The LiteBIRD mission:
probing inflation with CMB polarization

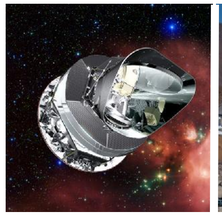
Marta Monelli
Kavli IPMU, The University of Tokyo
Kashiwa-no-ha, Japan

On behalf of the LiteBIRD collaboration

LiteBIRD Joint Study Group

Around 400 researchers from **Japan**, **North America** and **Europe**

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



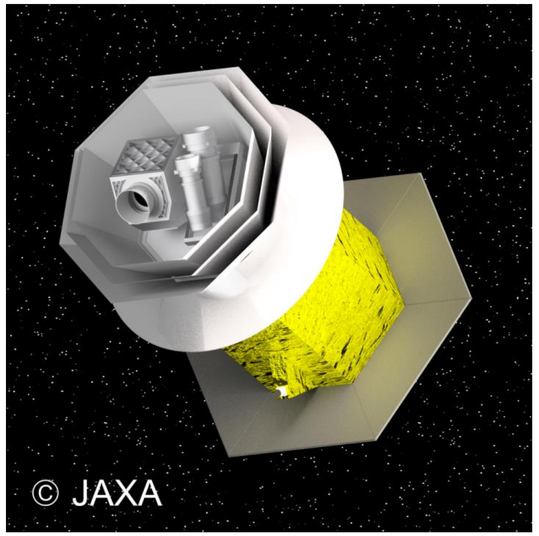


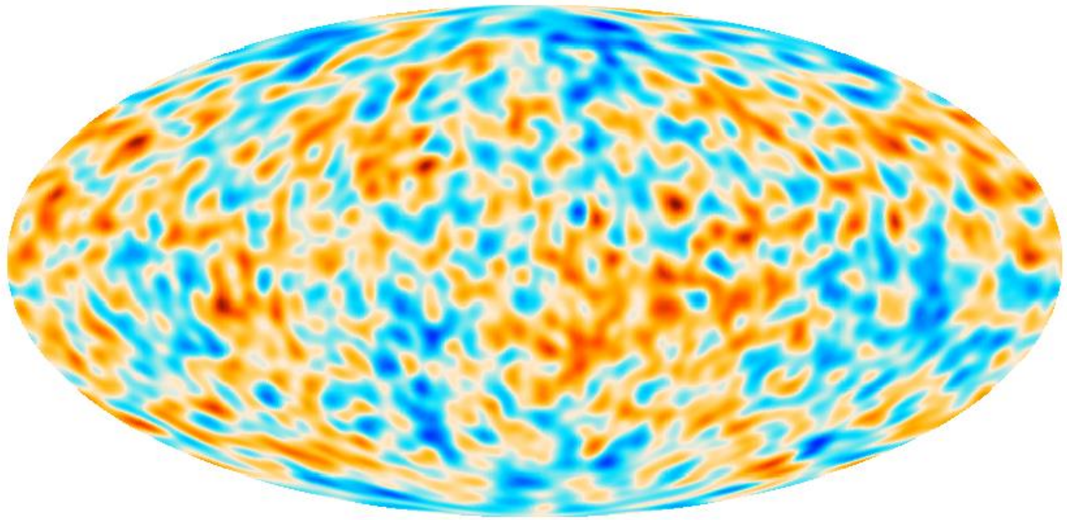

LiteBIRD

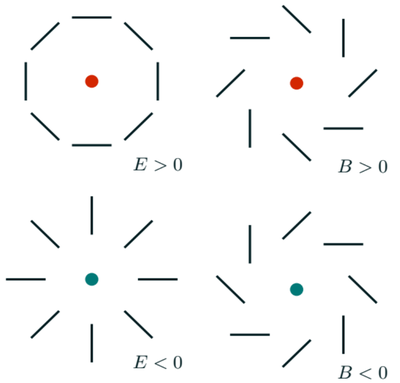
LiteBIRD overview

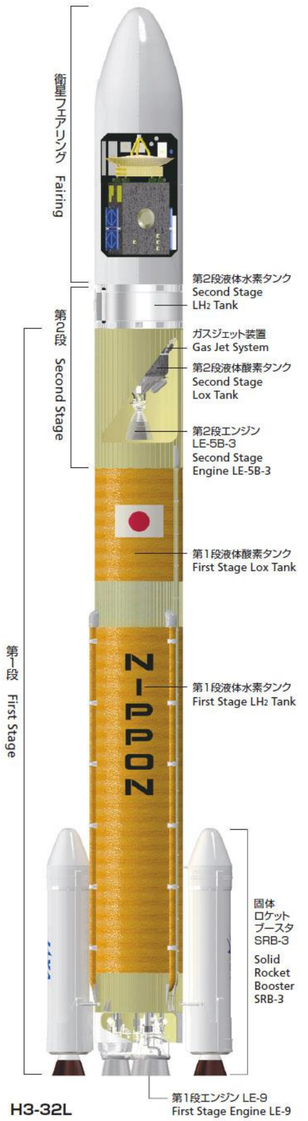
- Lite (Light) spacecraft for the study of *B*-mode polarization and Inflation from cosmic background Radiation Detection
- JAXA's L-class mission was selected in May 2019 to be launched by JAXA's H3 rocket
- **All-sky 3-year survey**, from Sun-Earth Lagrangian point L2
- Large frequency coverage (**40–402 GHz**, 15 bands) at **70–18 arcmin** angular resolution for precision measurements of the CMB *B* modes
- Final combined sensitivity: **2.2 μK·arcmin**

📖 LiteBIRD collaboration PTEP 2023



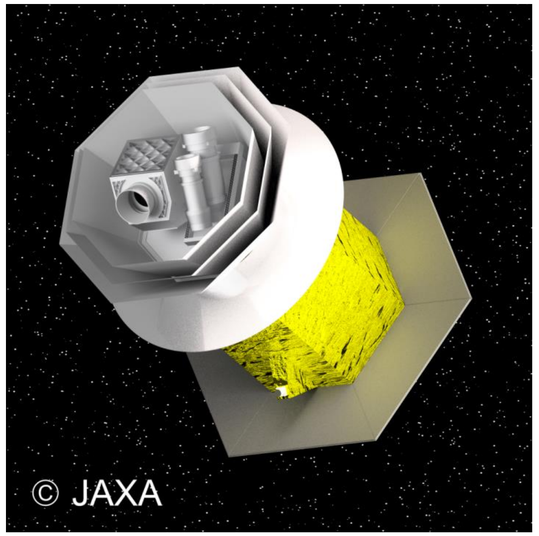


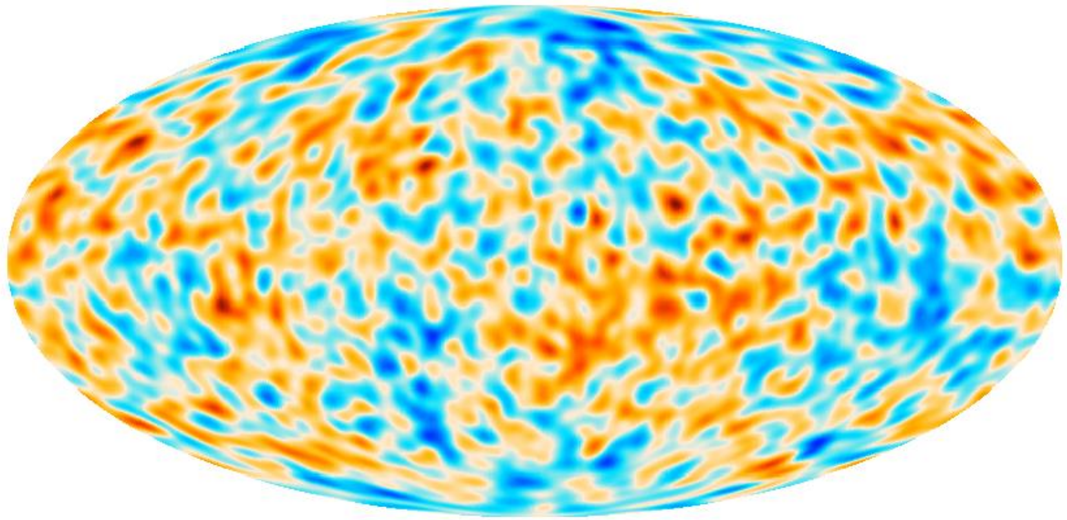




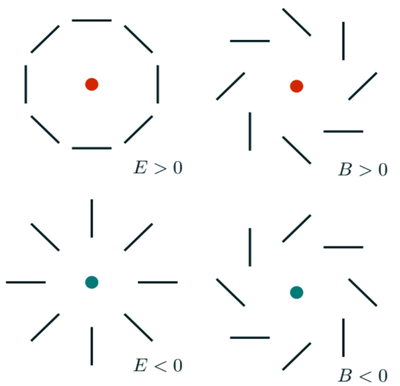
LiteBIRD overview

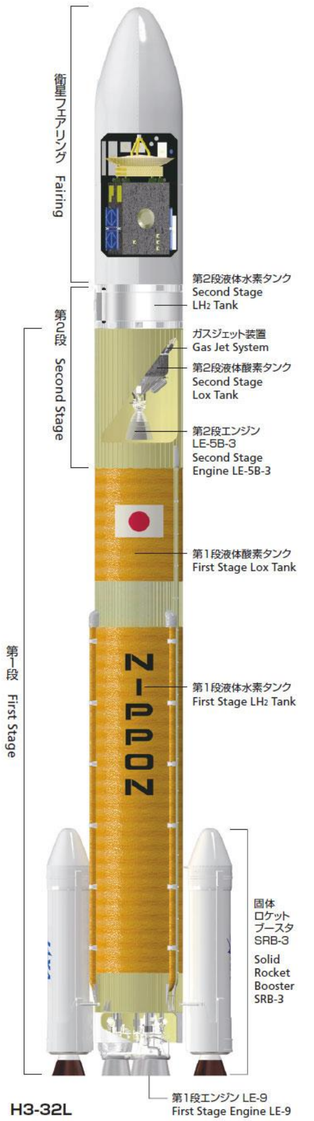
- Lite (Light) spacecraft for the study of *B*-mode polarization and Inflation from cosmic background Radiation Detection
- JAXA's L-class mission was selected in May 2019 to be launched by JAXA's H3 rocket
- **All-sky 3-year survey**, from Sun-Earth Lagrangian point L2
- Large frequency coverage (**40–402 GHz**, 15 bands) at **70–18 arcmin** angular resolution for precision measurements of the CMB *B* modes
- Final combined sensitivity: **2.2 μK·arcmin**





LiteBIRD collaboration PTEP 2023

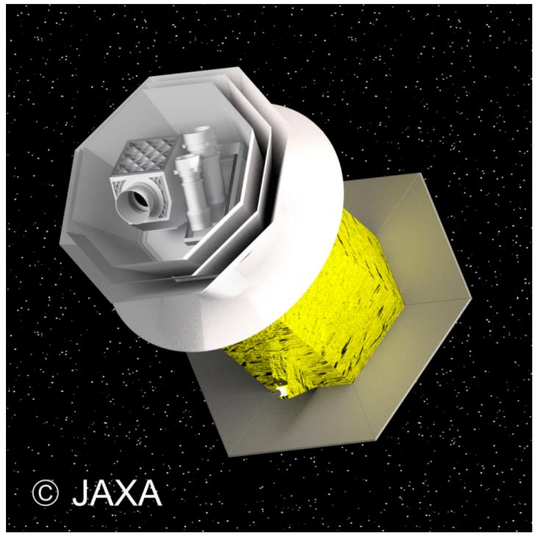


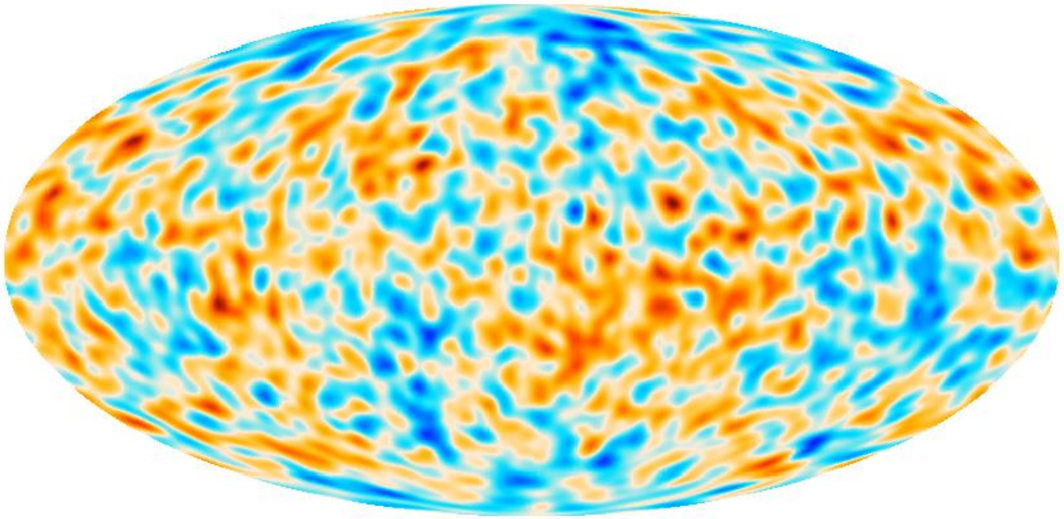


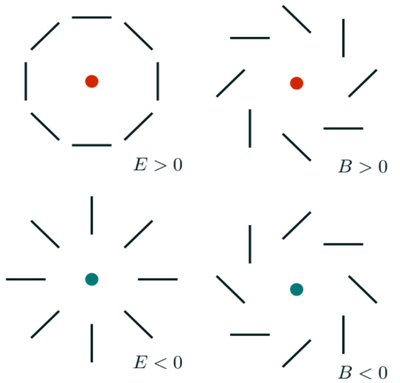
LiteBIRD overview

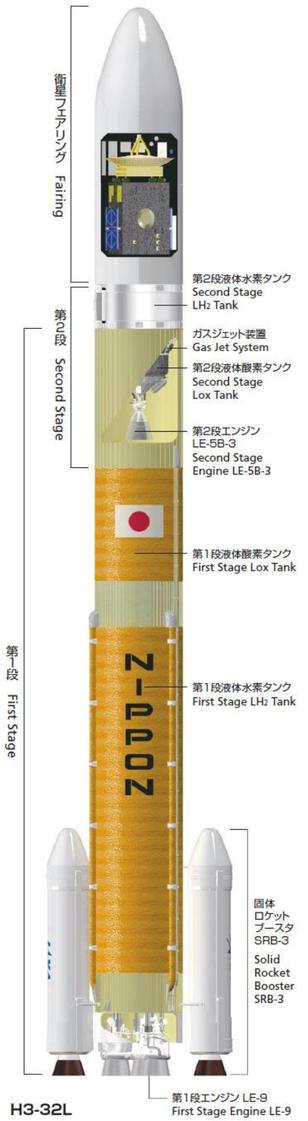
- Lite (Light) spacecraft for the study of *B*-mode polarization and Inflation from cosmic background Radiation Detection
- JAXA's L-class mission was selected in May 2019 to be launched by JAXA's H3 rocket
- **All-sky 3-year survey**, from Sun-Earth Lagrangian point L2
- Large frequency coverage (**40–402 GHz**, 15 bands) at **70–18 arcmin** angular resolution for precision measurements of the CMB *B* modes
- Final combined sensitivity: **2.2 μK·arcmin**

📖 LiteBIRD collaboration PTEP 2023





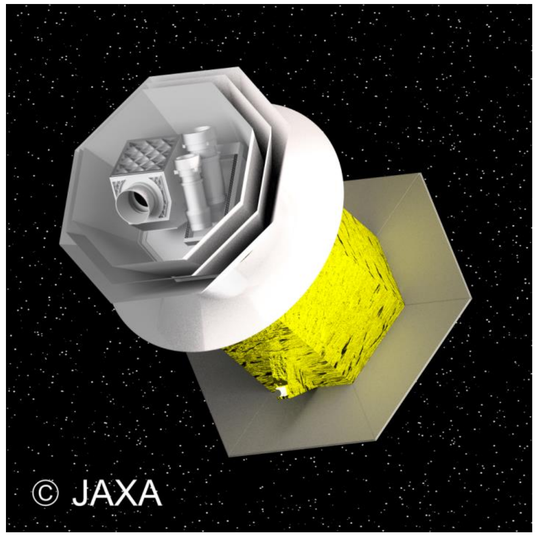


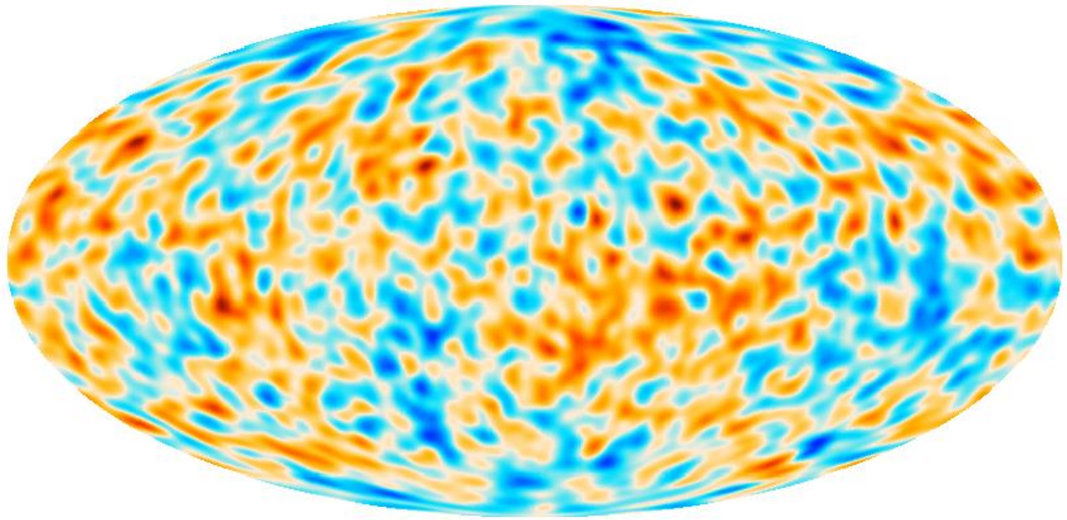


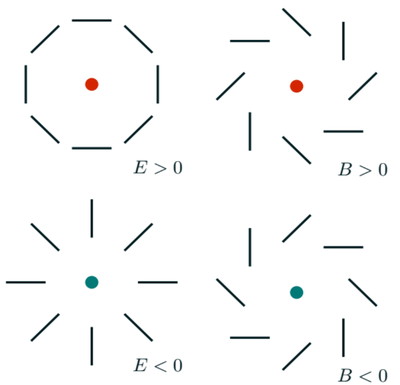
LiteBIRD overview

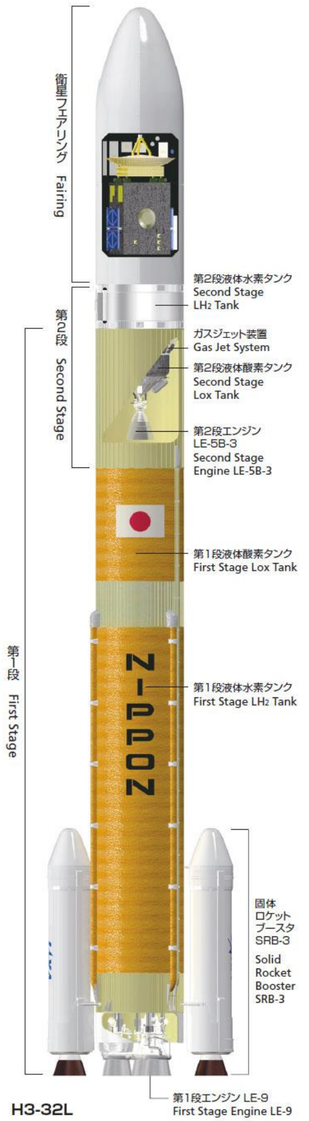
- Lite (Light) spacecraft for the study of *B*-mode polarization and Inflation from cosmic background Radiation Detection
- JAXA's L-class mission was selected in May 2019 to be launched by JAXA's H3 rocket
- **All-sky 3-year survey**, from Sun-Earth Lagrangian point L2
- Large frequency coverage (**40–402 GHz**, 15 bands) at **70–18 arcmin** angular resolution for precision measurements of the CMB *B* modes
- Final combined sensitivity: **2.2 μK·arcmin**

LiteBIRD collaboration PTEP 2023





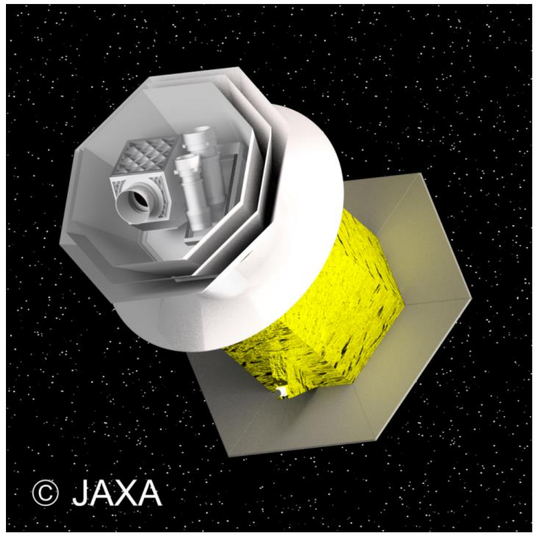


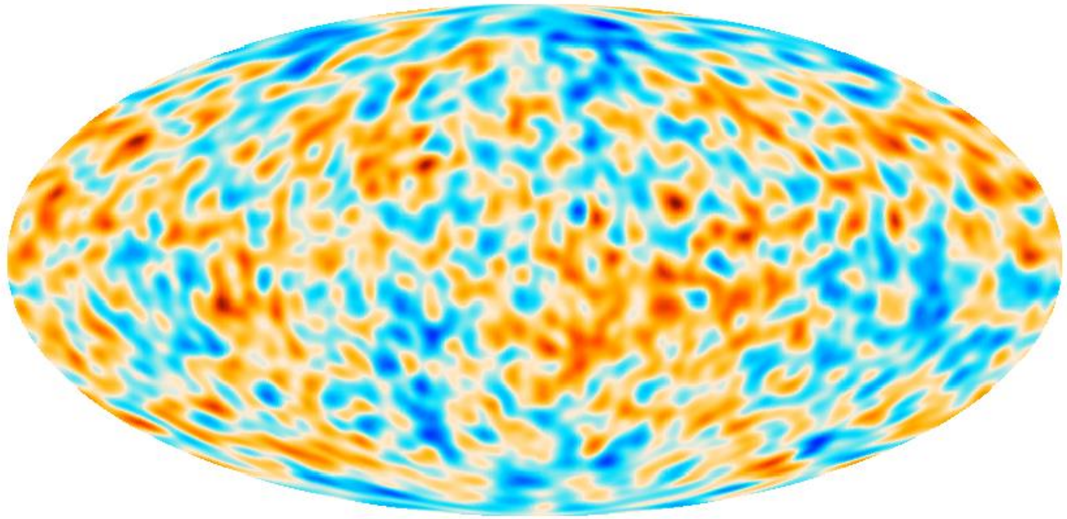


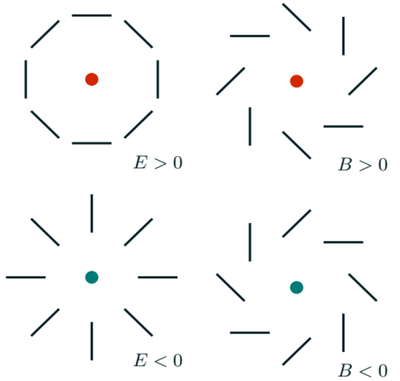
LiteBIRD overview

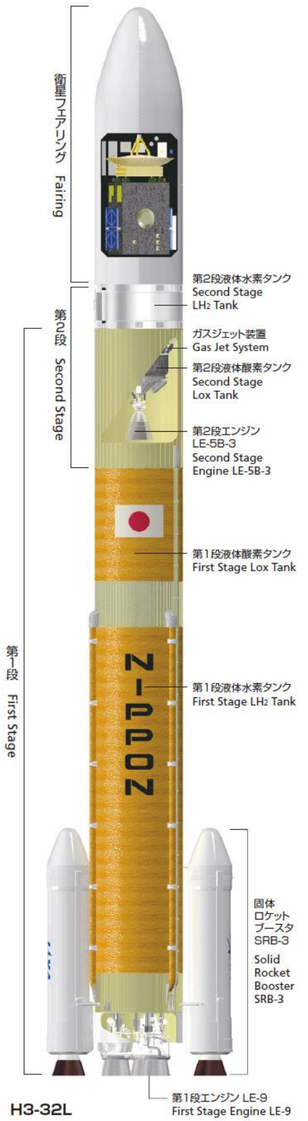
- Lite (Light) spacecraft for the study of *B*-mode polarization and Inflation from cosmic background Radiation Detection
- JAXA's L-class mission was selected in May 2019 to be launched by JAXA's H3 rocket
- **All-sky 3-year survey**, from Sun-Earth Lagrangian point L2
- Large frequency coverage (**40–402 GHz**, 15 bands) at **70–18 arcmin** angular resolution for precision measurements of the CMB *B* modes
- Final combined sensitivity: **2.2 μK·arcmin**

Ongoing **rescope studies** (~ late 2025) to consolidate the **mission's feasibility** while keeping the **same scientific objectives**



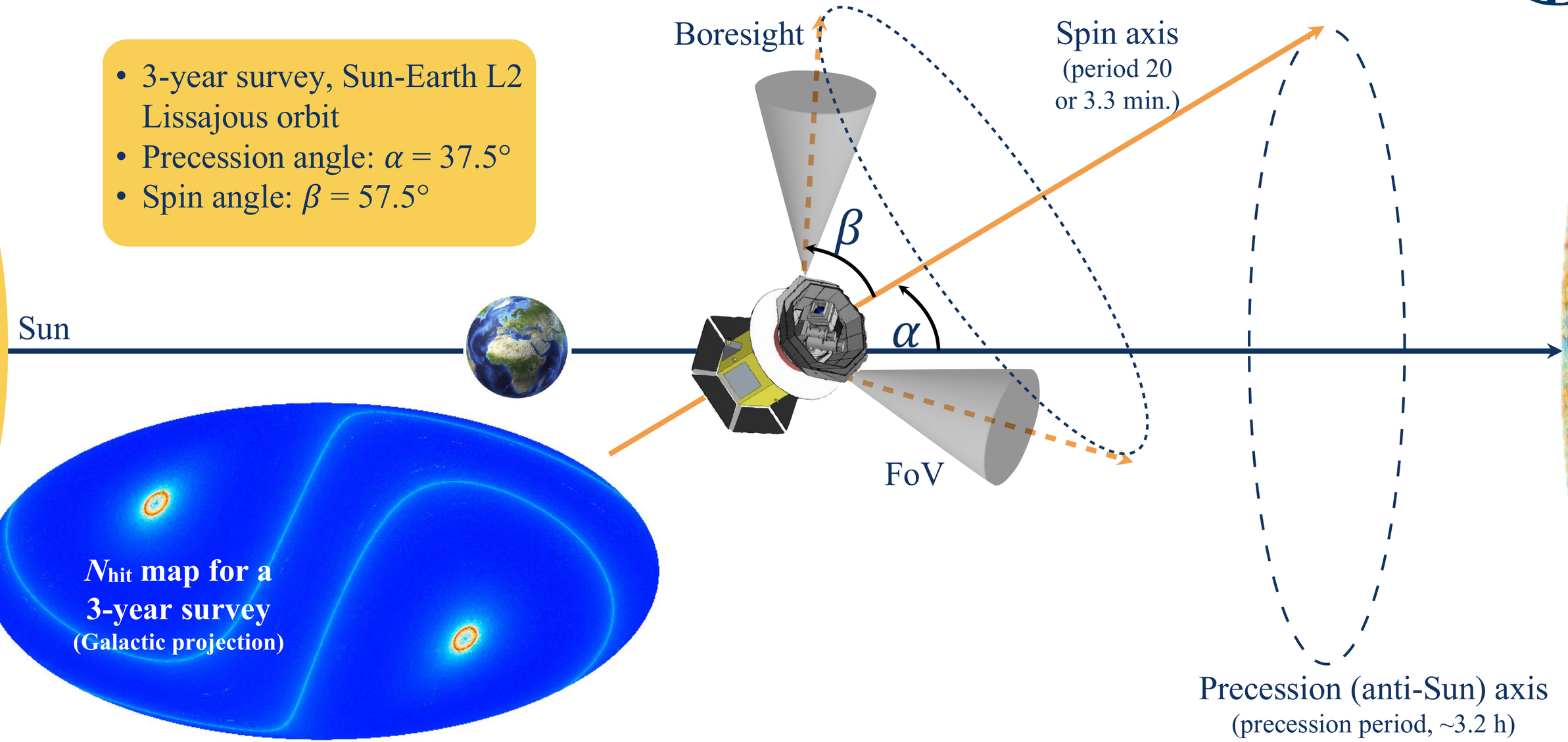


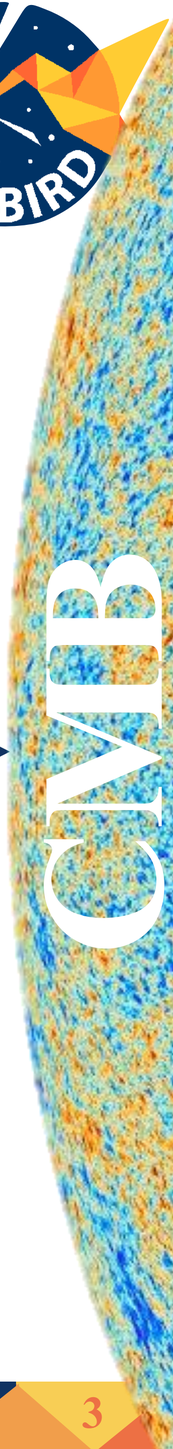




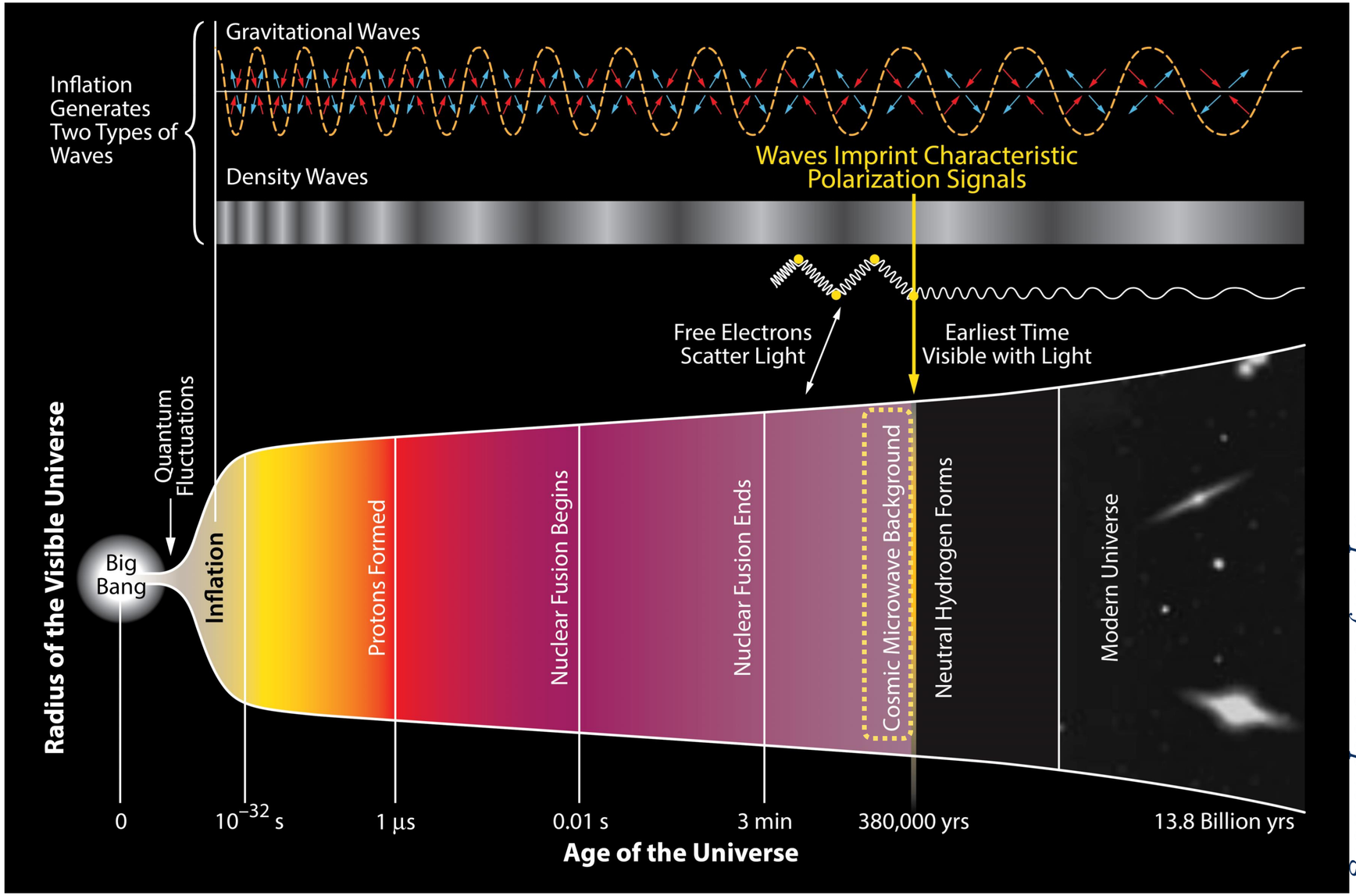
LiteBIRD scanning strategy

- 3-year survey, Sun-Earth L2 Lissajous orbit
- Precession angle: $\alpha = 37.5°$
- Spin angle: $\beta = 57.5°$





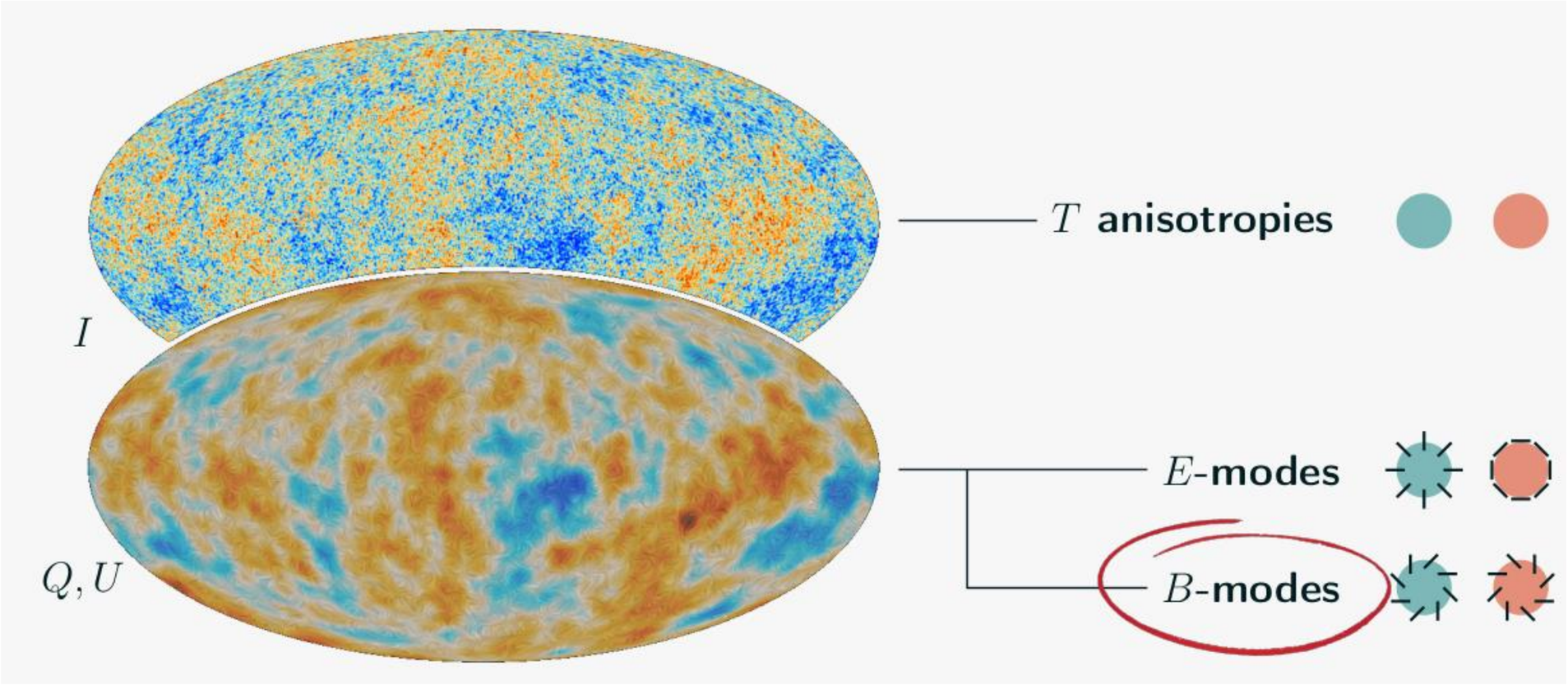
Why *B* modes (1/2)



Adapted from bicepkek.org

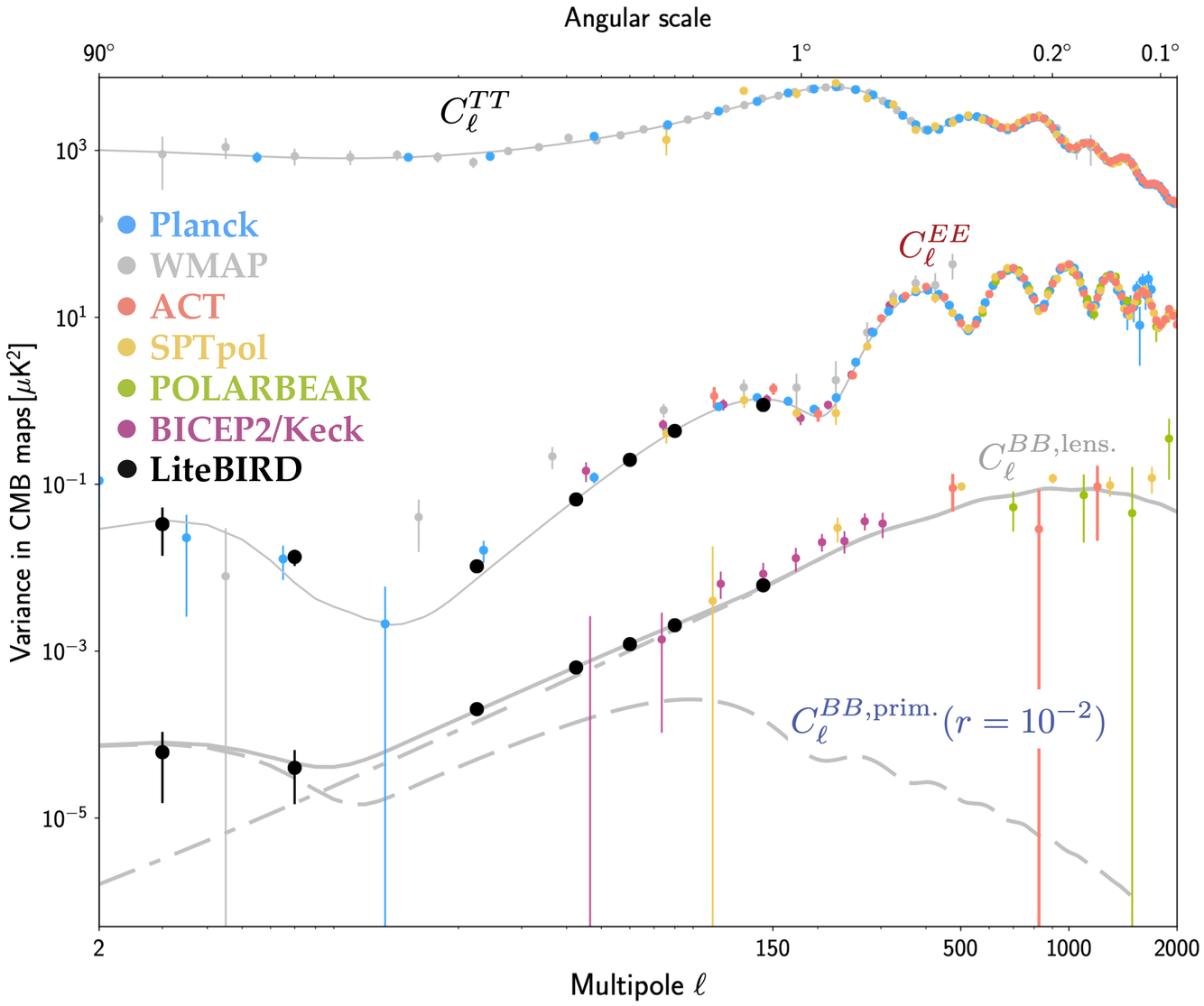
Why *B* modes (2/2)

Perturbations imprint **anisotropies** in the temperature and polarization of the CMB



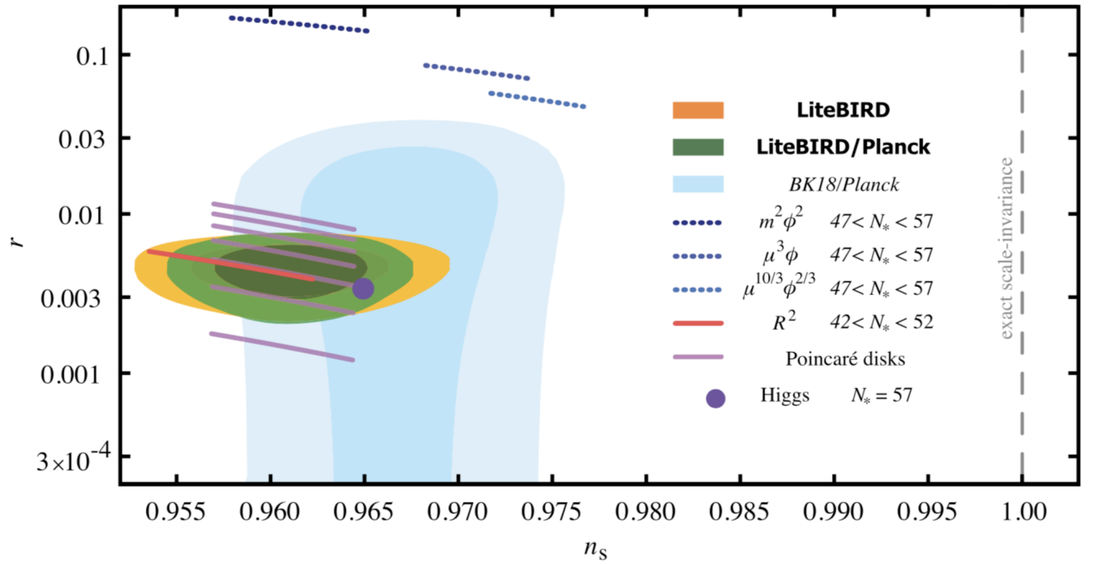
LiteBIRD main scientific objectives

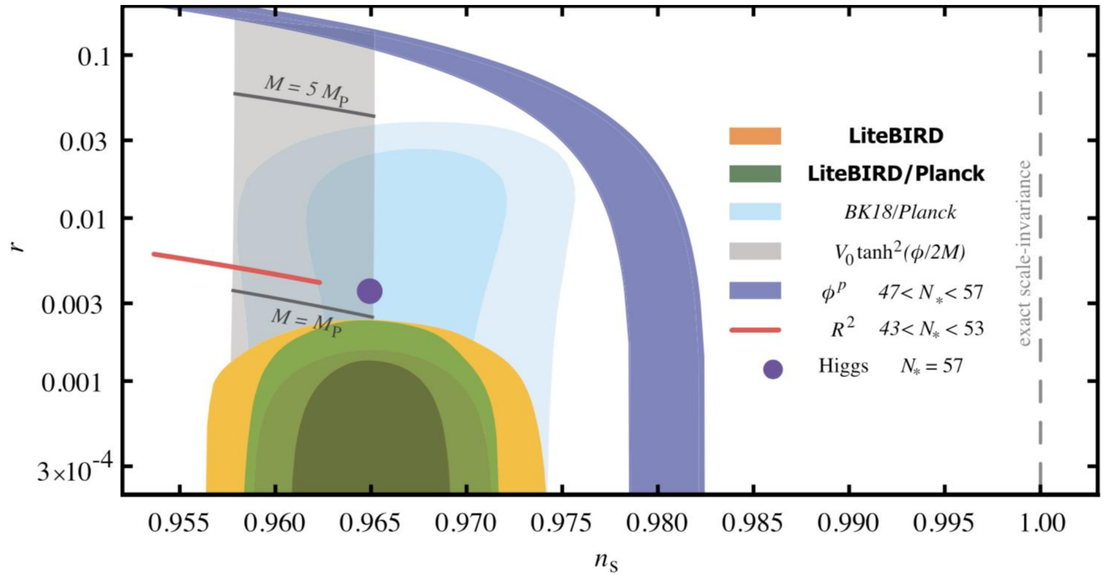
- Definitive search for the ***B*-mode signal** from **cosmic inflation** in the CMB polarization
  - Making a discovery or ruling out well-motivated inflationary models
  - Insight into the quantum nature of gravity
- The inflationary (i.e. primordial) *B*-mode power is proportional to the **tensor-to-scalar ratio, *r***
- Current best constraint: $r < 0.032$ (95% C.L.)
  (📖 Tristram et al. 2022, combining BK18 and Planck PR4)
- *LiteBIRD* will significantly improve the current sensitivity on *r*
- The final goal is to achieve **a total uncertainty of $\delta r \lesssim 0.001$ for r=0**



LiteBIRD constraints on inflation

- Huge discovery impact (evidence for inflation, knowledge of its energy scale, and distance traveled by the inflaton…)
- A detection of B-modes by *LiteBIRD* with $r > 0.01$ would imply an excursion of the inflation field that exceeds the Planck mass
  - Such a detection would **constrain theories of quantum gravity** such as superstring theories
- An upper limit from *LiteBIRD* would disfavour the simplest inflationary models, with $M > M_{\rm p}$
  - This includes the monomial models, α-attractors with a super-Planckian characteristic scale, including the **Starobinsky model** and models that invoke the Higgs field as the inflaton

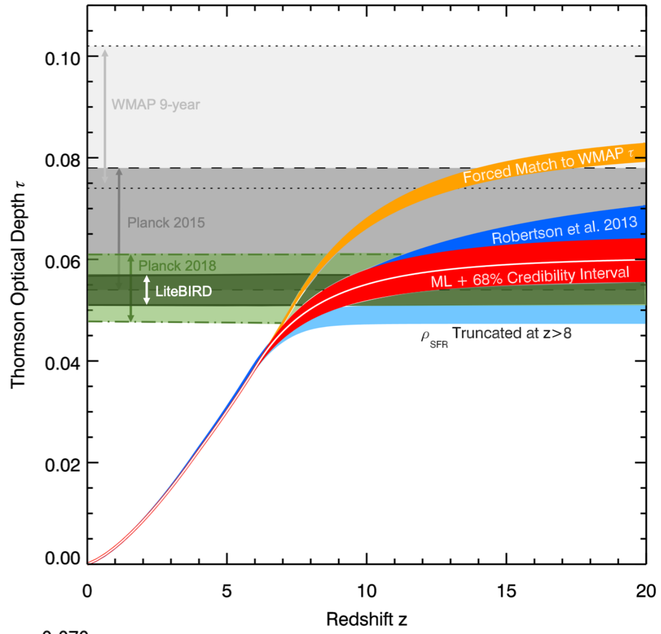




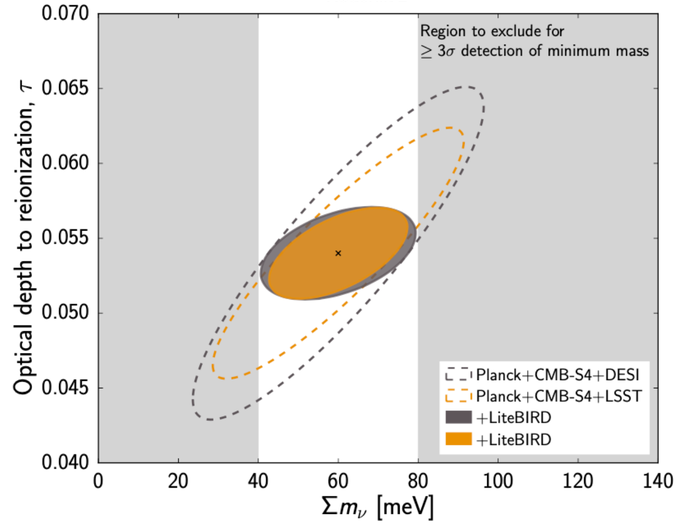
LiteBIRD other science outcomes

- 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** ($\sigma(\sum m_\nu) = 12$ meV)
3. Constraints on **cosmic birefringence**
4. **Gravitational lensing**
5. **SZ effect** (thermal, diffuse, relativistic corrections)
6. **Anisotropic distortions** of the CMB spectrum
7. Constraints on **primordial magnetic fields**
8. Elucidating **anomalies**
9. Physics of **Galactic emission** mechanisms
10. Catalogues of polarized **point sources**



Adapted from Robertson +2015



LiteBIRD collaboration PTEP 2023

The challenge of B-modes detection

- The *B*-mode signal is expected to have an amplitude at least 3 orders of magnitude below the CMB temperature anisotropies
- *LiteBIRD* is targeting a sensitivity level in polarization ~30 times better than Planck
- This extremely good statistical uncertainty must go in parallel with exquisite control of:
  1. **Instrument systematic** uncertainties
  2. **Galactic foreground** contamination
  3. **"Lensing B-mode signal"** induced by gravitational lensing
  4. Observer biases

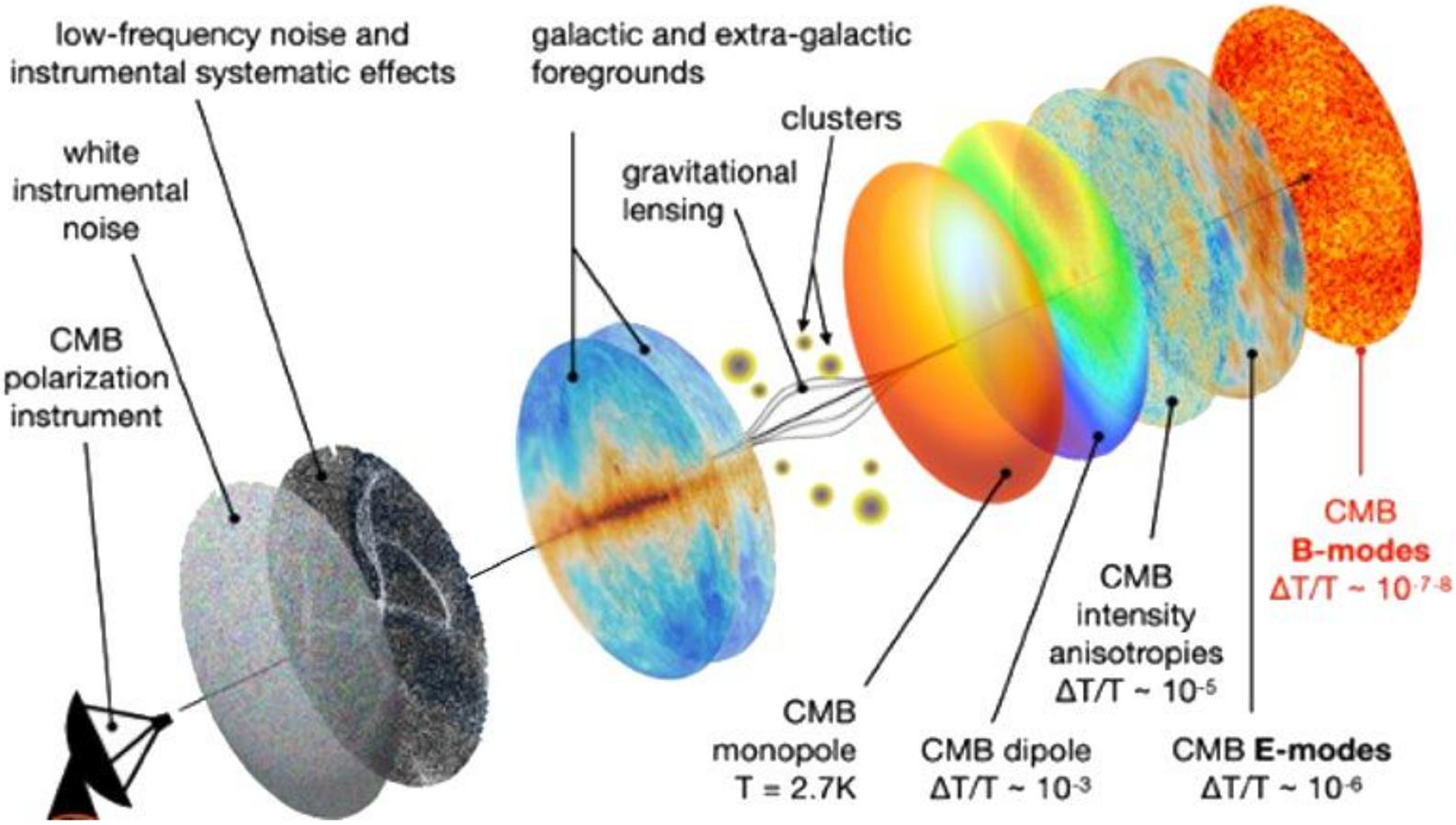
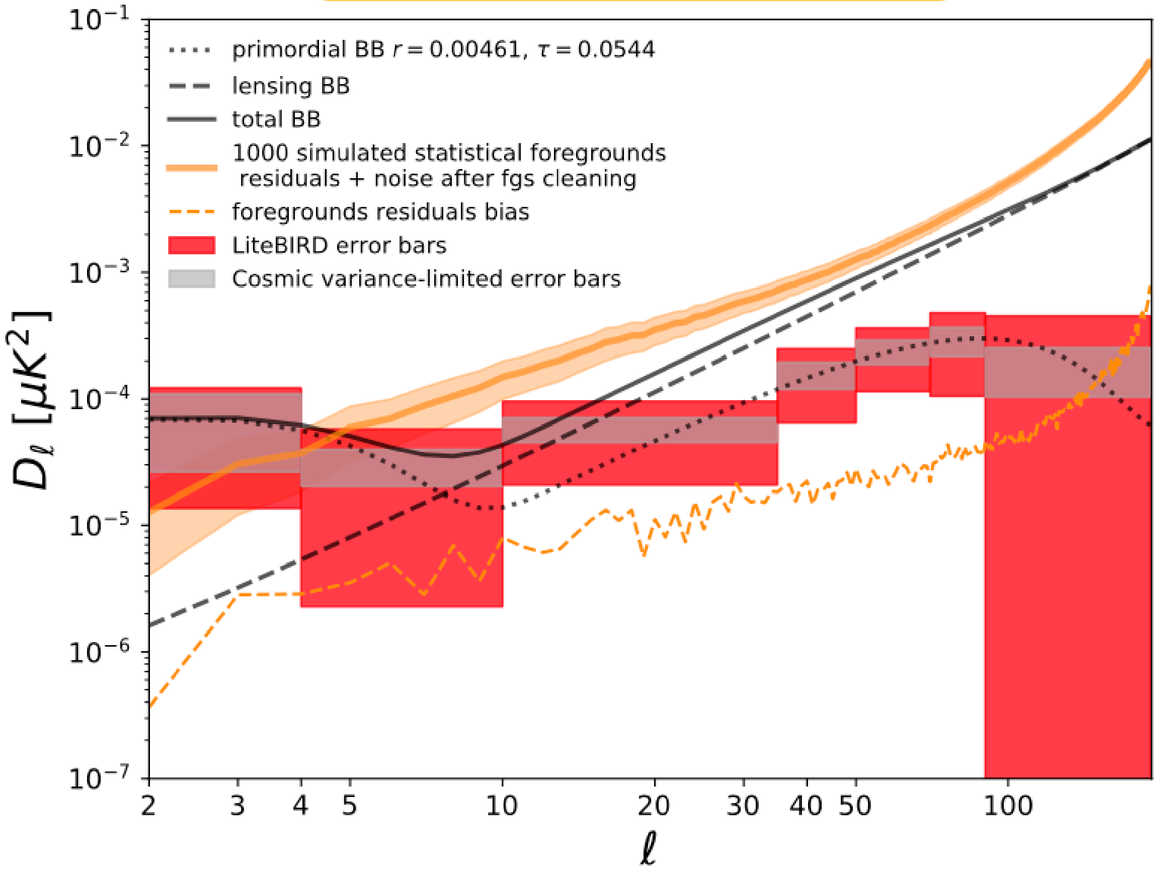


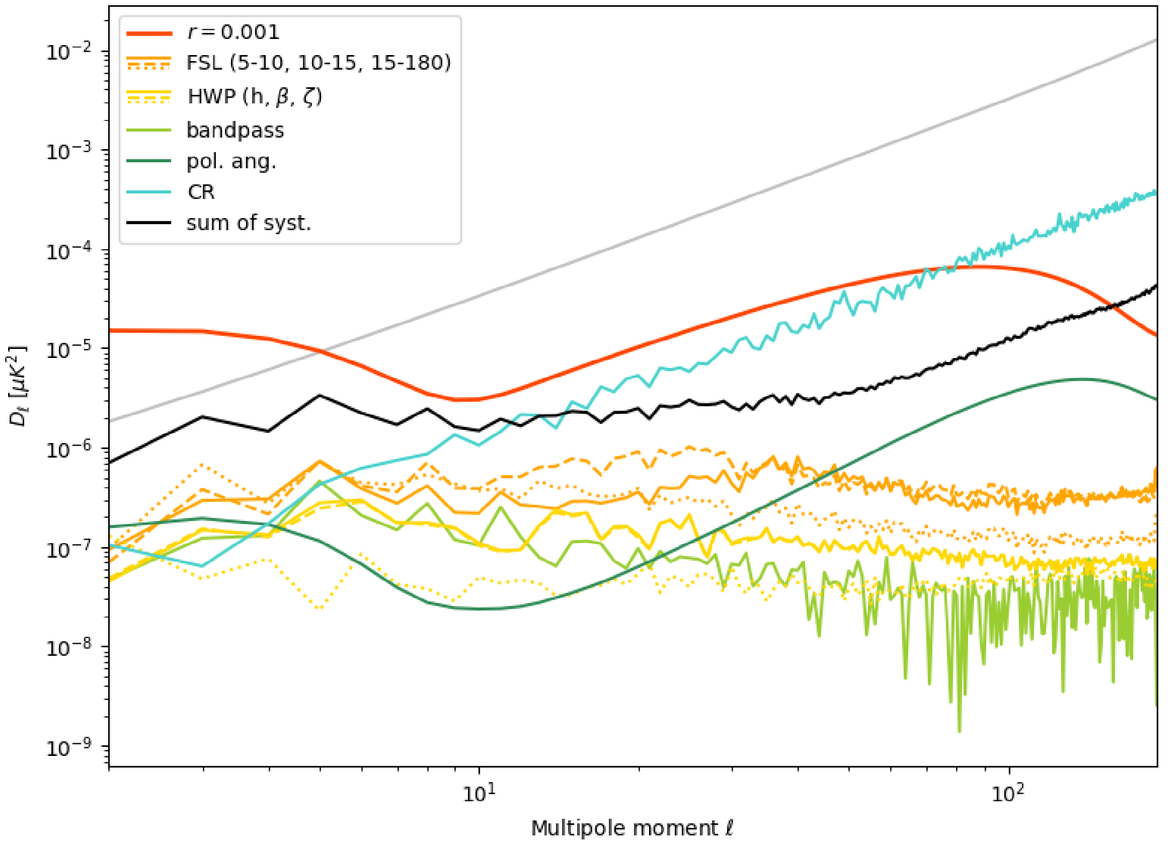
Image credit: Josquin Errard

The challenge of B-modes detection

Impact of foreground residual

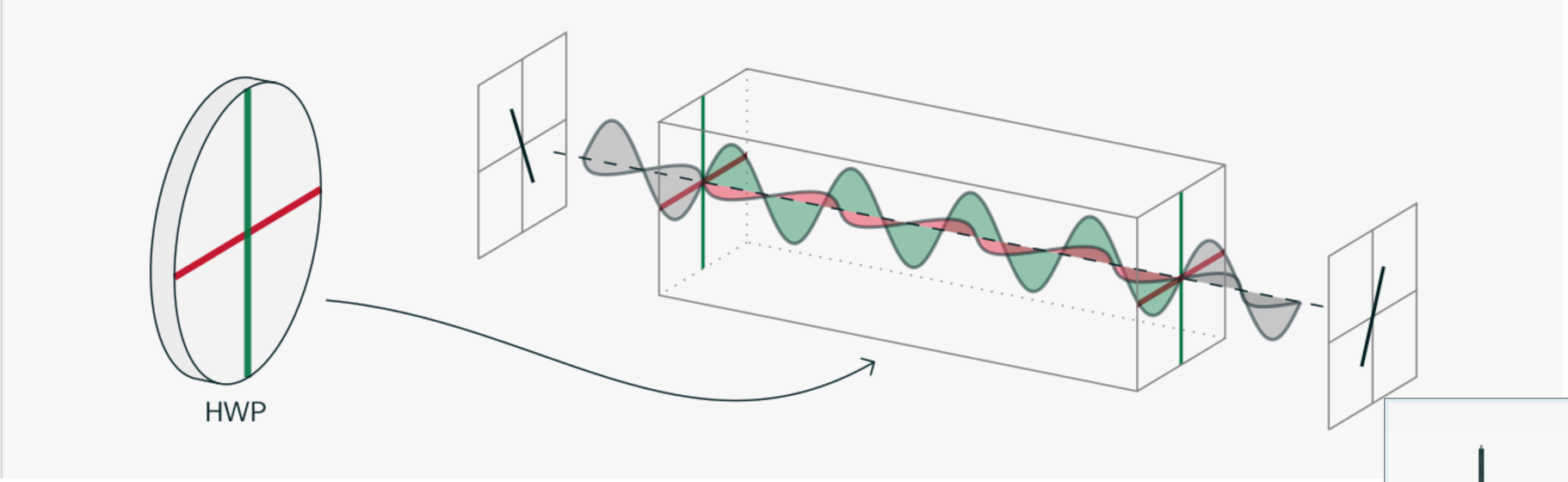


Impact of systematic effects



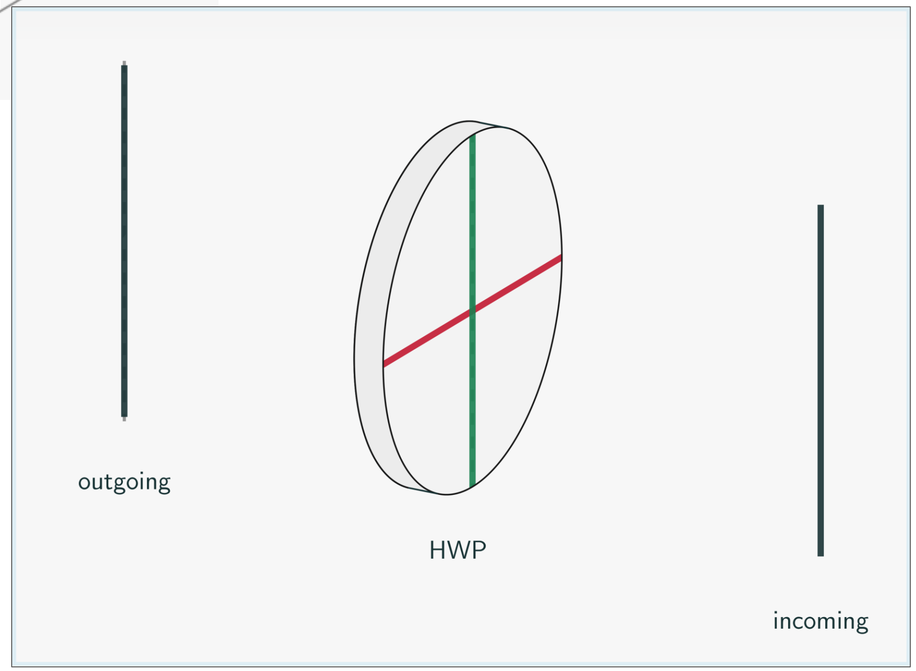
These residuals were obtained assuming an **half-wave plate (HWP)** as polarization modulator! *Why is this important?*

Ideal half-wave plate

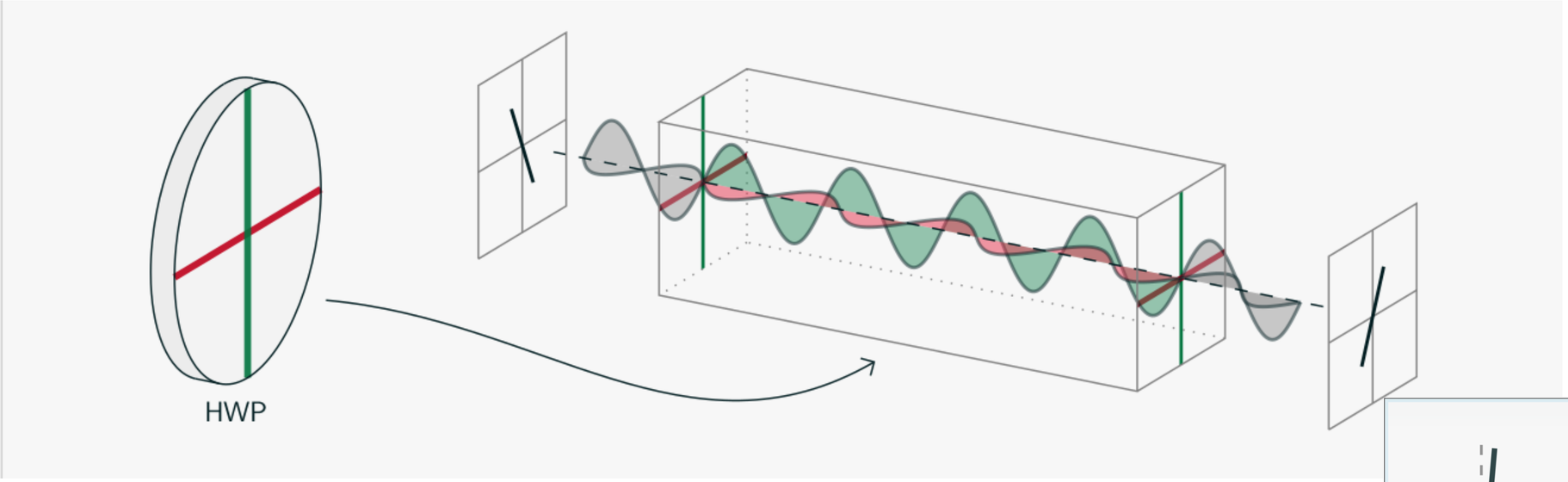


A **rotating (ideal) HWP** modulates the intrinsic polarized signal at $4f_{\mathrm{HWP}}$, and can help **to control systematic effects**:

- $1/f$ noise,
- pair-differencing systematics,
- beam asymmetries

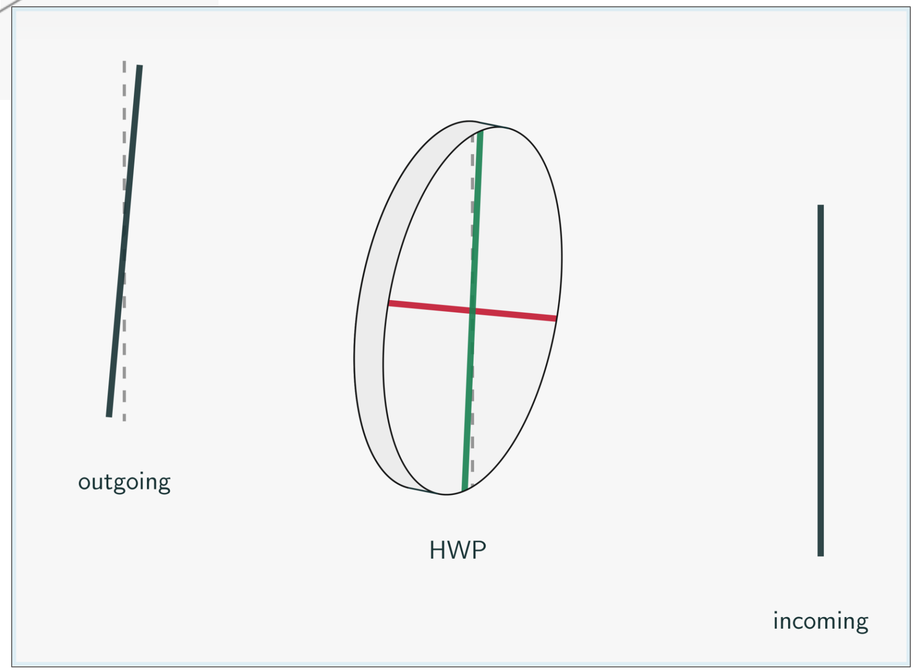


Ideal half-wave plate

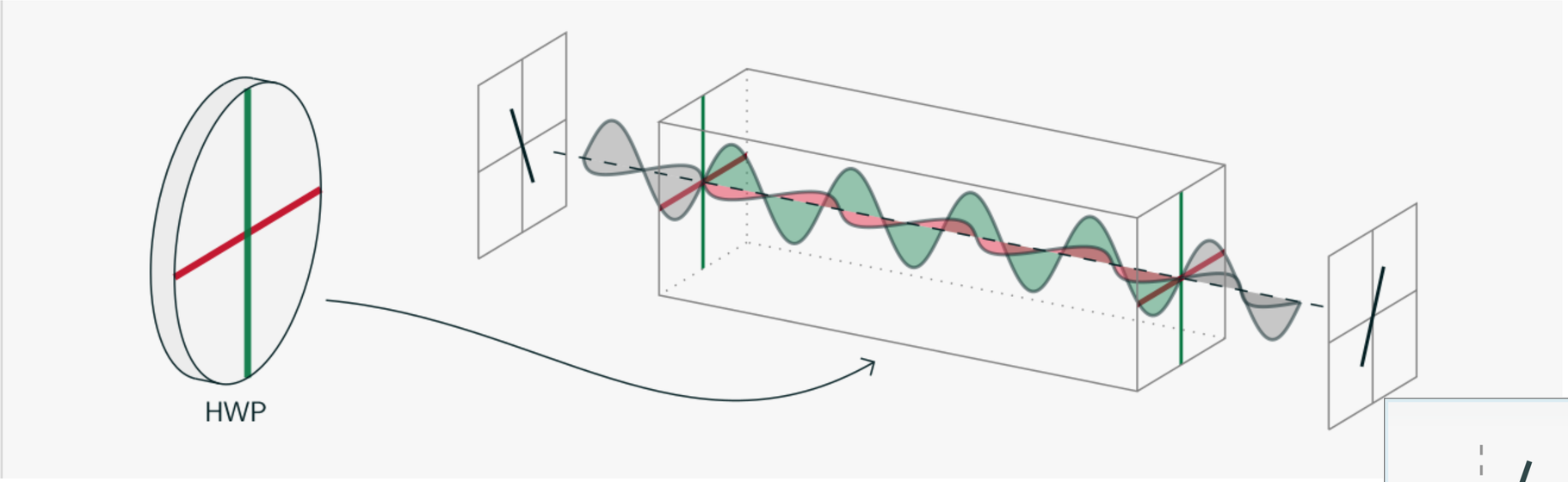


A **rotating (ideal) HWP** modulates the intrinsic polarized signal at $4f_{\mathrm{HWP}}$, and can help **to control systematic effects**:

- $1/f$ noise,
- pair-differencing systematics,
- beam asymmetries

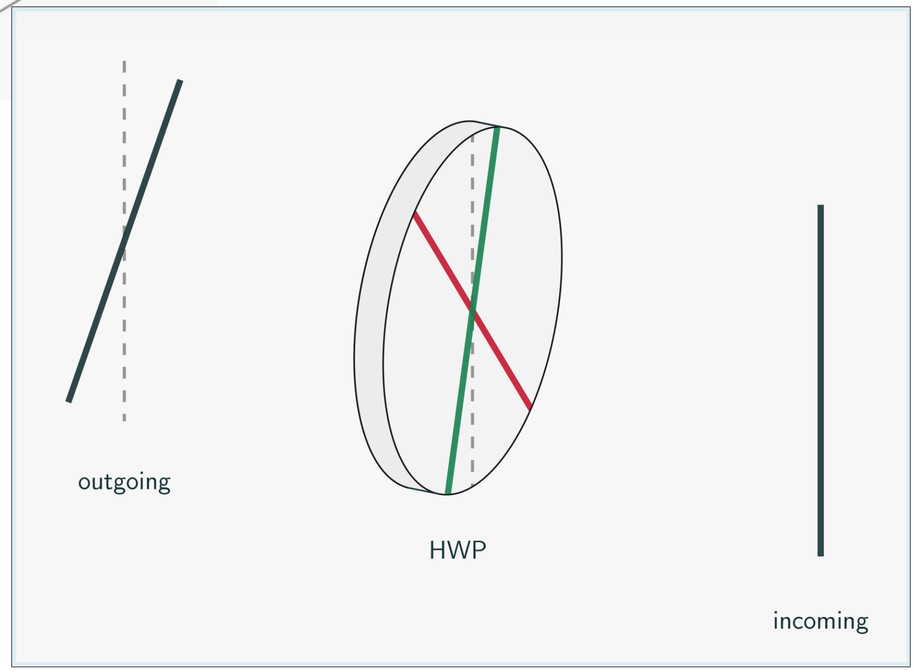


Ideal half-wave plate

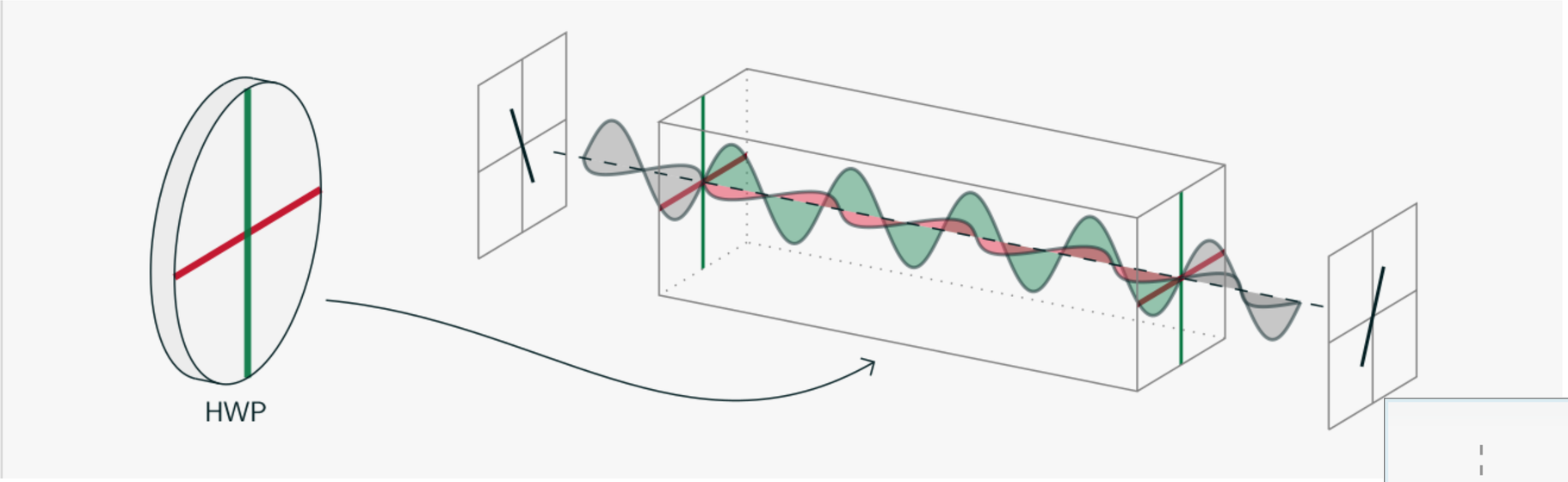


A **rotating (ideal) HWP** modulates the intrinsic polarized signal at $4f_{\mathrm{HWP}}$, and can help **to control systematic effects**:

- $1/f$ noise,
- pair-differencing systematics,
- beam asymmetries

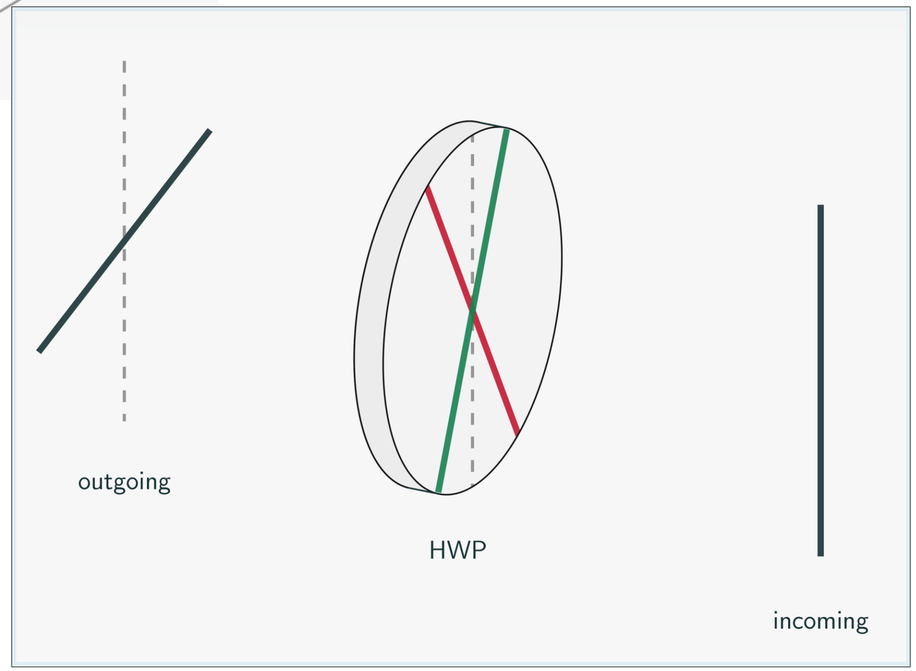


Ideal half-wave plate

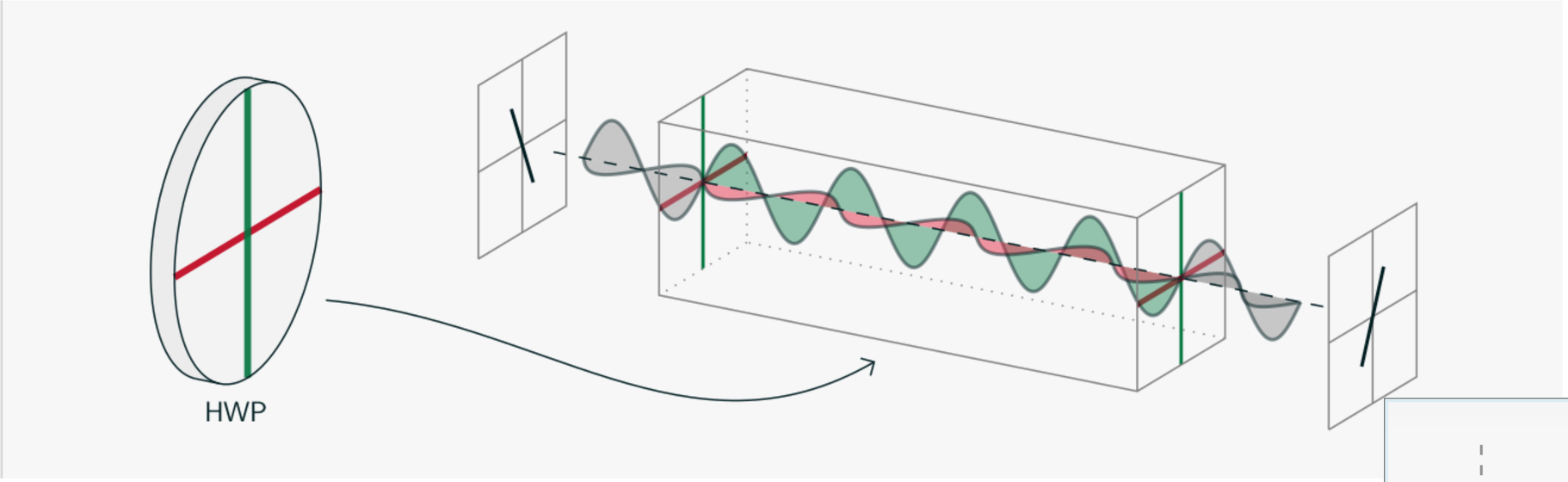


A **rotating (ideal) HWP** modulates the intrinsic polarized signal at $4f_{\mathrm{HWP}}$, and can help **to control systematic effects**:

- $1/f$ noise,
- pair-differencing systematics,
- beam asymmetries

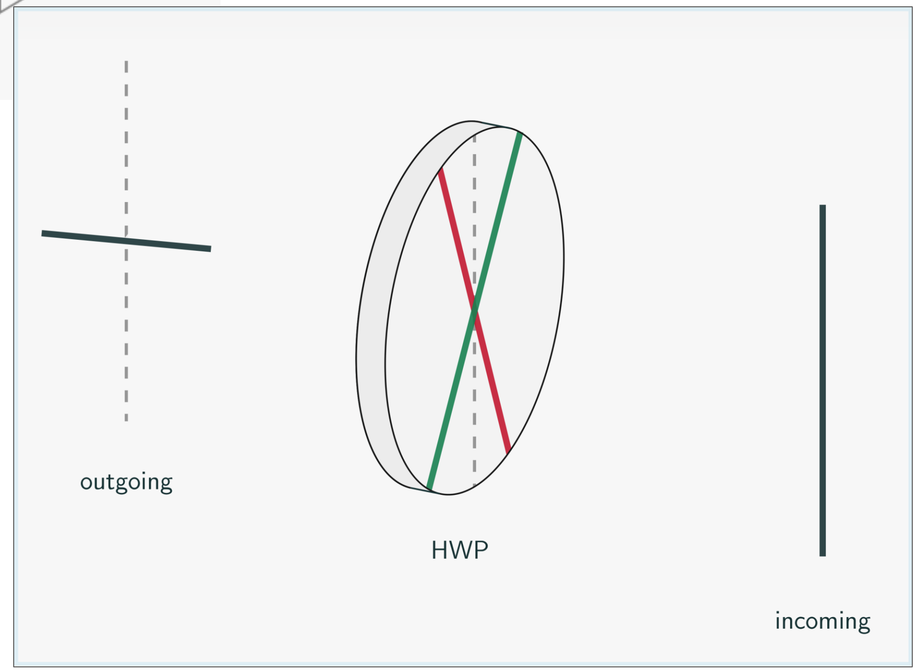


Ideal half-wave plate

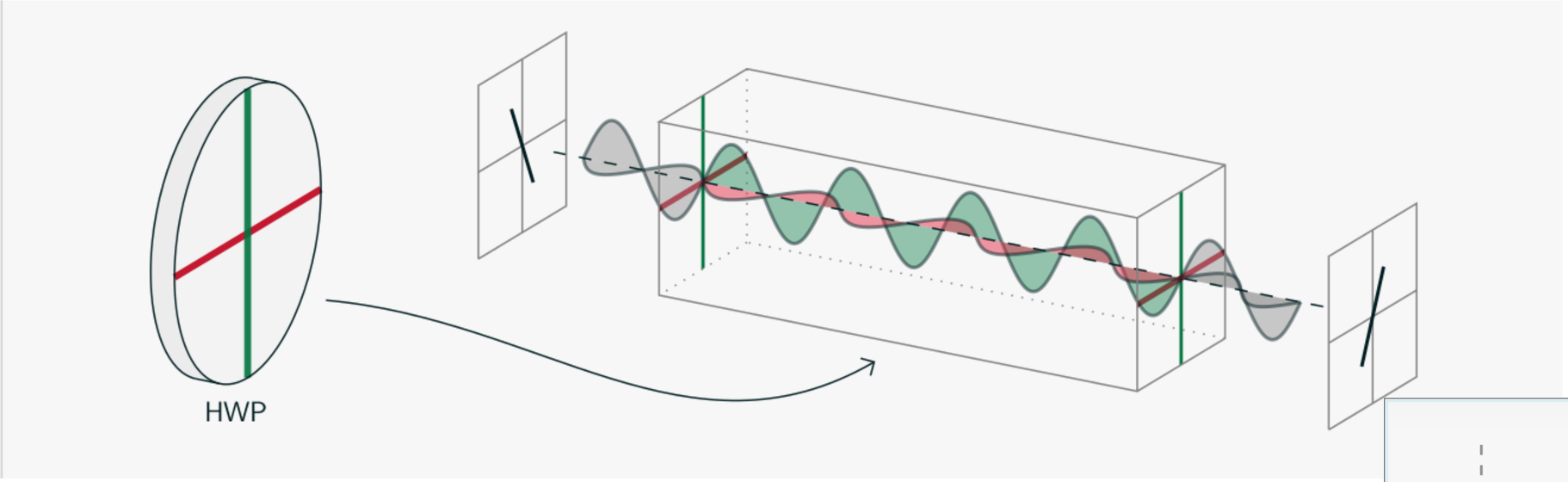


A **rotating (ideal) HWP** modulates the intrinsic polarized signal at $4f_{\mathrm{HWP}}$, and can help **to control systematic effects**:

- $1/f$ noise,
- pair-differencing systematics,
- beam asymmetries

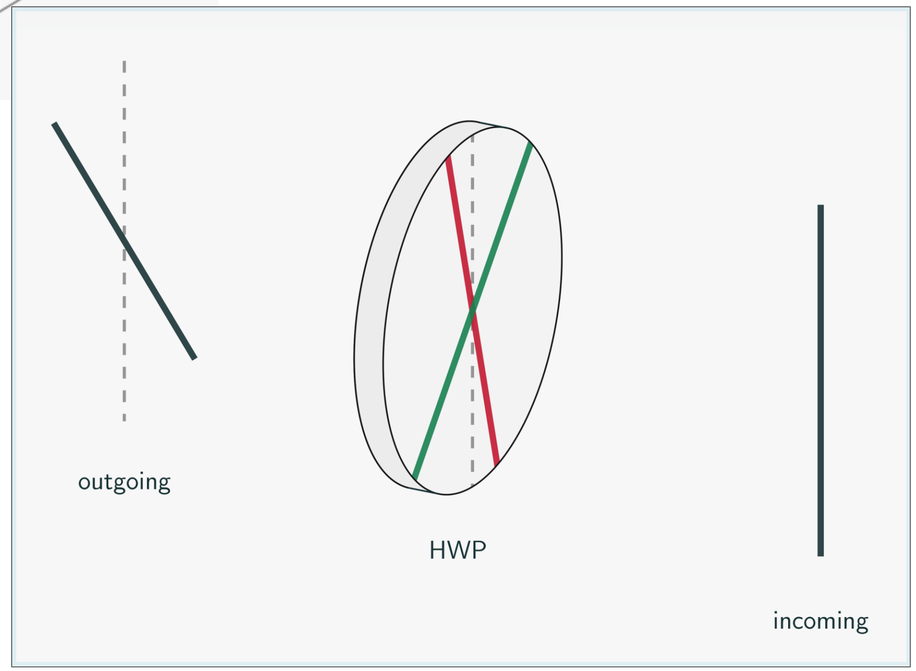


Ideal half-wave plate

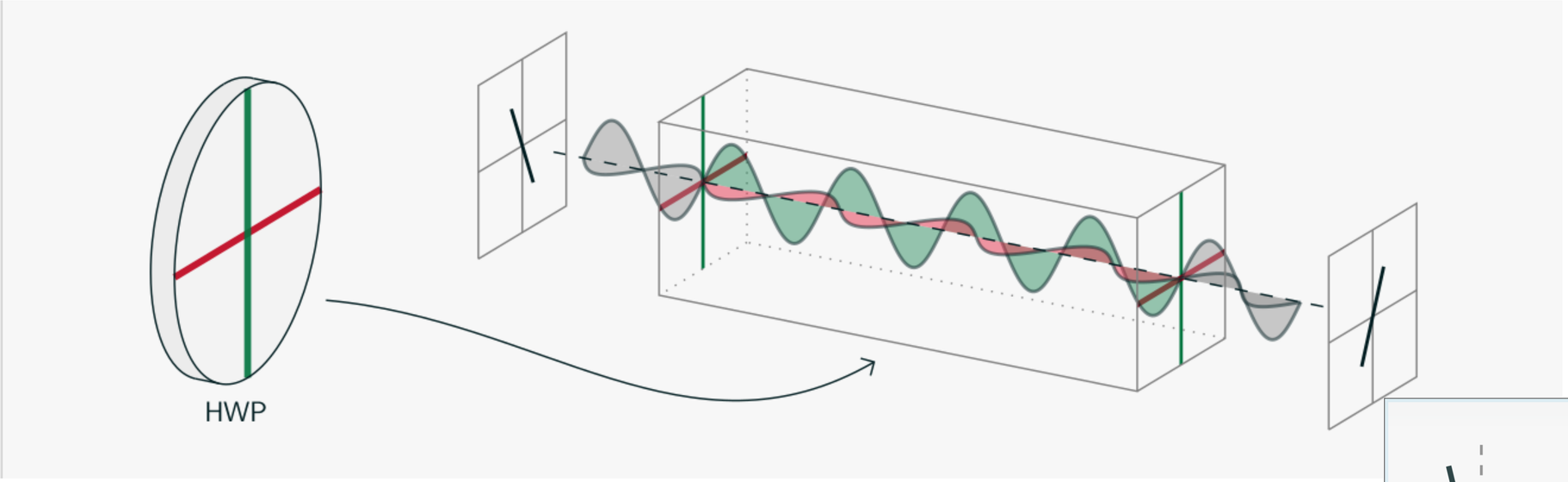


A **rotating (ideal) HWP** modulates the intrinsic polarized signal at $4f_{\mathrm{HWP}}$, and can help **to control systematic effects**:

- $1/f$ noise,
- pair-differencing systematics,
- beam asymmetries

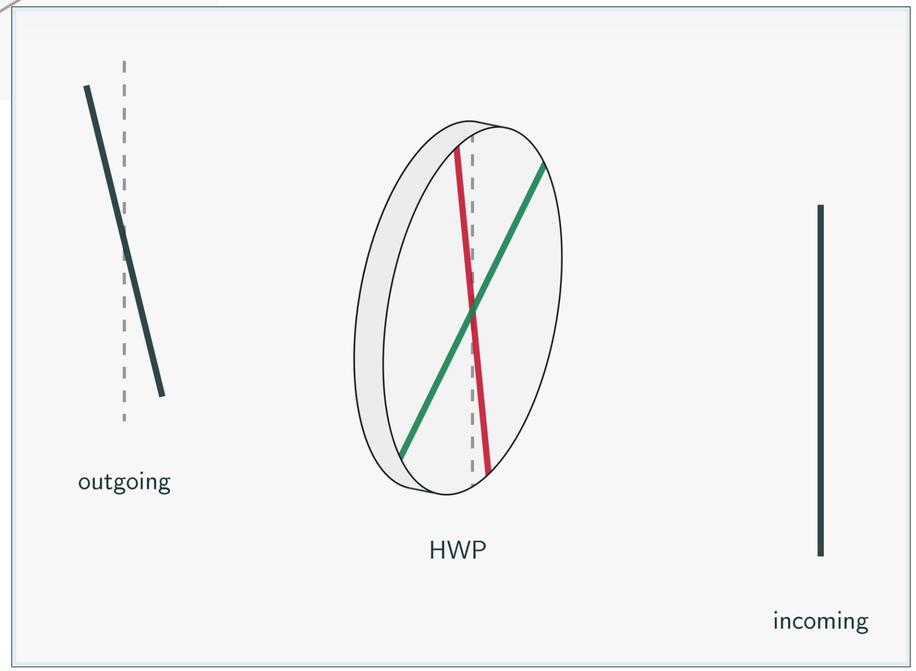


Ideal half-wave plate

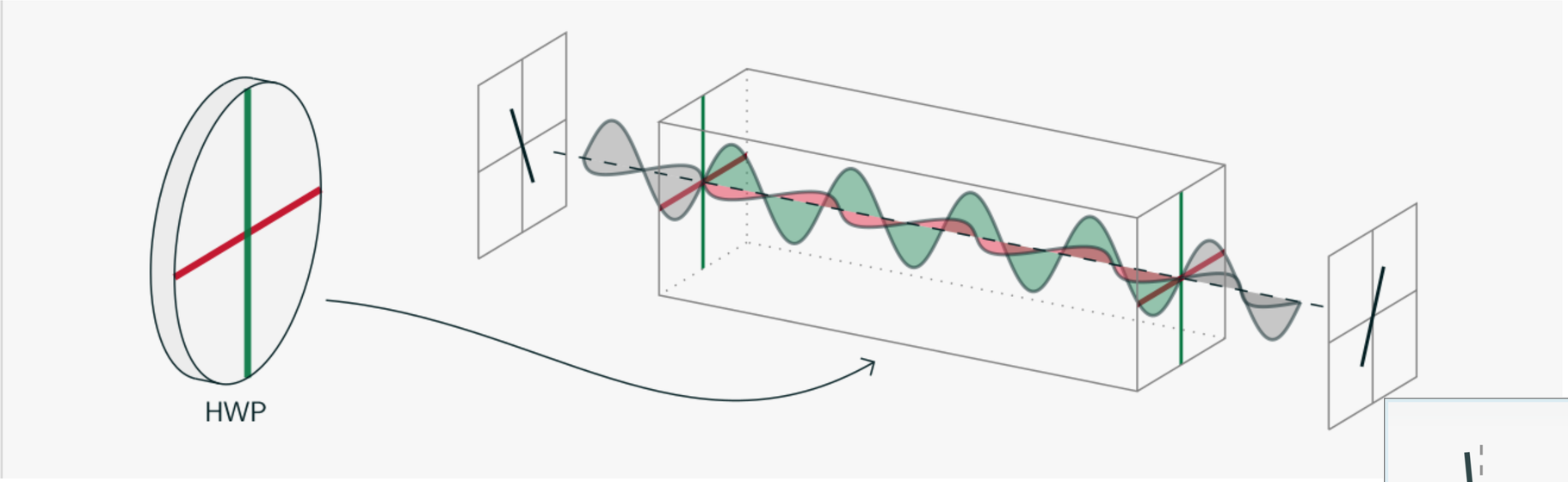


A **rotating (ideal) HWP** modulates the intrinsic polarized signal at $4f_{\mathrm{HWP}}$, and can help **to control systematic effects**:

- $1/f$ noise,
- pair-differencing systematics,
- beam asymmetries

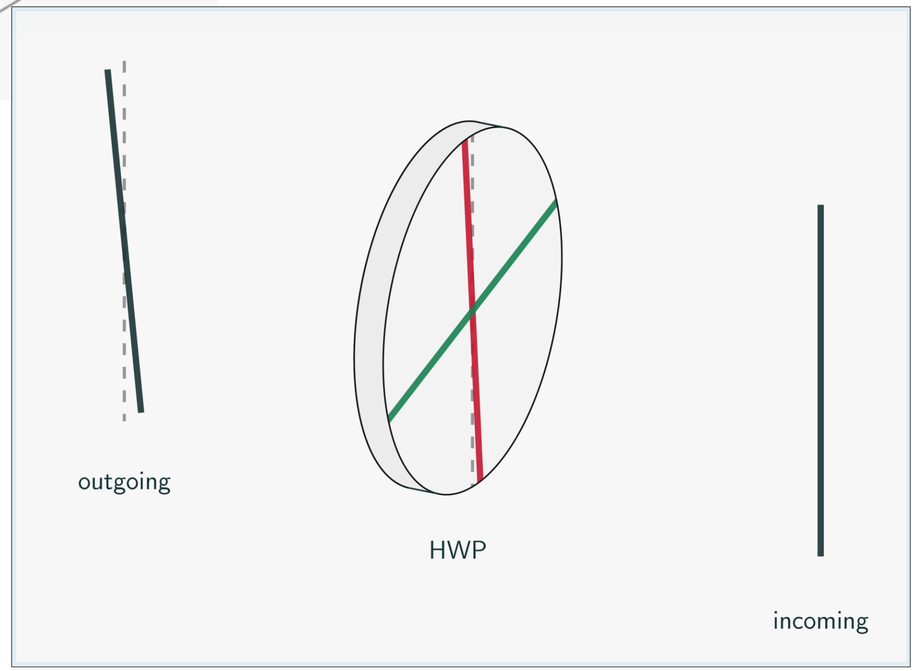


Ideal half-wave plate

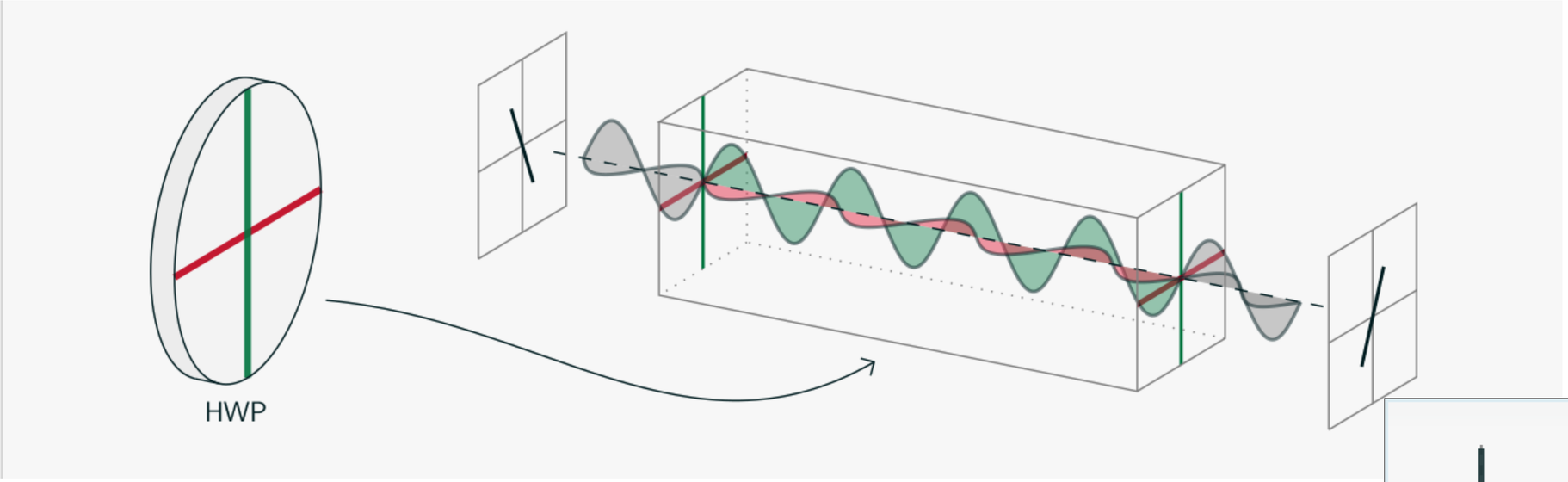


A **rotating (ideal) HWP** modulates the intrinsic polarized signal at $4f_{\mathrm{HWP}}$, and can help **to control systematic effects**:

- $1/f$ noise,
- pair-differencing systematics,
- beam asymmetries

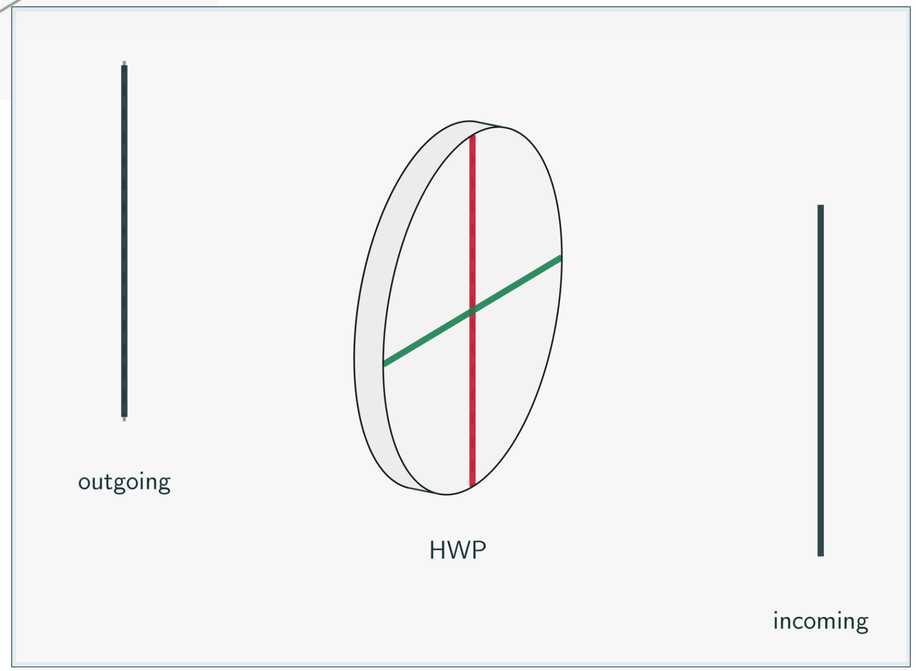


Ideal half-wave plate



A **rotating (ideal) HWP** modulates the intrinsic polarized signal at $4f_{\mathrm{HWP}}$, and can help **to control systematic effects**:

- $1/f$ noise,
- pair-differencing systematics,
- beam asymmetries



LiteBIRD reformation phase

- *Rescope studies:* **consolidate the mission's feasibility while keeping the same scientific objectives**
  - Revisit the error budget
  - **Simplify the mission configuration** (one single telescope instead of three; try to use existing technologies as much as possible)
  - **Simplify the cryogenic chain**
- The collaboration will spend approximately one year (~ late 2025) on the studies of the reformation plan

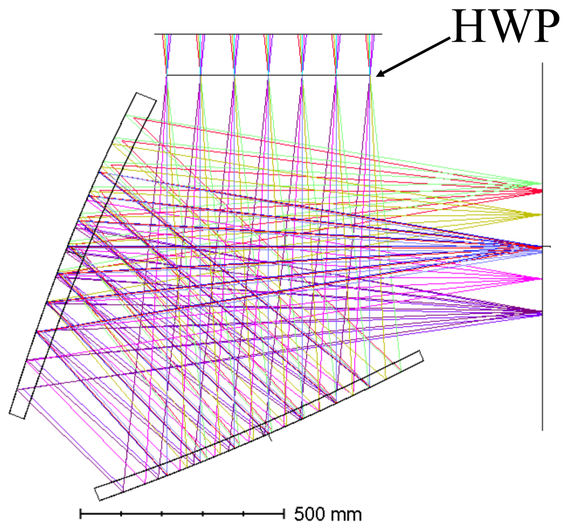
- **Two different configuration options** now being considered, both based on single Crossed-Dragone reflective telescope
- Option 1 (no HWP) requires a faster spin rate to minimize 1/*f* noise
- Option 2 is based on the possibility of using a wider-band HWP

Option 1

- Aperture 500 m
- 40-570 GHz
- No HWP
- Spin rate 0.3 rpm

Option 2

- Aperture 500 m
- 40-402 GHz
- Transmissive HWP
- Spin rate 0.05 rpm



LiteBIRD reformation phase

- *Rescope studies:* **consolidate the mission's feasibility while keeping the same scientific objectives**
  - Revisit the error budget
  - **Simplify the mission configuration** (one single telescope instead of three; try to use existing technologies as much as possible)
  - **Simplify the cryogenic chain**
- The collaboration will spend approximately one year (~ late 2025) on the studies of the reformation plan

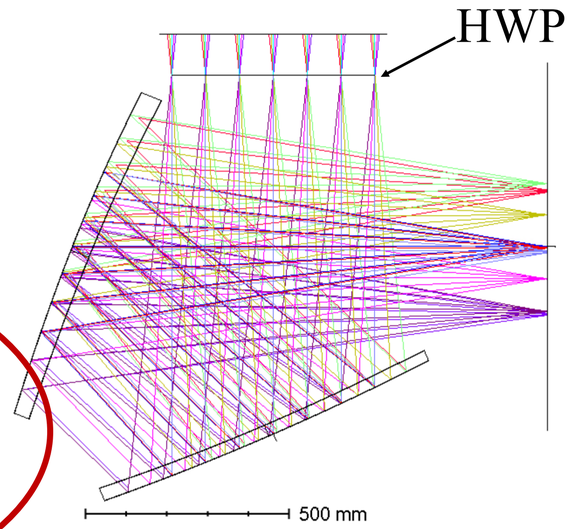
- **Two different configuration options** now being considered, both based on single Crossed-Dragone reflective telescope
- Option 1 (no HWP) requires a faster spin rate to minimize 1/*f* noise
- Option 2 is based on the possibility of using a wider-band HWP

Option 1

- Aperture 500 m
- 40-570 GHz
- No HWP
- Spin rate 0.3 rpm

Option 2

- Aperture 500 m
- 40-402 GHz
- Transmissive HWP
- Spin rate 0.05 rpm



Main systematic effects

Option 2

- Aperture 500 m
- 40-402 GHz
- Transmissive HWP
- Spin rate 0.05 rpm

→

- HWP non-idealities (multiplicative)
- Additive effects (1*f*, 2*f*, …)
- Detector non-linearities
- ...

Both options:

- Far side lobes
- Bandpass
- Polarization angle
- Gain
- ...

Option 1

- Aperture 500 m
- 40-570 GHz
- No HWP
- Spin rate 0.3 rpm

→

- 1/*f* noise
- Beam asymmetries
- Pair-differencing systematics (beam, bandpass, ...)
- ...

Main systematic effects

Option 2

- Aperture 500 m
- 40-402 GHz
- Transmissive HWP
- Spin rate 0.05 rpm

- HWP non-idealities (multiplicative)
- Additive effects (1*f*, 2*f*, …)
- Detector non-linearities
- ...

Both options:

- Far side lobes
- Bandpass
- Polarization angle
- Gain
- ...

Option 1

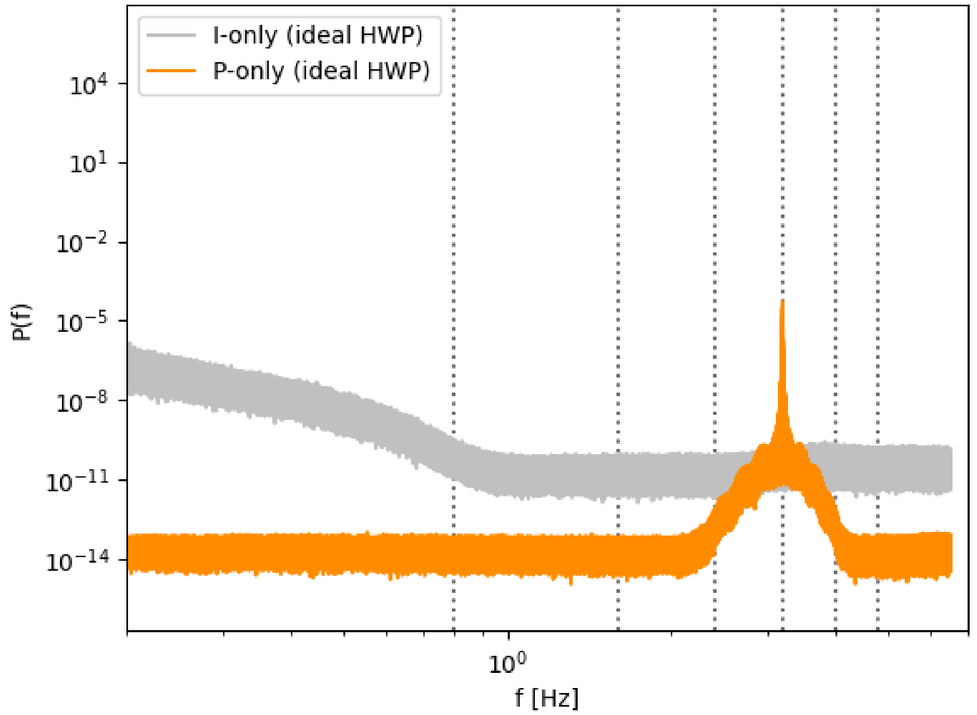
- Aperture 500 m
- 40-570 GHz
- No HWP
- Spin rate 0.3 rpm

- 1/*f* noise
- Beam asymmetries
- Pair-differencing systematics (beam, bandpass, ...)
- ...

HWP non-idealities

The effect of the HWP can be encoded in a **Mueller matrix** (acting on Stokes vectors)

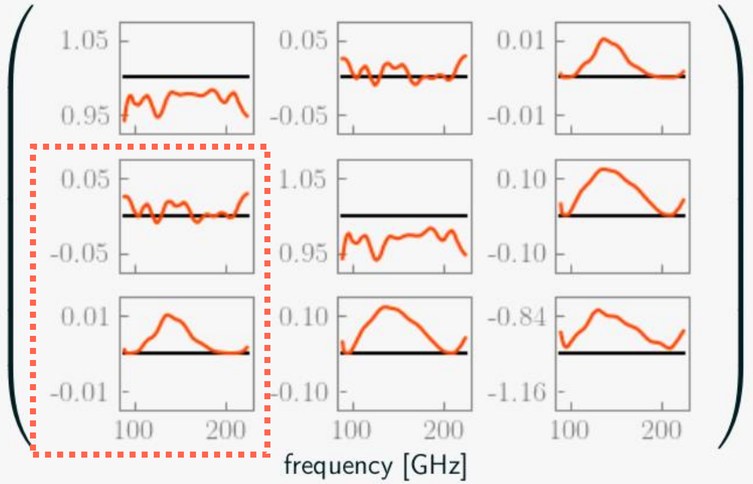
$$\mathcal{M}_{\mathrm{HWP}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -1 \end{pmatrix}$$

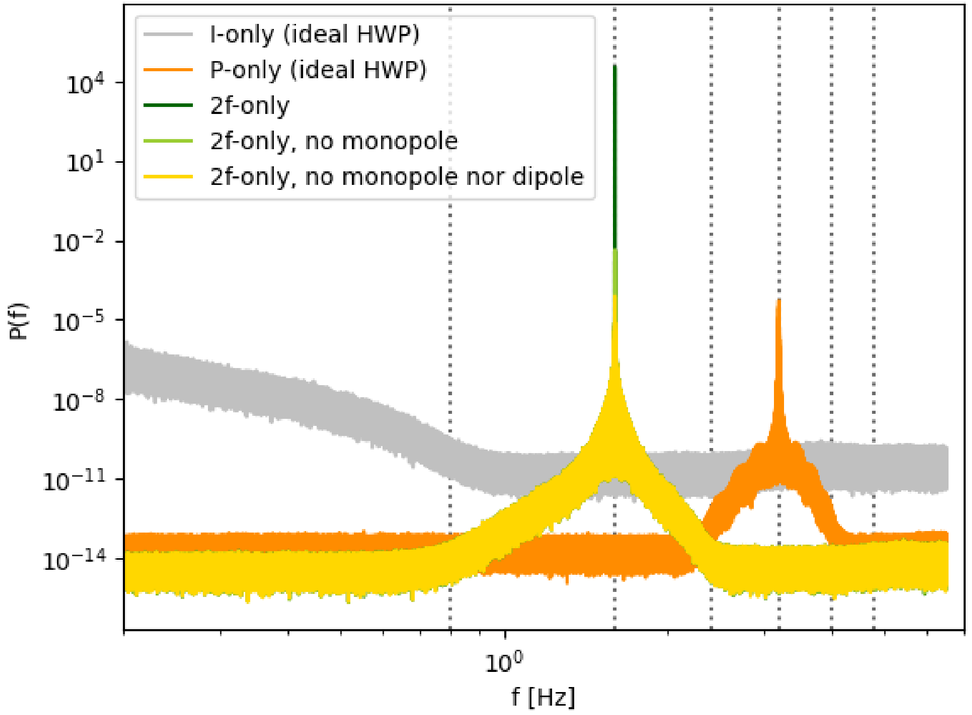


HWP non-idealities

The effect of the HWP can be encoded in a **Mueller matrix** (acting on Stokes vectors)

$$\mathcal{M}_{\mathrm{HWP}} =$$





The peak at $2f$ seems far enough from the science band. Still, monopole and dipole **leak** in pol. maps!

Monelli et al, in prep

Ongoing:

- **Characterization:** quantify *I-P* leakage induced by $2f$ term by realistic HWP
- **Requirements:** propagate to r, to derive requirements on the HWP non-idealities
- **Mitigation:** implement both notch-filtering and fitting to clean the signal, compare
- **Generalization:** include additive effects ($1f$, $2f$, …), non-linearities, $1/f$, ...

Main systematic effects

Option 2

- Aperture 500 m
- 40-402 GHz
- Transmissive HWP
- Spin rate 0.05 rpm

- HWP non-idealities (multiplicative)
- Additive effects (1*f*, 2*f*, …)
- Detector non-linearities
- ...

- Crucial to guide design (HWP speed, specifics)
- Mitigation strategies needed!

Both options:

- Far side lobes
- Bandpass
- Polarization angle
- Gain
- ...

Option 1

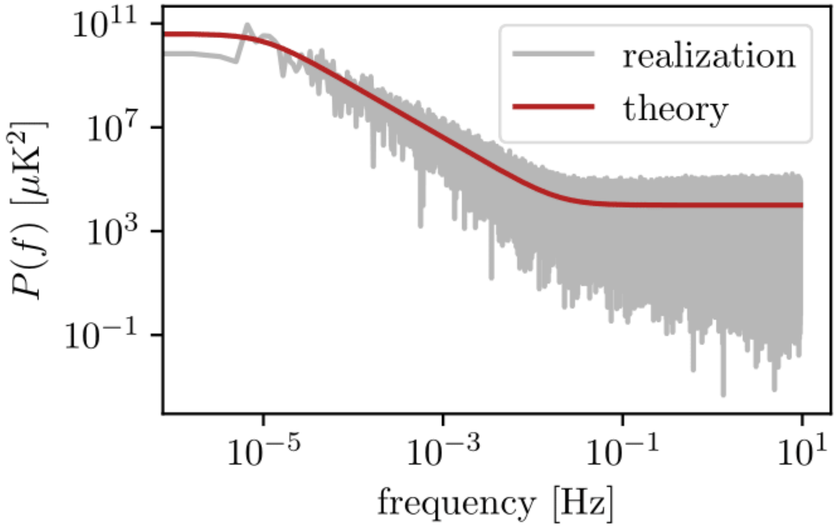
- Aperture 500 m
- 40-570 GHz
- No HWP
- Spin rate 0.3 rpm

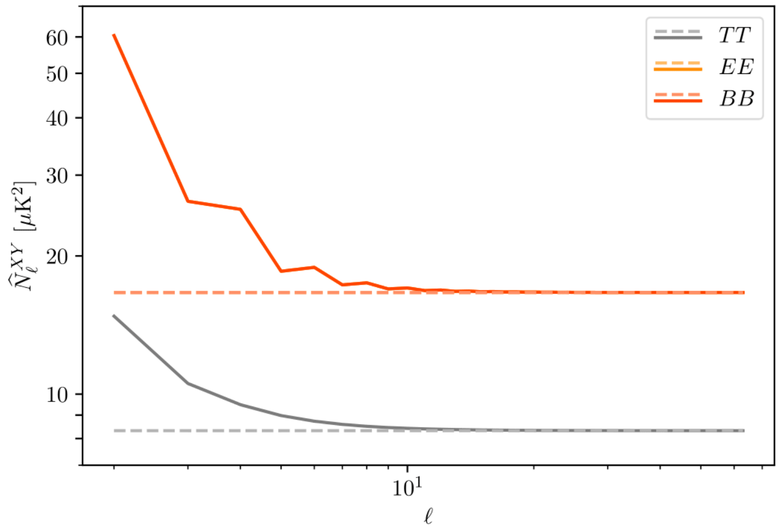
- 1/*f* noise
- Beam asymmetries
- Pair-differencing systematics (beam, bandpass, ...)
- ...

1/f noise

$$P(f) = \sigma^2 \left[1 + \left(\frac{f_{\rm knee}}{f}\right)^{\alpha}\right]$$

$$N_\ell^{BB}(A, \ell_{\rm knee}, \beta) = A \left[1 + \left(\frac{\ell_{\rm knee}}{\ell}\right)^{\beta}\right]$$





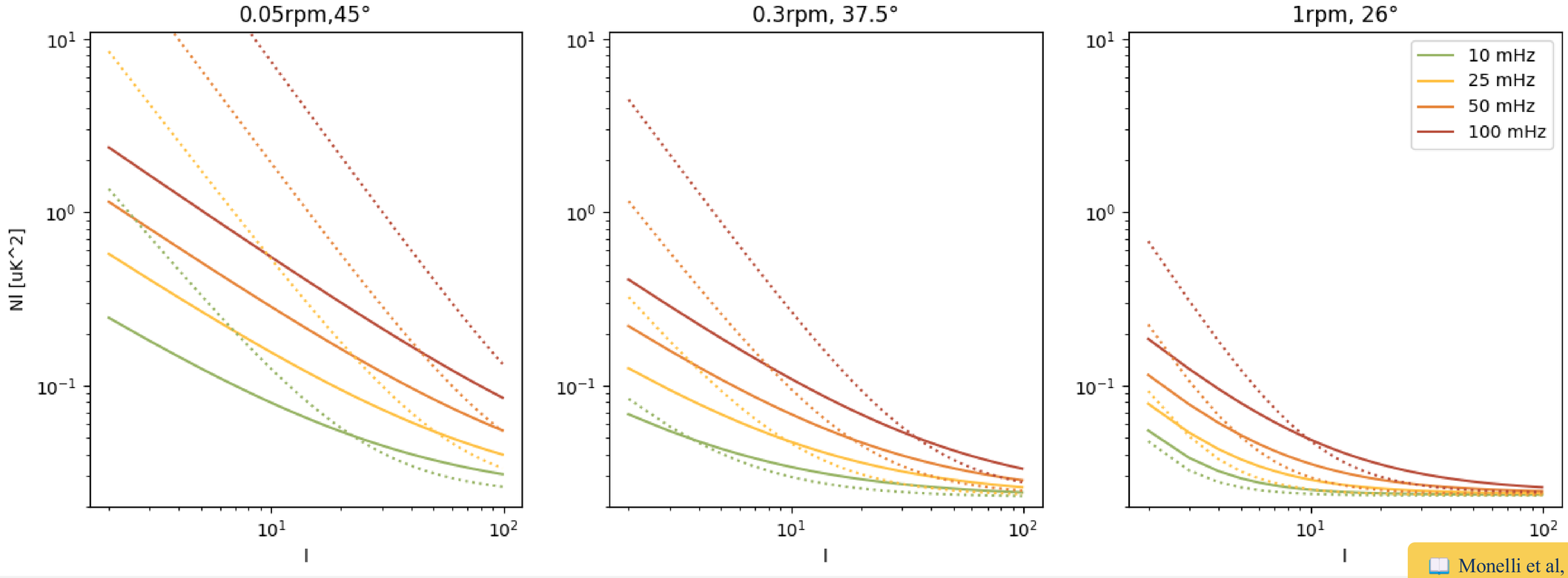
Mostly affecting **large scales**: problematic for the detection of primordial *B* modes!

Monelli et al, in prep

Ongoing:

- **Characterization:** derive relation between multipole and frequency space parameters (scan dependent)
- **Requirements:** propagate to *r*, to derive requirements on the instrumental noise parameters
- **Mitigation:** develop and implement TOD-inpainting at the map-making level
- **Application:** comparative study between *LiteBIRD*-, *Planck*- and PICO-like configurations

1/f noise



Monelli et al, in prep

Ongoing:

- **Characterization:** derive relation between multipole and frequency space parameters (scan dependent)
- **Requirements:** propagate to *r*, to derive requirements on the instrumental noise parameters
- **Mitigation:** develop and implement TOD-inpainting at the map-making level
- **Application:** comparative study between *LiteBIRD*-, *Planck*- and PICO-like configurations

Main systematic effects

Option 2

- Aperture 500 m
- 40-402 GHz
- Transmissive HWP
- Spin rate 0.05 rpm

- HWP non-idealities (multiplicative)
- Additive effects (1*f*, 2*f*, …)
- Detector non-linearities
- ...

- Crucial to guide design (HWP speed, specifics)
- Mitigation strategies needed!

Both options:

- Far side lobes
- Bandpass
- Polarization angle
- Gain
- ...

Option 1

- Aperture 500 m
- 40-570 GHz
- No HWP
- Spin rate 0.3 rpm

- 1/*f* noise
- Beam asymmetries
- Pair-differencing systematics (beam, bandpass, ...)
- ...

- Crucial to guide design (instr. noise parameters)
- Mitigation strategies needed!

Summing up

- LiteBIRD will measure CMB polarization with **unprecedented sensitivity**
- Huge discovery impact (**inflation** and other science)
- Ongoing **rescope studies**: simpler configuration, same scientific objectives
- Understanding **systematic effects** and develop mitigation strategies is crucial at this stage!
- Two of the main ones w/ and w/out HWP:
  - HWP non-idealities (multiplicative): *I*-*P* leakage especially problematic
  - 1/*f* noise: affects very large scales (high sensitivity to primordial *B* modes)

- Crucial to guide design choices
- Mitigation strategies needed!