Study of beam far side-lobes systematics and calibration for the LiteBIRD mission

Clément Leloup,
on behalf of the LiteBIRD collaboration

Outline

I. General context

II. Beam far side-lobes systematic effects

III. Requirements for LiteBIRD

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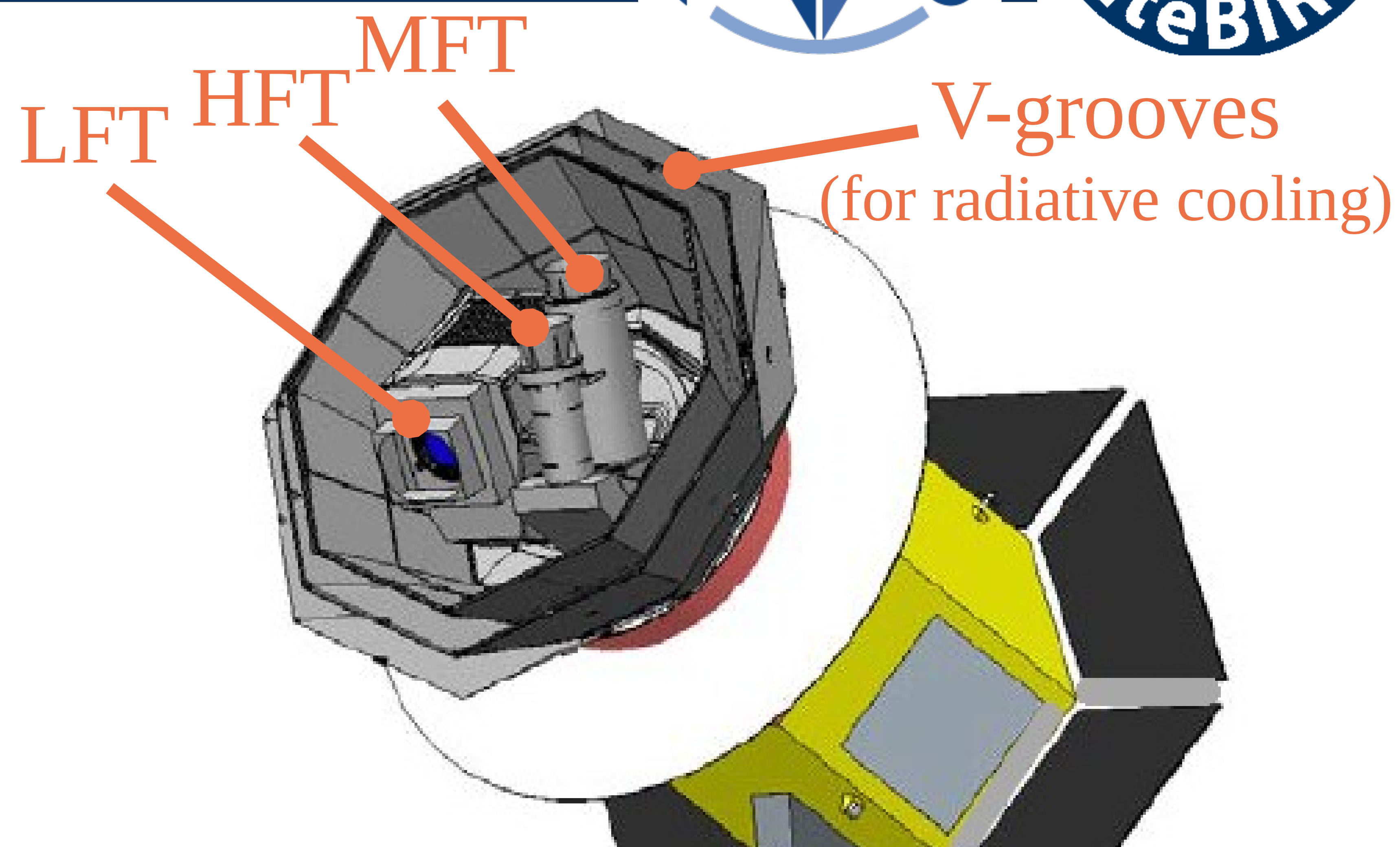
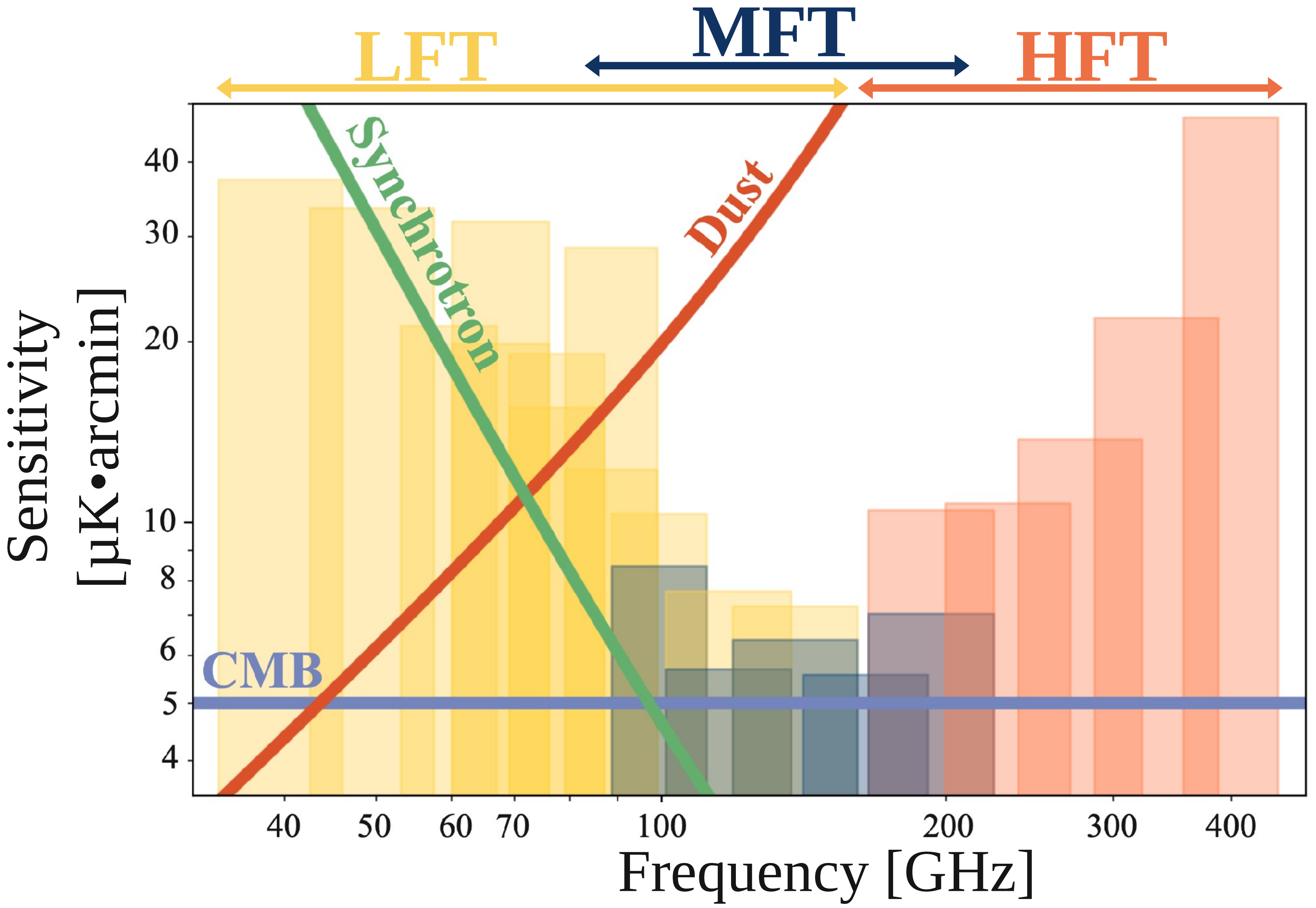
LiteBIRD overview

- Lite (Light) satellite for the study of *B*-mode polarization and Inflation from cosmic background Radiation Detection
- JAXA’s L-class mission selected in May 2019
- **All-sky 3-year survey**, from Sun-Earth Lagrangian point L2
- Large frequency coverage (**40–402 GHz**, 22 bands) at **70–18 arcmin** angular resolution for precision measurements of the **CMB *B*-modes**
- Final combined sensitivity: **2.2 μK·arcmin**, after comp. sep.





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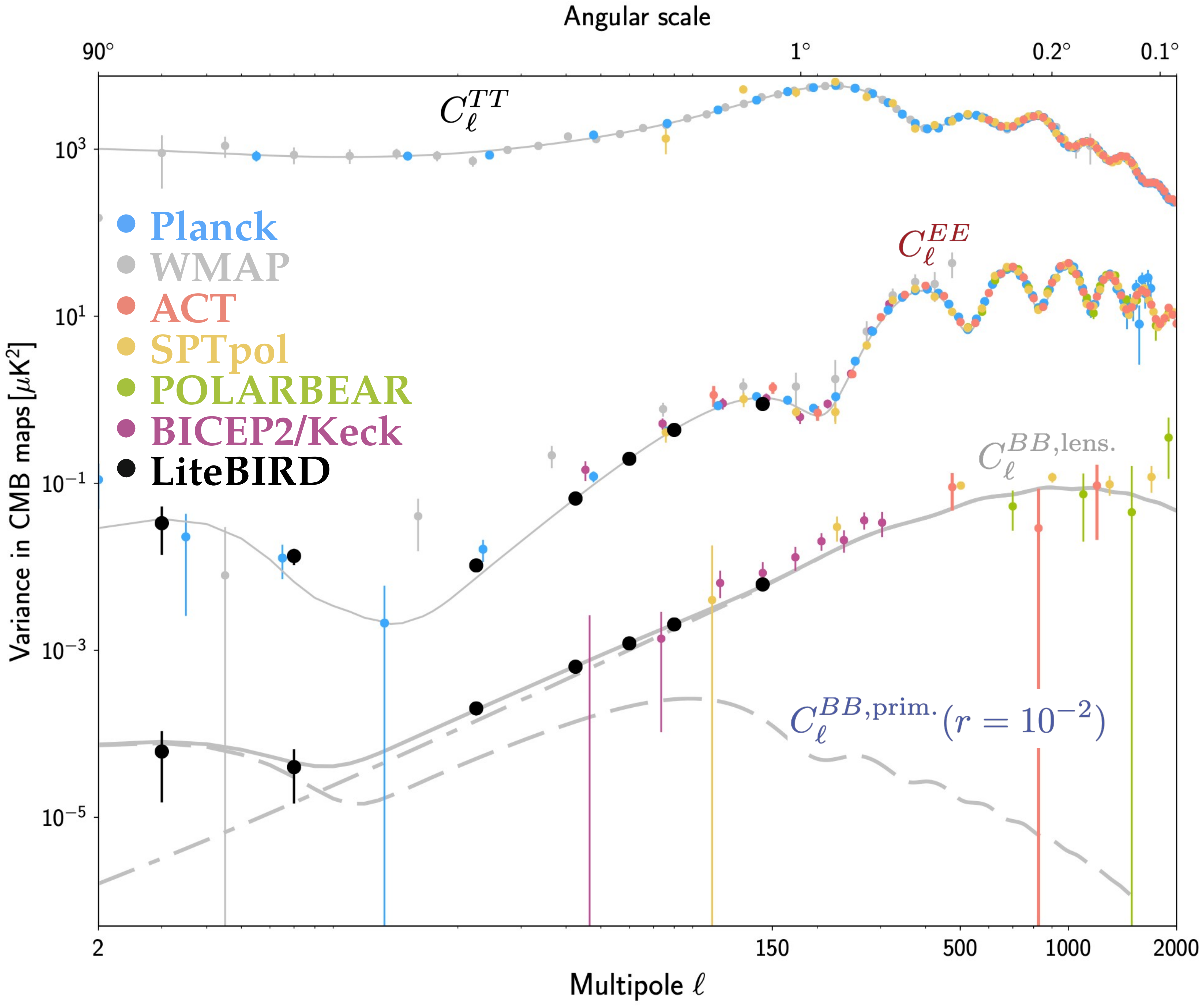
- Final combined sensitivity: **2.2 μK·arcmin**, after comp. sep.
- Definitive search for the ***B*-mode signal** from **cosmic inflation** in the CMB polarization
- Current best constraint: $r < 0.032$ (95% C.L.) (BICEP/Keck + Planck, see Tristram et al. 2021)
- LiteBIRD will improve current sensitivity on *r* by a factor ~50
- L1-requirements (no external data):
  - For $r = 0$, **total uncertainty (fg+stat+syst) of $\delta r < 0.001$**
  - For $r = 0.01$, 5-σ detection of the reionization ($2 < \ell < 10$) and recombination ($11 < \ell < 200$) peaks
- Most LB characteristics and expected results summarized in **arXiv:2202.02773**



Foreground cleaning

Foreground modeling

- **Synchrotron**: curved spectrum (AME is absorbed in the curvature)

$$[Q_\mathrm{s}, U_\mathrm{s}](\hat{n},\nu) = [Q_\mathrm{s},U_\mathrm{s}](\hat{n},\nu_\star)\cdot\left(\frac{\nu}{\nu_\star}\right)^{\beta_\mathrm{s}(\hat{n})+C_\mathrm{s}(\hat{n})\ln(\nu/\nu^\mathrm{c})}$$

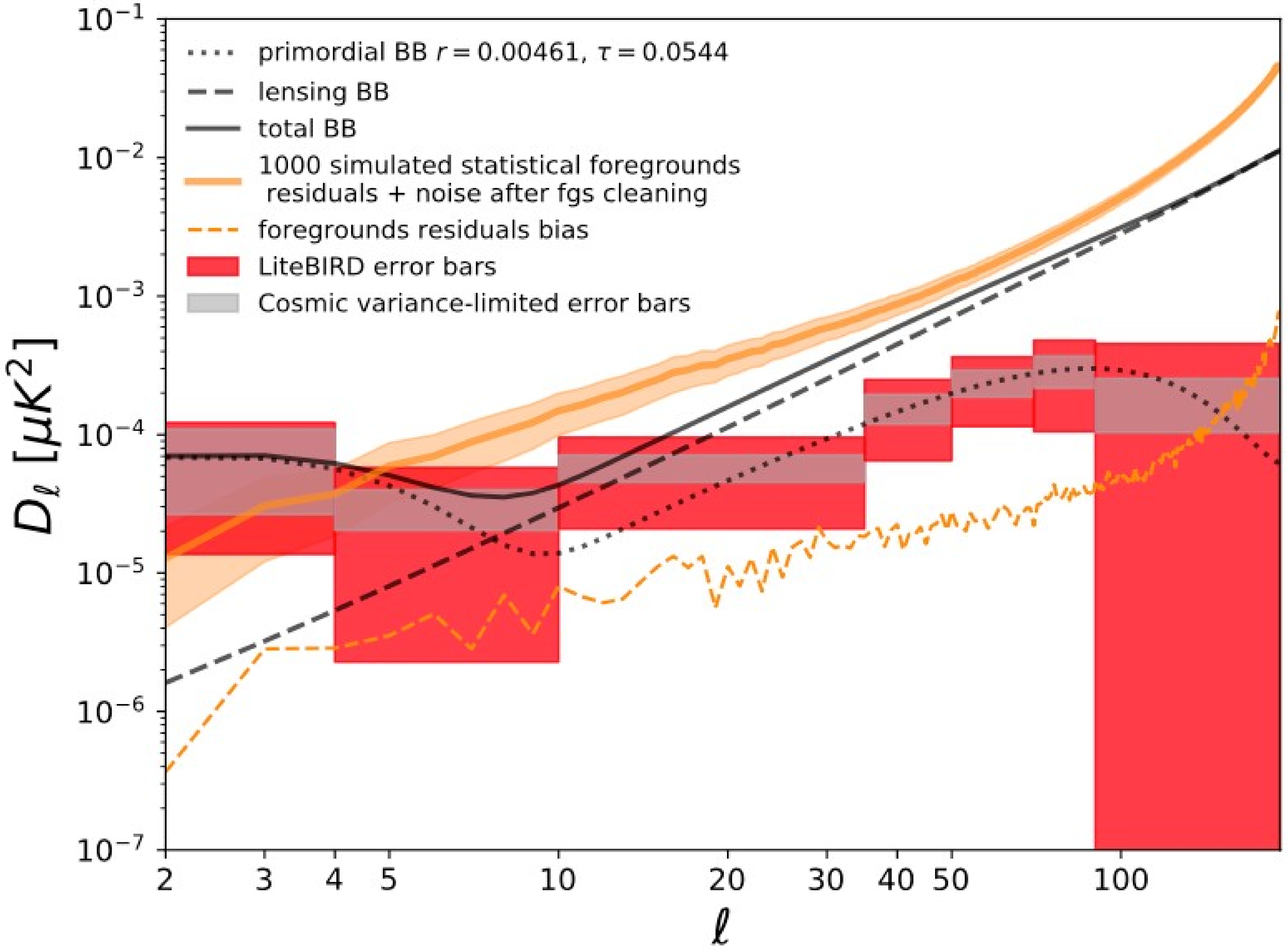
- **Dust**: modified blackbody

$$[Q_\mathrm{d}, U_\mathrm{d}](\hat{n},\nu) = [Q_\mathrm{d},U_\mathrm{d}](\hat{n},\nu_\star)\cdot\left(\frac{\nu}{\nu_\star}\right)^{\beta_\mathrm{d}(\hat{n})-2}\frac{B_\nu(T_\mathrm{d}(\hat{n}))}{B_{\nu_\star}(T_\mathrm{d}(\hat{n}))}$$

8 parameters in each sky patch

- "**Multipatch** technique" (extension of xForecast), to account for spatial variability

Impact of foregrounds residual



Control of systematics

Systematic error formalism

- Systematic errors originate from combination of:
  1. Imperfect knowledge of foregrounds
  2. Miscorrection of instrumental or environmental effects

↓

Bias on r

- Bias defined as the maximum of the cosmological likelihood, assuming r_{true}=0

$$\ln\mathcal{L}\left(r\right) = -f_{\rm sky}\sum_{\ell}\frac{2\ell+1}{2}\left[\frac{\hat{C}_\ell}{C_\ell}+\ln C_\ell\right]$$

$$\hat{C}_\ell = C_\ell^{\rm sys} + C_\ell^{\rm lens} + N_\ell$$

$$C_\ell = rC_\ell^{\rm tens} + C_\ell^{\rm lens} + N_\ell$$

Category	Systematic effect	Type
Beam	Far sidelobes	R
	Near sidelobes	R
	Main lobe	E
	Ghost	R
	Polarization and shape in band	R
Cosmic ray	Cosmic-ray glitches	E
HWP	Instrumental polarization	E
	Transparency in band	R
	Polarization efficiency in band	R
	Polarization angle in band	R
Gain	Relative gain in time	R
	Relative gain in detectors	R
	Absolute gain	E
Polarization angle	Absolute angle	E
	Relative angle	E
	HWP position	E
	Time variation	E
Pol. efficiency	Efficiency	E
Pointing	Offset	R
	Time variation	E
	HWP wedge	R
Bandpass	Bandpass efficiency	R
Transfer function	Crosstalk	R
	Detector time constant knowledge	R

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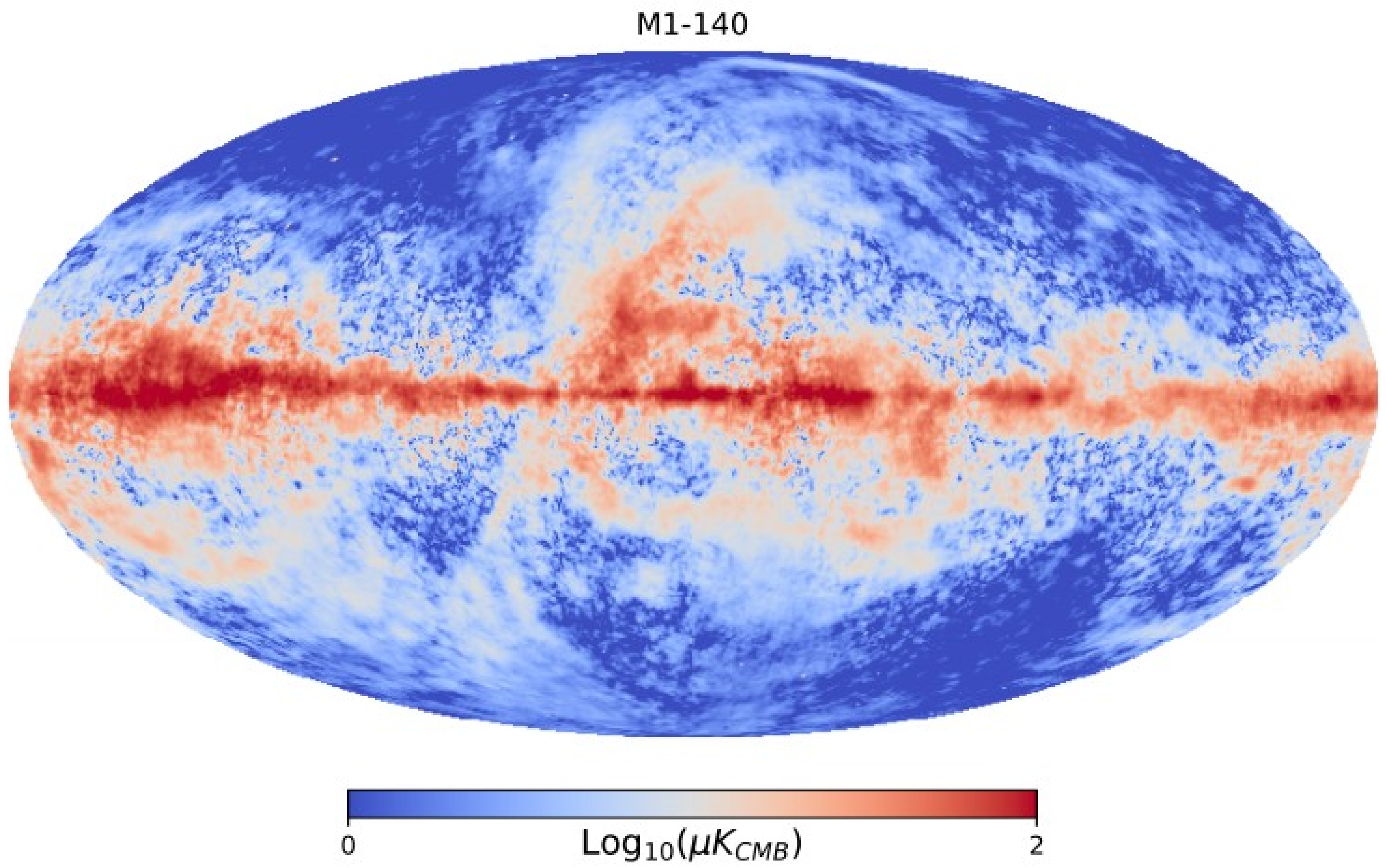
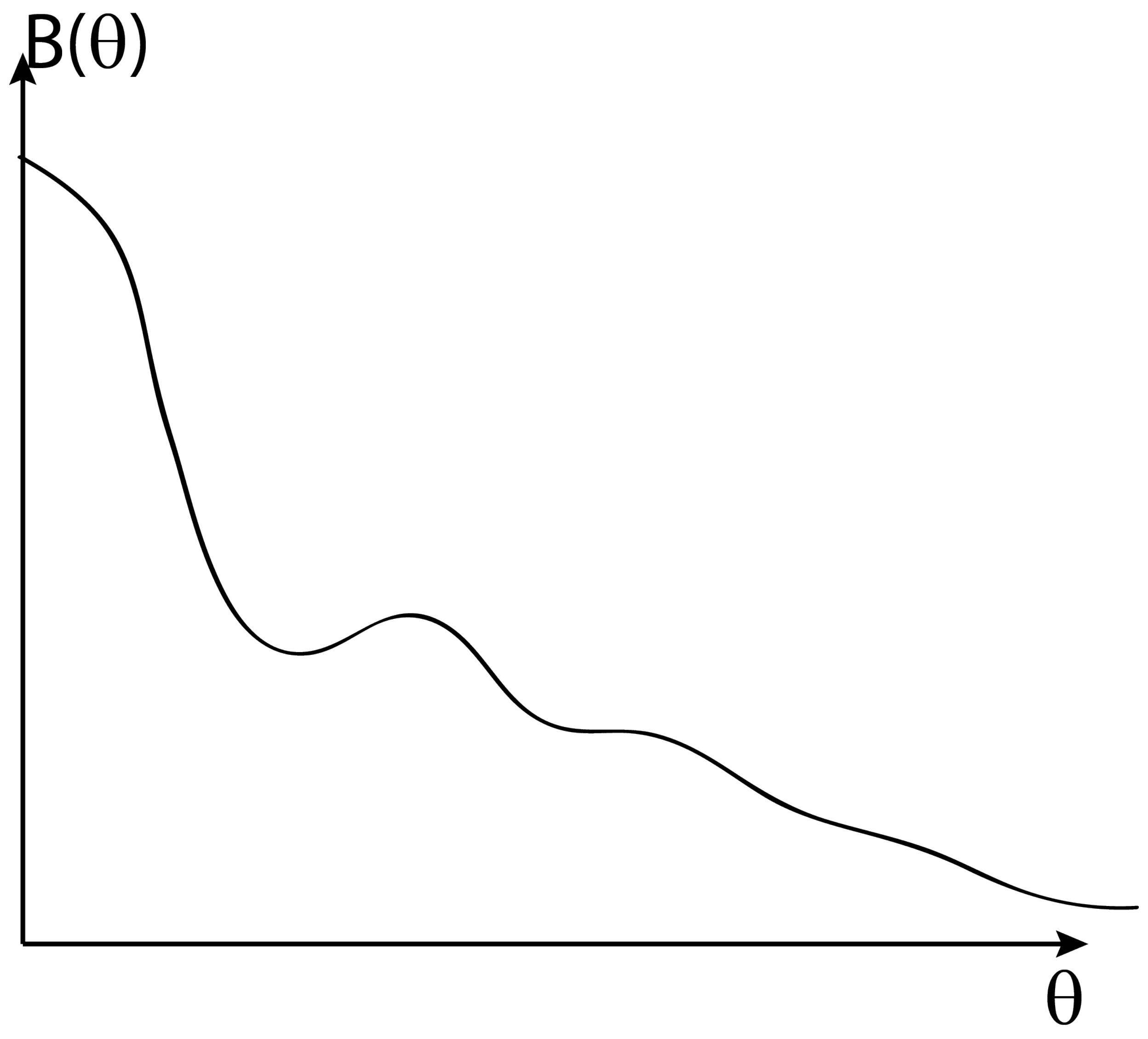
Beam convolution

Source of systematic error

- Because of the optical system, detectors' coverage of the sky is not perfect
- **Reflection and diffraction** on instrument parts
- Possibly high **power pick-up at large angle**
- Beam measurements are tricky and modeling at LB frequencies is hard and time consuming



- Schematic view of the beam profile. In reality :
  1. Depends on frequency
  2. **Depends on detector position on the focal plane**
  3. Has asymmetric structures



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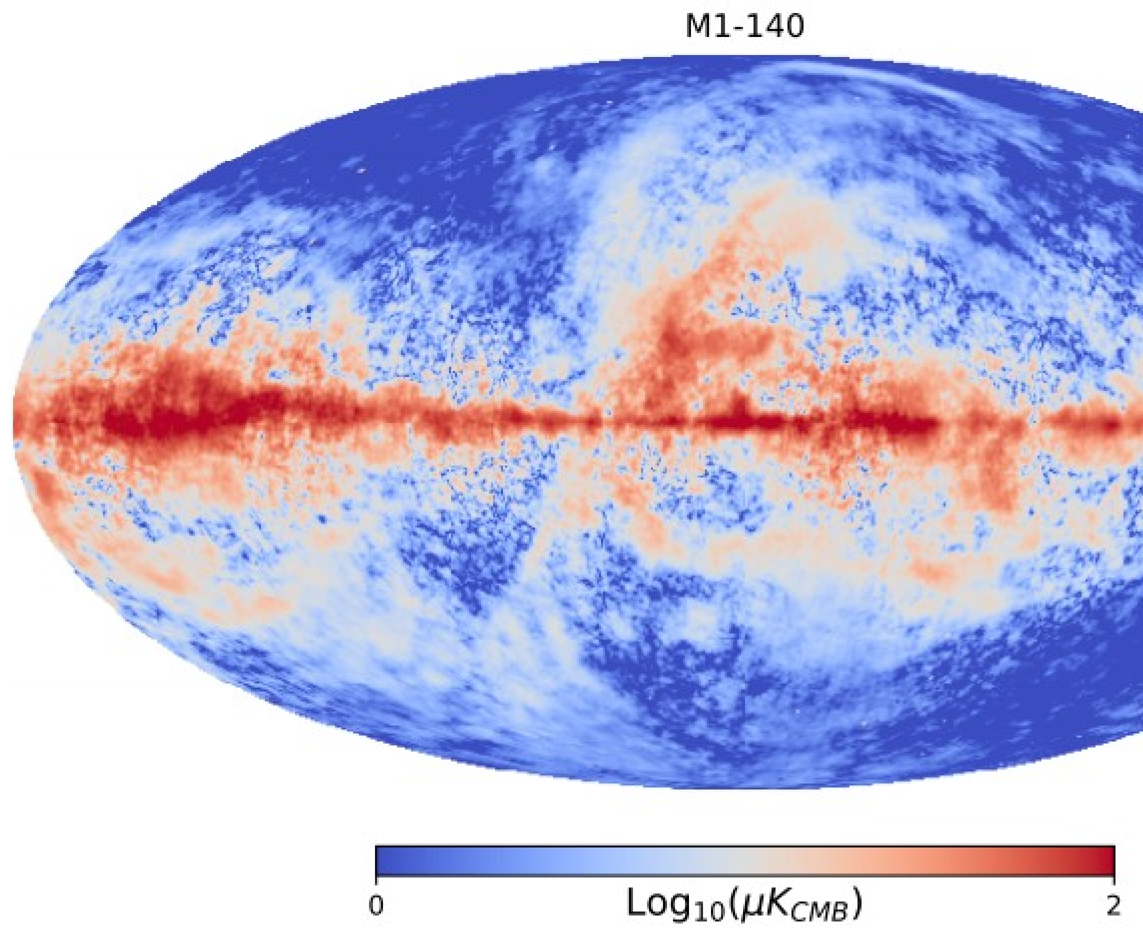
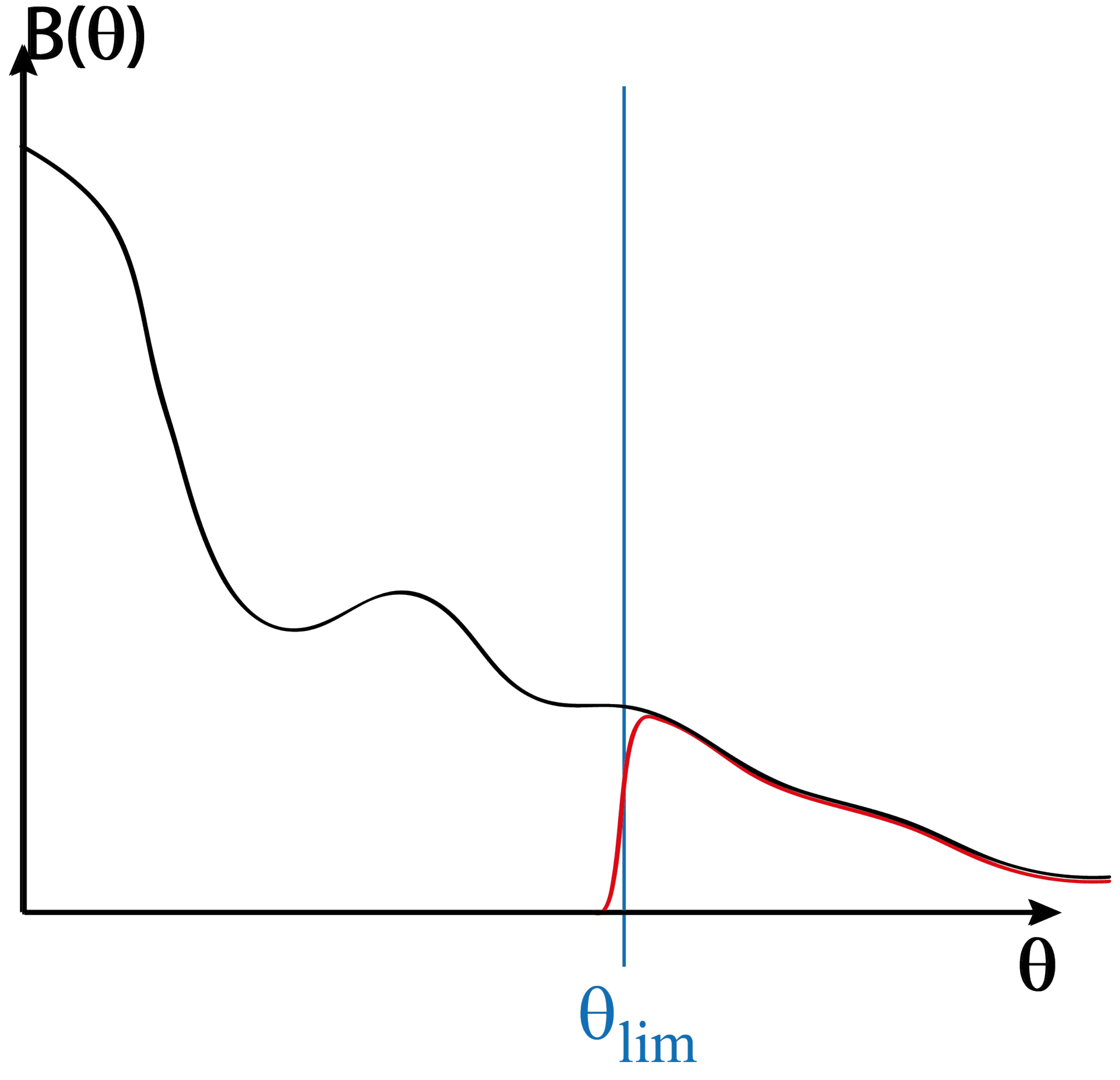
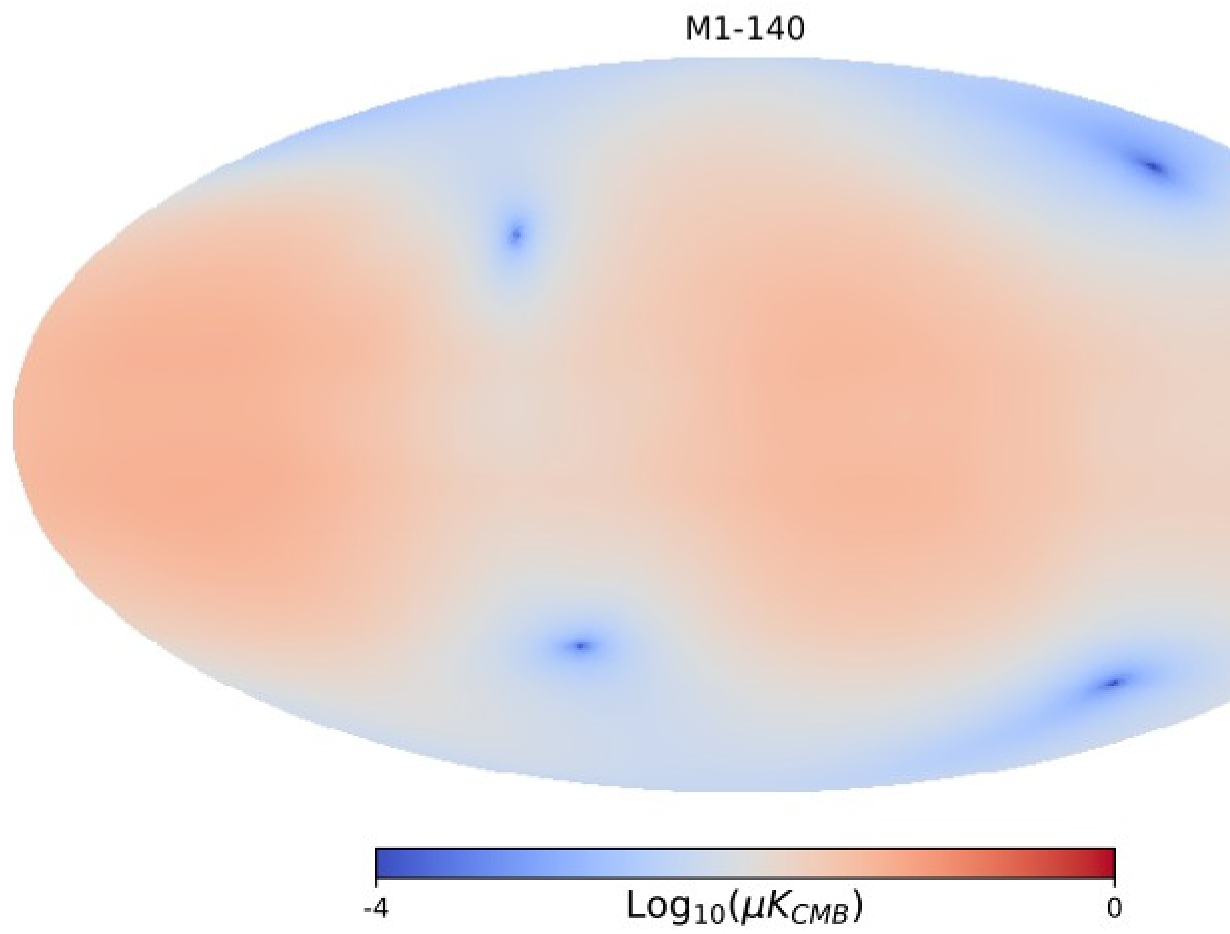
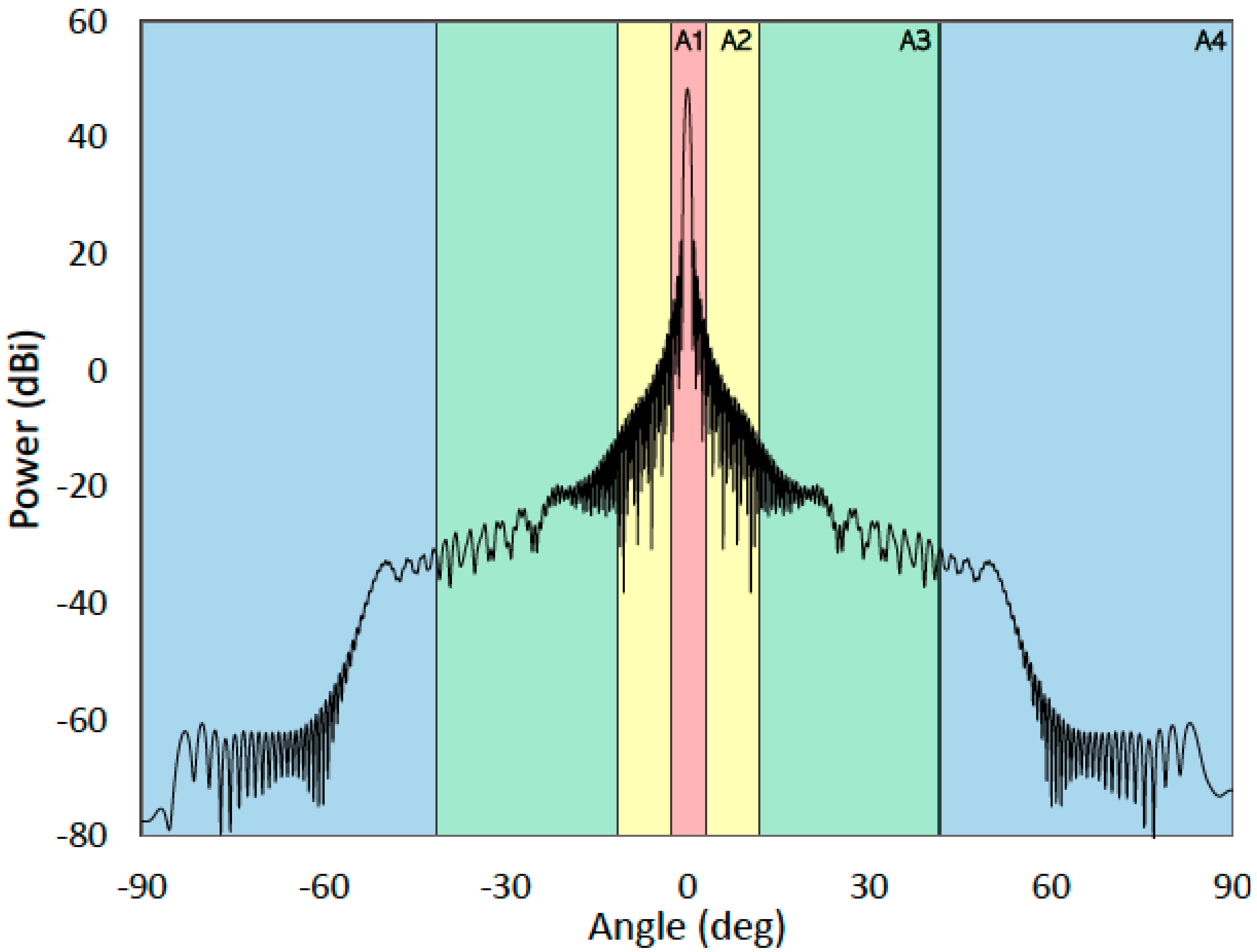


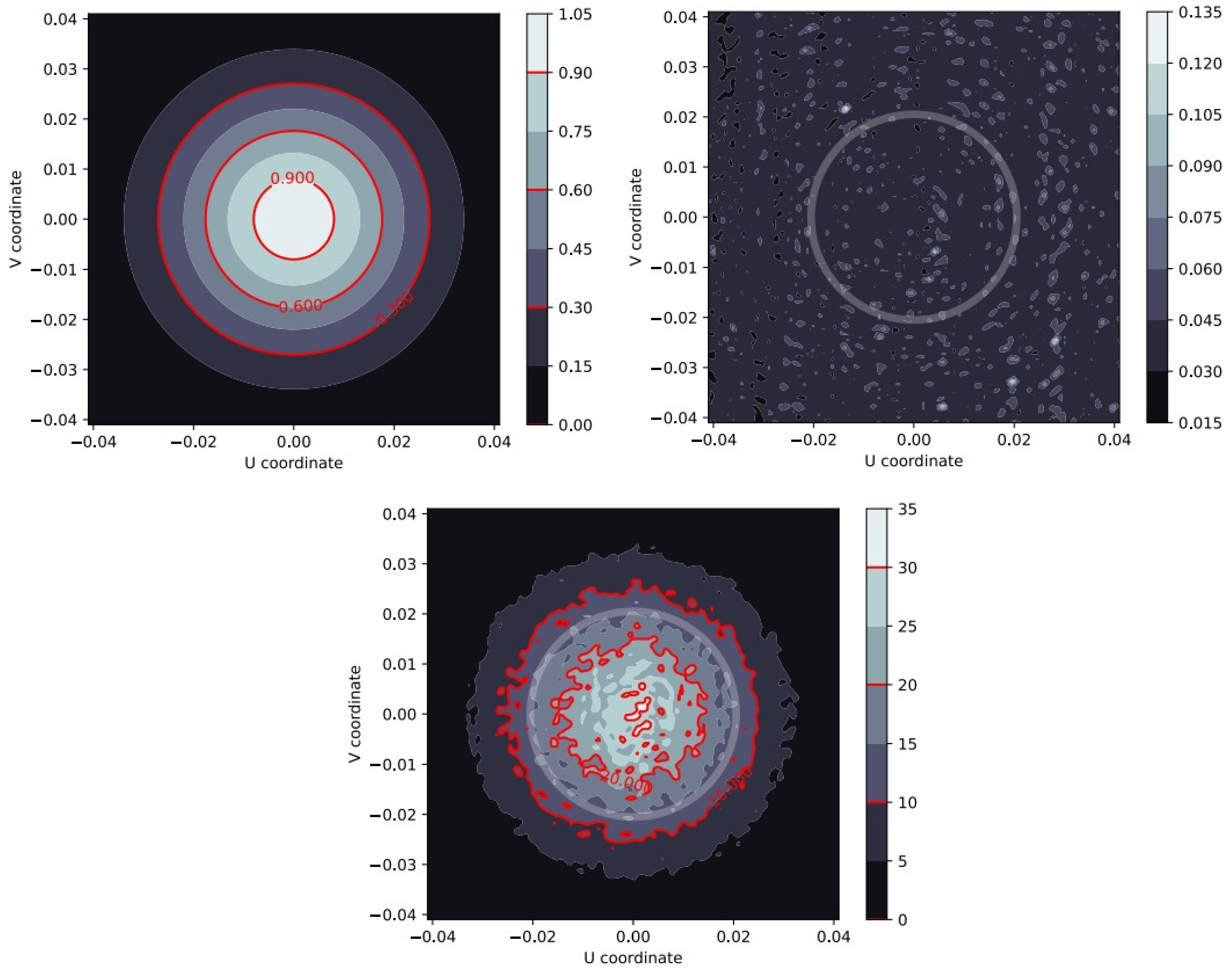
- Effect of far side-lobes
  1. **Galactic B-modes → CMB B-modes**
  2. E → B, w/o HWP
  3. Instrumental polarization





Calibration scheme





- 4 regions in beams depending on dominant effects
- Two calibration phases :

1. On the **ground**
2. **In flight** using planets

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- Beam systematics controled by calibration → setting **requirements** on calibration accuracy
- Simulate effect of calibration uncertainty through beam perturbation with variable amplitude

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Beam convolved maps

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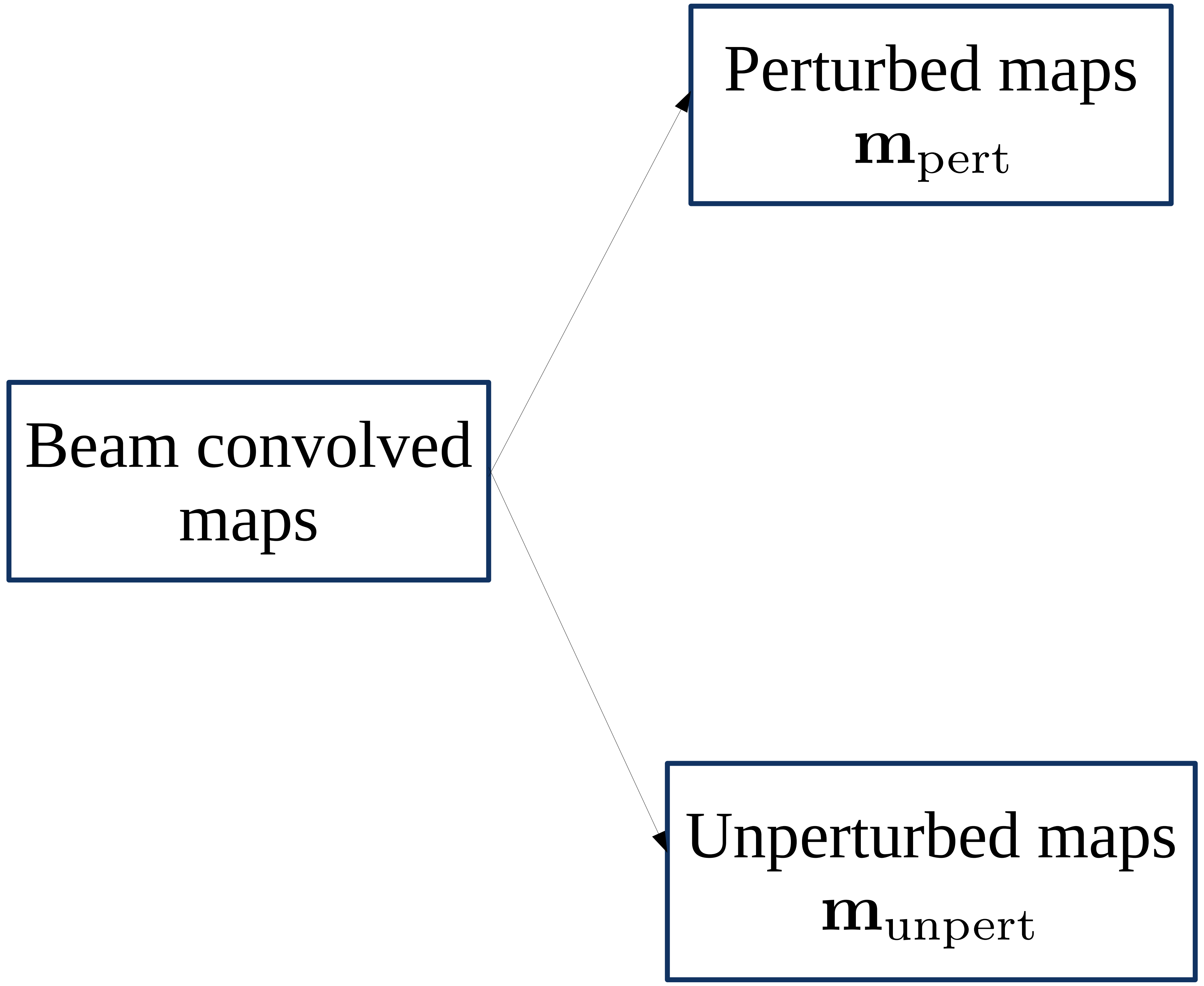
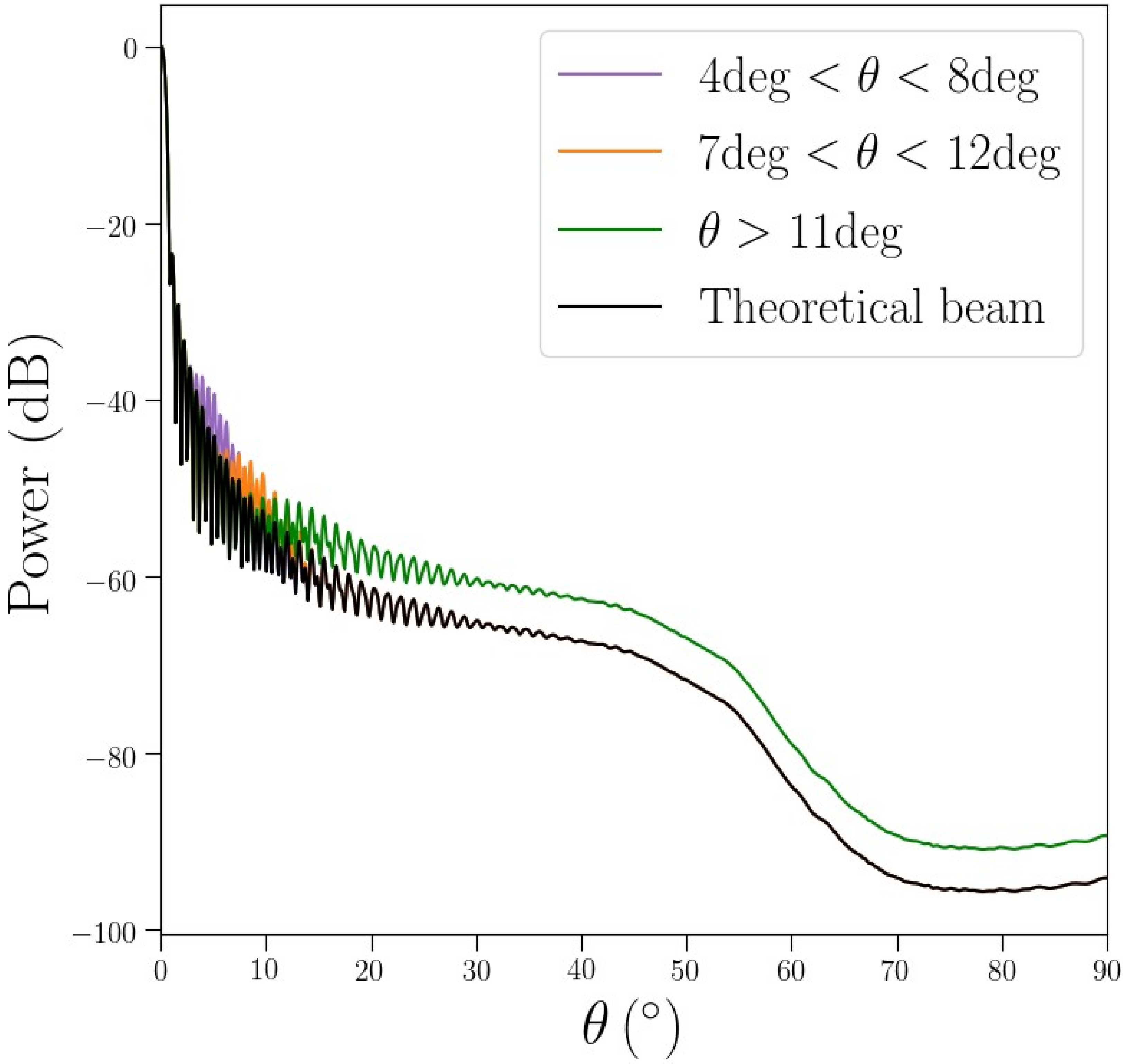
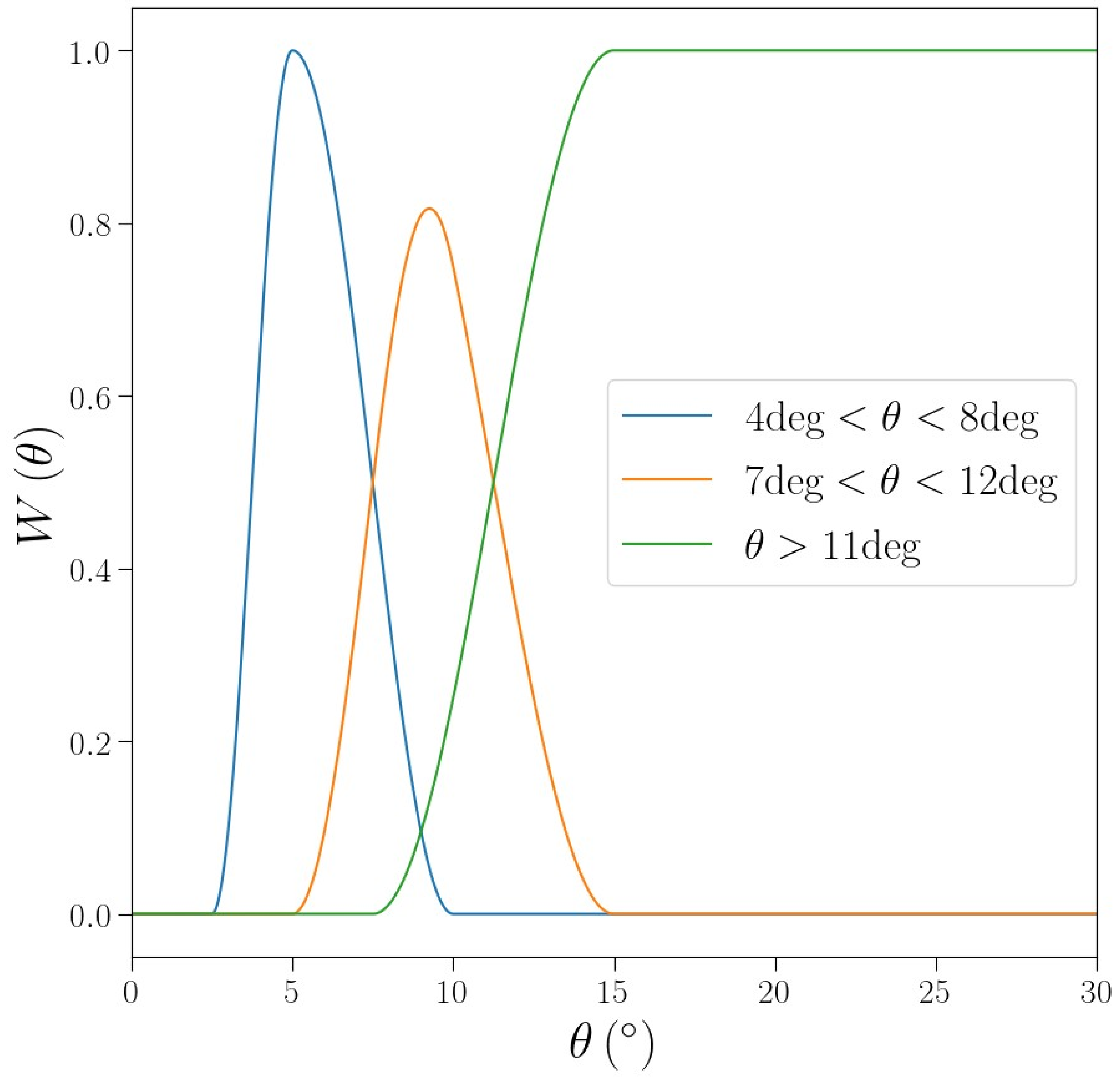


Beam convolved maps

Perturbed maps $\mathbf{m}_{\text{pert}}$

Unperturbed maps $\mathbf{m}_{\text{unpert}}$





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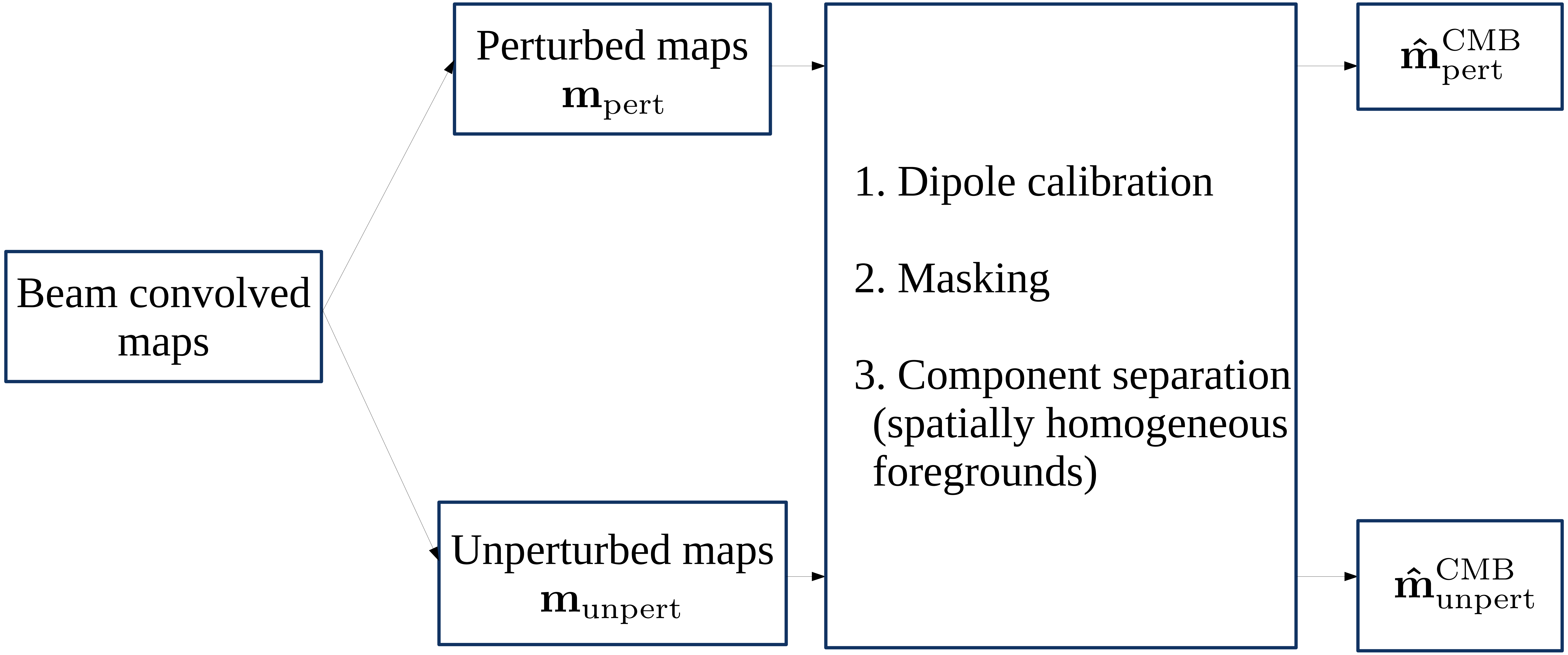

Beam convolved maps

Perturbed maps $\mathbf{m}_{\text{pert}}$

Unperturbed maps $\mathbf{m}_{\text{unpert}}$

1. Dipole calibration
2. Masking
3. Component separation (spatially homogeneous foregrounds)

$\hat{\mathbf{m}}^{\text{CMB}}_{\text{pert}}$

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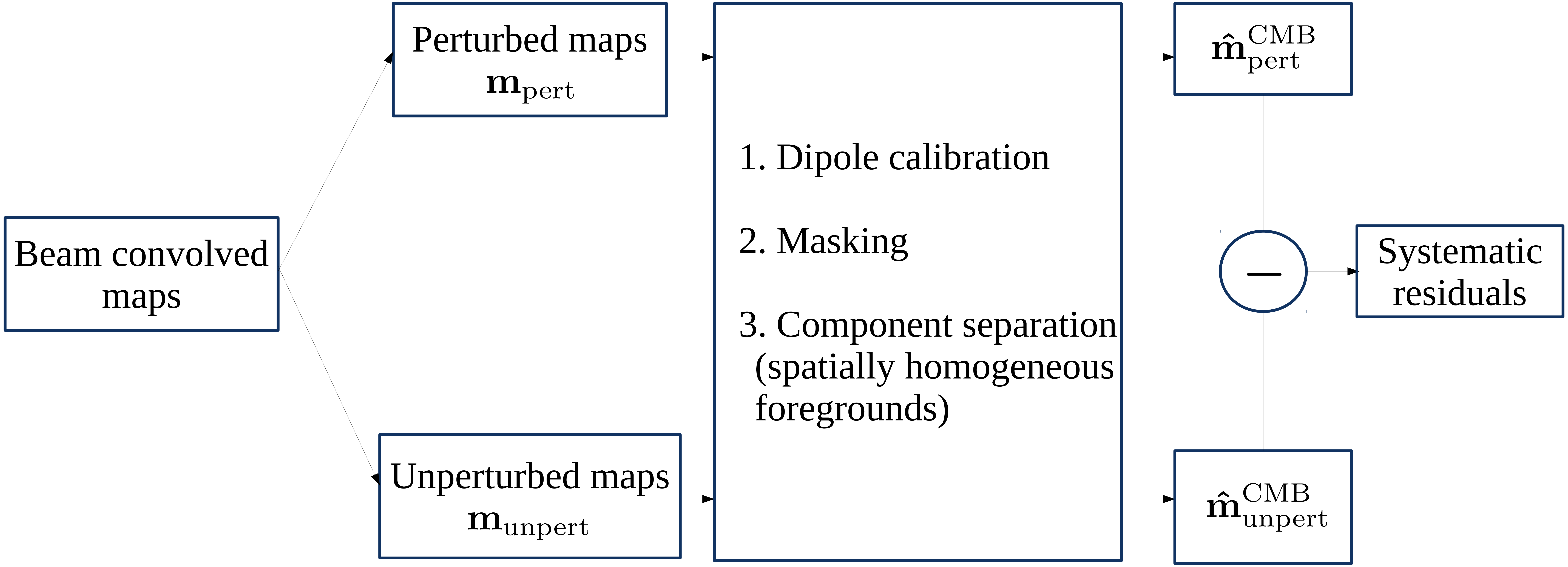

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Systematic residuals

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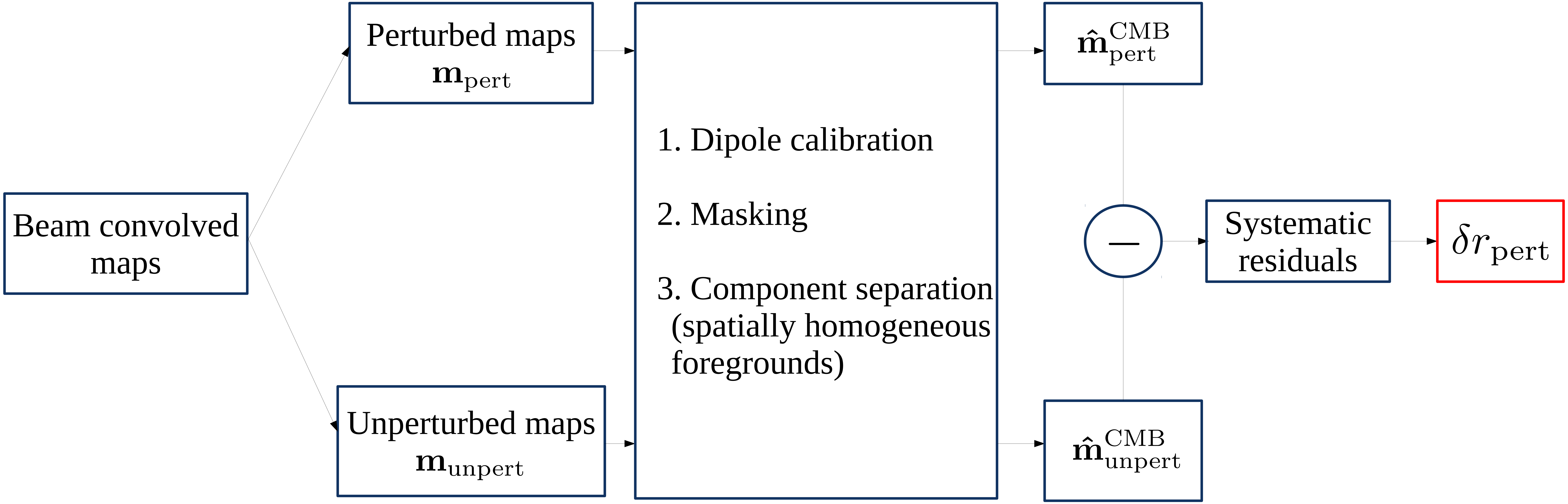

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Systematic residuals

δr_{pert}

Requirements on beam knowledge

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Beam perturbation → δr_{pert}

- Perturb beam in **one single freq channel and one single angular window** at a time to distinguish effect on total Δr_{FSL} from each channel
- Find perturbation δB in each channel such that the bias on r reaches the channel's budget δr^{ν}_{W}

$$\Delta r_{\text{FSL}} = \sum_{\nu,W} \delta r^{\nu}_{W}$$

- First case: assume same error budget in each channel and total **FSL error~3 % of total LB systematics**

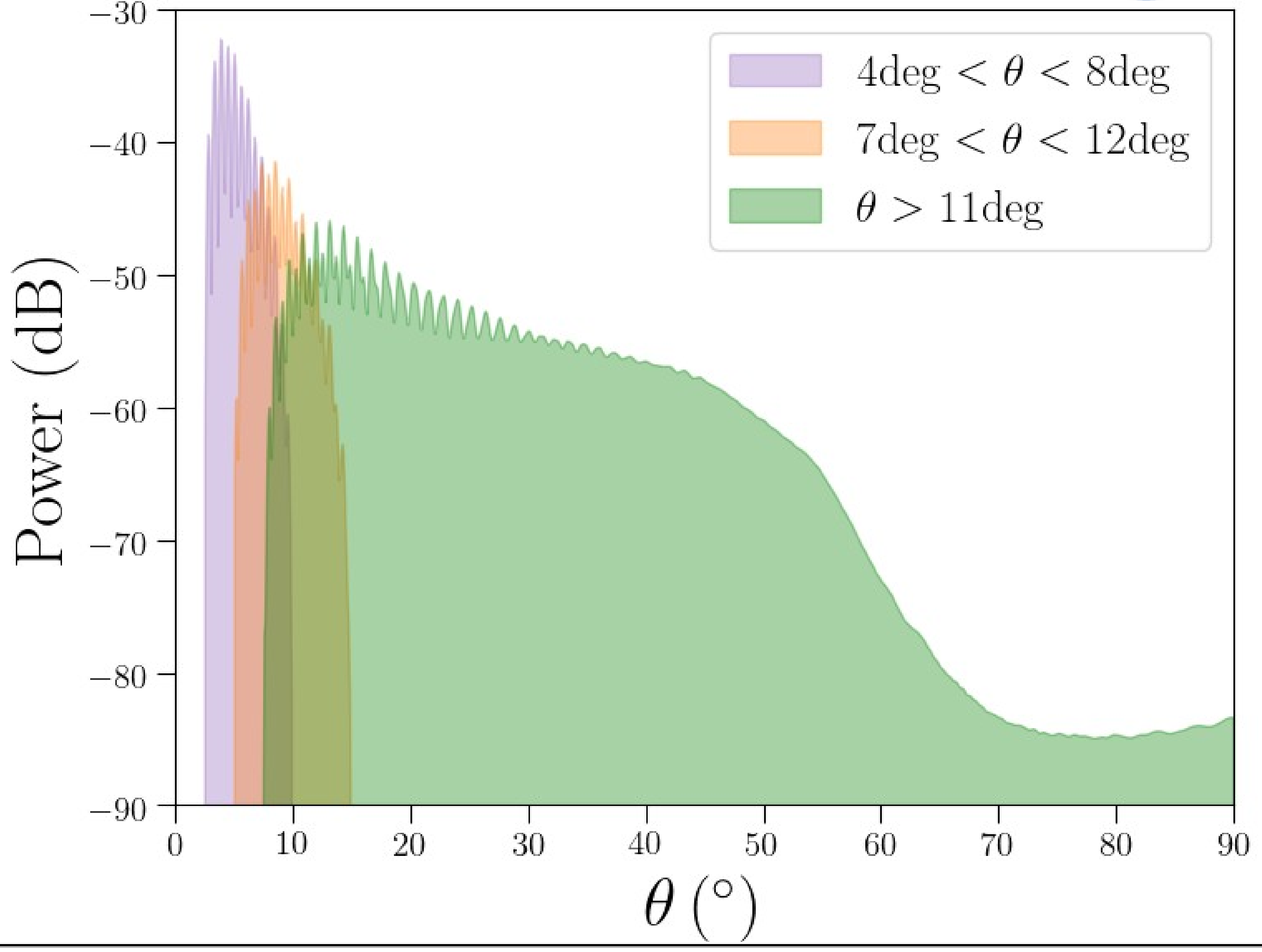
$$\delta r^{\nu}_{W} = \Delta r_{\text{FSL}} / \left(n_{\nu} \times n_{W}\right) = 1.9 \times 10^{-5}/66$$

Requirements on beam knowledge

- The requirements are set on physical quantities :

$$\delta R_{lim} = \frac{\int \delta B_{\mathrm{lim}}\left(\theta\right) W\left(\theta\right) d\Omega}{\int B\left(\theta\right) d\Omega}$$

➔Difference in power between unpert and pert



ν (GHz)	LFT										
	40	50	60	68		78		89		100	119
4 deg $< \theta <$ 8 deg	-23.54	-13.45	-17.68	-13.27	-8.02	-18.36	-16.43	-23.14	-15.50	-25.61	-27.57
7 deg $< \theta <$ 12 deg	-25.41	-15.51	-19.68	-15.75	-10.99	-19.21	-17.28	-24.13	-16.49	-26.59	-28.46
11 deg $< \theta$	-27.49	-17.44	-21.53	-18.20	-13.67	-17.41	-16.18	-23.40	-16.27	-26.01	-27.86

ν (GHz)	LFT	MFT					HFT				
	140	100	119	140	166	195	195	235	280	337	402
4 deg $< \theta <$ 8 deg	-23.23	-26.84	-29.71	-23.92	-34.64	-37.07	-33.00	-35.65	-32.52	-41.78	-38.03
8 deg $< \theta <$ 12 deg	-23.88	-27.90	-30.71	-24.61	-35.63	-37.89	-34.17	-36.60	-33.34	-42.66	-38.68
11 deg $< \theta$	-26.69	-25.74	-29.20	-29.83	-33.91	-34.30	-32.73	-34.38	-27.26	-37.79	-38.93

Requirements on beam knowledge

- Because of the denominator, **δR_{lim} is not directly measurable**

$$\delta R_{lim} = \frac{\int \delta B_{\mathrm{lim}}(\theta)\, W(\theta)\, d\Omega}{\int B(\theta)\, d\Omega}$$

- Yet, because it is robust under change of beam and/or perturbation shape, it is the relevant parameter

- So, we have to find another quantity, defined from δR_{lim}, closer to what is measured :

$$\delta B_{lim} = \frac{\int \delta B_{\mathrm{lim}}(\theta)\, W(\theta)\, d\Omega}{\int W(\theta)\, d\Omega}$$

➔Average of the perturbation amplitude in the window

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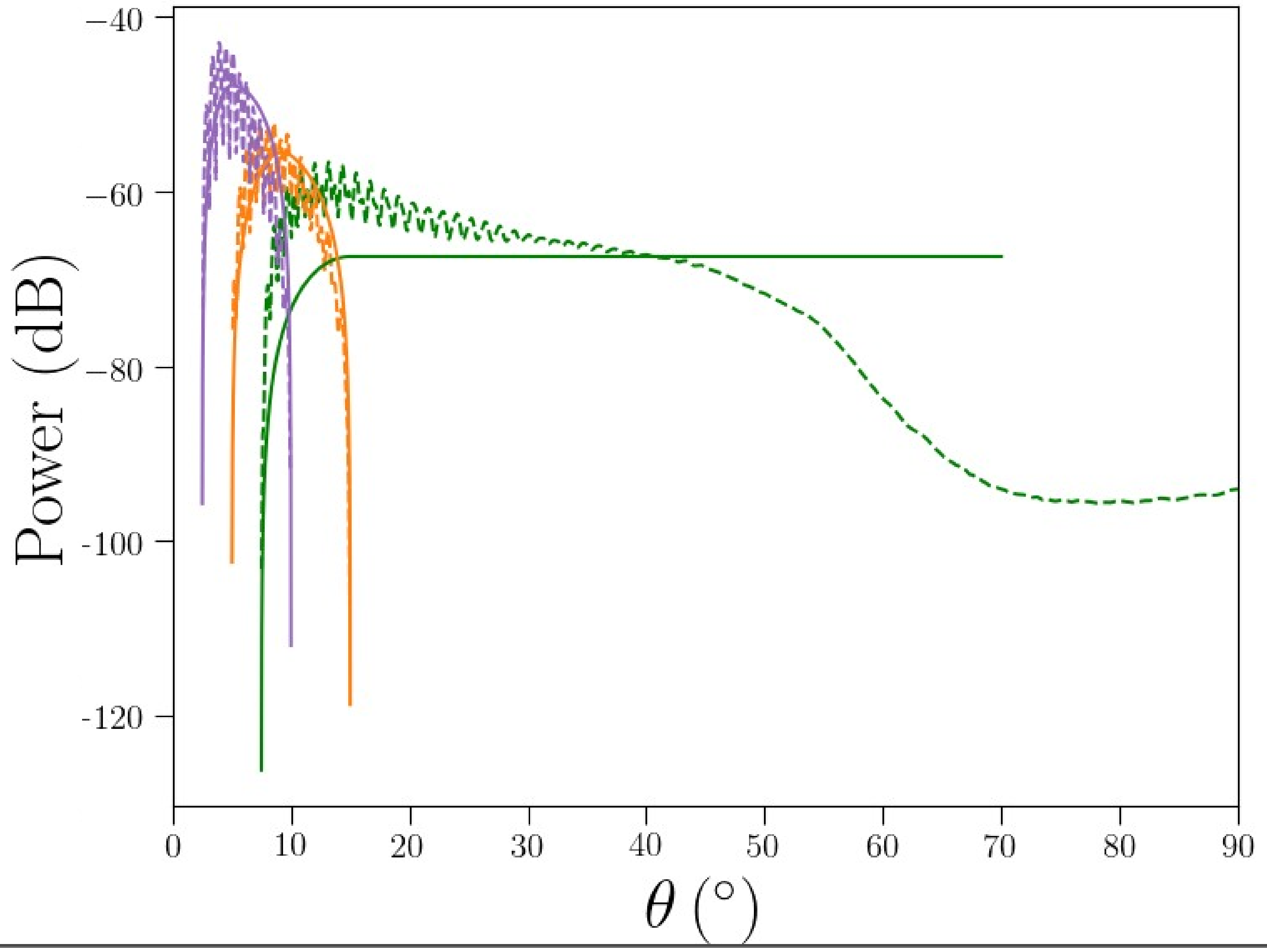

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7 deg $< \theta <$ 12 deg	-46.62	-38.35	-43.67	-41.38	-35.62	-45.87	-42.48	-51.75	-42.04	-54.98	-57.91
11 deg $< \theta$	-66.40	-57.98	-63.20	-61.52	-56.00	-61.76	-59.07	-68.70	-59.51	-72.09	-75.00

ν (GHz)	LFT	MFT					HFT				
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4 deg $< \theta <$ 8 deg	-51.25	-50.65	-54.58	-49.55	-60.87	-63.56	-59.01	-62.92	-60.57	-70.48	-67.91
7 deg $< \theta <$ 12 deg	-54.11	-53.91	-57.78	-52.45	-64.07	-66.58	-62.38	-66.07	-63.60	-73.57	-70.77
11 deg $< \theta$	-74.60	-69.44	-73.96	-75.36	-80.06	-80.69	-78.63	-81.55	-75.23	-86.41	-88.72

Requirements on beam knowledge

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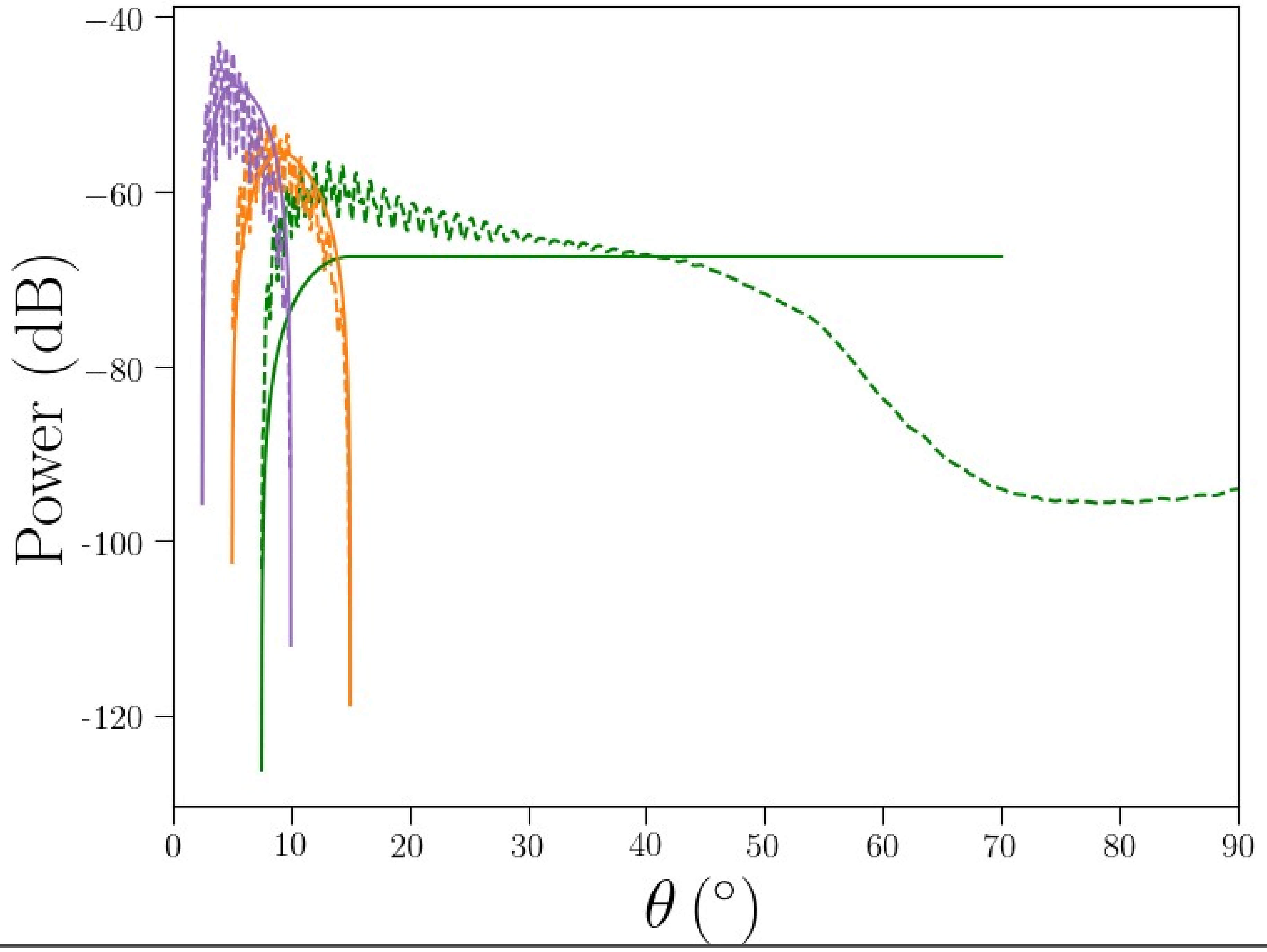

Depends a lot on the window

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Requirements on beam knowledge

- In a more realistic setting, we make many measurement in the same angular ring :

$$P_{\text{Calib}}(\vec{r}) = \int \overline{B_\nu}\, \omega(\vec{r}' - \vec{r})\, d\Omega' \, \frac{1}{\int \overline{B_\nu}\, \omega(\vec{r}')\, \mathrm{d}\Omega'} + n$$

Pixel window function

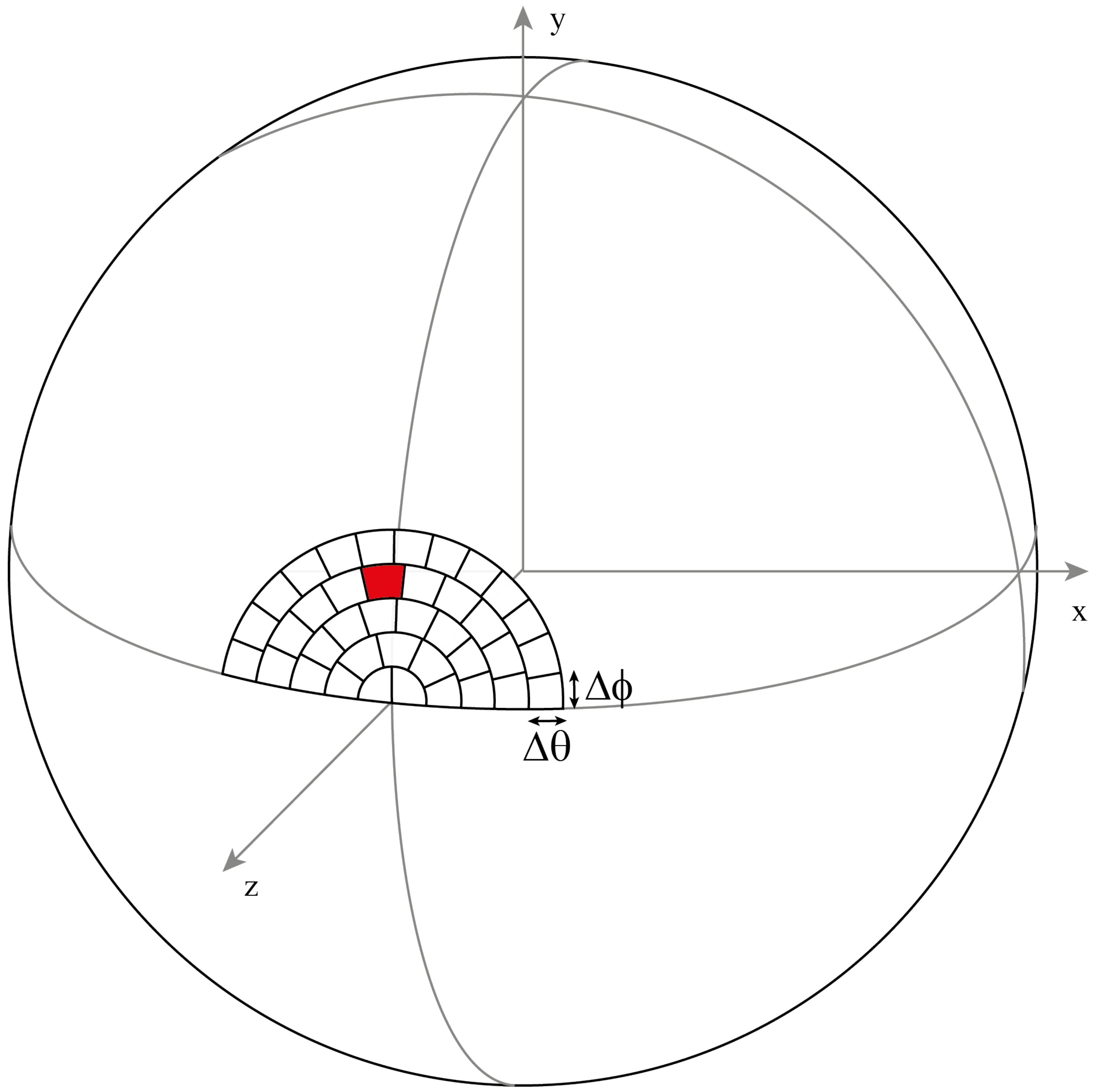
Noise

- Assuming **statistical uncertainties** only and **constant pixel size** $\Delta\Omega_{\text{pix}}$, we can link the accuracy of calibration to δB_{lim} :

$$\sigma_{\text{Calib}} = \text{Var}\left(P_{\text{Calib}}\right) = \frac{\int W(\theta)\, d\Omega}{\sqrt{\sum_{ij} W^2(\theta_{ij}) \Delta\Omega_{\text{pix}}}}\, \delta\overline{B}_{\text{lim}}$$

- In addition, we can tune the error budgets between channels to have a common σ_{Calib} throughout the frequency and angular range. Assuming **$\Delta\Omega_{\text{pix}}$=0.25x0.25deg^2** :

$$\boxed{\sigma_{\text{Calib}} = -56.90\ \text{dB}}$$



Summary

- LiteBIRD is expected to have unprecedented sensitivity on the measurement of the tensor-to-scalar ratio
- Need excellent control of foregrounds and systematic effects
- Among systematic effects, the lack of knowledge of beam **far side-lobes is dominant**
- The impact on cosmological results depends on the difference of power between the estimated and true beams, but it is not an observable quantity
- We find that the effect can be handled through ground and in-flight measurements with required accuracy found to be **σ_{calib}~-57dB**, assuming 0.5x0.5 deg^2 pixels
- For more details on this study, there is a CL et al. paper in prep

- This requirement on calibration accuracy will need to be further refined :
  - Increase the angular resolution
  - Improve the **optical modeling** and consolidate it with measurements on sub-systems.
  - Study the **very far region** where measurements are not possible
  - Study the impact of **beam asymmetries**

Grazie !