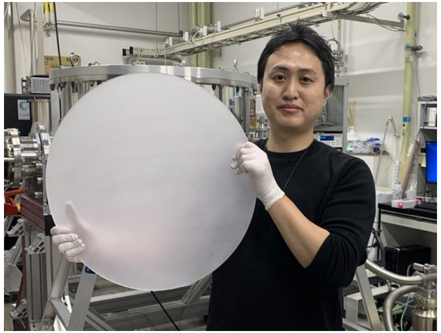
HWP development for LiteBIRD Low Frequency Telescope

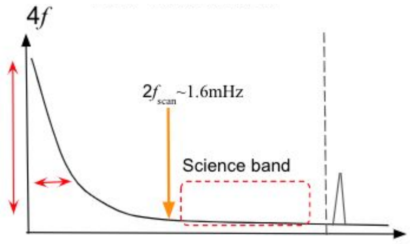
CMB systematics and calibration focus workshop

Yuki Sakurai (Kavli IPMU) and LFT PMU team

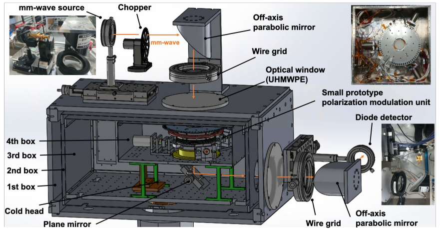


Summary

- Continuously rotating HWP is a powerful tool for $1/f$ noise rejection and differential systematics.
- LiteBIRD low-frequency telescope employs HWP and its development is in progress at Kavli IPMU (Japan).
  - sapphire broadband achromatic HWP
  - cryogenic rotation mechanism

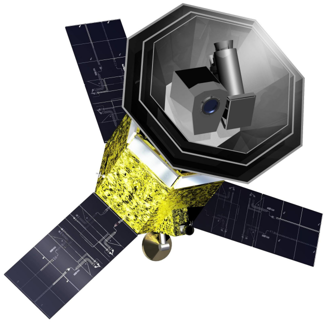


- Summarize HWP systematics based on hardware point of view.
  - AHWP efficiency: transmittance, modulation efficiency
  - Q/U mixing: angle reconstruction, frequency-dependent phase
  - spurious $4f$ signal
- Introduce optical measurement and calibration systems
  - Constructed φ50mm cold optical measurement setup
  - Large diameter setup and HWP+TES testbet are in prep.



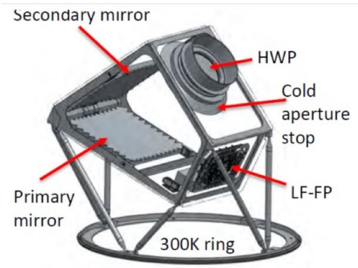
Introduction

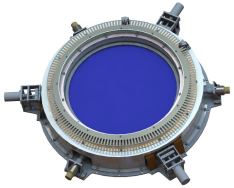
- The LiteBIRD mission part consists of three telescopes: reflective low-frequency telescope (LFT) and refractive medium-and-high-frequency telescopes (MHFT).
- Each telescope employs polarization modulation unit (PMU) to suppress $1/f$ noise and mitigates differential systematic uncertainties.
- LiteBIRD is in the conceptual design phase and we have developed the breadboard model (BBM) of the LFT PMU with a diameter of 330mm in preparation of a larger (500 mm) flight model.



Sugai et al

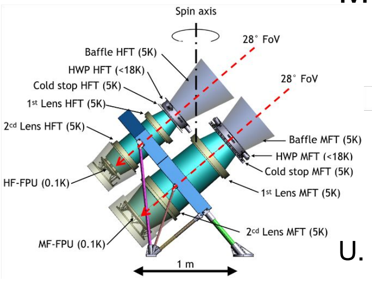
LFT





Kavli IPMU (Japan)

MHFT

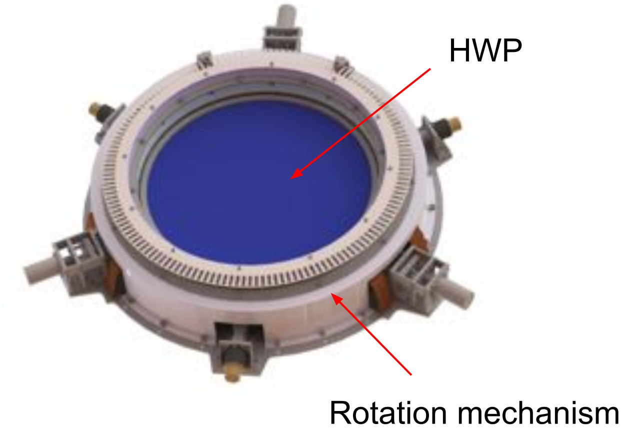


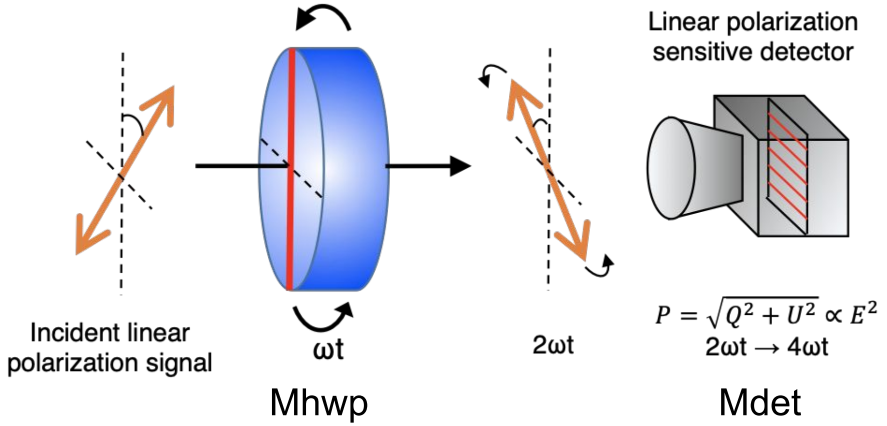
U. Roma Sapienza(Italy)
Cardiff U (UK)

Continuously rotating HWP

$$S_{out} = M_{det} R(-\omega_{hwp} t) M_{hwp} R(\omega_{hwp} t) S_{in}$$

$$S_{out}(\nu) = \frac{1}{2}\{I(\nu) + Q_{\mathrm{in}}(\nu)\cos(4\omega t - 2\psi_i) + U_{\mathrm{in}}(\nu)\sin(4\omega t - 2\psi_i)\}$$





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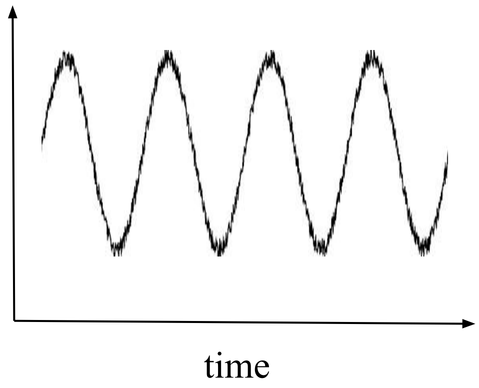
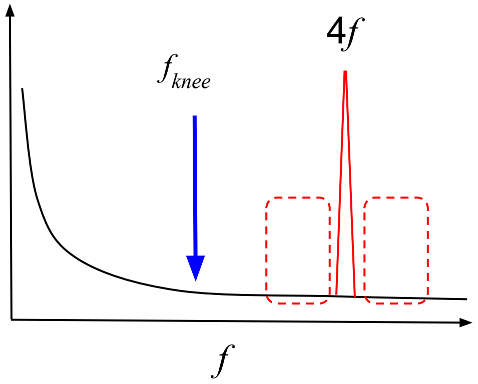
TOD



Before demodulation



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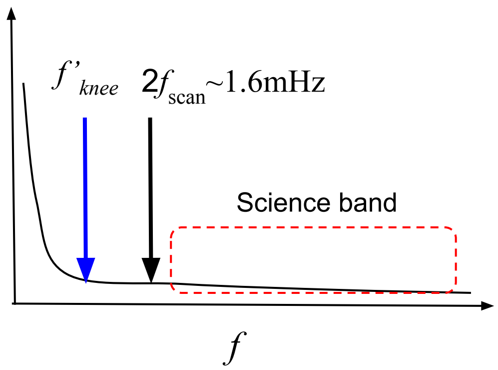
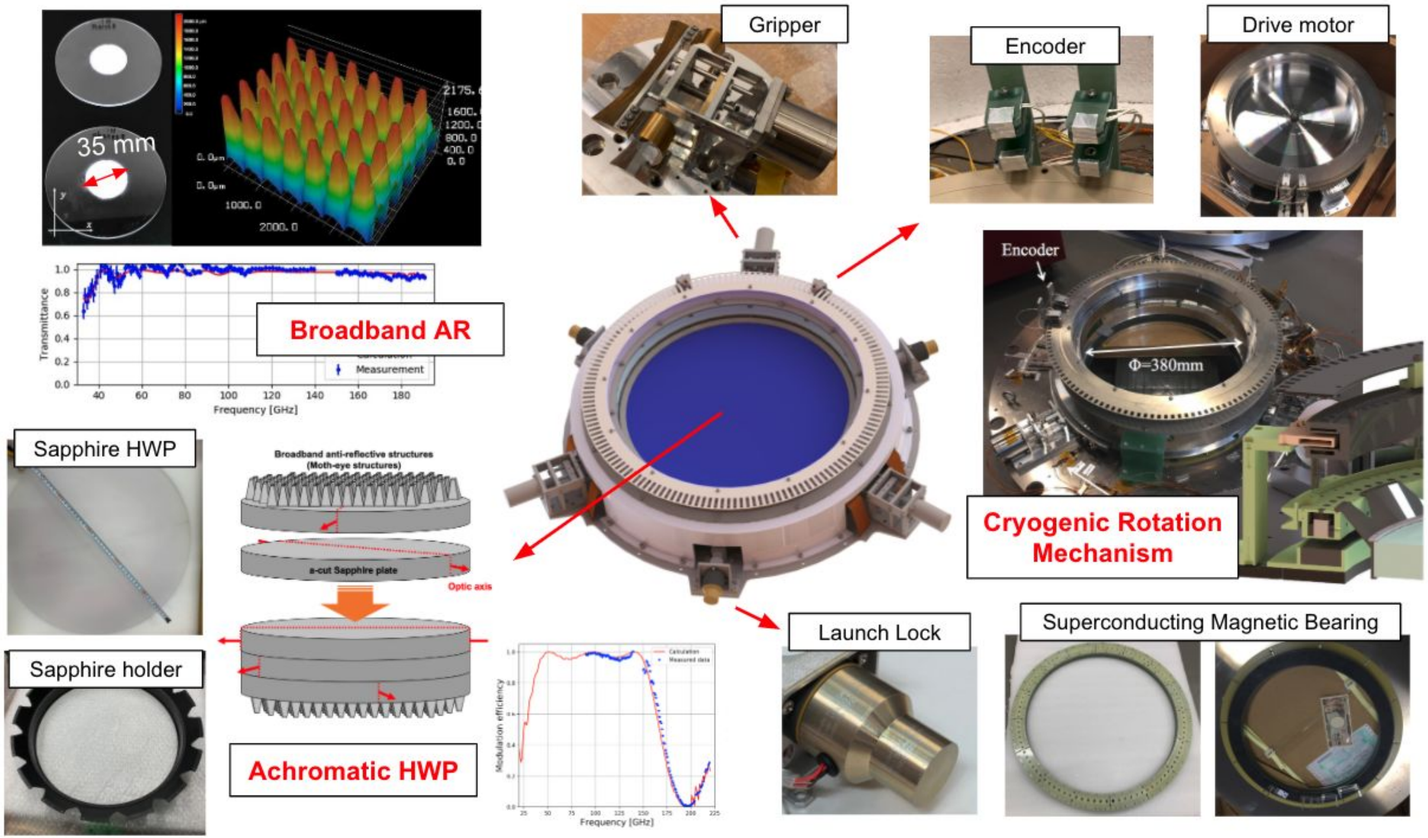


Why HWP needs in space?

Pros.	Cons.
$1/f$ noise rejection Systematics mitigation	HWP systematics Sensitivity effect System complexity

- Scan speed of LiteBIRD: f_{scan} = 0.05 rpm (20 min/rotation)
- Difficult to have guarantee for $1/f$ → continuously rotating HWP
- ABS, POLARBEAR, … successfully demonstrated f_{knee} ~2 mHz.
- Cons. depends on hardware performance and calibration.

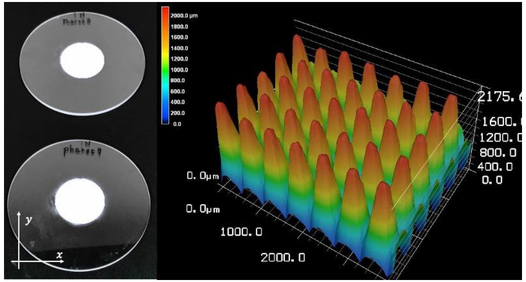
Polarization Modulation Unit for LiteBIRD

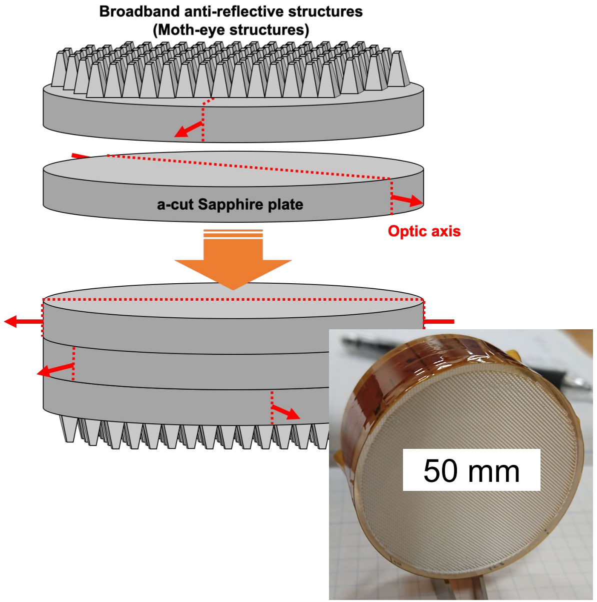


R. Takaku, K.Komatsu et al SPIE 2020 in prep.

Sapphire Achromatic HWP

- **Challenges**: broadband (34 - 161 GHz: 9 bands), large diameter (~500mm), , launch tolerance
- Broadband AR coating: sub-wavelength structure by laser ablation machining.
- Broadband AHWP: Pancharatnam-based 5-layers stacked sapphire.
- The designs of AR and AHWP are optimized to maximize transmittance and modulation efficiency.
- We fabricated φ50 mm small prototype sample and demonstrated optical performance.
- AHWP with large diameter (φ330mm) is in prep.



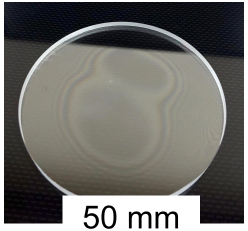


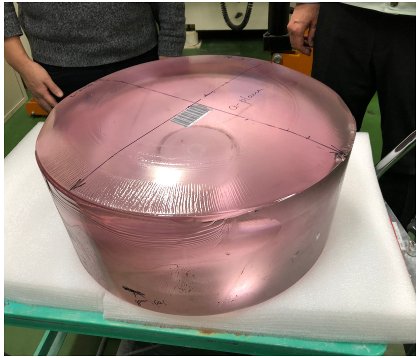
AHWP gluing and assembly

T. Toda et al SPIE in prep.

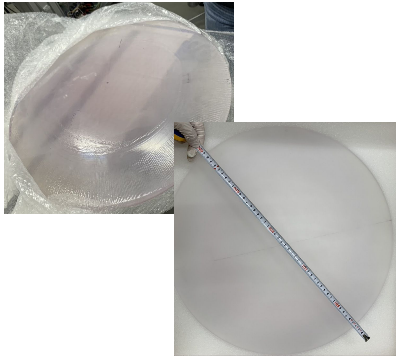
- We are developing sodium silicate bonding used in KAGRA and LIGO to glue each sapphire layer.
    - sufficient strength at launch and thermal contraction, non-optical effect
- We performed assembly test with φ330mm sapphire.
- CFRP holder was designed and fabricated
    - same thermal contraction with sapphire, stress relief mechanism

Chemical bonding wiht $(HO)_2AlOSi(HO)_3$ network

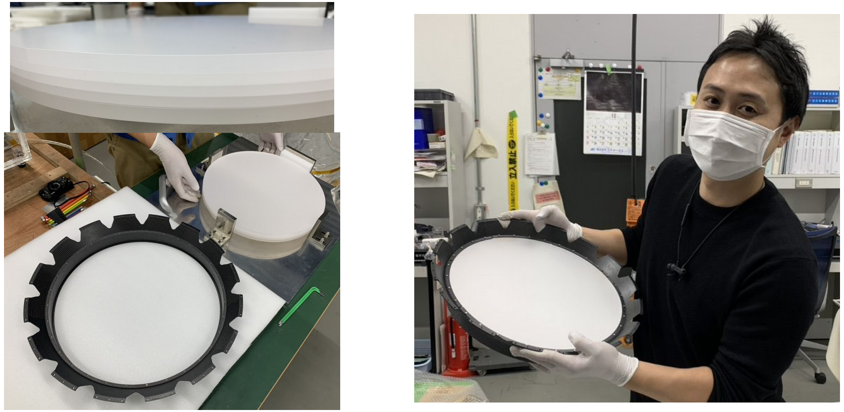




Raw sapphire ingot



Cutting into disks



Stacking and Assembling to holder

Cryogenic rotation mechanism

Challenges: cryogenically stable rotation with minimal heat dissipation < 4mW and T_{HWP} < 20 K

Superconducting magnetic bearing (SMB)

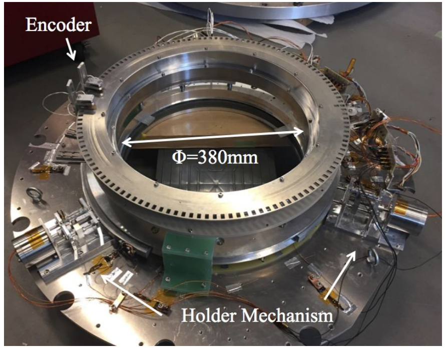
- SmCo ring (rotor) and YBCO bulks (stator).
- Minimize loss by improving the magnetic field uniformity.

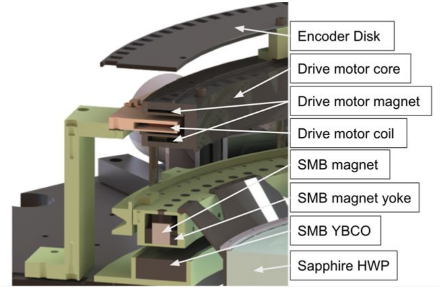
Hollow-bore synchronous motor with optical encoder

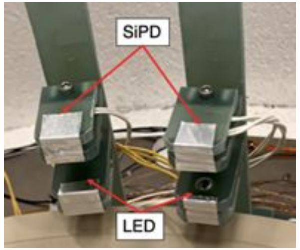
- Contactless motor consists of SmCo (rotor) and coils (stator)
- Improve the motor efficiency by high purity Cu coils and magnetic yokes.

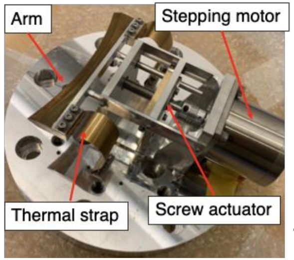
Gripper mechanism

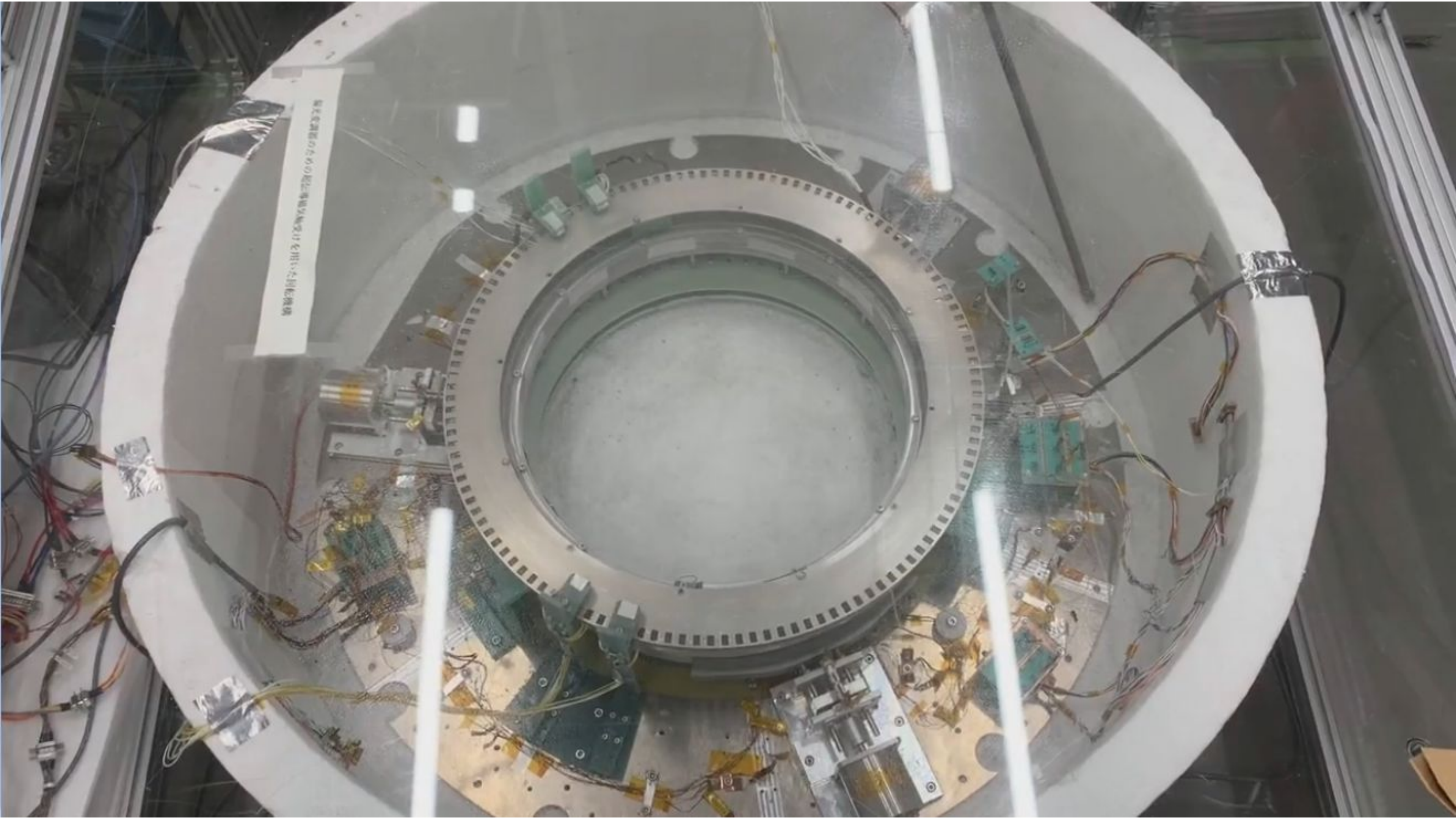
- Grip the rotor at 300 K and release it after field cooling.
- Linear actuator with a cryogenic stepping motor











Non-ideal HWP

$$S_{out} = M_{det} R(-\omega_{hwp} t) M_{hwp} R(\omega_{hwp} t) S_{in}$$

0*f* term

$$\begin{aligned} S_{\mathrm{out}}(t) = \frac{1}{2} [& \boxed{D_{0\mathrm{I}} I_{\mathrm{in}} + D_{0\mathrm{Q}} Q_{\mathrm{in}} + D_{0\mathrm{U}} U_{\mathrm{in}}} \\ & + \boxed{D_{2\mathrm{I}} I_{\mathrm{in}} \cos(2\omega_{\mathrm{hwp}} t - 2\psi - 2\phi_0) + D_2 \sqrt{Q_{\mathrm{in}}^2 + U_{\mathrm{in}}^2} \cos(2\omega_{\mathrm{hwp}} t - 2\psi - 2\phi_2)} \\ & + \boxed{D_4 \sqrt{Q_{\mathrm{in}}^2 + U_{\mathrm{in}}^2} \cos(4\omega_{\mathrm{hwp}} t - 2\psi - 4\phi_4)]} \end{aligned}$$

2*f* term

4*f* term

$$D_4 = \frac{1}{2} \sqrt{(M_{\mathrm{QQ}} - M_{\mathrm{UU}})^2 + (M_{\mathrm{QU}} + M_{\mathrm{UQ}})^2}$$ ←modulation efficiency

$$\phi_4 = \frac{1}{2} \tan^{-1} \frac{M_{\mathrm{QU}} + M_{\mathrm{UQ}}}{M_{\mathrm{QQ}} - M_{\mathrm{UU}}} + \frac{1}{4} \tan^{-1} \frac{U_{\mathrm{in}}}{Q_{\mathrm{in}}}.$$ ←frequency-dependent phase

Non-ideal HWP

$$S_{out} = M_{det} R(-\omega_{hwp} t) M_{hwp} R(\omega_{hwp} t) S_{in}$$

$0f$ term

$$S_{\mathrm{out}}(t) = \frac{1}{2}[D_{0\mathrm{I}} I_{\mathrm{in}} + D_{0\mathrm{Q}} Q_{\mathrm{in}} + D_{0\mathrm{U}} U_{\mathrm{in}}$$
$$+ D_{2\mathrm{I}} I_{\mathrm{in}} \cos(2\omega_{\mathrm{hwp}} t - 2\psi - 2\phi_0) + D_2 \sqrt{Q_{\mathrm{in}}^2 + U_{\mathrm{in}}^2} \cos(2\omega_{\mathrm{hwp}} t - 2\psi - 2\phi_2)$$
$$+ D_4 \sqrt{Q_{\mathrm{in}}^2 + U_{\mathrm{in}}^2} \cos(4\omega_{\mathrm{hwp}} t - 2\psi - 4\phi_4)]$$

$2f$ term

modulation efficiency

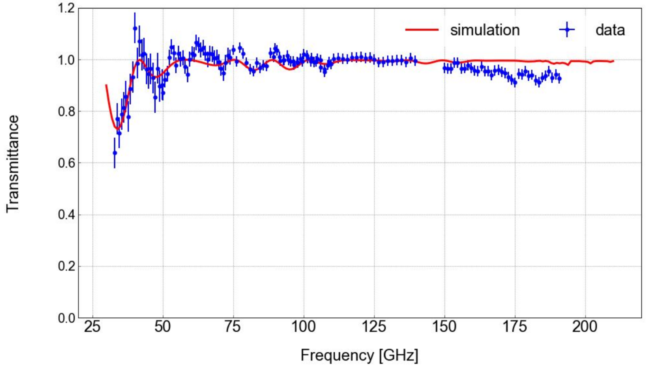
rotation speed

phase

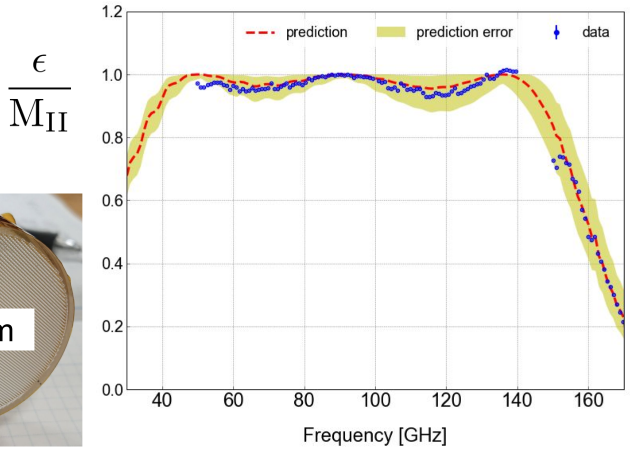
AHWP Efficiency

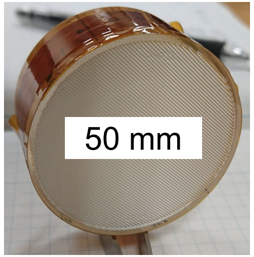
- Transmittance affects to both I→I and P→P.
- The SWS design optimized to cover LFT frequency range of 34 ~ 161 GHz.
  - Measured transmittance: > 91% (34 - 46 GHz), >97% (45 - 161 GHz)
- Modulation efficiency affects to P→P.
  - A(4f) / A(0f) is obtained from modulation data
  - > 95% (50 - 140 GHz), reduced at low and high frequency region
- Determination of requirements needs iteration with sensitivity and systematics studies.
- Knowledge of frequency dependence must be calibrated at ground test.

R. Takaku et al (2020)



K. Komatsu et al SPIE in prep.

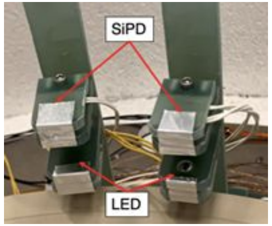


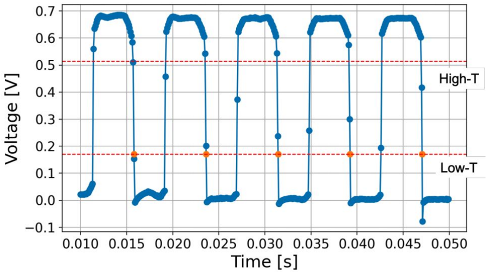


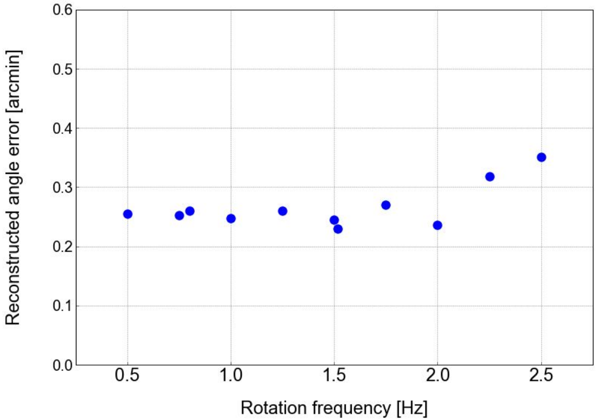
Q/U mixing: Angle reconstruction

S. Sugiyama et al SPIE in prep.

- Miss reconstruction of HWP angle causes Q/U mixing.
- Angle is measured incremental optical encoder; LED, silicon photodiode, and chopper disk.
- Apply a simple threshold algorithm to determine angle from encoder signal.
- We confirmed the angle uncertainty is < 0.25 arcmin, and the rotation stability is 1.42 mHz (for 1 pulse time window)
- The uncertainty dominated by electrical noise from crosstalk with the motor drive signal.



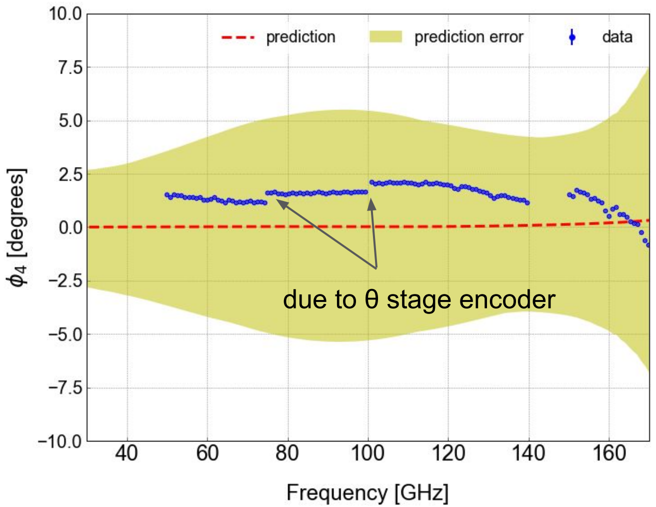




Q/U mixing: AHWP frequency-dependent phase

$$S_{out}(\nu) = \frac{1}{2}[I(\nu) + \epsilon(\nu)[\boxed{Q_{\rm in}(\nu)}\cos(4\omega t - 2\psi_i - 4\phi_4(\nu)) + \boxed{U_{\rm in}(\nu)}\sin(4\omega t - 2\psi_i - 4\phi_4(\nu))]$$
$$= \frac{1}{2}[I(\nu) + \epsilon(\nu)[\boxed{Q'_{\rm in}(\nu)}\cos(4\omega t - 2\psi_i) + \boxed{U'_{\rm in}(\nu)}\sin(4\omega t - 2\psi_i)]$$

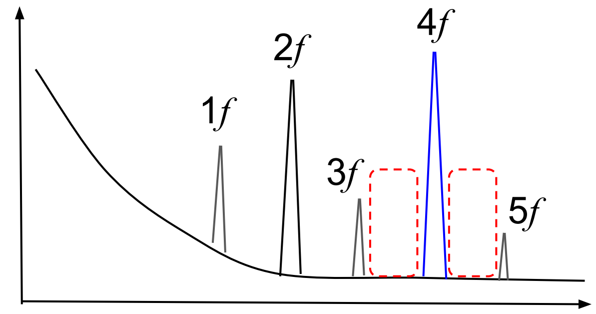
- Q and U components are mixed if there is frequency-dependent phase φ_4.
- The flat phase can be obtained by the AHWP design optimization.
  - non-flat phase, wider mod. eff.
  - flat phase, reduced mod. eff. at low & high frequency edge
- We are in progress to investigate necessity of the flat phase and its knowledge
  - e.g) δr estimation after foreground removal with Q' and U'.



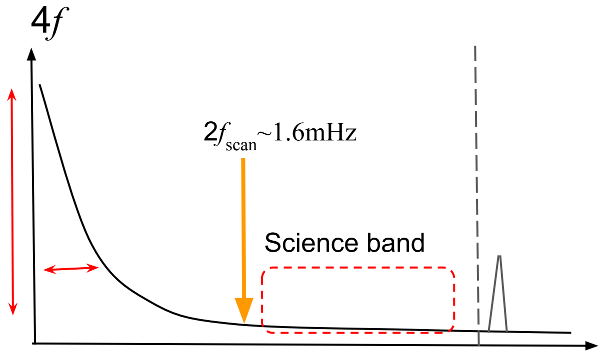
Any spurious $4f$ signals

- effect to $4f$ peak
  - height
    - temperature variation (quadrupole)
    - rotational synchronous effect, e.g. wobble
  - width
    - rotation instability / encoder inaccuracy
- effect to the sideband of $4f$
  - leakage due to differential transmission/emissivity + oblique angle
  - ghosting (higher order)
- effect to $3f$ (or $5f$) that potentially limit the science bandwidth
  - leakage from the rotational synchronous effect
  - sapphire optic axis alignment
- Any large spurious signal
  - differential transmission/emission + detector non-linearity /time constant variation. (T_{cmb} ~ 3K can be 30mK by 1% of diff. trans. while ΔT from dipole is 3mK.)

Before demodulation



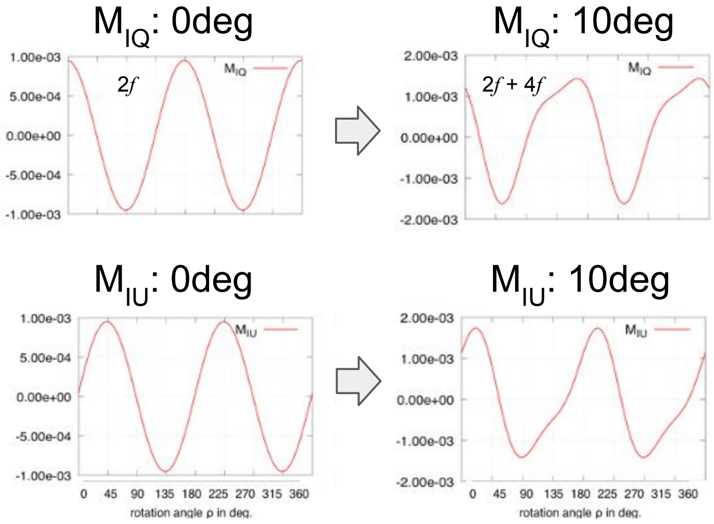
After demodulation



Example of spurious 4*f* signals

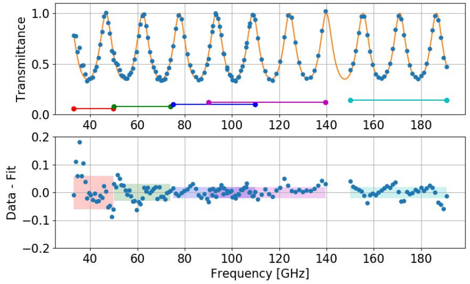
- normal incident: differential transmission / emissivity appear in only 2*f* term
- oblique incident makes 2*f* + 4*f* terms
- RCWA based simulation was performed to obtain Mueller matrix.
- The 2*f* term due to I→P with a normal incident angle is 10^{-3} order.
- The 4*f* term due to I→P with an 10 deg. incident angle is 10^{-4} order.

H. Imada et al (2018)



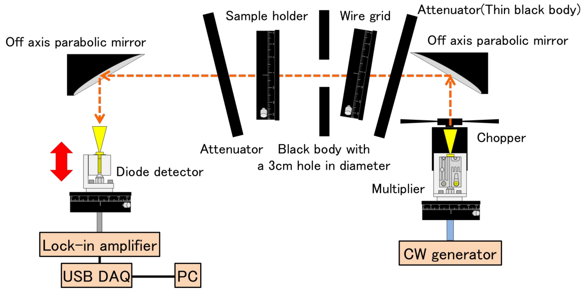
Optical measurement setup

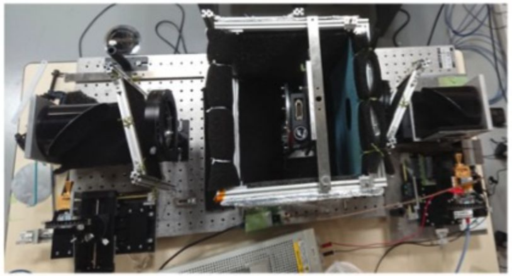
R. Takaku et al (2020)



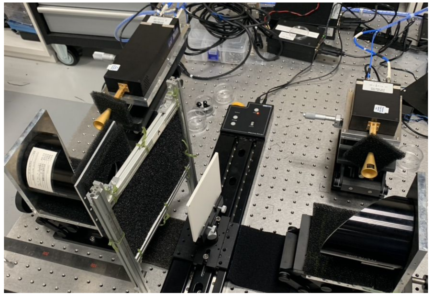
- Room temperature measurement systems at Kavli IPMU

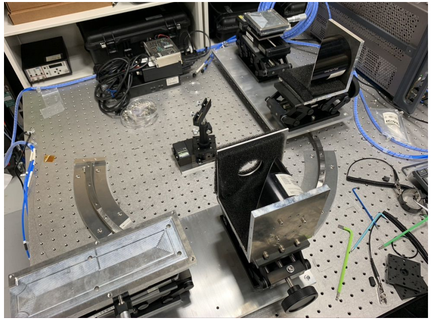
Transmittance measurement system
CW + diode detector
26.5 - 260 GHz



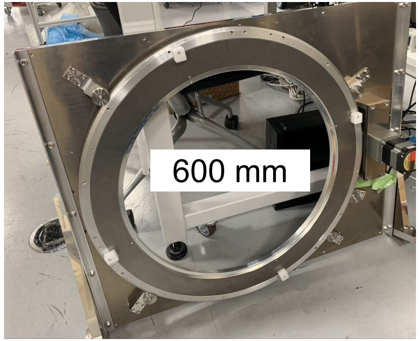


VNA measurement system
26.5 GHz - 330 GHz



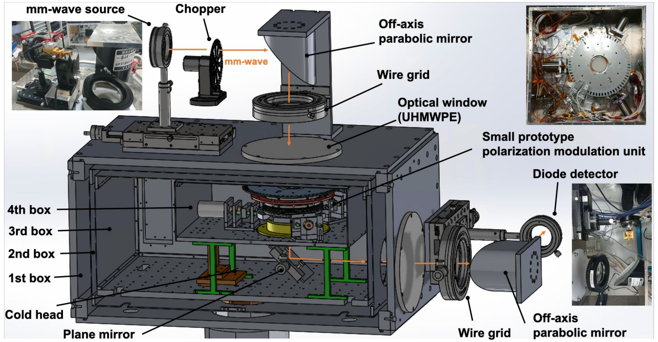


Large diameter rot. mech.



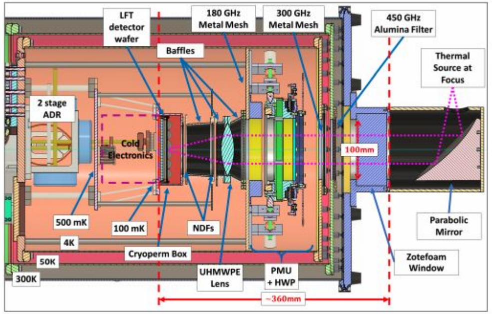
Optical measurement setup

K. Komatsu et al SPIE in prep.

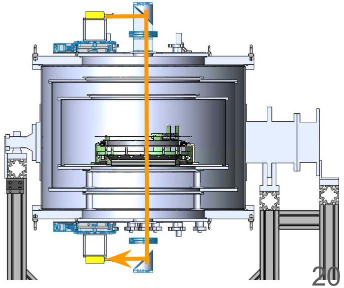


- Already constructed φ50mm cryogenic optical measurement system at Kavli IPMU
- In preparation of the large cryogenic optical measurement system
- Planing a cold beam mapping combined with mirror (mimic LFT) or lens optics.
- HWP + TES testbed is also planning.

Large cryostat system



T. Ghigia et al (2020)



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