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

Progress with LiteBIRD

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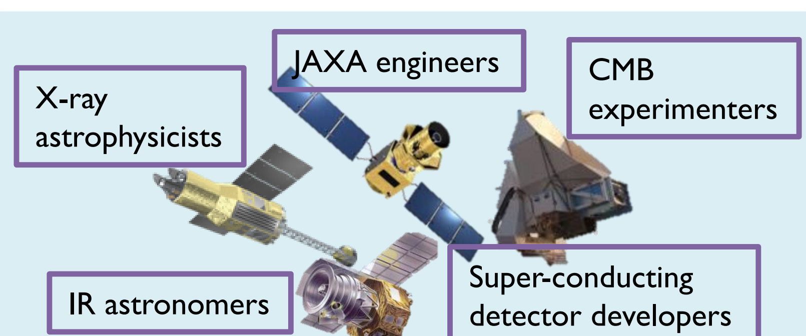
LiteBIRD working group



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

Special importance of primordial CMB B-mode

- Direct evidence for cosmic inflation

- GUT-scale physics

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

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 !

(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 !

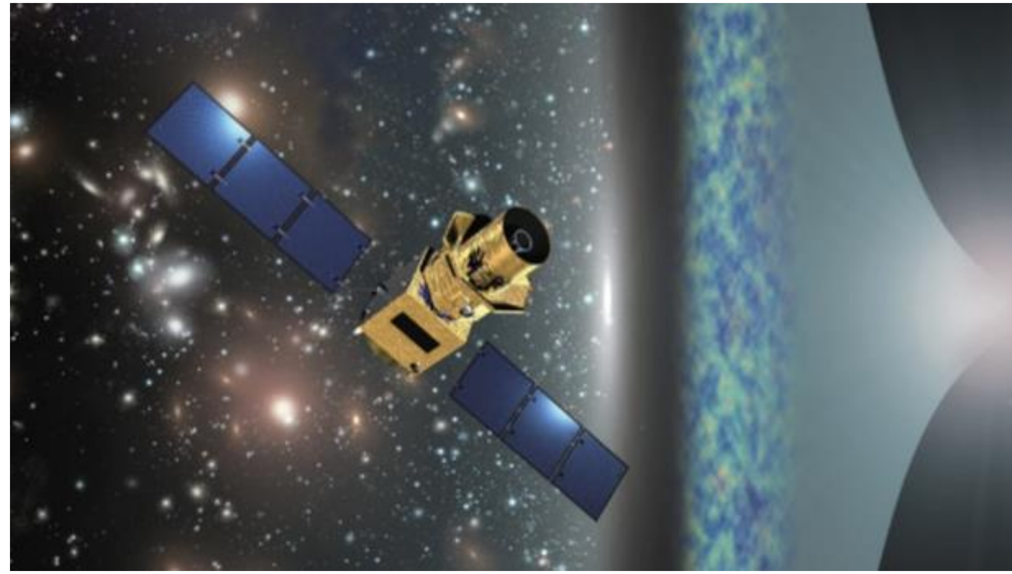
JAXA

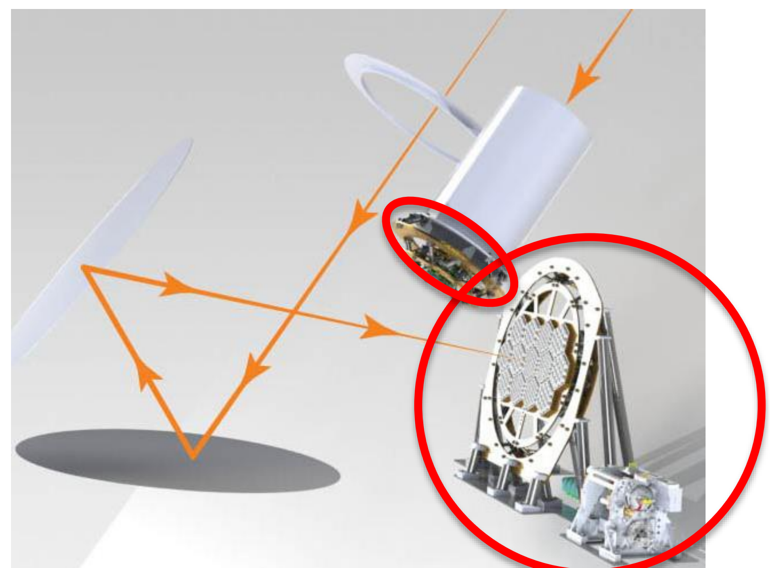
- Main mission
- Cost cap $300M (same as ASTRO-H/Hitomi)
- Will soon start conceptual design phase (Phase A1)

Seeking for European partnership ! (dedicated talk on international collaboration tomorrow)

NASA

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





International collaboration

- International collaboration essential.
  - LiteBIRD Joint Study Groups w/ external collaborators have been formed.
- Talk on “Japanese plans w.r.t. international collaboration” tomorrow afternoon

LiteBIRD

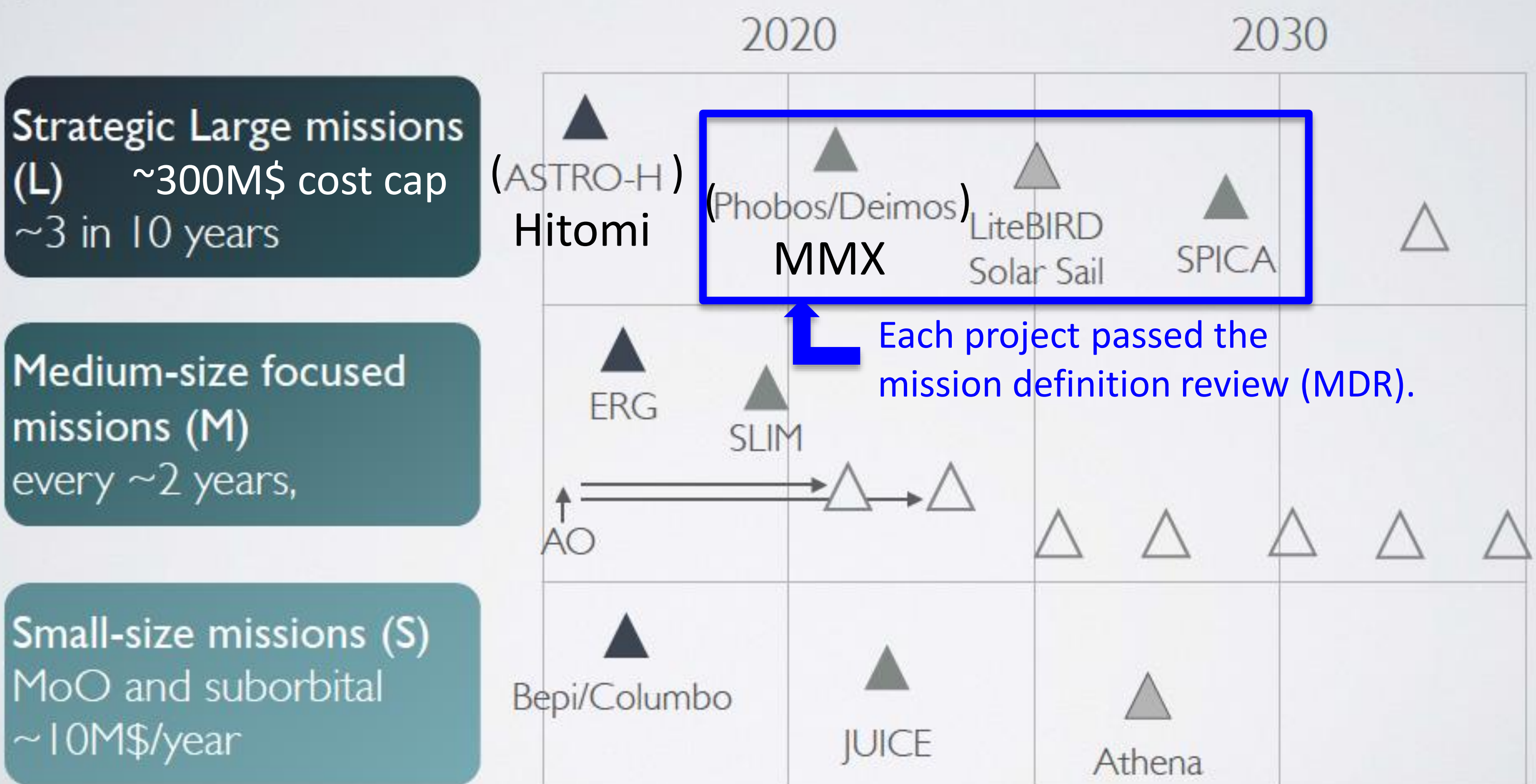
Space science and exploration at ISAS/JAXA

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.



Full success of LiteBIRD

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

<u>Remarks</u>

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

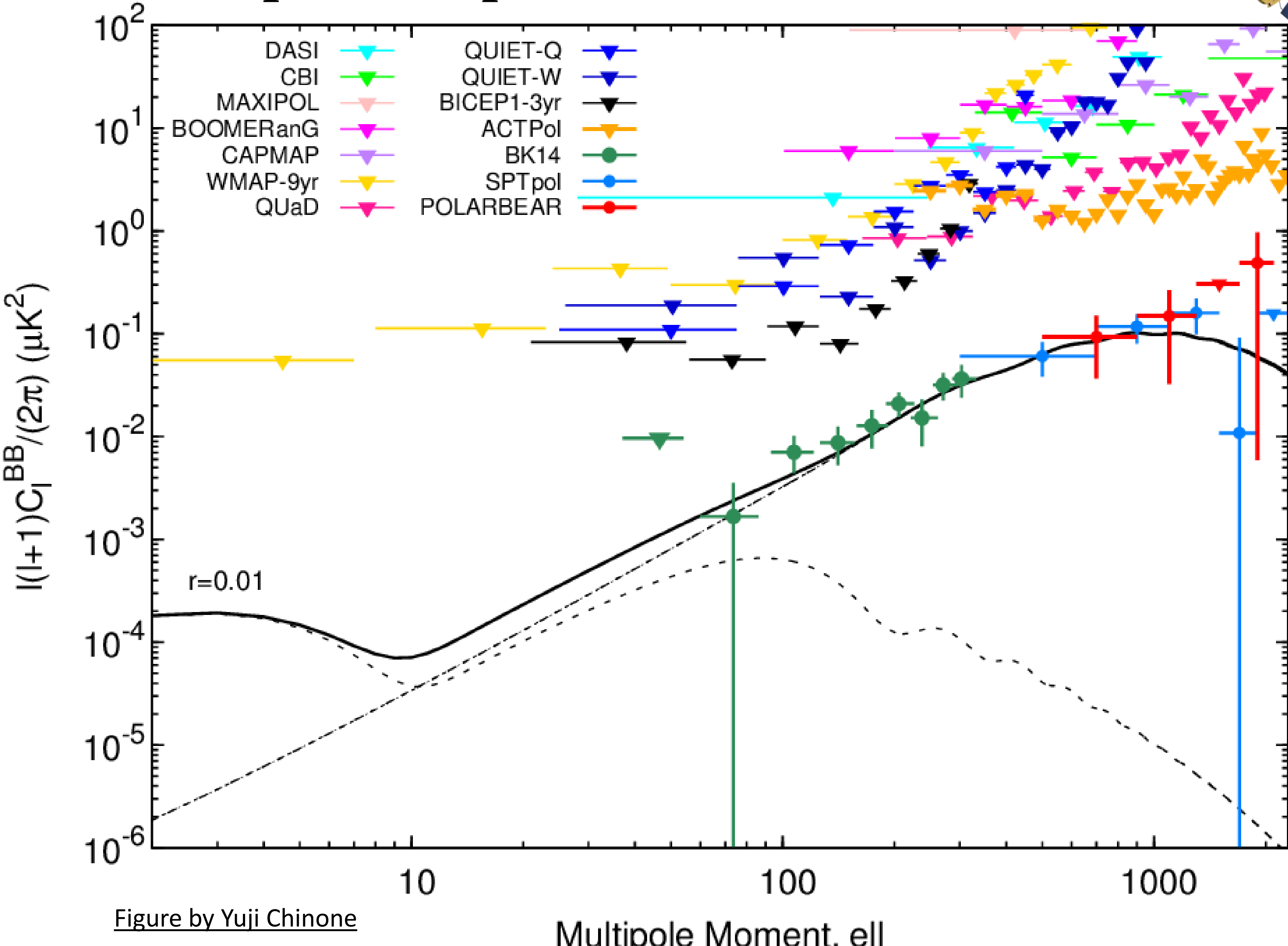


Figure by Yuji Chinone

B-mode power spectrum measurements

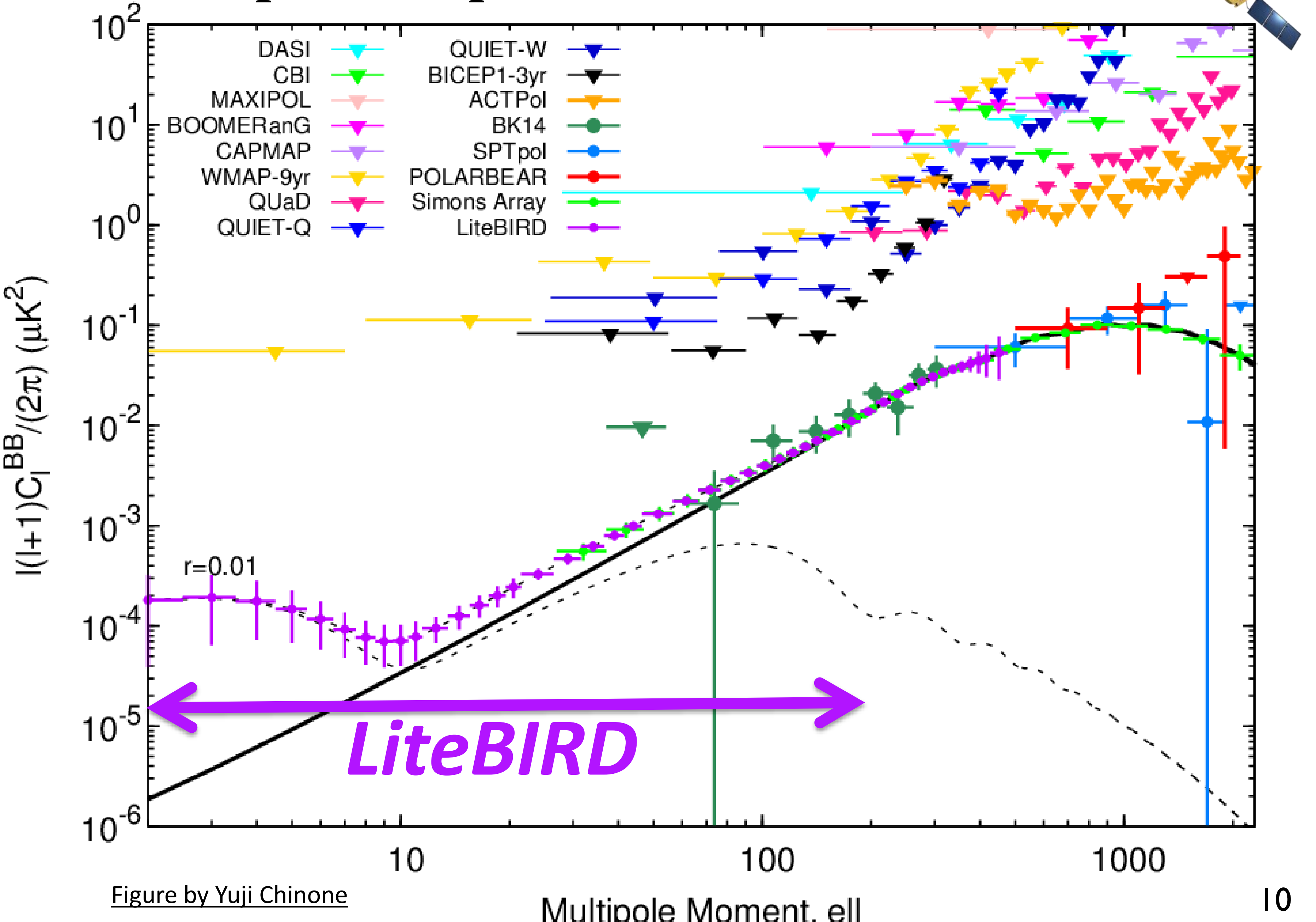


Figure by Yuji Chinone

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

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

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

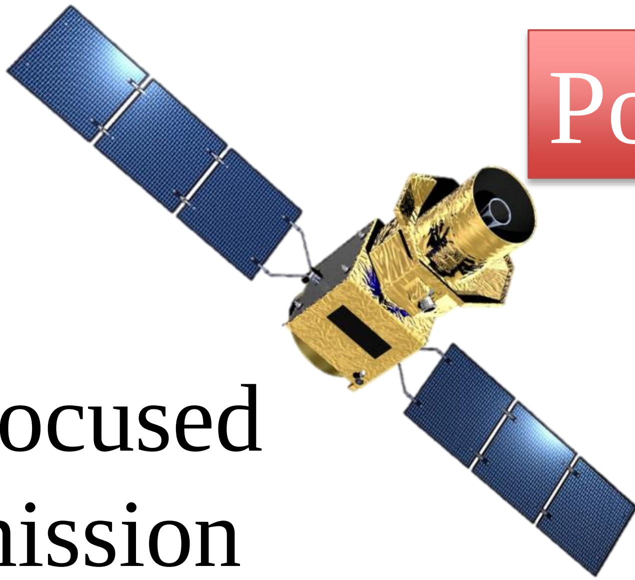
- r is fairly large → Comprehensive studies by LiteBIRD !
- Much more precise measurement of r from LiteBIRD will play a vital role in identifying the correct inflationary model.
- LiteBIRD will measure the B-mode power spectrum w/ high significance for each bump if $r>0.01$.
  - Deeper level of fundamental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

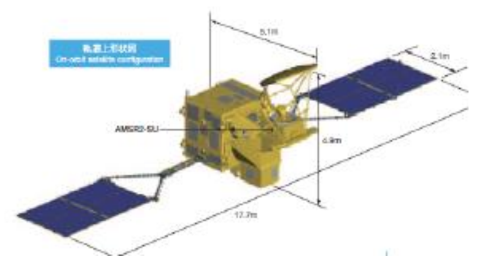
Topic	Method	Example
Delensing	Large CMB telescope array	CMB-S4 data Namikawa and Nagata, JCAP 1409 (2014) 009
	Cosmic infrared background	Herschel data Sherwin and Schmittfull, Phys. Rev. D 92, 043005 (2015)
	Radio continuum survey	SKA data Namikawa, Yamauchi, Sherwin, Nagata, Phys. Rev. D 93, 043527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

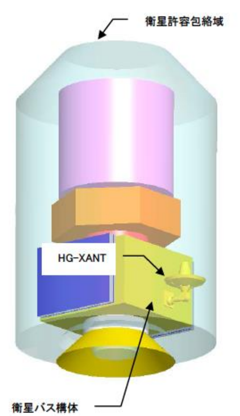
- Delensing improvement to σ(r) can be factor ~2 or more.
- Need to make sure systematic uncertainties are under control.

LiteBIRD Phase-A baseline design

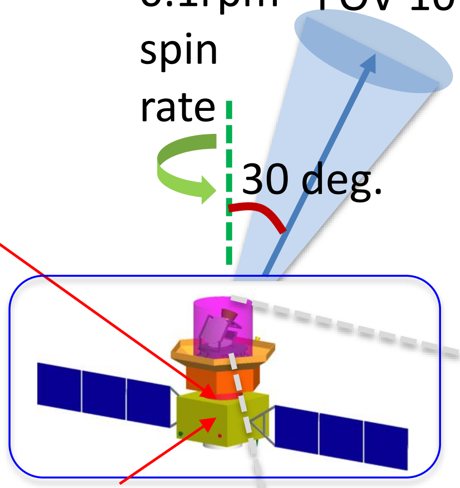
- Mission module benefits from heritages of other missions (e.g. ASTRO-H) and ground-based experiments (e.g. POLARBEAR).
- Bus module based on high TRL components

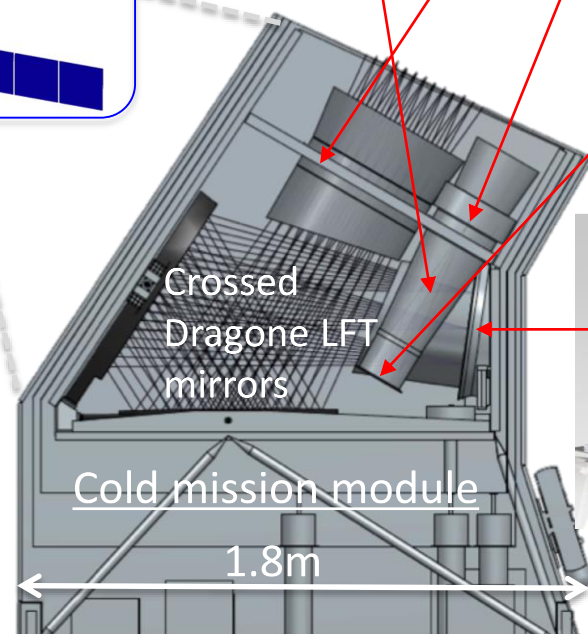
Slip-ring technology used for Shizuku





Fit in H2 envelope



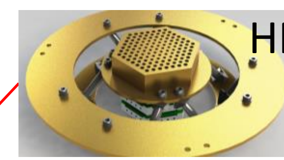


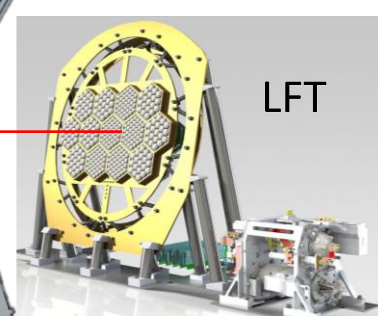
Cryogenics

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

Continuously-rotating half wave plate (HWP)

Multi-chroic TES focal plane detectors





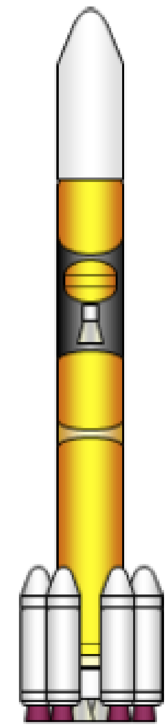
Launch Vehicle

H-II A

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

H-II B

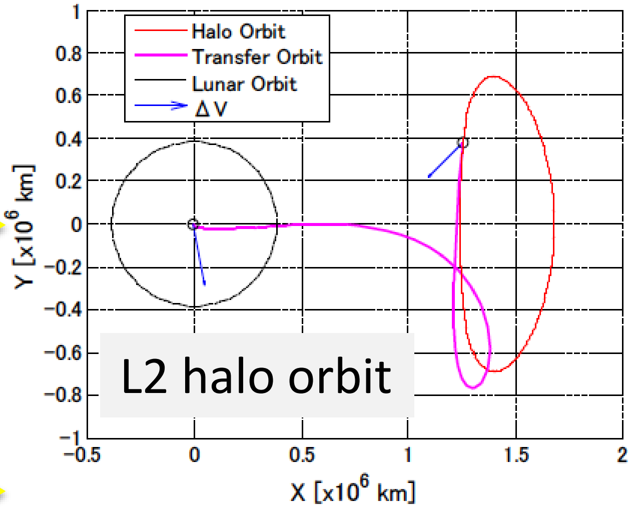
- First Flight in 2009
- **4** successful flights/4 of 16.5 ton HTV to ISS
- GTO 8 ton class capability

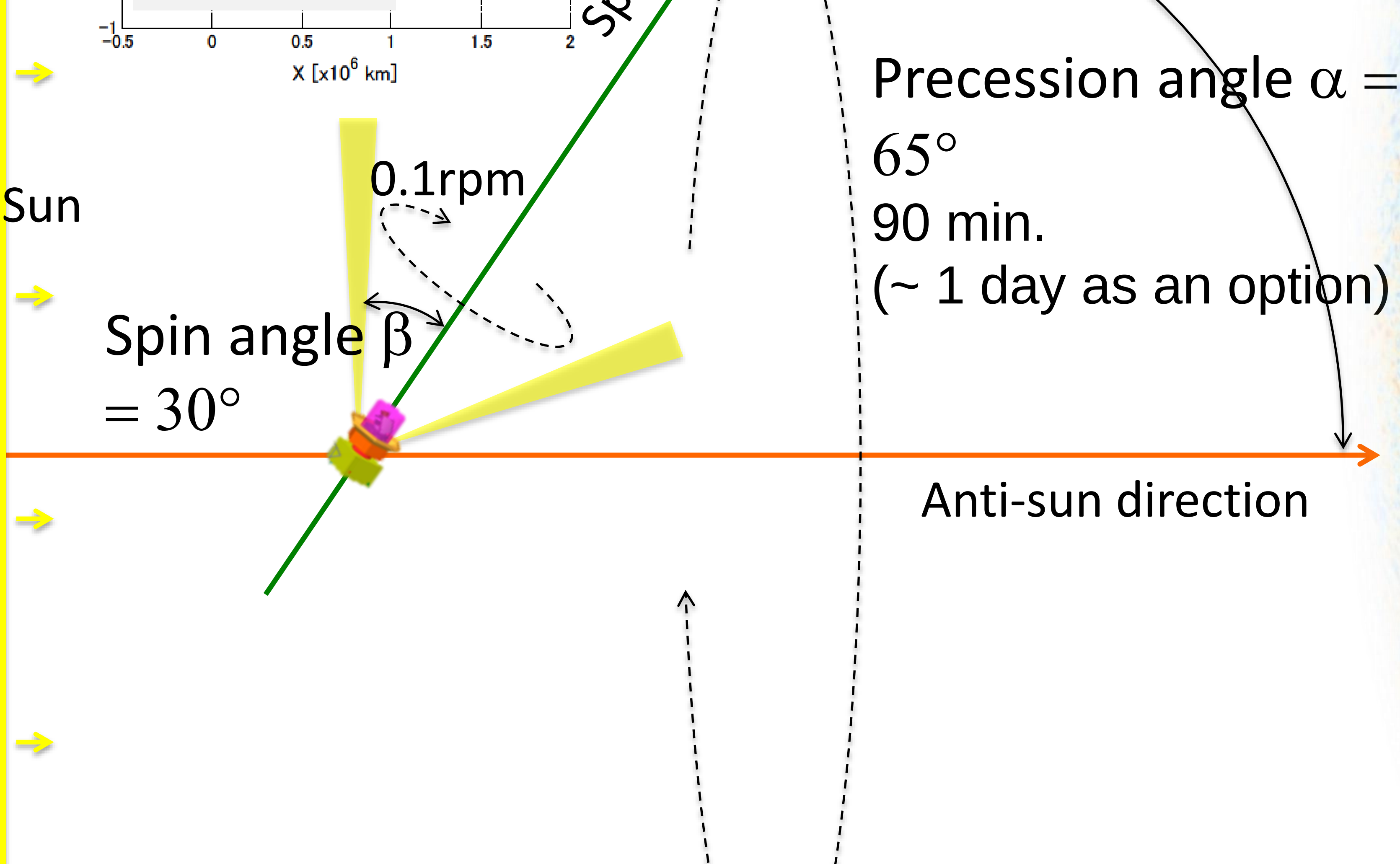


H3

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

Orbit and scan strategy



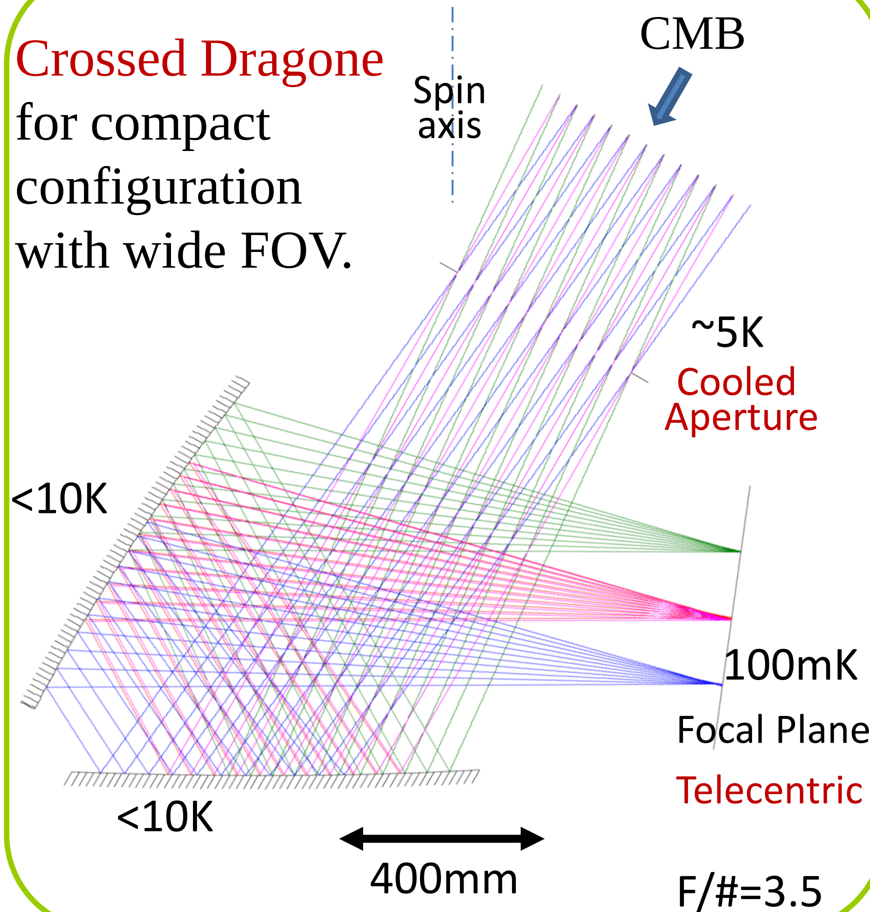


Main specifications (Phase-A baseline design)

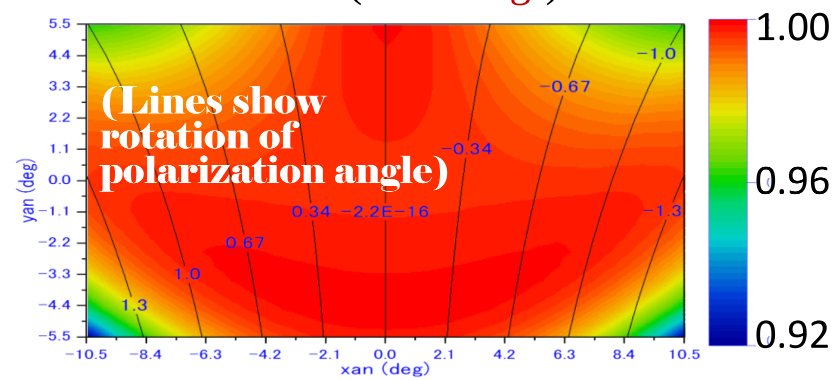
Item	**Specification**
Orbit	L2 halo orbit
Launch year (vehicle)	2024-2025 (H3 or H2A)
Observation (time)	All-sky CMB survey (3 years)
Mass	2.2 t
Power	2.5 kW
Mission instruments	• Superconducting detector arrays • Continuously-rotating half-wave plate (HWP) • Crossed-Dragone mirrors (+ small refractive 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)

Design of low frequency telescope (LFT)

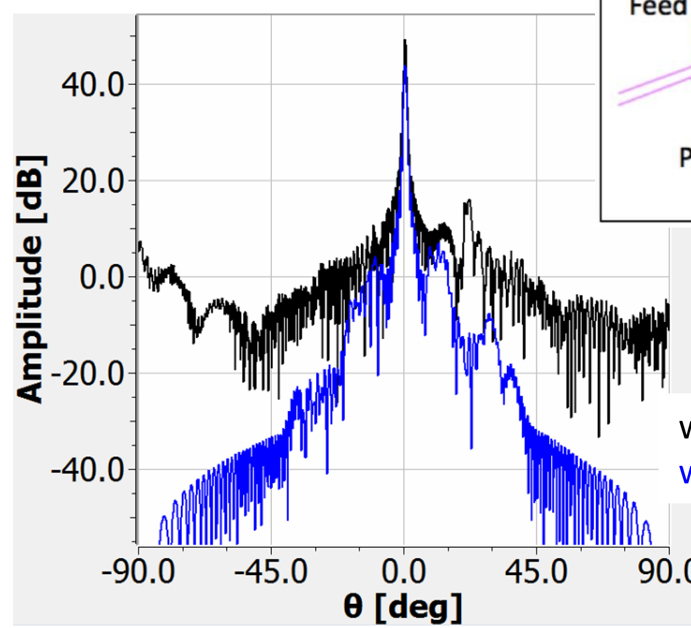
Crossed Dragone for compact configuration with wide FOV.

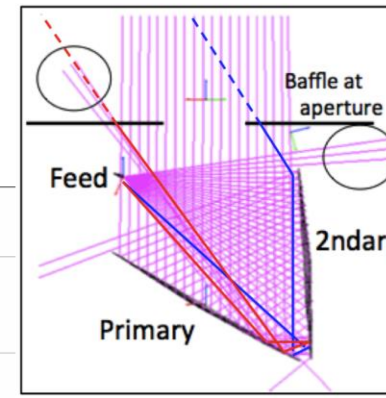


Strehl ratio @150GHz over wide (10x20deg^2) FOV on LFT



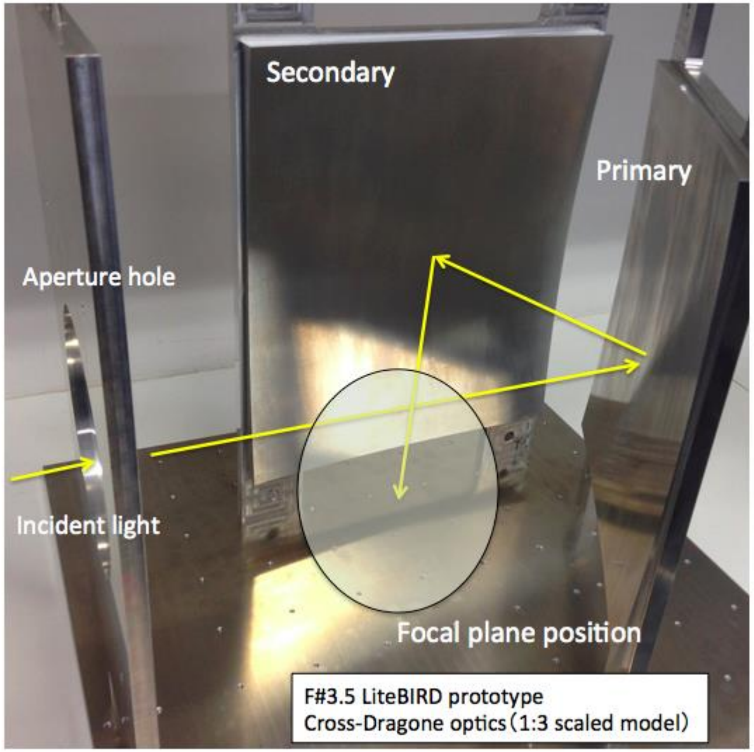
Sidelobe features

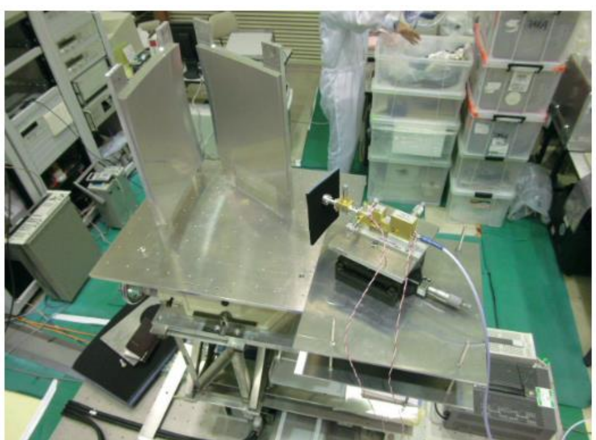




Very good overall performance !

Experimental evaluation

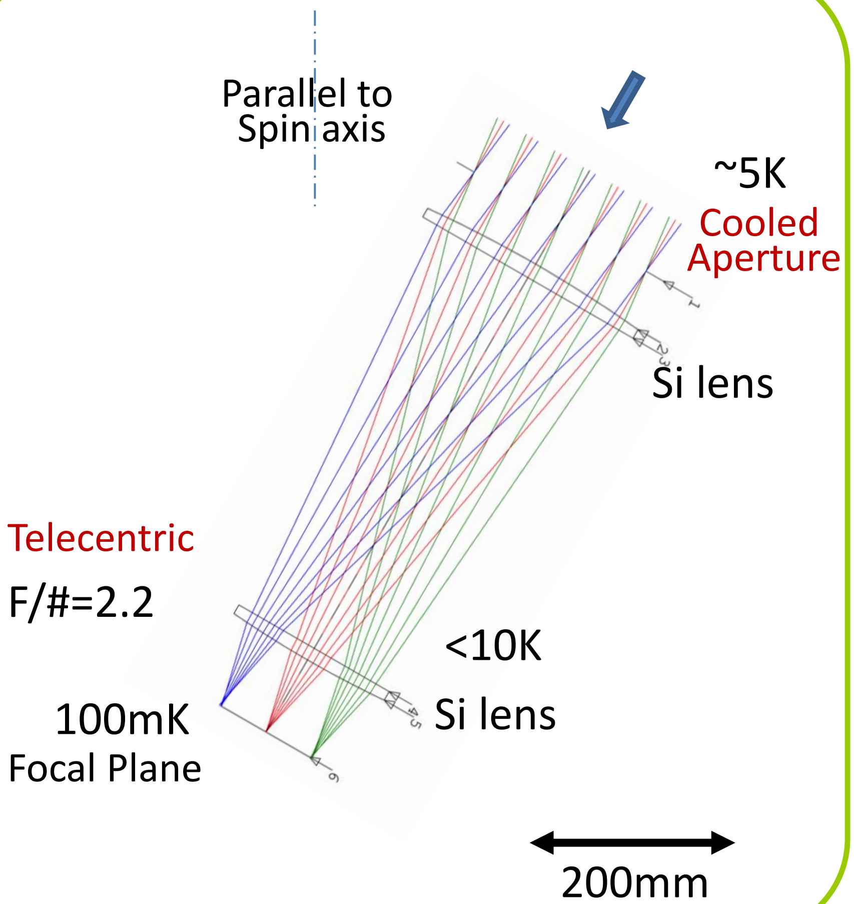




Experimental setup at JAXA

- 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)

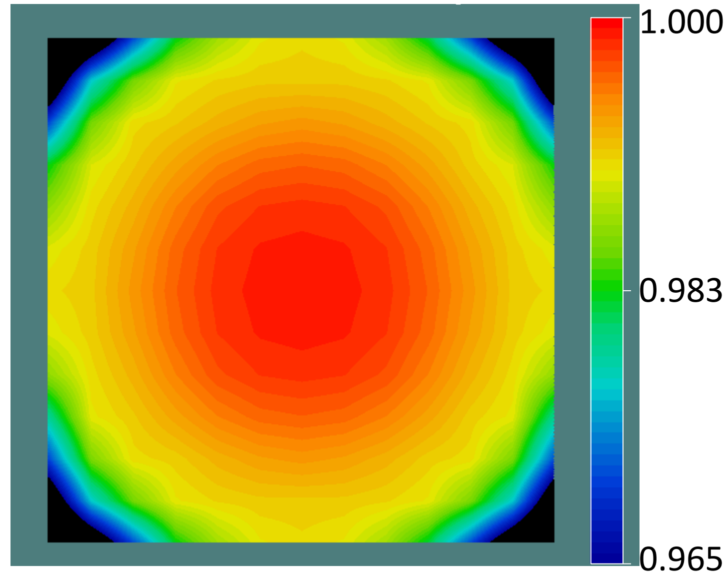


High Frequency (280-402GHz) telescope

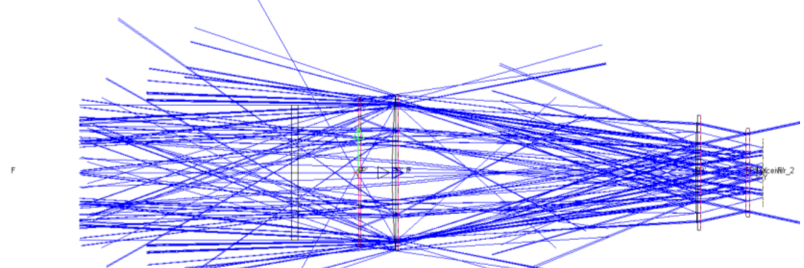
Two plano-convex aspherical Si lenses (**φ<250mm**).

Cryogenically cooled entrance aperture to control sidelobe of feed.

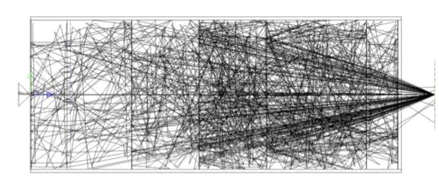
Strehl ratio @340GHz over **13x13deg^2**



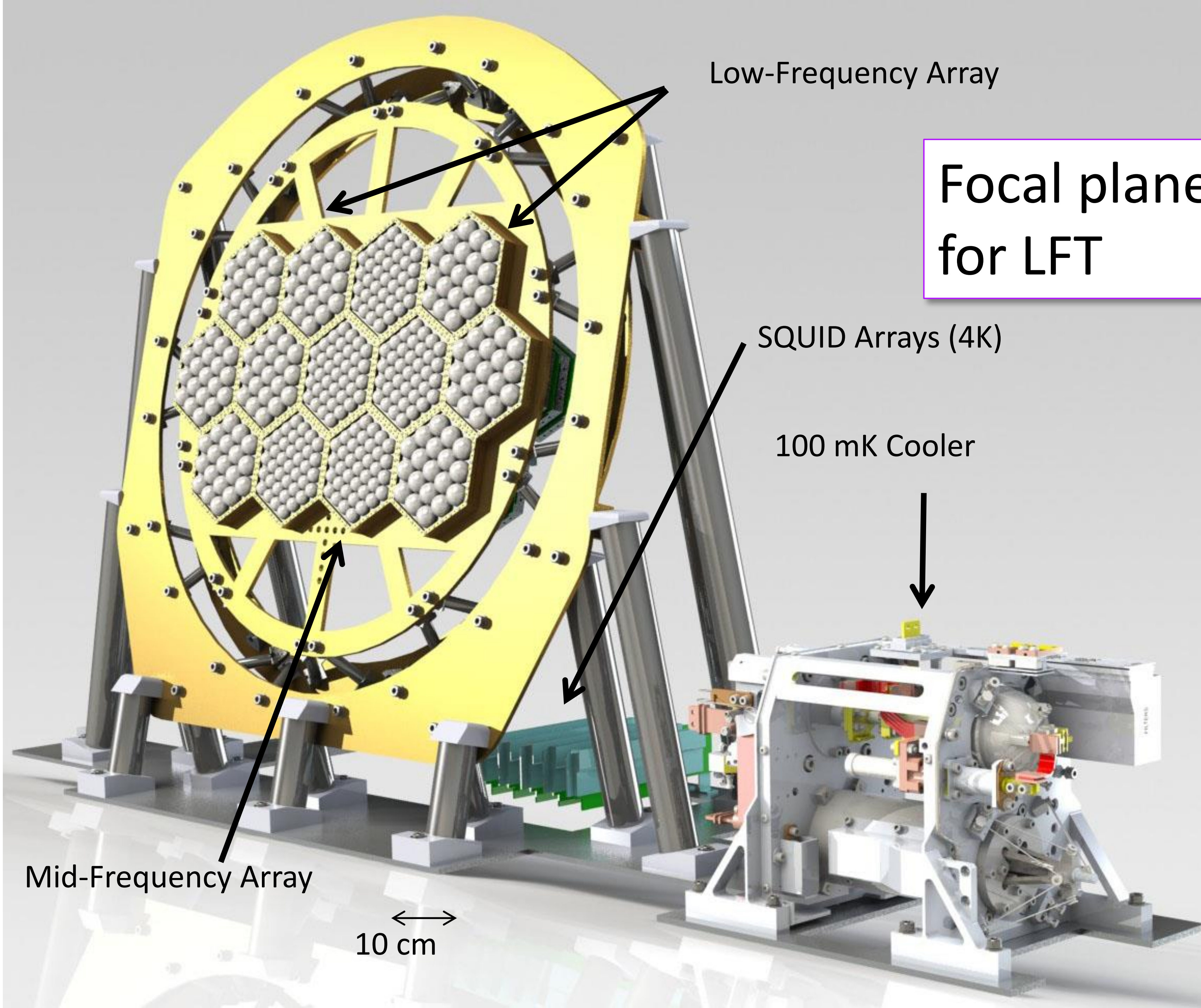
Ghost analysis by using LightTools



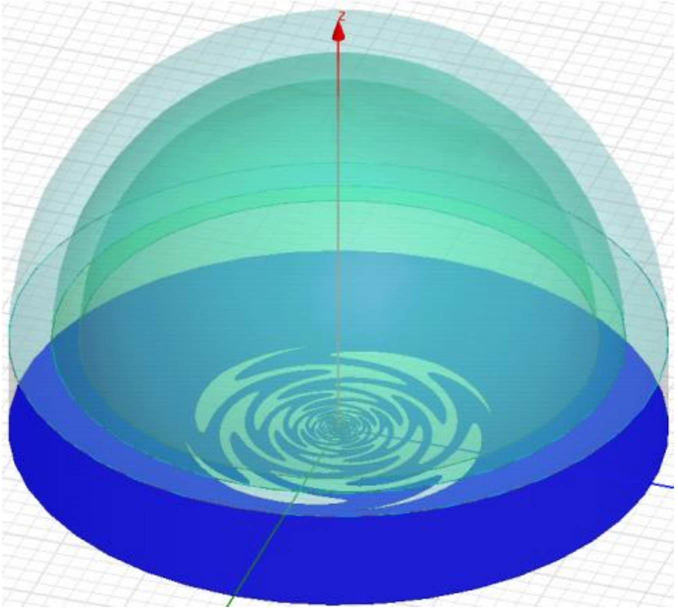
Stray Light analysis by using LightTools

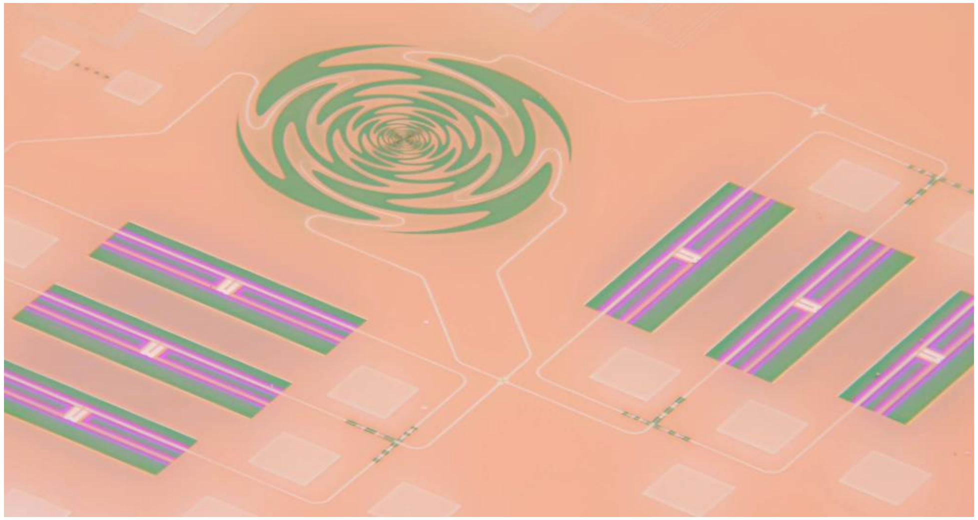


Focal plane for LFT



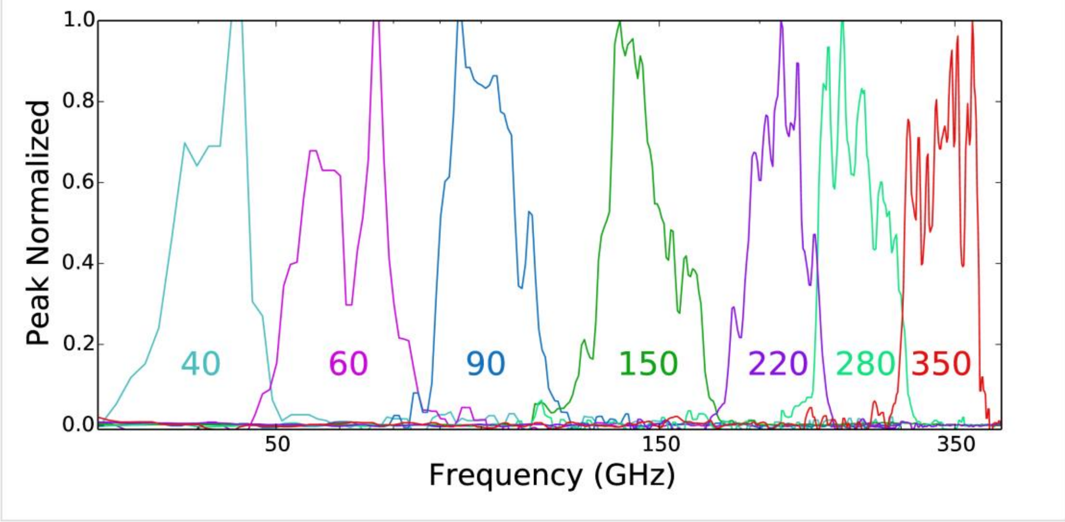
Low- and Mid-Frequency Arrays



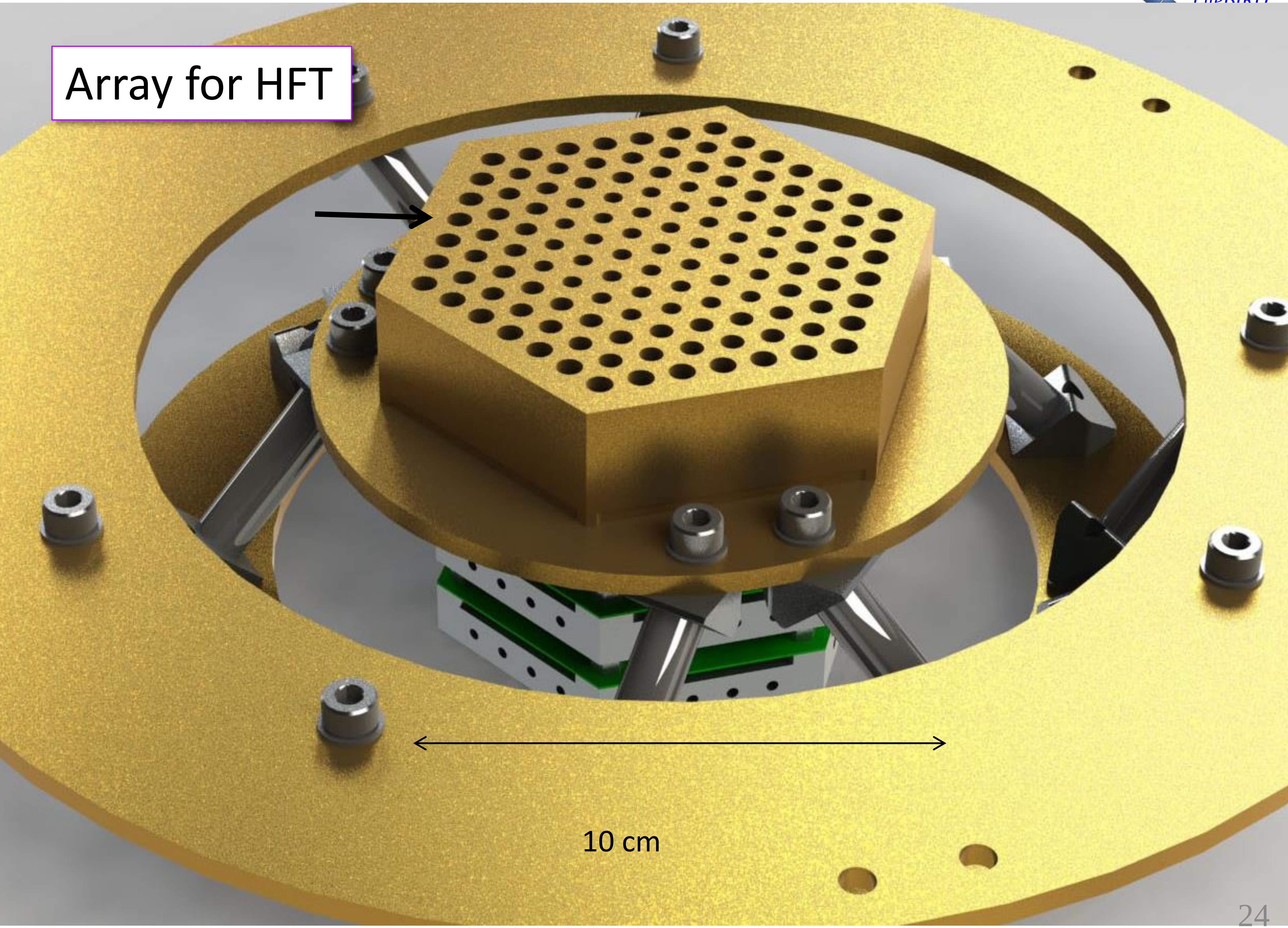


UC Berkeley

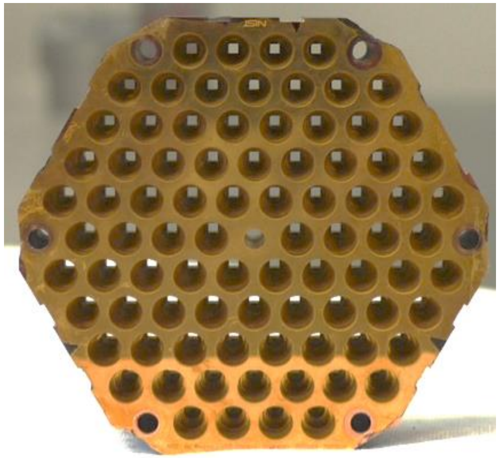
Sinuous, 3-band and 4-band pixels

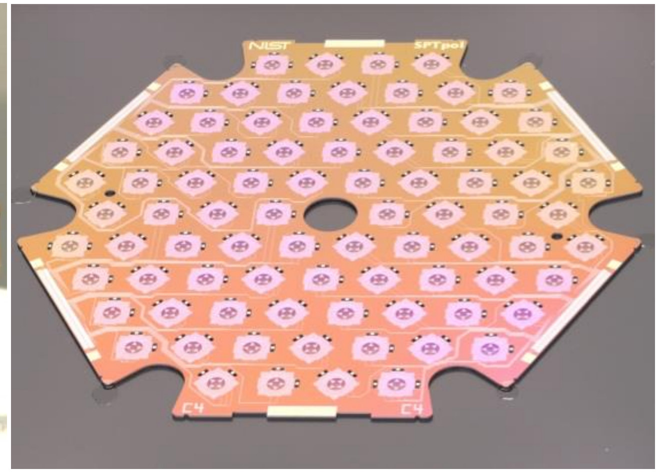


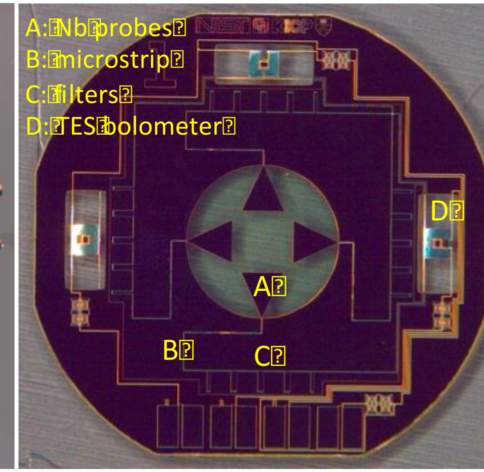
- Sinuous Antenna → Broadband Trichroic Pixels
- 3:1 Bandwidth → enables high band count within fixed field-of-view


Array for HFT
10 cm

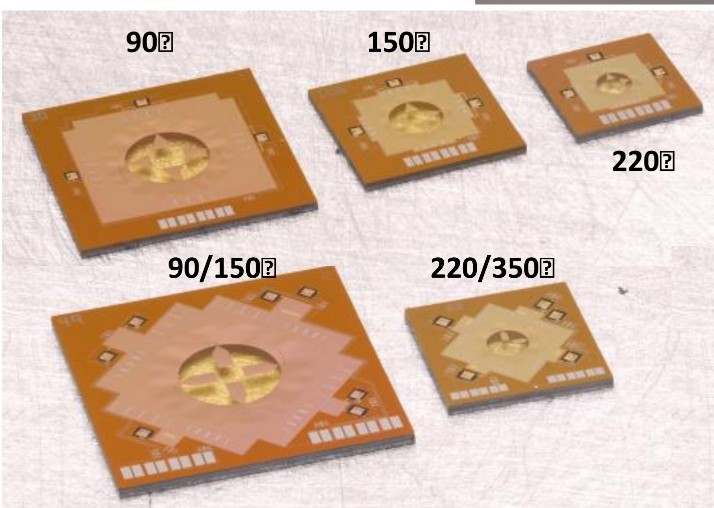
High-Frequency Array

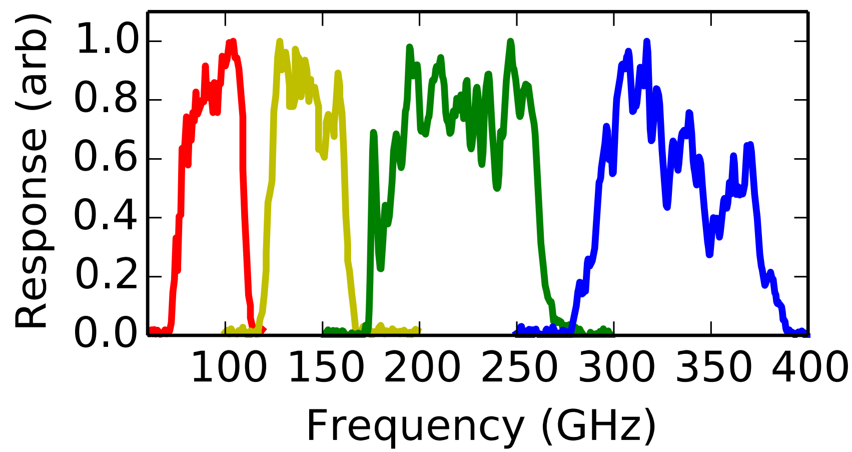






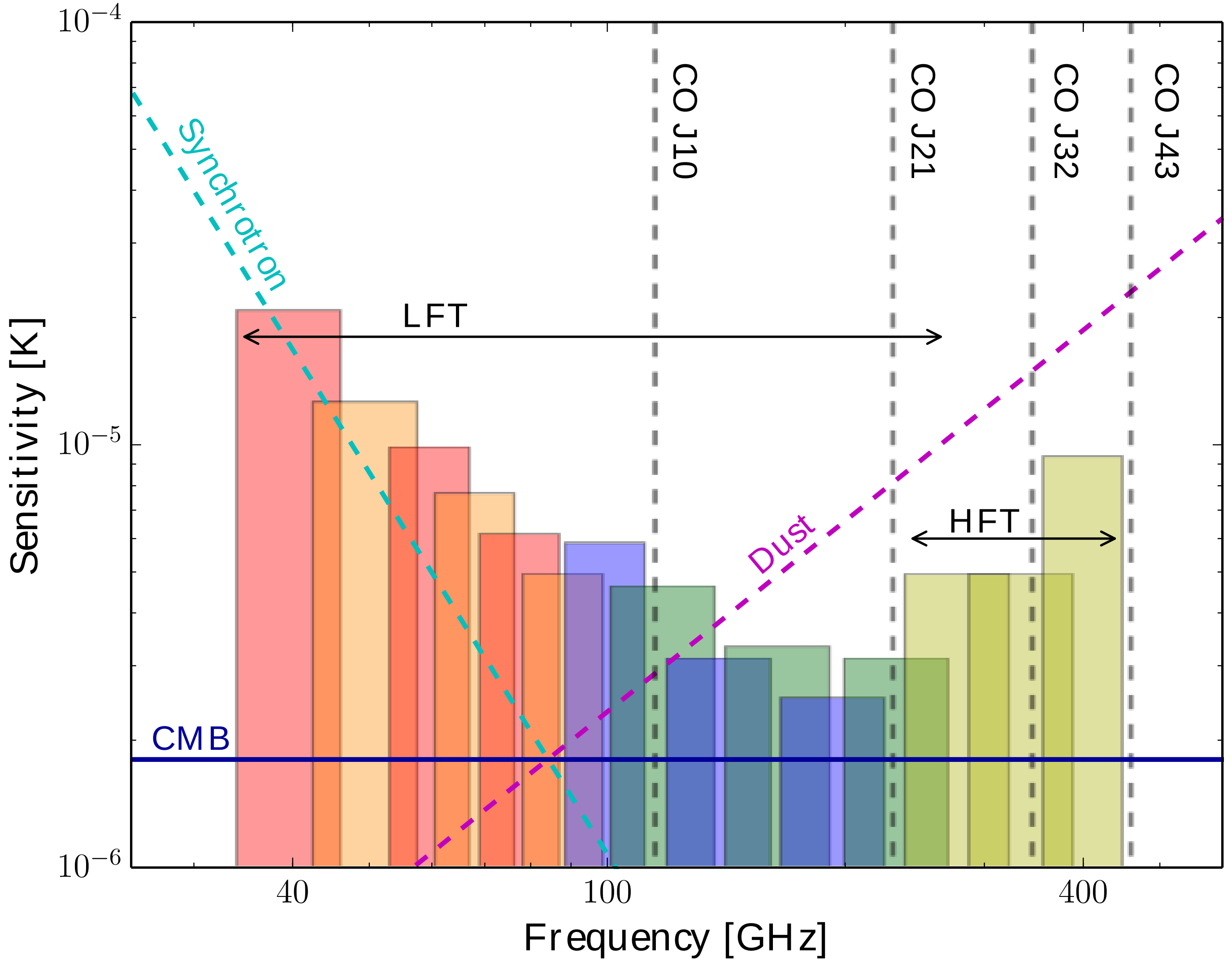
NIST





- Horn Coupled Array: Demonstrated performance at high frequency.

15 Frequency Bands



LiteBIRD Specifications

LiteBIRD

3-year observation assumed

Array	Band (GHz)	Bandwidth ($\Delta\nu/\nu$)	NEP ($aW/\sqrt{Hz}$)	NET ($\mu K\sqrt{s}$)	N_{bolo}	NET_{arr} ($\mu K\sqrt{s}$)	Sensitivity with margin (μK arcmin)
Low	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
Mid	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
High	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) $1.25\times$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

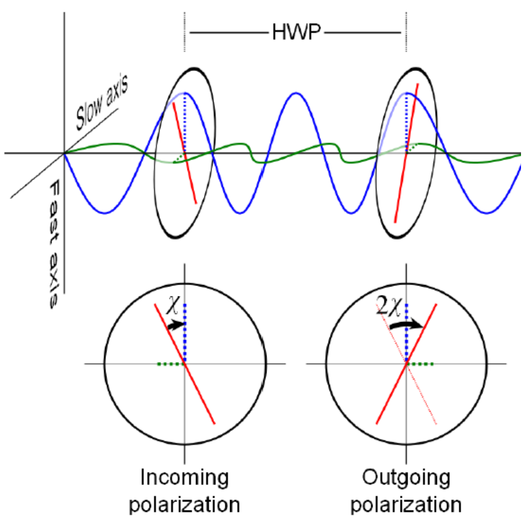
NIST

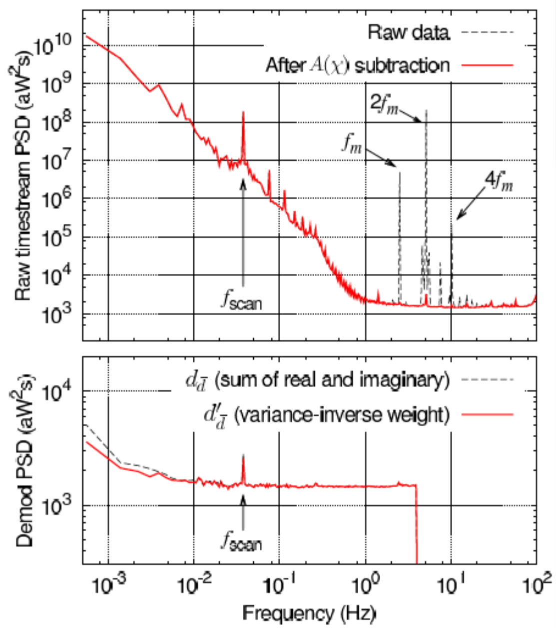
Berkeley

Continuously-rotating half-wave plate (HWP)

LiteBIRD

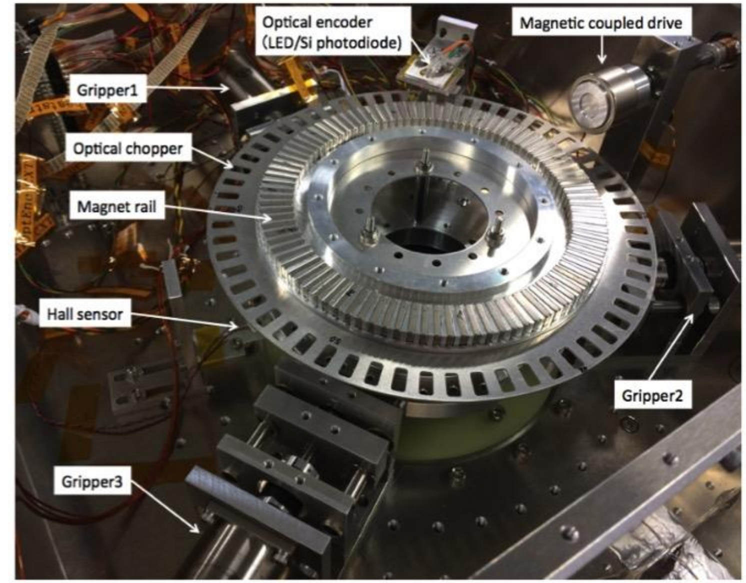
- Mitigate 1/f noise (signal at 4f)
- Mitigate “differential systematics”

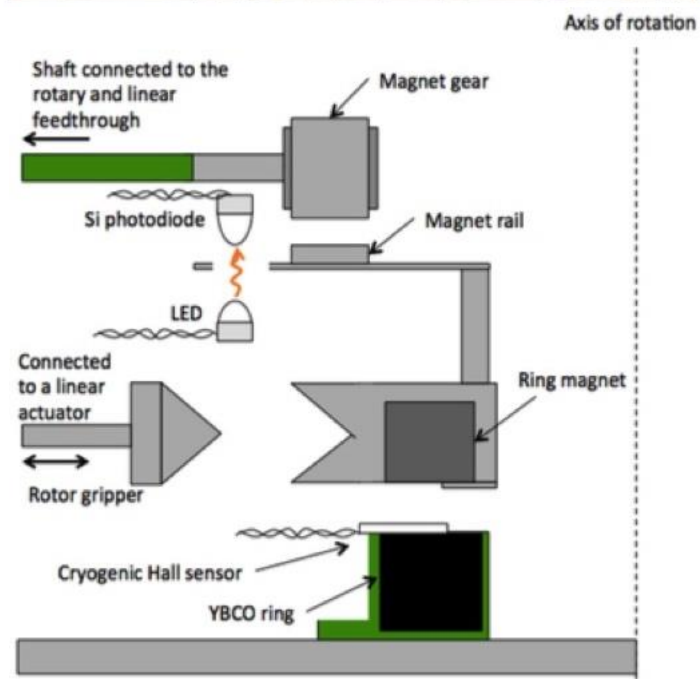




Example from ABS Project

HWP system BBM at JAXA





Cryogenic system (1): above 1K

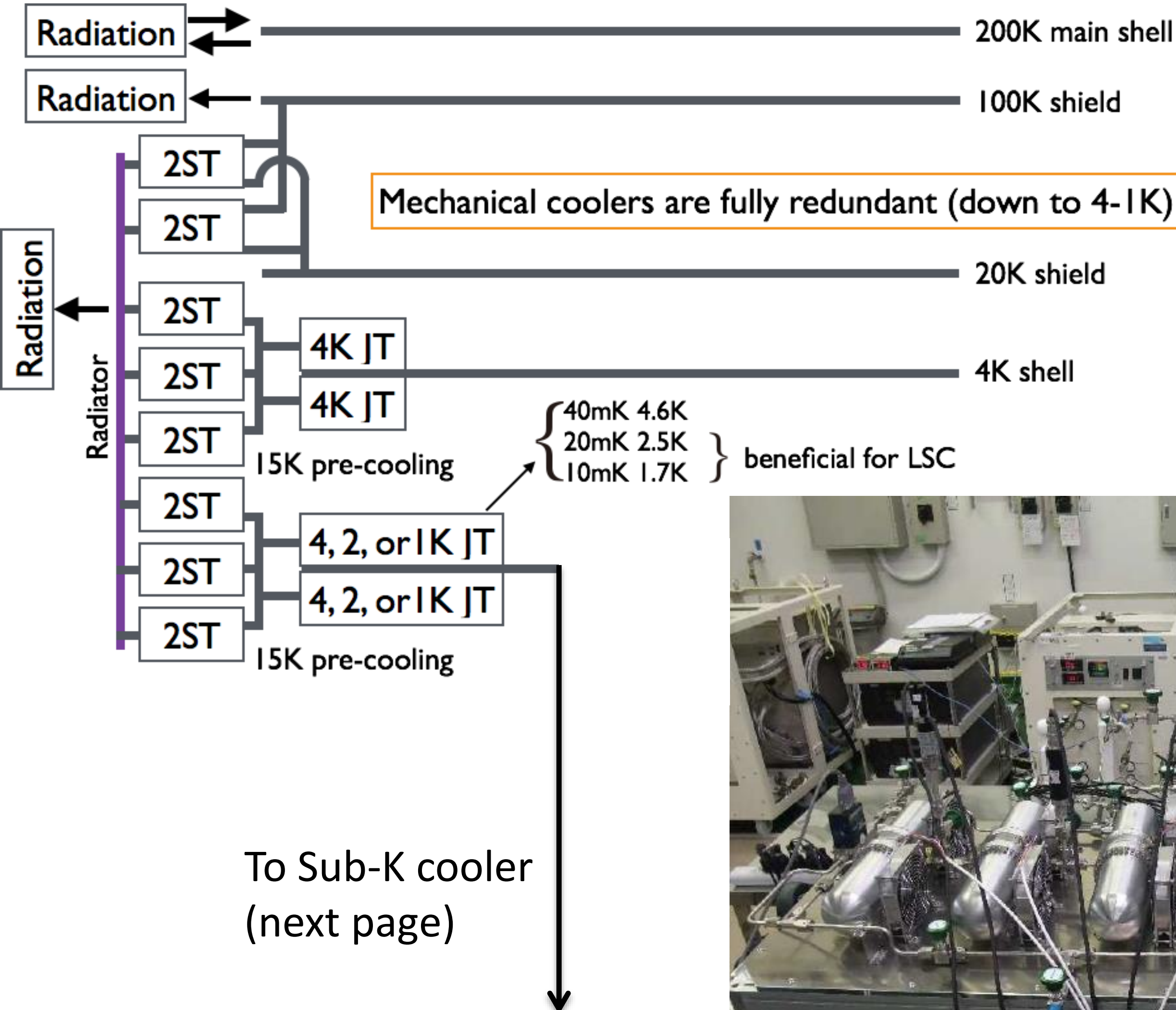
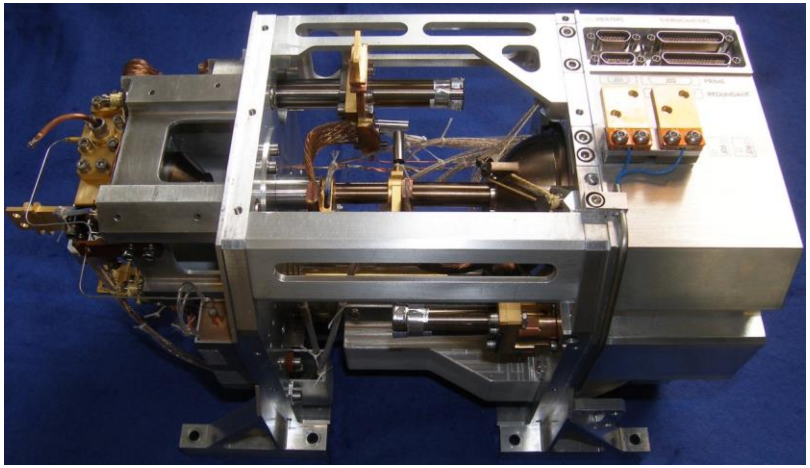


Photo of the 1K-JT Cryocooler Unit (©JAXA)

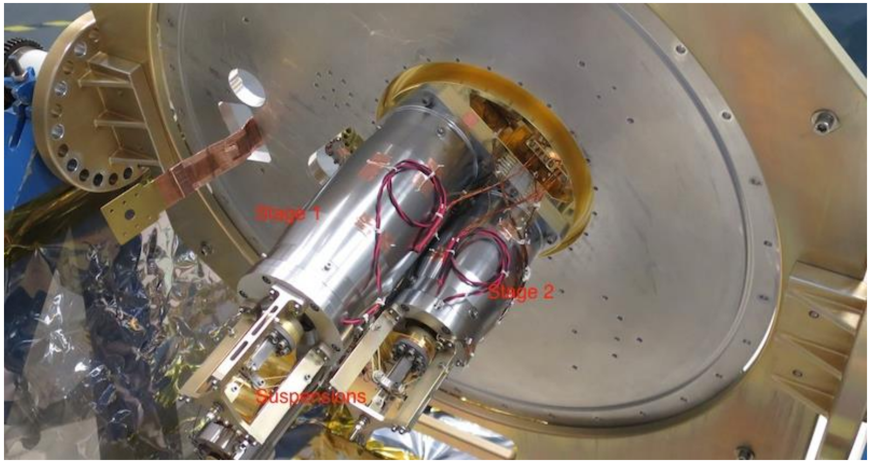
Cryogenic system (2): below 1K

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

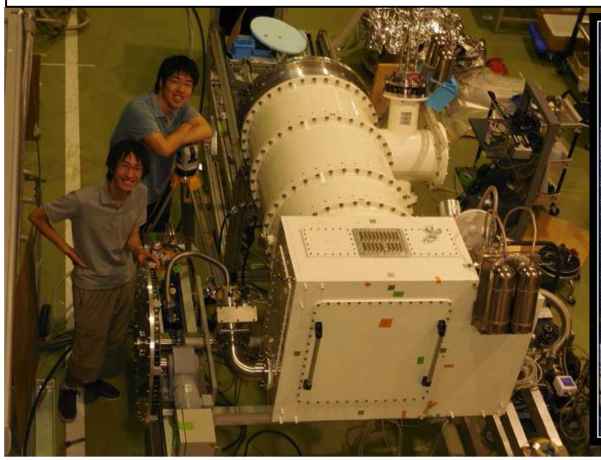


2. NASA
   - Based on Hitomi (Astro-H) design
   - 2-stage:
     - Salt pills at 100 mK and 300-800 mK
     - Depends on 1.8 K and 4.5 K provided
   - 3/4-stage options also considered
     - E.g., 100 mK, 500 mK, 1.2 K (continuous in 4-stage option)
     - No 1.8-K JT cooler required

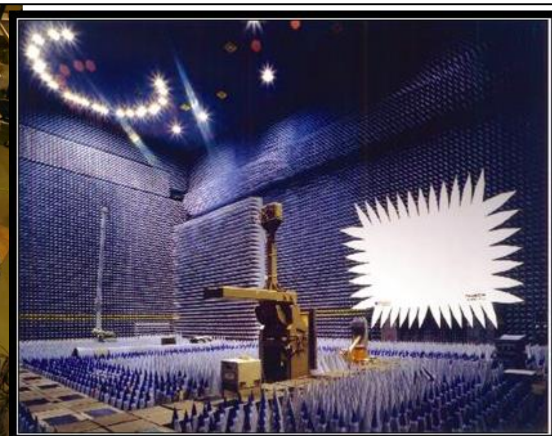


Testing and integrations

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



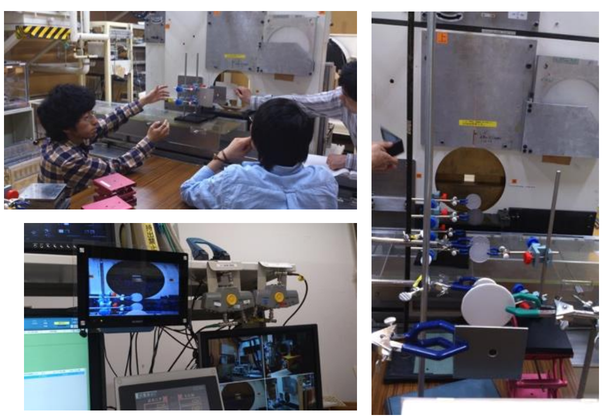
POLARBEAR2 integration is ongoing at KEK with sub-K cryogenic system and UC Berkeley TES bolometers.



JAXA Antenna test facility

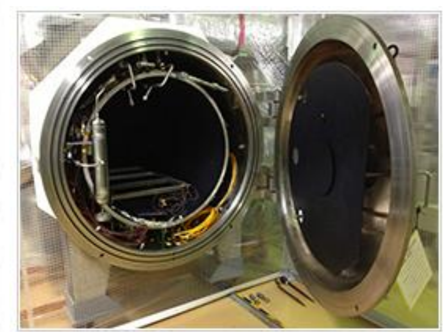
JAXA 13-m diameter space chamber

Astro-H test is done here.



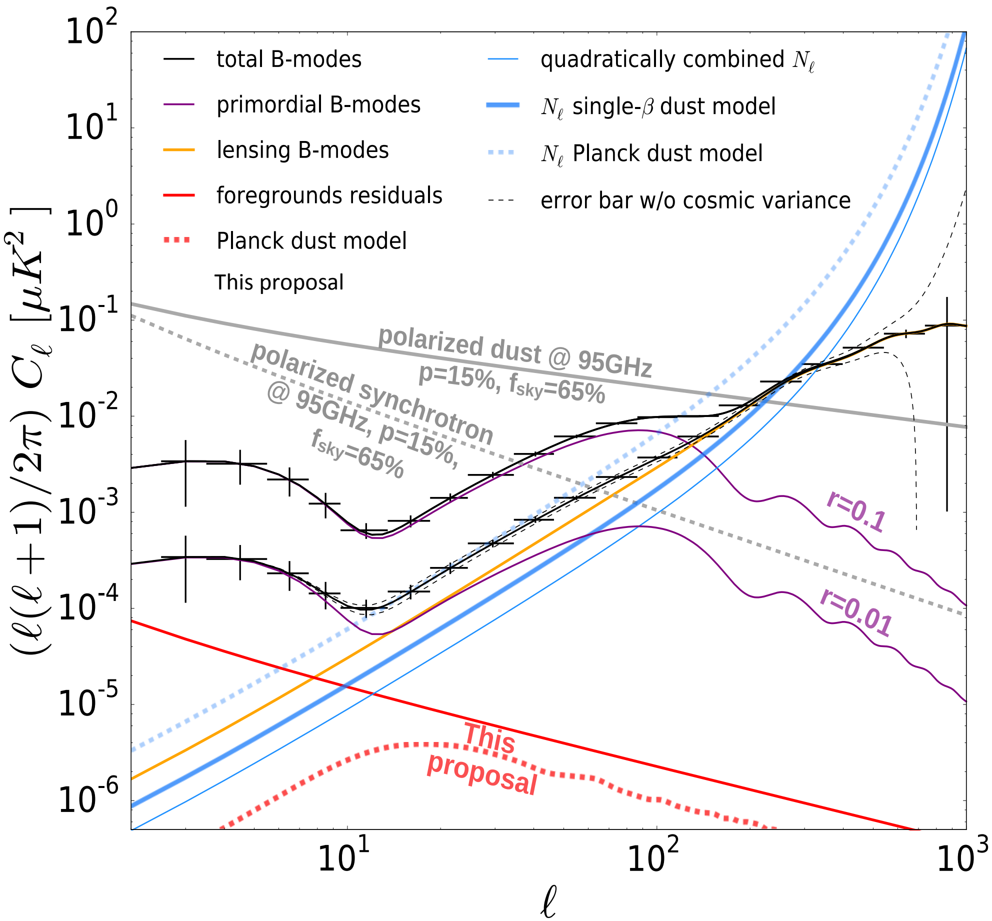
Proton irradiation tests at HIMAC

JAXA 6-m diameter space chamber



JAXA 1-m diameter space chamber

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%	

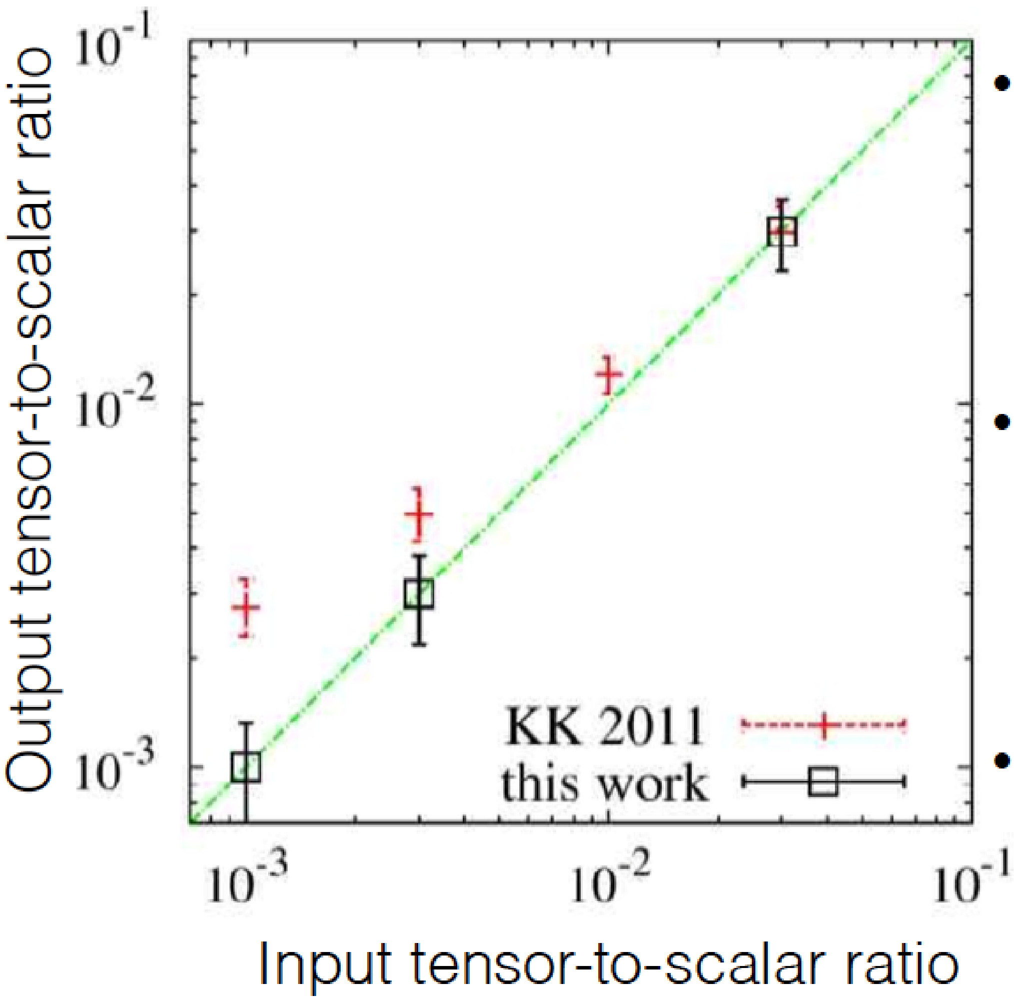
HWP angle dependence (in the new studies these are treated based on Muller matrix-like parameters)

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

Slide by Eiichiro Komatsu

Ichiki et al. (in prep)

Baseline Method



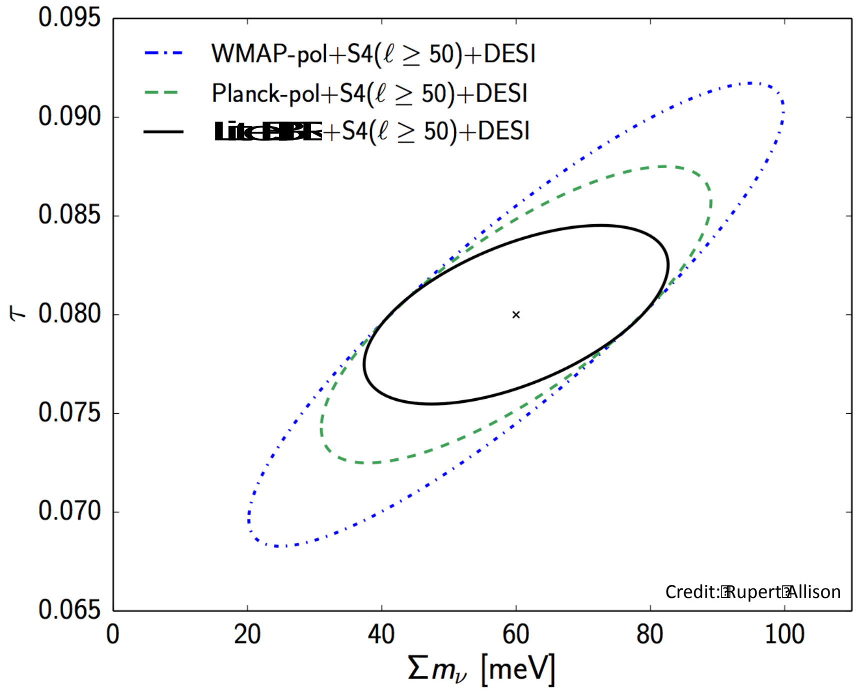
- We use *two* lower frequencies (e.g., 60 and 78 GHz) to solve for the spectral index variation
- **It removes the bias completely**, if the emission law is a power-law
- Inclusion of the curvature is straightforward

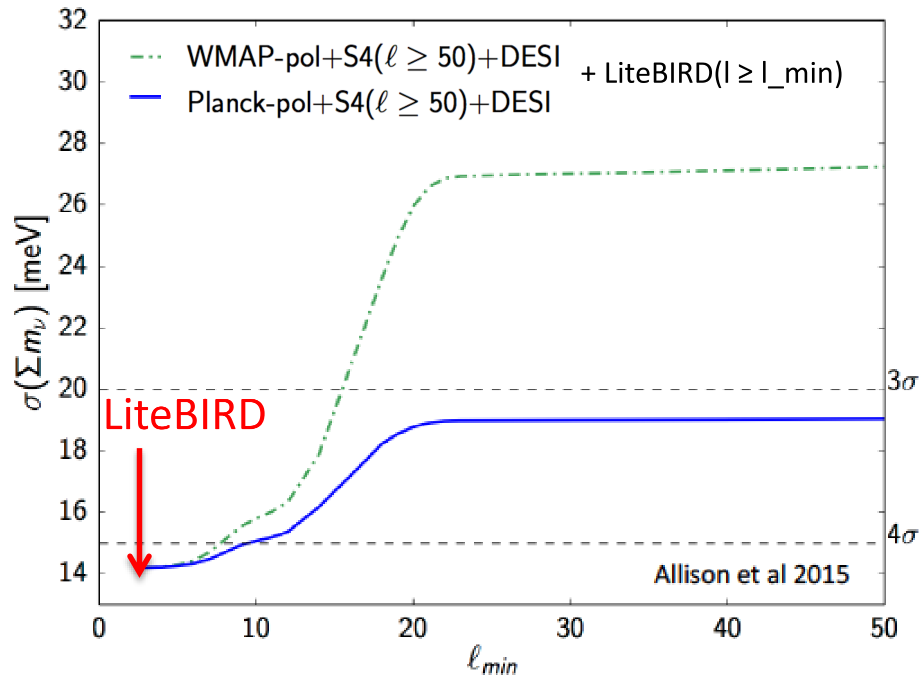
Scientific shopping list

1) C_l^{BB} → inflation and quantum gravity (r, n_t)
   → lensing B-mode to very low ℓ
2) C_l^{EE} → reionization history, better τ and sum of neutrino masses
3) Power spectrum deviation from ΛCDM
   → e.g. 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
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

2) τ(optical depth) and neutrino mass

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





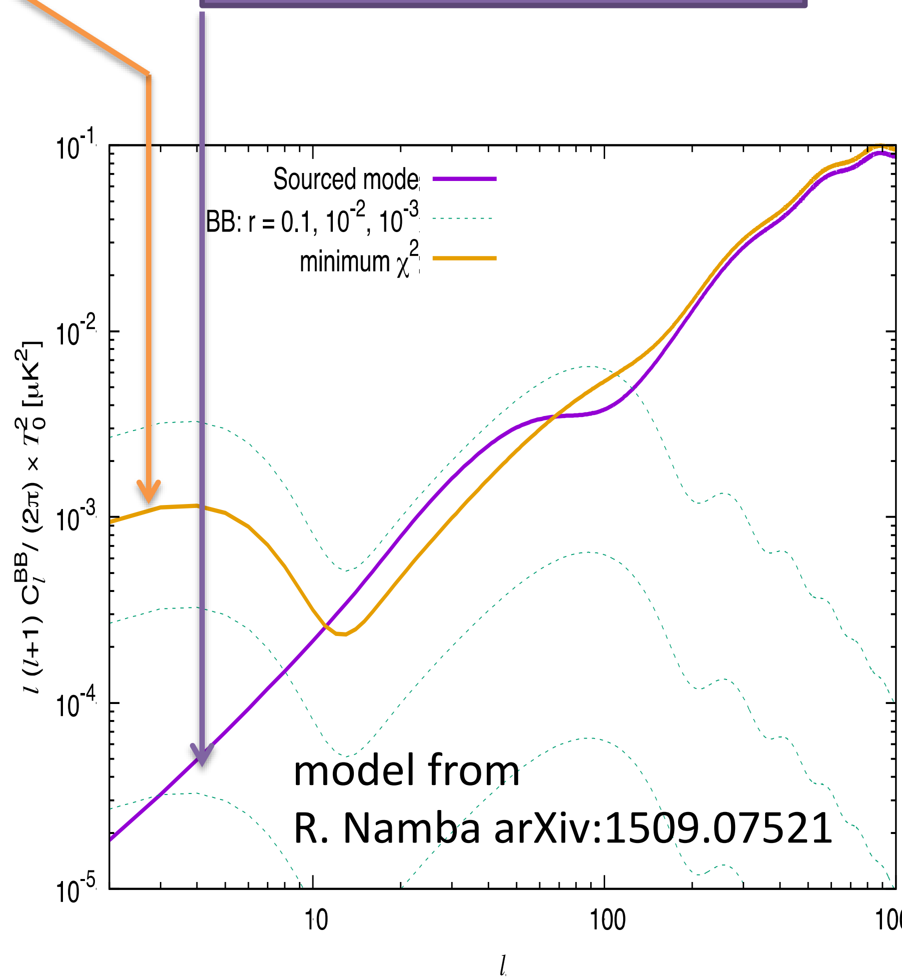
Low ℓ measurements contribute to Σm_ν !

3) and 4) Origin of gravitational waves

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 >3σ



M. Shiraishi et al. in preparation

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 !

Please join !