A measurement of atmospheric circular polarization with POLARBEAR

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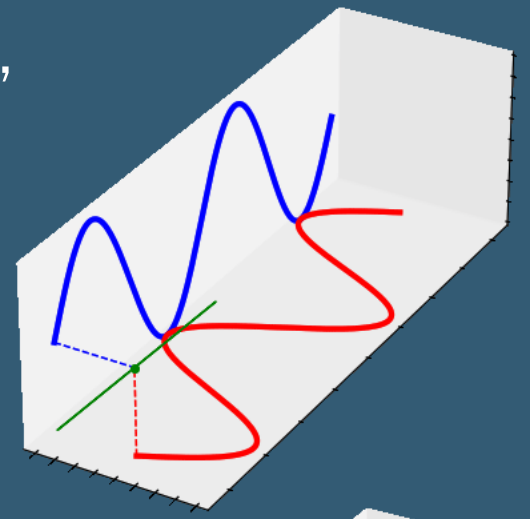
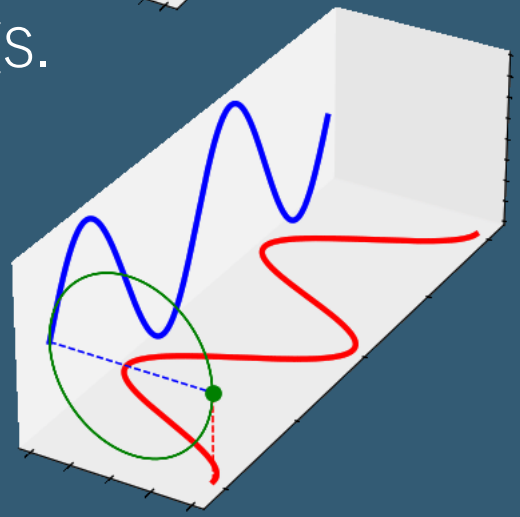
Conference name

Introduction

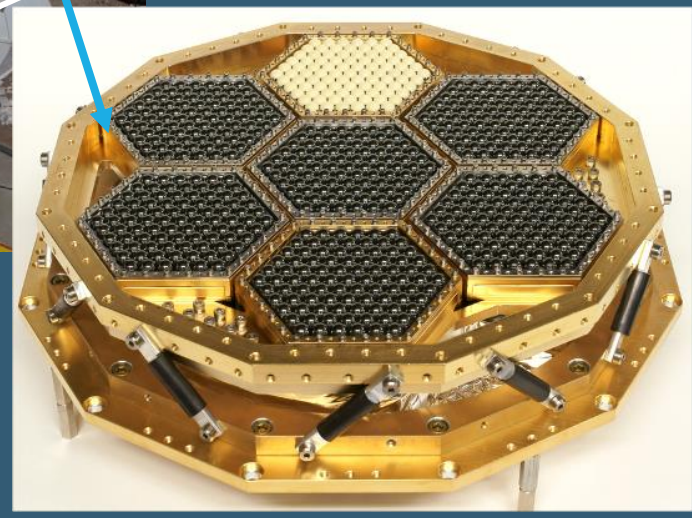
- The Cosmic Microwave Background (CMB) is the “background” radiation from farthest away
- CMB is known to be only slightly linearly polarized
- Some exotic theories predict linear to circular polarization conversion during its propagation
  1. Faraday conversion due to the magnetic field in the first star remnants [S. De and H. Tashiro 2015]
  2. Lorentz-violating electrodynamics [F. Finelli and M. Galaverni 2009]
  - Any objects in the universe affect the state of observed CMB
- We aim to search for CMB circular polarization using POLARBEAR data





The POLARBEAR Experiment

- CMB observation experiment (2012-2017)
- Main target: B-mode polarization
- Frequency: 150 GHz
- 1274 TES detectors on 7 wafers
- A continuously rotating half-wave plate (HWP) was installed in 2014
  - For linear polarization modulation
- Main results: Detection of lensing B-mode polarization in 2014 [POLARBEAR collaboration, 2014 ApJ 794 171]

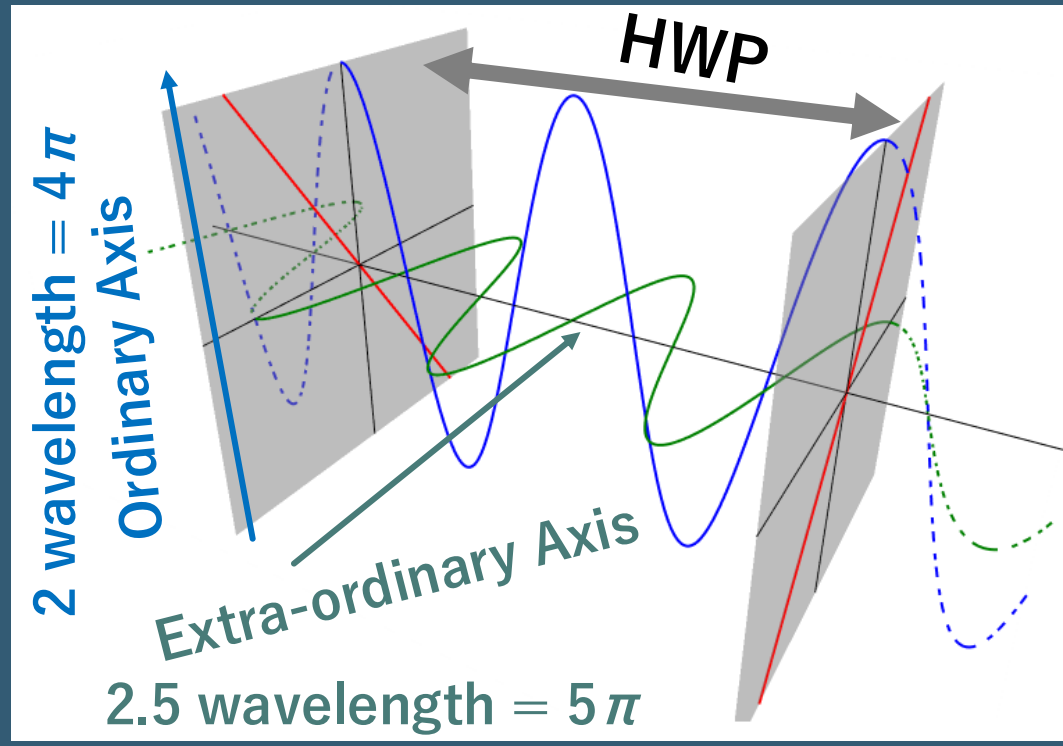


Measurement Method in Circular Polarization Measurement

The optics of POLARBEAR are designed to be linear polarization sensitive

⇒ Using a leakage of a half-wave plate (HWP)

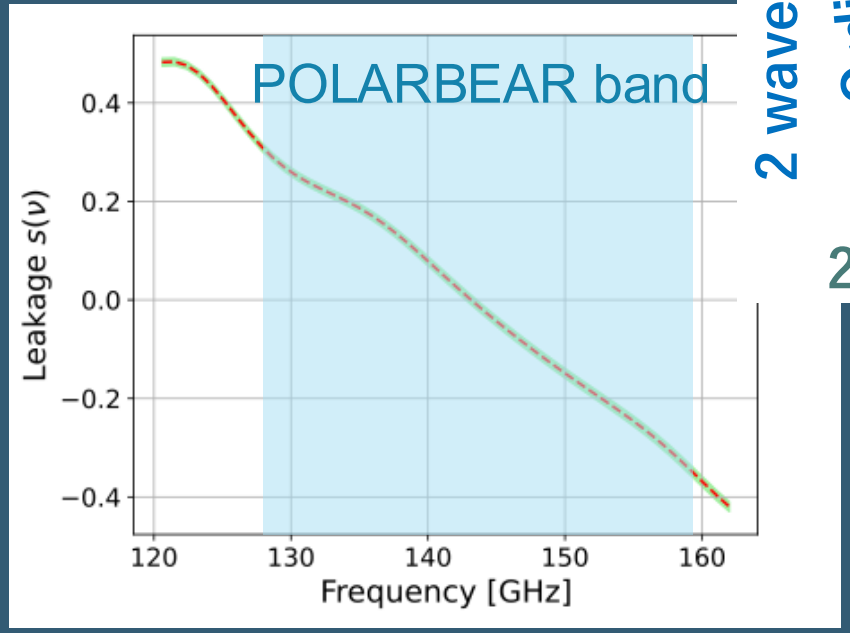
- An optical device that creates the optical path difference of half a wavelength (↔ phase of π)
  - Usually birefringent material (e.g., Sapphire) is used
  - Flip the linear polarization
- Widely used as a linear polarization modulator

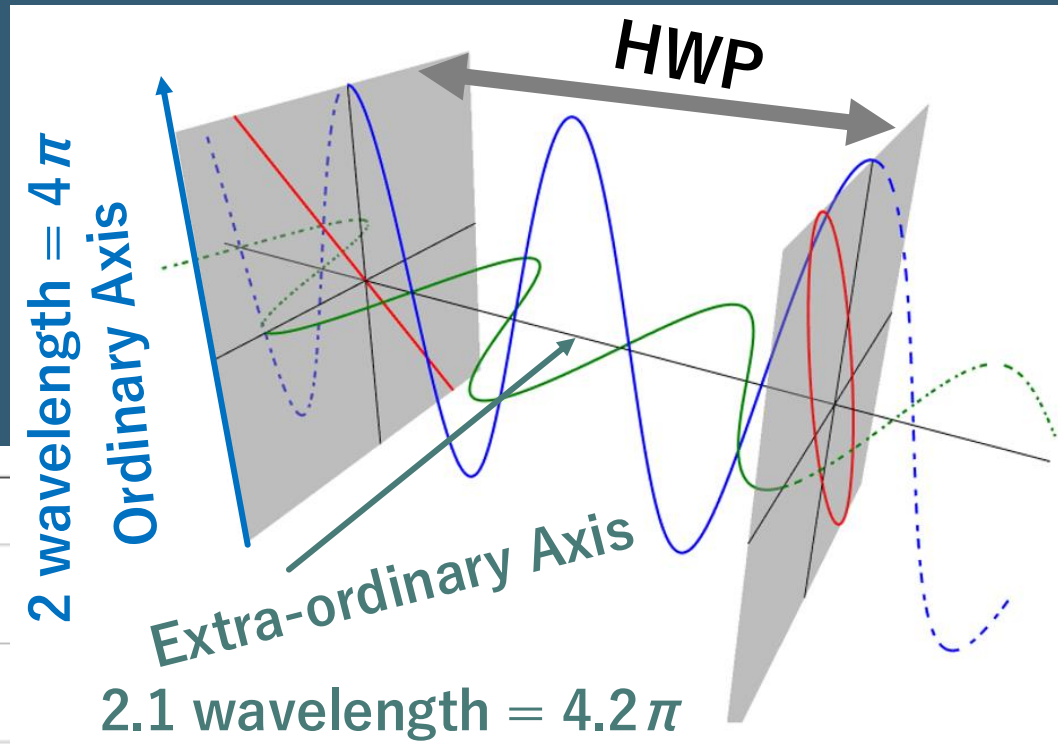


Measurement Method in Circular Polarization Measurement

- Outside the target frequency, the phase difference shift from π
  - Mix the linear and circular polarization states

Leakage between linear and circular polarization occurs





Measurement Method in Circular Polarization Measurement

- The circular polarization appears in the second harmonics (2f) signal
  - ↔ Usual linear polarization signal appears in 4f signal

Leakage from circular to linear polarization

Leakage from Intensity to linear polarization

$$d_{2\mathrm{f}} = [\rho I + isV]\exp(-2i(\theta_{\mathrm{WHWP}} + \theta_{\mathrm{det}})) + \rho[Q + iU]\exp(-2i\theta_{\mathrm{WHWP}})$$

Leakage from linear polarization to intensity

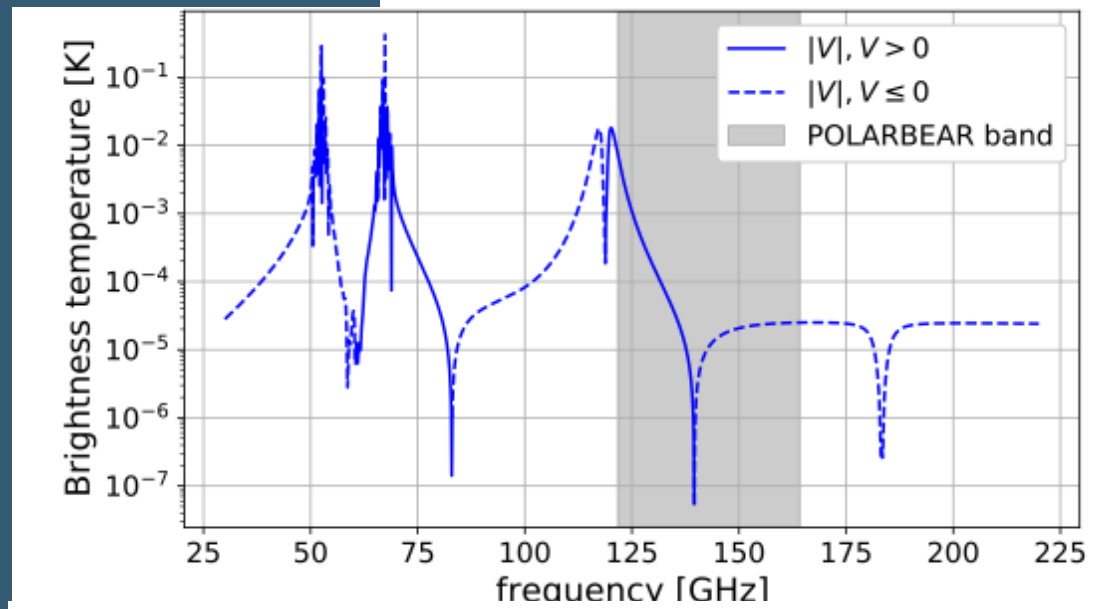
- Separable using angle dependence, Re/Im separation, …

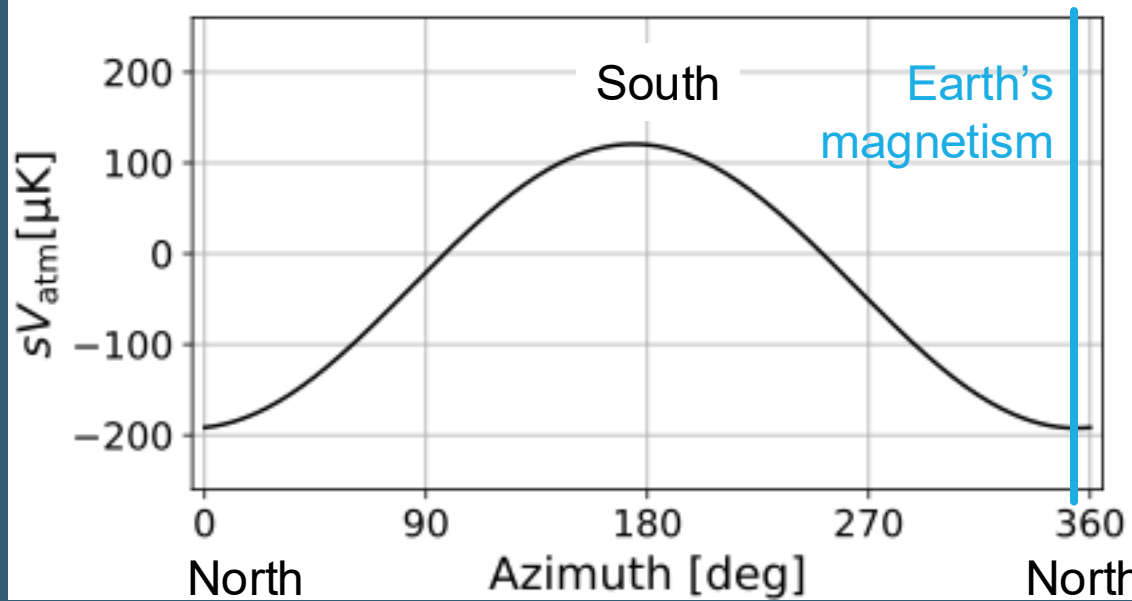
I: Intensity signal
Q/U: Linear pol
V: Circular pol
ρ: Leakage between I and Q due to HWP
s: Leakage between U and V due to HWP
θ_{WHWP}: HWP angle
θ_{det}: Detector angle

Evaluate this method using a bright circular polarization signal

A Bright Signal: Atmospheric Circular Polarization

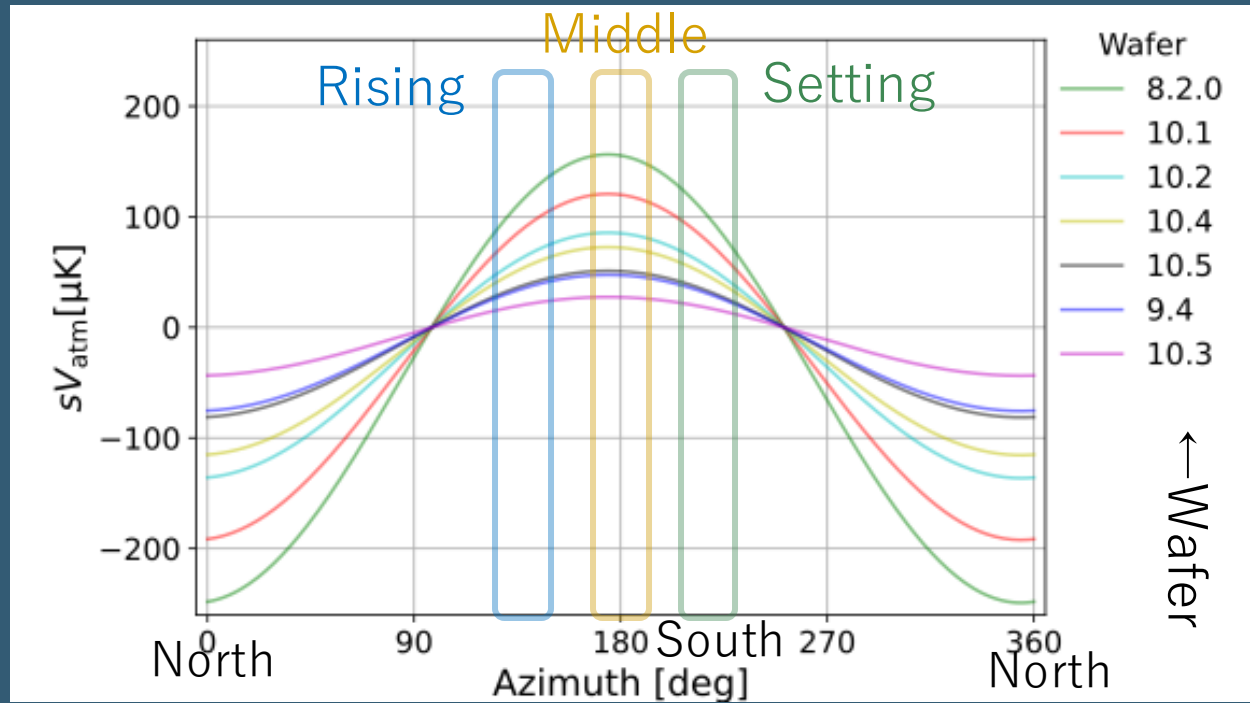
- Caused by the Zeeman splitting of the Oxygen molecules in the atmosphere due to Earth's magnetism
- Sharp positive and negative peaks around 50-70 GHz and 120 GHz
- Larger than cosmological signals
  - ~ 100 μK in POLARBEAR band
- Directional dependence
  - The absolute signal amplitude is maximum when the observation direction aligns with that of Earth's magnetism





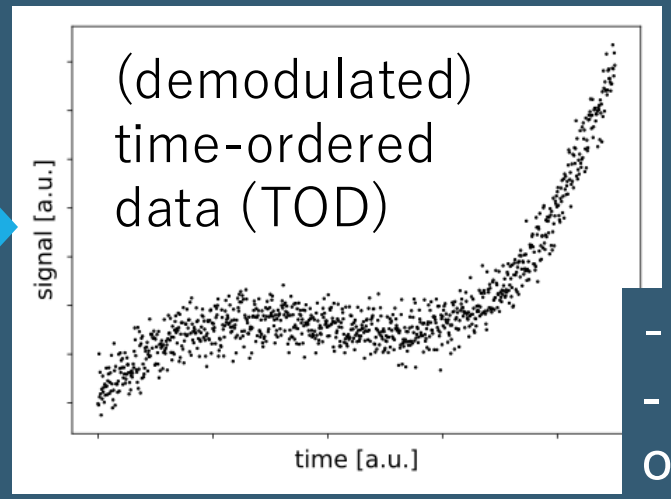
Observed data Used in the Analysis

- POLARBEAR data after installation of HWP
  - From May 2014 to January 2017, ~ 3 years
- Observation directions are categorized into 3
  - (az, el) = Rising: (145°, 30°), Middle: (180°, ~ 55°), Setting: (215°, 35°)
- Calculated the azimuthal "slope" for the evaluation
- The expected amplitude differs between wafers



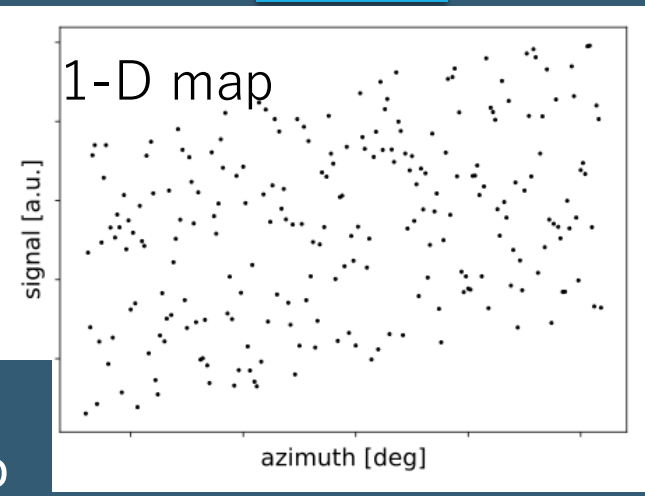
Sketch of Data Analysis Procedure

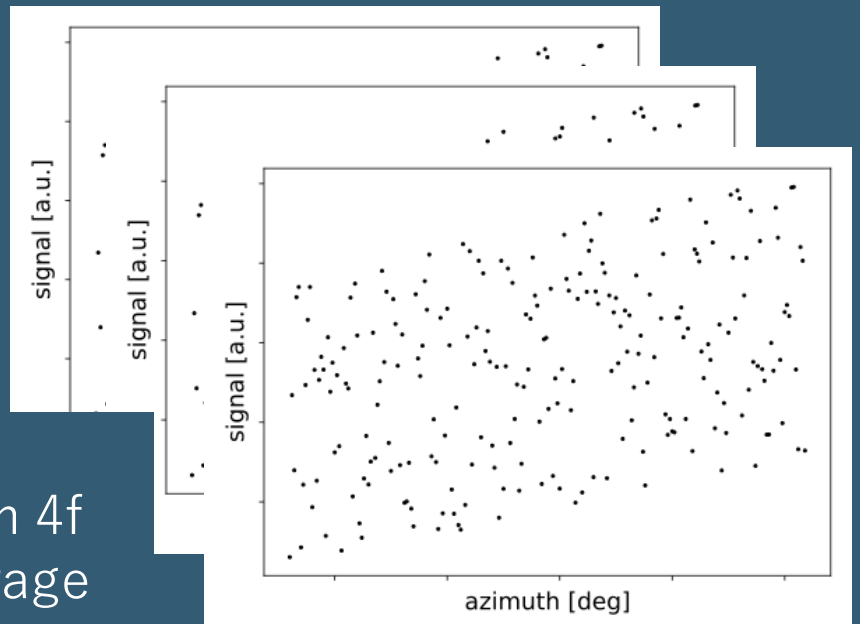
Observe the sky



Observed direction
$(\theta_{\mathrm{az}}(t), \theta_{\mathrm{el}}(t))$

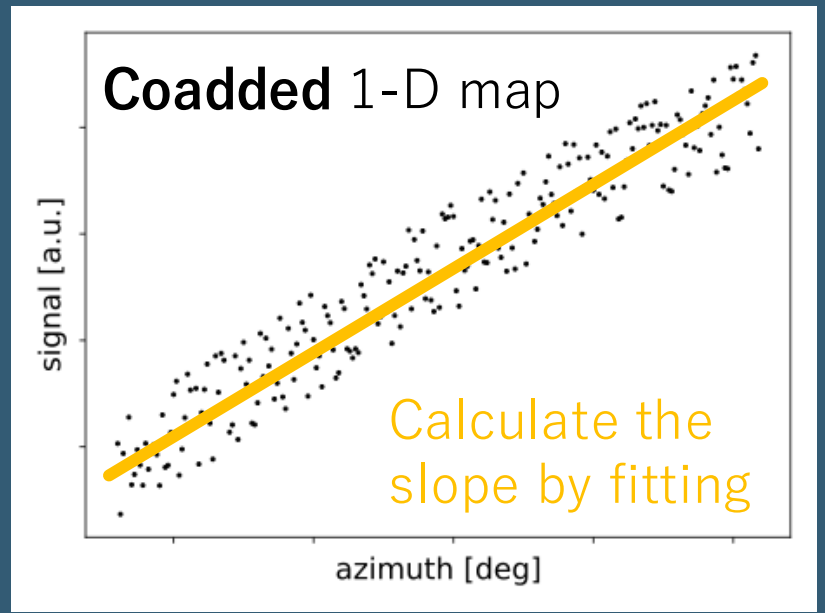
- Remove leakage from 0f
- Convert time information to observation direction





- Coadd data from detectors and observations

- Remove leakage from 4f
- Weight average



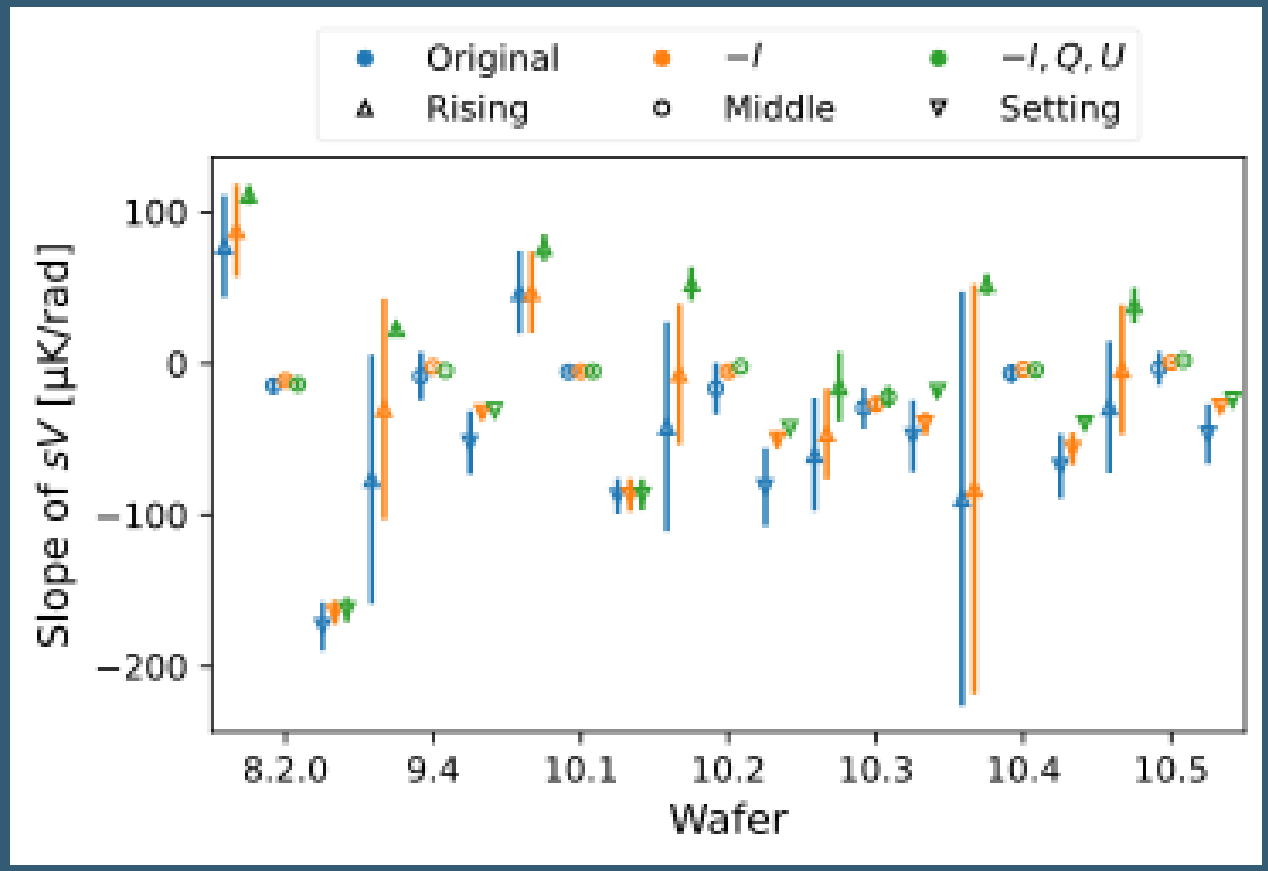
Leakage Subtractions

- Found Additional leakage from intensity and linear polarization

◆ Intensity
- Signal source:
  Atmospheric emission
- Leakage Cause:
  Nonlinearity of detectors

◆ Linear polarization
- Signal source:
  Instrumental polarization
- Leakage Cause
  Slant incidence on the HWP

Remove them by taking correlation between 2f signal and 0f/4f signal



Systematic Error Estimations

- Evaluated various systematic errors
- In this slide I focus on two major errors
  1. Uncertainties of polarization angle
  2. Uncertainties of the detector bandpass

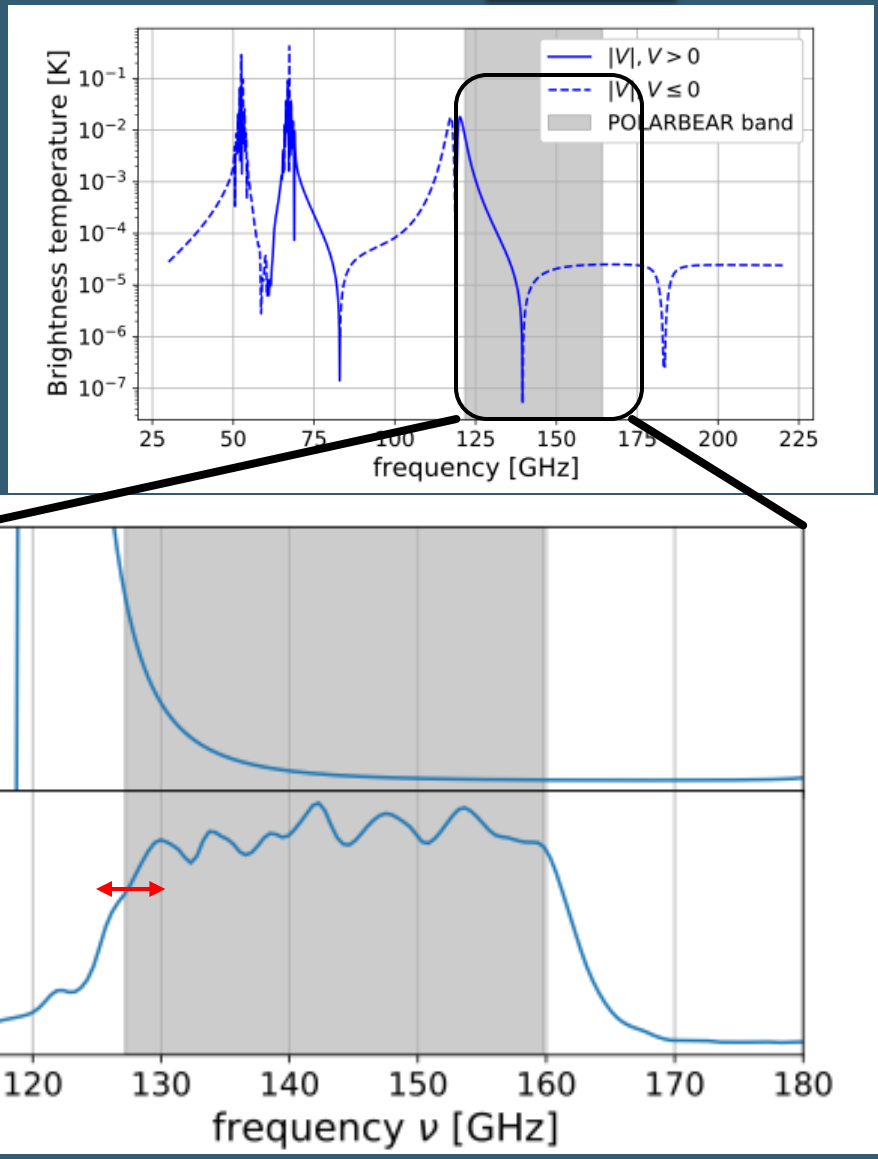
Systematic Error Estimation 1: Polarization Angle Uncertainty

- The polarization angle dependence differs between 2f (∋ circular pol) and 4f (≒ linear pol) signals
  - $d_{4f}(t) = \big(Q(t) + iU(t)\big)\exp(4i\theta + 2i\phi)$
  - $d_{2f}(t) = \big(\rho I(t) + isV(t)\big)\exp(2i\theta + 2i\phi) + \rho\big(Q(t) + iU(t)\big)\exp(2i\theta)$

  θ: absolute angle of HWP ϕ: detector polarization angle
- The angle calibration calibrate , thus is not calibrated
- Estimate θ from Tau A data before/after HWP installation
- Estimate $\Delta\theta$ from the variation of the real/imaginary component of the 2f signal

Systematic Error Estimation 2: Bandpass Uncertainty

- Atmospheric signals have sharp frequency dependence around the bandpass edge
- Consider the “frequency” uncertainty of the bandpass measurement
  - Estimate the effect from the frequency resolution of the FTS (1 GHz) and center frequency
- The effect is large at low frequency wafer

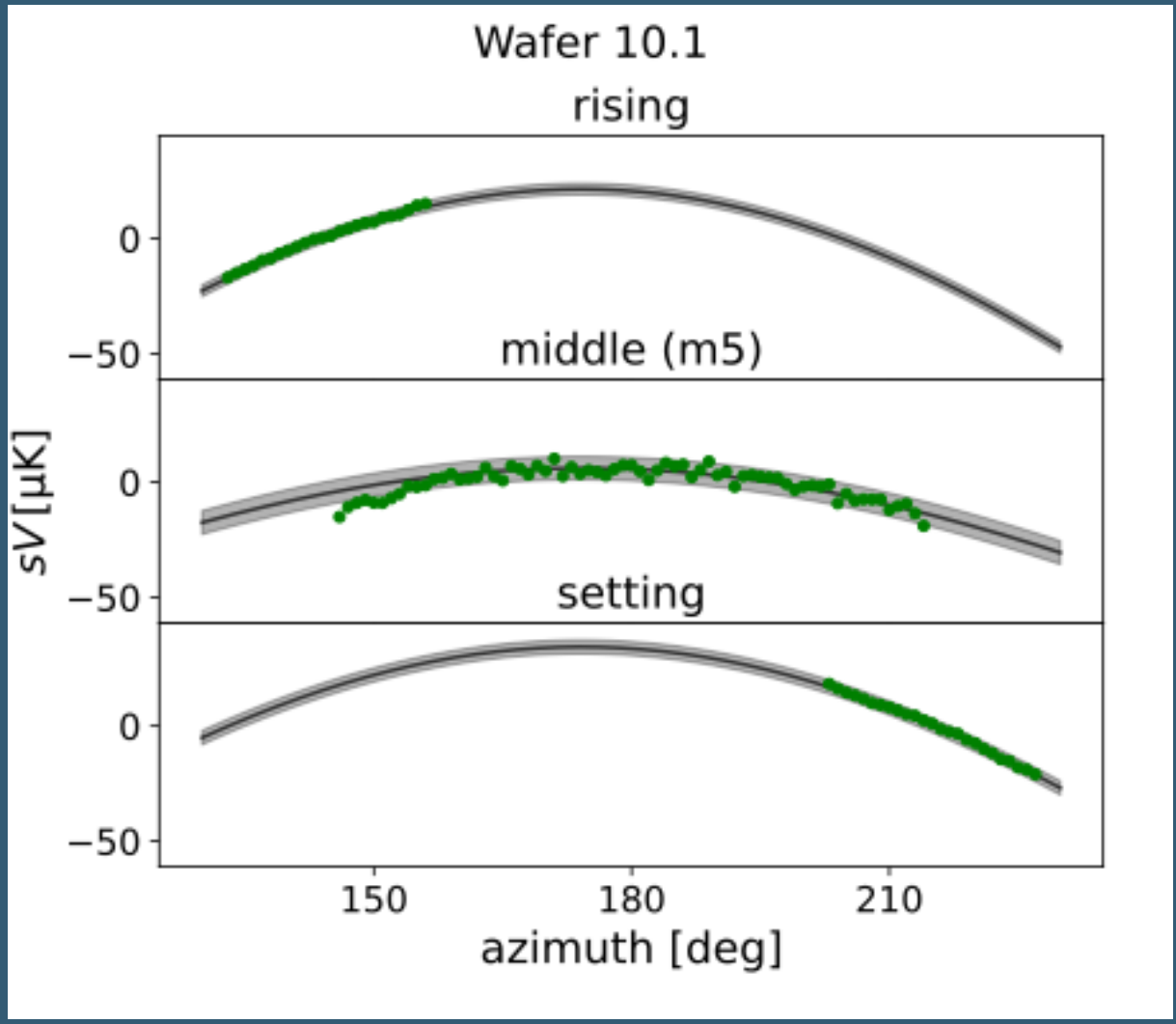


Results 1: Azimuthal Profiles

Example of azimuthal profiles

- Green points: observed signals
- Gray band: Simulation

- See a part of the sinusoidal curve
- Roughly confirm the consistency between observed data and simulation

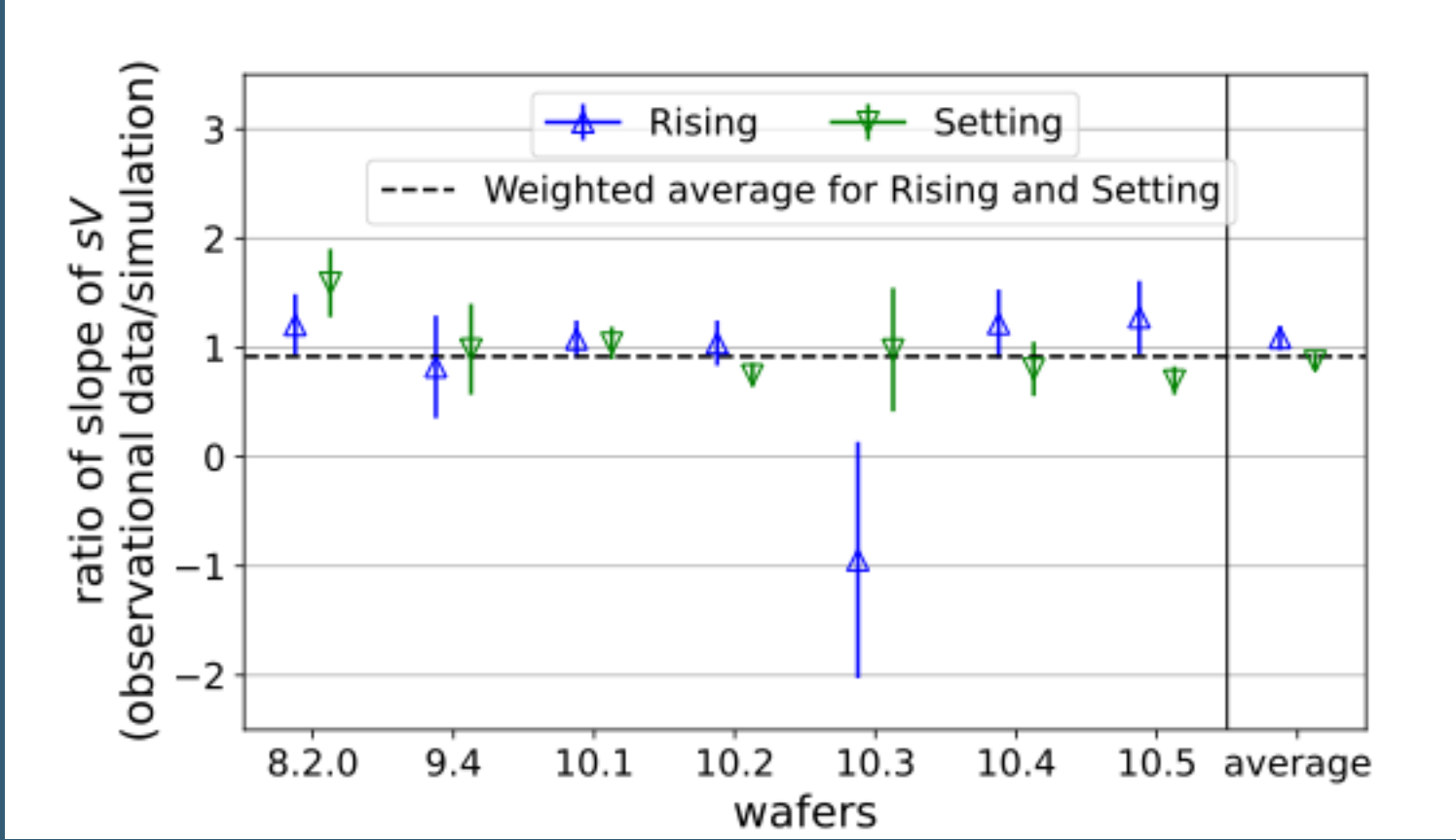


Results 2: Comparison with Simulation

- Calculate the ratio of azimuthal slope between observed data and simulation
- Rising: 1.09 ± 0.11
- Setting: 0.88 ± 0.08
- Total: 0.92 ± 0.07

Consistent within 1.1σ!

Confirmed that the observational and analysis method works correctly



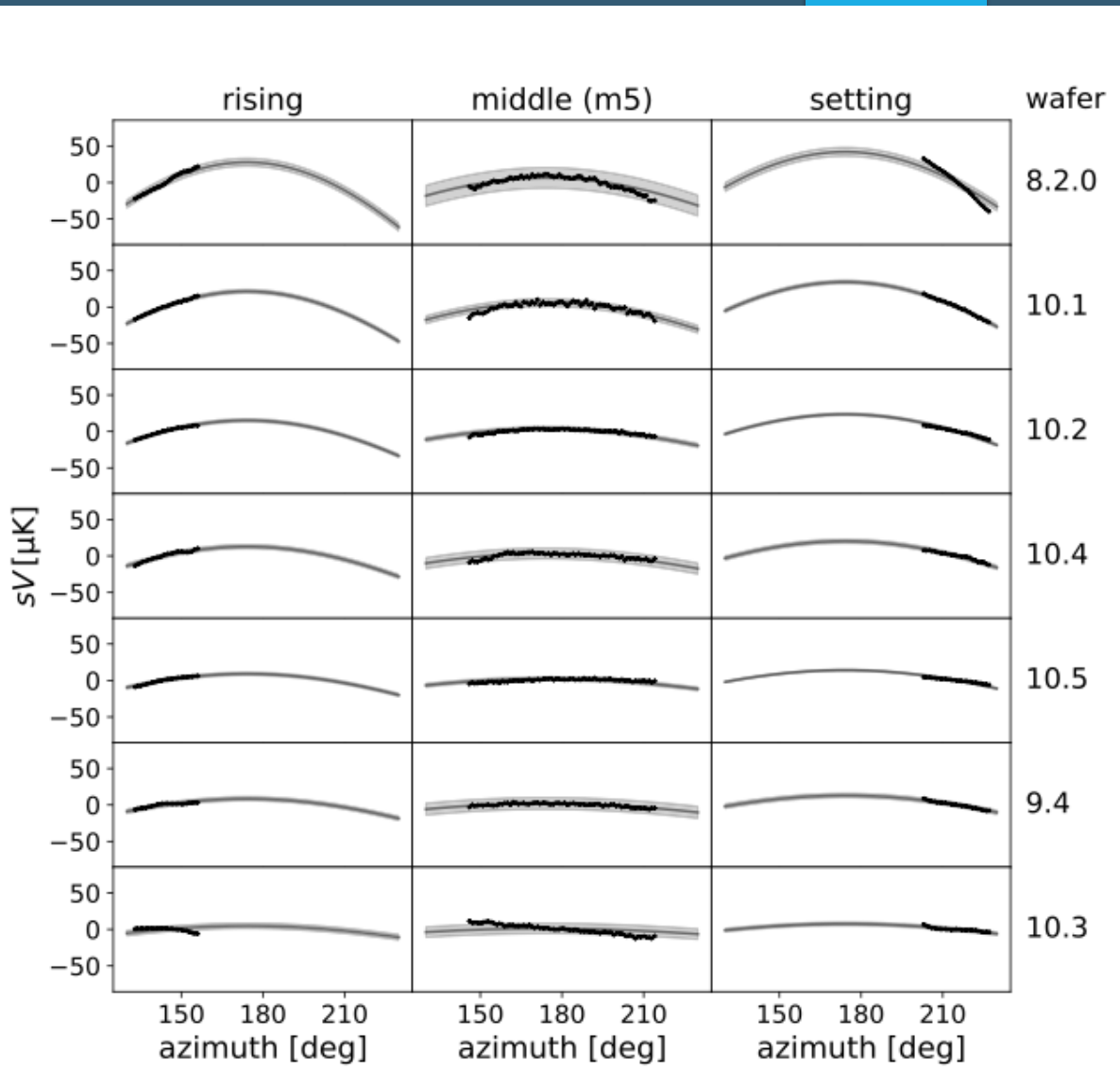
Summary

- CMB circular polarization observation could be a new tool to search for the universe
- We studied the circular polarization observation method with HWP using the POLARBEAR data
- We detected the atmospheric circular polarization signal using this method
  - Consistent with simulation within 1.1 σ
  - We also performed a detailed systematic error estimation
- This method is available for future CMB experiments

See the paper for details
https://doi.org/10.3847/1538-4357/ada89b

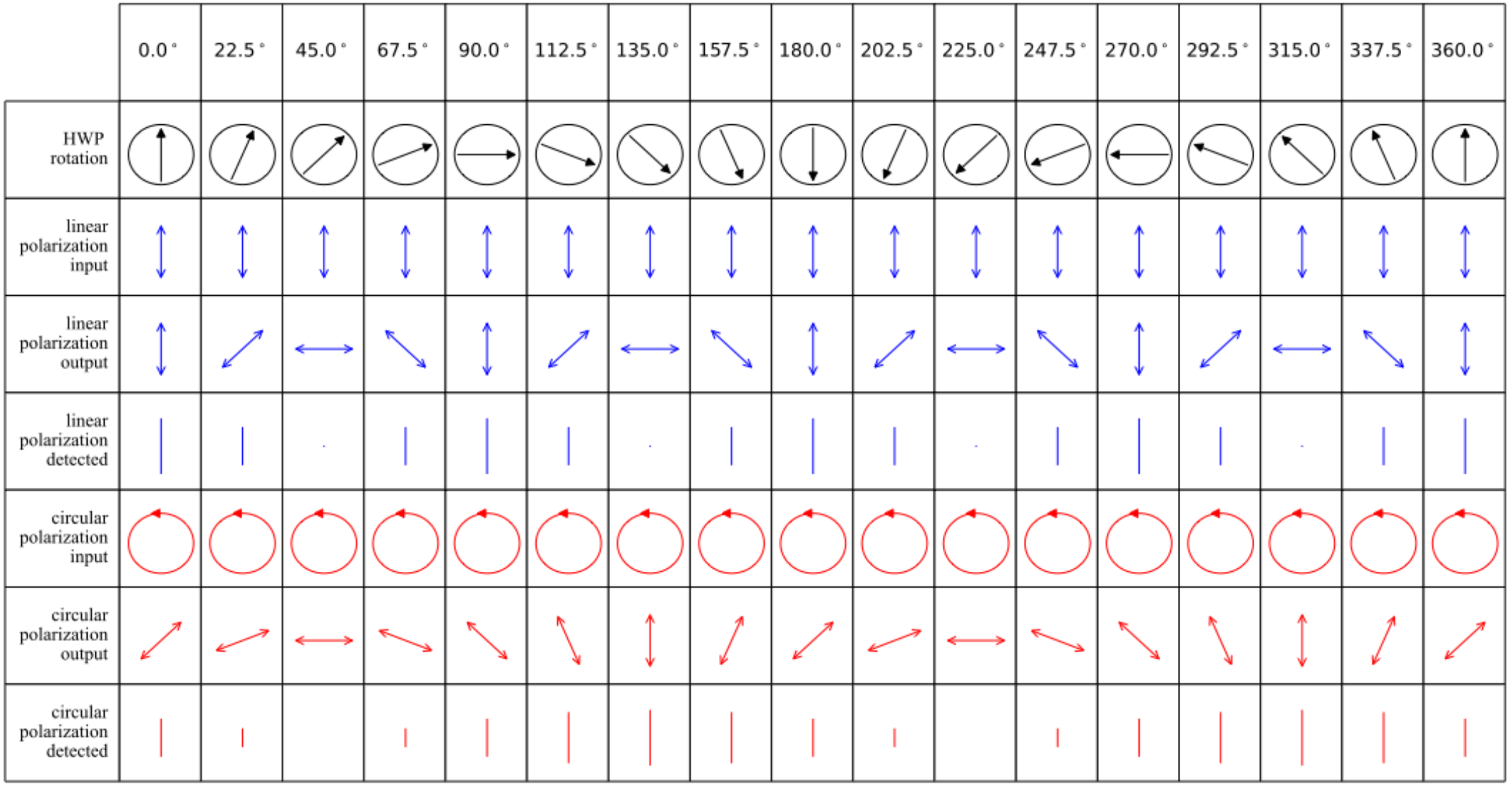
All 1-D maps

Wafer	Lowest freq.	Wafer	Lowest freq.
8.2.0	136.9 GHz	9.4	146.9 GHz
10.1	142.1 GHz	10.2	143.5 GHz
10.3	148.7 GHz	10.4	144.0 GHz
10.5	145.5 GHz		



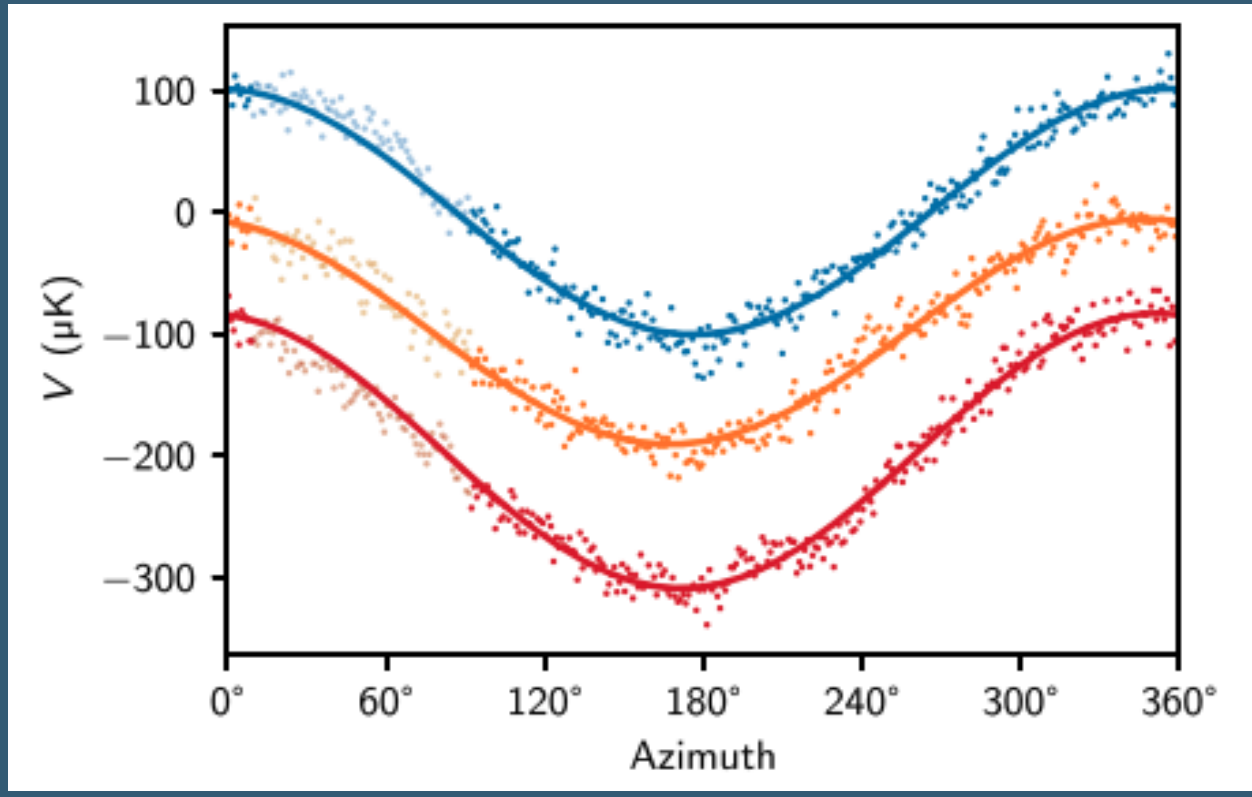
Systematic errors

No.	Source of (systematic) errors	Effect to the averaged ratio
0	(Statistical uncertainty)	(0.01)
1	Leakage subtraction	0.01
2	Uncertainty between observation periods	0.02
3	Polarization angle uncertainty	0.05
4	Uncertainty of gain	0.02/0.02
5	Bandpass uncertainty	0.04
6	Uncertainty of HWP model	0.03
7	Time variation of atmospheric model	< 0.01

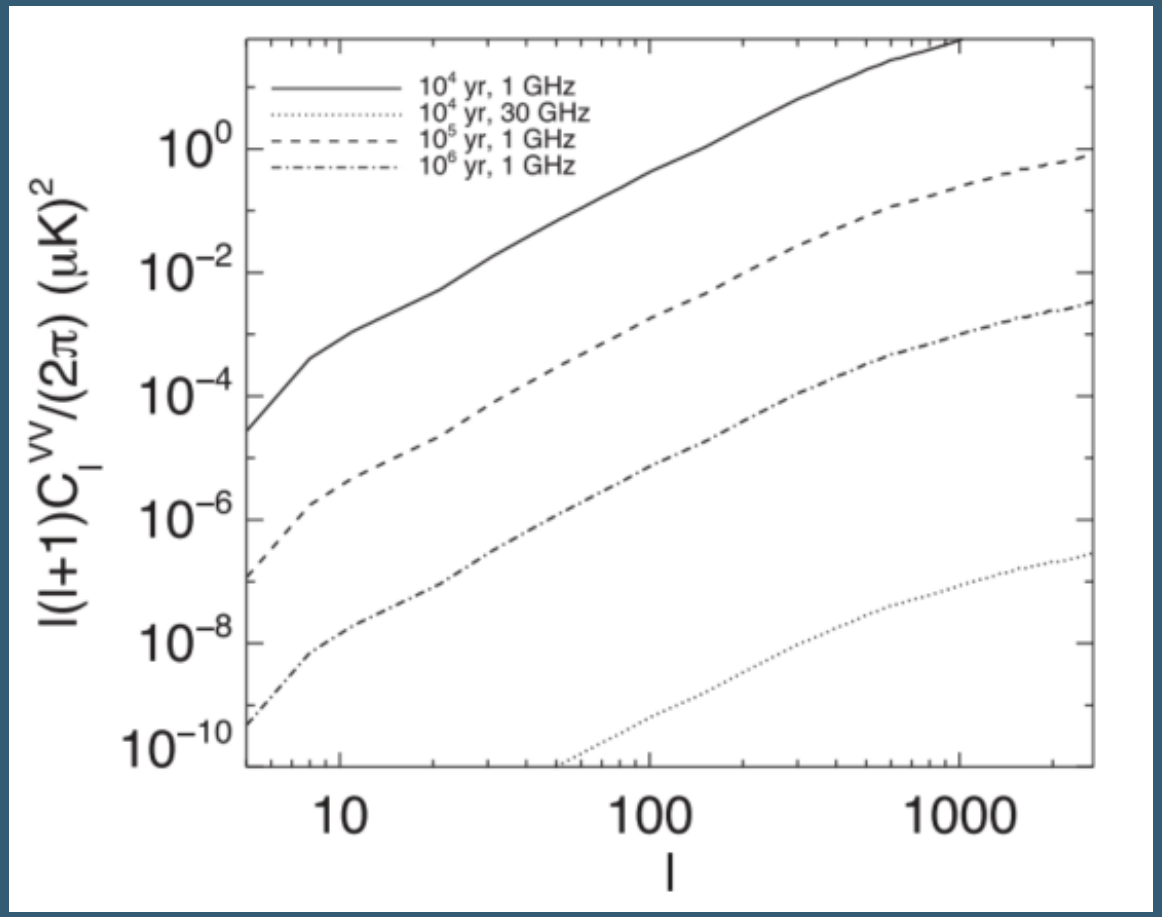

0.0°
22.5°
45.0°
67.5°
90.0°
112.5°
135.0°
157.5°
180.0°
202.5°
225.0°
247.5°
270.0°
292.5°
315.0°
337.5°
360.0°
HWP rotation
linear polarization input
linear polarization output
linear polarization detected
circular polarization input
circular polarization output
circular polarization detected

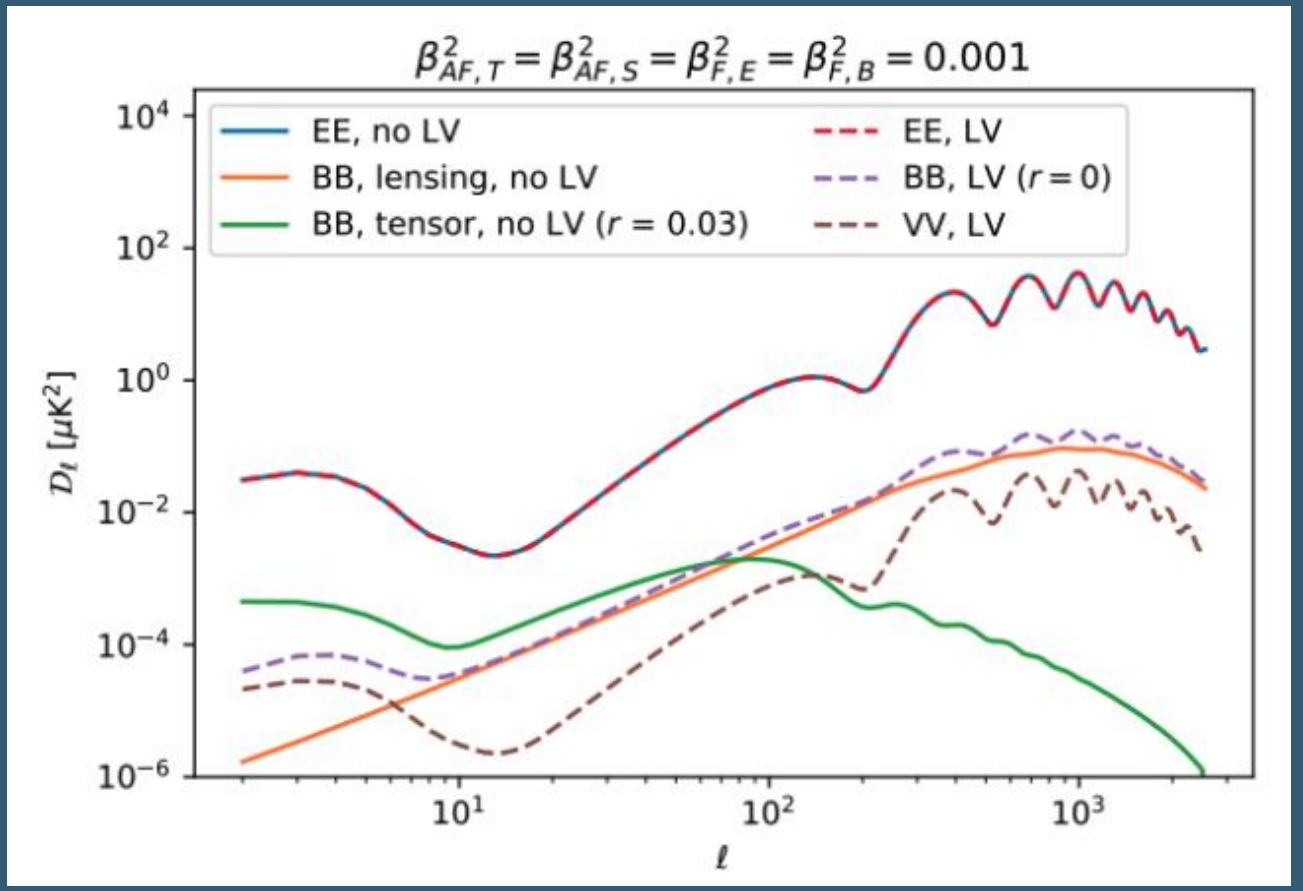
Past observations

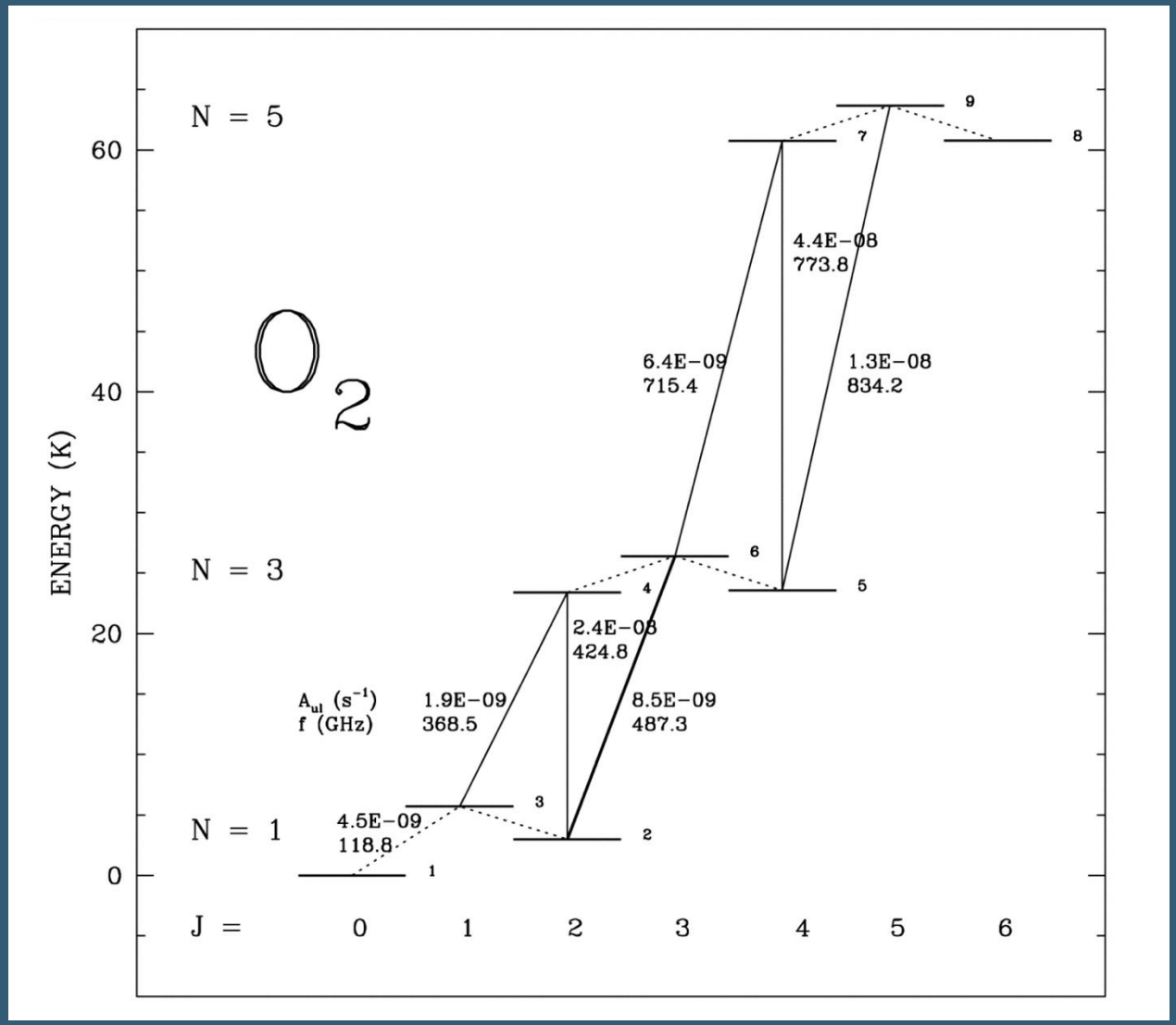
- The CLASS experiment
  - 40 GHz
  - Variable-delay Polarization Modulator (VPM)
  - Chile
  - 2016-9 – 2018-2

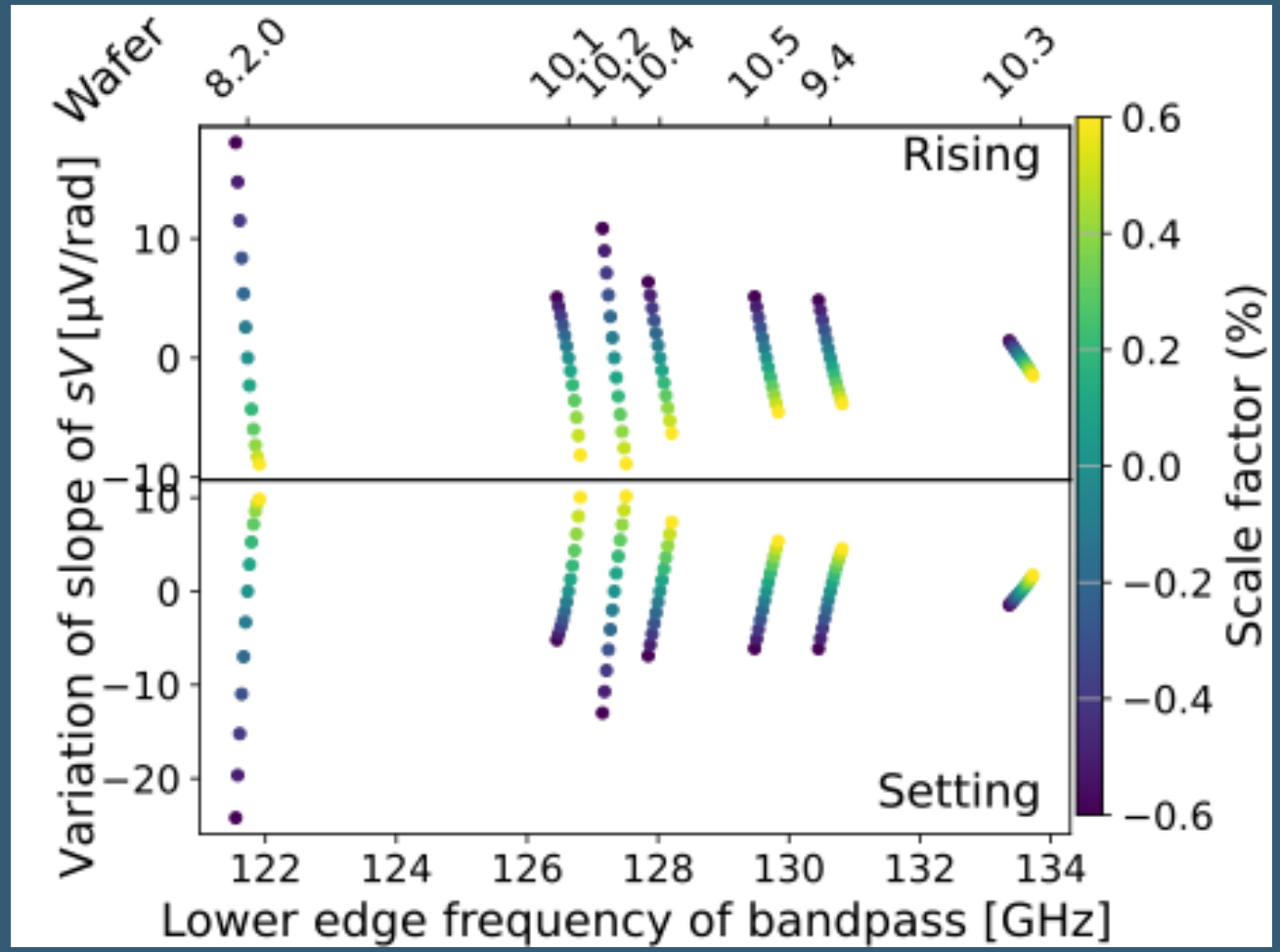


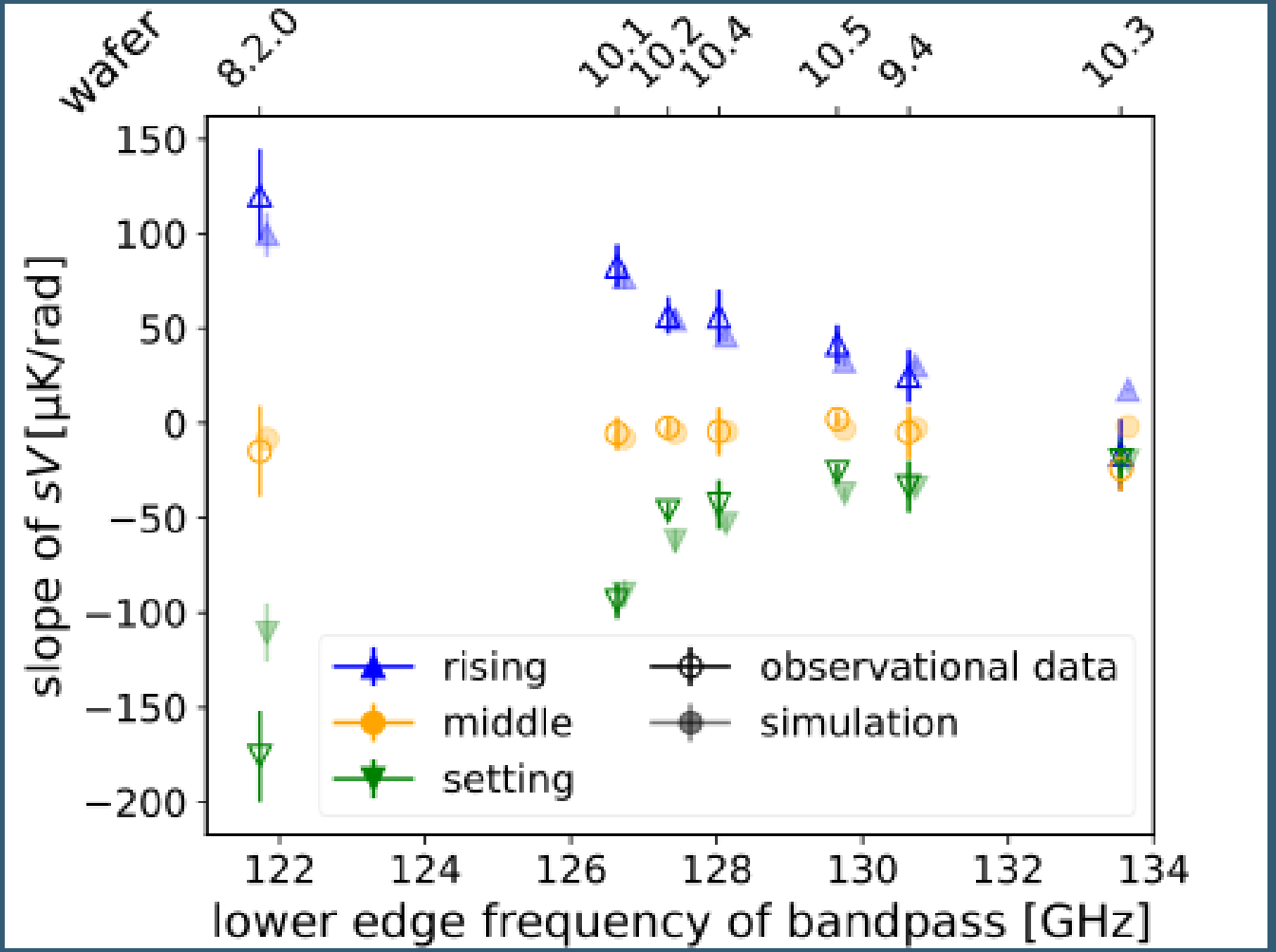
C_ℓ^{VV}


10^4 yr, 1 GHz
10^4 yr, 30 GHz
10^5 yr, 1 GHz
10^6 yr, 1 GHz
$l(l+1)C_l^{VV}/(2\pi)$ $(\mu K)^2$
10^0
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10
100
1000
l


$\beta^2_{AF,T} = \beta^2_{AF,S} = \beta^2_{F,E} = \beta^2_{F,B} = 0.001$
EE, no LV
BB, lensing, no LV
BB, tensor, no LV (r = 0.03)
EE, LV
BB, LV (r = 0)
VV, LV
$\mathcal{D}_\ell$ [μK^2]
10^4
10^2
10^0
10^{-2}
10^{-4}
10^{-6}
10^1
10^2
10^3
ℓ


N = 5
N = 3
N = 1
O2
ENERGY (K)
60
40
20
0
J = 0 1 2 3 4 5 6
1
2
3
4
5
6
7
8
9
4.4E−08
773.8
6.4E−09
715.4
1.3E−08
834.2
2.4E−08
424.8
A_ul (s^-1)
f (GHz)
1.9E−09
368.5
8.5E−09
487.3
4.5E−09
118.8


Wafer
8.2.0
10.1
10.2
10.4
10.5
9.4
10.3
Rising
Setting
Variation of slope of sV [μV/rad]
10
0
−10
−20
122
124
126
128
130
132
134
Lower edge frequency of bandpass [GHz]
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
Scale factor (%)


wafer
8.2.0
10.1
10.2
10.4
10.5
9.4
10.3
150
100
50
0
−50
−100
−150
−200
slope of sV [μK/rad]
rising
middle
setting
observational data
simulation
122
124
126
128
130
132
134
lower edge frequency of bandpass [GHz]