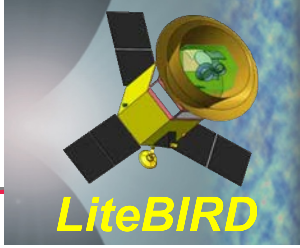
LiteBIRD for B-mode from space

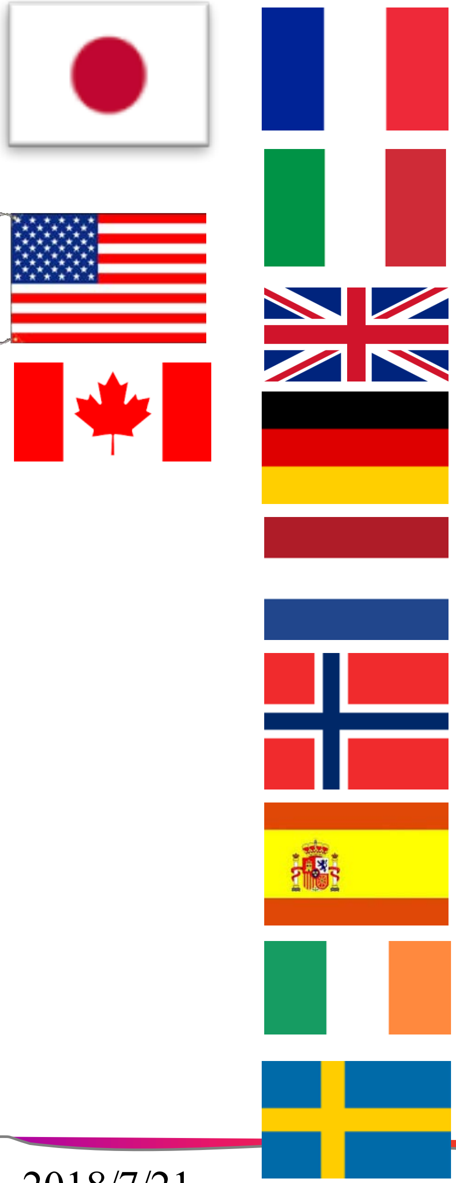
Masashi Hazumi

1) Institute of Particle and Nuclear Studies (IPNS), High Energy Accelerator Research Organization (KEK)
2) Kavli Institute for Mathematics and Physics of the Universe (Kavli IPMU), The University of Tokyo
3) Institute of Space and Astronautical Science (ISAS), Japan Aerospace Exploration Agency (JAXA)
4) Graduate School for Advanced Studies (SOKENDAI)

for LiteBIRD Joint Study Group

LiteBIRD Joint Study Group





About 180 researchers from all over the world

Y. Sekimoto[14,37], P. Ade[2], K. Arnold[49], J. Aumont[12], J. Austermann[29], C. Baccigalupi[11], A. Banday[12], R. Banerji[56], S. Basak[7,11], S. Beckman[49], M. Bersanelli[44], J. Borrill[20], F. Boulanger[4], M.L. Brown[53], M. Bucher[1], E. Calabrese[2], F.J. Casas[10], A. Challinor[50,60,64], Y. Chinone[16,47], F. Columbro[46], A. Cukierman[47,36], D. Curtis[47], P. de Bernardis[46], M. de Petris[46], M. Dobbs[23], T. Dotani[14,37], L. Duband[3], JM. Duval[3], A. Ducout[16], K. Ebisawa[14], T. Elleflot[49], H. Eriksen[56], J. Errard[1], R. Flauger[49], C. Franceschet[54], U. Fuskeland[56], K. Ganga[1], J.R. Gao[35], T. Ghigna[16,57], J. Grain[9], A. Gruppuso[6], N. Halverson[51], P. Hargrave[2], T. Hasebe[14], M. Hasegawa[5,37], M. Hattori[42], M. Hazumi[5,14,16,37], S. Henrot-Versille[19], C. Hill[21,47], Y. Hirota[38], E. Hivon[61], D.T. Hoang[1,63], J. Hubmayr[29], K. Ichiki[24], H. Imada[19], H. Ishino[30], G. Jaehnig[51], H. Kanai[59], S. Kashima[25], K. Kataoka[30], N. Katayama[16], T. Kawasaki[17], R. Keskitalo[20,48], A. Kibayashi[30], T. Kikuchi[14], K. Kimura[31], T. Kisner[20,48], Y. Kobayashi[39], N. Kogiso[31], K. Kohri[5], E. Komatsu[22], K. Komatsu[30], K. Konishi[39], N. Krachmalnicoff[11], C.L. Kuo[34,36], N. Kurinsky[34,36], A. Kushino[18], L. Lamagna[46], A.T. Lee[21,47], E. Linder[21,48], B. Maffei[9], M. Maki[5], A. Mangilli[12], E. Martinez-Gonzalez[10], S. Masi[46], T. Matsumura[16], A. Mennella[54], Y. Minami[5], K. Mistuda[14], D. Molinari[52,6], L. Montier[12], G. Morgante[6], B. Mot[12], Y. Murata[14], A. Murphy[28], M. Nagai[25], R. Nagata[5], S. Nakamura[59], T. Namikawa[27], P. Natoli[52], T. Nishibori[15], H. Nishino[5], C. O'Sullivan[28], H. Ochi[59], H. Ogawa[31], H. Ogawa[14], H. Ohsaki[38], I. Ohta[58], N. Okada[31], G. Patanchon[1], F. Piacentini[46], G. Pisano[2], G. Polenta[13], D. Poletti[11], G. Puglisi[36], C. Raum[47], S. Realini[54], M. Remazeilles[53], H. Sakurai[38], Y. Sakurai[16], G. Savini[43], B. Sherwin[50,65,21], K. Shinozaki[15], M. Shiraishi[26], G. Signorelli[8], G. Smecher[41], R. Stompor[1], H. Sugai[16], S. Sugiyama[32], A. Suzuki[21], J. Suzuki[5], R. Takaku[14,40], H. Takakura[14,39], S. Takakura[16], E. Taylor[48], Y. Terao[38], K.L. Thompson[34,36], B. Thorne[57], M. Tomasi[44], H. Tomida[14], N. Trappe[28], M. Tristram[19], M. Tsuji[26], M. Tsujimoto[14], S. Uozumi[30], S. Utsunomiya[16], N. Vittorio[45], N. Watanabe[17], I. Wehus[56], B. Westbrook[47], B. Winter[62], R. Yamamoto[14], N.Y. Yamasaki[14], M. Yanagisawa[30], T. Yoshida[14], J. Yumoto[38], M. Zannoni[55], A. Zonca[33],

LiteBIRD project overview

- JAXA L-class mission candidate
- Currently in Phase-A1 for concept development at ISAS/JAXA (Sep.2016 – Aug. 2018)
  - The most advanced status among all CMB space mission proposals in the world
- International contributions
  - US technology development (NASA)
  - Science contribution studies and science maturity studies (CSA)
  - Studies at Concurrent Design Facility (ESA) with LiteBIRD European Consortium
  - Phase A commitment by ASI
  - Phase A commitment by CNES

Schedule after Phase-A1

- Final down selection in early 2019
  - for a strategic L-class mission of JAXA
- Launch in mid 2020's (likely to be 2027)
- Observation for 3 years in L2

Full success

1. The mission shall measure the tensor-to-scalar ratio r with a total uncertainty of $\delta r < 1 \times 10^{-3}$. This value shall include contributions from instrument statistical noise fluctuations, instrumental systematics, residual foregrounds, lensing B-modes, and observer bias, and shall not rely on future external datasets.

2. The mission shall obtain full-sky CMB linear polarization maps for achieving >5σ significance using data between ell =2 and ell =10, data between ell=11 and ell=200 separately, assuming r=0.01. We assume a fiducial optical depth of $\tau = 0.05$ for this calculation.

Full Success (simplified version)

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

Extra success

LiteBIRD

Improve σ(r) with external observations

Topic	Example Method	Example Data
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, QUIJOTE upgrade, etc.

- Delensing improvement to σ(r) can be factor ~2 or more.
  - e.g. ~6sigma observation in case of Starobinsky model
  - Need to make sure systematic uncertainties are under control.

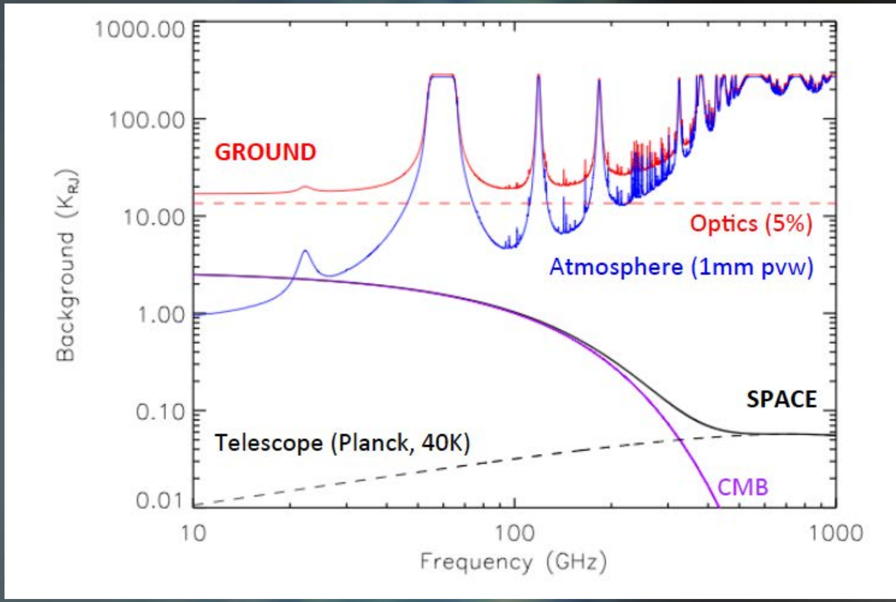
Science Outcomes

1. Full success
2. Extra success
3. Characterisation of B-mode
   (e.g scale-invariance, non-Gaussianity, and parity violation)
4. Large-scale E mode and its implications
   for reionisation history and the neutrino mass
5. Birefringence
6. Power spectrum features in polarization
7. SZ effect (thermal and relativistic correction)
8. Anomaly
9. Cross-correlation science
10. Galactic science

Why Measurements in Space ?

LiteBIRD

- Superb Environment !
  - No statistical/systematic uncertainty due to atmosphere
  - No limitation for the choice of observing bands
  - No ground pickup



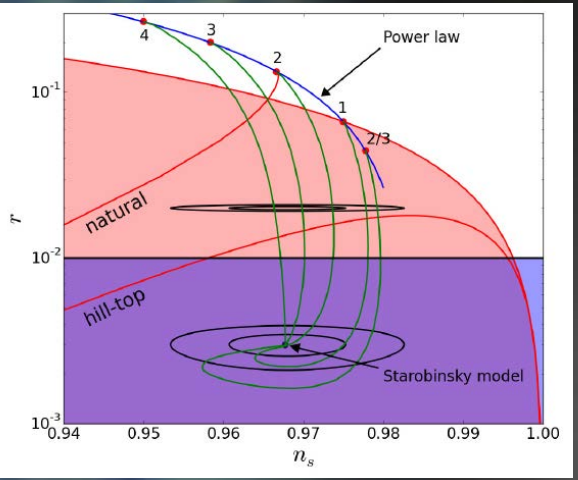
Rule of thumb: 1,000 detectors in space ~ 100,000 detectors on ground

- Only way to access lowest multipoles w/ precision/accuracy
  - Both bumps need to be observed for the firm confirmation of cosmic inflation → We need measurements in space.

Impacts of discovery

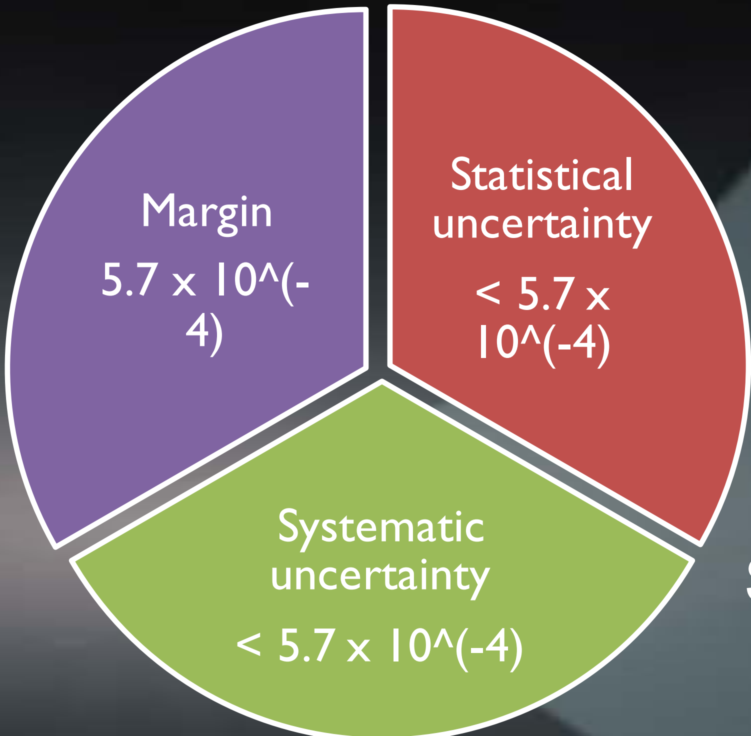
- Direct evidence for cosmic inflation
  - Many models predict $0.003 < r < 0.07$
  - Narrowing down models in r vs. n_s plane
- Shed light on GUT-scale physics

$$V^{1/4} = 1.04 \times 10^{16} \times \left(\frac{r}{0.01}\right)^{1/4} [GeV]$$



- New era of physics w/ experimental tests of QG
  - First observation of quantum fluctuation of space-time
  - Studies on top-down constraints in string theory in progress
    - r > 0.01 not easy (super-Planckian field excursions)
- Sense of wonder beyond science!

Design drivers



$\delta r < 1 \times 10^{-3}$

Statistical uncertainty includes
- foreground subtraction
- lensing B-mode

⇩

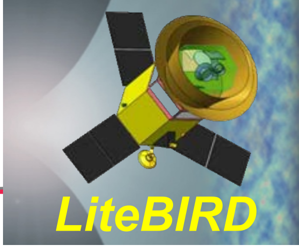
Broadband 34 – 448 GHz (15 bands)

Systematic uncertainty includes
- Polarization efficiency and its knowledge
- Disturbance to instrument
- Off-boresight pick up
- Calibration accuracy

⇩

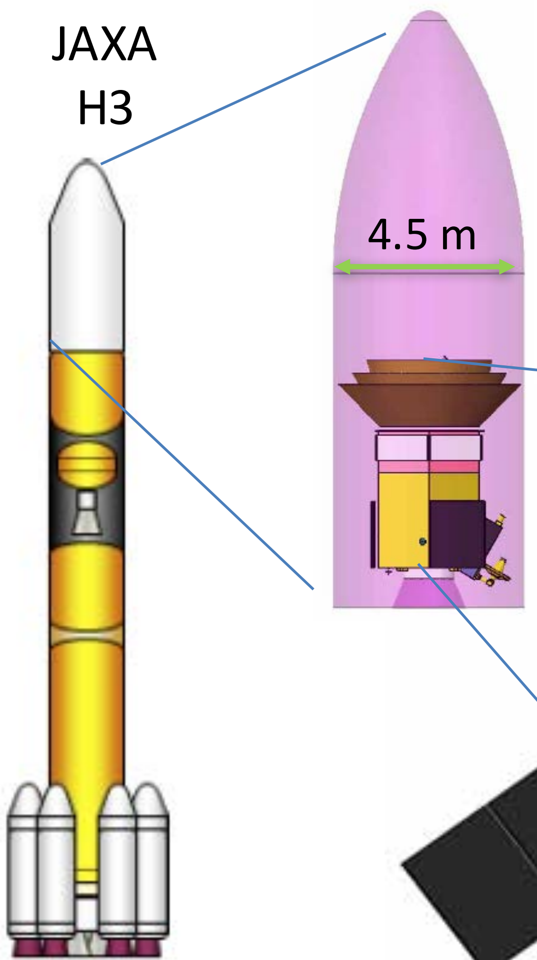
Polarization Modulation

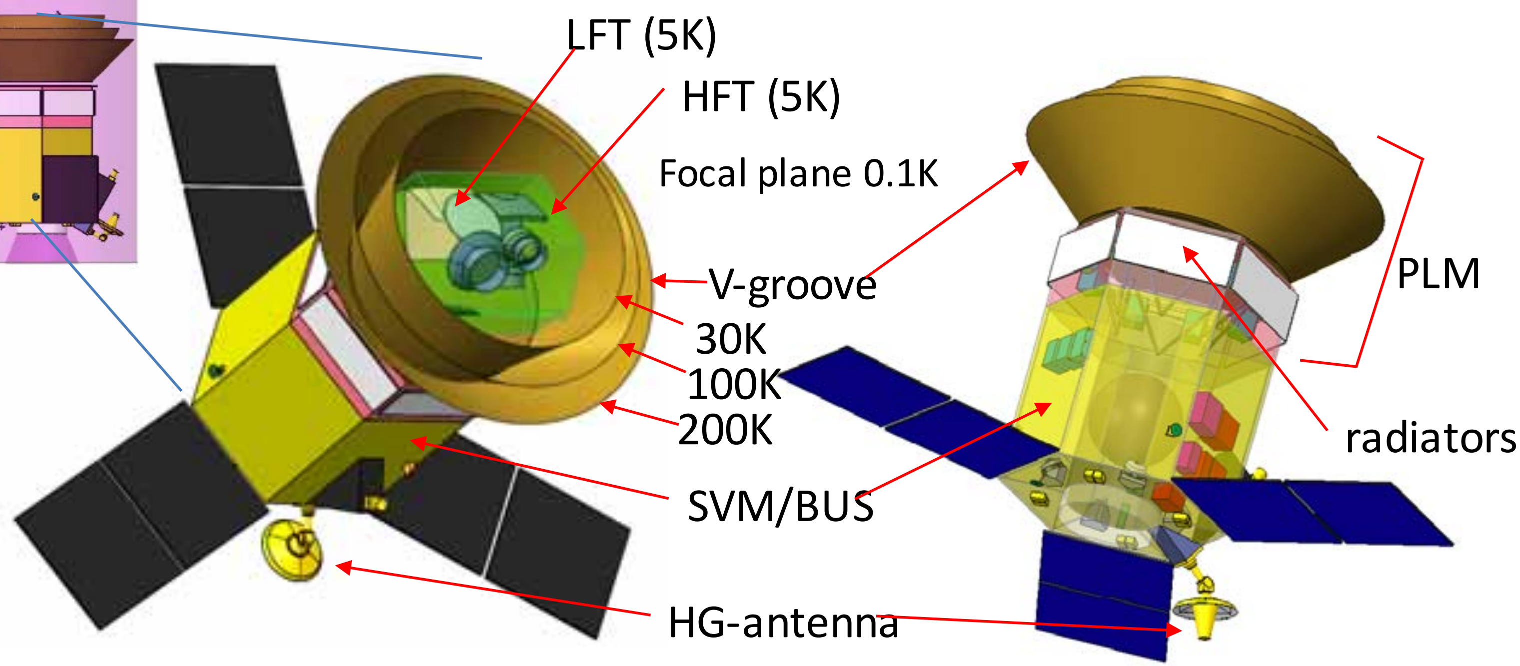
LiteBIRD Spacecraft



LFT (Low frequency telescope) 34 – 161 GHz : Synchrotron + CMB

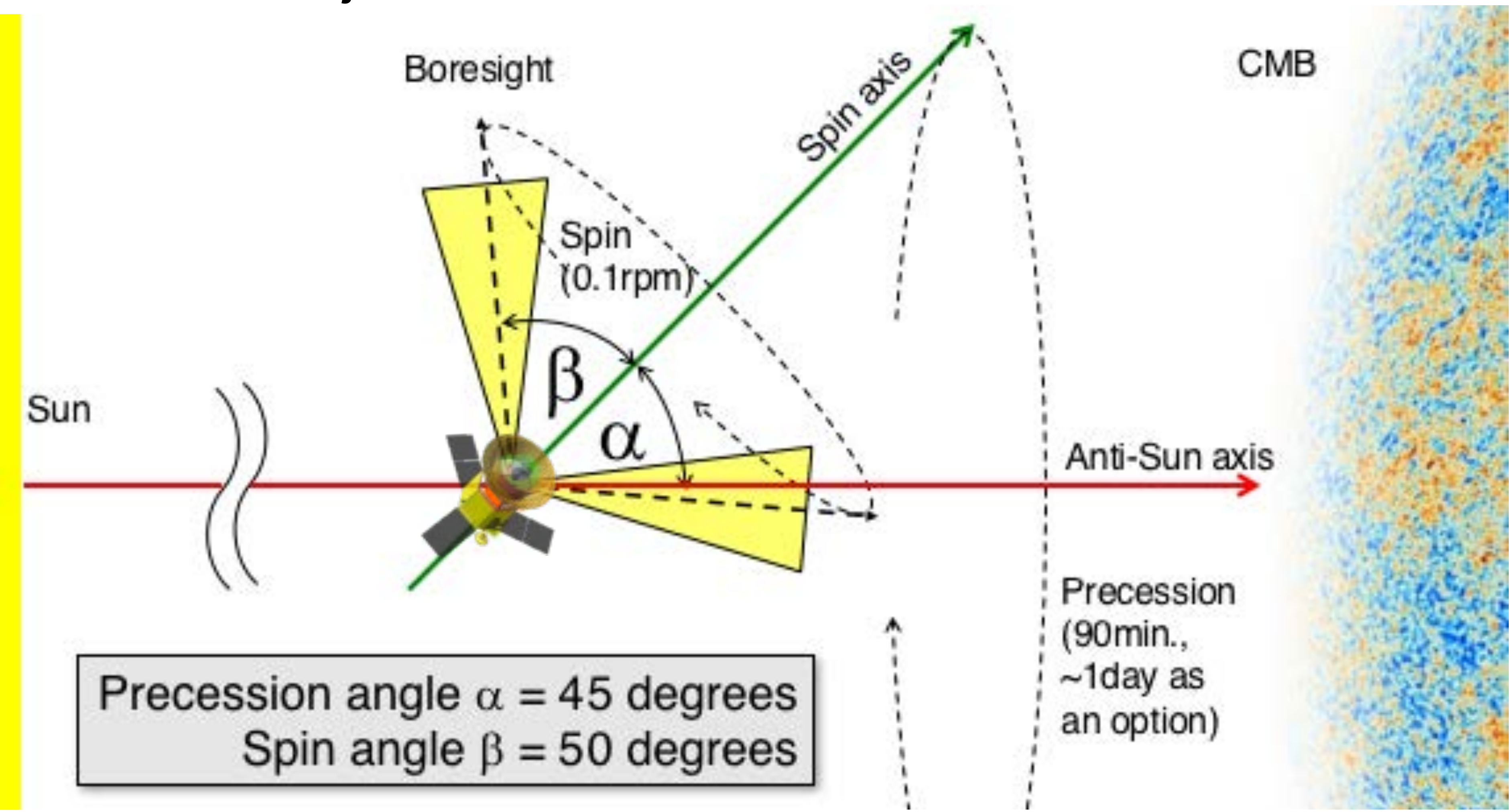
HFT (high frequency telescope) 89 – 448 GHz : CMB + Dust





Scan strategy

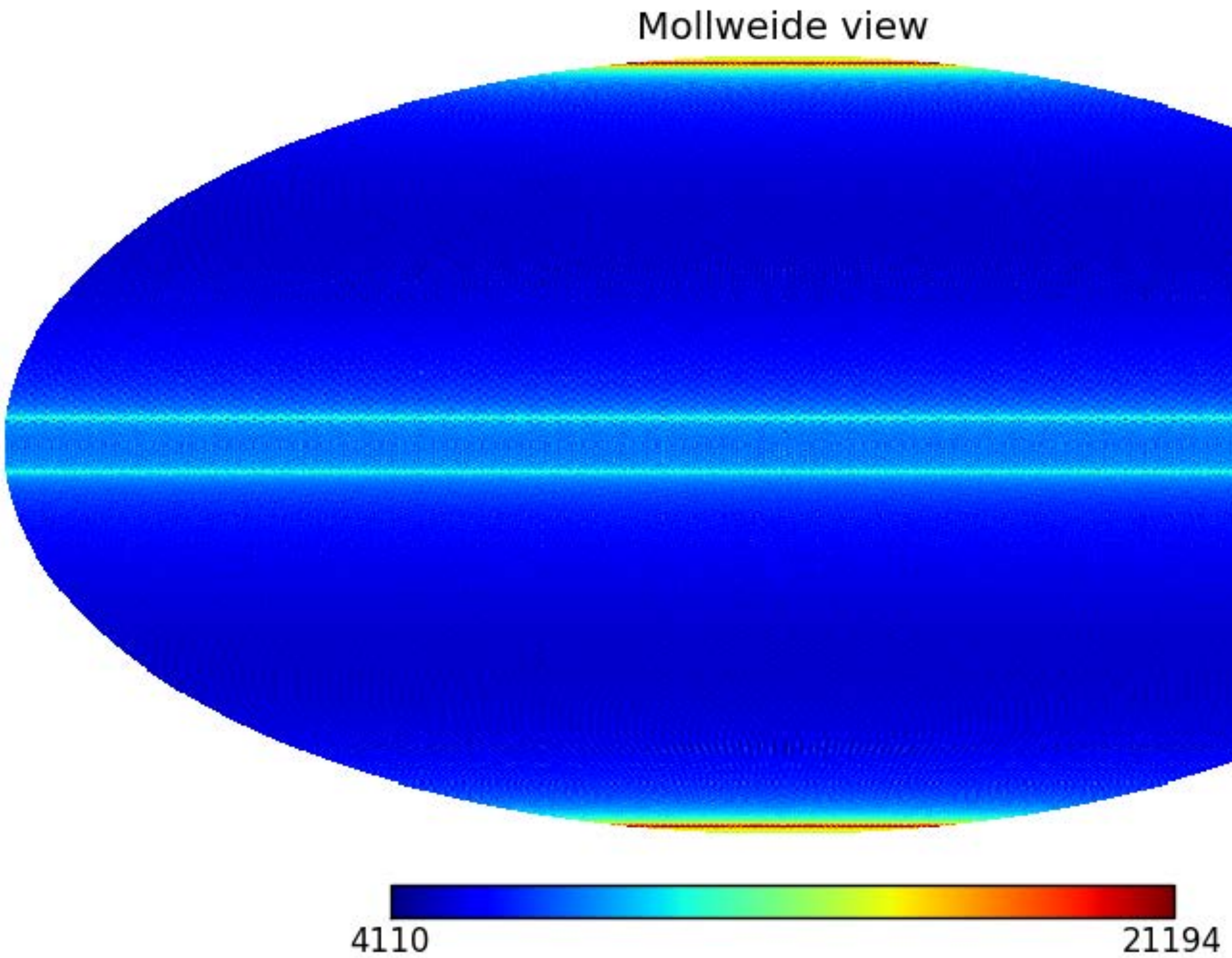
Orbit: L2 Lissajous



of observations for each sky pixel

w/ a single detector

1 year



Ground station (GREAT)

for Deep Space Exploration and Telecommunication

Summary of Ground Stations

station	Antenna diameter	Bands	Comments
GN (Ground Network)	10m	S up/down/range	3 stations in Japan, 4 outside Japan
USC "Uchinoura Space Center"	34m	S up/down/range X up/down Ka down	
	20m	S up/down/range X down	
KTU4	20m	S up/down/range X down	
UDSC	64m	S up/down/range X up/down/range	Will be replaced with the 54m antenna.
"Usuda Deep Space Center"	54m	X up/down/range Ka down	Under construction. Operational from 2019.

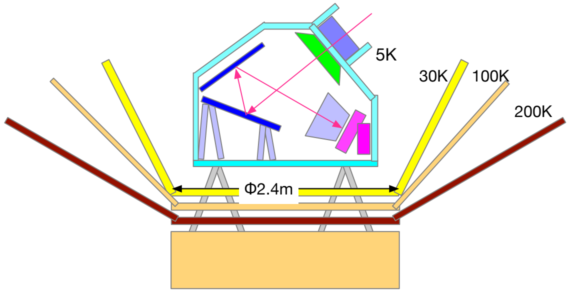
Antenna available for L2 mission in 2020s.

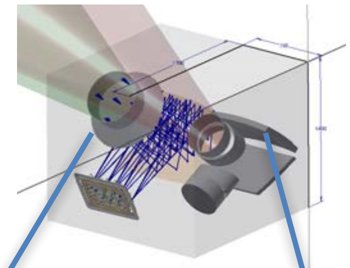
Only the limited data transfer is possible at L2.

Larger datalink capability

LiteBIRD product tree

LFT 34 – 161 GHz
HFT 89 – 448 GHz

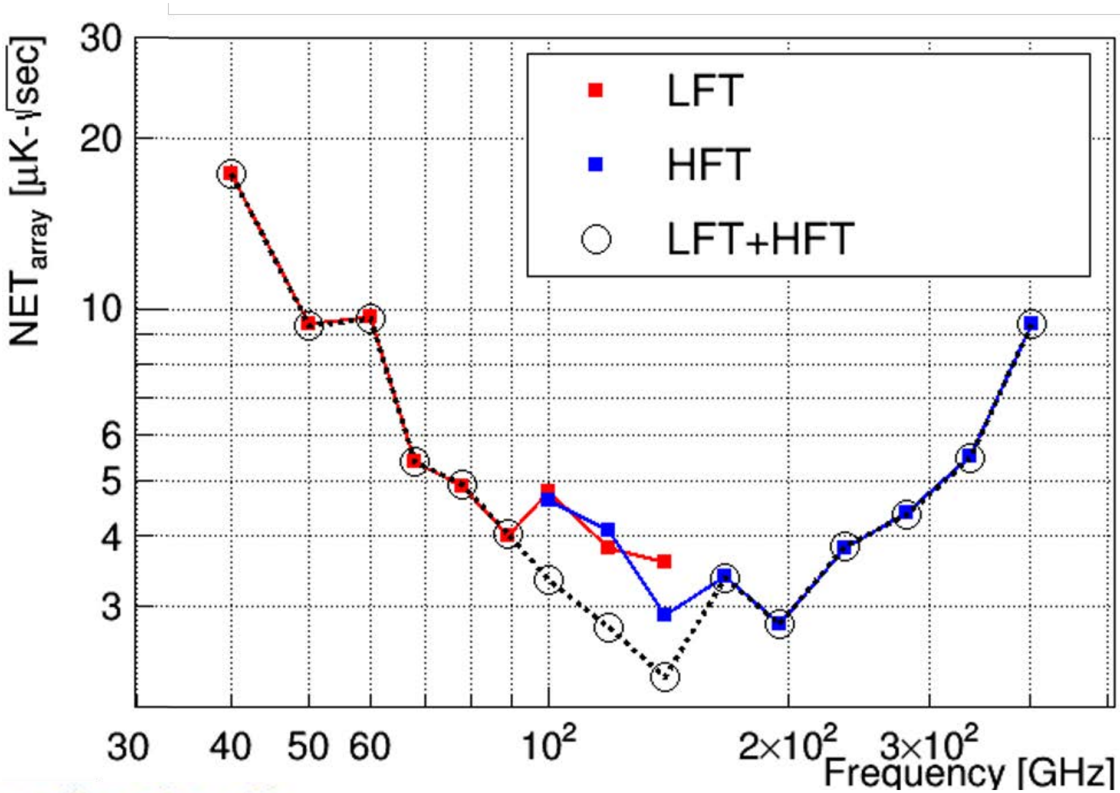




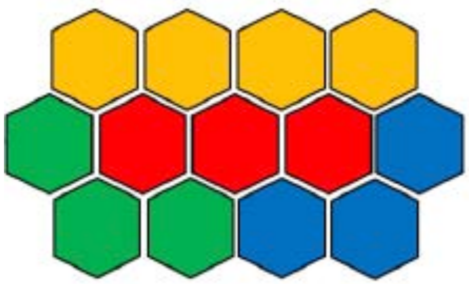
- LiteBIRD
  - SVM/BUS
  - PLM/Mission
    - 300K PLM
      - warm readout
      - compressors
      - drivers
      - digital electronics
      - radiators heat pipes
    - Cryo-Structure
      - Structure
      - JT/ STcoolers
      - V-groove
      - sub-K cooler
    - LFT
      - antenna
      - structure
      - HWP
      - focal plane
      - cold readout
    - HFT
      - antenna
      - structure
      - HWP
      - focal plane
      - cold readout

EU	US	Japan	Canada

Sensitivity

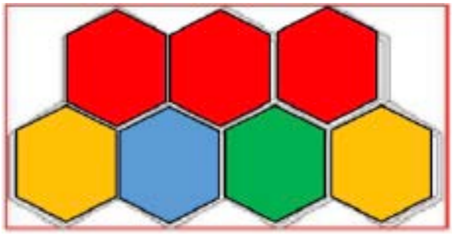


Enough sensitivity
to foreground cleaning



LFT 34 – 161 GHz

	LFT	HFT
Number of bands	9	9
	15 (3 bands overlapping)	

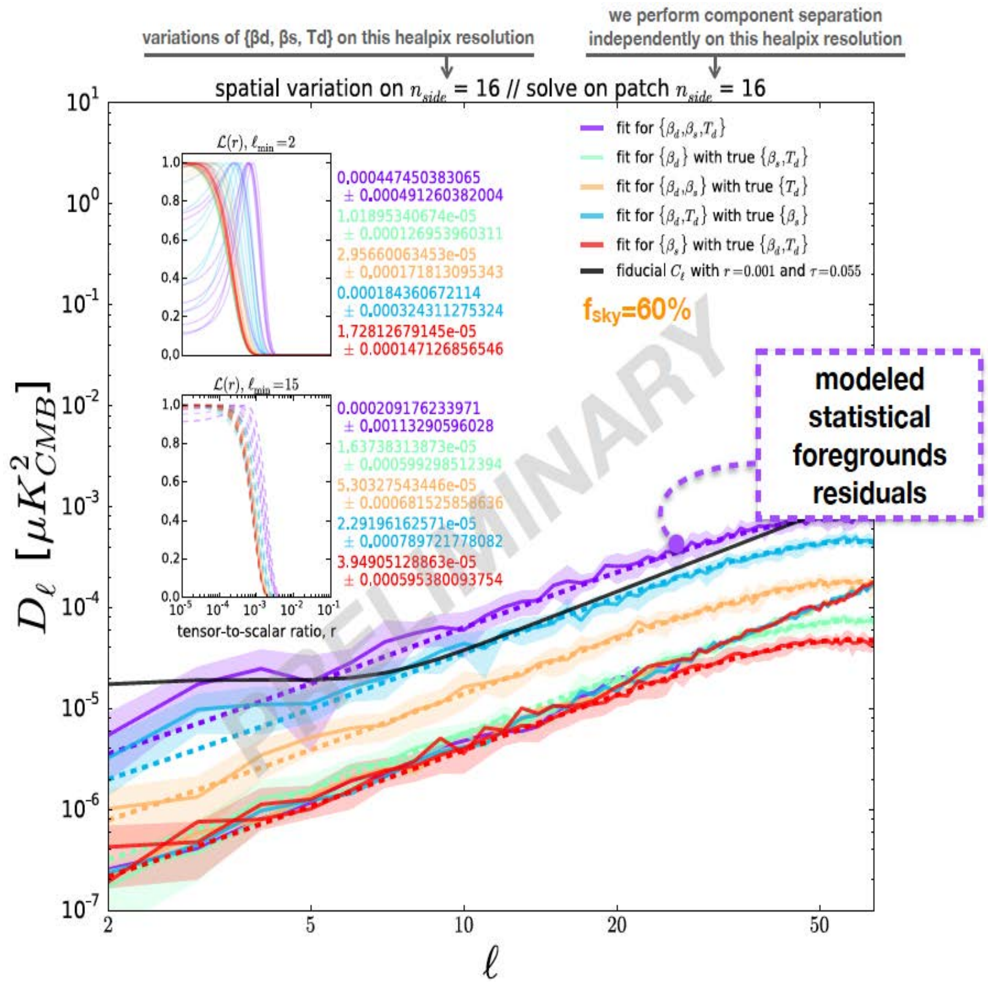


HFT 89 – 448 GHz

Foreground cleaning

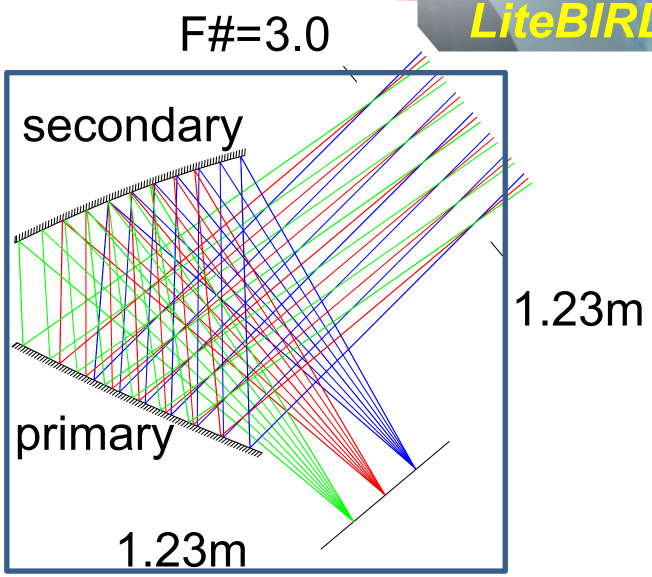
Team of world experts !

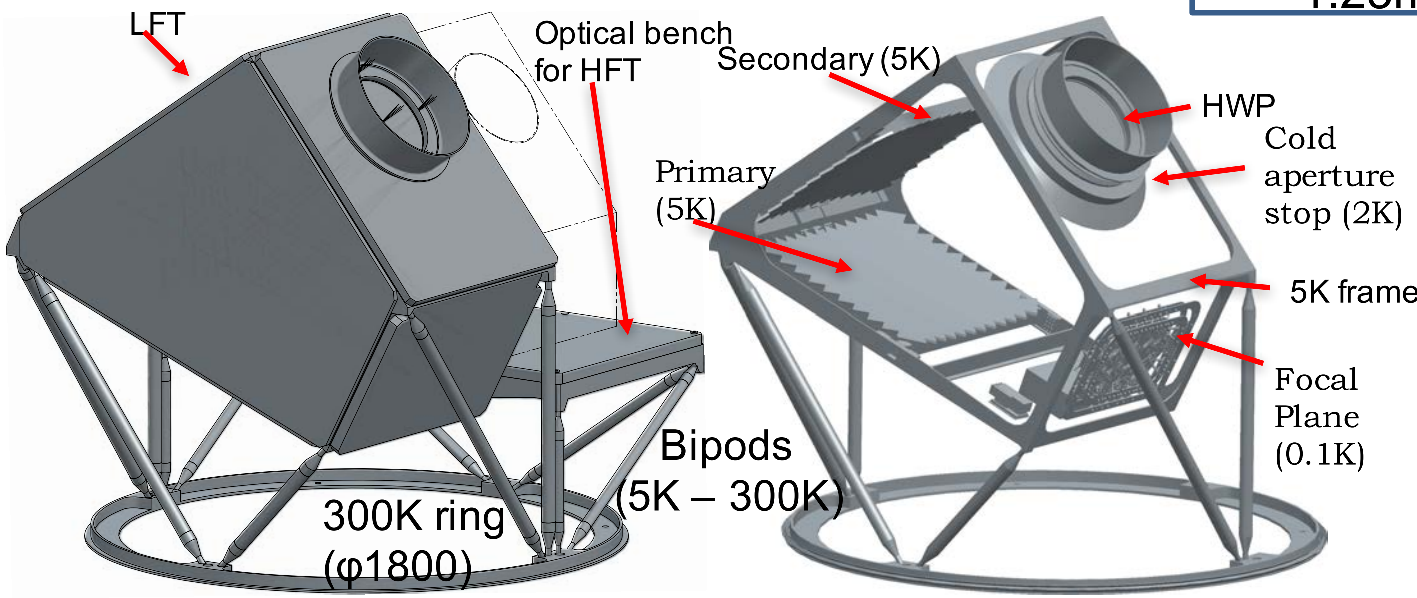
- Can reach bias on r less than 0.001, considering input sky simulations with spatial variations of spectral indices over nside=16
  - A multipatch approach, combined with a deprojection of the statistical residuals, leads to **r ~ 0.0004 +/- 0.0005 (ell >= 2)**
- Complicating the sky (spatial variations on nside=32 with synchrotron curvature) leads to **r = 0.0007 +/- 0.0007 (ell >= 2)**
  - Synchrotron curvature leads to a larger bias if not fitted for in the modeling



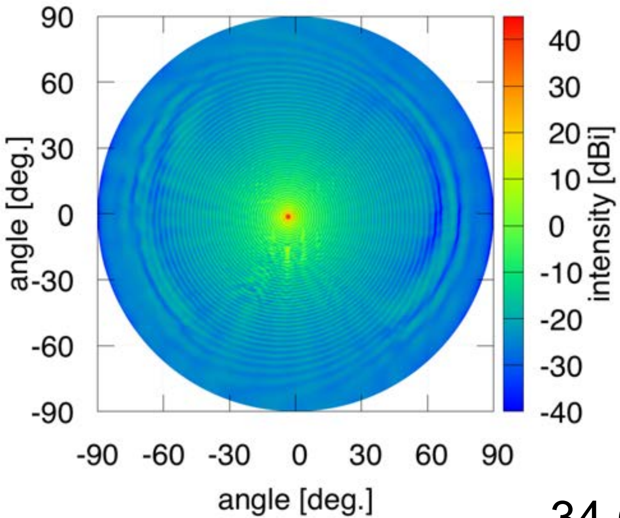
LFT crossed Dragone optics

- Aperture diameter 400 mm
- Field of view 20 deg x 10 deg
- F#3.0 & crossed angle of 90 degree
- All 5K parts are made of Aluminum
- Less than 150 kg
- S. Kashima et al. 2018 Appl. Optics

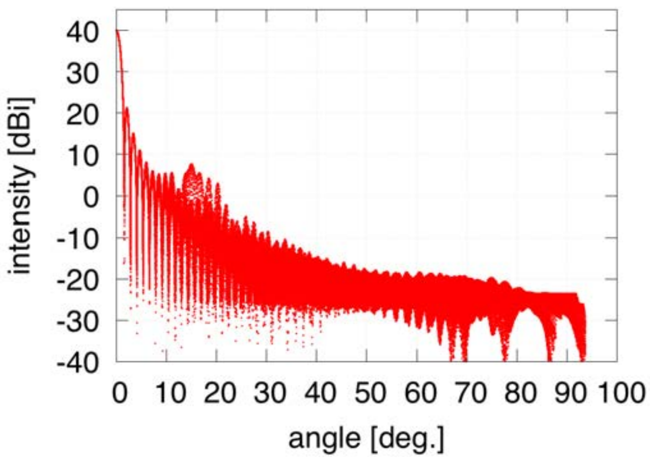


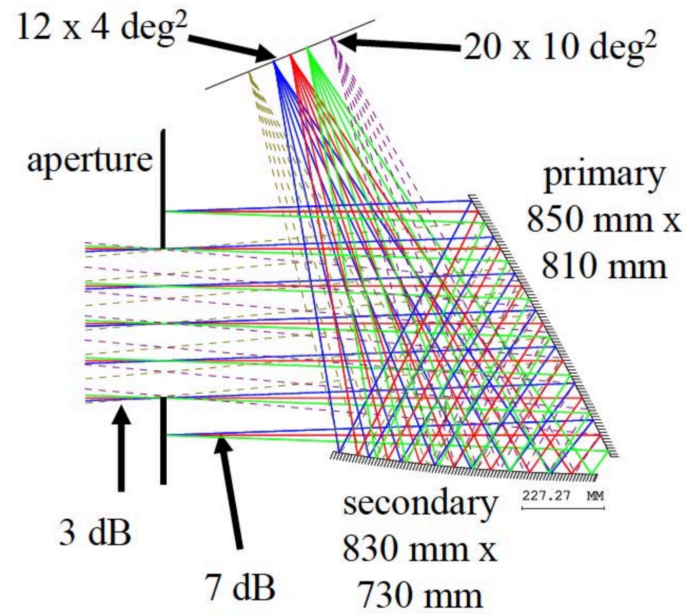


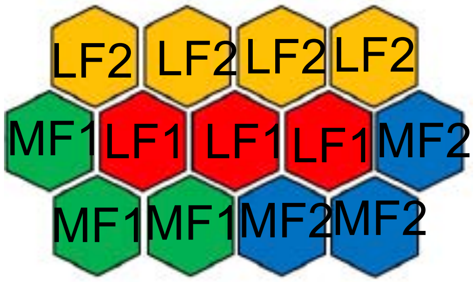
LFT physical optics with GRASP



34 GHz





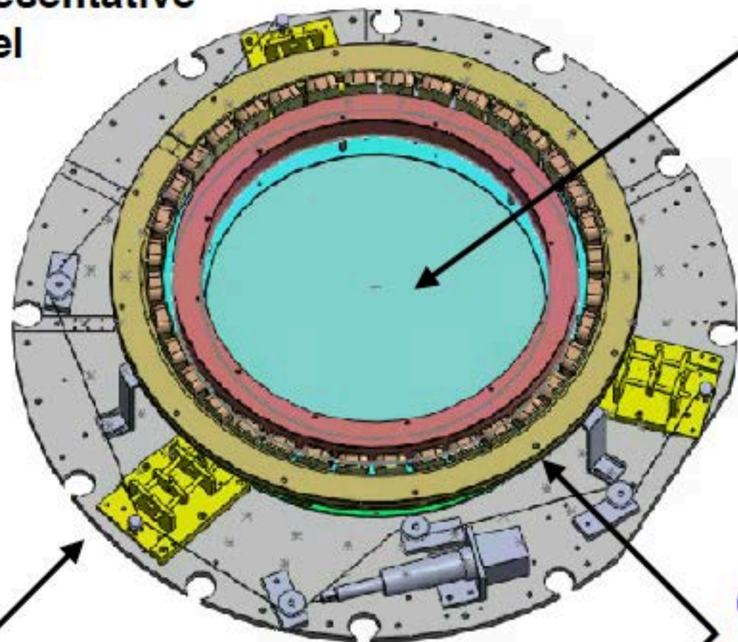


[SPIE 10698-157] H. Imada et al. "The Optical design and physical optics analysis of a cross-Dragonian telescope for LiteBIRD"

LFT Half wave plate (HWP)

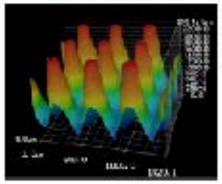
ϕ 400mm flight representative demonstration model

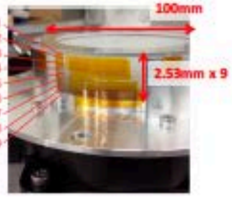
ϕ~1m 4K cryostat

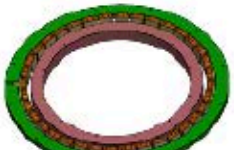


Anti-Reflection (AR)

Achromatic HWP (AHWP)



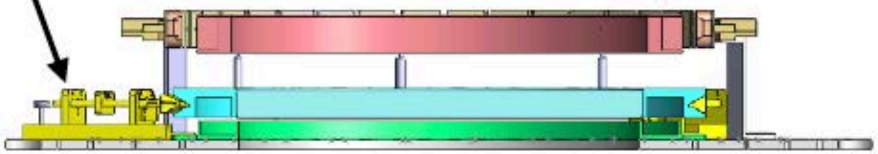


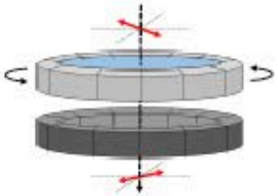


Cryogenic Synchronous Motor

Encoding System

Gripper Mechanism





Superconducting Magnetic Bearing

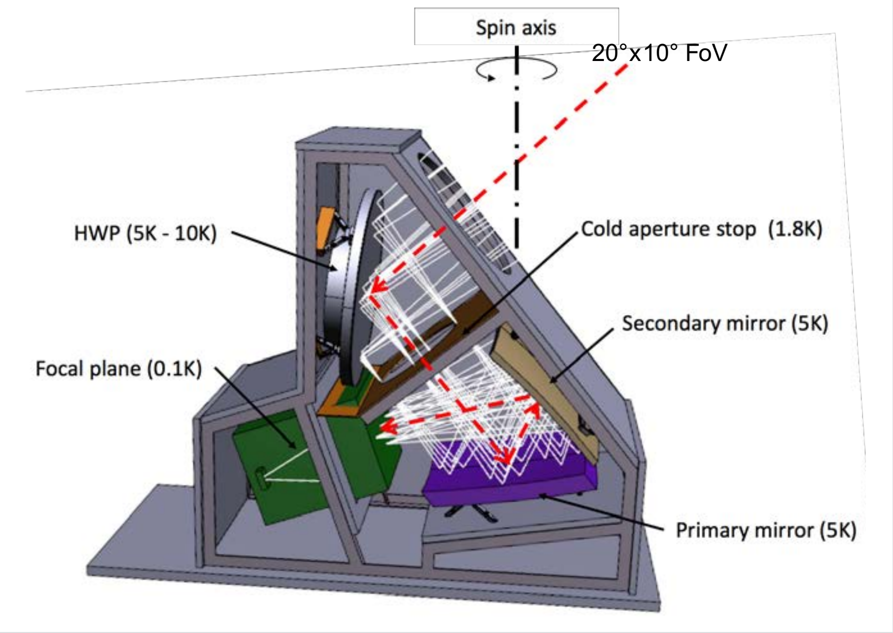
[SPIE 10708-12] Y. Sakurai et al. "Design and development of a polarization modulator unit based on a continuous rotating half-wave plate for LiteBIRD"
[SPIE 10708-142] K. Komatsu et al. "Prototype design and evaluation of the nine-layer achromatic half-wave plate for the LiteBIRD low frequency telescope"

HFT design status

Two concepts under study by the European consortium

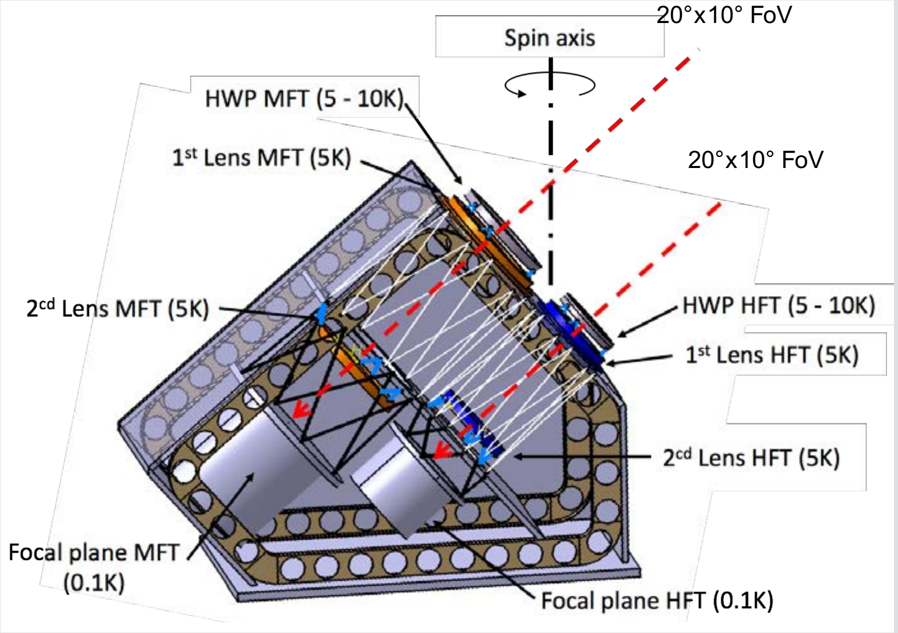
Reflective solution

- Crossed Dragone telescope - F/3.5
- Frequency coverage: 89 - 448 GHz
- Continuous rotating HWP mechanism
- Reflective Embedded Metal-mesh HWP tilted at 45°



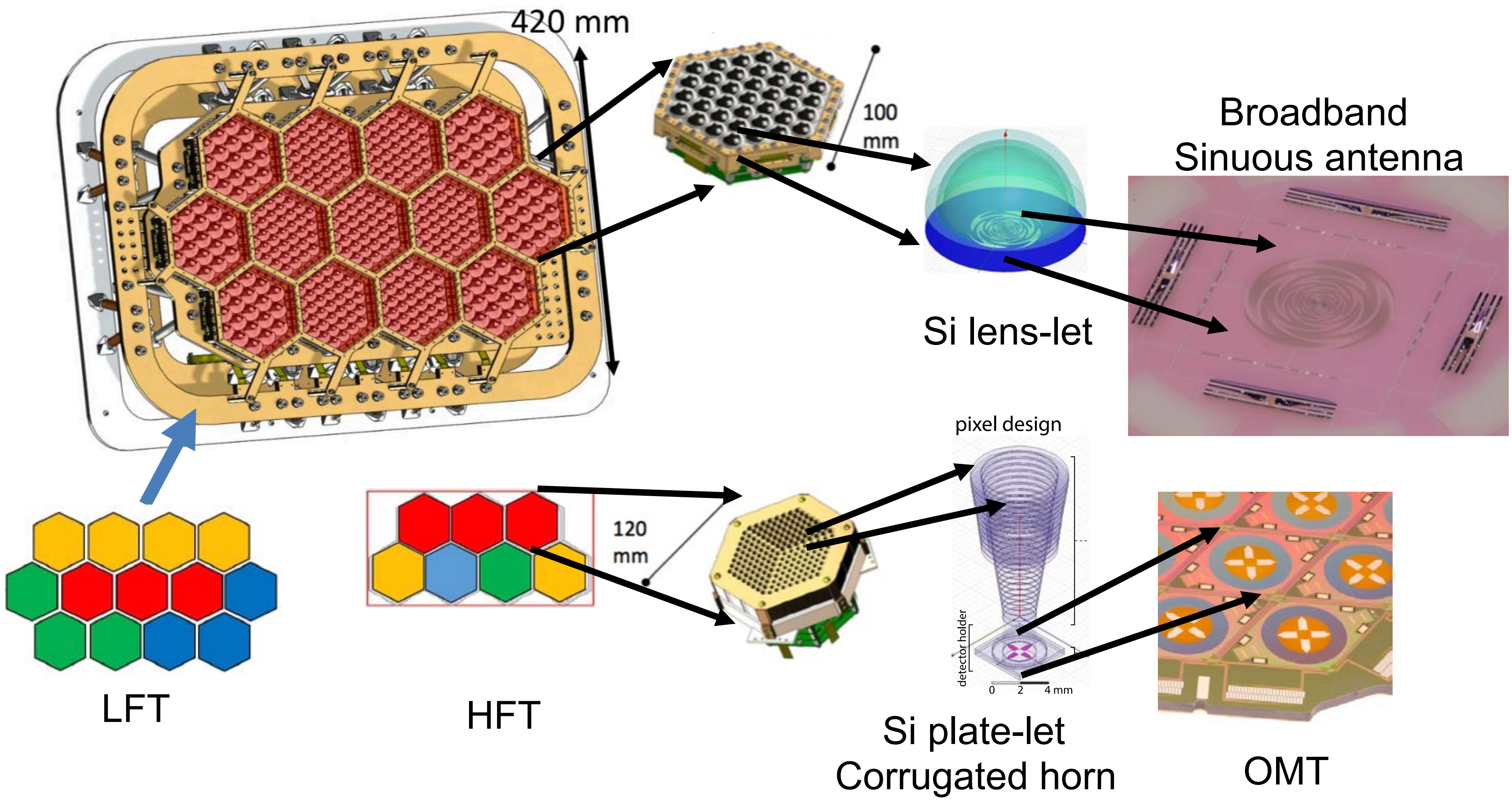
Refractive solution

- Two telescopes - F/2.2
    - MFT: 89 - 270 GHz
    - HFT: 238 - 448 GHz
- Silicon lenses
- Continuous rotating HWP mechanism
- Transmissive Metal-mesh HWP



Focal Planes : TES

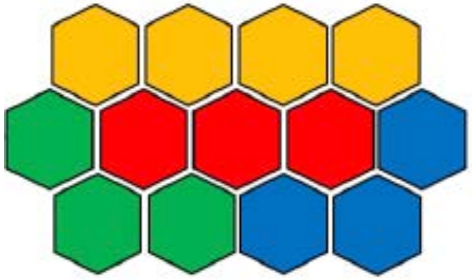
A. Suzuki et al. 2018 JLTP arXiv:1801.06987

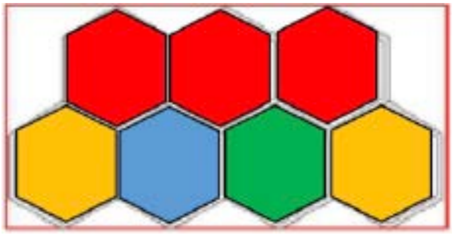


[SPIE 10708-89] S. M. Beckman et al. "Development of cosmic ray mitigation techniques for the LiteBIRD space mission"

Focal plane optical configuration

	Type	Center Frequencies [GHz]	BW	Low [GHz]	High [GHz]	Num. of wafers	TES channels Opt/wf	TES channels Total
LFT 34 - 161 GHz	1	40	0.30	34	46	3	14	42
		60	0.23	53	67	3	14	42
		78	0.23	69	87	3	14	42
	2	50	0.30	43	58	4	14	56
		68	0.23	60	76	4	14	56
		89	0.23	79	99	4	14	56
	3	68	0.23	60	76	3	38	114
		89	0.23	79	99	3	38	114
		119	0.30	101	137	3	38	114
	4	78	0.23	69	87	3	38	114
		100	0.23	89	112	3	38	114
		140	0.30	119	161	3	38	114
HFT 89 - 448 GHz	5	100	0.23	89	112	3	74	222
		140	0.30	119	161	3	74	222
		195	0.30	166	224	3	74	222
	6	119	0.30	101	137	2	74	148
		166	0.30	141	191	2	74	148
		235	0.30	200	270	2	74	148
	7	235	0.30	200	270	1		
		337	0.30	286	388	1	338	338
	8	280	0.30	238	322	1	338	338
		402	0.23	356	448	1	338	338
Total								3102
LFT								978
HFT								2124

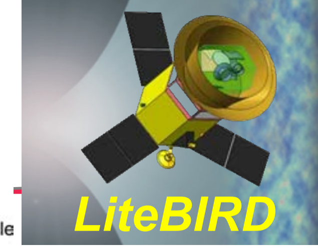




This table shows a number of optical TES channels.
There are additional dark TESs.

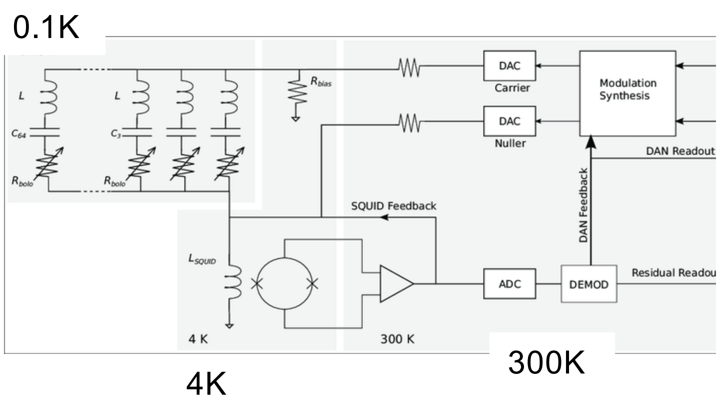
DfMUX Readout

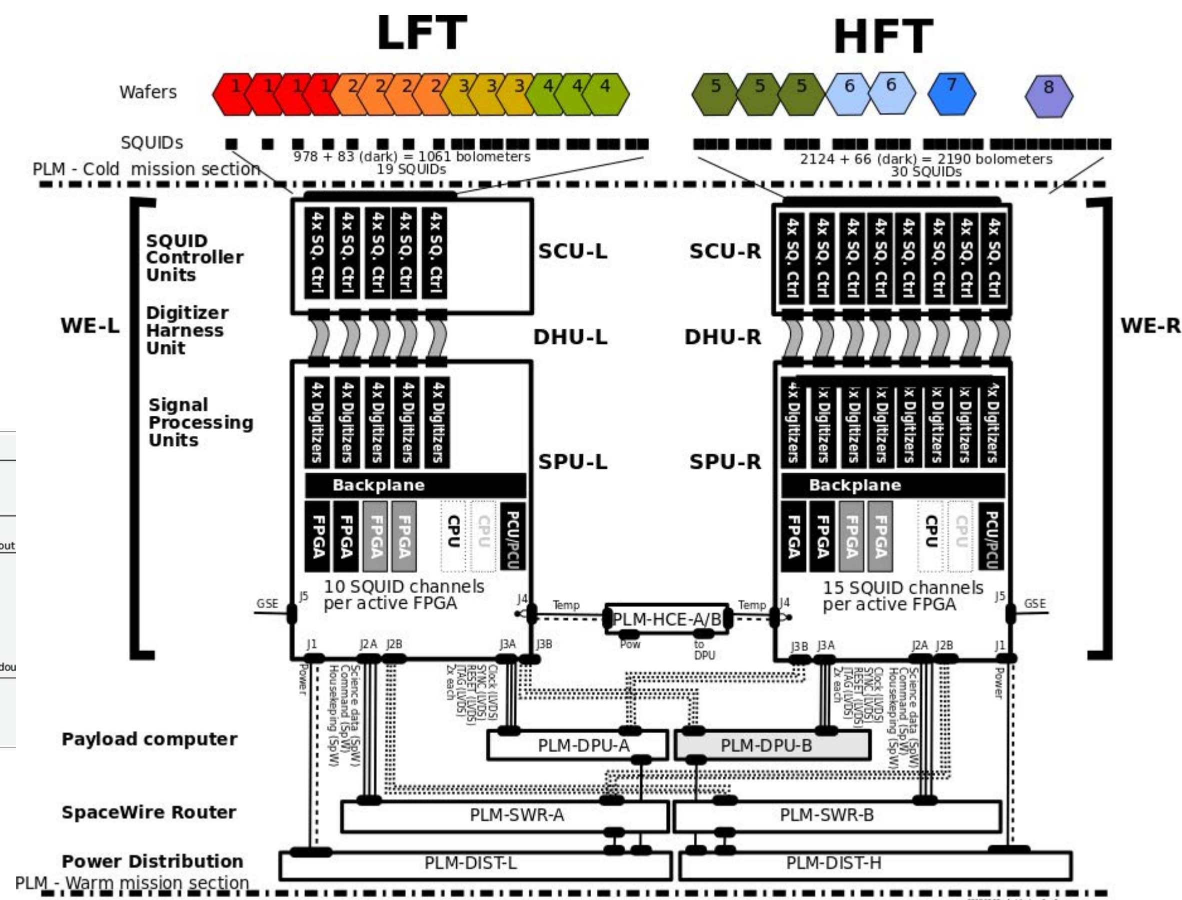
Canadian Space Agency Agence spatiale canadienne



- Frequency Multiplexed Readout
  - USA: Cold components (SQUID)
  - Canada: warm electronics

- Based on system deployed for South Pole Telescope and POLARBEAR.

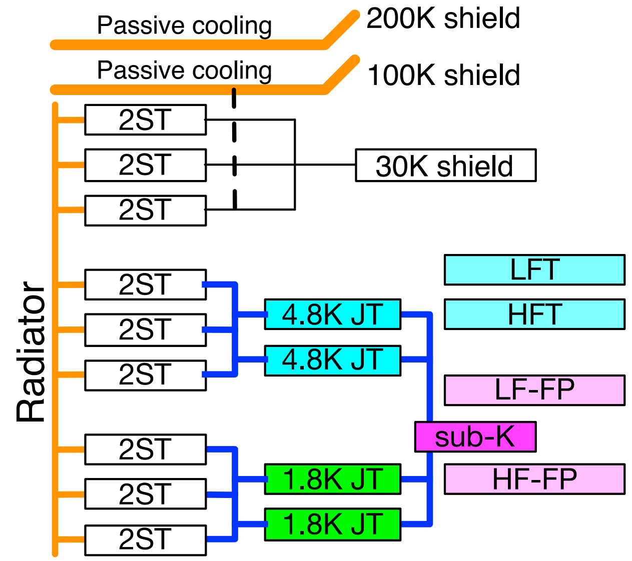


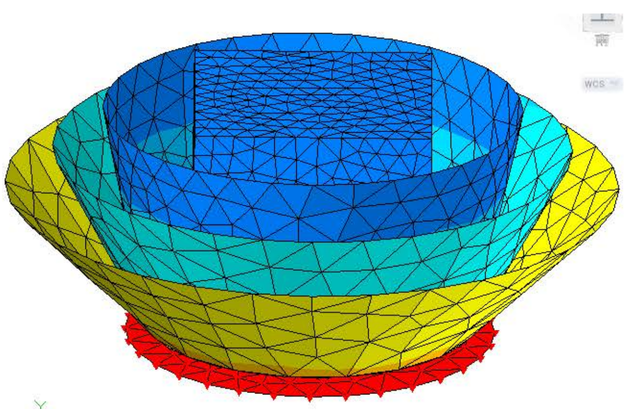


Thermal design

- Based on SPICA design study
- Redundant for mechanical coolers (1.8KJT, 4.8KJT, 2ST)
- Passive cooling with V-grooves

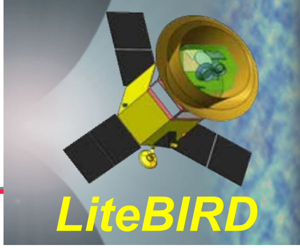
	4.8K JT	1.8K JT
cooling capacity @EOL	40 mW	10 mW
margin	10 mW	3 mW
conductive and radiative loads	12 mW	
HWP, subK coolers, focal plane	18 mW	
cold aperture stop and focal plane and suK coolers		7 mW

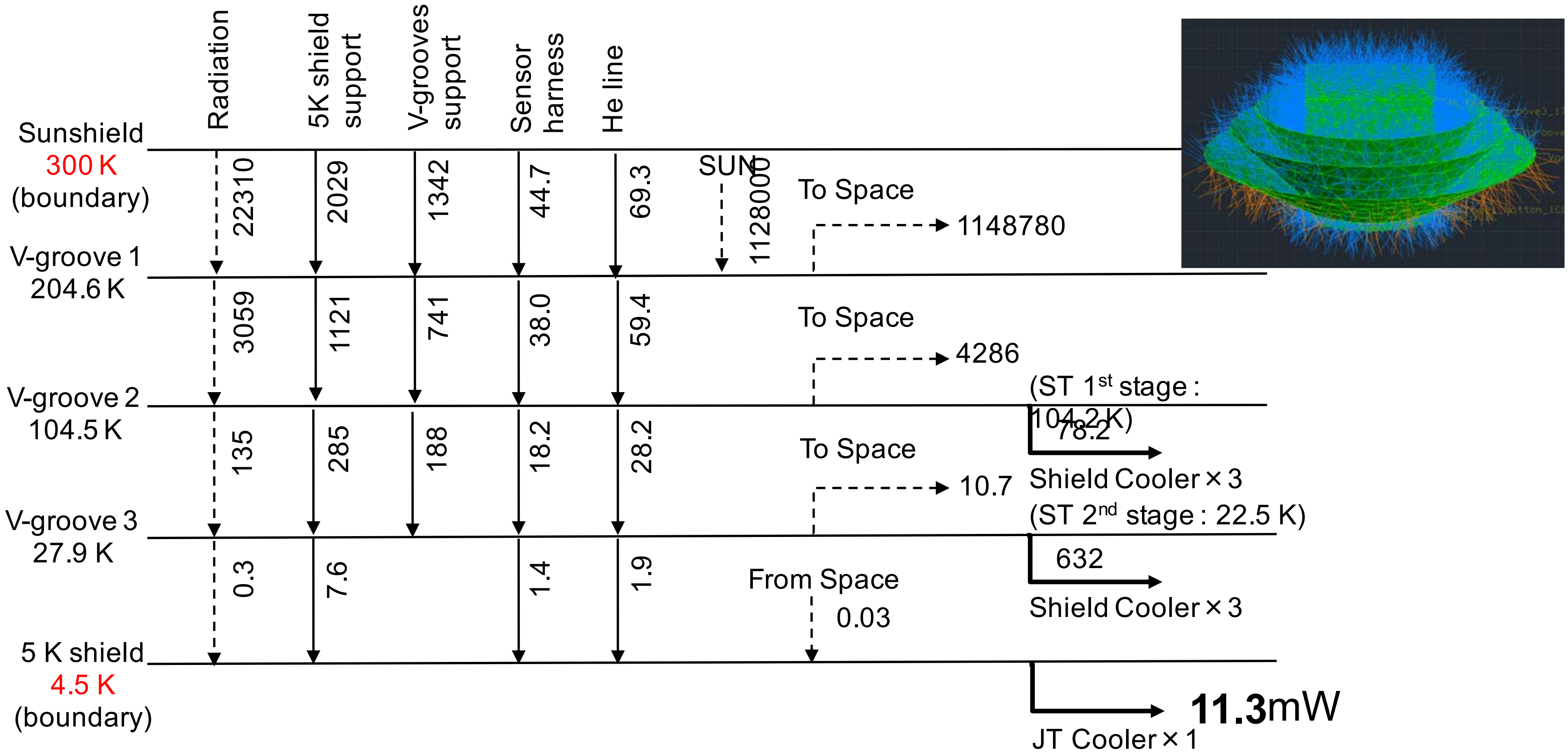




[SPIE 10698-219] T. Hasebe et al. "Thermal design utilizing radiative cooling for the payload module of LiteBIRD"

Heat flow diagram





4.8K JT cooler
cooling capacity 30 mW + margin 10 mW

18 mW for HWP and sub-K coolers

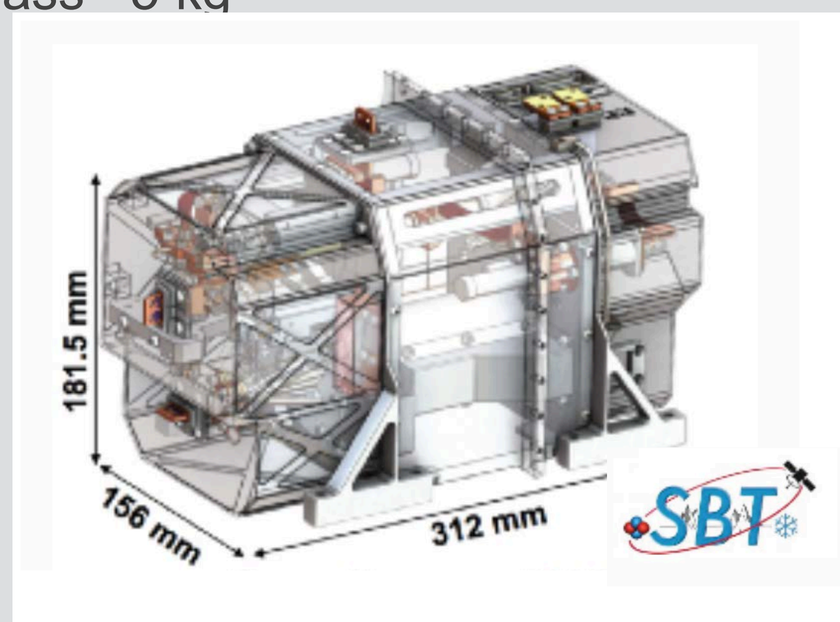
[SPIE 10698-219] T. Hasebe et al. "Thermal design utilizing radiative cooling for the payload module of LiteBIRD"

Sub-Kelvin cooler

Two technologies available in France

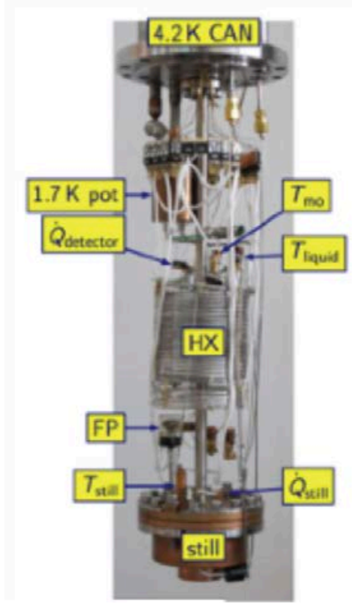
Hybrid Adiabatic Demagnetization Refrigerator

- CEA-SBT
- Single shot - Duty Cycle: ~80%
- TRL - 6
- Heat lifts
  - 0.4µW @ 100 mK
  - 14µW @ 300 mK
- mass ~5 kg



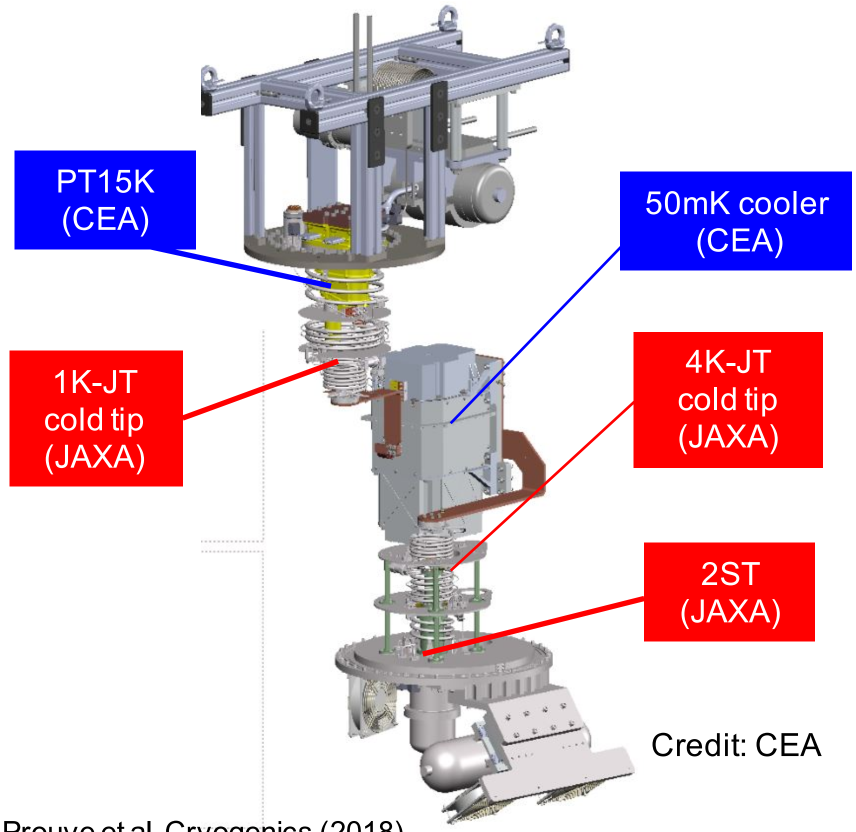
Closed Cycle Dilution Refrigerator

- NEEL / IAS / CNES
- Continuous - Duty Cycle: 100%
- TRL - 4
- Heat lifts
  - 3µW @ 100 mK
  - 10µW @ 300 mK
- mass < 6 kg



End-to-end cooling chain verification

- In the framework of ESA Core Technology Program, Cryo-Chain CTP (CC-CTP) project has been promoted during 2016-2018, in the international collaboration led by CNES, with JAXA and CEA.
- Thermal interface from 300K to 100mK/50mK (end-to-end) has been demonstrated for LiteBIRD, SPICA, and Athena.



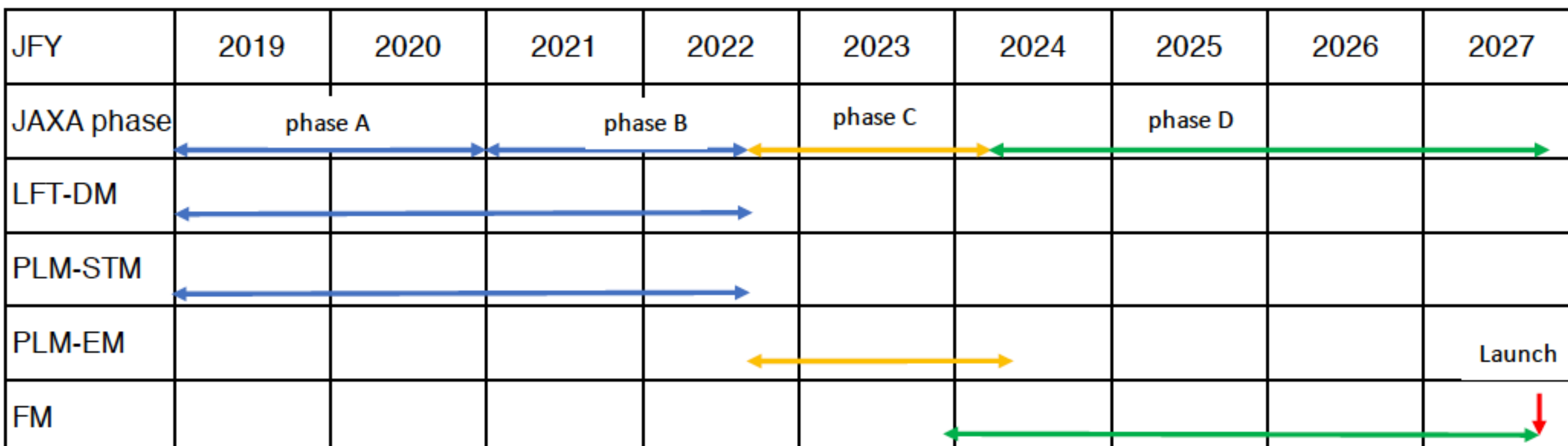
T.Prouve et al. Cryogenics (2018)
T.Prouve et al. ESCW (2018)

LiteBIRD basic parameters

	Low Frequency Telescope (LFT)	High Frequency Telescope (HFT)
Frequency	34 ~ 161 GHz	89 ~ 448 GHz
field of view	> 20 deg ×10 deg	> 20 deg ×10 deg
aperture diameter	400 mm	300 mm
angular resolution	20 ~ 70 arcmin	10 ~ 40 arcmin
rotational HWP	88 rpm	170 rpm
number of detectors	~1000	~2100
Uncertainty of r	δr < 1 × 10^(−3)	
Observation period	3 years	
Scan	L2 Lissajous, precession angle 45 deg, spin angle 50 deg (0.1 rpm)	
Sensitivity	< 3 μK·arcmin	
pointing knowledge	< 3 arcmin	
focal plane array	bath temperature 100 mK	
	NET^{P}array = 1.7 μK√s@ 100 mK	
	f_{knee} < 20 mHz	
data transfer	7 GByte/day	
mass	2.6 ton	
electrical power	3.0 kW	

Development model philosophy

- LFT demonstration model (DM) :
  - PLM 5K (LFT only) with LF-focal plane at 0.1K
  - beam, spectral, polarization, multiple reflection at cryogenic temperature.
- PLM structure thermal model (STM) :
  - 300K to 5K structures, mechanical coolers (incl. 0.1K), V-groove
  - Check mechanical and thermal interfaces
- PLM engineering model (EM) :
  - Integration of PLM including HFT without SVM
  - Check PLM interfaces equivalent to FM
  - Noise and optical efficiency verification, EMC
- Flight model (FM) :

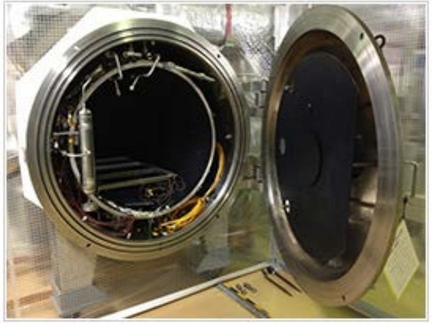


Facilities for verification and testing

JAXA 6-m diameter space chamber

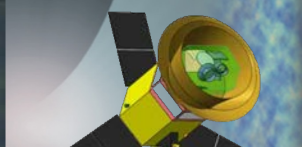
JAXA 13-m diameter space chamber
Astro-H test was done here.

JAXA Antenna test facility

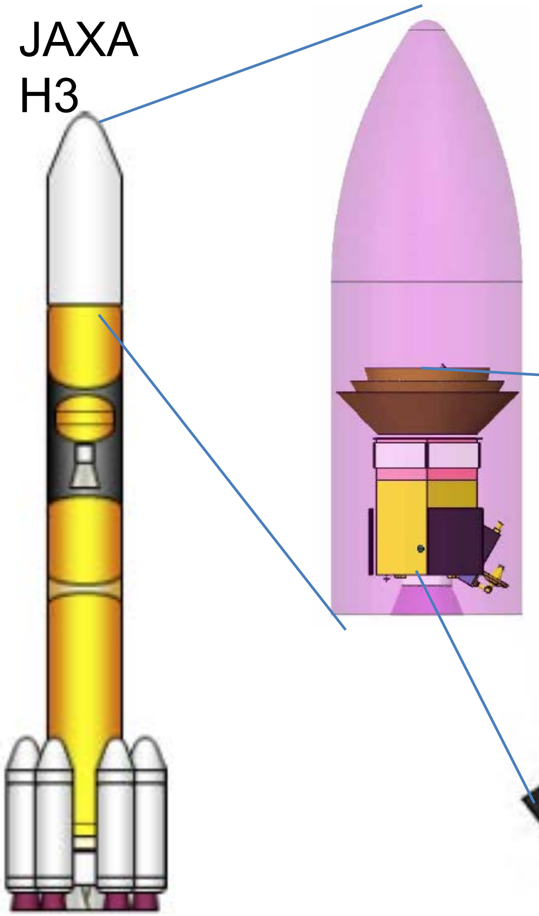


JAXA 1-m diameter space chamber

LiteBIRD summary



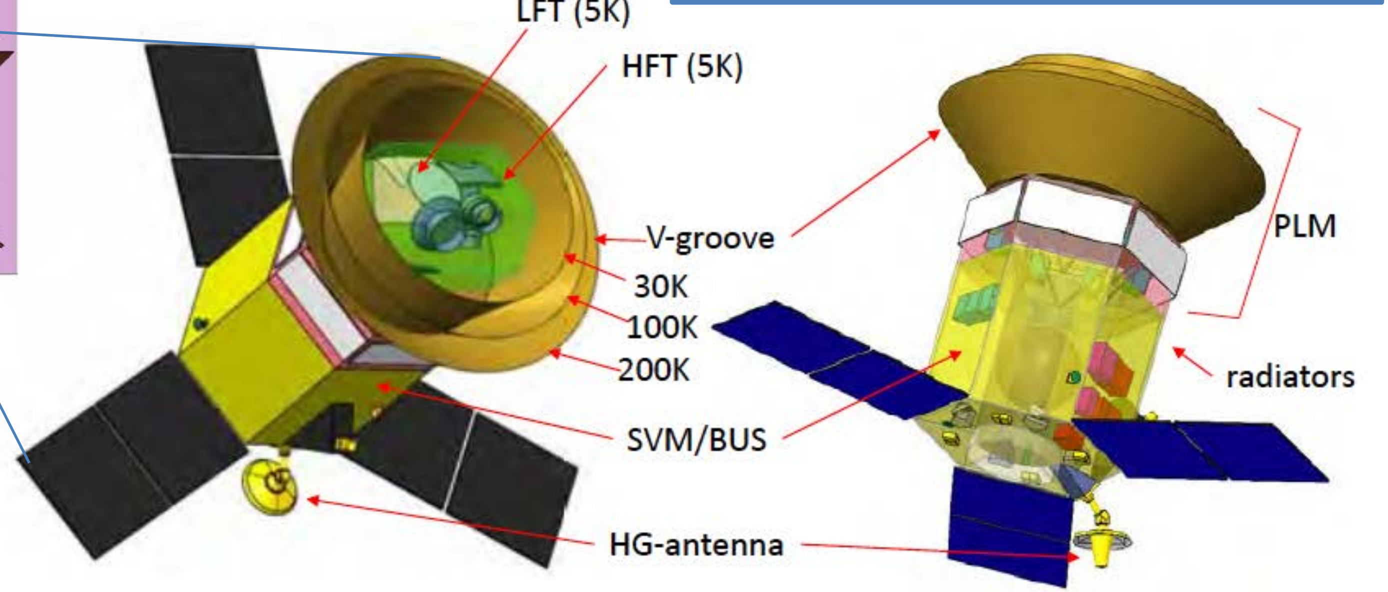
- JAXA-led international mission proposal (12 countries)
- Status: Phase A (concept development)
- 3yr observations at L2



- **The only space mission proposal in Phase A in the world**
- Final selection in 2019
- Launch in 2027

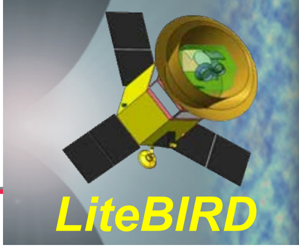
Full Success:
$\sigma(r) < 1 \times 10^{-3}$ (for r=0)
$2 \leq \ell \leq 200$

Extra Success: Improve σ(r) w/ external data (foreground cleaning and delensing)



Backup slides

About predictions on r



- Many models predict r > 0.01 → >10sigma discovery at LiteBIRD
- More general (less model-dependent) prediction
  - Focus on the simplest models based on Occam's razor principle.
  - Single-field slow-roll (SFSR) models 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

  - Model-dependent exercises come to the same conclusion (w/ very small exceptions).
    - Thus, large-field variation ($\Delta\phi > m_{pl}$), which is well-motivated phenomenologically, leads to r > 0.002.
  - 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.

With $\sigma(r) < 0.001$ for $2 \leq \ell \leq 200$, LiteBIRD would provide a fairly definitive statement about the validity of large-field single-field slow-role models, which is a milestone in cosmology.

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

No-Lose Theorem of LiteBIRD