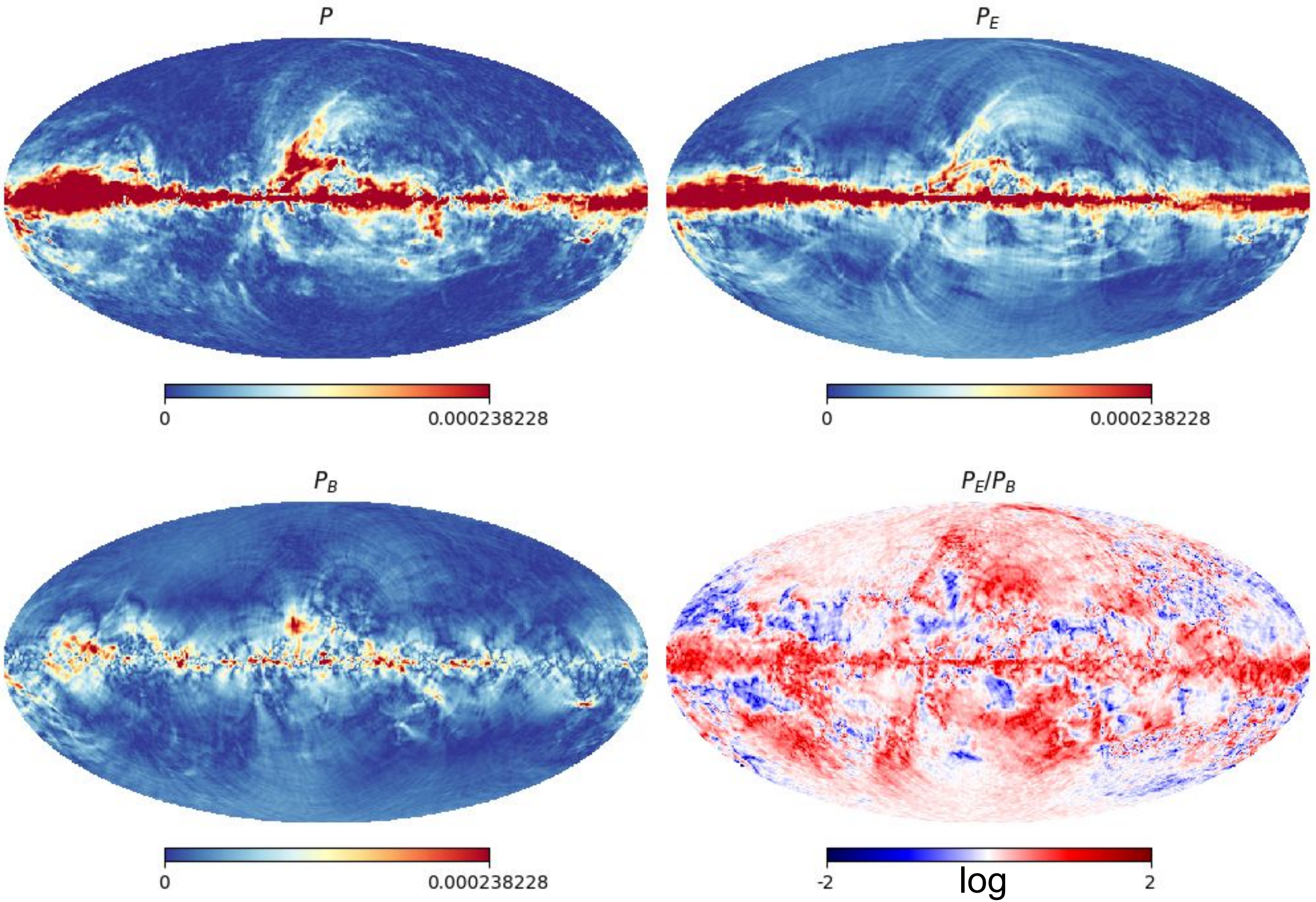

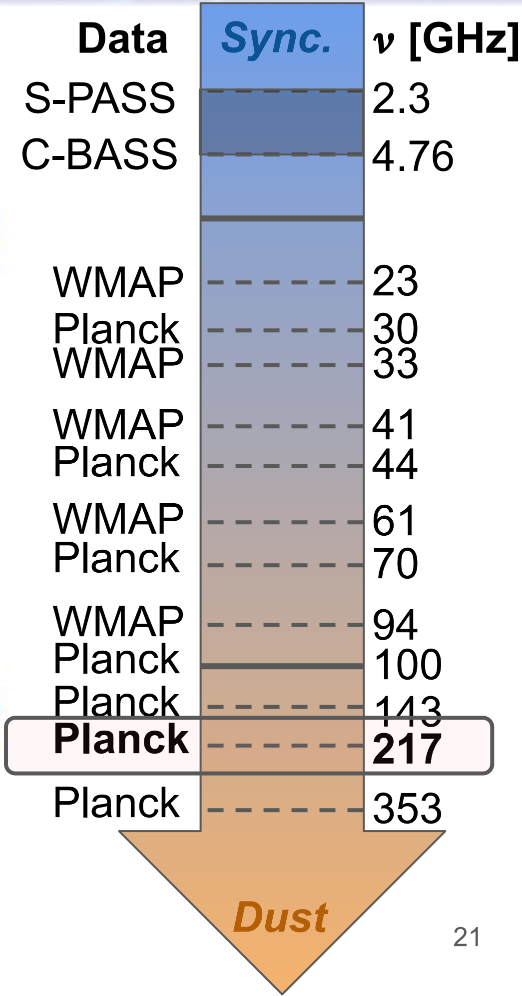

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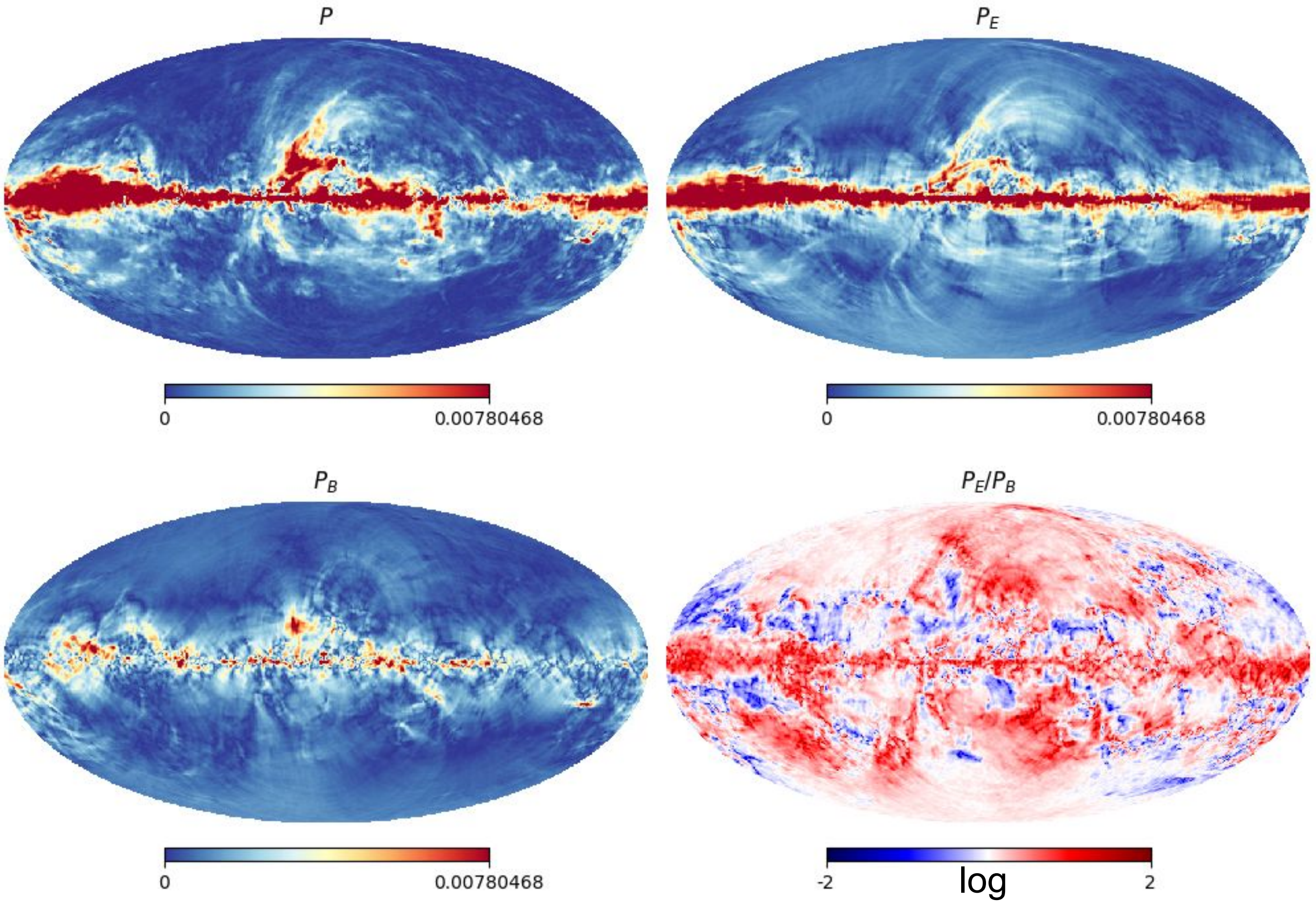

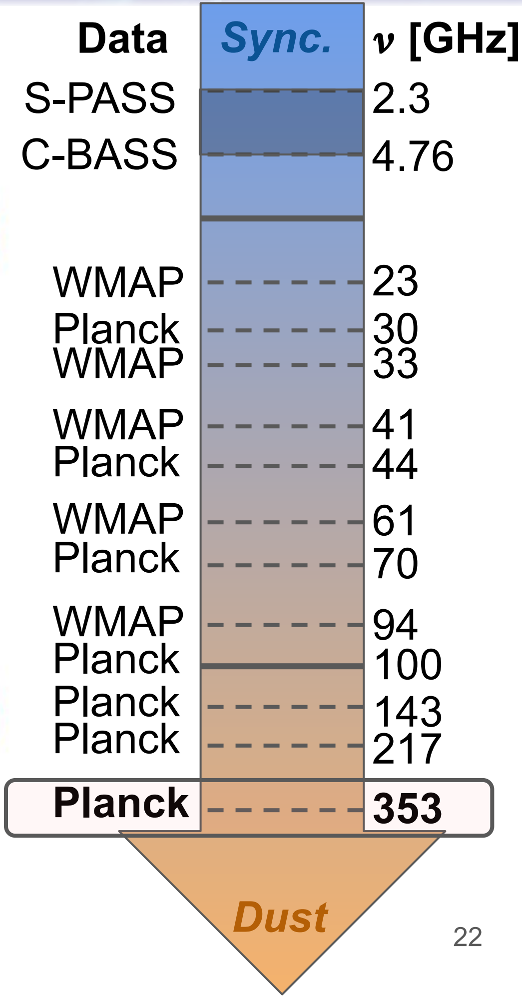

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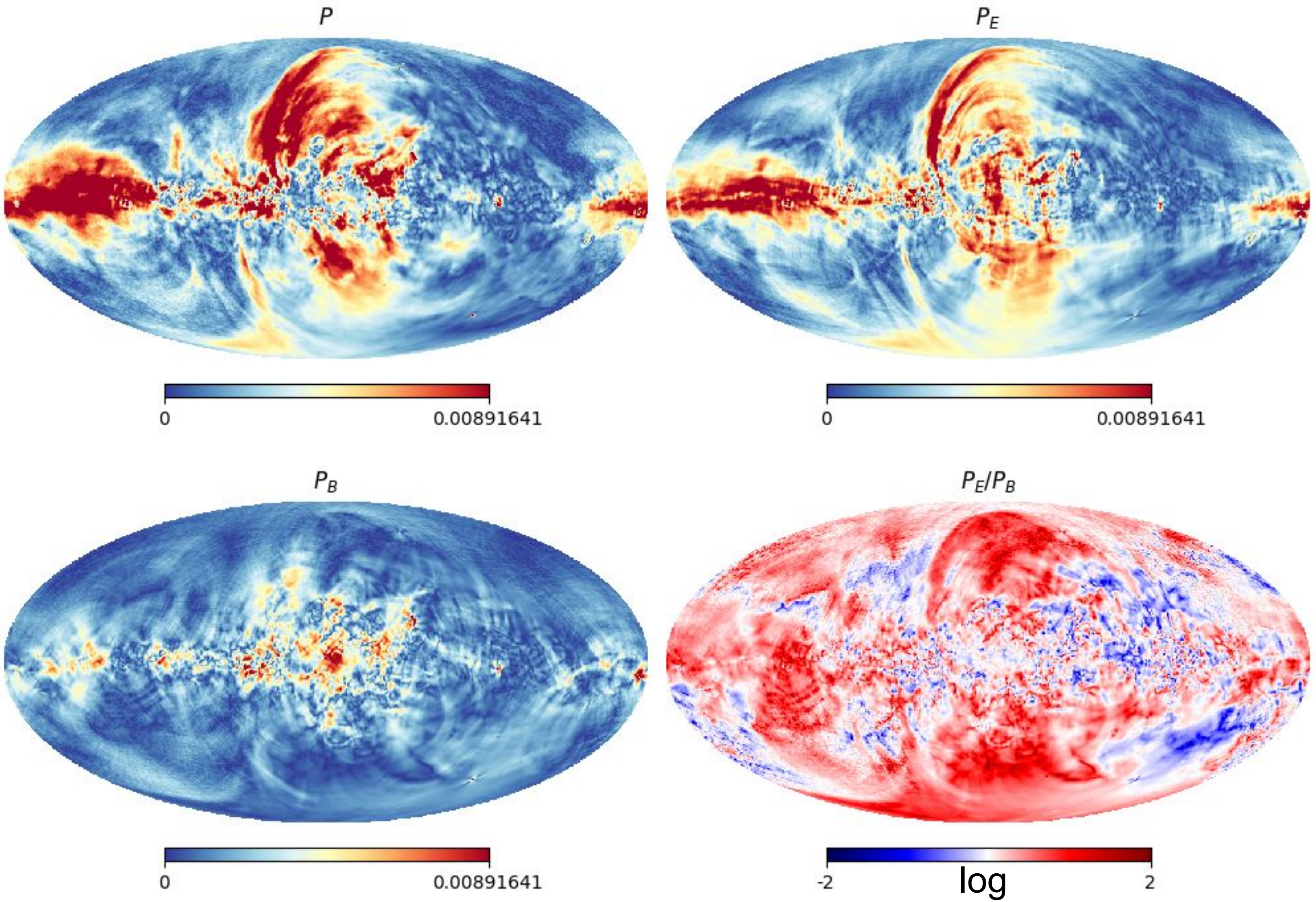
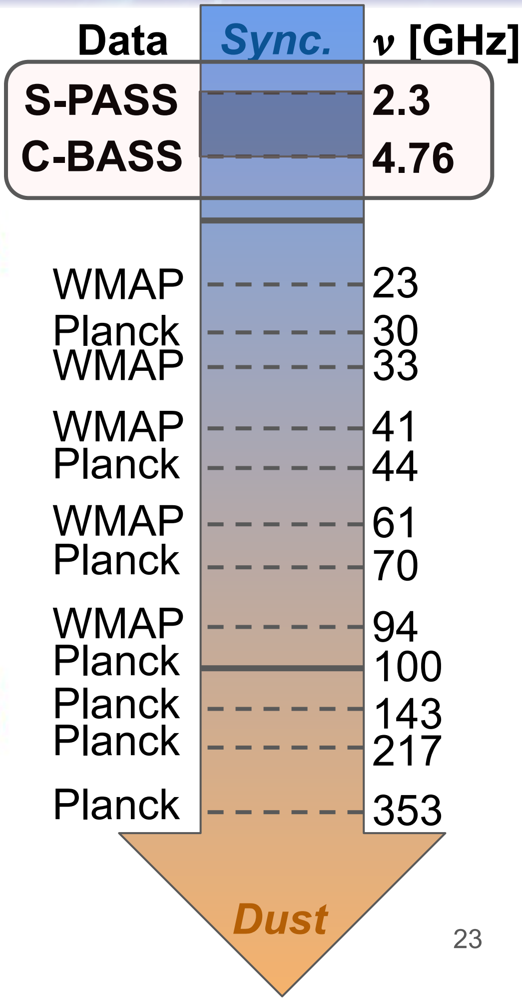




What is the *spectral complexity* in each field?

Angle stability, order in spectral expansions…

- **in** ***P***?
- **Additional spectral complexity in P_E & P_B?**
    - Should we **model** ***P*** or P_E **&** P_B? In which contexts?
    - What field characterizes best **Galactic structures**?
      … is simpler to **extrapolate to CMB frequencies**?
    - Do we prefer to model complex fields **spin-2** $\underline{P}_E$ **&** $\underline{P}_B$ or real **spin-0 |*E*| and |*B*|**?
    - We need an **SED beyond rigid-angle power-law** (for sync).
      Which one to go for?

Complex moments

around uniform rigid-angle power law:

$$s \equiv \log\left(\frac{\nu}{\nu_0}\right)$$

$$\underline{X}_\nu = \left(\frac{\nu}{\nu_0}\right)^{\overline{\beta}} \left(\underline{w}_0 + \underline{w}_1 s + \frac{\underline{w}_2}{2} s^2 + \cdots\right)$$

Since $\underline{P}_\nu = \underline{P}_{E,\nu} + \underline{P}_{B,\nu}$

$$\underline{w}_{n,E} = \underline{L}_E[\underline{w}_n], \qquad \underline{w}_{n,B} = \underline{L}_B[\underline{w}_n],$$

$$\underline{w}_n = \underline{w}_{n,E} + \underline{w}_{n,B}$$

Complex log-Taylor

$$\underline{X}_\nu = \underline{A}\exp\left(\underline{\beta}\, s + \tfrac{1}{2}\underline{\gamma}\, s^2 + \cdots\right)$$

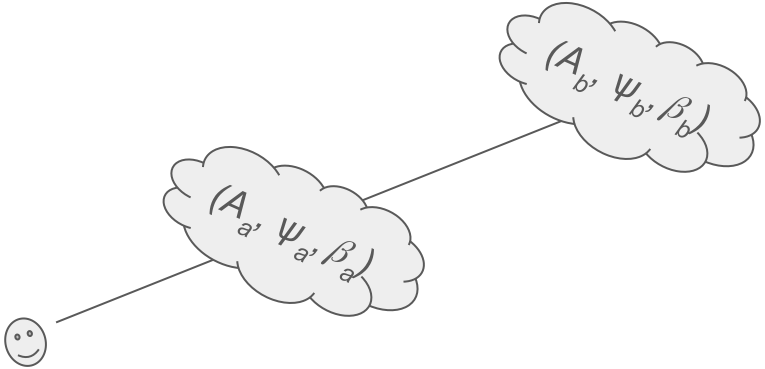
Asymptotically equivalent:

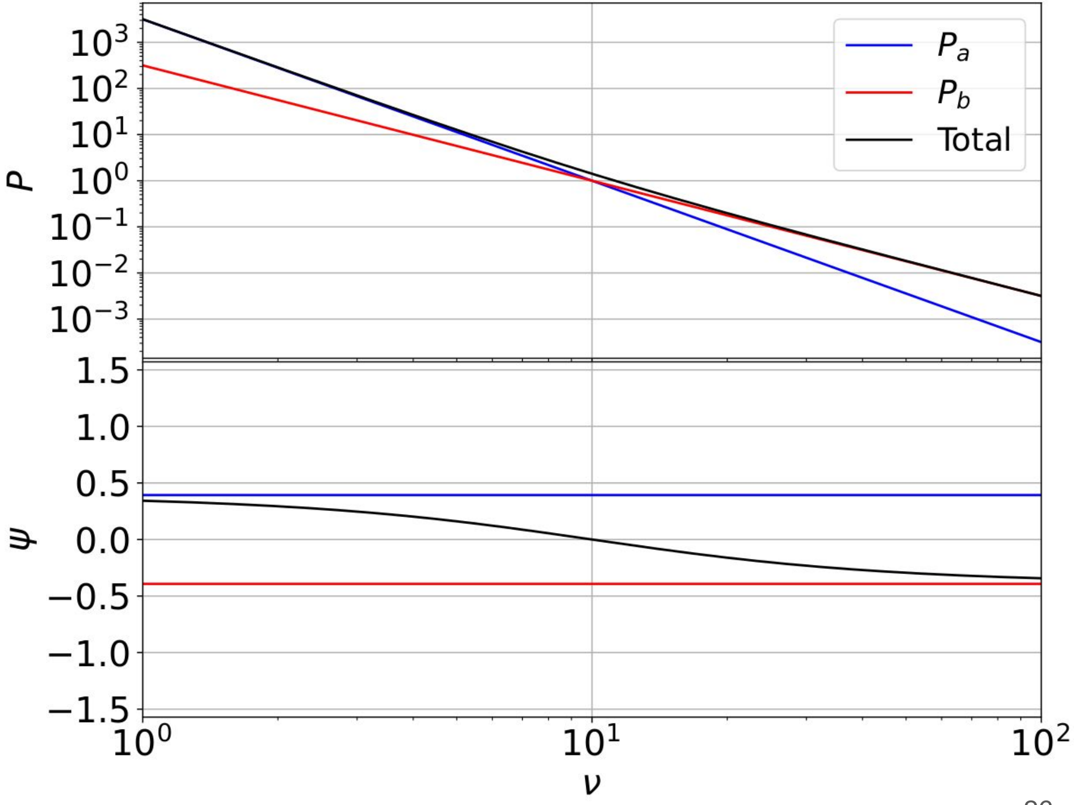
$$\begin{cases} \underline{A} = \underline{w}_0, \\ \underline{\beta} = \overline{\beta} + \dfrac{\underline{w}_1}{\underline{w}_0}, \\ \underline{\gamma} = \dfrac{\underline{w}_2}{\underline{w}_0} - \left(\dfrac{\underline{w}_1}{\underline{w}_0}\right)^2. \end{cases}$$

Next sections: focus on synchrotron focus.
At 0-th order, we expect a **rigid-angle power-law in each LoS**.

Derivation of a **general formula** that, from a modification to a uniform rigid-angle power law $\underline{P}$, allows to **predict moments and log-Taylor parameters**.

<u>Effect 1</u>: line-of-sight superimposition





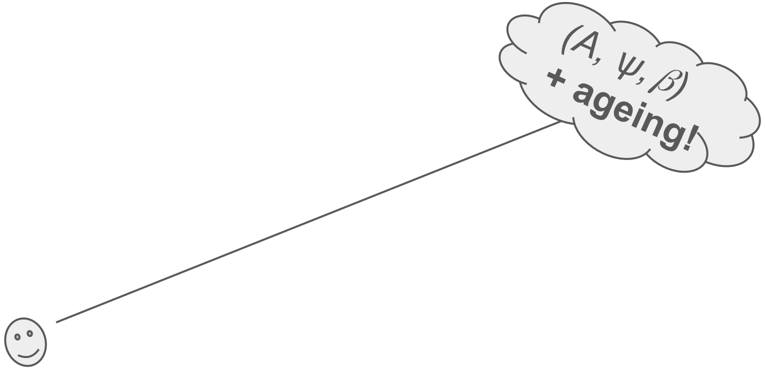
That induce **curvature** and **angle-evolution** (and also ***E* / *B* redistribution**!)

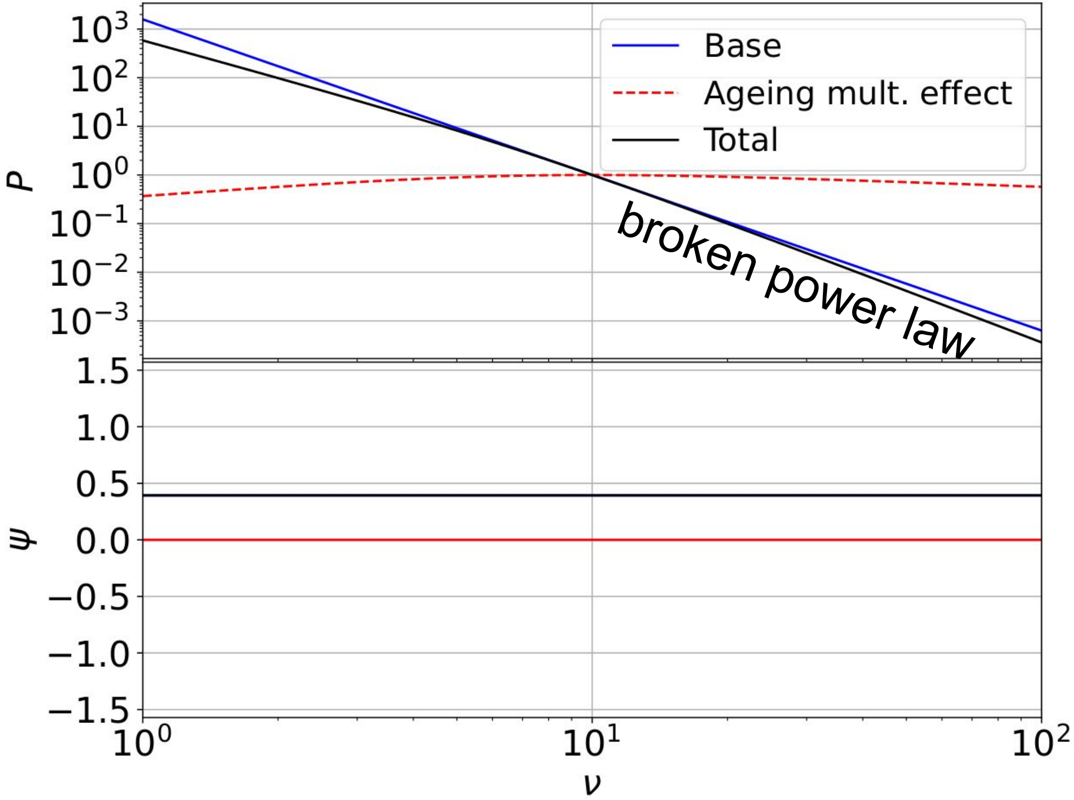
We can also **predict** spectral parameters…

$$\frac{d\psi}{ds} = \frac{1}{2}\Im\left[\frac{A_a\,\beta_a + A_b \mathrm{e}^{i2\psi_a}\,\beta_b}{A_a\mathrm{e}^{i2\psi_a} + A_b\mathrm{e}^{i2\psi_a}}\right],$$

$$\gamma = \Re\left[\frac{A_a\mathrm{e}^{i2\psi_a}\beta_a^2 + A_b\mathrm{e}^{i2\psi_a}\beta_b^2}{A_a\mathrm{e}^{i2\psi_a} + A_b\mathrm{e}^{i2\psi_a}} - \left(\frac{A_a\,\beta_a + A_b\mathrm{e}^{i2\psi_a}\,\beta_b}{A_a\mathrm{e}^{i2\psi_a} + A_b\mathrm{e}^{i2\psi_a}}\right)^2\right].$$

<u>Effect 2</u>: synchrotron ageing





That induce **curvature** but NO angle evolution (hence no *E* / *B* redistribution!*)*

We can also **predict** spectral parameters…

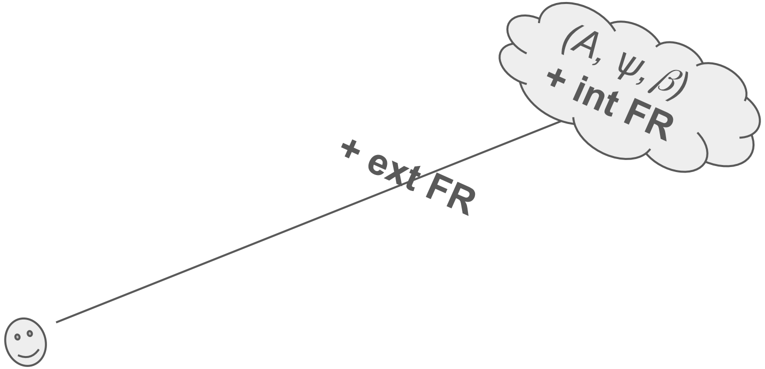
$$\beta = \overline{\beta} + \left.\frac{d \log C_{\rm age}}{ds}\right|_0 = \overline{\beta},$$

$$\gamma = \left.\frac{d^2 \log C_{\rm age}}{ds^2}\right|_0 = -\frac{\Delta\alpha}{\sigma}\frac{a}{(1+a)^2}$$

First, what's the spectral complexity in $\underline{P}$? LoS

Section 3.6, Fig 4

<u>Effect 3</u>: Faraday rotation

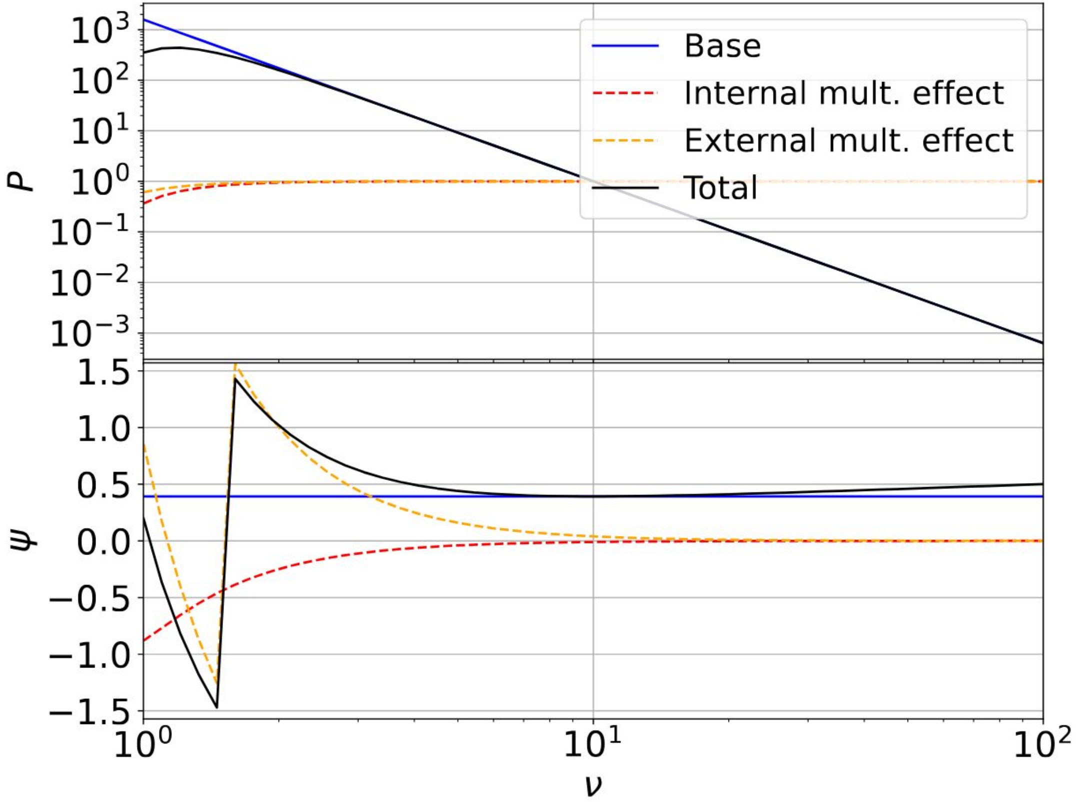


That induce **curvature** and **angle-evolution** (and also ***E / B* redistribution**!)

We can also **predict** spectral parameters…

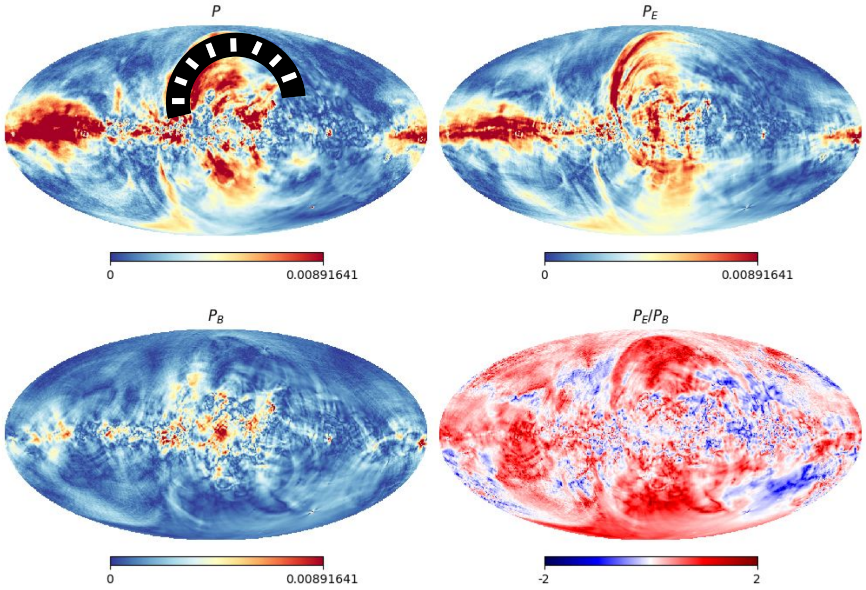
$$\beta = \overline{\beta} + \left.\frac{d \log \underline{C}_{\rm FR}}{ds}\right|_0 = \overline{\beta},$$

$$\underline{\gamma} = \underline{S}_0'' \, f(\underline{S}_0) + \underline{S}_0'^2 f'(\underline{S}_0) - 32\,\sigma^2_{\rm RM,ext} c^4/\nu_0^4 + 8i{\rm RM}_{\rm ext}\, c^2/\nu_0^2,$$



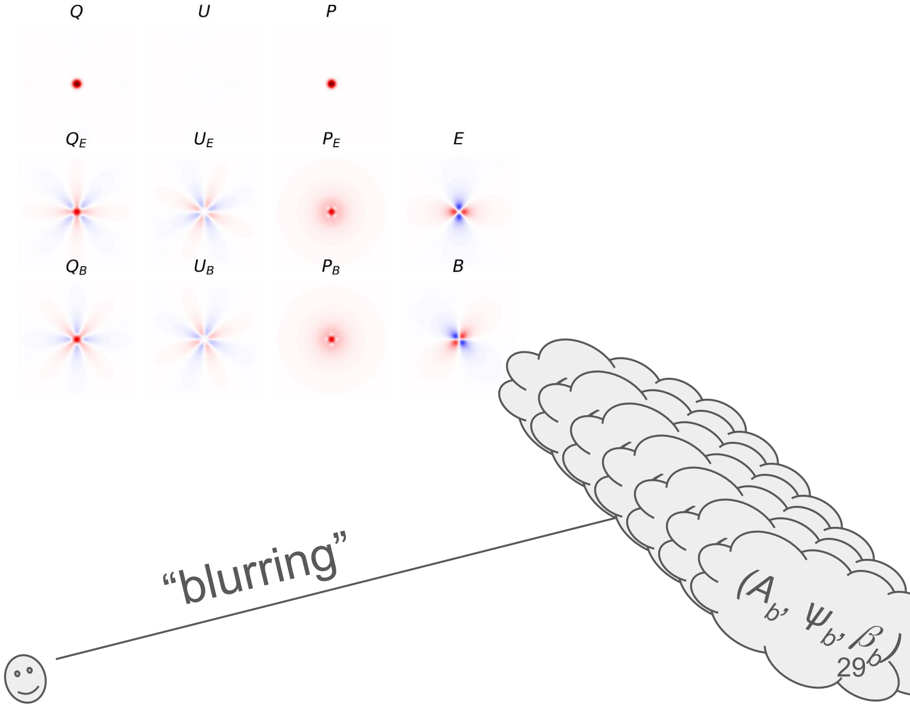
Two additional sources of complexity for what concerns $\underline{P_E}$ and $\underline{P_B}$ and that leads to distinct *E* and *B* complexity.

4) Sources are extended and they are **more or less *E*- or *B*- like as an emergent property.**



e.g. Loops are more *E*-like polarization patterns.
(with specific spectral properties)

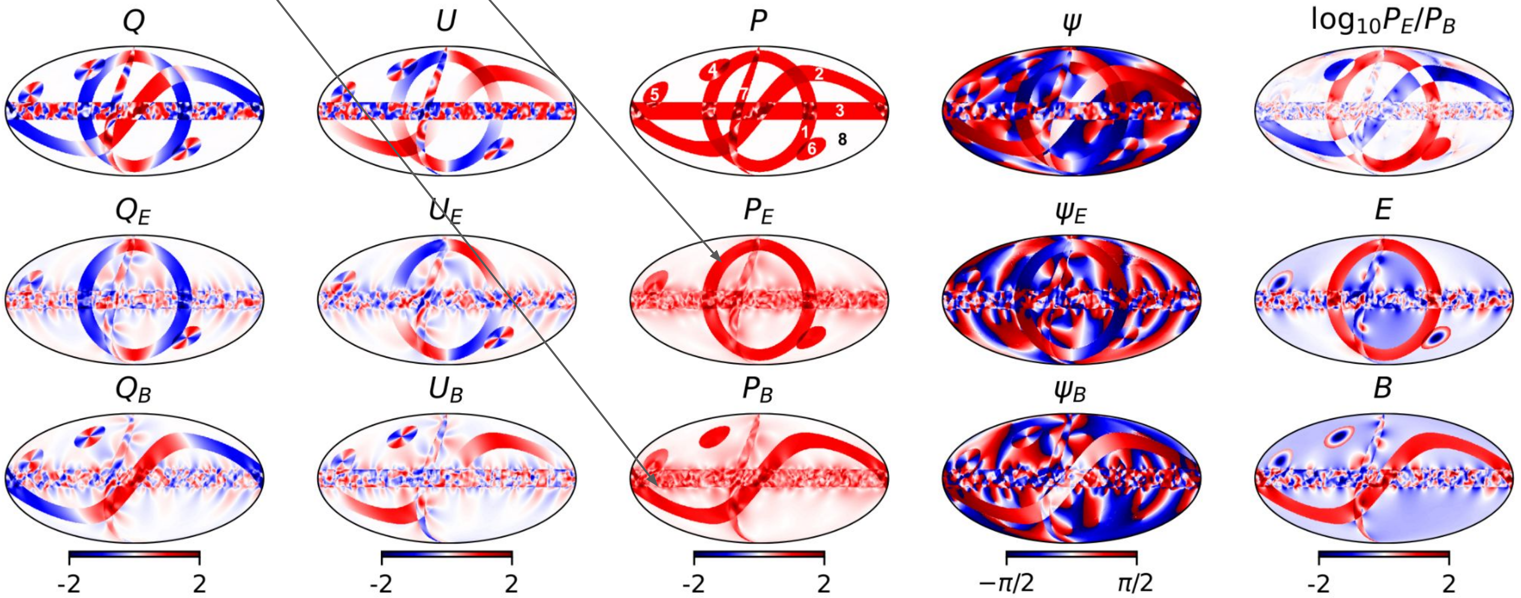
5) ***E/B* transform is not fully-local**
Effect 1 occurs.

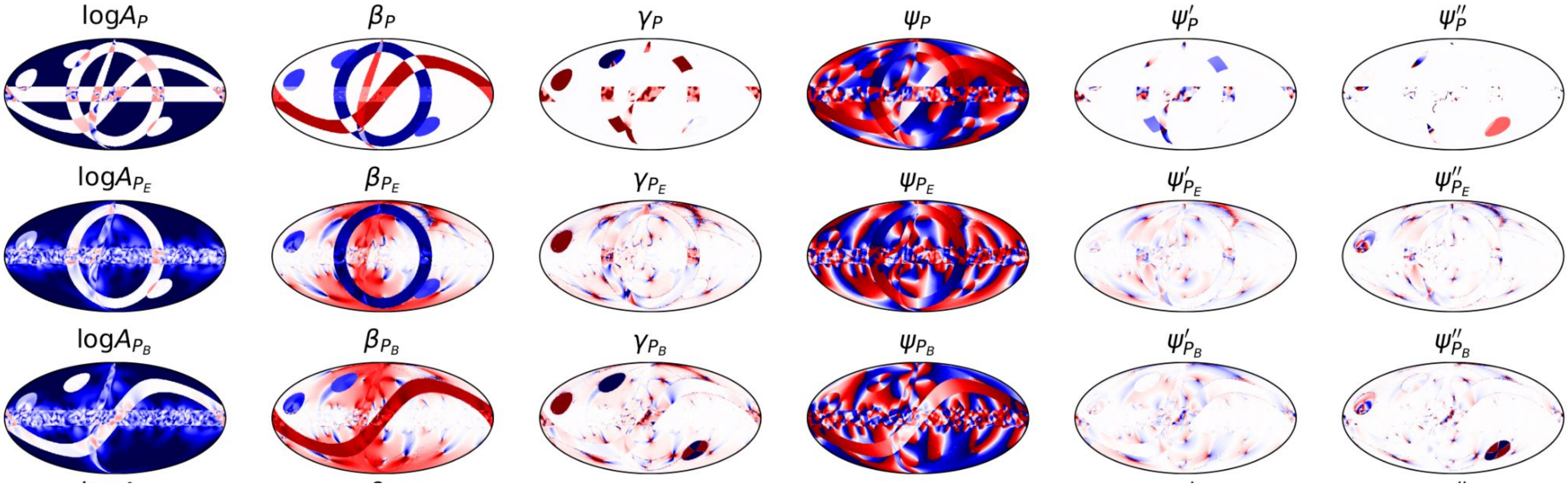


(Sec 4.1) Toy model:

"*B* loop" "*E* loop"

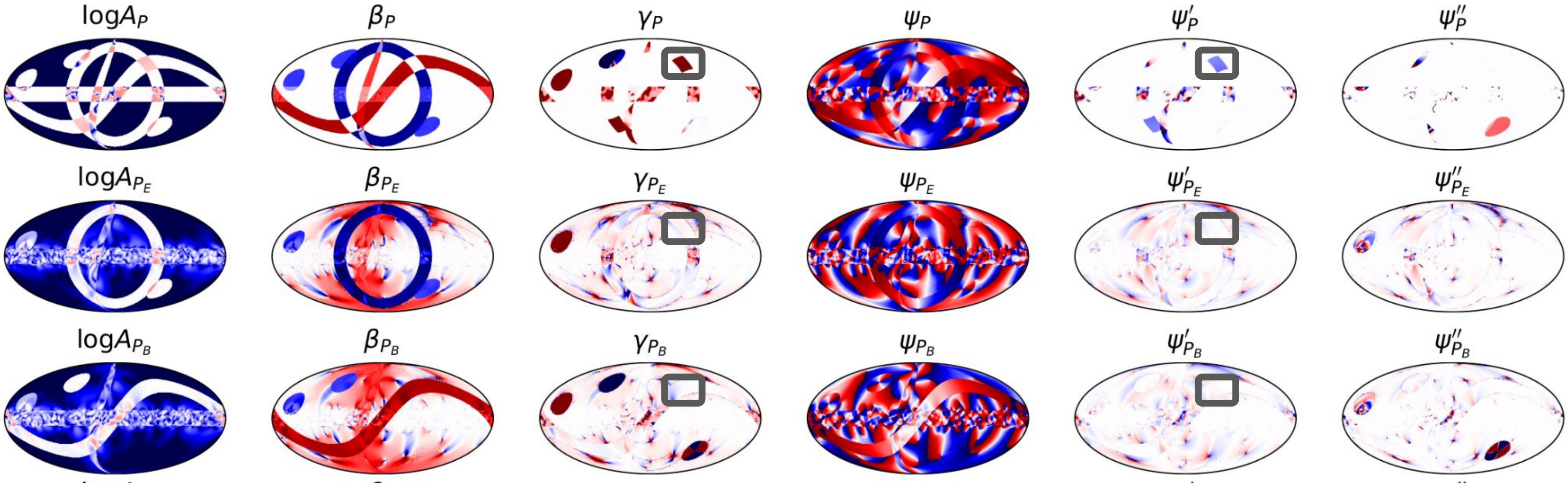
	E/B	A	β	Other prop.
(1) E loop	$+\infty$	1	-3.4	–
(2) B loop	0	1	-2.6	–
(3) Random-angle galaxy	rand (5°)	1	-3.0	–
(4) Circular source	0	1	-3.2	Aged
(5) Circular source	1	1	-3.2	$\gamma > 0$
(6) Circular source	$+\infty$	1	-3.2	Faraday
(7) Stochastic-angle stripe	rand (20°)	1	-2.8	–
(8) Random-angle bg.	rand (20°)	0.01	-3.0	–





γ_X, β_X, Ψ'_X quantify the **spectral complexity**. Especially Ψ'_X tells about the **angle stability**.

Those can be **numerically fitted** or **analytically predicted** => **<u>same maps</u>**!
Our **analytical formulae are validated** & can be used for modelling.

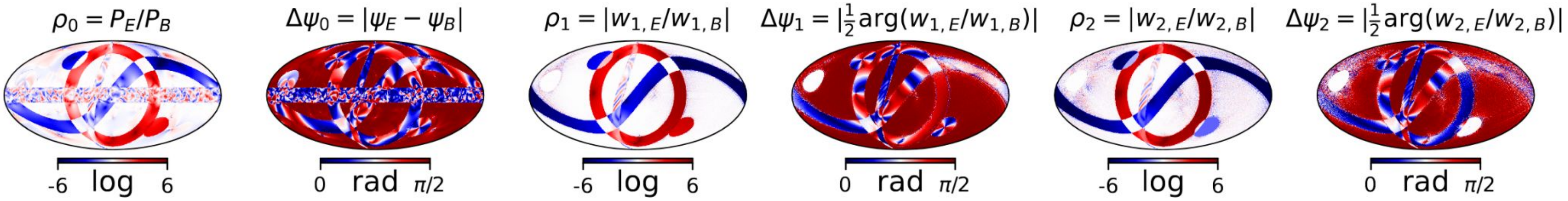


Overlap between “E loop” and “B loop”:

More spectral complexity in *P* than in P_E, P_B !
(Consequence of effect 4)

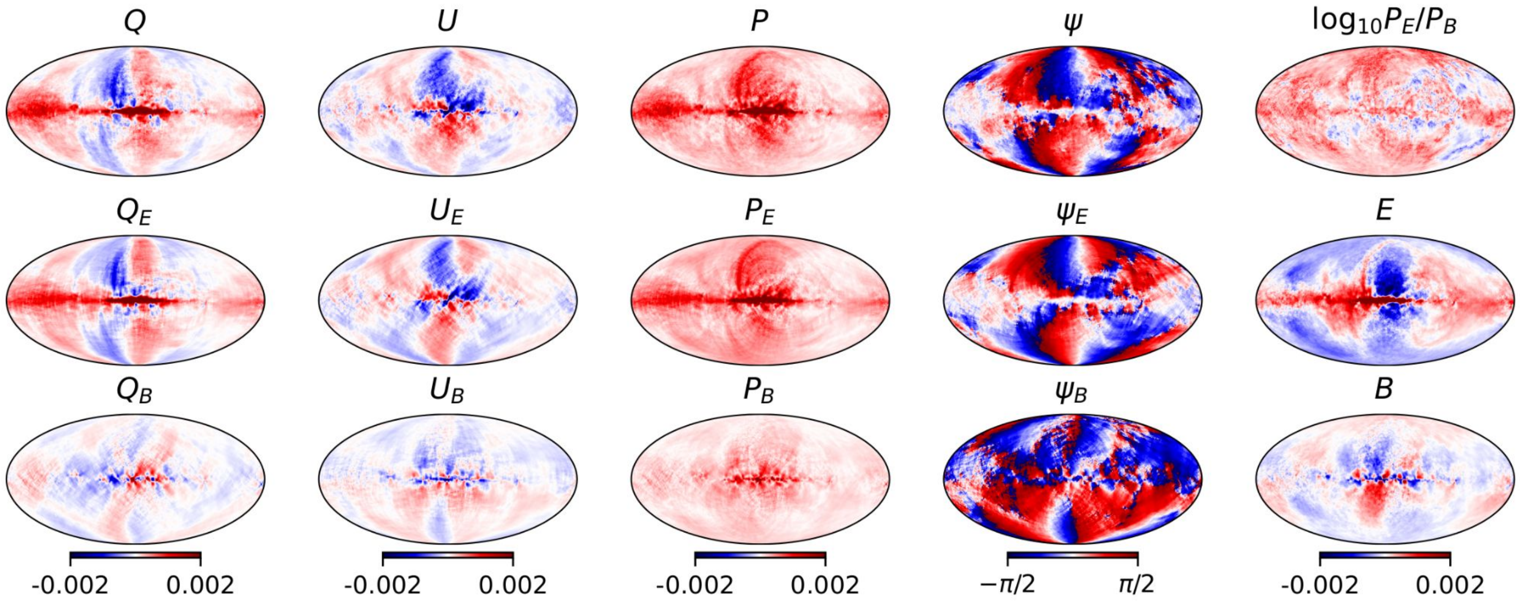
We also can **generalise** the ***E*-to-*B* ratio thanks to spin-2 decomposed moments**:

$$\rho_n = \left| \frac{\underline{w}_{n,E}}{\underline{w}_{n,B}} \right|, \qquad \Delta\psi_n = \frac{1}{2} \arg \left[\frac{\underline{w}_{n,E}}{\underline{w}_{n,B}} \right],$$



(Sec 4.2) PySM s5 model:

- Rigid-angle (*i.e. P* morphology is conserved across frequencies),
- Power law in *P*.



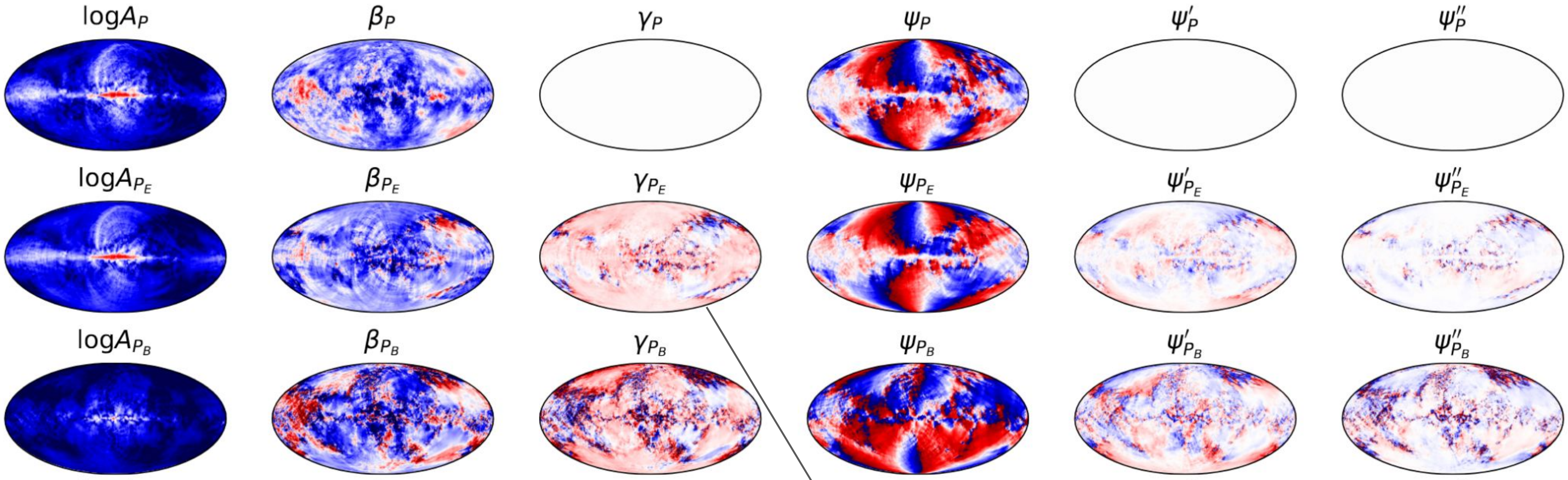
- Very clearly distinct morphology between P_E and P_B.

More realistic sky model

App D, Fig 20

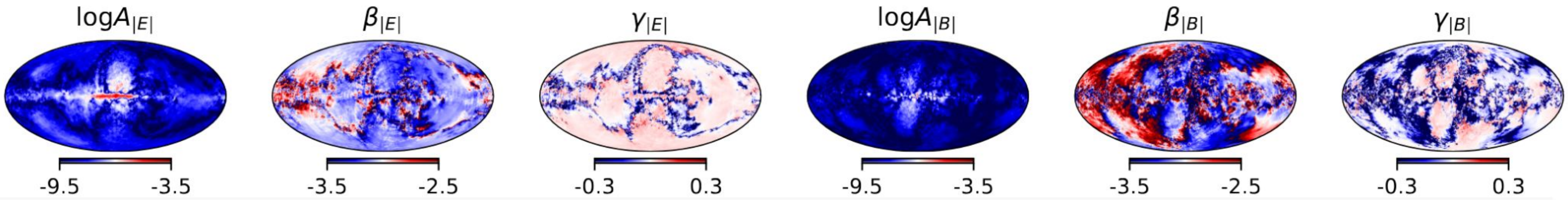
<u>*Complex* log-Taylor fit of spin-2:</u>

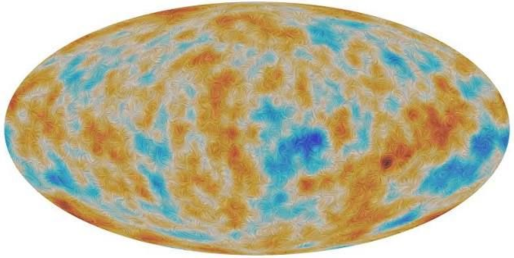
(<u>*P*</u> spectrally trivial)



<u>*Real* log-Taylor fit of spin-0:</u>

In general (for realistic morphologies), **$\underline{P}_E$ & $\underline{P}_B$ are spectrally simpler than *E* & *B***





Concrete CMB oriented application cases

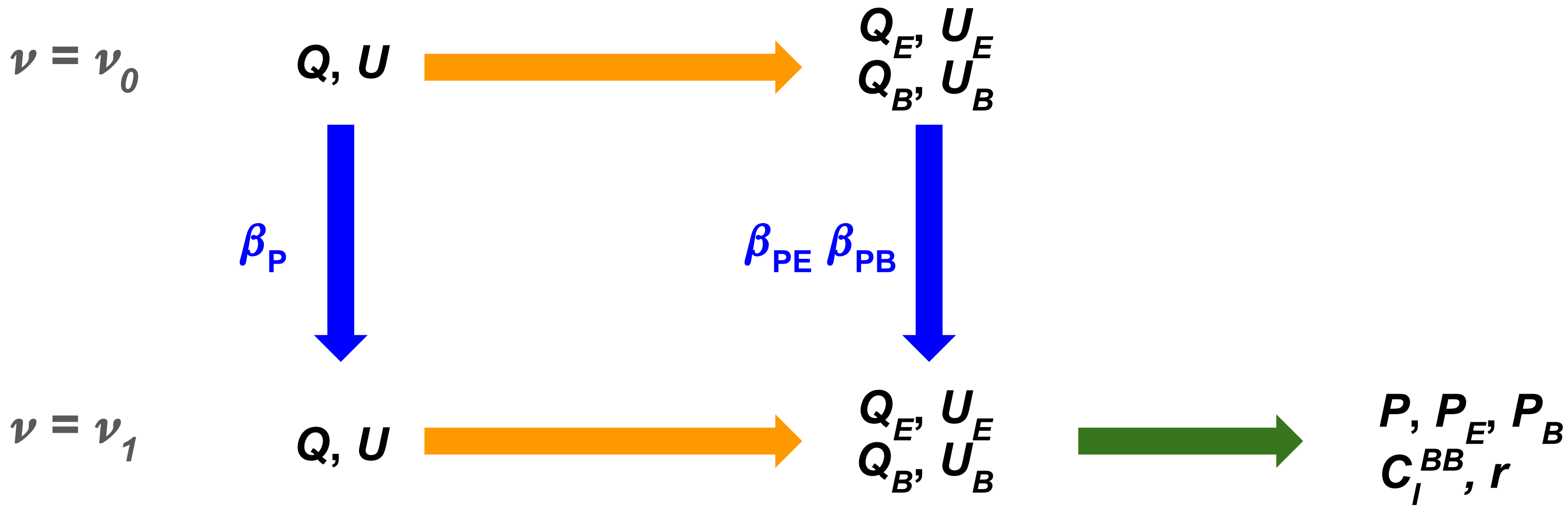
Simplified schematics for **CMB** and ***r* foregrounds mitigation**

Fg modelling → **Comp. sep. (or fg cleaning)** → **Masking of residuals** → **Cl^{BB} and *r* estimation**

- Fg modelling: In $\underline{P}_E$, $\underline{P}_B$ or in $\underline{P}$?
- Comp. sep. (or fg cleaning): In $\underline{P}_E$, $\underline{P}_B$ or in $\underline{P}$?
- Masking of residuals: In $\underline{P}_E$, $\underline{P}_B$ or in $\underline{P}$?
- Cl^{BB} and *r* estimation: In $\underline{P}_E$, $\underline{P}_B$ or in $\underline{P}$?

Step 1: Extrapolation to high frequency (v2) Section 5.1

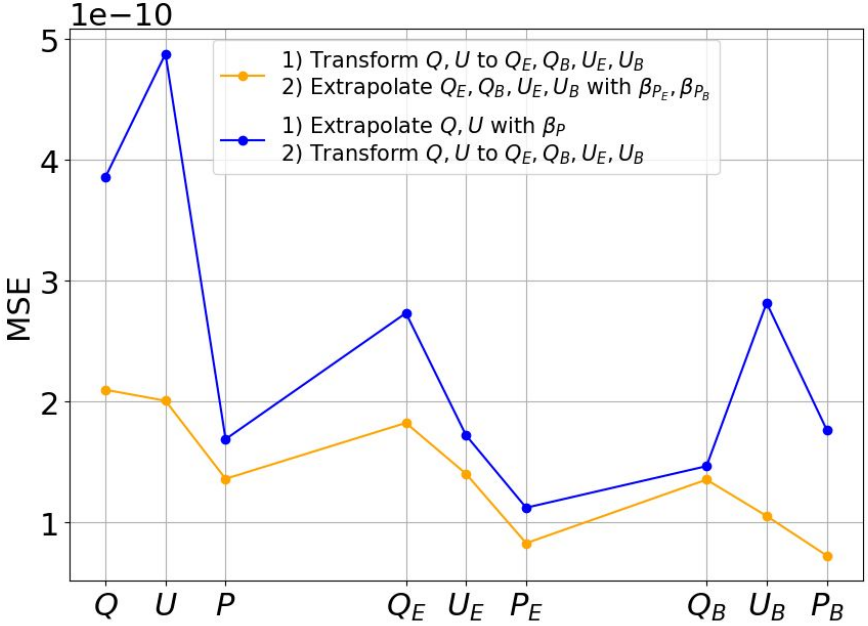
With limited number of channels & fixed # parameters:
does one **prefer to model P or P_E & P_B**?



Which path to follow?

In prep

With limited number of channels:
does one **prefer to model *P* or P_E & P_B**?



MSE of the two paths on data.

(C-BASS x S-PASS Planck extrapolated to 33 GHz, and compared to WMAP 33 GHz)

Which path to follow? Answer is definitely not trivial *on data*:
P_E P_B modelling is perf. viable, & is perhaps already favoured by data!

What contaminates CMB *B* modes? Foreground variance!
=> philosophy of **minimal variance ILC**.

$$\hat{s}(p) = \sum_{\nu} w^{\nu}_{\mathcal{D}(p)}\, d_{\nu}(p) \quad \text{where} \quad w^{\nu}_{\mathcal{D}} = \frac{\sum_{\nu'} (C^{-1}_{\mathcal{D}})^{\nu\nu'}}{\sum_{\nu\nu'} (C^{-1}_{\mathcal{D}})^{\nu\nu'}} \quad \& \quad C^{\nu\nu'}_{\mathcal{D}} = \frac{1}{N_{\mathcal{D}}} \sum_{p\in\mathcal{D}} d_{\nu}(p)\, d^{*}_{\nu'}(p) \,.$$

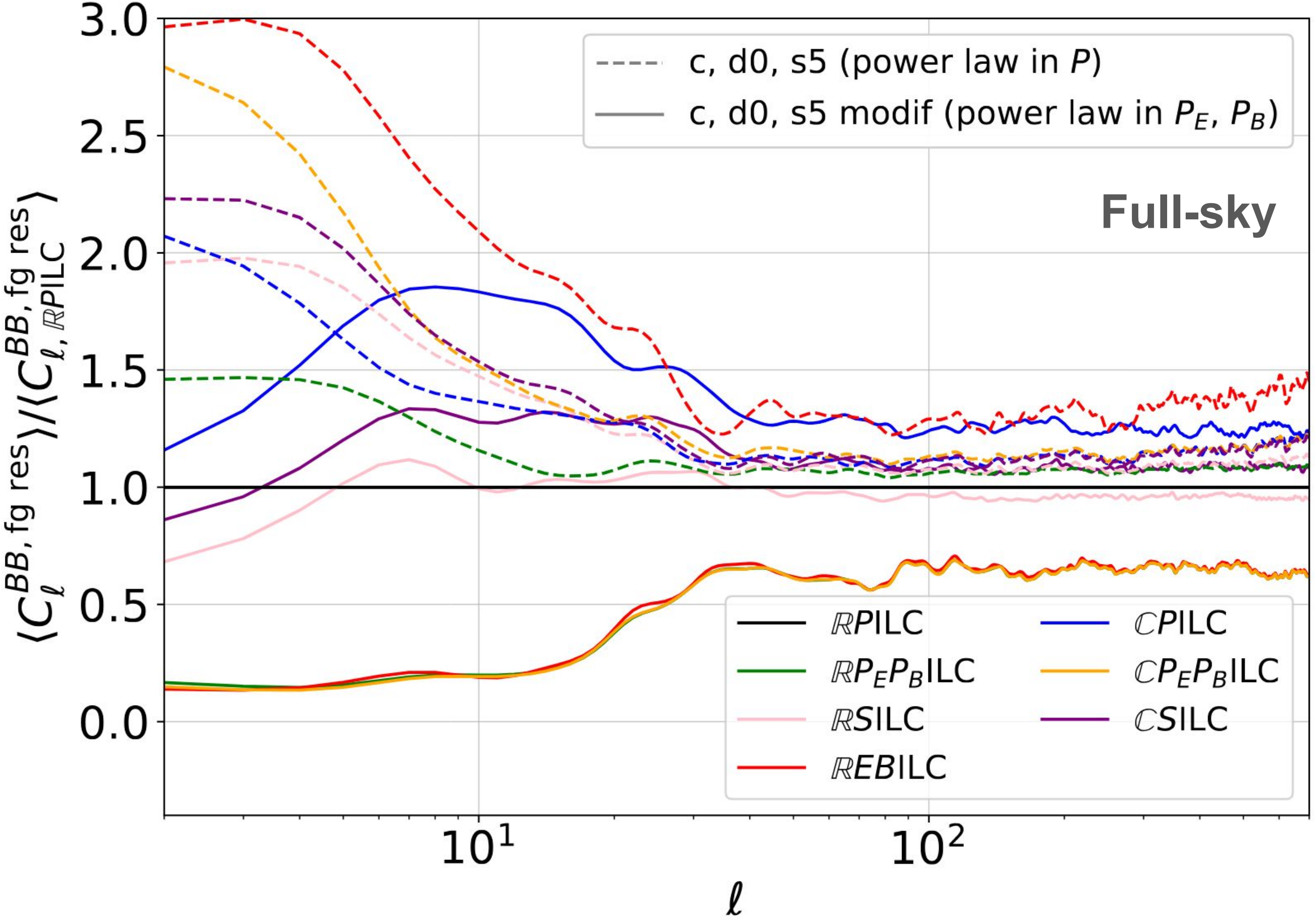
… but we have **lot of freedom** left:

ILC	weights
ℝ*P*ILC	w_P
ℝ$P_E P_B$ILC	w_{PE}, w_{PB}
ℝSILC	w_S
ℝ*EB*ILC	w_E, w_B
ℂ$\underline{P}$ILC	$w_P + i\mathcal{W}_P$
ℂ$\underline{P_E}\,\underline{P_B}$ILC	$w_{PE} + i\mathcal{W}_{PE}$, $w_{PB} + i\mathcal{W}_{PB}$
ℂ$\underline{S}$ILC	$w_S + i\mathcal{W}_S$

Step 2: map-space ILC's Cls residuals

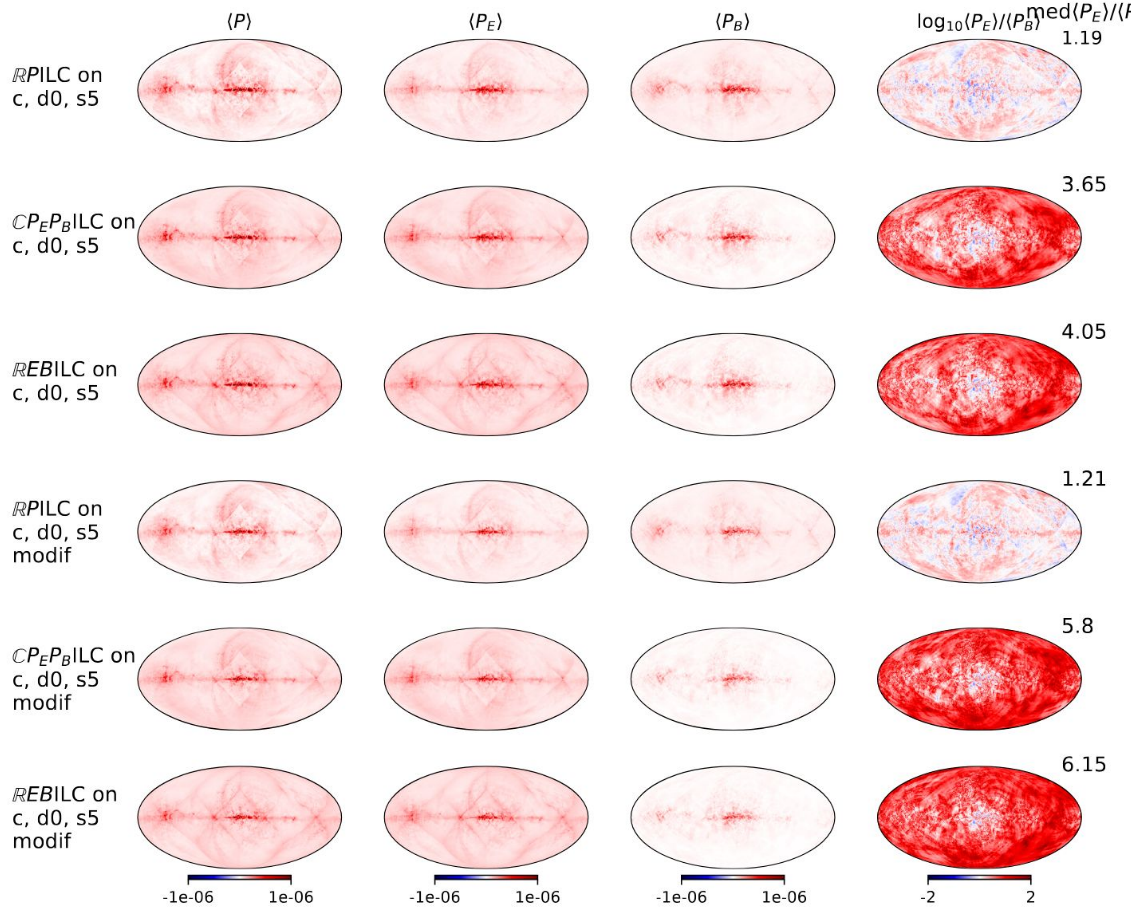
(v2) Sec 5.2, Fig. 14

Cl space proxy for the residual contaminant to *r*



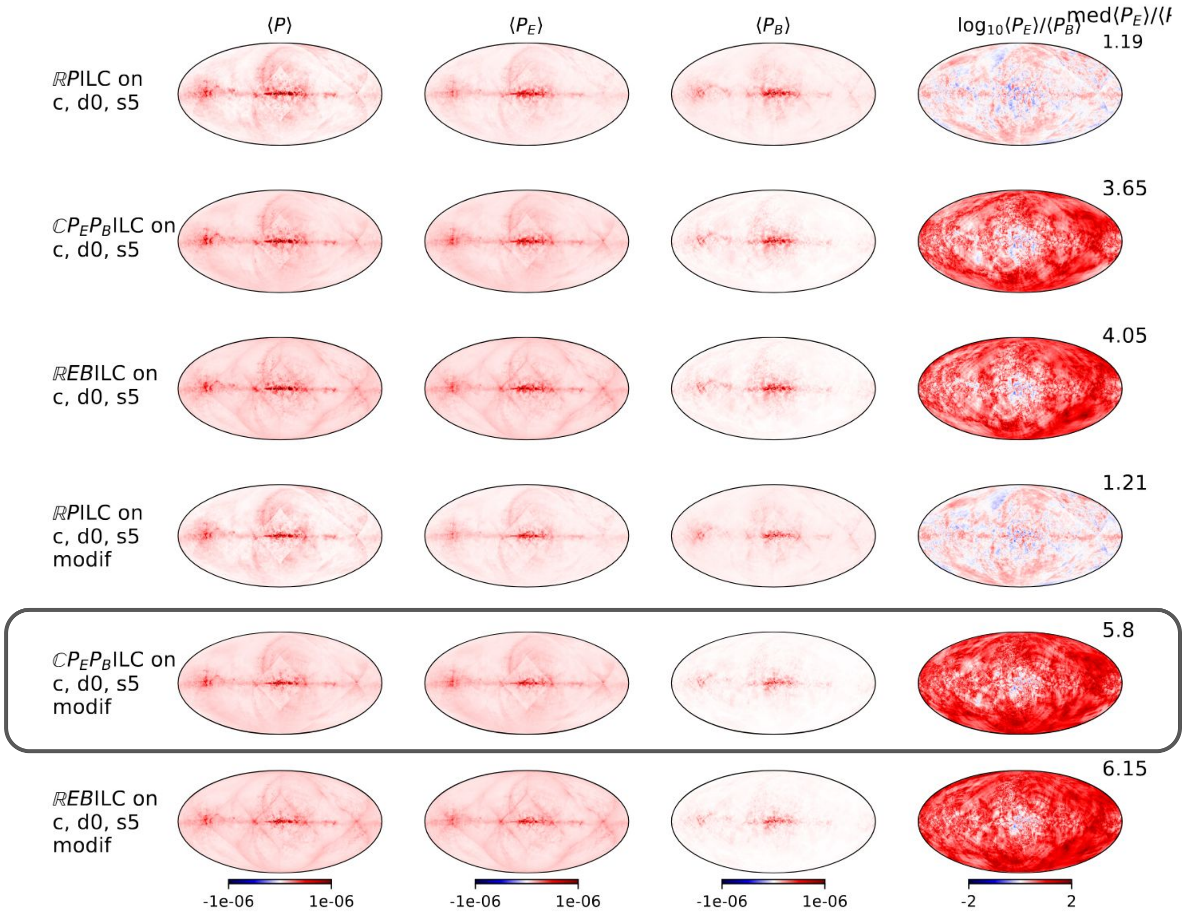
Step 2: map-space ILC's residuals

map space proxy for the residual contaminant to *r*



Step 3: Masking strategy of the residuals (v2) Sec 5.2, Fig. 15

map space proxy for the residual contaminant to *r*

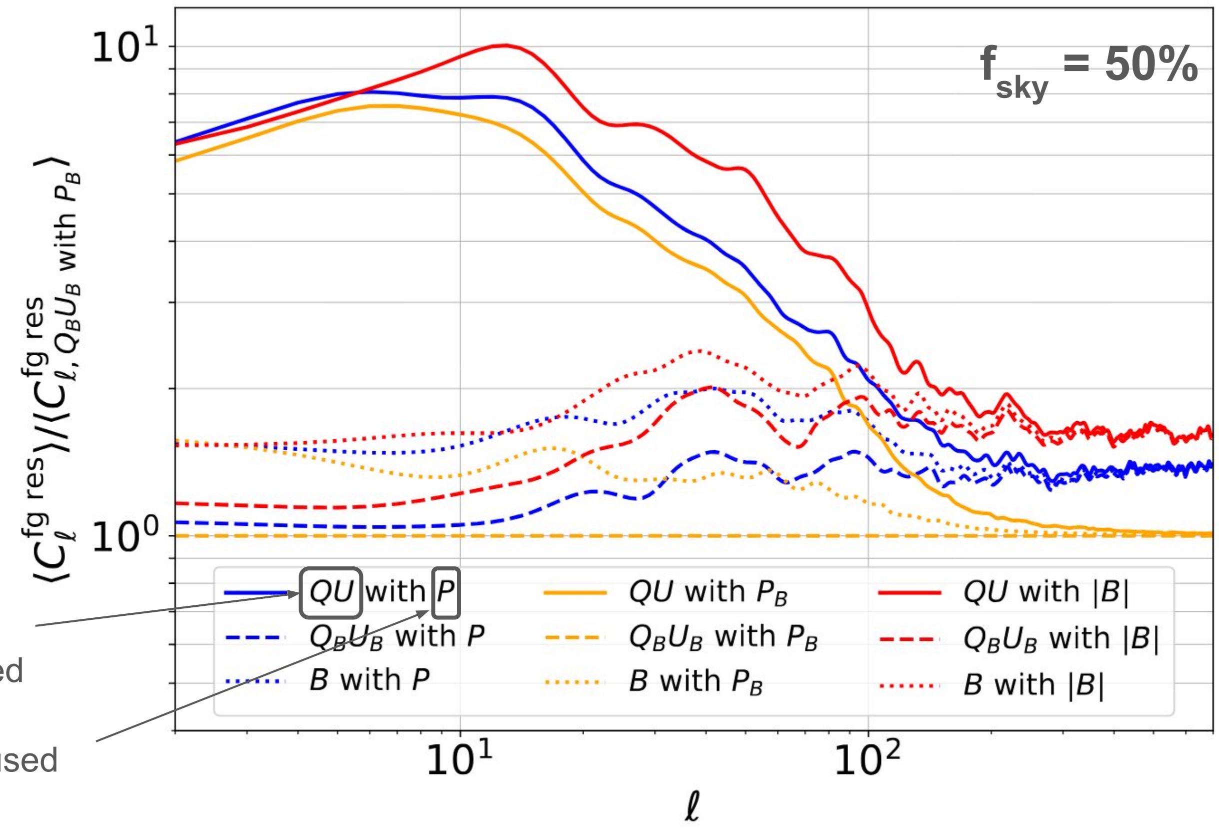


Step 3: Masking strategy of the residuals

(v2) Sec 5.3, Fig. 17

What masking strategy for further reducing the residuals?

Cl space proxy for the residual contaminant to r

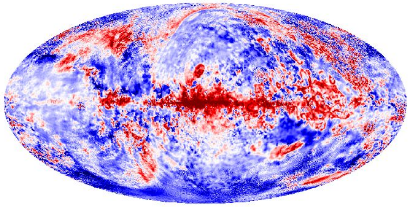


field that is being masked

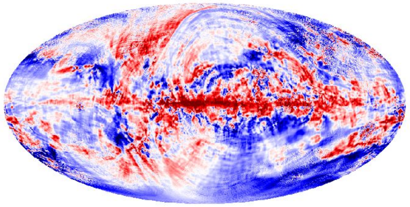
field that is used as a tracer

Preliminary results on data

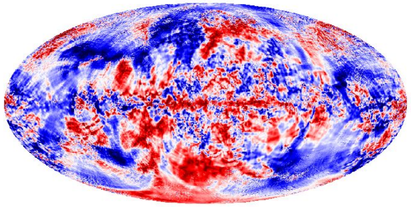
β_{P}



β_{PE}



β_{PB}



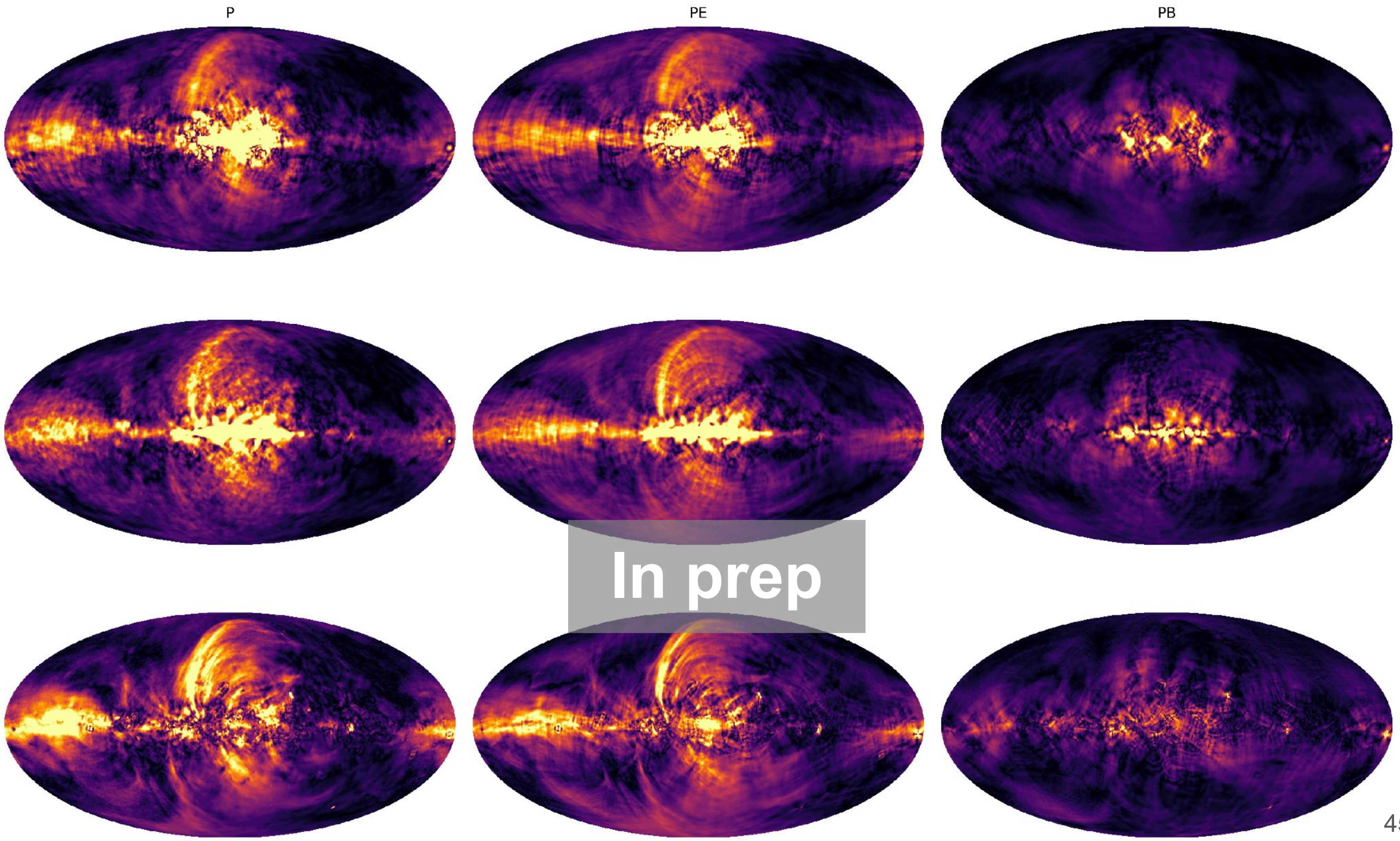
P, P_E, P_B synchrotron morphology

Bonus data

s1

s7

C-BASS
S-PASS
Preliminar



In prep

Inputs:
sync: C-BASS x S-PASS
dust: Planck 353

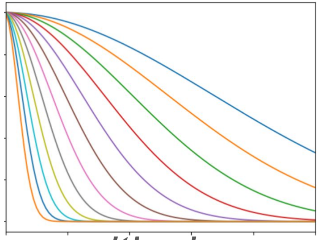
$|\lambda_1(\sigma;\mathbf{n})| \leq |\lambda_2(\sigma;\mathbf{n})|$ are eigenvalues of $H_{ab}(\sigma;\mathbf{n}) \equiv \nabla_a \nabla_b f_\sigma(\mathbf{n})$

where $f_\sigma(\mathbf{n}) \equiv (\mathcal{G}_\sigma * f)(\mathbf{n})$ are **smoothed *P*** (sync or dust) **maps**.

degree of anisotropy ("blobness"): $R_B(\sigma;\mathbf{n}) \equiv \left|\frac{\lambda_1(\sigma;\mathbf{n})}{\lambda_2(\sigma;\mathbf{n})}\right|,$

overall 2nd derivative contrast: $S(\sigma;\mathbf{n}) \equiv \left[\lambda_1(\sigma;\mathbf{n})^2 + \lambda_2(\sigma;\mathbf{n})^2\right]^{1/2},$

Multiscale analysis:
Done for logspace(2°, 30°, 12).



$$V(\mathbf{n}) \equiv \max_{\sigma\in\Sigma} V(\sigma;\mathbf{n}),$$

$$\sigma_\star(\mathbf{n}) \equiv \arg\max_{\sigma\in\Sigma} V(\sigma;\mathbf{n}).$$

In prep

$$V(\sigma;\mathbf{n}) = \mathbb{I}_{\lambda_2(\sigma;\mathbf{n})<0} \exp\left[-\frac{R_B(\sigma;\mathbf{n})^2}{2\beta^2}\right]\left[1-\exp\left(-\frac{S(\sigma;\mathbf{n})^2}{2c^2}\right)\right]$$

***V* is supp-ressed**:

(iii) for valley-like features (l2 > 0).

(ii) for blob-like structures (R_B -> 1),

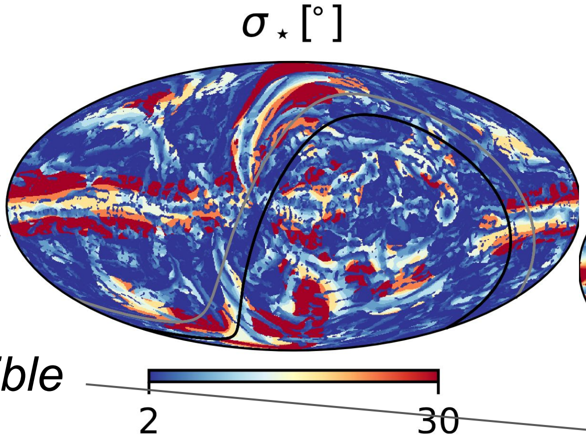
(i) in regions with negligible curvature (S -> 0),

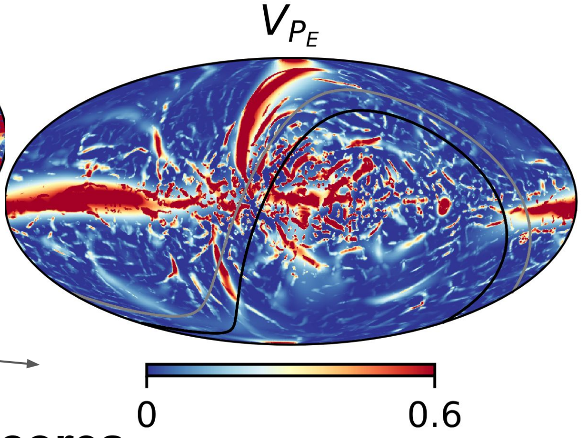
3 *dof's*: β, γ, *c*

Will affect:

- which scale is selected

- how well filaments are visible



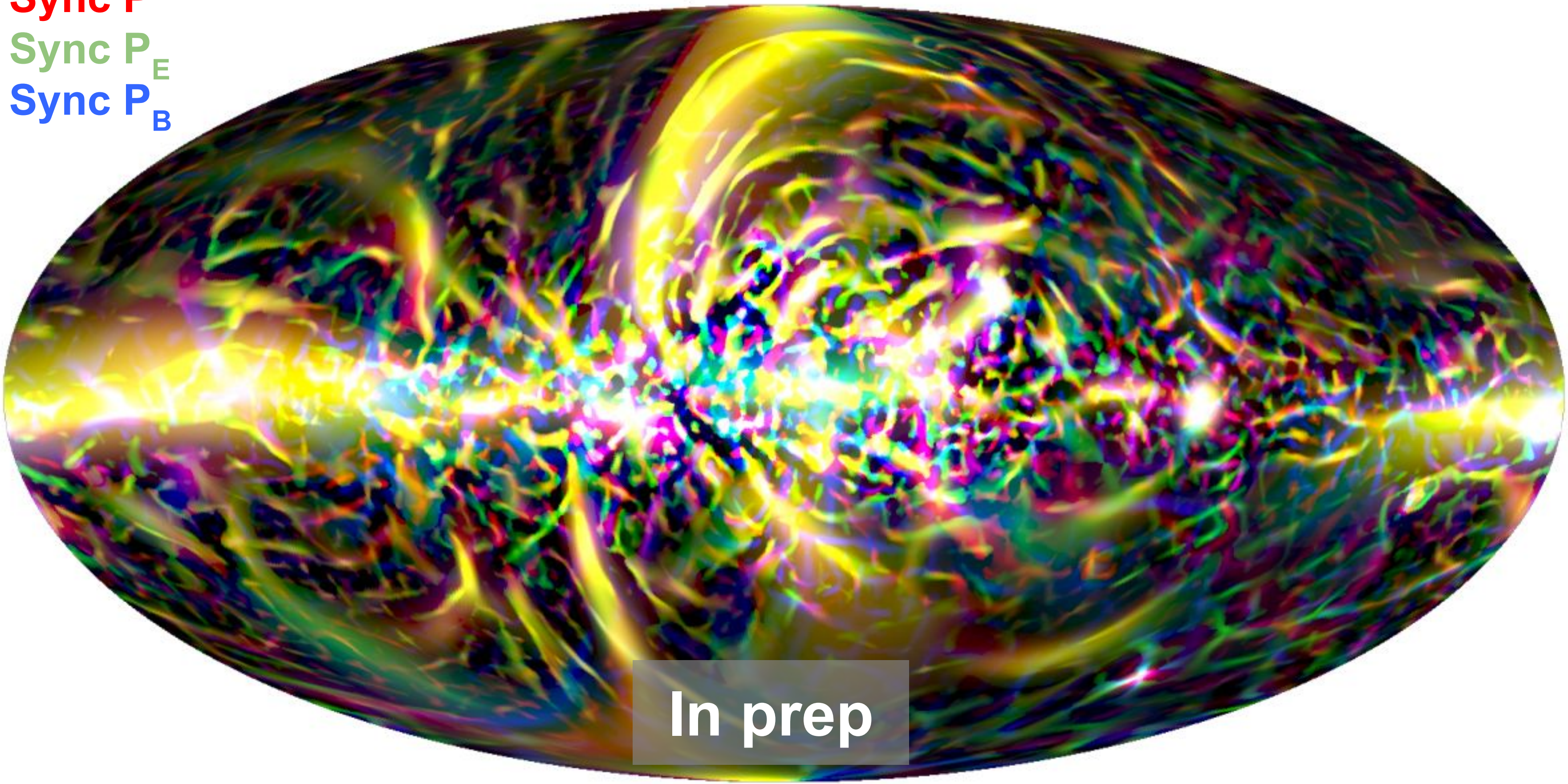


We represent on common maps those **adimensional scores**…
(allow to do a complementary non-Gaussian diagnosis to power spectra)

P, P_E, P_B Synchrotron vessels

Bonus data

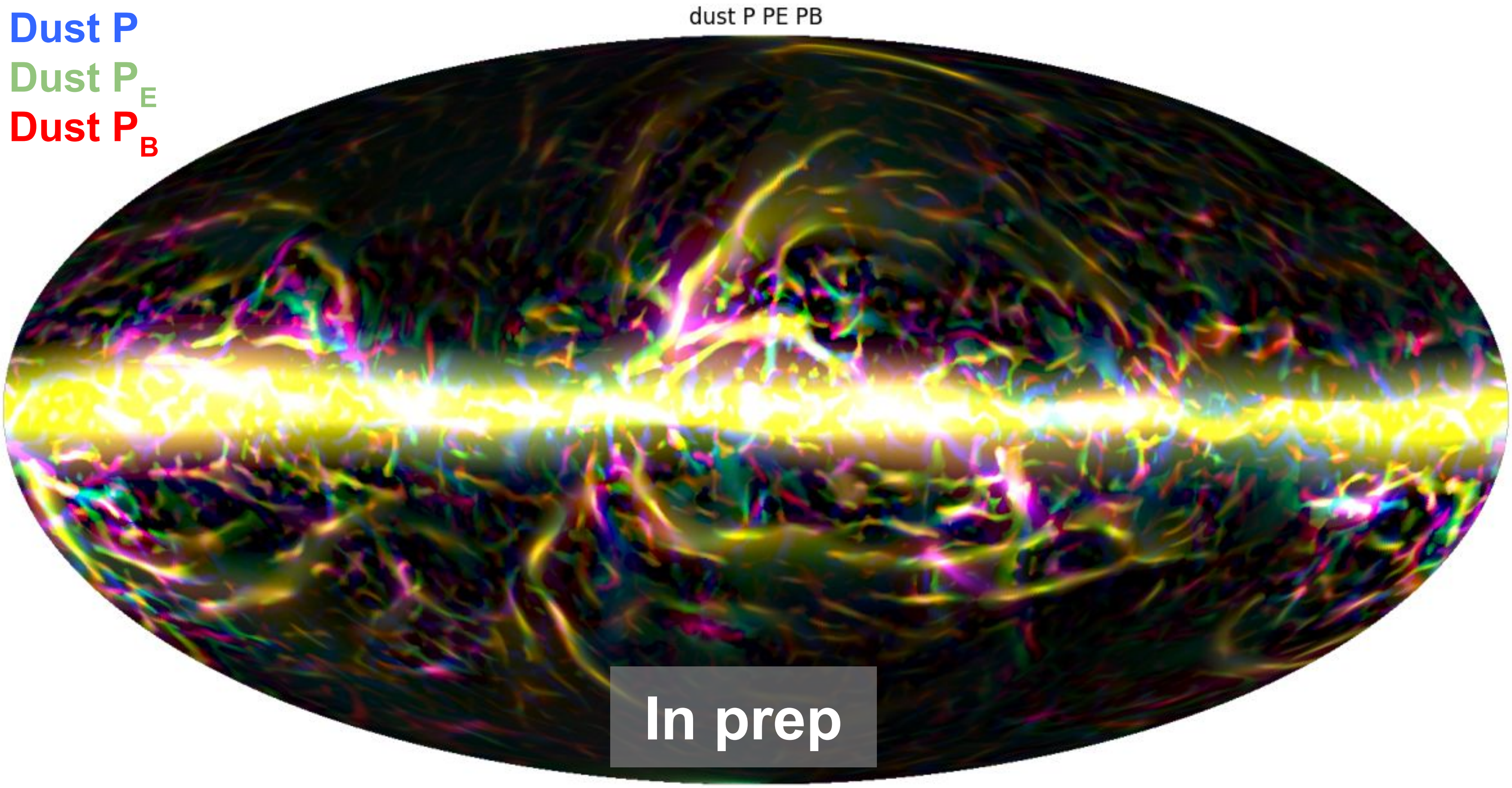
Sync P
Sync P_E
Sync P_B



Dust P

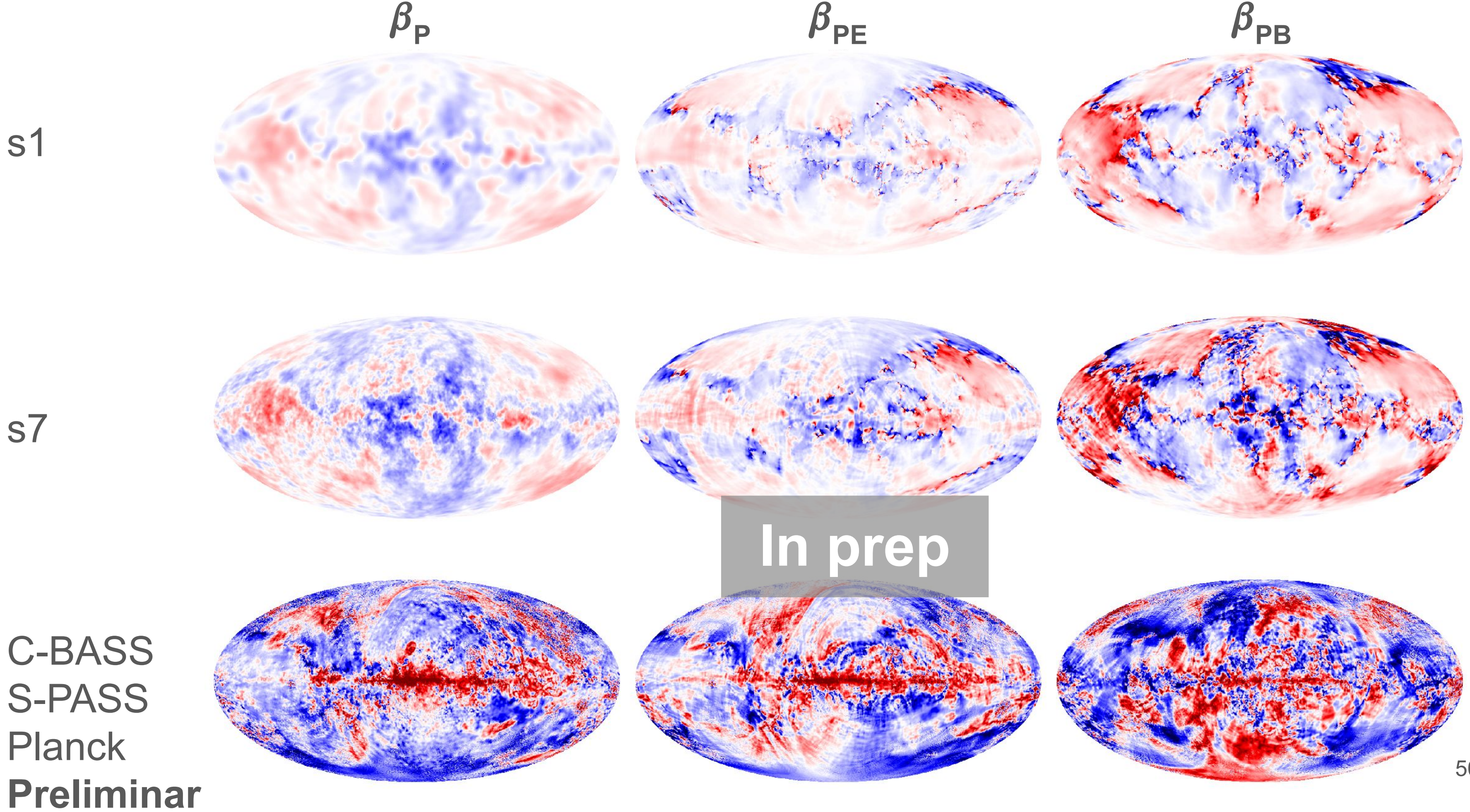
Dust P_E

Dust P_B



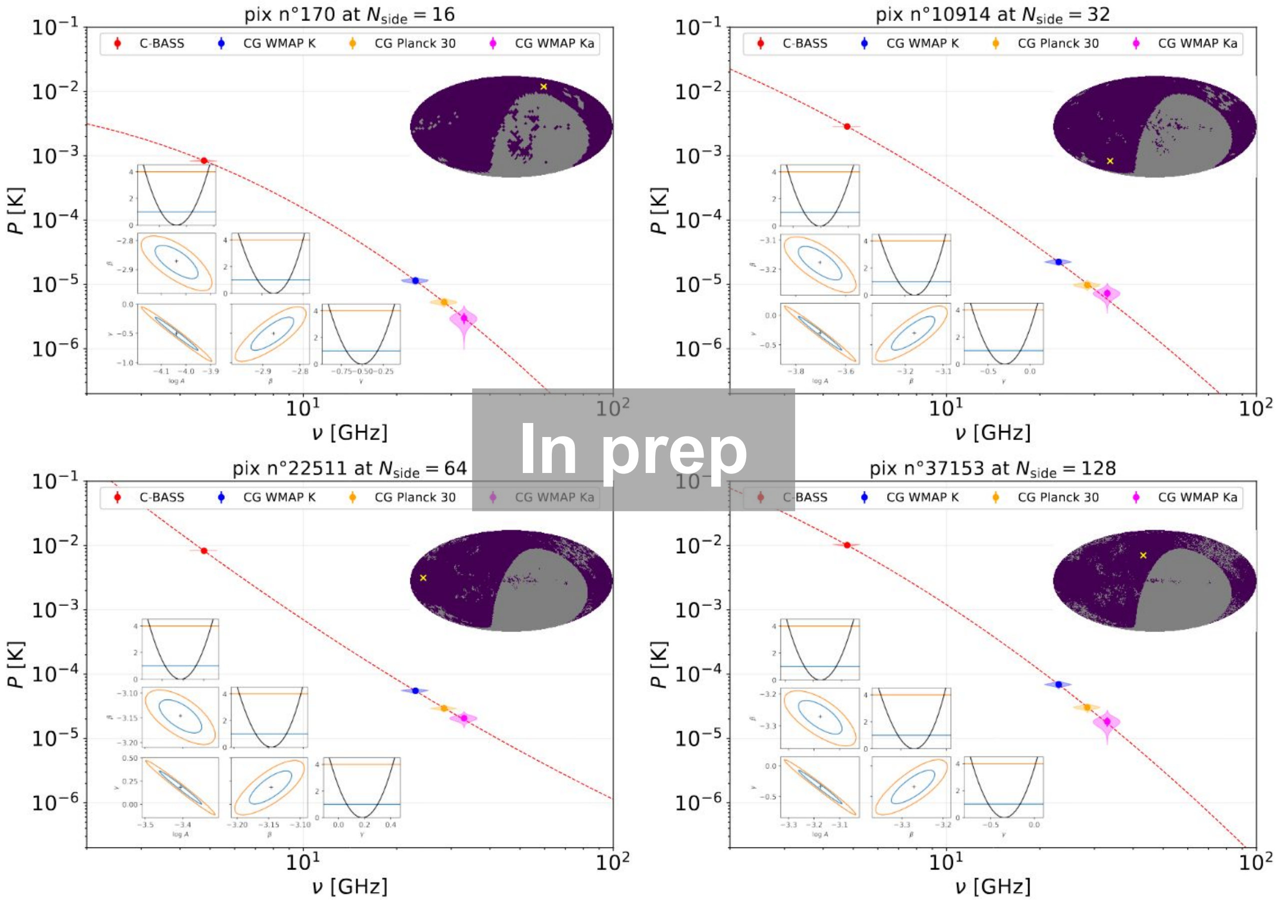
P, P_E, P_B synchrotron spectral indices

Bonus data



Higher orders:

- Curvature (first results)
- Rotation measures (first results)
- …



Conclusions

Why should we care about *E* and *B* decomposition? Yes!...

1) Some sources emit more *E* modes than *B* modes,
2) *B* modes are the contaminant of C_l^{BB}.

Why are $\underline{P}_E$ and $\underline{P}_B$ especially appealing for that?

1) Nice mathematical properties,
2) Easily interpretable,
3) **Better tracer of astrophysical structures.**

Should we worry about additional spectral complexity there? Yes, but…

1) We already **expect spectral complexity in $\underline{P}$**,
2) Theoretically justified that in some specific cases, **$\underline{P}_E$ and $\underline{P}_B$ are simpler than $\underline{P}$**.
3) Available measures indicate first hints for this!

What's next?

1) Build a **new model of polarised synchrotron** …
   … with novel **C-BASS** data (morphology, β, …)
   … with physical spectral complexity in *P (relaxing the rigid-PL-in-P assumption).*
2) Apply **novel P_E, P_B ideas for CMB analyses** -> improving our syst./stat. error on *r*

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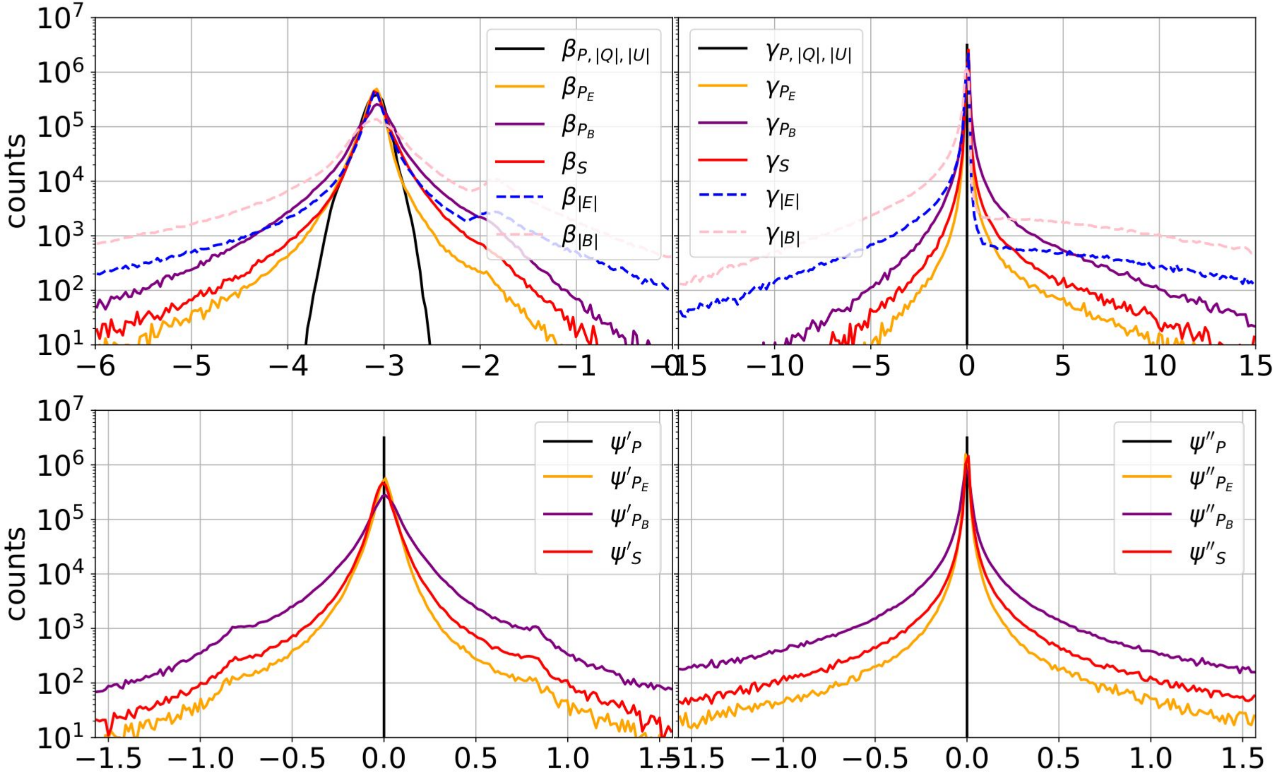
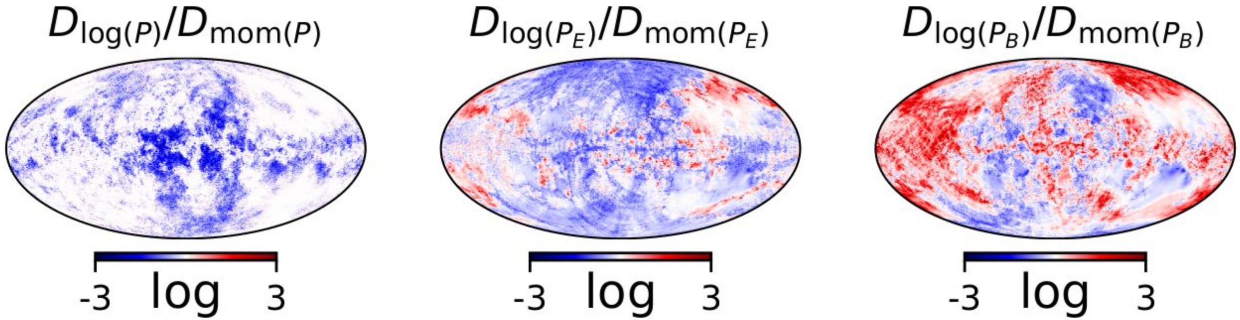
Additional material



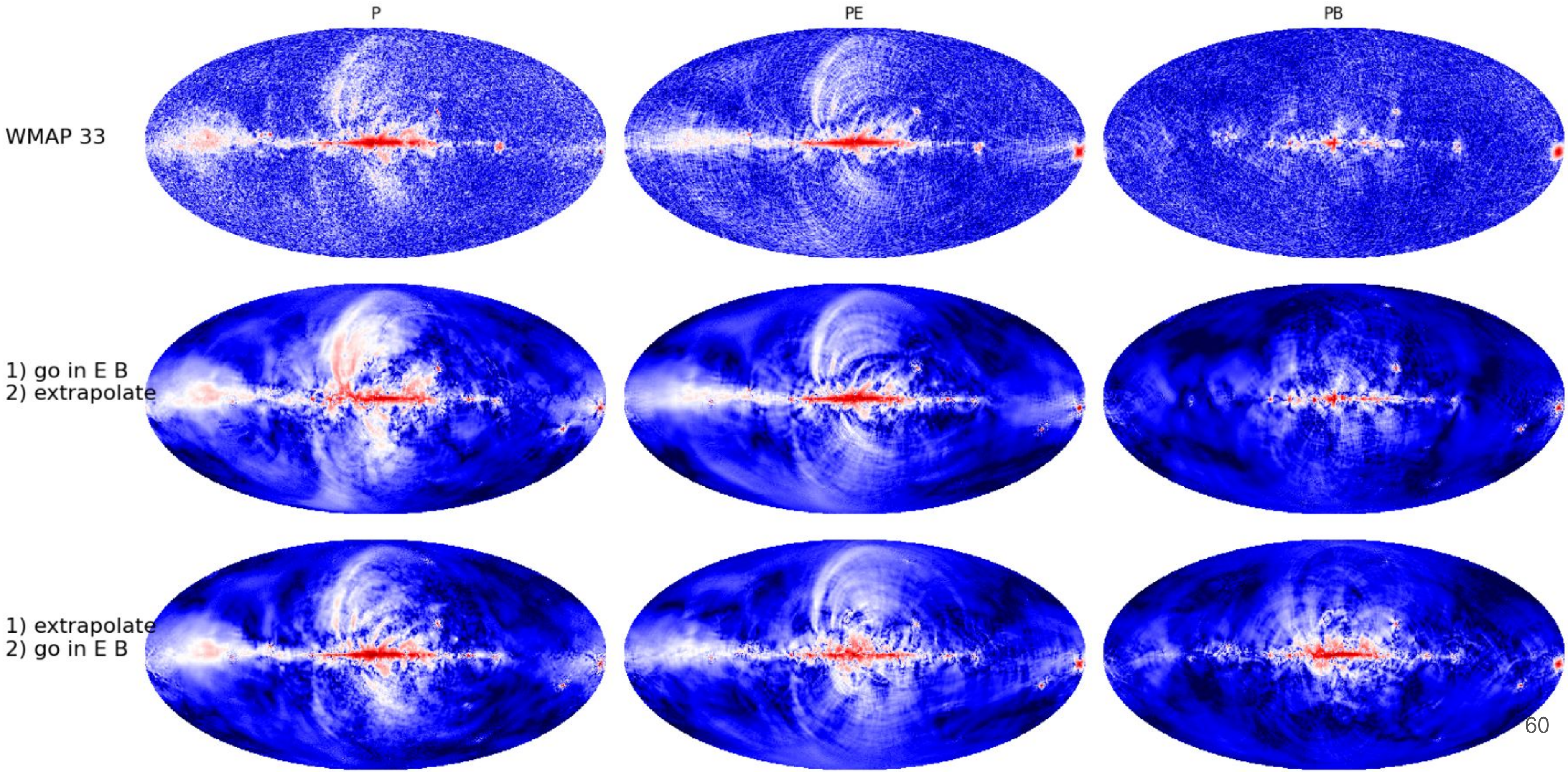
|E| & |B| are spectrally more complex than others.

With limited number of channels:
does one **prefer to model with log-Taylor or moments**?

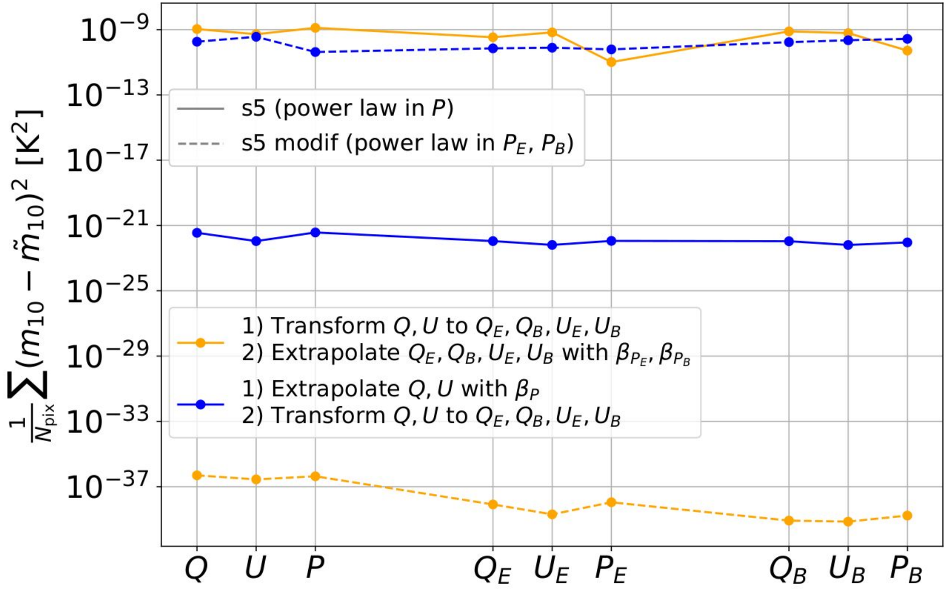
$$D_{\underline{X}} = \sqrt{\frac{1}{N_{\mathrm{ch}}} \sum_{i=1}^{N_{\mathrm{ch}}} \left| \frac{\underline{X}_{\nu_i}^{\mathrm{model}}}{\underline{X}_{\nu_i}^{\mathrm{input}}} - 1 \right|^2},$$



For *P*: log-Taylor exact (expected for PySM),
for P_E & P_B: no clear preference.


P
PE
PB
WMAP 33
1) go in E B
2) extrapolate
1) extrapolate
2) go in E B

With limited number of channels:
does one **prefer to model *P* or P_E & P_B**?



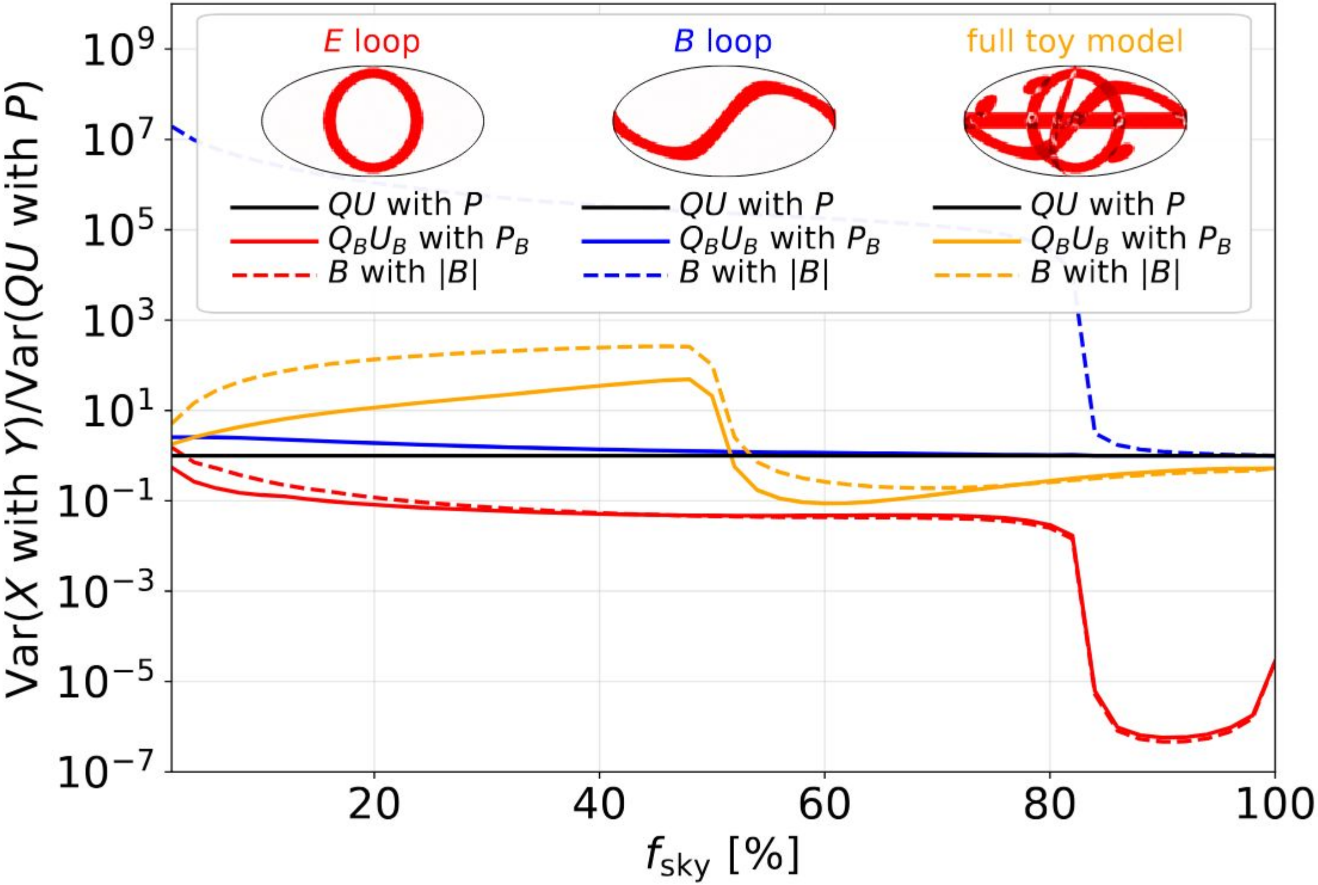
MSE of the two paths for two models:

- *power law in P or*
- *power-law in P_E, P_B*

Which path to follow? Answer is ~~not a priori~~ trivial *for PySM models*.
(because rigid-angle power-law in *P*)

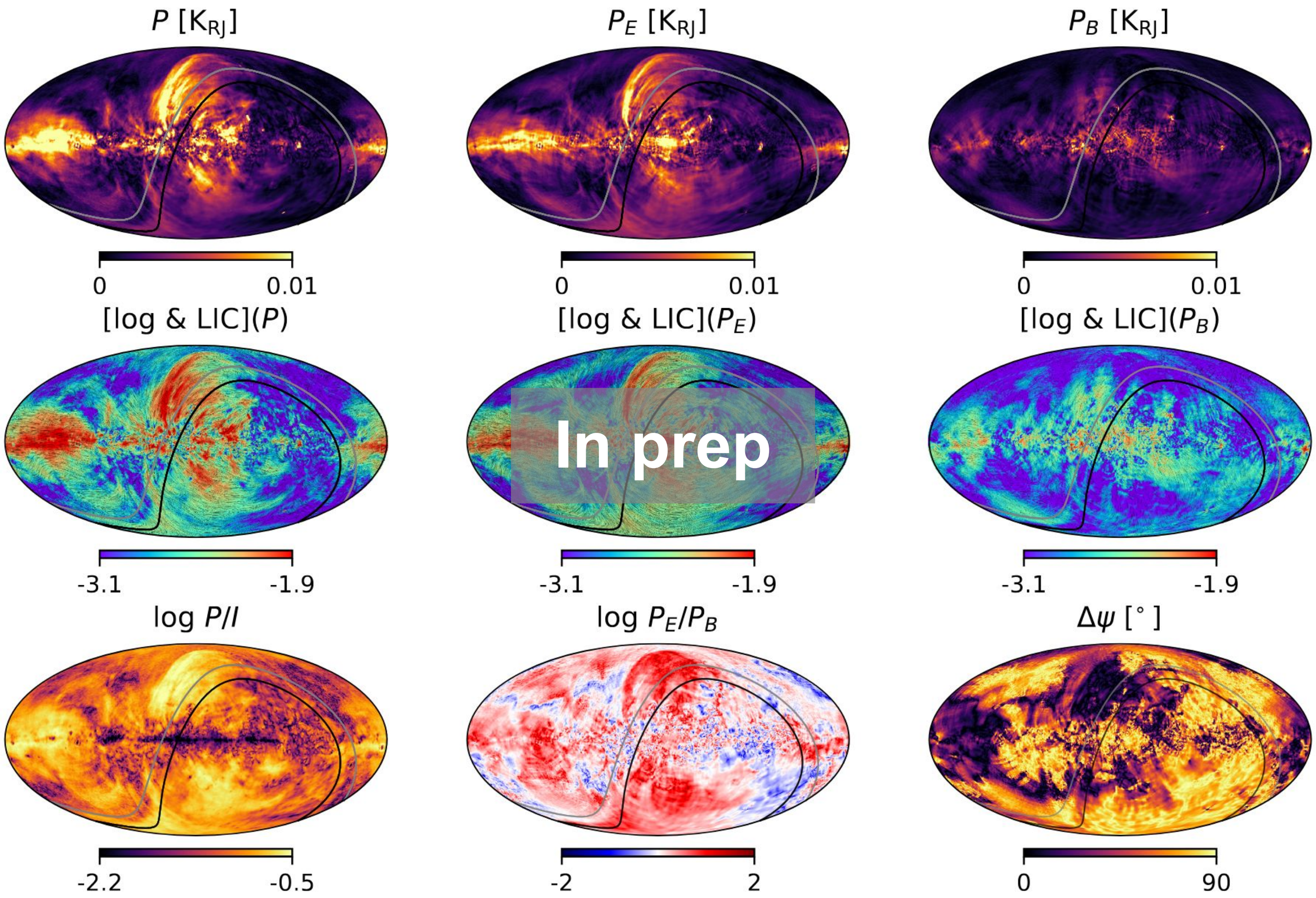
Step 3: Masking strategy of the residuals

(v2) Sec 5.3, Fig. 16



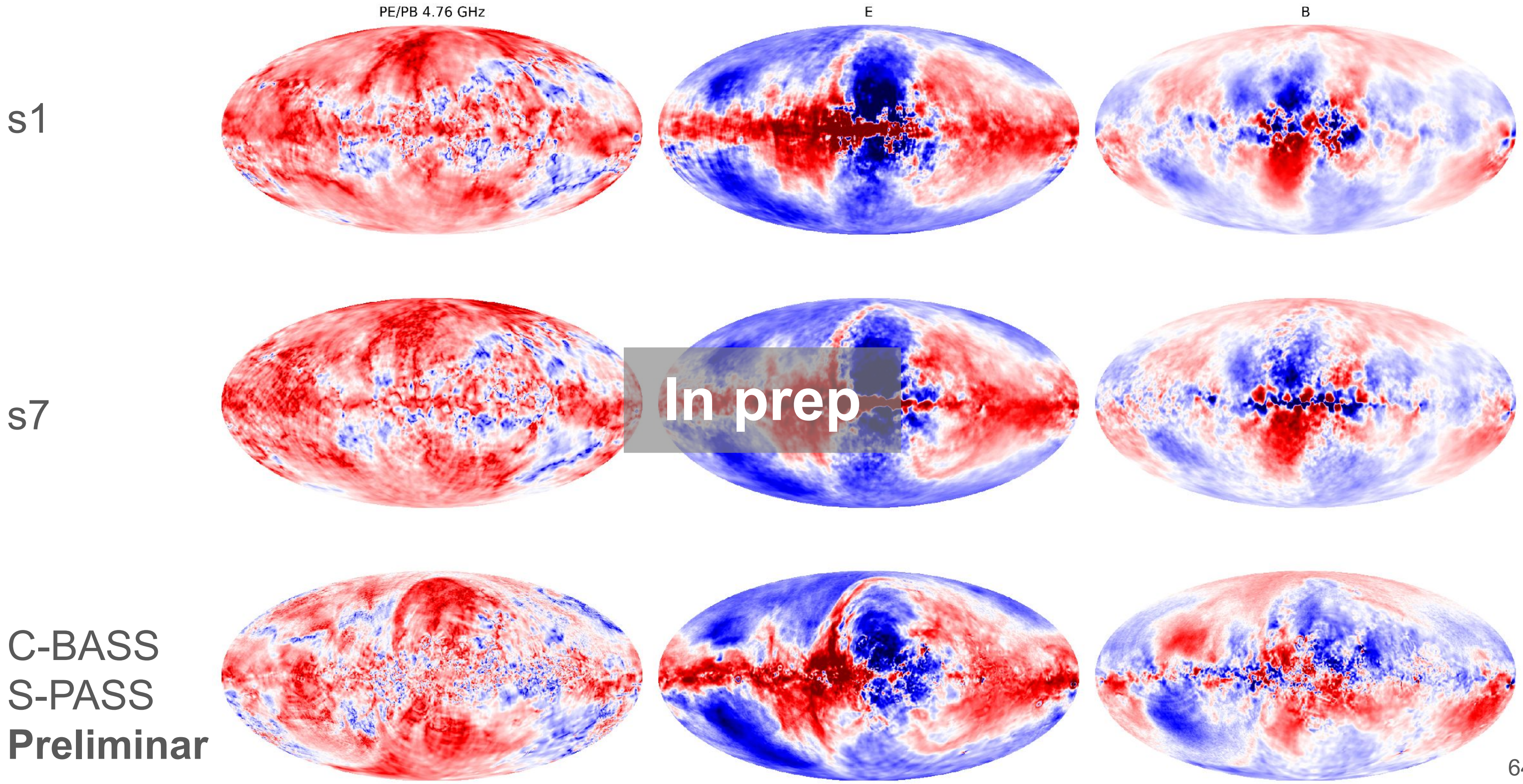
Model buiding with upcoming C-BASS data

Bonus data



Model buiding with upcoming C-BASS data

Bonus data

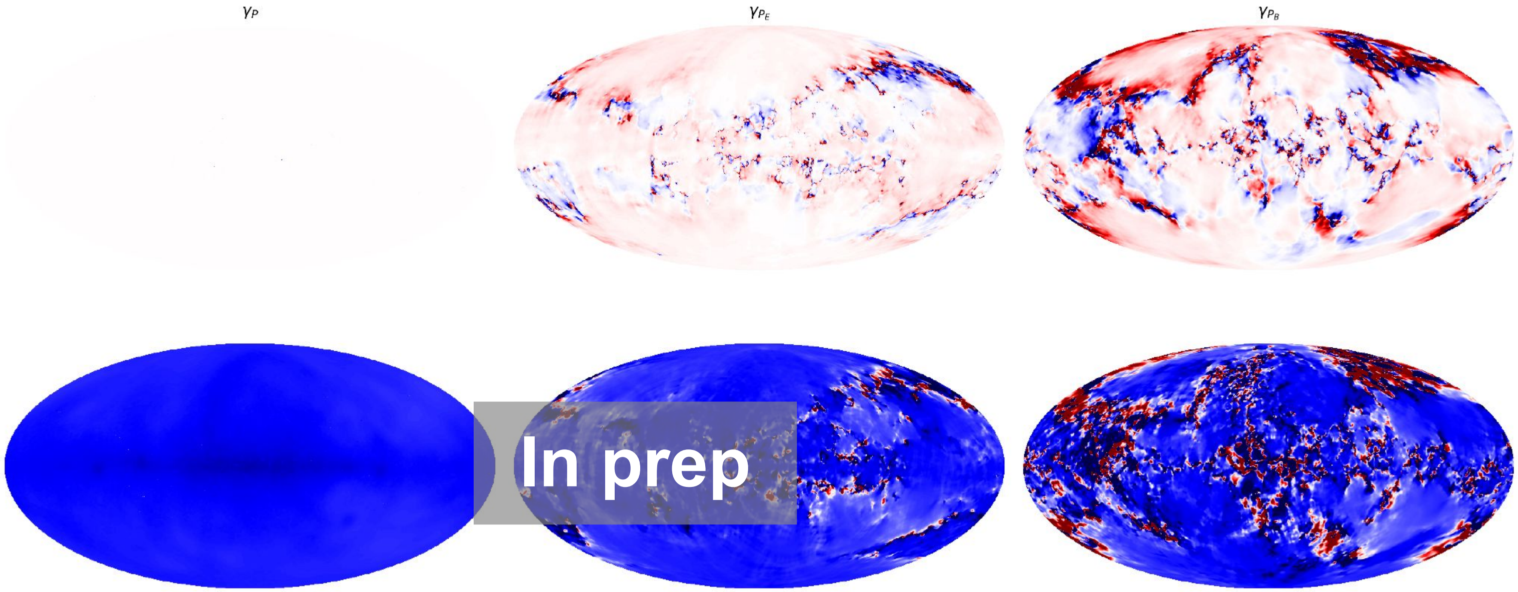


Model buiding with upcoming C-BASS data

Bonus data

s1

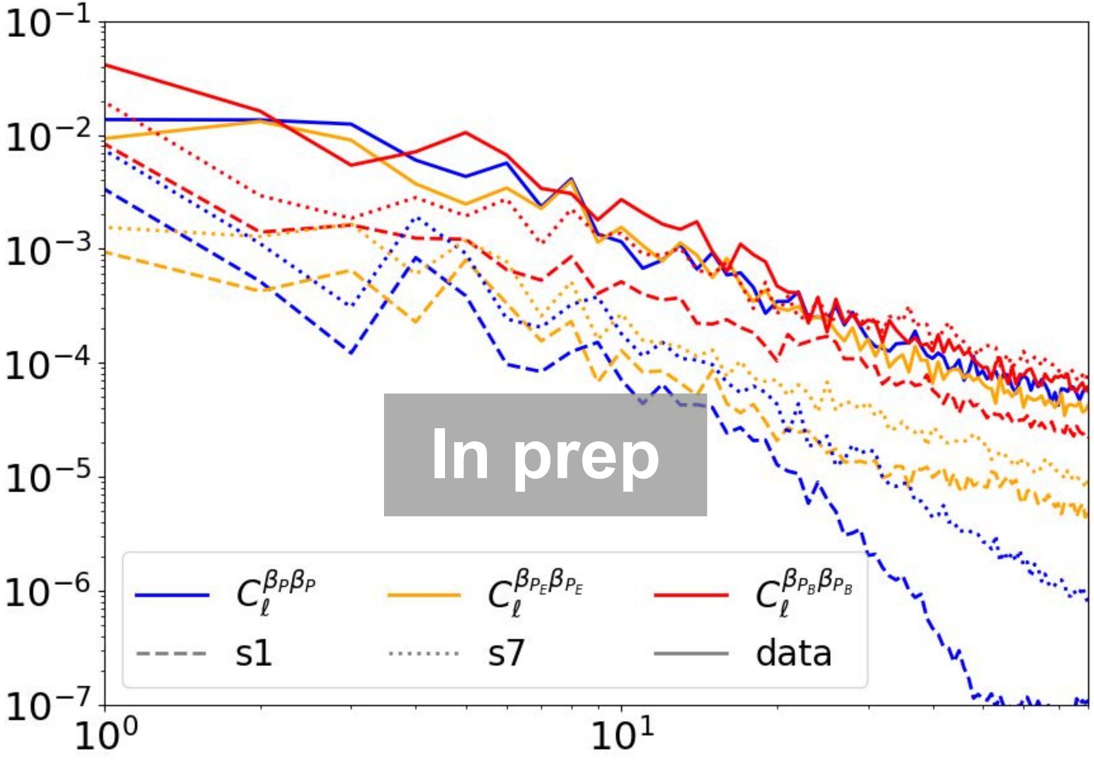
s7



C-BASS
S-PASS
WMAP
Planck
Preliminar

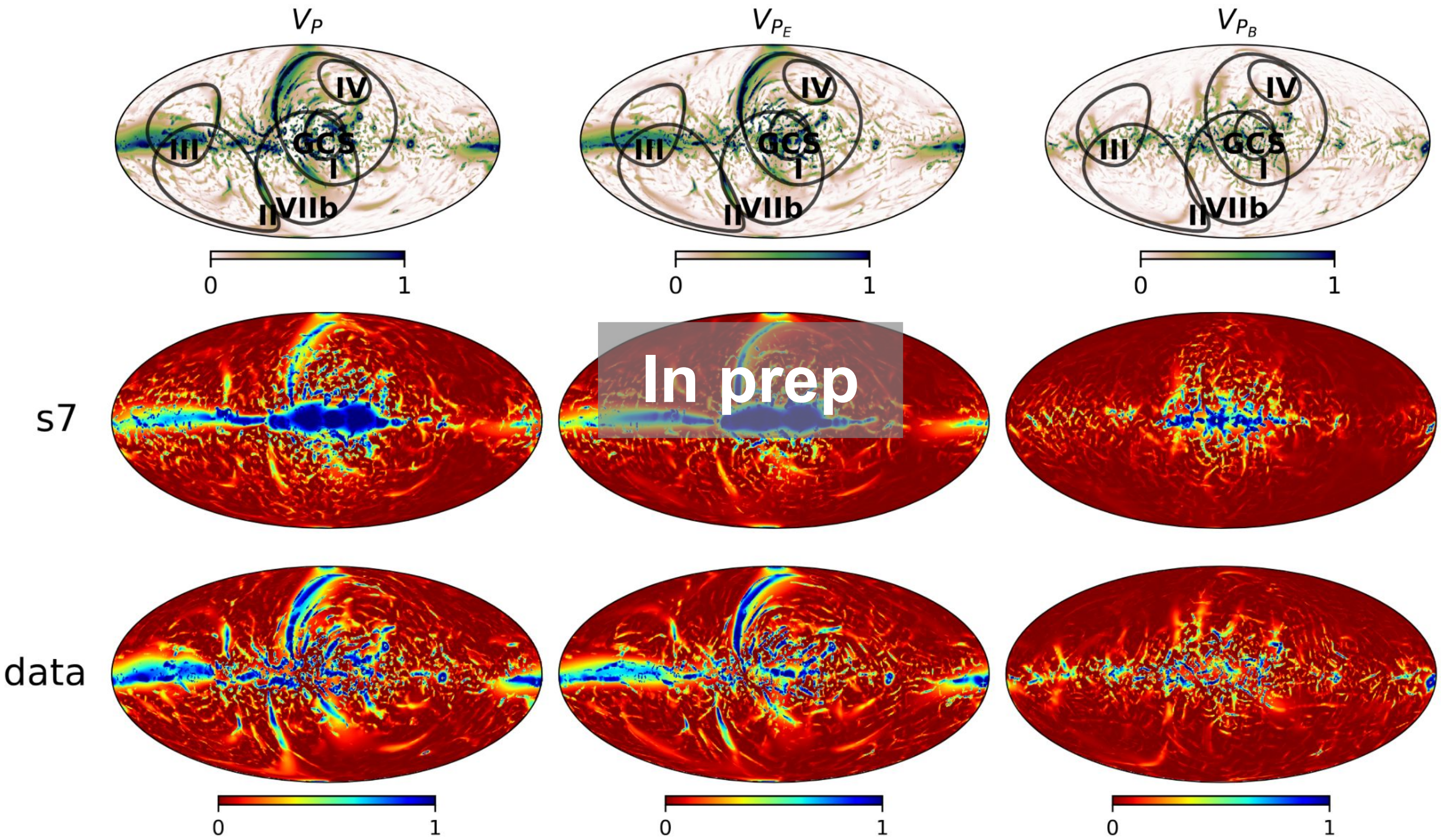
soon!

+ QUIJOTE w/



More spatial variability than expected? To be continued…

Multiscale vesselness score: acts as an additional filter for filament-like structures!



Model buiding with upcoming C-BASS data — Bonus data

P RM [rad/m^2] | P_E RM [rad/m^2] | P_B RM [rad/m^2]

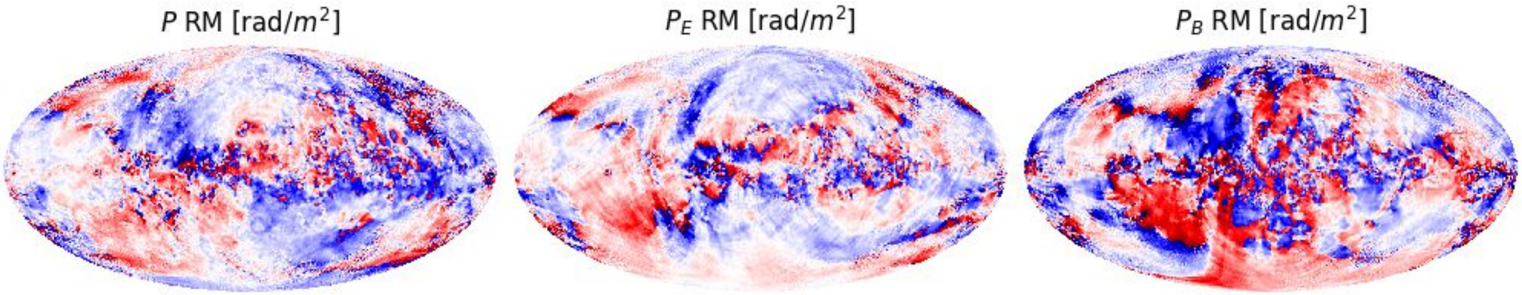
s1

… some $P_E P_B$-transform-induced RM ..

s7

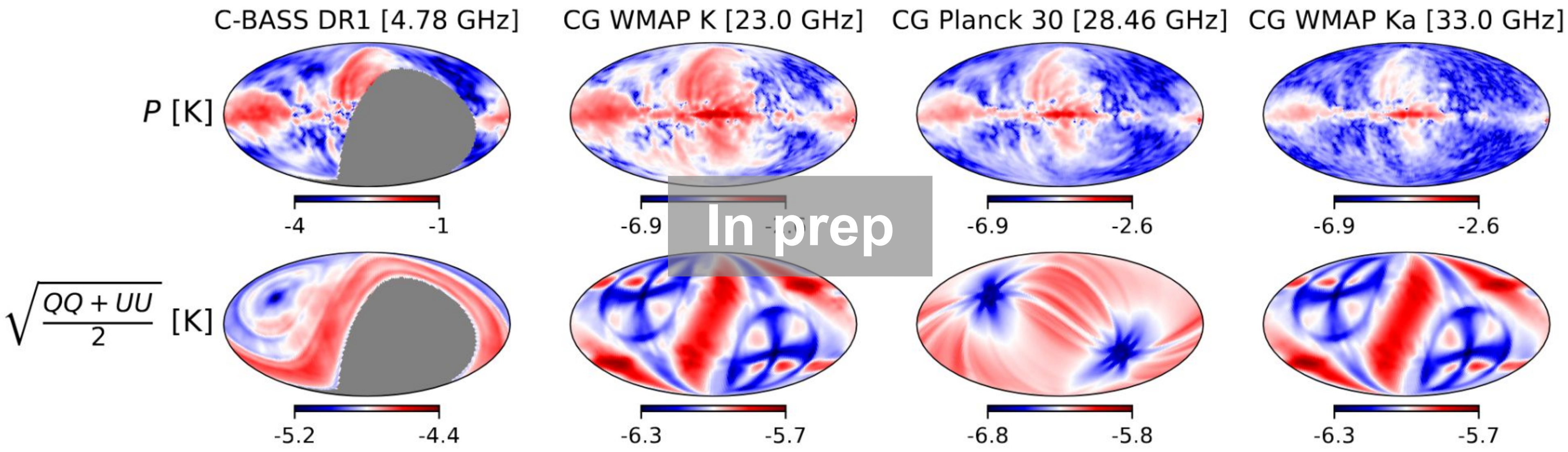
In prep

C-BASS
S-PASS
Planck
Preliminar



Input

Funded by
the European Union



Curvature estimation

Funded by
the European Union

$$\mathcal{L}_i(P_i|x_i,\sigma_i) = \frac{P_i}{\sigma_i^2}\exp\left[-\frac{P_i^2+x_i^2}{2\sigma_i^2}\right] I_0\left(\frac{P_i x_i}{\sigma_i^2}\right)$$

In prep

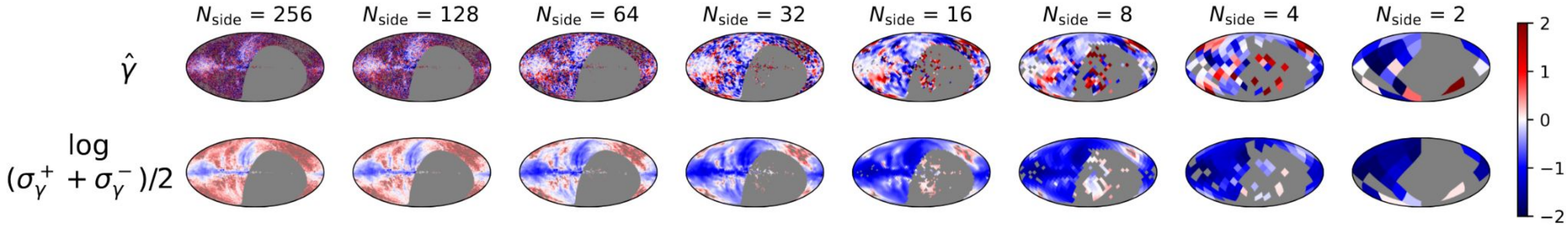
$$P_\nu^{\mathrm{model}} = A\left(\frac{\nu}{\nu_0}\right)^{\beta+\frac{\gamma}{2}\ln(\nu/\nu_0)}$$

$$\nu_0 \simeq \sqrt{4.78\times 30}\,\mathrm{GHz} \simeq 12\,\mathrm{GHz}$$

minos est of maxL & errors

$\hat{\gamma}$ $\sigma_{\gamma,-}$ $\sigma_{\gamma,+}$

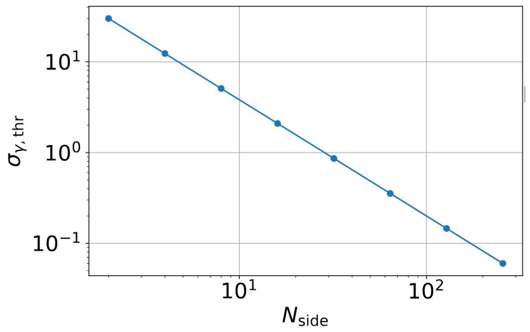
with stringent convergence requirements…

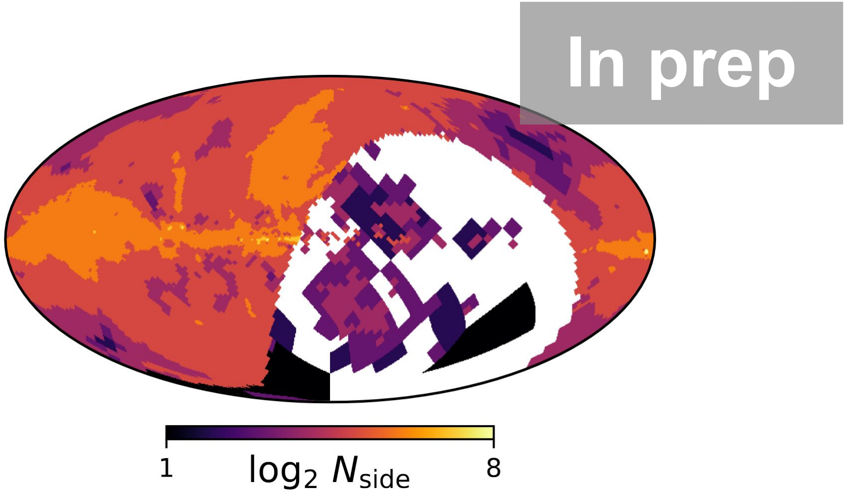


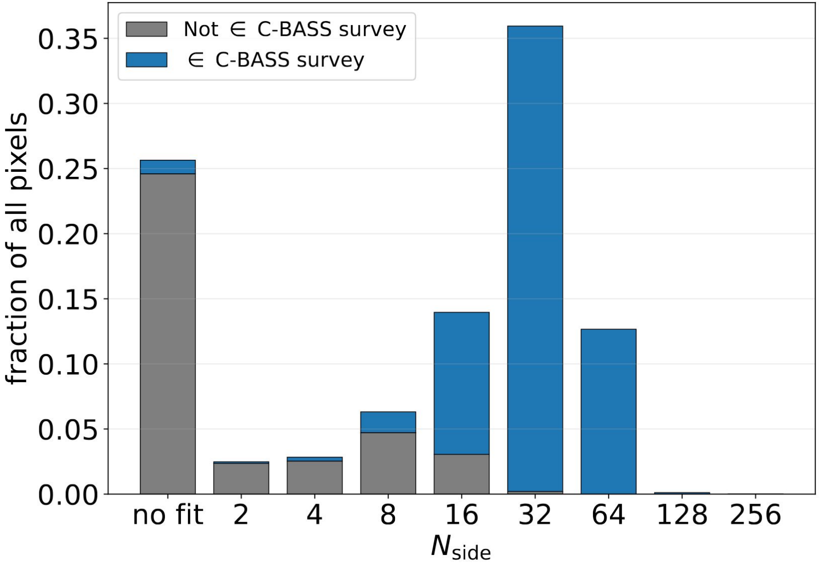
Multi-resolution

The fit is done at all N_{side} = [2, 4, …, 128, 256].
A multi-res map by selecting the highest N_{side} st.

$$\frac{1}{2}\left(\sigma_{\gamma,-} + \sigma_{\gamma,+}\right) < \sigma_{\mathrm{thr}}(N_{\mathrm{side}})$$







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