Lite (Light) Satellite for the Studies of B-mode Polarization and Inflation from Cosmic Background Radiation Detection

Cosmology and Particle Physics with LiteBIRD

Masashi Hazumi
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for the LiteBIRD working group

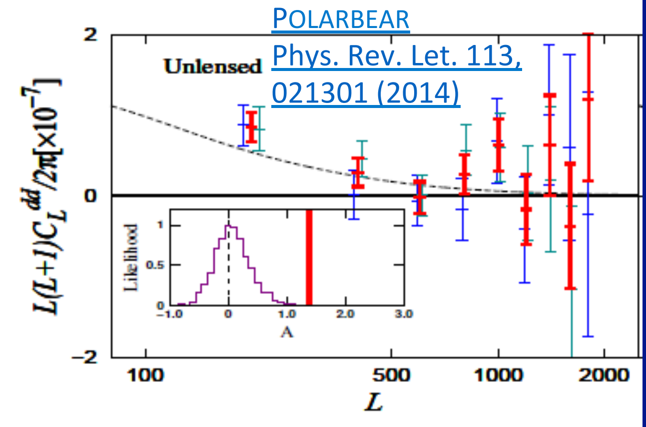
IPNS-KEK Experimental Cosmology - CMB B-Mode Detection

QUIET, POLARBEAR, Simons Array, LiteBIRD

Degree-scale Cosmic Microwave Background (CMB) polarization B-mode is the smoking-gun evidence for inflation and primordial gravitational waves.

Sub-degree CMB B-mode is a powerful tool to constrain the sum of neutrino masses.

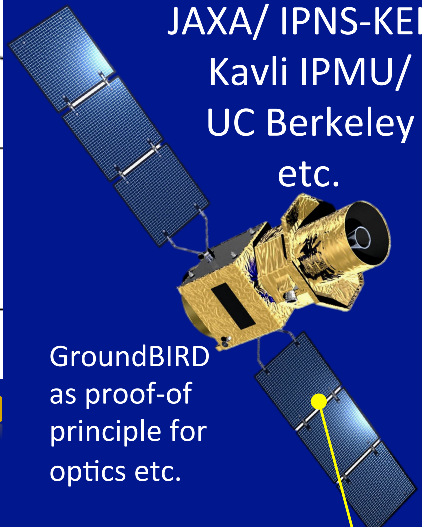
Experimental Cosmology and Super High-Energy Physics !



POLARBEAR Phys. Rev. Lett. 113, 021301 (2014)

POLARBEAR: EVIDENCE FOR B-MODE POLARIZATION LENSING BASED ON PURELY CMB INFORMATION

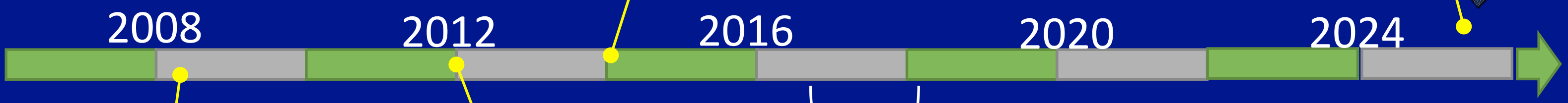
LiteBIRD Satellite
JAXA/ IPNS-KEK/
Kavli IPMU/
UC Berkeley
etc.



GroundBIRD as proof-of principle for optics etc.

KEK CMB Group

Past, Present, Future



QUIET (2008.9 First Light)

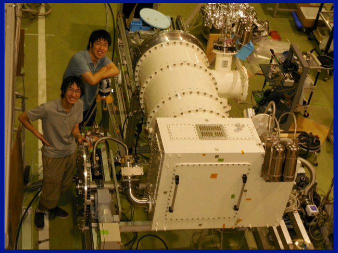
Atacama, Chile

KEK, FNAL, Chicago, Caltech, Princeton, Columbia etc.

POLARBEAR → (2012.1 First Light)

Atacama, Chile

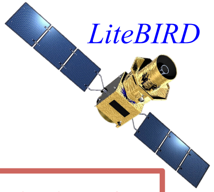
Upgrade to Simons Array (First receiver system in preparation at KEK)



KEK, JAXA, Kavli IPMU, NIFS, UC Berkeley, LBNL, UCSD, Colorado, McGill, APC, Cardiff, SISSA, IC, Dalhousie etc.

POLARBEAR/Simons Array Group

LiteBIRD working group



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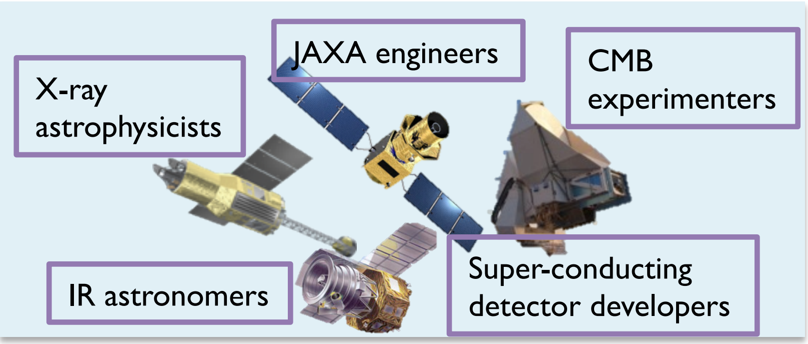

JAXA engineers

CMB experimenters

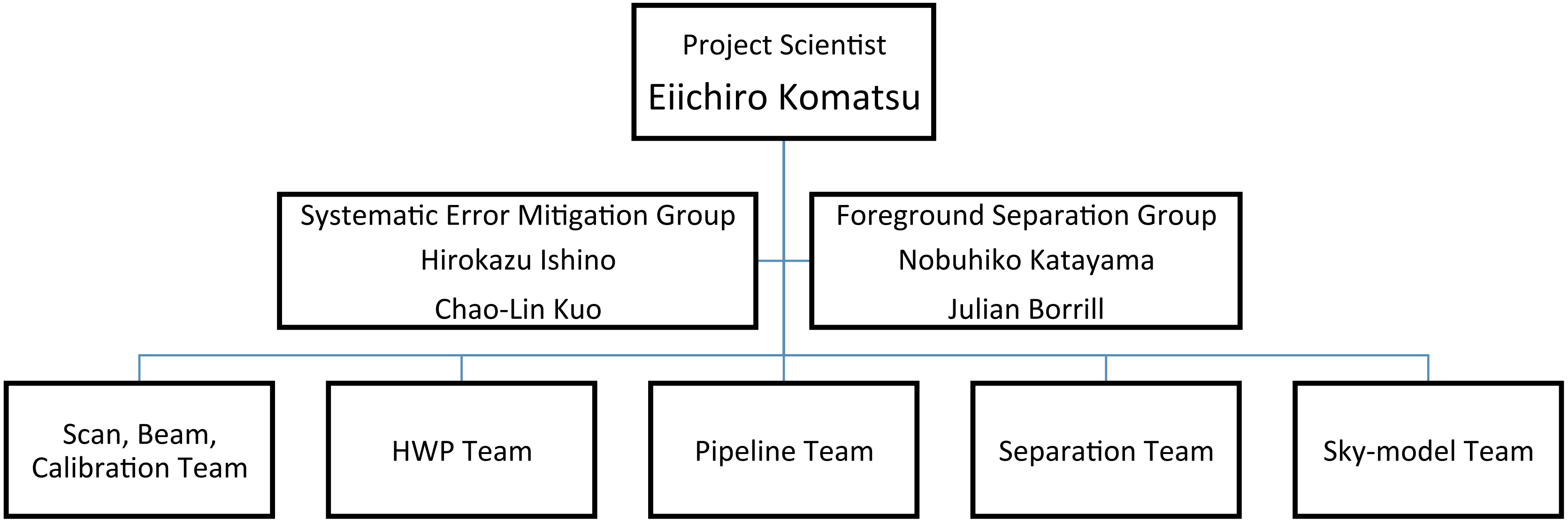
X-ray astrophysicists

IR astronomers

Super-conducting detector developers

138 members, international and interdisciplinary (as of May 1, 2016)

Joint study group (JSG)



Project Scientist
Eiichiro Komatsu

Systematic Error Mitigation Group
Hirokazu Ishino
Chao-Lin Kuo

Foreground Separation Group
Nobuhiko Katayama
Julian Borrill

Scan, Beam, Calibration Team

HWP Team

Pipeline Team

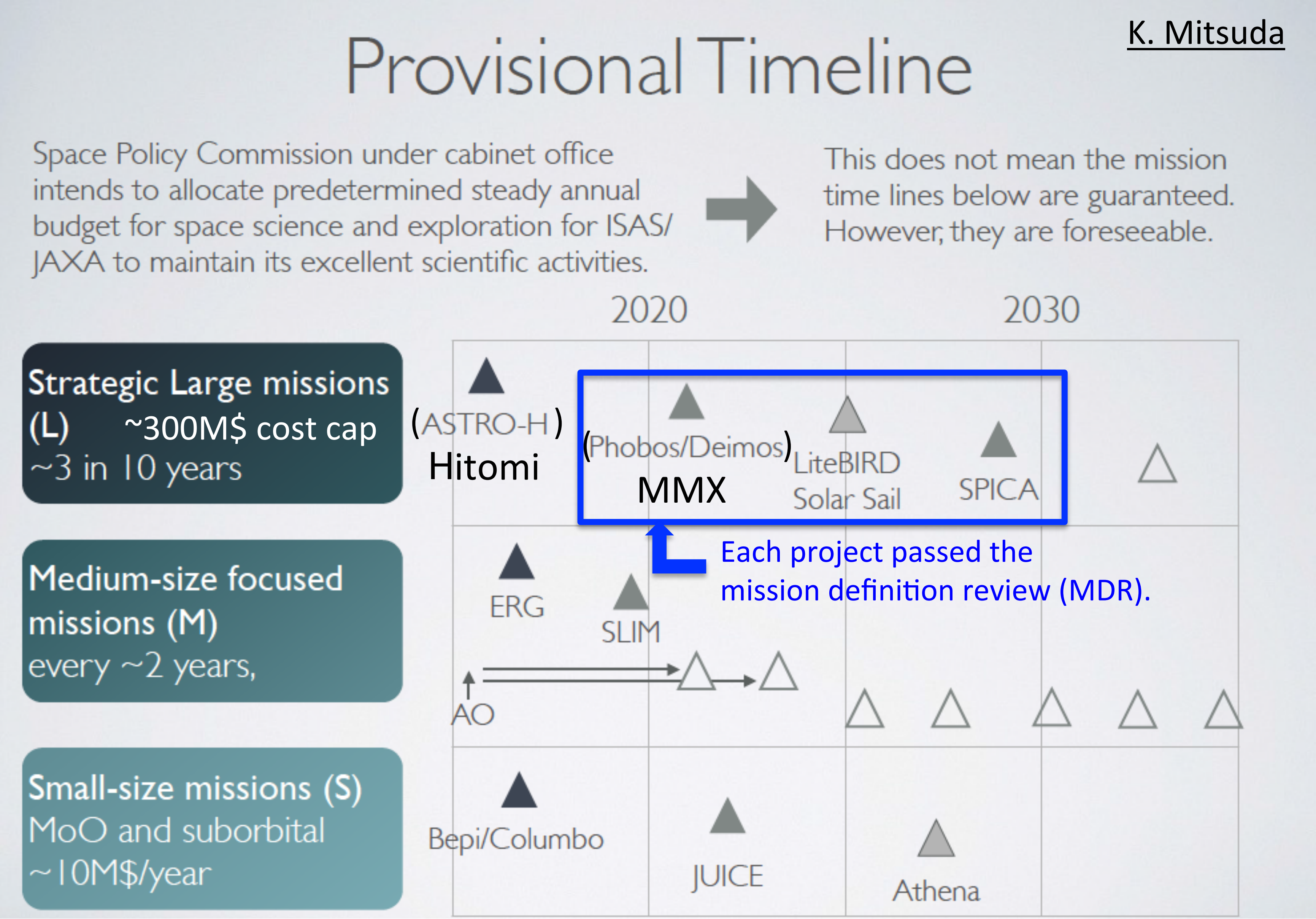
Separation Team

Sky-model Team

Conveners and Scopes

Name	Japan	US	Scope
Foreground Separation Group Conveners	Nobuhiko Katayama (Kavli IPMU)	Julian Borrill (LBNL)	Come up with a reasonable estimate of the foregrounds and algorithms to remove them, develop tools for simulation and analysis, come up with the requirements for the system
Systematic Error Mitigation Group Conveners	Hirokazu Ishino (Okayama U.)	Chao-Lin Kuo (Stanford U.)	Make a list of systematic errors and estimate each of them, evaluate mitigations with HWP (and other methods if needed), come up with the requirements for the system

Space science and exploration at ISAS/JAXA



K. Mitsuda

Provisional Timeline

Space Policy Commission under cabinet office intends to allocate predetermined steady annual budget for space science and exploration for ISAS/JAXA to maintain its excellent scientific activities.

This does not mean the mission time lines below are guaranteed. However, they are foreseeable.

Strategic Large missions (L) ~300M$ cost cap
~3 in 10 years

(ASTRO-H) Hitomi

(Phobos/Deimos) MMX

LiteBIRD
Solar Sail

SPICA

Each project passed the mission definition review (MDR).

Medium-size focused missions (M)
every ~2 years,

ERG

SLIM

AO

Small-size missions (S)
MoO and suborbital
~10M$/year

Bepi/Columbo

JUICE

Athena

(Non-cosmic) Background

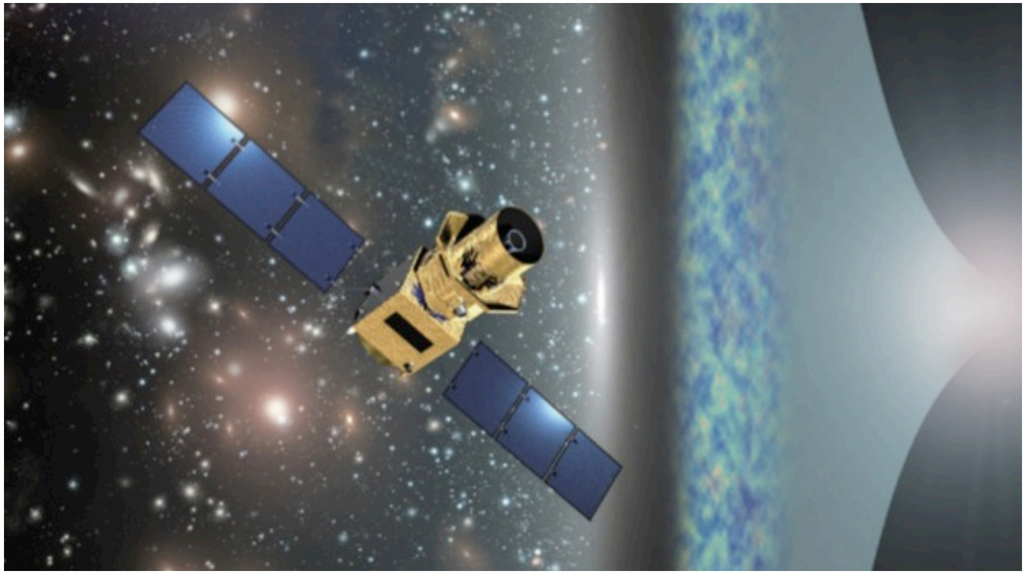
- 2012: New category "missions for fundamental physics authorized by Steering Committee for Space Science (SCSS) of Japan
- 2013: "ISAS/JAXA Framework toward Roadmap for Space Science and Exploration" lists "tests of cosmic inflation with the CMB B-mode" as a top-priority scientific objective.
- 2014 Dec.: US proposal for LiteBIRD NASA Mission of Opportunity
- 2015 Feb.: LiteBIRD ISAS/JAXA mission definition review

Both proposals in Japan and US successfully passed the initial selection !

JAXA

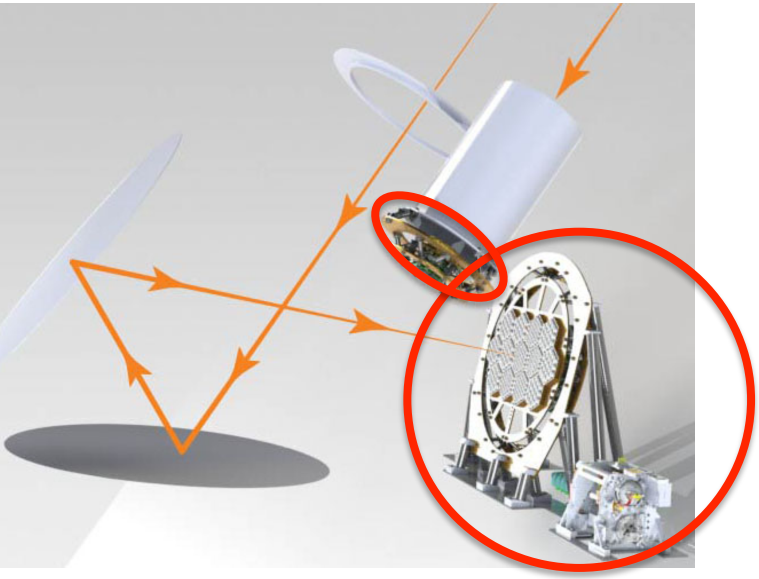
- Main mission
- Cost cap \$300M (same as ASTRO-H/Hitomi)
- Will soon start conceptual design phase (Phase A1)

Seeking for European partnership !



NASA

- Sub-K system as a package, incl. focal plane detectors and Sub-K coolers
- Cost cap \$65M
- in Phase A now



Full success of LiteBIRD

- $\sigma(r) < 1 \times 10^{-3}$ (for $r=0$)
- All sky survey (for $2 \leq \ell \leq 200$)

Remarks

1. $\sigma(r)$ is the total uncertainty on the r measurement that includes the following uncertainties*
    - statistical uncertainties
    - instrumental systematic uncertainties
    - uncertainties due to residual foregrounds
    - uncertainties due to lensing B-mode
    - cosmic variance (for $r > 0$)
    - observer bias
2. The above be achieved without delensing.

* We also use an expression $\delta r = \sigma(r=0)$, which has no cosmic variance.

B-mode power spectrum measurements

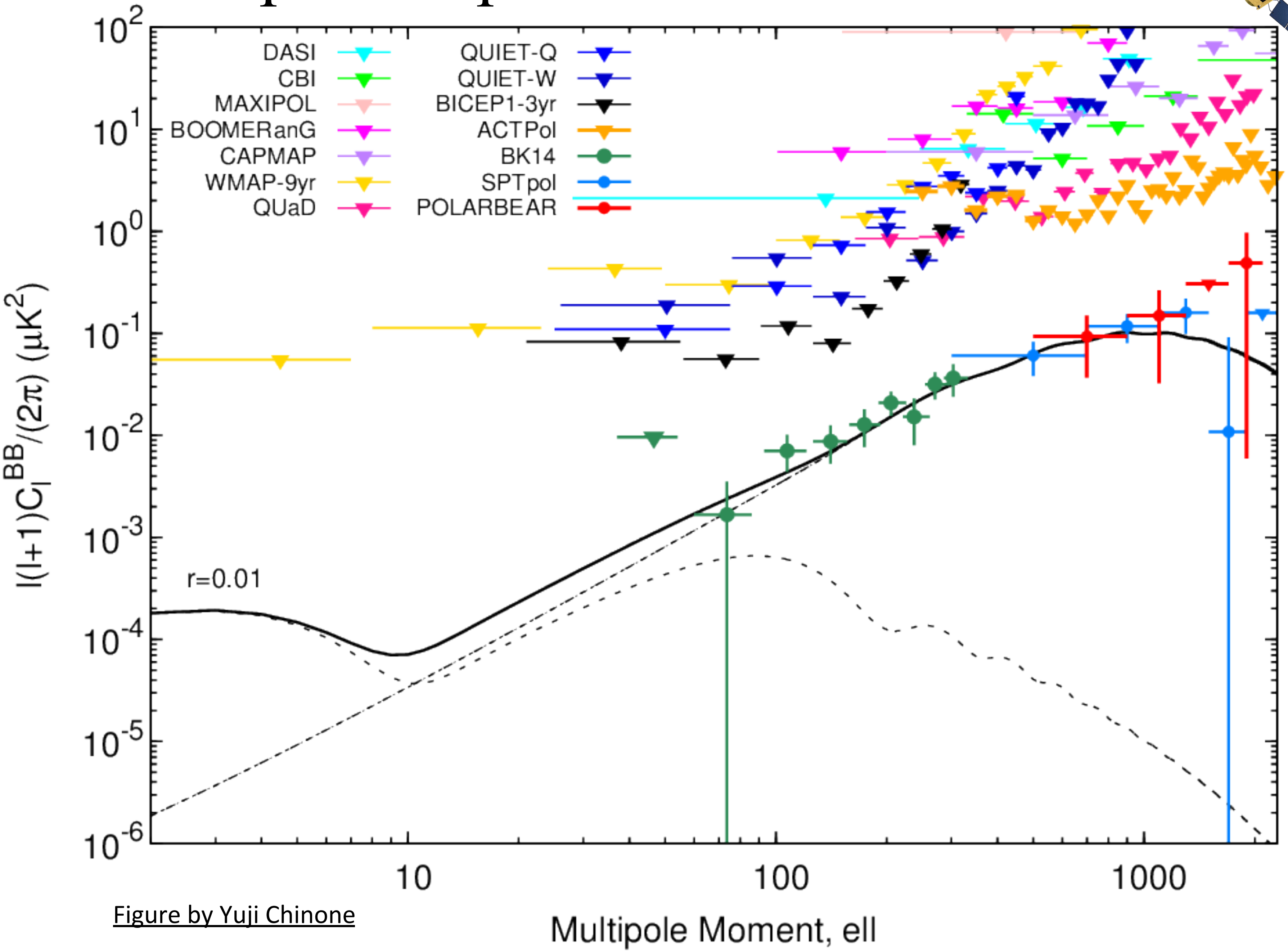


Figure by Yuji Chinone

B-mode power spectrum measurements

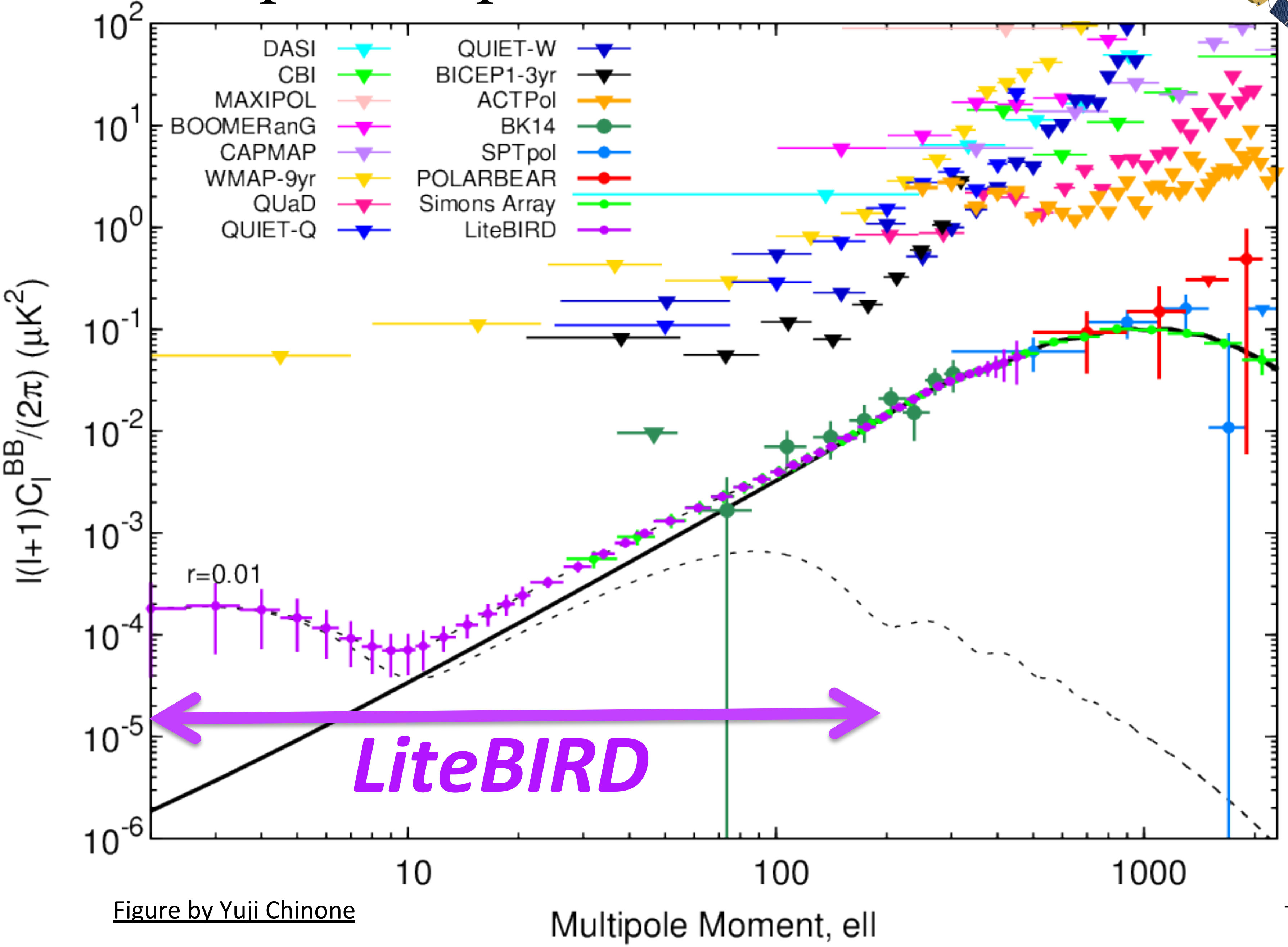


Figure by Yuji Chinone

Special importance of primordial CMB B-mode

- Direct evidence for cosmic inflation

- GUT-scale physics

$$\boxed{V^{1/4} = 1.06 \times 10^{16} \times \left(\frac{r}{0.01}\right)^{1/4} \quad [\mathrm{GeV}]}$$

V: Inflaton potential
r: tensor-to-scalar ratio ← proportional to the B-mode power

- Arguably the first observation of quantum fluctuation of space-time !
  - Observational tests of quantum gravity !

σ(r) < 0.001 is a well-motivated target !

- Many models predict r > 0.01 → >10sigma discovery if σ(r) < 0.001
- Less model-dependent prediction
  - Focus on the simplest models based on Occam's razor principle.
  - Single field models that satisfy slow-roll conditions give

Lyth relation $$\boxed{r \simeq 0.002\left(\frac{60}{N}\right)^2\left(\frac{\Delta\phi}{m_{pl}}\right)^2}$$

N: e-folding
m_{pl}: reduced Planck mass

  - Thus, large-field variation ($\Delta\phi > m_{pl}$), which is well-motivated phenomenologically, leads to r > 0.002.
    - Model-dependent exercises come to the same conclusion (w/ very small exceptions).
  - Detection of r > 0.002 establishes large-field variation (Lyth bound).
    - Significant impact on superstring theory that faces difficulty in dealing with $\Delta\phi > m_{pl}$
  - Ruling out large-field variation is also a significant contribution to cosmology and fundamental physics.

→ σ(r) < 0.001 is needed to rule out large field models that satisfy the Lyth relation with >95%C.L.

If evidence is found before launch

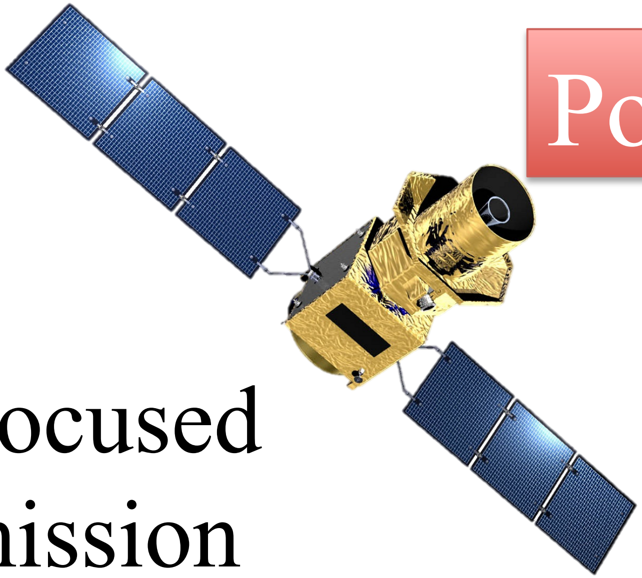
- r is fairly large → Comprehensive studies by LiteBIRD !
- Much more precise measurement of r from LiteBIRD will play a vital role in identifying the correct inflationary model.
- LiteBIRD will measure the B-mode power spectrum w/ high significance for each bump if $r>0.01$.
  - Deeper level of fundamental physics

$\sigma(r) < 0.001$ for $2 \leq \ell \leq 200$ is what we need to achieve in any case to set the future course of cosmology

No-Lose Theorem of LiteBIRD

Basic Strategy

Powerful Duo



Focused mission

σ(r)<0.001

$2 \leq \ell \leq 200$

w/ many byproducts

X

Telescope arrays on ground

$30 \leq \ell \leq 3000 \sim 10000$

e.g. CMB-S4

Improving σ(r) by delensing with other observations is defined as “extra success” in LiteBIRD Mission Definition.

Extra success

Improve σ(r) with external observations

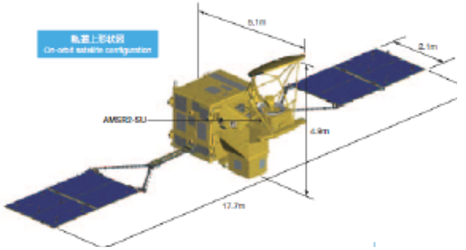
Topic	Method	Example
Delensing	Large CMB telescope array	CMB-S4 data Namikawa and Nagata, JCAP 1409 (2014) 009
	Cosmic infrared background	Herschel data Sherwin and Schmittfull, Phys. Rev. D 92, 043005 (2015)
	Radio continuum survey	SKA data Namikawa, Yamauchi, Sherwin, Nagata, Phys. Rev. D 93, 043527 (2016)
Foreground removal	Lower frequency survey	C-BASS upgrade

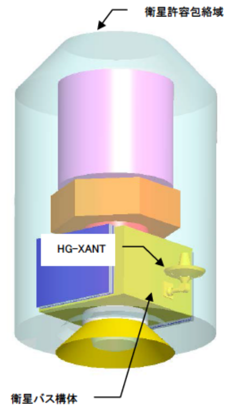
- Delensing improvement to σ(r) can be factor ~2 or more.
- Need to make sure systematic uncertainties are under control.

LiteBIRD Phase-A baseline design

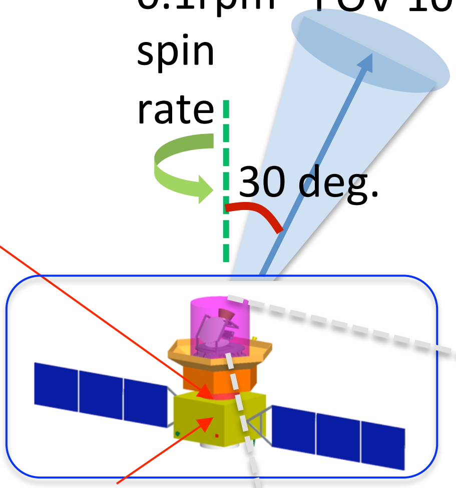
- Mission module benefits from heritages of other missions (e.g. ASTRO-H) and ground-based experiments (e.g. POLARBEAR).
- Bus module based on high TRL components

Slip-ring technology used for Shizuku



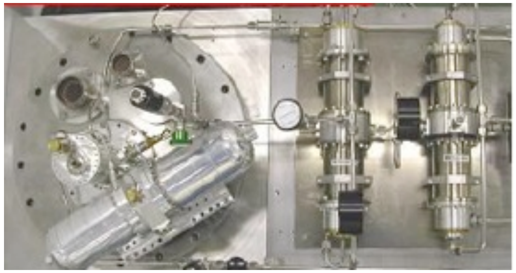


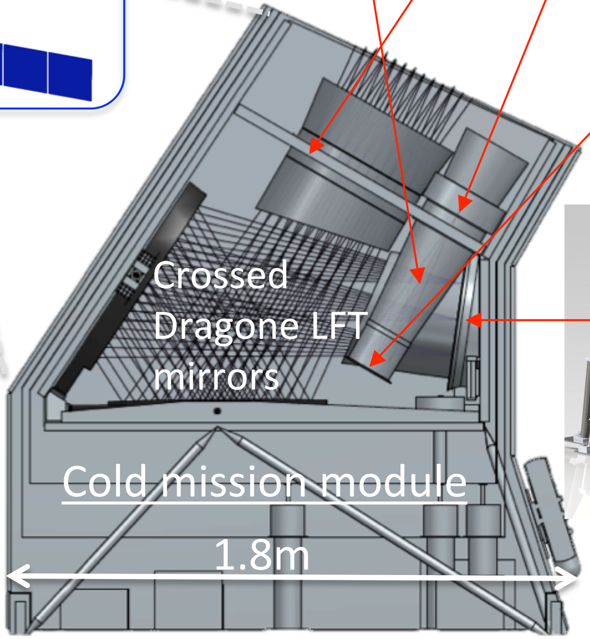
Fit in H2 envelope



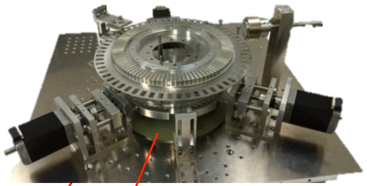
Bus module

Cryogenics
- JT/ST and ADR (ASTRO-H heritage)

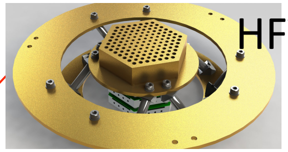


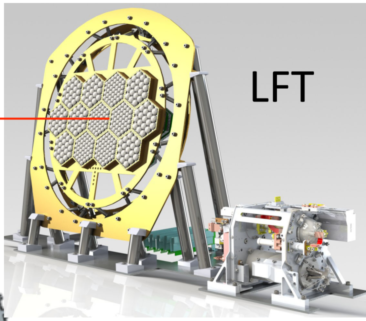


Continuously-rotating half wave plate (HWP)



Multi-chroic TES focal plane detectors





Launch Vehicle

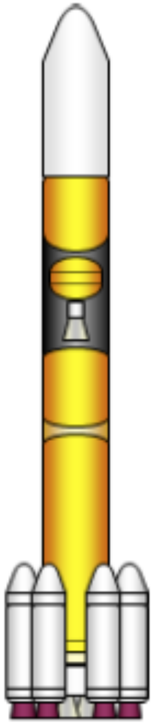
To be replaced with H-III in 2020

H-II A

- First Flight in 2001
- **23** successful launches/24
- Latest one: GPM
- GTO 4-6 ton class capability

H-II B

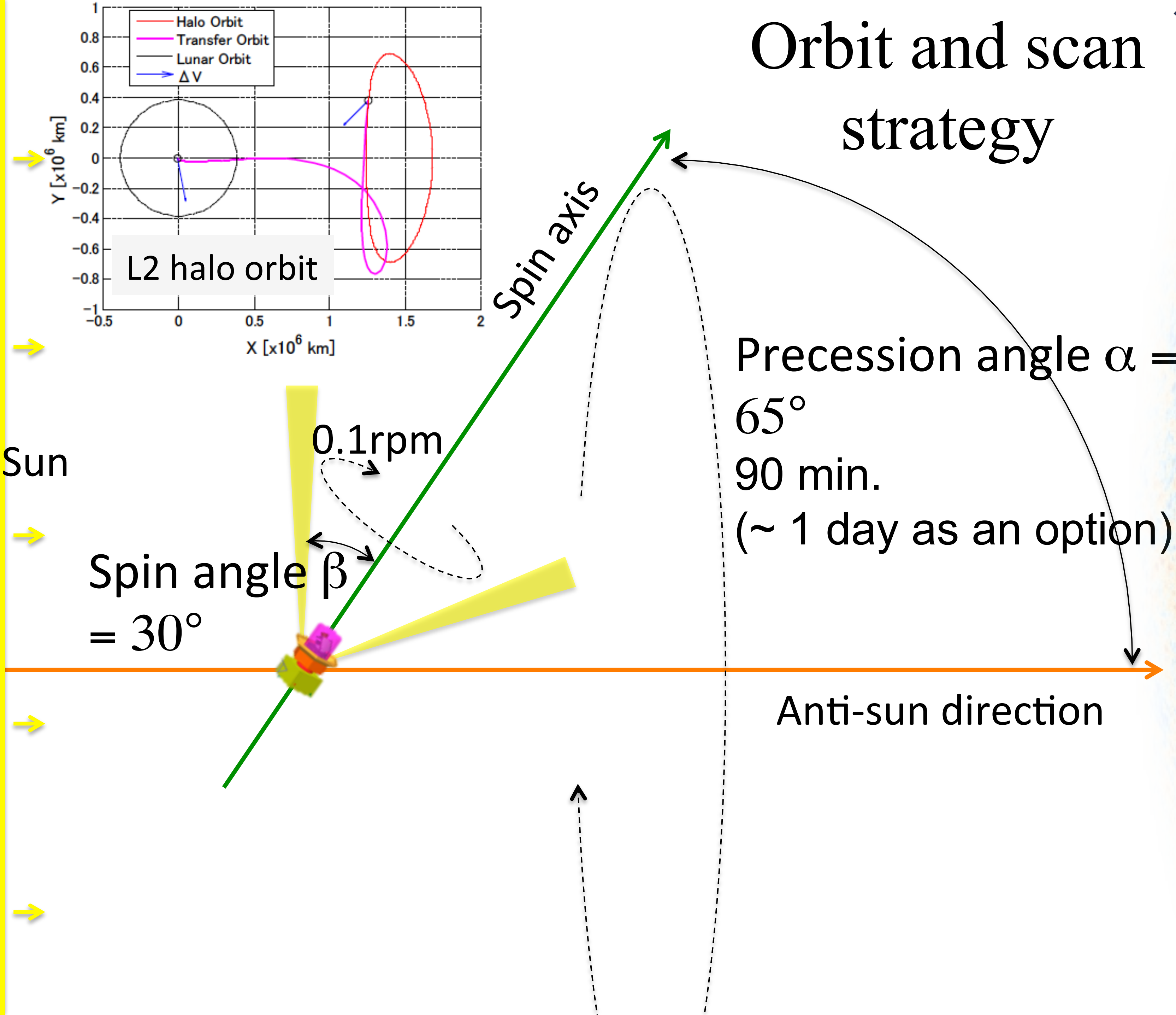
- First Flight in 2009
- **4** successful flights/4 of 16.5 ton HTV to ISS
- GTO 8 ton class capability



H3

- First test launch in 2020
- ½ cost w/ same capability (comparison w/ H-II B)

Orbit and scan strategy



L2 halo orbit

Sun

Spin axis

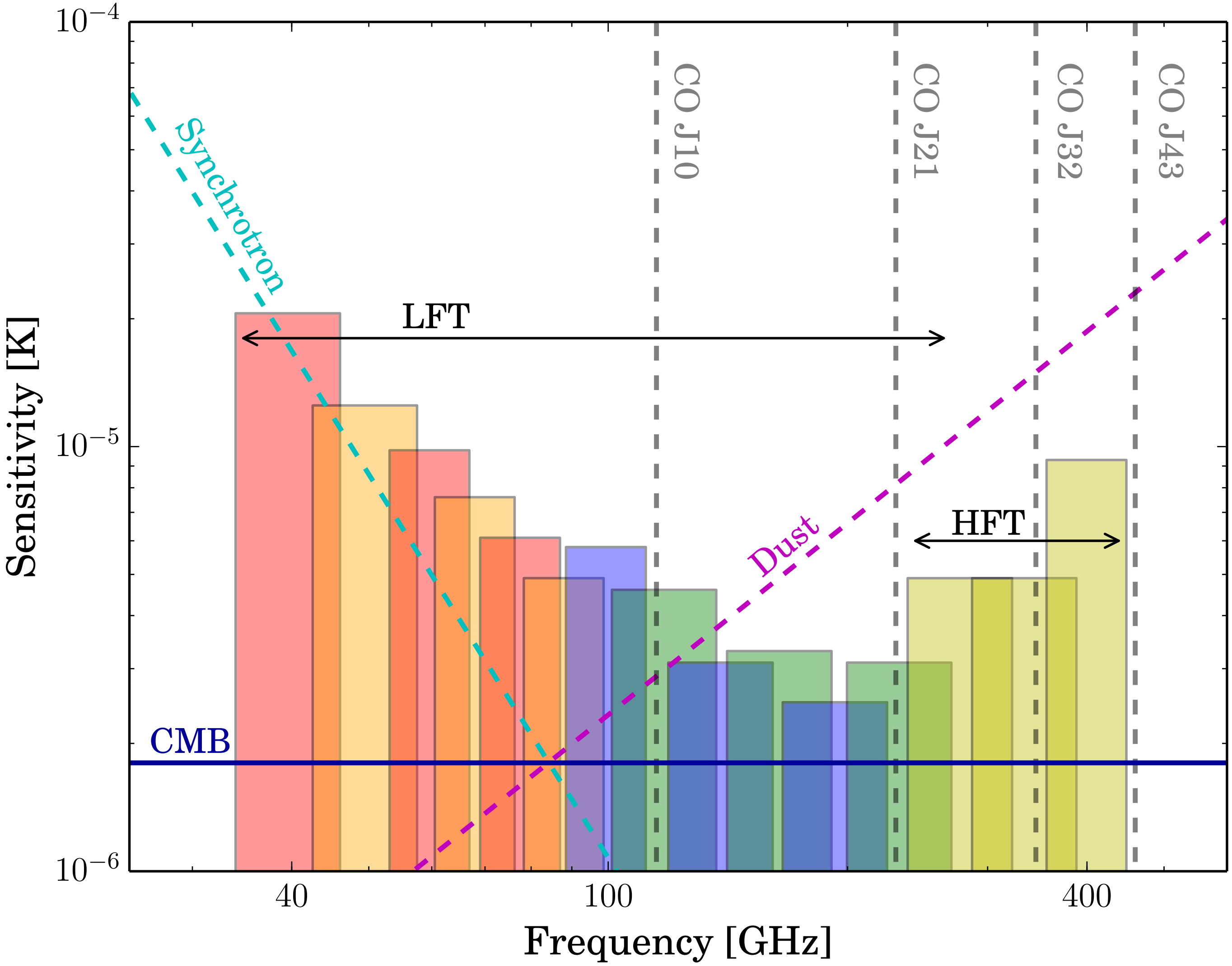
0.1rpm

Spin angle β = 30°

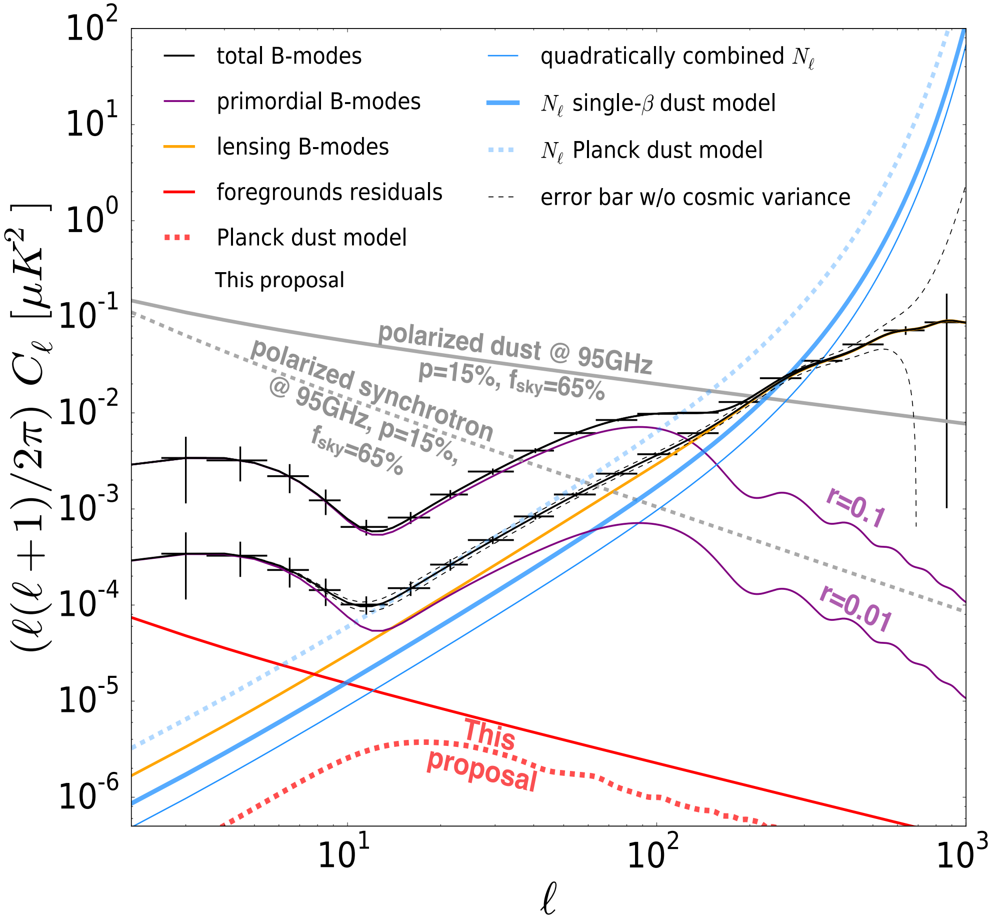
Precession angle α = 65°
90 min.
(~ 1 day as an option)

Anti-sun direction

15 Frequency Bands



LiteBIRD forecast (as of MDR, Apr. 2015)



* Foreground residual estimation with Errard et al. 2011, Phys. Rev. D 84, 063005, and JCAP03 (2016) 052

** "Delensing the CMB with the Cosmic Infrared Background", B. D. Sherwin, M. Schmittfull, Phys. Rev. D 92, 043005 (2015)

$\sigma(r) = 0.45 \times 10^{-3}$ J. Errard

for r = 0.01, including foreground removal*, cosmic variance and delensing w/ CIB**

$r < 0.4 \times 10^{-3}$ (95% C.L.)

for undetectably small r

Note: $\sigma(r{=}0) = \delta r = 2 \times 10^{-4}$

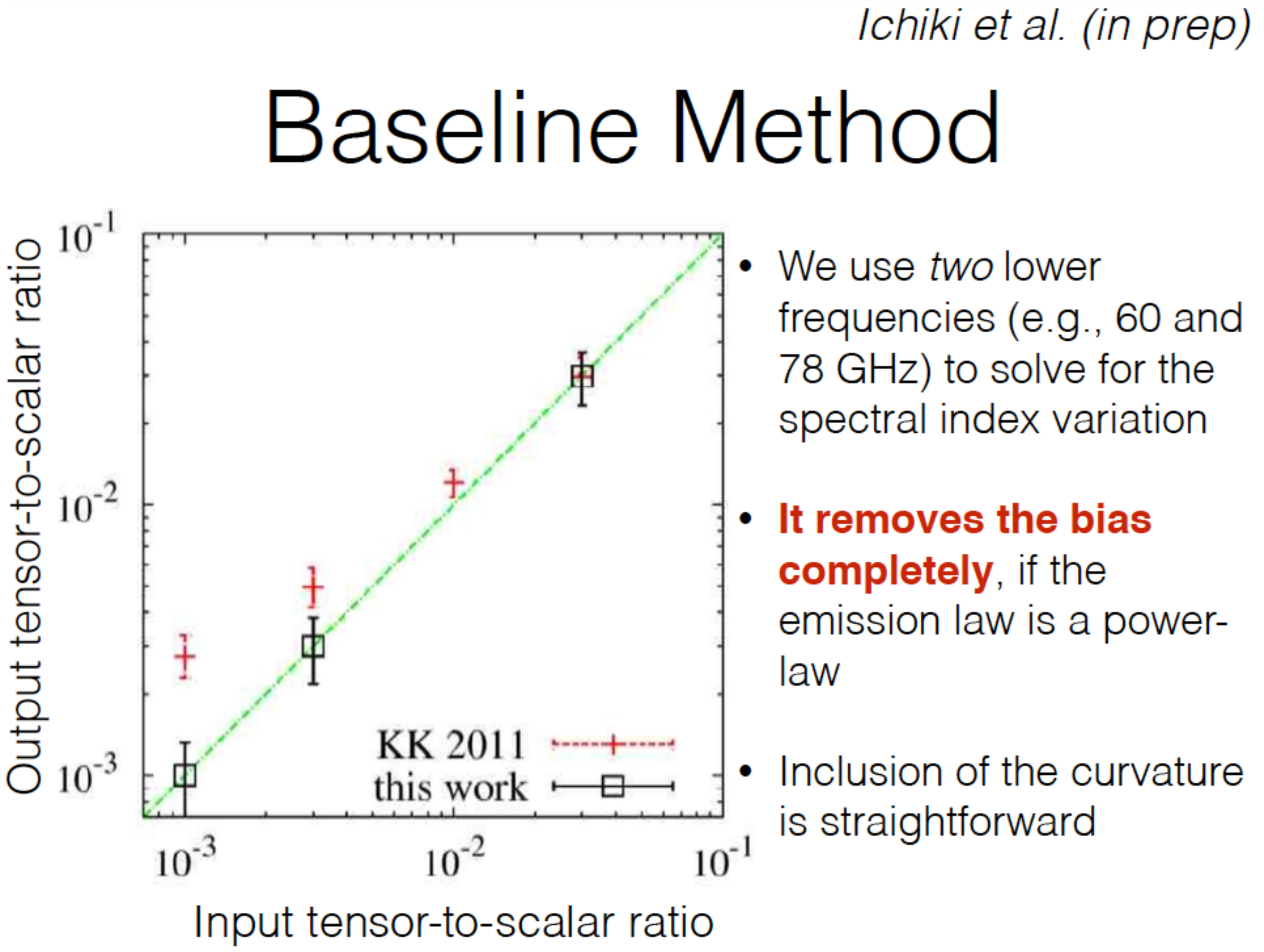
$\sigma_{sys}(\text{total}) = 1.1 \times 10^{-4}$ R. Nagata

Source	Expctd. error	Reasoning
Boresight Pointing	0.23 arcmin	Star tracker spec.
Angle calibration	1 arcmin	C_l^{EB} method
Gain	0.6%	CMB dipole
Beam width	<1%	Optical simulation, HWP experience (normized w/ beam size)
Ellipticity	<1%	
Pixel pointing	<1%	

HWP angle dependence (in the new studies these are treated based on Muller matrix-like parameters)

Studies on foregrounds/systematics w/ nastier assumptions in progress !

Foreground Removal (Slide by Eiichiro Komatsu)



Ichiki et al. (in prep)

Baseline Method

- We use *two* lower frequencies (e.g., 60 and 78 GHz) to solve for the spectral index variation
- **It removes the bias completely**, if the emission law is a power-law
- Inclusion of the curvature is straightforward

Scientific shopping list (1)

1) C_l^{BB} Error on n_t ~0.04
   - ✓ inflation and quantum gravity (r, n_t)
   - ✓ improvement w/ delensing
   - – lensing B-mode to very low ℓ
2) C_l^{EE}
   - – reionization history
   - ✓ better τ and sum of neutrino masses

Scientific shopping list (2)

3) Power spectrum deviation from ΛCDM
   - parity violation in gravity
   - quantum loop gravity
   - primordial magnetic field
   - ✓ new source fields for gravitational waves

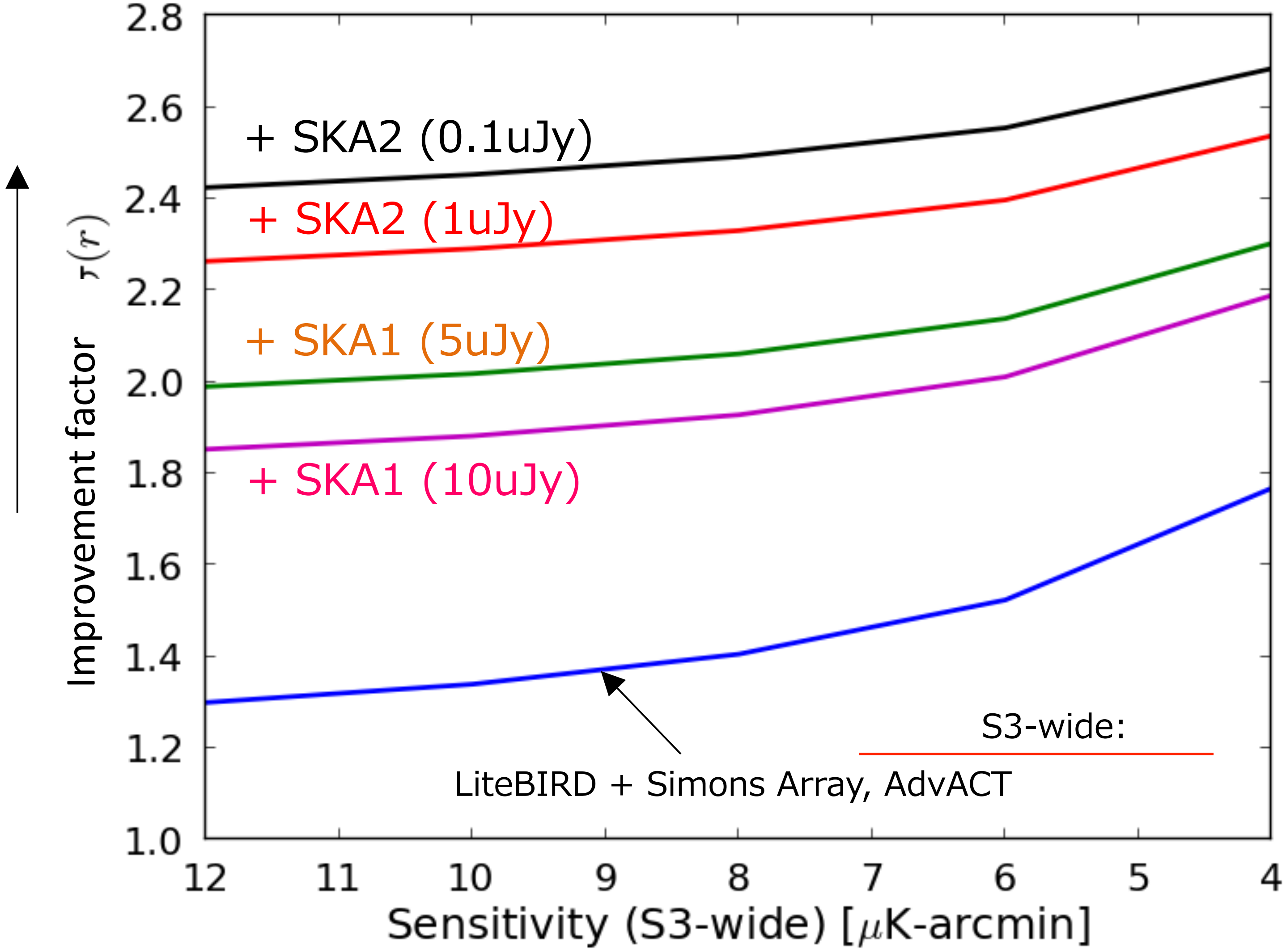
4) Bi-spectrum (BBB etc.)
   - ✓ tensor non-Gaussianity
   - ✓ origin of gravitational waves

Scientific shopping list (3)

5) Non-standard patterns (e.g. bubbles) in the maps
    → e.g. multiverse
6) Foreground science
7) Galactic magnetic field (in particular at large galactic attitude)
8) Legacy all-sky multi-frequency maps of E-mode/ B-mode/Foregrounds
    → various astronomical studies

1) Delensing:
Synergy w/ SKA radio galaxy survey

Namikawa, Yamauchi, Sherwin, Nagata, Phys. Rev. **D93** (2016) 043527



Namikawa, Yamauchi, Sherwin, Nagata, Phys. Rev. **D93** (2016) 043527

Gravitational lensing potential reconstruction w/ radio galaxies as mass tracer

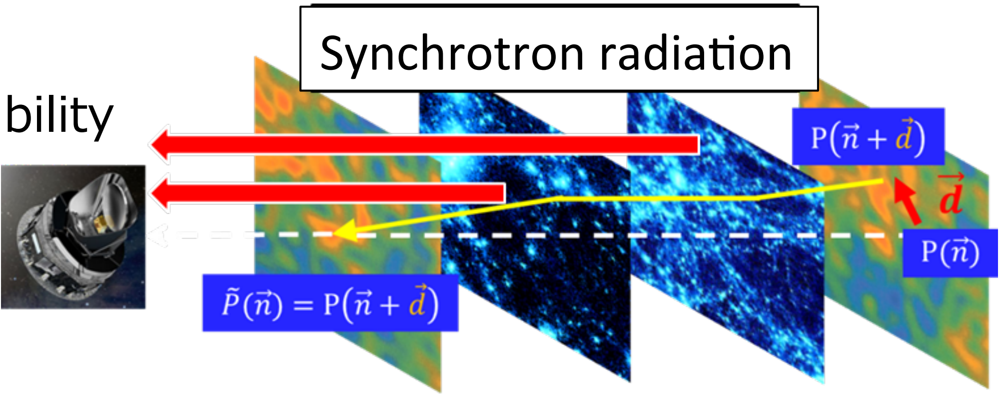
SKA radio continuum survey

- Number density of galaxies from difuse (continuum) radio survey using synchrotron radiation from galaxies
- Mapping over 30000 deg^2 up to high z (z≦3~6) w/o effects of foregrounds (dust etc.). 10^8~9 galaxies expected to be detected

CMB gravitational lensing

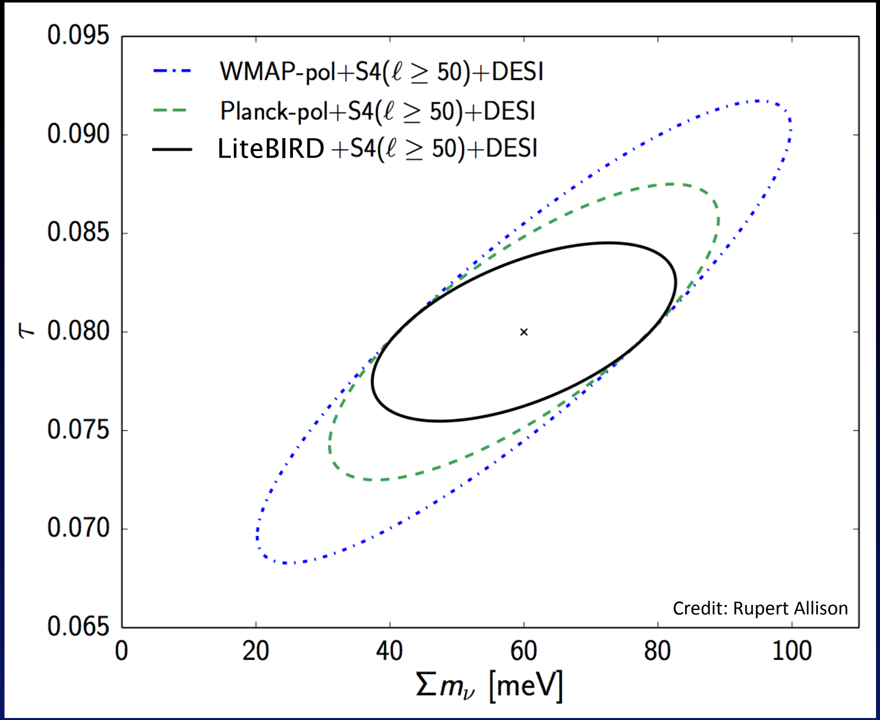
Galaxy distribution for each z ⇒ matter density fluctuation at each z
⇒ Gravitational potential responsible for lensing at each z

- Most of lensing CMB B-mode reconstructable thanks to the capability of accessing high z
- Efficient delensing leads to better sensitivity on primordial B-mode

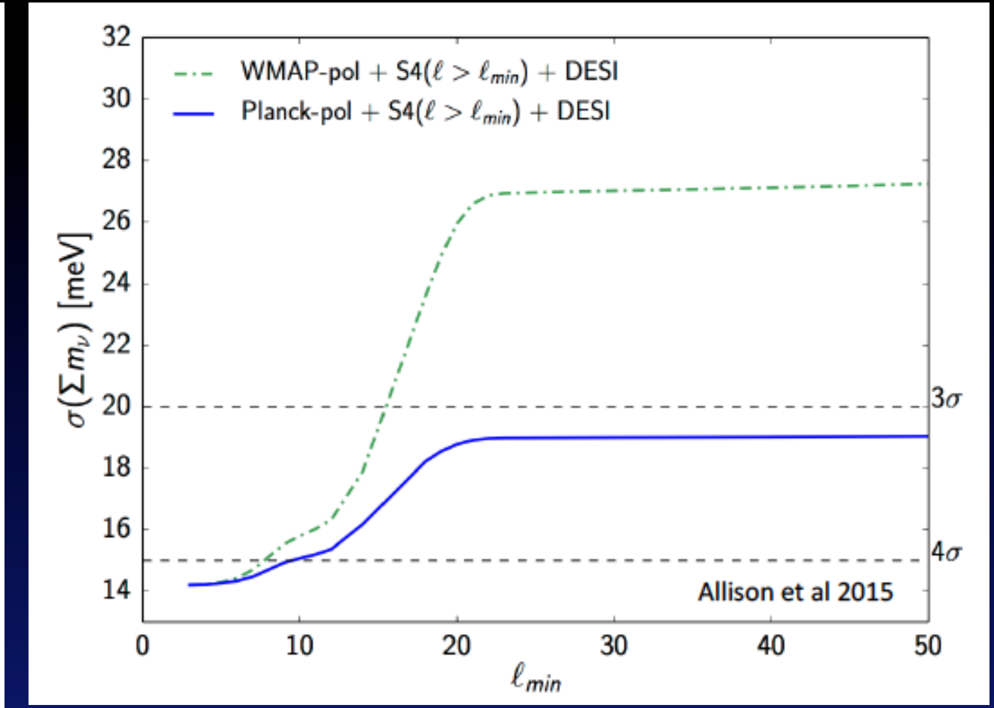


2) τ(optical depth) and neutrino mass

- Better E-mode measurement for < 20 improves τ
- Better τ improves Σm_ν
- $\Sigma m_\nu > 58$meV from oscillation measurements



Credit: Rupert Allison



Allison et al 2015

Low ℓ measurements contribute to Σm_ν !

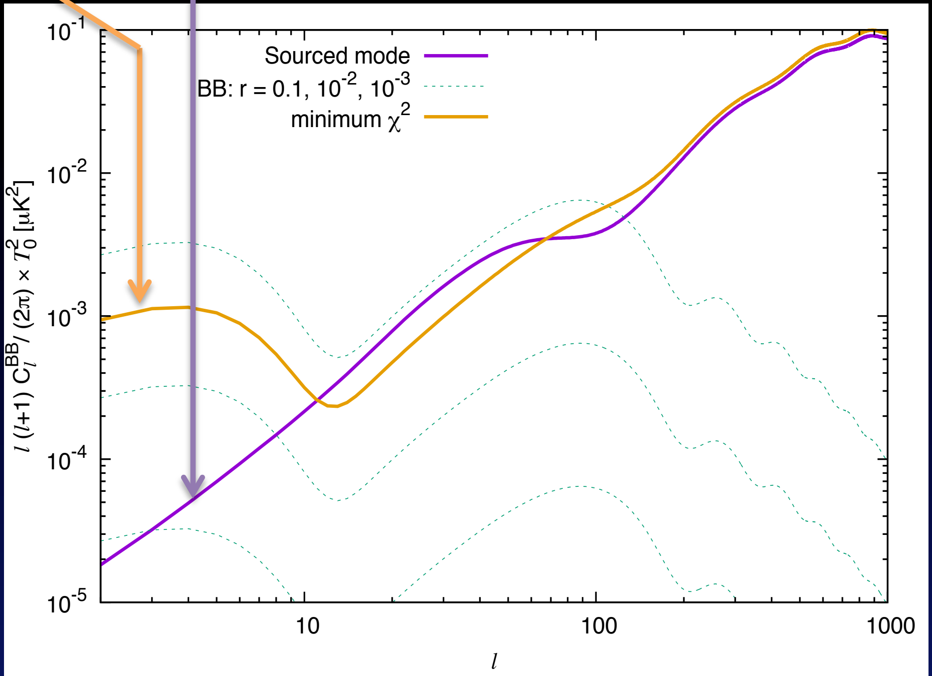
3)/4) Origin of gravitational waves

M. Shiraishi, C. Hikage, T. Namikawa, R. Namba, MH, arXiv:**1606.06082**

Vacuum fluctuation vs. **Source fields**

Observation of l < 10 is required to distinguish between two.

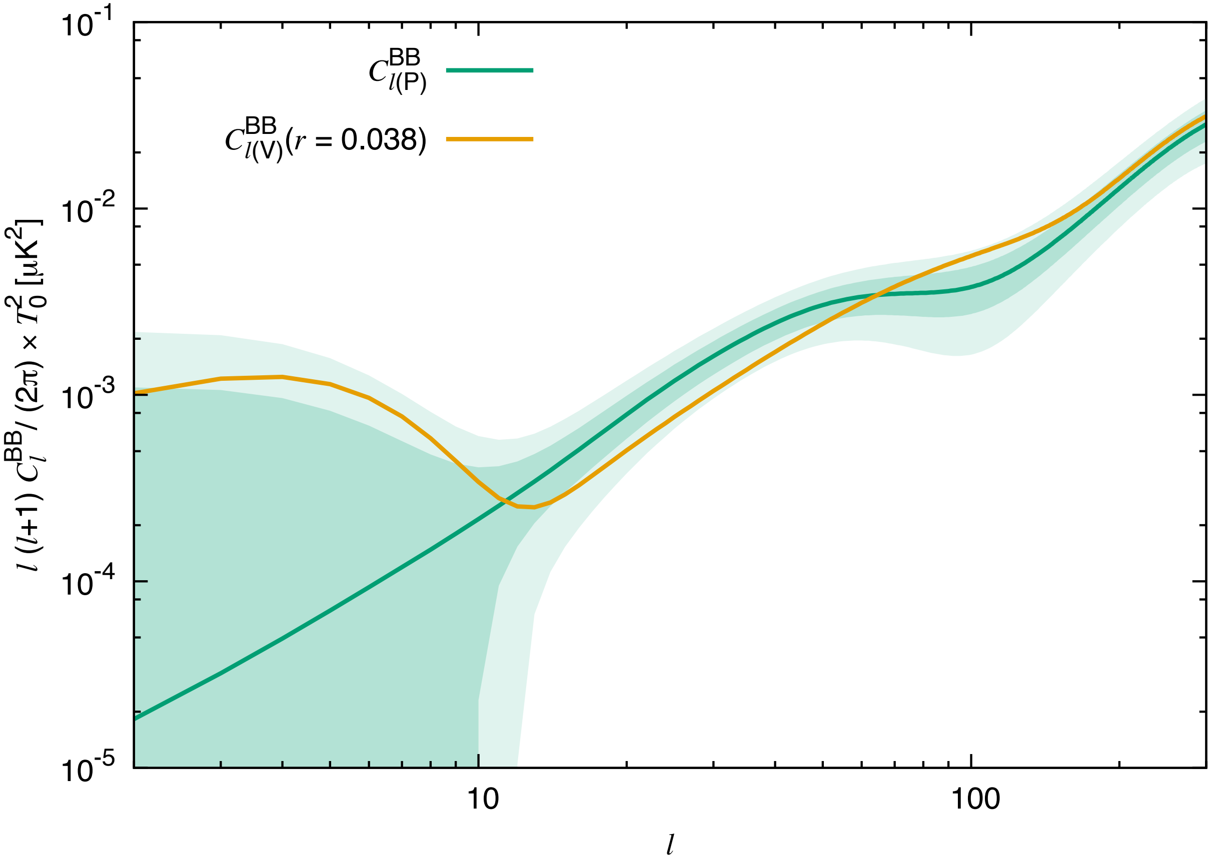
At LiteBIRD, this can be done. easily.
Moreover, B-mode bi-spectrum ("BBB") is also used to detect source-field-originating non-Gaussianity at $>3\sigma$



"Pseudoscalar model" from Namba, Peloso, Shiraishi, Sorbo, Unal, arXiv1509.07521 as an "evil example model"; indistinguishable w/ BB for ell > 10 alone.

Separation power w/ "BB"

$$\chi^2_{BB}(r) = \sum_{\ell=\ell_{\min}}^{\ell_{\max}} \frac{2\ell+1}{2} \left(\frac{C^{BB}_{\ell(\mathrm{V})}(r) - C^{BB}_{\ell(\mathrm{P})}}{C^{BB}_{\ell(\mathrm{V})}(r) + N^{BB}_{\ell}} \right)^2$$



reduced chi^2

$\chi^2_{BB}/(l_{max}-l_{min})$

= 1.1

Simple-minded chi^2 does not work.

Separation w/ B-mode bispectrum “BBB”

Parity-violating B-mode non-Gaussianity arises in the pseudoscalar model we consider here.
→ sizable BBB signal

If the pseudoscalar model is the correct model, can the vaccum fluctuation hypothesis be ruled out ?

$$\chi^2_{BBB}(r) = \sum_{\substack{\ell_1,\ell_2,\ell_3=\ell_{\rm min} \\ \ell_1+\ell_2+\ell_3 = {\rm even}}}^{\ell_{\rm max}} \frac{\left| B^{BBB}_{\ell_1\ell_2\ell_3({\rm P})} \right|^2}{6\prod_{n=1}^{3}\left(C^{BB}_{\ell_n({\rm V})}(r) + N^{BB}_{\ell_n} \right)}$$

<u>= 13 @ LiteBIRD → 3.6σ rejection !</u>

Checking “BBB” is MUST-DO when the primordial B-mode is discovered.

Remarks

- l_{max} = 100 saturates the BBB sensitivity
- lmin = 30 → rejection significance is 1.9σ, which is not sufficient.

→ LiteBIRD is an ideal tool to investigate B-mode bispectrum, in particular BBB.

- The pseudoscalar model we consider here also produce TB, EB signals. Sensitivity is however reduced due to cosmic variance. Angle calibration w/ EB also complicates the analysis.

LiteBIRD Summary

- The only CMB polarization proposal in phase-A status now
- Aiming at timely launch in 2024-2025
- Focusing on well-motivated target of $\sigma(r) < 0.001$
- $2 \leq \ell \leq 200$ to cover both bumps
- Powerful duo w/ ground-based projects (e.g CMB-S4)
- Many important byproducts
- Phase-A baseline design w/ strong heritages

Exciting science !

Dreams of an experimentalist for future

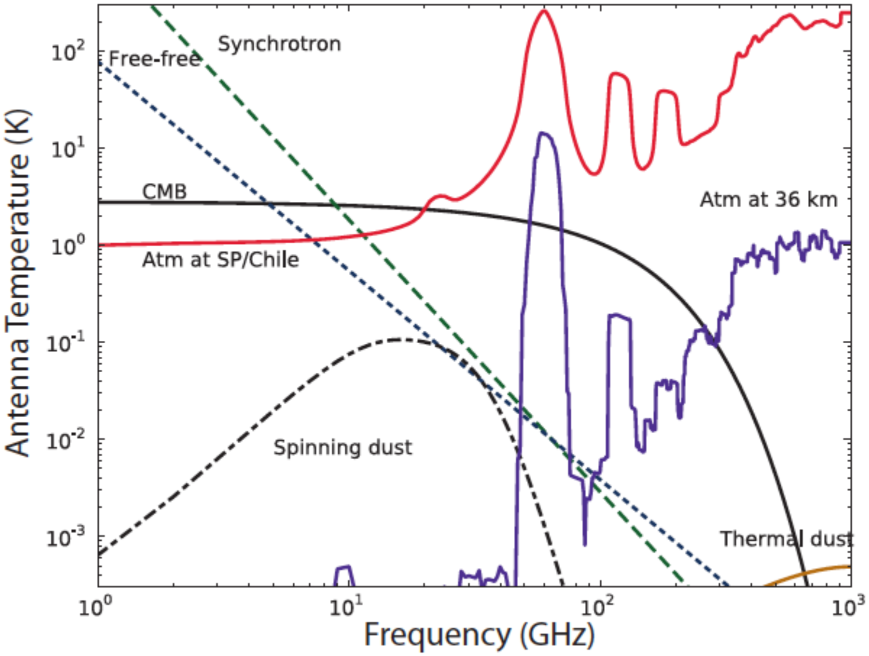
1. Testing Bunch-Davies vacuum
2. Testing multiverse
3. Probing universe before inflation
4. Testing quantum gravity both from cosmological observations and lab. experiments

Appendix

Advantages in space

- Frequency bands are much less limited in space
  → better foreground rejection capability
  - Lines due to O_2 and H_2O need to be avoided on ground
  - Balloons also suffer from O_2 lines around 60 GHz
  - High frequencies (e.g. 353GHz that Planck relies on for foreground removal) are hard to access on ground
- No atmospheric noise
- Can observe the full sky and lowest multipoles
  - Both bumps (reionization, recombination) can be detected
  - Lensing B-mode small even for $r < 0.01$

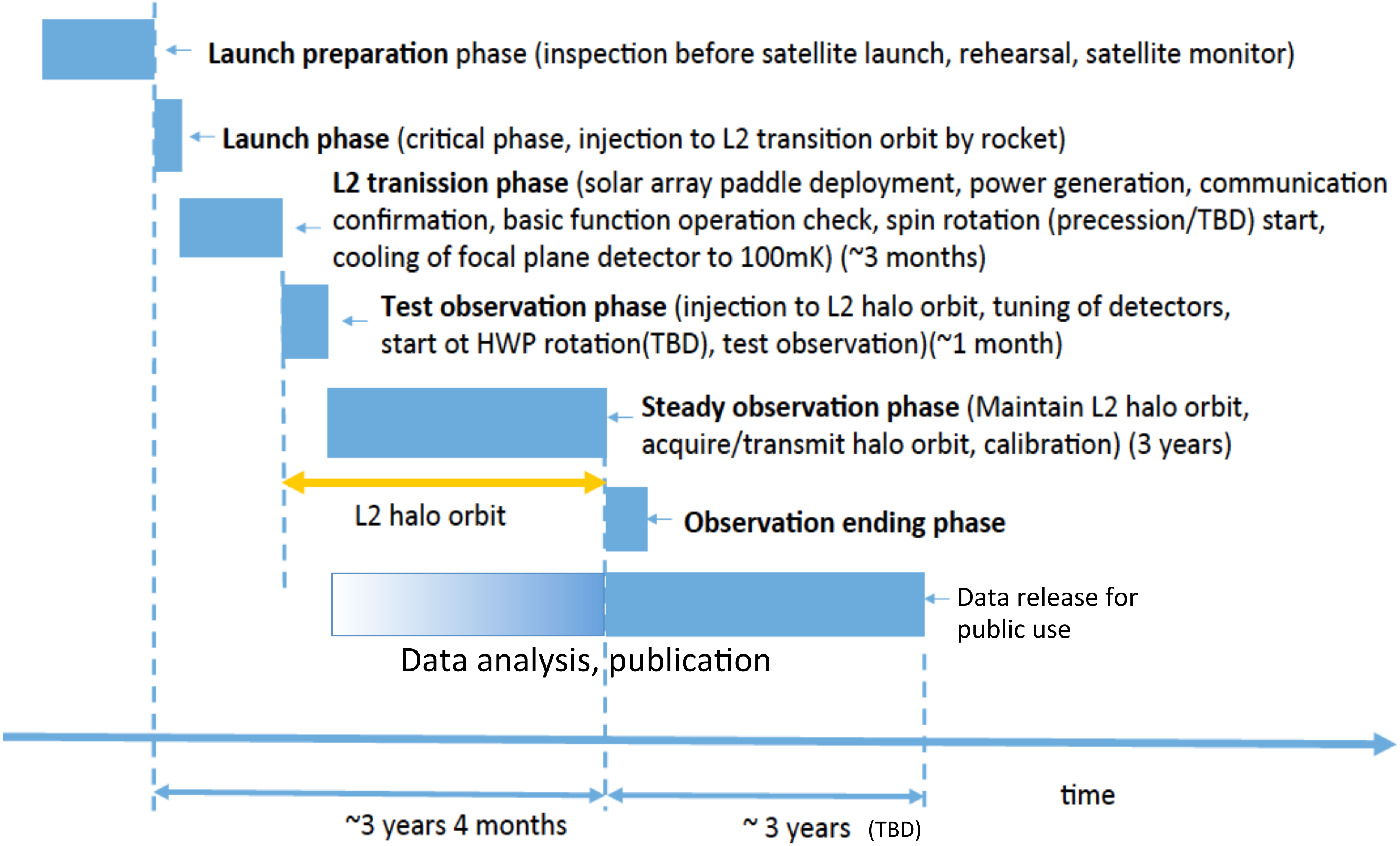
Hanany, Niemack, Page, arXiv:1206.2402



Main specifications (Phase-A baseline design)

Item	**Specification**
Orbit	L2 halo orbit
Launch year (vehicle)	2024-2025 (H3 or H2A)
Observation (time)	All-sky CMB survey (3 years)
Mass	2.2 t
Power	2.5 kW
Mission instruments	• Superconducting detector arrays • Continuously-rotating half-wave plate (HWP) • Crossed-Dragone mirrors (+ small refractive telescope) • 0.1K cooling system (ST/JT/ADR)
Frequencies (# of bands)	40 – 400 GHz (15 bands)
Data size	4 GB/day
Sensitivity	3 μKarcmin (3 years) with margin
Angular resolution	0.5deg @ 100 GHz (FWHM)

Operation concept



Launch preparation phase (inspection before satellite launch, rehearsal, satellite monitor)

Launch phase (critical phase, injection to L2 transition orbit by rocket)

L2 tranission phase (solar array paddle deployment, power generation, communication confirmation, basic function operation check, spin rotation (precession/TBD) start, cooling of focal plane detector to 100mK) (~3 months)

Test observation phase (injection to L2 halo orbit, tuning of detectors, start ot HWP rotation(TBD), test observation)(~1 month)

Steady observation phase (Maintain L2 halo orbit, acquire/transmit halo orbit, calibration) (3 years)

L2 halo orbit

Observation ending phase

Data release for public use

Data analysis, publication

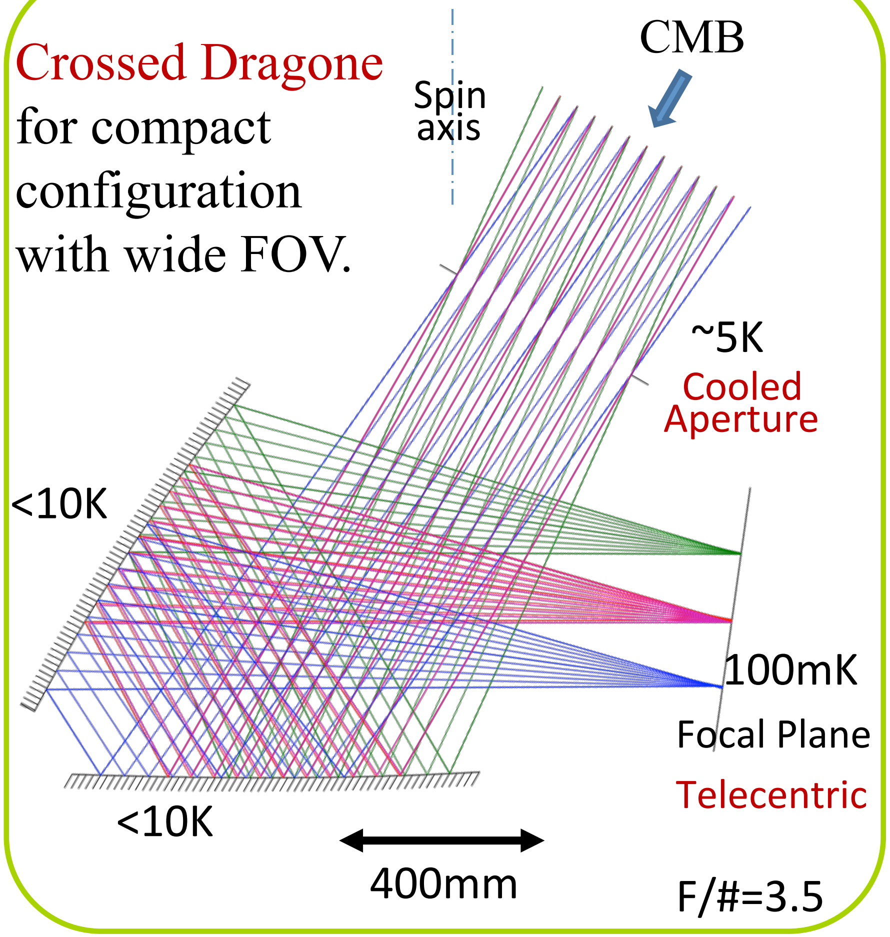
time

~3 years 4 months

~ 3 years (TBD)

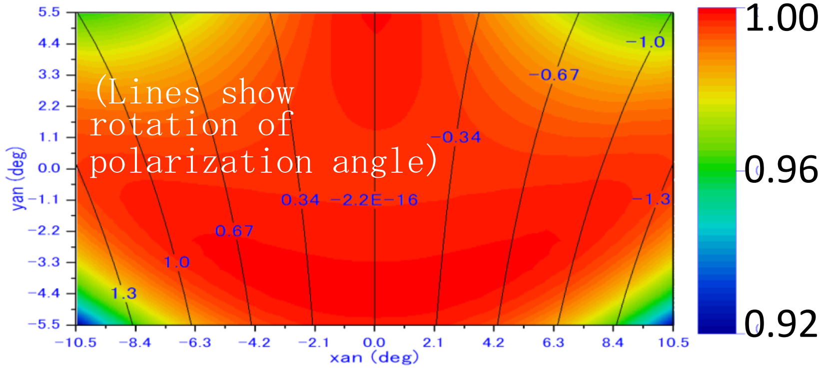
More information in Appendix

Design of low frequency telescope (LFT)

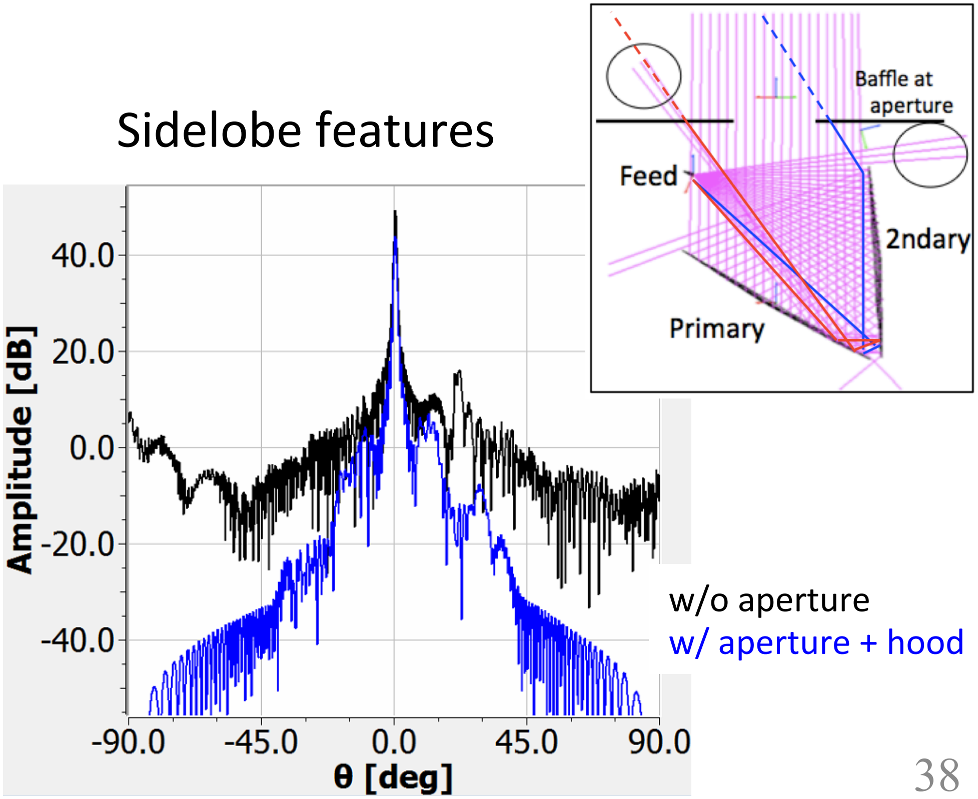


Crossed Dragone for compact configuration with wide FOV.

Strehl ratio @150GHz over wide (10x20deg^2) FOV on LFT

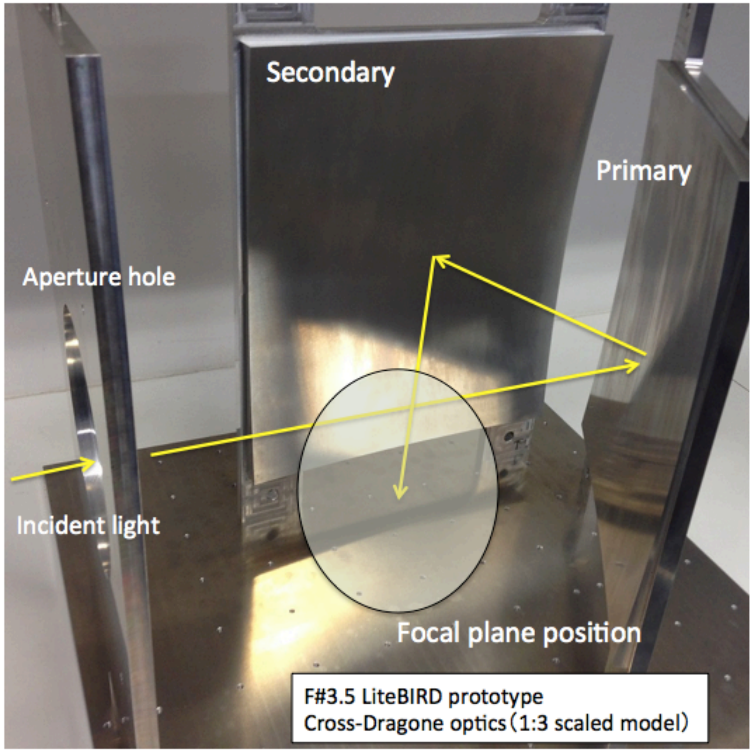


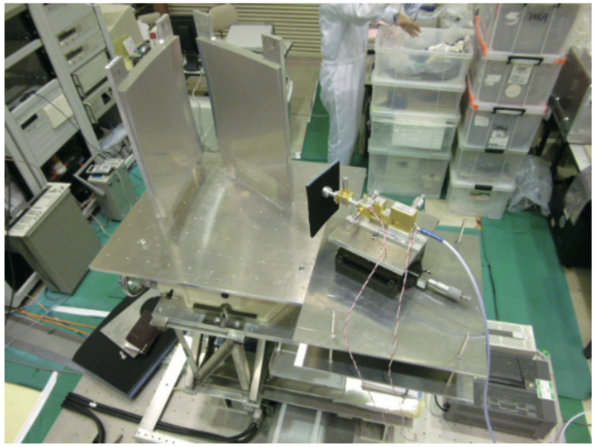
Sidelobe features



Very good overall performance !

Experimental evaluation



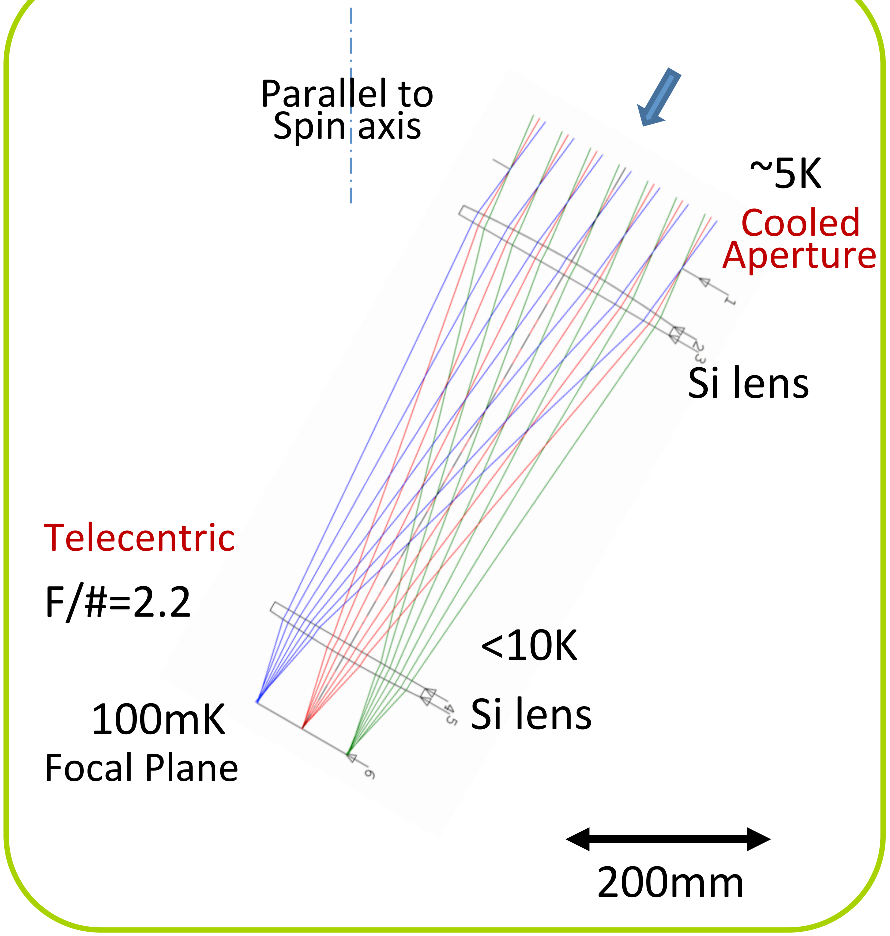


Experimental setup at JAXA

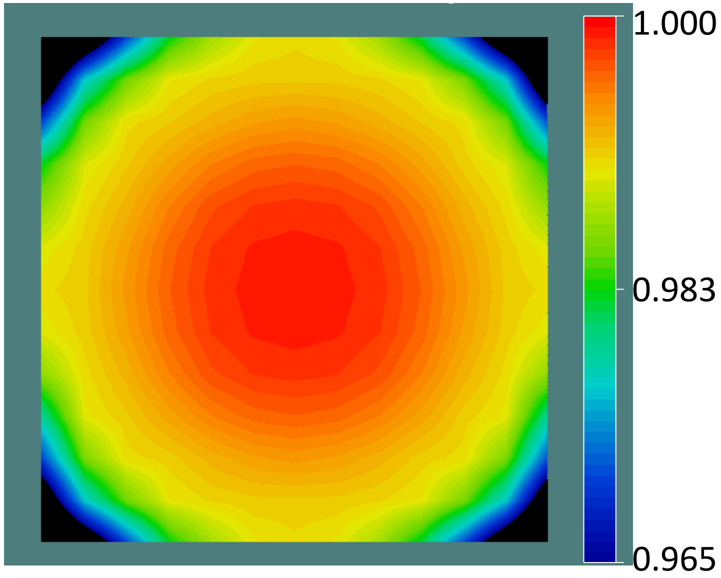
- To verify the calculated sidelobe feature, we fabricated a scaled model (1:3) with F/#=3.5 Crossed-Dragone telescope.
- We measured the main and far sidelobe pattern at 200 GHz and compared with the GRASP10.
- We will also study the mitigation of the main beam and sidelobe pattern using various baffle configurations
- The measurements are ongoing and the results are soon to be reported.

Design of high frequency telescope (HFT)

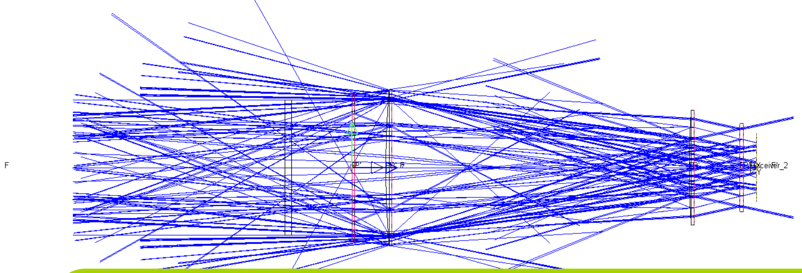
LiteBIRD



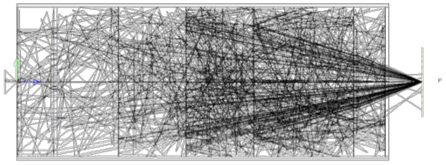
Strehl ratio @340GHz
over **13x13deg^2**



Ghost analysis by using LightTools



Stray Light analysis by using LightTools

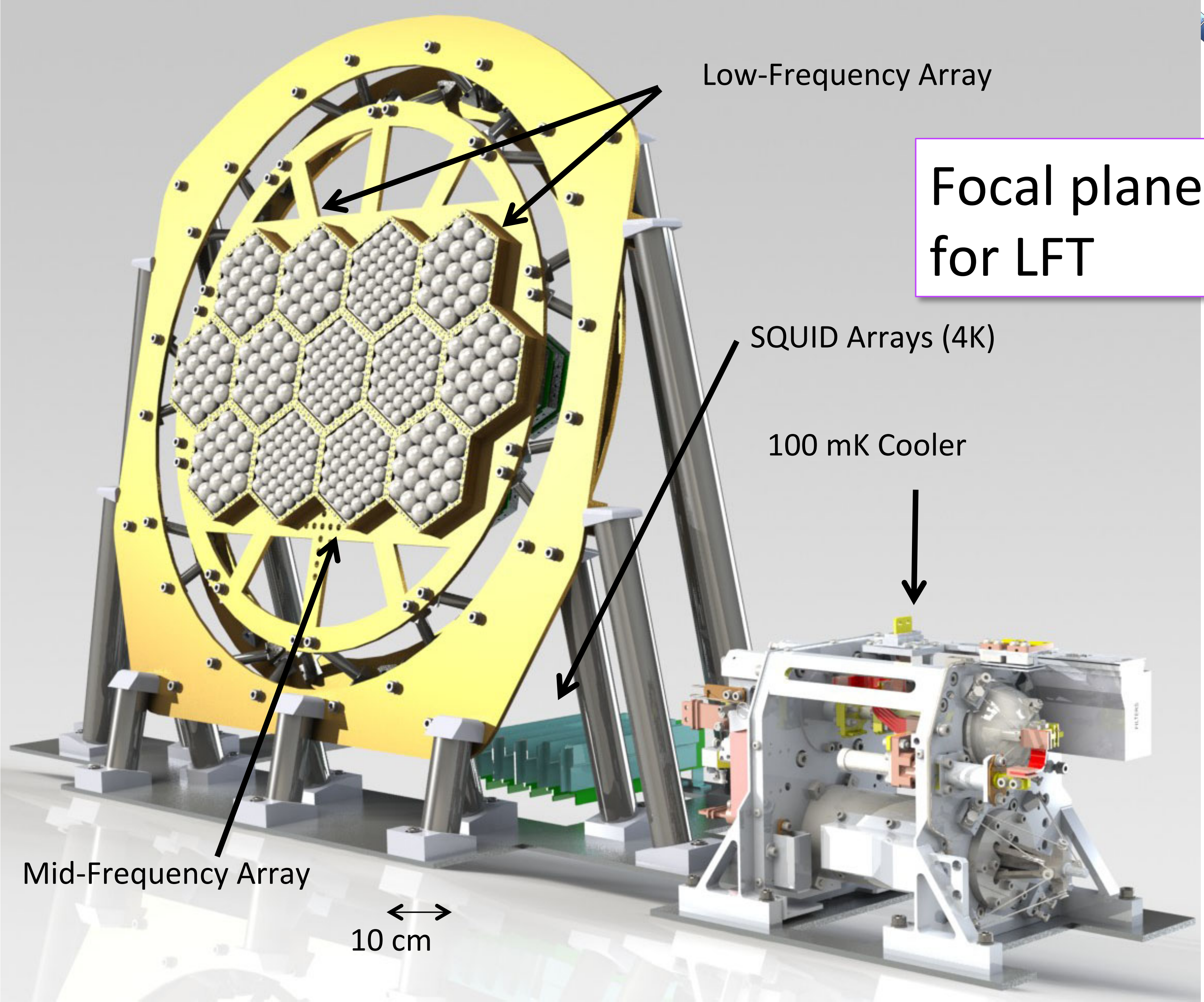


High Frequency (280-402GHz) telescope

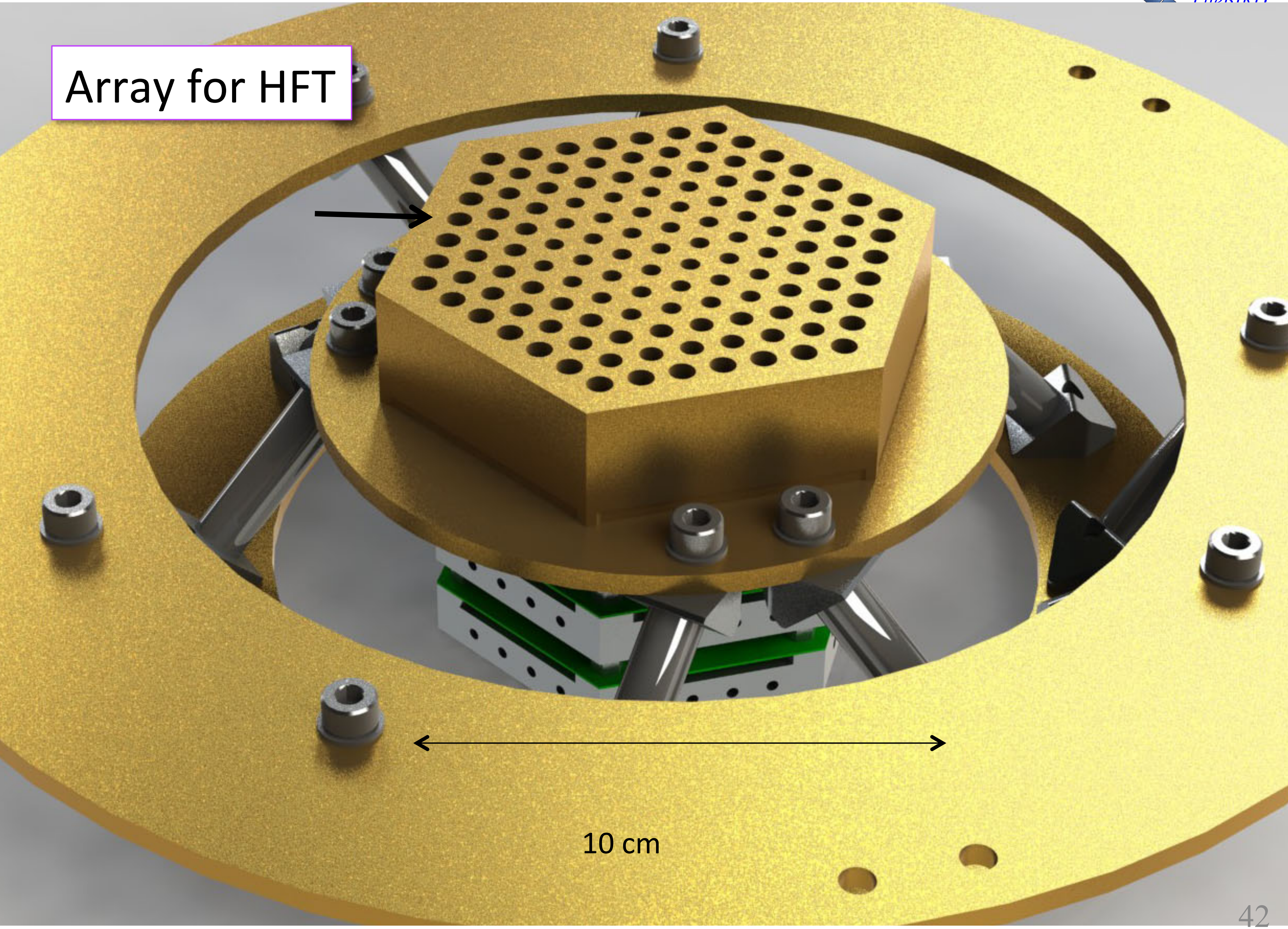
Two plano-convex aspherical Si lenses (**φ<250mm**).

Cryogenically cooled entrance aperture to control sidelobe of feed.

Focal plane for LFT

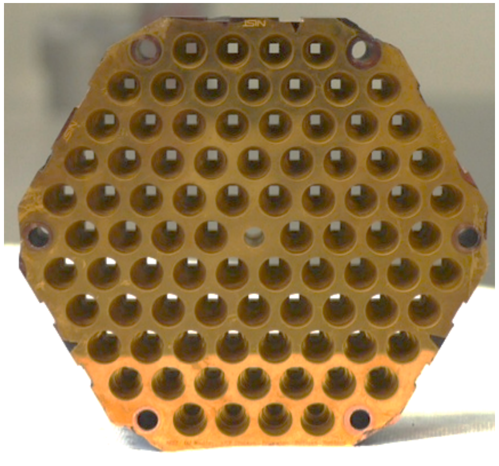


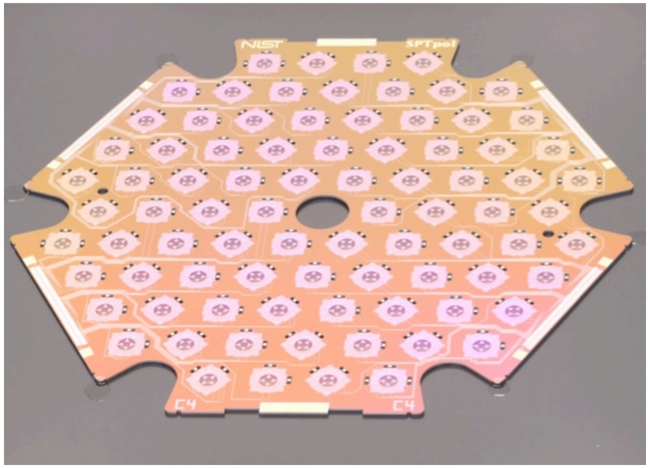
Array for HFT

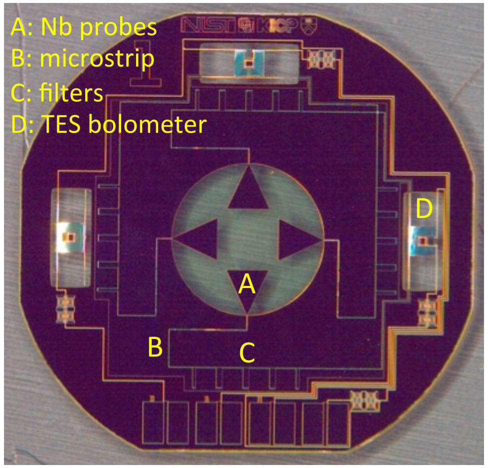


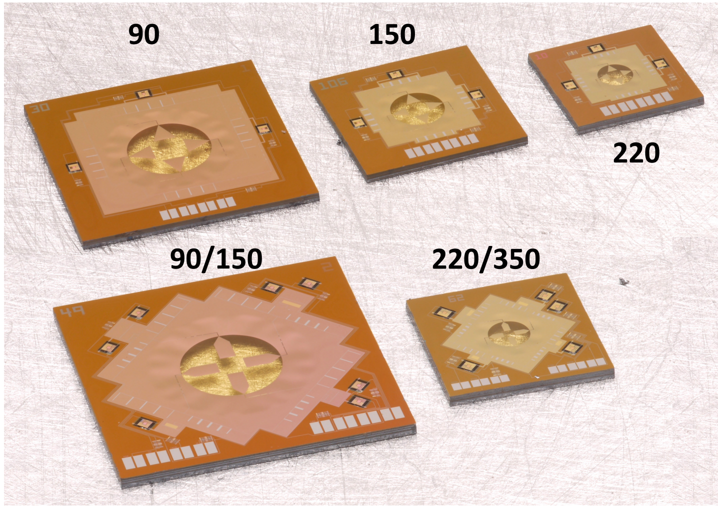
High-Frequency Array

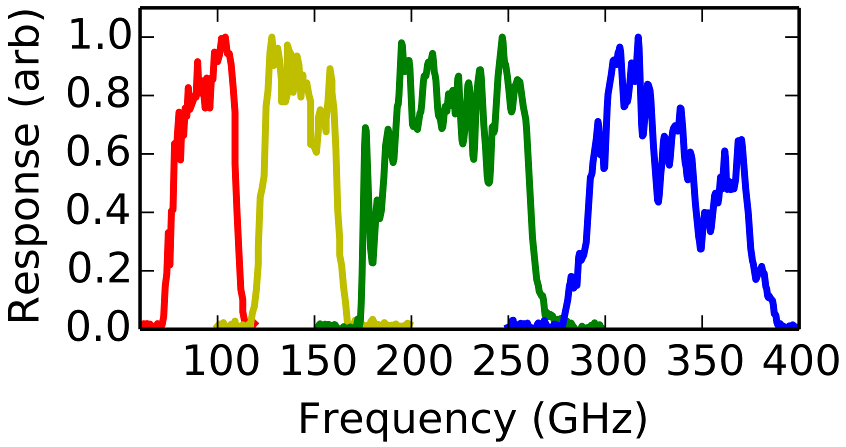
NIST











- Horn Coupled Array: Demonstrated performance at high frequency.

LiteBIRD Specifications

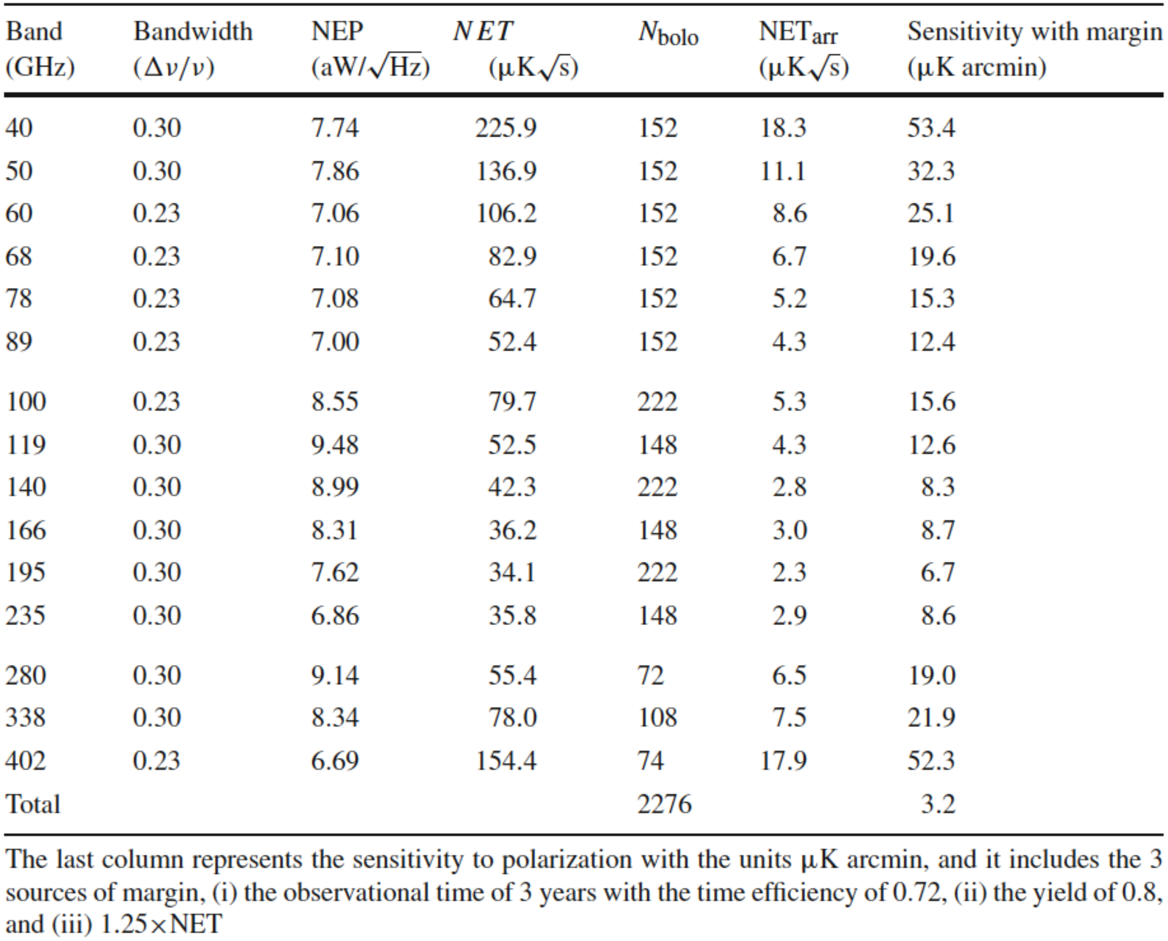
3-year observation assumed

Array

Low

Mid

High



Band (GHz)	Bandwidth ($\Delta\nu/\nu$)	NEP (aW/$\sqrt{\text{Hz}}$)	NET (μK$\sqrt{\text{s}}$)	N_{bolo}	NET$_{\text{arr}}$ (μK$\sqrt{\text{s}}$)	Sensitivity with margin (μK arcmin)
40	0.30	7.74	225.9	152	18.3	53.4
50	0.30	7.86	136.9	152	11.1	32.3
60	0.23	7.06	106.2	152	8.6	25.1
68	0.23	7.10	82.9	152	6.7	19.6
78	0.23	7.08	64.7	152	5.2	15.3
89	0.23	7.00	52.4	152	4.3	12.4
100	0.23	8.55	79.7	222	5.3	15.6
119	0.30	9.48	52.5	148	4.3	12.6
140	0.30	8.99	42.3	222	2.8	8.3
166	0.30	8.31	36.2	148	3.0	8.7
195	0.30	7.62	34.1	222	2.3	6.7
235	0.30	6.86	35.8	148	2.9	8.6
280	0.30	9.14	55.4	72	6.5	19.0
338	0.30	8.34	78.0	108	7.5	21.9
402	0.23	6.69	154.4	74	17.9	52.3
Total				2276		3.2

The last column represents the sensitivity to polarization with the units μK arcmin, and it includes the 3 sources of margin, (i) the observational time of 3 years with the time efficiency of 0.72, (ii) the yield of 0.8, and (iii) 1.25×NET

Detector Experience

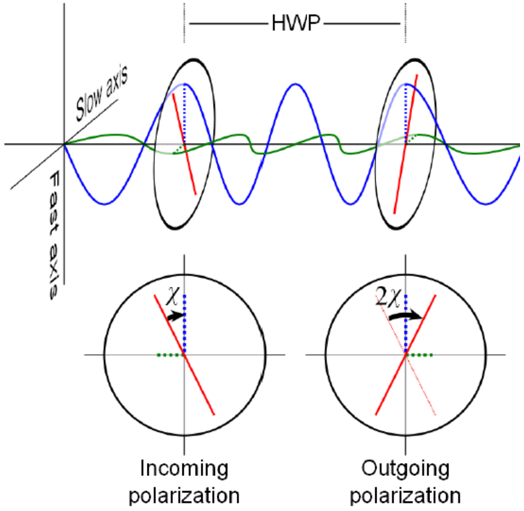
- Berkeley
  - Past: APEX-SZ, SPT-SZ, POLARBEAR-1, EBEX, ASTE
  - Future: POLARBEAR-2 and Simons Array
- NIST/Stanford
  - Past: ABS, SCUBA-2, ACTPOL, SPT-POL, MUSTANG
  - Future: AdvACT, SPIDER

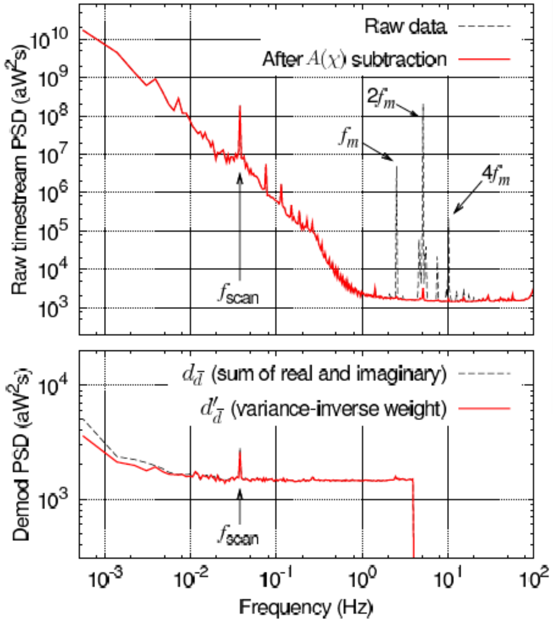
NIST

Berkeley

Continuously−rotating half-wave plate (HWP)

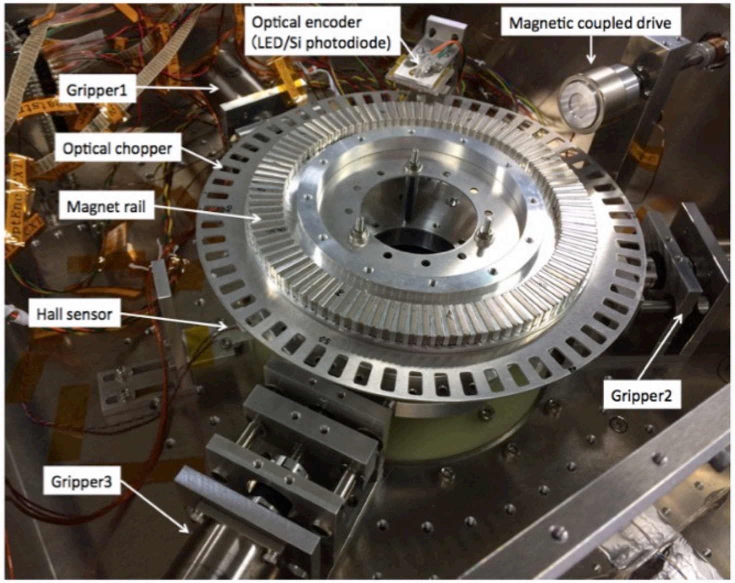
- Mitigate 1/f noise (signal at 4f)
- Mitigate "differential systematics"

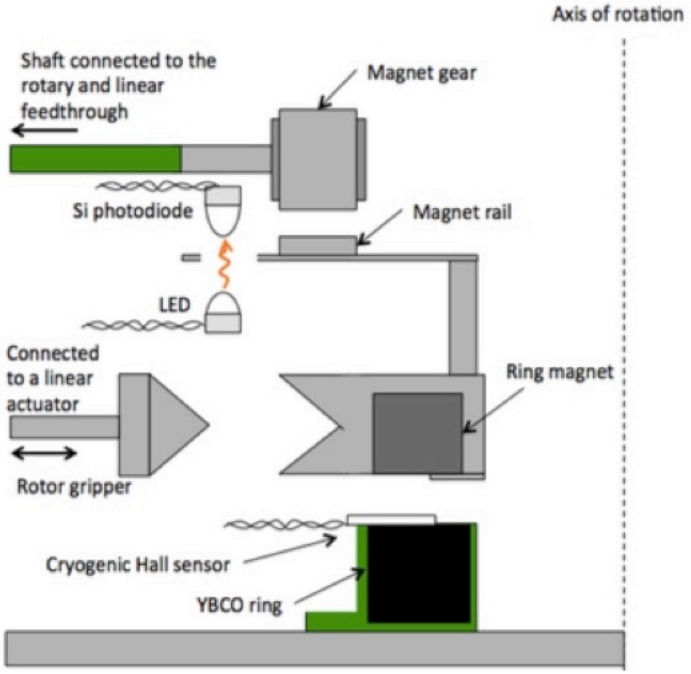




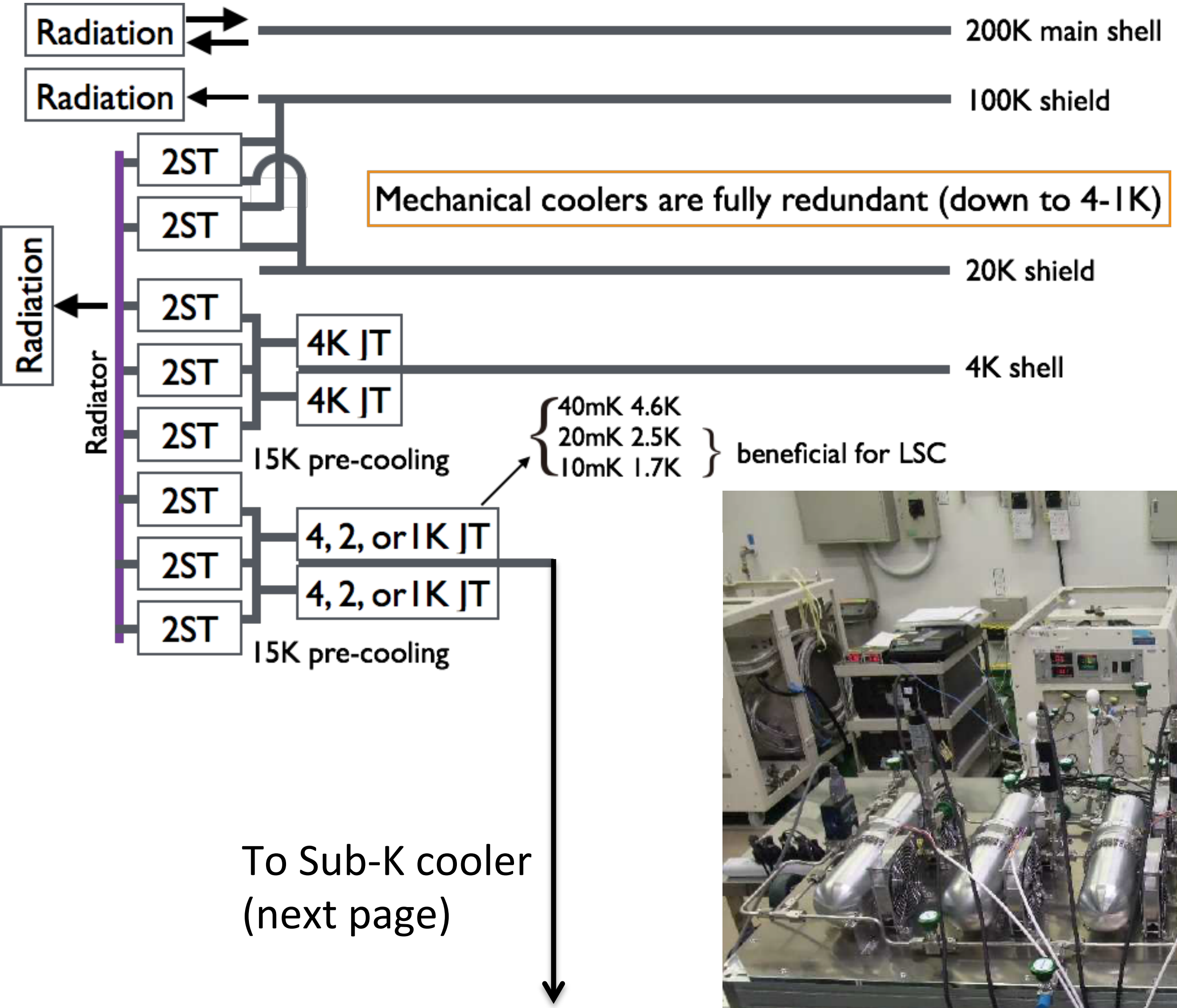
Example from ABS Project

HWP system BBM at JAXA





Cryogenic system (1): above 1K



Radiation

200K main shell

Radiation

100K shield

2ST

2ST

Mechanical coolers are fully redundant (down to 4-1K)

20K shield

Radiation

Radiator

2ST

2ST

2ST

4K JT

4K JT

4K shell

15K pre-cooling

40mK 4.6K
20mK 2.5K
10mK 1.7K

beneficial for LSC

2ST

2ST

2ST

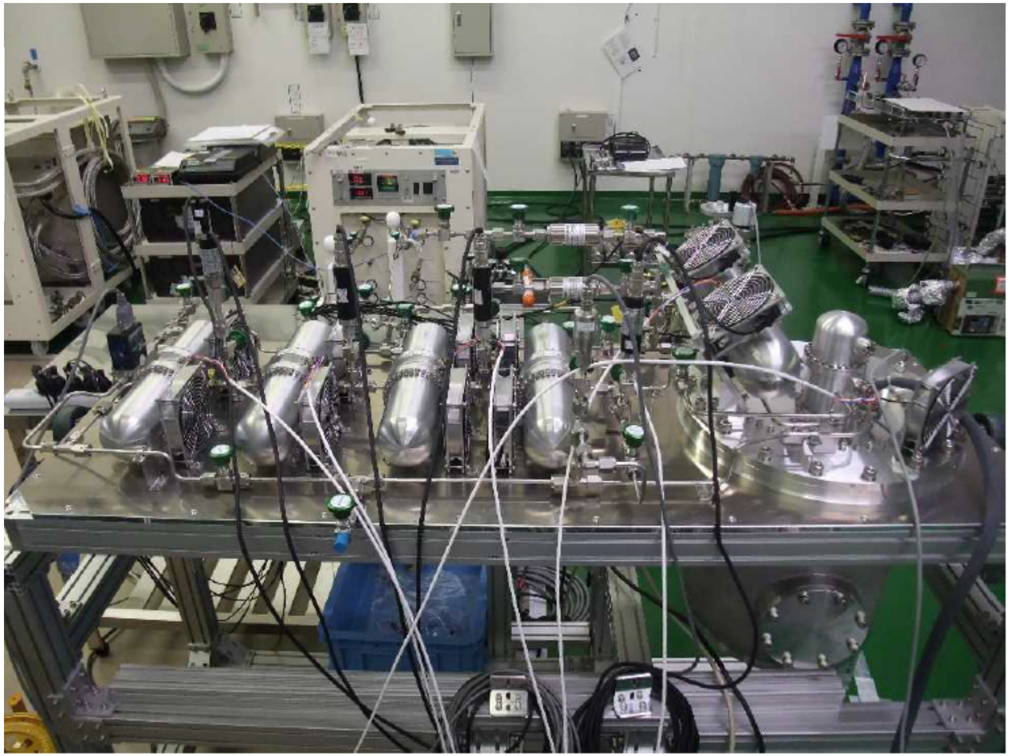
4, 2, or 1K JT

4, 2, or 1K JT

15K pre-cooling

To Sub-K cooler (next page)

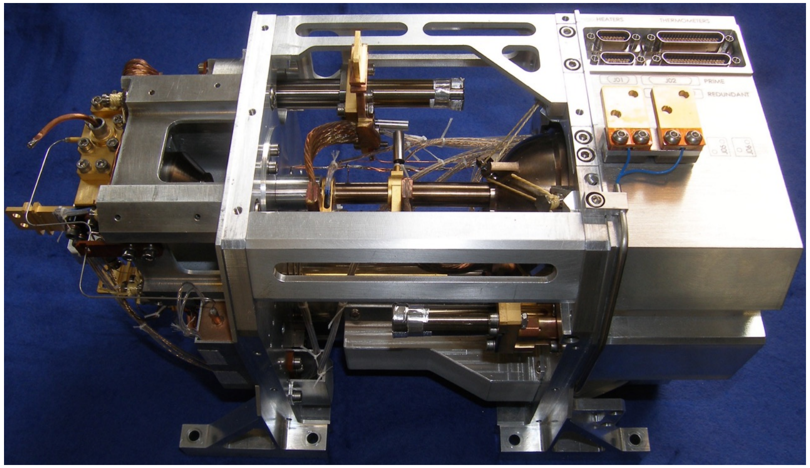
Photo of the 1K-JT Cryocooler Unit (©JAXA)



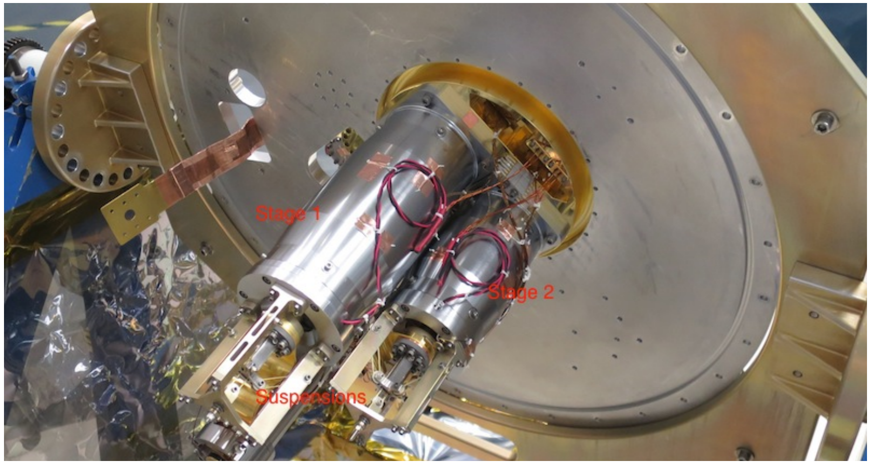
Cryogenic system (2): below 1K

Two options are being evaluated (part of US phase A)

1. CEA
   - Based on SPICA-SAFARI design
   - 100-mK salt pill, 300-mK He3 sorption
   - Depends on 1.8 K and 4.5 K provided

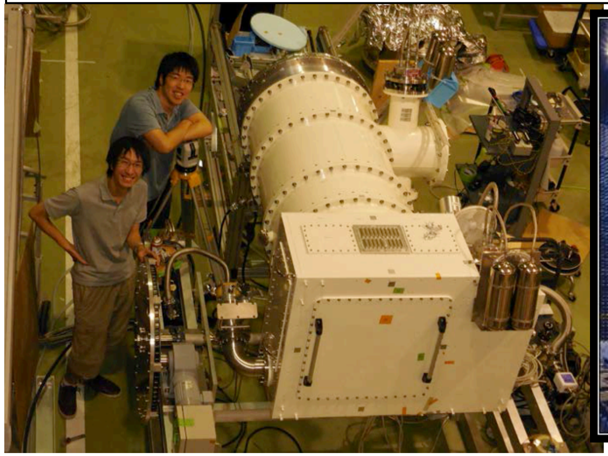


2. NASA
   - Based on Hitomi (Astro-H) design
   - 2-stage:
     - Salt pills at 100 mK and 300-800 mK
     - Depends on 1.8 K and 4.5 K provided
   - 3/4-stage options also considered
     - E.g., 100 mK, 500 mK, 1.2 K (continuous in 4-stage option)
     - No 1.8-K JT cooler required

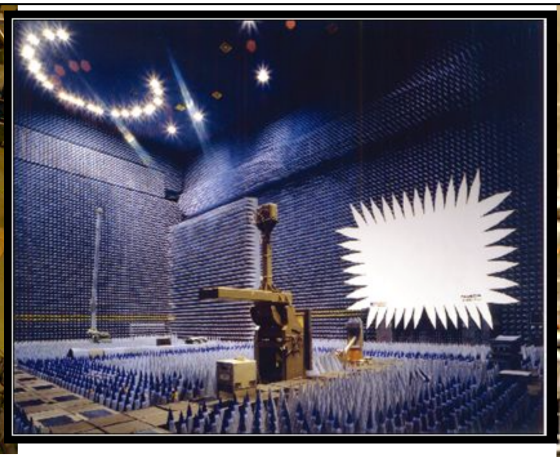


Testing and integrations

LiteBIRD has members with the CMB instrument integration expertise, satellite integration expertise, HEP radiation expertise together with the fully equipped facilities.



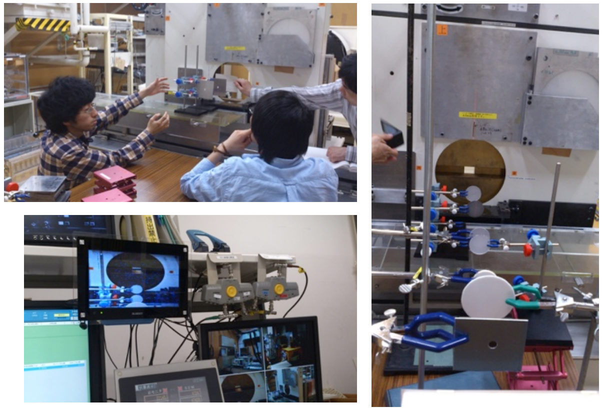
POLARBEAR2 integration is ongoing at KEK with sub-K cryogenic system and UC Berkeley TES bolometers.



JAXA Antenna test facility

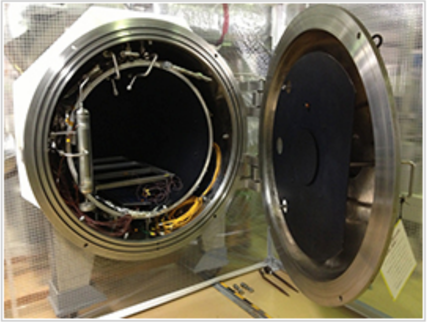
JAXA 13-m diameter space chamber

Astro-H test is done here.



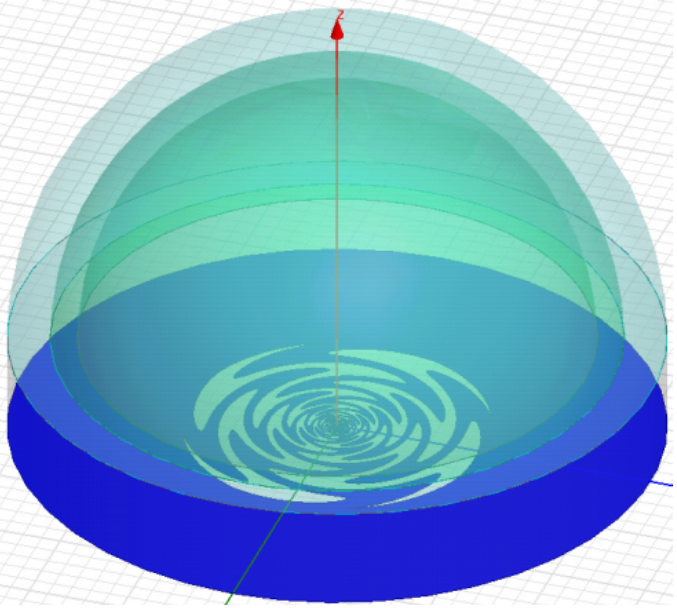
Proton irradiation tests at HIMAC

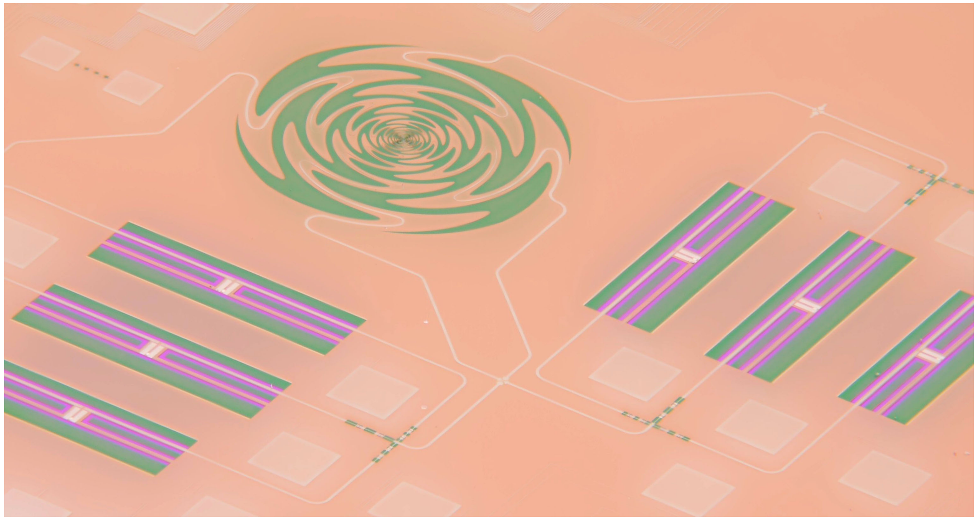
JAXA 6-m diameter space chamber



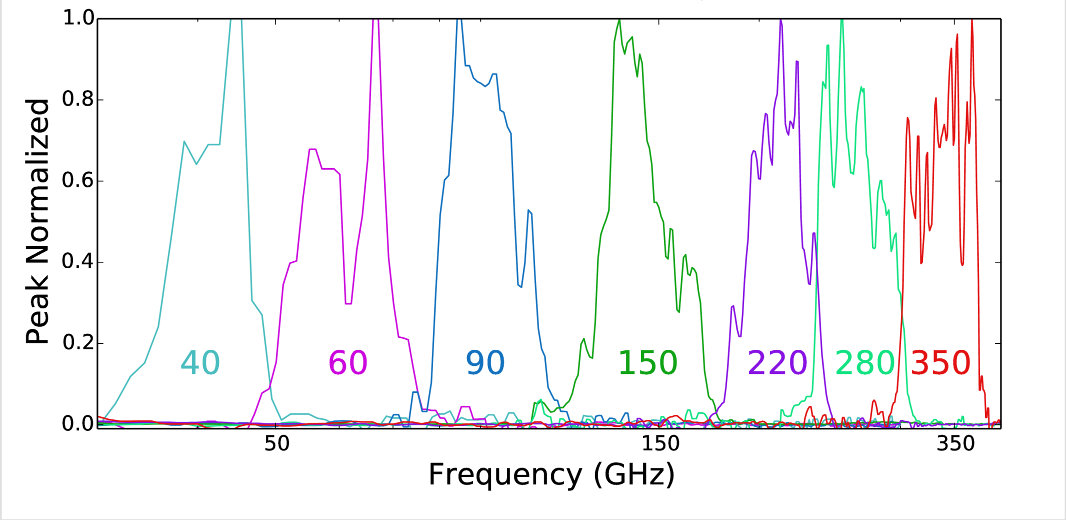
JAXA 1-m diameter space chamber

Low- and Mid-Frequency Arrays





UC Berkeley



Sinuous, 3-band and 4-band pixels

- Sinuous Antenna → Broadband Trichroic Pixels
- 3:1 Bandwidth → enables high band count within fixed field-of-view