# LiteBIRD systematics

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Okayama University
1st of Dec., 2020
CMB systematics and calibration focus workshop

# One Minute Summary

- LiteBIRD systematics ~70 sources.
  - Individual systematic studies will be published in coming months.
- In this talk, I focused on:
  - The sky scanning strategy to cover all the sky area with uniform angle observation
    - A combination of precession and spin with the angles/rate.
  - The HWP spinning rate determination
    - Lower limit is set not to overlap the science band to the 3/5f harmonic
    - Upper limit would be the time constant.
  - The data sampling rate studies.
    - The rate giving less systematic effects but manageable with the data transfer system.
  - Cosmic ray studies
    - Glitch effects in simulation/hardware
    - Total does effects using HIMAC
  - HWP systematics
    - IP can be corrected using CMB dipole.

# Systematics and Calibration

- One of the largest study groups at LiteBIRD
- Systematic approach for systematic uncertainties

List sources
14 categories
70 items

→ Assign each 1% of total budget
$\sigma(r)_{sys} < 5.7 \times 10^{-6}$

→ Define method (incl. calib. meth.)
estimate of $\sigma(r)_{sys}$

→ Allocate special budget for outstanding items

→ Sum on map base
total $\sigma(r)_{sys}$

iterartion

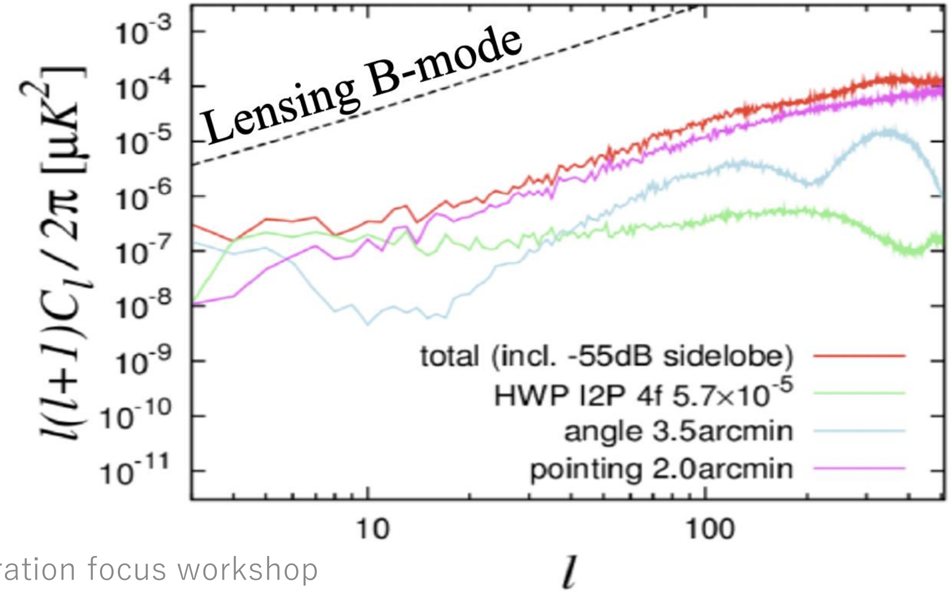
- Example: studies of systematic errors due to HWP imperfection

Realistic HWP for different frequencies and incident angles

→ Mueller matrix M from RCWA sim.
$1M_{IQ}$, $M_{IU} \sim 10^{-4}$
(worst case)

→ Obtain leakage Maps and BB power
$\sigma(r)_{sys}$

All known systematics will be adequately mitigated!

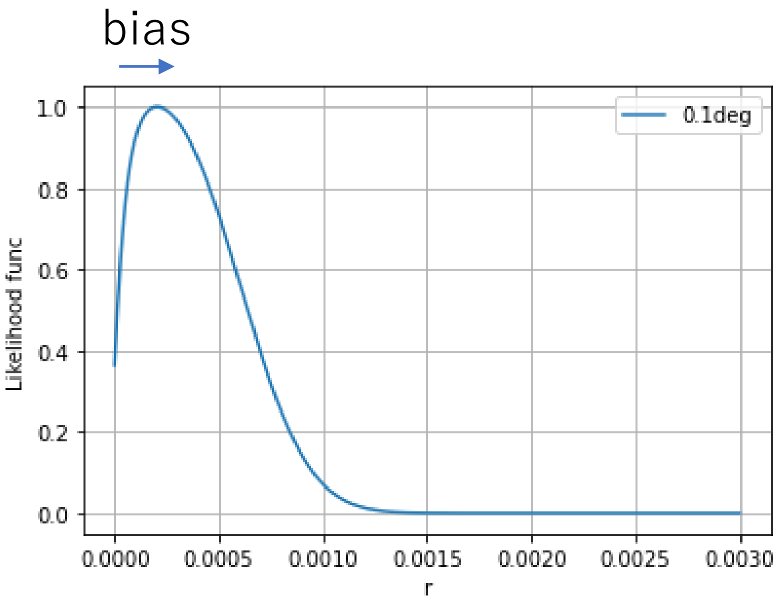


# The systematic error

- We quantify the systematics as a bias of the tensor-to-scalar ratio r:

$$\frac{\sum_\ell (2\ell+1) C_\ell^{\rm tens} C_\ell^{\rm sys}}{\sum_\ell (2\ell+1)(C_\ell^{\rm tens})^2}$$

assuming r=0




- The systematic effects in $C_l$ is given

$$C_\ell^{\rm sys} = \sum_i C_\ell^{BB\ {\rm sys}\ (i)} + \sum_{i \neq j} \langle B_{\ell m}^{{\rm sys}\ (i)} B_{\ell m}^{{\rm sys}\ (j)*} \rangle$$

First term: single systematic power spectrum

Second term: correlation between two effects

- The systematic effect is an additive quantity with possible correlations.

# Possible Systematic Sources

Transfer function

Electric noise

$$d(t) = g(t)H_t \otimes \left[n_s(t) + \frac{1}{2}\int d\nu W(\nu) \int d\Omega' p(t, \nu, \hat{n}' - \hat{n}, \hat{s})\right] + n_J(t) + \sum_a T_a(t),$$

Gain, Non-linearity

Bandpass

Pointing

Extra noises:
Cosmic ray, 1/f etc

Co-polar beam

$$\begin{aligned} p(t, \nu, \hat{n}, \hat{s}) \quad = \quad & B_{\|}(t, \nu, \hat{n}, \hat{s})[I(t, \nu, \hat{n}) + \epsilon(t, \nu)(Q(t, \nu, \hat{n}) \cos 2\psi(t, \nu, \hat{s}) + U(t, \nu, \hat{n}) \sin 2\psi(t, \nu, \hat{s}))] \\ & + B_{\perp}(t, \nu, \hat{n}, \hat{s})[I(t, \nu, \hat{n}) - \epsilon(t, \nu)(Q(t, \nu, \hat{n}) \cos 2\psi(t, \nu, \hat{s}) + U(t, \nu, \hat{n}) \sin 2\psi(t, \nu, \hat{s}))], \end{aligned}$$

Cross-polar beam

Pol. eff.

Pol. angle

s: det. pos.
n: sky pos.

HWP

$$\begin{pmatrix} I(t, \nu, \hat{n}) \\ Q(t, \nu, \hat{n}) \\ U(t, \nu, \hat{n}) \end{pmatrix} = M_{\rm opt}(\Theta) M_{\rm H}(\Theta, \beta, \nu) \begin{pmatrix} I_{\rm in}(t, \nu, \hat{n}) \\ Q_{\rm in}(t, \nu, \hat{n}) \\ U_{\rm in}(t, \nu, \hat{n}) \end{pmatrix}$$

Opt. sys.

Θ: inc. ang.
β: rot. ang.

# List of the systematics of LiteBIRD

| Sources | Details |
|---|---|
| Gain | absolute, relative(var. in time, dets in array., inter freq.) |
| Non linearity | det. res., time var. of g/tau, HWP 2f leak, data proc. |
| Transfer func. | time const., digit. filter, crs. talks |
| Bandpass | pos., width, shape, eff., pol. wobble, beam, HWP, outer band |
| Pointing | STT(offset, var. in time), HWP wedge |
| Noise | 1/f, common, inter. freq., modeling, var. of loading., thermal stab. |
| Cosmic ray | glitch, common mode, data proc., instr. |
| Beam, Opt. syst. | Co/x pol., main, near sl., far sl., ghost., multi refl., HWP, crs. talk |
| Polarization efficiency | detector, HWP(freq. dep. of retard., trans. Q/U) |
| Instr. pol. w/ HWP | HWP (4f I->P, leak from nf, ) |
| Polarization angle | absolute, relative, HWP(Q/U mix, pos., time const.), STT |
| Diff. effects w/o HWP | gain, beam, pointing, ellipticity, bandpass(CO, FG) |
| Instr. pol. w/o HWP | optical system(reflections) |
| Others | rad. dose effect, CO, FG |

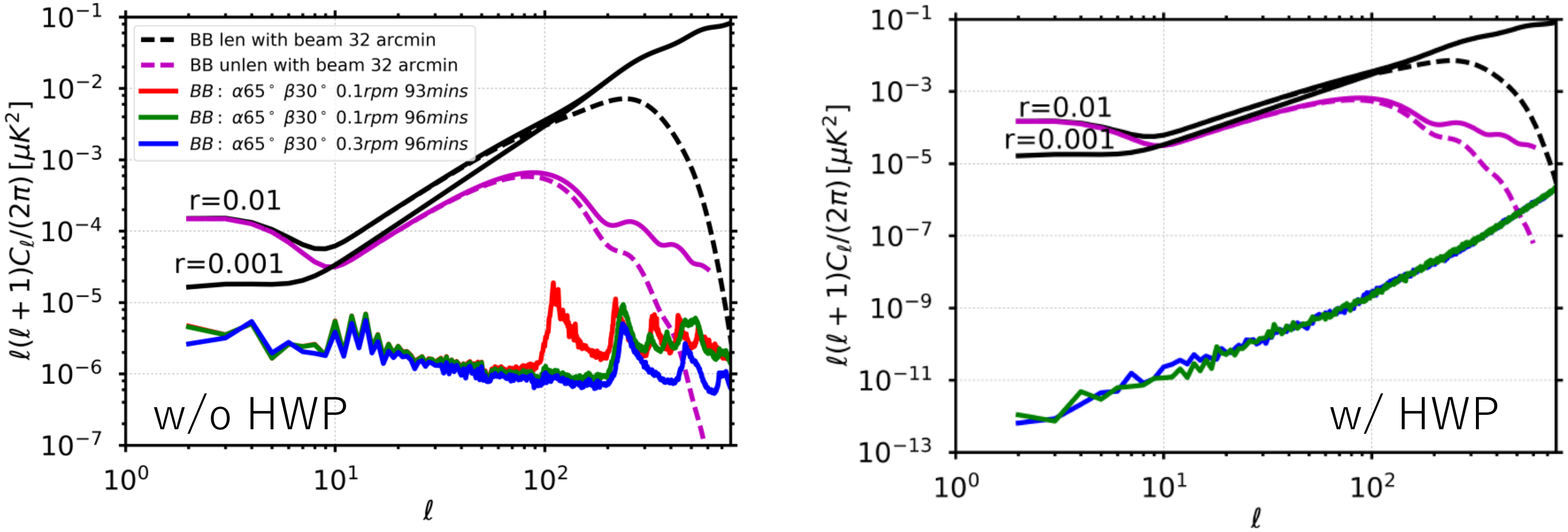
Many contributions in LiteBIRD team, especially from younger researchers.

# Mitigation of systematic effects using polarization modulation w/ spinning HWPs

- Suppression of 1/f type noise to push the signal band above the knee frequency.
- Enabling us to measure polarization using a detector sensitive to a single polarization orientation, no need to differentiate a pair of detectors
- Enabling us to have uniform polarization measurement coverage in sky pixels.

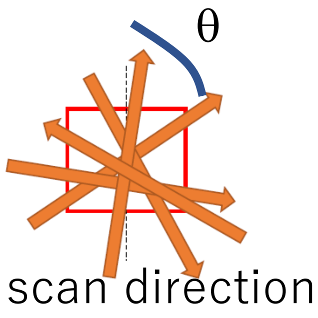
Differential Bandpass effects

FG T->P leakage




D. T. Hoang et al., JCAP12 (2017) 015

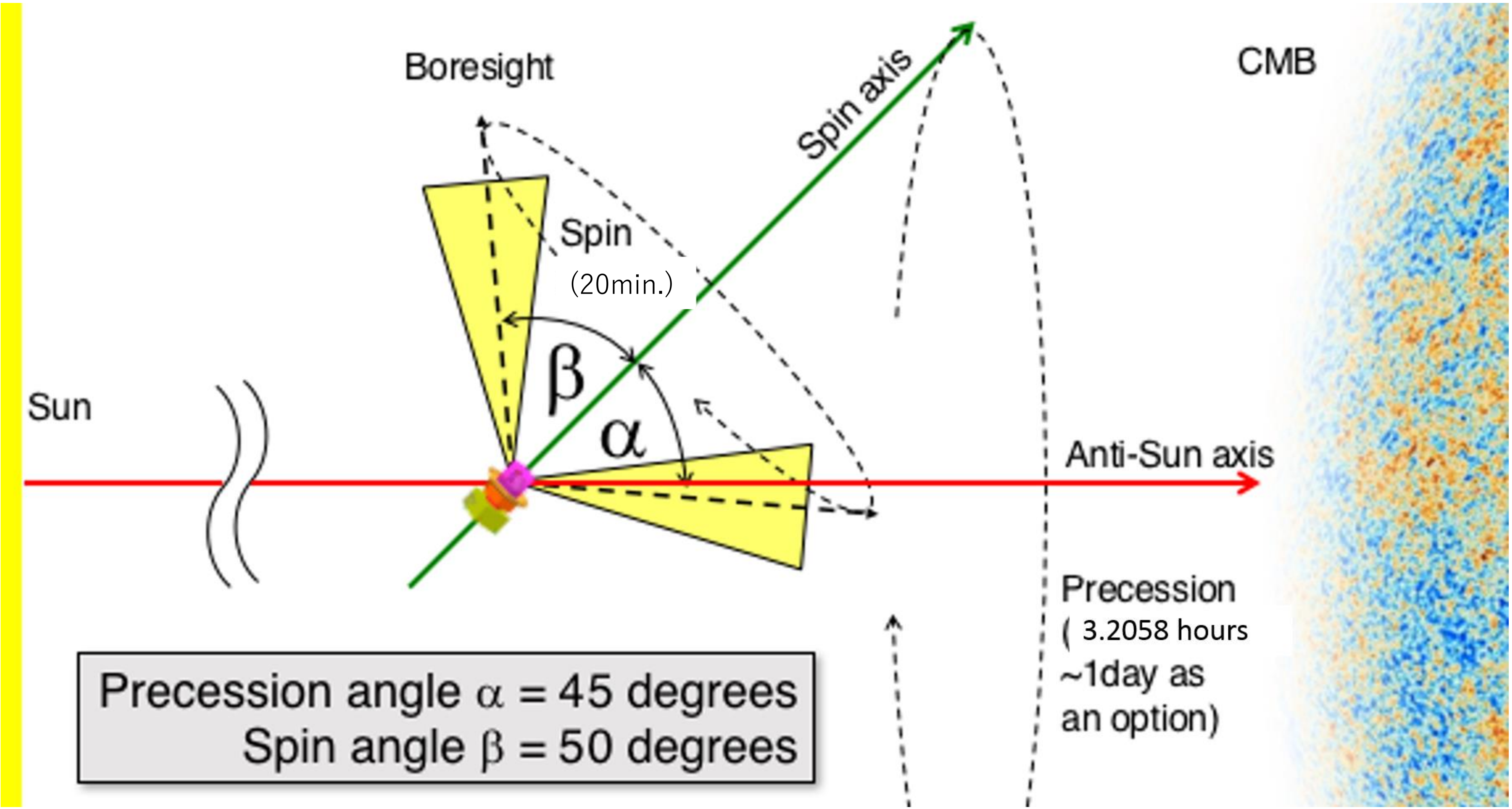
# Mitigation of systematic effects with observation strategy and specification of the instruments.




- Uniform observation
  - coverage of observation in all the sky area
  - coverage of the observation polarization angle
    - small cross-link values: spin n cross link is defined as

$$\langle \cos(n\theta) \rangle^2 + \langle \sin(n\theta) \rangle^2$$

- HWP design
  - to assure the transmittance/pol. eff. in the required band width
  - spinning rate under some requirements.
- Data sampling rate
  - sufficient rate under the limitation of data transferable rate


Boresight
Spin axis
CMB
Spin
(20min.)
β
α
Sun
Anti-Sun axis
Precession
( 3.2058 hours
~1day as
an option)
Precession angle α = 45 degrees
Spin angle β = 50 degrees

# The precession angle ($\alpha$) and spin angle ($\beta$) determination

$$\alpha + \beta = 95 \text{ degrees}$$

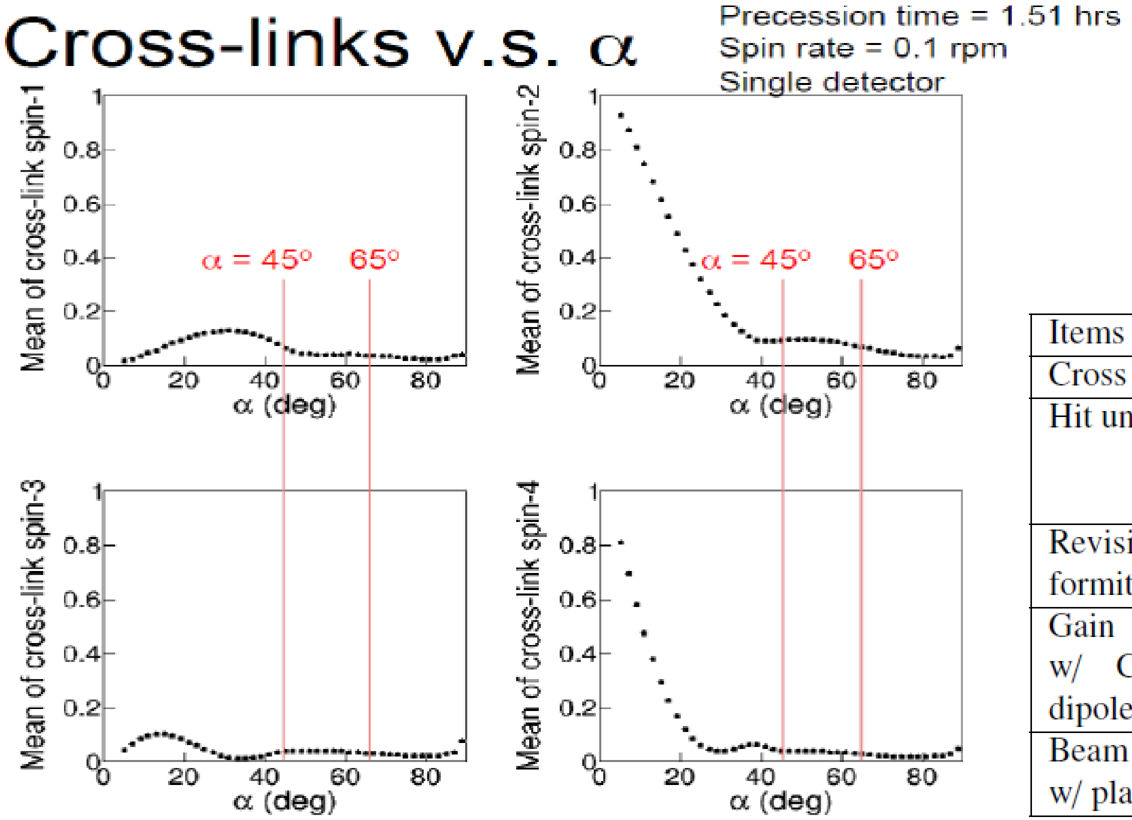


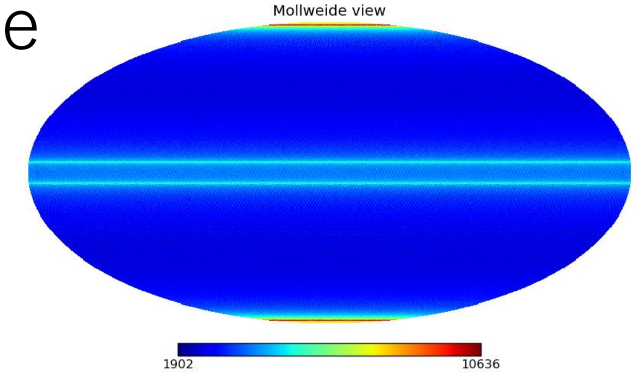

**Figure 1.** Cross link values as a function of $\alpha$ for the spins $n = 1, 2, 3$ and 4.

To cover all sky area with FOV $\alpha + \beta \geq 95$.
To reduce the input power from the sun, the earth and the moon $\alpha + \beta \leq 95$

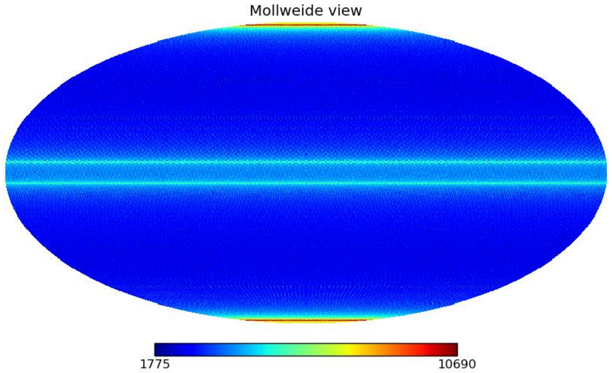
| Items | $\alpha = 65$ | $\alpha = 45$ | Comments |
|---|---|---|---|
| Cross link | OK | OK | Figure 1 |
| Hit uniformity | Larger hole, small RMS | Smaller hole, Larger RMS | Hits concentrate more around the center of hole for smaller $\alpha$ option |
| Revisit time uniformity | Large gaps | Better | Smaller hole size for small $\alpha$ option |
| Gain calibration w/ CMB solar dipole | Not Bad | Better | ~10% better with small $\alpha$ option |
| Beam calibration w/ planets | Not Bad | Good | Planet visible time twice longer with small $\alpha$ option. |

# spin rate

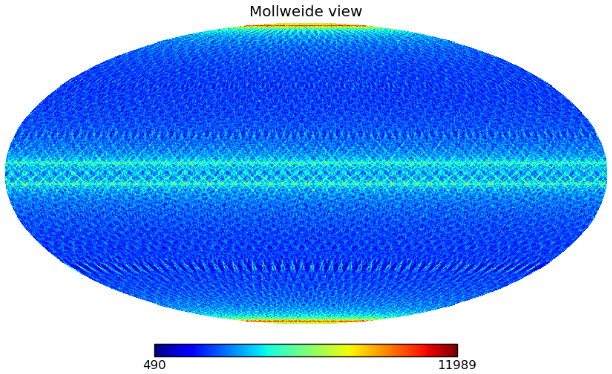
0.1 rpm
=10 min.



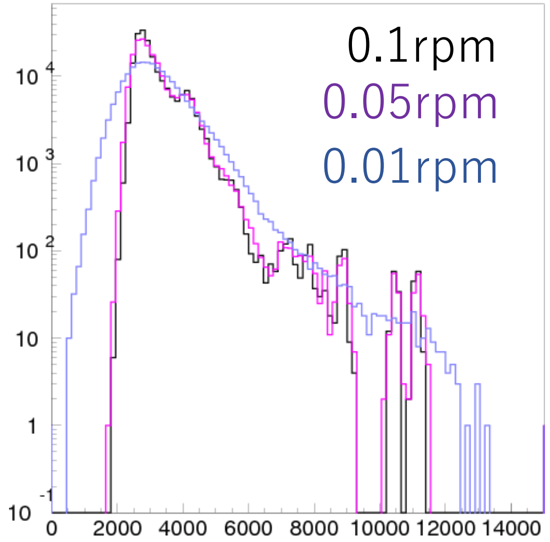

0.05 rpm
=20 min.



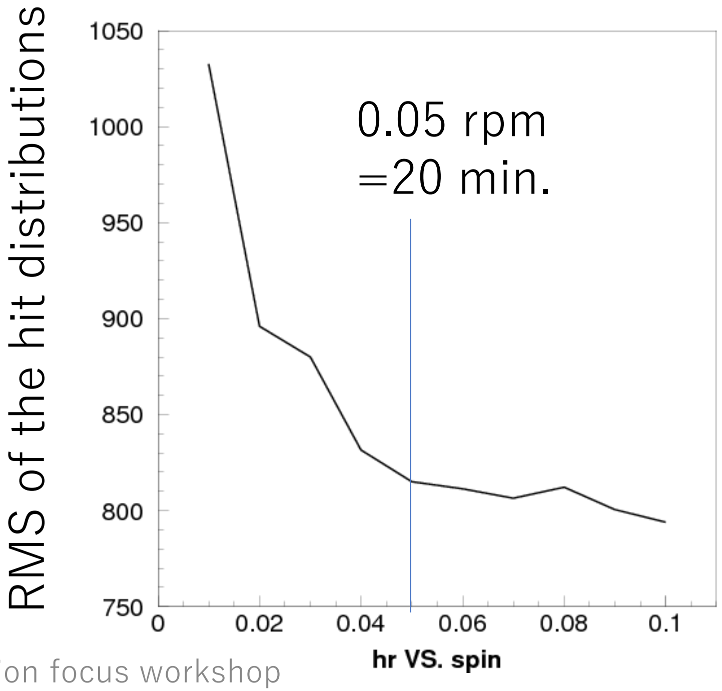

0.01 rpm
=100 min.




# Hit map




boresight only.

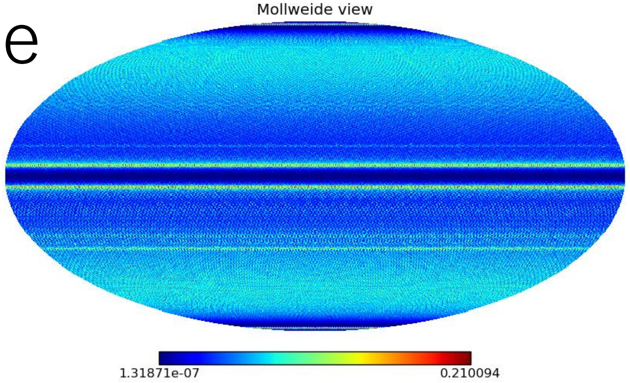



Spin rate (rpm)

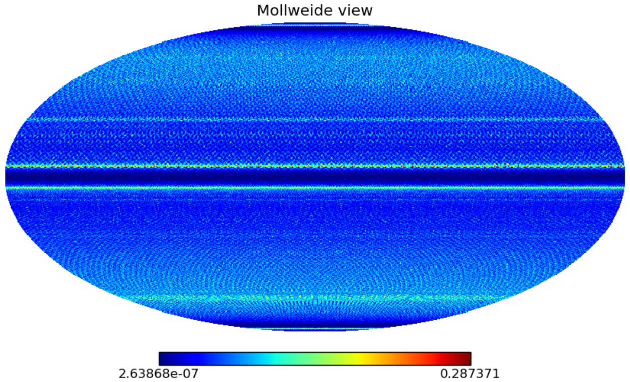
10% variance of RMS depending on the FP position.

# spin rate

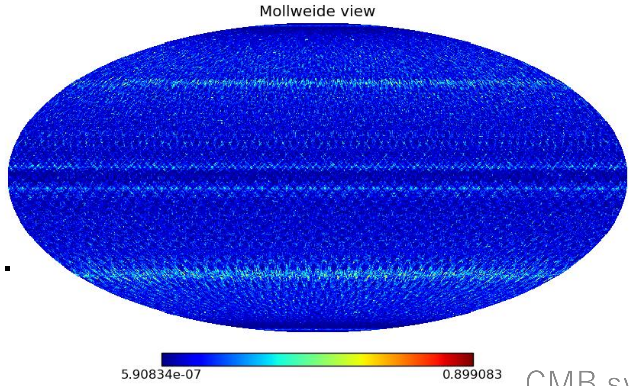
0.1 rpm
=10 min.




0.05 rpm
=20 min.

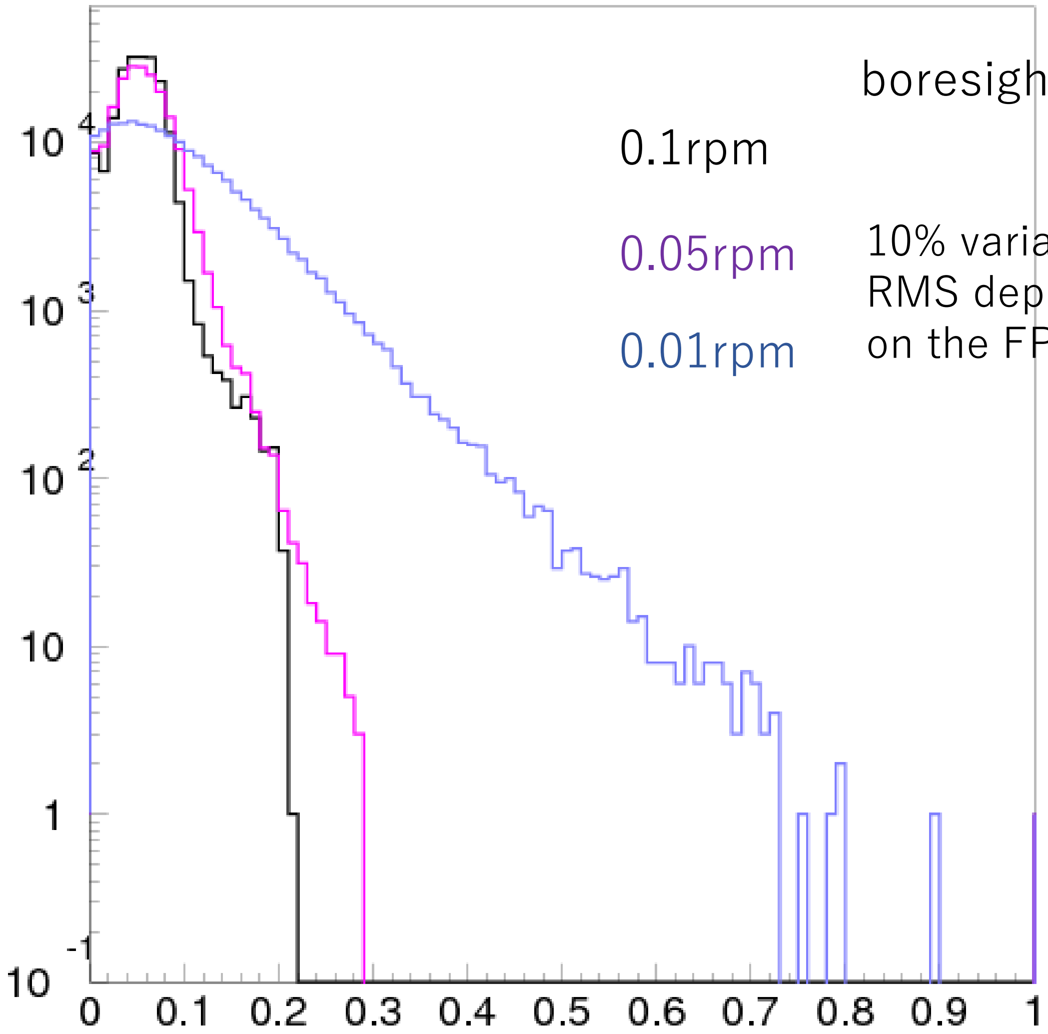



0.01 rpm
=100 min.




# spin 1 cross-link

$$\langle\cos(n\theta)\rangle^2 + \langle\sin(n\theta)\rangle^2, n = 1$$

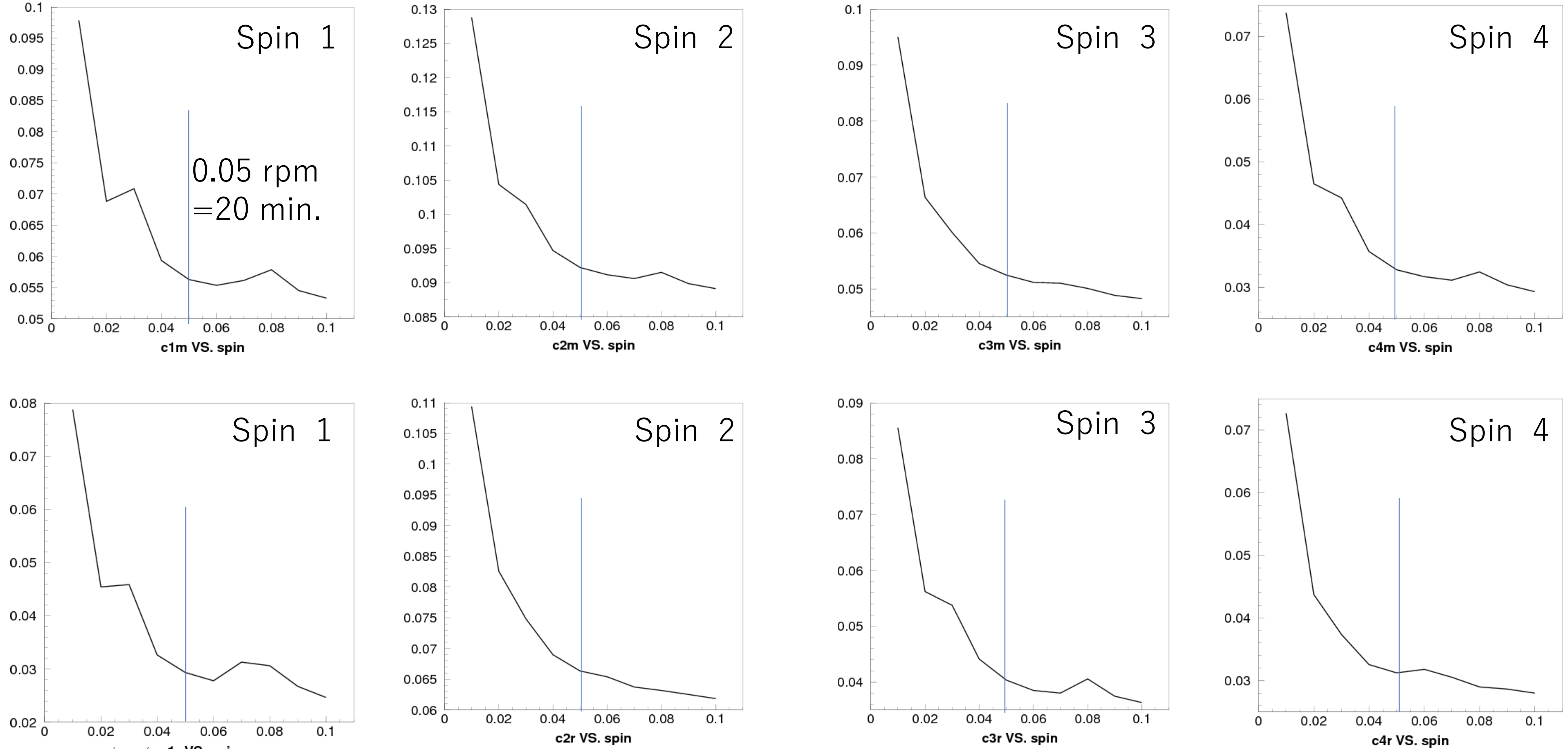



boresight only.

10% variance of
RMS depending
on the FP position.

Mean values

RMS values



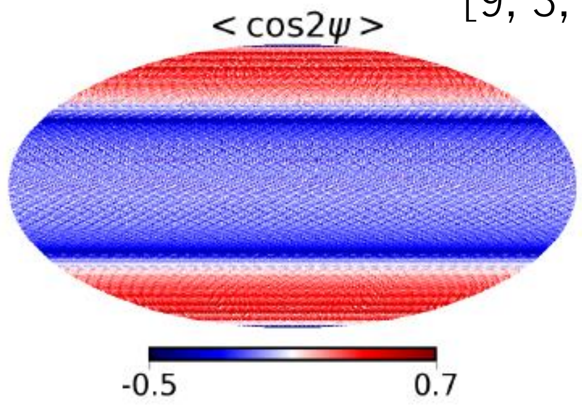
# The ratio of the precession rate to the spin rate:

$$\theta = \omega_{spin}/\omega_{prec}$$

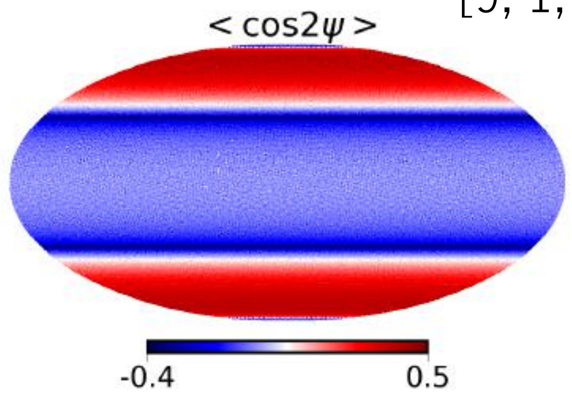
- It has been know that, if the ratio $\theta$ is simple fractions of the form p/q where p and q are relative prime, the hit/cross-link maps show visible Moire patterns.
- Martin Bucher proposed to use an irrational ratio with continued fraction representation of [9, 1, 1, ..]=9.618

$$\theta = [a_0, a_1, a_2, \ldots] = a_o + \cfrac{1}{a_1 + \cfrac{1}{a_2 + \ldots}}$$

[9, 3, 3]

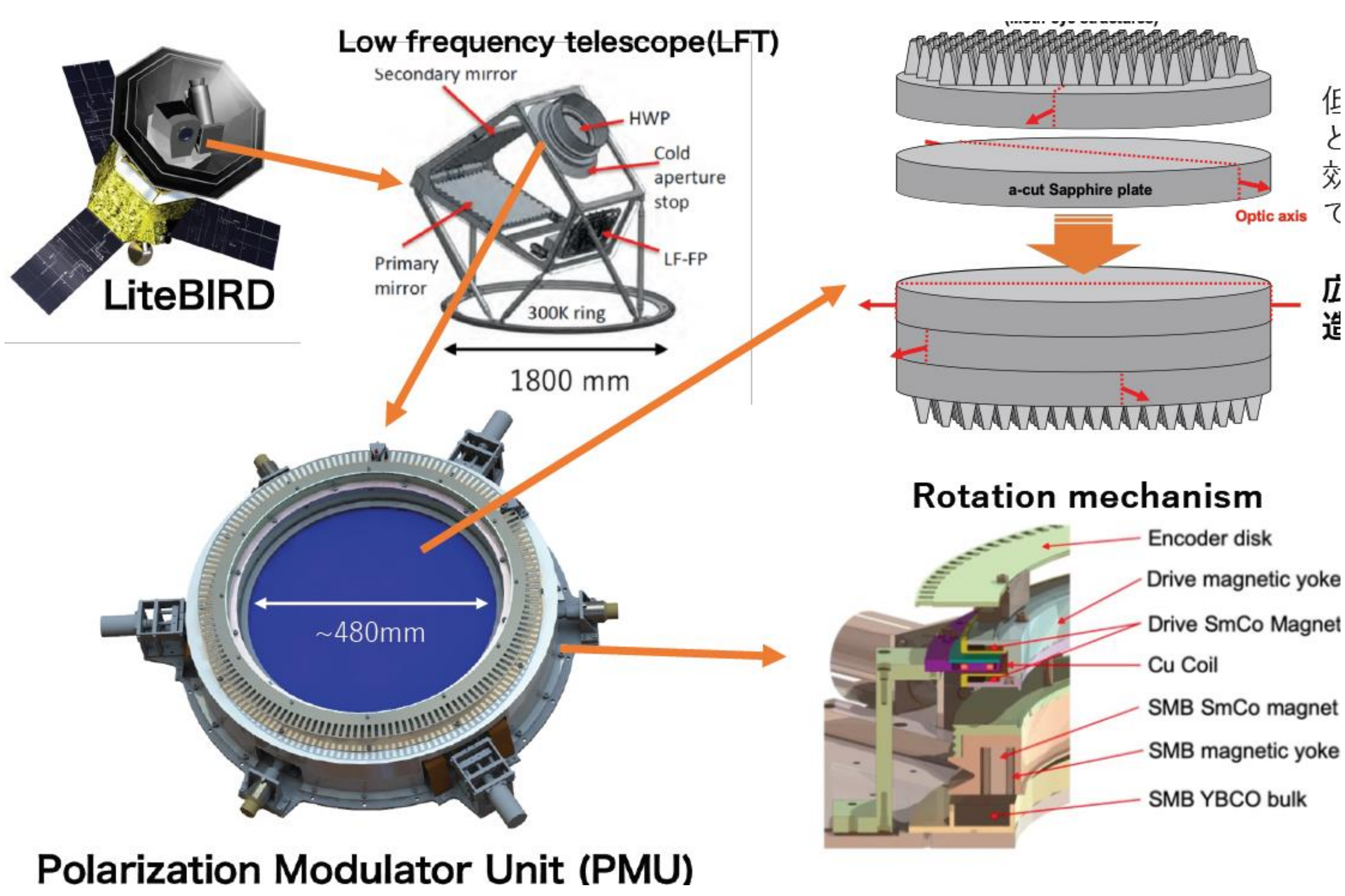


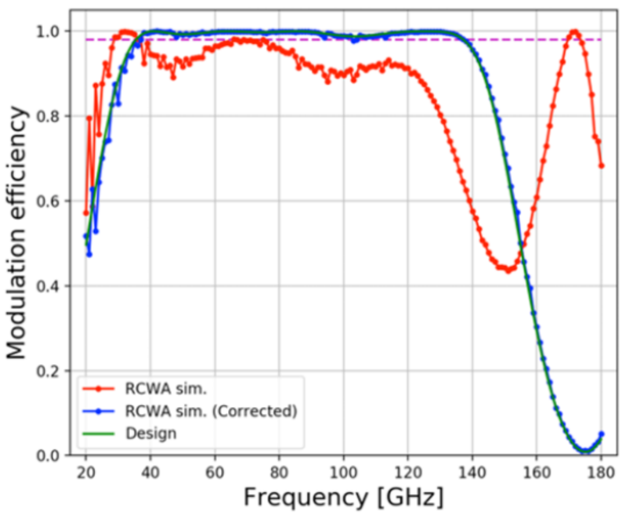

[9, 1, 1, ⋯]




Details are shown in JCAP 12 (2017) 015

# Polarization modulation with spinning HWPs is a critical technique to mitigate systematics




K. Komatsu et al. SPIE.

High modulation efficiency in the wide frequency range is demonstrated.

Y. Sakurai, F. Columbro in SPIE, in preparation

# HWP spinning rate $f_h$ is one of the most important parameters (1)

The pre-demod. TOD is

$$d \sim e^{i\omega_s t} \sum_{n=0}^{\infty} P_k^n e^{in\omega_h} \qquad \omega_s = v_s k, \quad v_s \text{ is the scan speed}$$

After demodulation:

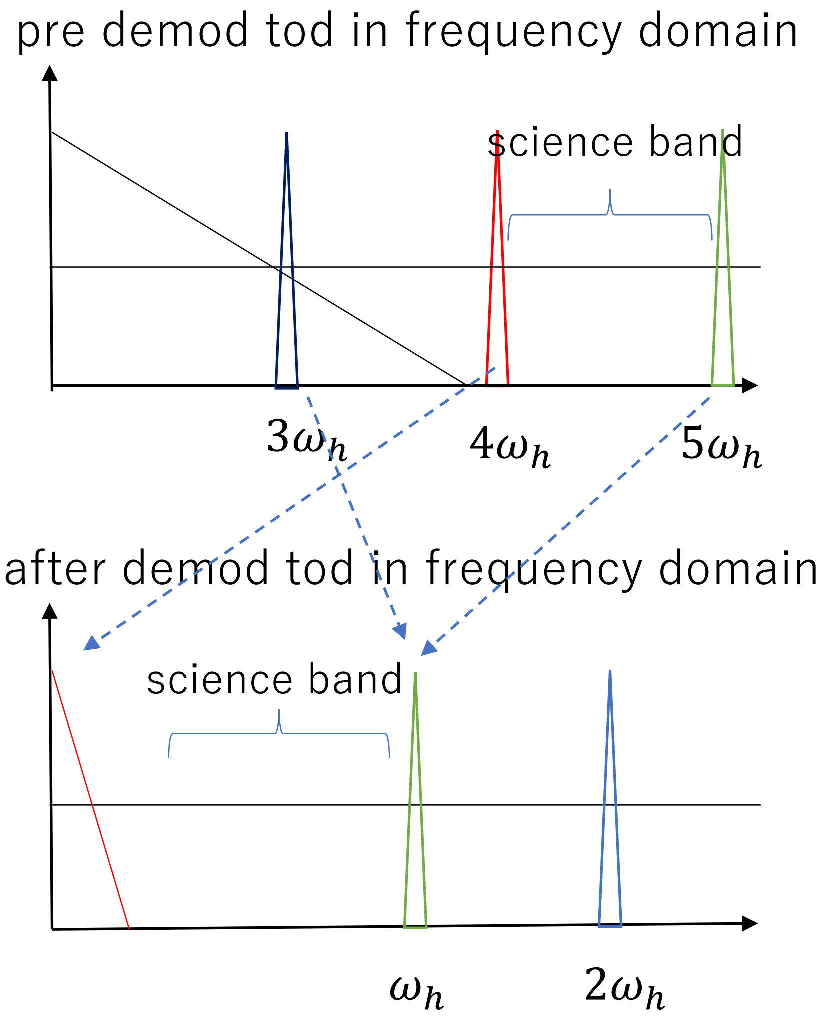
$$d e^{-4i\omega_h t} \sim e^{i\omega_s} \sum_{n'=0}^{\infty} P_k^{|n'-4|} e^{in'\omega_h} \qquad n' = |n-4|$$

We impose

$$\omega_s = 2\pi \frac{v_s}{b} < \omega_h \qquad \text{the smearing of the beam width } b.$$

With the scan speed of 0.3 deg./s, we obtain

$$f_h = \frac{\omega_h}{2\pi} > 0.6Hz \left( \frac{30\ arcmin}{beam\ width} \right)$$




T. Matsumura, H. Ishino

For 5f discussions, K. Komatsu et al., JATIS 5(4), 044008 (2019)

# HWP spinning rate $f_h$ is one of the most important parameters (2)

We impose that the roll off frequency of the transfer function to be larger than the science band $5f_h$.

$$A(f) = \frac{1}{\sqrt{1 + (2\pi f \tau)^2}}$$

$$A(5f_h) > 0.99 \; with \; \tau = 3 \; msec \;\; \rightarrow f_h < 1.5Hz$$

We wish to suppress the $1/f$ noise with the condition:

$$\left(\frac{f_{\rm knee}}{4 f_h}\right)^{\alpha} < 0.1$$

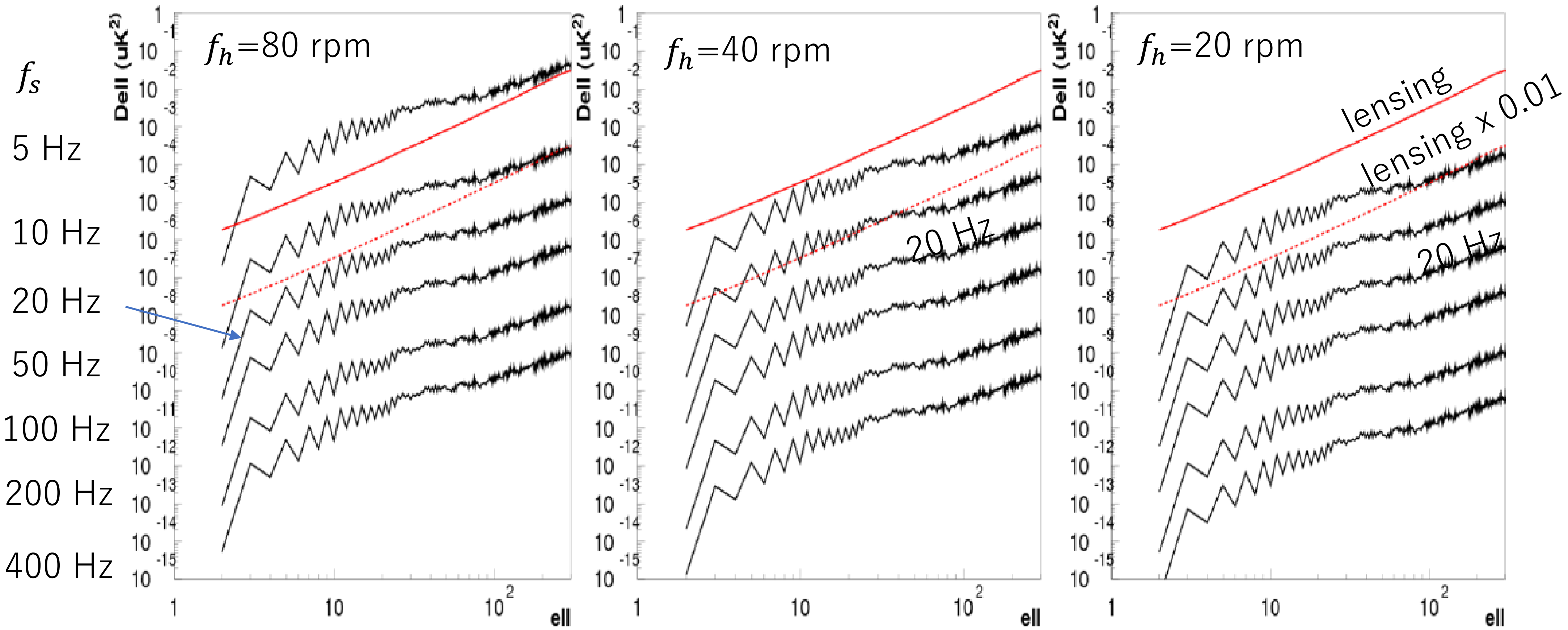
With $f_h$=0.6Hz, $f_{knee} < 2.4$ Hz for $\alpha$ =1.

The current LiteBIRD baseline values are determined basically by the lower limit in the previous page.

| LFT | MFT | HFT |
|---|---|---|
| 46 rpm =0.77Hz | 39 rpm =0.65Hz | 61 rpm =1.0Hz |

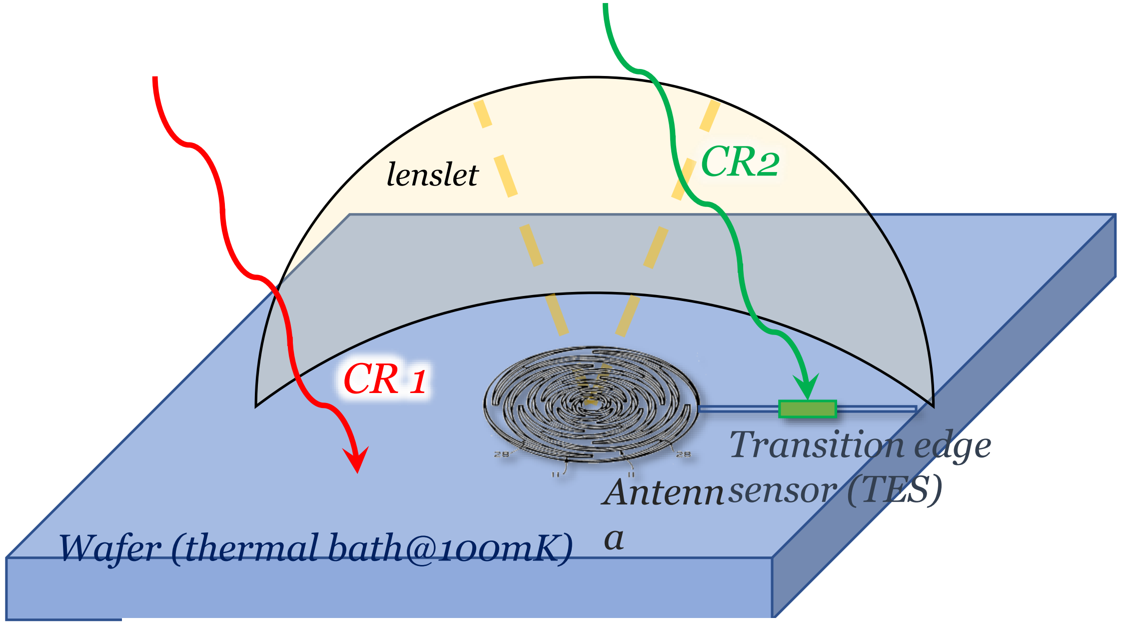
# Data sampling rate $f_s$ systematic effects

- 140 GHz sky maps CMB+FG only, one year observation
- Top hat window function in time domain is assumed in this calculation.

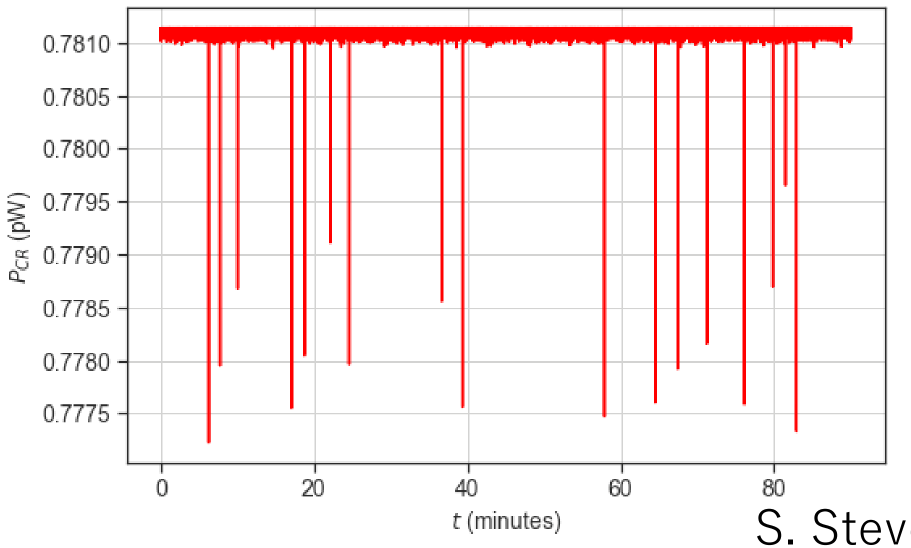


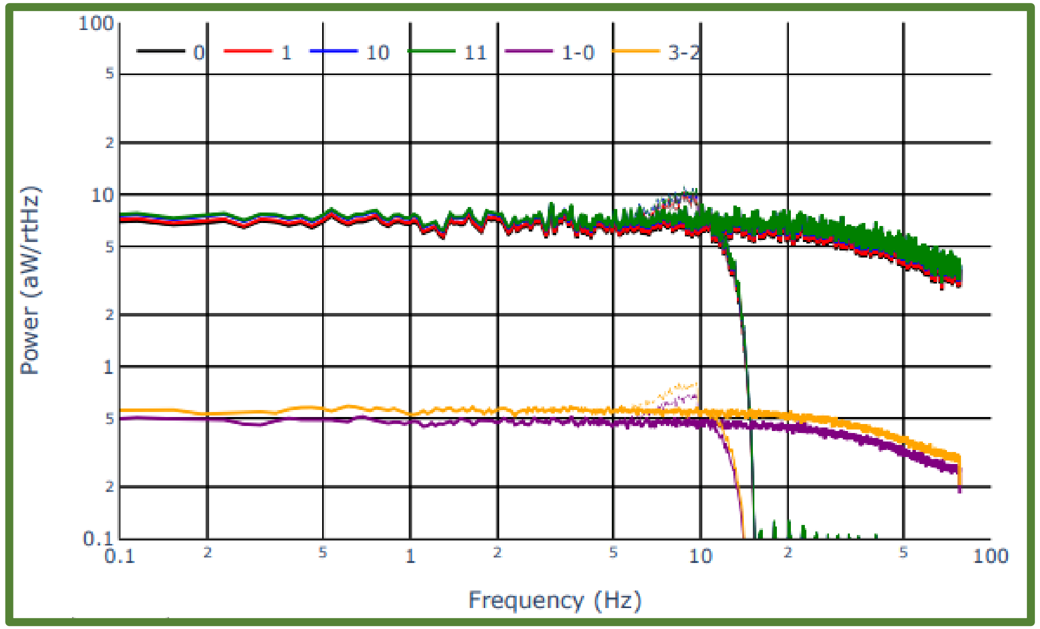

The current baseline is 20Hz sampling
-> 18 GB per day, manageable with current data transfer system.

# Cosmic ray effect is one of the most important systematics in LiteBIRD



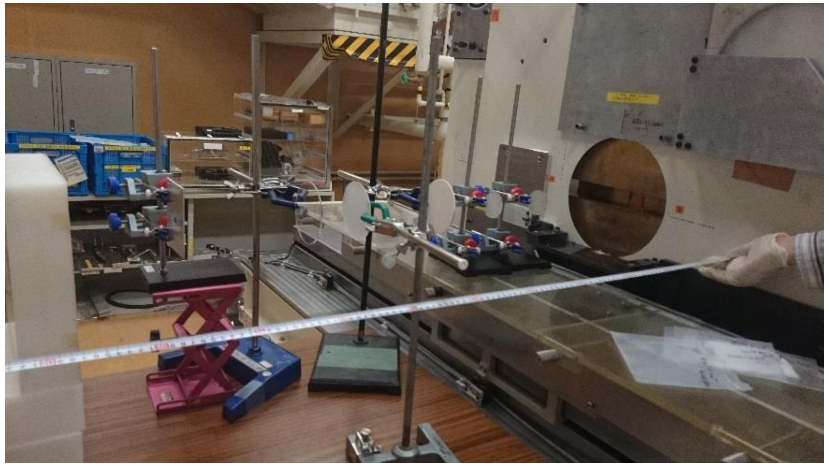

- Simulation studies:
  - CR rate/energy, TES response, on board data process with down-sampling and filters, TOD generation, sky map and Cl estimation.
- Hardware studies:
  - TES irradiation tests on going.
- High rate sampling (>1kHz) for a short time period is considered to characterize the CR glitches.

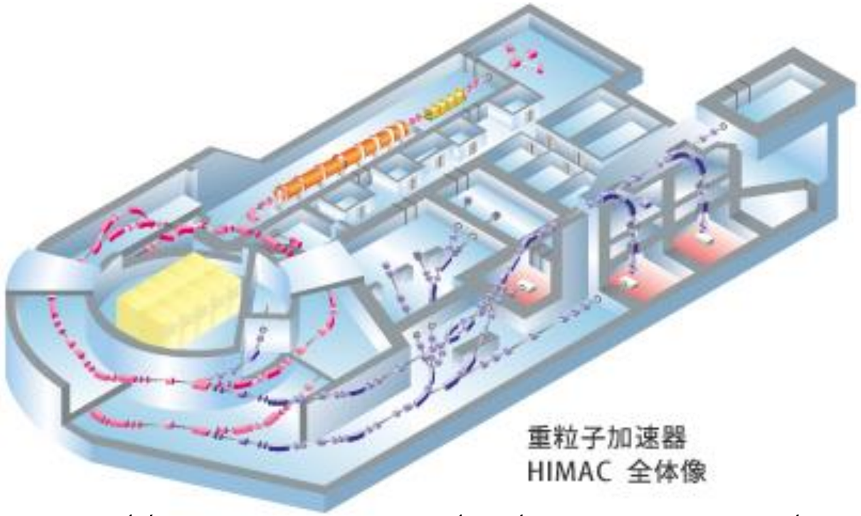



S. Stever, T. Ghigna, M. Tominaga, M. Tsujimoto et al., SPIE, JCAP

# Cosmic ray integrated dose effect tests using HIMAC

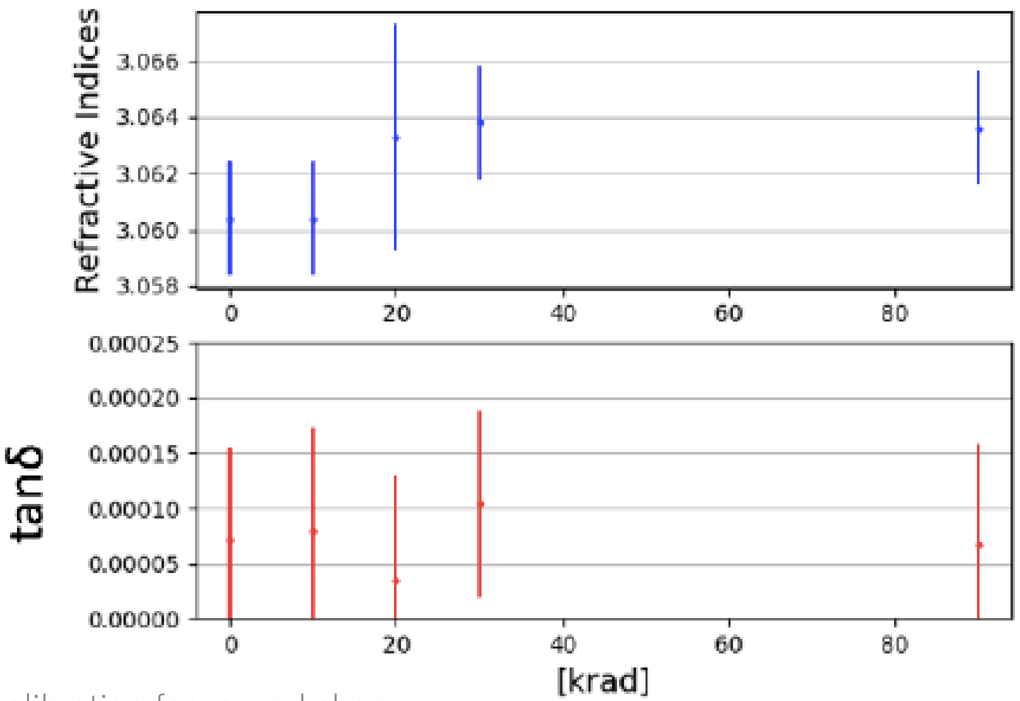





http://www.nirs.go.jp/rd/collaboration/himac/outline.shtml

- 160MeV proton beam irradiation tests (2014-17)
  - up to 100 krad
  - Sapphire, Silicon, PP, TES, MKID, LED, YBCO
  - No degradation is found for all the specimens.
- Next series of tests will start in JFY 2021.

Sapphire



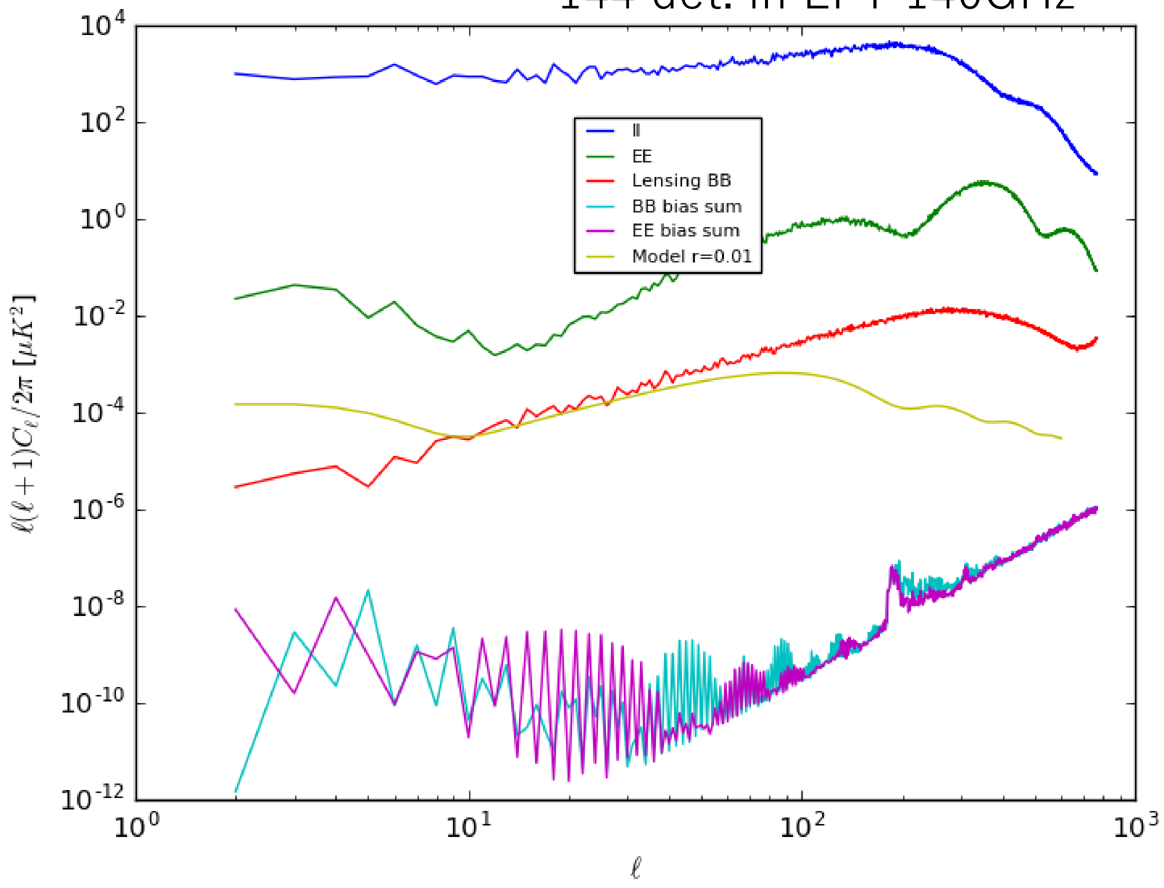
# HWP systematics

One of the systematic effects: Instrumental Polarization (IP) at 4f

$$M(\psi) = \begin{pmatrix} M_{II} & M_{QI} & M_{UI} & M_{VI} \\ M_{IQ} & M_{QQ} & M_{UQ} & M_{VQ} \\ M_{IU} & M_{QU} & M_{UU} & M_{VU} \\ M_{IV} & M_{QV} & M_{UV} & M_{VV} \end{pmatrix}$$

- The HWP IP is expected to happen in the order of $10^{-5}$.
  - Estimated by H. Imada.
- G. Patanchon points out the effect can be calibrated and corrected using CMB dipole, as shown in right figure.
- Other HWP systematics will be presented by S. Giardiello.
- Preparing for publication.

144 det. in LFT 140GHz




G. Patanchon