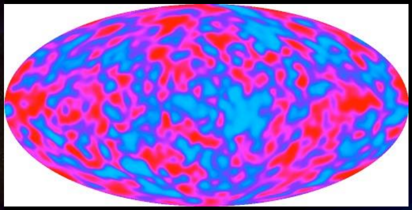
T. Matsumura（ISAS/JAXA） on behalf of the LiteBIRD WG

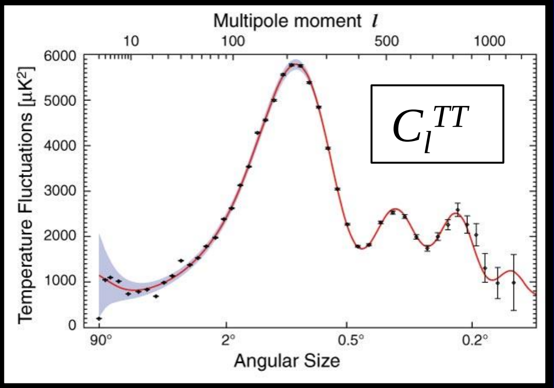
LiteBIRD

Lite satellite for the study of B-mode polarization and Inflation from cosmic microwave background radiation detection

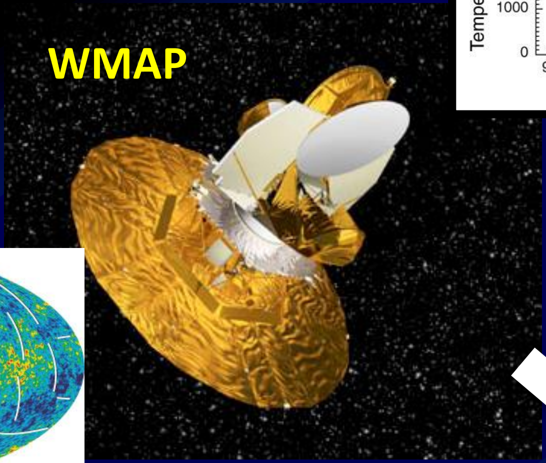
Background

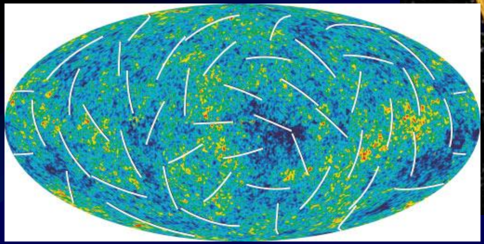
COBE



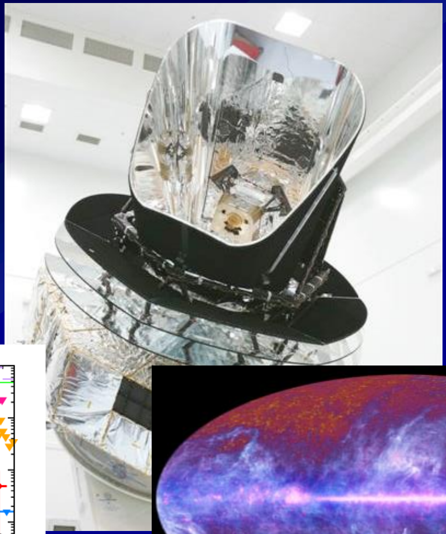


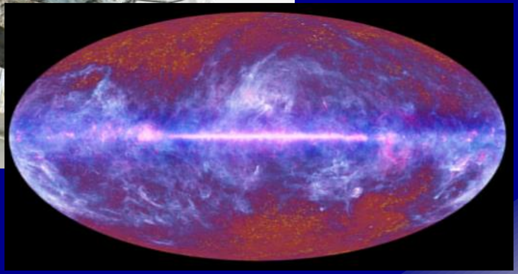
WMAP

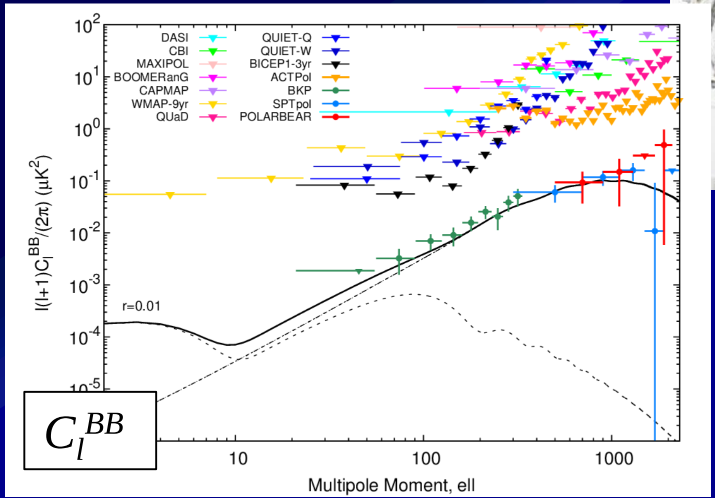




Planck



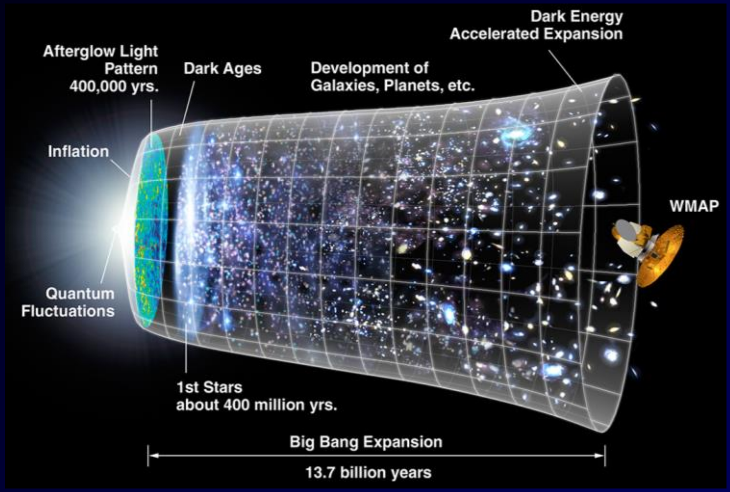


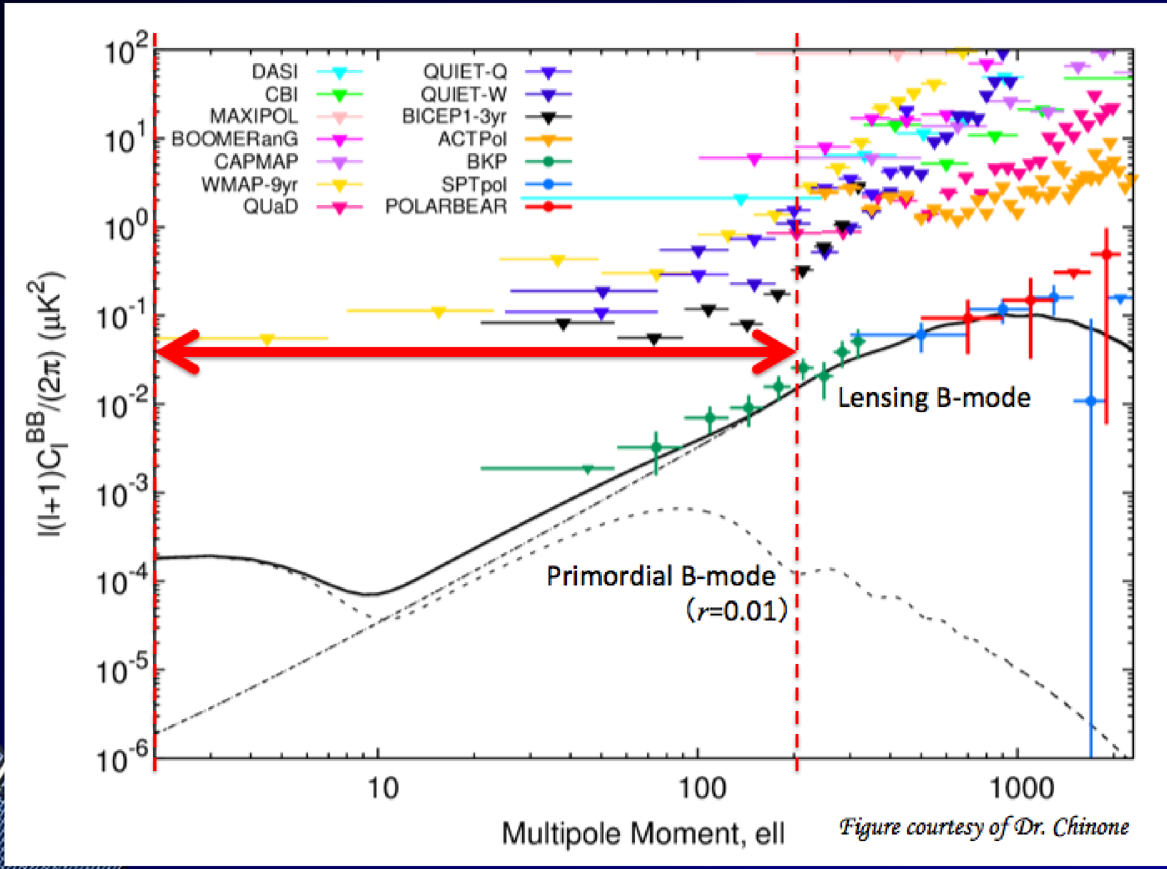


Next generation satellite

LiteBIRD

LiteBIRD is a next generation CMB polarization satellite that is dedicated to probe the inflationary B-mode. The science goal of LiteBIRD is to measure the tensor-to-scalar ratio with the sensitivity of $\sigma_r = 0.001$. In this way, we test the major large-single-field slow-roll inflation models.





LiteBIRD working group

121 members, international and interdisciplinary.

JAXA
H. Fuke
I. Kawano
H. Matsuhara
T. Matsumura
K. Mitsuda
T. Nishibori
K. Nishijo
A. Noda
A. Okamoto
S. Sakai
Y. Sato
K. Shinozaki
H. Sugita
Y. Takei
M. Utsunomiya
T. Wada
N. Yamasaki
T. Yoshida
K. Yotsumoto

Osaka U.
S. Kuromiya
M. Nakajima
S. Takakura
K. Takano

Osaka Pref. U.
M. Inoue
K. Kimura
M. Kozu
H. Ogawa
N. Okada

Okayama U.
H. Ishino
A. Kibayashi
Y. Kibe
Y. Kida
A. Okamoto
Y. Yamada

NIFS
S. Takada

Kavli IPMU
K. Hattori
N. Katayama
H. Sugai

KEK
M. Hazumi (PI)
M. Hasegawa
N. Kimura
K. Kohri
H. Morii
T. Nagasaki
R. Nagata
H. Nishino
S. Oguri
T. Okamura
N. Sato
T. Suzuki
O. Tajima
T. Tomaru
M. Yoshida

SOKENDAI
Y. Akiba
Y. Inoue
H. Ishitsuka
Y. Segawa
H. Watanabe

NAOJ
A. Dominjon
J. Inatani
K. Karatsu
S. Kashima
T. Nitta
T. Noguchi
S. Sekiguchi
Y. Sekimoto
S. Shu

Saitama U.
M. Naruse

NICT
Y. Uzawa

Konan U.
I. Ohta

U. Tokyo
N. Tomita

Kansei Gakuin U.
S. Matsuura

U. Tsukuba
M. Nagai

TIT
S. Matsuoka
R. Chendra

Tohoku U.
M. Hattori
T. Morishima

Nagoya U.
K. Ichiki

Yokohama Natl. U.
T. Fujino
F. Irie
K. Mizukami
S. Nakamura
K. Natsume
T. Yamashita

RIKEN
S. Mima
C. Otani

APC Paris
R. Stompor

CU Boulder
N. Halverson

McGill U.
M. Dobbs

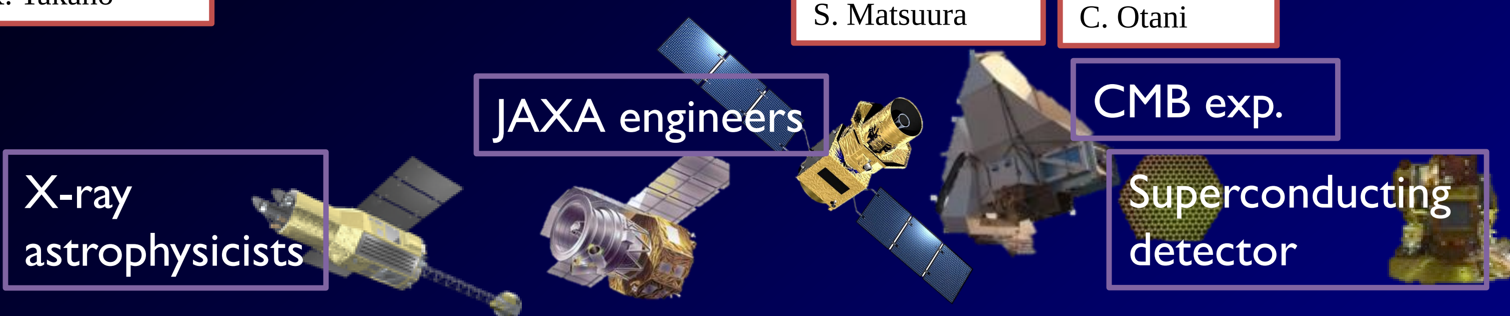
MPA
E. Komatsu

NIST
G. Hilton
J. Hubmayr

Stanford U.
K. Irwin
C.-L. Kuo
T. Namikawa

UC Berkeley / LBNL
J. Borrill
Y. Chinone
A. Cukierman
T. de Haan
J. Errard
N. Goeckner-wald
P. Harvey
C. Hill
Y. Hori
W. Holzapfel
O. Jeong
A. Kusaka
A. Lee(US PI)
E. Linder
P. Richards
U. Seljak
B. Sherwin
A. Suzuki
P. Turin
B. Westbrook
N. Whitehorn

UC San Diego
K. Arnold
T. Elleflot
B. Keating
G. Rebeiz



Project status of LiteBIRD

- ISAS/JAXA has three mission categories:
  1. Strategic Large Missions with HIIA ($300M)
  2. Competitively-chosen medium-sized focused mission with Epsilon rocket (<$150M)
  3. Missions of opportunity ($10M per year) for foreign agency-led mission, sounding rocket, ISS.

- We proposed LiteBIRD to the JAXA strategic large missions early this year, and LiteBIRD is down-selected as one of three candidate missions. Currently, LiteBIRD is in transition to the phase-A study.
- We also proposed to the NASA missions of opportunity and the proposal is under the review for down-selection.
- The target launch year is in early 2020s.

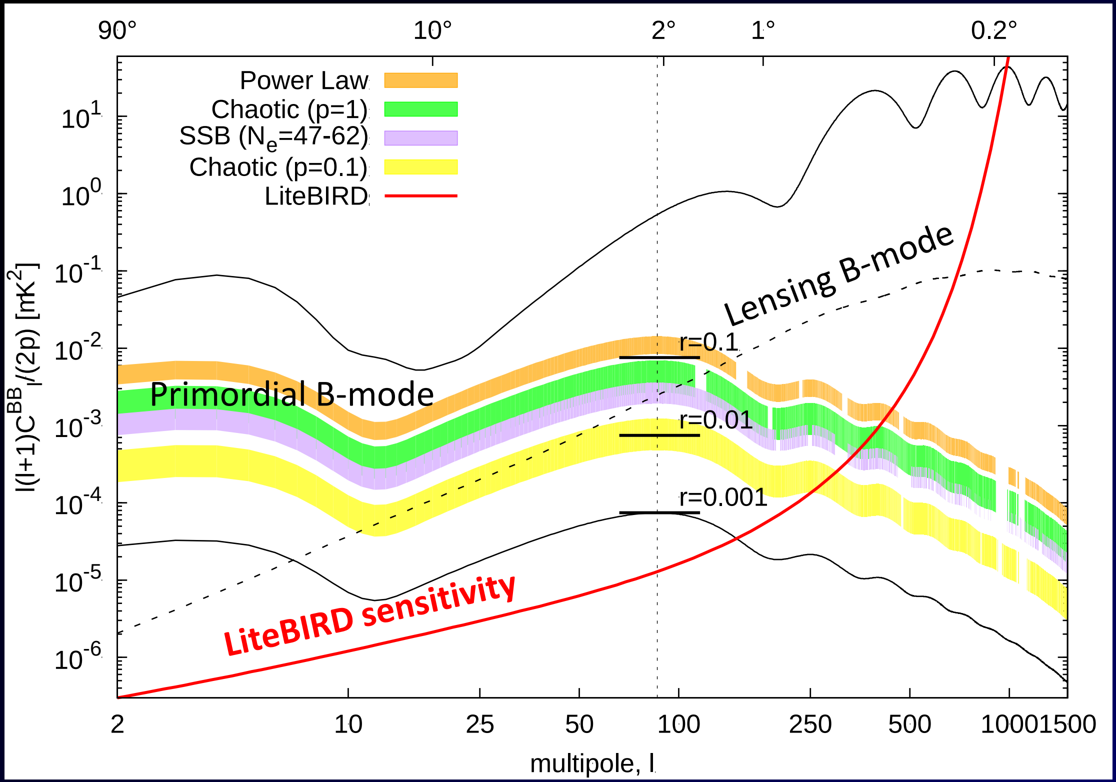
Overview of the baseline LiteBIRD design

Key design parameters

The mission sensitivity relies on a few key parameters.

Angular resolution

Array sensitivity

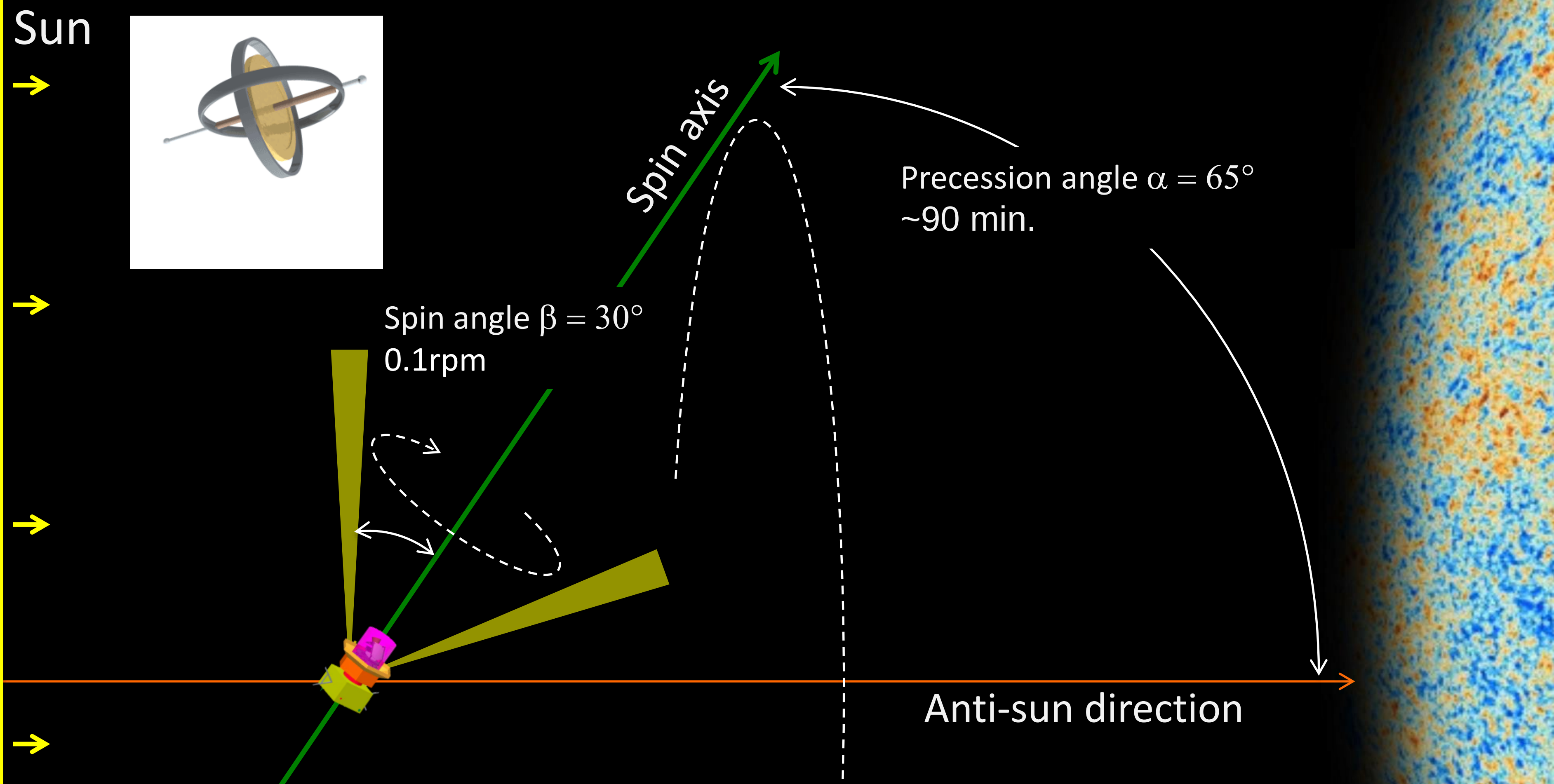


Sky coverage

M. Hazumi et al. 2012

- Foreground subtraction: Observing frequency and the sensitivity at each band
- Array sensitivity: Optical system and detectors
- Angular coverage: Optical system
- Full sky observation: Orbit and Scan strategy

Scan strategy at *L2*



<u>Major Specifications</u>

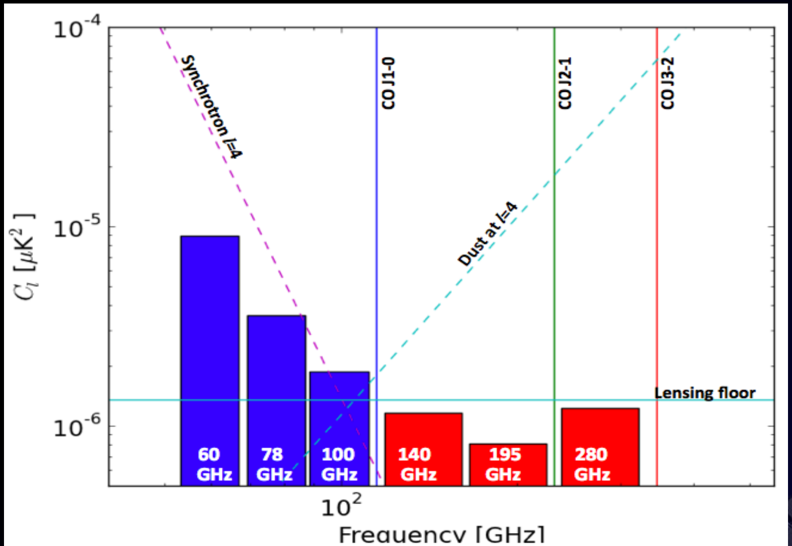
- Weight: ~1300kg
- Power: ~2000W
- Observing time: ≥3 years
- Spin rate: ~0.1rpm (=1.6mHz)

<u>Signal modulation</u>

The signal is modulated by the scan strategy and the rotating HWP to mitigate the $1/f$ noise and the systematics.

Mission instrument overview (1/2)

Observing band

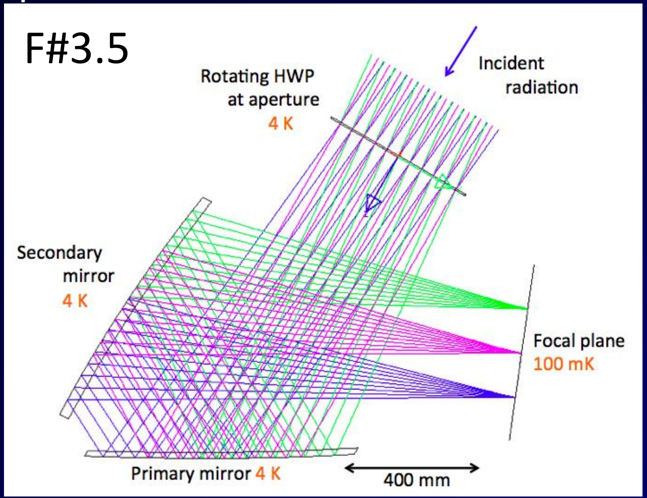


- Place 6 bands at
  60, 78, 100, 140, 195, 280 GHz.
- Avoid CO lines.
- In case of a need for more bands, we have an option to vary the band center for each detector and increase the number of bands effectively.

Extended observing frequency coverage is in option. (see later slide)

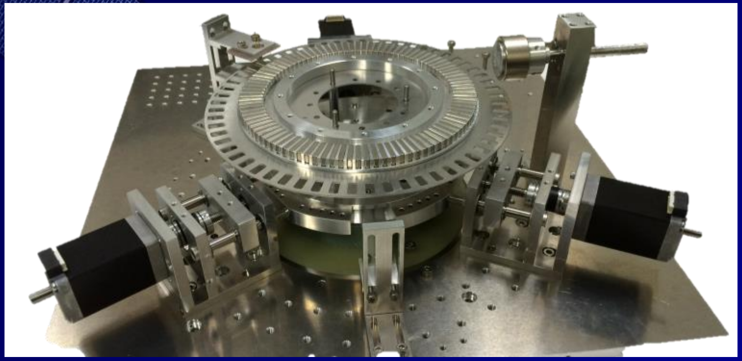
Optical system

Optical system Modified cross-Dragone optics 10x20 degrees^2 field-of-view with >99% Strehl ratio over all the observing bands. The telecentric focal plane (D=300mm w/ F#=3.5). Similar telescope from QUIET and ABS.



Polarization modulator

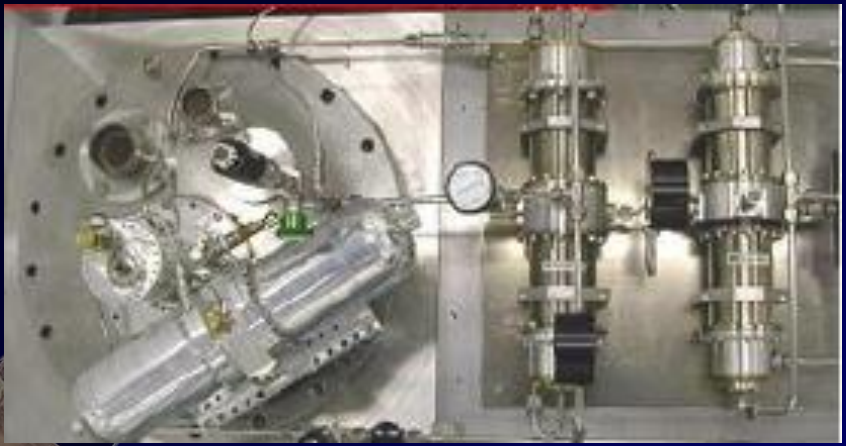
Continuously rotating achromatic HWP mechanism at cryogenic temperature. Heritage from EBEX, and ongoing observations using the continuous rotation in ABS and POLARBEAR.



Mission instrument overview (2/2)

Cryogenics

- Warm launch
- 3 years of observations
- 4K for the mission instruments (optical system)
- 100mK for the focal plane



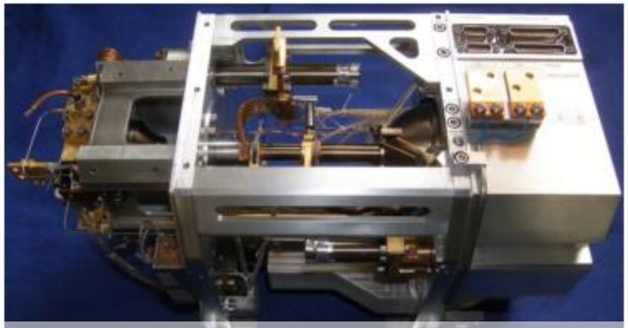
Mechanical cooler

- The 2-stage Stirling cooler and 4K-JT cooler from the heritage of the JAXA satellites, Akari (Astro-F), JEM-SMILES and Astro-H.
- There is an option to employ the 1K-JT that provides the 1.7 K interface to the sub-Kelvin stage.

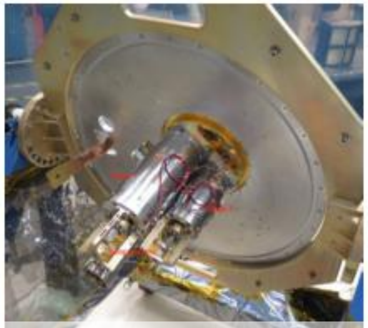
Sub-Kelvin cooler

- ADR has a high-TRL and extensive development toward SPICA, Astro-H, and Athena.
- Closed dilution with the Planck heritage is also under development.

	ADR + 3He sorption (CEA)	3-stage ADR (NASA/GSFC)	2-stage ADR (JAXA/SHI)
TRL	5 for SPICA 7 (sorption for Herschel)	6 for Astro-H	4
Thermal interface	1.7 K	4 K	4 K



ADR from CEA



ADR from GSFC

ADR from JAXA/SHI

Focal plane and detector technology

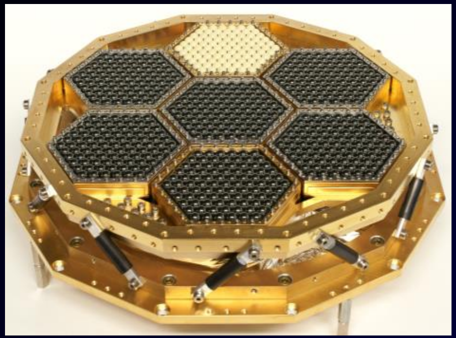
Detector and readout

Requirements

- Sensitivity : Optical NEP ～ aW/√Hz
- Broad frequency coverage : 50 – 300 GHz
- Multi-pixel array: ~2000
- Stability
- High yield
- Low power consumption (< 100W total)
- Controlled sidelobe at a feed
- High TRL

Transition edge sensor (TES) bolometer

Example from POLARBEAR focal plane



Z. Kermish Ph.D. thesis
UC Berkeley

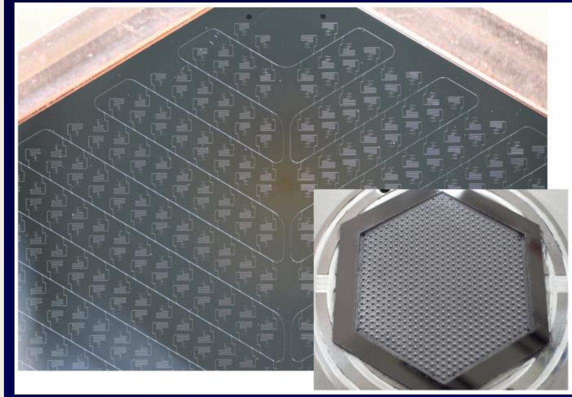
PB-1
1274 TESs with 80% yield.
NET per array: 23 μK√s

PB-2
2 bands/pixel （95,150GHz）
7588 TESs (1897×2pol×2band)
Readout is DfMUX with
MUX=32(+) by McGill Univ.

Matured technology used by the various CMB experiments. Need space qualified low loading TES and low power consumption readout.

Microwave kinetic inductancedetector (MKID)

Example of MKID from NAOJ.



K. Karatsu et al. 2013

NEP ～ 6×10^{-18} W/√Hz
Single band at 200GHz
MUX=600

More examples from JPL, SRON and others.

Attractive features and rapid progress in the MKID development. Potential candidate for a future mission in next a few years.

Detector and readout

Requirements

Talk/Poster

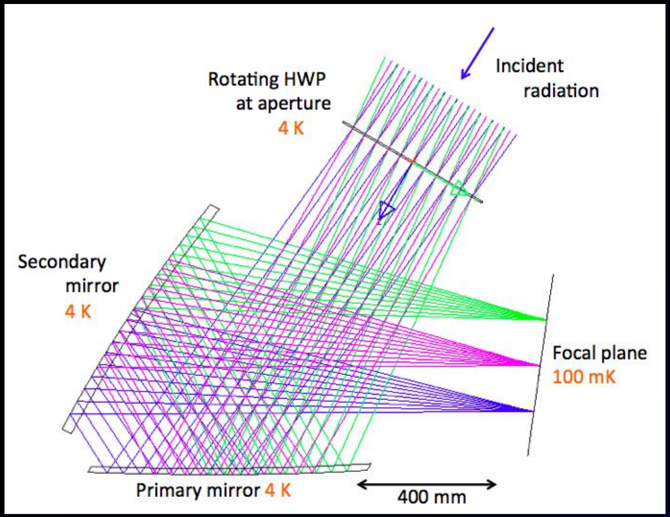
TES, readout, lenslet AR coating technology

- A. Bender et al. "SPT-3G: The Next Generation Receiver for the South Pole Telescope"
- K. Hattori et al. "Development of readout electronics for POLARBEAR-2 Cosmic Microwave Background experiment."
- A. Suzuki et al. "The POLARBEAR-2 and the Simons Array Experiment."
- O. Jeong et al. "Broadband plasma sprayed anti-reflection coating for millimeter-wave astrophysics experiments."
- K. Rotermund et al. "Planar Lithographed Superconducting LC Resonators for Frequency Domain Multiplexed Readout Systems."
- P. Siritanasak et al. "The broadband anti-reflection coated extended hemispherical silicon lenses for Polarbear-2 Experiment."
- B. Westbrook et al. "Development of the next generation of multi-chroic sinuous antenna coupled transition edge sensor detectors for CMB polarimetry."

MKID, corrugated horn

- K. Karatsu et al. "Radiation Tolerance of Al Microwave Kinetic Inductance Detector."
- S. Sekiguchi et al. "Direct machined broadband corrugated horn array for millimeter." observations"
- Y. Sekimoto et al. "Design of Corrugated Horn Coupled MKID Focal Plane for CMB Bmode polarization satellite : LiteBIRD."
- S. Shu et al. "Design of the planar OMT-MKID for corrugated horn."

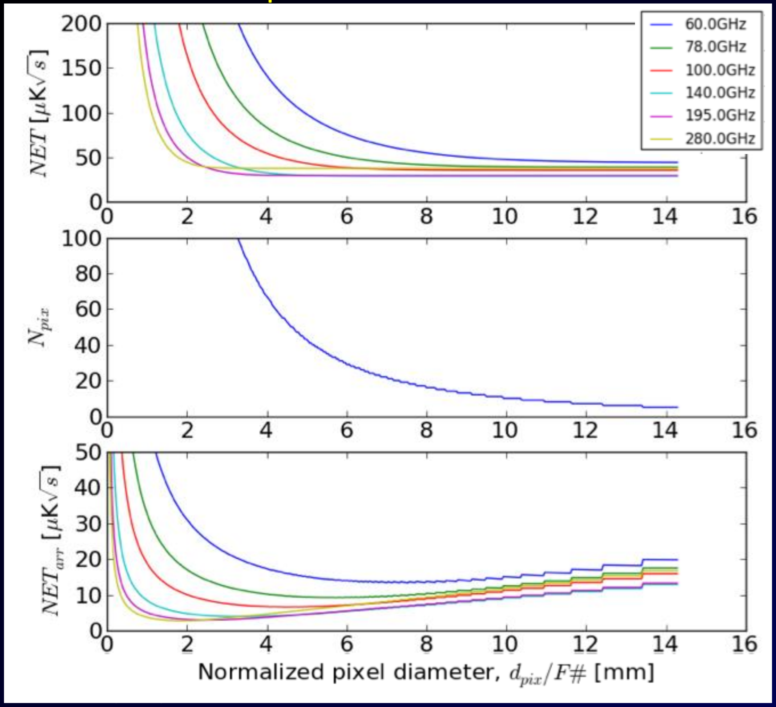
Baseline instrument model and sensitivity



Source	Temperature [K]	Emissivity	Efficiency
CMB	2.725	1	1
Achromatic half-wave plate	4	0.1	0.98 (AR)
Aperture	4	1	$1-\epsilon_s$
Primary and secondary mirrors	4	0.005	1
Infrared filter	1	0.1	0.95
Lens	0.1	0	0.99 (AR)
Antenna and micro-strip related	0.1	N.A.	0.73

The cross-Dragone telescope provides the diffraction limited focal plane size of D=300mm.
We employed the tri-chroic pixel using TES to optimize the focal plane configurations.

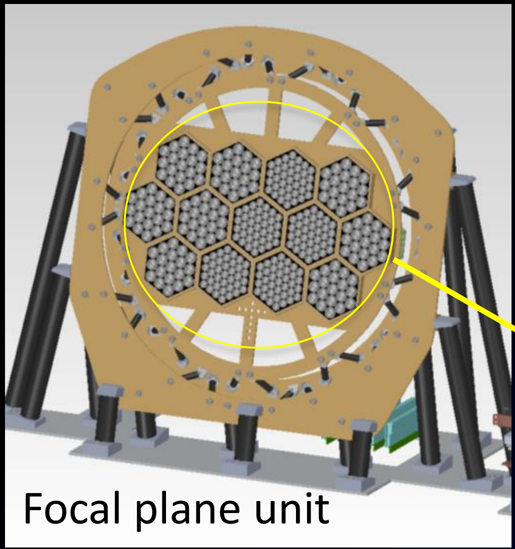
NET with TES option



Band [GHz]	N_{det}	P_{load} [pW]	G_{ave} [pW/K]	NEP [aW/√Hz]	NET [μK√s]	w^{-1} [μK.arcmin]
60	304	0.296	6.49	8.28	94.07	15.72
78	304	0.301	6.61	8.61	58.97	9.86
100	304	0.286	6.27	8.72	42.26	7.06
140	370	0.361	7.92	10.56	36.89	5.59
195	370	0.243	5.32	9.45	31.00	4.70
280	370	0.123	2.70	7.57	37.54	5.69
Combined	2022					2.65

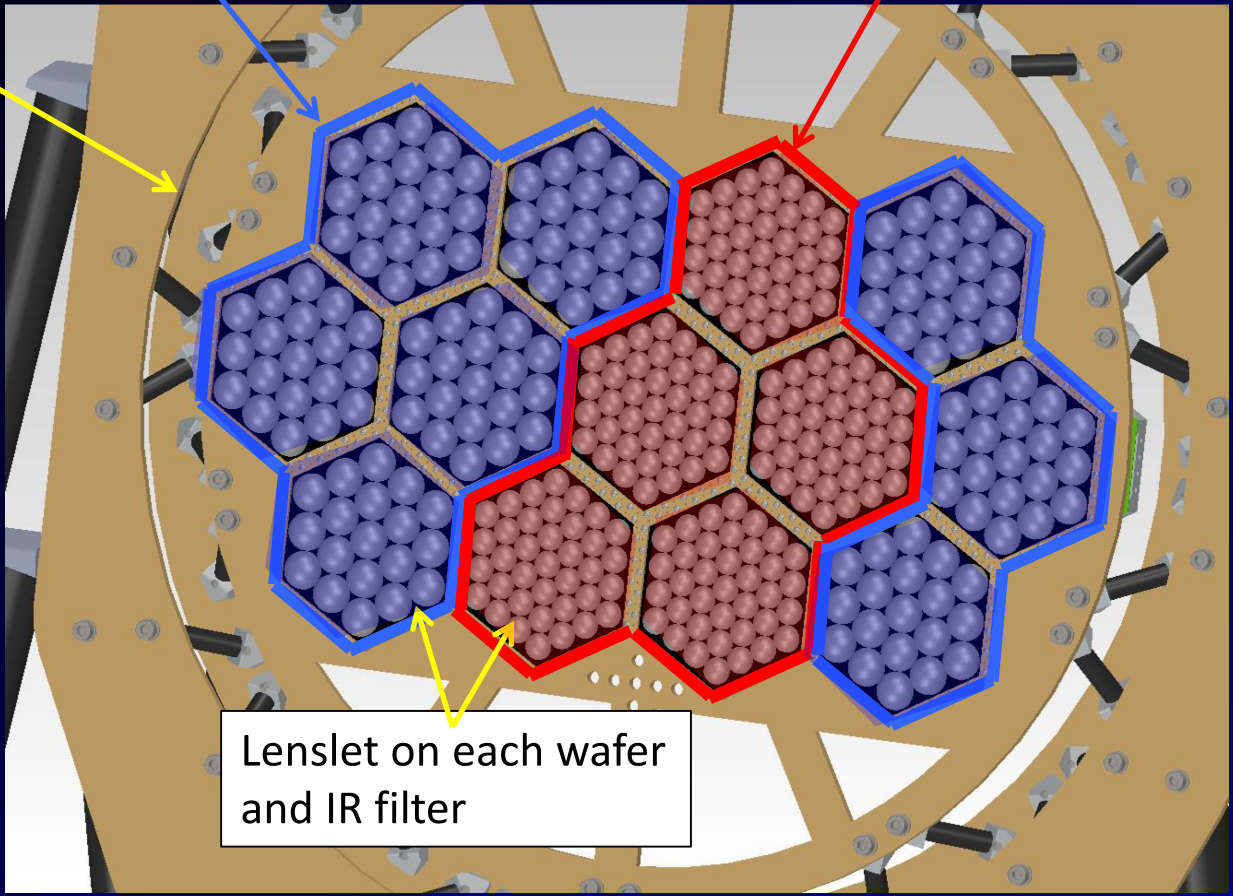
Note: The sensitivity w^{-1} is computed with the following assumptions:
1. Observational time of 3 years with the efficiency of 72%.
2. The detector yield is 80 %.
3. NET has a margin of 1.25.

Baseline design for TES option using tri-chroic pixel



- Low Frequency Wafer (× 8）
  with (60/78/100) GHz
- 185 pixels with 18 mm Si-lens diameter.
- IR filter < 140GHz

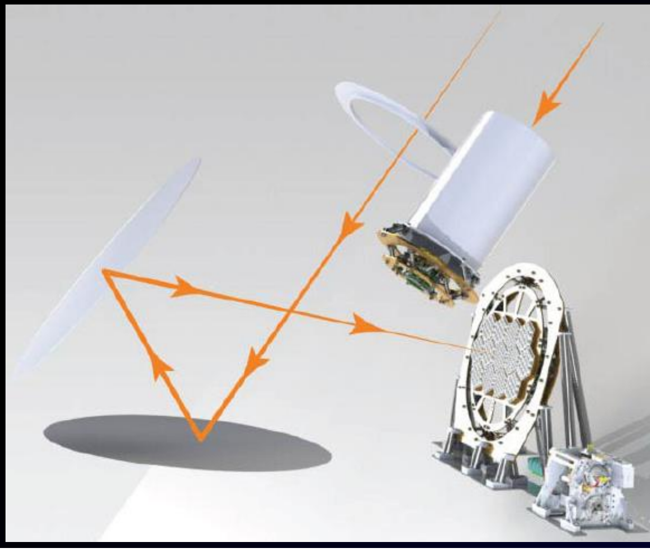
- High Frequency Wafer (× 5）
  with (140/195/280) GHz
- 152 pixels with 12 mm Si-lens diameter
- IR filter < 350 GHz



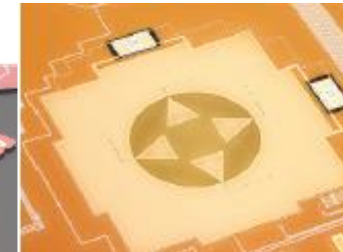
- All the detectors are within the Strehl ratio > 99 %.
- The IR low-pass filters are placed at each wafer to minimize the thermal load to the 100mK stage.
- The corresponding readout is based on the SQUID/DfMUX with the mux factor of 64. We keep the total power consumption by the readout is less than 100W.
- The corresponding date rate is 1.4 GB/day.

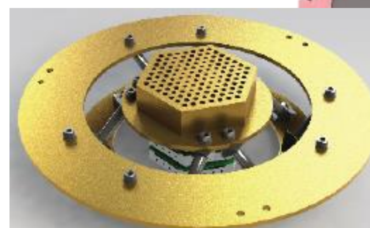
Extended focal plane configurations

Extended band and its focal plane

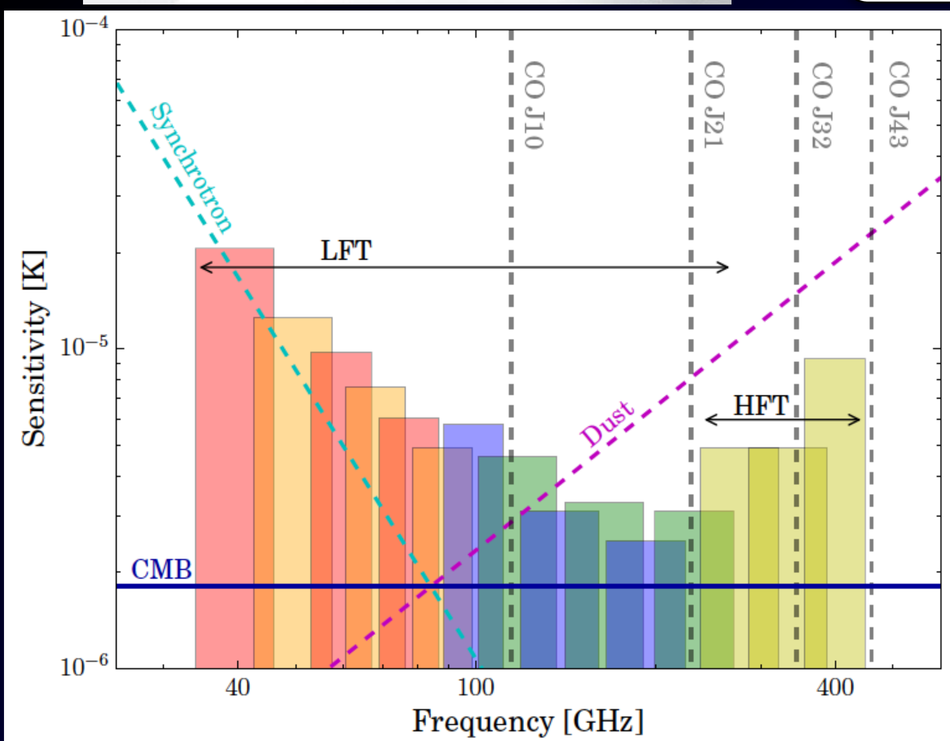


High Frequency telescope (HFT)

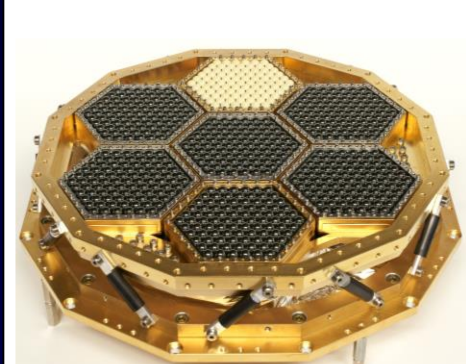


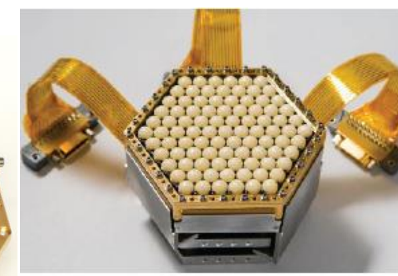


The TES array with corrugated feedhorn developed for ABS, ACTpol, SPTpol by UC Boulder, NIST, and Stanford.



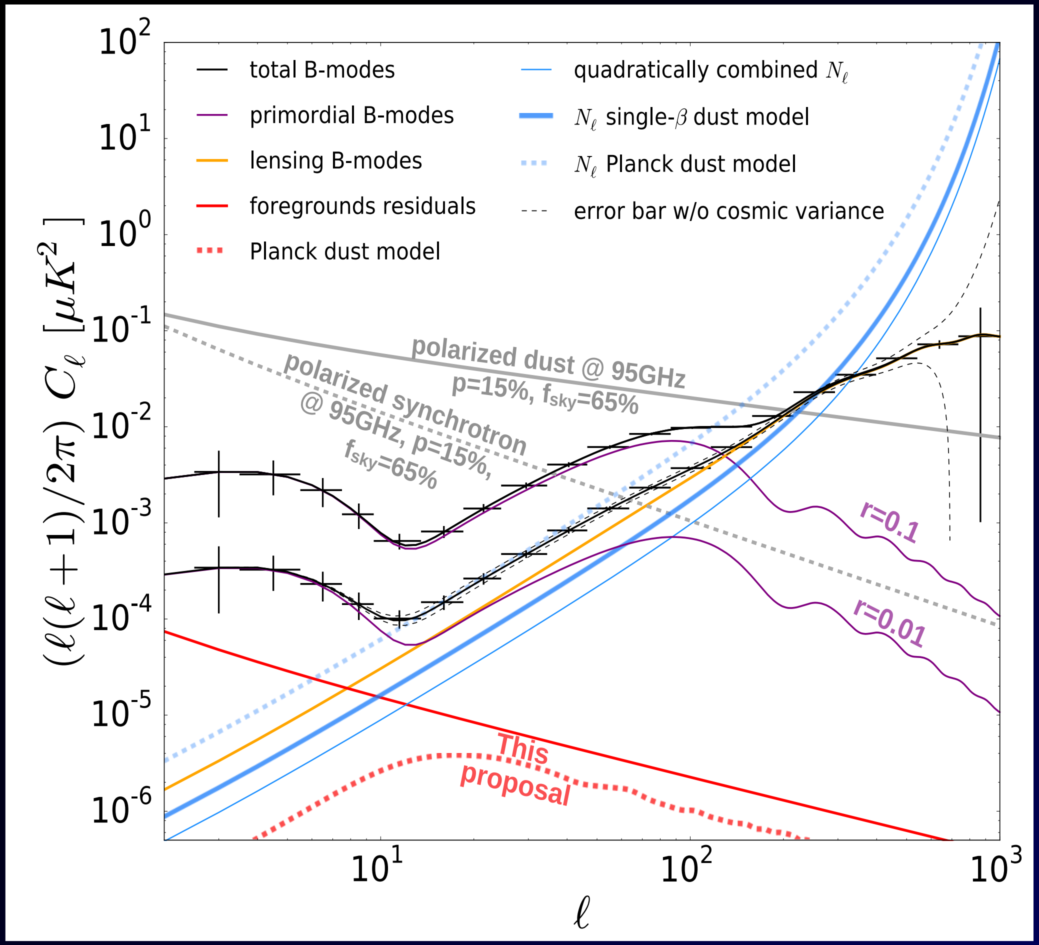
Low Frequency telescope (LFT)





The TES array with a lenslet developed for POLARBEAR by UC Berkeley and UCSD.

Sensitivity w/ foreground subtraction



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

for r = 0.01, including foreground removal and cosmic variance

$r < 0.4 \times 10^{-3}$

(95% C.L.)

for undetectably small r

Residual computation method: Errard et al. 2011, Phys. Rev. D 84, 063005 and another paper in preparation

Summary

- LiteBIRD is a dedicated satellite mission to probe the primordial B-mode polarization.

- LiteBIRD is in the transition to the phase-A study. During this period, we will go through the tradeoff in the various options in the mission instrumental design and solidify the feasibility to achieve the science goal.

Acknowledgement: This work was supported by JSPS Core-to-Core Program, A. Advanced Research Networks.

B mode from Space -- Part 1: The cience goals, status of spaceborne projects, foregrounds (Dec 10 -12), Part 2: Mission design, technologies and challenges for the spaceborne observations (Dec 14 -16) --

10-16 December 2015
Asia/Tokyo timezone

Purpose of this Workshop:
The goal of the workshop is to discuss the science goals, status of CMB polarization projects, foregrounds and mission design, technologies and challenges for the spaceborne observations of CMB polarization to detect primordial gravitational waves and thus to prove the inflation theory. The workshop will be the first meeting where the LiteBIRD mission is focused on.

Dates: Dec 10 (Thu) - 16 (Wed), 2015

Part 1: Dec. 10 -12th: the science goals, status of spaceborne projects, foregrounds

Part 2: Dec. 14 -16th: mission design, technologies and challenges for the spaceborne observations

Venue: Lecture Hall (1F), Kavli IPMU main building

Program: not yet vailable

Organizers: M. Hasegawa (KEK), M. Hazumi (Kavli IPMU/KEK), H. Ishino (Okayama), T. Matsumura (ISAS/JAXA), Y. Sekimoto (NAOJ), H. Sugai (Kavli IPMU), N. Katayama (Kavli IPMU)

Contact Address: : Kavli Institute for the Physics and Mathematics of the Universe (Kavli IPMU), the University of Tokyo, 5-1-5 Kashiwanoha, Kashiwa City, Chiba 277-8583, Japan

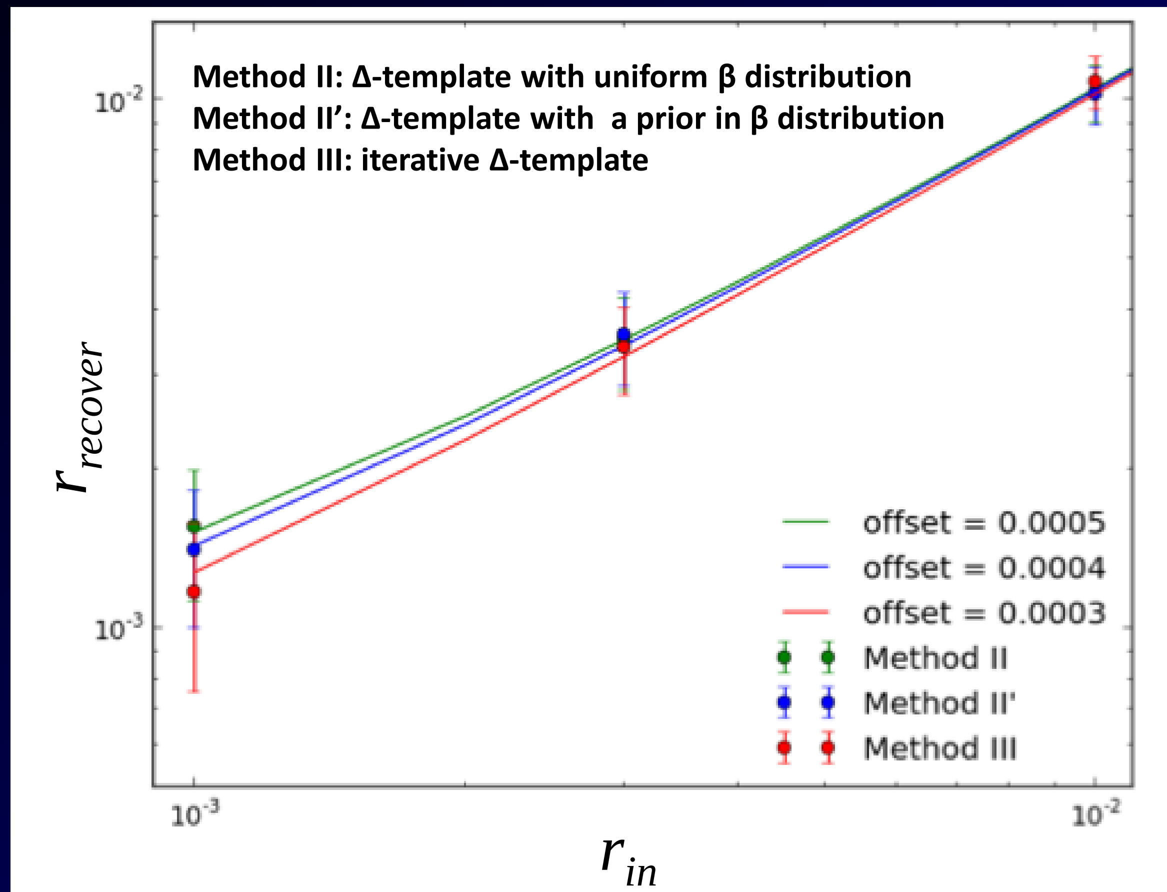
LTD properties we keep eye on…

Characteristic parameters	NET	Obs. Time × # of Det.	Filtering effect	Calibration requirement	System requirement
White noise	○				
1/f knee	○		○	Gain	
Dynamic range		○			
Linearity				Responsivity	
Tuning time		○			
MUX					Thermal design req.
Tolerance to the cosmic ray (Glitch)	○	○			Data rate
Tolerance to the cosmic ray (Degradation)	○			Band path, beam	
Time constant			○	Beam degeneracy	
Frequency coverage					Impact to FG remov.
Required bath temperature stability	△		○	Gain	Thermal design req.
Required power (incl. the readout)					Power and mass
Beam coupling and beam shape				Beam	Thermal design req.
Freq. dependent polarization angle				Polarization	
Yield		○			
Susceptibility to the external magnetic field	△		○	Gain	Mass

Foreground subtraction exercise using a template method with 6 bands

We apply the template method to the Planck sky model (Dust polarization fraction is set to be ×3) using the 6 bands, and test the recovery of tensor-to-scalar ratio, r. Use l <47 and f_{sky} of 50%.

Band (GHz)	Sensitivity (μK arcmin)
60	10.3
78	6.5
100	4.7
140	3.7
195	3.1
280	3.8
Total	1.8 (2.9[b])



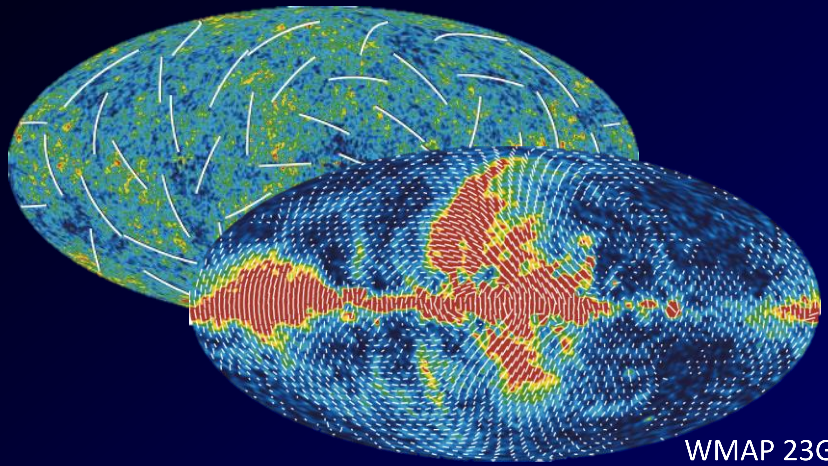
Planck CMB polarization data will be released in late 2014 and we will revisit to this optimization with Planck data.

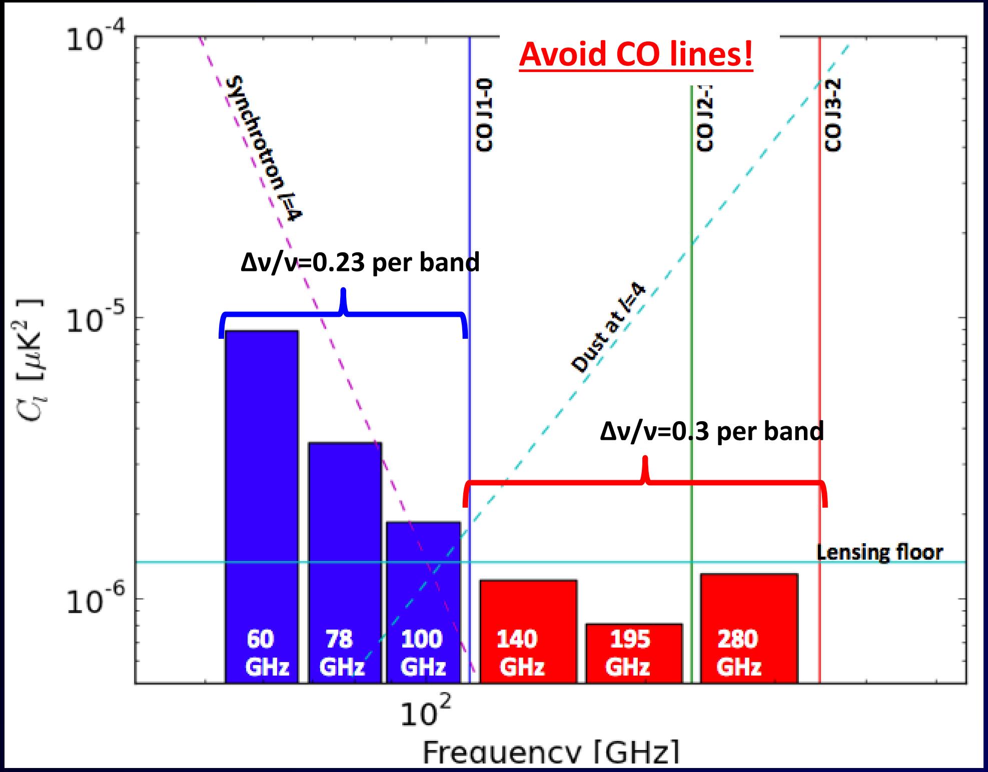
Katayama et al. in prep.

Observing frequency range

N. Katayama and E. Komatsu (ApJ 737, 78 (2011), arXiv:1101.5210) employed the "the pixel-based polarized foreground removal using template method" and survey the proper observing frequency range:

→ ≥ 5 bands in 50-270GHz





- Place 6 bands at
  60, 78, 100, 140, 195, 280 GHz.
- Avoid CO lines.
- In case of a need for more bands, we have an option to vary the band center for each detector and increase the number of bands effectively.

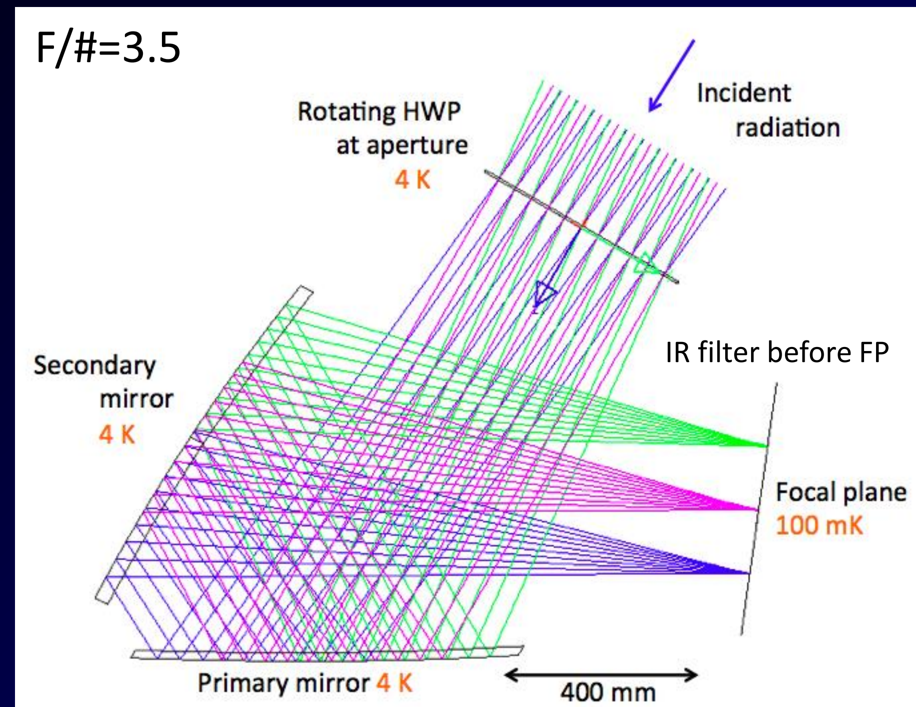
Extended observing frequency coverage is in option. (see later slide)

Optical system

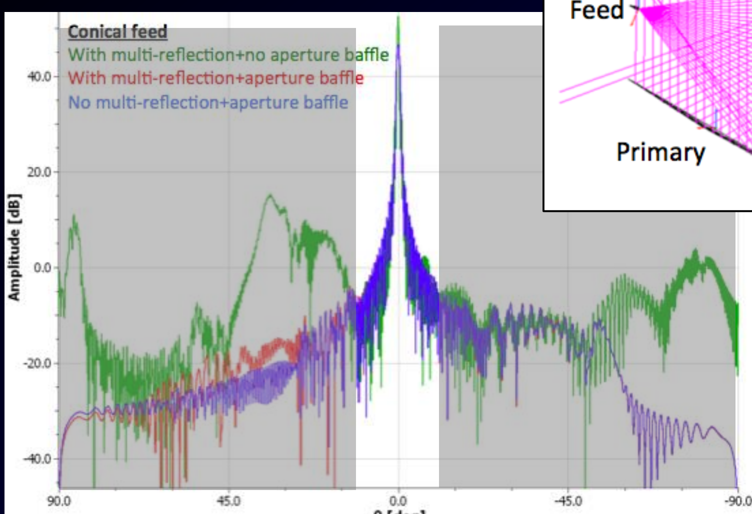
Requirements

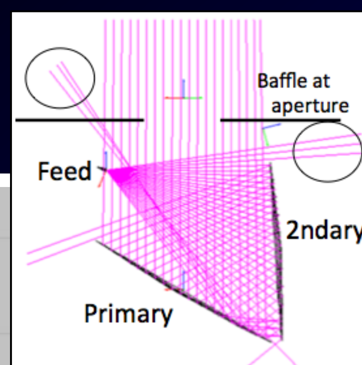
- Beam size of <1 deg at all the observing bands
- Wide field of view ±15 degs
- Size （<～ϕ2m×t2m）
- Telecentric focal plane
- Low sidelobe performance
- Beam calibration capability
- Cryogenically cooled at 4K

Modified cross-Dragone optics
compact and wide field-of-view



GRASP10 simulations

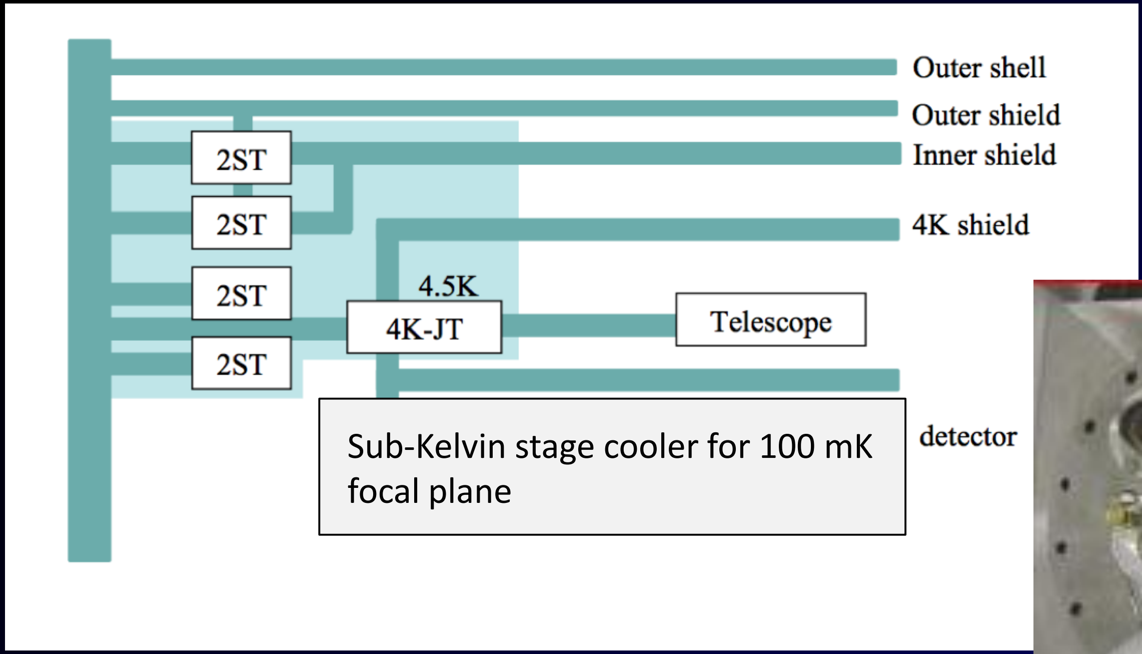




- The modified cross-Dragone optics achieves the field-of-view of 10x20 degrees^2 with the Strehl ratio above 99% for all the observing bands.
- The sidelobe is suppressed by the entrance aperture and the baffles.

Cryogenic system

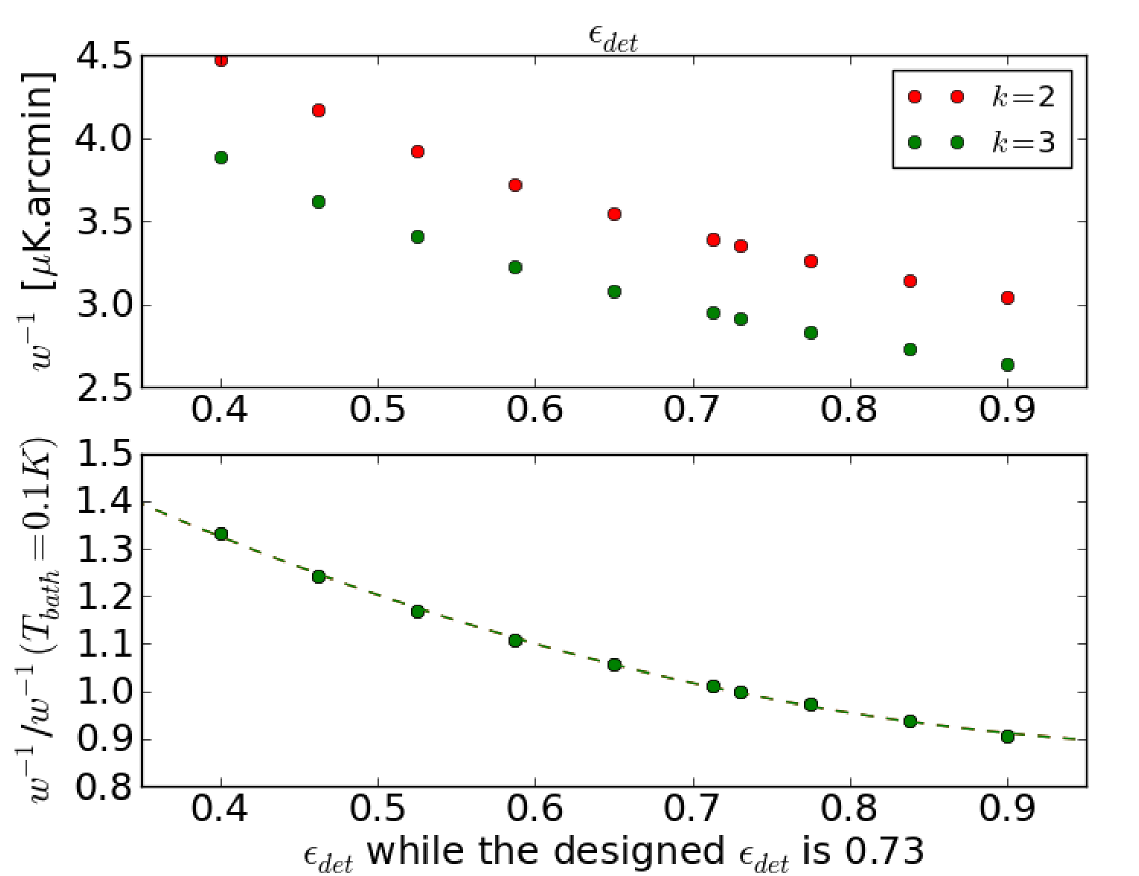
- Warm launch with no cryogen.
- The focal plane needs to be cooled down to 100 mK.
- The aperture in the optical system needs to be cooled down to ～4 K.
- Continuous cooling is ideal but the cycled cooler is acceptable with the eff. of 0.85.



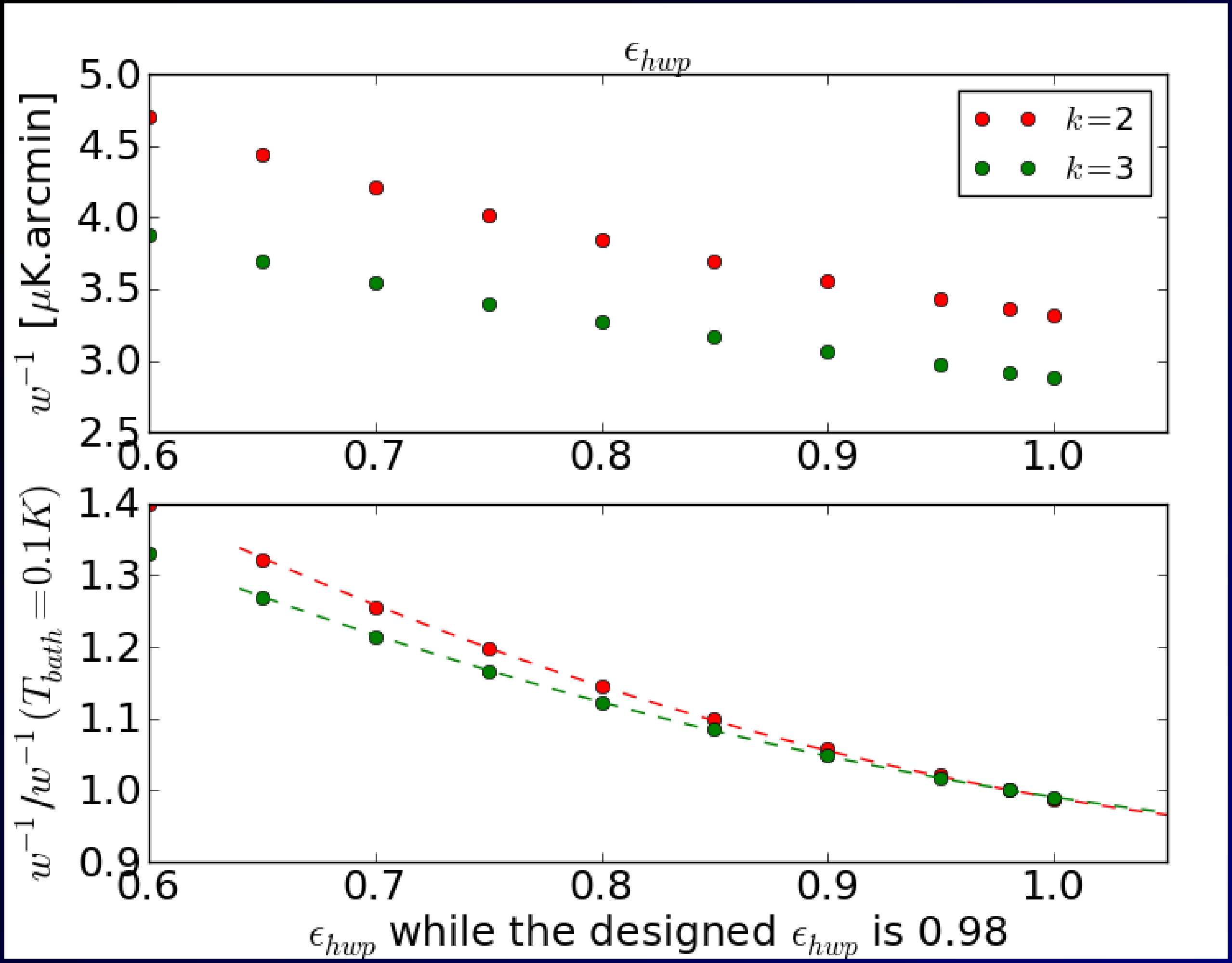
2-stage Stirling and 4K-JT system

- The 2-stage Stirling cooler and 4K-JT cooler from the heritage of the JAXA satellites, Akari (Astro-F), JEM-SMILES and Astro-H.
- There is an option to employ the 1K-JT that provides the 1.7 K interface to the sub-Kelvin stage.

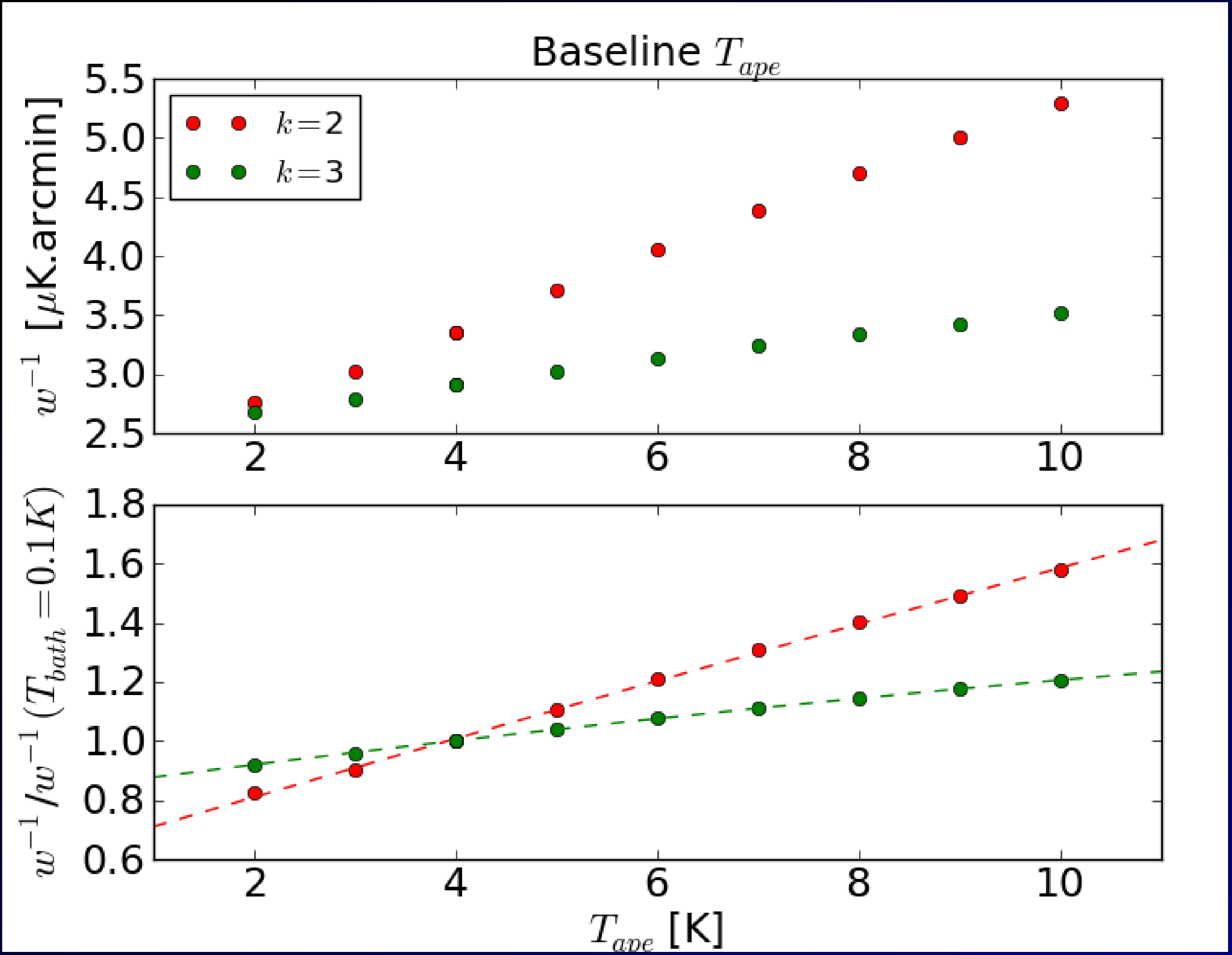
System parameter susceptibility



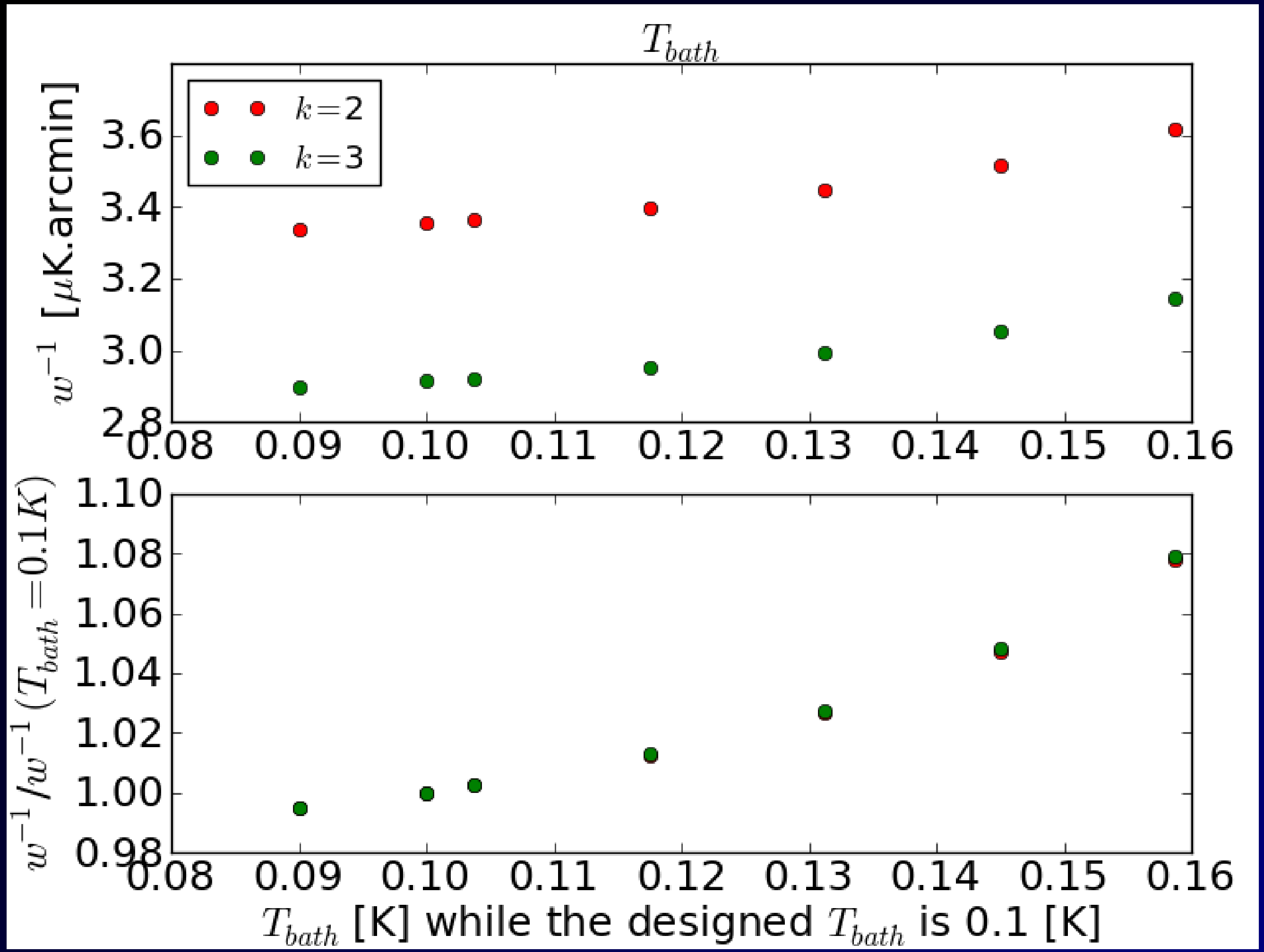
Efficiency	
Load Resistor	1
Microstrip Filter	0.9
Antenna mismatch	0.988
Antenna backlobe	0.91
Cumulated efficiency	0.809



ϵ_{hwp}
w^{-1} [μK.arcmin]
5.0
4.5
4.0
3.5
3.0
2.5
$k=2$
$k=3$
0.6
0.7
0.8
0.9
1.0
$w^{-1}/w^{-1}(T_{bath}=0.1K)$
1.4
1.3
1.2
1.1
1.0
0.9
ϵ_{hwp} while the designed ϵ_{hwp} is 0.98

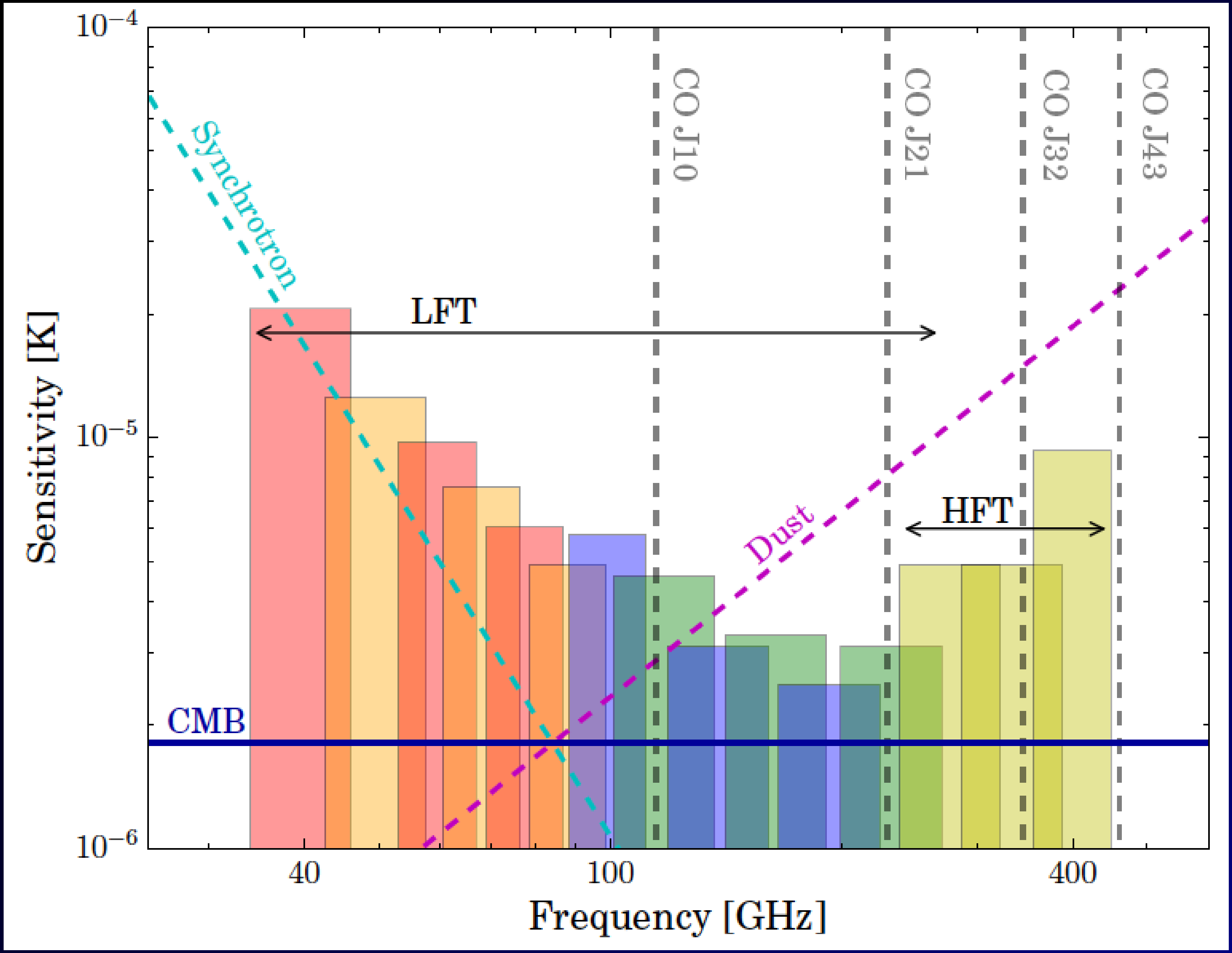


Baseline T_{ape}
5.5
5.0
4.5
4.0
3.5
3.0
2.5
w^{-1} [μK.arcmin]
$k=2$
$k=3$
2
4
6
8
10
1.8
1.6
1.4
1.2
1.0
0.8
0.6
$w^{-1}/w^{-1}(T_{bath}=0.1K)$
T_{ape} [K]

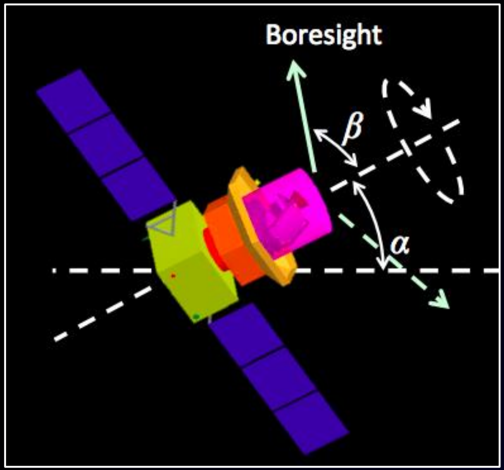


T_{bath}
$k=2$
$k=3$
w^{-1} [μK.arcmin]
3.6
3.4
3.2
3.0
2.8
0.08 0.09 0.10 0.11 0.12 0.13 0.14 0.15 0.16
$w^{-1}/w^{-1}(T_{bath}=0.1K)$
1.10
1.08
1.06
1.04
1.02
1.00
0.98
T_{bath} [K] while the designed T_{bath} is 0.1 [K]

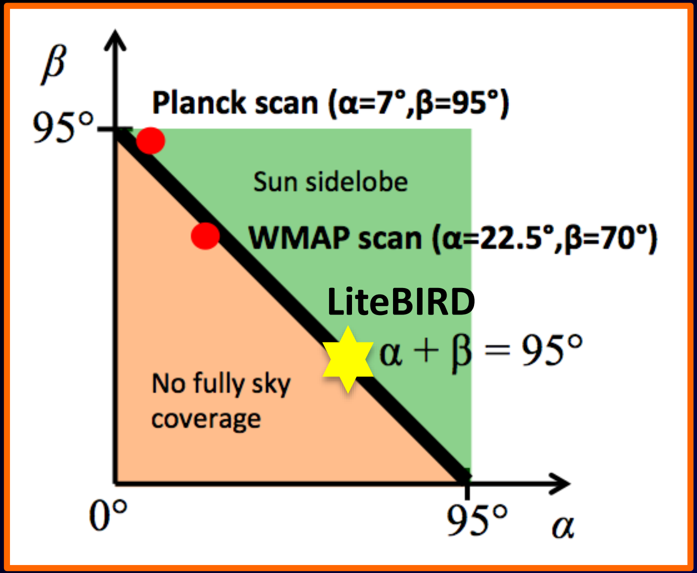
Extended frequency coverage

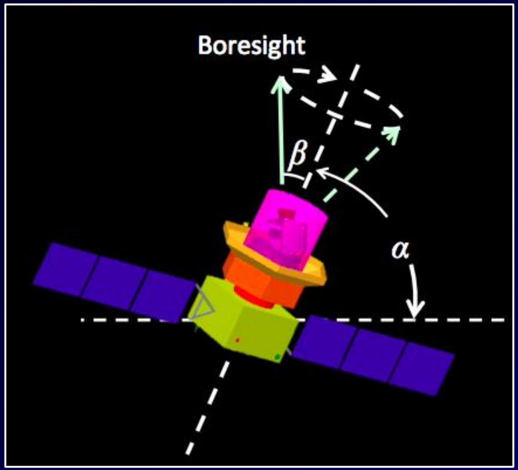


Scan strategy, scan angle α, β

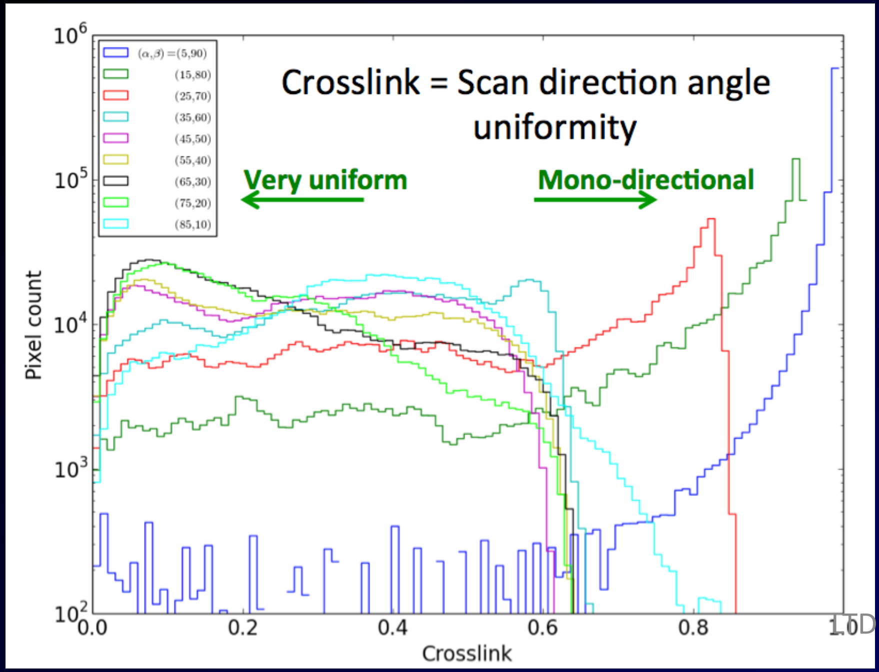


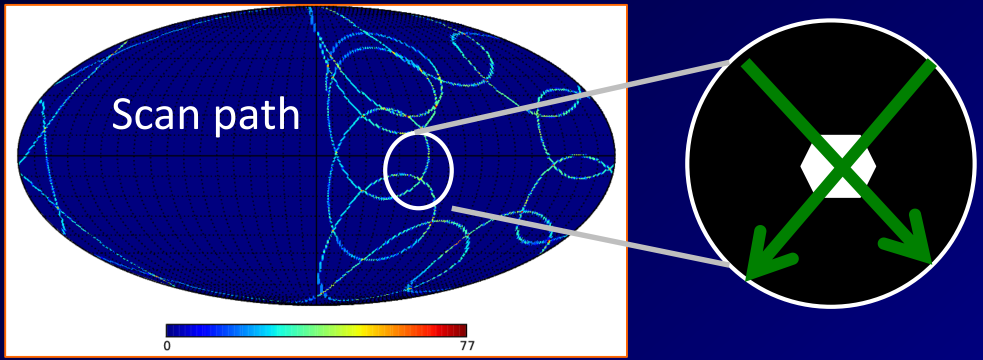
Robust to large angular scale signal (low l) with given 1/f noise.





Higher crosslink and robust to the polarization systematics.





We choose（α、β)=(65,30) degs in order to optimize to both crosslink and dipole amplitude in every spin period.

Abstract

- Title: Lite satellite for the study of B-mode polarization and Inflation from cosmic microwave background radiation detection, LiteBIRD

- LiteBIRD is a next generation CMB polarization satellite to probe the inflationary B-mode signal. The sensitivity is designed to measure the tensor-to-scalar ratio of 0.002 with 95% C.L. This allows us to test the major large-single-field slow-roll inflation models.

- LiteBIRD will observe the full sky by spinning the satellite at the 2nd Lagrange point (L2) for the minimum of three years. The baseline design covers the observational frequency of 50-320 GHz with 6 bands in order to subtract the galactic foreground emissions. We are considering an extended focal plane with spectral bands spanning 40-400 GHz to better characterize galactic foregrounds. We have two detector candidates, transition edge sensor (TES) bolometer and microwave kinetic inductance detector (MKID). In both cases, a telecentric focal plane consists of approximately 2000 superconducting detector arrays of which individual detector is designed to have noise equivalent power less than <10 aW/rtHz. In this presentation, we will present the overview of LiteBIRD and the project status. We will discuss the required specifications of the mission instruments, including the detector, readout electronics, and focal plane design and associating cryogenics, in order to achieve the science goal. Currently LiteBIRD is under the selection process to be a JAXA strategic large mission. The targeted launch year is in early 2020s.