GroundBIRD

Observation of CMB polarization with wide-sky survey and fast rotation scanning

Shunsuke Honda (Astro. Obs.)

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- CMB basics
- GroundBIRD overview
- Sensitivity calculation for one cosmological parameter

- MKID developments
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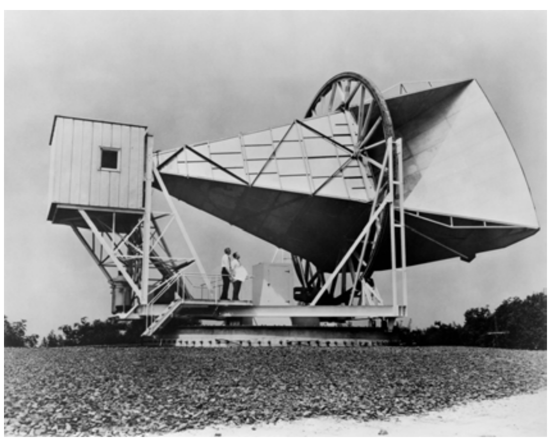
- Observation results

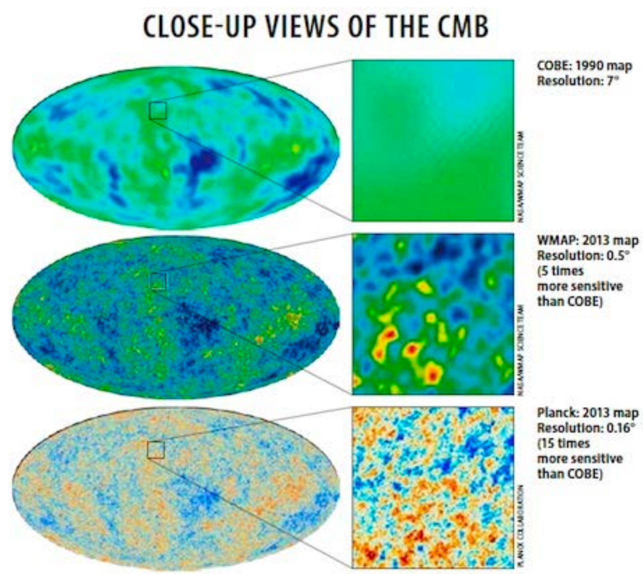
CMB Polarimeter : GroundBIRD

Shunsuke Honda

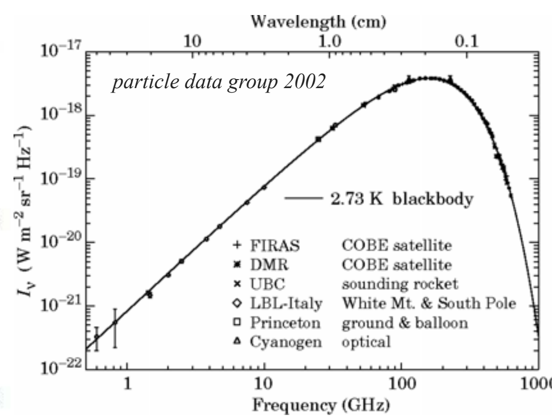
cosmic microwave background
discovered by Penzias and Wilson



taken from wikipedia



taken from https://astronomy.com/magazine/2018/07/decoding-the-cosmic-microwave-background

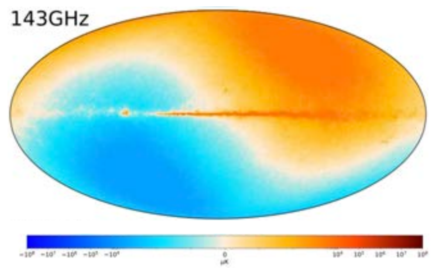


almost perfect/uniform blackbody at 2.7 K !

Anisotropy

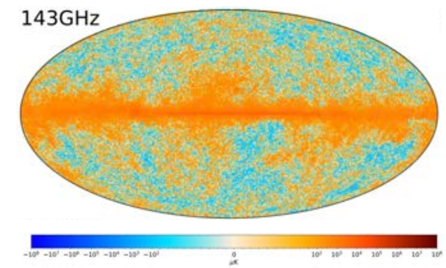
"Extrinsic" dipole due to our motion

deviation from T_{CMB}



linear scale btw -3 and +3 mK

+ after dipole subtraction



linear scale btw -100 and +100 μK

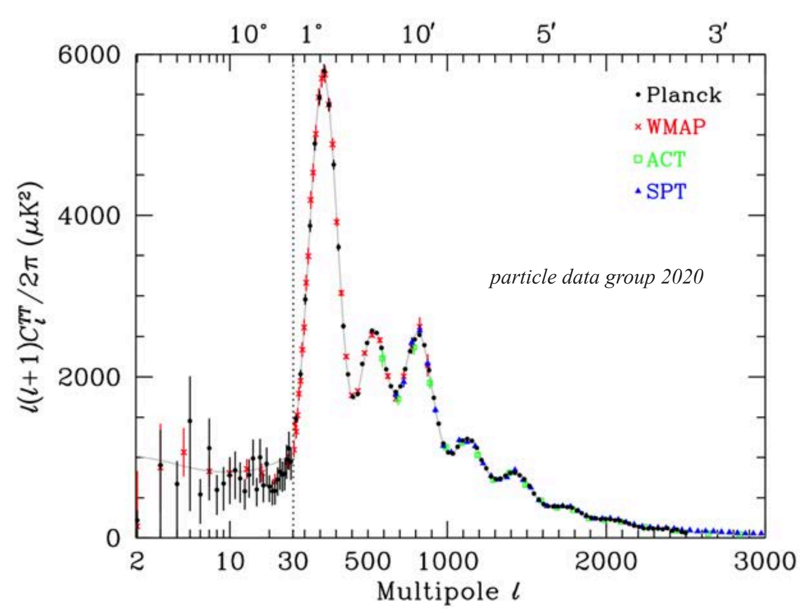
Planck intermediate results LVII. Joint Planck LFI and HFI data processing, A&A 643, A42 (2020)

CMB anisotropy expanded with spherical harmonics

$$\Delta T(\hat{n}) = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell m} Y_\ell^m(\hat{n})$$

power spectrum

$$C_\ell = \frac{1}{2\ell+1} \sum_{m=-\ell}^{\ell} a_{\ell m} a_{\ell m}^*$$

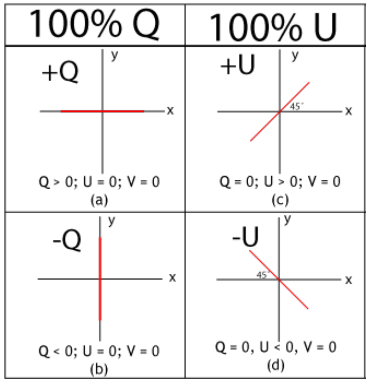


Polarization

maps taken from "A&A Volume 641, September 2020, Planck 2018 results"

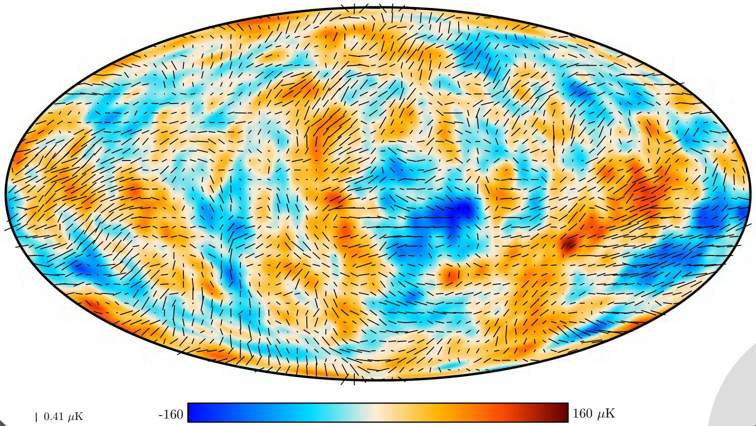
CMB polarization power = O(0.1–1) μK

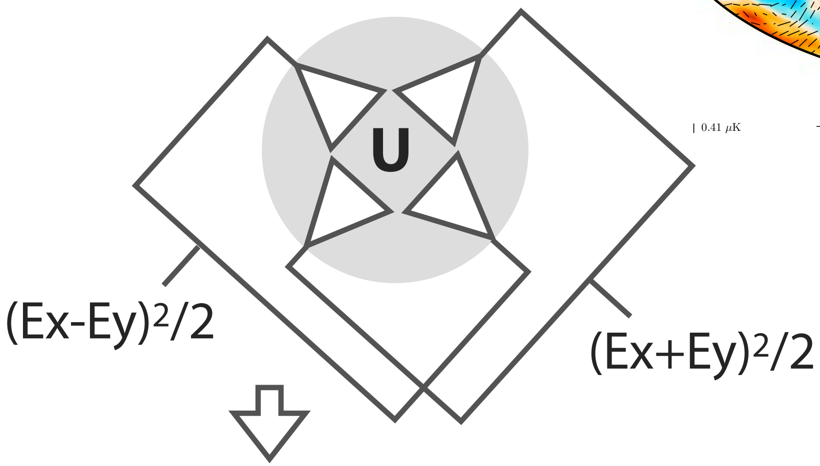
linear polarization measured with two orthogonal parameters, Q and U

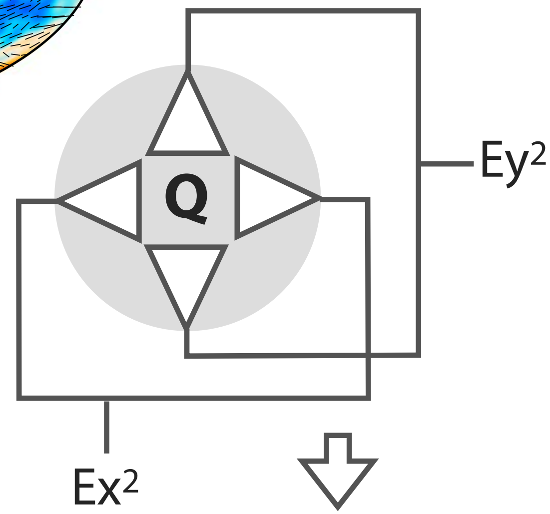


color: intensity

rods: pol. ampl. and direc.

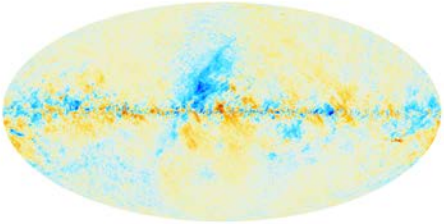


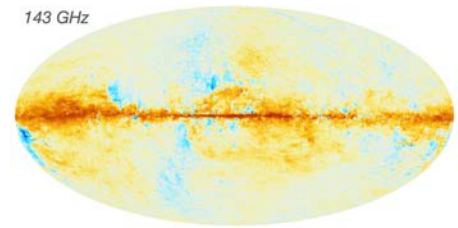




$U = (Ex-Ey)^2/2 - (Ex+Ey)^2/2 = 2ExEy$

$Q = Ex^2 - Ey^2$





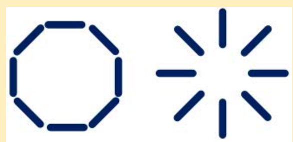
E and B modes

$$Q(\hat{n}) \pm iU(\hat{n}) = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} a_{\pm 2,\ell m} \; {}_{\pm 2}Y_{\ell}^{m}(\hat{n})$$

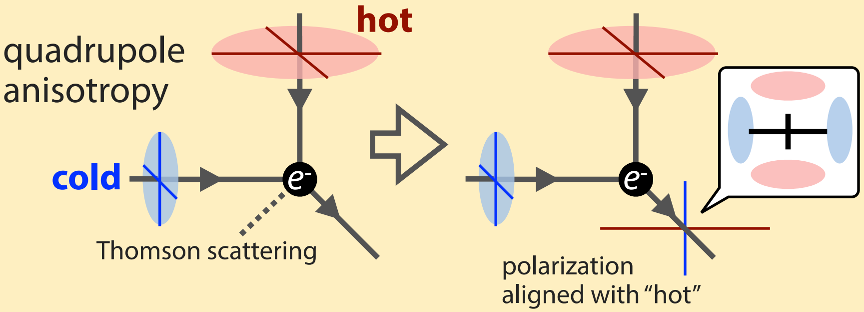
E mode (even parity)

$$a_{E,\ell m} = -\left(a_{+2,\ell m} + a_{-2,\ell m}\right)/2$$

converted to real space →



- combination of electron scattering and temperature isotropy



- primordial gravitational wave: ℓ<100

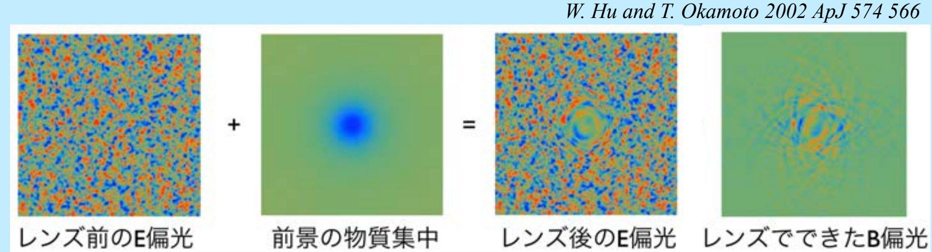
B mode (odd parity)

$$a_{B,\ell m} = i\left(a_{+2,\ell m} - a_{-2,\ell m}\right)/2$$

converted to real space →

- gravitational lensing: ℓ~O(100-1000)
  → leakage from E to B

W. Hu and T. Okamoto 2002 ApJ 574 566



- primordial gravitational wave: ℓ<100

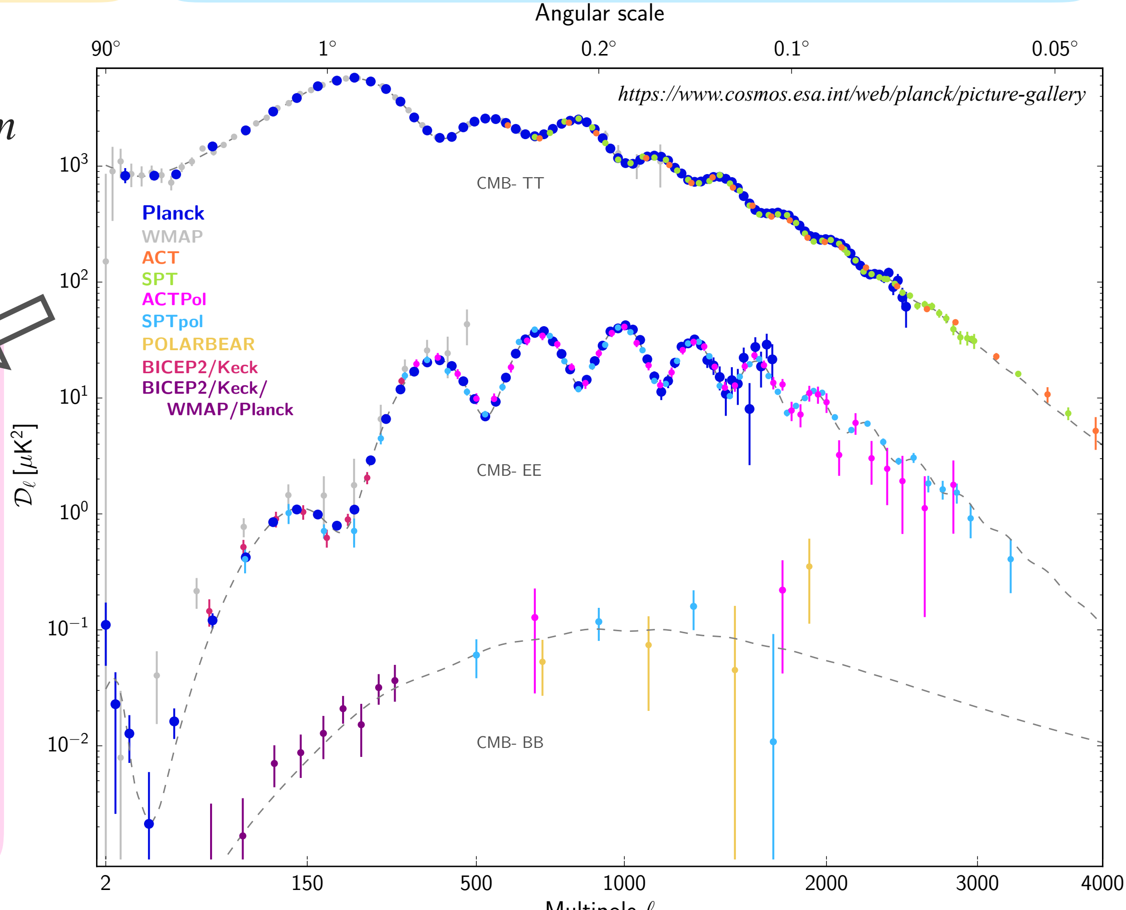
E and B modes

$$Q(\hat{n}) \pm iU(\hat{n}) = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} a_{\pm 2,\ell m} \; {}_{\pm 2}Y_{\ell}^{m}(\hat{n})$$

$$a_{E,\ell m} = -\left(a_{+2,\ell m} + a_{-2,\ell m}\right)/2$$

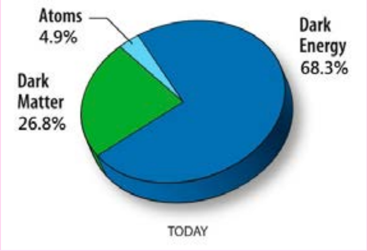
$$a_{B,\ell m} = i\left(a_{+2,\ell m} - a_{-2,\ell m}\right)/2$$

$$\Rightarrow \; C_\ell = \frac{1}{2\ell+1} \sum_{m=-\ell}^{\ell} a_{\ell m} a_{\ell m}^{*}$$



cosmological parameters

densities: $\Omega_b h^2$, $\Omega_c h^2$



initial condition: A_S, n_S

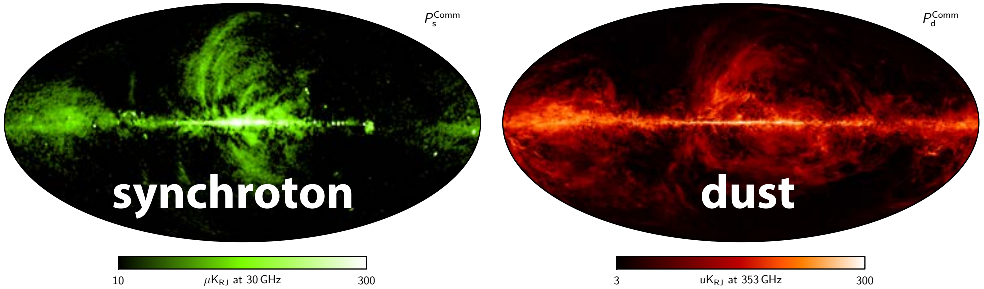
expansion rate: H_0

reionization depth: τ

Atmosphere and foreground

To measure CMB precisely, foreground and atmospheric components should be carefully removed from the data.

https://www.cosmos.esa.int/web/planck/picture-gallery



Atmosphere contributions

→ non-pol. radiations

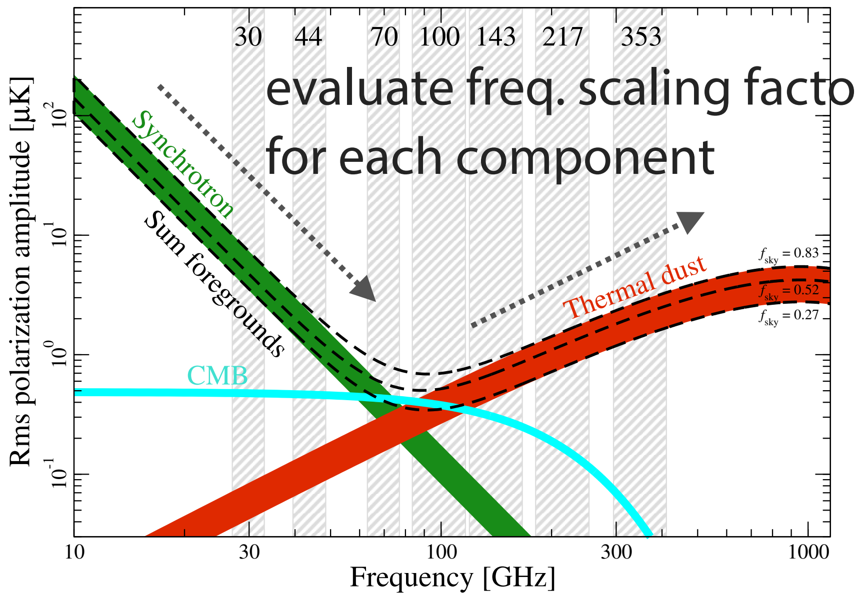
No realistic sensitivity for intensity at all

Could not be affected so much in pol.

if time scale <10sec

→ large scale observation is difficult

for the ground experiments…



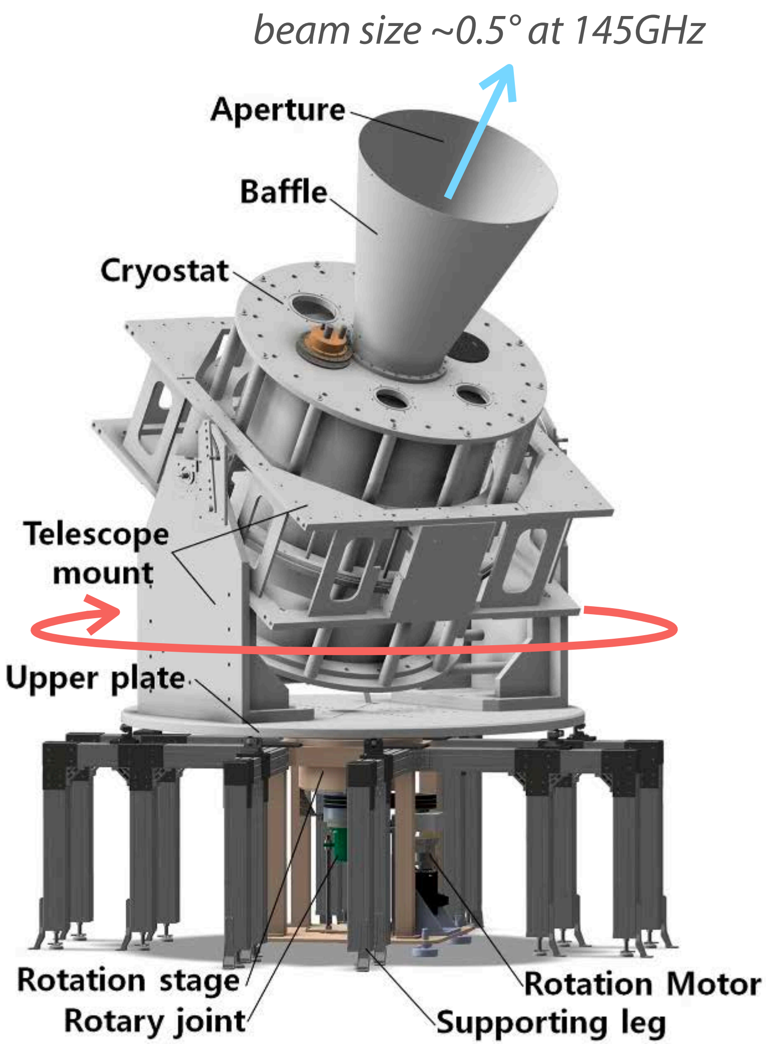
https://www.cosmos.esa.int/web/planck/picture-gallery

→ multiple observational freq. bands are essential

GroundBIRD (GB)

Compact telescope for large scale CMB-polarization observations

Installed at the observatory in 2019 and achieved the first light with moon



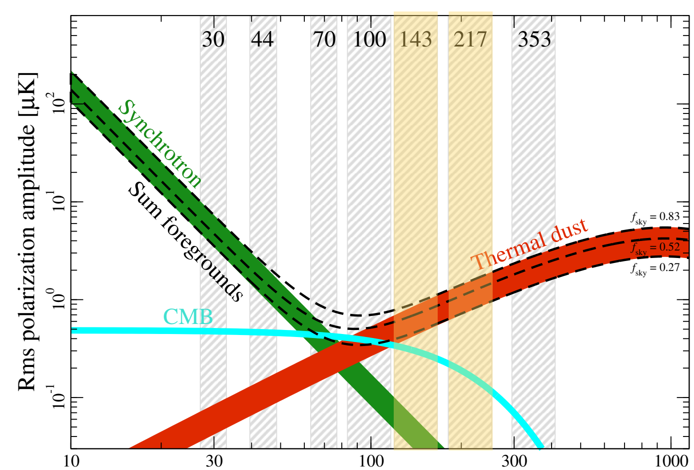
Selectable elevation from 60° to 90°

Superconducting detector "MKIDs"

faster time response than sampling rate of 1ksps
*two observational frequency bands = **145GHz and 220GHz***

Continuous azimuth rotation at 20RPM

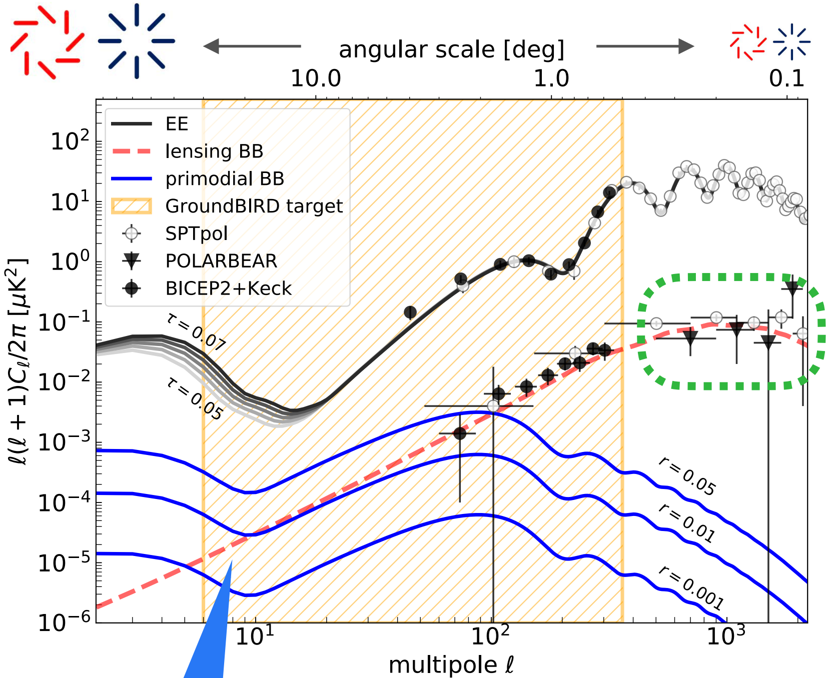
mitigating effects of atmospheric fluctuation
→ Cutting out any 1/f on timescales longer than 3 seconds



https://www.cosmos.esa.int/web/planck/picture-gallery

Science Targets

High sensitivity measurements of large angular-scale polarizations



B-mode at large angular scale

→ constraint on **"r"**

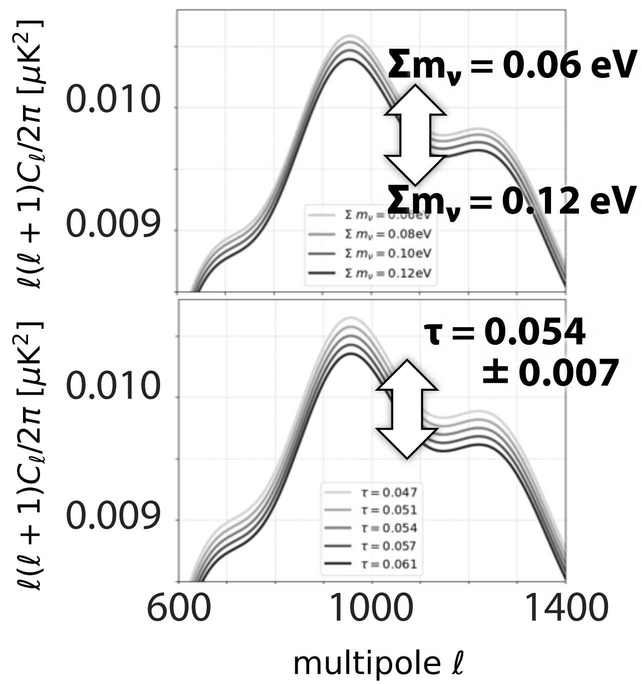
tensor-to-scalar ratio

⬇

inflation theory evaluation

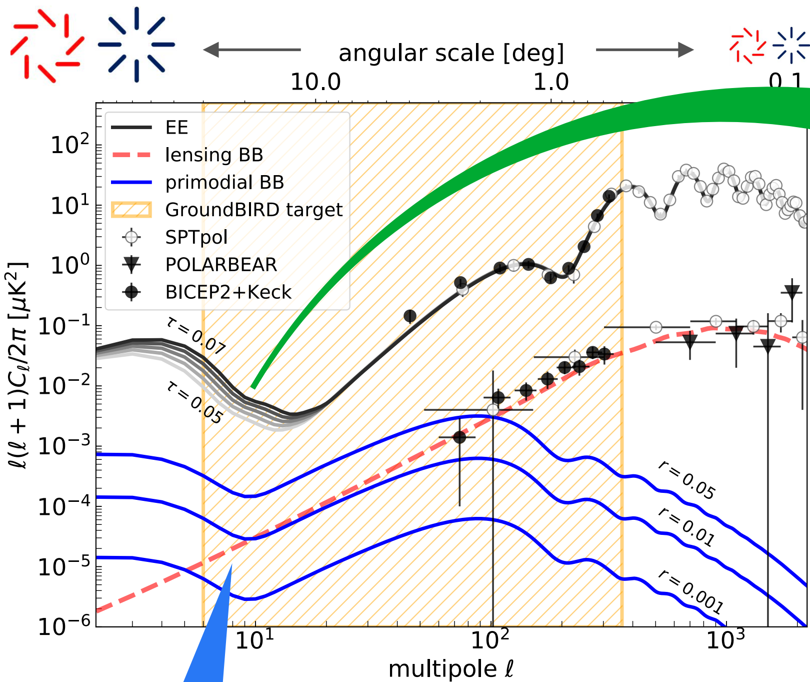
Neutrino mass from CMB…?

degeneracy in lensing BB: Σmν ⇔ τ



Science Targets

High sensitivity measurements of large angular-scale polarizations



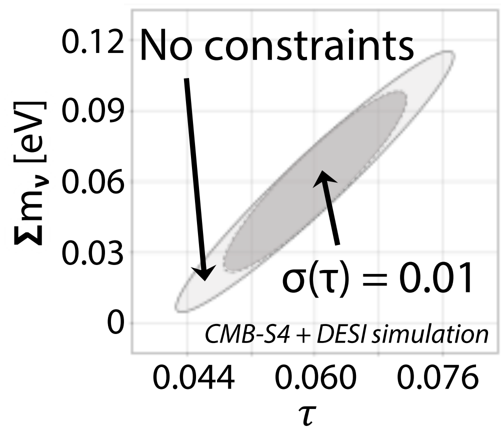
E-mode at large angular scale

→ constraint on **"τ"**

optical depth of reionization

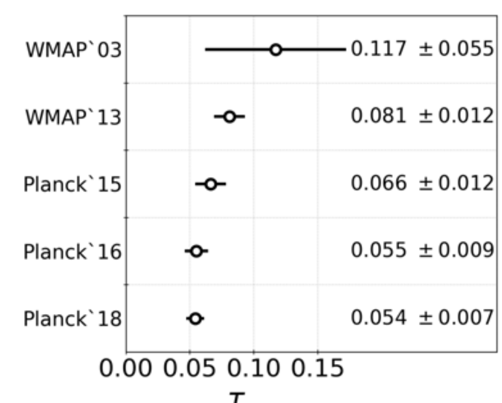
↓

neutrino mass measurement



unfolding correlations

: $\Sigma m_\nu \Leftrightarrow \tau$



B-mode at large angular scale

→ constraint on **"r"**

tensor-to-scalar ratio

↓

inflation theory evaluation

τ by space missions getting smaller…
(depending on FG systematics)
→ good to validate this with other observations

Telescope property: cryogenics

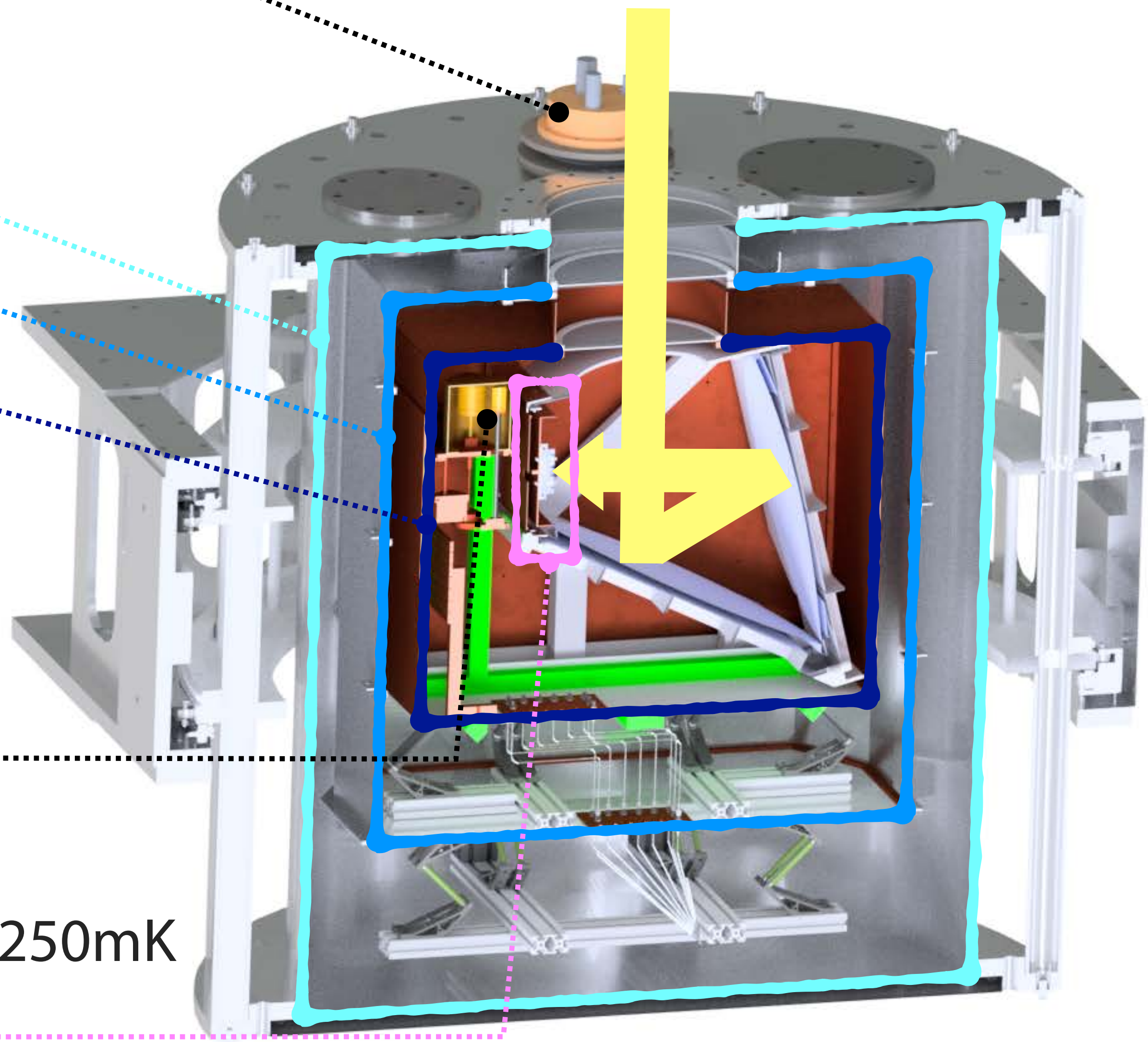
- **Pulse tube cooler** with three thermal shields

300K

40K

4K

Cold optics with cross-Dragone mirror (FOV=±10°)

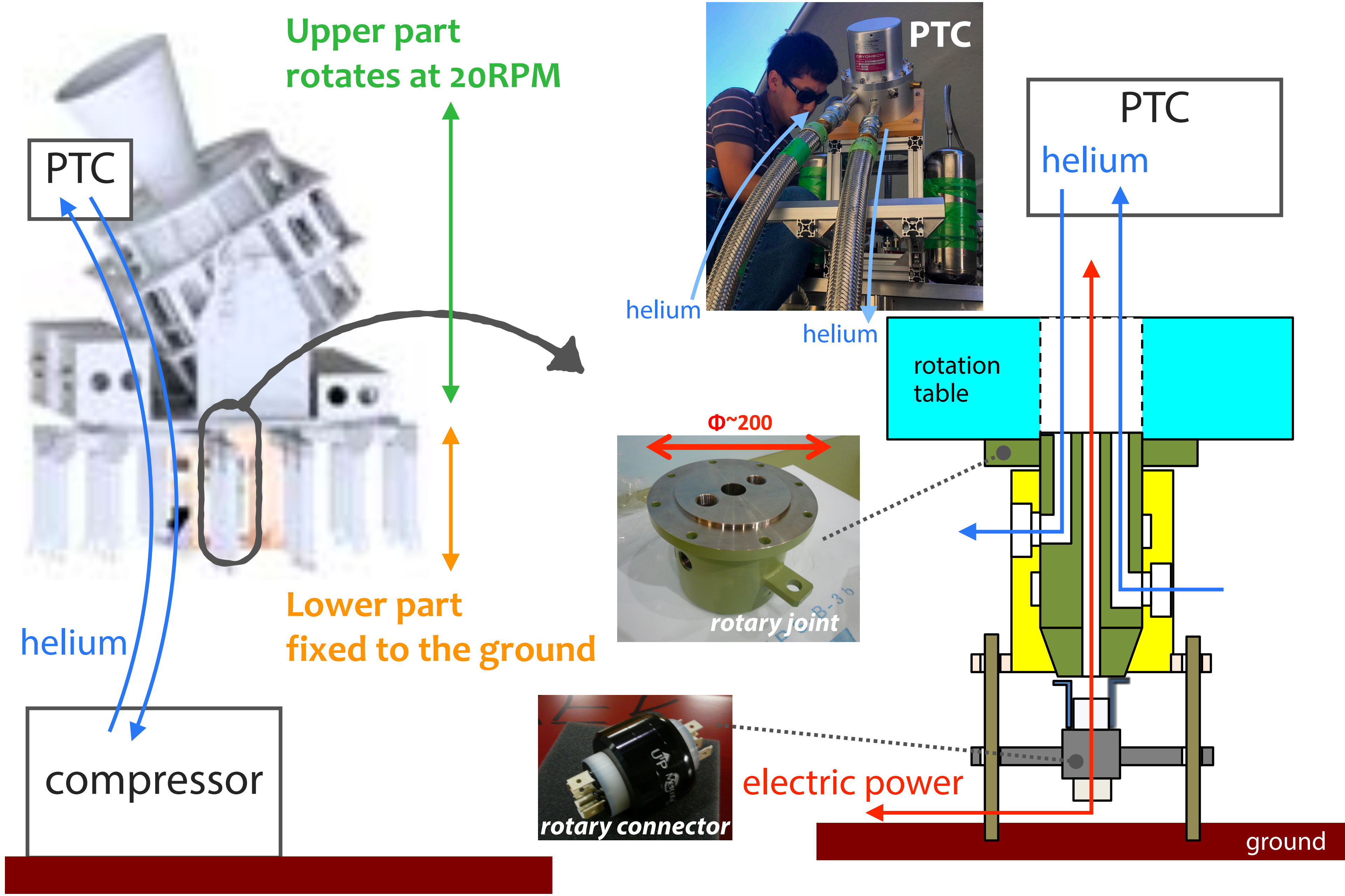


- **Sorption cooler (3 stages with He10)**

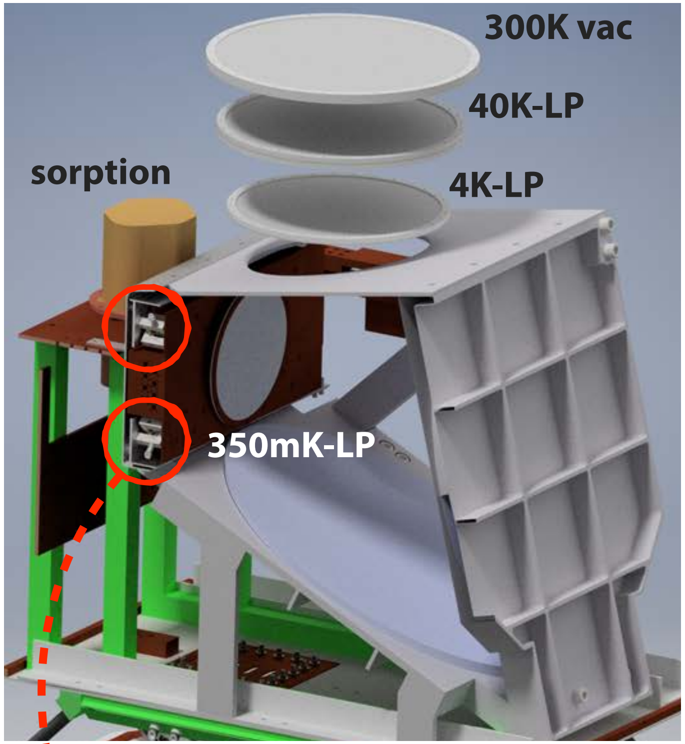
Detector cooled down to 250mK

- **Focal plane**

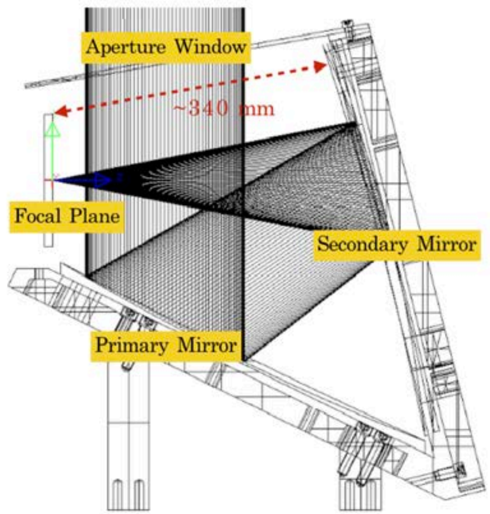
Telescope property: rotary joint



Telescope property: cold mirror and focal plane



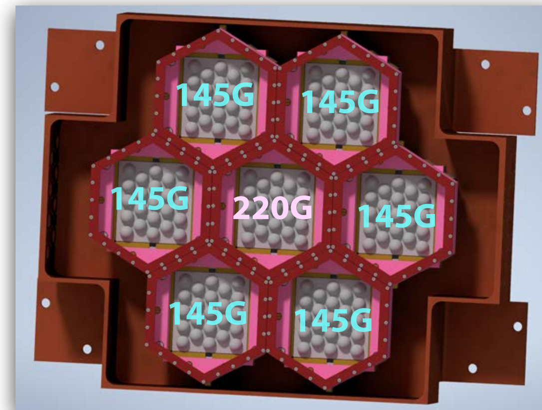
mirror design



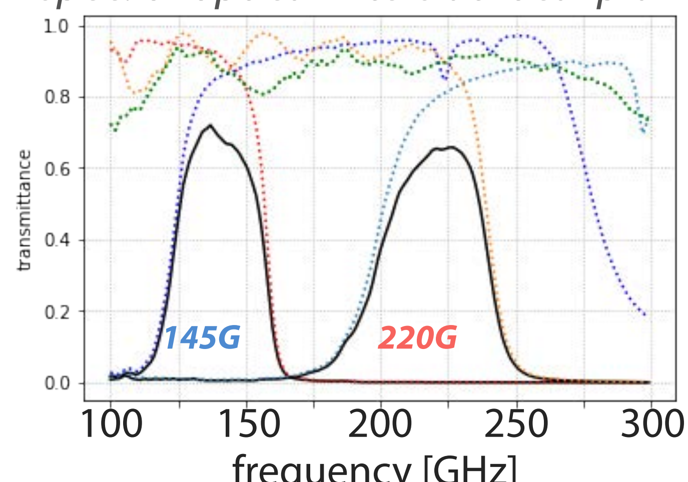
7 wafers on the focal plane

23pix. for each wafer

- 138 pix. with 145GHz for CMB
- 23 pix. with 220GHz for dust



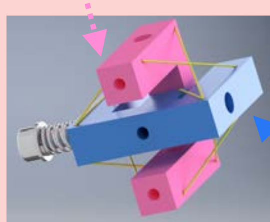
spec. of optical filters at focal plane



Kevlar small jigs for thermal isolation

Thermal isolation well achieved by tensions of Kevlar wires

temp. 1



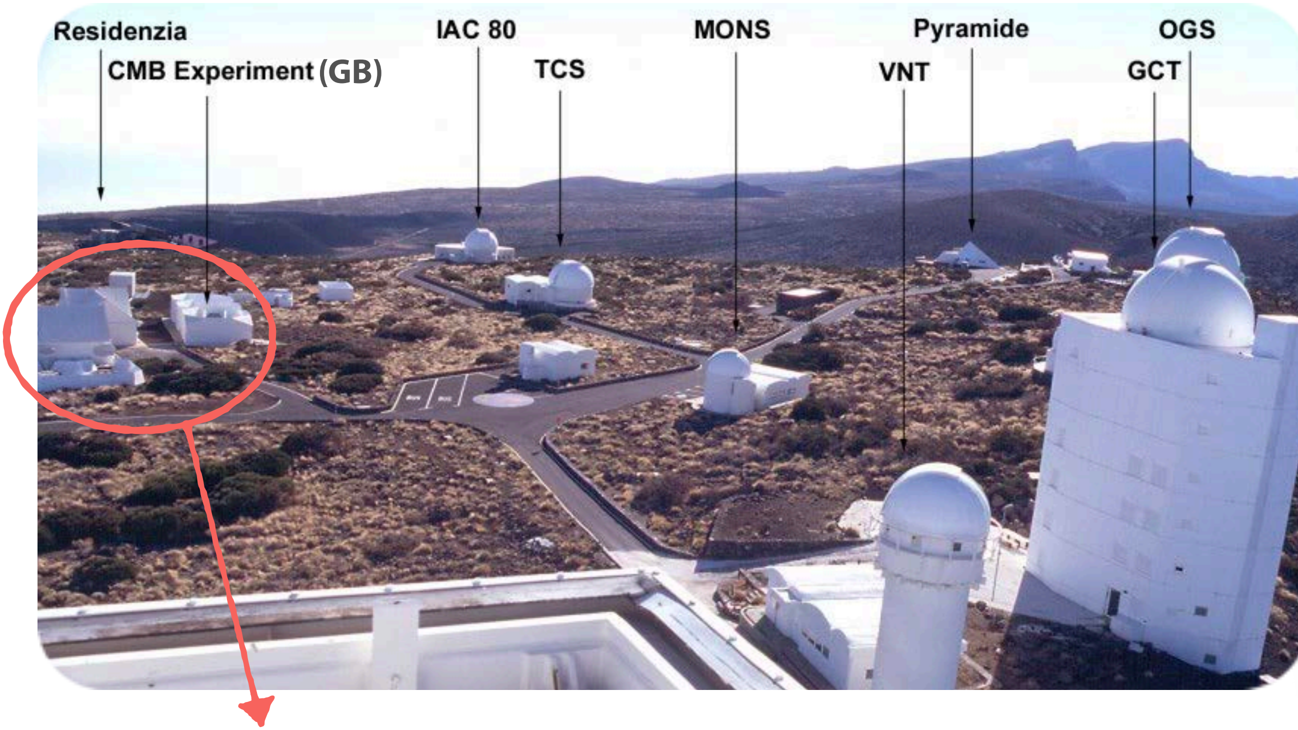
temp. 2

thermal conductivity

~ 0.0064 [mW/K]

Observation at Teide Mountain

Teide Observatory at 2400m altitude

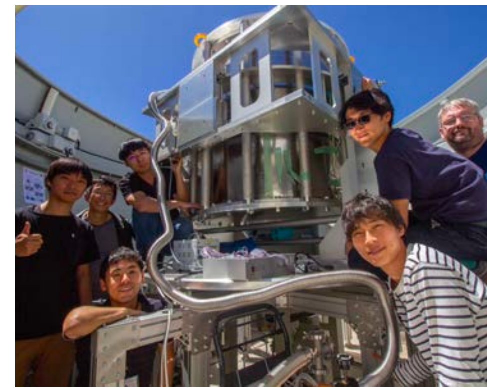


Telescope Installation and First Light

S.Honda et al. (2020) Proc. SPIE

Deployment at Teide Observatory (TO) - *2400m alt. in Tenerife*

Demonstration of high-speed-rotation scan at 20RPM

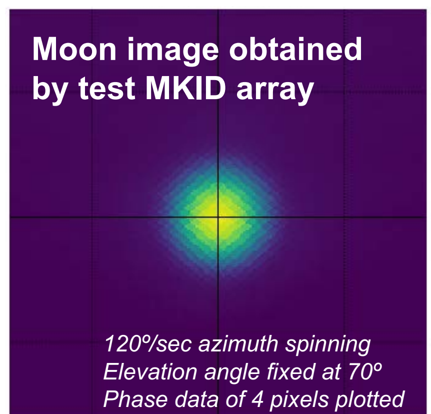


First light (Moon) Sep. 2019

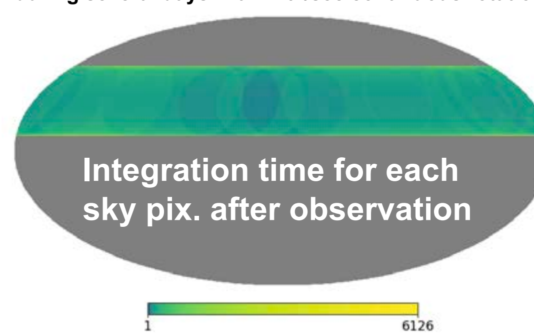
→ Confirmation of optical design

Demonstration of large-sky coverage

→ End-to-end function test



Integration time [ms] indicating how much data was taken at each sky pixel. Test MKID array took data during several days with 120°/sec continuous rotation.



** Test MKID for the first-light campaign was borrowed from SRON.*

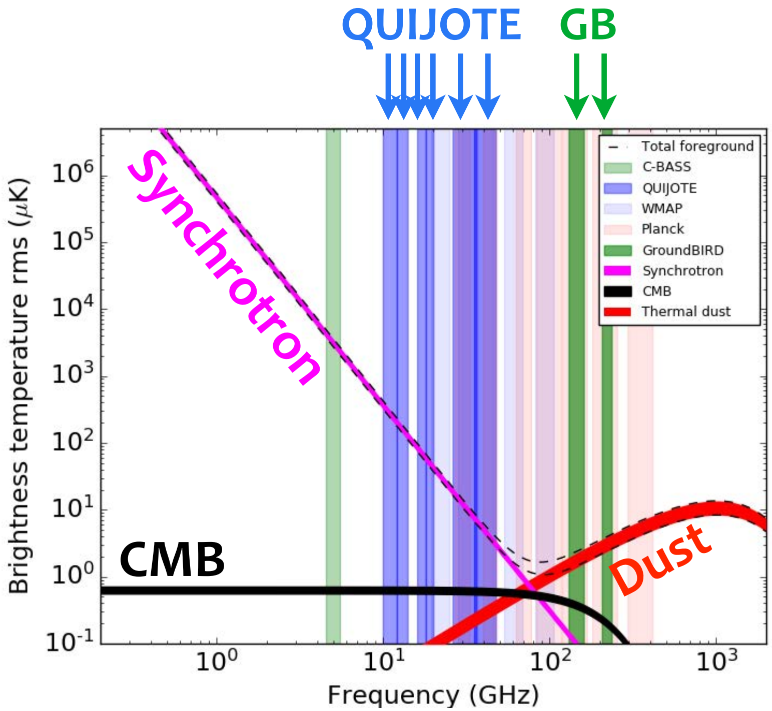
GroundBIRD and QUIJOTE

QUIJOTE

- continous azimuth rotation at 2-10 RPM
- elevation up to 30°
- installed just next to GB
- low-frequency bands covered with two telescopes:
  - 11, 13, 17, 19 GHz with QJ1
  - 30, 40 GHz with QJ2

GroundBIRD + QUIJOTE combined observation = eight freq. bands 10 - 220GHz

→ widest frequency analysis to accurately remove foregrounds + extract CMB

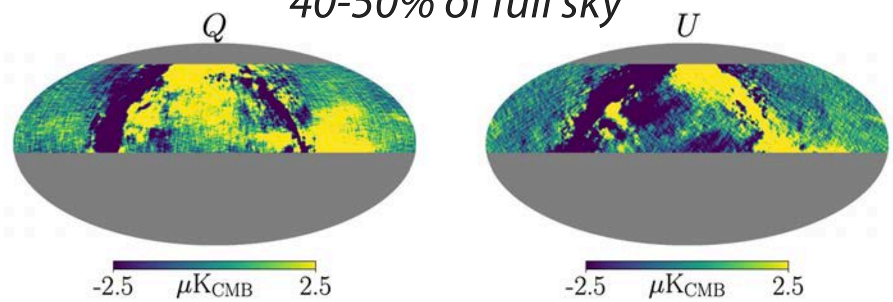


21 Forecast of τ with large scale E-mode

K. Lee et al 2021 ApJ 915 88

CMB, synchrotron, and dust simulated maps with cosmological parameters given by Planck

40-50% of full sky



(a) Frequency map at 145 GHz, Q (b) Frequency map at 145 GHz, U

⊗

(b) Galactic plane mask

→ 22.8% of full sky in total

- Three year observations in GB+QJ
- Artificial noises

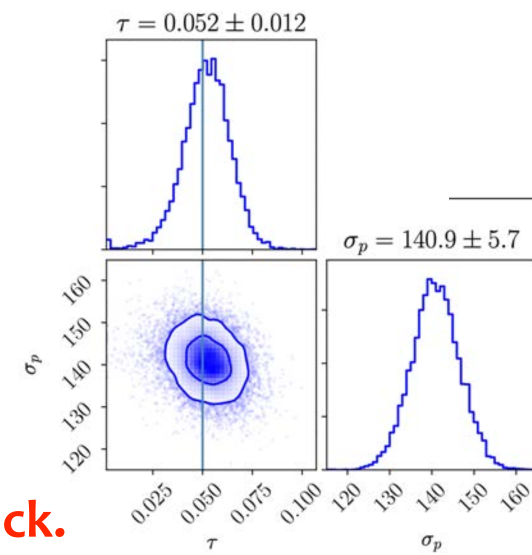
Frequency (GHz)	Noise level (μK arcmin)
11	3600
13	3600
17	5100
19	5100
30	160
40	91
145	110
220	780

+ 1/f noise to GB not QJ (knee at 0.1Hz)

- Result

$$\mathbf{m}_{\text{combined}} = \sum_{\nu} c_\nu \mathbf{m}^\nu$$

Frequency (GHz)	ILC coefficients
11	−0.011±0.001
13	−0.009±0.002
17	−0.003±0.002
19	−0.002±0.002
30	−0.14±0.04
40	1.12±0.04
145	0.13±0.03
220	−0.077±0.008



GroundBIRD + QUIJOTE combined analysis can provide τ value with similar unc. of Planck.

Summary

The cosmic Microwave Background is the key to understanding our universe.

To evaluate the anisotropy, the power spectrum is calculated.

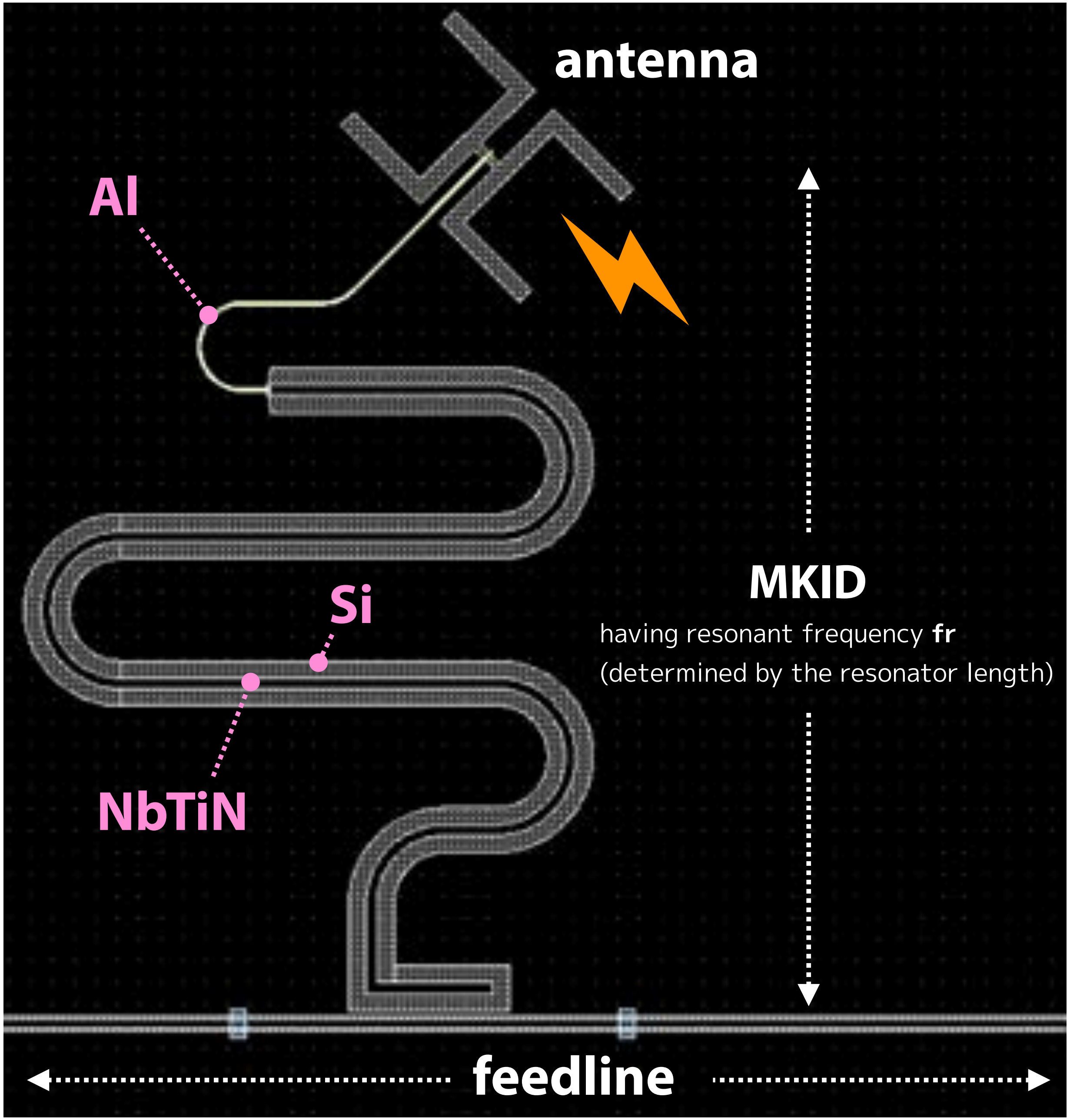
GroundBIRD observes CMB polarization at a large angular scale with high-speed rotation at 20RPM

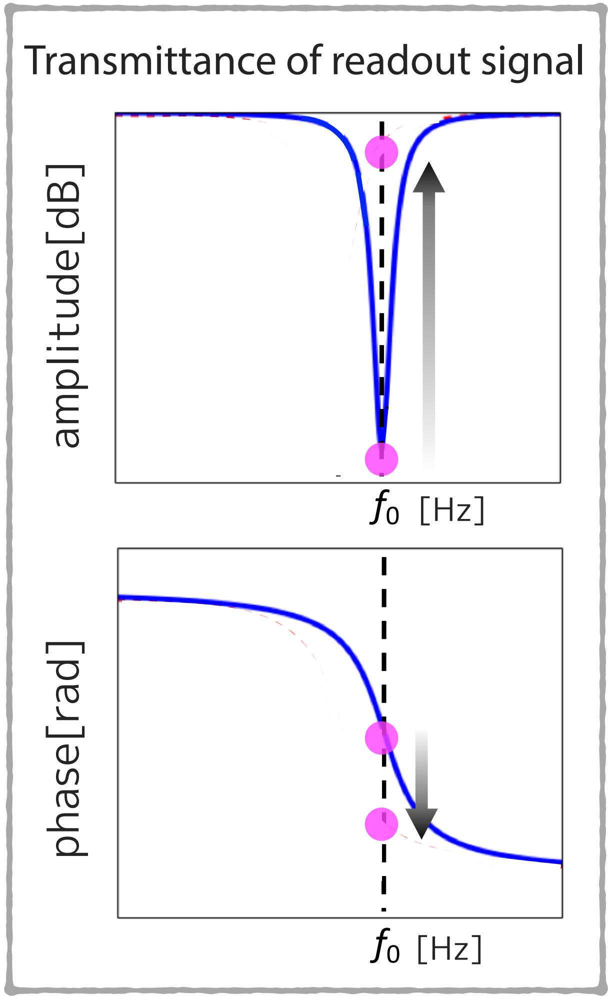
- Unique technologies: high-speed rotation scanning at 120°/sec with the custom rotary joint
- Installation at Teide observatory in 2019 → First light achieved
- The τ sensitivity is estimated with GB+QJ combined analysis

MKID and DAQ system in GroundBIRD

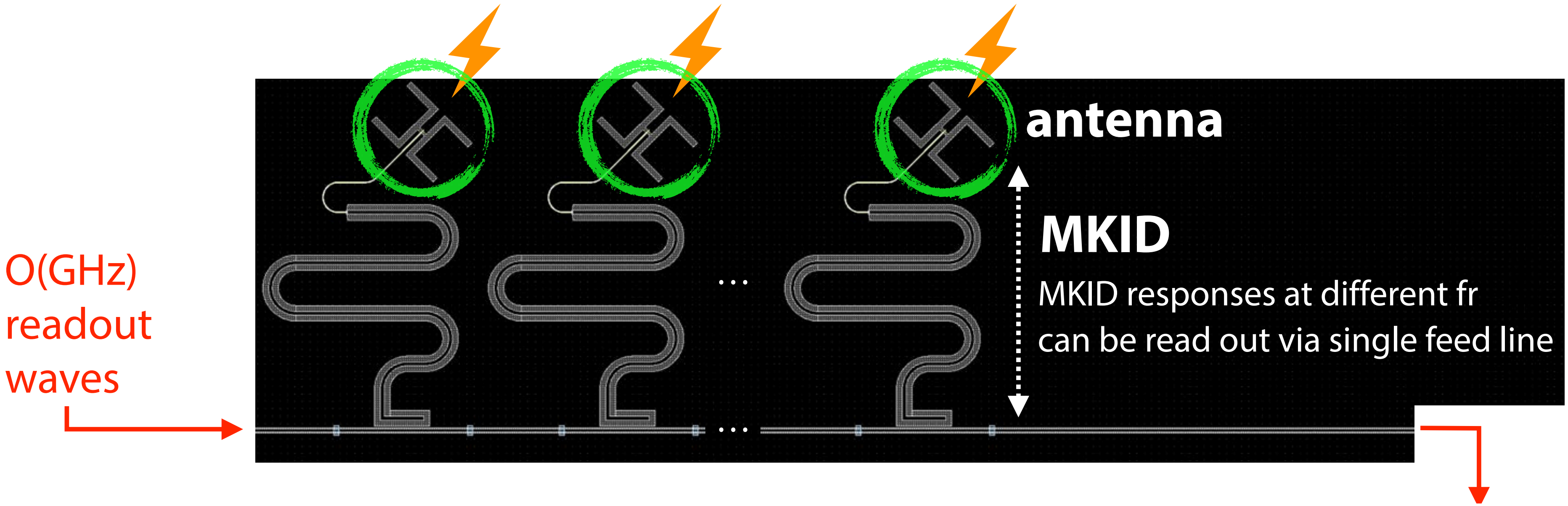
Shunsuke Honda

MKID


antenna
Al
Si
NbTiN
MKID
having resonant frequency **fr**
(determined by the resonator length)
feedline

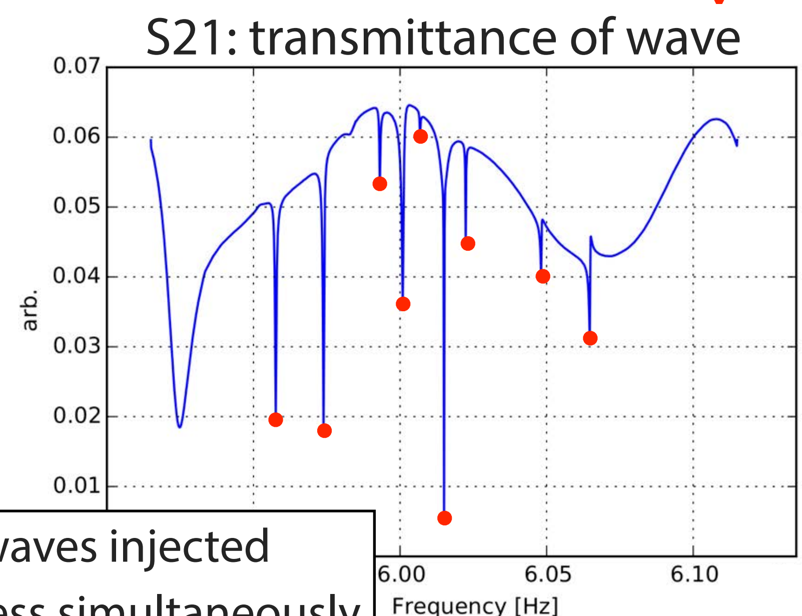

Transmittance of readout signal
amplitude[dB]
f0 [Hz]
phase[rad]
f0 [Hz]

MKID and readout method



MKIDはGHz帯域の読み出し信号に光応答情報を載せる

→MKIDの共振周波数の信号を同時に入力。
その時系列データで検出器応答を測定。
(図中●)



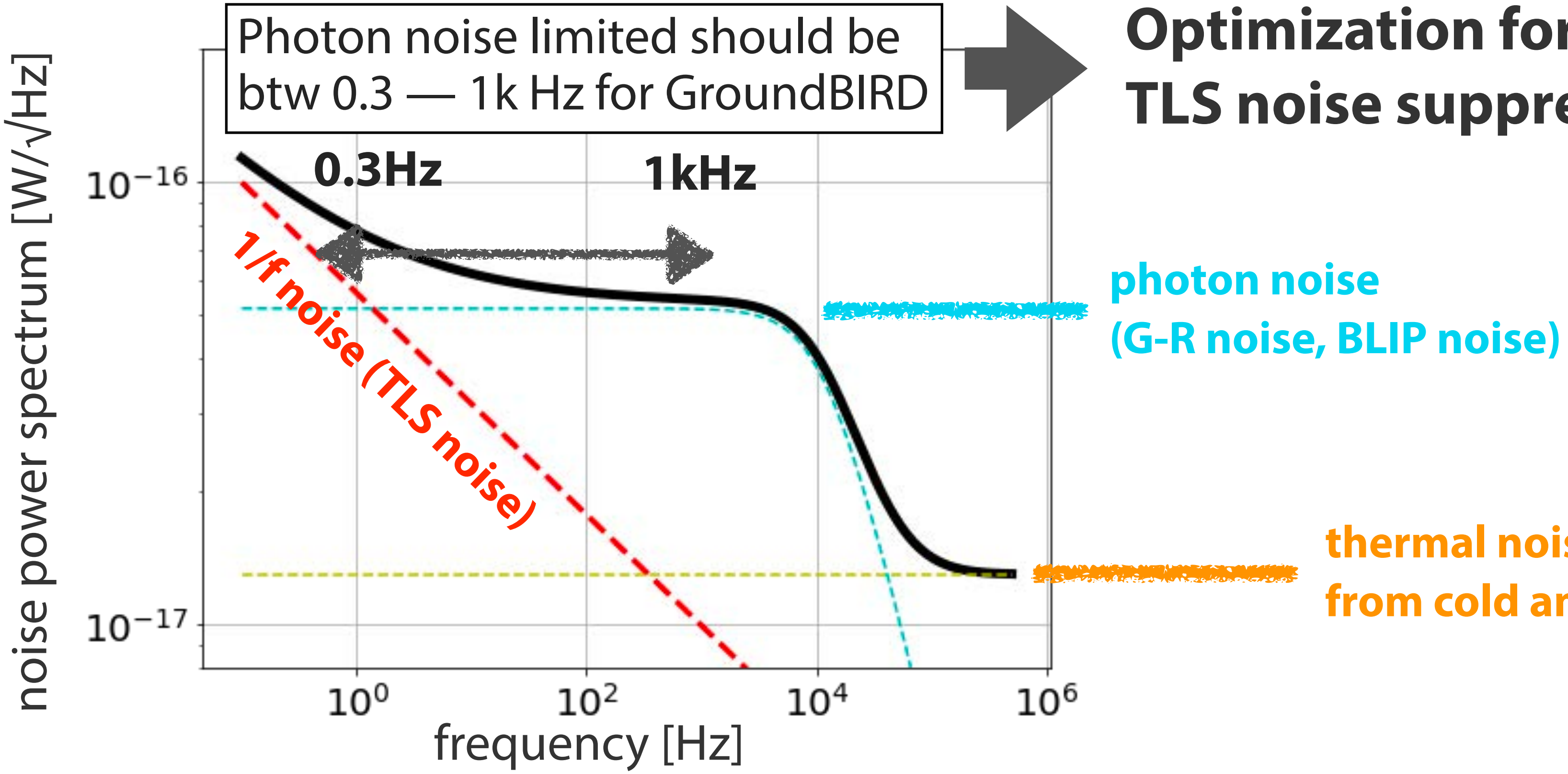
9 different frequency waves injected
then, readout responsess simultaneously

Developments for GroundBIRD MKID

New MKID sensor for GroundBIRD developed with SRON

- Hybrid MKID with Al-NbTiN for 150GHz band
- Systematic method established to maximize the sensitivity with simulations.

Typical MKID power spectrum



Optimization for TLS noise suppression

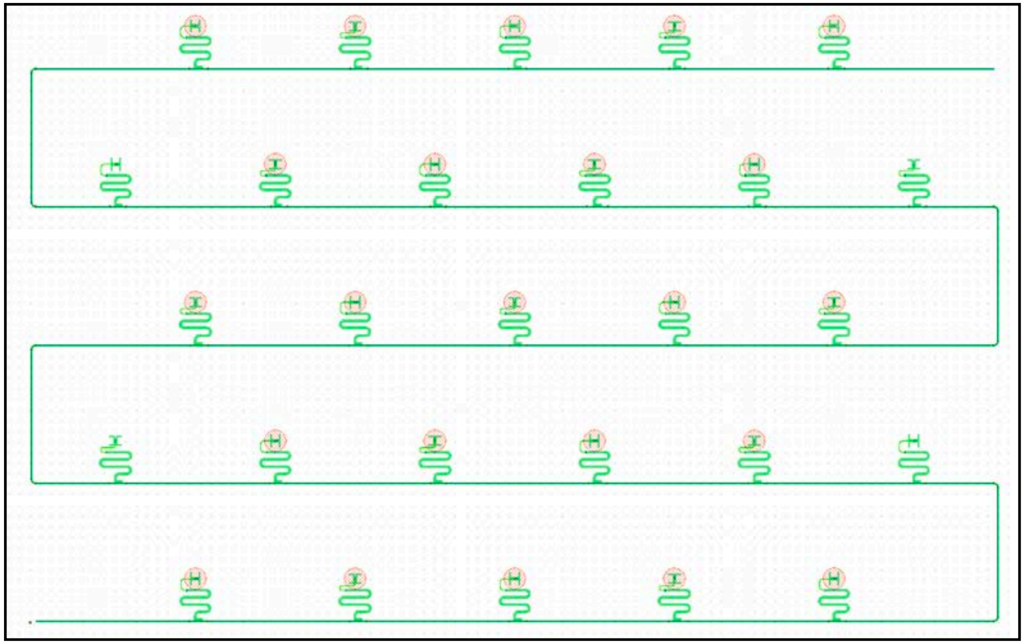
Optimization of TLS noise in Hybrid-MKID

ASJ 2022.03 H. Kutsuma

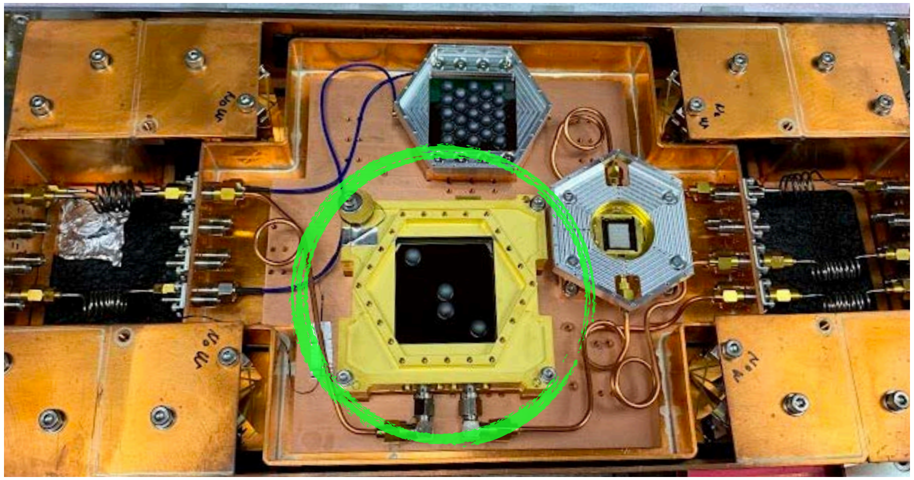
GB-KID for science observation

Proto-type sensor chip

- 23 pixels for observations
  + 4 pixels without lenslets
- antenna and lenslet for 150GHz
- Based on TLS suppressed design



Installed to GroundBIRD in cooling run of 2021.07



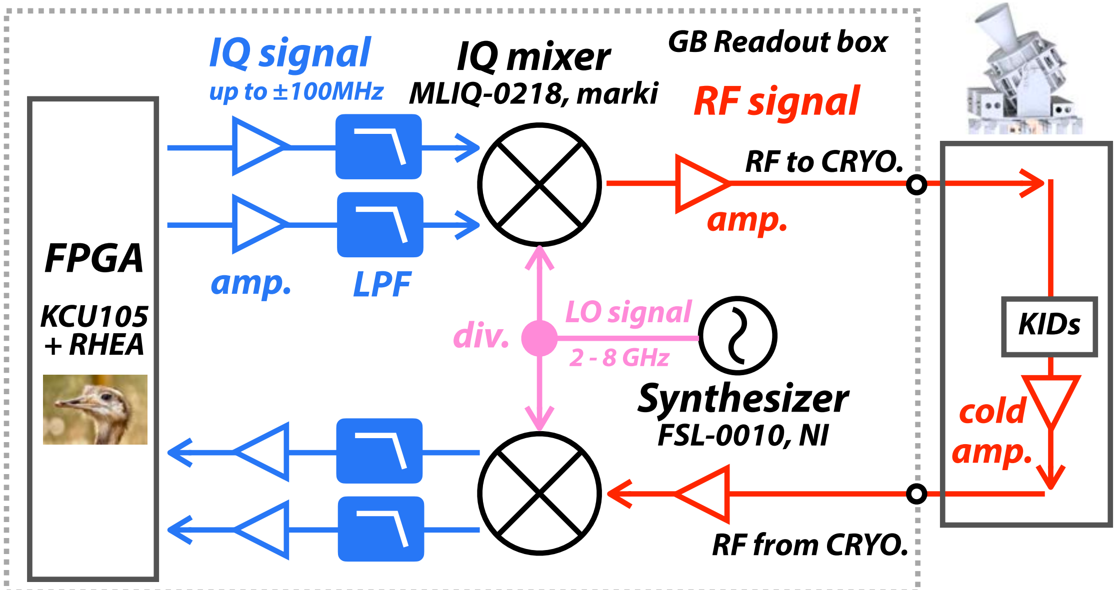
SRON MKID: Al-NbTiN MKID 23pix

for tests of our science observations

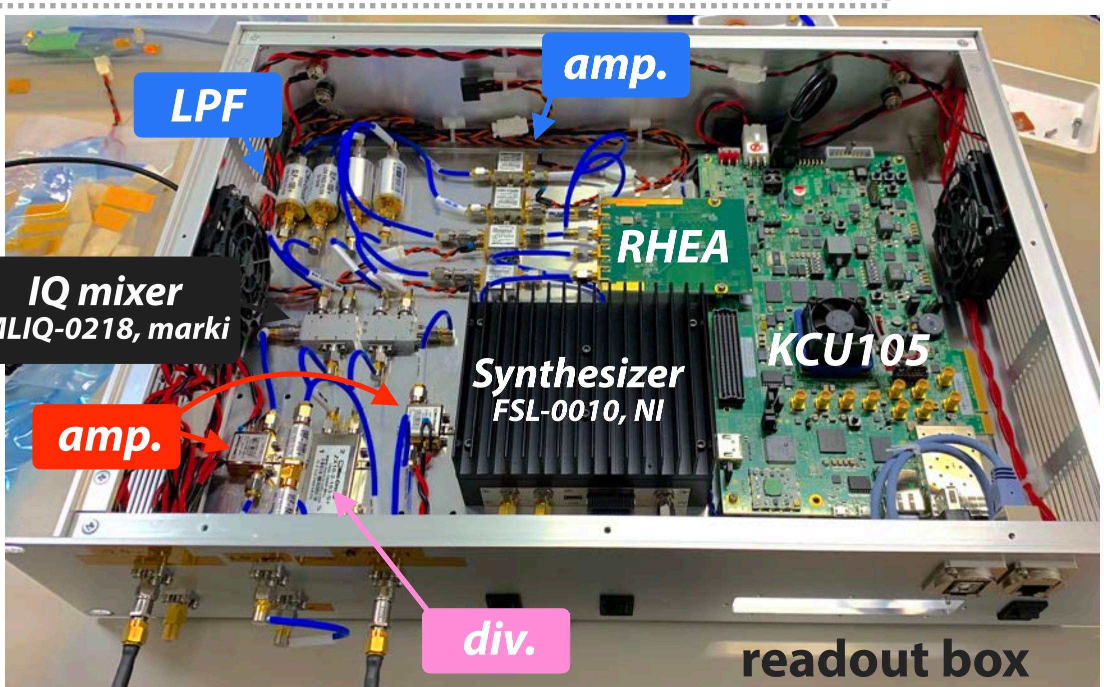
4/27 pixels with lenslets for performance checks

In the readout, we need to use 32 tones for MKID + noise measurements.

GroundBIRD readout system



- Simple readout system
- Generating/receiving RF signals
- 32 tones demonstrated
  → could be 128 tones
- Trigger function implemented
- Tones within LO ± 100MHz



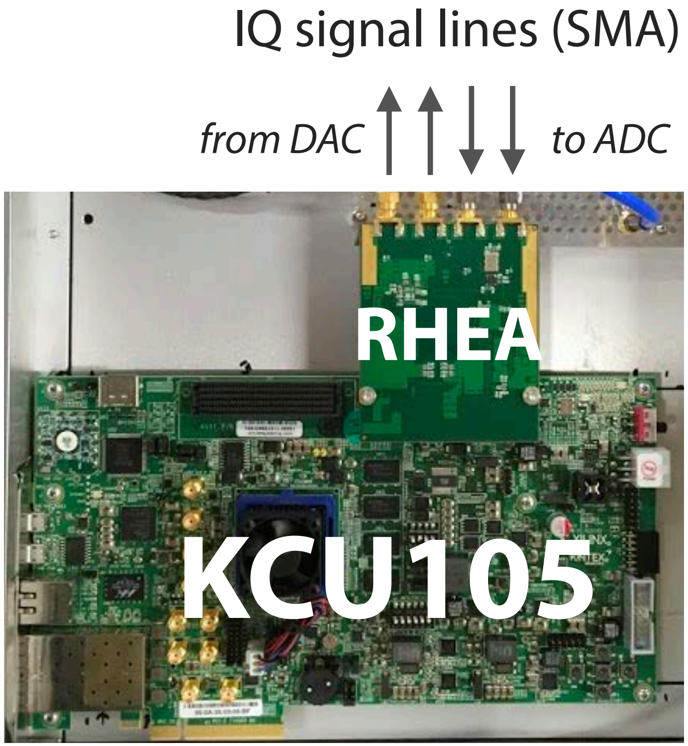
readout box

Four readout box installed!

GroundBIRD DAQ Board

- FPGA evaluation board: **KCU105** from XILINX
- Analog board for ADC/DAC: **RHEA** (custom-ordered board)
  - Tuned for GroundBIRD experiment

board	KCU105 + RHEA
max. multiplexing	128
sampling rate sent to PC	1kSPS for 128 mux 1MSPS for ~4 mux
power	~23W
data rate	1.7MB/s for 1kSPS (120mux)
communication	LAN(TCP/UDP)
ADC Spec.	2 Vpp, 14bit, 2 lines
DAC Spec.	1 Vpp, 16bit, 2 lines
sampling rate on ADC/DAC	200MSPS
band width	200MHz (LO freq. ± 100MHz)

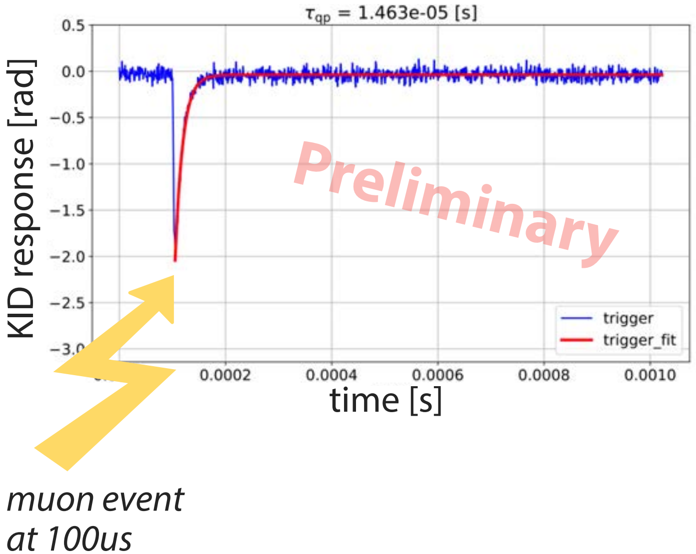


Readout with particle detection

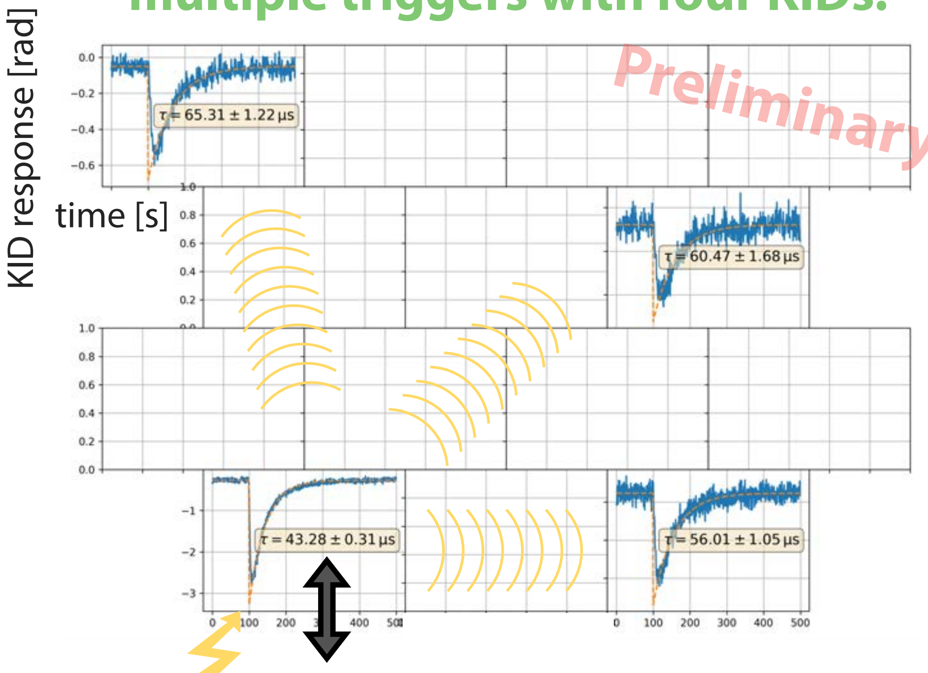
The trigger function was implemented to check the MKID performance originally

→ Can be directly usable for the particle detection.

- sampling rate = normally 1MSPS / DAQ is triggered with OR of all KIDs



multiple triggers with four KIDs.



almost compatible to the PSD fit ~ 41.8us

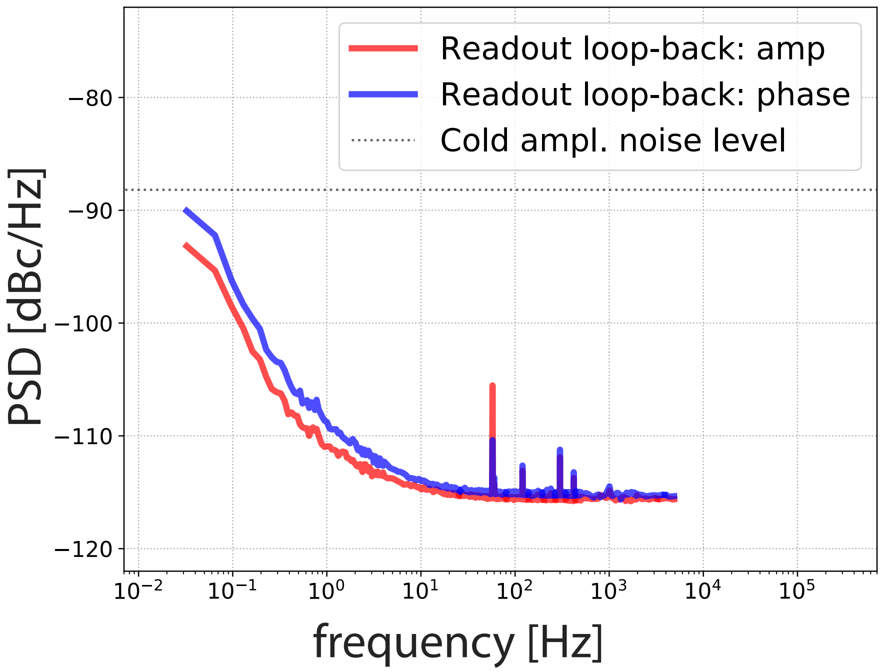
32 Measurement of readout performance

S.Honda et al. (2020) Proc. SPIE

Evaluation of readout system performance

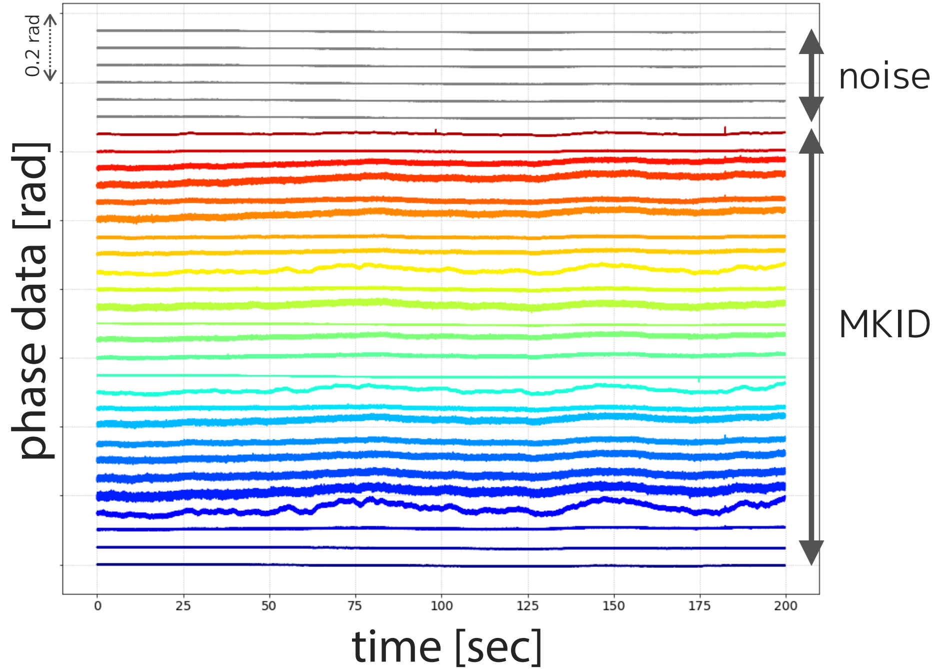
noise spectrum of readout system

data taken with 32tones → 27 tones evaluated



TOD during the observation

(チャンネルごとにオフセットをつけて見やすく表示している)

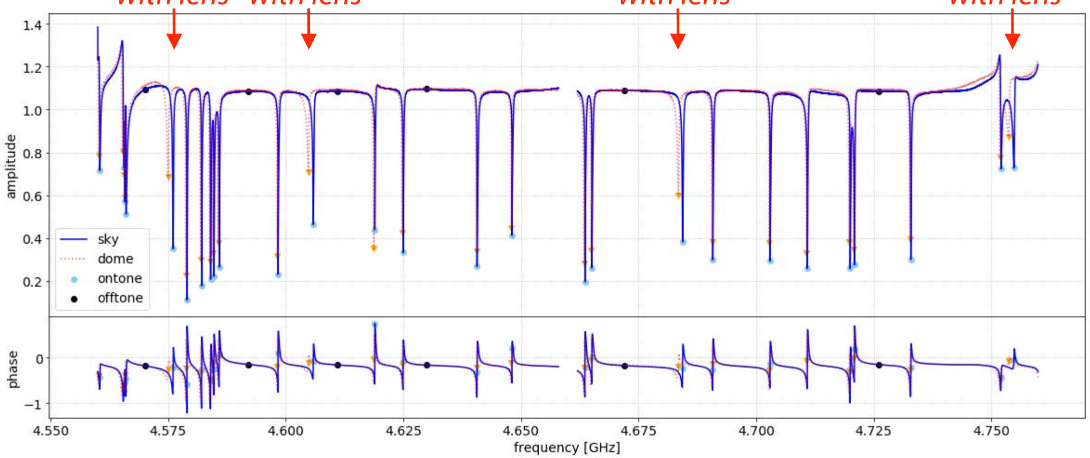


- **Low enough noise level rather than a cold amp. noise**
- **Successed simultaneous observations with 32 tones!**

Observation Results

MKID property

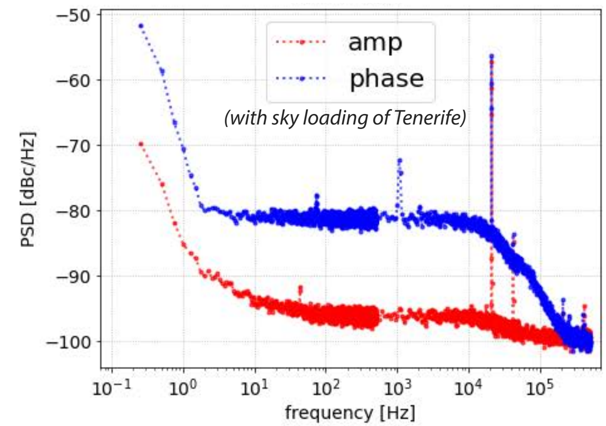
frequency sweeping (LO ± 100MHz)



26/27 pixels in readout band width

PSD of one MKID with lenslet

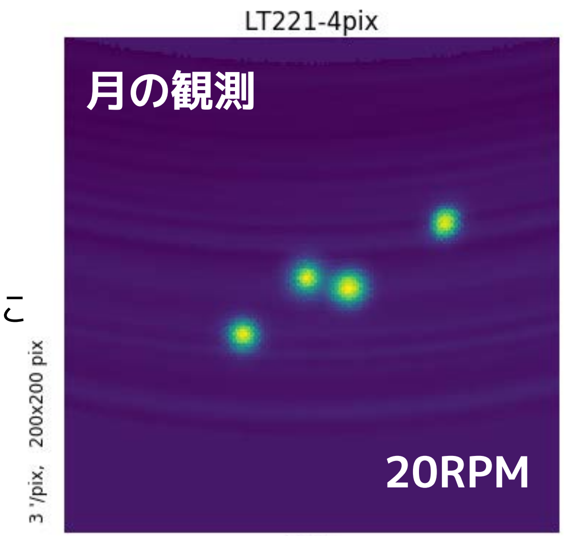
seeing roll-off shape both in amp. and phase



observations with 1kSPS dominated by the photon noise

Moon observations with new MKID

焦点面位置に応じてピクセルごとに
別の位置で月が撮像される

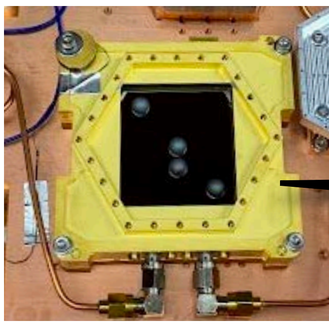


Current Status

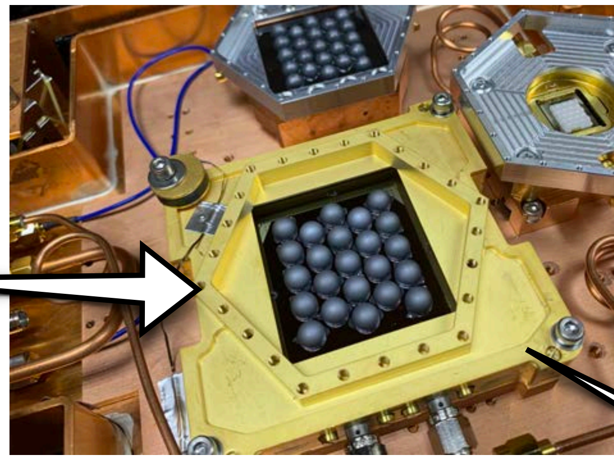
Test sensor upgraded with 23pixels+lenslets

→ Performance check all pixels in 2022

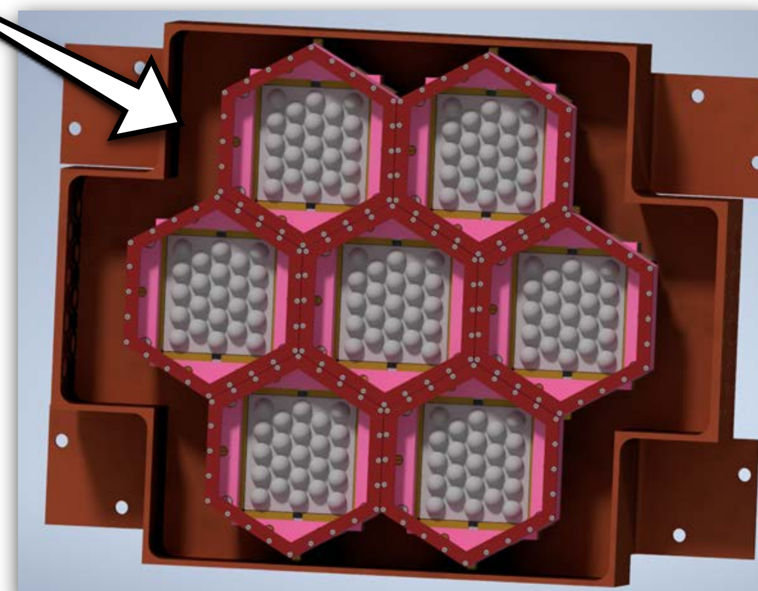
cooling run 2021.07



cooling run 2021.12



full array installation 2023.03



Full array installations in 2023.03

- compact chip size
- antennas with 4 directions for Q and U
- AR coating on the lenslet

Summary

GroundBIRD uses MKID as the focal plane detector

- Fast time response, easy to be multiplexed

To suppress 1/f noise given by the detector chip, we developed the simulation model for hybrid MKIDs.

→ GB-KID was designed based on this evaluation

Proto-type was fabricated and tested in GroundBIRD

→ The performances are very nice

This evaluation will be published as the paper after fabricating the first GB-KID chip in this year.

The readout system was given by the FPGA + frequency conversion.

→ Noise level is enough lower than the LNA white noise at 4K.