Studying polarisation with KIDs detectors

Second year PhD seminar

Sofia Savorgnano - March 14, 2024

COSMO-ML team

NÉEL institut

LPSC GRENOBLE | MODANE

POLARISATION

What is it?

Which effects generate it?

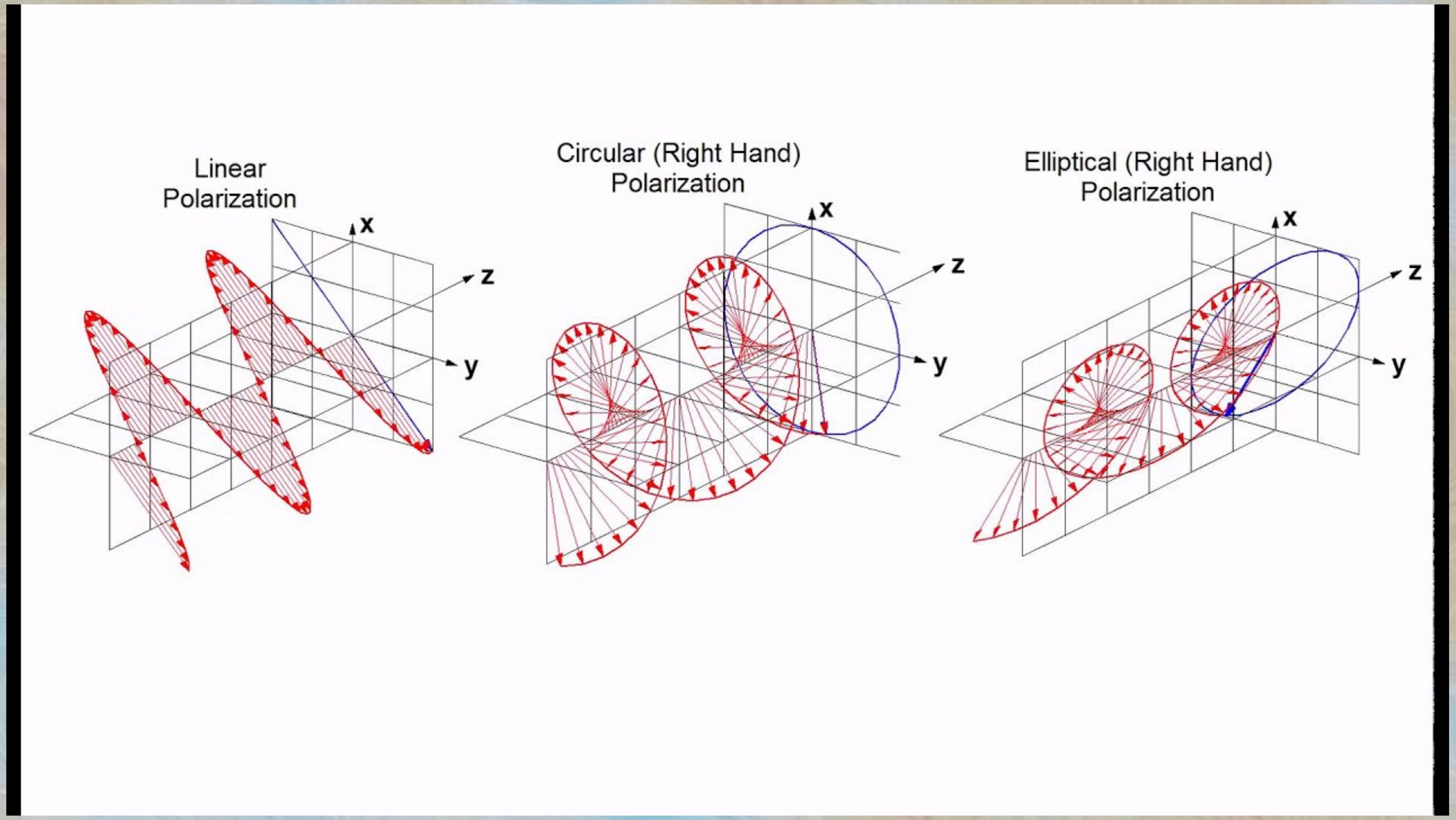
What kind of signal do I observe from the sky?

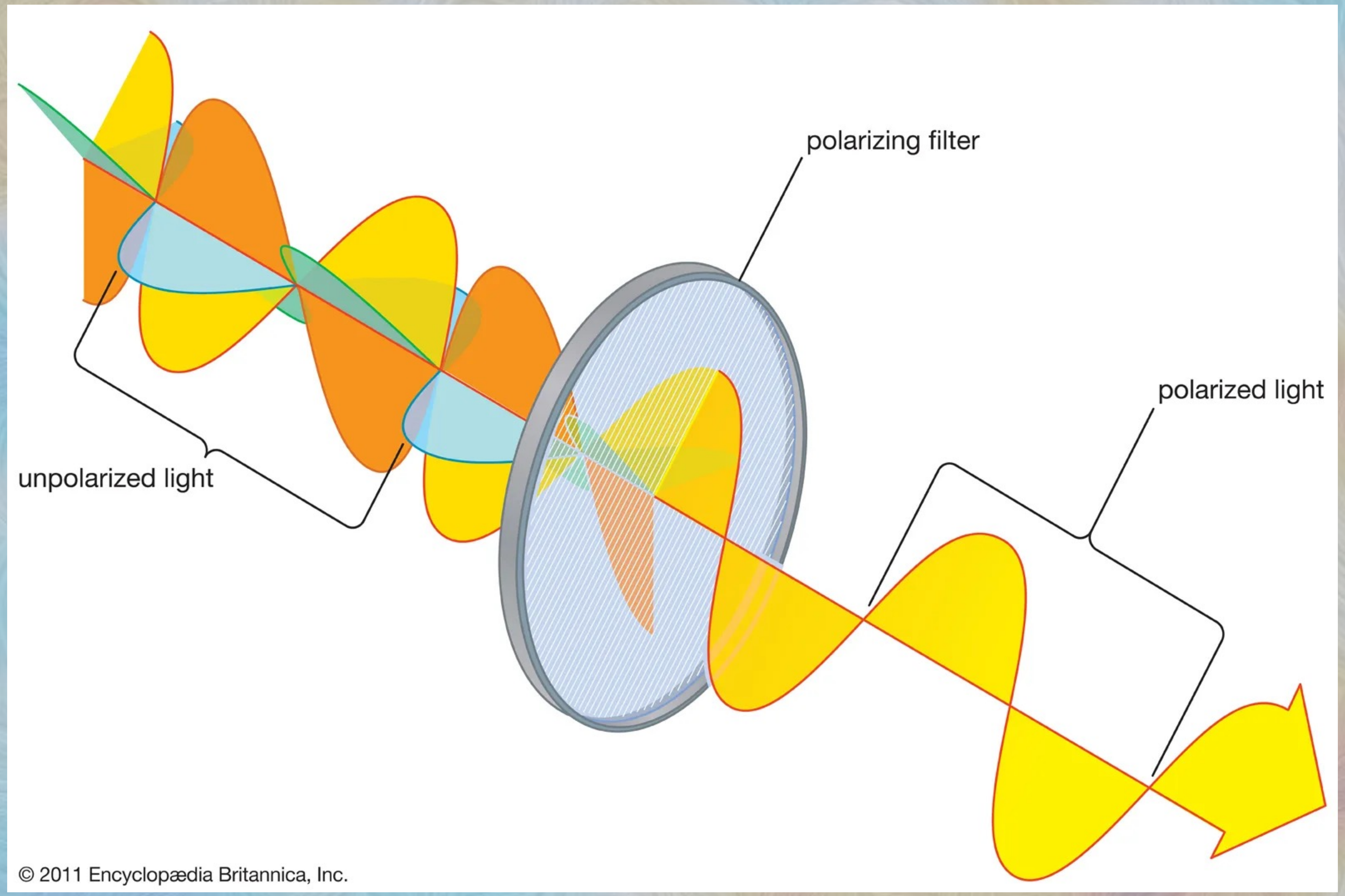
How can we observe the polarised signal from the sky?

Polarisation: what is it?

- Def: a property of electromagnetic waves to oscillate in a specific direction

- Different modes of polarisation depending on oscillation direction of electric field





How do we describe polarisation?

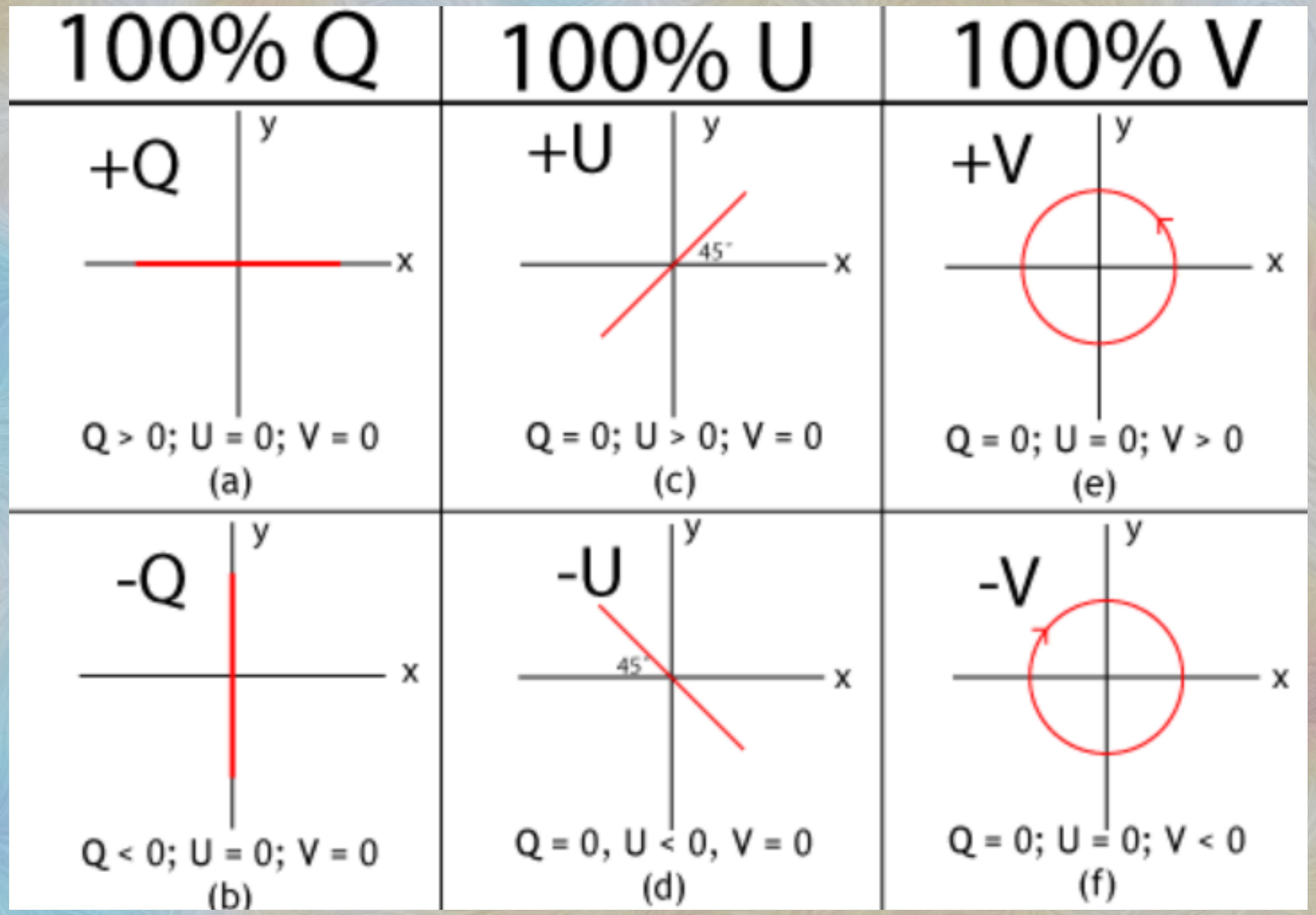
- The Stokes formalism: the most "handy" from observational perspective

- (I, Q, U, V) →

  (intensity, linear + polarisation, linear x polarisation, circular polarisation)

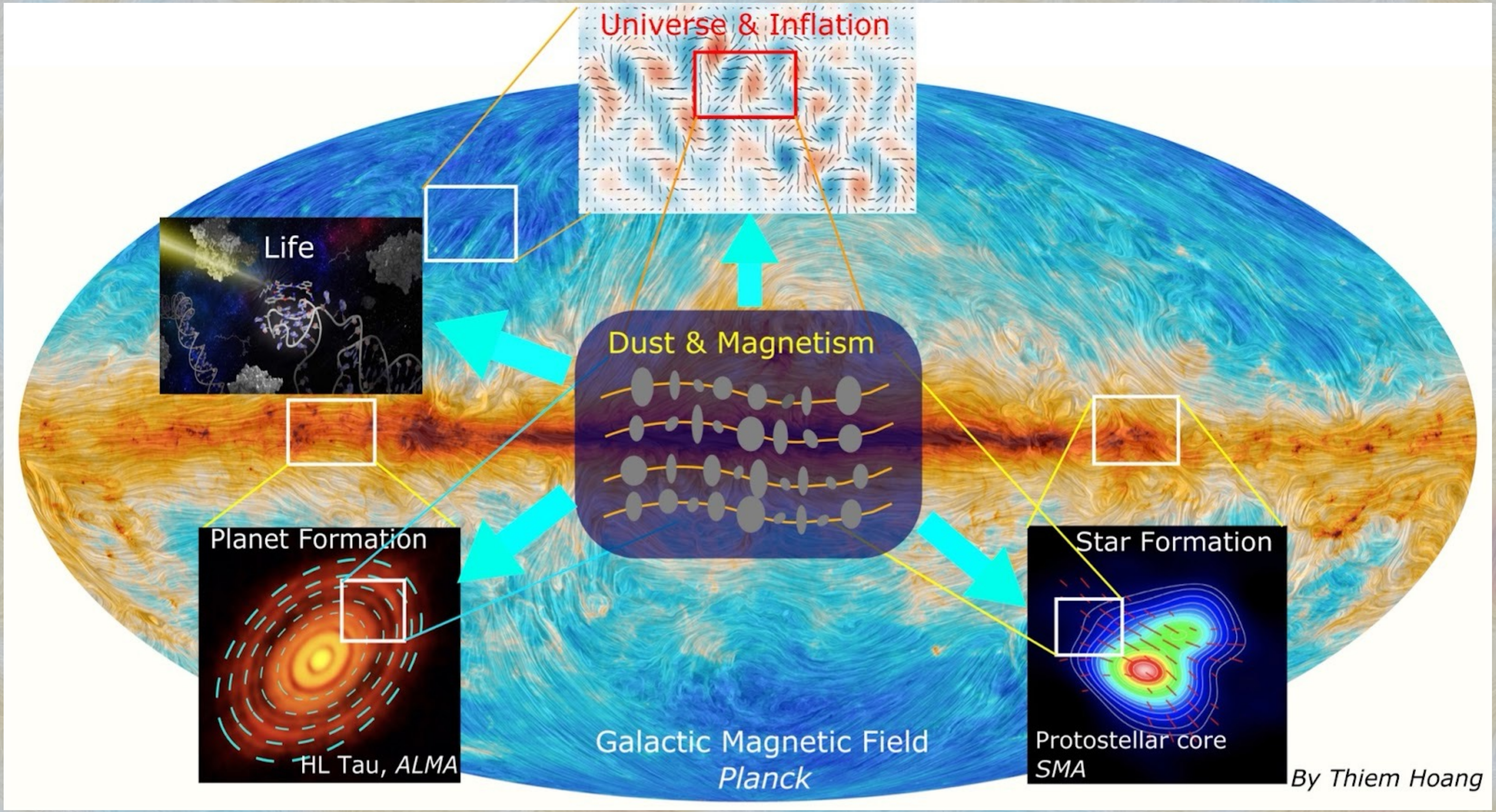
- Polarisation amplitude $P = \sqrt{Q^2 + U^2}$

- Polarisation angle $\alpha = \frac{1}{2}\, atan\left(\frac{U}{Q}\right)$



By Dan Moulton

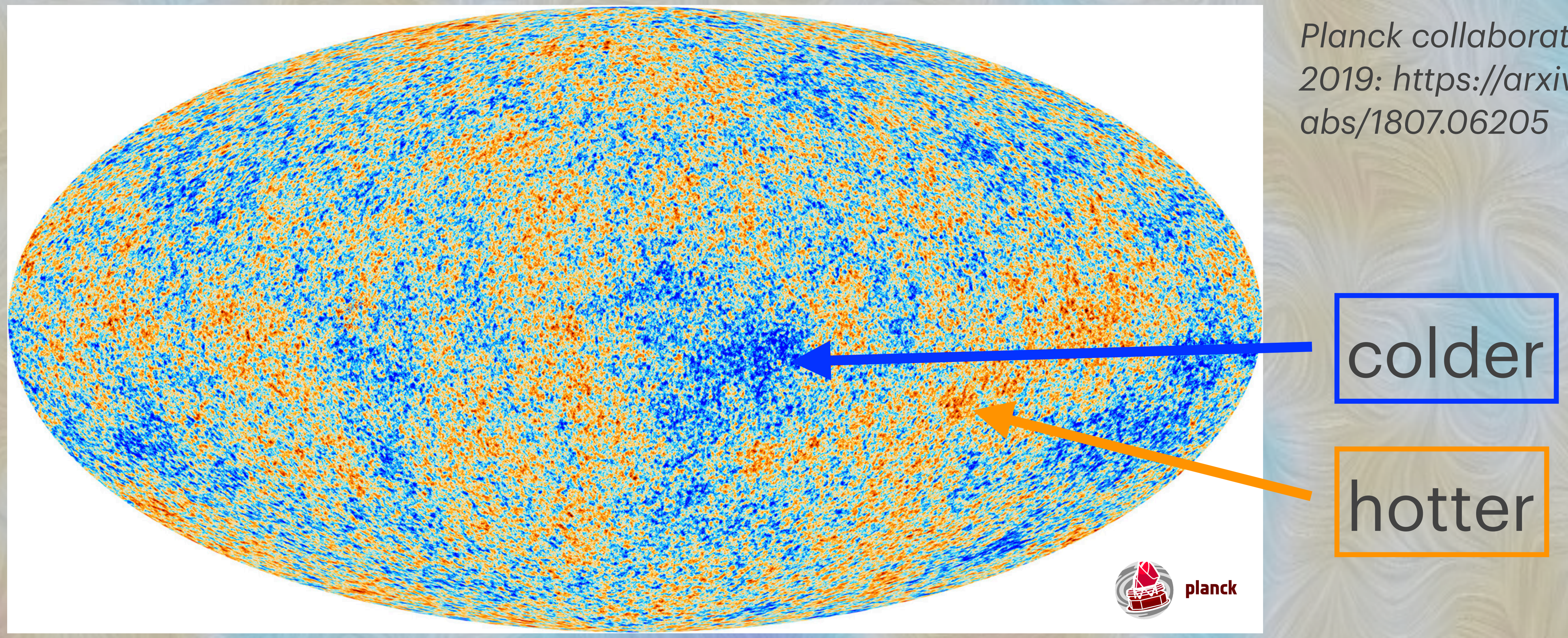
It is everywhere!



Cosmic Microwave Background

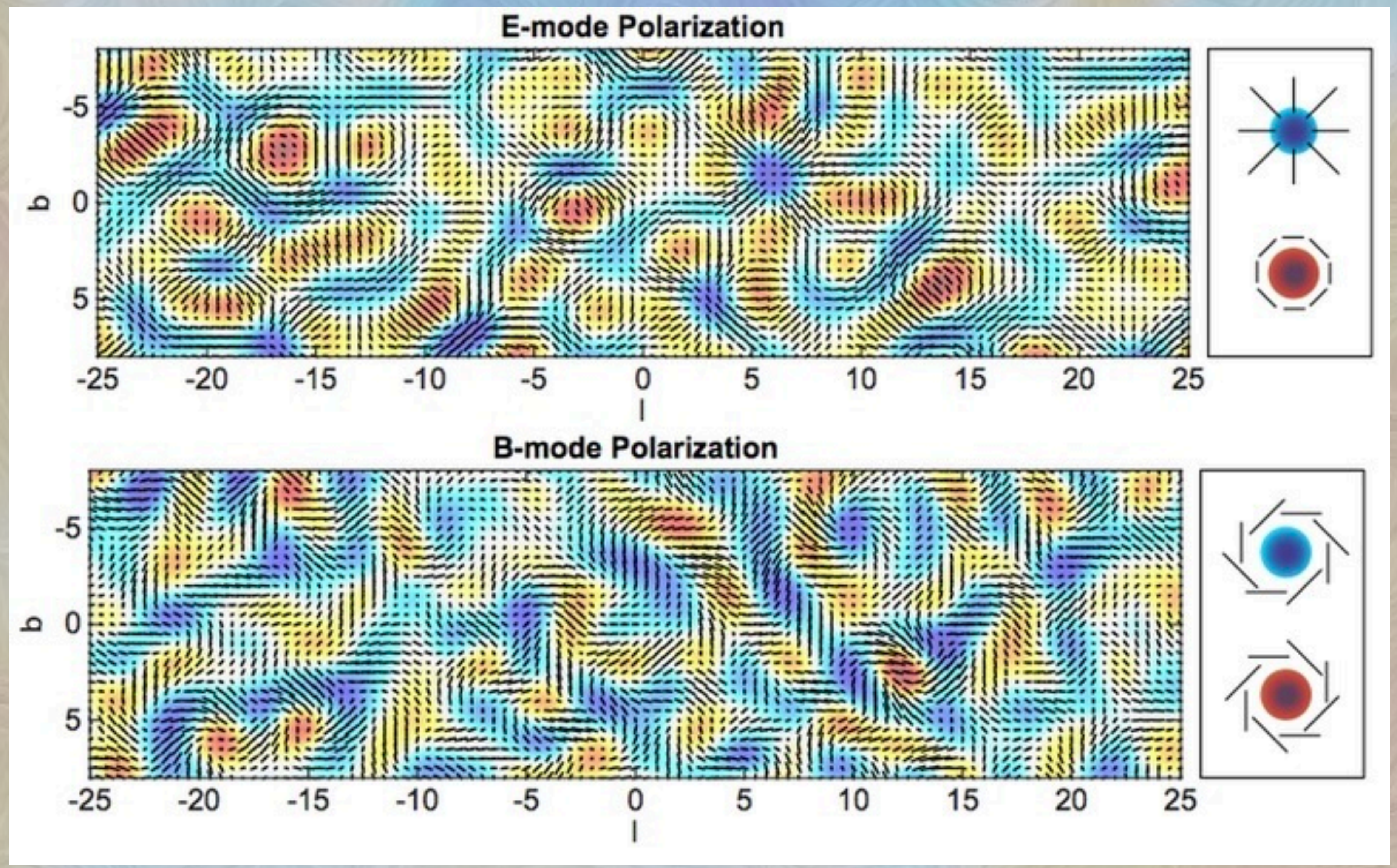
- The CMB is a black body at T = 2.72 K
- <u>But</u> with temperature anisotropies of the order of $\Delta T / T \sim 10^{-5}$
- These anisotropies induce linear polarisation in CMB photons
- Fraction of CMB photons is polarised
- Two possible polarisations (E-B formalism)

Temperature anisotropies map



Planck collaboration, 2019: https://arxiv.org/abs/1807.06205

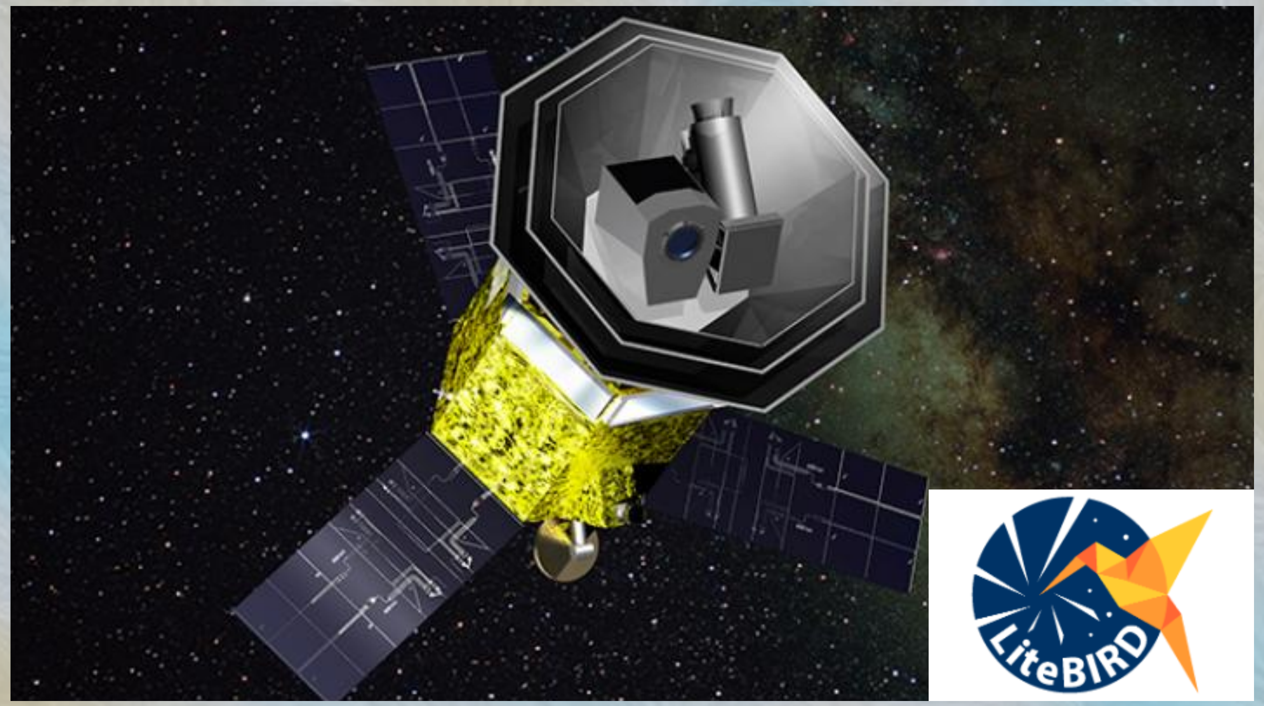
Simulated E-B modes pattern in galactic coordinates



Kamionkowski+2016, https://arxiv.org/abs/1510.06042

How do we observe polarisation?

mm wavelength instruments



- Ingredients to observe polarisation:
  1. Polarimetric receivers (bolometers, KIDs)
  2. Modulation techniques
  3. Calibration system
  4. Control systematic effects

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1. **Polarimetric receivers (bolometers, KIDs)**
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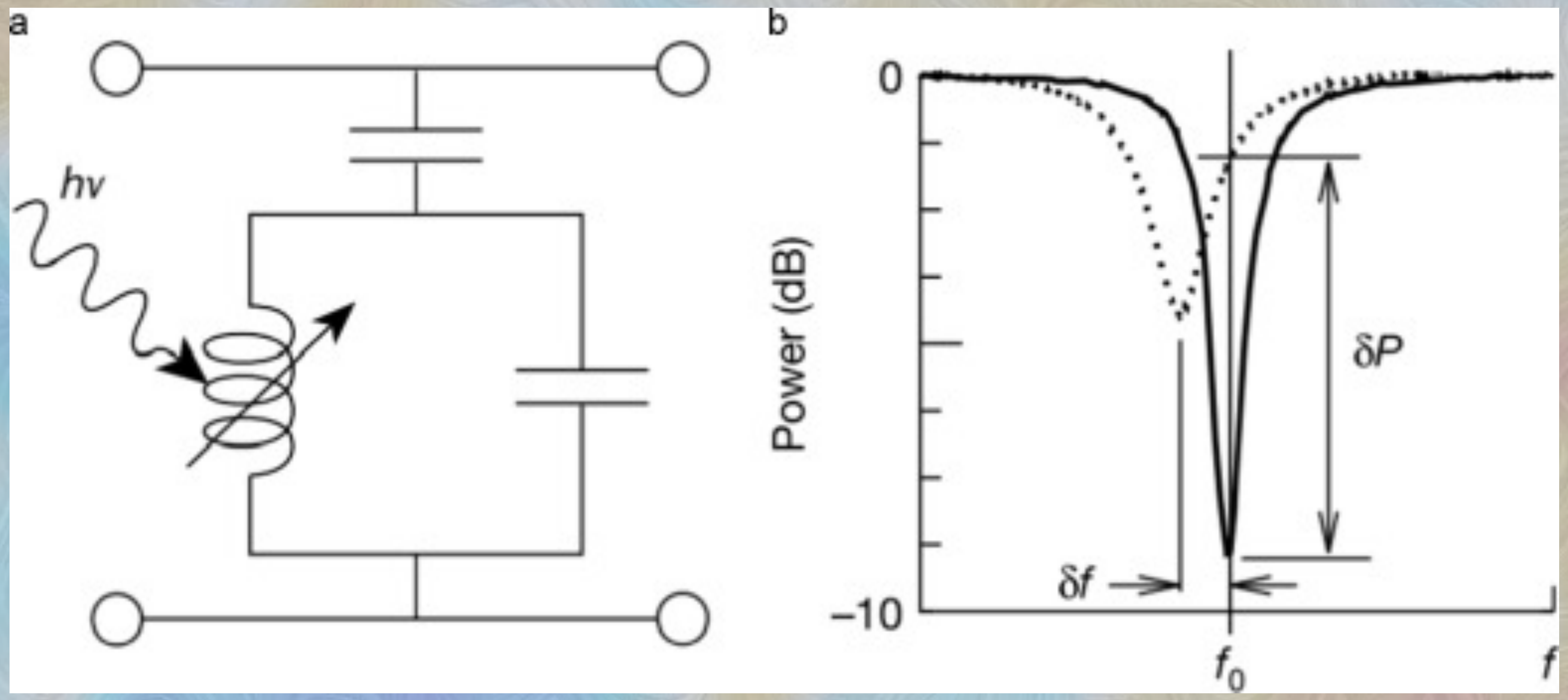
LEKIDs detectors

- LEKID : Lumped Element Kinetic Inductance Detector
- Superconducting detectors with working temperature below 300 mK
- RLC resonating circuit where
- $L_k \propto \frac{1}{n_{CP}}$ and $f_r \propto \frac{1}{\sqrt{L_k C}}$
- → we can detect incident photons by observing a shift in the resonance frequency



Mazin+2004, SPIE proceeding vol. 5368

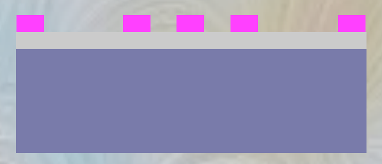
MAIN ADVANTAGES

1. Highly sensitive, reaching photon noise limit ($\sim 20\ mJy\sqrt{s}$)
2. Applicable to broad band (mm and sub-mm)
3. Small time constant (tens of μs)
4. High multiplexing factor (400)
5. Relatively simple fabrication process

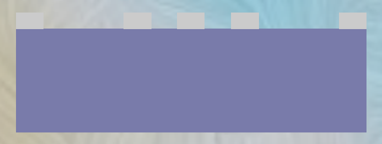
LEKIDs fabrication

CLEAN ROOM

Evaporate a thin layer of **aluminium** on a 4 inch **silicon** mono crystalline and high purity (> 1000 Ωcm) **wafer**



Impress the pattern through a **mask** with **optical lithography**



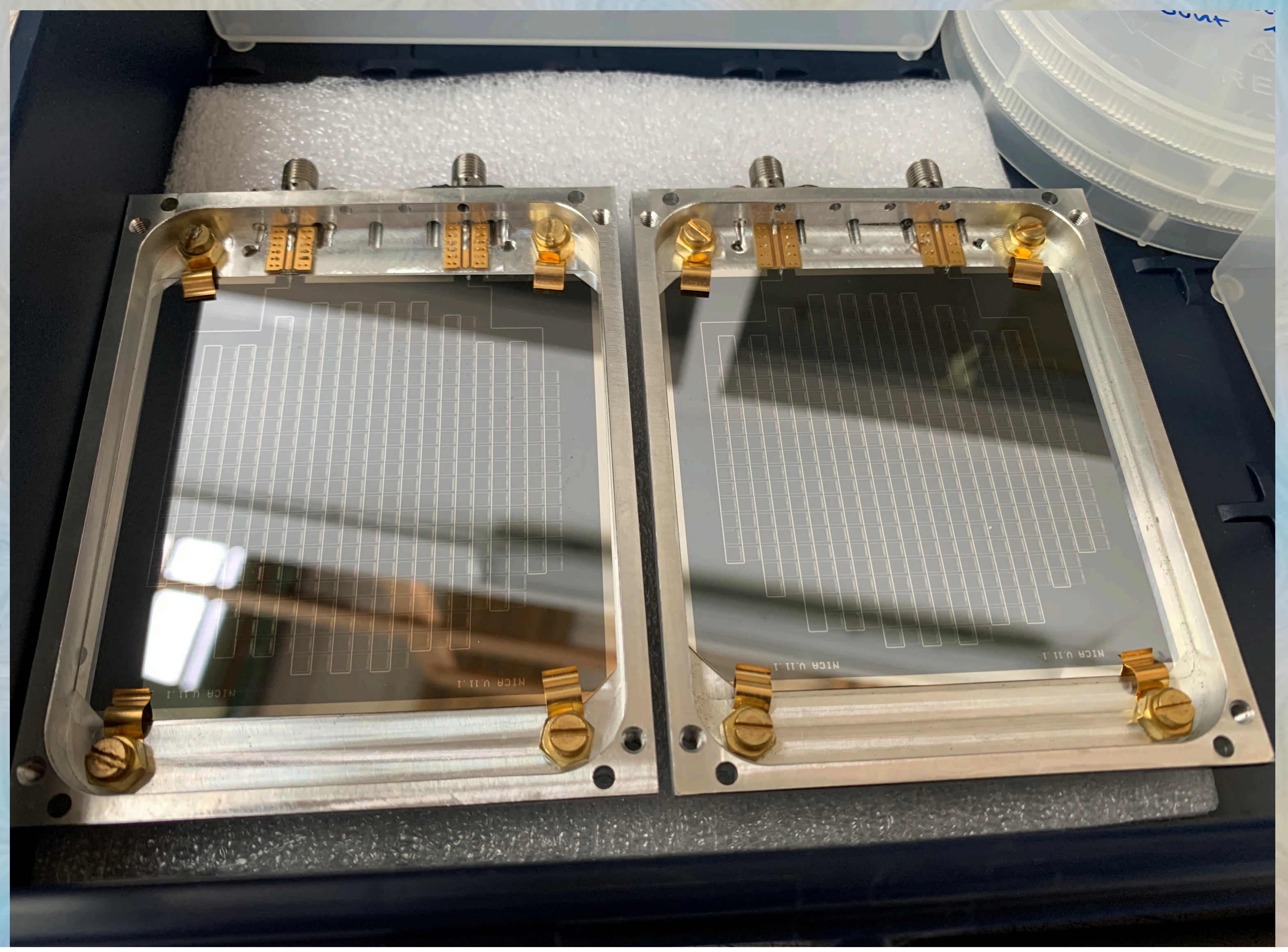
Etch the layer with wet attack and strip the resin

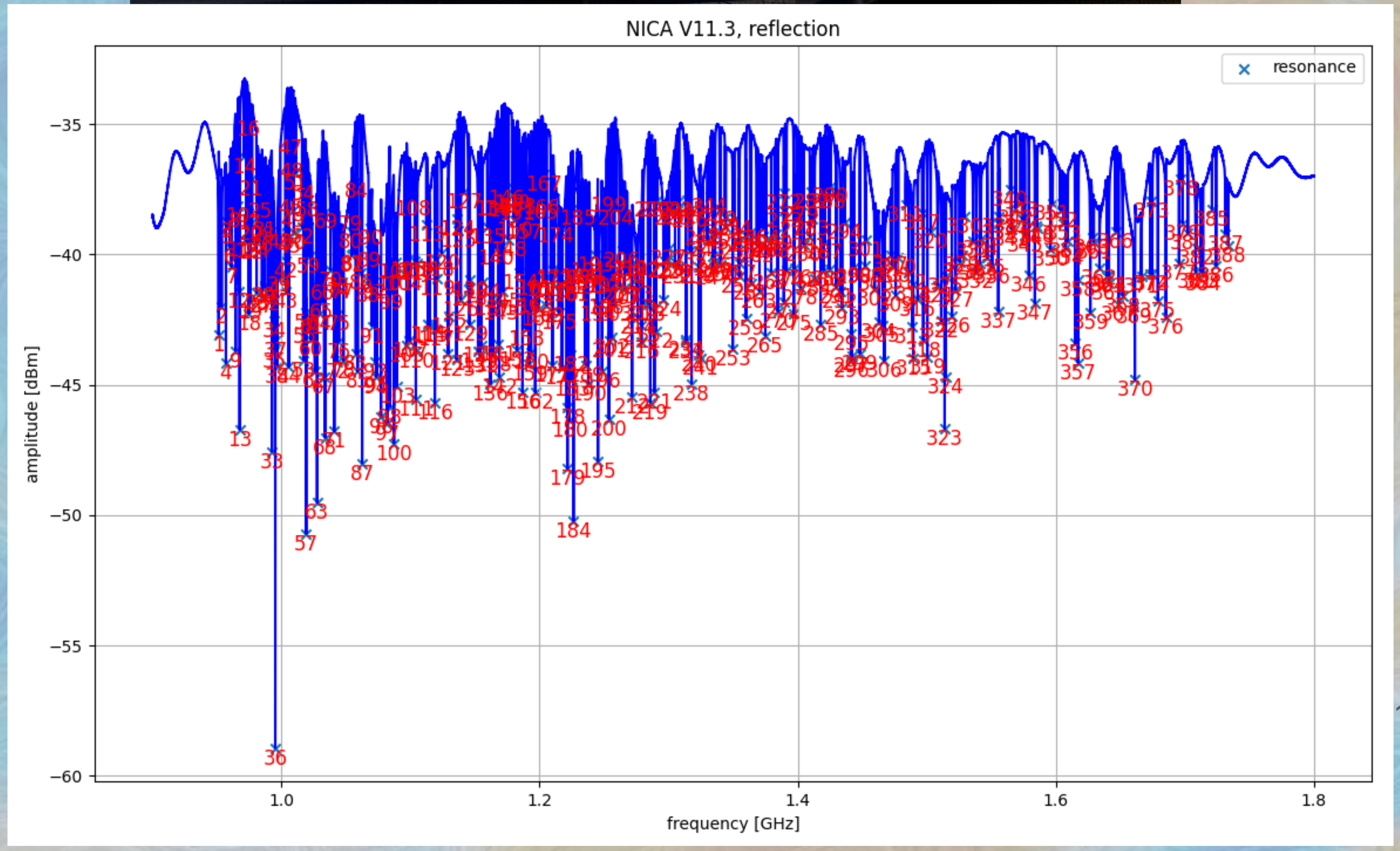
LAB

- Dicing of the array
- Mount on dedicated holders
- Micro bonding connection

RESULT

Made by me in CEA's clean room





- Ingredients to observe polarisation:

  1. Polarimetric receivers (bolometers, KIDs)
  2. **Modulation techniques**
  3. Calibration system
  4. Control systematic effects

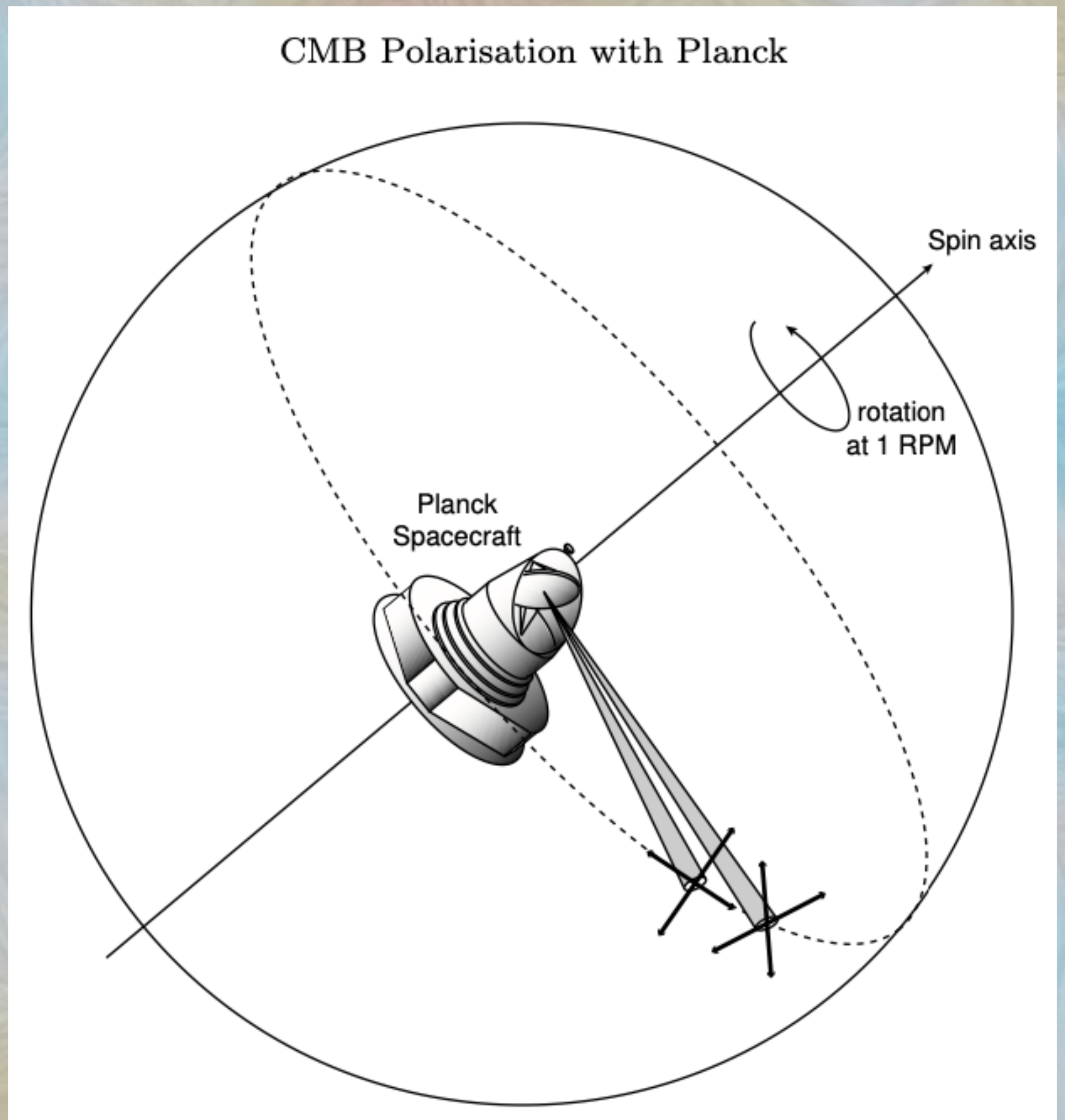
Two main modulation techniques

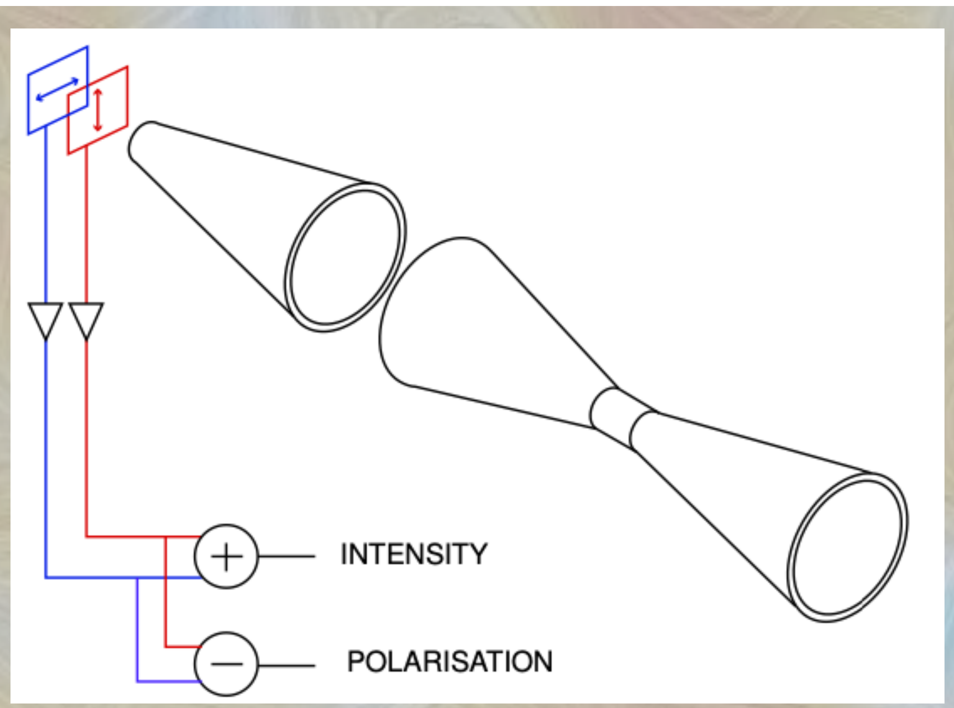
On-sky modulation

planck

Example: PLANCK

- 16 pairs of polarimeters oriented at 90º wrt each other
- Same feed horn, orthogonal polarisations are split on two Polarisation Sensitive Bolometers (PSB)
- 2 separate readout channels
- ISSUE : inter-calibration among detectors





Optical element modulation

Example: NIKA2, SO, LiteBIRD

- Already tested on ground-based instruments
- Proposed for space-based instruments
- Rotating retarder + polariser to analyse polarisation components
- ISSUE : systematics due to the fast rotation of a hot optical component

NIKA2

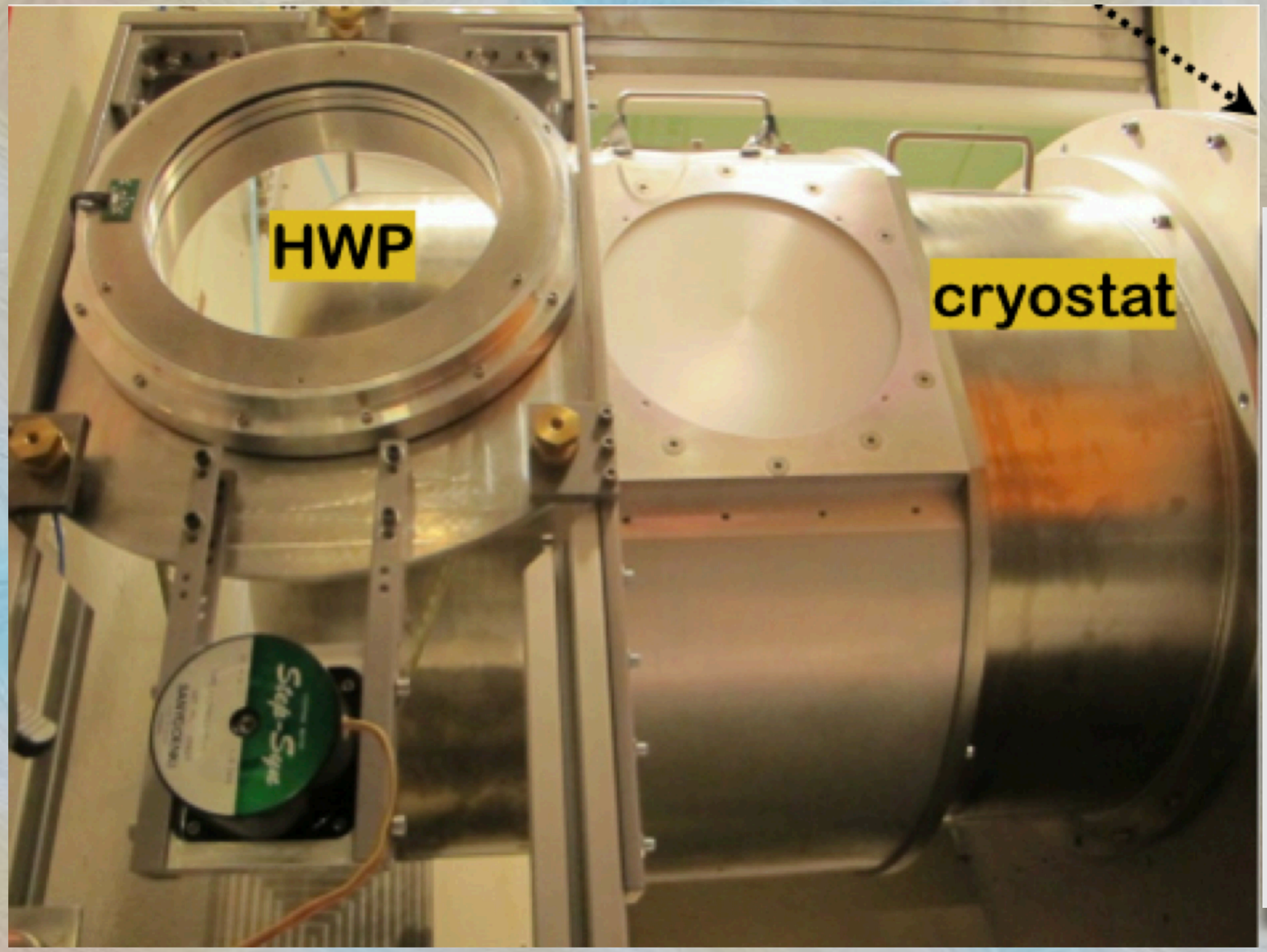
SIMONS OBSERVATORY

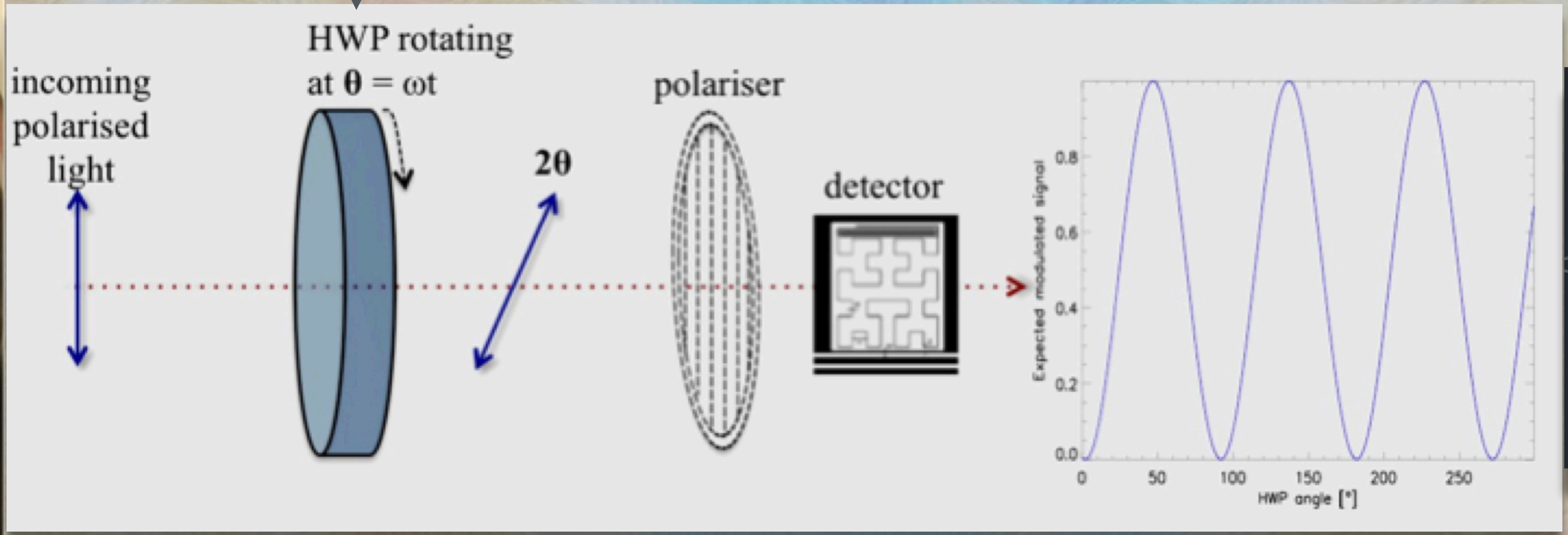
Our own modulation strategy

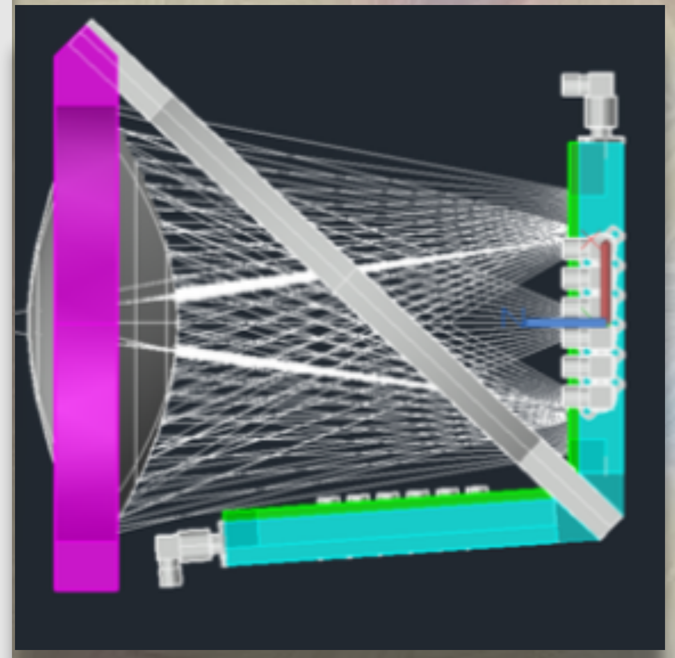
CONTINUOUSLY ROTATING HALF WAVE PLATE

- Optical device that dephases the polarisation state of linearly polarised light travelling through it
- Index of refraction is different along two perpendicular axes
- It is possible to introduce a controlled phase shift between the two polarisation components
- Select and study each polarisation state separately

Continuous rotation of an HWP permits quasi-simultaneous observations of I,Q,U Stokes parameters







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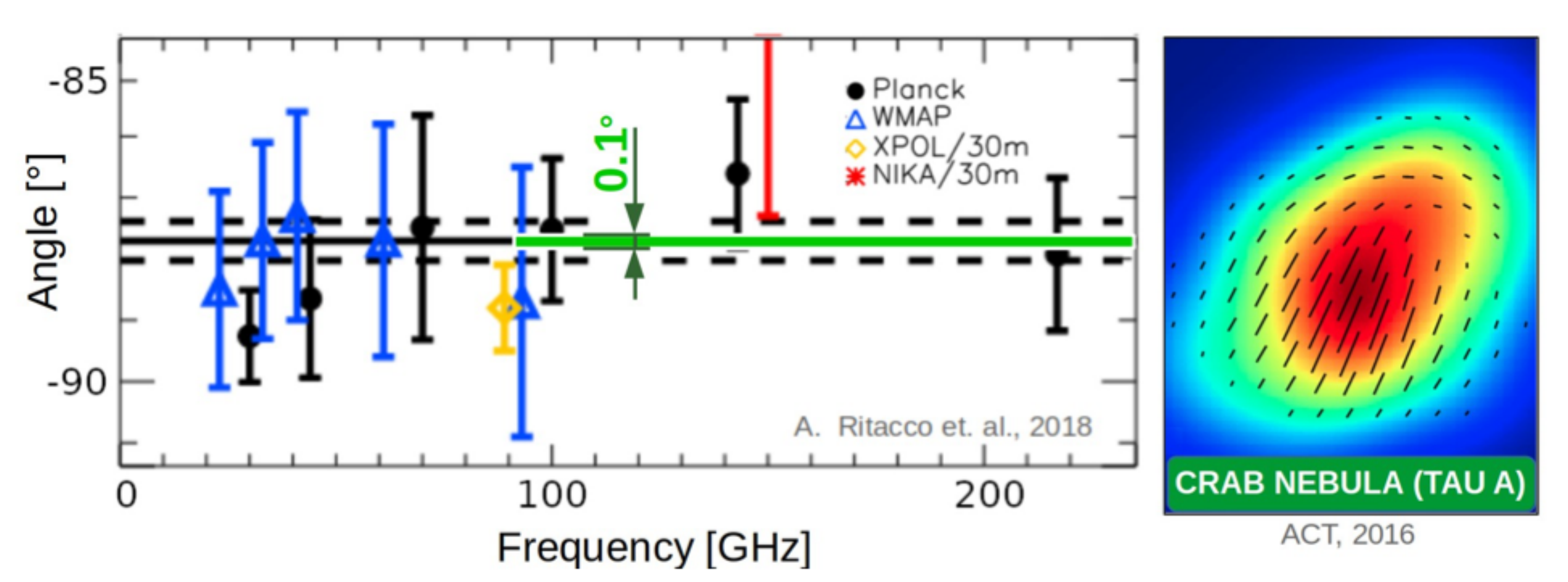
The problem of calibration

By F. Nati

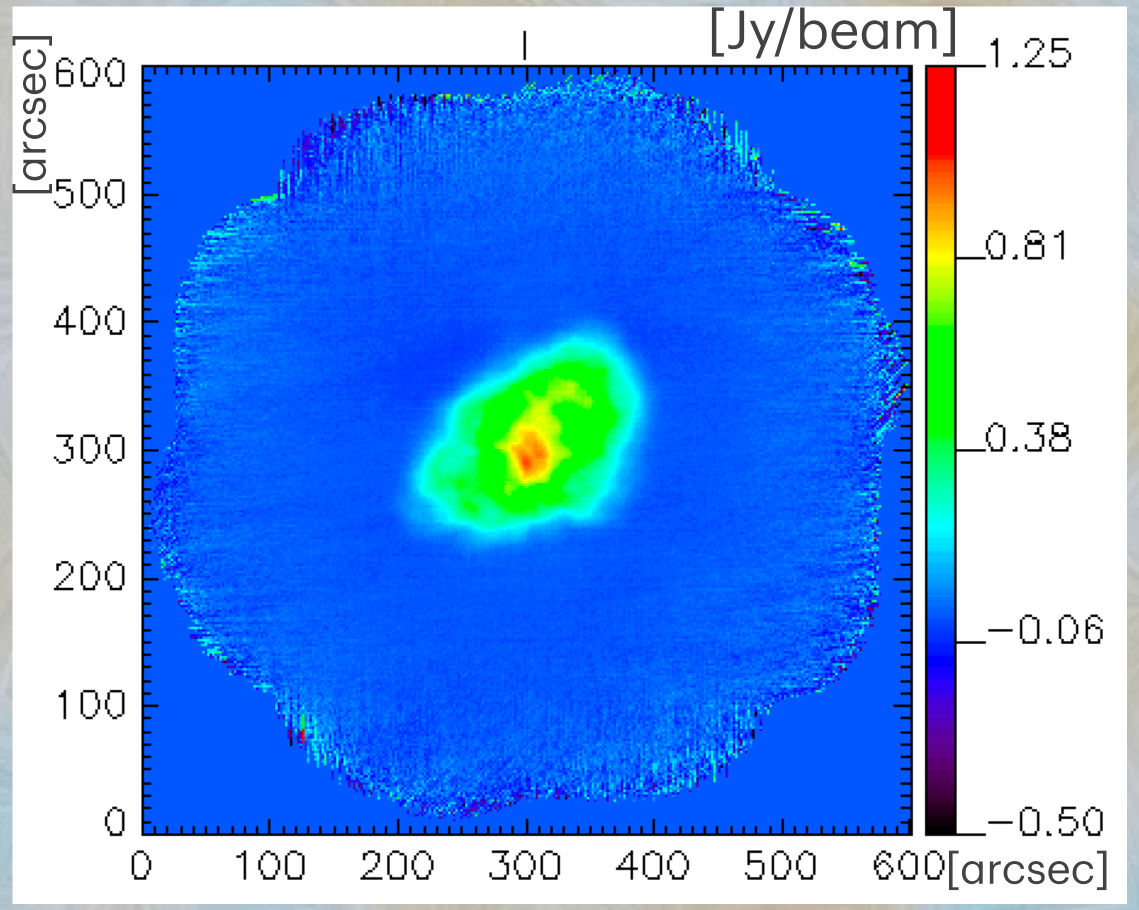
- B-modes search is limited by systematic effects
- Absolute miscalibration of the polarisation angle is one of them
- Current in-lab calibration methods can only offer accuracies up to ~ 1º

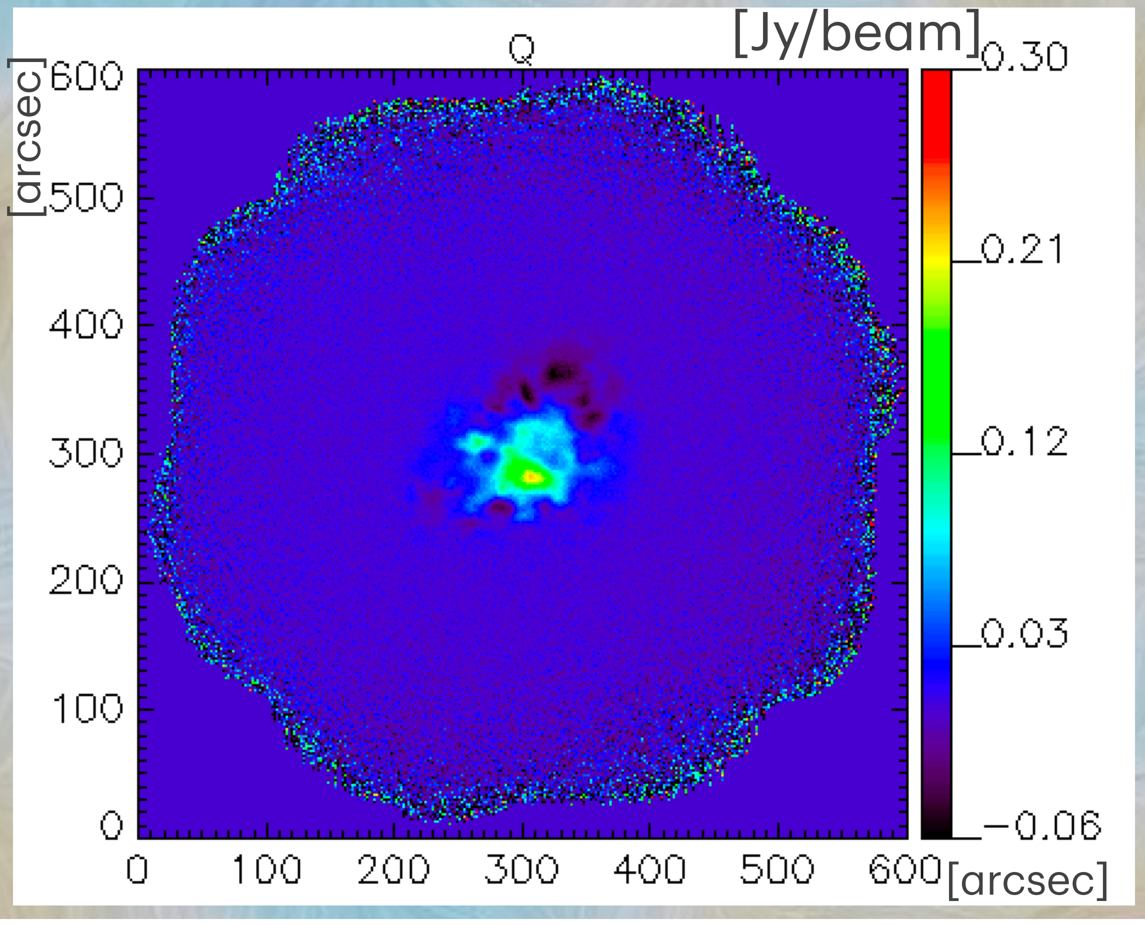
Can we use astrophysical sources?
YES and NO

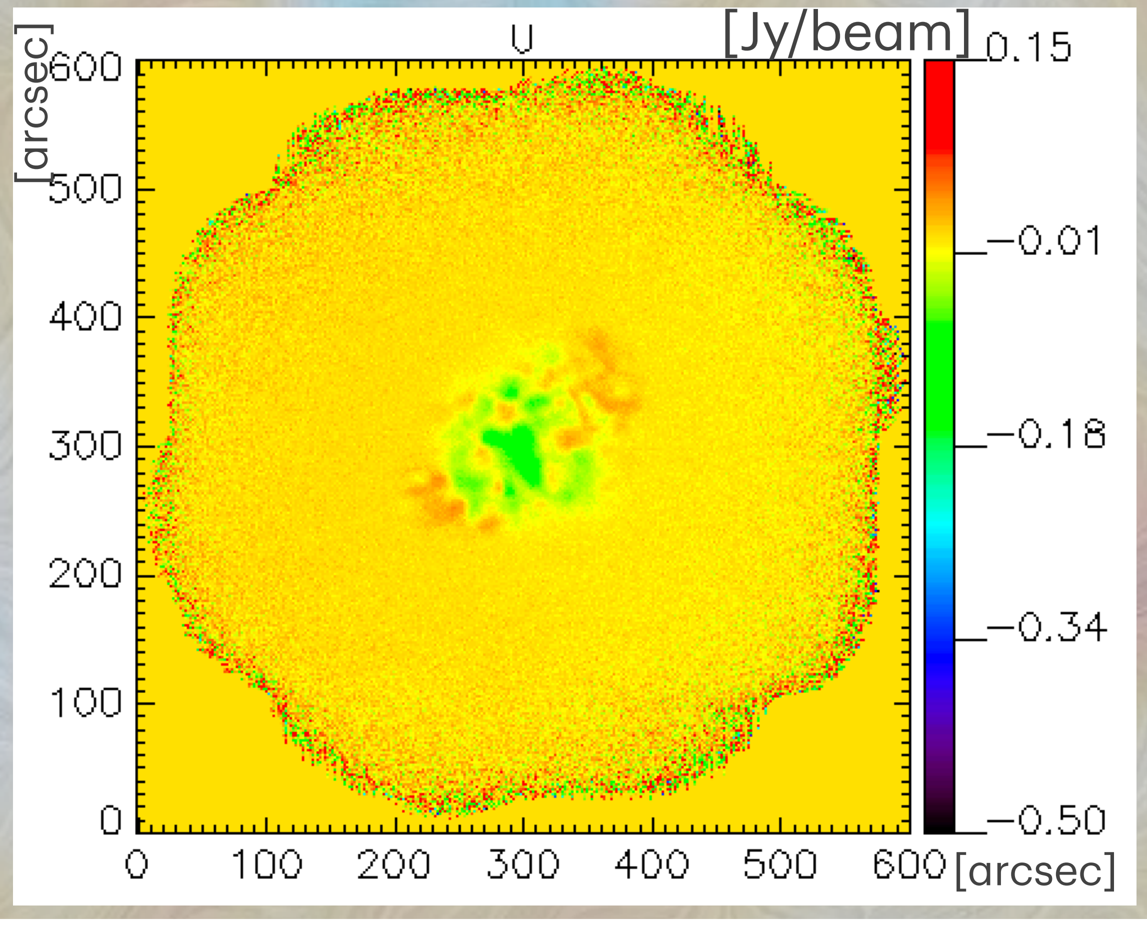


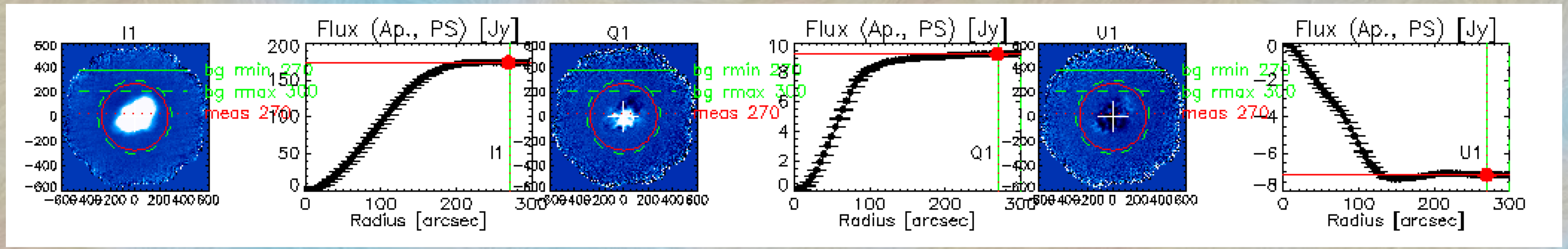
The Crab Nebula as polarisation calibrator

- NIKA2 data from November 2020 campaign at 1mm
- From these data, I obtained **I,Q,U maps**
- Contribution to the pipeline development
- Estimated the **fluxes** with aperture photometry and **polarisation angle**
- **Goal**: add this estimation to existing data from Planck and other experiments







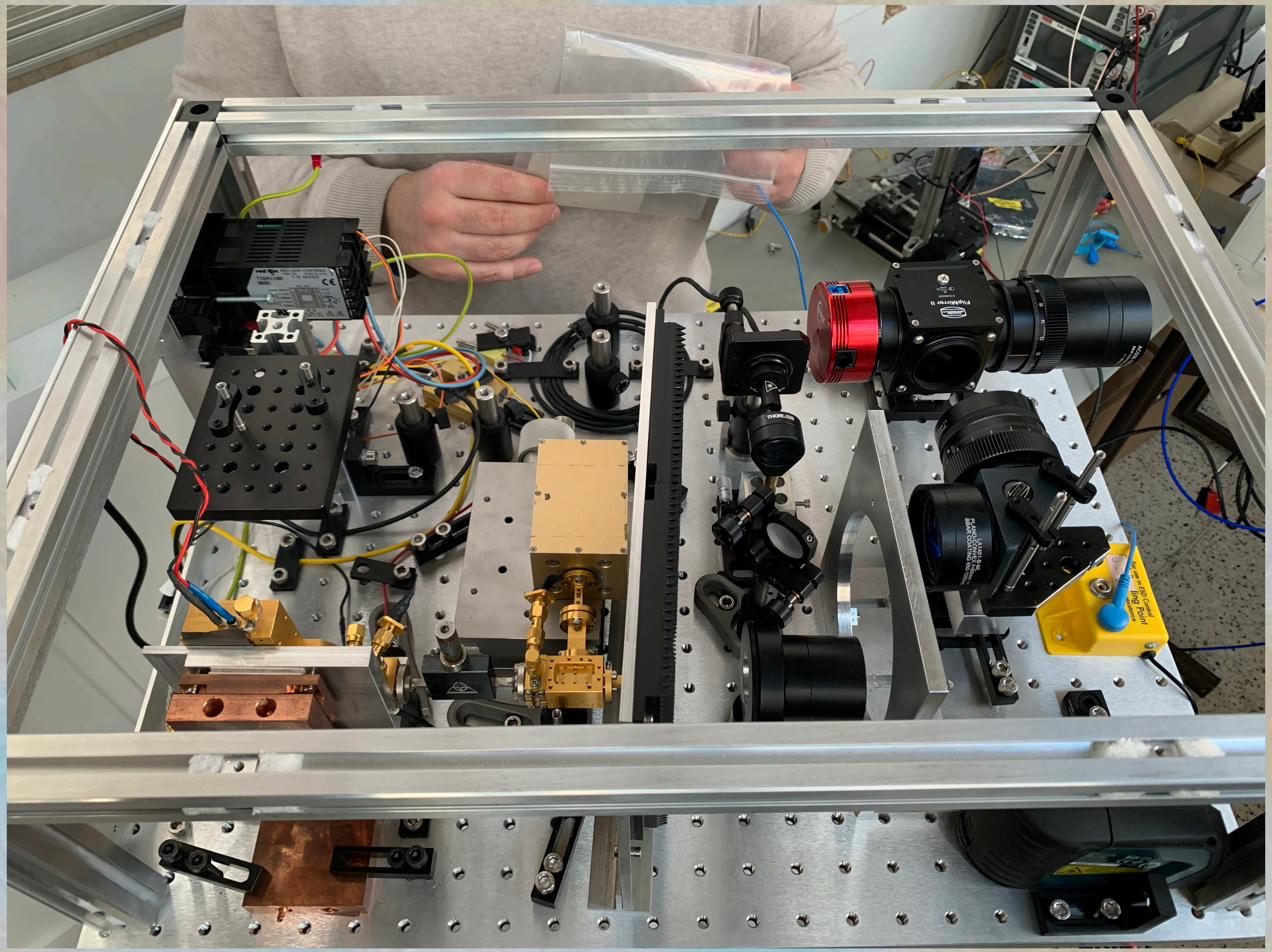


A. Ritacco, S. Savorgnano et al, in prep

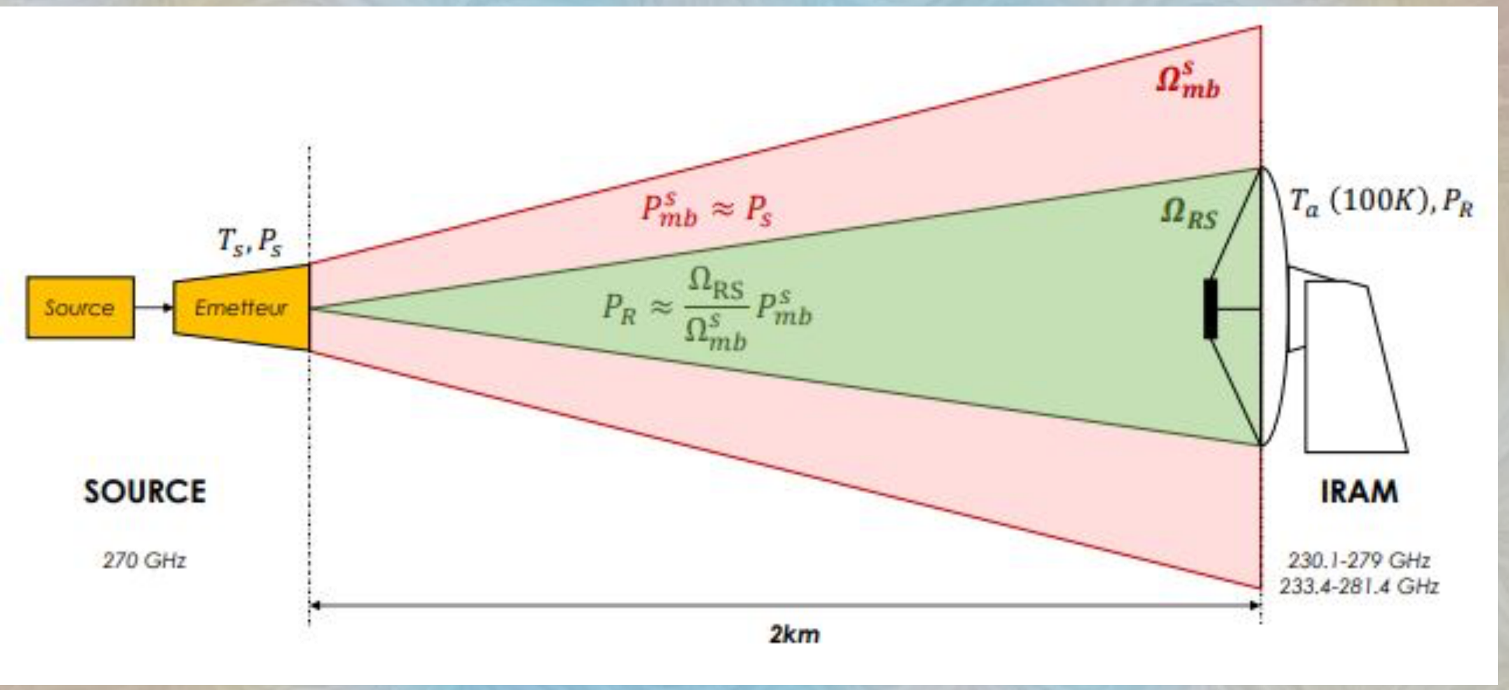
A possible solution: the COSMOCal project

What is it?

A polarised millimetre source that can calibrate large telescopes with an accuracy <1º



Grenoble lab: proof of concept



IRAM: first telescope test

Orbit: final goal

Polarisation measurements for COSMOCal

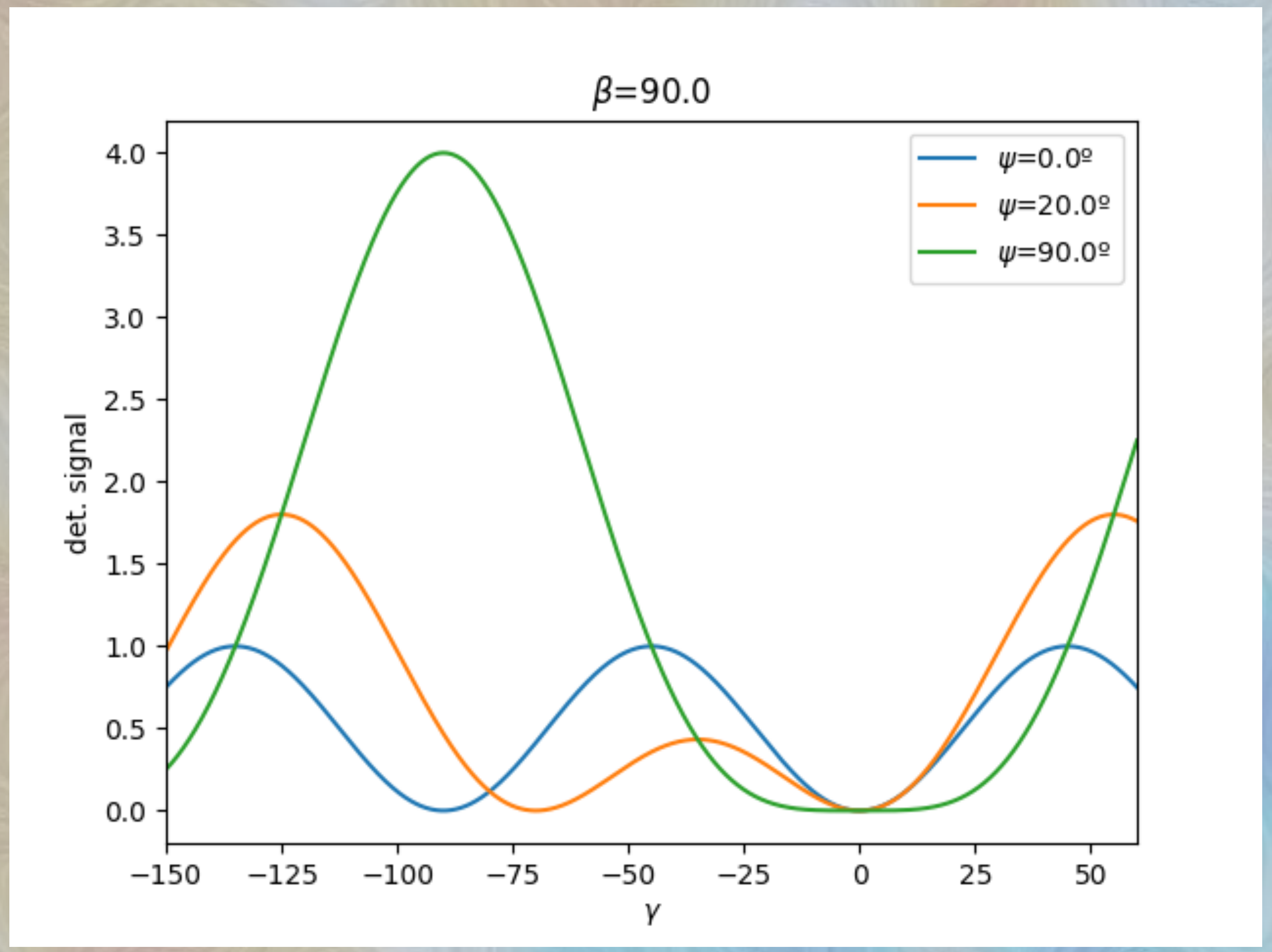
- Experimental setup:

1. Source + 1st polariser (ψ)

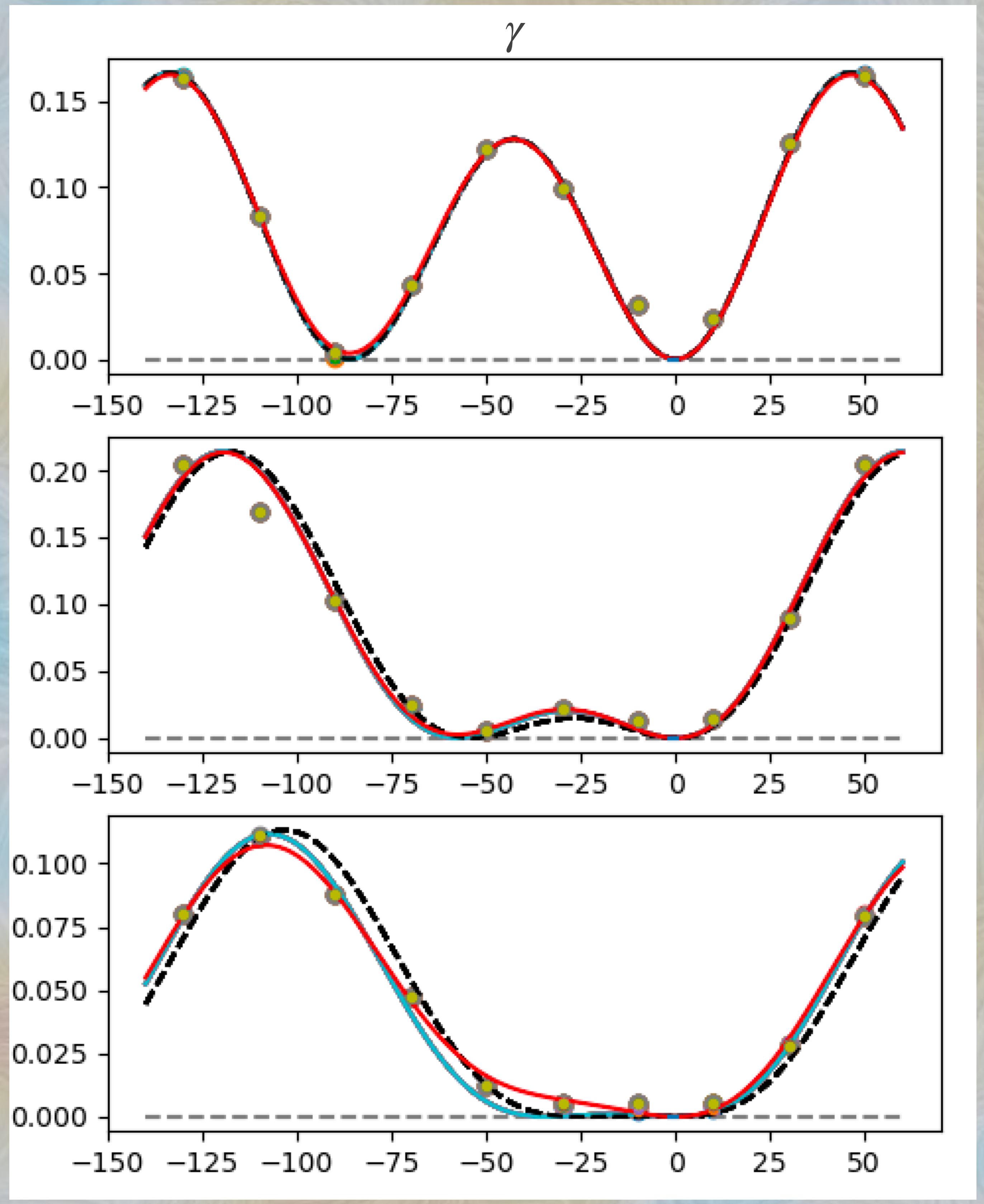
2. 2nd rotating polariser (γ)

3. Cryostat + 3rd fix polariser (β)

MODEL



REAL DATA



GOAL: estimate the ψ angle with error <1º

RESULTS:

Best fit error on ψ =0.89º

A. Ritacco, L. Bizzarri, S. Savorgnano et al, in prep

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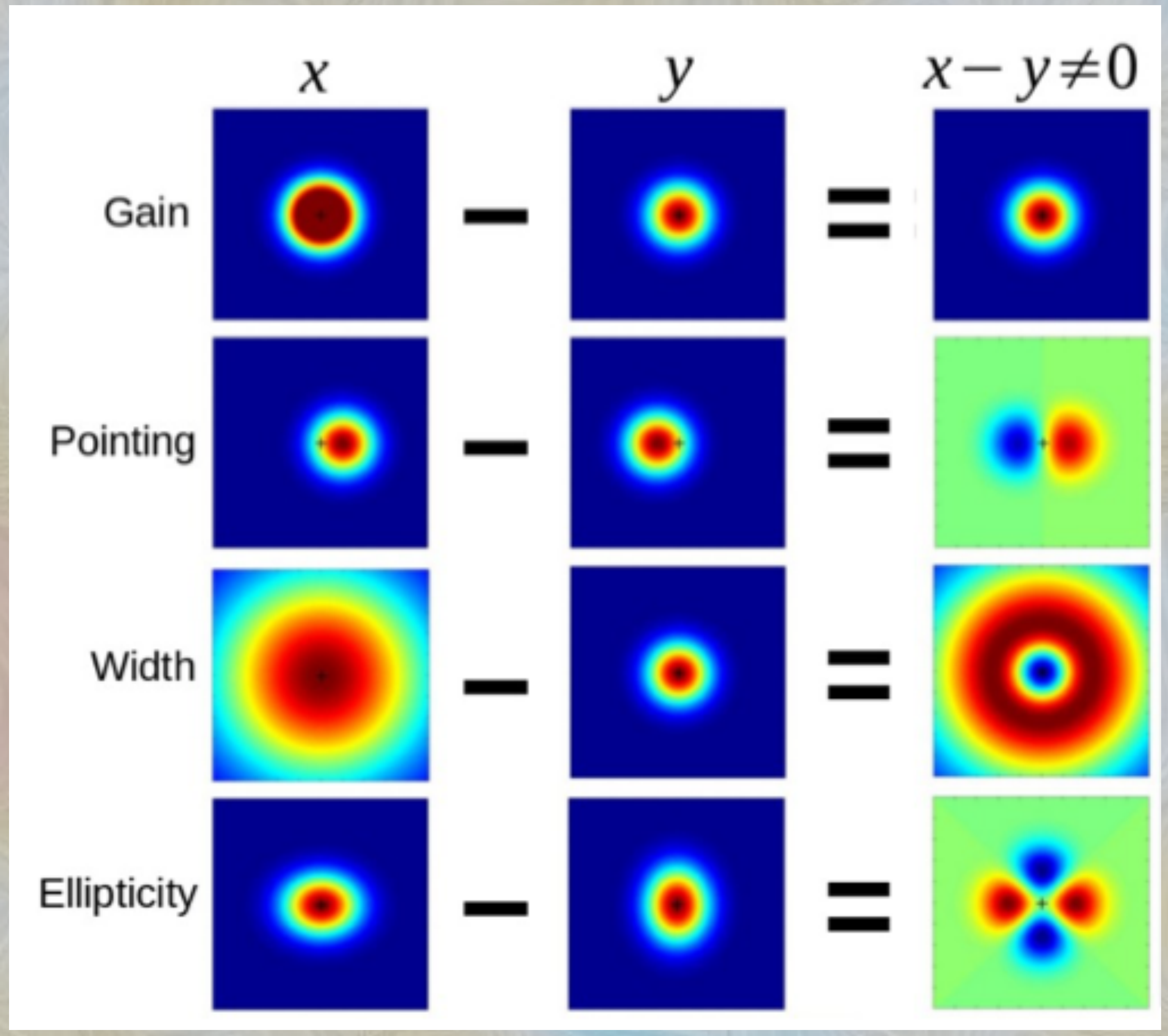
The problem of systematics

Instrumental systematic effects can impact polarisation detection



By F. Nati

PolarKID project

- Duration: 2023 - 2025
- Main goal: characterisation of systematic effects related to the polarisation measurements
- Detectors: LEKIDs
- Setup: sky simulator reproducing atmosphere + CMB signal
- Interchangeable photometric and polarised sources
- Structure that simulates a telescope scanning

CNES CENTRE NATIONAL D'ÉTUDES SPATIALES

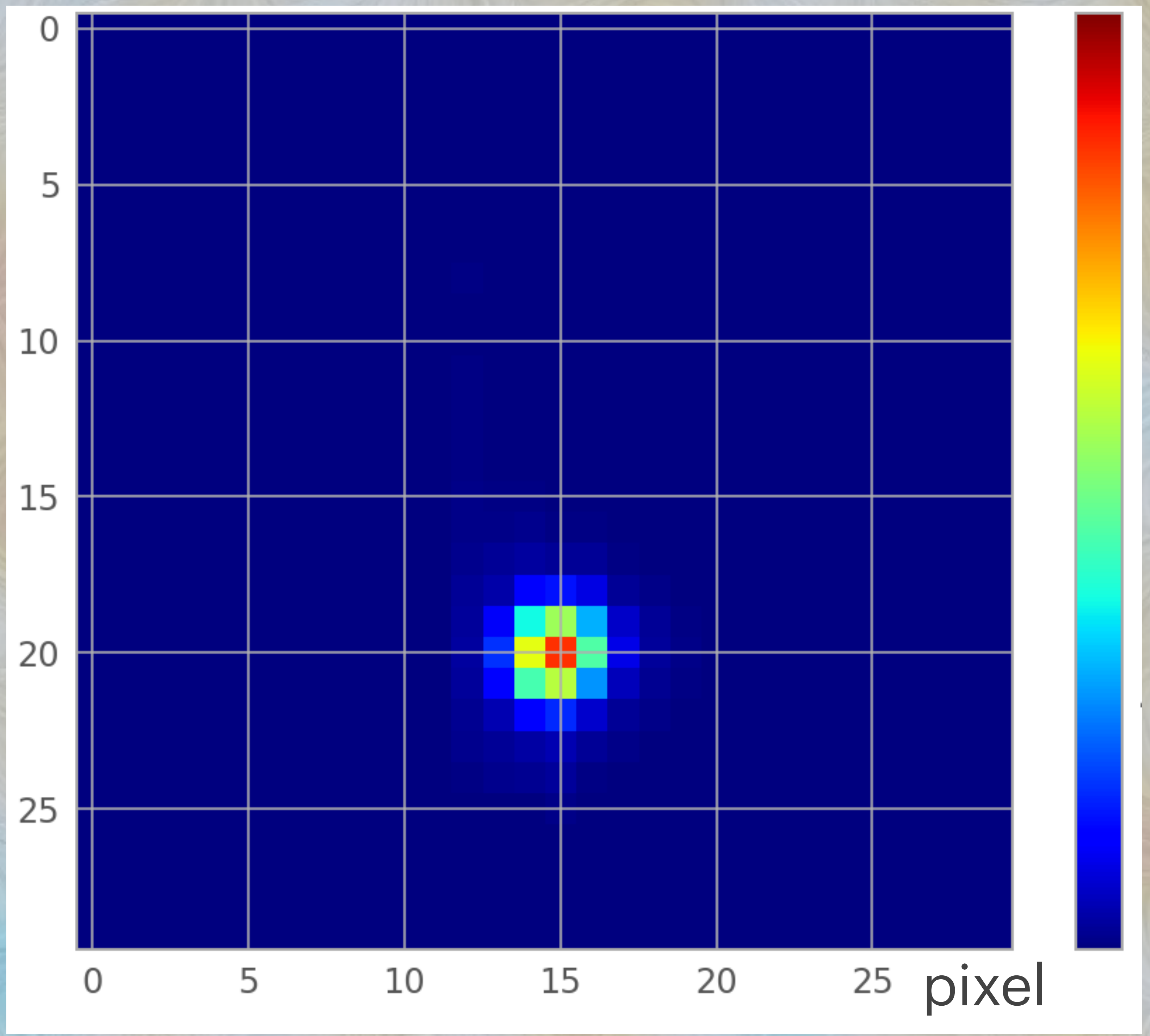
FOCUS Focal Plane Array for Universe Sensing

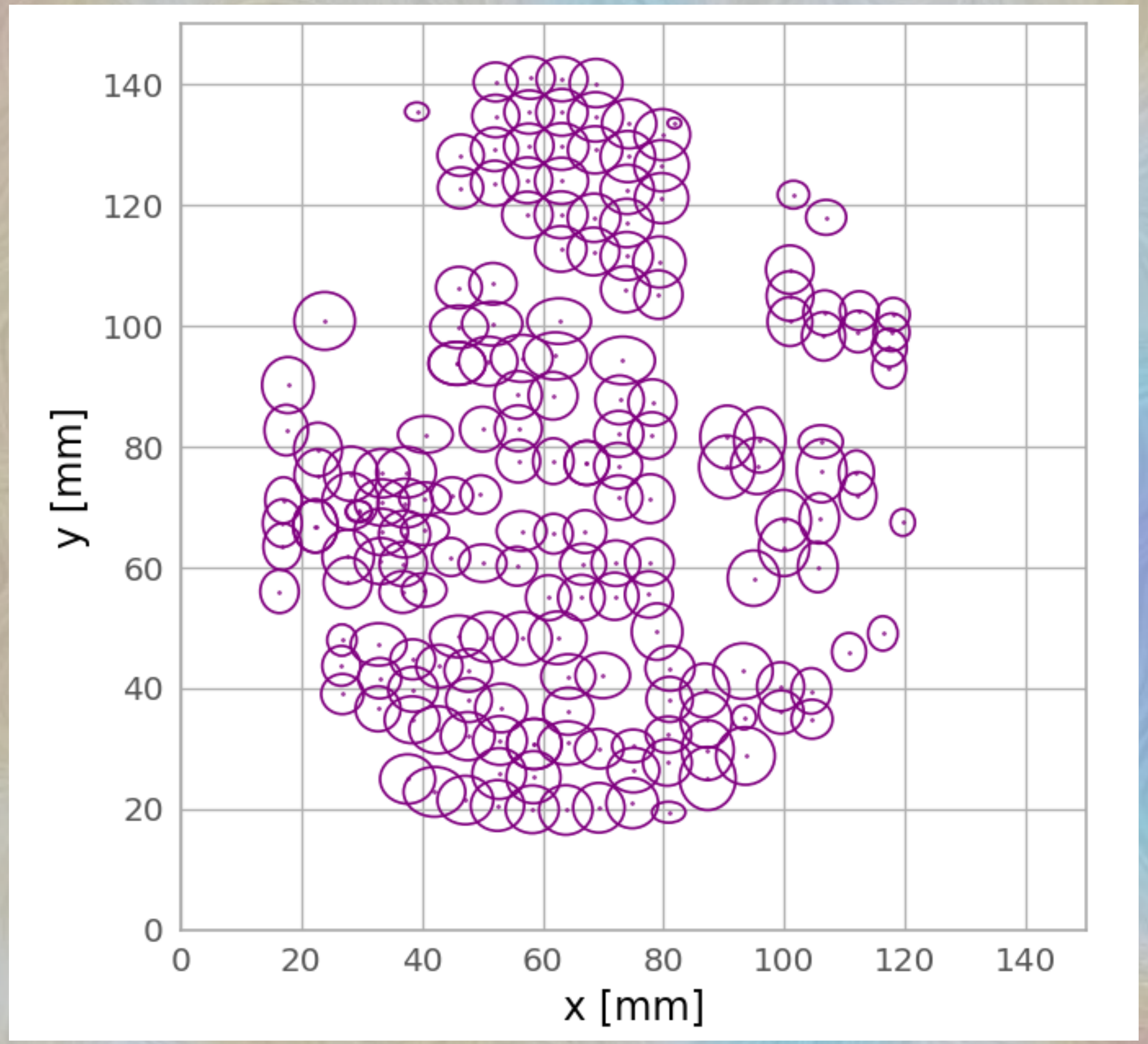
Preliminary results on photometry measurements

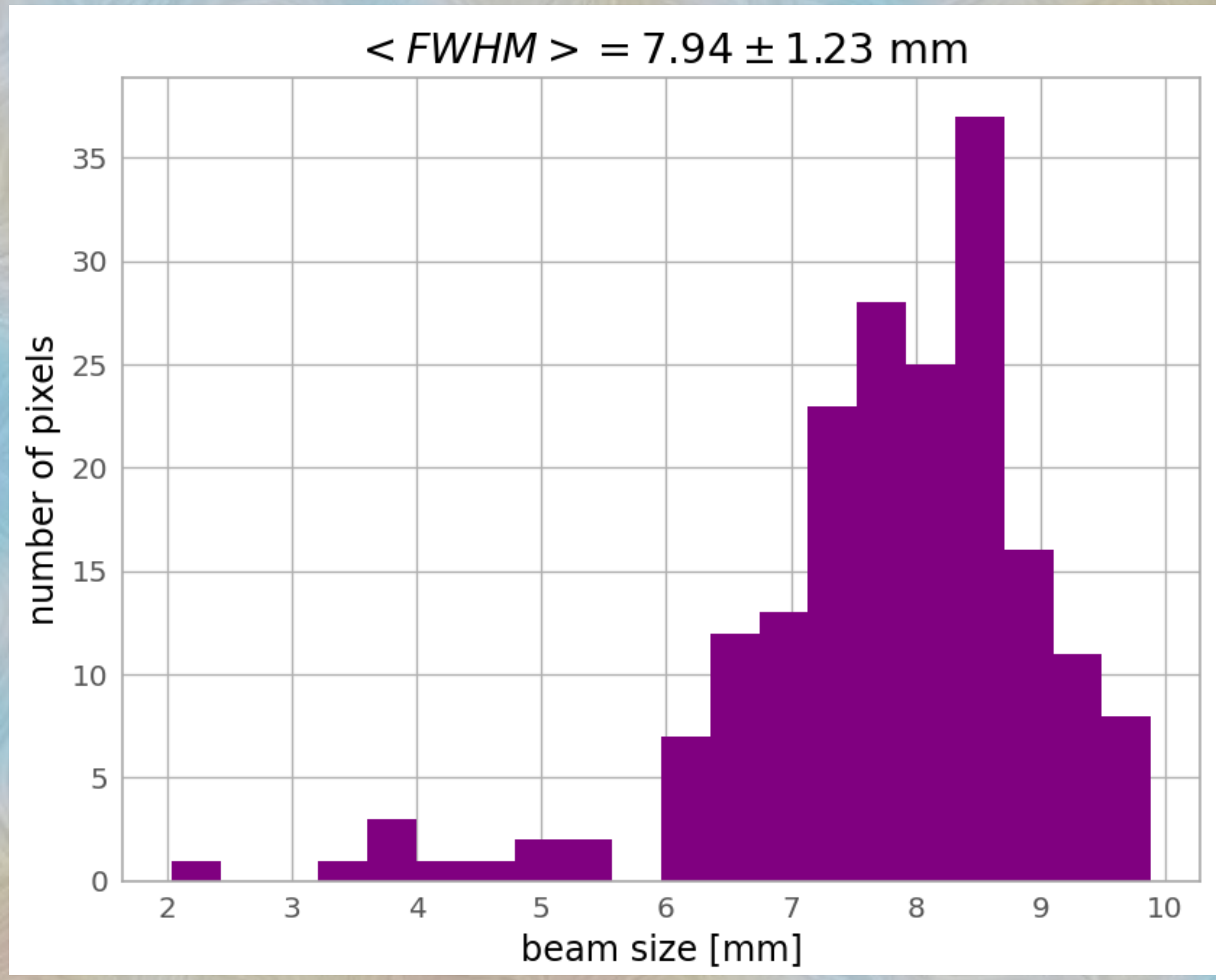
Reconstruction of a "planet" map

Geometry of the LEKIDs array

Estimated beam of the LEKIDs pixels







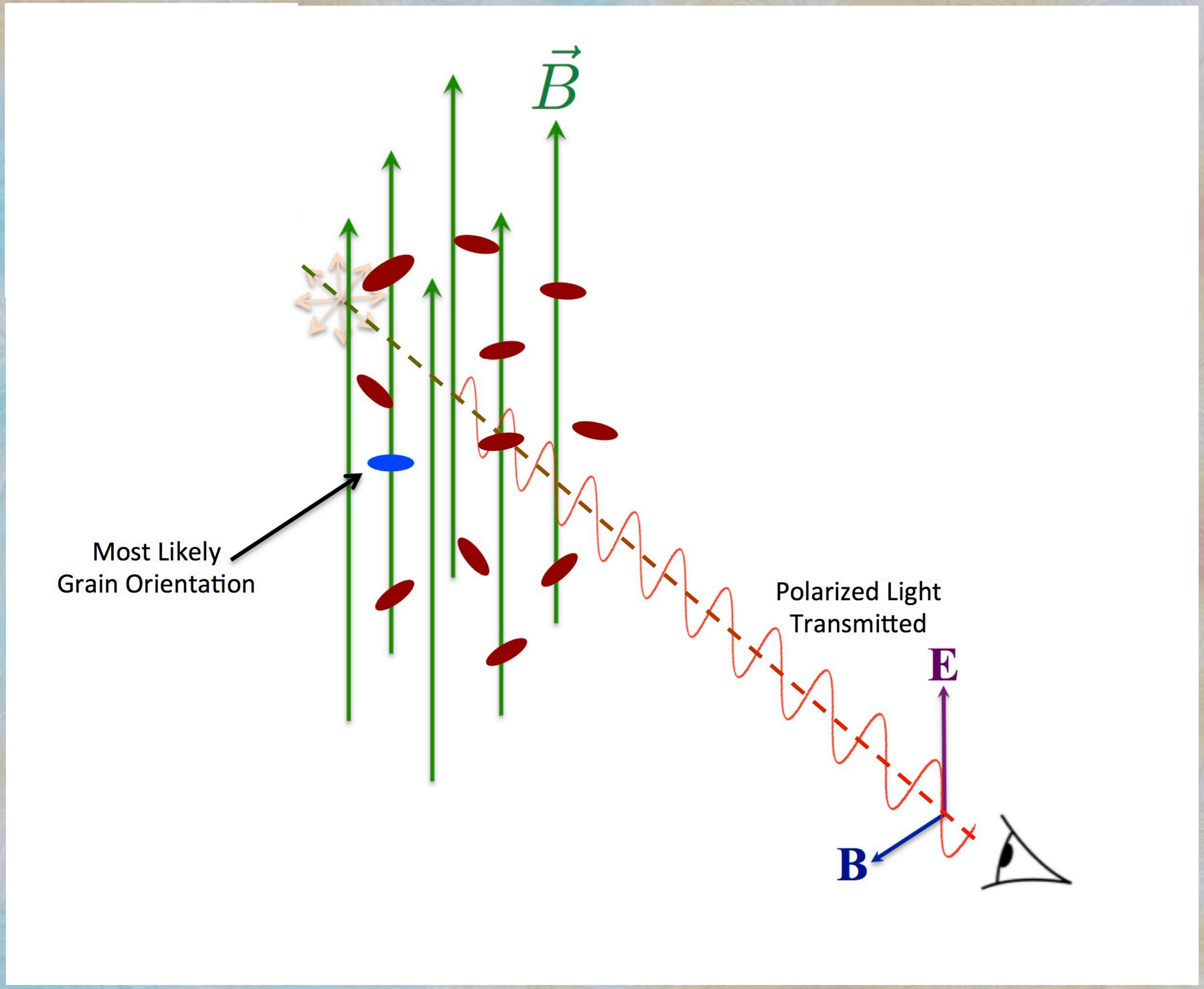
Ready to perform polarised measurements !

S. Savorgnano et al, in prep

Polarisation as a probe of magnetic fields in star formation

- MF within star-forming regions align **dust grains** along its direction → thermal emission from these aligned dust grains becomes **polarised**

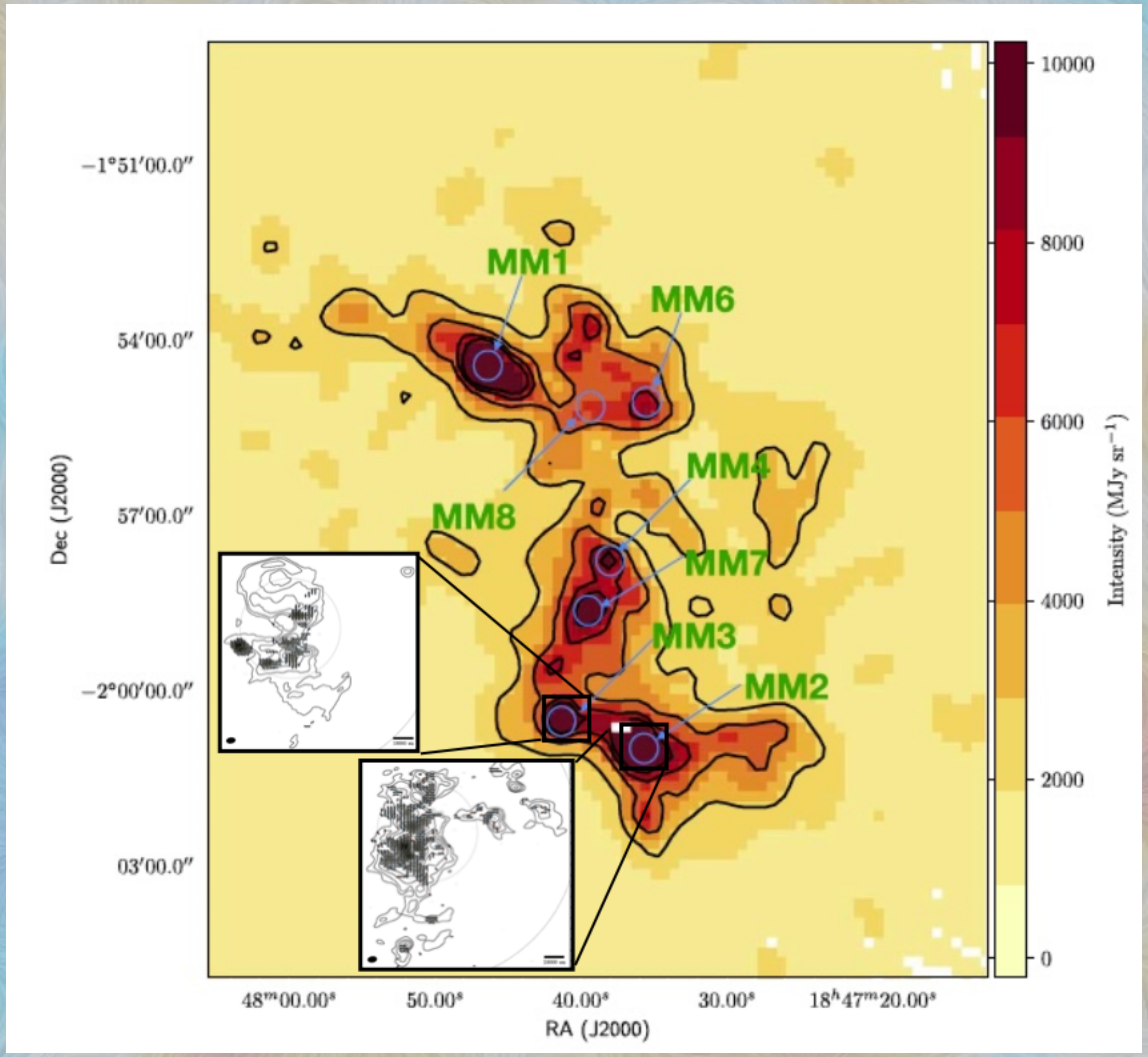
- Polarisation measurements of this emission provide direct information about the **orientation of magnetic fields** in the region



By B.G. Andersson

What do I observe in polarisation?

- Target: **W43** star formation region in Eagle constellation
- **Scientific purpose**: study the role of magnetic fields in star formation process
- **How**: reconstructing the Stokes parameters through polarised observations with NIKA2
- Just submitted proposal as P.I. requesting 20h in the upcoming summer campaign



Motte+2003, https://arxiv.org/abs/astro-ph/0208519

Cortes+2019, https://doi.org/10.3847/1538-4357/ab378d

Final remarks

- Polarisation at mm wavelength is involved in a variety of **interesting phenomena**
- In the quest for detecting primordial polarisation, we MUST improve our **calibration techniques** and the **control over systematics**
- We can probe **star formation regions** in polarisation, grasping crucial information on how magnetic fields influence the birth of massive stars
- We manage the **whole chain** from the fabrication of detectors, the cryogenics, the optics to the pipeline and final results, using a fully equipped lab (also in **collaborations** with external teams)
- With "home-made" **KIDs detectors**, we dispose of a powerful tool to investigate astrophysics, cosmology and also dark matter physics

Thank you !

Which phenomena generate polarisation?

Mostly non-thermal processes

Astrophysical

- Scattering → photons get scattered by gas or dust particles in a particular direction
- Magnetic fields → via the Zeeman effect, atoms or molecules split due to the presence of MF and photons interacting with them get polarised
- Synchrotron radiation → emitted in regions where high-energy charged particles spiral along MF

Cosmological

- Thomson scattering → during decoupling, photons get scattered off free electrons perpendicular to their motion
- Gravitational lensing → clusters or dark matter structures bend passing photons and induce polarisation
- Re-ionisation → imprint of newly formed stars and galaxies on CMB photons

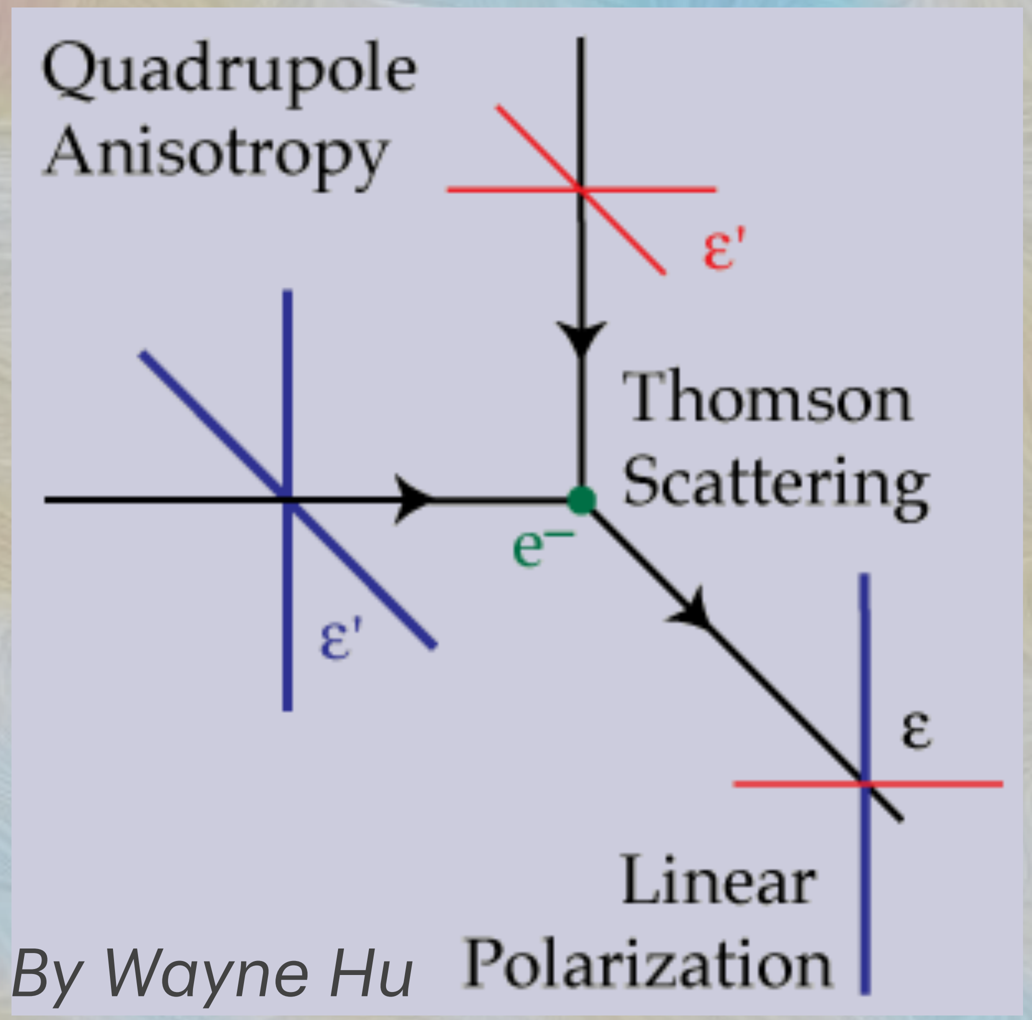
CMB polarisation

E modes

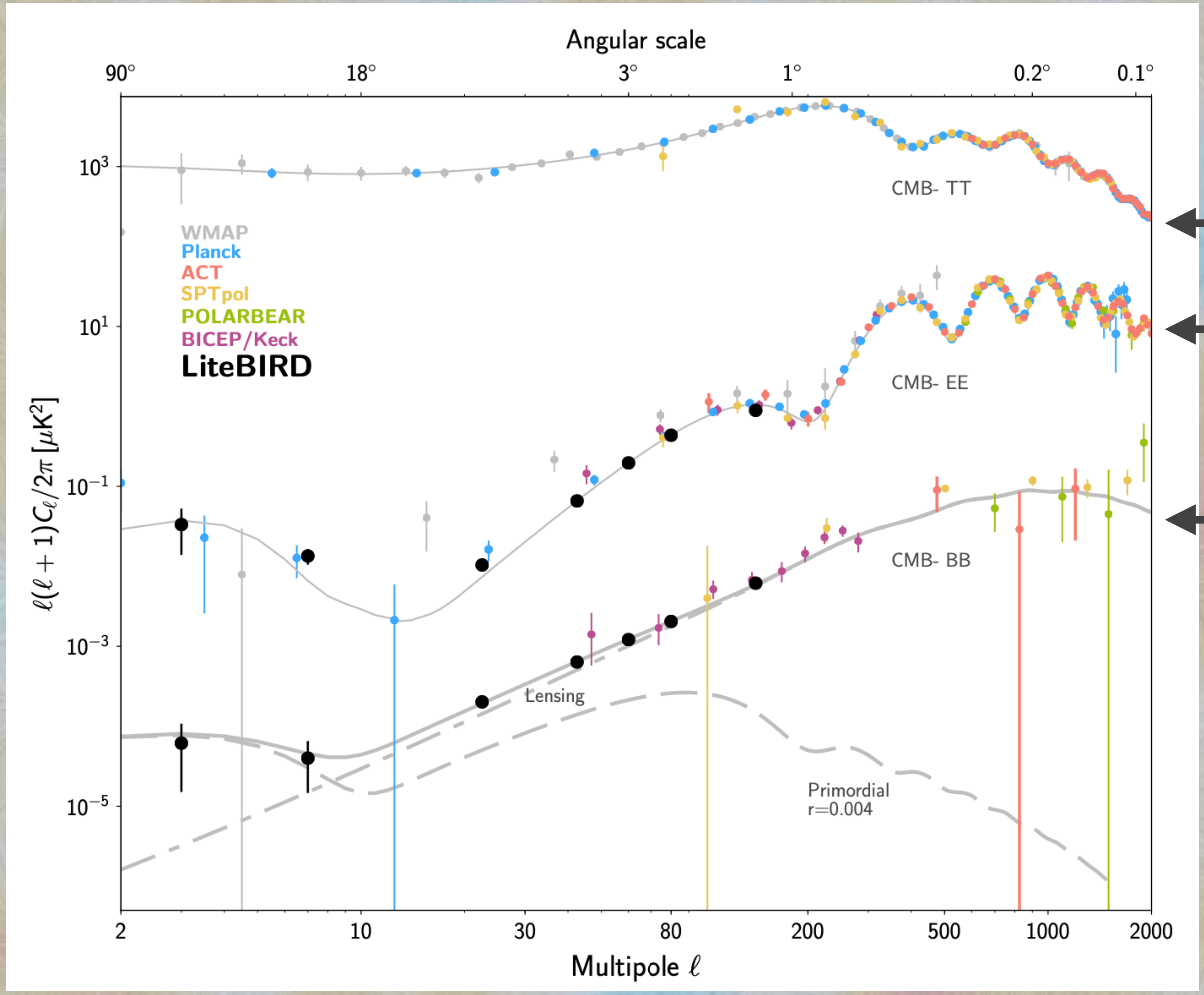
- Arise from density fluctuations and scattering

B modes

- Arise (allegedly) from gravitational waves produced during cosmic inflation



By Wayne Hu



Maffei+2021

Many points, low error bars

Many points, higher error bars

Few points, huge error bars

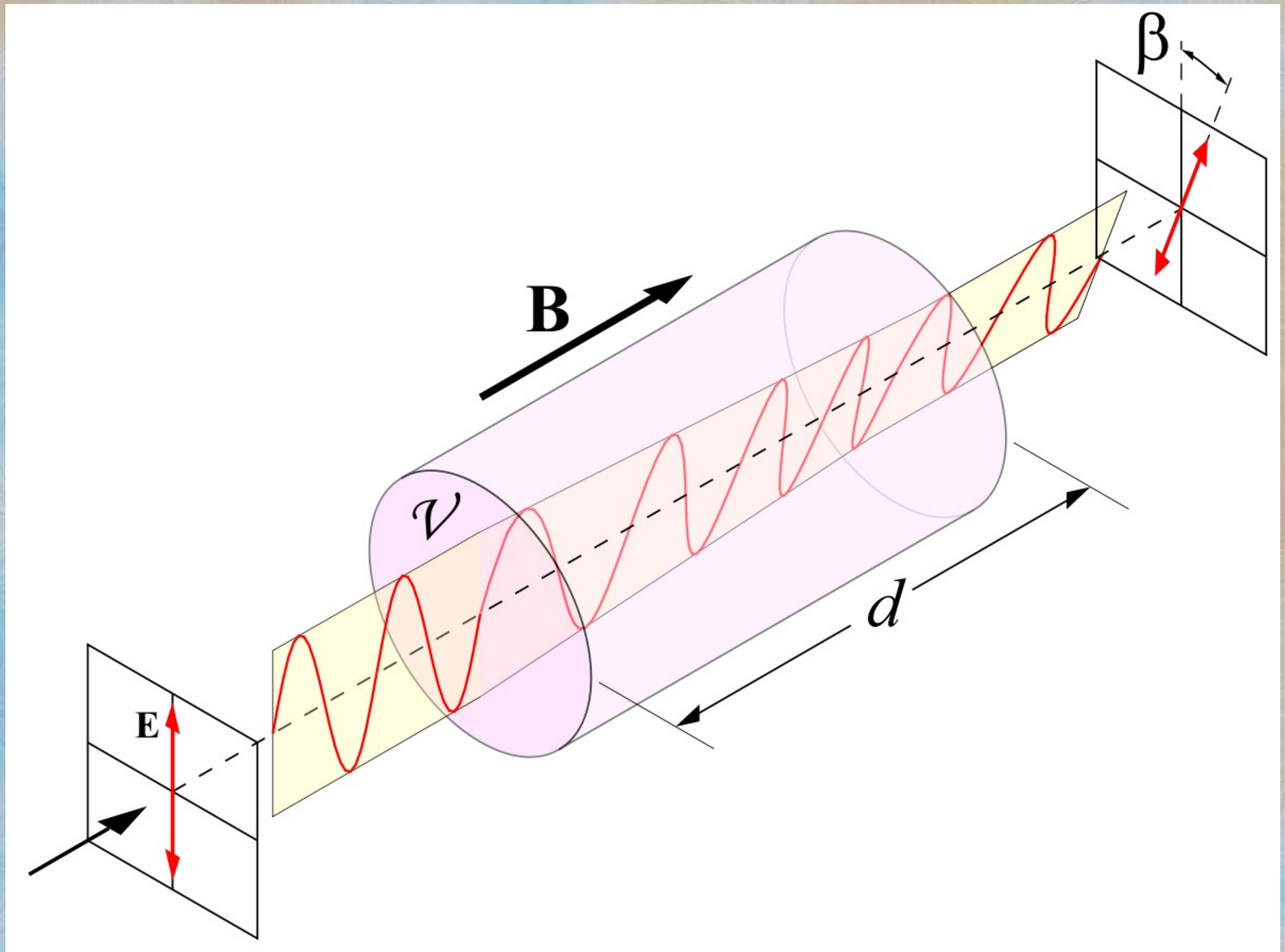
Faraday rotation

An example of process that generate circular polarisation

- Phenomenon in which the plane of linear polarisation rotates as it propagates through a medium with MF

- The amount of rotation is directly proportional to the strength of MF and the distance traveled through the medium

- It is one of the spurious effect that change E-modes into B-modes



With KIDs we can also look for dark matter !

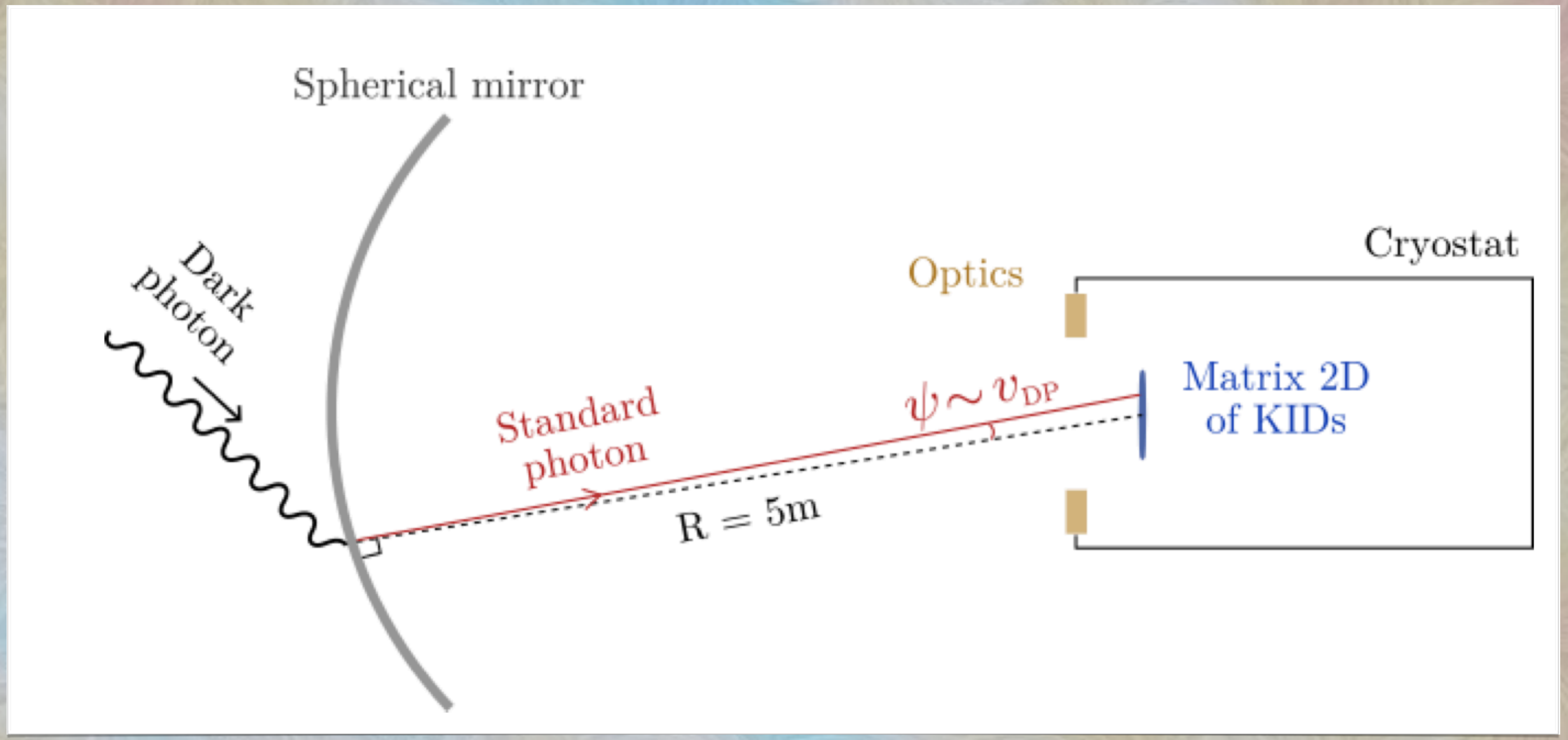
Directional detection of meV dark photons with Dandelion

C. Beaufort,[a] M. Bastero-Gil,[b,a] A. Catalano,[a] D-S. Erfani-Harami,[a] O. Guillaudin,[a] D. Santos,[a] S. Savorgnano,[a] and F. Vezzu[a]

[a]Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS/IN2P3, 38000 Grenoble, France
[b]Departamento de Física Teórica y del Cosmos, Universidad de Granada, Granada-18071, Spain

E-mail: cyprien.beaufort@lpsc.in2p3.fr, mbg@ugr.es, daniel.santos@lpsc.in2p3.fr

Working principle of Dandelion



Setup installed in the cryogenic lab in November 2023

Acquisition of the first data and raw analysis in January 2024

Currently working on data analysis