Towards a parametric model to describe HWP non-idealities for primordial B-modes detection

CMB-CAL @ Bicocca, Milan 2024

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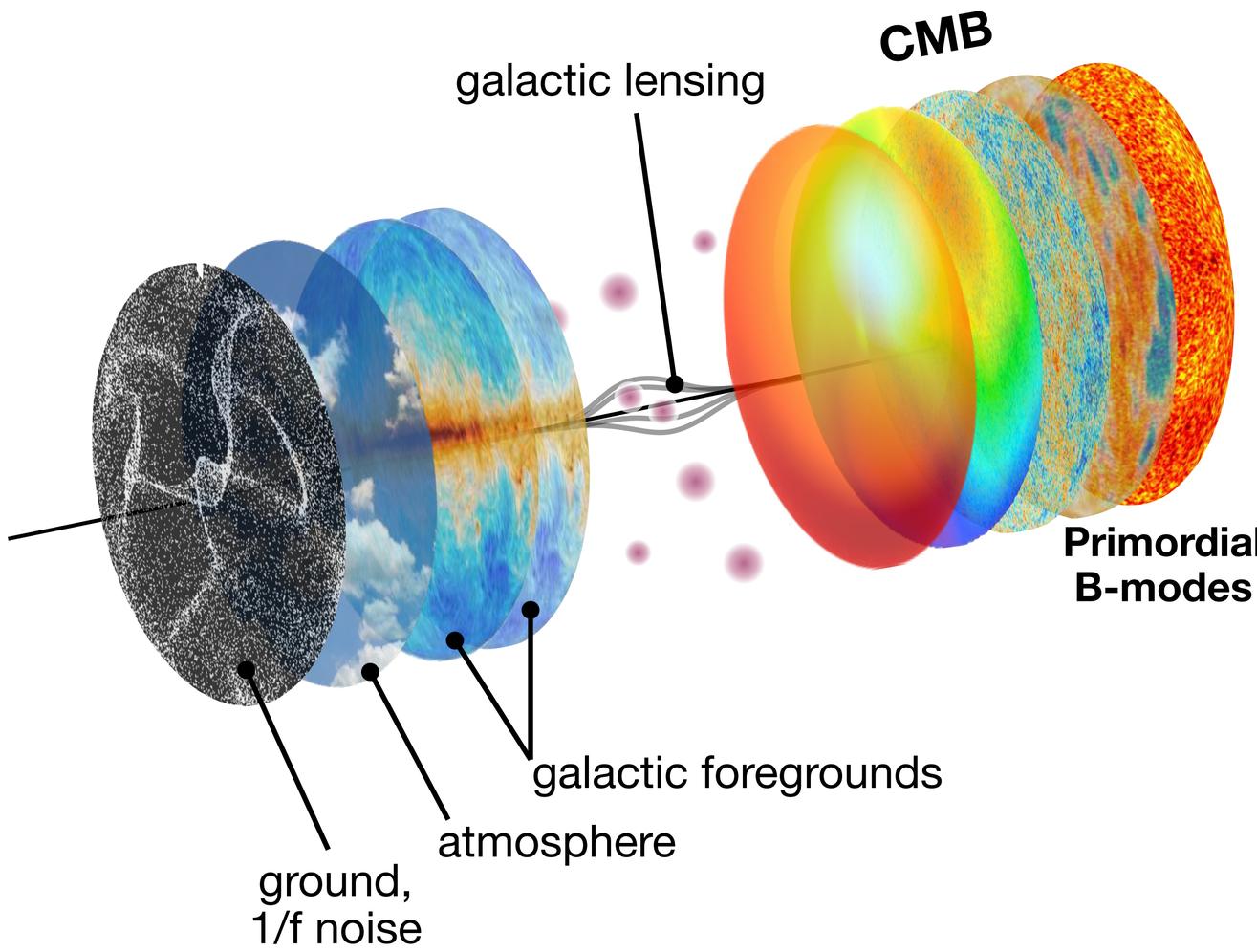
07/11/2024

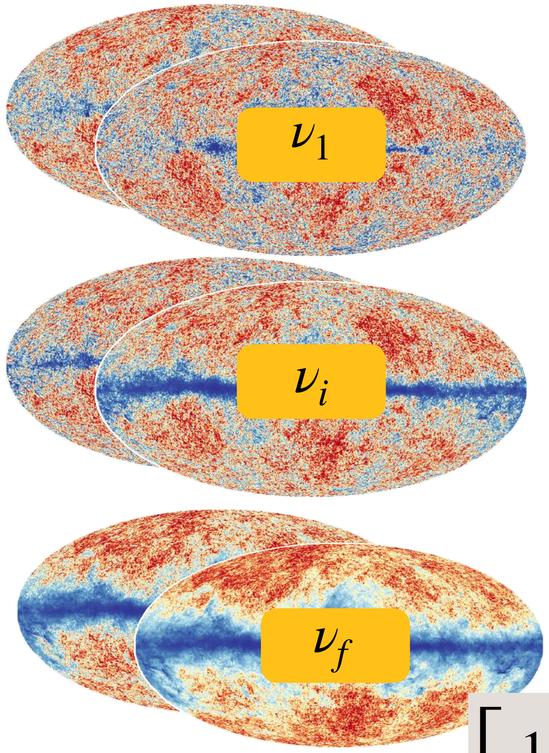
Observational challenges

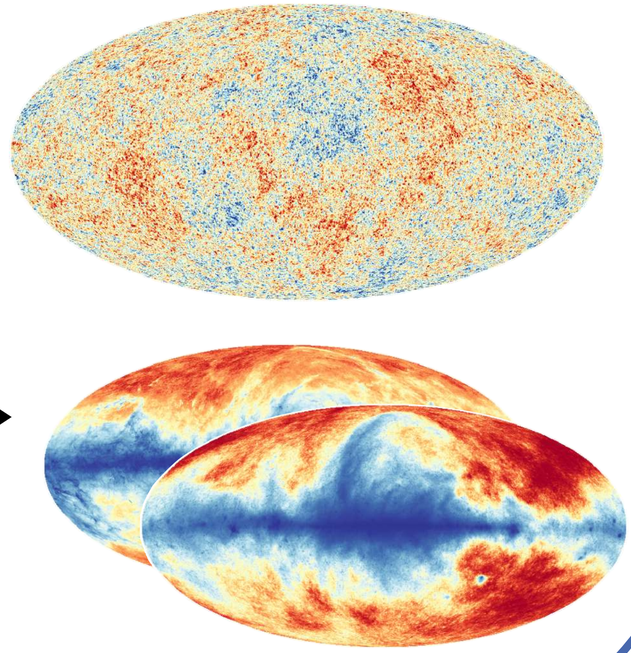


Credit: Josquin Errard

A short recap of component separation

Frequency maps:
Q/U maps for each observed frequency





Component maps:
Q/U map for each component

Data model (observed):

$$d = \begin{bmatrix} 1 & a^{dust}(\nu_1) & a^{synch}(\nu_1) \\ \vdots & \vdots & \vdots \\ 1 & a^{dust}(\nu_f) & a^{synch}(\nu_f) \end{bmatrix} \begin{bmatrix} s_{cmb} \\ s_{dust} \\ s_{synch} \end{bmatrix} + n$$

$\mathbf{A}(\beta, \nu)$ **mixing matrix (Nfreq x Ncomponent)**:
gives the frequency scaling of each sky component (MBB for dust, power law for synchrotron), assumed parametrised by *spectral parameters* β

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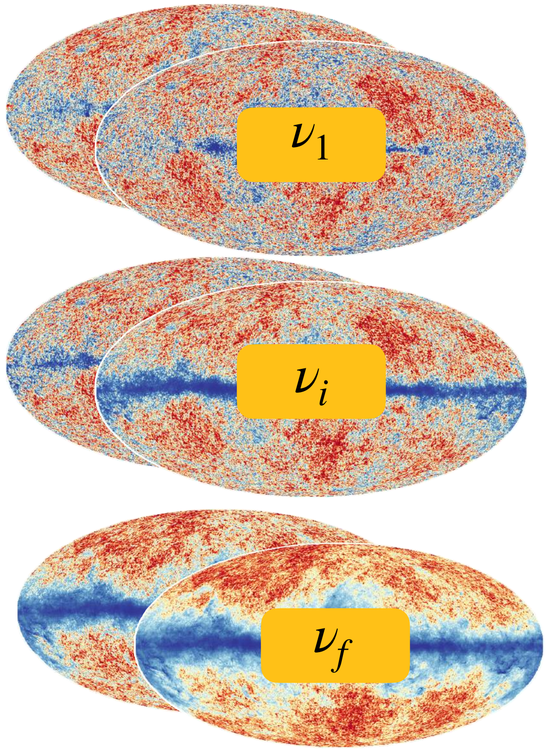
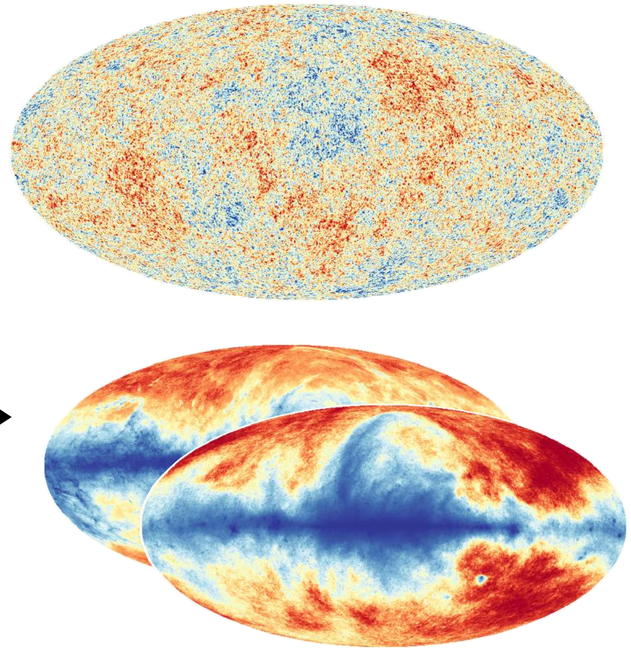




Component maps:
Q/U map for each component

Data model (observed): $d = \mathbf{A}(\beta)\ s + n$

generalised least squares solution

Likelihood of the data: $2\log\mathscr{L}(s,\beta) = (d-\mathbf{A}s)^T\mathbf{N}^{-1}(d-\mathbf{A}s)$ → $\tilde{s} = (\mathbf{A}^T\mathbf{N}^{-1}\mathbf{A})^{-1}\mathbf{A}^T\mathbf{N}^{-1}d$

Spectral likelihood: $2\log\mathscr{L}_{spec}(\beta) = d^T\mathbf{N}^{-1}\mathbf{A}(\mathbf{A}^T\mathbf{N}^{-1}\mathbf{A})^{-1}\mathbf{A}^T\mathbf{N}^{-1}d$ → $\tilde{\beta}$

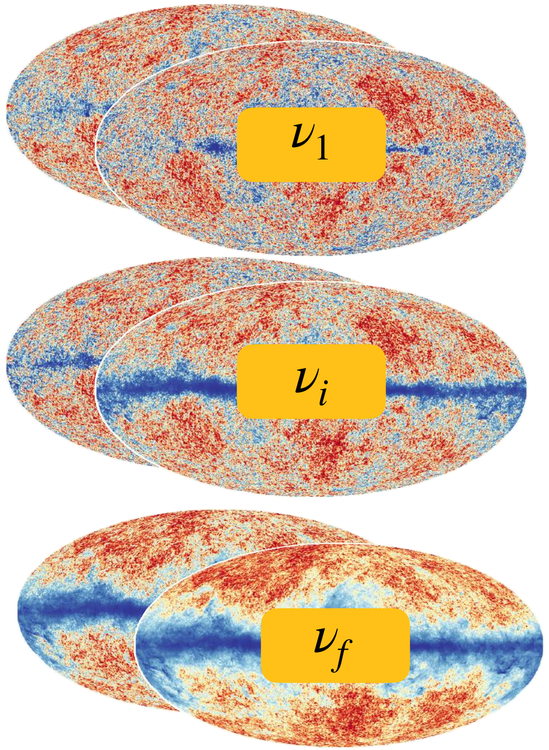
Stompor & al. (2009)

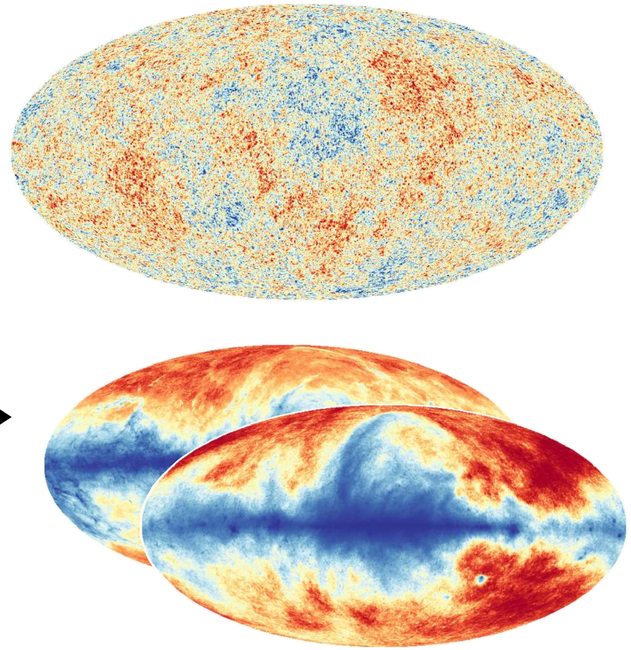
Generalised component separation

Vergès et al. (2020)
Jost et al. (2023)

Frequency maps:
Q/U maps integrated maps for each observed frequency

$$\bar{\mathrm{X}}(\nu_c) = \frac{\int \mathrm{d}\nu B(\nu, nu_c)\mathbf{X}(\nu)}{\int \mathrm{d}\nu B(\nu)}$$





Component maps:
Q/U map for each component

Data model (observed):

$$d = \int \mathrm{d}\nu B(\nu)\, \mathrm{M}_{inst}(\gamma, \nu)\, \mathbf{A}(\beta, \nu)\, s + n$$

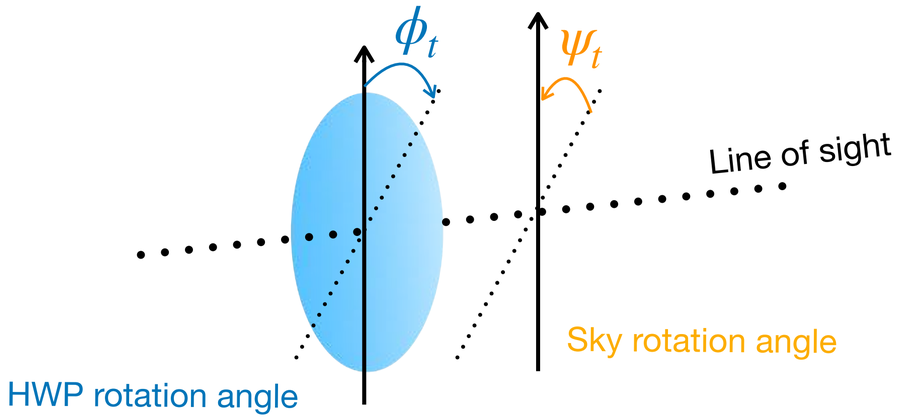
Generalised mixing matrix:
parametrised by *spectral parameters* and *hardware parameters*
$\longrightarrow$ **HWP effects**

Generalised component separation

Vergès et al. (2020)

Monochromatic model at the map level:

$$d = \mathrm{I} + \cos(4\phi + 2\psi_t)\,\mathrm{Q} + \sin(4\phi + 2\psi_t)\,\mathrm{U}$$
$$= \mathrm{M}_{00}\mathrm{I} + \mathrm{M}_{01}\mathrm{Q} + \mathrm{M}_{02}\mathrm{U}$$



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generalisation

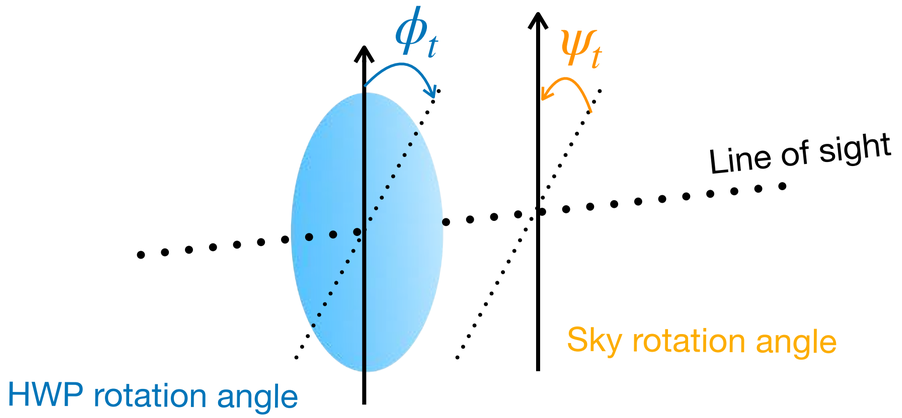
Multifrequency model:

$$M_{0i} = \sum_{k=0,4} \mathrm{C}_{i,k}\cos(k\phi + 2\psi_t) + \sum_{k=0,4} \mathrm{S}_{i,k}\sin(k\phi + 2\psi_t)$$

regroup terms according to their time dependence: **mixed Stokes maps**

$$\begin{pmatrix} \tilde{I}(\gamma_t,\nu) \\ \tilde{C}_0(\gamma_t,\nu) \\ \tilde{S}_0(\gamma_t,\nu) \\ \tilde{C}_4(\gamma_t,\nu) \\ \tilde{S}_4(\gamma_t,\nu) \end{pmatrix} = \begin{bmatrix} \mathrm{M}_{00}(\nu) & 0 & 0 \\ 0 & \mathrm{C}_{Q;0}(\nu) & \mathrm{C}_{U;0}(\nu) \\ 0 & \mathrm{S}_{Q;0}(\nu) & \mathrm{S}_{U;0}(\nu) \\ 0 & \mathrm{C}_{Q;4}(\nu) & \mathrm{C}_{U;4}(\nu) \\ 0 & \mathrm{S}_{Q;4}(\nu) & \mathrm{S}_{U;4}(\nu) \end{bmatrix} \mathbf{A}(\beta,\nu) \begin{pmatrix} I(\gamma_t,\nu) \\ Q(\gamma_t,\nu) \\ U(\gamma_t,\nu) \end{pmatrix}$$

$$d = \mathrm{M}_{hwp}(\gamma,\nu)\,\mathbf{A}(\beta,\nu)\,s$$



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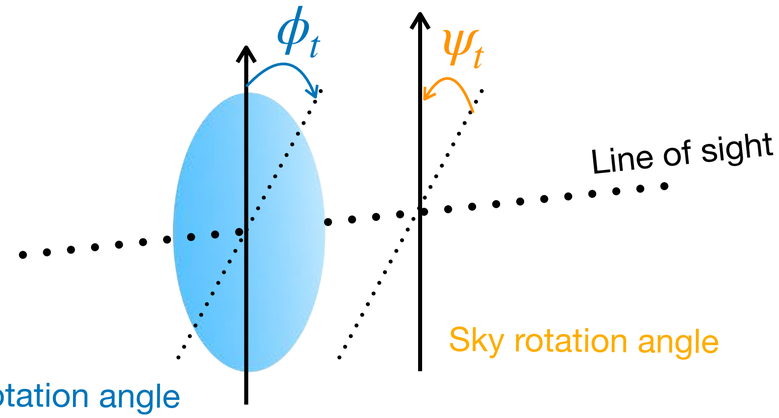


- Output of the mapmaking procedure are not pure Q/U maps at each frequency but **mixed Stokes maps**
  → under the assumption of a perfectly uniform sky coverage
  → not trivial Q/U demodulation
- **Estimation of HWP** parameters from component separation:
  → **need of priors**, necessity hardware calibration
  → considering the fact that they apply to more than one frequency band
- Interplay between instrumental and foreground parameters
  → mitigation: **time domain component separation**

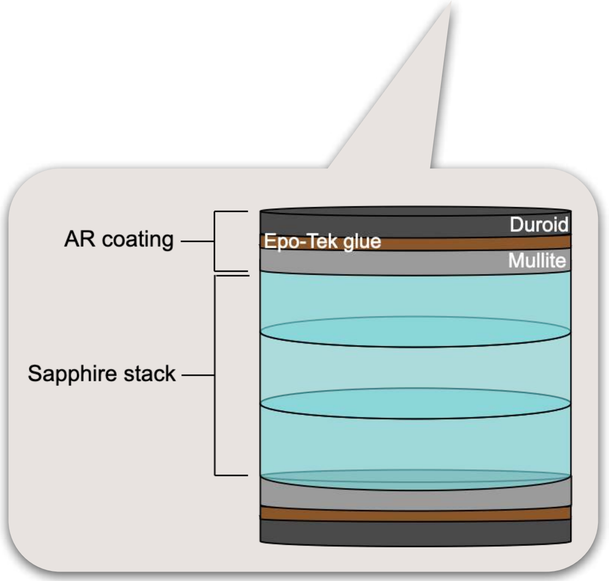
Extension of the former model

Increased sensitivity of CMB experiment requires control of systematics: need for a reliable model of the optic chain

Consider a f**requency-dependent analytical model** for the hwp and study 2 cases:

- **No bandpass case**:
  → An effective hwp can be built to make up for non-idealities of the hwp

- **Band-pass integrated case**:
  → No effective model efficient enough to reduce the bias due to hwp-related systematics



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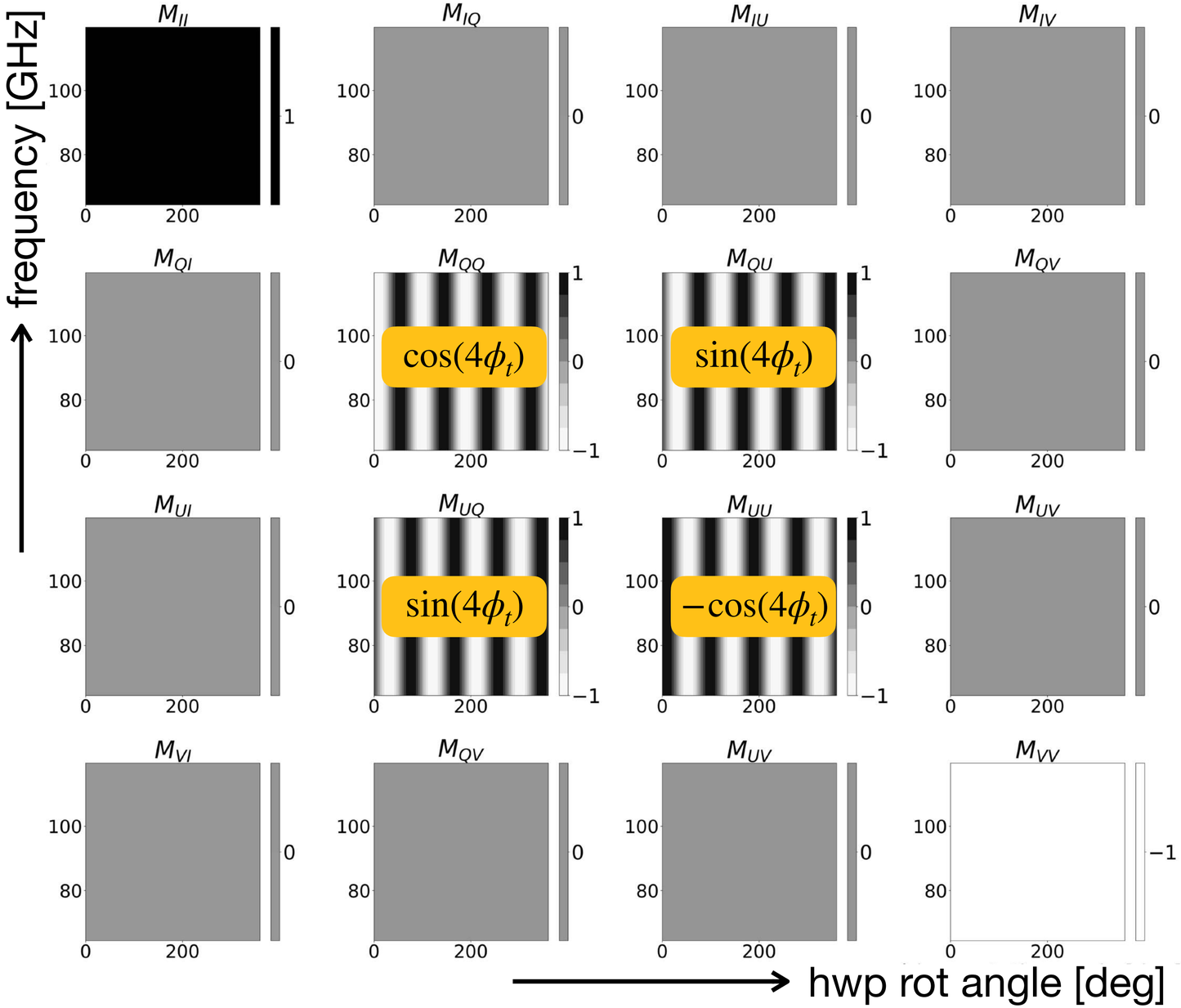
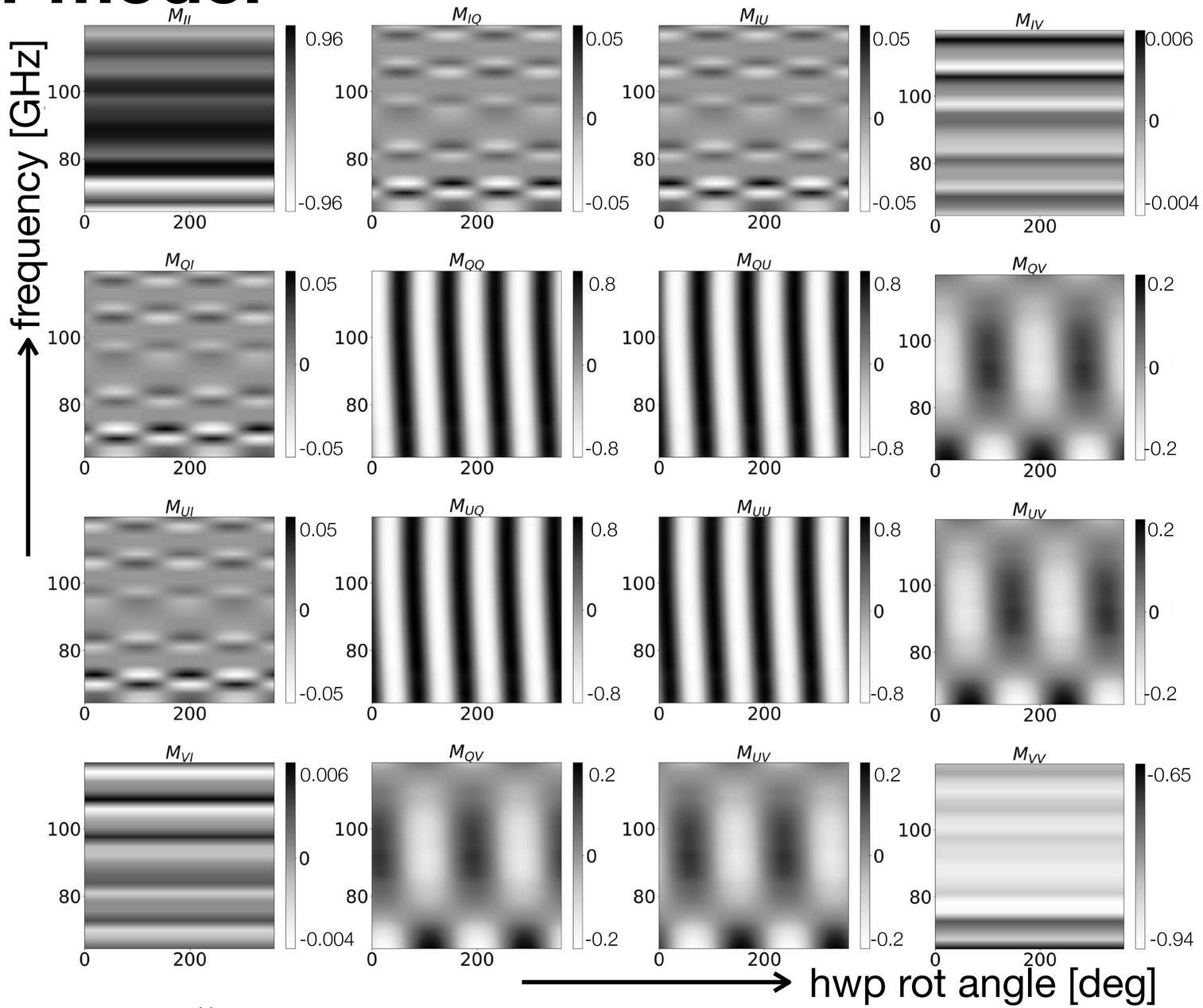
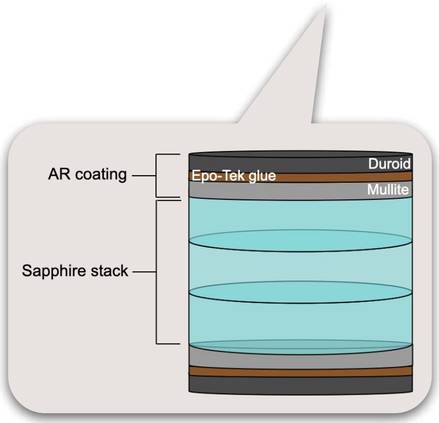


Extension of the former model

Parameters from Sakaguri & al. (2024)
MF2, 0° incident angle

- Effects of transmission and reflection occurring in a hwp stack: transfer matrix method from Essingler-Hileman (2014)





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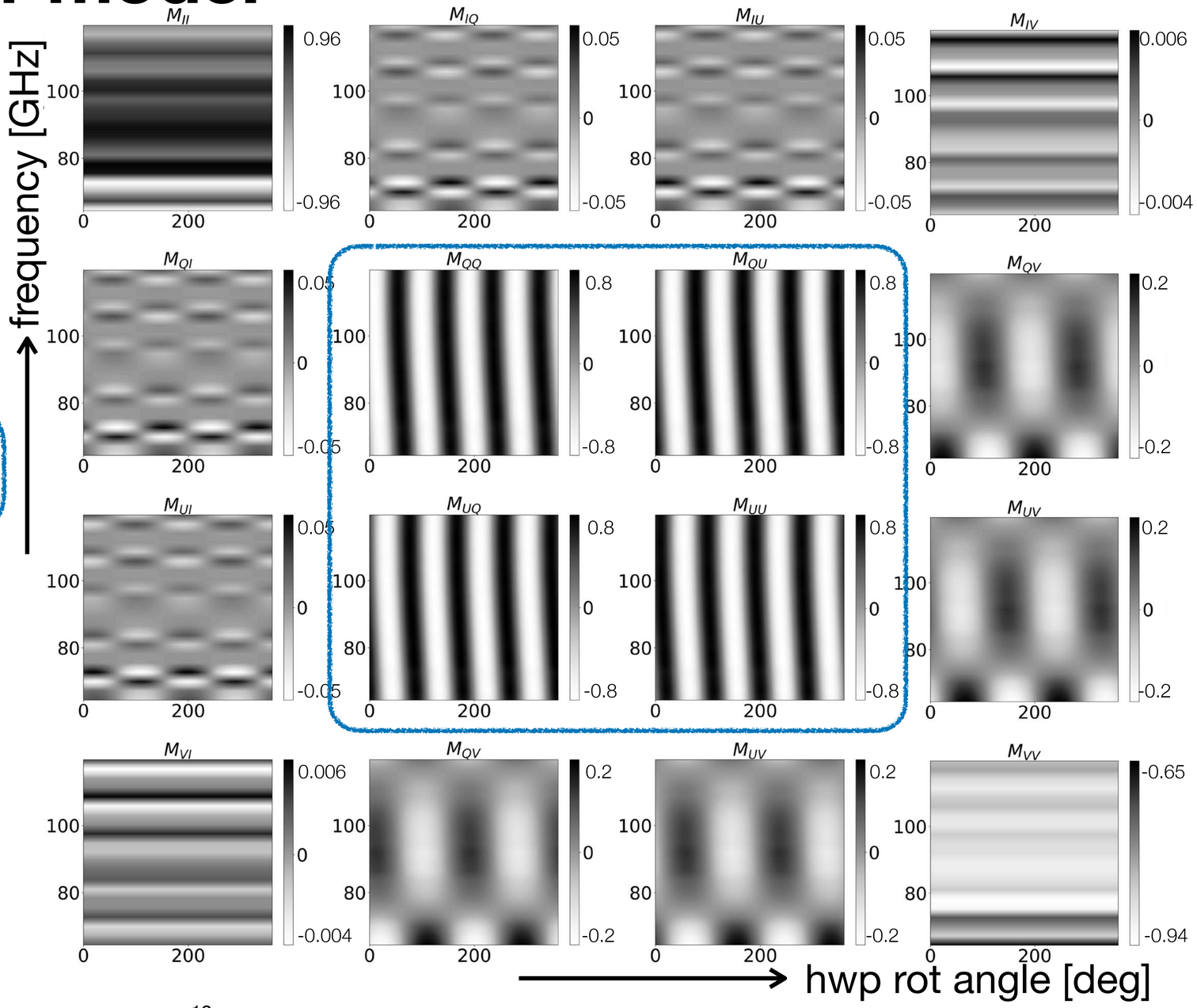
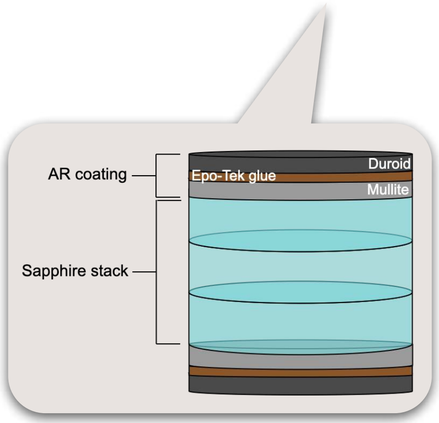
✳**Frequency dependent phase-shift**
✳Less efficient modulation than the ideal case





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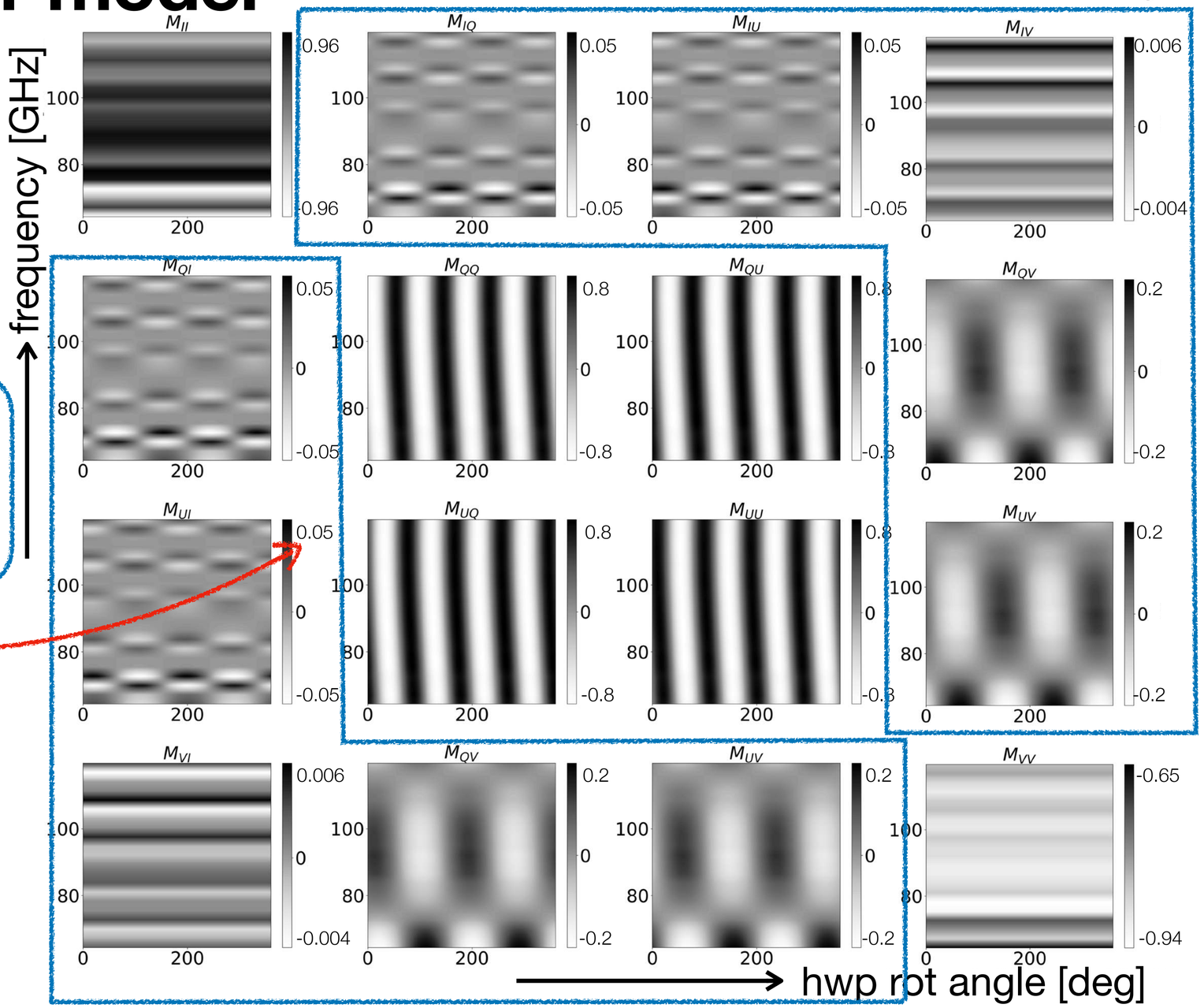
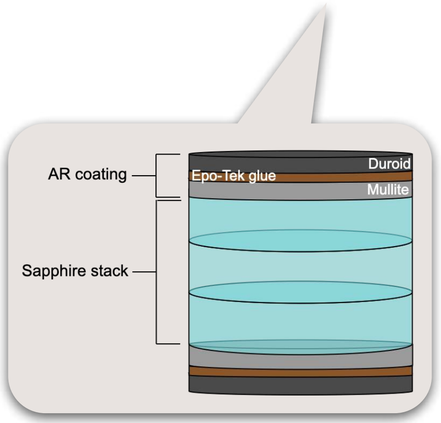
✳I → P leakage + V → Q/U
✳2f modulation





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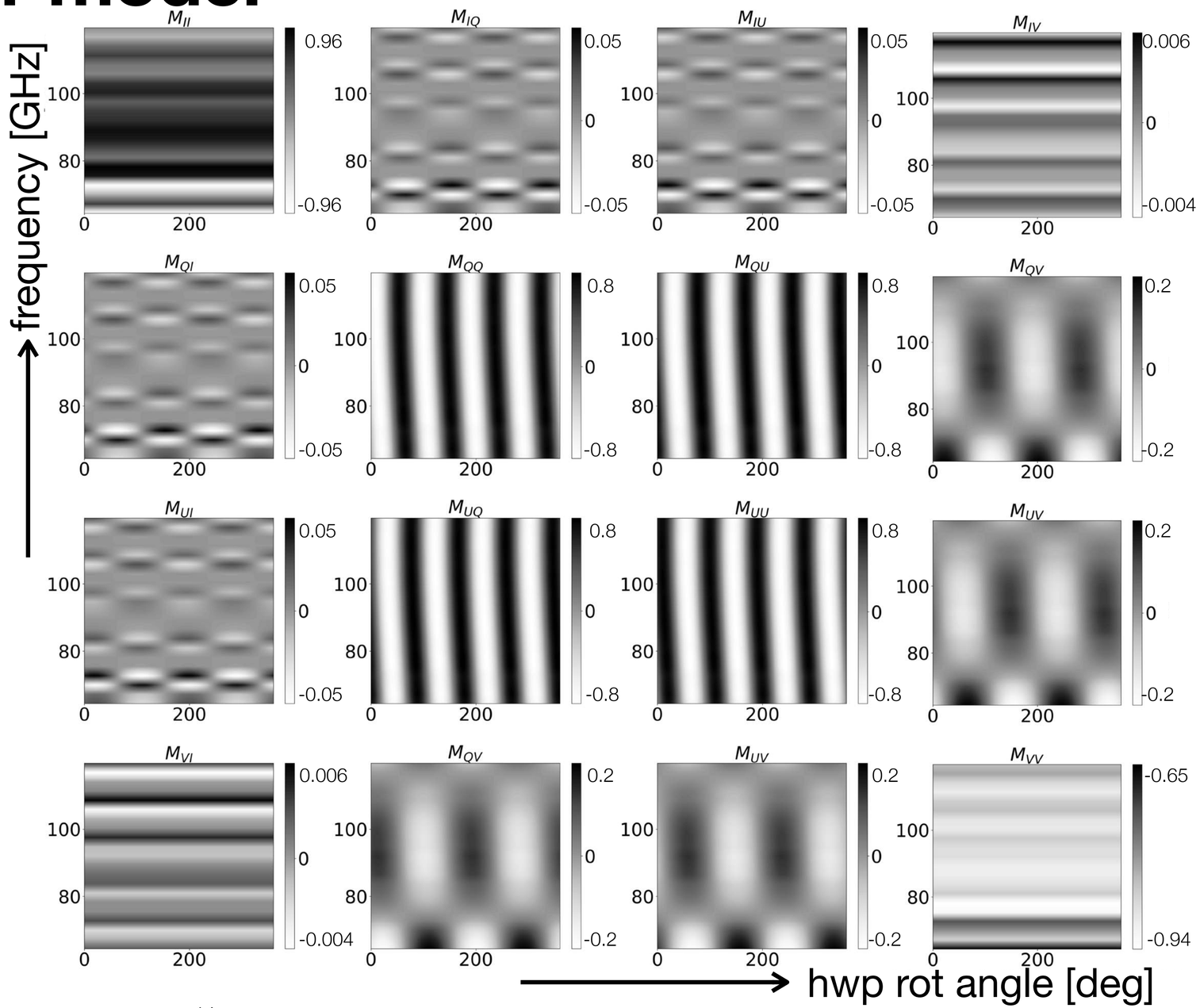
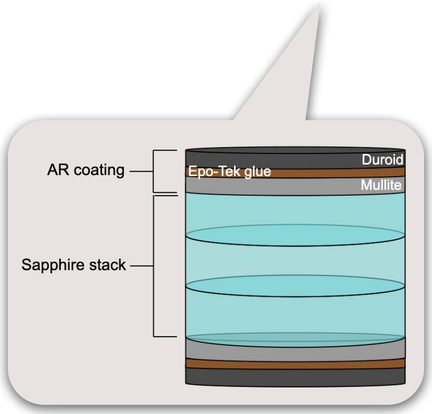
✳Frequency dependent phase-shift
✳Less efficient modulation than the ideal case
✳I → P leakage + V → Q/U
✳2f modulation
✳Relevant parameters: layers thickness, incident angle (for each det)

This figure is derived from EM theory, so is expected even for a perfectly known hwp





No band-pass case

Pipeline:   → See Josquin's talk on Friday!

- Modularity, extensibility, simplicity:

```
h = pol @ hwp @ mixing_matrix @ sampling
sol = ((h.T @ h).I @ h.T)(tod)
```

No band pass case

Pipeline: FURAX SciPol erc → See Josquin's talk on Friday!

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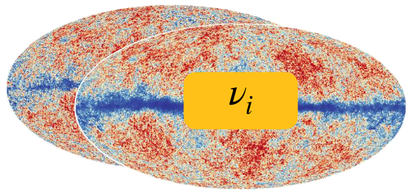
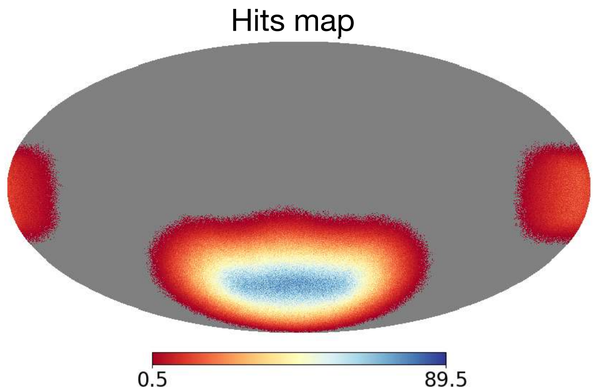


Q/U single frequency maps

- PySm templates: cmb, dust @ 353 GHz, synchrotron @ 30 GHz
- No noise
- Scanning strategy: random hits on SO SAT like mask



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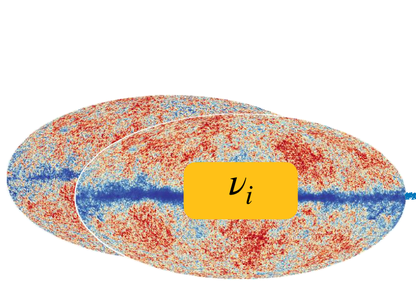
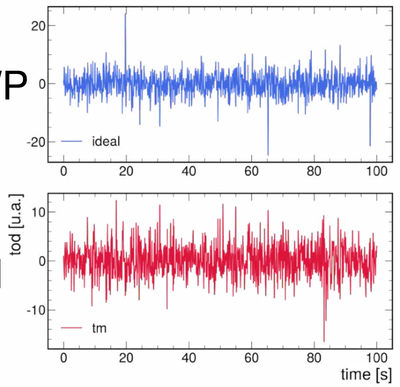


Q/U single frequency maps

HWP modulation

Ideal HWP

Non ideal HWP



Ideal HWP sky reprojection

Q/U residuals single frequency maps

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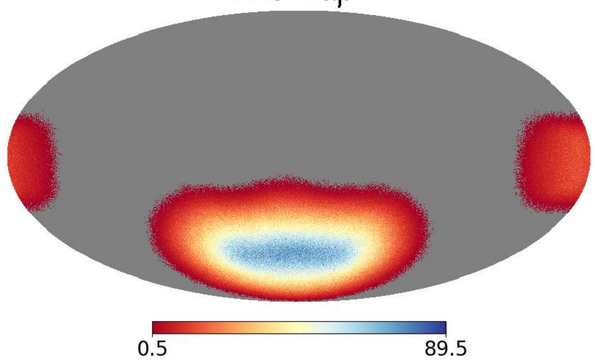
Hits map



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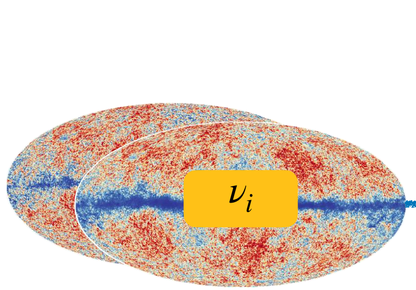

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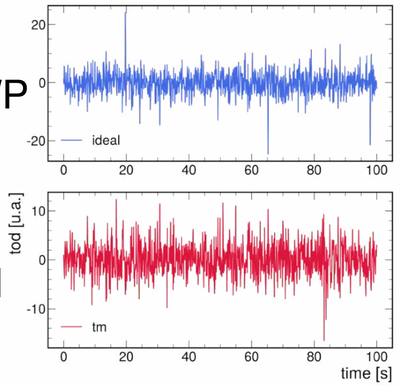

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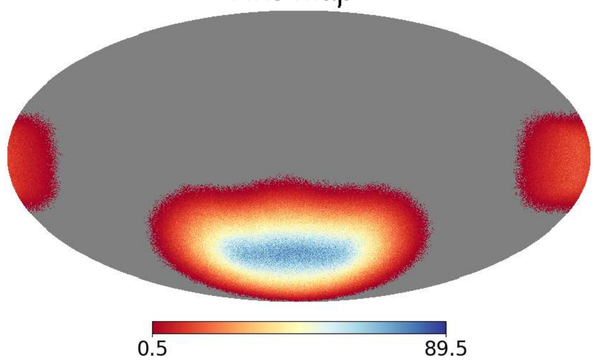
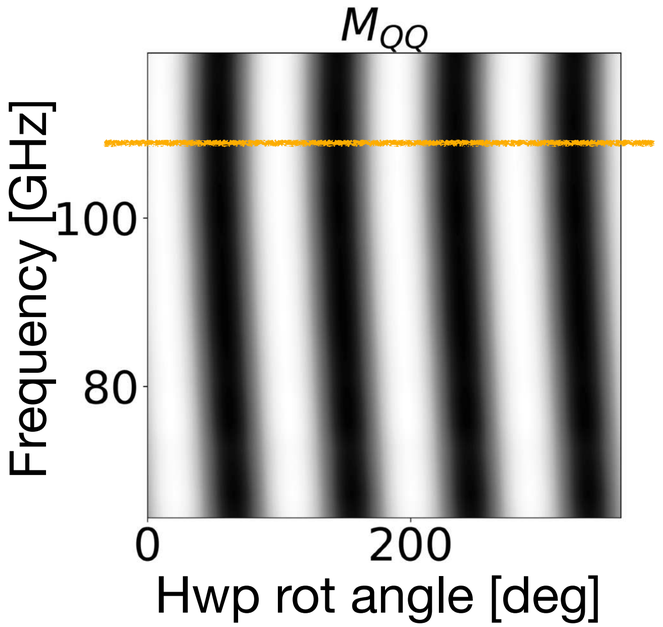


Reproject on the sky with an **effective ideal hwp**: calibrate the non-ideal hwp on the ideal one at tod level

No band pass case

Effective hwp model: fit



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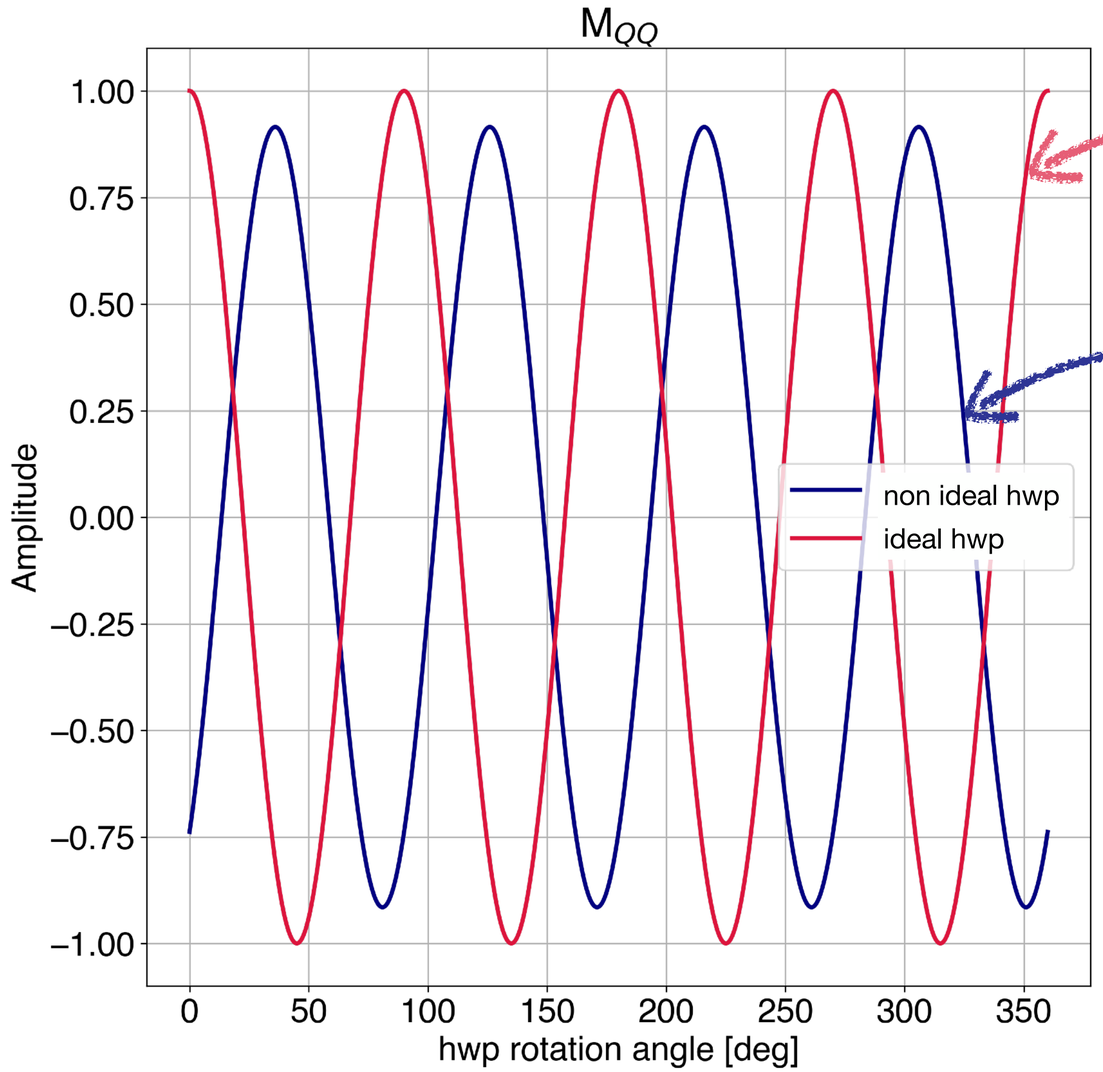
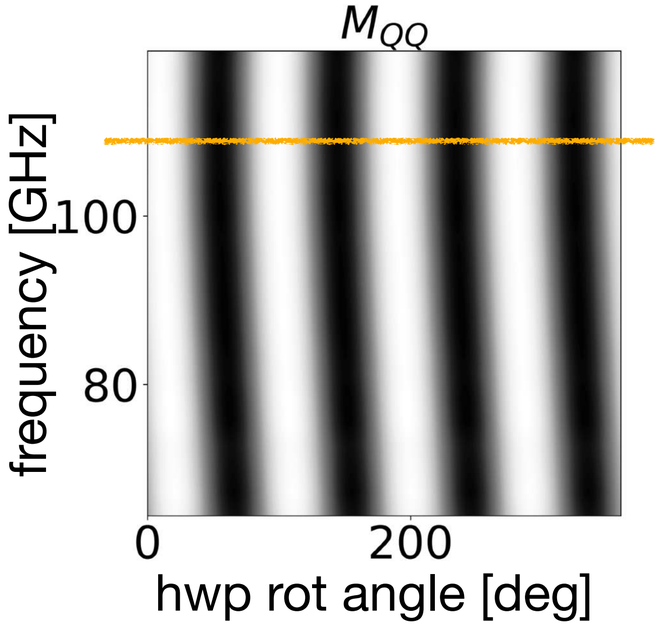


$\cos(4\phi_t)$



Fit for $\varepsilon(\nu)\ \cos(4\phi_t + \varphi(\nu)) + \alpha(\nu)$

Free frequency-dependent parameters of the fit

- ε: amplitude
- φ: phase-shift
- α: offset

No band pass case

Effective hwp model

Pipeline: FURAX SciPol erc

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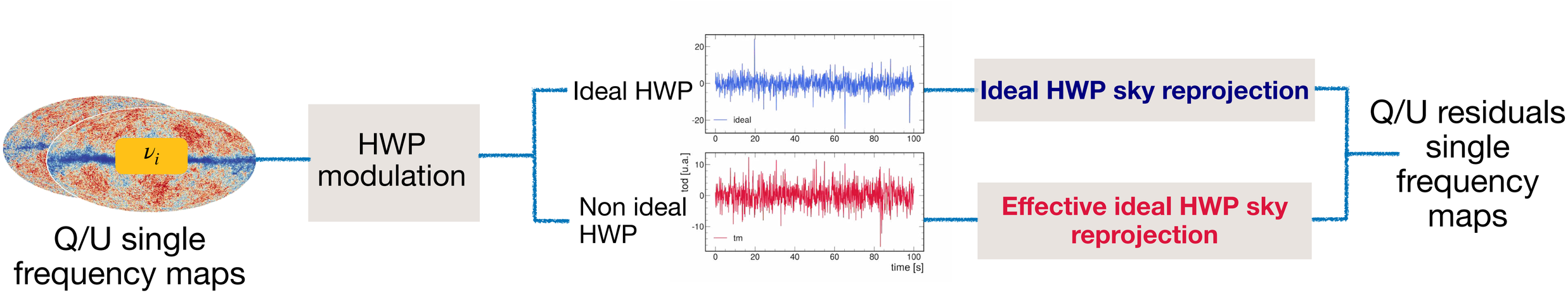


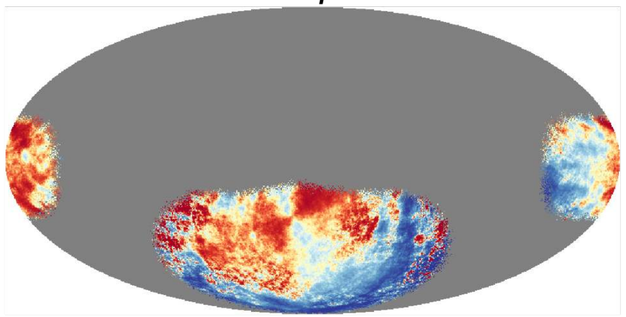
No band pass case

Effective hwp model

Work in progress

UHF2, `comp=[cmb+dust+synch]`

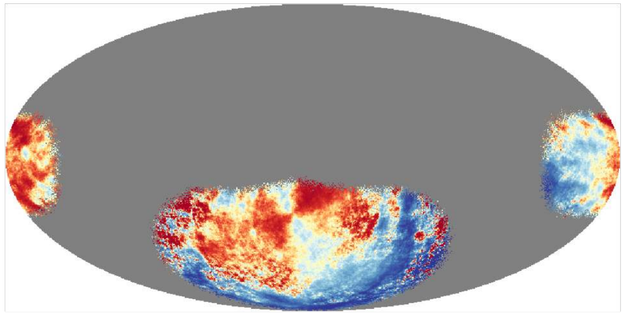
Q_{input}



μK_{CMB}

-183.059 289.649

Q_{id}



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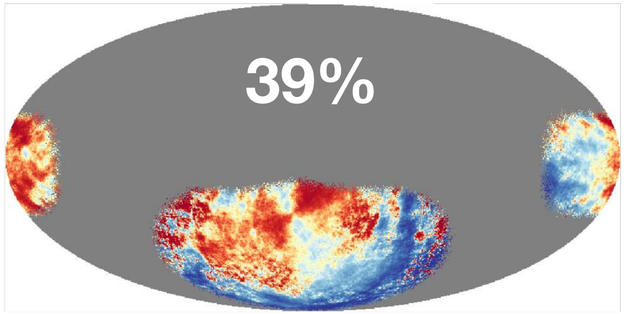
Modulation with **ideal** hwp
Reprojection with **ideal** hwp

Q_{non_id}

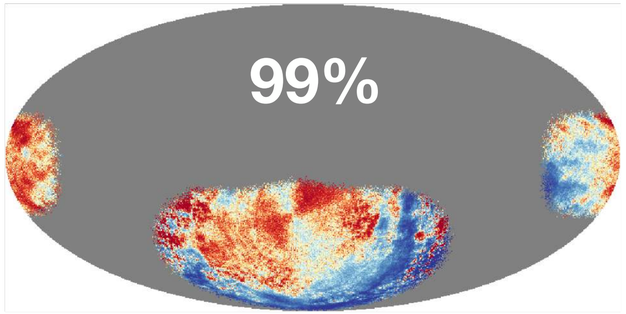


μK_{CMB}

-71.7852 113.549

Modulation with **non-ideal** hwp
Reprojection with **ideal** hwp

Q_{eff}

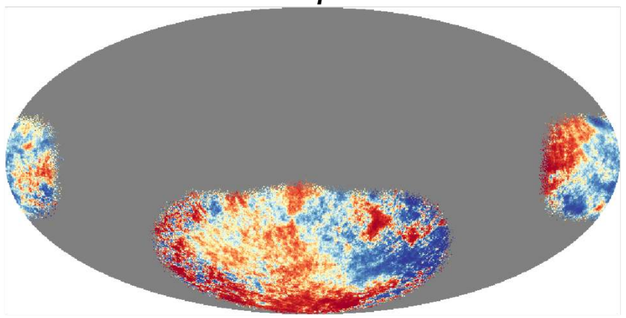


μK_{CMB}

-184.175 289.053

Modulation with **non-ideal** hwp
Reprojection with **effective** hwp

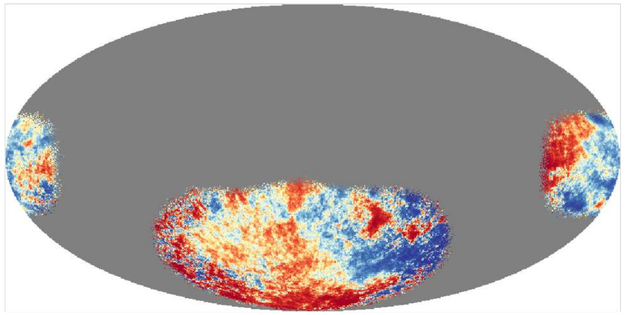
U_{input}



μK_{CMB}

-92.7897 135.79

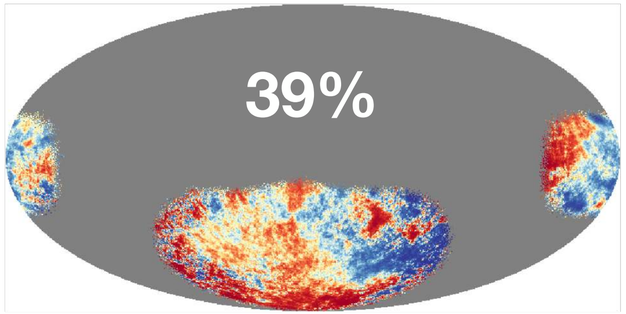
U_{id}



μK_{CMB}

-92.7897 135.79

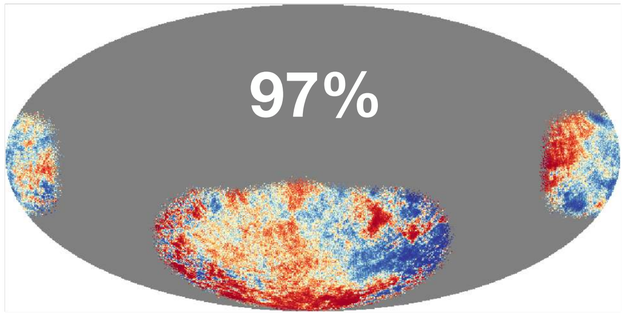
U_{non_id}



μK_{CMB}

-36.3482 53.0246

U_{eff}



μK_{CMB}

-89.7097 139.851

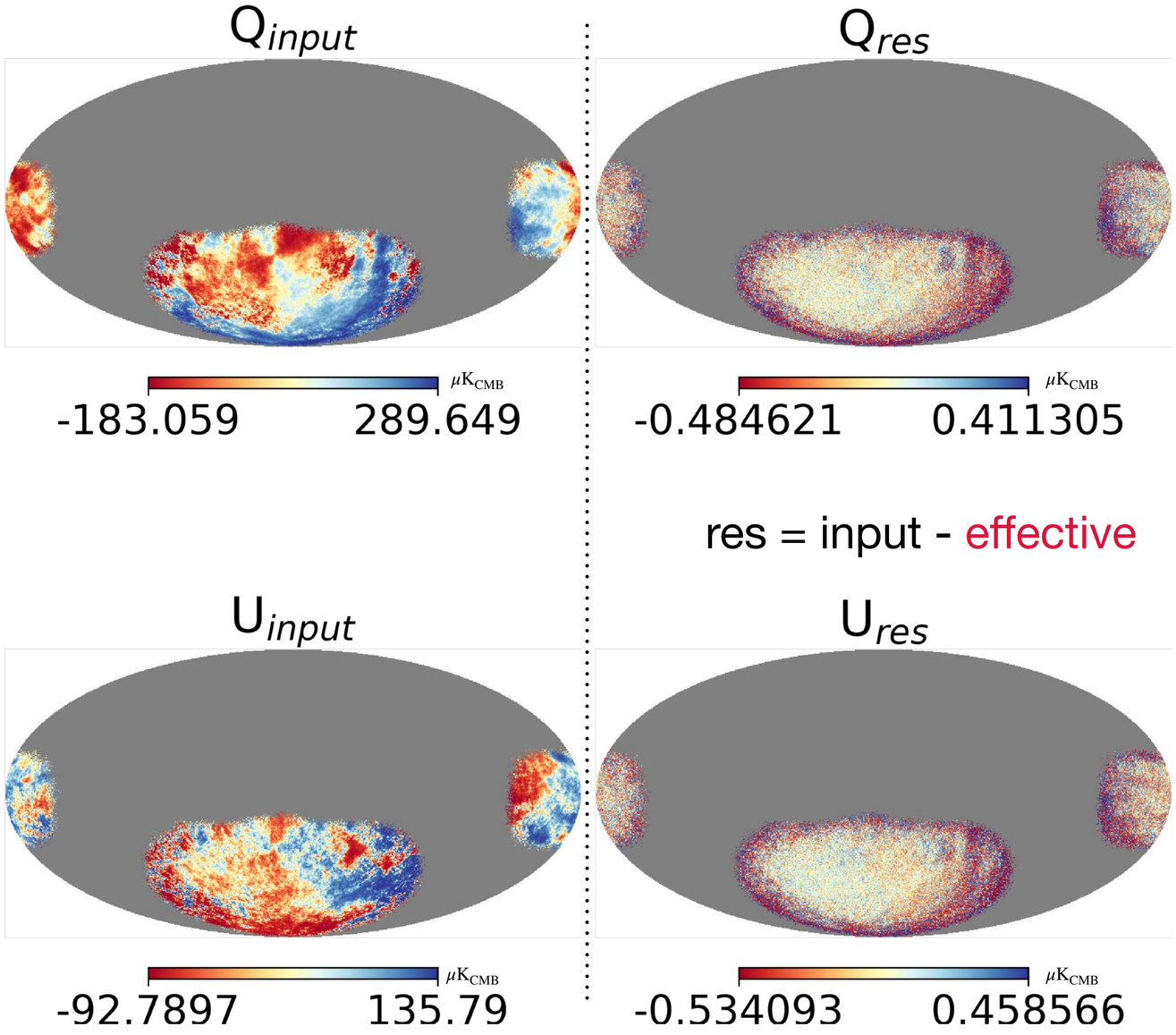
No band pass case

Effective hwp model

Work in progress

UHF2, `comp=[cmb+ dust+synch]`

✅ Validation of the effective model



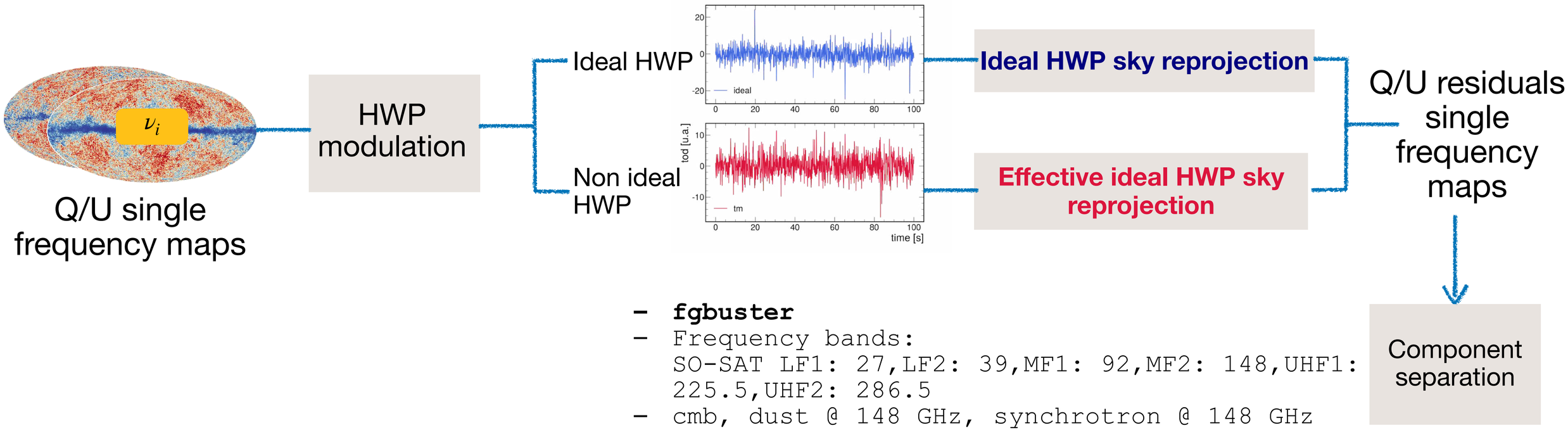
No band pass case

Effective hwp model

Pipeline: FURAX SciPol erc

- Modularity, extensibility, simplicity:

```
h = pol @ hwp @ mixing_matrix @ sampling
sol = ((h.T @ h).I @ h.T)(tod)
```



- **fgbuster**
- Frequency bands: SO-SAT LF1: 27,LF2: 39,MF1: 92,MF2: 148,UHF1: 225.5,UHF2: 286.5
- cmb, dust @ 148 GHz, synchrotron @ 148 GHz

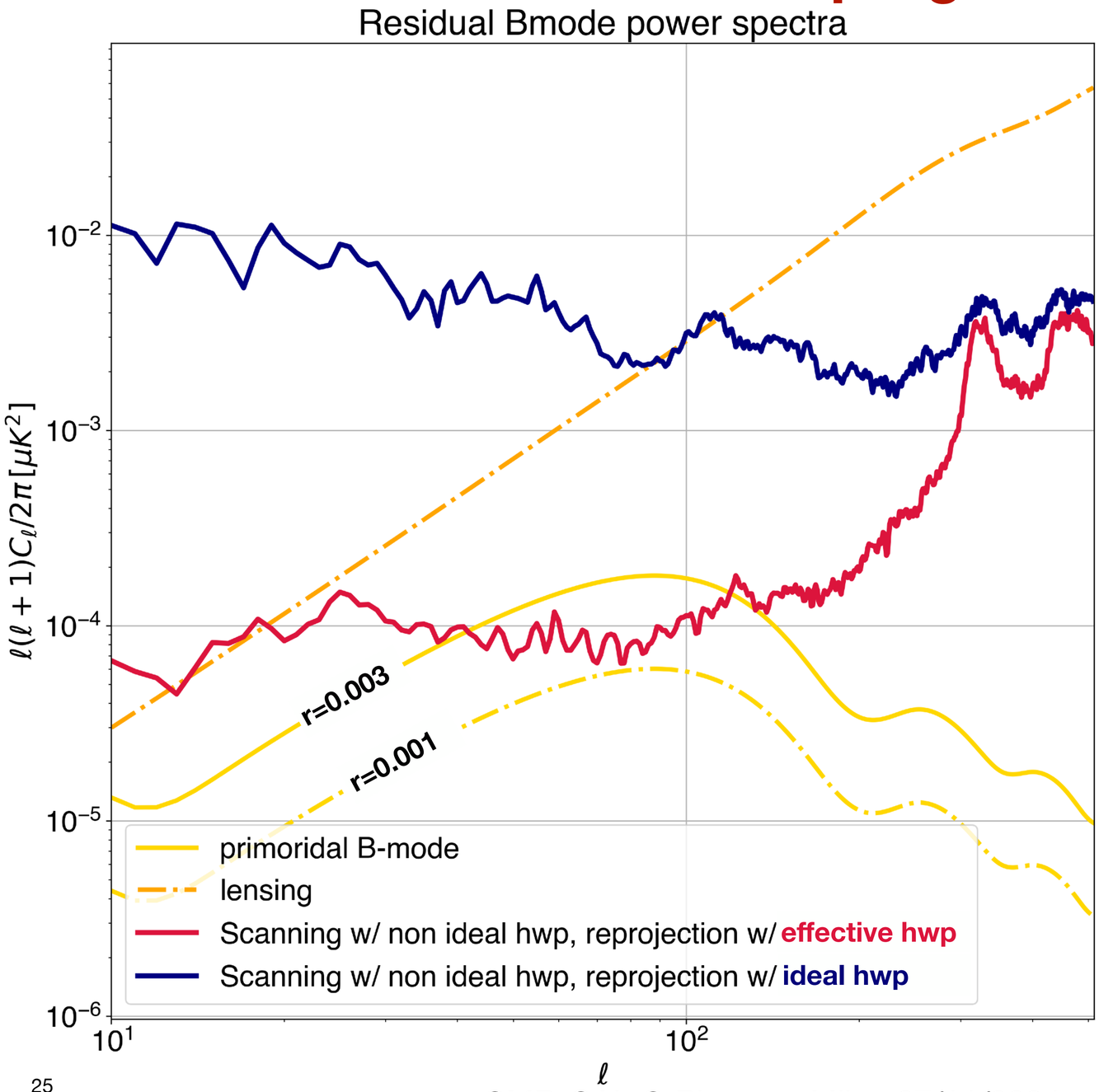
No band pass case

Effective hwp model

- Frequency bands:
  SO-SAT LF1: 27,LF2: 39,MF1: 92,MF2:
  148,UHF1: 225.5,UHF2: 286.5
- cmb, dust @ 148 GHz, synchrotron @ 148 GHz

Foreground parameter	β_d	β_{pl}
Input d0s0	1.54	-3.0
Ideal case	1.54	-3.0
Effective case	1.52515383	-3.00331785
Non ideal case (with priors)	1.	-2.86768798

Work in progress



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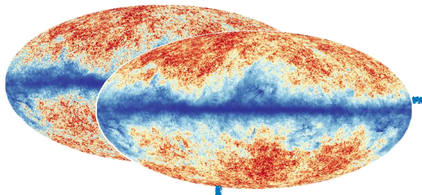
Band-pass integrated frequency case

Pipeline: FURAX SciPol erc

- Modularity, extensibility, simplicity:

```
h = pol @ bandpass @ hwp @ mixing_matrix @ sampling
sol = ((h.T @ h).I @ h.T)(tod)
```

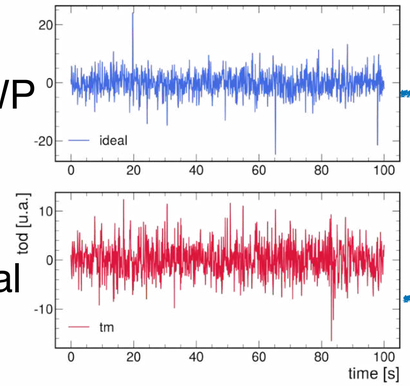
Q/U integrated frequency maps



HWP modulation

Ideal HWP

Non ideal HWP

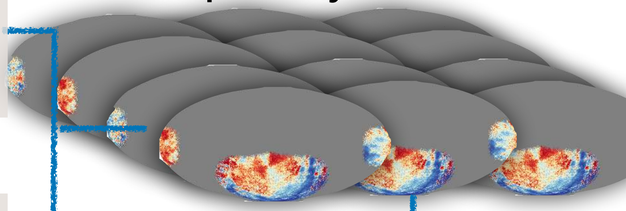


$$\bar{d} = \int d\nu \mathbf{M}_{\mathrm{instr}}(\nu)\mathbf{A}_{\mathrm{SED}}(\nu)s_{\mathrm{sky}} + n$$

Ideal HWP sky reprojection

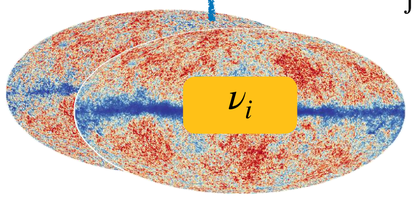
Effective ideal HWP sky reprojection

Q/U frequency maps for 6 frequency channels



Component separation

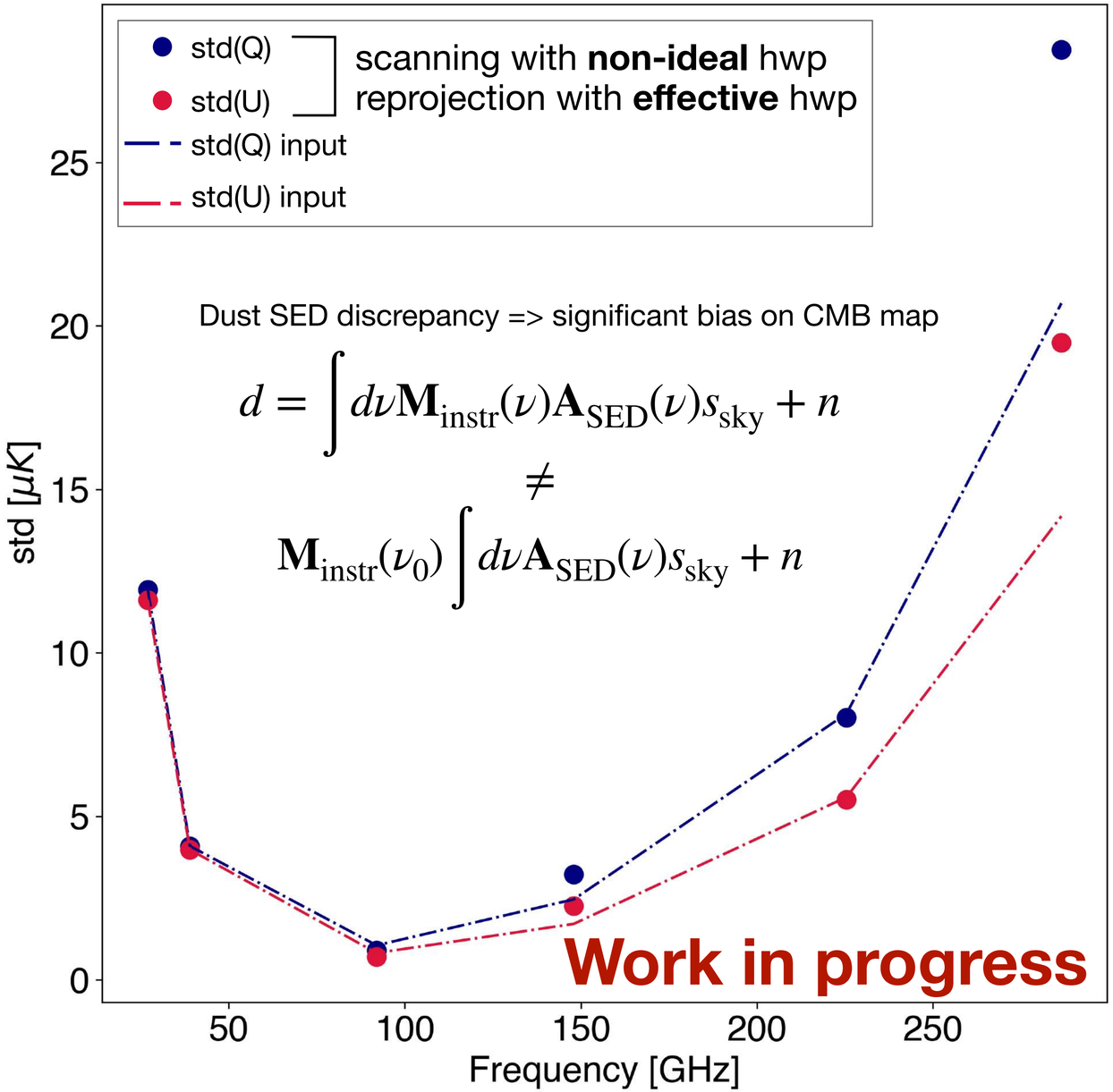
$$\bar{\mathrm{X}}(\nu_c) = \frac{\int \mathrm{d}\nu B(\nu, nu_c)\mathbf{X}(\nu)}{\int \mathrm{d}\nu B(\nu)}$$



Q/U single frequency maps

- PySm templates: cmb, dust @ 353 GHz, synchrotron @ 30 GHz
- No noise
- Scanning strategy: random hits on SO SAT mask

Band-pass integrated frequency case



- The interplay between instrumental systematics and foreground mitigation calls for a **time-domain component separation**
  → need for **priors**, precise calibration of instruments parameters (*drone*)
- Building of a framework that **includes instrumental systematic effects in the component separation** process : HWP, bandpass
- Extensions:
  → add **more effects** (beams, readout, polarisation angle) (Jost et al. 2023)
  → testing the parametric model against real SO data sets, but also test with LiteBIRD and CMB-S4 configurations if the HWP solution is confirmed
  → paper is in prep.