Initial Results of the Pol. Angle Calibration using Sparse Wire Grid with a Small Aperture Telescope in SO

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- on behalf of Simons Observatory Collaboration -

CMB-CAL @Bicocca

科研費
KAKENHI

Core-to-Core Program
研究拠点形成事業

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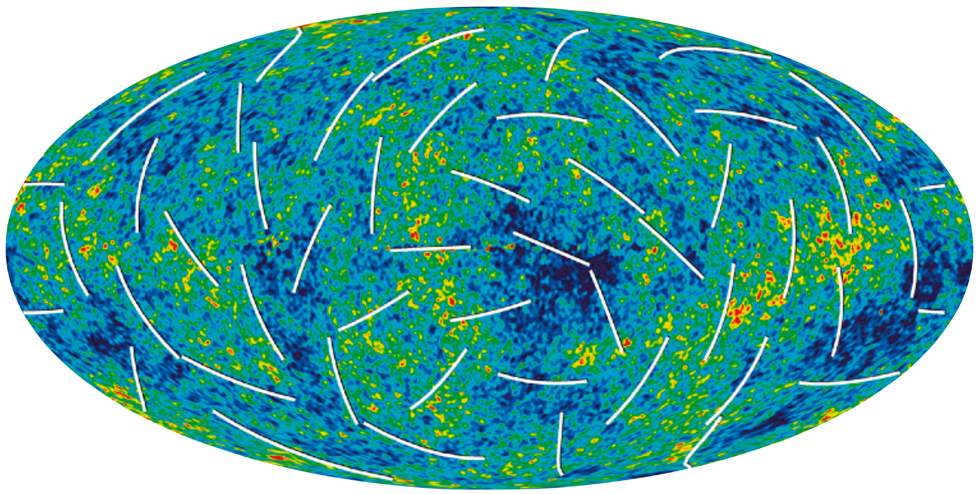
WCU WEST CHESTER UNIVERSITY

Science Goal: Primordial B-mode

Target: Primordial Gravitational Wave
≒ Evidence of the Inflation

Current Limit on r:

$r < 0.036$ (BICEP2/Keck)



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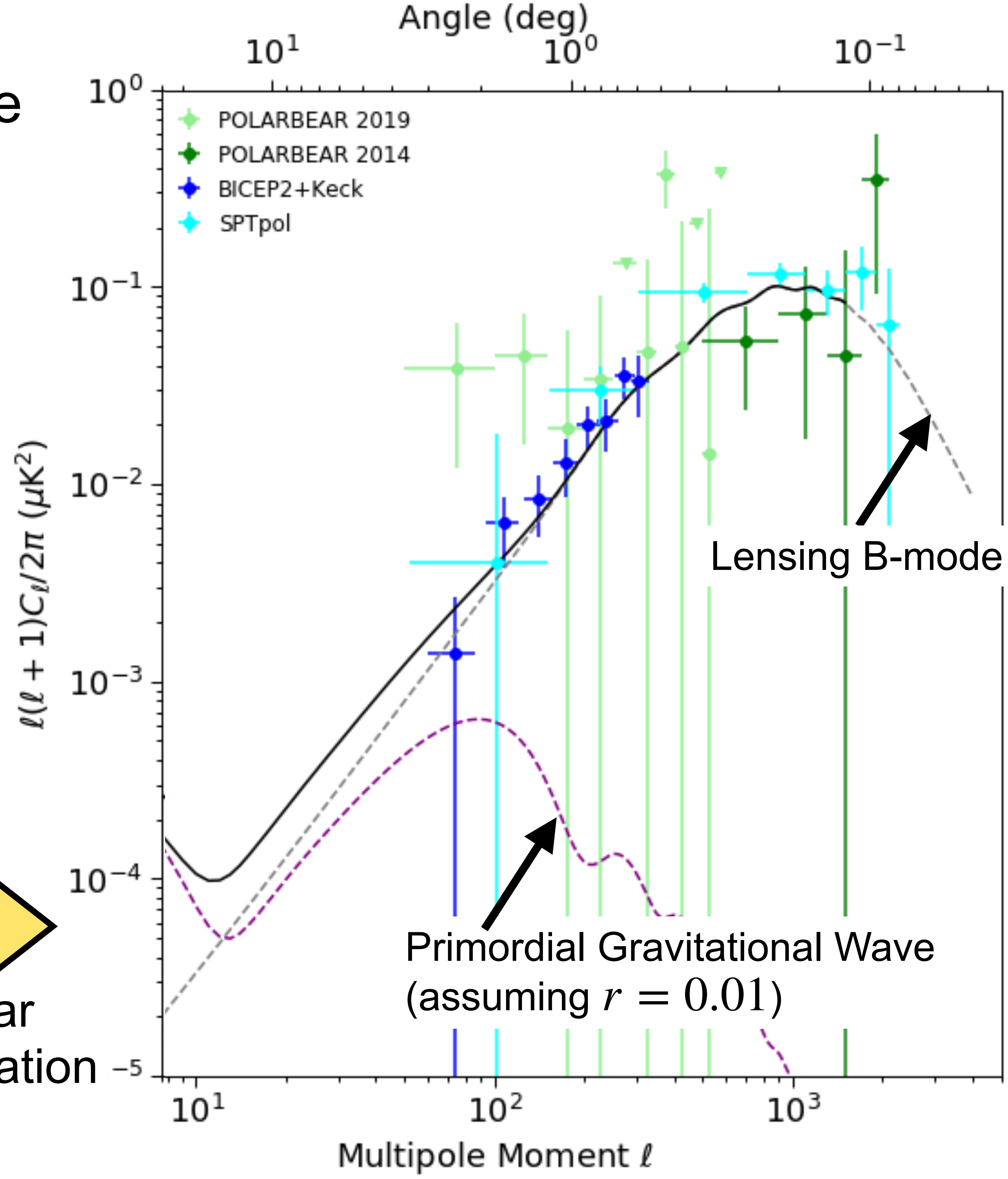
angular correlation



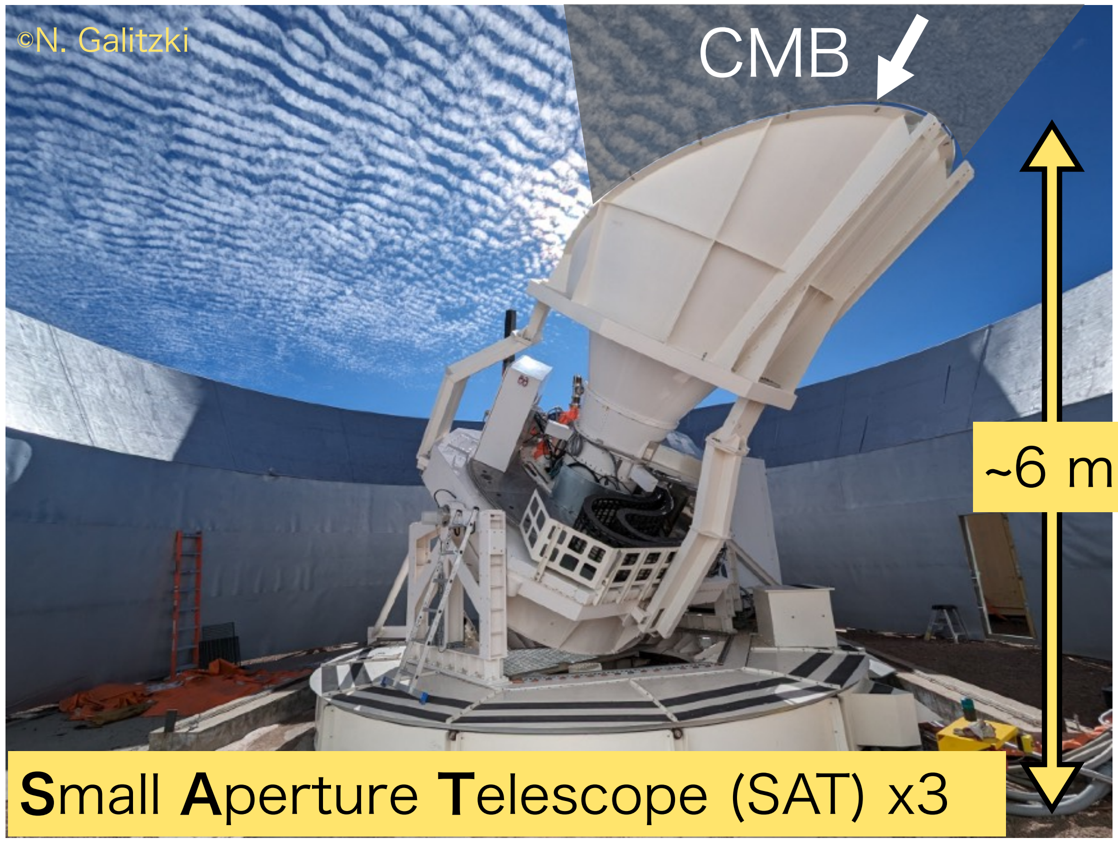
Lensing B-mode

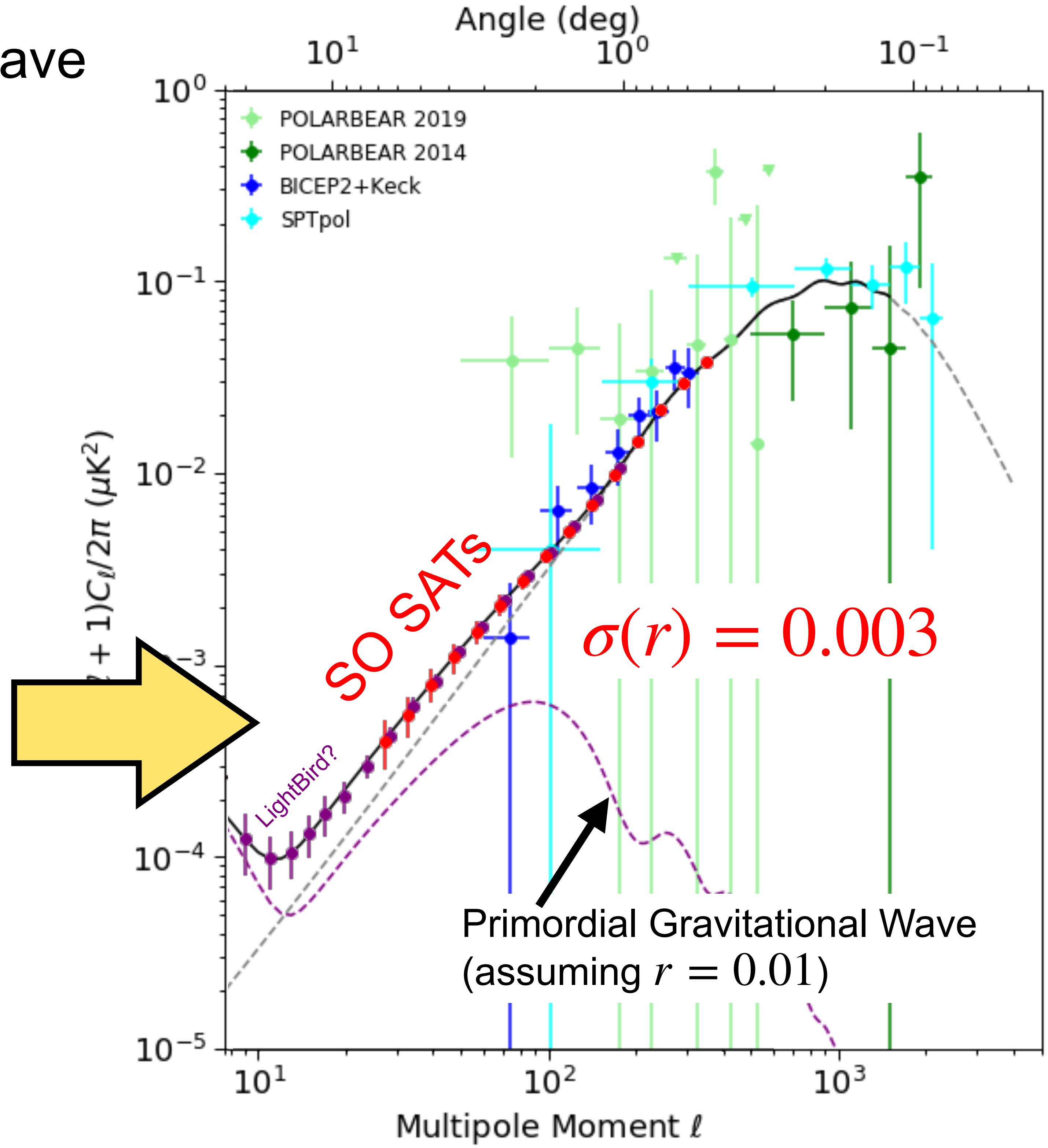
Primordial Gravitational Wave
(assuming $r = 0.01$)

Primordial B-mode for Simons Obs.

Target: Primordial Gravitational Wave
≒ Evidence of the Inflation

We aims to achieve
the measurement of
the primordial B-mode w/
$\sigma(r) = 0.003$ **[5-years observation]**



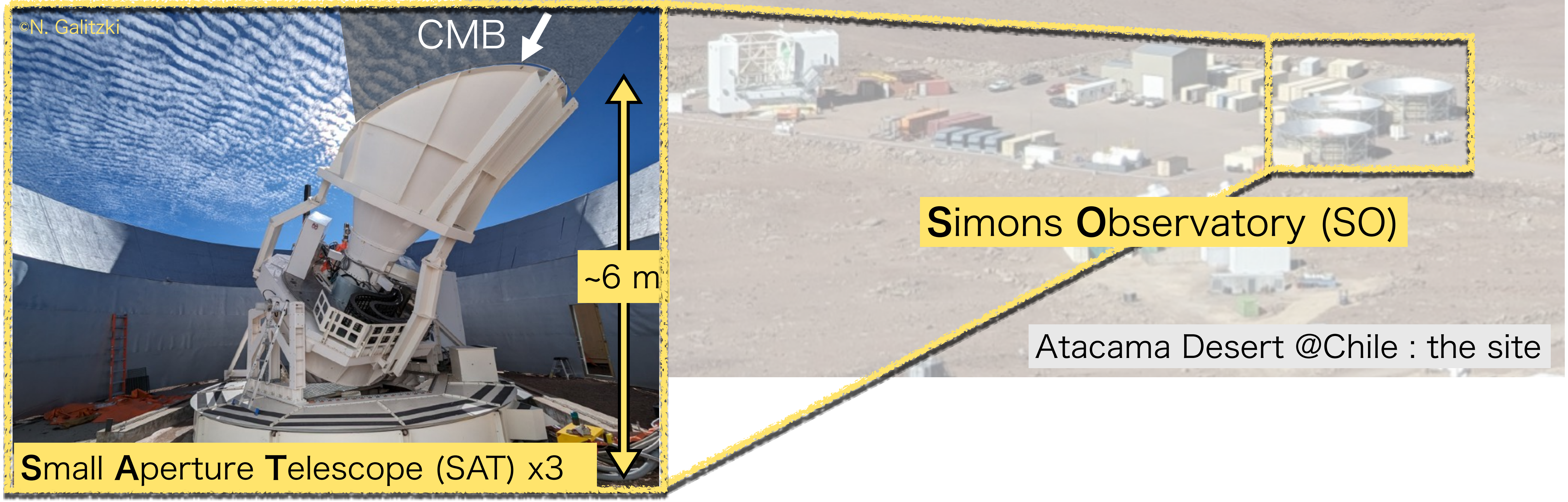


SAT in Simons Observatory

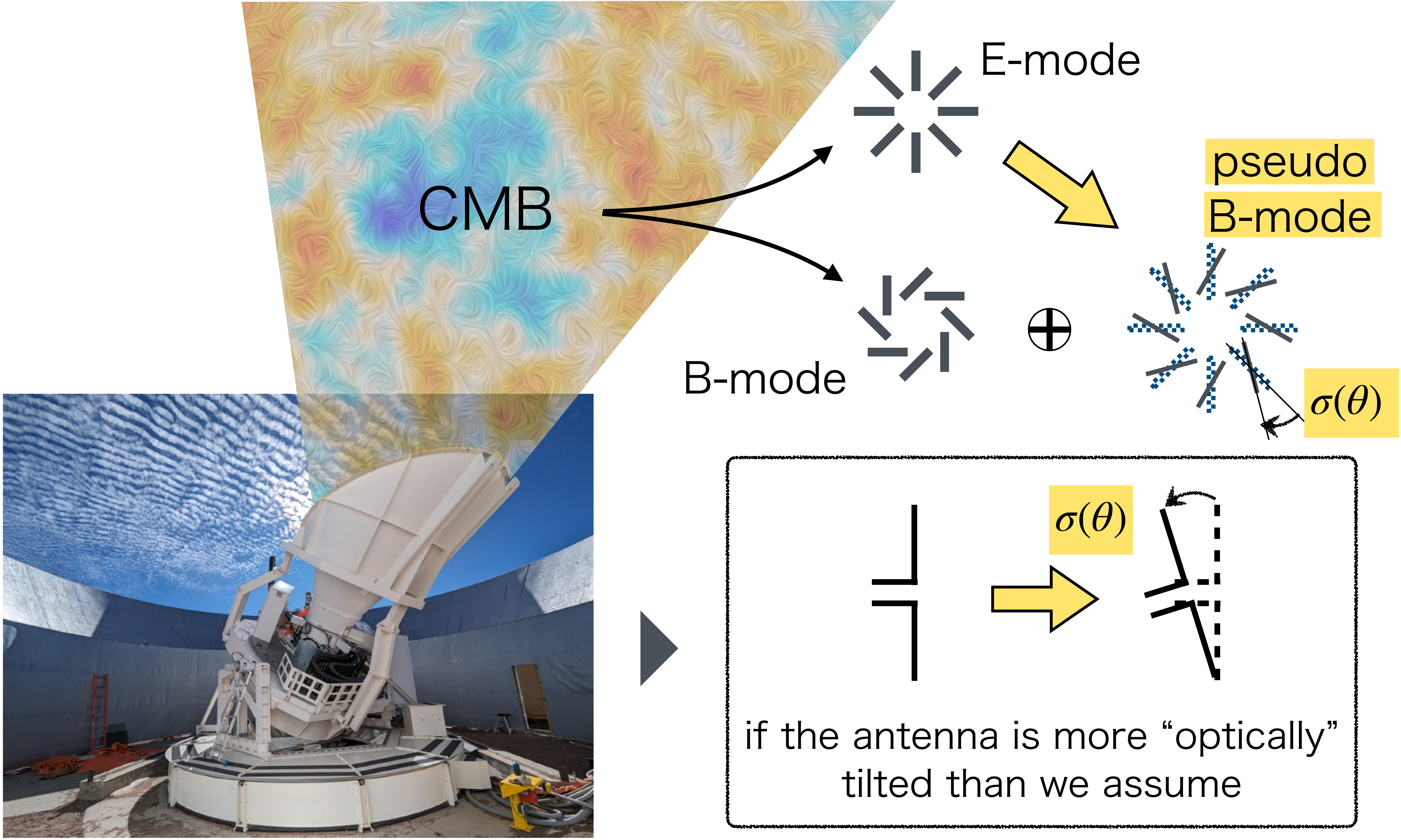
- Simons Observatory(SO) is located
  in Atacama Desert (Chile), 5,200 m above sea level
- SO has two kinds of telescopes for different science goals.

★ **Small Aperture Telescopes (SAT) x3: large scale**

★ Large Aperture Telescope (LAT) x1: small scale

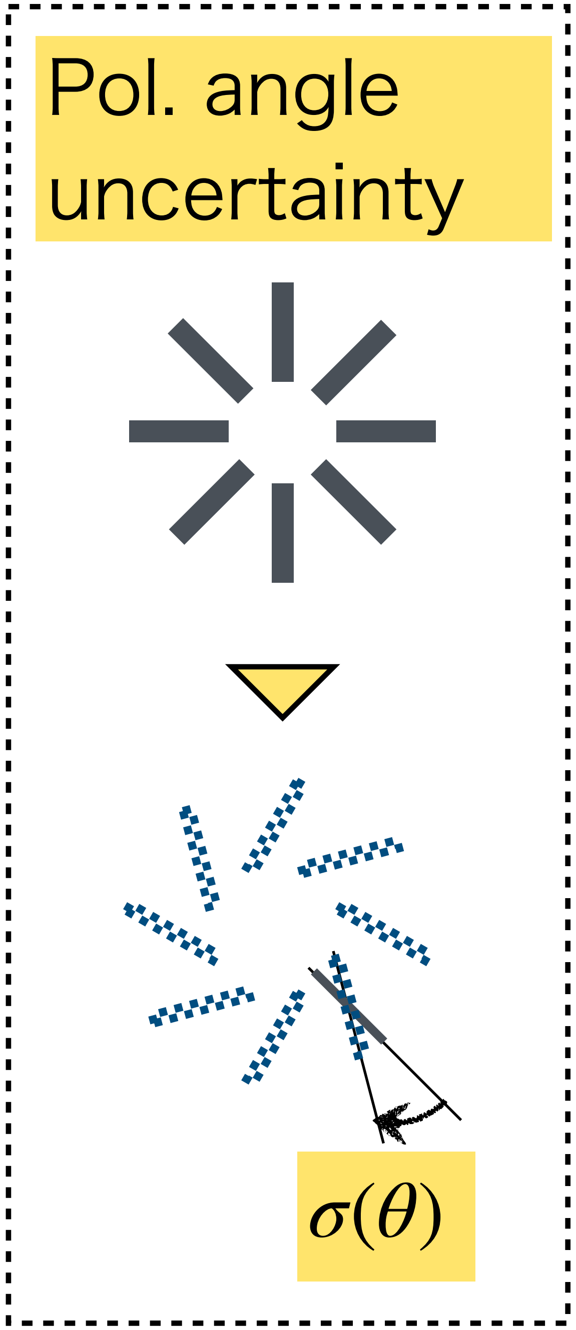


Why the Pol. Angle Calibration?



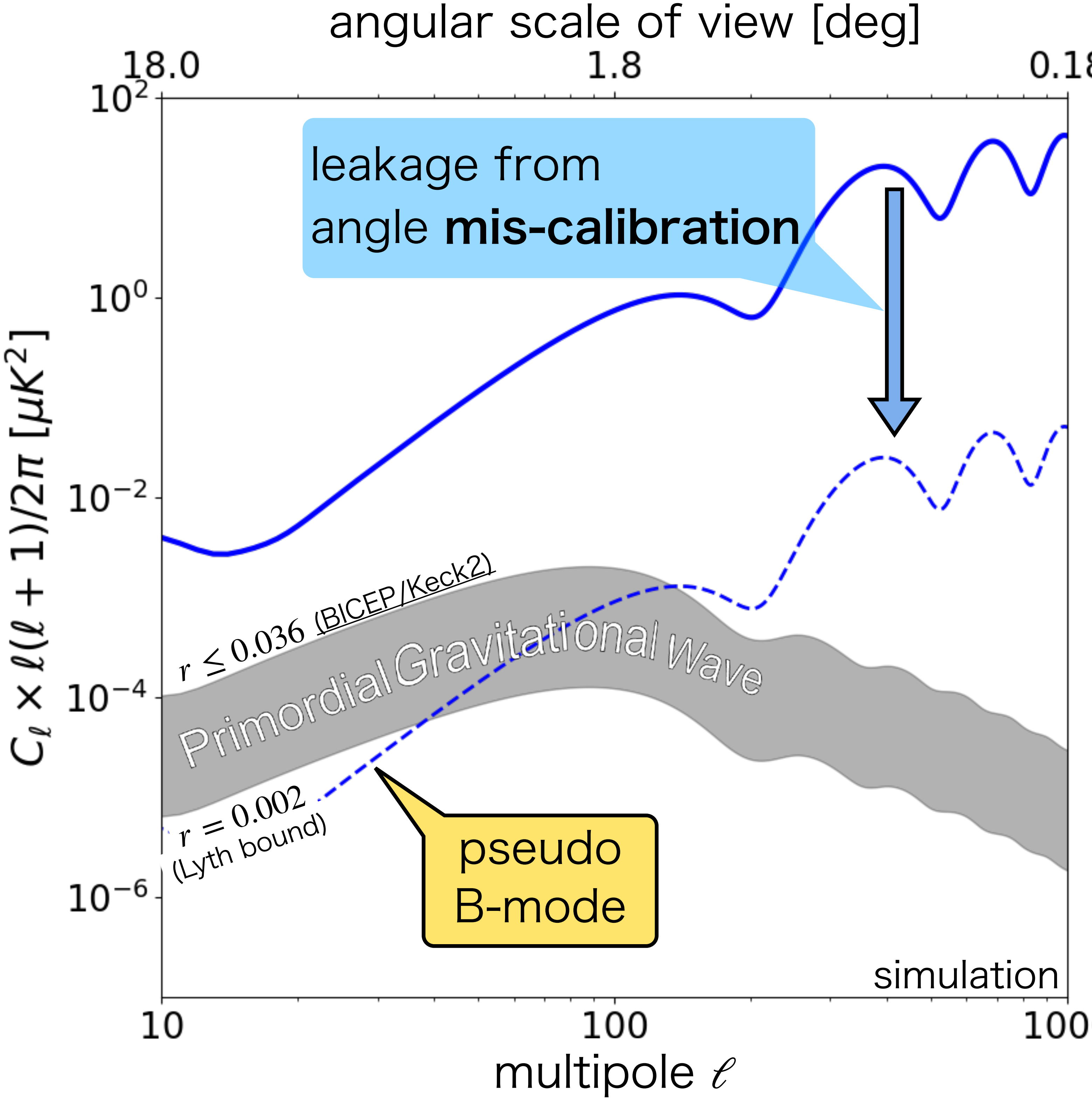
if the antenna is more “optically” tilted than we assume

Uncertainty with 1 deg



Pol. angle uncertainty

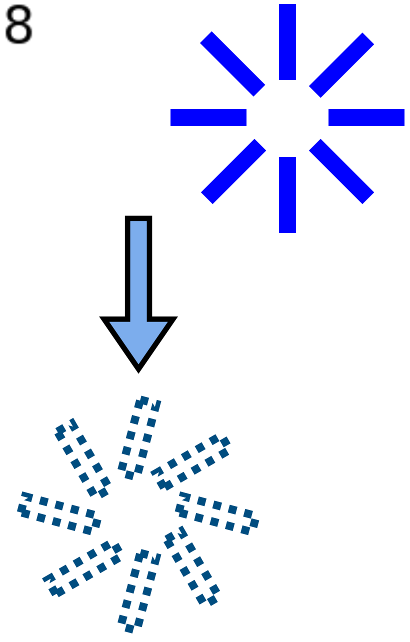
$\sigma(\theta)$



leakage from angle **mis-calibration**

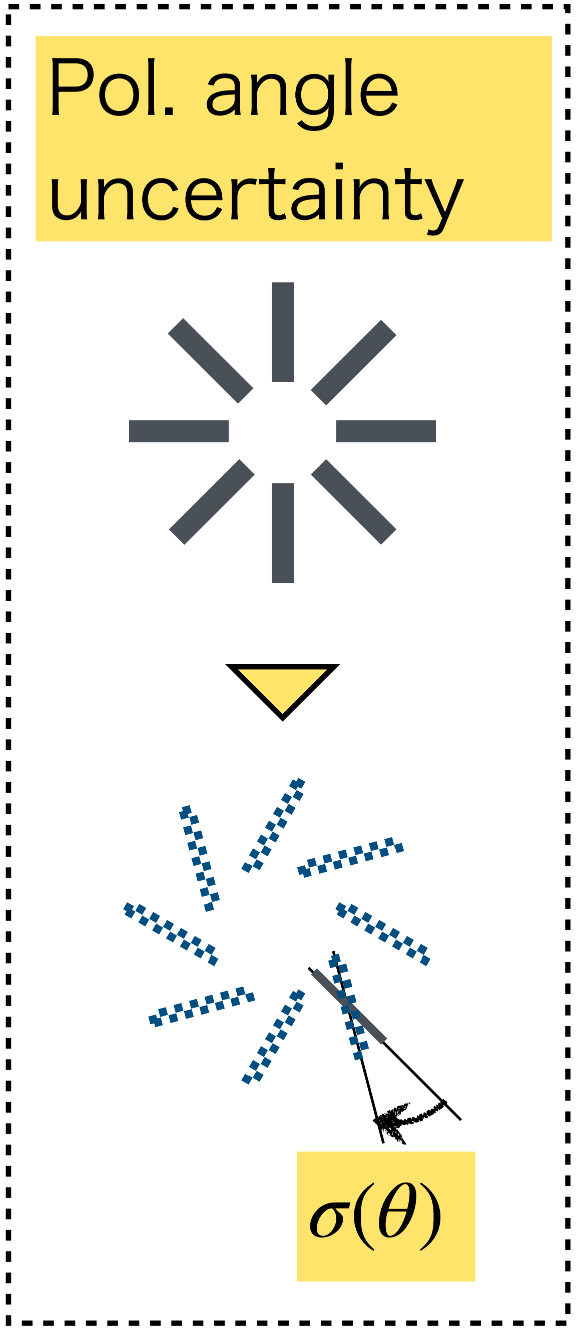
pseudo B-mode

E-mode



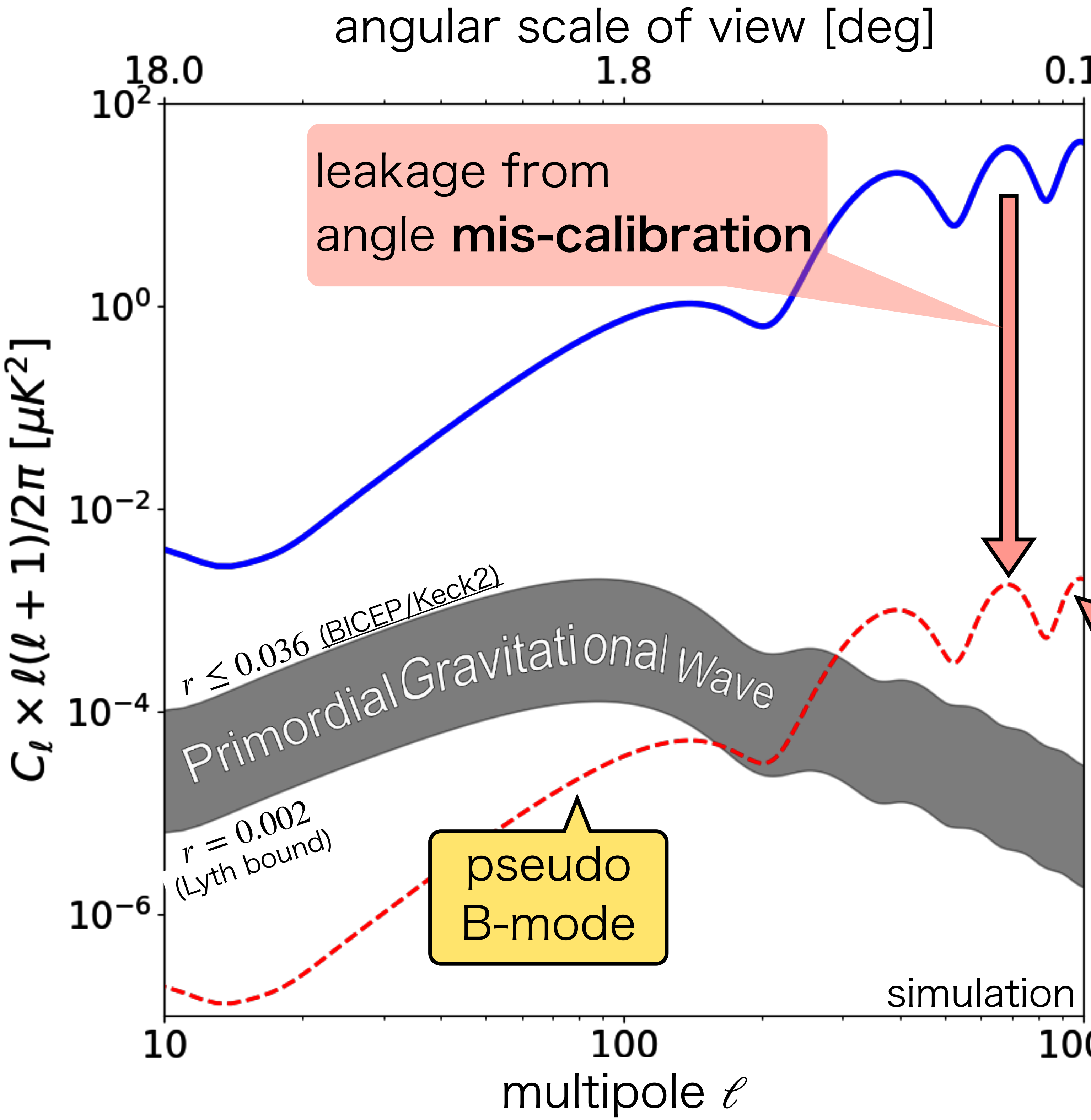
$\sigma(\theta) = 1.0$ deg

Uncertainty with 0.2 deg



Pol. angle uncertainty

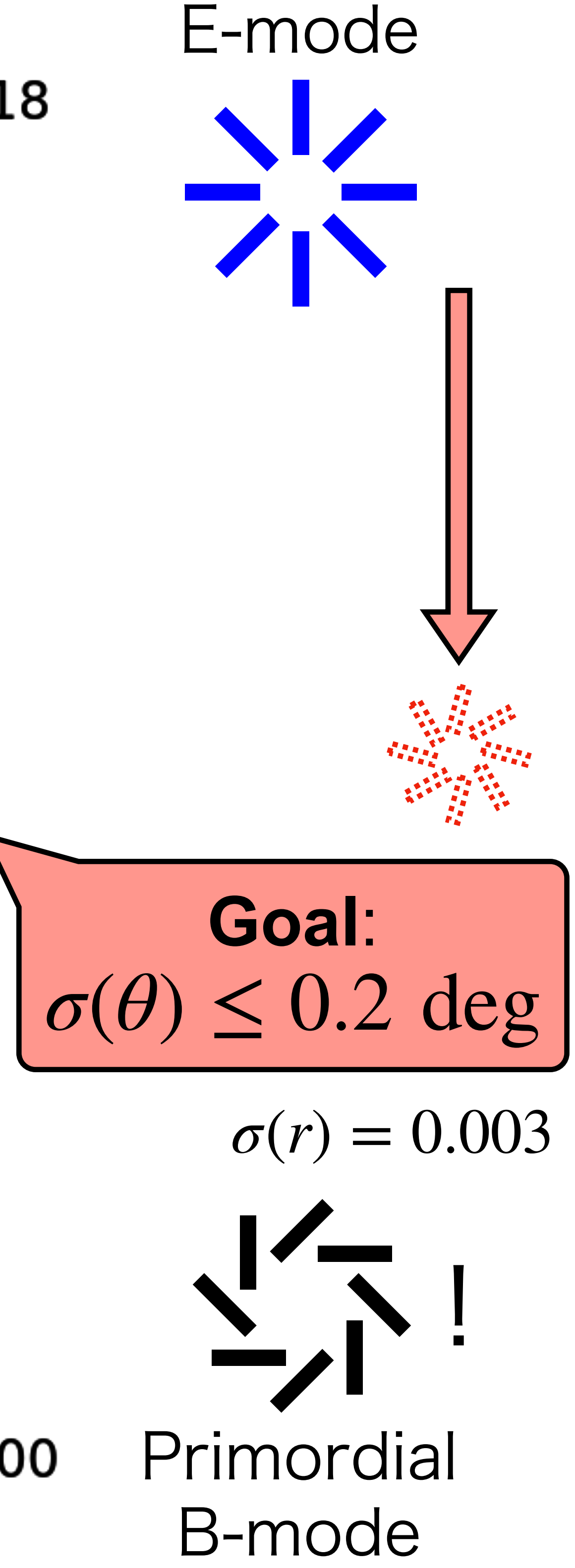
$\sigma(\theta)$



leakage from angle **mis-calibration**

pseudo B-mode

simulation

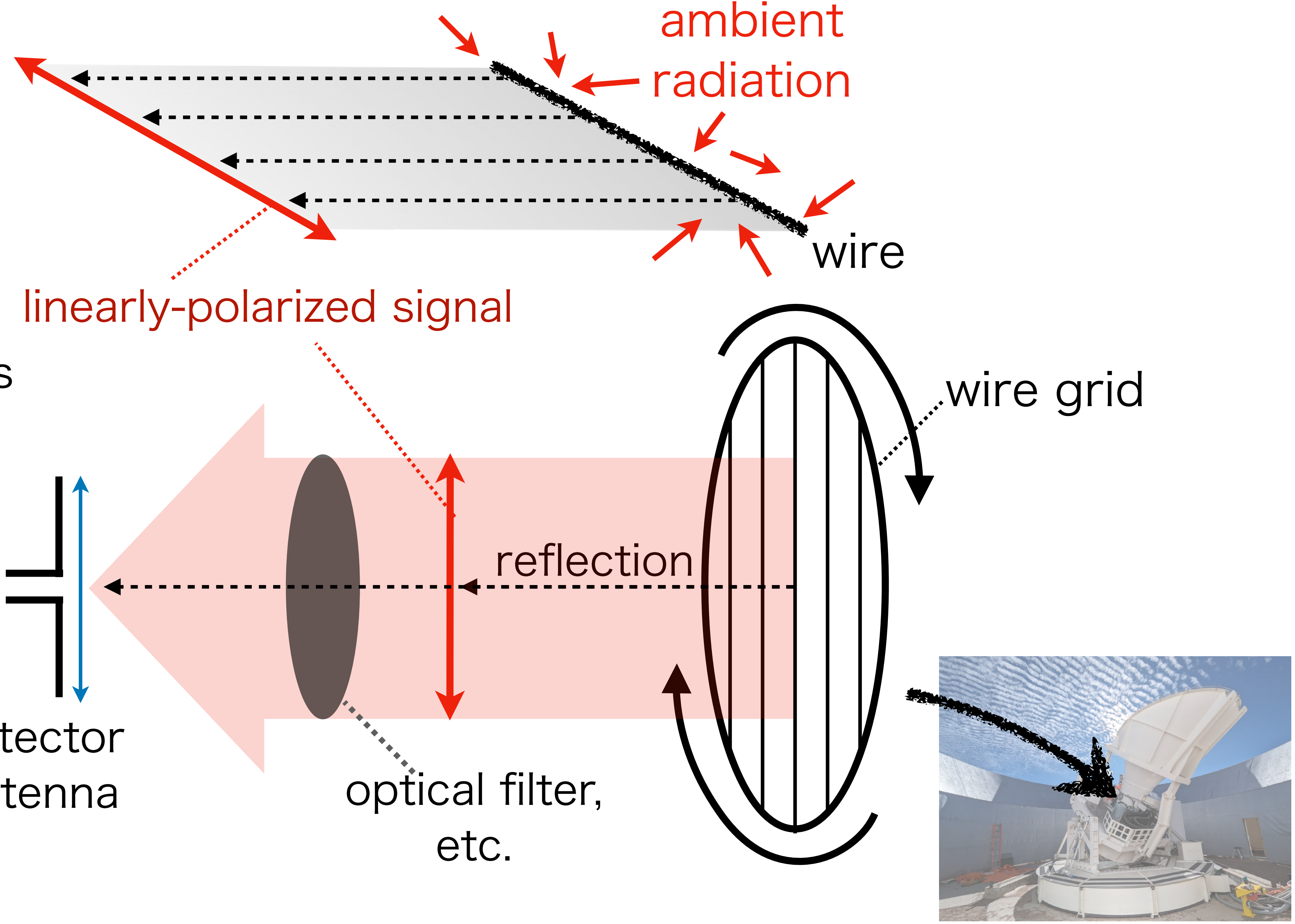


Goal: $\sigma(\theta) \leq 0.2$ deg

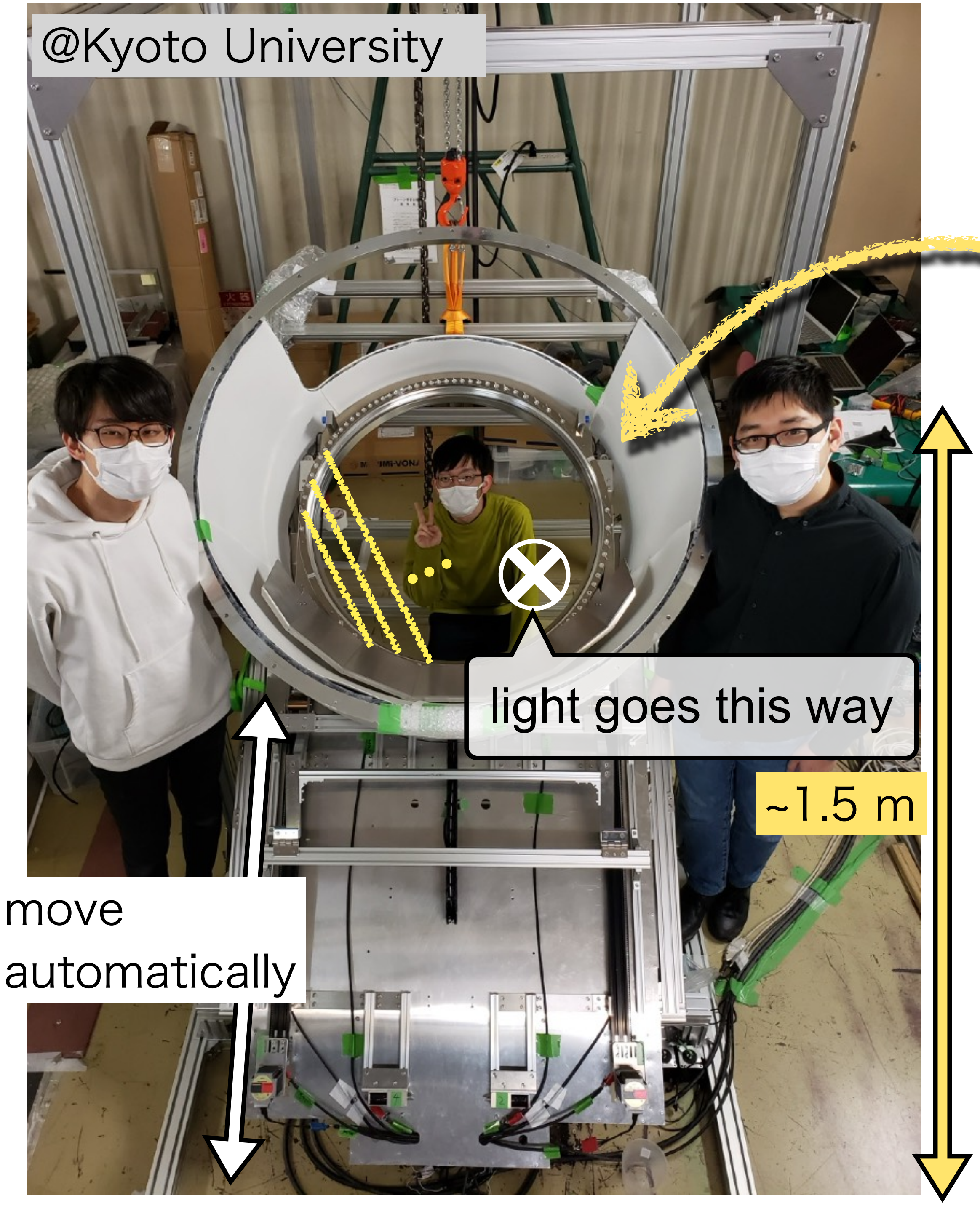
$\sigma(r) = 0.003$

Concepts of the calibration using wires

- wire creates linearly-polarized signal by reflecting radiation of its surroundings
- this can be used as an artificial source

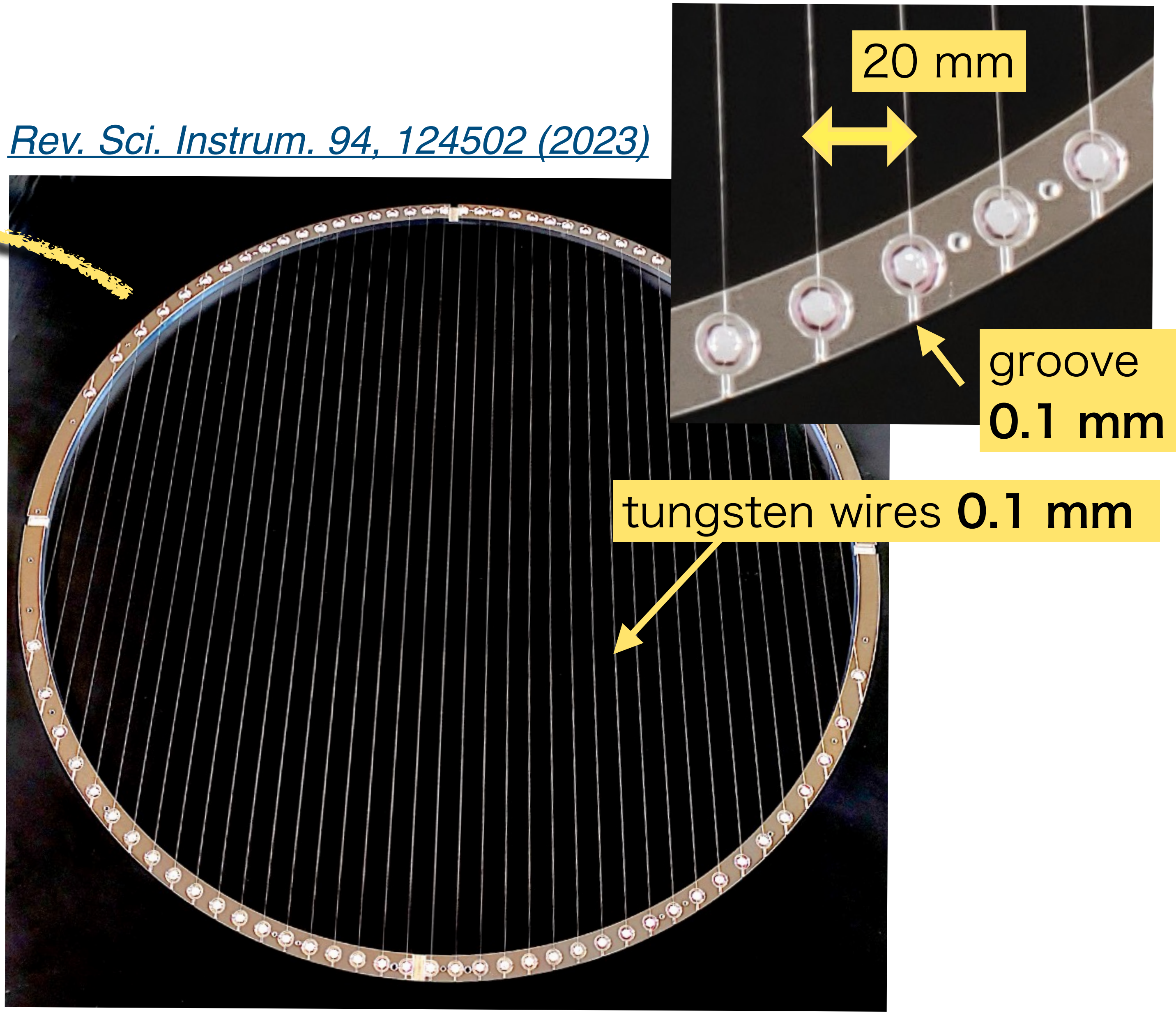


Sparse Wire Grid Calibrator (SWG)

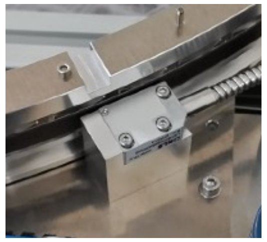


Sparse Wire Grid Calibrator is equipped with automatic loading system Sparse Wire Grid Calibrator is **equipped with automatic loading system**

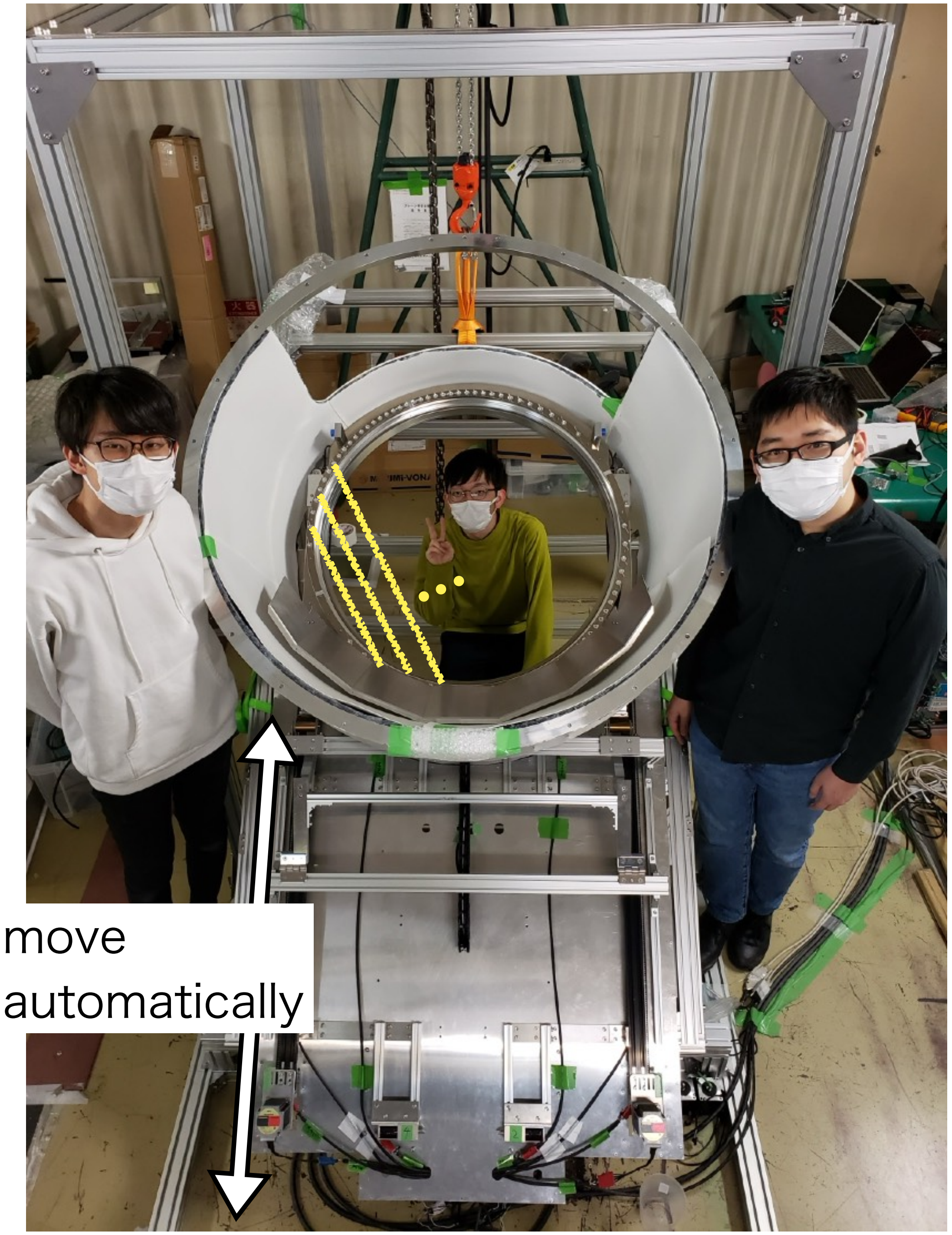
Rev. Sci. Instrum. 94, 124502 (2023)



The direction of wires is guaranteed by its mechanical design, and the angle is monitored very accurately $\approx 0.007\ \mathrm{deg}$ by an encoder→



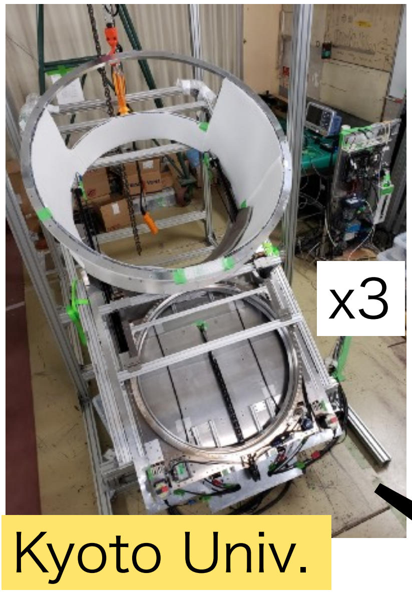
The function of two actuators



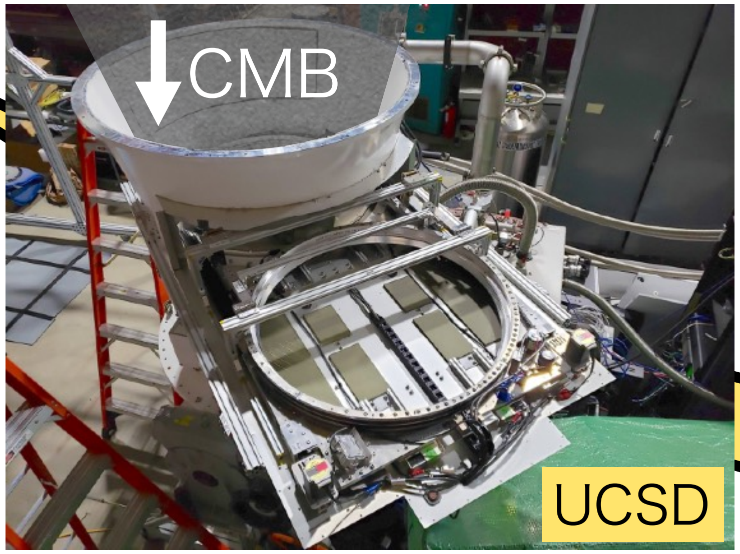
Sparse Wire Grid Calibrator is **equipped with automatic loading system**

We can perform the calibration regularly!

Deployment of SWG



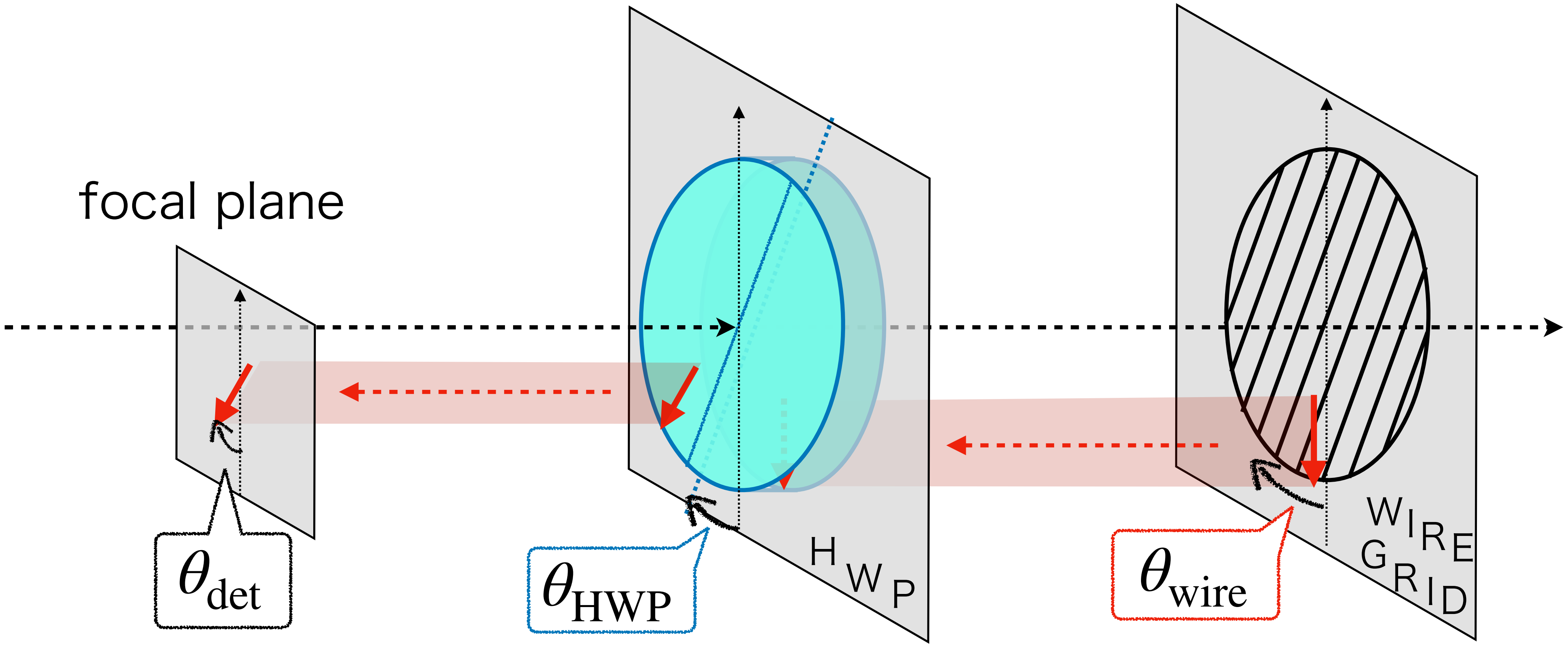
- Development of **three calibrators** at Kyoto Univ. & UTokyo



Deployed two of them:

	SAT-MF1	SAT-MF2	SAT-UHF
SWG	✓	✓	installing

Calibration method in a nut shell



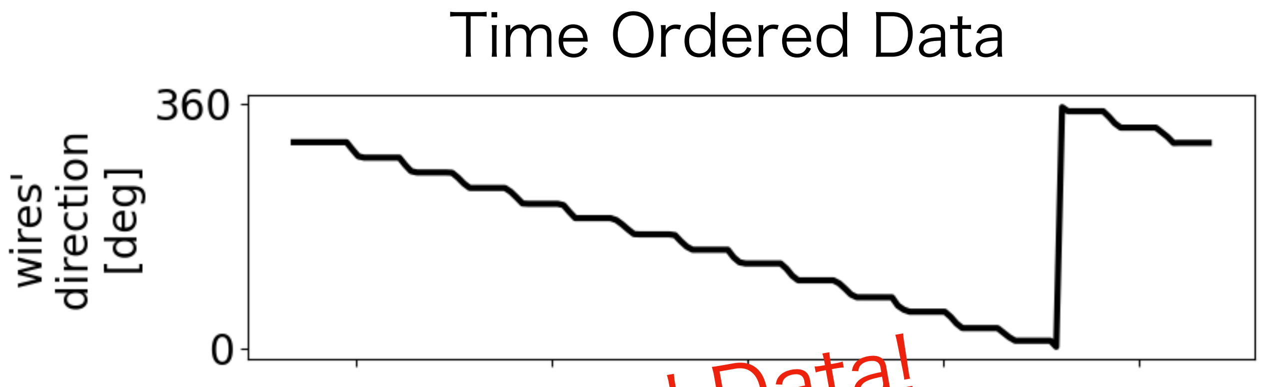
$$d_{raw} = I + \boxed{\left[A_{wire} + \mathcal{O}(\varepsilon)\right] \exp i \left[\cancelto{0 \text{ by demodulation}}{-4\theta_{HWP}} + 2\theta_{det} + 2\theta_{wire}\right]} + c.c.$$

$$\Rightarrow Q_{wire} + iU_{wire}$$

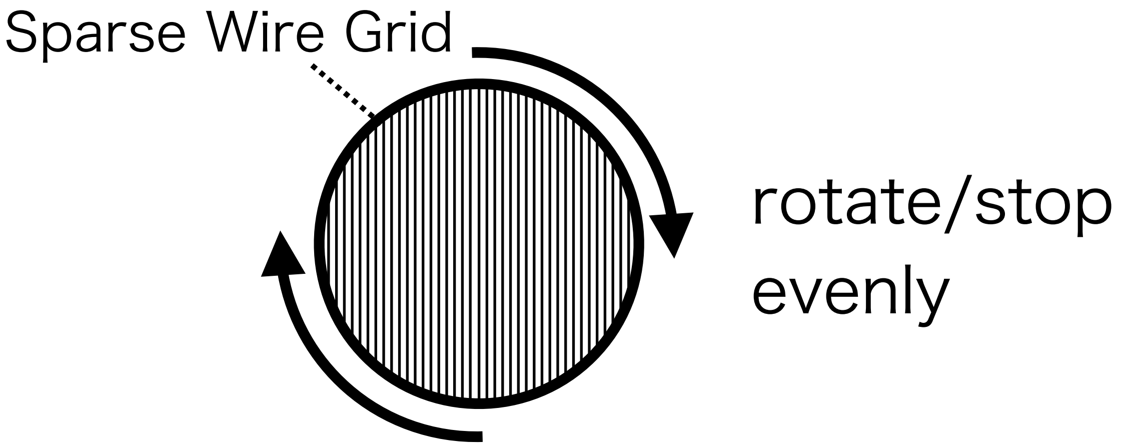
$$\boxed{\theta_{det} = \frac{1}{2} \arg\left(U_{wire}/Q_{wire}\right) - \theta_{wire}}$$

- We can use the wires' polarization as the reference for the detector response (polarization calibration)

Step 1



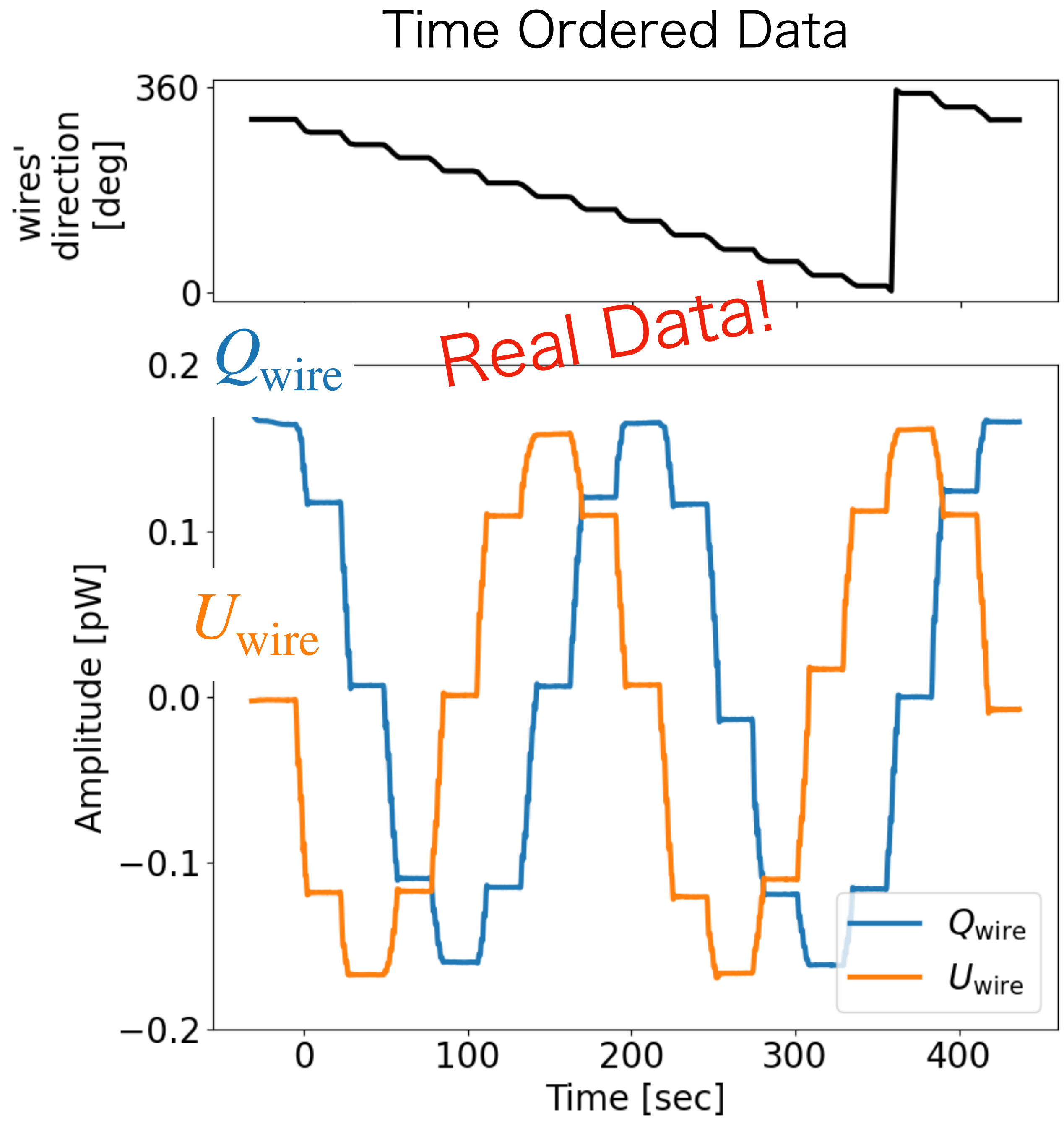
Real Data!


Sparse Wire Grid

rotate/stop evenly

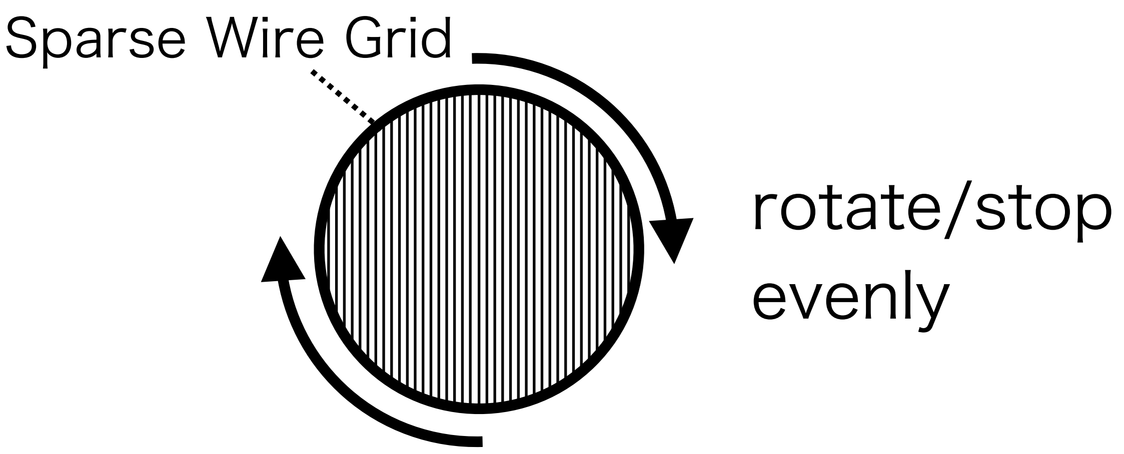
1. For example, when we stop the wire grid in 16 steps, we can see the steps in the encoder data as well.

Step 2



Time Ordered Data

Real Data!



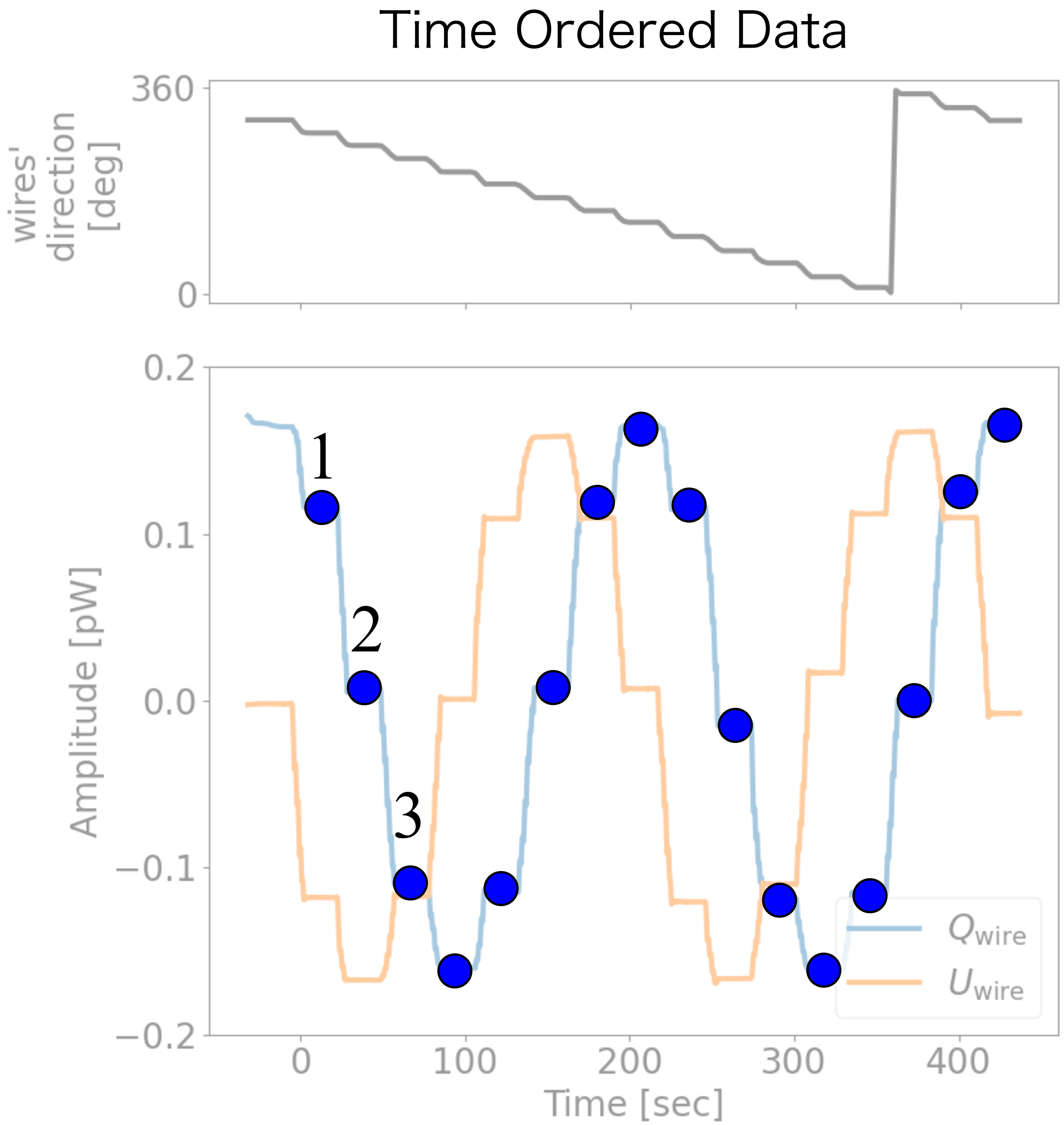
Sparse Wire Grid

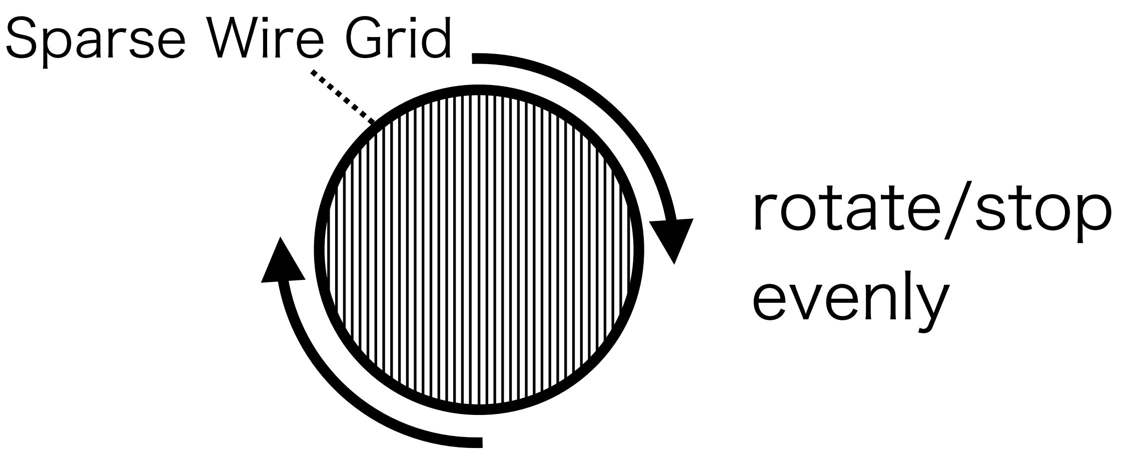
rotate/stop evenly

1. For example, when we stop the wire grid in 16 steps, we can see the steps in the encoder data as well.

2. According to the motion of the wire grid, time streams of detectors will have step wise shapes.

Step 3



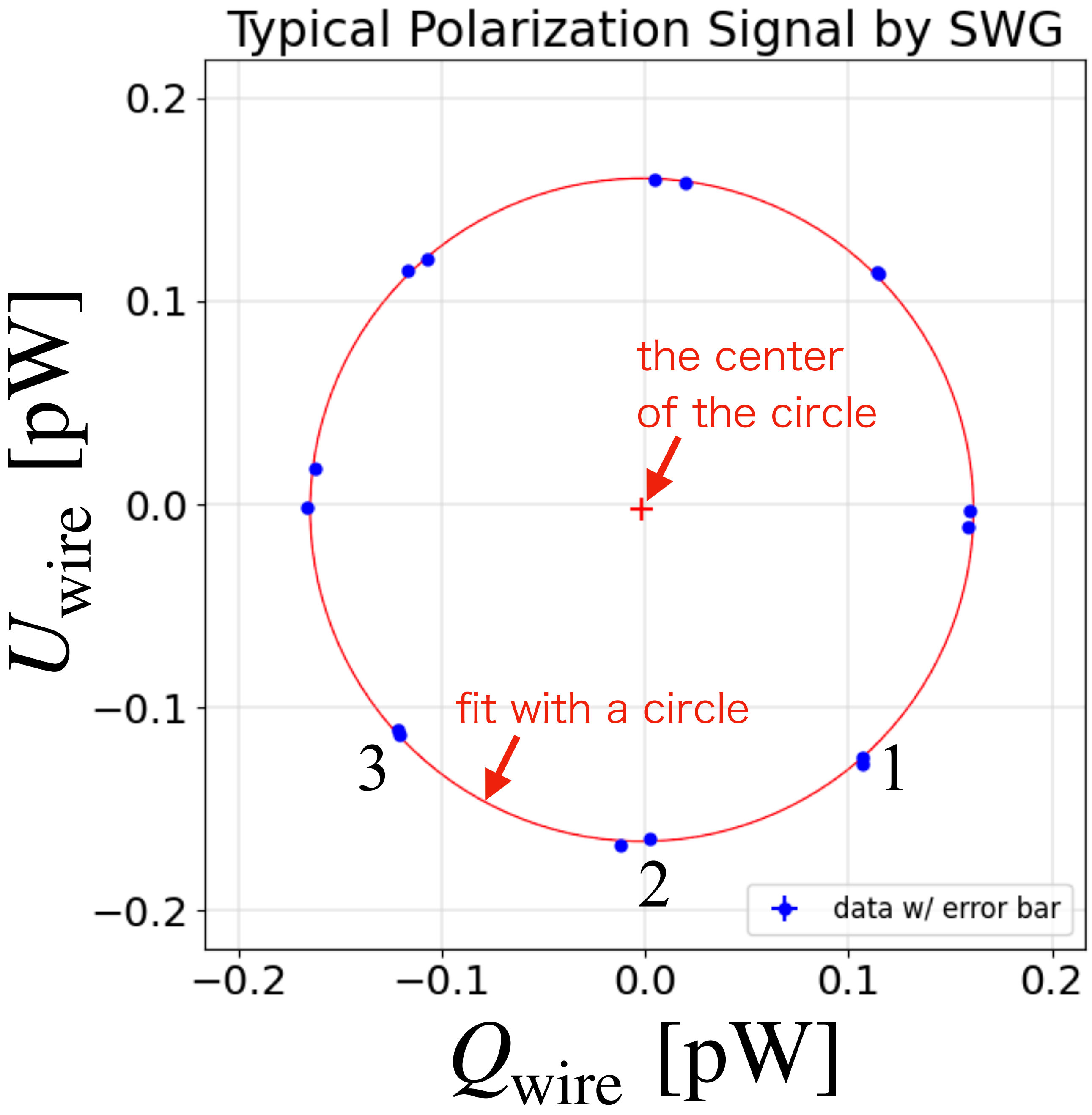


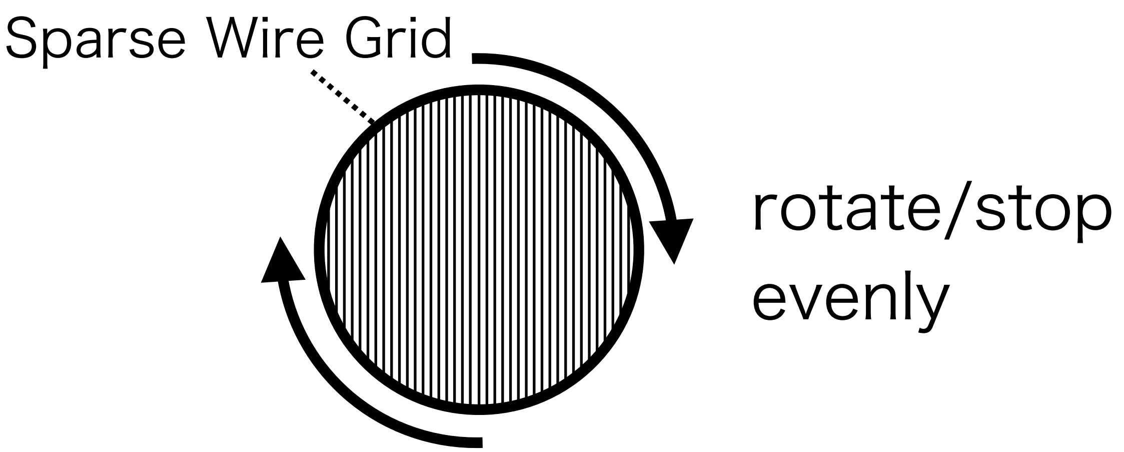
1. For example, when we stop the wire grid in 16 steps, we can see the steps in the encoder data as well.

2. According to the motion of the wire grid, time streams of detectors will have step wise shapes.

3. Further, by fitting all points together for Q and U components, we can get a circle (calibration circle).

Step 3 (cont’d)





1. For example, when we stop the wire grid in 16 steps, we can see the steps in the encoder data as well.

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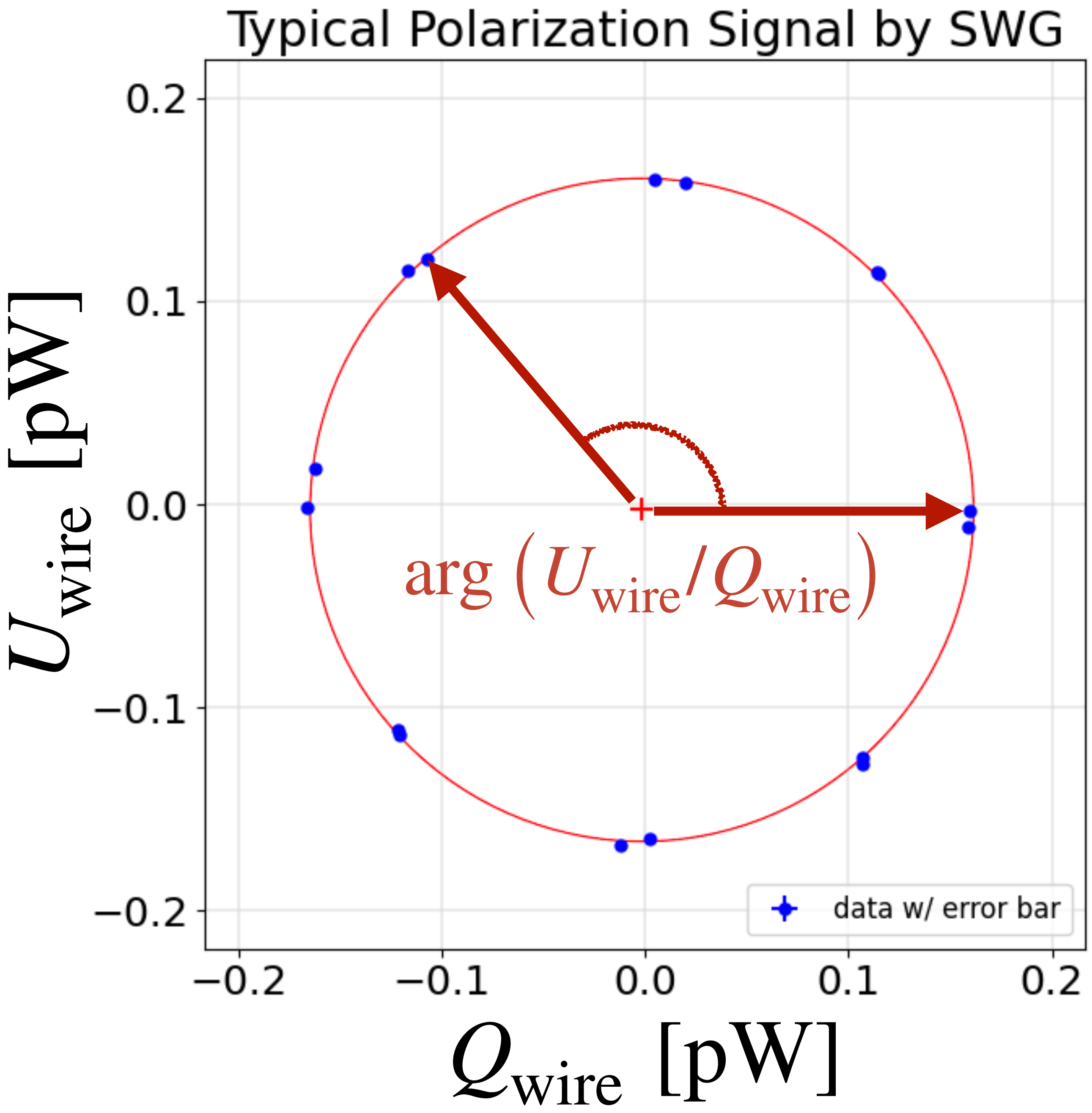
Finally



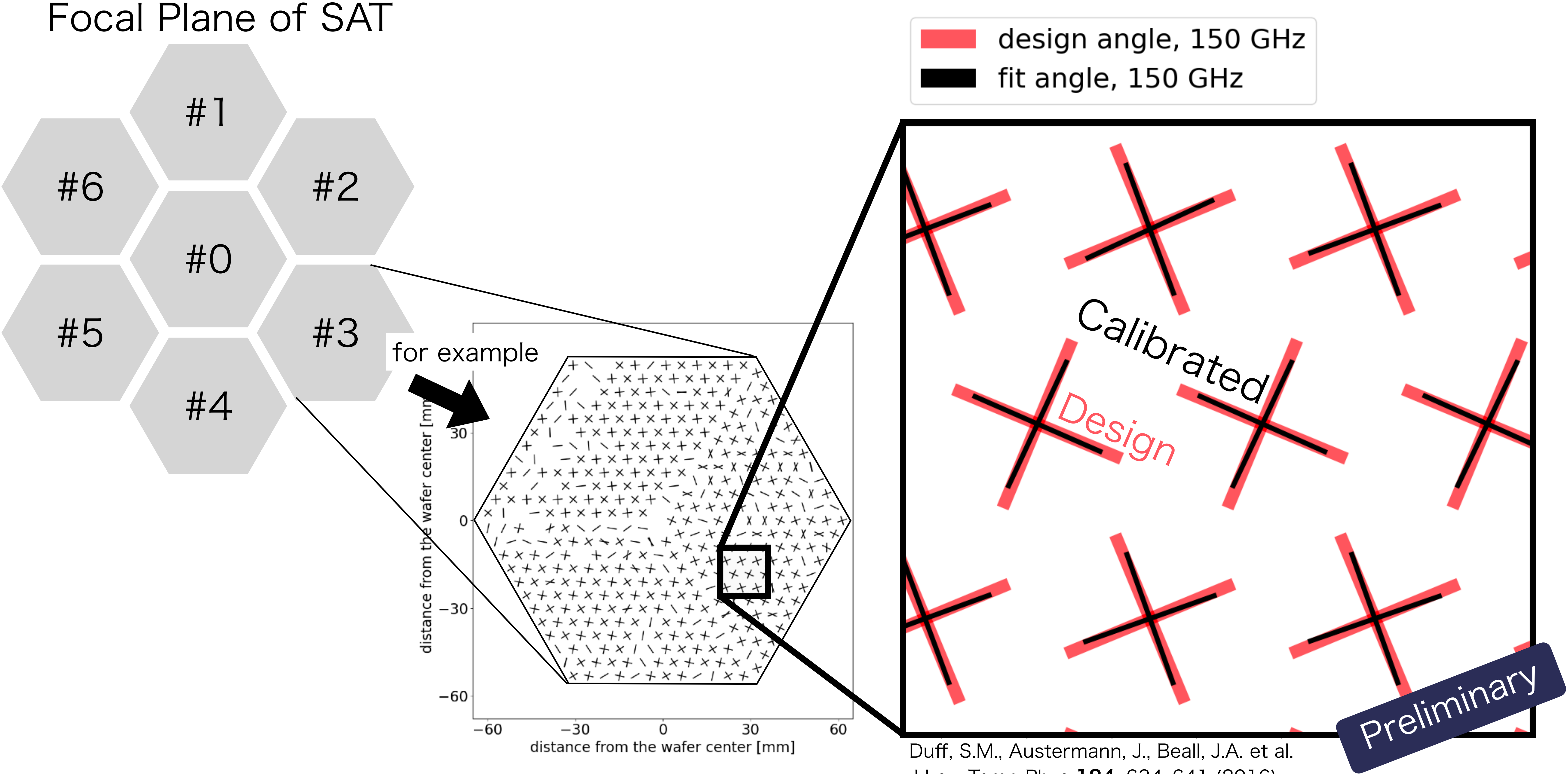
4. Finally, the calibrated angles are given by subtracting the direction of the wires.

$$\boxed{\theta_{\mathrm{det}} = \frac{1}{2}\arg\left(U_{\mathrm{wire}}/Q_{\mathrm{wire}}\right) - \theta_{\mathrm{wire}}}$$

Great advantage of the calibrator is that we can **calibrate all the polarization response angle in the focal plane at the same time** (with a single calibration run).

visual check the printed design

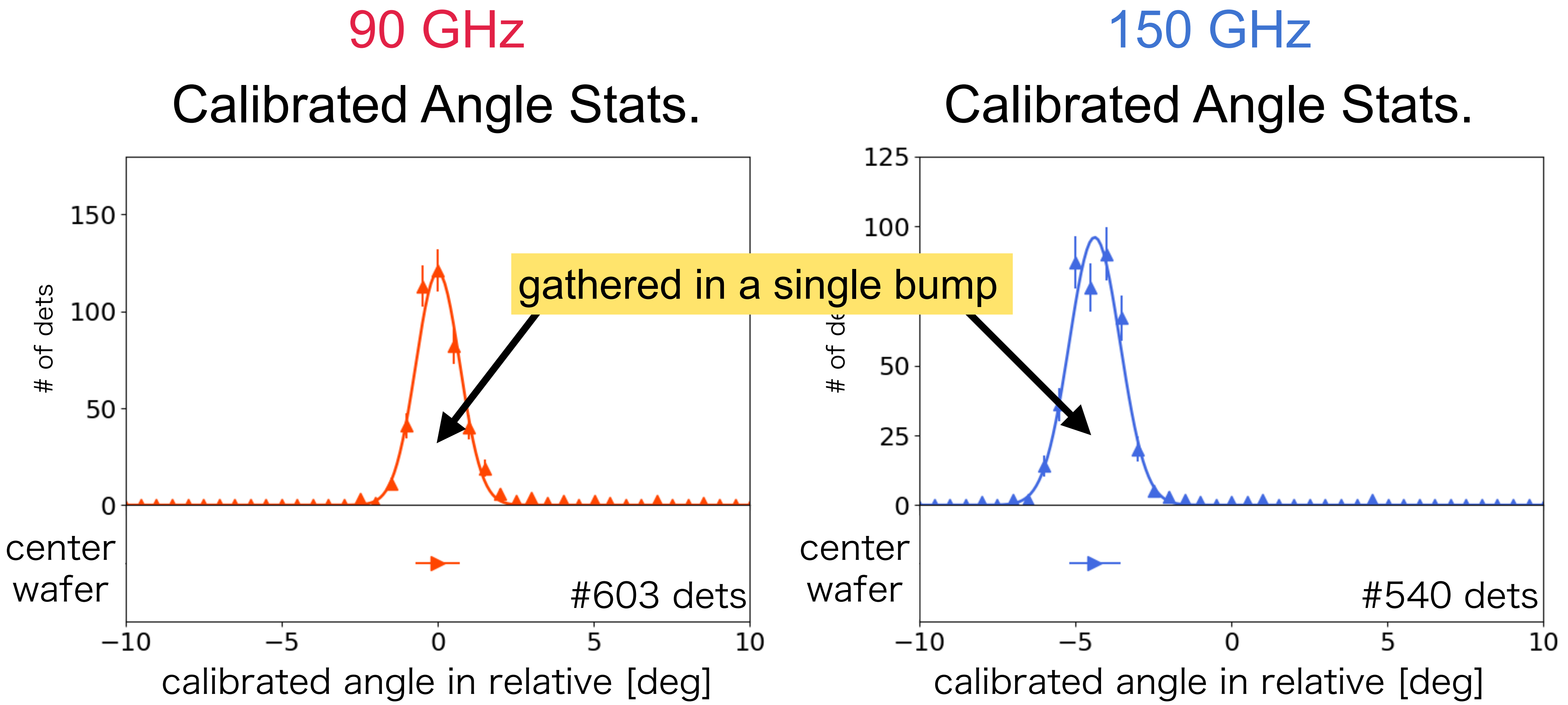
Focal Plane of SAT



Duff, S.M., Austermann, J., Beall, J.A. et al.
J Low Temp Phys **184**, 634–641 (2016).

- We confirmed good agreement between the calibrated polarization angles and the design antenna pattern

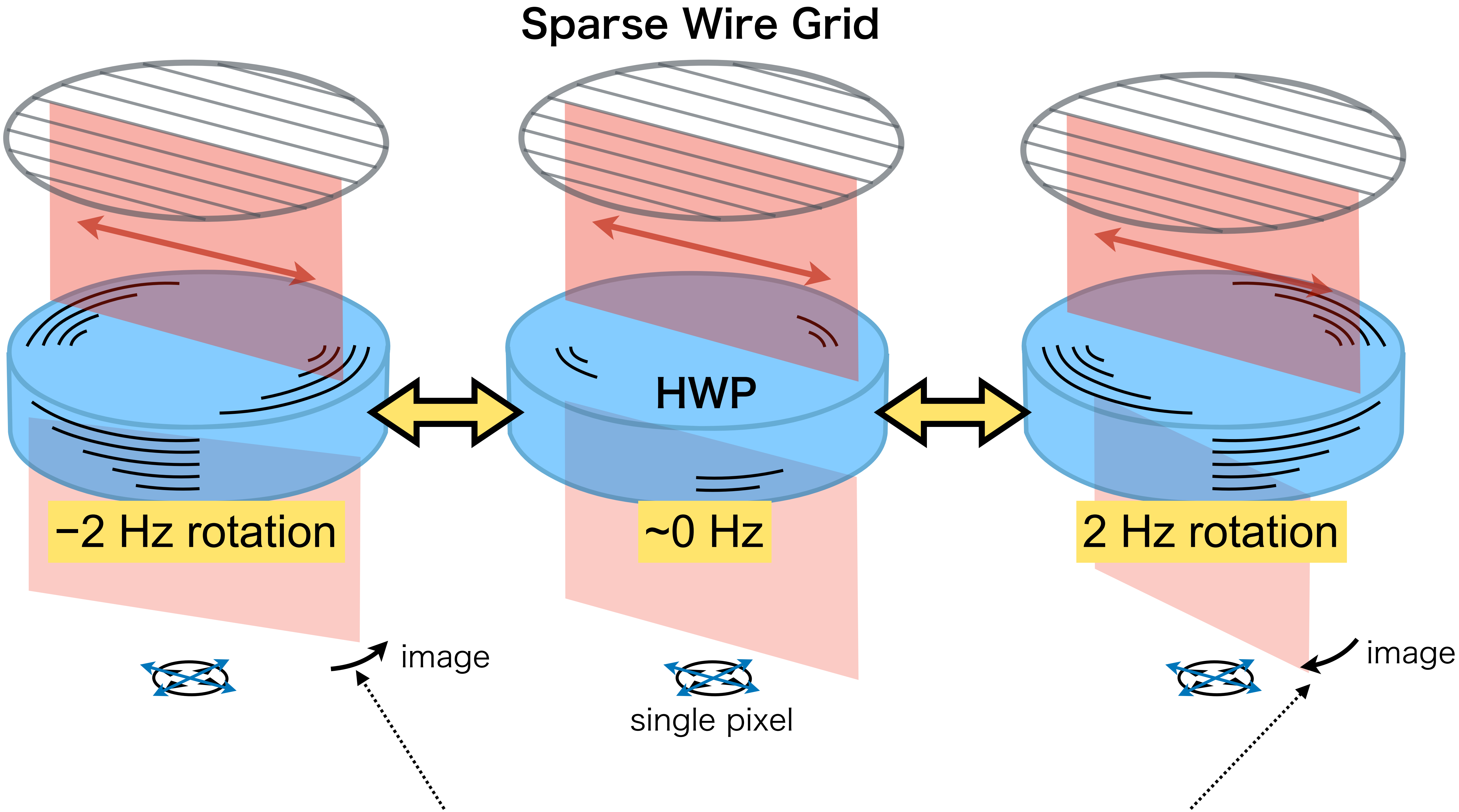
Statistics of the calibration



gathered in a single bump

- **Detectors' matching** & **calibration pipeline** work very well!
- Further, this artificial polarization source can be used **to measure the time constants of TES bolometers** → next page.

How to measure Det. time const.

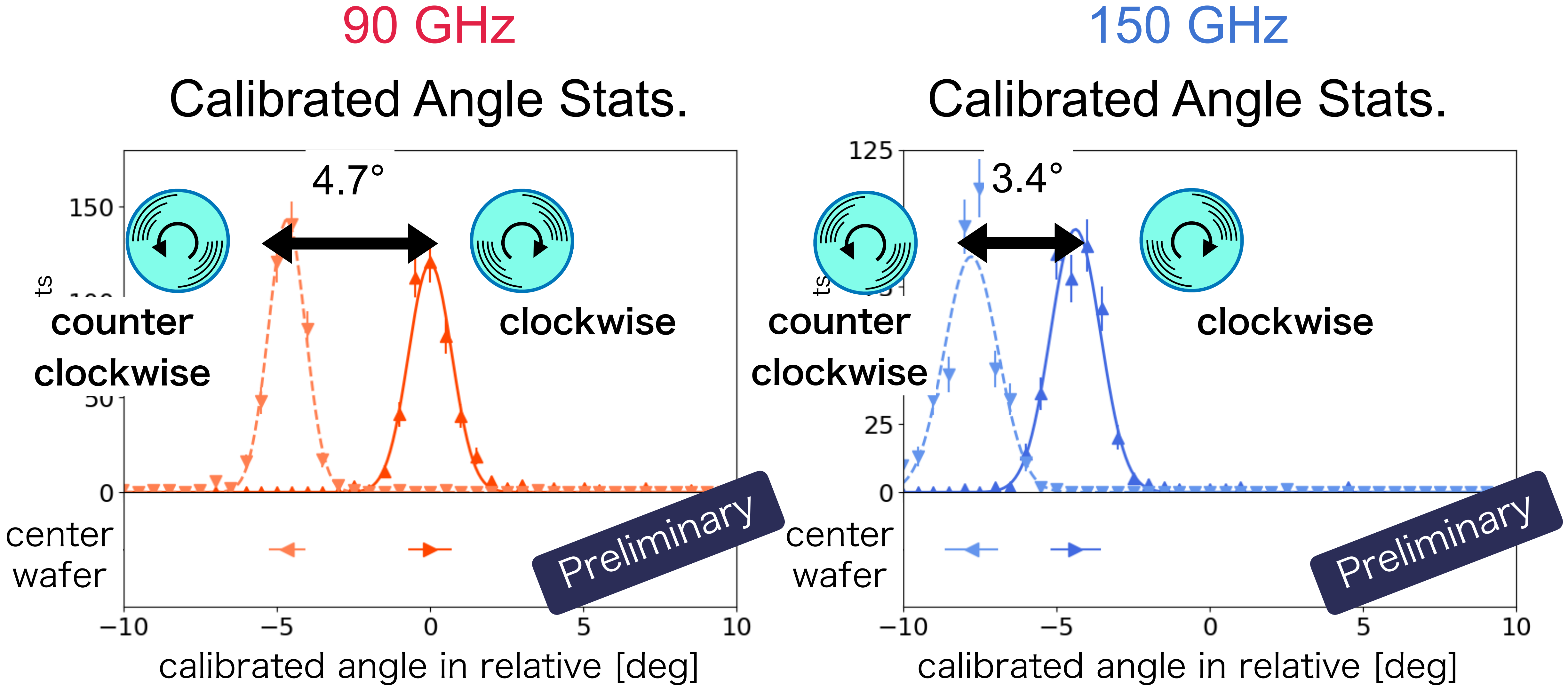


Due to the detectors' time constant, the signal delays as a function of HWP speed

Calibration at +/- 2 Hz HWP rotation

90 GHz

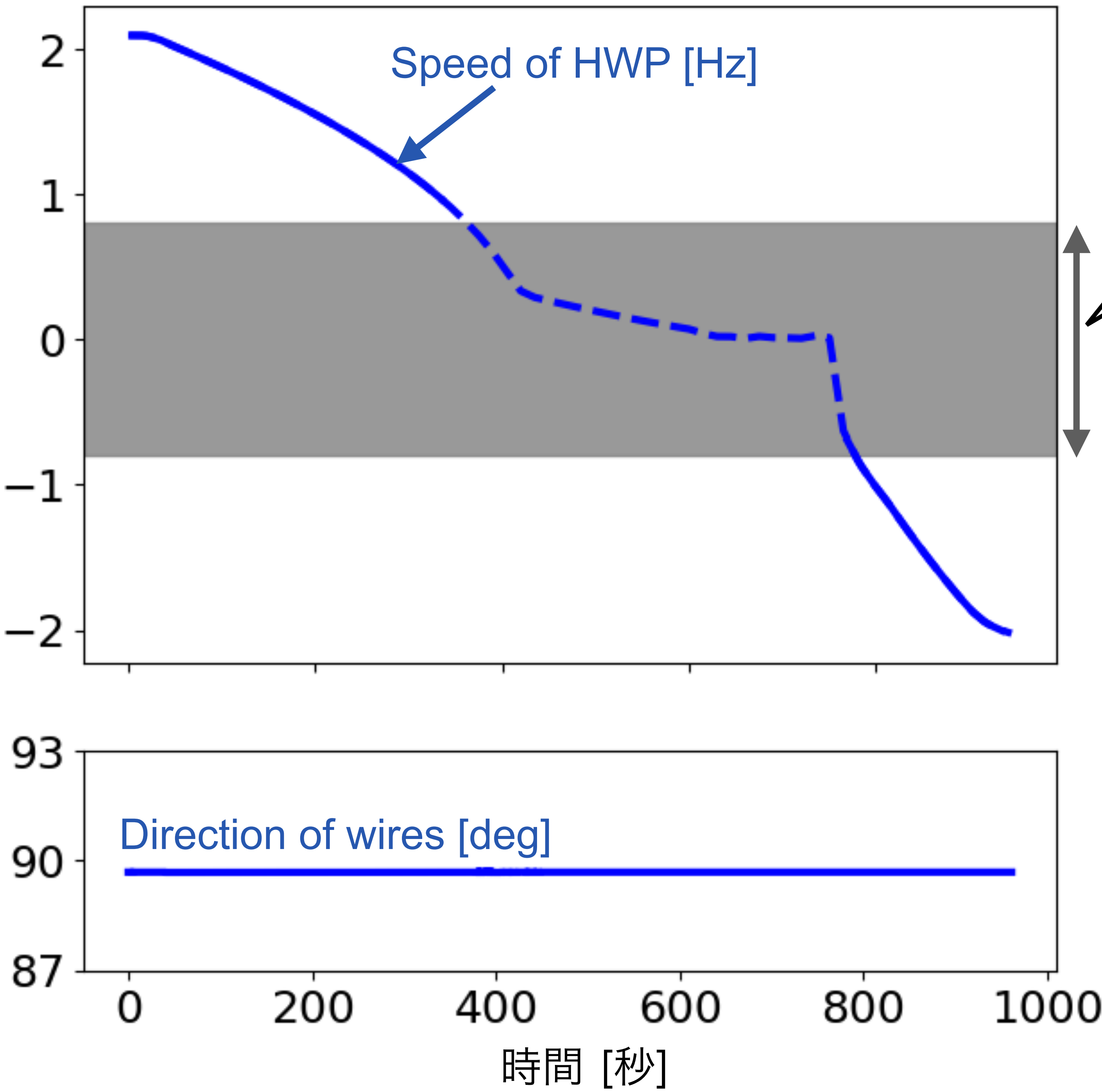
150 GHz



- The angle difference between +2Hz and -2Hz due to the time constant can be seen.

Operation for time constant measurement

HWP/wire grid status during time const. measurement



This range is not used in the analysis because of picking up mechanical/ electrical noise.

time const. dependence

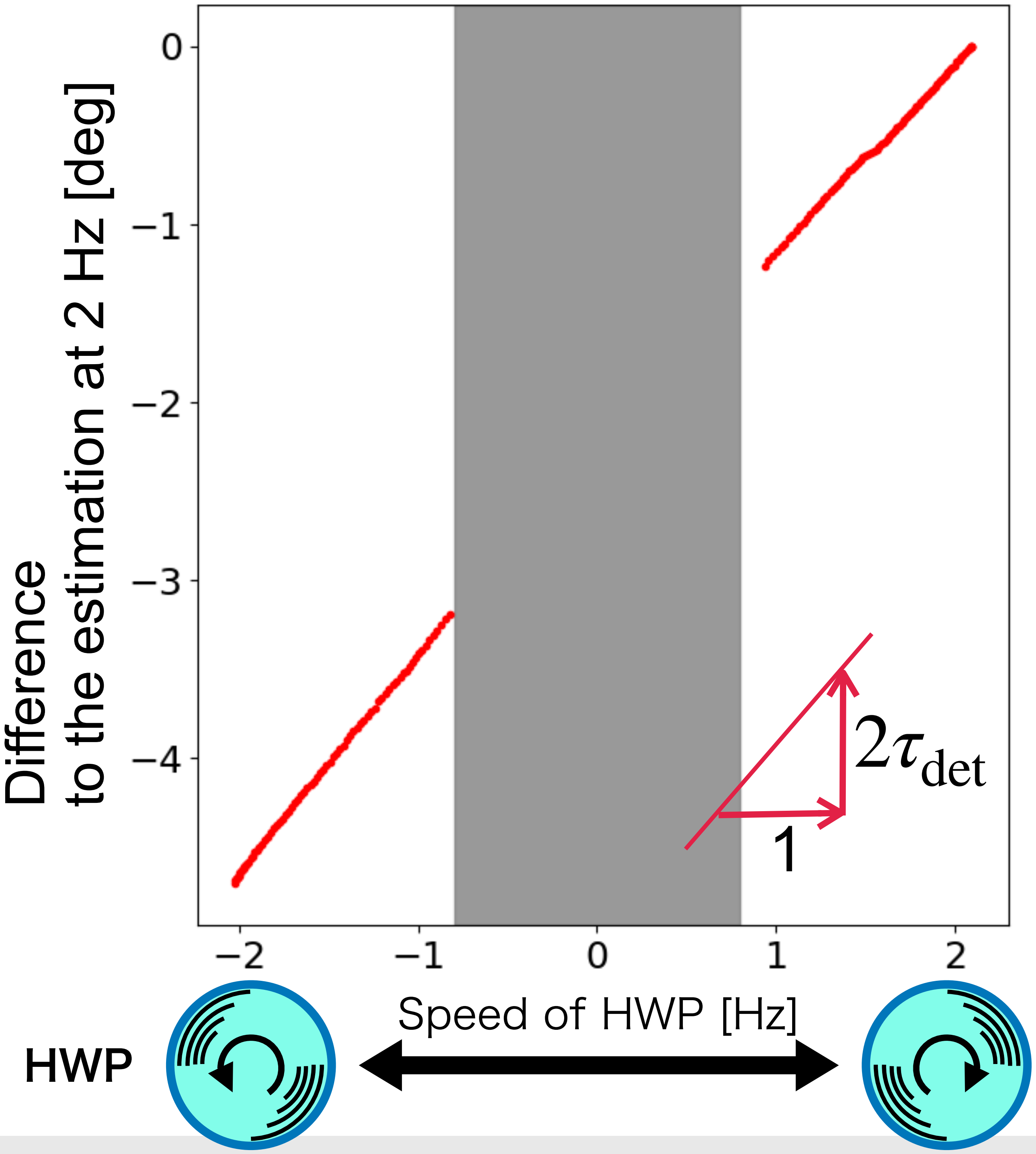
$$\mathrm{TOD} \propto \exp i \left[-4(\theta_{\mathrm{HWP}} - \tau_{\mathrm{det}}\omega_{\mathrm{HWP}}) + 2(\theta_{\mathrm{wire}} + \hat{\theta}_{\mathrm{det}}) \right]$$

$$\theta_{\mathrm{det}} = \hat{\theta}_{\mathrm{det}} + 2\tau_{\mathrm{det}}\omega_{\mathrm{HWP}}$$

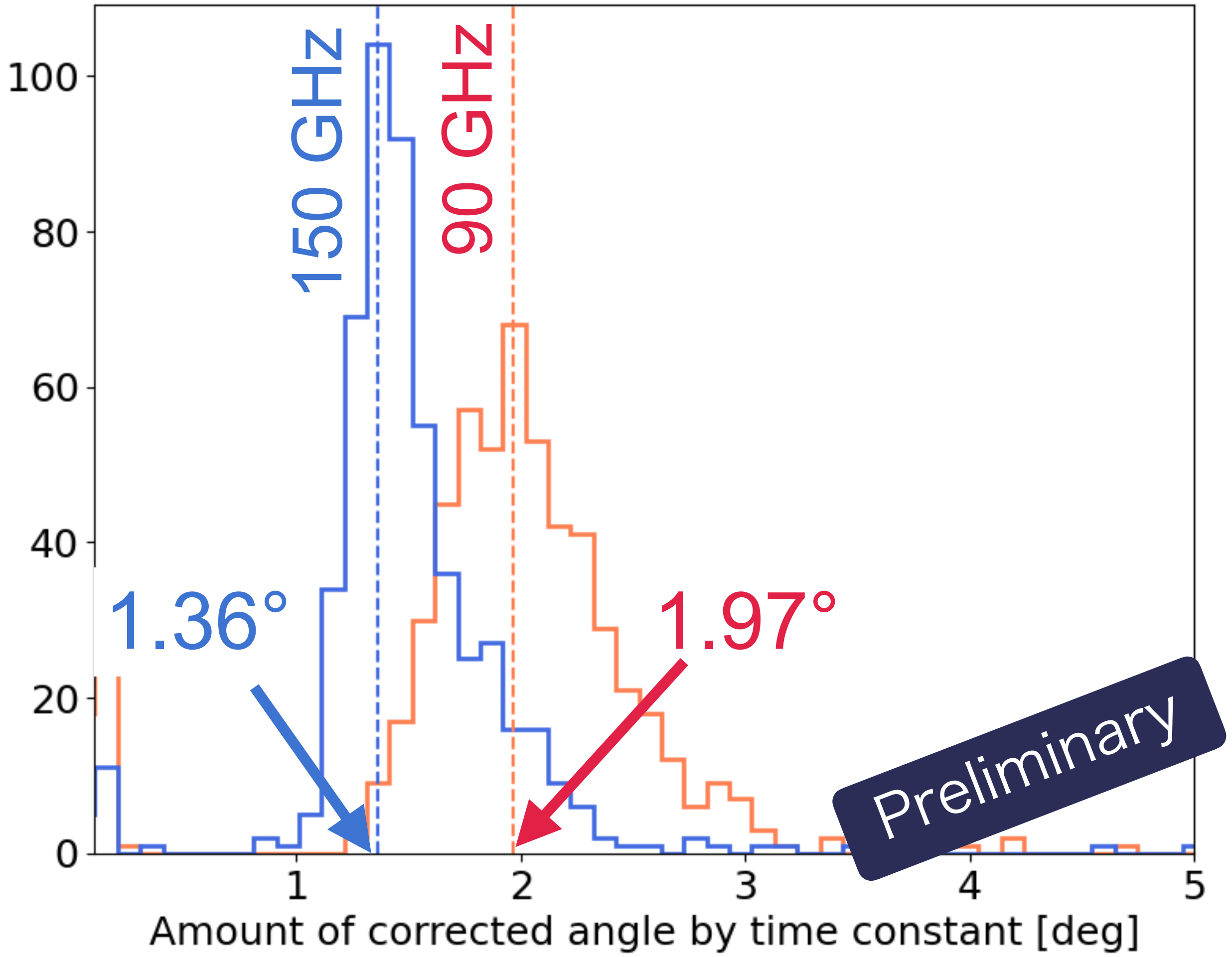
effects on calibration

How to derive the time constants

Changing of the calibrated angle about the single detector



Angle correction for one direction



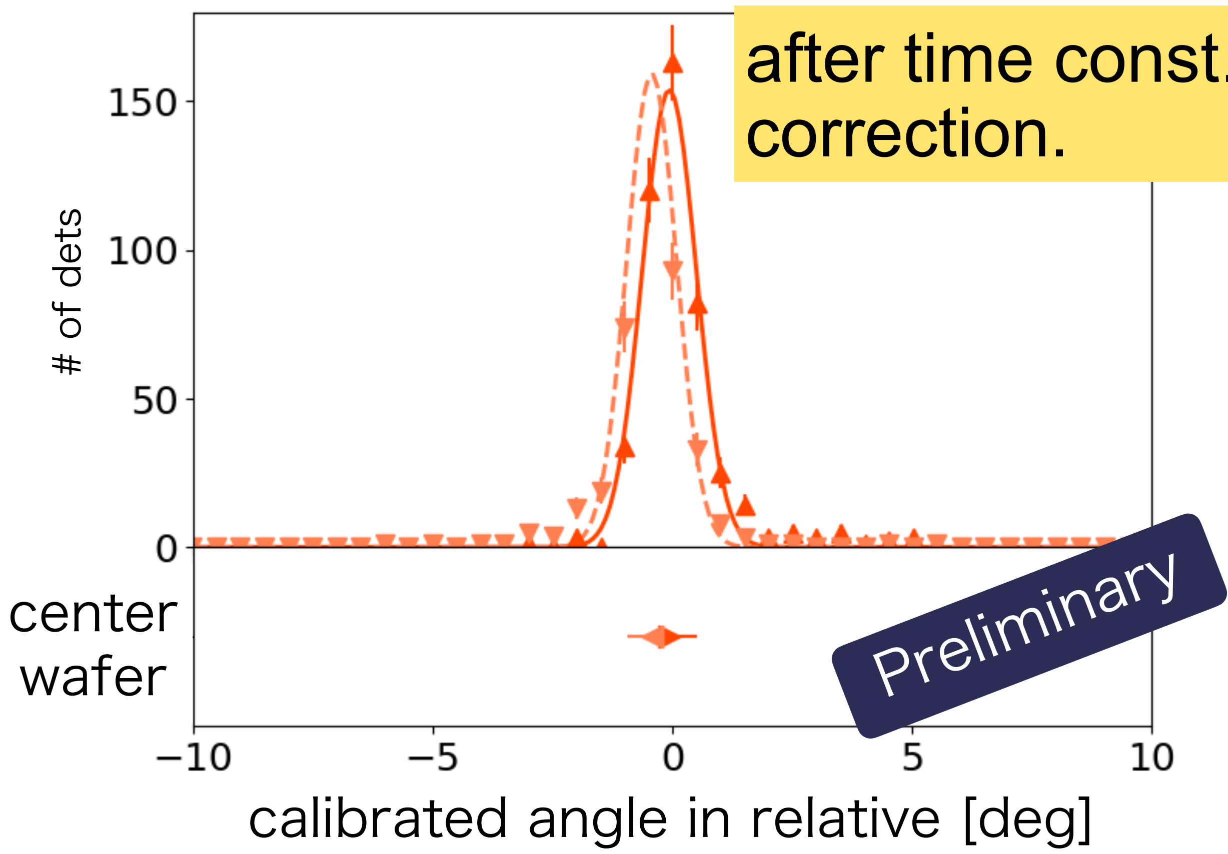
$$\theta_{\mathrm{det}} = \hat{\theta}_{\mathrm{det}} + \boxed{2\tau_{\mathrm{det}}}\omega_{\mathrm{HWP}}$$

slope = time constant

After the correction

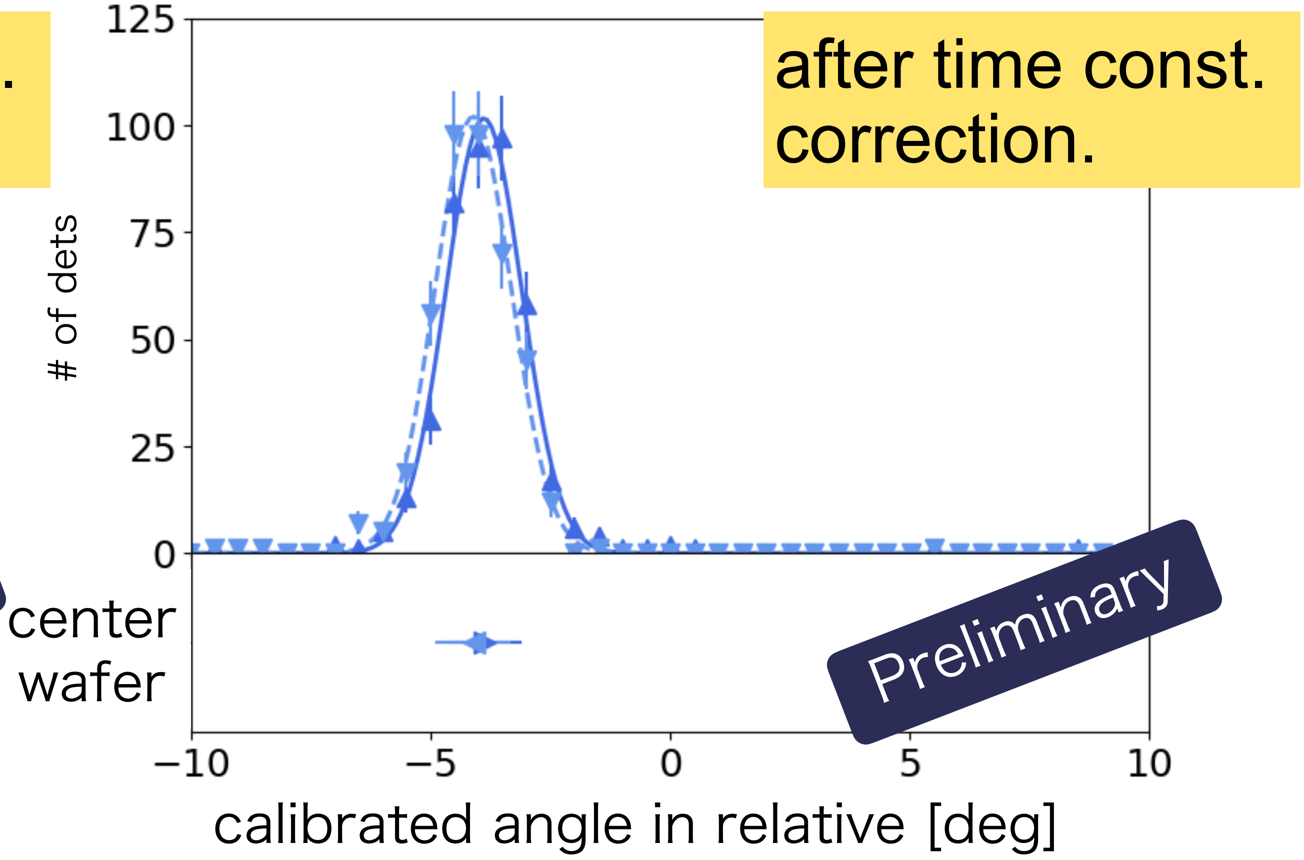
90 GHz

Calibrated Angle Stats.



150 GHz

Calibrated Angle Stats.



- The time constant correction works successfully!

Summary

- Very precise polarization angle calibration, $\sigma(\theta_{\mathrm{stat,\ sys}}) \leq 0.2\ \mathrm{deg.}$, is required to measure the primordial B-mode with $\sigma(r) = 0.003$.

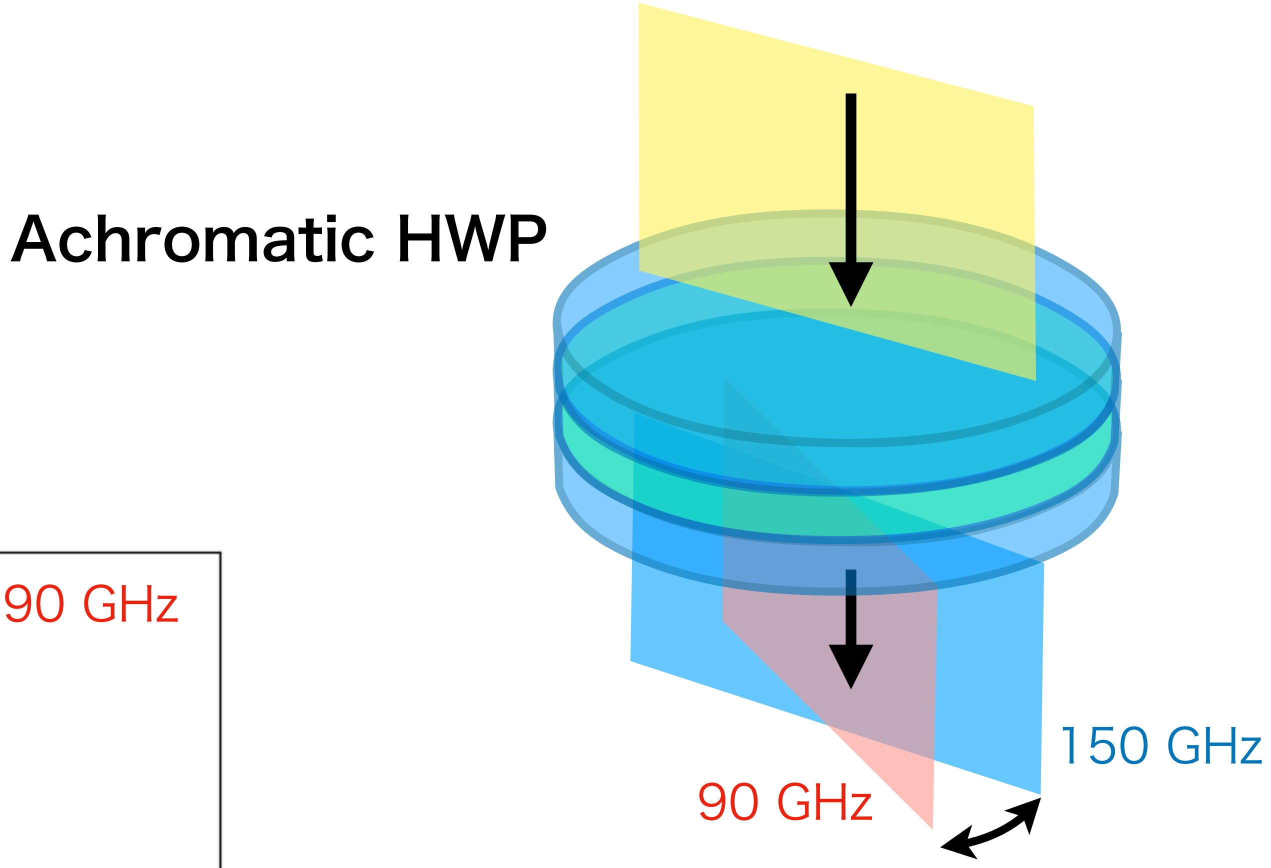
- We have developed an **automatic** calibration system using Sparse Wire Grid, which can **calibrate all the detector simultaneously** and **provides the reproducible calibrations** in just 10-mins. run.

- We have validated the methodology **with the site data.** Further, we successfully **measured the bolometer time constant** using sparse wire grid and HWP rotation

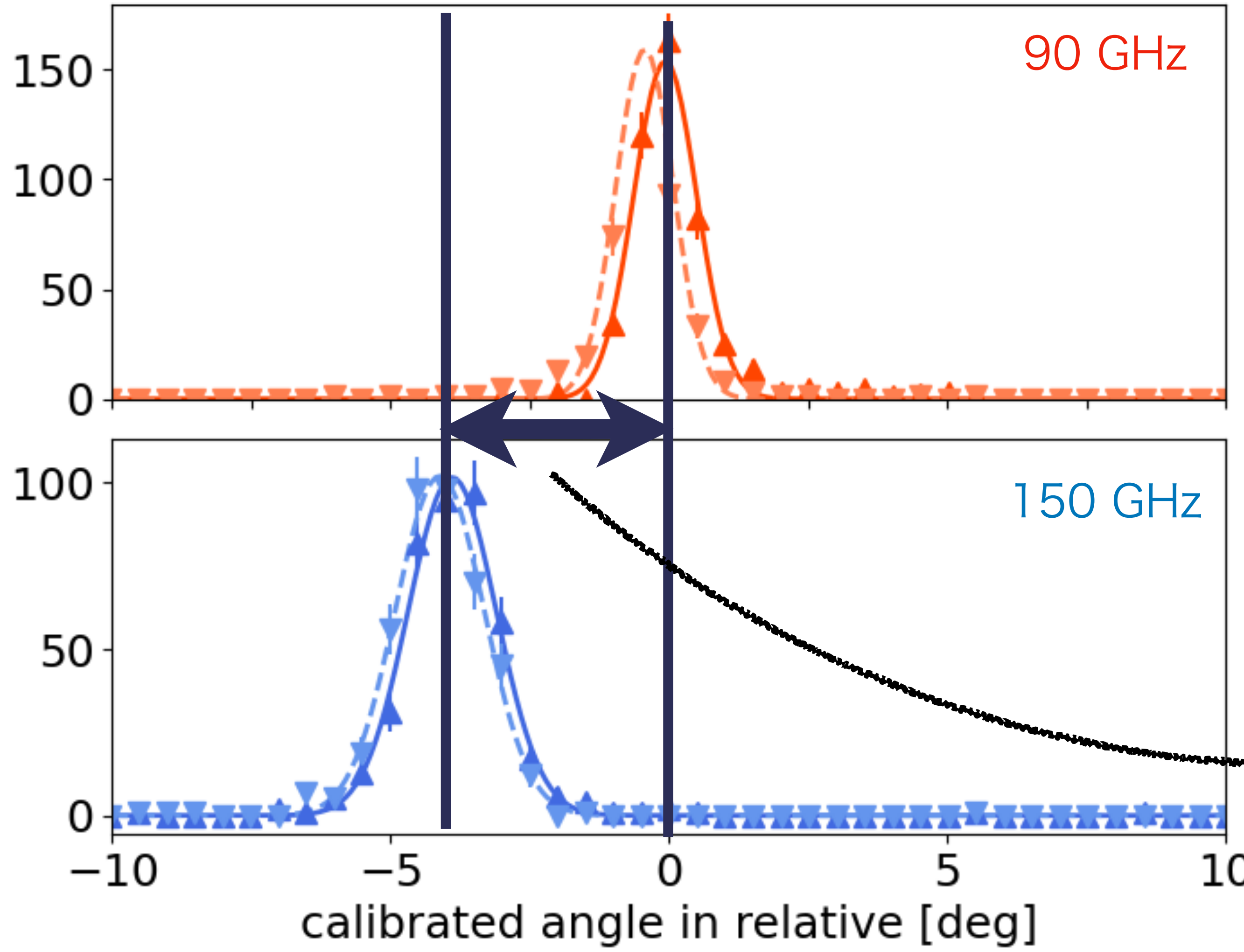
- In future plan: to combine the results with other complemental methods, drone and Tau A.

Backup

Effect of the Achromatic HWP



$$\theta^{\text{design}}_{\text{HWP},\Delta 90/150} \approx 1.9^\circ$$



Consistent!

$$\text{Diff.} = 2\times\theta^{\text{measured}}_{\text{HWP},\Delta 90/150}$$

$$= 2\times 1.905^\circ$$