KAVLI IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

LiteBIRD

Interfacing the instrument and data analysis pipeline developments for the observation of primordial CMB B modes with LiteBIRD

Ema Tsang for the COS-01 project

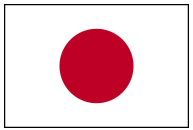
APC

Laboratoire de Physique des 2 infinis Irène Joliot-Curie

Context of the project

1. Context of the project
2. Report from JFY 2024
3. Prospects for JFY 2025

The teams



IPMU group:

- Clément Leloup (PI)
- Tomotake Matsumura
- Ryosuke Akizawa (PhD student)
- Kosuke Aizawa (PhD student)

APC group:

- Josquin Errard
- **Ema Tsang (PhD student)**
- Simon Biquard (PhD student)

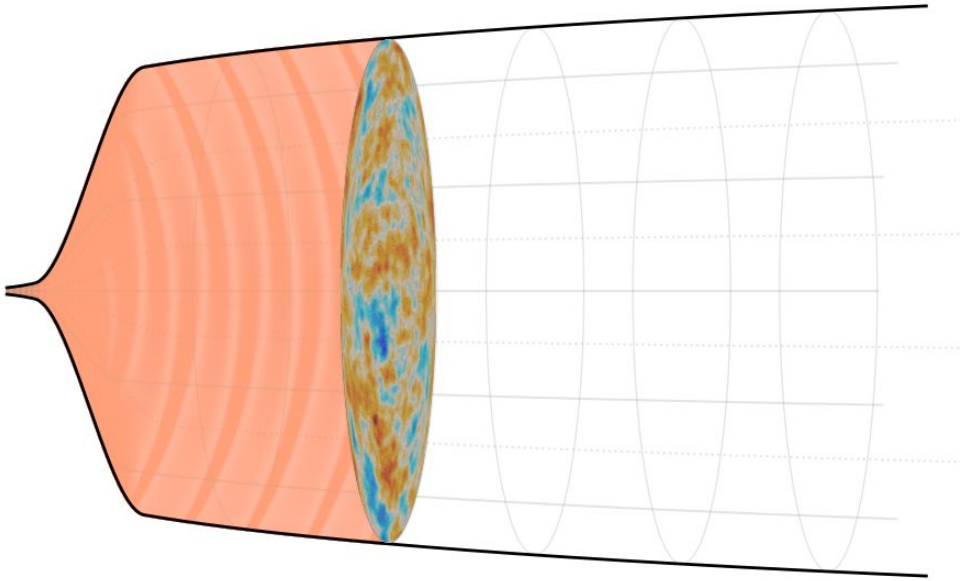
IJCLab group:

- Sophie Henriot-Versillé
- Matthieu Tristram

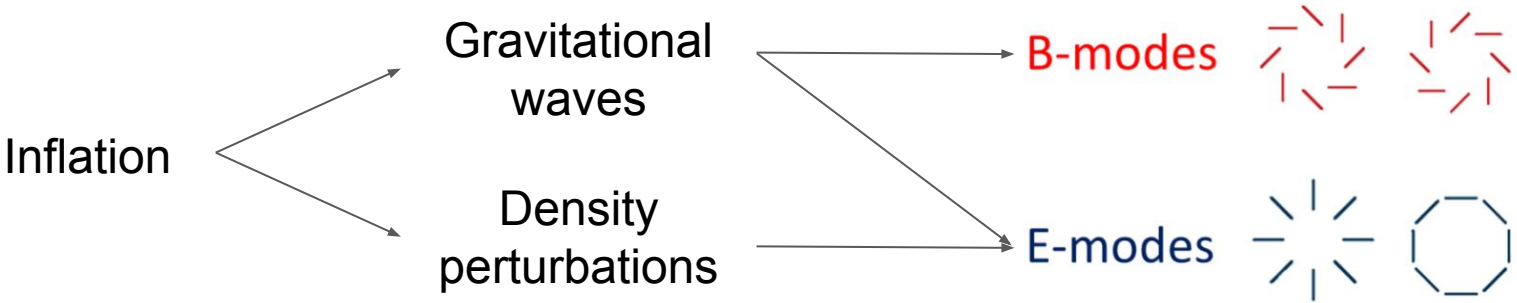
Scientific context

Cosmic inflation is the most popular scenario to explain:

- why the Universe looks **flat** ?
- why the Universe is **homogeneous** ?
- where the **large-scale structures** come from ?

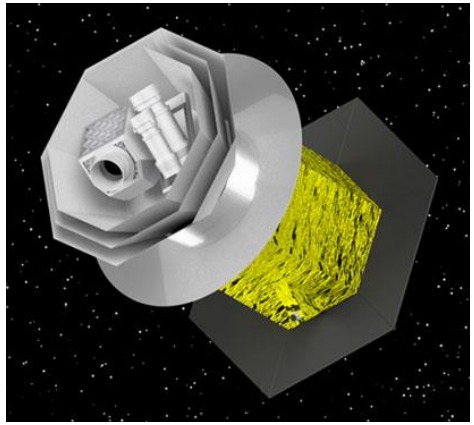


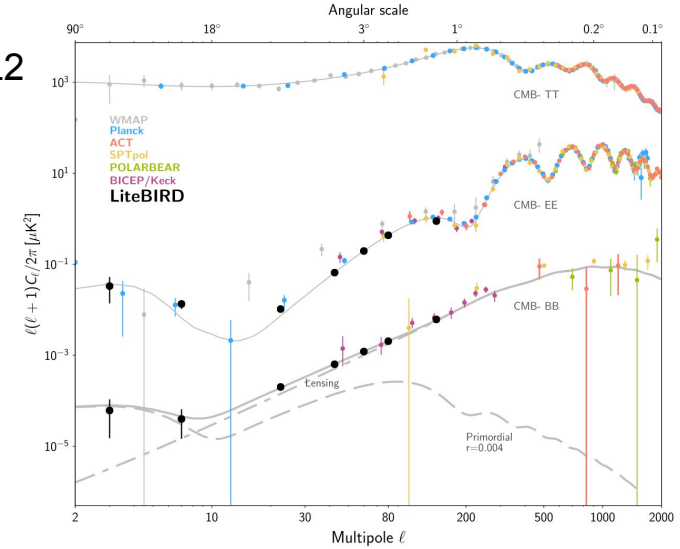
Currently, indirect hints but no direct evidence

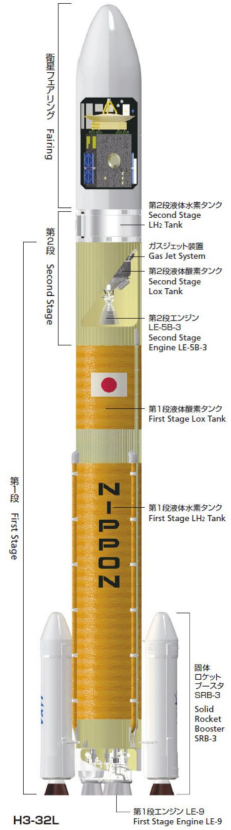


LiteBIRD overview

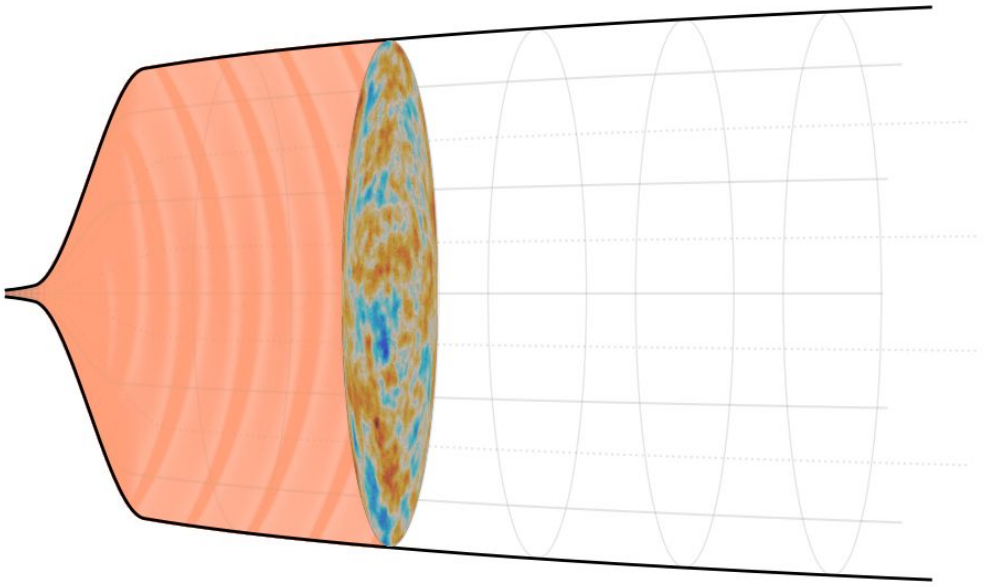
- Lite (Light) spacecraft for the study of B-mode polarization and Inflation from cosmic background Radiation Detection
- JAXA's L-class mission, selected in May 2019, to be launched with new H3 rocket
- All-sky 3-year survey, from Sun-Earth Lagrange point L2
- Large frequency coverage (40-402 GHz) at 70-18 arcmin angular resolution
- Final combined sensitivity: 2.2 μK-arcmin
- The inflationary B-mode power is proportional to the tensor-to-scalar ratio r
- LiteBIRD will have a sensitivity on r improved by ~50

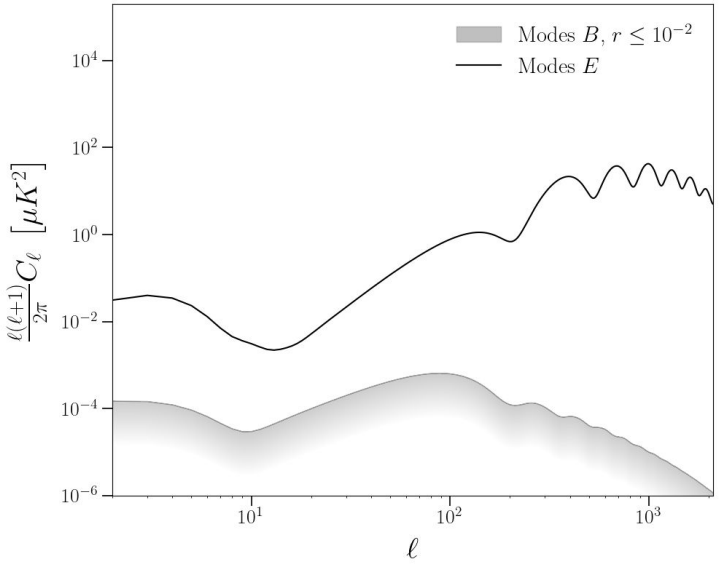






Challenges of CMB B modes





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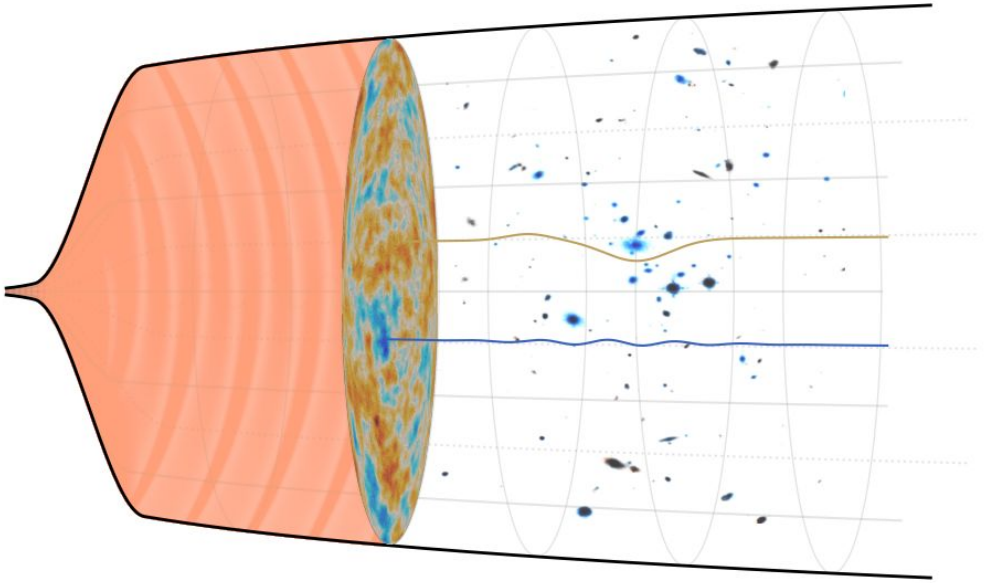
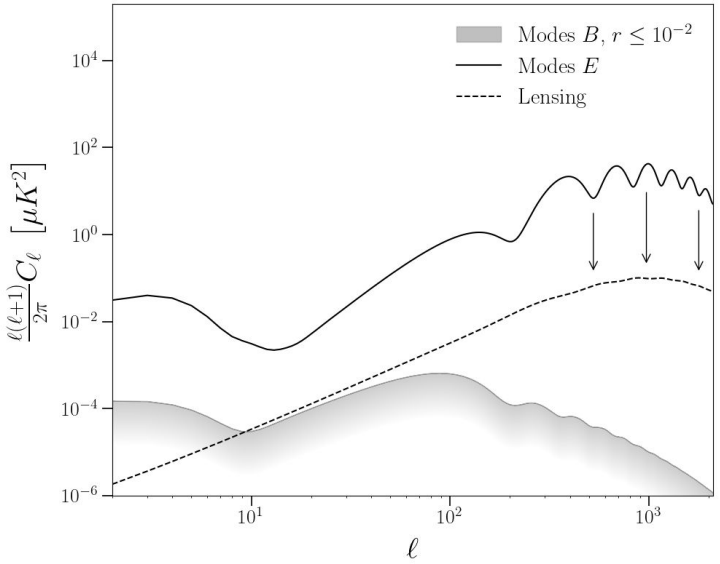
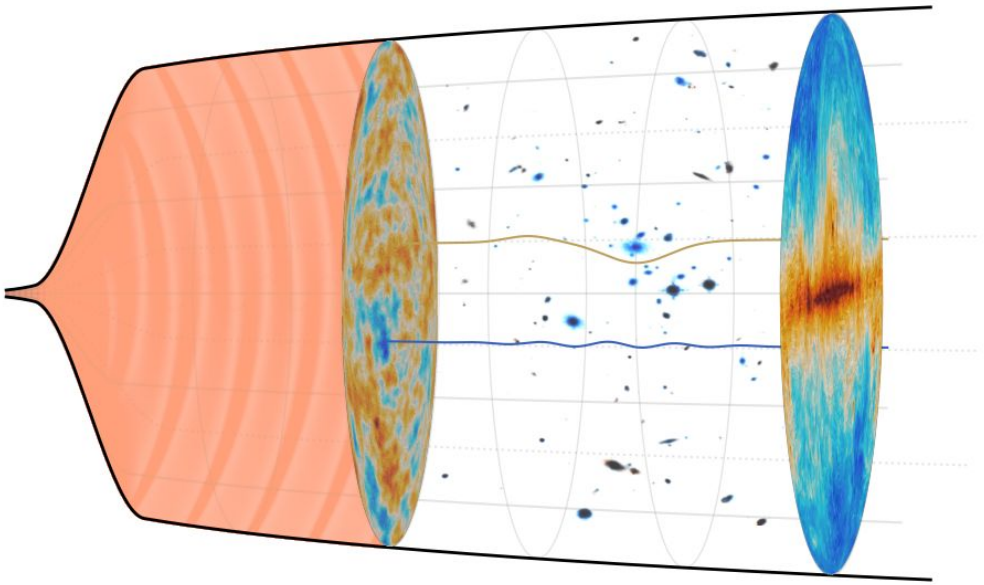


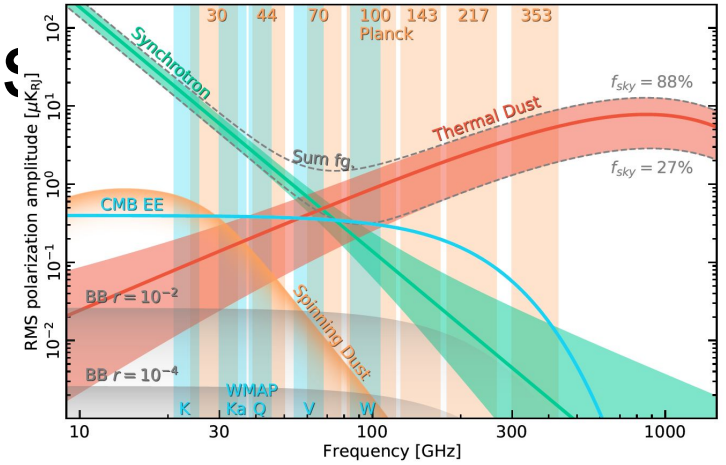
1. **Lensing B modes**

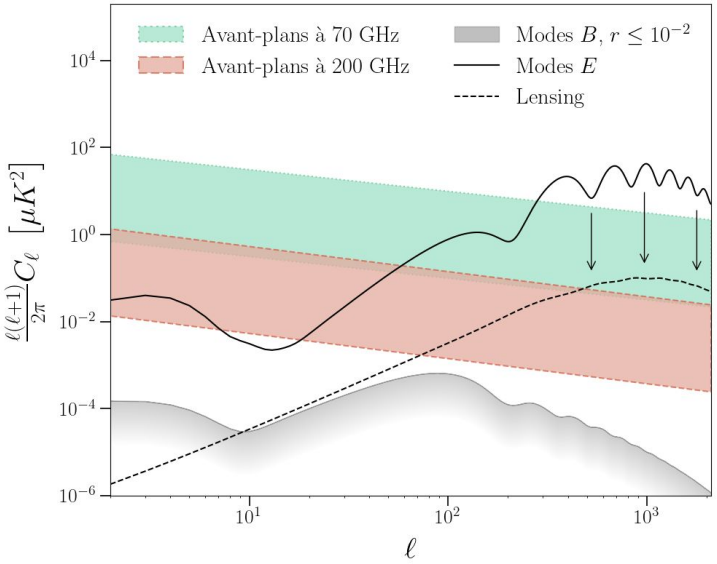


Challenges of CMB B modes



1. **Lensing B modes**
2. **Galactic foregrounds**





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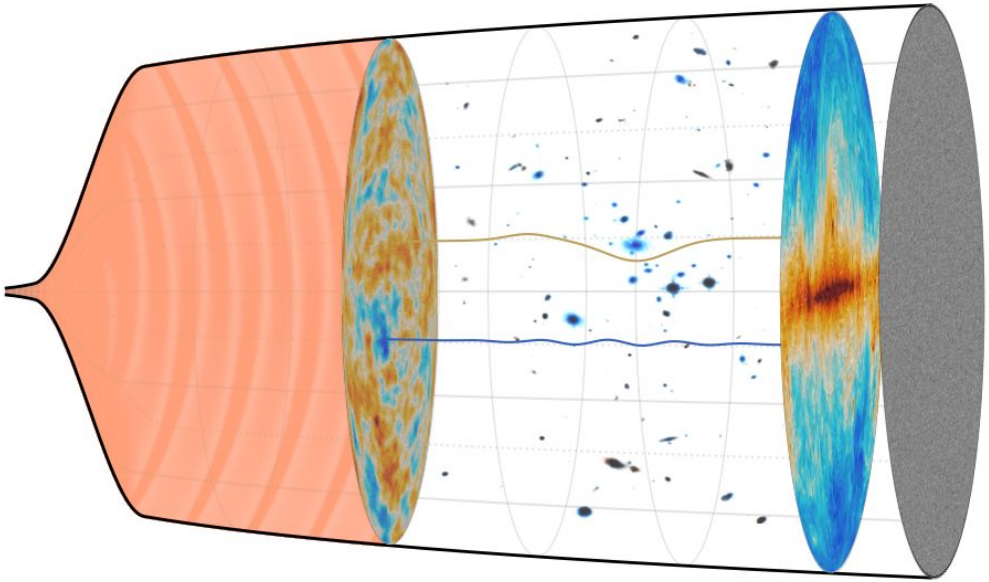
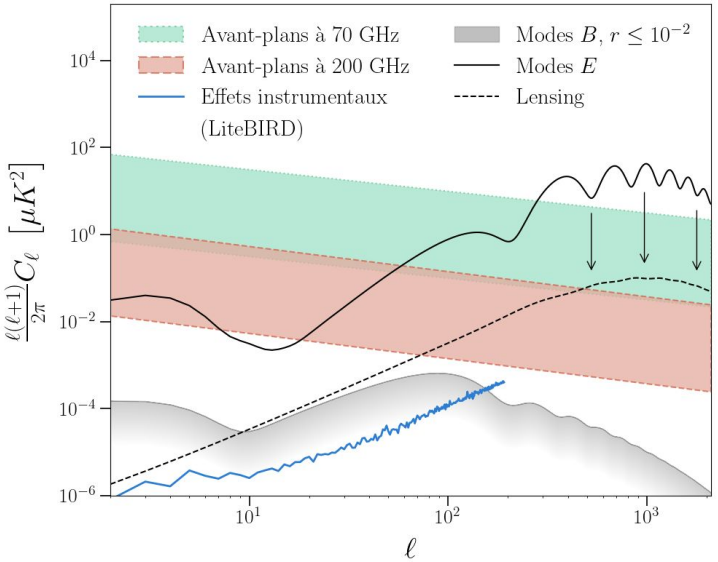
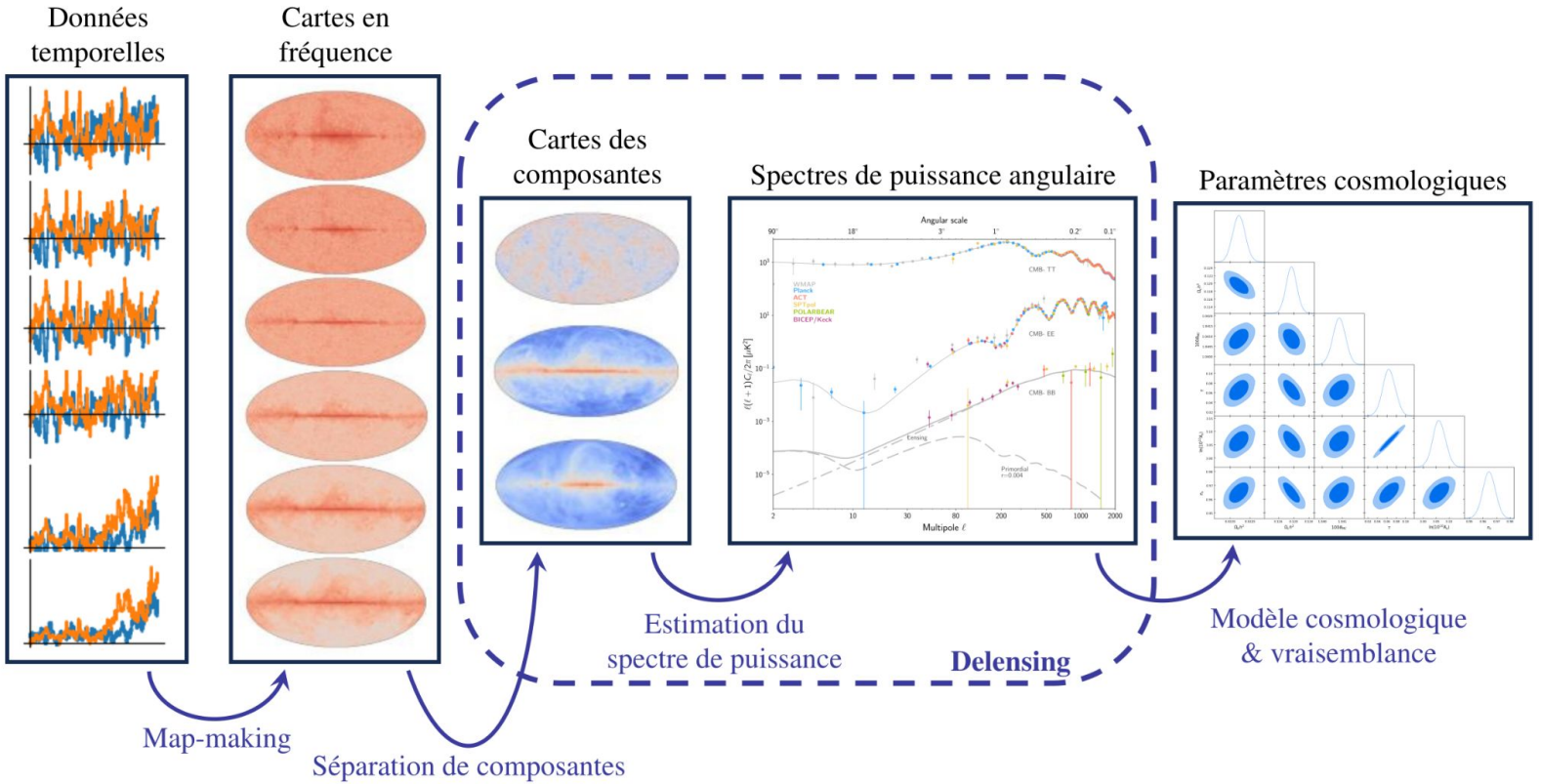


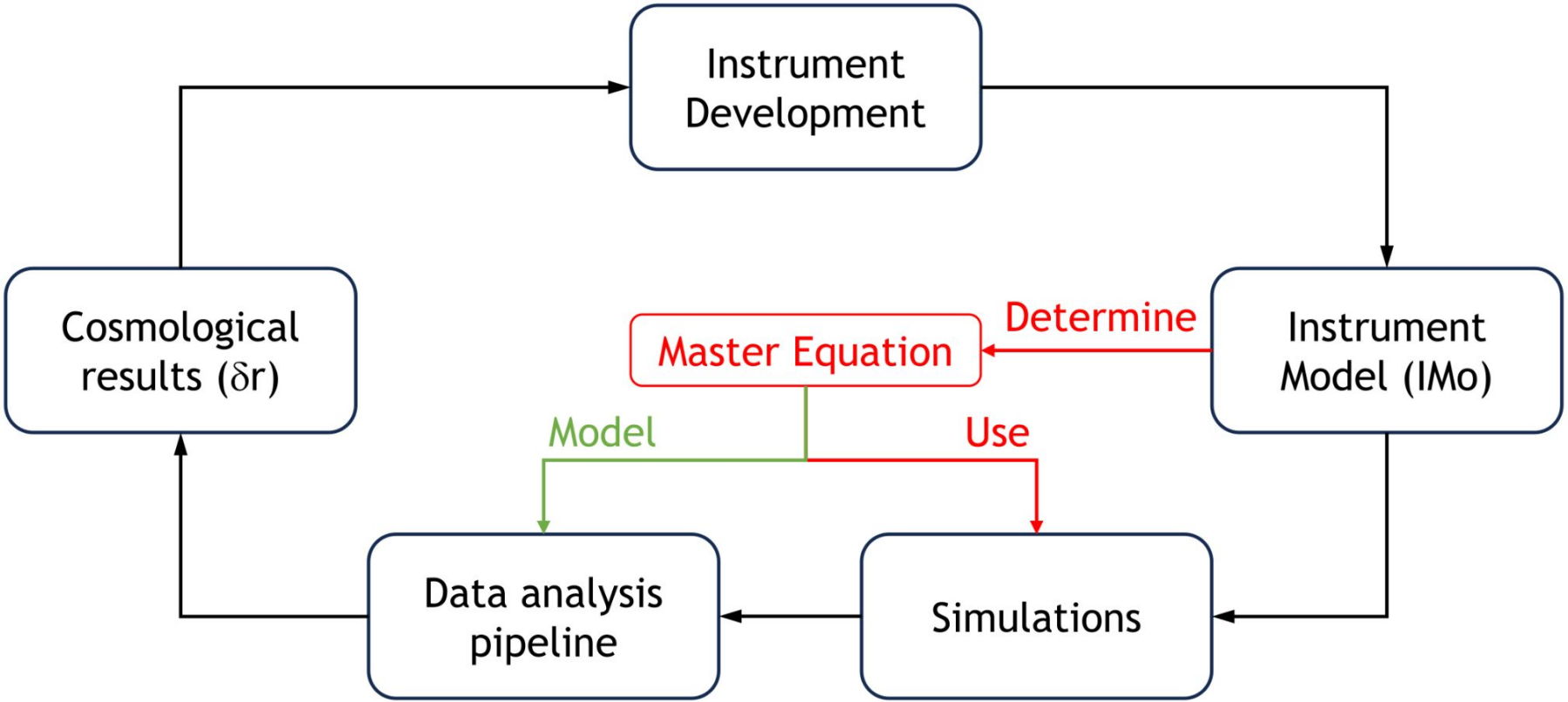
1. **Lensing B modes**
2. **Galactic foregrounds**
3. **Instrumental systematics**



CMB data analysis pipeline

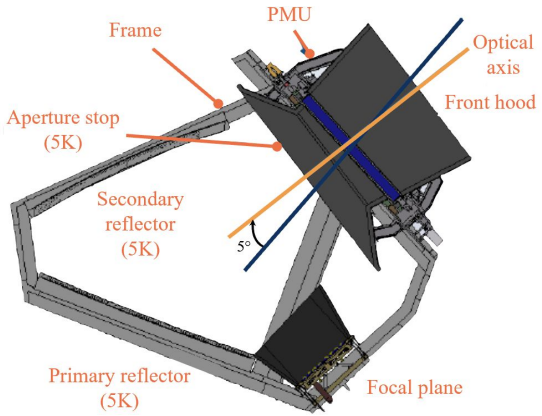


Impact studies of instrumental effects



Master equation

- Correctly characterize the **master equation is critical** for the mission
- It is described in terms of Mueller matrices operating on Stokes vectors (I,Q,U,V), integrated over bandpasses and beams



LiteBIRD LFT

$$\vec{S}_{\mathrm{out},i} \simeq \int B_i(\Omega)\, G_i(\nu)\, \mathcal{D}_i \mathcal{F}_i \mathcal{O}_i \mathcal{M}_{HWP} \Phi_i \mathcal{R}_i(\psi)\, \vec{S}_{\mathrm{in}}\, d\nu d\Omega$$

Beam

Bandpass

Detectors

Filters

Optical system

Half-wave plate

Forebaffles

Telescope rotation

Report from JFY 2024

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Program

2024

Q2

- Realistic HWP simulations
- Characterization of HWP/PMU properties
- Extended data model

Q3

- Trip to France
- Input from PMU/HWP dev. in the data model
- Extension of instrument simulation

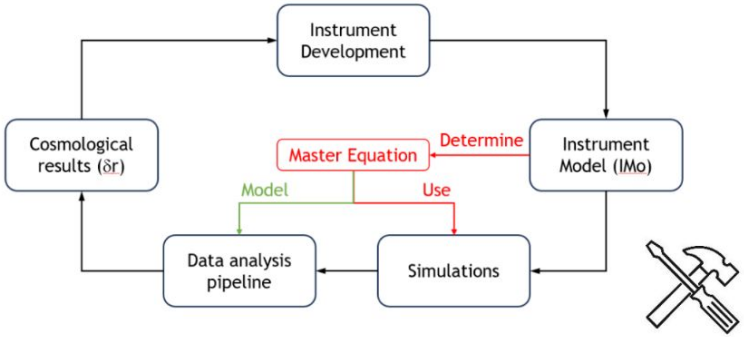
Q4

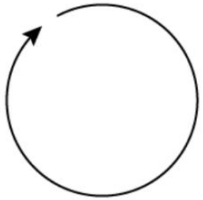
- Trip to Japan
- Validate extension of the data model
- First results from the full pipeline

2025

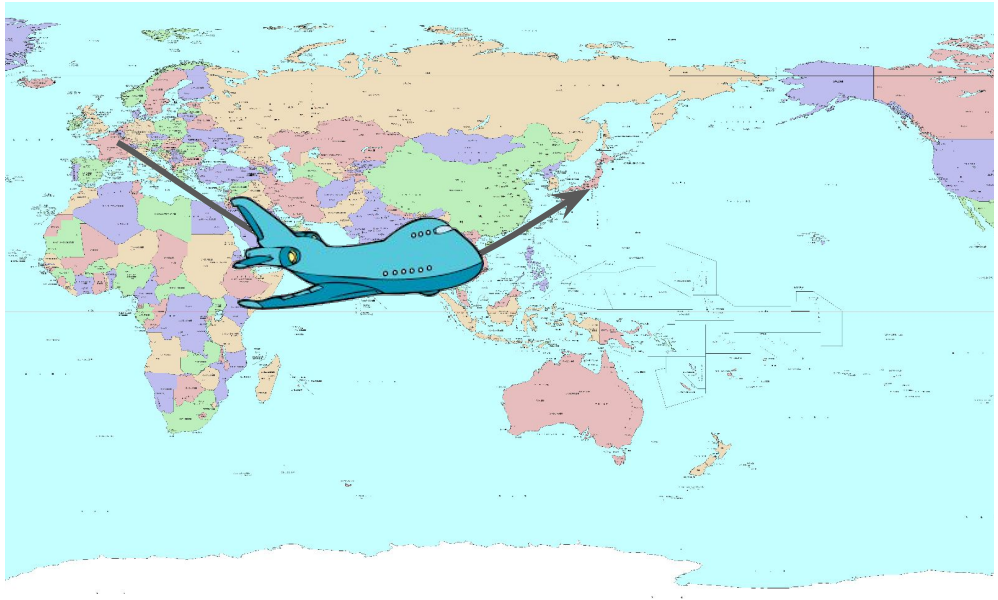
JFY

- Full exploitation of the analysis pipeline with extended data model
- Derivation of requirements for instrumental design and calibration
- Reiterate the process with other elements (beams, detector systems, ...)





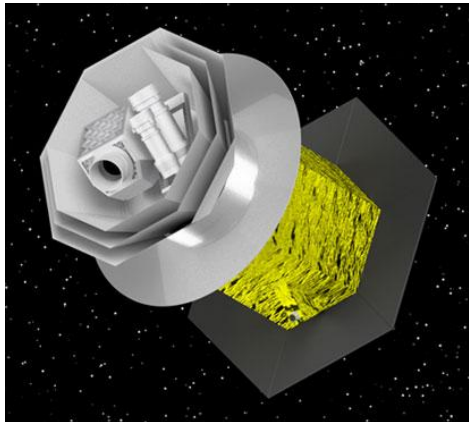
Activities of the year



Trip to Japan (IPMU):

- 2 PhD students (Ema and Simon) came in January 2025
- Participation to the LiteBIRD Face-to-Face meeting
- Talk at the CMB B-mode NEXT conference

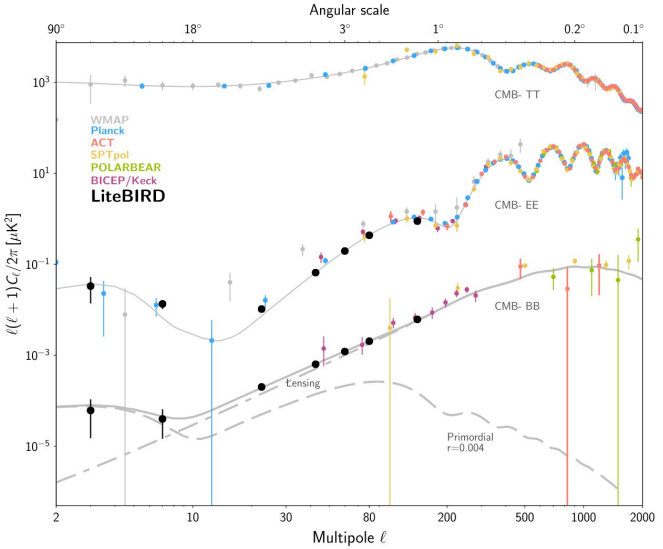
LiteBIRD overview

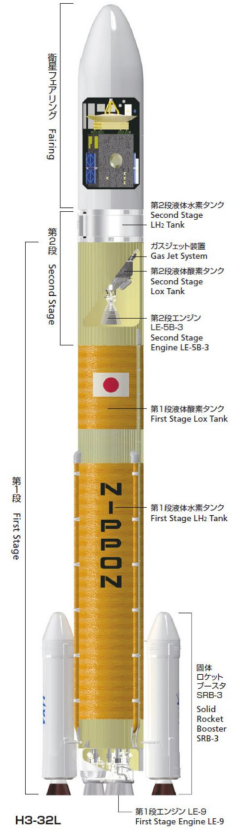


Reformation phase:

- After the ISAS/JAXA mission definition review, LiteBIRD is under rescope studies to consolidate the mission's feasibility with the same scientific objectives.
- The LiteBIRD collaboration will spend approximately one year (~ late 2025) on the studies of the reformation plan.

July 2024: start of the reformation phase →





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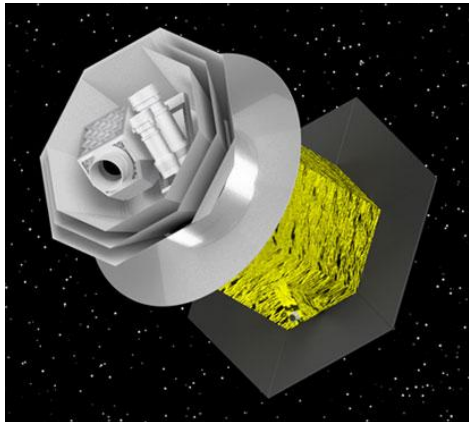

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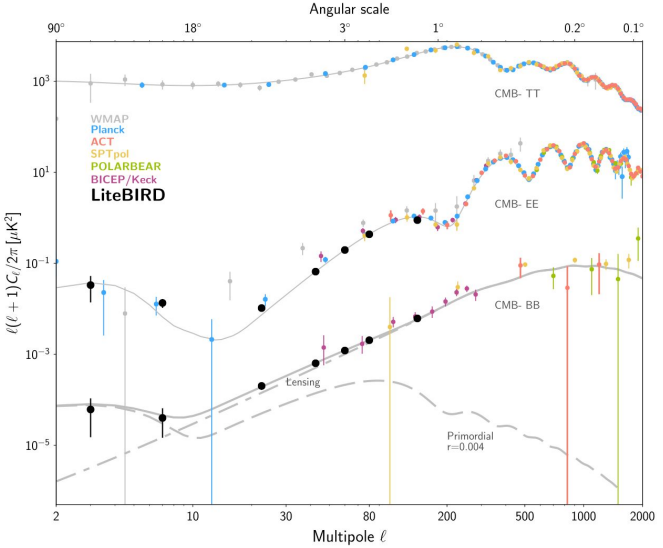
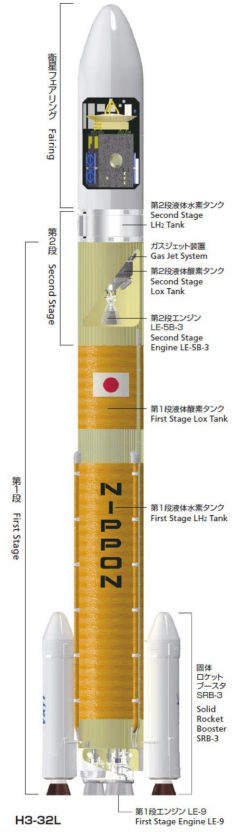
July 2024

September 2024: JAXA KDP





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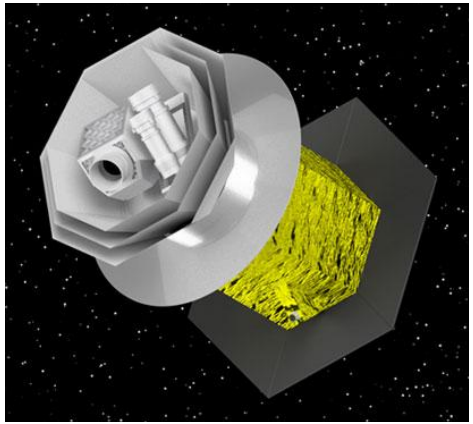

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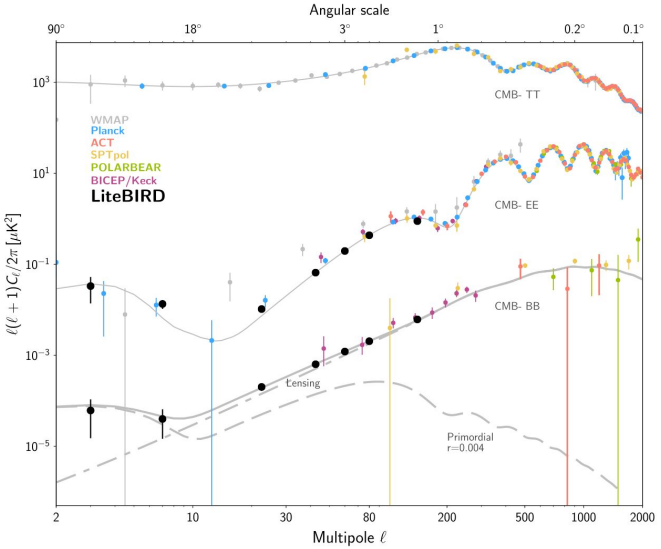
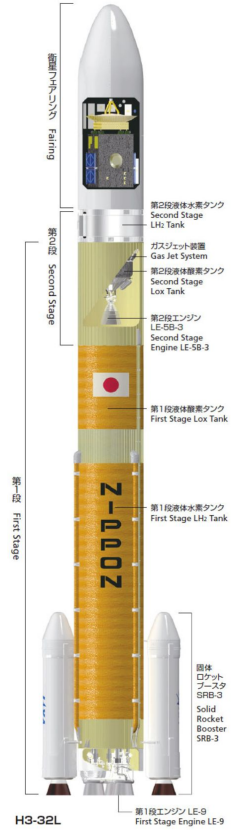
July 2024 — September 2024 — April 2025: CNES KP





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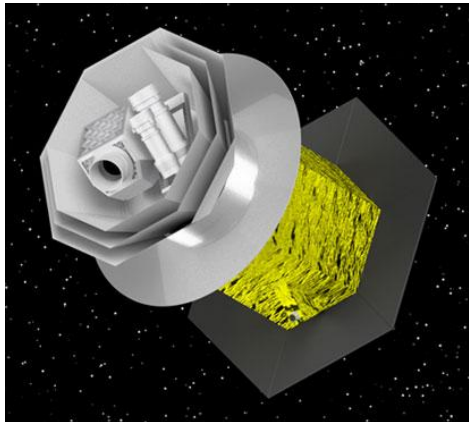

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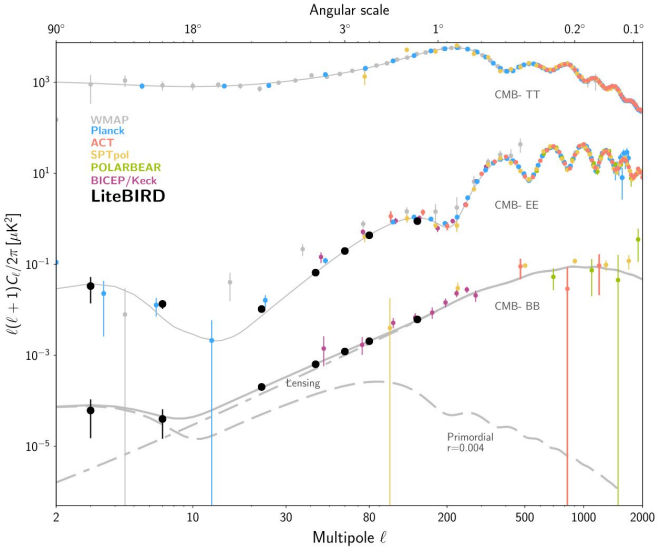
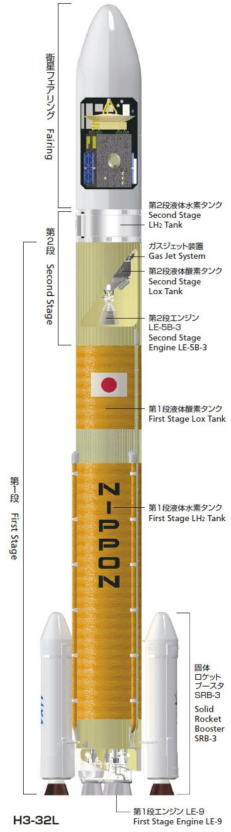
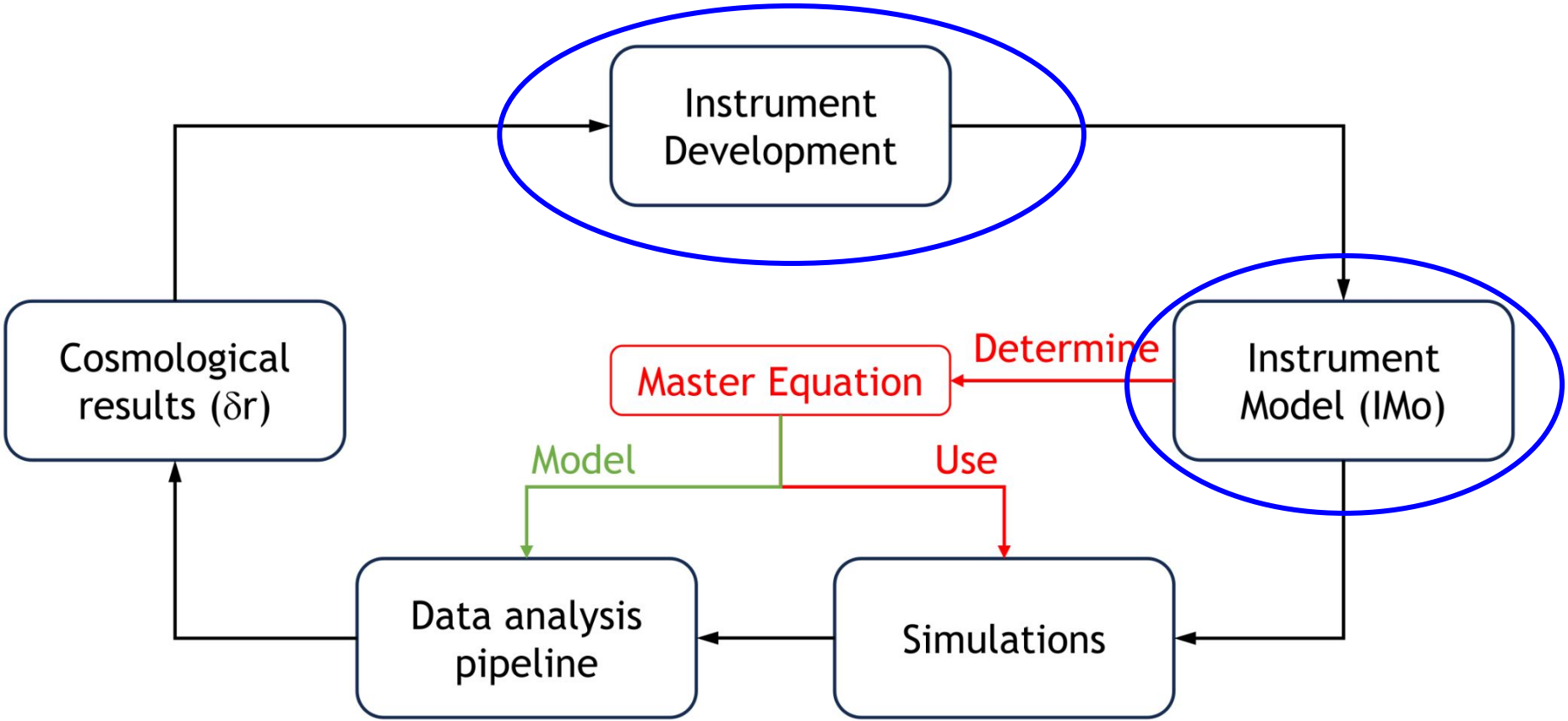
July 2024 — April 2025

September 2024 — September 2025: JAXA KDP2



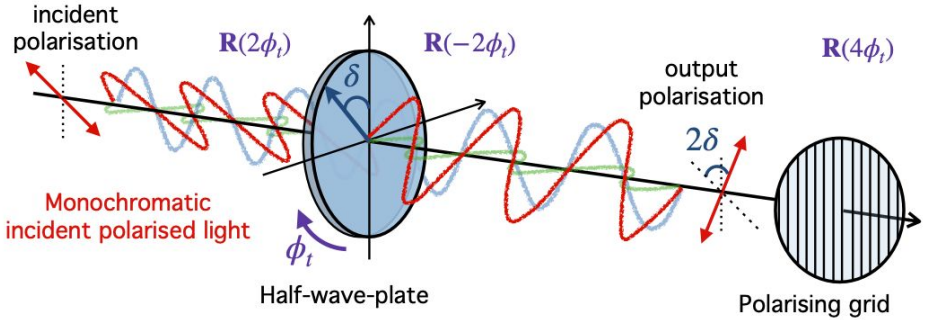


Impact studies of instrumental effects



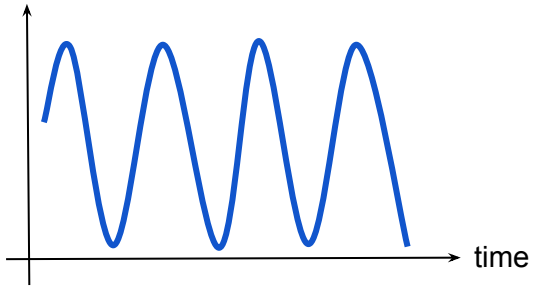
Half-Wave-Plate (HWP)

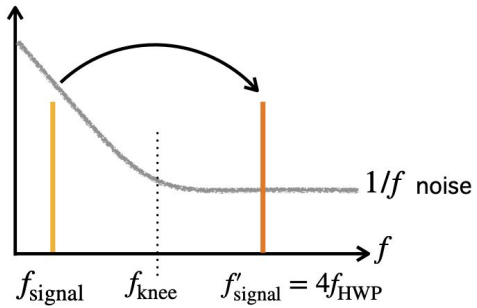
CMB experiments use polarization modulation unit to suppress 1/f noise and mitigates differential systematic uncertainties



$$d_t = \mathrm{I} + \Re[(\mathrm{Q} + i\mathrm{U})\ \exp(-i4\phi_t)]$$

$$\tilde{d}_f = \mathrm{I} + \frac{1}{2}[\mathrm{Q} + i\mathrm{U}]\ \exp(4f_{\mathrm{HWP}})$$





Frequency dependent HWP

$$
\begin{aligned}
d &= \mathbf{M}\, s \\
&= \mathbf{R}(-2\psi_t)\mathbf{M}_{\mathrm{det}}\mathbf{R}(2\phi_t)\mathbf{M}_{\mathrm{HWP}}(\delta=\pi)\mathbf{R}(2\phi_t)\, s \\
&= \mathrm{I} + \mathrm{Q}\cos(4\phi_t + 2\psi_t) + \mathrm{U}\sin(4\phi_t + 2\psi_t)
\end{aligned}
$$

$$
\mathbf{M}_{\mathrm{HWP}} = \begin{bmatrix}
1 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & \cos(\delta=\pi) = -1 & \sin(\delta=\pi) \\
0 & 0 & \sin(\delta=\pi) & -\cos(\delta=\pi)
\end{bmatrix}
$$

Frequency dependent HWP

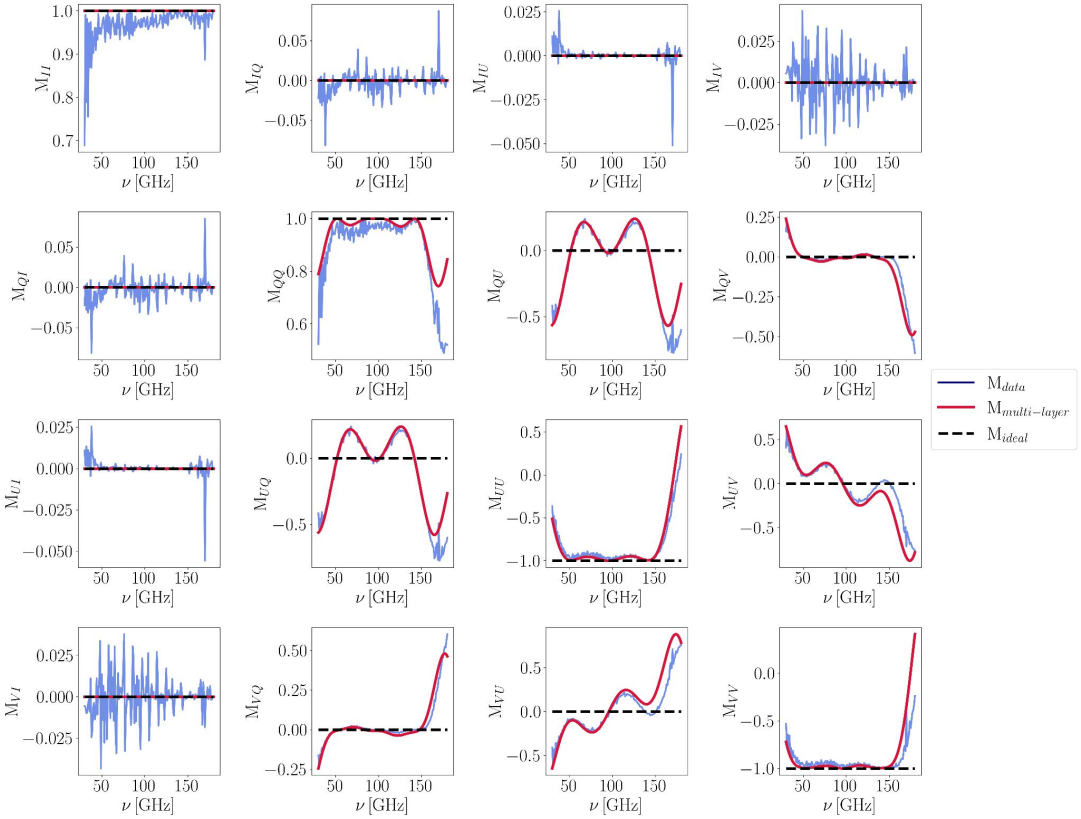
$$d = \mathbf{R}(-2\psi_t)\mathbf{M}_{\rm det}\mathbf{R}(-2\phi_t)\mathbf{M}_{\rm HWP}\mathbf{R}(2\phi_t)\,s$$

$$\mathbf{M}_{\rm HWP} = \prod_{i=1}^{n_{\rm layers}} \mathbf{R}(-2\alpha_i)\mathbf{M}_{\rm layer,i}\mathbf{R}(2\alpha_i)$$

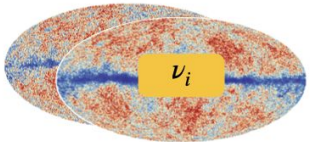
$$\mathbf{M}_{\rm layer} \equiv \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & \cos\delta & -\sin\delta \\ 0 & 0 & \sin\delta & \cos\delta \end{pmatrix}$$

$$\delta \equiv \frac{2\pi\theta_{\rm hwp}\,|n_o - n_e|\nu}{c}$$

We use 5 layers configuration of IPMU's sapphire low frequency HWP



Sky simulations

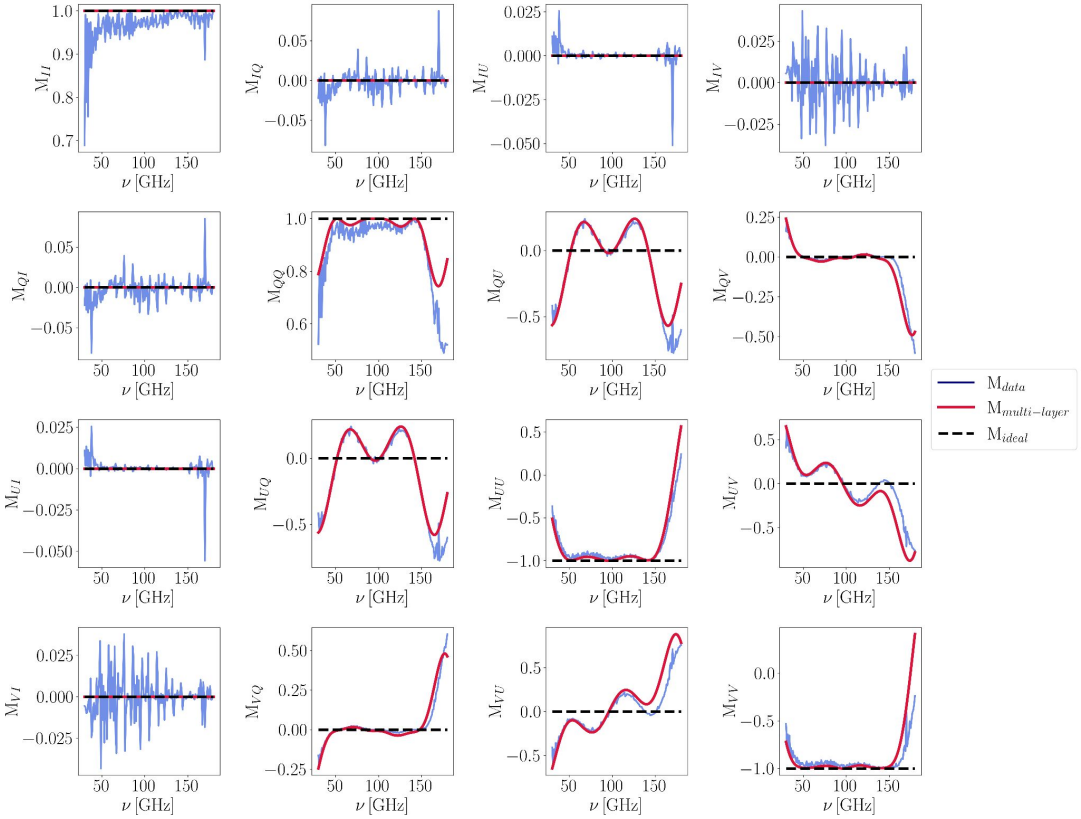


HWP modulation
w/ lab HWP

Map-Making

Uncorrected maps: sky reprojection w/ **ideal HWP**

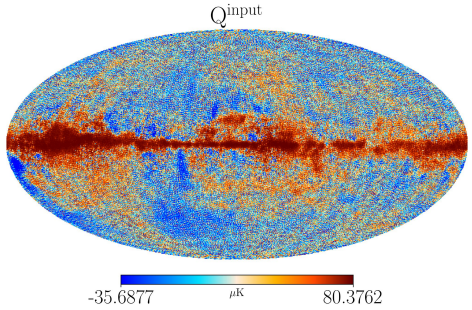
Corrected maps:
sky reprojection w/ **lab HWP**
sky reprojection w/ **HWP multi-layer model**

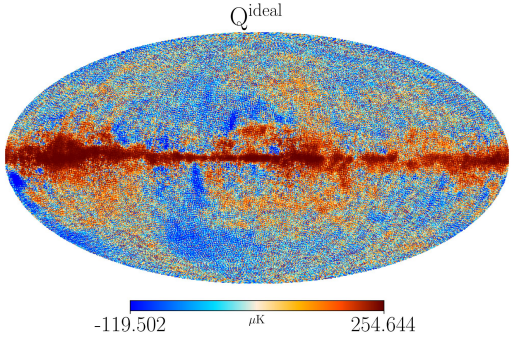


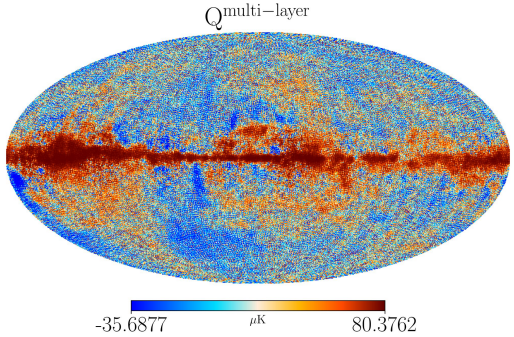

```
h = pol @ hwp @ mixing @ sampling
sky_template = ((h.T @ h).I @ h.T)(tod)
```

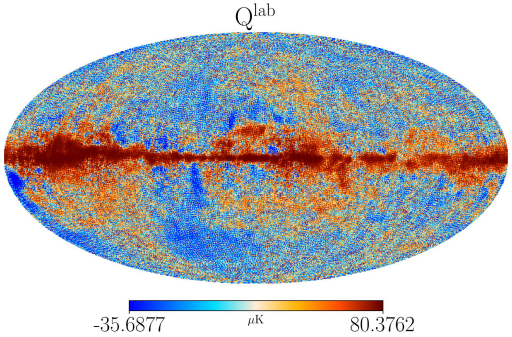
https://github.com/CMBSciPol/furax

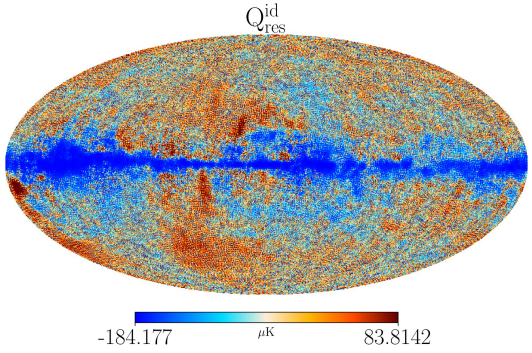
140 GHz for cmb + dust + synch

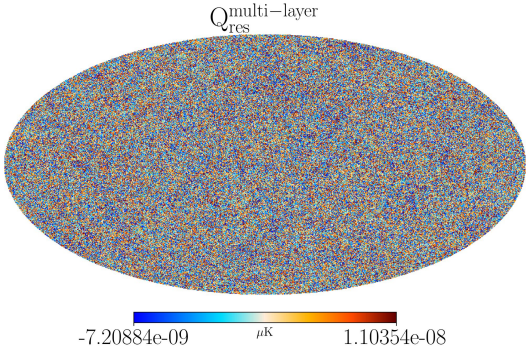


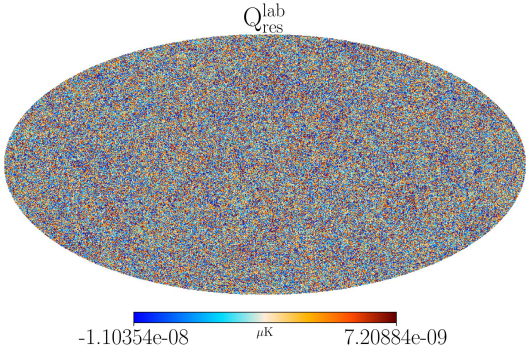


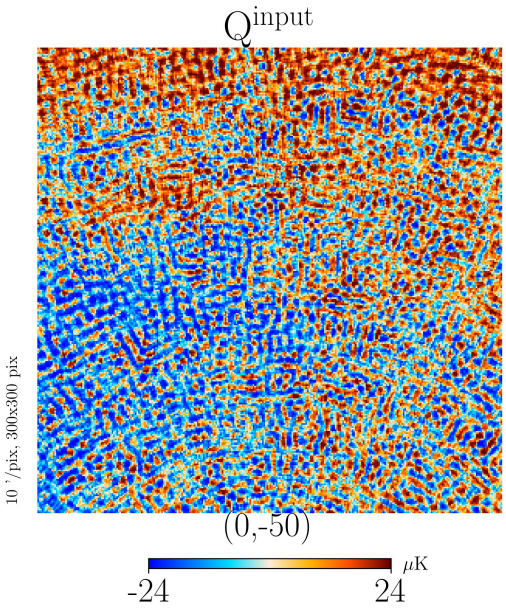


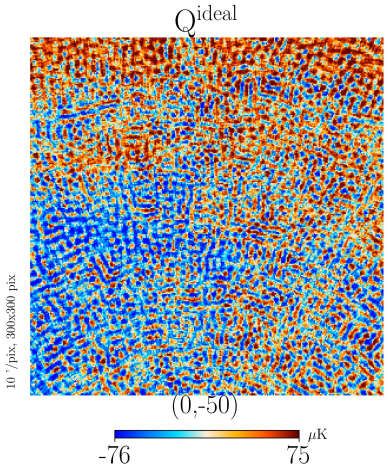


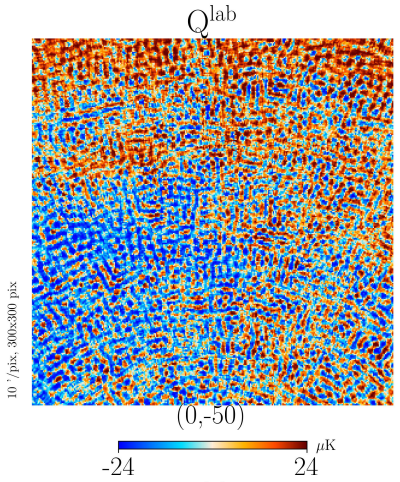


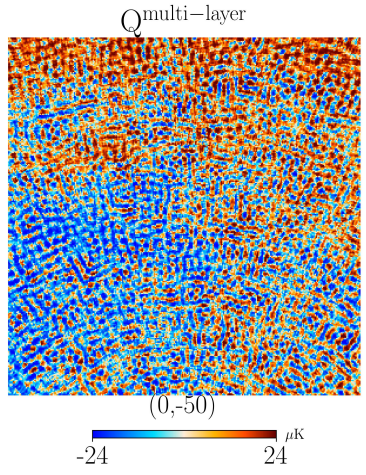


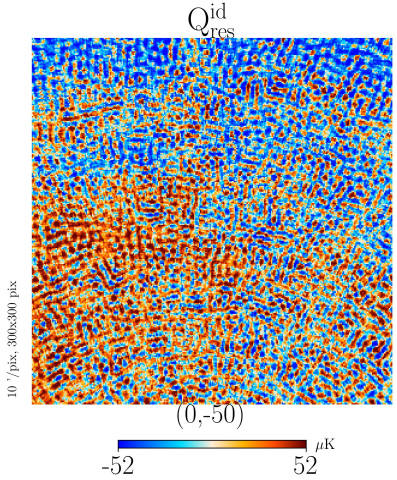


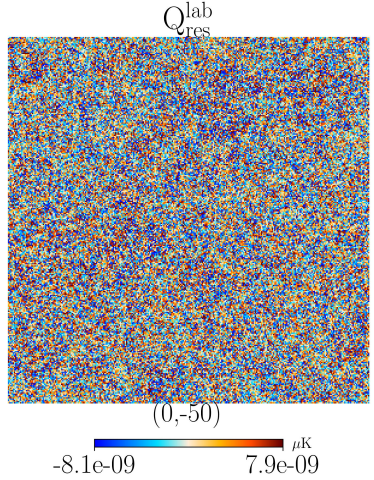

Q^input
10 ’/pix, 300x300 pix
(0,-50)
-24
24
μK

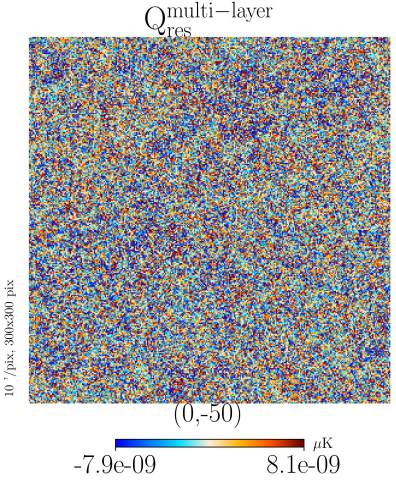

Q^ideal
10 ’/pix, 300x300 pix
(0,-50)
-76
75
μK


Q^lab
10 ’/pix, 300x300 pix
(0,-50)
-24
24
μK


Q^multi−layer
10 ’/pix, 300x300 pix
(0,-50)
-24
24
μK


Q^id_res
10 ’/pix, 300x300 pix
(0,-50)
-52
52
μK


Q^lab_res
10 ’/pix, 300x300 pix
(0,-50)
-8.1e-09
7.9e-09
μK


Q^multi−layer_res
10 ’/pix, 300x300 pix
(0,-50)
-7.9e-09
8.1e-09
μK

Prospects for JFY 2025

1. Context of the project
2. Report from JFY 2024
3. Prospects for JFY 2025

Prospects

2025

2026

JAXA KDP2

JFY

Q2

- Update HWP simulations
- Characterize HWP/PMU properties
- Define physical model

Q3

- **Trip to France**
- Study the HWP impact on cosmological results
- Inform the decision for the new instrument design

Q4

- **Trip to Japan**
- Adapt the framework to other effects (beams, detector systems, ...)
- Derive performance requirements

- Develop a general strategy for the mitigation of instrumental systematic effects
- Implement specific cases at the map-making and component separation stages
- Update specific requirements in the presence of mitigation techniques