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

Clément Leloup,
on behalf of the LiteBIRD collaboration

LiteBIRD Joint Study Group

Over 300 researchers from **Japan**, **North America** and **Europe**

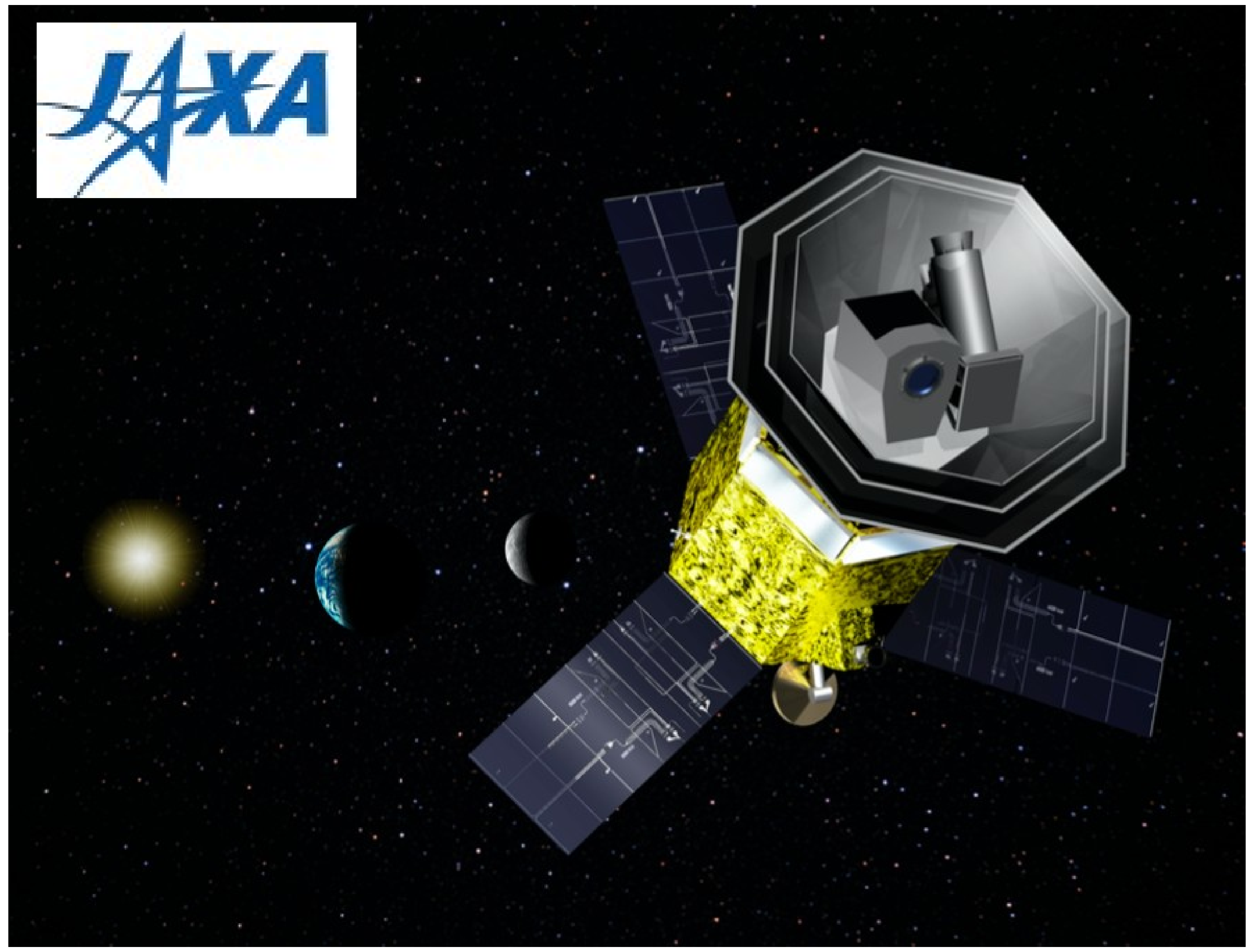
Team experience in CMB experiments, X-ray satellites and other large projects (ALMA, HEP experiments, …)

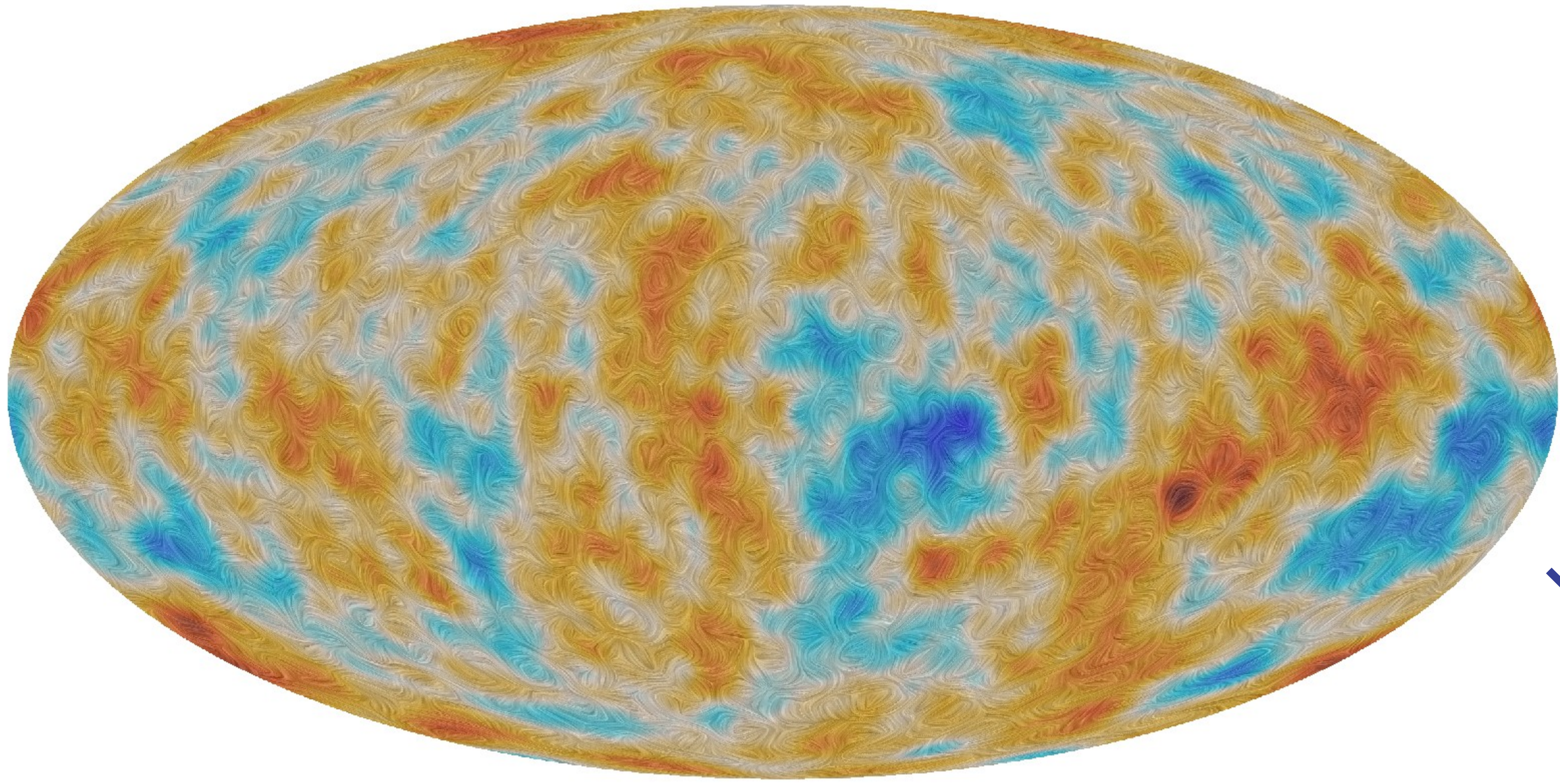
LiteBIRD Global F2F meeting
December 11-13, 2019 at MPE

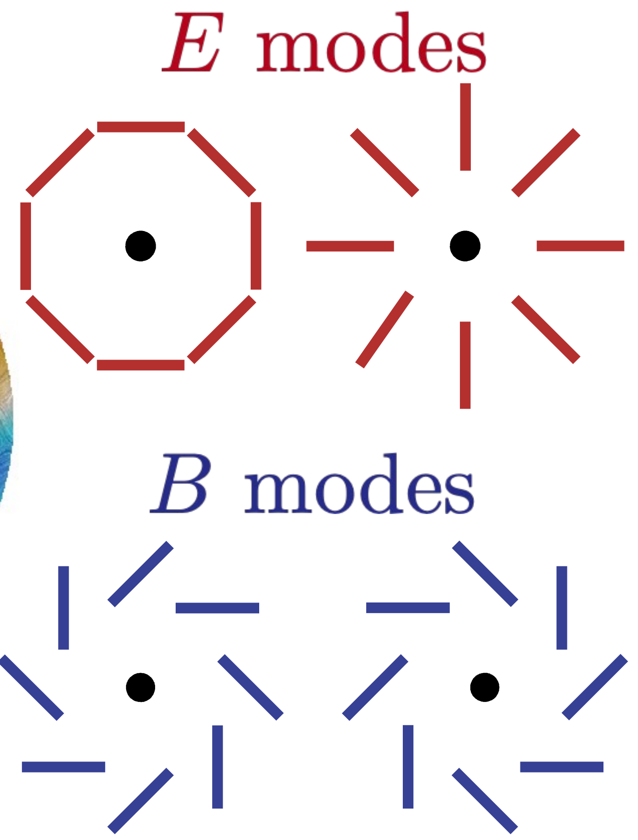
LiteBIRD overview

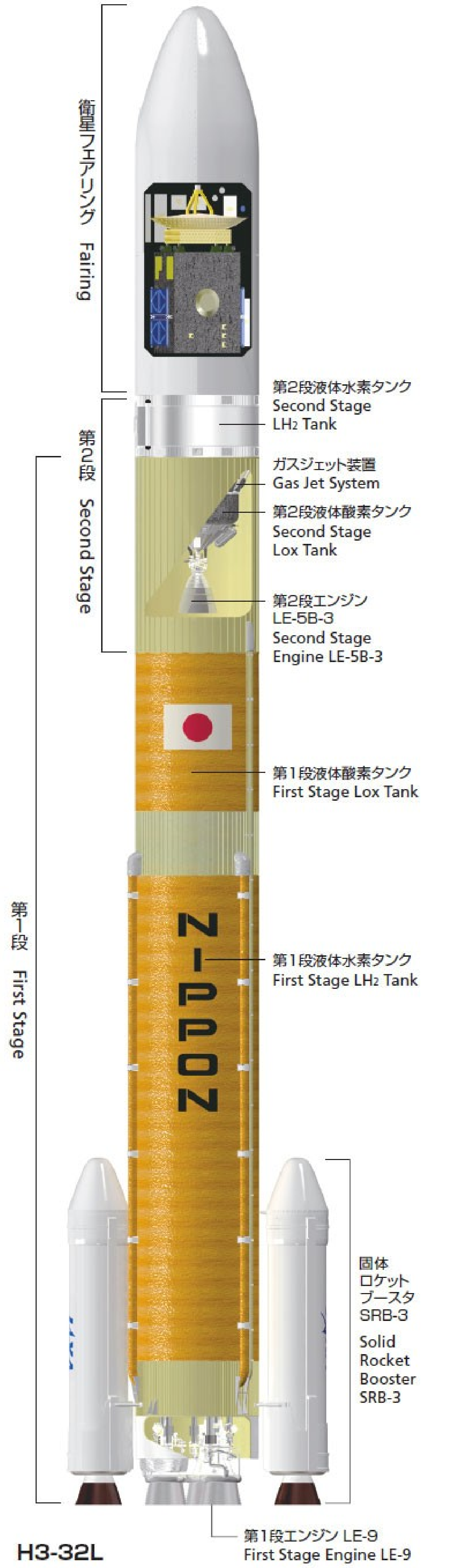
Hazumi+ SPIE 2020

- 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
- Expected launch in late **2029** with JAXA’s H3 rocket
- **All-sky 3-year survey**, from Sun-Earth Lagrangian point L2
- Large frequency coverage (**40–402 GHz**, 15 bands) at **70–18 arcmin** angular resolution for precision measurements of the **CMB *B*-modes**
- Final combined sensitivity: **2.2 μK·arcmin**, after component separation



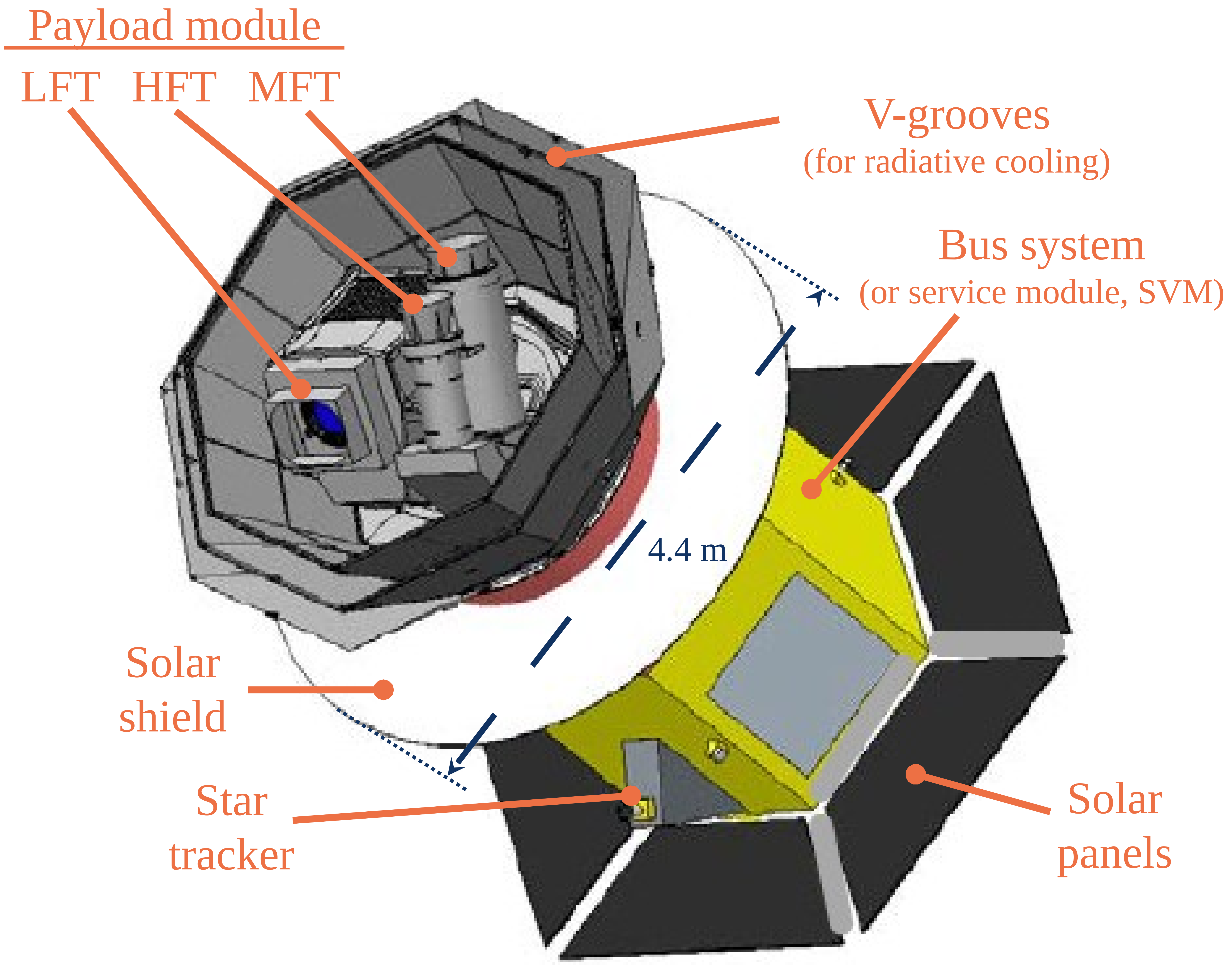




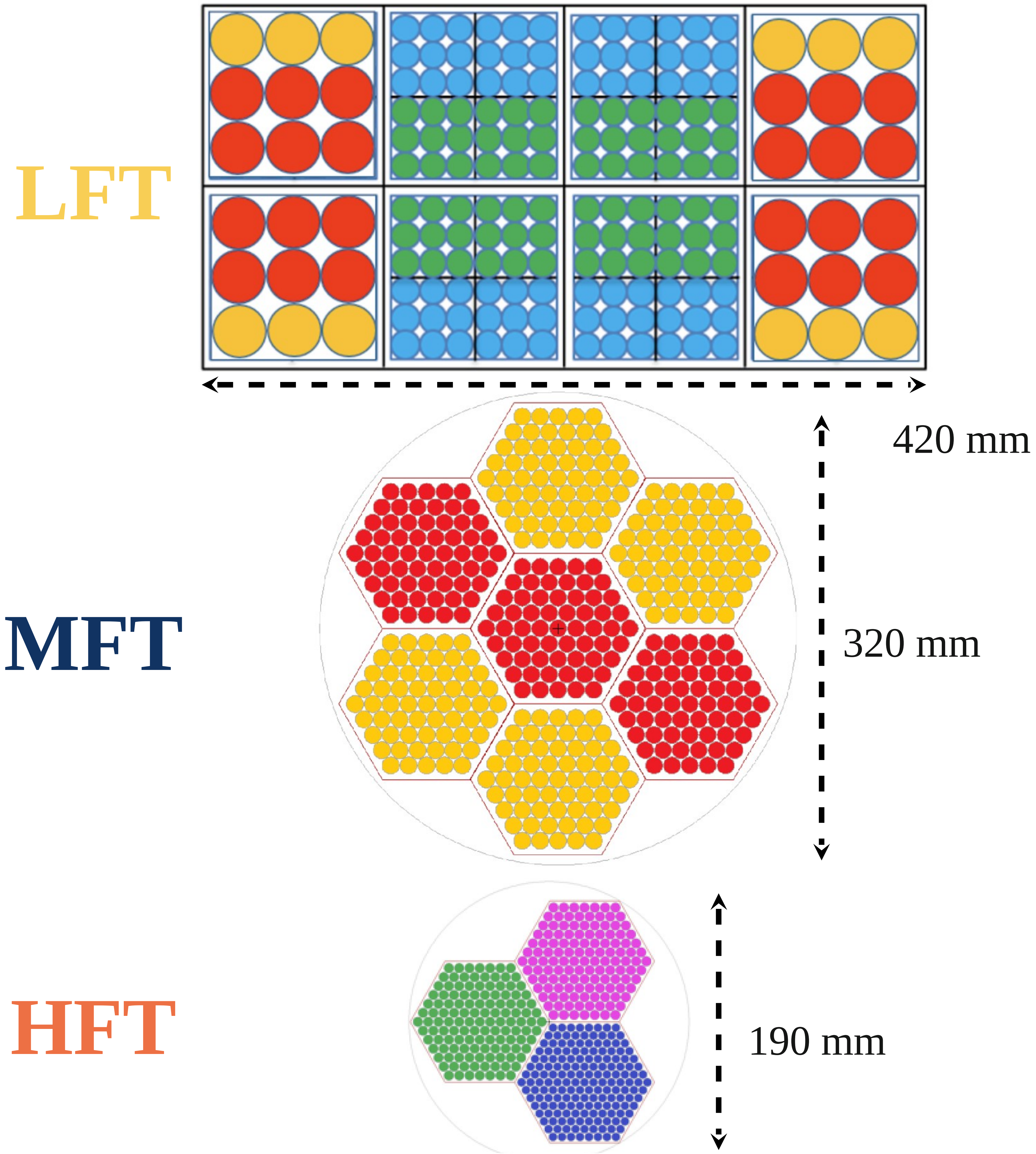


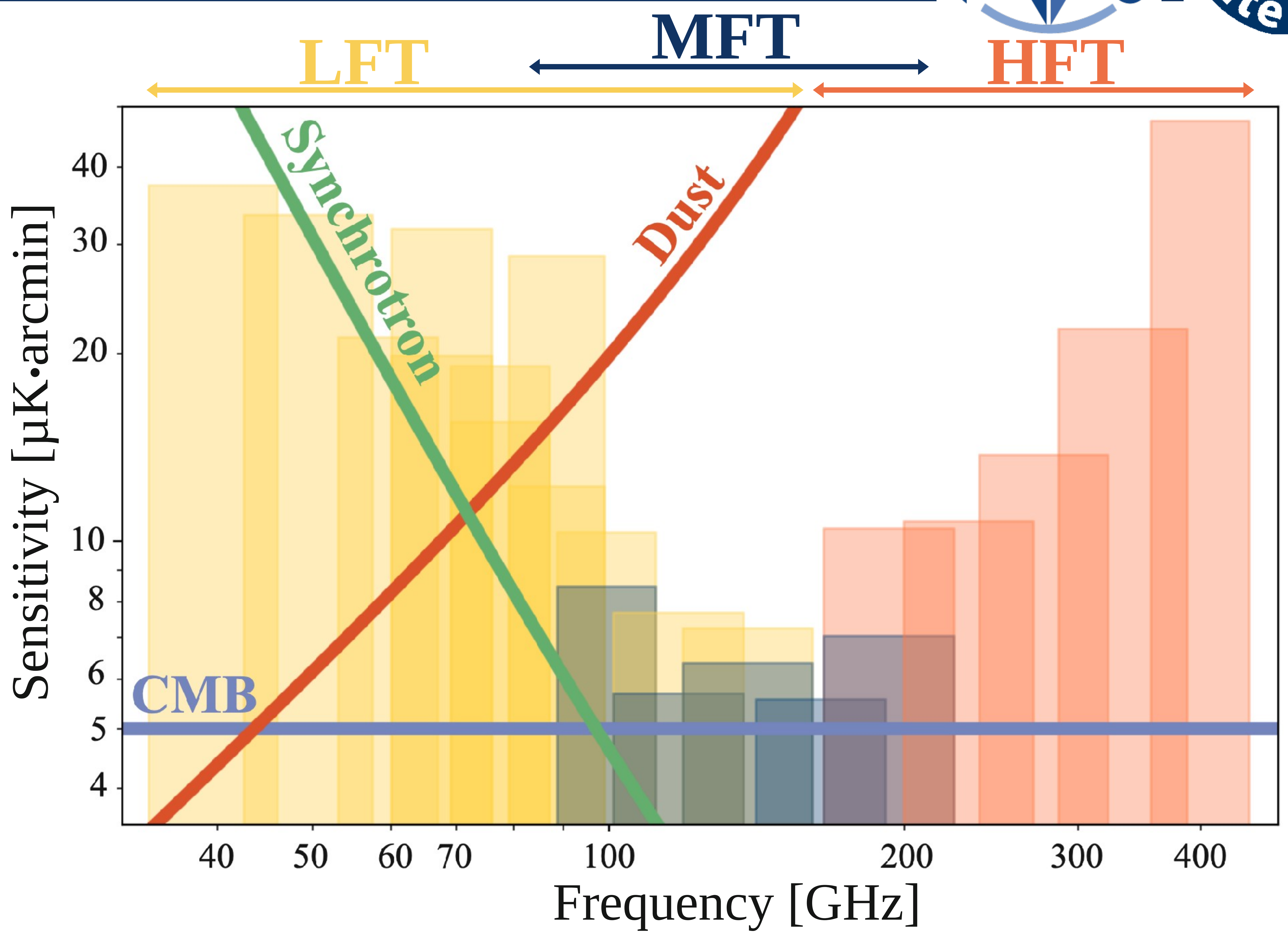
LiteBIRD spacecraft overview

- **3 telescopes** are used to provide the **40-402 GHz** frequency coverage
  1. **LFT** (low frequency telescope)
  2. **MFT** (middle frequency telescope)
  3. **HFT** (high frequency telescope)
- MHFT instrument in the middle of design **phase A** study, **led by CNES**
- Multi-chroic transition-edge sensor (TES) **bolometer arrays** cooled to **100 mK**
- Polarization modulation unit (PMU) in each telescope with **rotating half-wave plate** (HWP), for 1/*f* noise and systematics reduction
- Optics cooled to **5 K**



LiteBIRD sensitivities



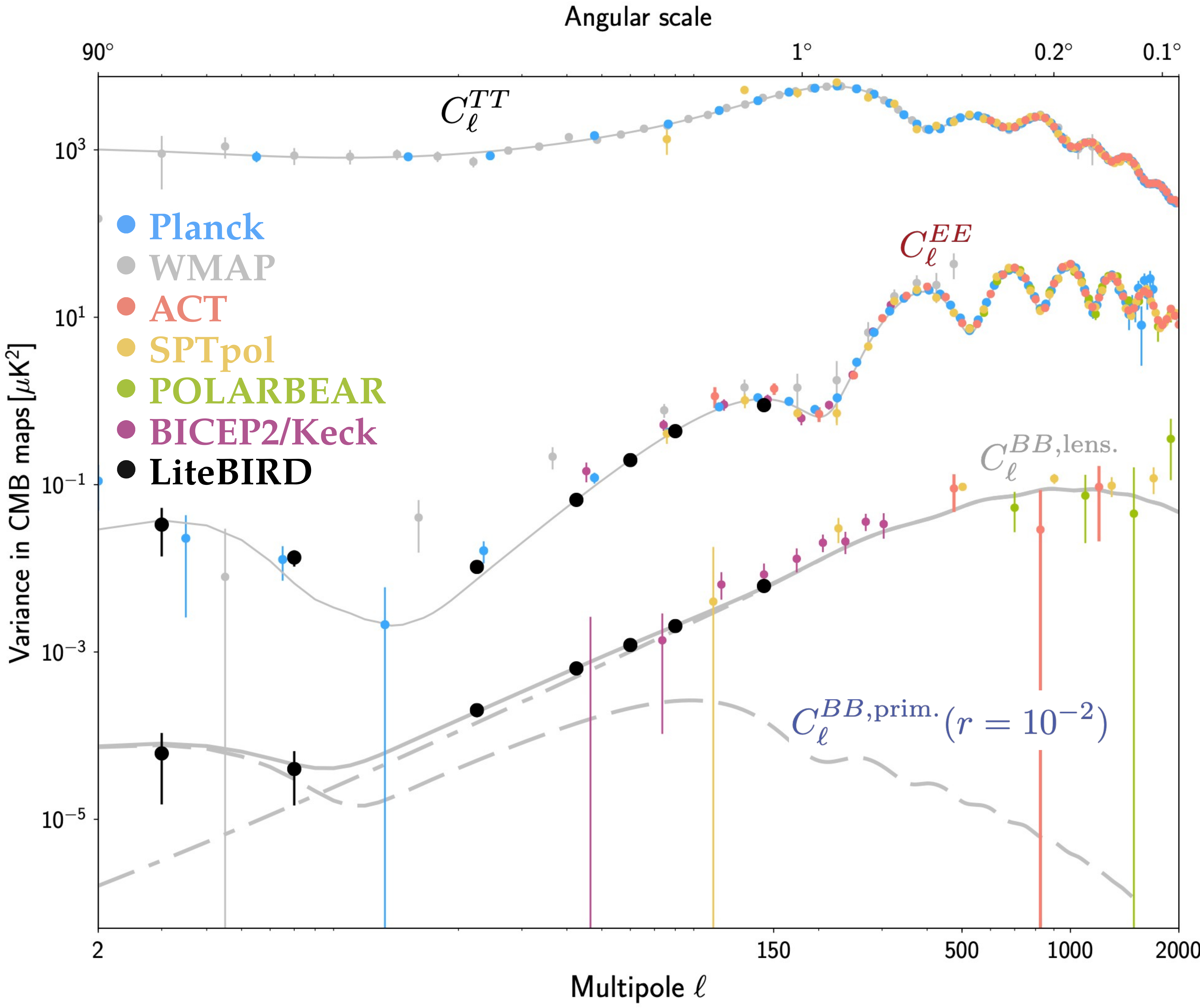


Hazumi+ SPIE 2020

- Projected **polarization sensitivities** for a **3-year full-sky survey**
- Best of 4.3 µK·arcmin @ 119 GHz (Hazumi+ 2020)
- Combined sensitivity to primordial CMB anisotropies (after foreground removal): **2.2 µK·arcmin**

LiteBIRD main scientific objectives

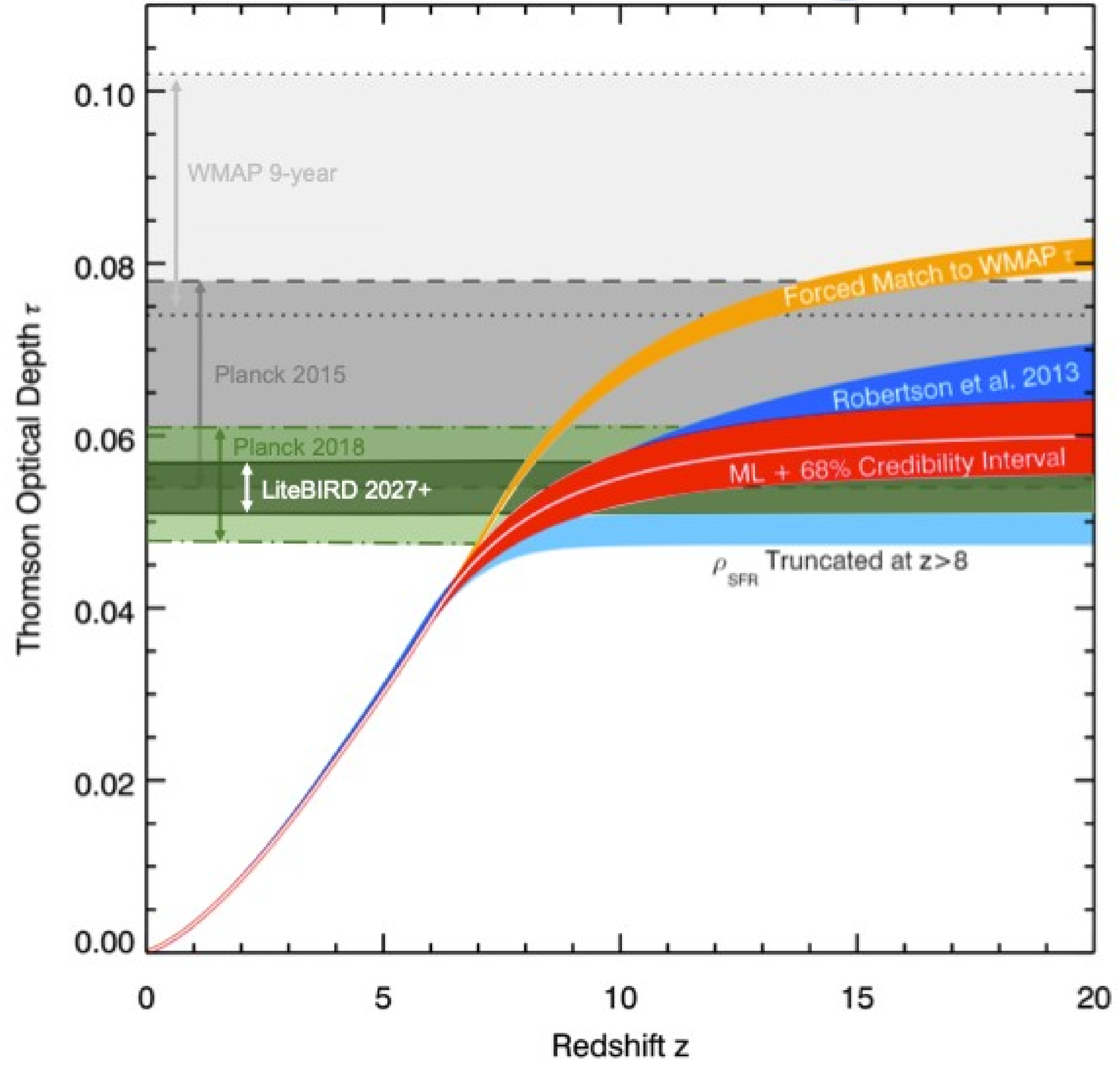
- Definitive search for the ***B*-mode signal** from **cosmic inflation** in the CMB polarization
- The inflationary (i.e. primordial) *B*-mode power is proportional to the **tensor-to-scalar ratio, *r***
- Current best constraint: $r < 0.036$ (95% C.L.)
- (BICEP/Keck collaboration)
- LiteBIRD will improve 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 independently
- Huge discovery impact (evidence for inflation, knowledge of its energy scale, …)
- Most LB characteristics and expected results summarized in a paper to be submitted to the PTEP journal



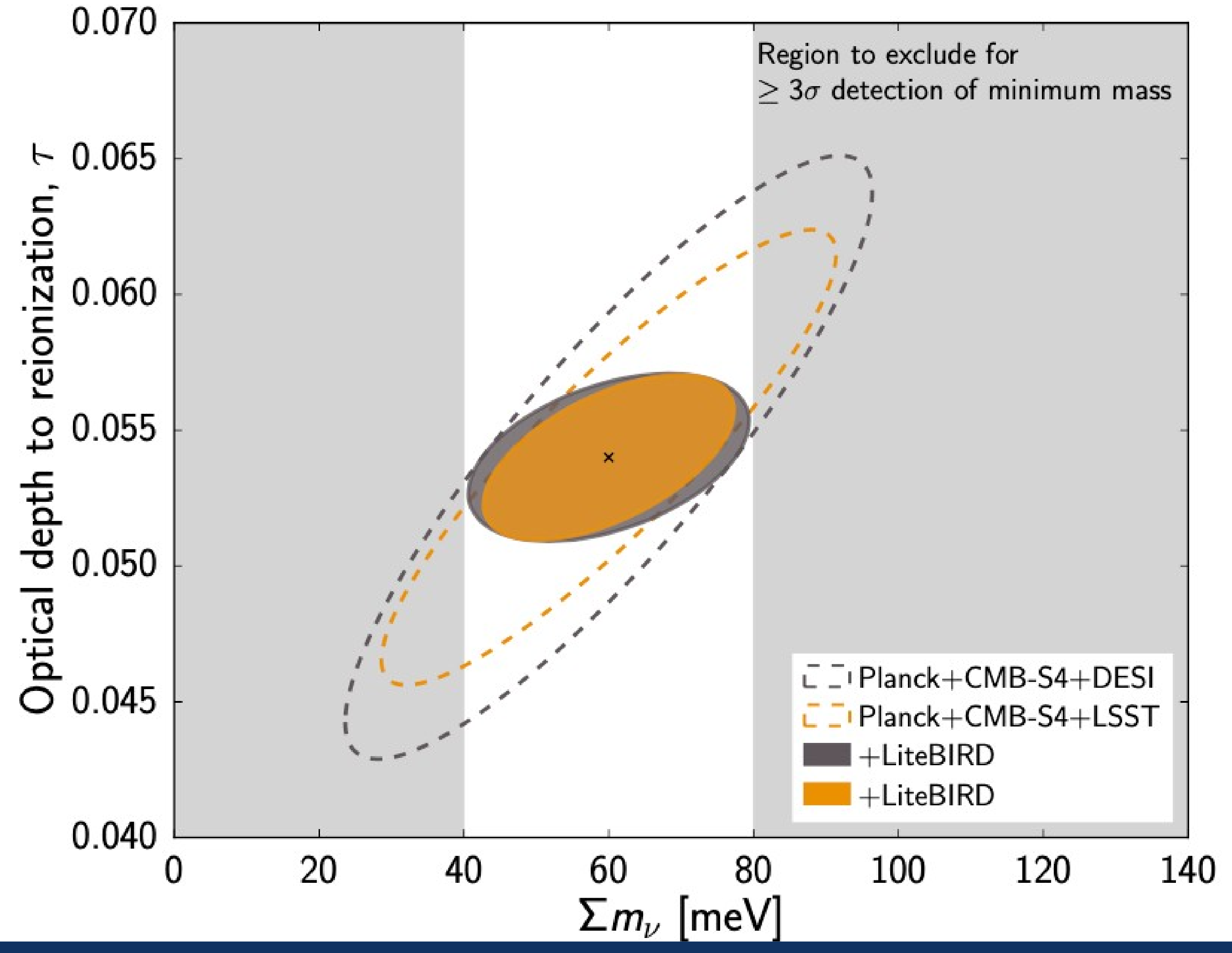
LiteBIRD other science outcomes

- The mission specifications are driven by the required sensitivity on *r*
- Meeting those sensitivity requirements would allow to address other important scientific topics, such as:

1. Characterize the *B*-mode power spectrum and search for source fields (e.g. scale-invariance, non-Gaussianity, parity violation, …)
2. Power spectrum features in polarization
    - Large-scale ***E*-modes**
    - **Reionization** (improve $\sigma(\tau)$ by a factor of 3)
    - **Neutrino mass** ($\sigma(\Sigma m_\nu) = 15$ meV)
3. Constraints on **cosmic birefringence**
4. **SZ effect** (thermal, diffuse, relativistic corrections)
5. Elucidating **anomalies**
6. **Galactic science**
    - Characterizing the foreground SED
    - Large-scale Galactic magnetic field
    - Models of dust polarization



adapted from Robertson+2015



adapted from Calabrese+2017

Foreground cleaning

Foreground modeling

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

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

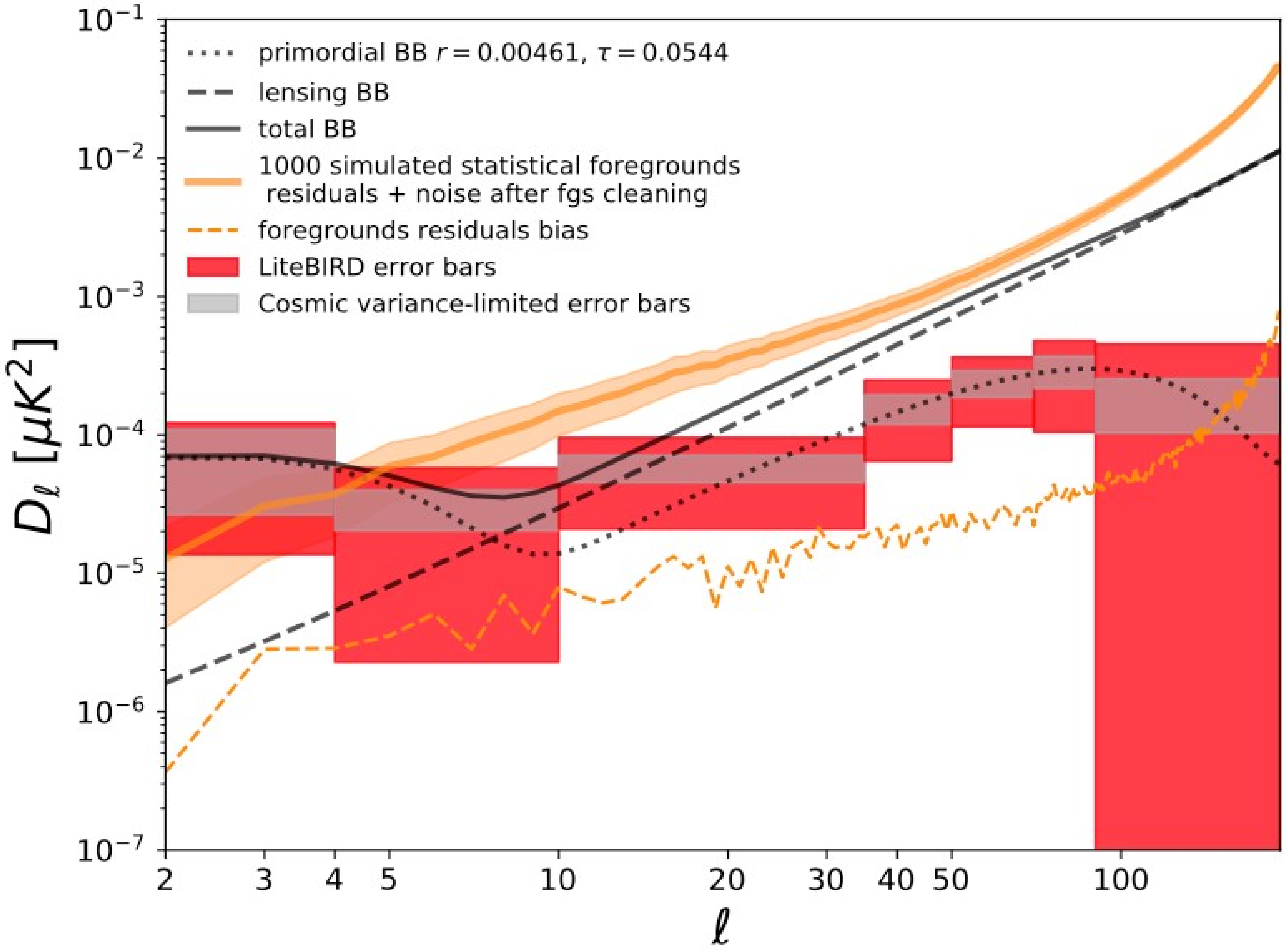
- **Dust**: modified blackbody

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

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 $r_{\text{true}}=0$

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

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

$$C_\ell = r C_\ell^{\text{tens}} + C_\ell^{\text{lens}} + N_\ell$$

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

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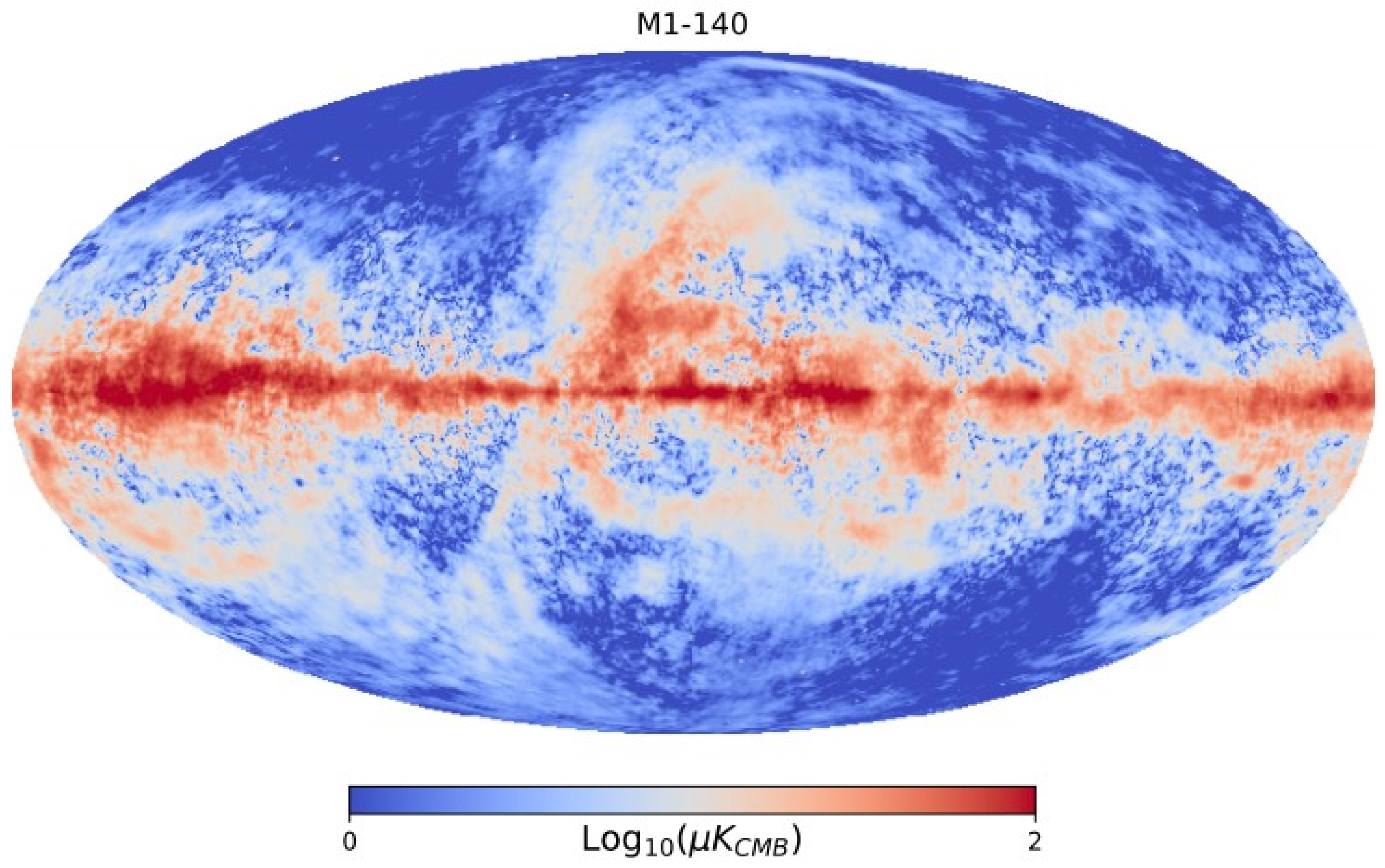
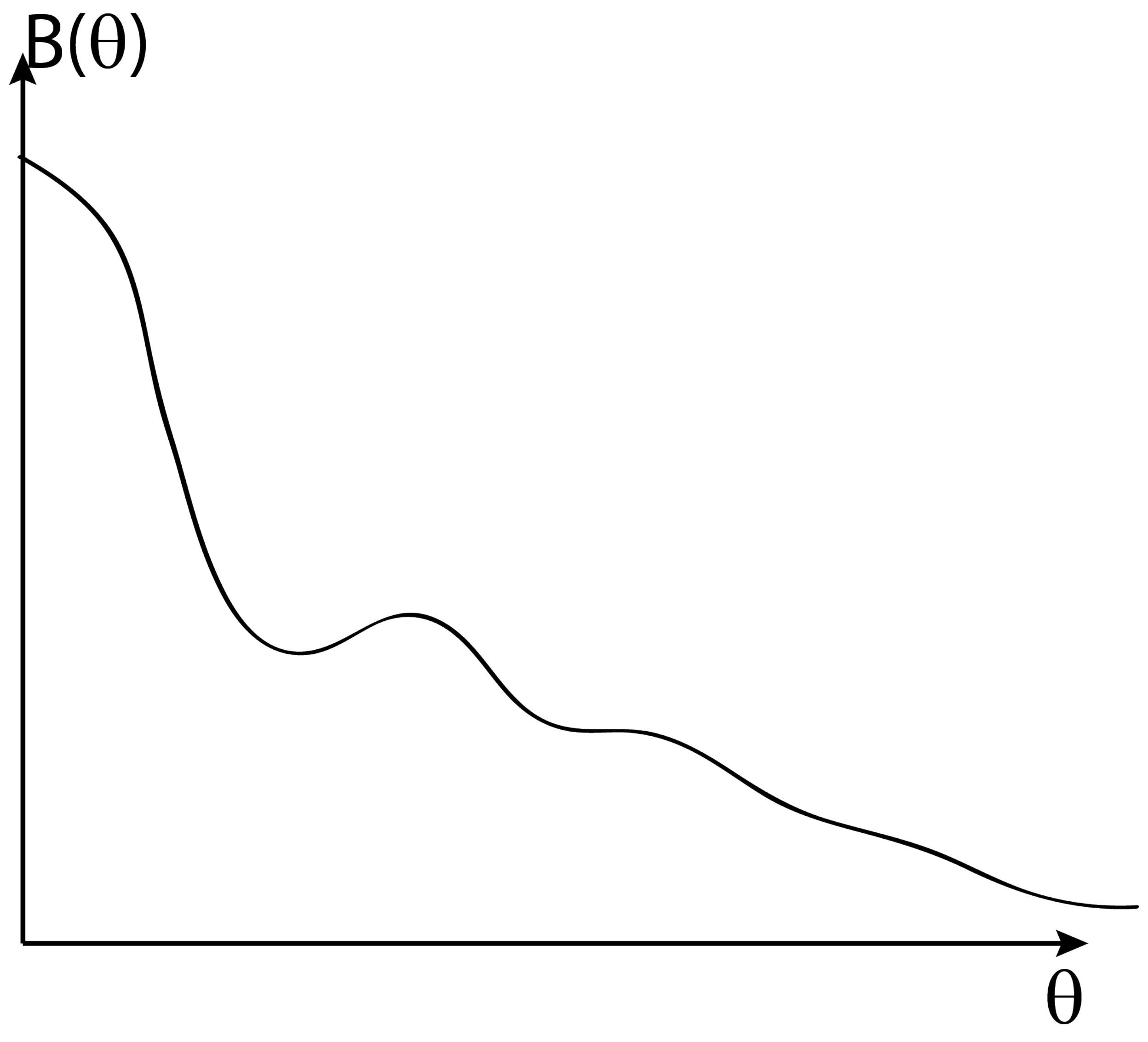
Beam convolution

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. Asymmetric



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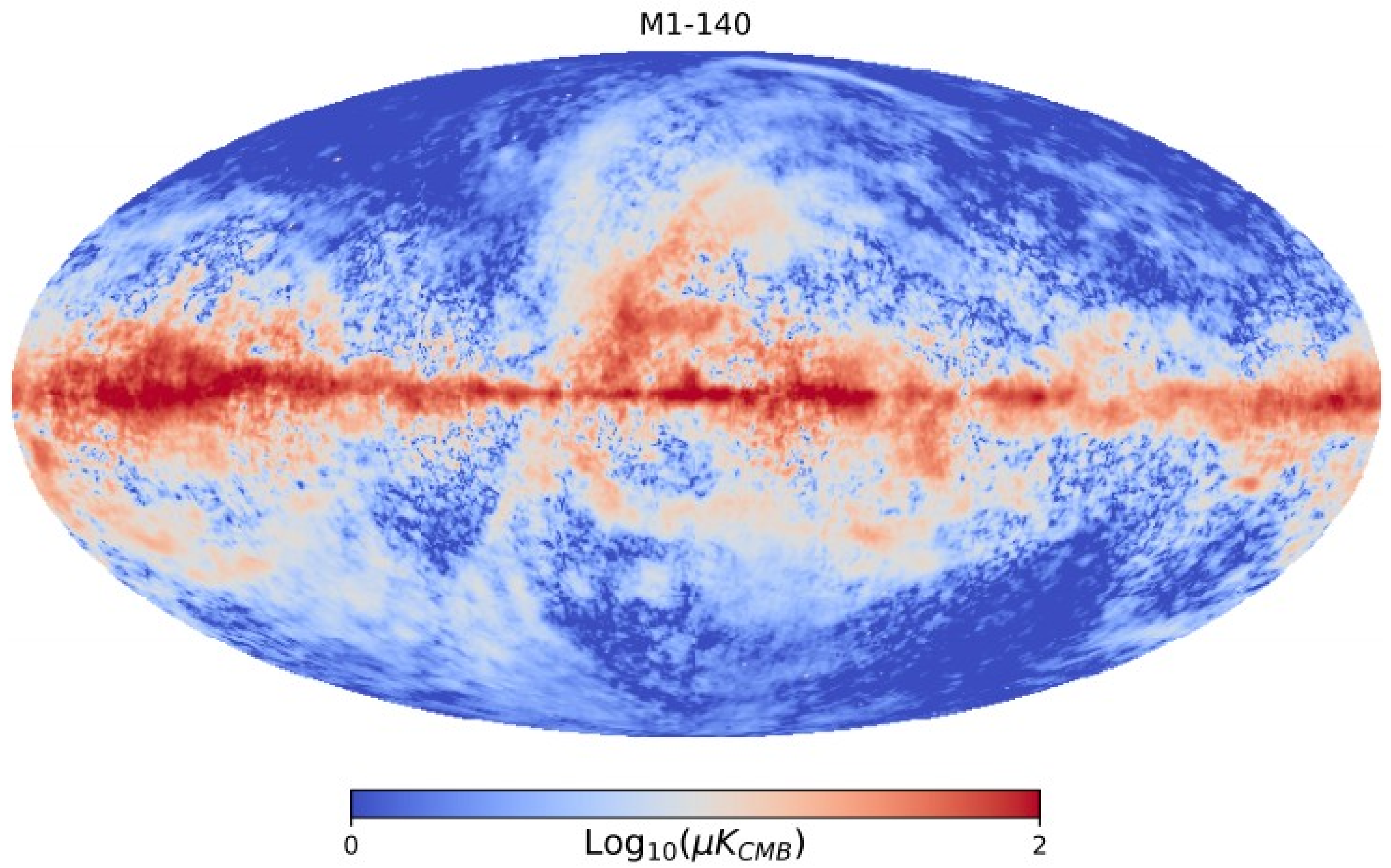
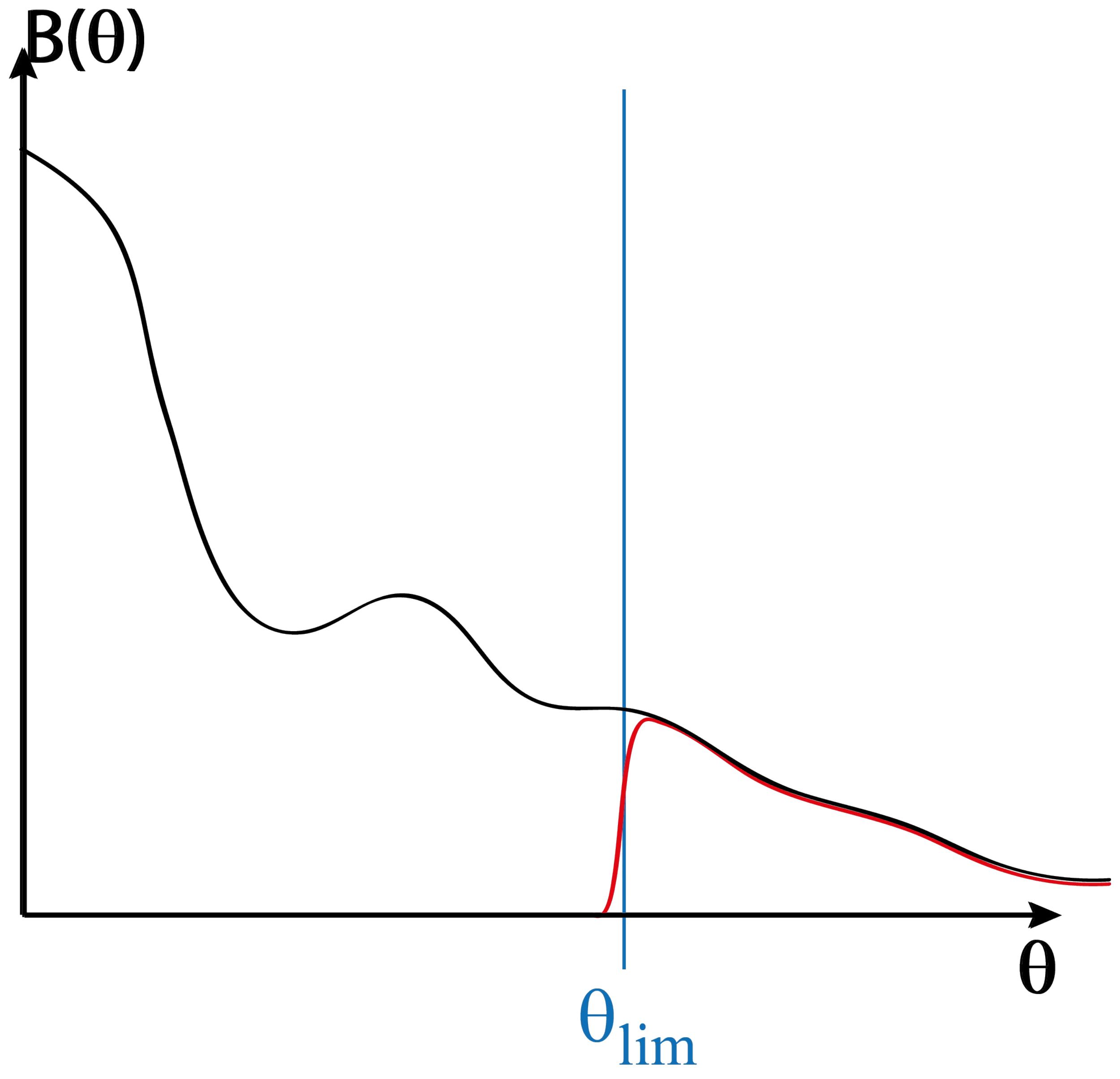
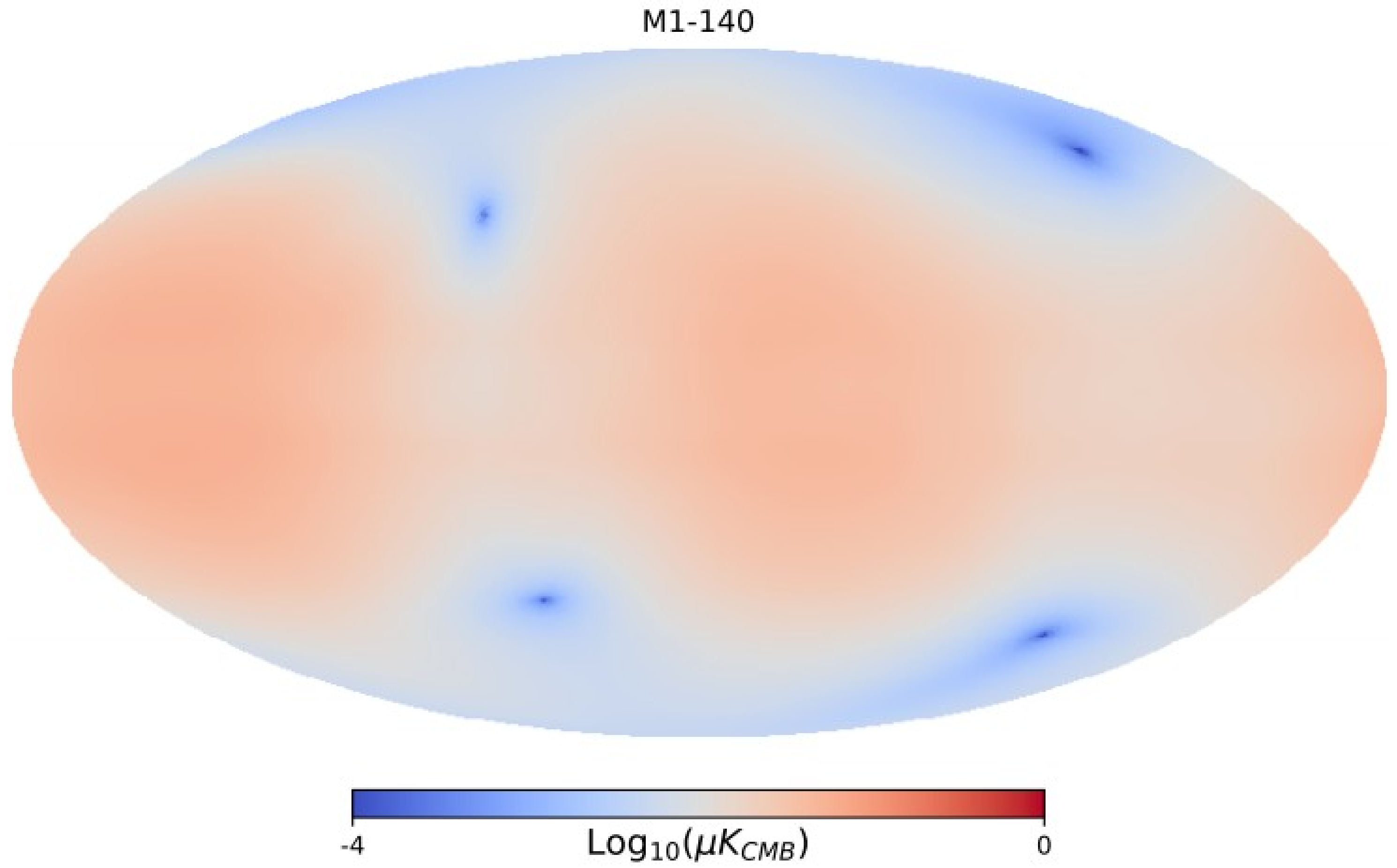
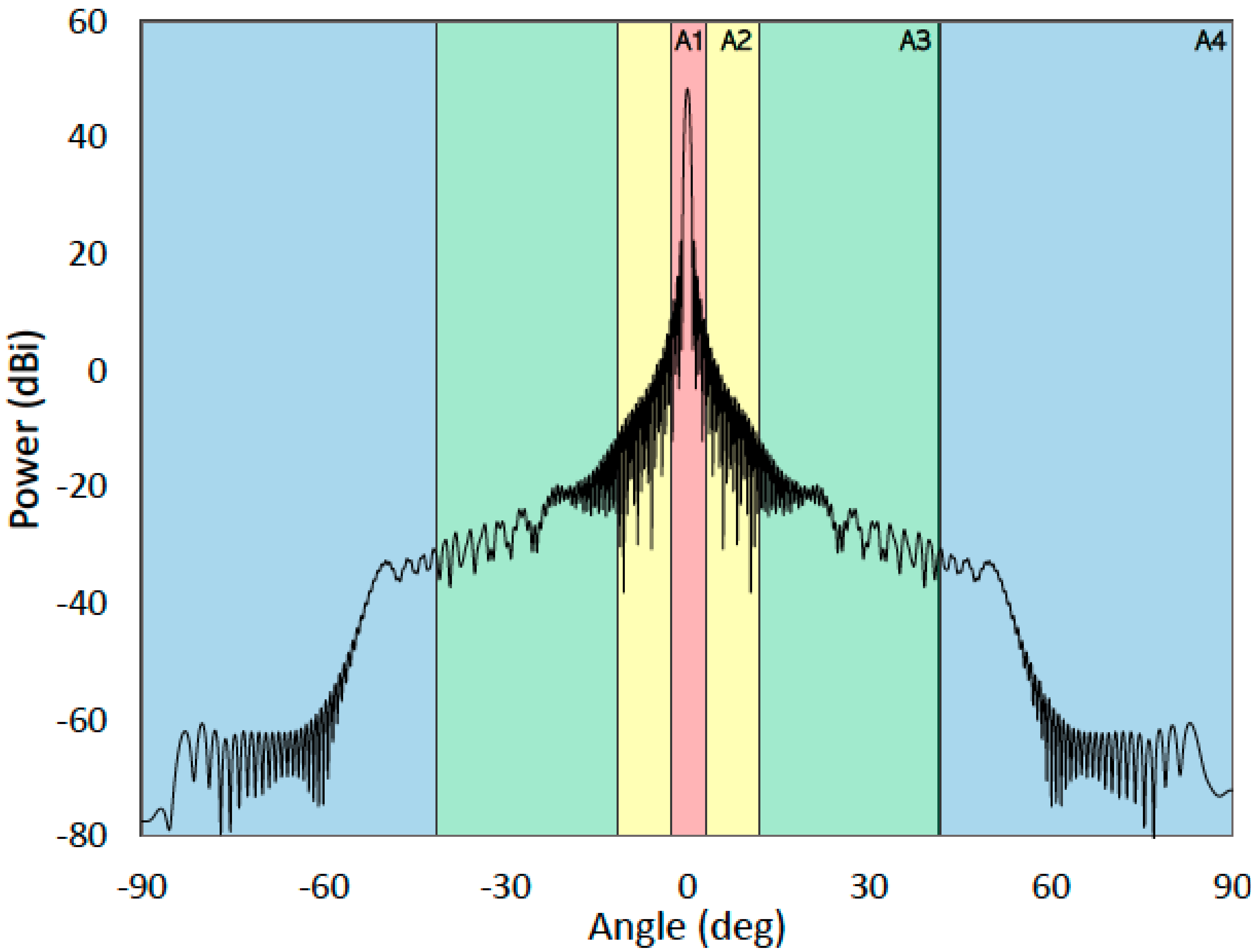


- Effect of far side-lobes
  1. Galactic B-modes → CMB B-modes
  2. E → B, w/o HWP
  3. Instrumental polarization

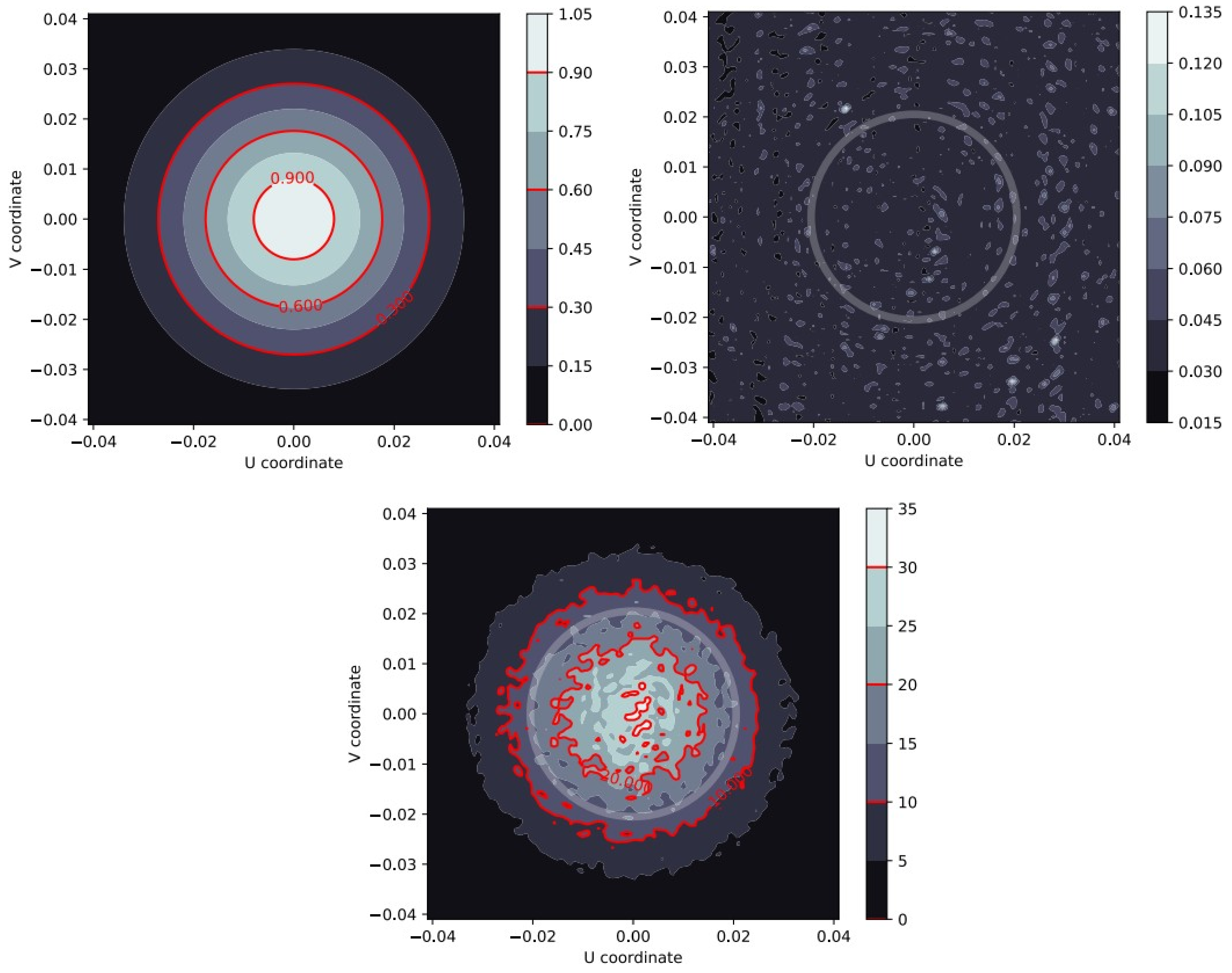




Calibration scheme



- 4 regions in beams depending on dominant effects
- Two calibration phases :
  1. On the ground
  2. In flight using planets



Requirements on beam knowledge

- Beam systematics controlled 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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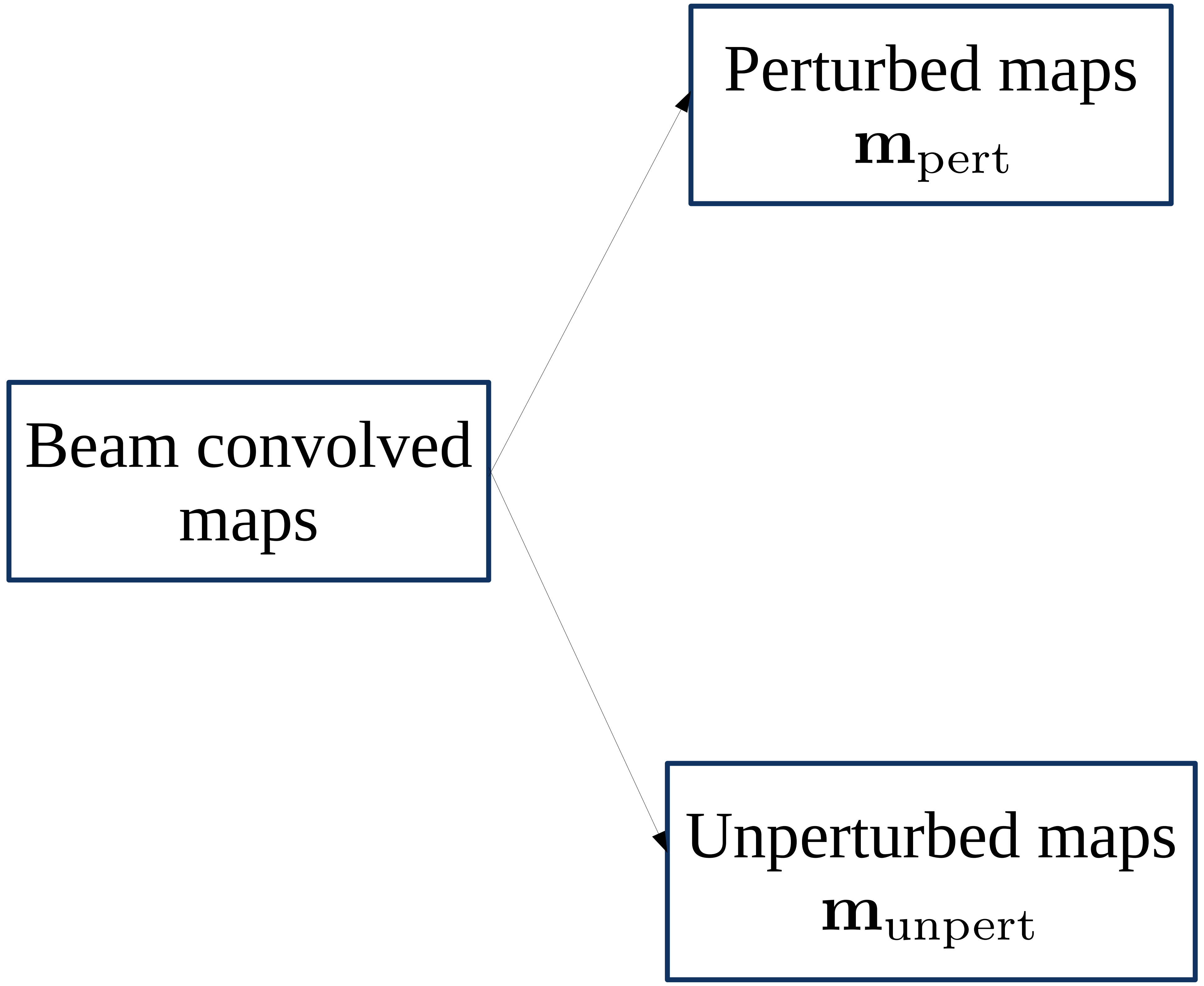
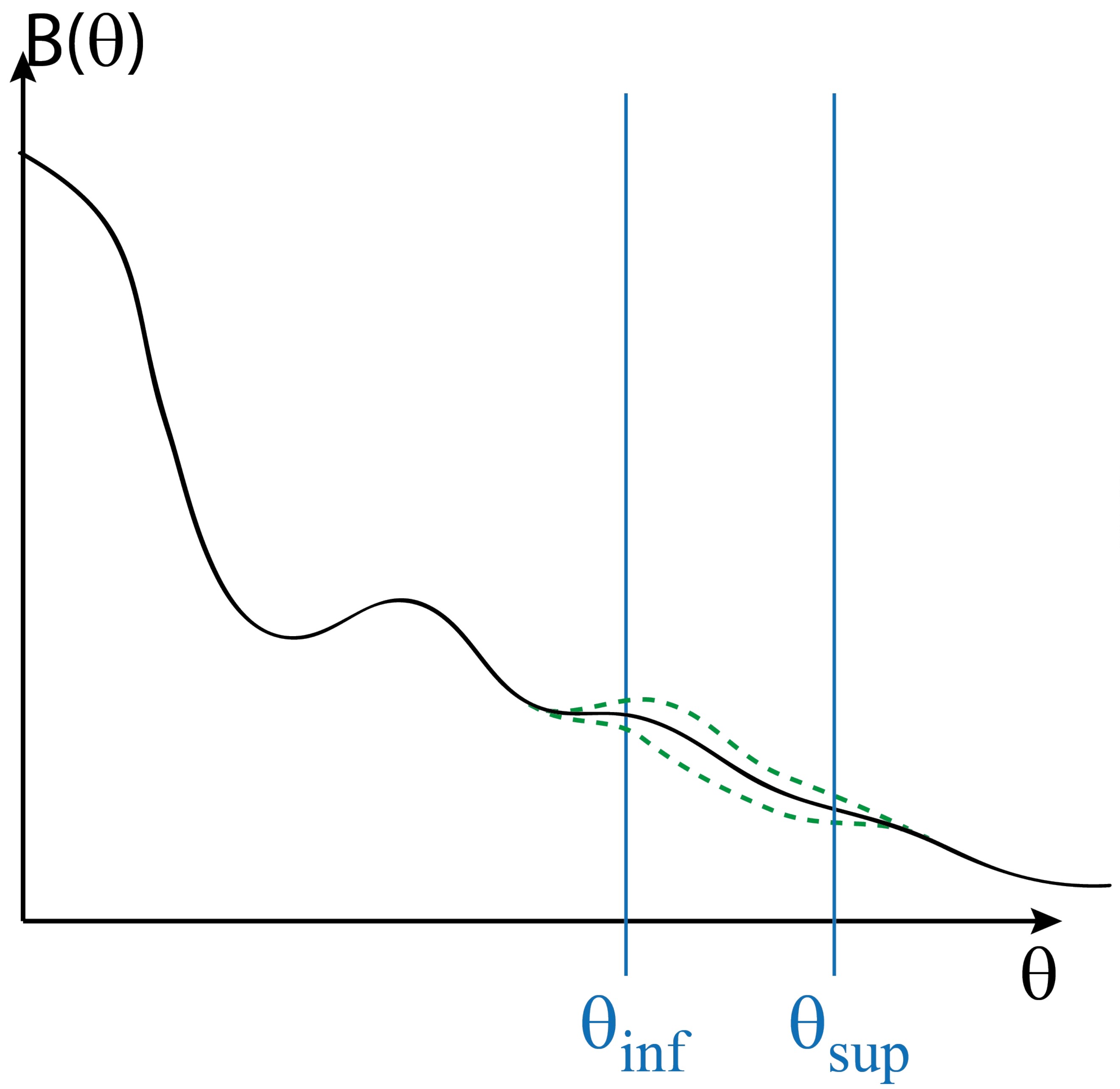
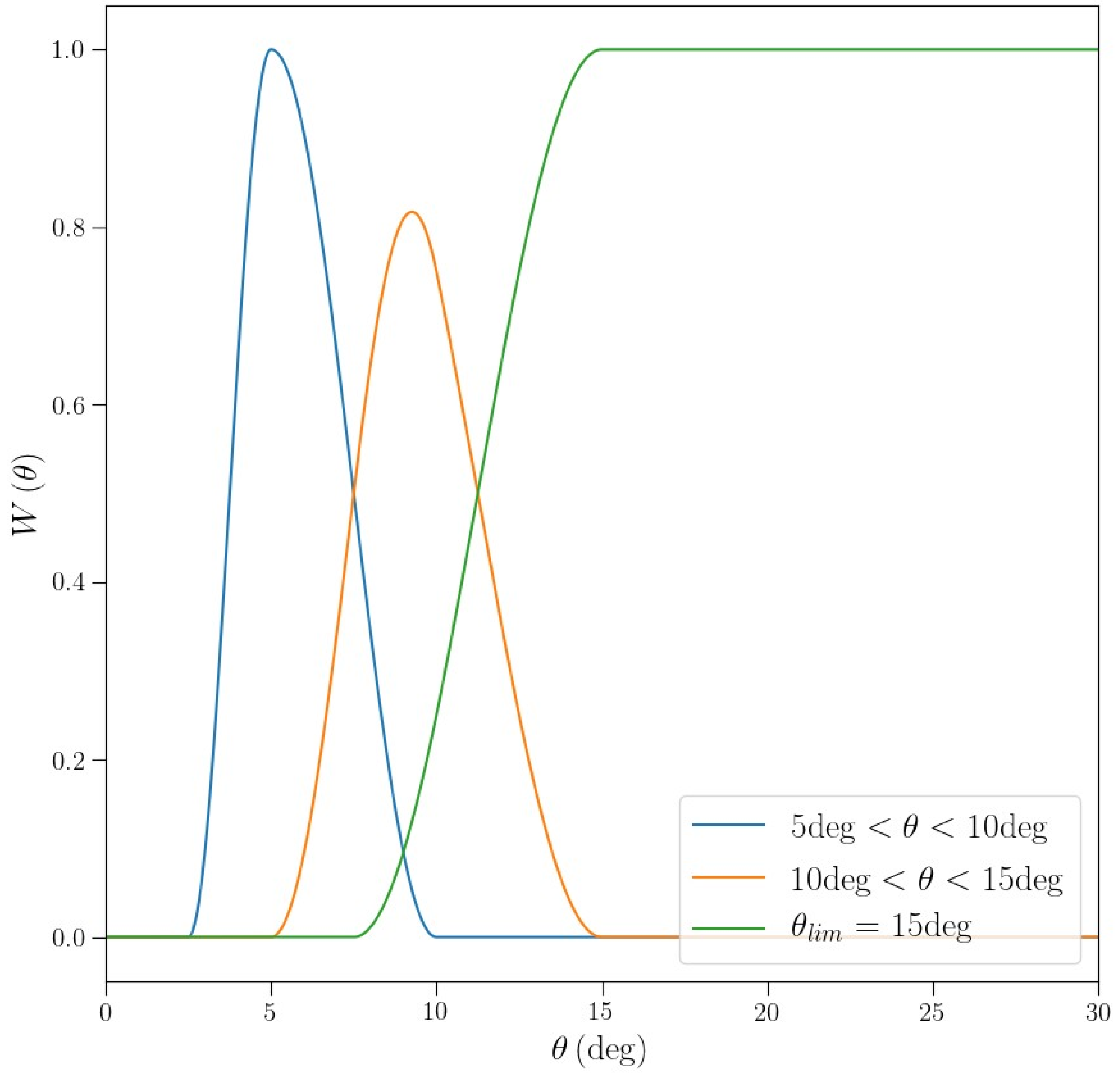


Beam convolved maps

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

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





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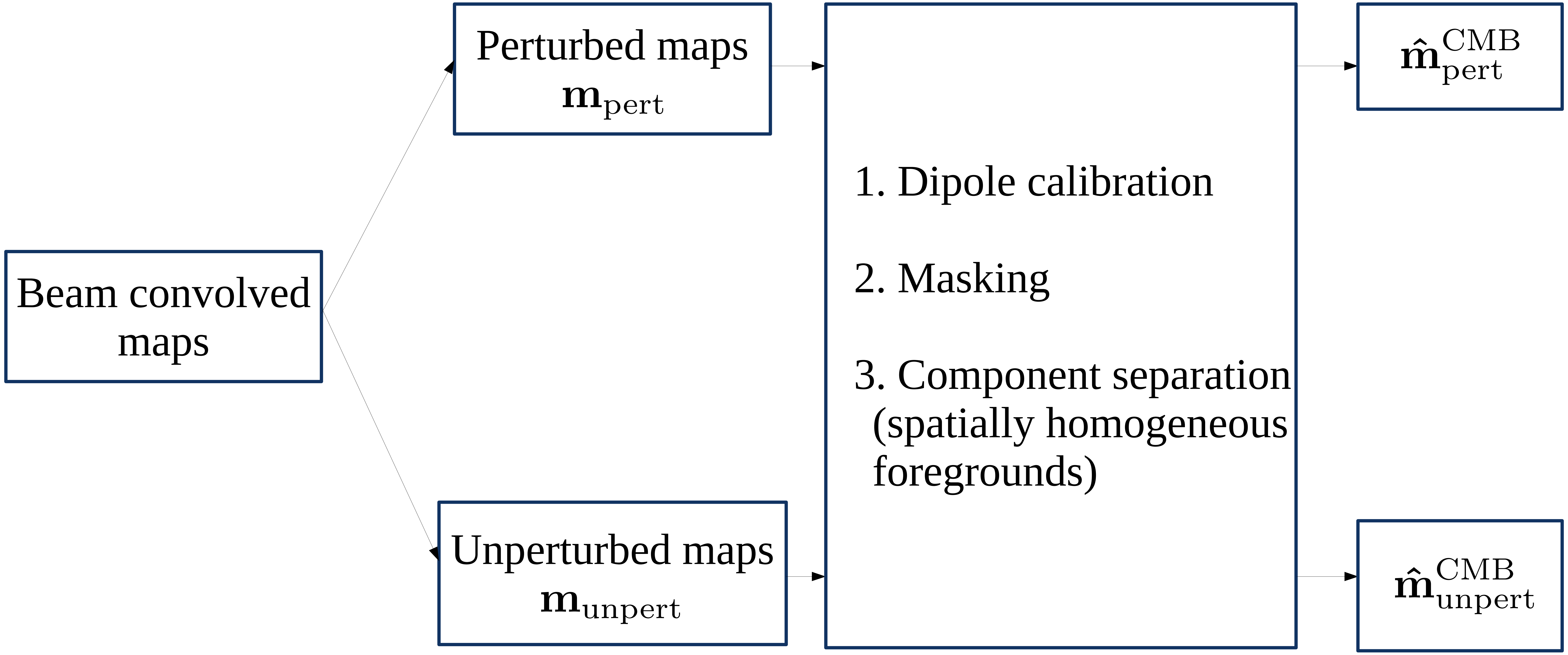

Beam convolved maps

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

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

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

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

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

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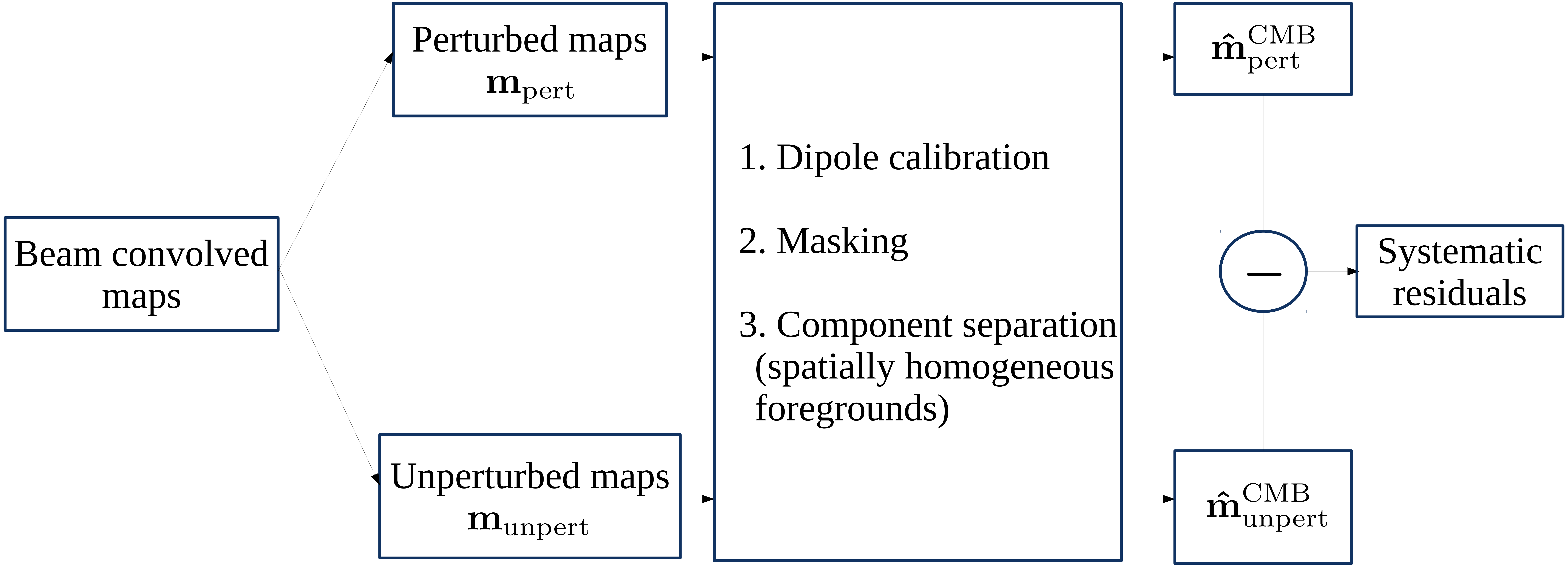

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$-$

Systematic residuals

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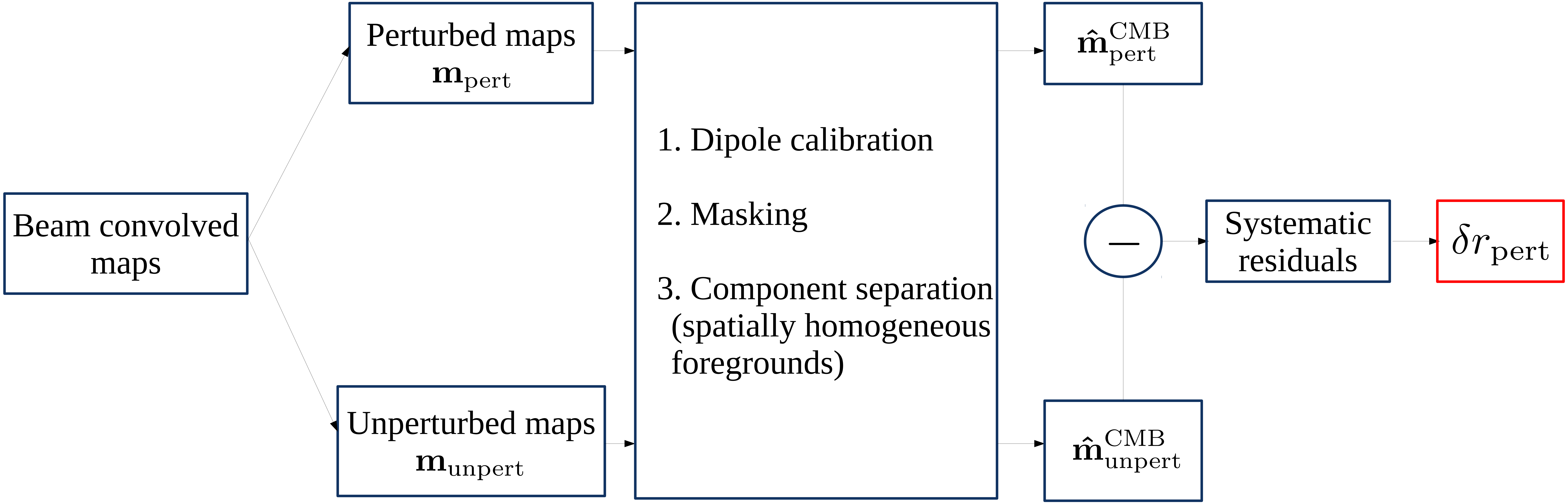

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$-$

Systematic residuals

δr_{pert}

Requirements on beam knowledge

- Assume independent effect from each frequency channel ν and angular window W → perturb one channel at a time to get δr^{ν}_{W}
- Total bias from beam far side-lobes systematics is then :

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

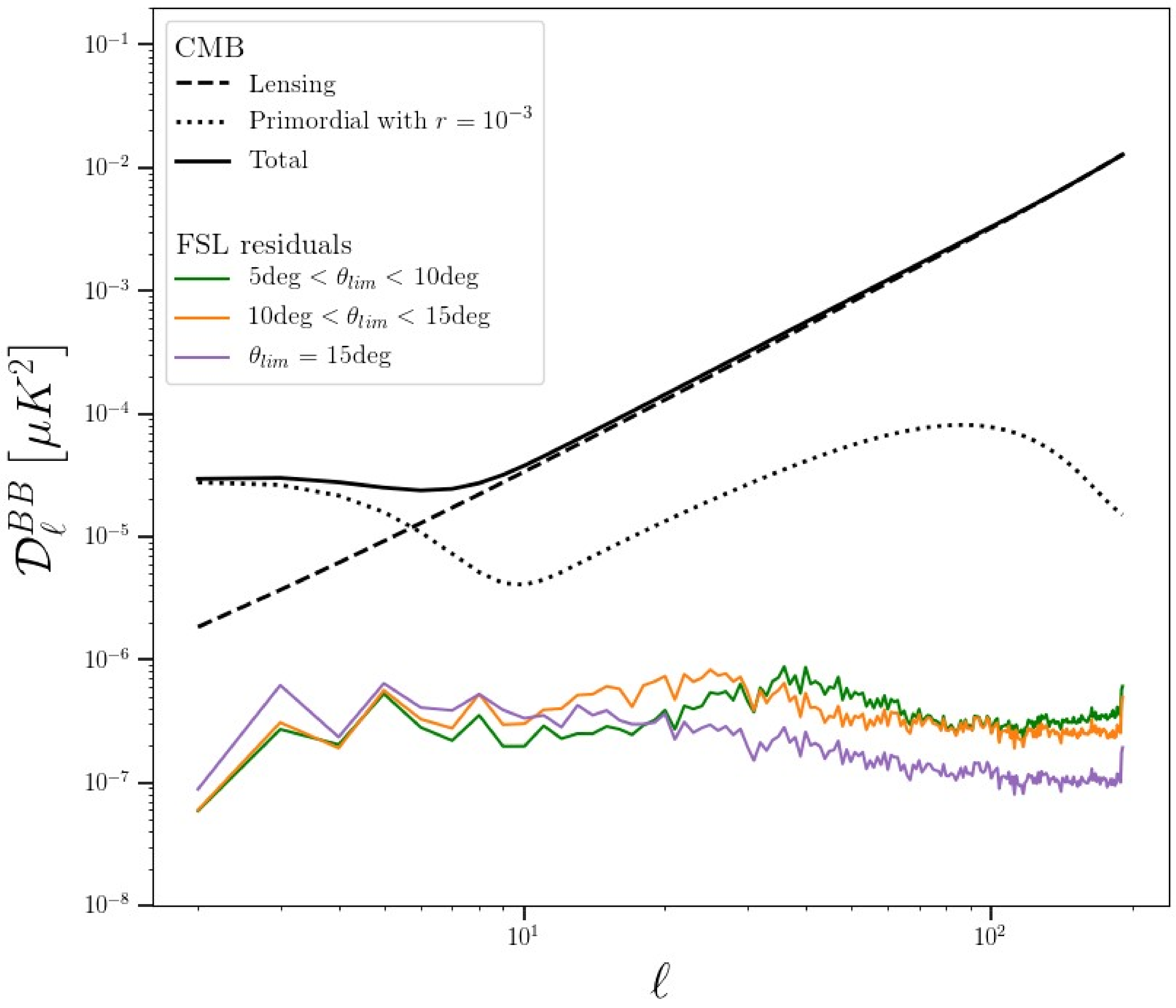
- FSL error budget in LB is 10 % of total systematic error budget :

$$\Delta r_{\mathrm{FSL}} \lesssim 5.7 \times 10^{-5}$$

- Assuming same calibration accuracy σ_{calib} throughout the frequency and angular ranges, on pixels of size 0.5x0.5 deg^2, we find that this is achieved when :

$$\sigma_{\mathrm{calib}} \lesssim -54.4\ \mathrm{dB}$$

(normalized to the peak)



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 dominant one comes from the lack of knowledge of the beams far side-lobes
- This will be handled through ground and in-flight measurements with required accuracy found to be σ_{calib}~-55dB, 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. An MHFT prototype in particular will help (in the coming year)
  - Study the very far region where measurements are not possible
  - Study the impact of beam asymmetries