Circular polarization measurement using continuously rotating half-wave plate

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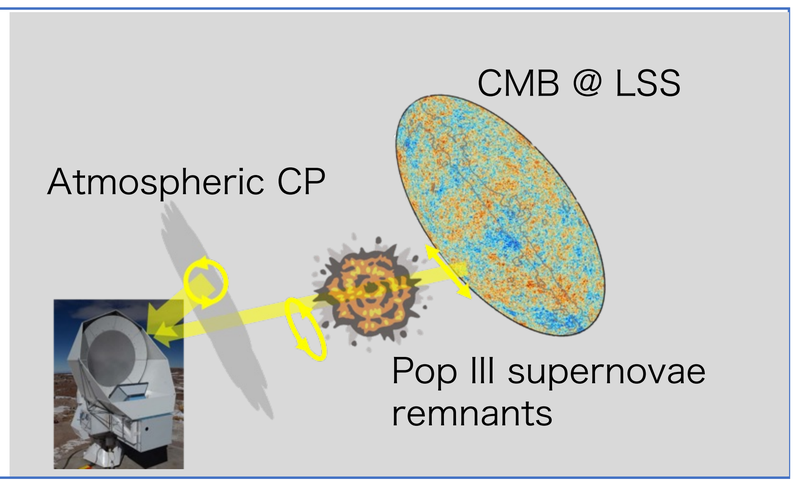
Introduction

- Cosmic Microwave Background (CMB) has only **linear polarization** at the last scattering surface (LSS)
  - Due to the Compton scattering
  - Measuring the B-mode polarization pattern of the CMB will reveal the inflation theory
- **Possibility of circular polarization (CP) of CMB** during propagation of the universe
  - Faraday conversion by Pop III supernovae remnants, galaxy clusters
  - Lorentz violation etc.
- Atmospheric circular polarization
  - Much larger than extragalactic CP → Foreground (noise)
- Measure atmospheric circular polarization to demonstrate the CP measurement / remove foreground signal using POLARBEAR data

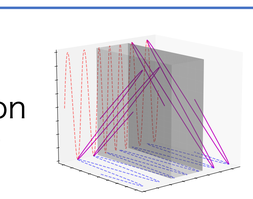


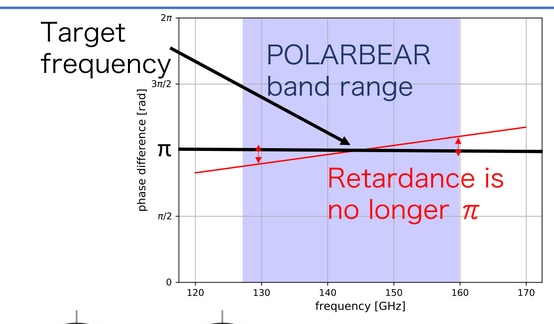
How to measure the circular polarization?

- Most of current/future CMB experiments are sensitive to linear polarization
- Use leakage between circular and linear polarization due to the frequency dependence of half-wave plate (HWP)
  - An optical device that creates a half-wave optical path difference (π retardance) between orthogonal waves
  - Continuously rotating HWP works as a modulator of linear polarization
- The optical path difference depends on the wavelength ↔ frequency
- The retardance at the frequency out of the target frequency is no longer π

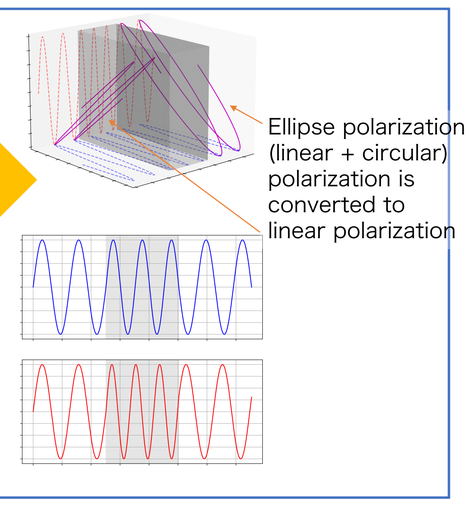
→ **leakage between circular and linear polarization**

- CP signal in the second harmonics of the HWP rotation frequency ↔ linear polarization in fourth harmonics



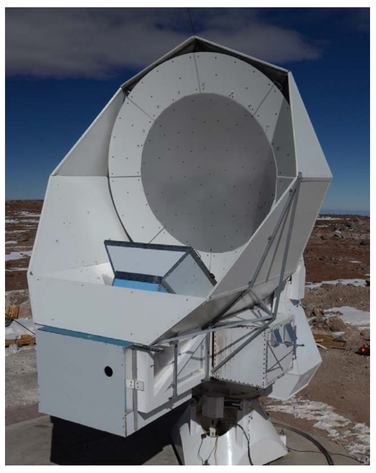


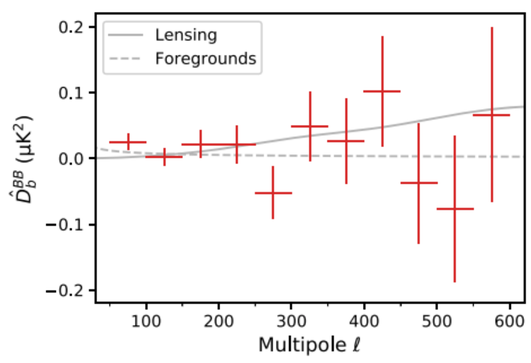
(A. Kusaka, T. Essinger-Hileman et al., 2014)



The POLARBEAR experiment

- Ground-based CMB experiment
  - At Atacama, Chile (James Ax Observatory)
  - From January 2012 to December 2016
  - Observed around 150 GHz
  - Off-axis Gregorian with 2.5 m primary mirror
  - 1,274 transition edge sensor (TES) bolometers
  - Using continuously rotating HWP from May 2014
    - Suppress 1/f noise
- Science results
  - Detection of lensing B-mode power spectrum using CMB self-correlation (POLARBEAR Collaboration, 2014)
  - Tensor-to-scalar ratio r < 0.33 at 95% confidence level (POLARBEAR collaboration, 2022)
  - Constraints on axion-like polarization oscillations (POLARNEAR collaboration, 2023) → Yuji's talk on Wednesday, 13



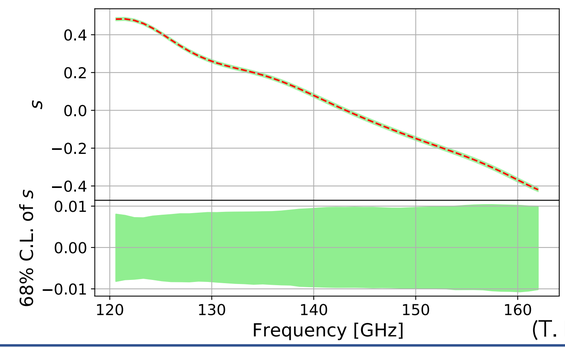


HWP of POLARBEAR

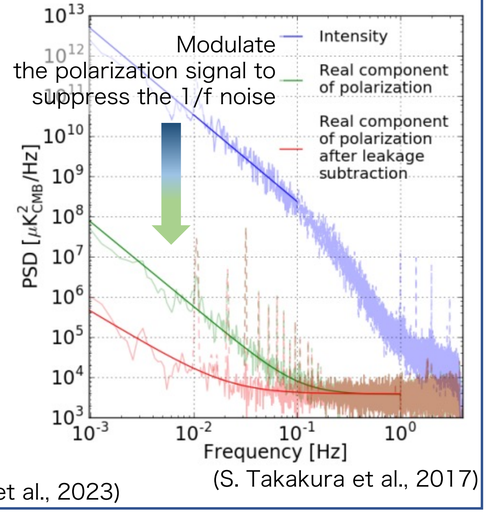
- Sapphire with anti-reflection (AR) coating
  - 28 cm diameter & 3.1 mm thick
  - Rotated at 2 Hz (Modulation frequency = 8 Hz)
  - Placed at the prime focus of the telescope

Evaluate the leakage between circular and linear polarization using lab data

- Data were taken in April 2014 before installing the telescope at the KEK laboratory
- ~ 30% leakage at the edge of the band (~ 10% after band-averaging)



(T. Fujino et al., 2023)



(S. Takakura et al., 2017)

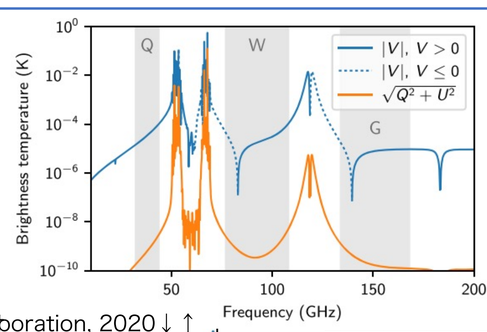
Atmospheric circular polarization

Source: Zeeman effect of Oxygen molecules in the atmosphere

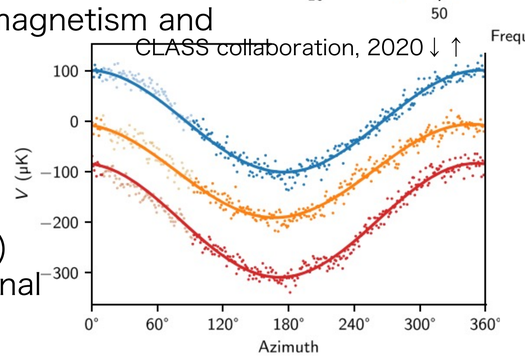
- Oxygen molecules cause the Zeeman effect by the Earth's magnetism
- Right or left circular polarization appears at the lower or higher side of the resonance line
  - Resonance lines: 118.8 GHz, 50 – 70 GHz
- Depend on the angle difference between Earth's geomagnetism and observation direction

Past Results

- CLASS observed the atmospheric CP at 40 GHz (CLASS collaboration, 2020)
  - Using a Variable-delay polarization modulator (VPM)
    - Modulate both linear and circular polarization signal
  - Also calculated expected spectrum

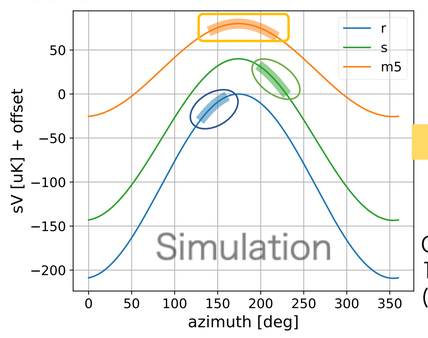


CLASS collaboration, 2020 ↓ ↑



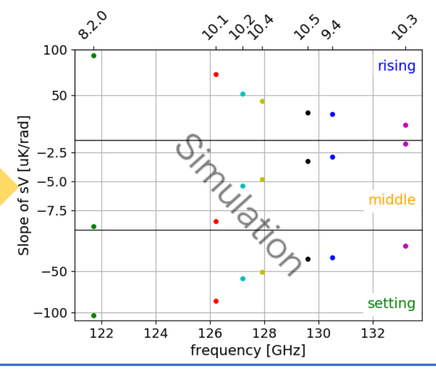
POLARBEAR case

- POLARBEAR hasn't observed a full sky region → Calculating slope of CP signal as a parameter
- We may see the frequency dependence coming from wafer (detector) fabrication
- **The analysis is in progress** with Satoru at Kyoto Univ.



We observed a part of the sky → Calculate the slope of CP signal

Observed some 1-D maps (constant elevation)



Summary

- Circular polarization of CMB is a new tool for searching the universe
- POLARBEAR can observe the CP signal using the continuously rotating HWP leakage
- Removal of atmospheric CP as a foreground noise is important
  - We observe this signal to remove noise/to demonstrate the CP signal detection

Expected CP sensitivity

- From HWP leakage and noise level from B-mode observation
- POLARBEAR has an advantage in the high-ell region