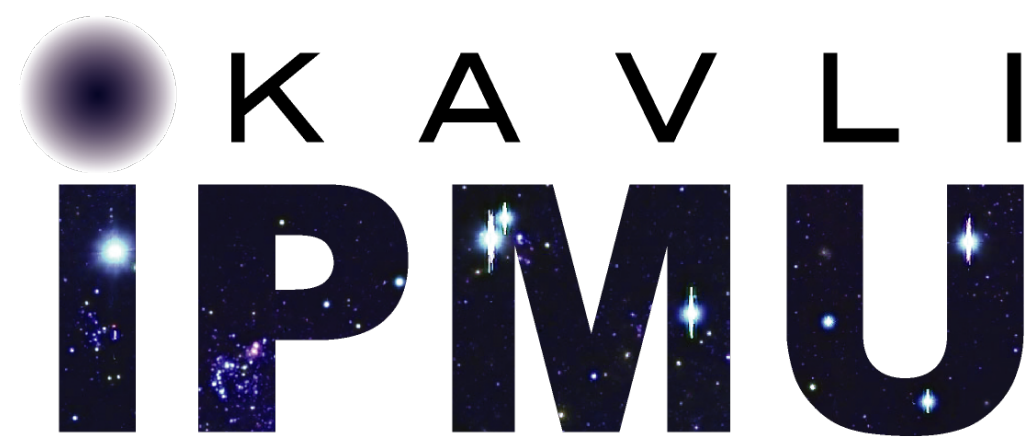




Instrumental systematics

Challenges at the CMB Frontier - July 1, 2026

Marta Monelli - Project Researcher - Kavli IPMU

arXiv:1911.03164v1 [astro-ph.CO] 8 Nov 2019

Absolute calibration of the polarisation angle for future CMB B-mode experiments from current and future measurements of the Crab nebula

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Abstract. A tremendous international effort is currently dedicated to observing the so-called primordial *B* modes of the Cosmic Microwave Background (CMB) polarisation. If measured, this faint signal imprinted by the primordial gravitational wave background, providing a rigorous test of fundamental physics far beyond the reach of accelerators. At the unprecedented sensitivity level that the new generation of CMB experiments aims to reach, every uncontrolled instrumental systematic effect will potentially result in an analysis bias that is larger than the much sought-after CMB *B*-mode signal. The absolute calibration of the polarisation angle is particularly important in this sense, as any associated error will end up in a leakage from the much larger *E* modes into *B* modes. The Crab nebula (Tau A), with its bright microwave synchrotron emission, is one of the few sources in the sky that can be used as absolute polarisation calibrators.

1 Introduction
Cosmic Inflation
Bang scenario
could have produced
imprints in the CMB
Background
scaled by a factor
to the energy density
*e-mail: j...

New physics from the polarised light of the cosmic microwave background

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ABSTRACT

Cosmology requires new physics beyond the Standard Model of elementary particles and fields. What is the fundamental physics behind dark matter and dark energy? What generated the initial fluctuations in the early Universe? Polarised light of the cosmic microwave background (CMB) may hold the key to answers. In this article, we discuss two new developments in this research area. First, if the physics behind dark matter and dark energy violates parity symmetry, their coupling to photons rotates the plane of linear polarisation as the CMB photons travel more than 13 billion years. This effect is known as ‘cosmic birefringence’: space filled with dark matter and dark energy behaves as if it were a birefringent material, like a crystal. A tantalising hint for such a signal has been found with the statistical significance of 3σ . Next, the period of accelerated expansion in the very early Universe, called ‘cosmic inflation’, produced a stochastic background of primordial gravitational waves (GW). What generated GW? The leading idea is vacuum fluctuations in spacetime, but matter fields could also produce a significant amplitude of primordial GW. Finding its origin using CMB polarisation opens a new window into the physics behind inflation. These new scientific targets may influence how data from future CMB experiments are collected, calibrated, and analysed.

The standard cosmological model, called Λ CDM, demands new physics beyond the Standard Model (SM) of elementary particles and fields¹. ‘ Λ ’ denotes Einstein’s cosmological constant, which is the simplest (but most difficult to understand^{2,3}) candidate of dark energy responsible for the accelerated expansion of the Universe^{4,5}. ‘CDM’ stands for cold dark matter, which accounts for 80% of the matter density in the Universe⁶. The existence of dark matter and dark energy, as well as their mysterious and elusive nature, are well known to the public.

Yet, the most extraordinary ingredient of the model is perhaps not as well known. This ingredient, which is not contained in the name of Λ CDM, is the idea that the origin of all structures in the Universe, such as galaxies, stars, planets and life, was the quantum-mechanical vacuum fluctuation generated in the early Universe^{7–11}. The observed properties of the cosmic structures, most notably those of the afterglow of the fireball Universe called the cosmic microwave background (CMB), agree with this idea^{12,13}.

What is the physical nature of dark matter and dark energy? What generated the initial quantum vacuum fluctuation and how? Polarised light of the CMB may help answer these questions. Their importance is widely recognised, and there are beautiful measurements of CMB polarisation from two space-based experiments: the Wilkinson Microwave Anisotropy Probe (NASA) Wilkinson Microwave Anisotropy Probe (WMAP) and the European Space Agency (ESA) Planck¹⁴, as well as ground-based experiments using radio telescopes¹⁵ and balloon-borne experiments¹⁶.

tially with time. If it were not for the CMB research, such a dramatic improvement and innovation in microwave sensor technology would not have been made.

There will be ever more powerful CMB polarisation experiments in the coming decade, including ground-based observatories such as Simons Observatory²³, South Pole Observatory²⁴ and CMB Stage-4²⁵, and a space mission LiteBIRD²⁶ led by the Japan Aerospace Exploration Agency (JAXA). These experiments will reduce the noise level by another order of magnitude. We are now at the stage where not only the statistical uncertainty but also the systematic uncertainty (including both instrumental and astrophysical ones) must be controlled with unprecedented precision. What kind of systematics should we characterise better and how well depends on what kind of new physics we wish to discover from such observations.

In this article, we focus on two new developments in the quest for new physics. First, CMB polarisation is sensitive to physics violating parity symmetry under inversion of spatial coordinates²⁷. We discuss a tantalising hint for such a signal, called ‘cosmic birefringence’^{28–30}, in the polarisation data obtained by Planck^{31–33}. The statistical significance is currently about 3σ . If confirmed with higher significance in the future, it would have profound implications for the fundamental physics behind dark energy^{34,35} and dark matter^{36,37}, as well as for theory of quantum gravity^{38,39}.

BEYONDPLANCK I. Global Bayesian analysis of the Planck Low Frequency Instrument data

BeyondPlanck Collaboration^{*}: K. J. Andersen¹, R. Aurlien¹, R. Banerji¹, A. Basyrov¹, M. Bersanelli^{2,3,4}, S. Bertocco⁵, M. Brilenkov¹, M. Carbone⁶, L. P. L. Colombo^{2,4}, H. K. Eriksen¹, J. R. Eskilt¹, M. K. Foss¹, C. Franceschet^{2,4}, U. Fuskeland¹, S. Galeotta², M. Galloway¹, S. Gerakakis⁶, E. Gjerløw¹, B. Hensley⁷, D. Herman¹, M. Iacobellis⁸, M. Ieronymaki⁶, H. T. Ihle¹, J. B. Jewell⁸, A. Karakei¹, E. Keihänen^{9,10}, R. Kesitalo¹¹, J. G. S. Lunde¹, G. Maggio⁵, D. Maino^{2,3,4}, M. Maris², A. Mennella^{2,3,4}, S. Paradiso^{2,4}, B. Partridge¹², M. Reinecke¹³, M. San¹, N.-O. Stutzer¹, A.-S. Suur-Uski^{9,10}, T. L. Svalheim¹, D. Tavagnacco^{5,14}, H. Thommesen¹, D. J. Watts¹, I. K. Wehus¹, and A. Zacchei¹
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¹¹ Haverford College Astronomy Department, 370 Lancaster Avenue, Haverford, Pennsylvania, U.S.A.
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¹³ Dipartimento di Fisica, Università degli Studi di Trieste, via A. Valerio 2, Trieste, Italy
September 13, 2022

We describe the BEYONDPLANCK companion...

ABSTRACT

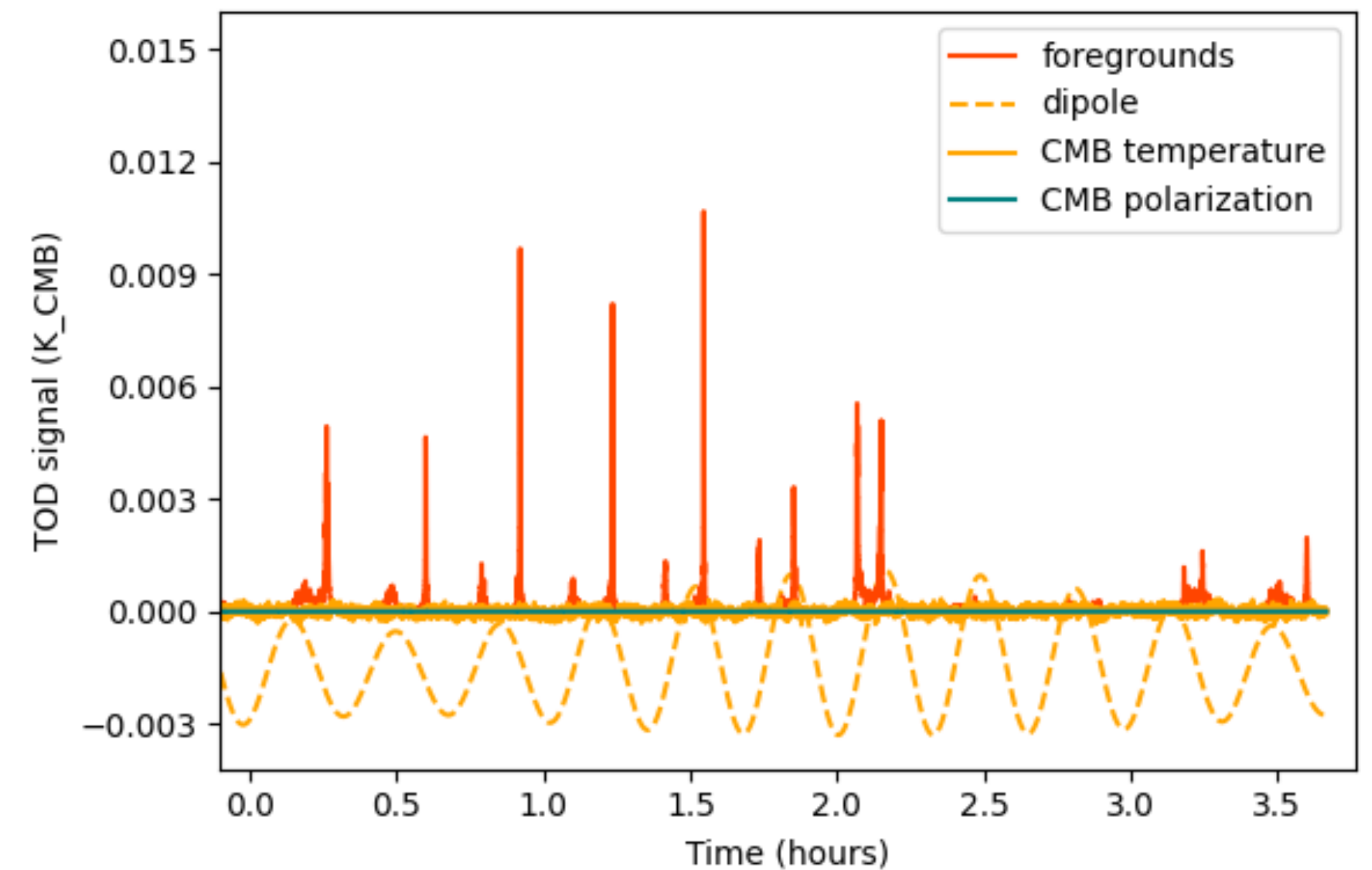
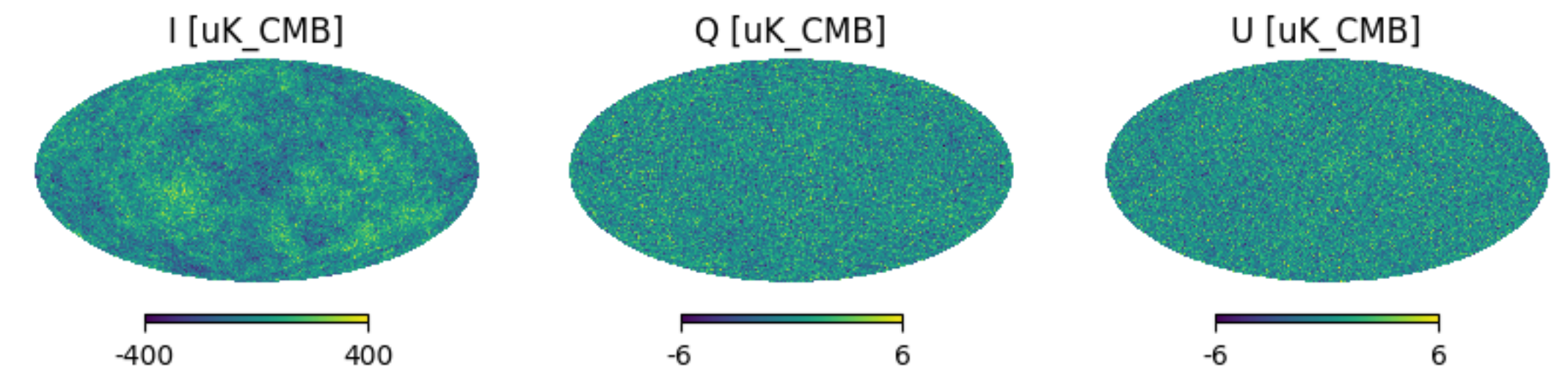
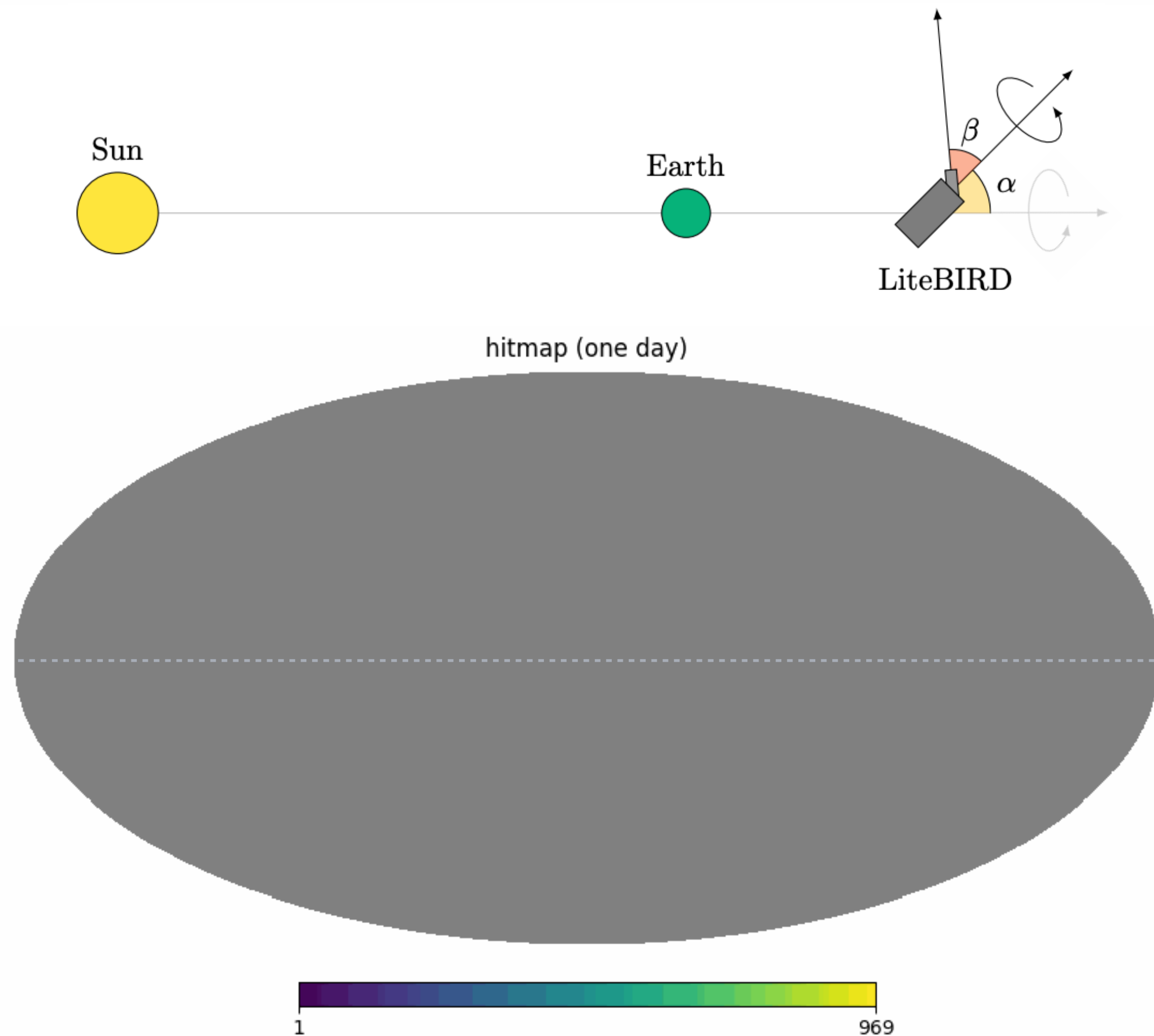
Methodology and main products, and provide a guide to a set of directly on experience from ESA’s Planck mission, we implement the set of all free instrumental (gain, correlated noise, mission etc.), and cosmological (CMB map, power spectrum) and instrumental effects in the most natural basis for each one single framework. As a practical demonstration of this reduction with Planck LFI. In this process, we identify several lines, including gain over-smoothing and time-variable and mitigating both previously known and newly discovered M model, and we constrain the reionization optical depth to exceed of 32%. This uncertainty is about 30% larger on the posterior distribution without the need of any ad-hoc unmodelled systematic effects remaining in the Planck CMB experiments, including LiteBIRD, and it will model. All software is made publicly available under an <http://beyondplanck.science>.

microwave background, diffuse radiation – Galaxy:

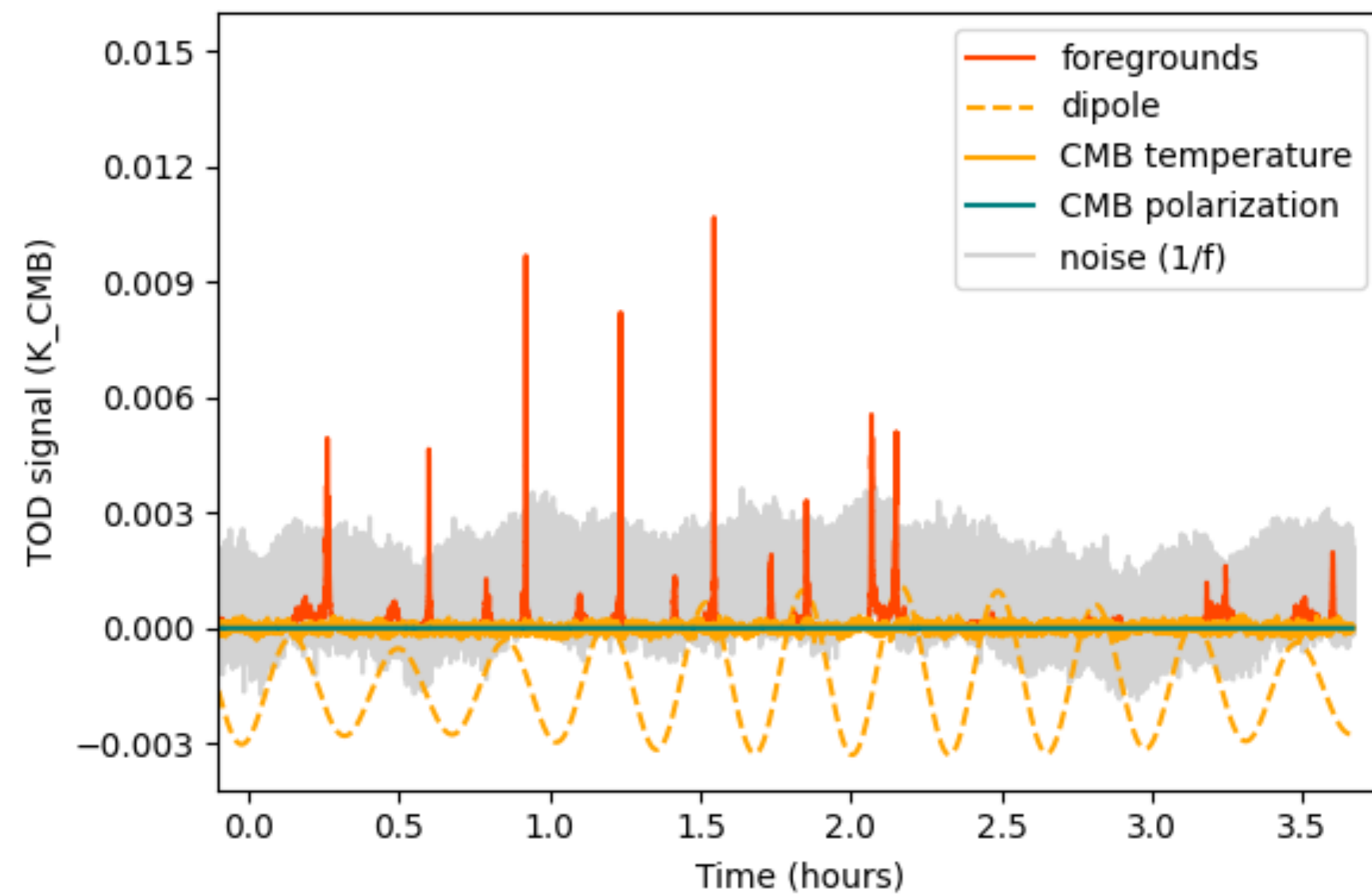
Planck	3
Large-scale CMB polarization, the reionization optical depth, and systematic errors	4
Lessons learned from Planck	5
Next frontier: Primordial gravitational waves	6
BEYONDPLANCK program	6
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“We are now at the stage where not only the statistical uncertainty but also the **systematic** uncertainty (including both instrumental and astrophysical ones) must be controlled with unprecedented precision.”

What we actually measure: the TOD

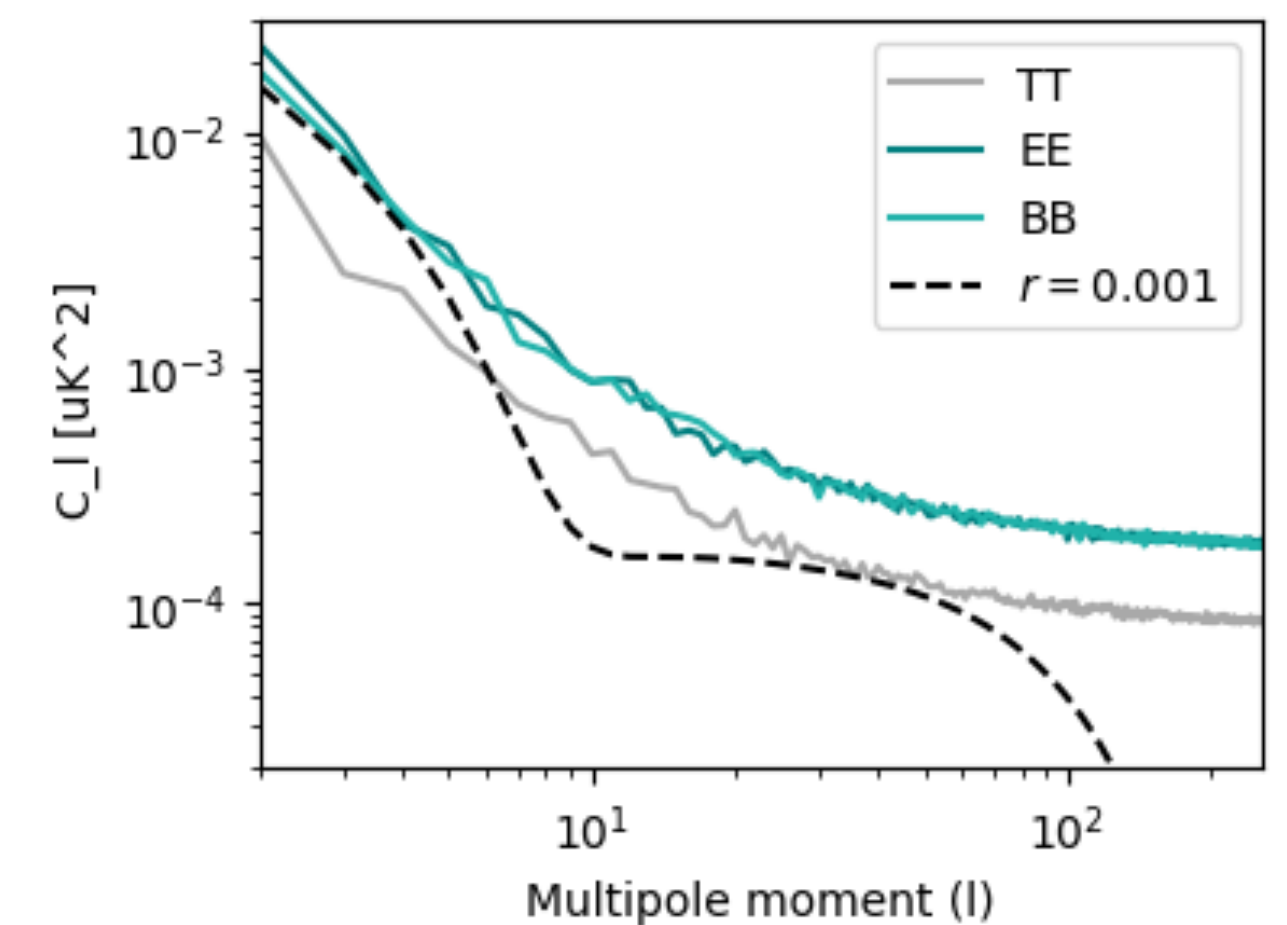
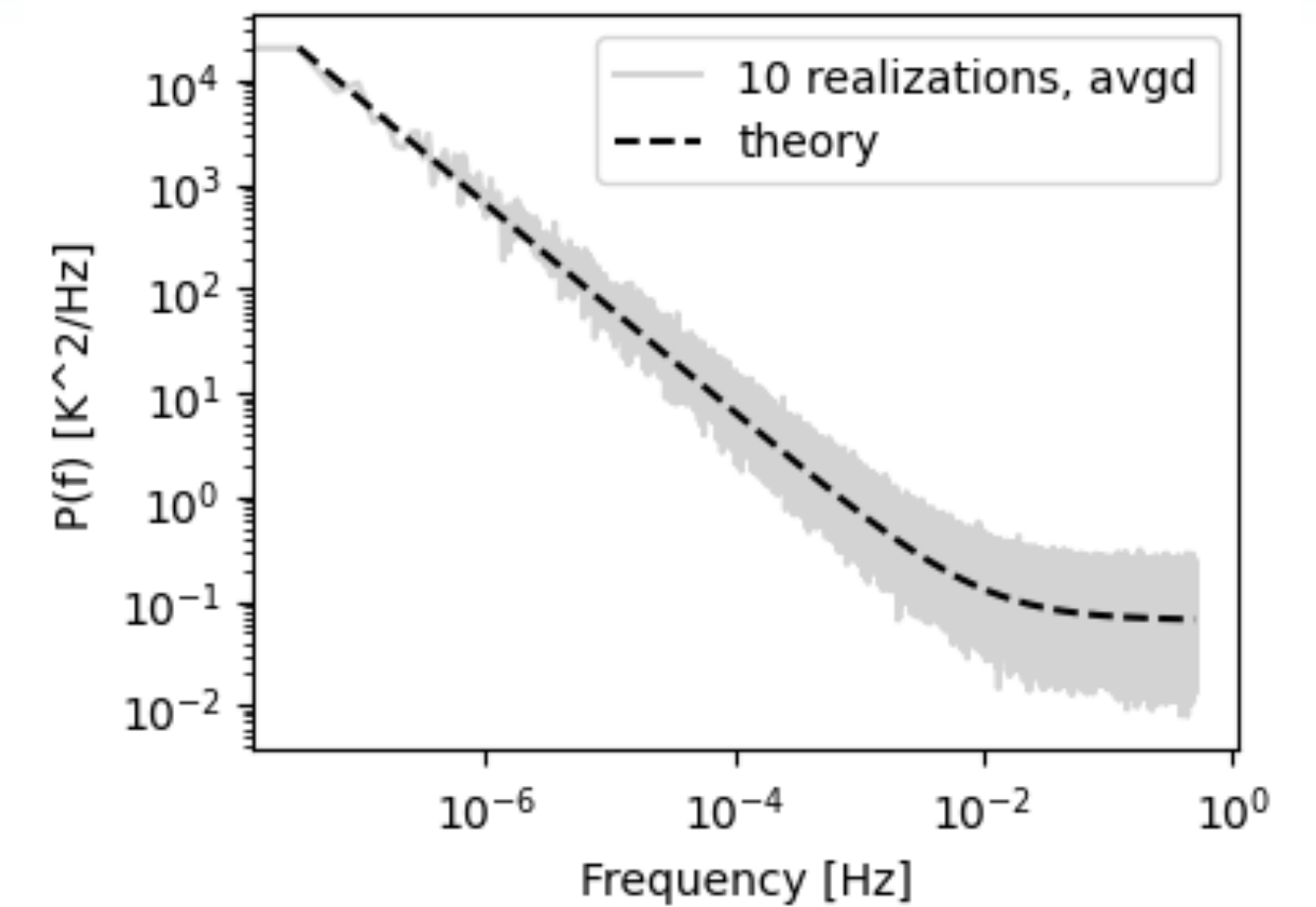


What we actually measure: the TOD

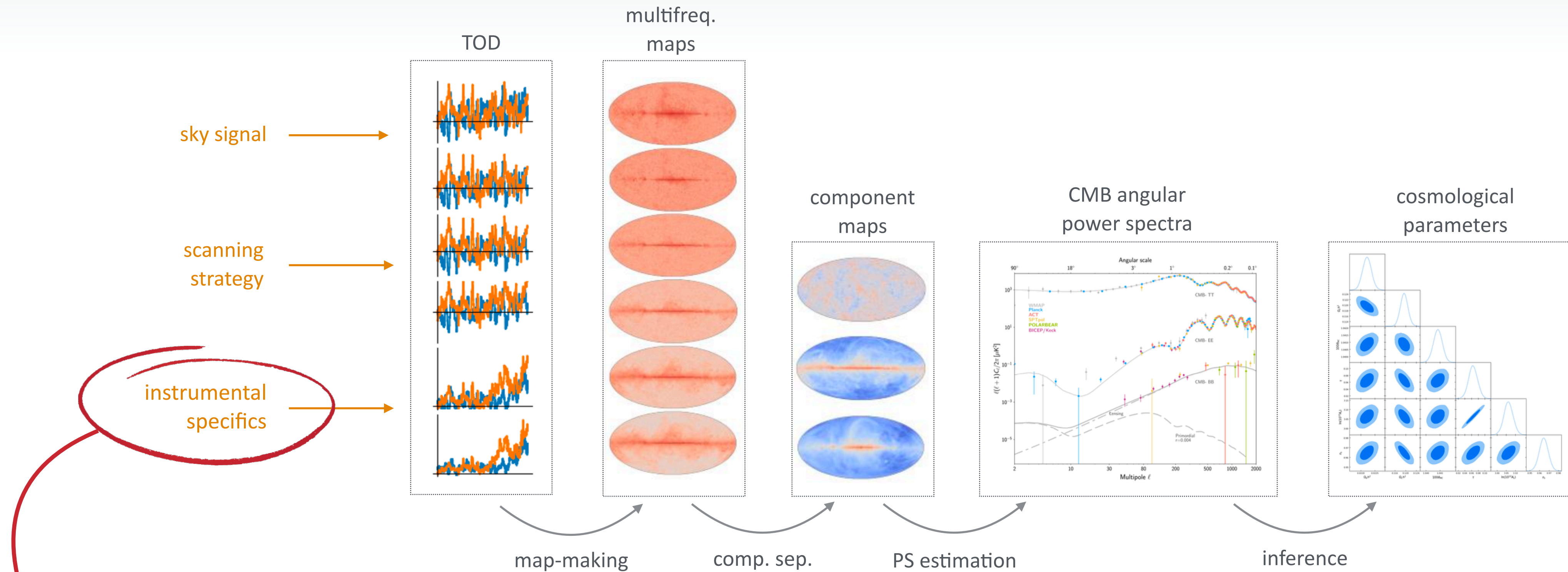


$$P(f) \propto 1 + \left(\frac{f_{knee}}{f} \right)^\alpha$$

$$N_\ell \propto 1 + \left(\frac{\ell_{knee}}{\ell} \right)^\alpha$$

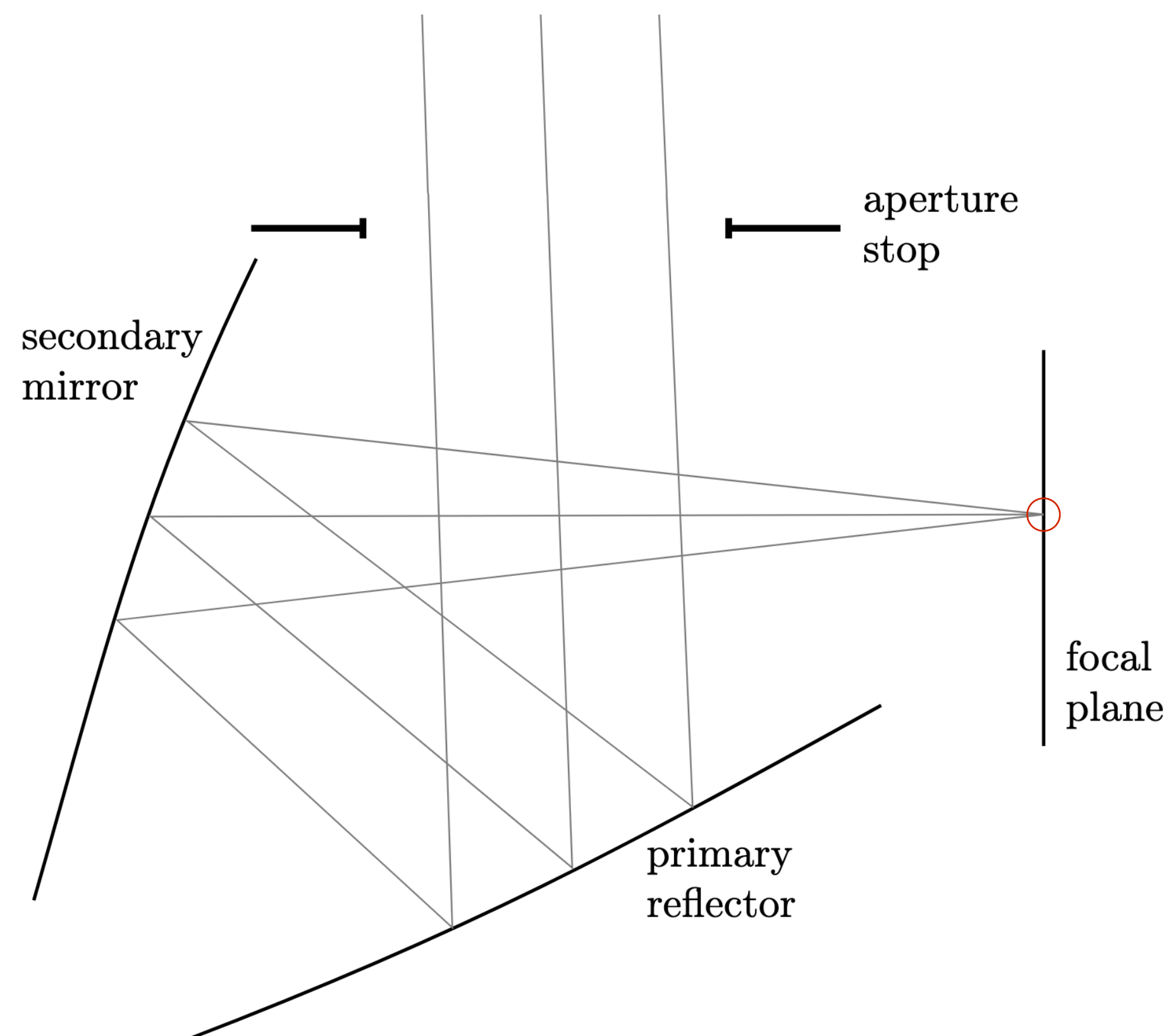


From data to fundamental physics



They will **inevitably** affect the data!
We need to take care of them at the
hardware and/or software level.

Building blocks of a CMB instrument

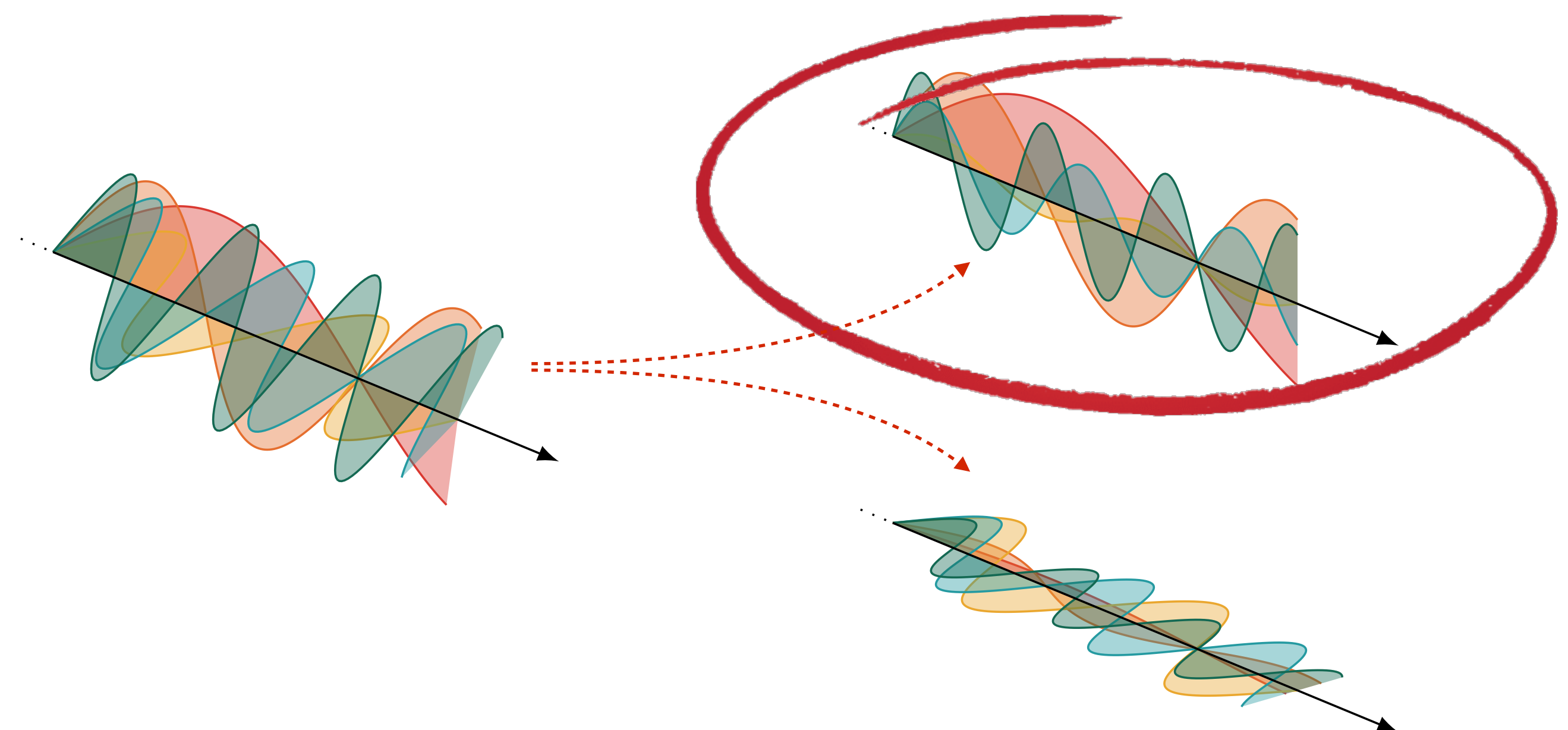


- **Optics**

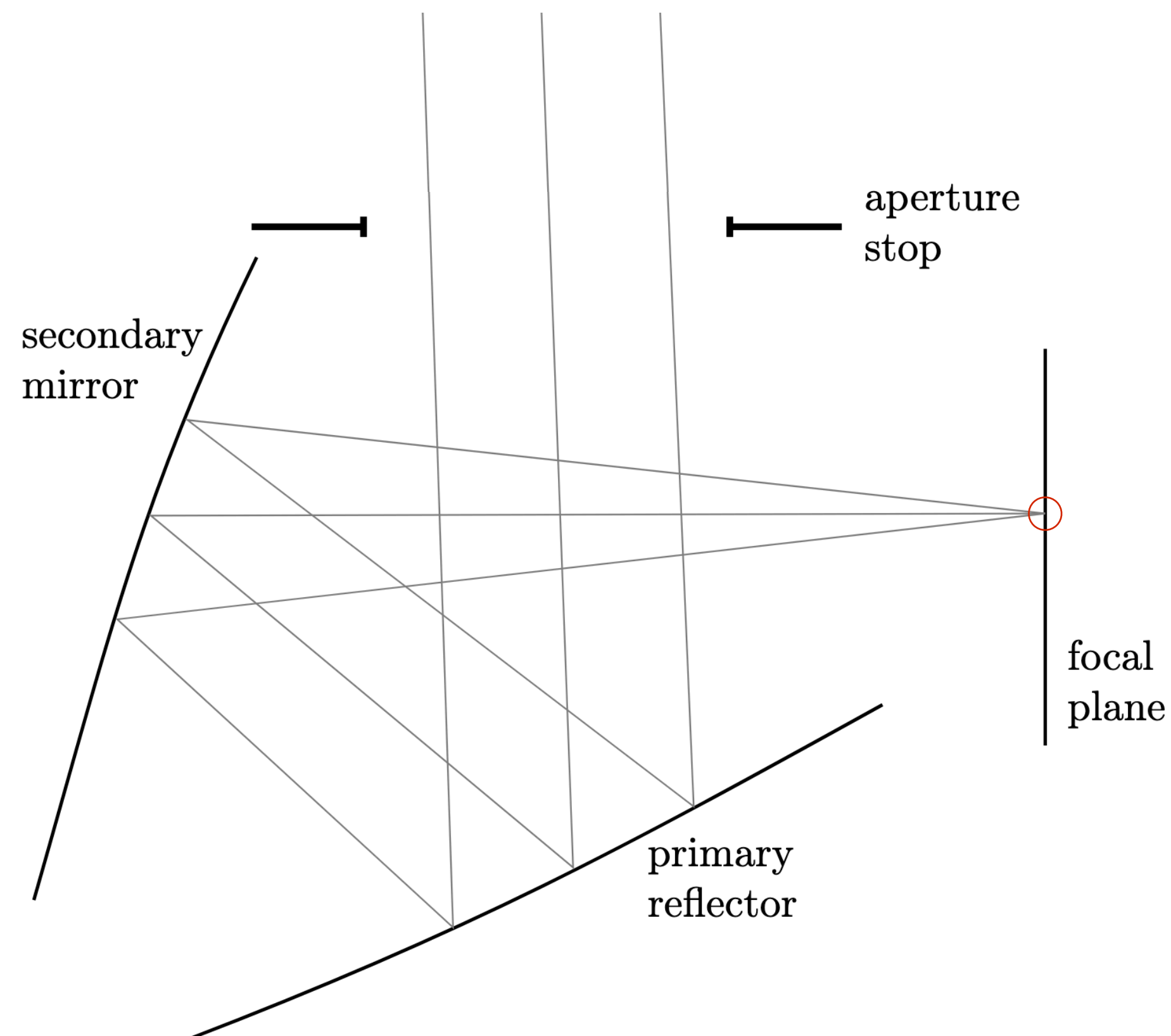
Focus incoming light on the focal plane.

- **Antenna**

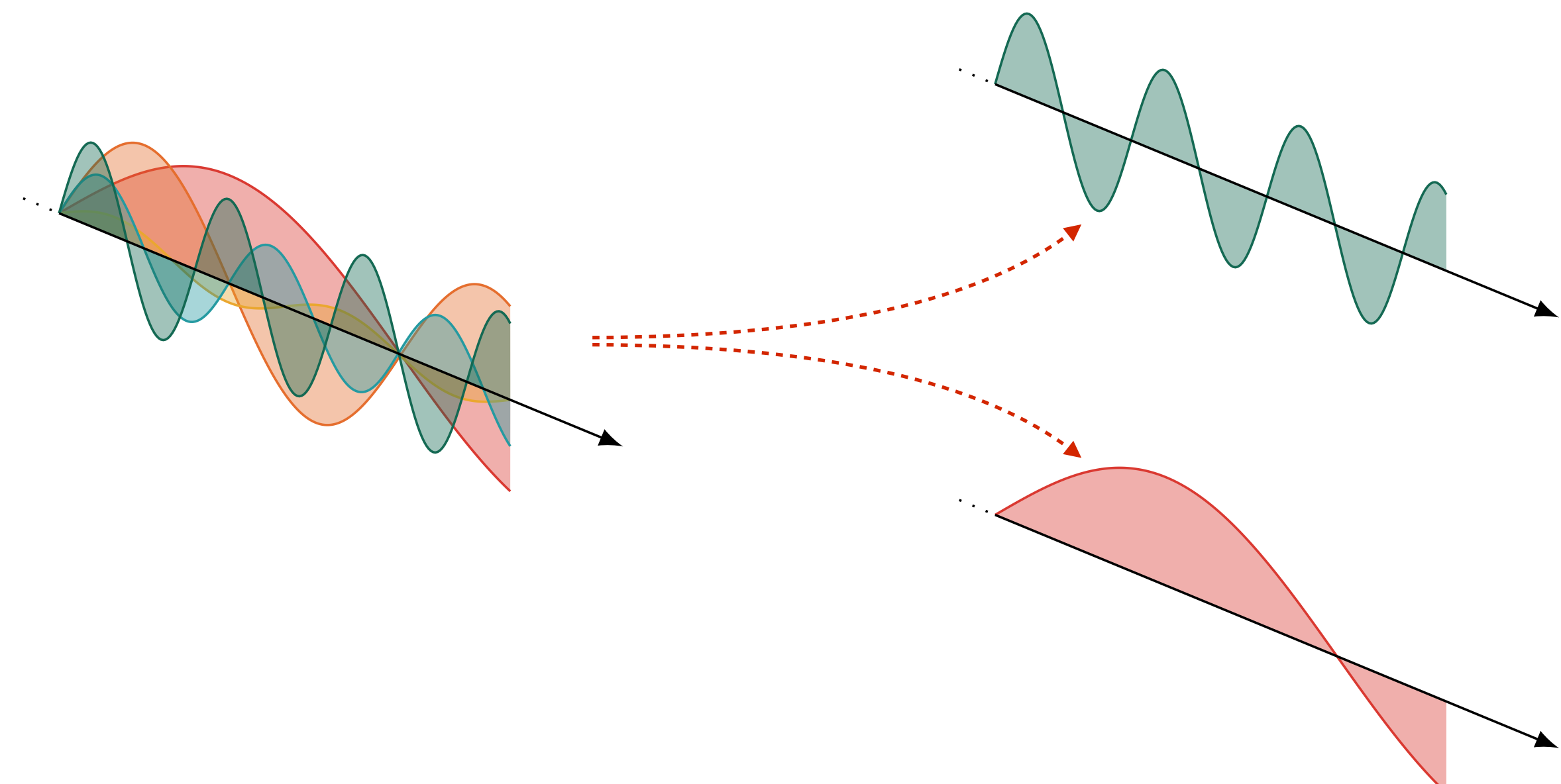
Separate signal into two orthogonal linear polarizations.



Building blocks of a CMB instrument



- **Optics**
Focus incoming light on the focal plane.
- **Antenna**
Separate signal into two orthogonal linear polarizations.
- **Band-pass filters**
Split signal into two (or three) frequency bands.



Building blocks of a CMB instrument

- **Optics**

Focus incoming light on the focal plane.

- **Antenna**

Separate signal into two orthogonal linear polarizations.

- **Band-pass filters**

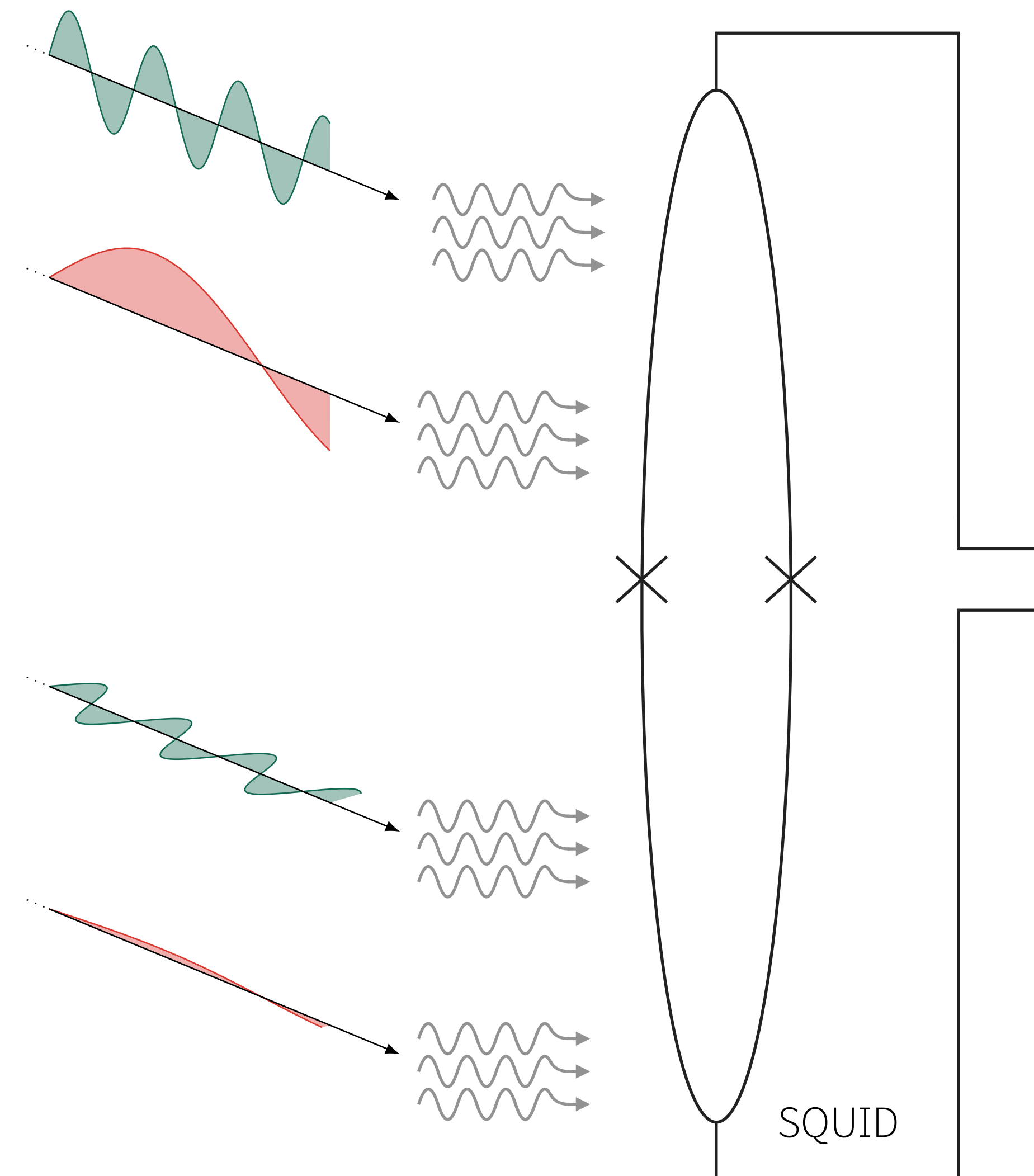
Split signal into two (or three) frequency bands.

- **Detectors (TES bolometers)**

Absorb EM radiation and convert it into electric signal.

- **SQUID array amplifier**

Receive signal from many pixels.



Building blocks of a CMB instrument

- **Optics**

Focus incoming light on the focal plane.

- **Antenna**

Separate signal into two orthogonal linear polarizations.

- **Band-pass filters**

Split signal into two (or three) frequency bands.

- **Detectors (TES bolometers)**

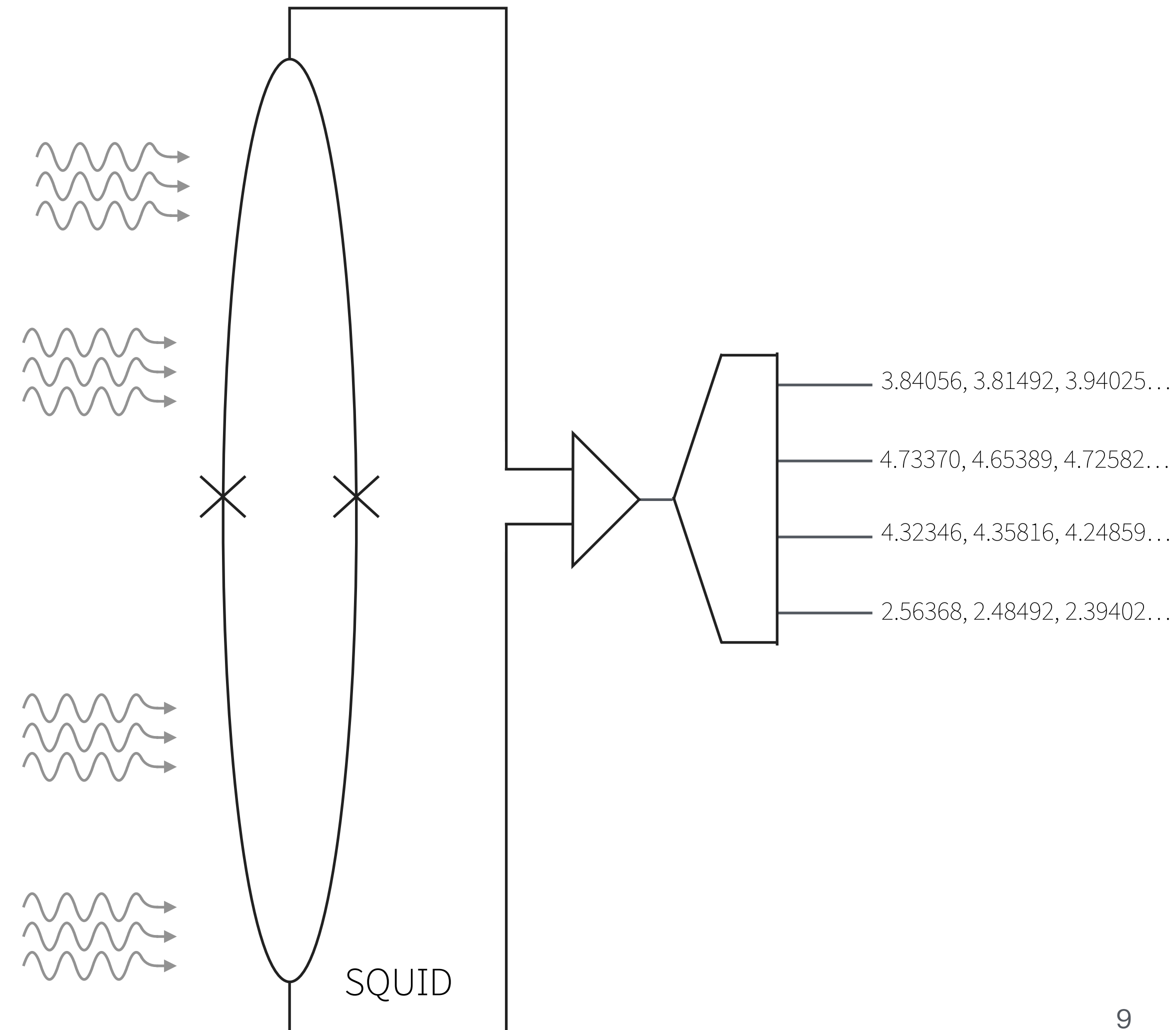
Absorb EM radiation and convert it into electric signal.

- **SQUID array amplifier**

Receive signal from many pixels.

- **Warm electronics**

Further amplify the signal and digitally demodulate it.



Modeling the TOD

- Optics
- Antenna
- Band-pass filters
- Detectors (TES)
- SQUID array amplifier
- Warm electronics

$$d_i(t) = \int R_i(t - t') \left[\int H_i(t' - t'') \left[\int b_i(\nu) B_i(\nu, t'') \star (S(\nu) + D(t'') + M) d\nu + n_i(t'') + \dots \right] dt'' + n'_i(t') + \dots \right] dt' + \sum_j C_{ij} d_j + \dots$$

Things can go wrong in **many** places! We need robust mitigation strategies.

A simple example: pair-differencing syst

$$d_0 = (I + Q) \times g_0$$

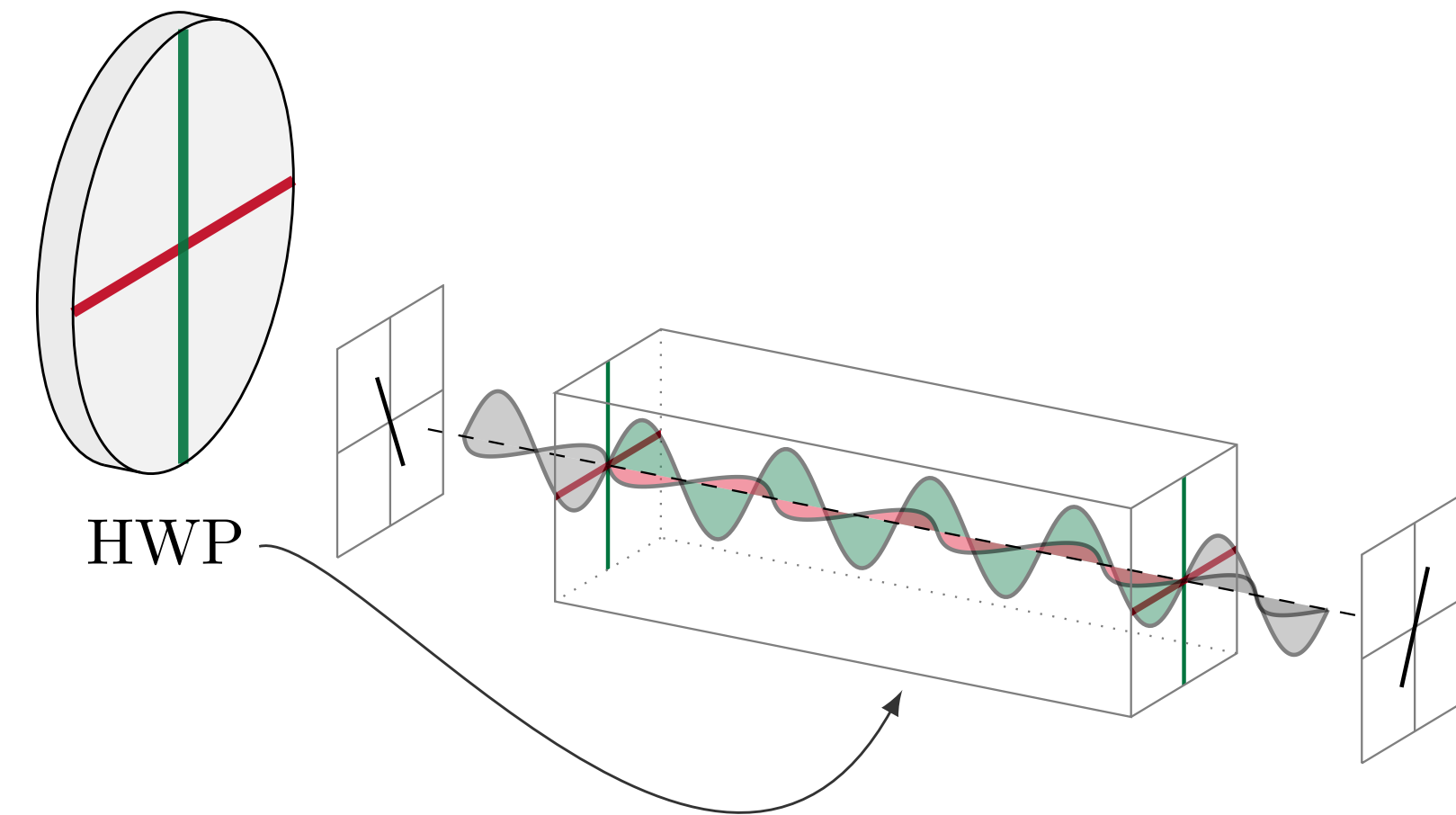
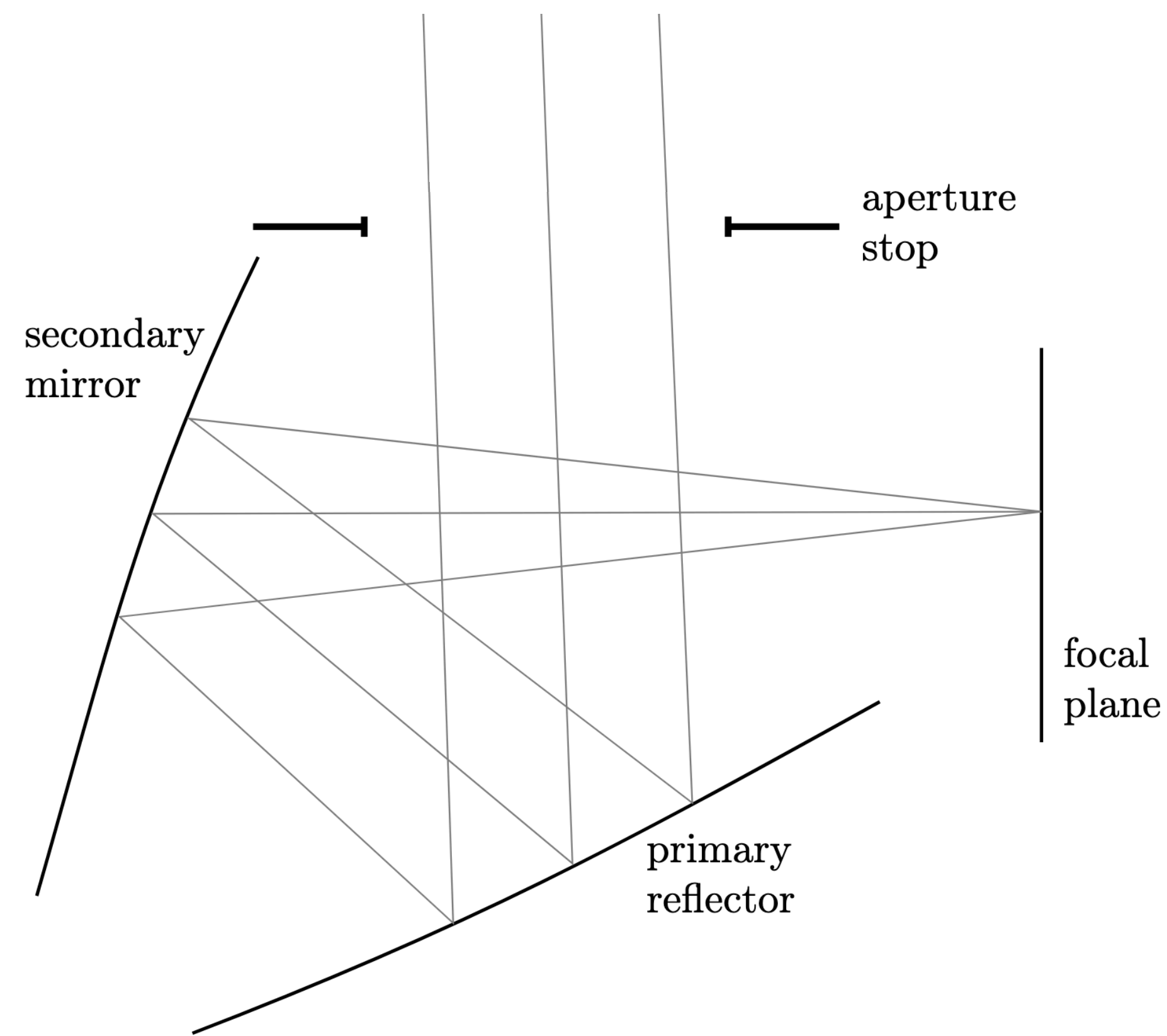
$$d_{90} = (I - Q) \times g_{90}$$

$$\hat{I} = \frac{d_0 + d_{90}}{2}$$

$$\hat{Q} = \frac{d_0 - d_{90}}{2} = \frac{(g_0 - g_{90})I + (g_0 + g_{90})Q}{2}$$

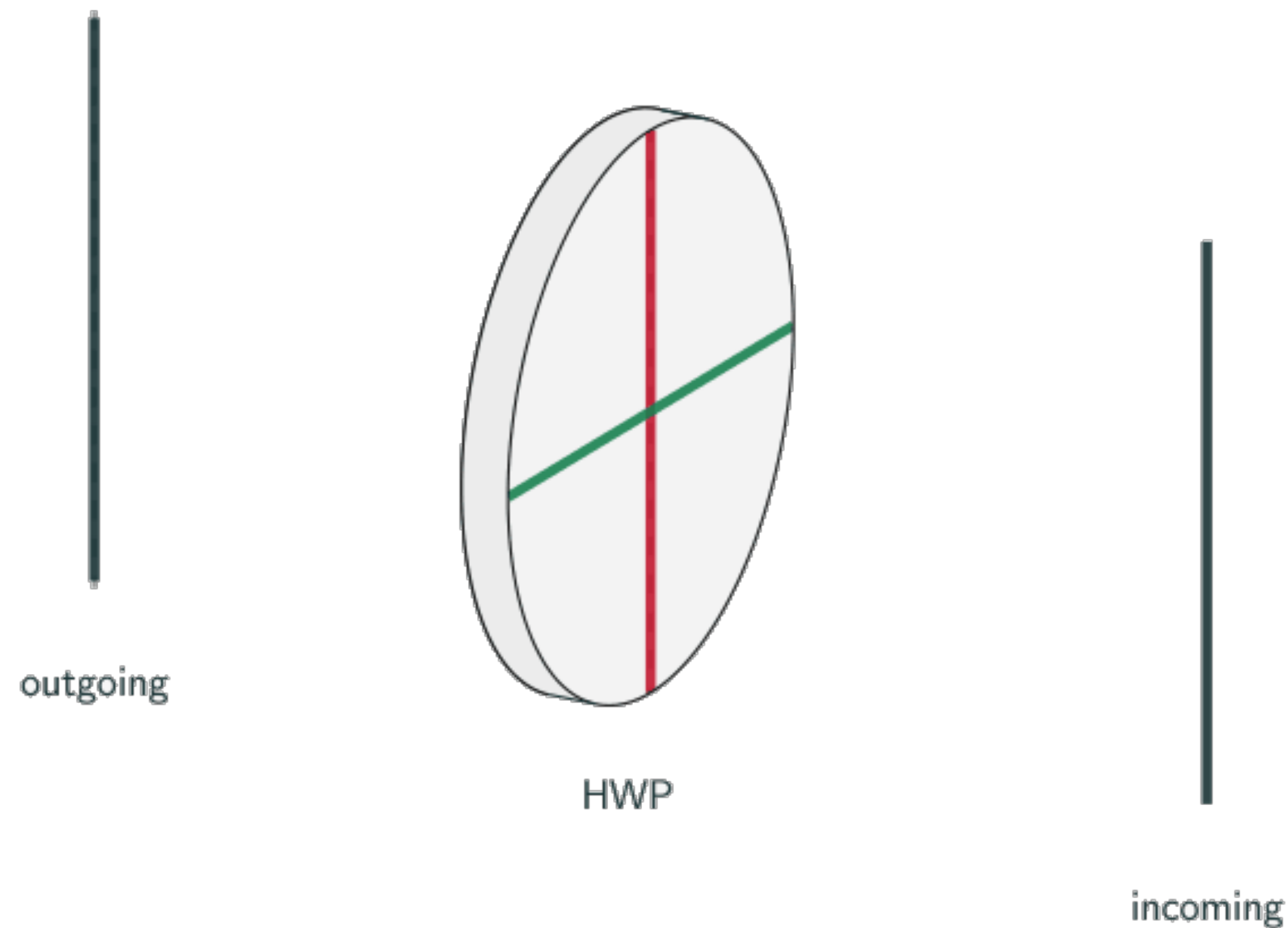
When pair-differencing, any uncontrolled mismatch (bandpasses, beams, gain, ...) in the detector pair will result in **intensity-to-polarization leakage**.

Mitigating systematics at the hardware level



A rotating half-wave plate (HWP) as **first optical element** can help control systematic effects!

HWPs: pros...



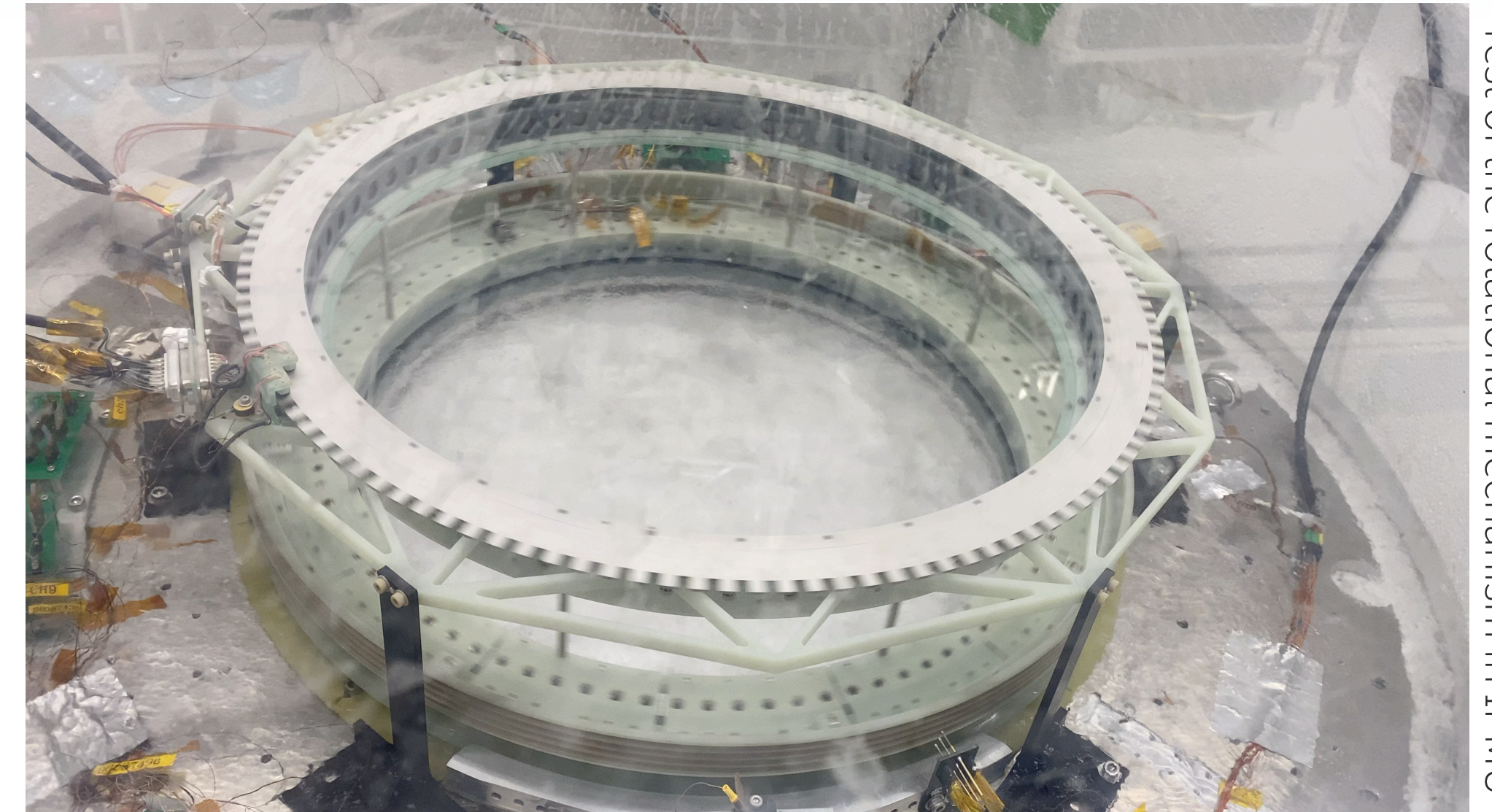
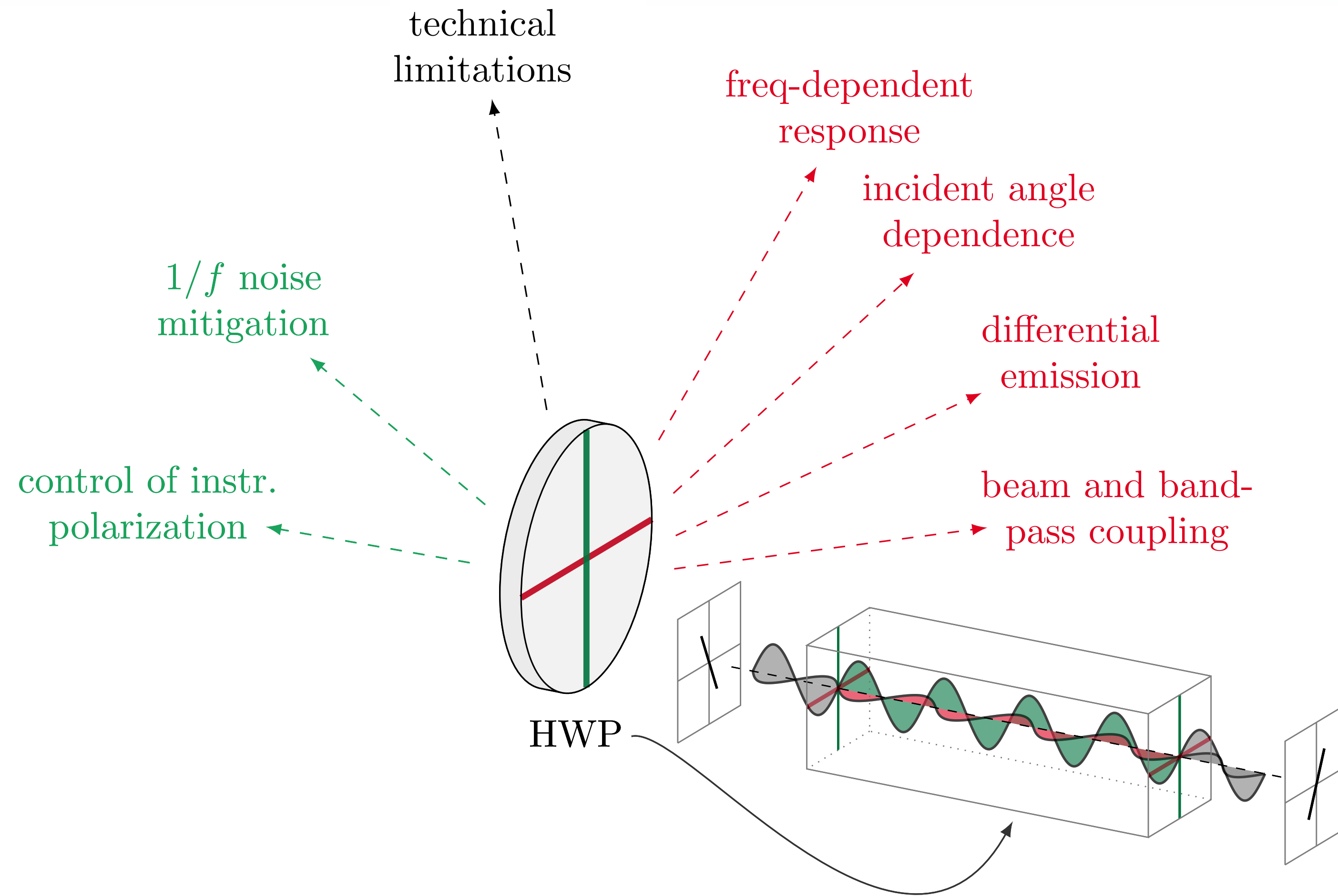
A rotating HWP modulates the polarized signal at **4 times its rotation frequency!**

If the rotation frequency is high enough:

- We effectively “escape” $1/f$ noise,
- A single detector can solve polarization.

Mitigation of systematic effects!

HWPs: and cons

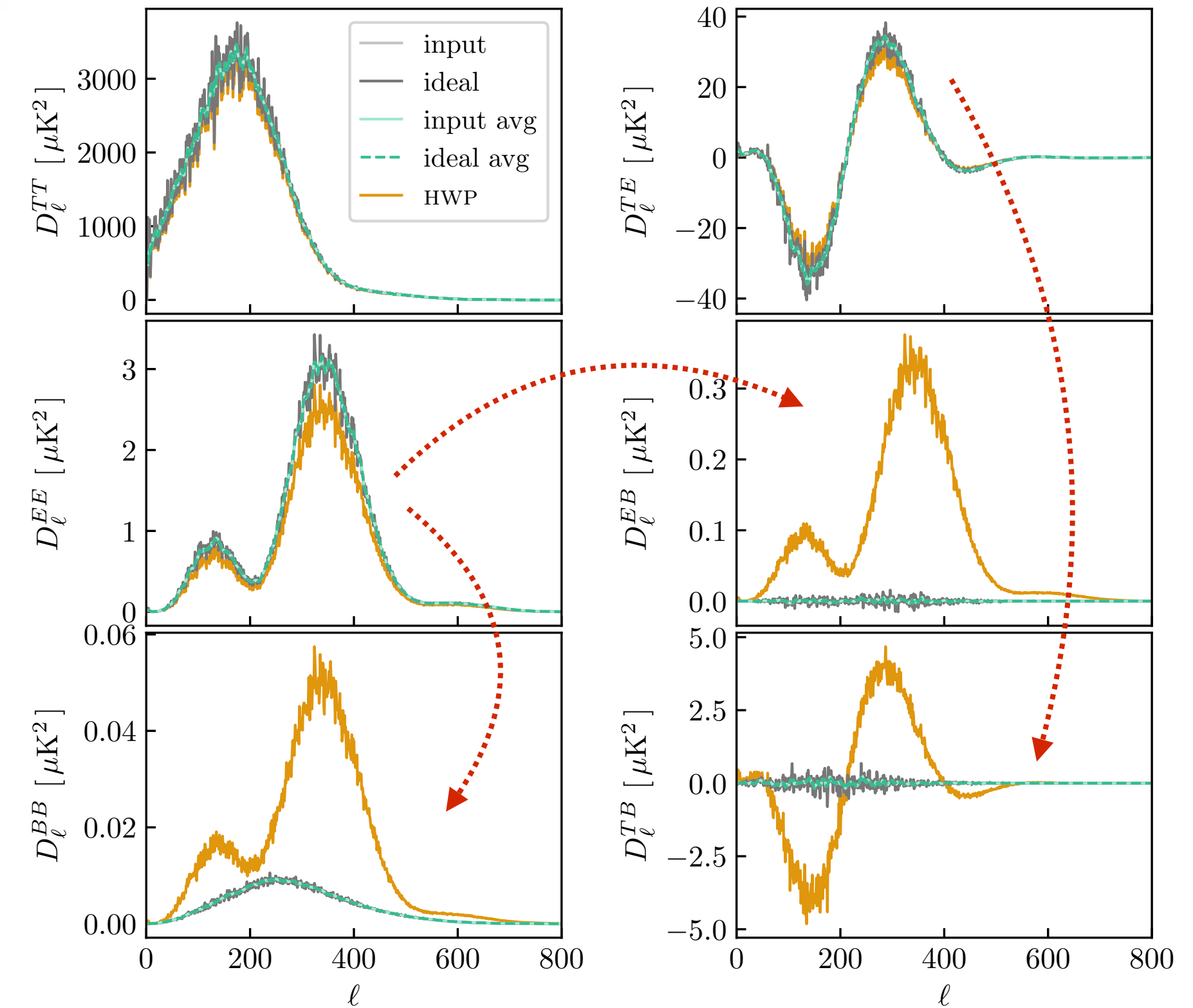
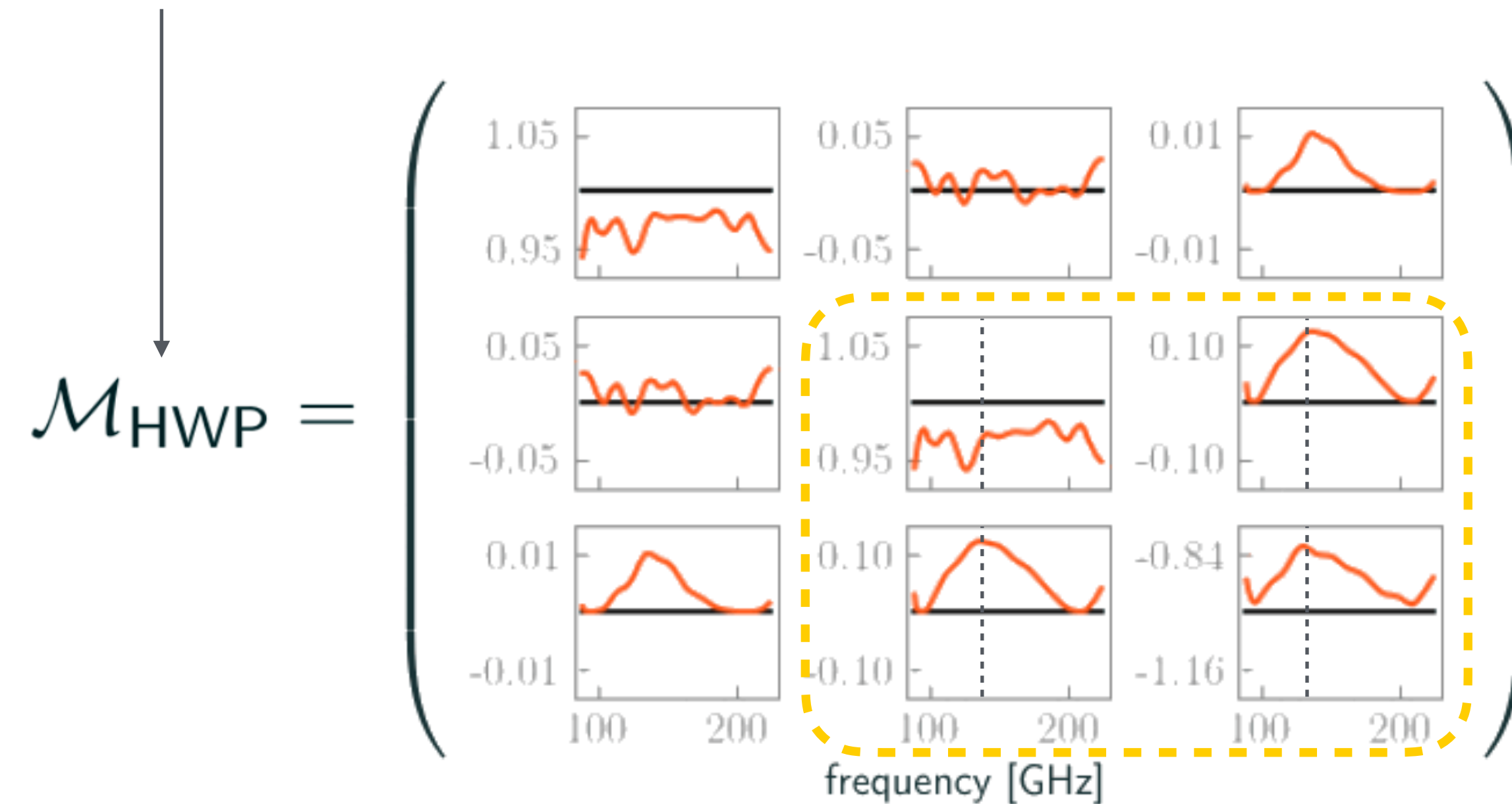


Test of the rotational mechanism in IPMU

Trade-off studies are needed!

HWP non-idealities: single frequency

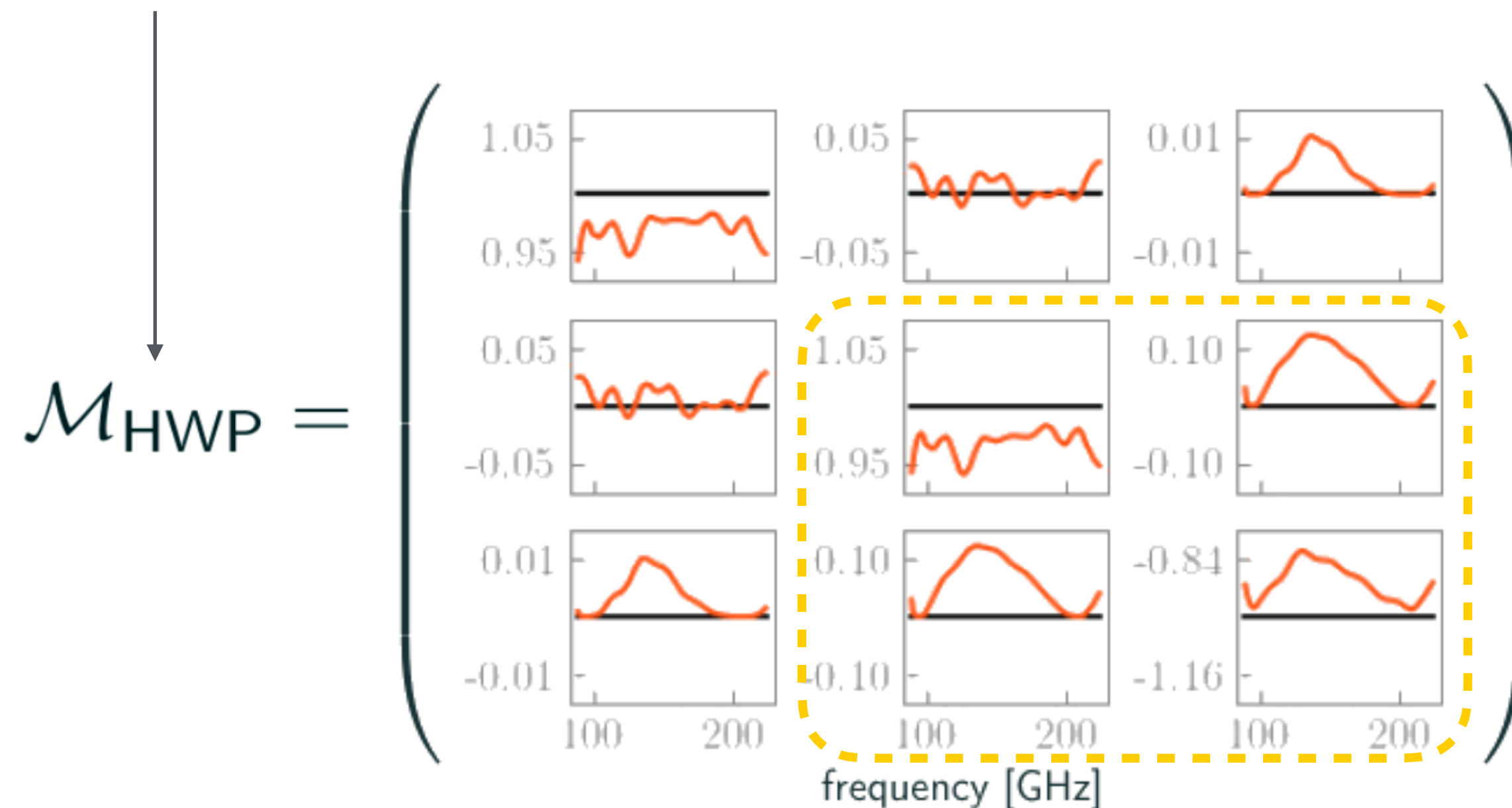
The effect of the HWP can be encoded in a **Mueller matrix** (acting on Stokes vectors)



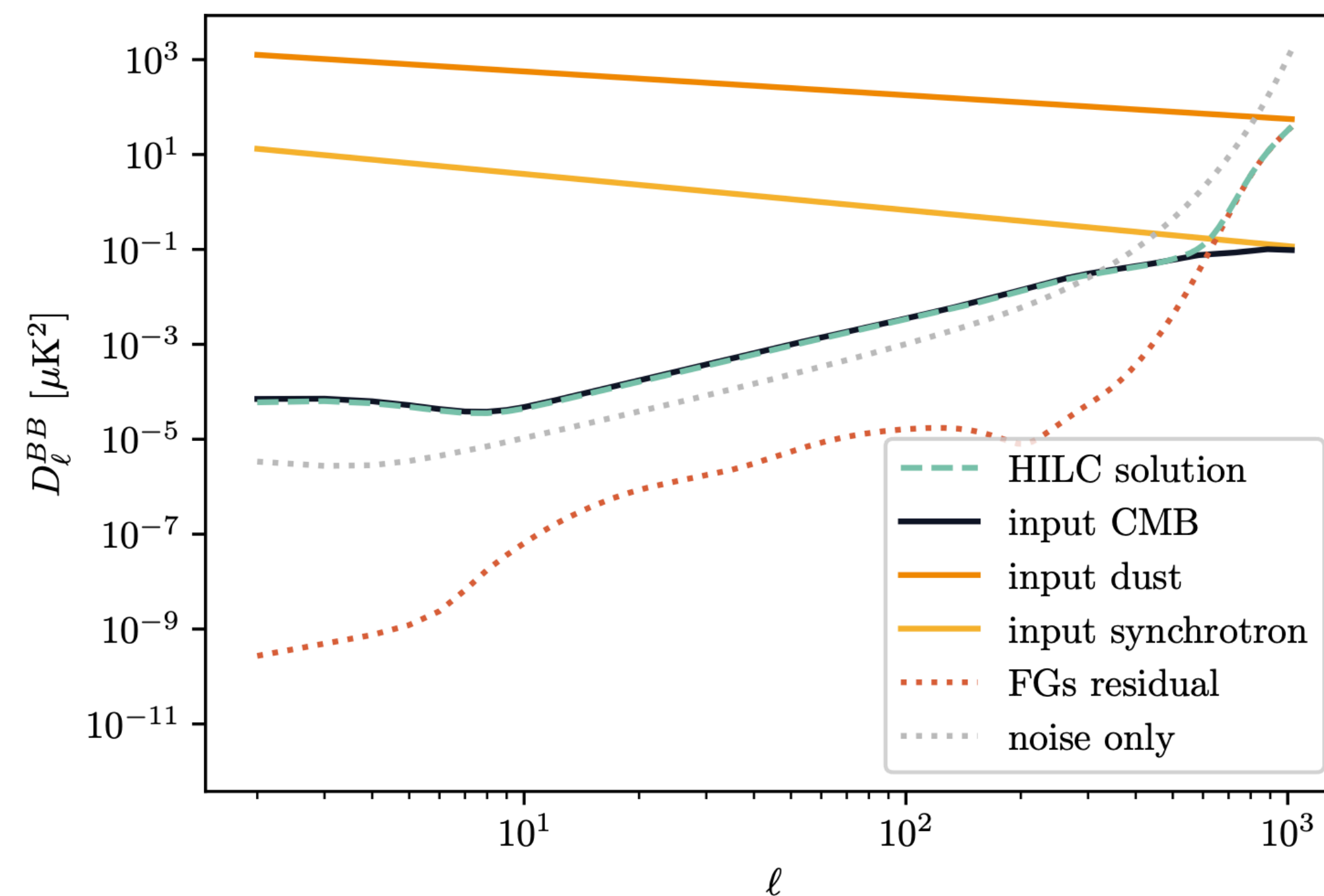
Effective miscalibration of $\theta \simeq 3.8^\circ$
degenerate with cosmic birefringence

HWP non-idealities: multifrequency

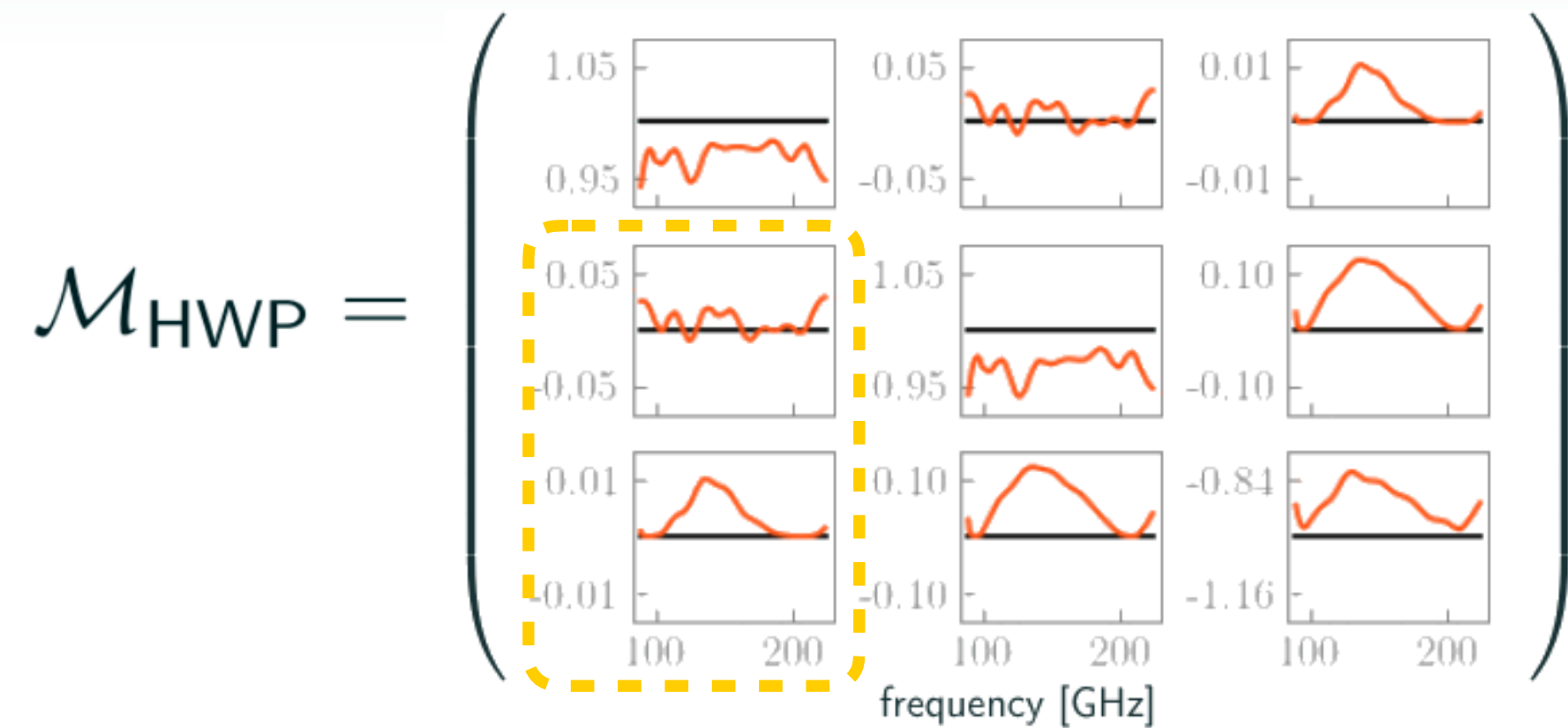
The effect of the HWP can be encoded in a **Mueller matrix** (acting on Stokes vectors)



Crucial to study the **interplay** of systematic effects and data analysis!

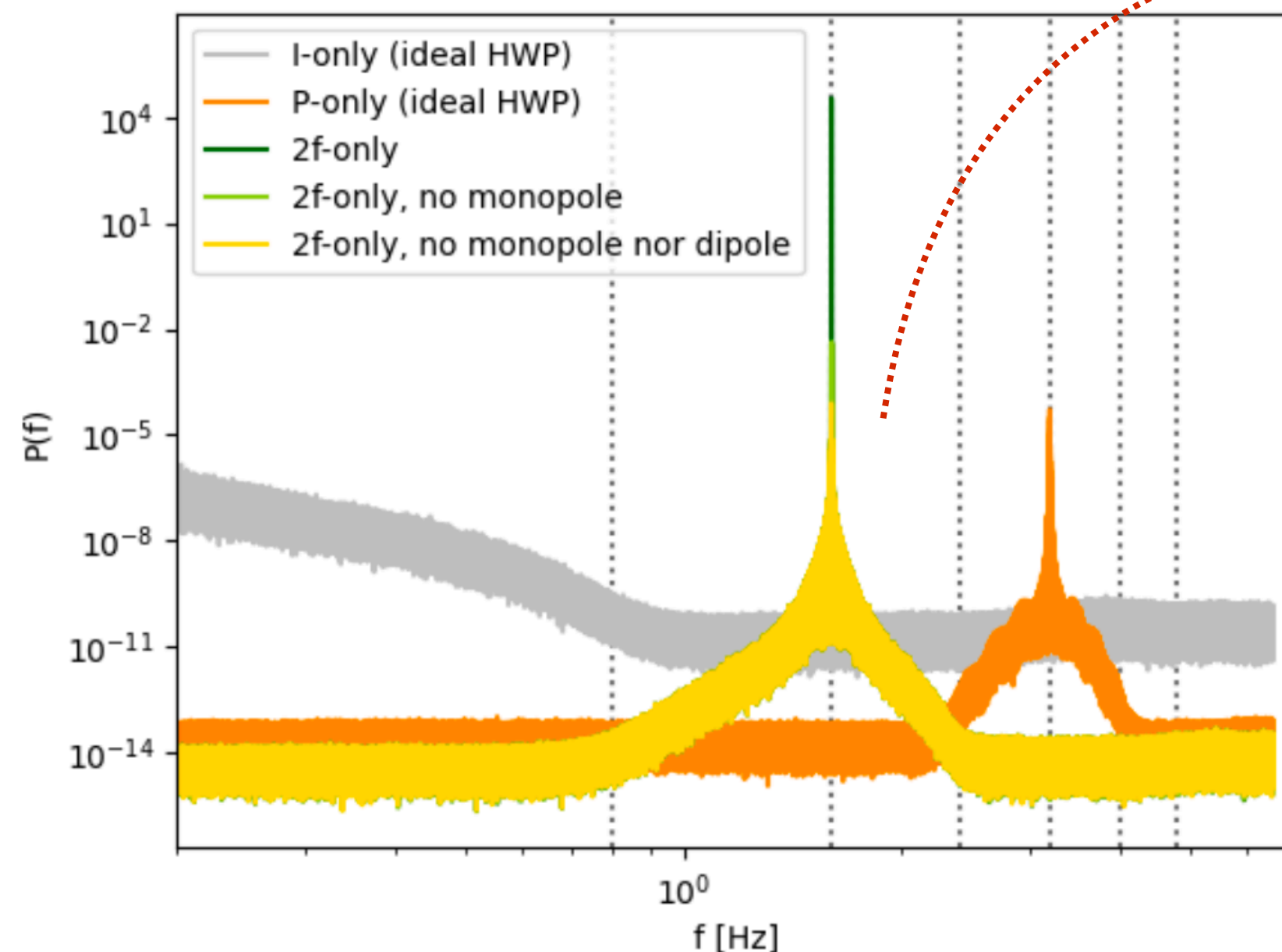


HWP rotation speed



- Instrumentalists: “The **slower** the better!”
- Theorists: “The **faster** the better!”

For 0.8 Hz, the 2f peak is far from the science band.
Still, **monopole and dipole leak** to polarization!



Ongoing work:

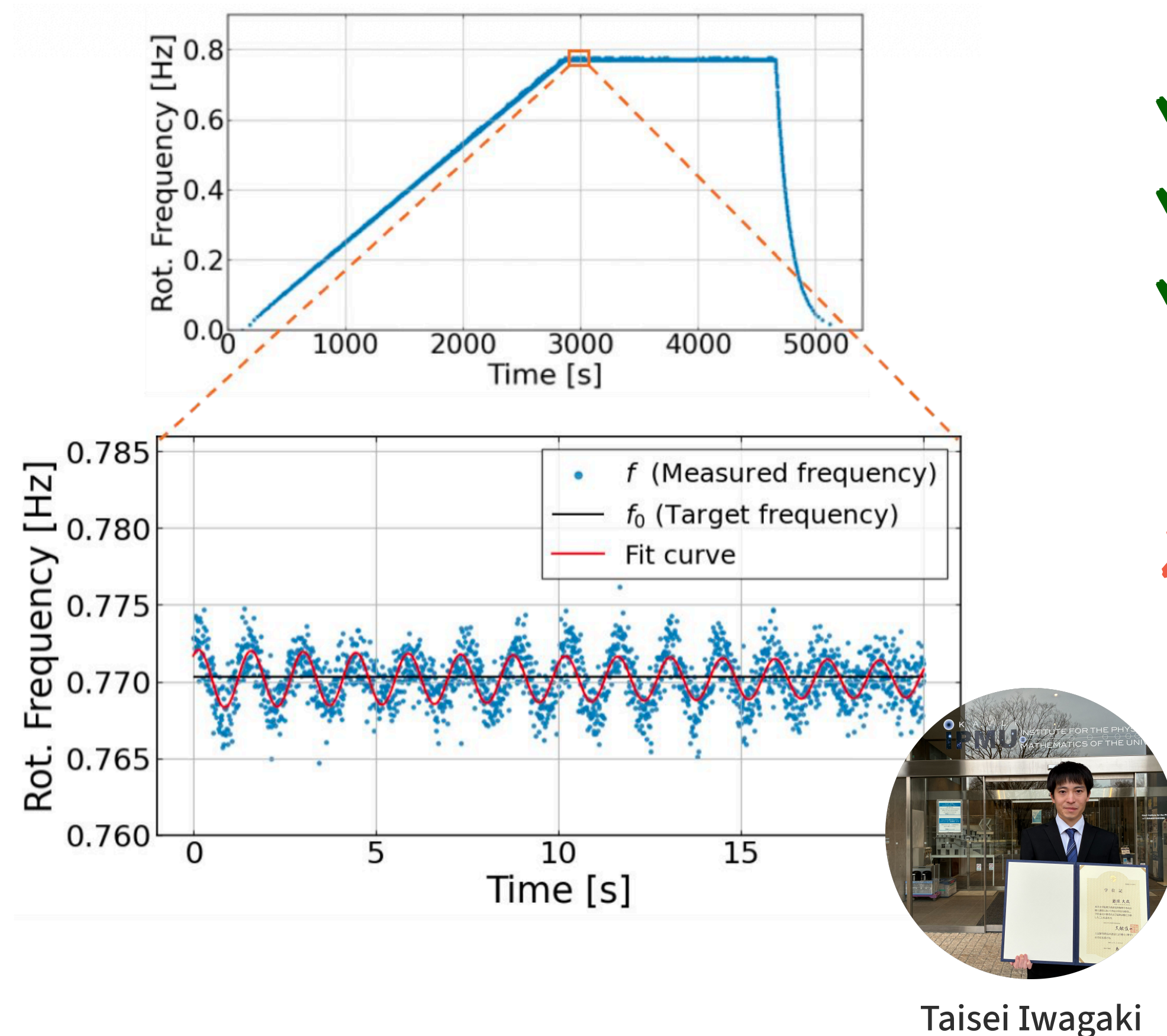
Quantify I-P leakage for realistic HWP

Derive requirements

Implement notch filtering and fitting to mitigate

Generalize study (additive effects, NLs, 1/f, ...)

Time-dependent HWP rotation frequency



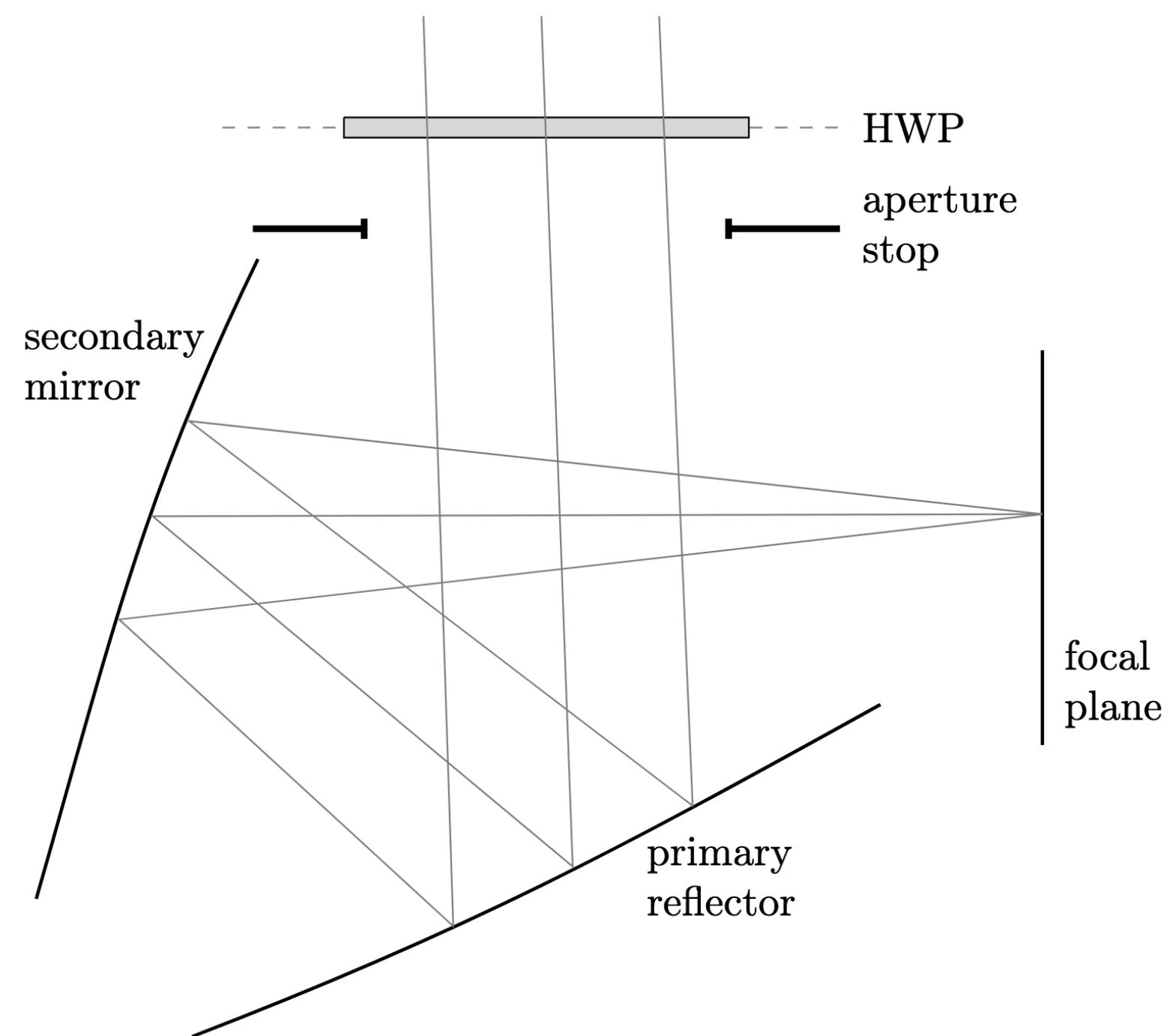
- ✓ Implement the wobbling in `litebird_sim`.
- ✓ Propagate the effect to the observed maps.
- ✓ Check the impact on the observed power spectrum:
 - Loss in polarization efficiency,
 - Small miscalibration of the polarization angle.
- ✗ Check the impact **after component separation**.



Shoken Myozen

Ongoing work: upstream polarization w/ HWP

$$d_i(t) = \int R_i(t' - t'') \left[\int H_i(t' - t'') \left[\int b_i(\nu) B_i(\nu, t'') \star (S(\nu) + D(t'') + M) d\nu + n_i(t'') + \dots \right] dt'' + n'_i(t') + \dots \right] dt' + \sum_j C_{ij} d_j + \dots$$

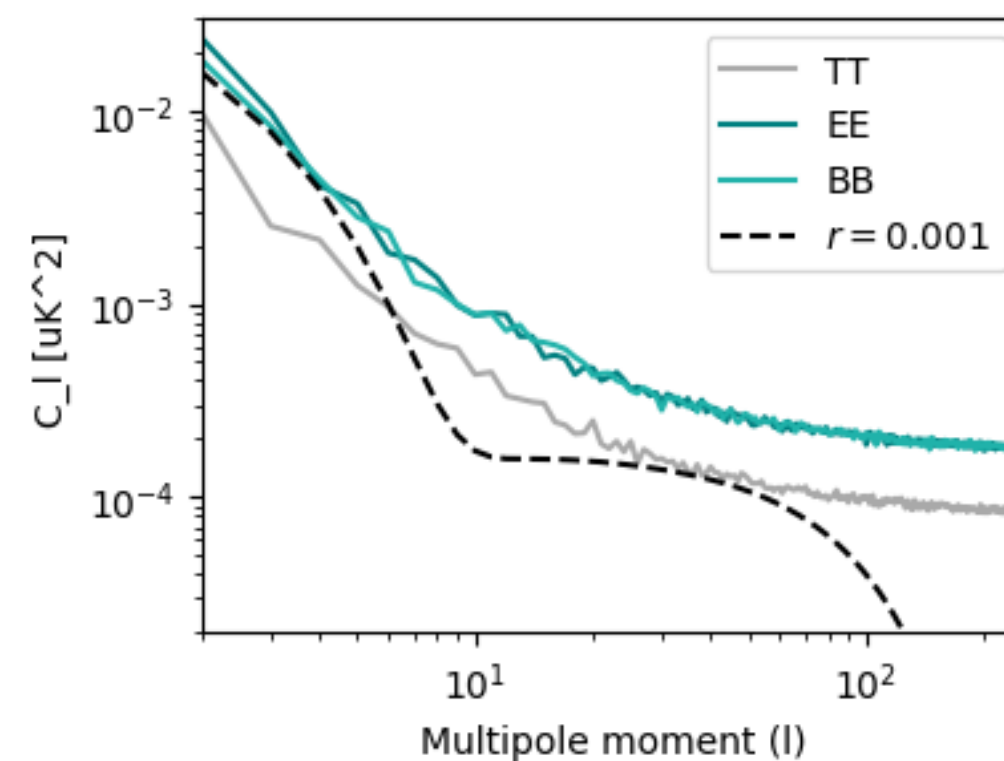
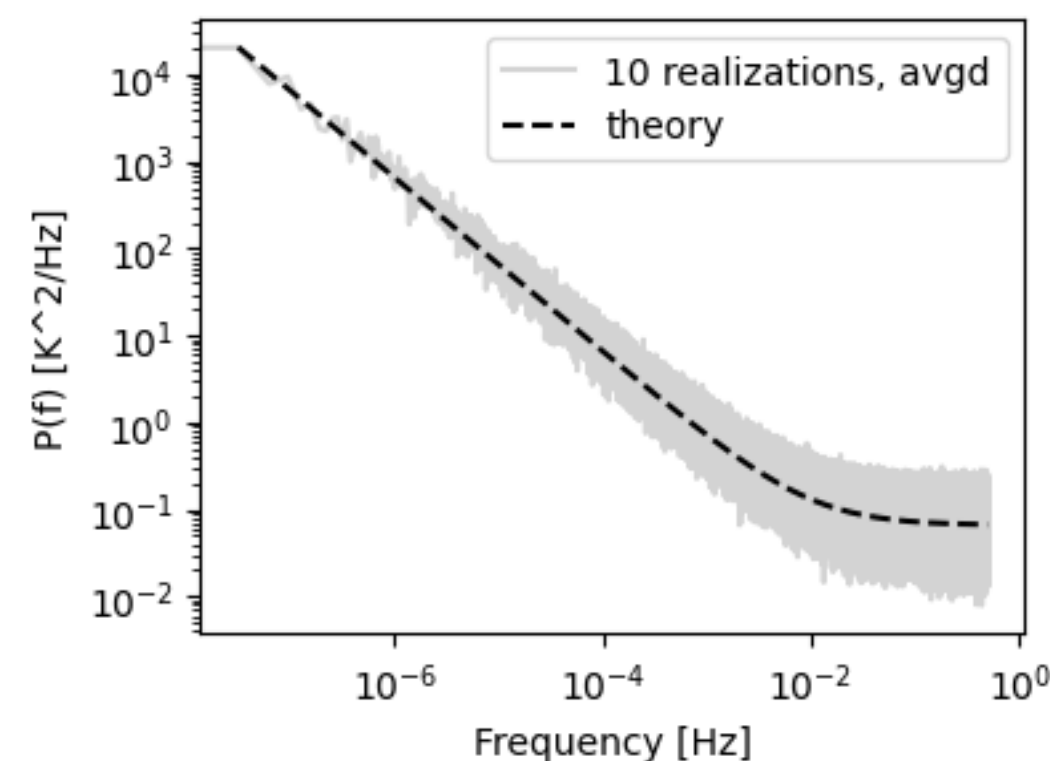


- The HWP can be modeled in the beam.
- Current beam convolution codes assume the HWP to be the first element of the optical chain.
- However, the HWP is “sandwiched” between optical elements.

Upstream optical elements, (forebaffle, V-grooves) introduce spurious polarization, which is modulated by the HWP and therefore detected. *We need new tools to simulate this effect!*

Mitigating $1/f$ noise at the software level

$$P(f) \propto 1 + \left(\frac{f_{knee}}{f}\right)^\alpha \longrightarrow N_\ell \propto 1 + \left(\frac{\ell_{knee}}{\ell}\right)^\alpha$$



GLS map-making “weights away” the noise, so it **doesn’t project** into the reconstructed maps.

$$\hat{\mathbf{m}} = \left(\hat{\mathbf{A}}^T \hat{\mathbf{N}}^{-1} \hat{\mathbf{A}} \right)^{-1} \hat{\mathbf{A}}^T \hat{\mathbf{N}}^{-1} \mathbf{d}$$

Inverting a realistic noise covariance matrix is however non trivial!

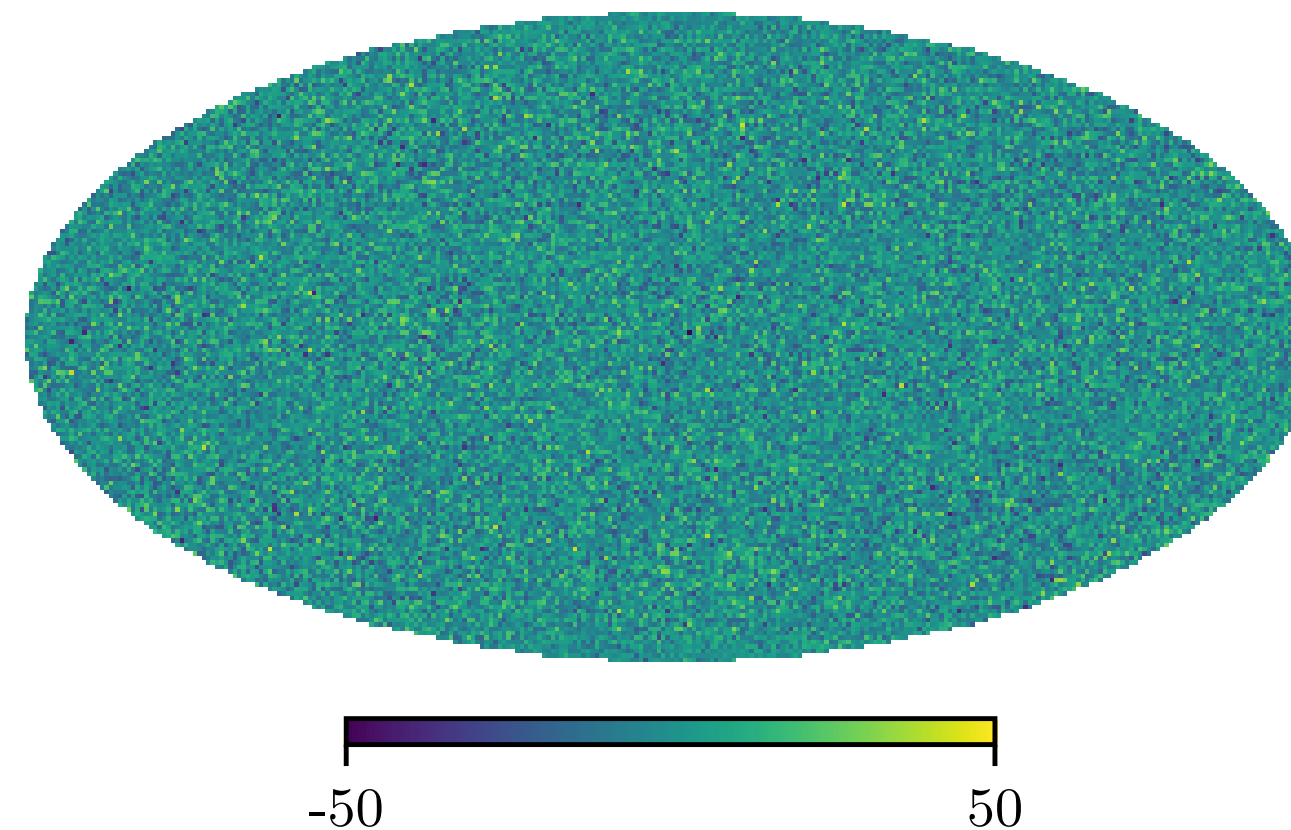
- Computational challenge (*see Avinash’s talk*)
- Making assumptions and working around them

Ongoing work: preprocessing w/ inpainting

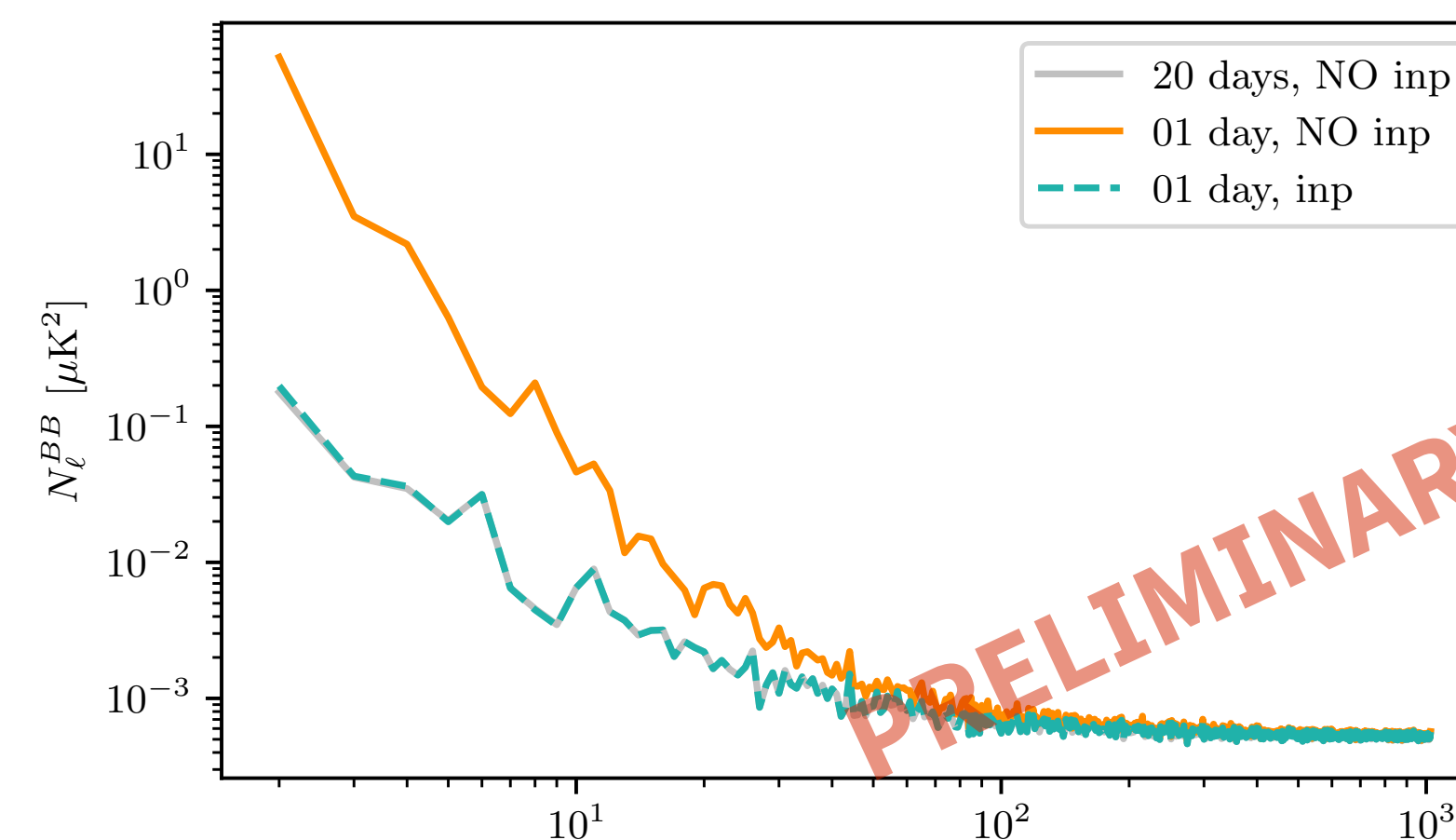
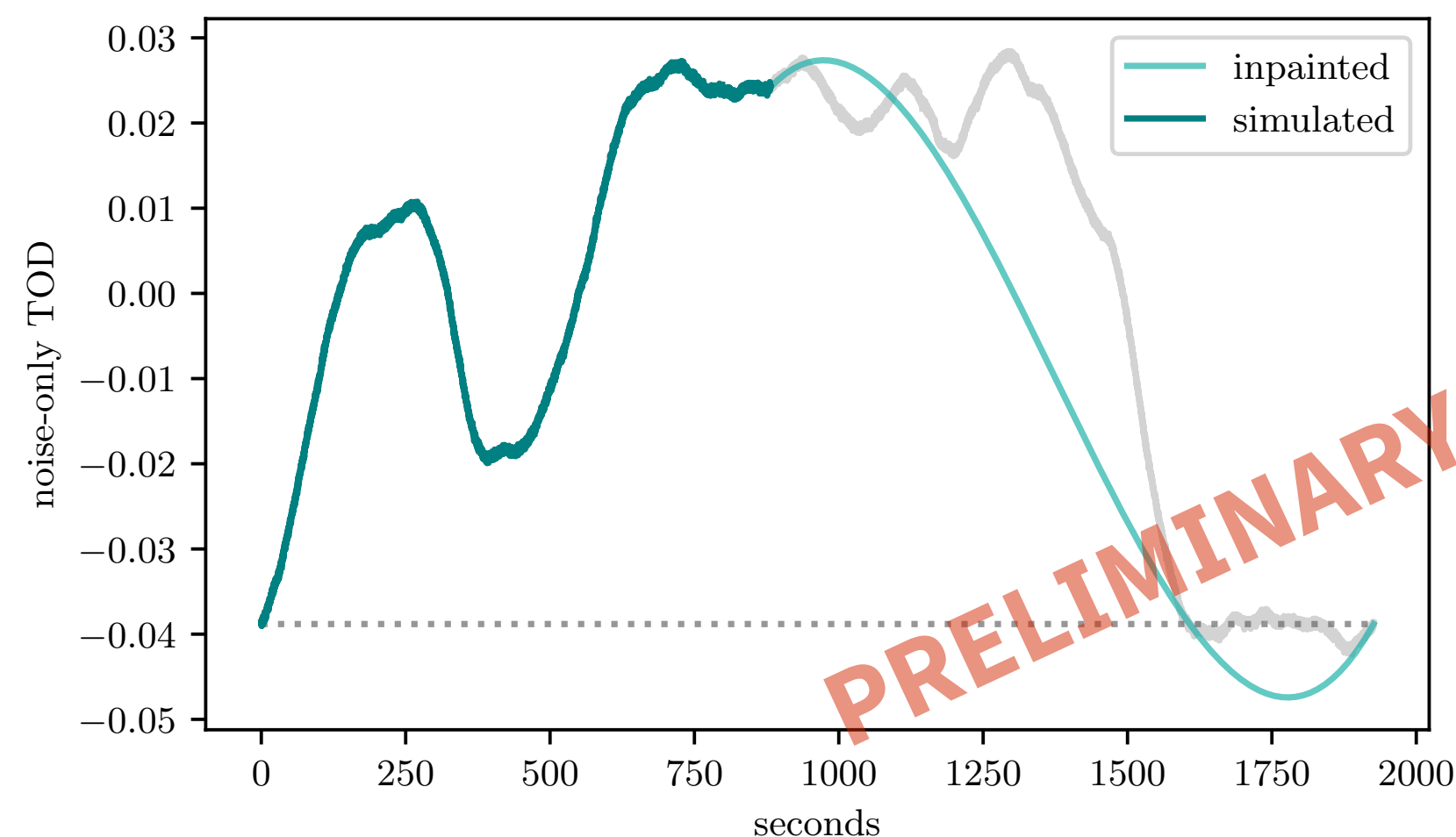
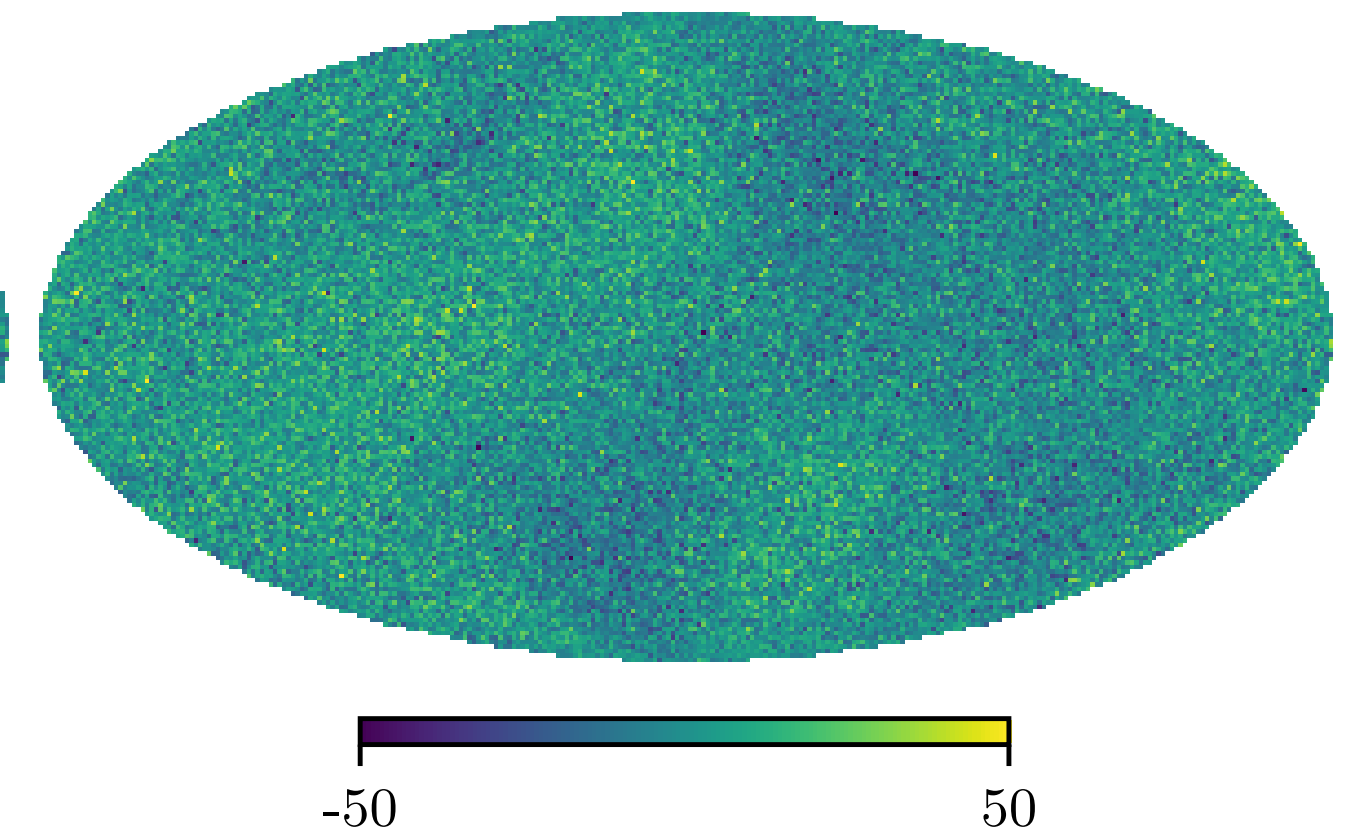
$$\hat{\mathbf{m}} = \left(\hat{\mathbf{A}}^T \hat{\mathbf{N}}^{-1} \hat{\mathbf{A}} \right)^{-1} \hat{\mathbf{A}}^T \hat{\mathbf{N}}^{-1} \mathbf{d}$$

Assuming the noise covariance matrix to be **circulant** makes it easy to invert.

Q from circulant noise chunks [μK]



Q from noise subchunks [μK]



To sum up

- **Instrumental systematic effects** represent a huge challenge for the community.
- We need to take care of them at the hardware or software level.
- At the hardware level, a **rotating HWP** can help.
- Still, this is technologically challenging and induces **additional systematics**.
- Crucial to develop realistic **simulation tools** and **mitigation strategies** to understand and control them.