GroundBIRD: Preliminary Results on Polarization Angle Calibration with a Sparse Wire Grid

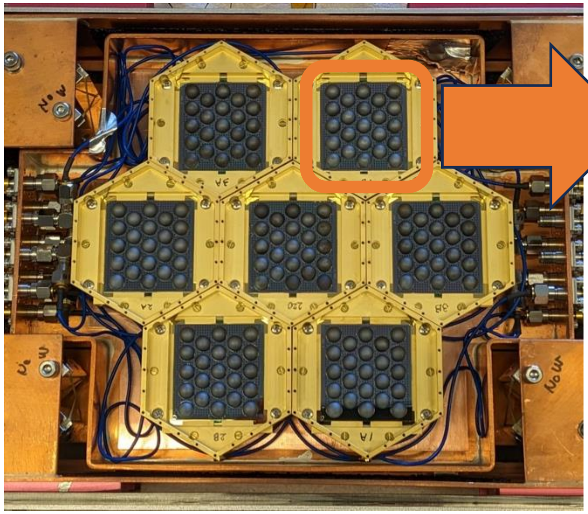
Miku Tsujii on behalf of the GroundBIRD collaboration

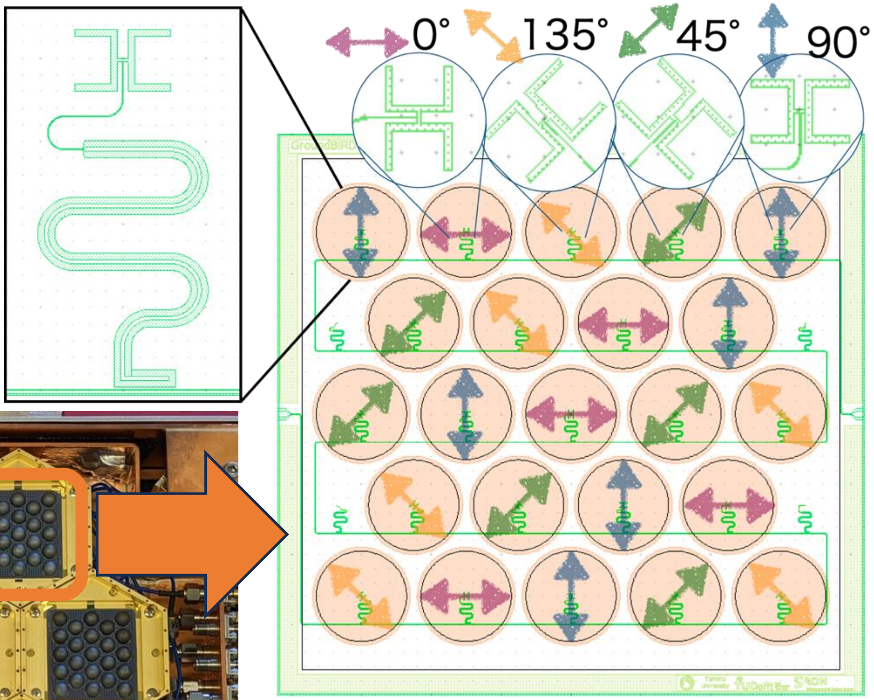
Outline

1. Detector design & calibration need
2. Choice of Calibration Method
3. Physics: how a wire generates polarization
4. Wire grid design
5. Preliminary results
6. Summary & next steps

Detector Design & Calibration Need

145 GHz 6 arrays × 23 kids, 220 GHz 1 array × 23 kids
Each detector has one of 4 antenna orientations: 0° / 45° / 90° / 135°





- The scan direction is aligned to the pixel arrangement (ref. Suzuki)
- Designed to sample all Stokes parameters across the focal plane
- Actual sky-projected angle can deviate from design due to instrumental and optical effects

→ **Polarization angle calibration is essential!**

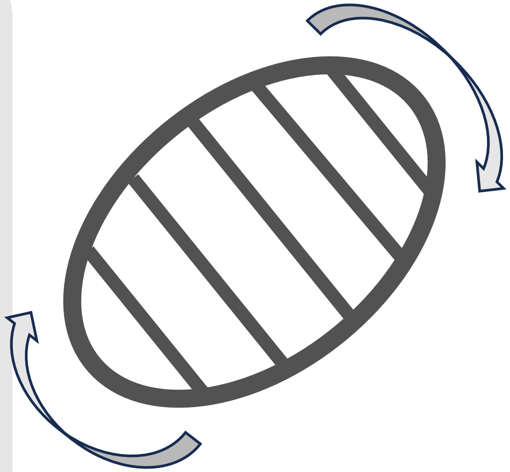
Choice of Calibration Method

Astronomical sources are difficult for GroundBIRD

- Tau A: wide beam → requires long integration time
- Moon: extended source, requires intensity correction

→ **We use a sparse wire grid (SWG)**

- Metal wires spaced much wider than the observing wavelength
- An artificial source: usable anytime, with a proven track record



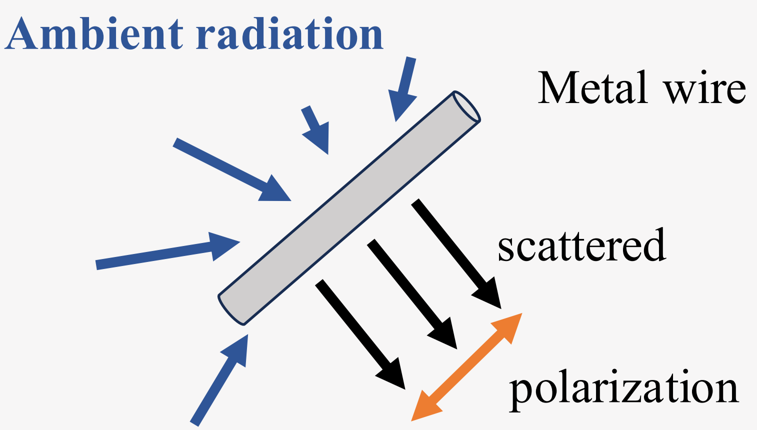
<u>Target accuracy</u>

- We plan to do a joint analysis with QUIJOTE
- QUIJOTE's angle accuracy is $0.5° - 0.96°$ → **Choose $0.5° - 0.96°$ as our target**

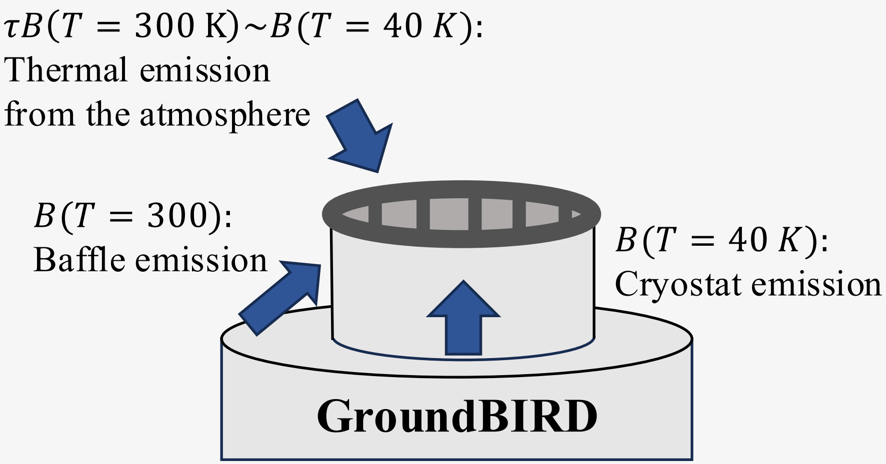
How a Wire Generates Polarization?

Polarization is generated along the wire direction

Wire scattering schematic



Light sources scattered by the wire



Overview

1. Ambient radiation is scattered along the wire axis
    - Wire-perpendicular component: transmitted light, from the atmosphere
    - Wire-parallel component: scattered light, mostly from sources warmer than the atmosphere (e.g. baffle)
      → polarized along the wire
2. Rotating the wire within the field of view modulates the detected polarization signal
3. Fit the modulation → recover detector sensitivity angle

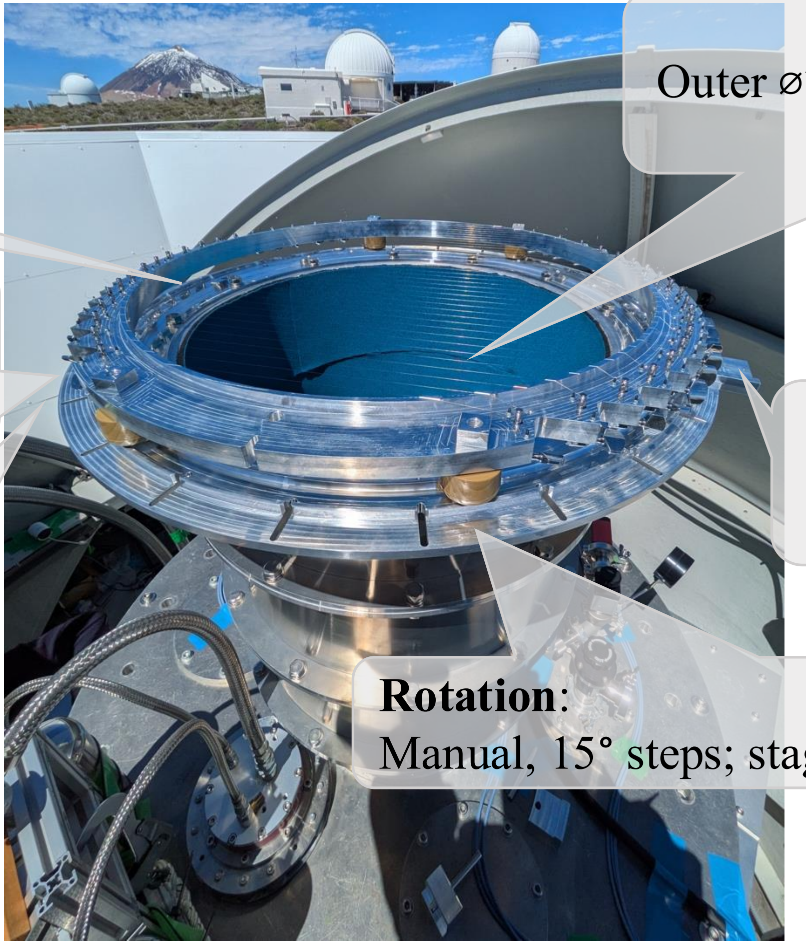
Wire grid design

Wire grid — overview

Wires: 39 × tungsten, ⌀0.3 mm, 15 mm pitch

Tensioning
: Guitar pegs (one side)
+ bead stopper (other)

Tension control:
chromatic tuner



Frame:
Outer ⌀700 mm / inner ⌀600 mm
(A5052 Al)

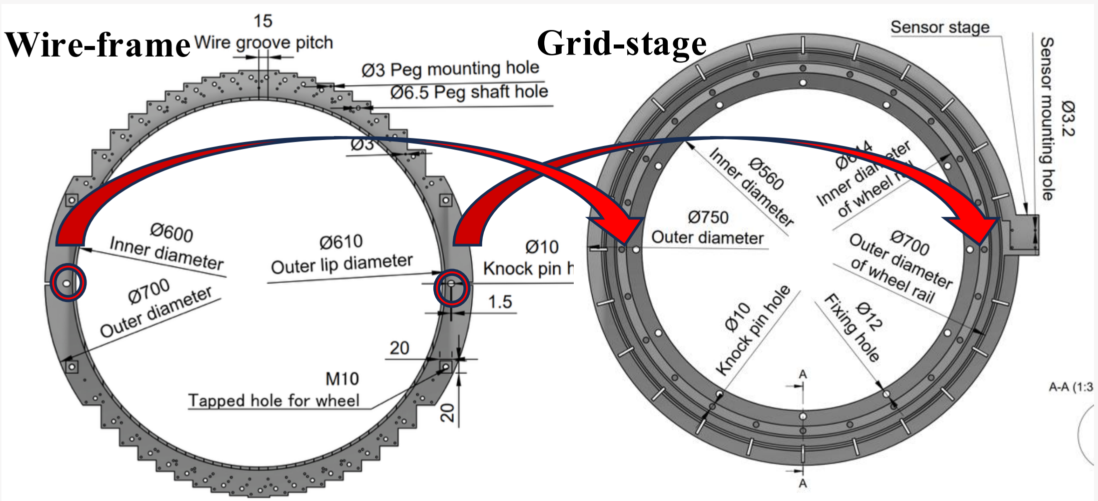
Angle sensor:
Gravity sensor → absolute wire angle

Rotation:
Manual, 15° steps; stage + wheels + knock pins

Combined instrumental angular uncertainty: ~0.31°

Wire Grid — Design Details

Wire-frame & grid-stage drawings



Rotate the wire-frame by hand.

- Two knock pins engage with the stage holes to lock the rotation angle.

Wires: 39 × tungsten, 15 mm pitch

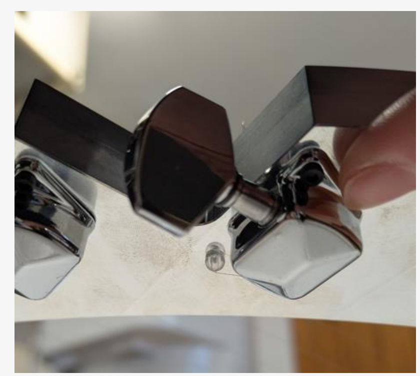
- Pitch ≫ wavelength
  → keeps wires "sparse"
- Smaller pitch → more wires
  → stronger signal

15 mm pitch: a balance between these two

Wire attachment

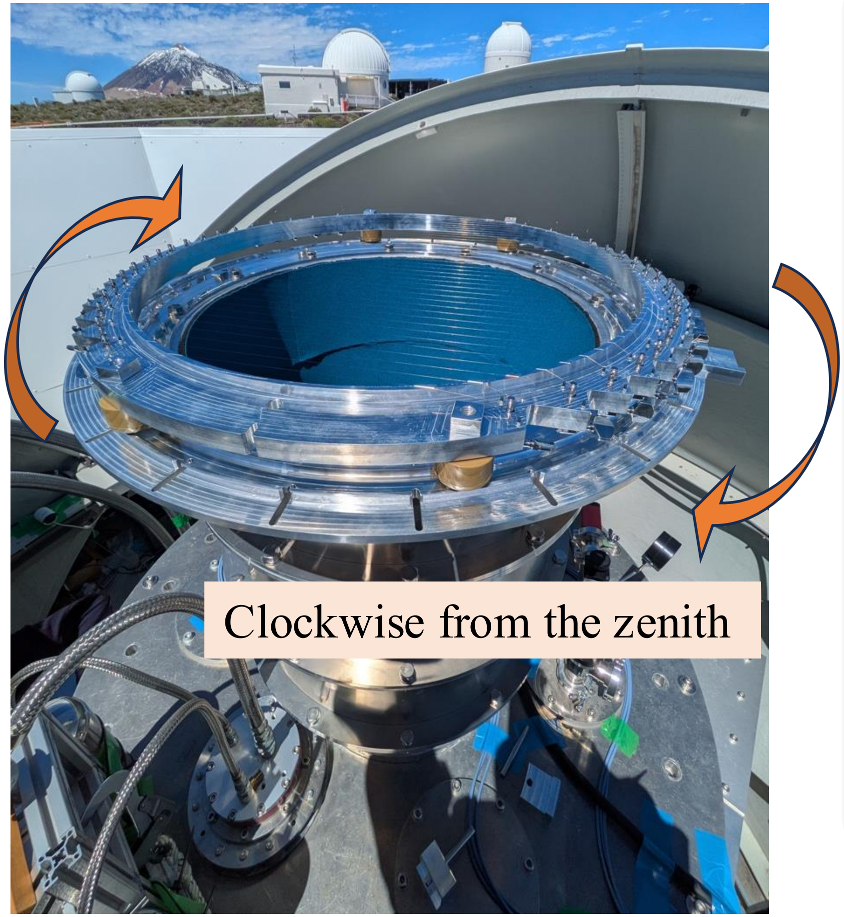
Keep the wires straight and field-serviceable by a single person

→ Guitar pegs+ bead stopper



Preliminary results

Measurement Procedure



Observation sequence

01 Point telescope to zenith and keep it fixed

02 Mount wire grid on aperture

03 Rotate the wire grid by hand in $30°$ $(= \Delta\theta)$ steps, clockwise from the zenith

04 Lock each step using the knock pins, which fix the relative rotation angle

05 At each angle, hold the wire grid still and record detector data (stare-mode)

06 Repeat for all steps to cover a full 360° rotation (~12 positions, ~1 min per step)

Analysis Pipeline

1. Select range
Manually select time segments with shadows excluded and low noise

2. Median per angle
Compute median detector output at each wire rotation angle

3. Initial fit
Fit with the model using weighted least squares to obtain initial {a, p, b, c}

4. Common-mode noise subtraction
Group detectors by angle (0°/45°/90°/135°)
Estimate & subtract shared noise C(θ)

5. Re-fit & iterate
Repeat steps 3–4 until convergence
→ final amplitude a and sensitivity angle p

Fitting model

$$y(\theta) = a \sin\left(\frac{2(\theta - p)}{180}\pi\right) + \underline{b + c\theta}$$

linear baseline for drifts during observation (e.g., thermal fluctuations)

Parameter	Description	Constraint
a	Amplitude	$a \geq 0$
p	Detector angle (phase offset) [deg]	none
b	Constant baseline	none
c	Linear drift coefficient	none
$\boldsymbol{\theta}$	Wire grid angle	

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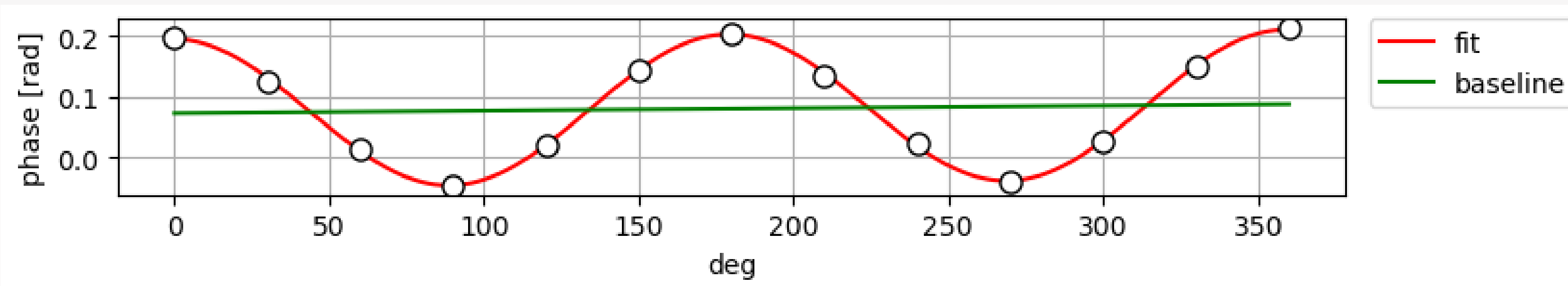
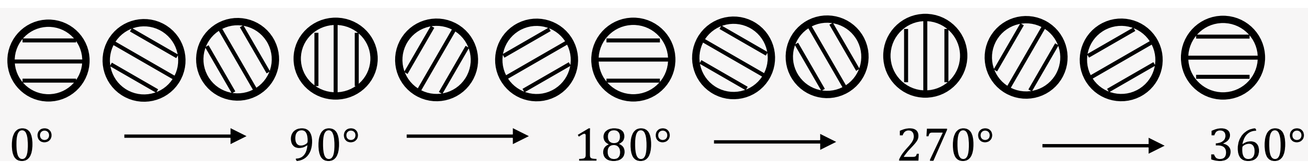


Wire grid angle



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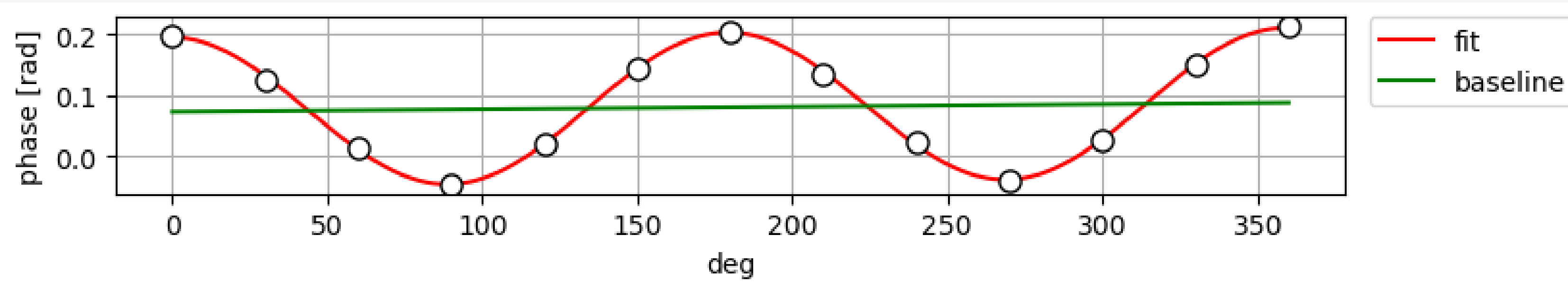
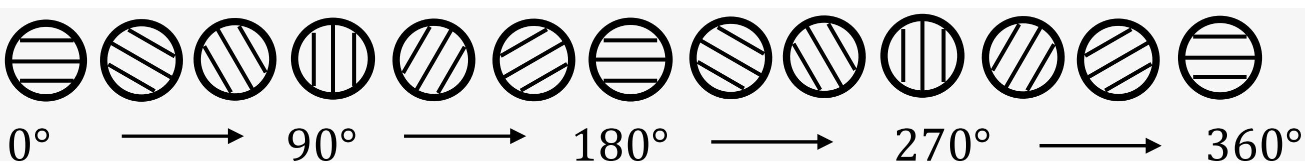


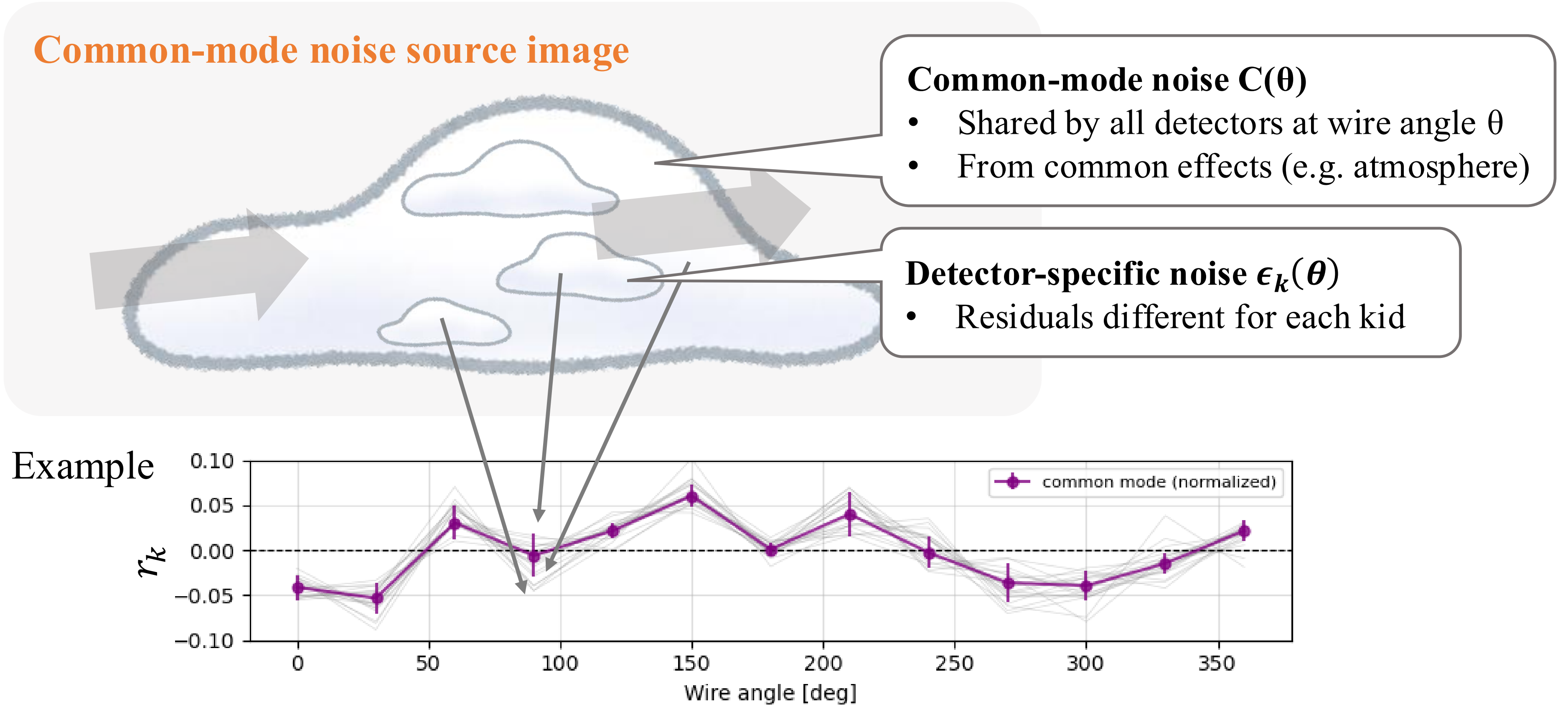
Wire grid angle



Common-Mode Noise: Definition and Example

How common-mode noise C(θ) is estimated from the residuals:

$$r_k(\theta) = \frac{y_k(\theta) - \mathrm{fit}_k(\theta)}{a_k} = C(\theta) + \epsilon_k(\theta)$$



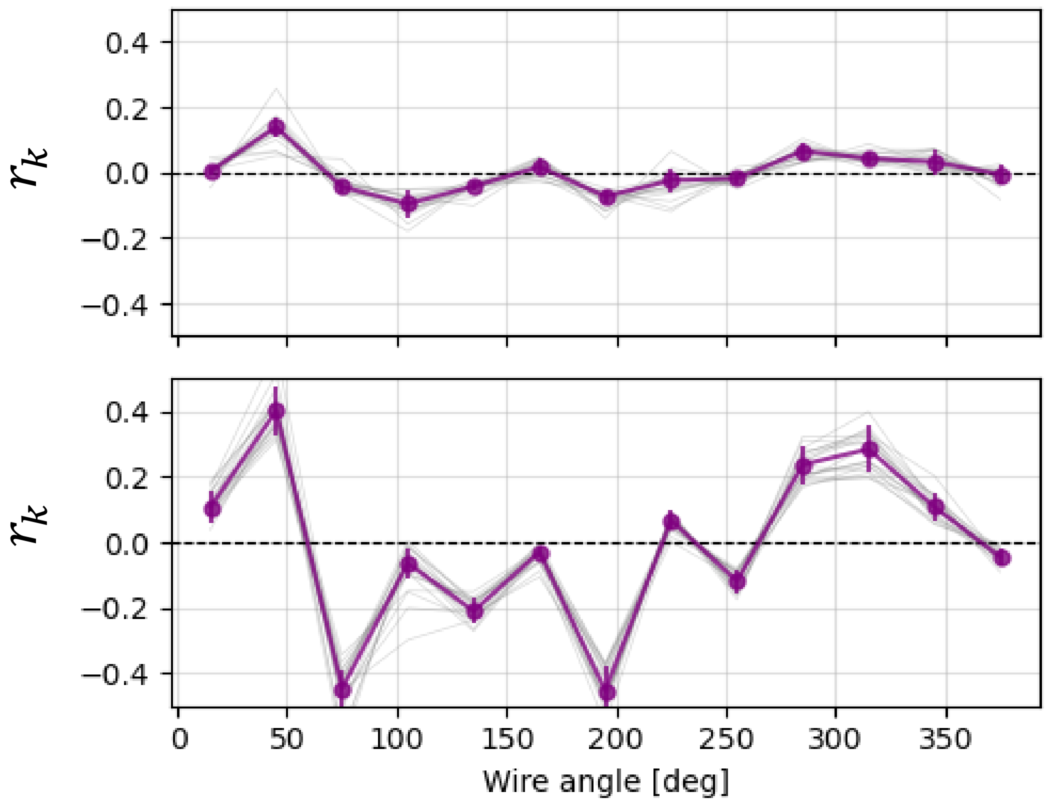
Preliminary Results — Common-Mode Noise vs. Atmospheric Conditions

The 220 GHz common mode is visibly larger than the 145 GHz common mode

2026-05-16, ~04:00 UTC, PWV:~3.2 [mm]

common mode at 145 GHz

common mode at 220 GHz



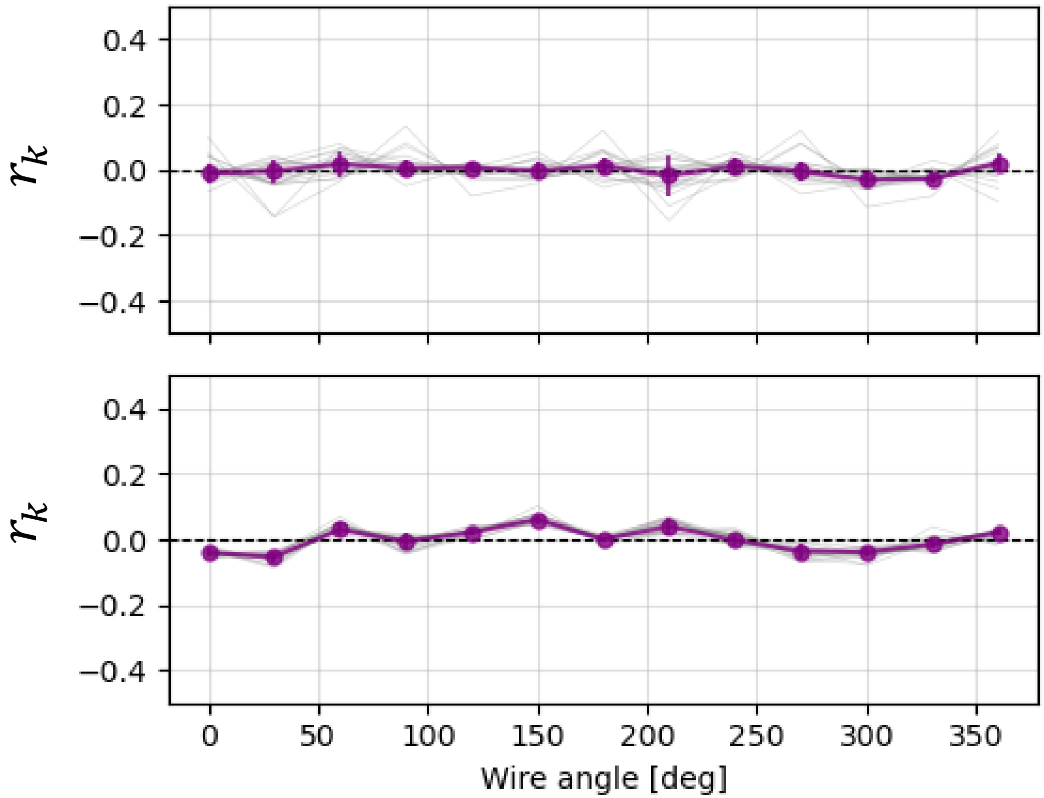
Preliminary Results — Common-Mode Noise vs. Atmospheric Conditions

Under good atmospheric conditions, the common-mode noise amplitude is small

2026-05-09, ~05:00 UTC, PWV: 0.3~2 [mm]

common mode at 145 GHz

common mode at 220 GHz

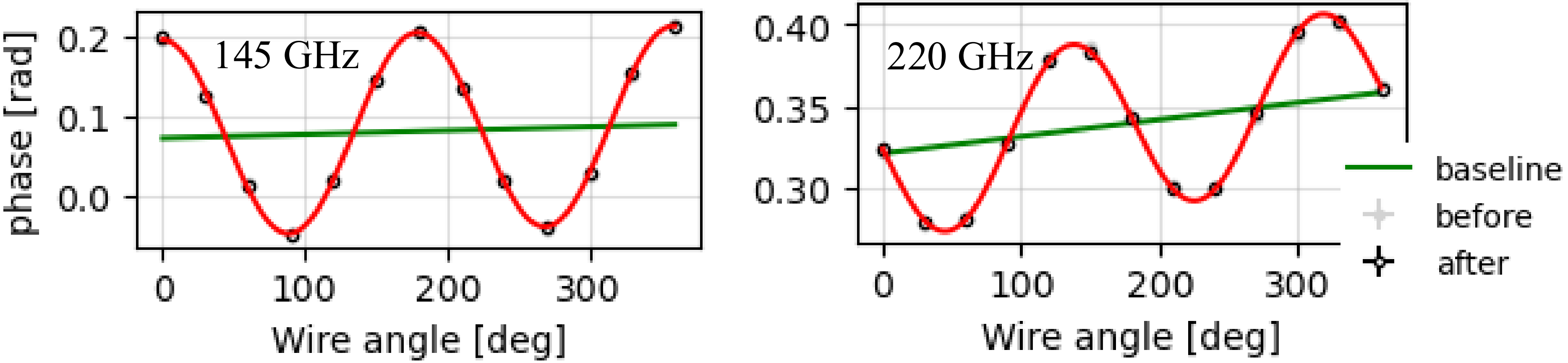


→ At 145 GHz, it is small enough to be buried in individual detector noise, with no clear common pattern.

Preliminary Results — Fit Examples (145 & 220 GHz)

Example detector fits show clear periodic modulation with wire angle

Data taken on 2026-05-09, ~05:00 UTC



Before CMN subtraction (initial fit)

	p	$\tilde{\chi}^2$
145 GHz detector	133.98±0.13	10.2
220 GHz detector	91.57±0.21	4.9

After CMN subtraction (converged)

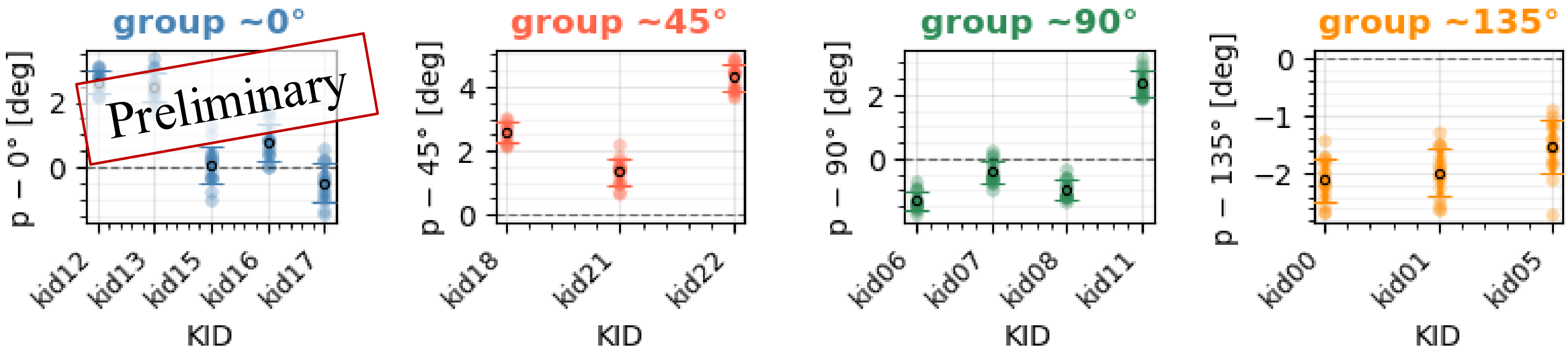
	p	$\tilde{\chi}^2$
145 GHz detector	133.92±0.18	2.0
220 GHz detector	91.59±0.22	0.5

- $\boldsymbol{p}$ remains stable before and after subtraction
- $\tilde{\chi}^2$ drops confirming noise removal

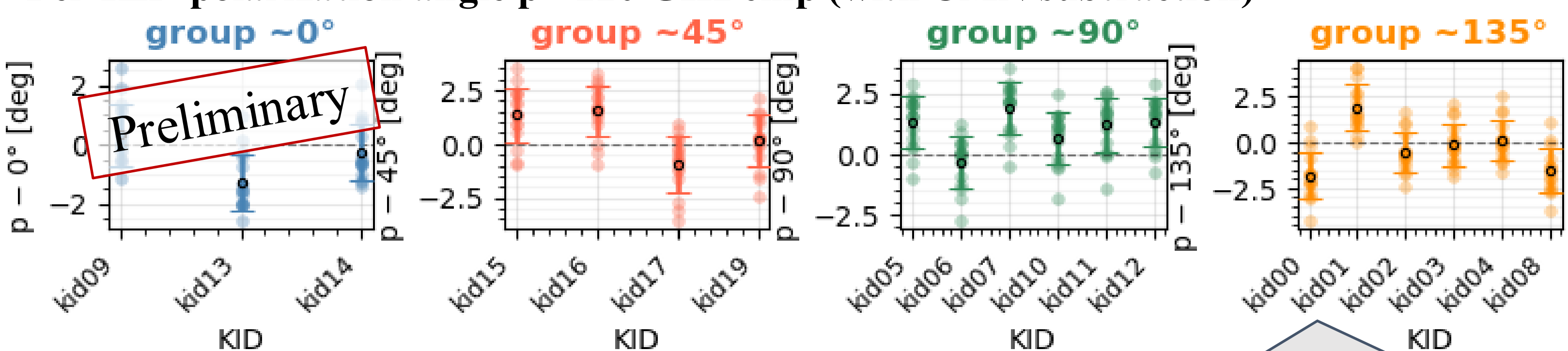
Preliminary Results — Per-Detector Angle Distribution

Per-KID polarization angle p, grouped by design angle.
Error bars (± SD) show the spread across multiple measurements.

Per-KID polarization angle p -145 GHz chip (with CMN subtraction)



Per-KID polarization angle p - 220 GHz chip (with CMN subtraction)



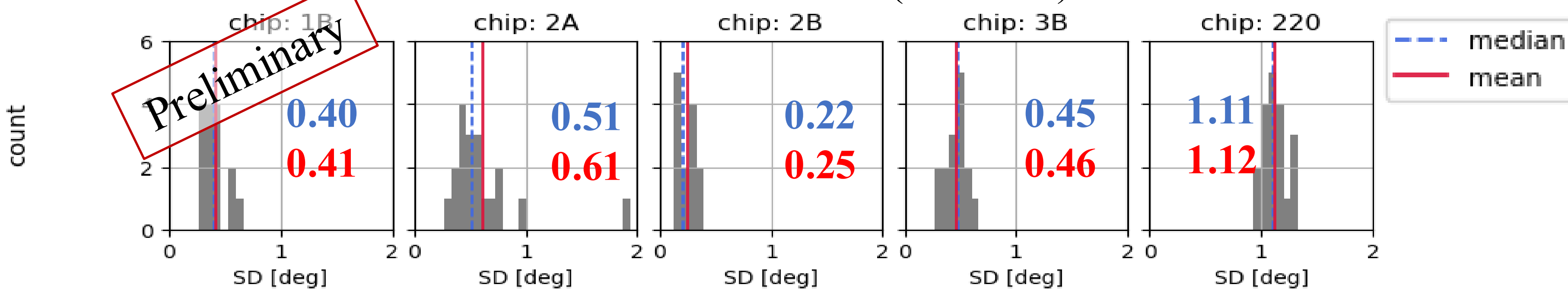
Each detector clusters around a consistent value

Data period: May 7–9, 2026
(PWV: 0–3.5 mm; not available on May 7)

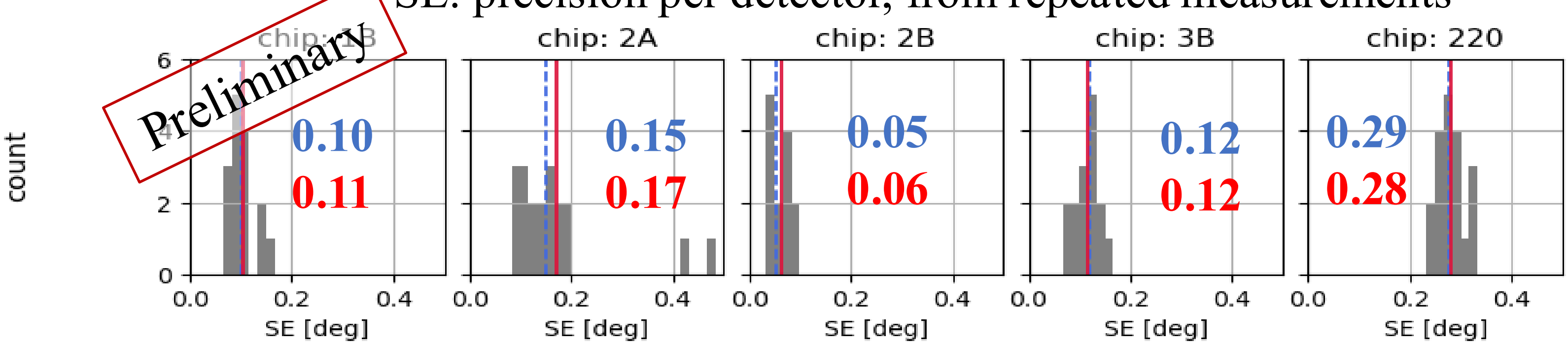
Per-Detector Precision: SD and SE by Chip

Per-detector SD and SE, by chip
- SD reflects detector-to-detector scatter
- SE reflects the precision from repeated measurements

SD: scatter across detectors (reference)



SE: precision per detector, from repeated measurements



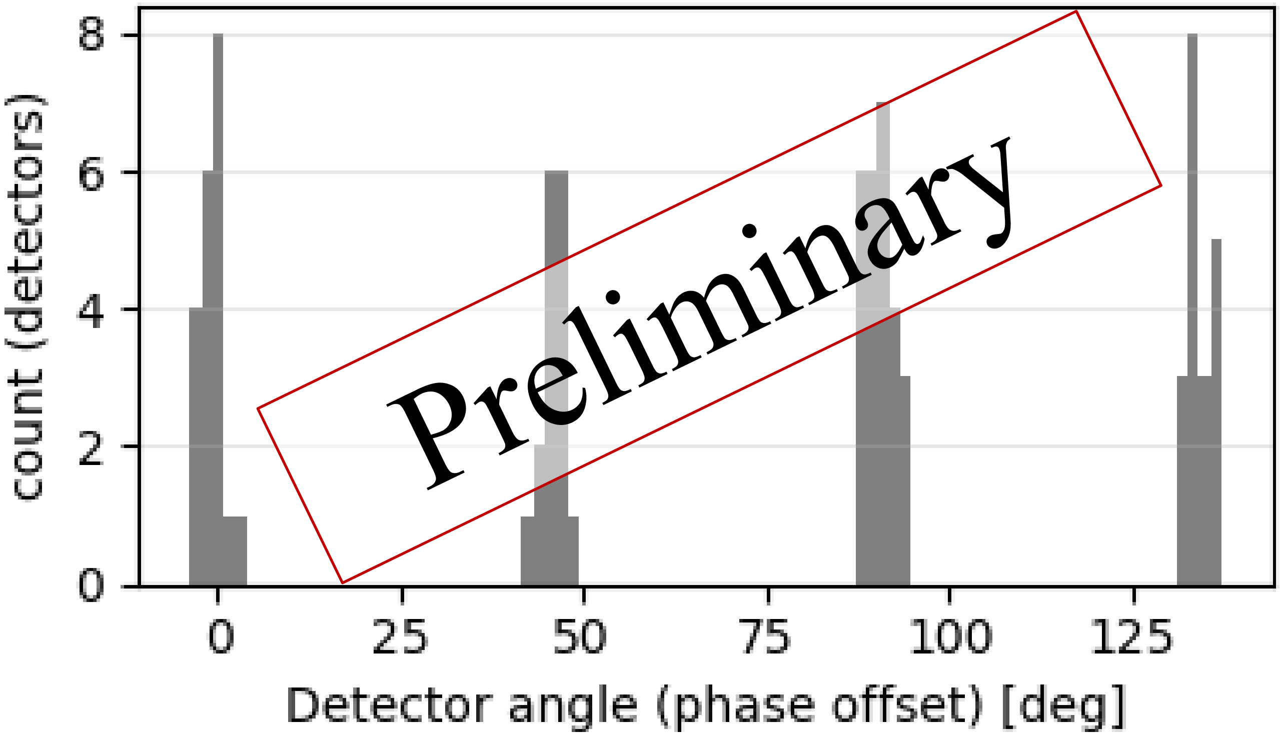
SE is expected to shrink as more measurements accumulate

→ Precision will improve with more statistics

→ Our preliminary results indicate that the 0.5° − 0.96° target accuracy is within reach

All Detectors Resolve into Four Design Angles

Distribution of fitted sensitivity angles p, all chips combined



The four design orientations (0° /45° /90° /135°) are clearly separated

Summary & Next steps

- **What was achieved**
  - Designed, built, and operated a sparse wire-grid calibrator for polarization angle calibration of GroundBIRD
  - Obtained preliminary per-detector sensitivity angles for both 145 and 220 GHz detectors
  - Developed a common-mode noise subtraction method, and found that its impact depends strongly on atmospheric conditions (PWV)
  - Preliminary results suggest our target is achievable, with further improvement expected as we accumulate more data
- **Next steps**
  - Extend the analysis to all detectors and multiple datasets to obtain final sensitivity angles
  - Cross-check the results with simulations
  - Repeat measurements over time to assess the long-term stability of detector angles