CMB foregrounds for B-mode studies

Tenerife, Spain, October 15-18, 2018

LiteBIRD

Masashi Hazumi

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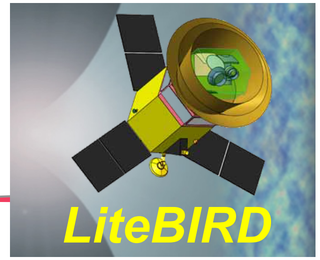
3) Institute of Space and Astronautical Science (ISAS), Japan Aerospace Exploration Agency (JAXA)
4) Graduate School for Advanced Studies (SOKENDAI)

for LiteBIRD Joint Study Group

LiteBIRD Joint Study Group

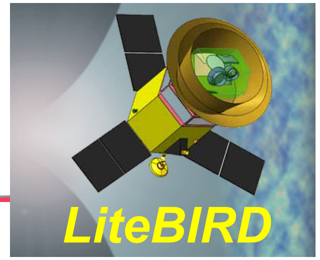


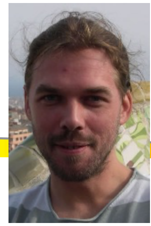
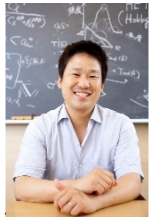
About 180 researchers from Japan, North America & Europe

Experience: CMB exp., X-ray satellites, other large proj. (HEP, ALMA etc.)

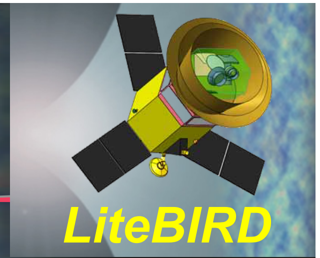
Y. Sekimoto[14,37] , P. Ade[2], K. Arnold[49], J. Aumont[12], J. Austermann[29], C. Baccigalupi[11], A. Banday[12], R. Banerji[56], S. Basak[7,11], S. Beckman[49], M. Bersanelli[44], J. Borrill[20], F. Boulanger[4], M.L. Brown[53], M. Bucher[1], E. Calabrese[2], F.J. Casas[10], A. Challinor[50,60,64], 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],

European consortium leadership



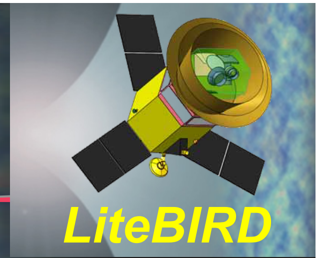
- *Spokesperson:* Ludovic Montier (IRAP, France)…............. 
- *Deputy Spokesperson:* Erminia Calabrese (Cardiff U. UK)…........... 
- *Systems Engineer:* Baptiste Mot (IRAP, France)…................................ 
- *Steering Committee Chair:* Nicola Vittorio (U. Rome Tor Vergata)….................. 
- *Steering Committee members:*
  - *France:* Ludovic Montier (IRAP),
    Radek Stompor (ACP)….. 
  - *Germany:* Eiichiro Komatsu (MPA) …........... 
  - *Italy:* Nicola Vittorio (U. Rome Tor Vergata),
    Paolo de Bernardis (U. Rome La Sapienza)......... 
  - *Netherlands:* Jian-Rong Gao…... 
  - *Norway:* Ingunn Kathrine Wehus (U. Oslo)….. 
  - *Spain:* Enrique Martinez-Gonzalez (IFCA)…... 
  - *UK:* Erminia Calabrese (Cardiff U.),
    Giampaolo Pisano (Cardiff U)…........................ 
  - *Ireland and Sweden to be added*

LiteBIRD project overview



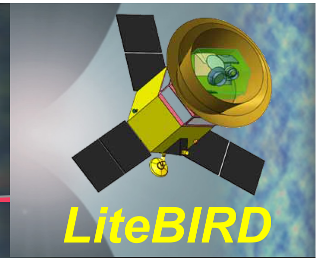
- JAXA L-class mission candidate with a solid basis in Japan
  - JAXA prefers a focused mission even for L-class
  - Test of inflation is one of the most important objectives in JAXA roadmap
  - MEXT (funding agency) chose LiteBIRD as one of 10 flag-ship future large projects among all areas of research
- Phase-A1 concept development at ISAS/JAXA (Sep.2016 – Aug. 2018) completed
  - The most advanced status among all CMB space mission proposals in the world
- Strong international contributions
  - US: Focal plane/cold readout technology development (NASA)
  - Canada: Science contribution studies and science maturity studies (CSA)
  - Europe:
    - Studies at Concurrent Design Facility (ESA) with the European consortium
    - Italy: Phase A commitment (ASI)
    - France: Phase A commitment (CNES)

Schedule after Phase-A1

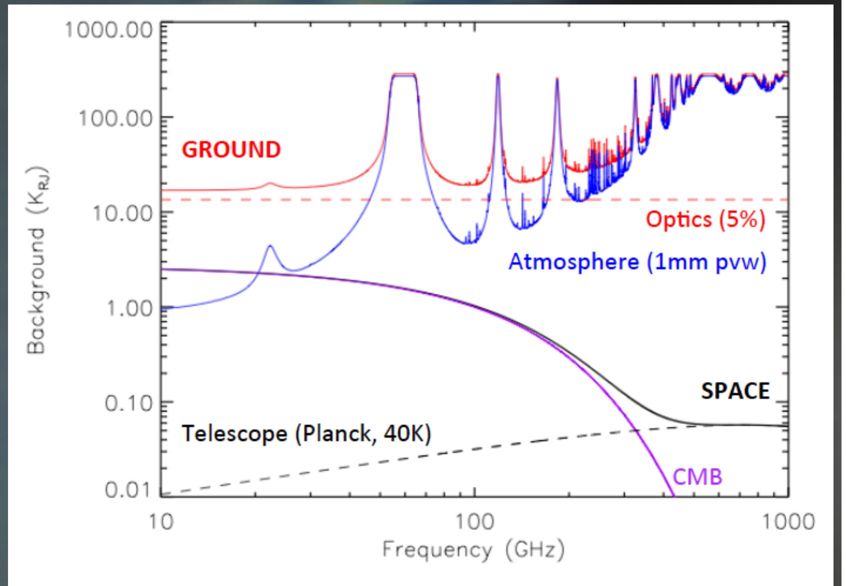


- Final down selection in early 2019
  - LiteBIRD or OKEANOS (solar-power sail), i.e. only two candidates remain
- Launch in 2027
- Observation in L2 for 3 years

Why measurements in space?



- Superb environment !
  - No statistical/systematic uncertainty due to atmosphere (cf. polarization due to icy clouds in POLARBEAR obs., S. Takakura et al. 2018)
  - No limitation for the choice of observing bands (except CO lines)
  - No ground pickup



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

- Only way to access lowest multipoles w/ $\delta r \sim O(0.001)$
  - Both B-mode bumps need to be observed for the firm confirmation of cosmic inflation → We need measurements in space.

LiteBIRD 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)
- $2 \leq \ell \leq 200$

LiteBIRD extra success

Improve σ(r) with external observations

Topic	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 cleaning	Lower frequency survey	C-BASS, S-PASS, QUIJOTE etc. and their upgrades

- 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.

LiteBIRD science outcomes

1. Full success

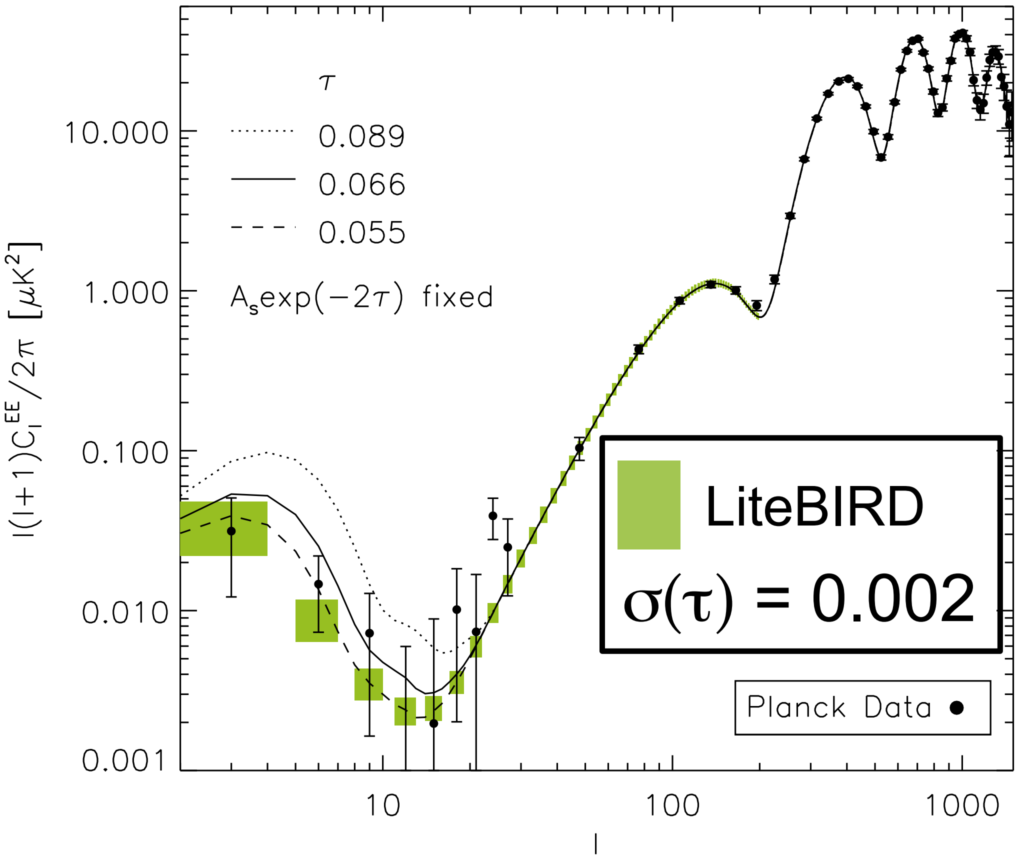
System requirements from 1. only

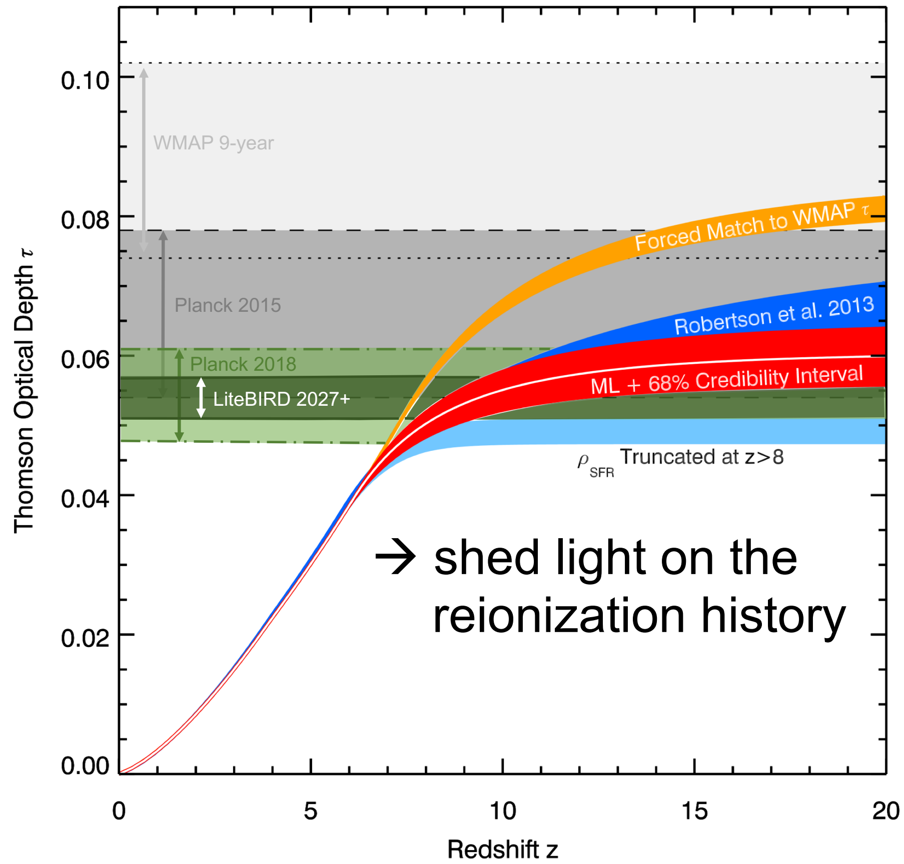
2. Extra success (see previous page)
3. Characterization of B-mode
   (e.g scale-invariance, non-Gaussianity, and parity violation)
4. Large-scale E mode and its implications
   for reionization history and the neutrino mass
5. Birefringence
6. Power spectrum features in polarization
7. SZ effect (thermal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

3. – 10. almost guaranteed if full success is achieved.

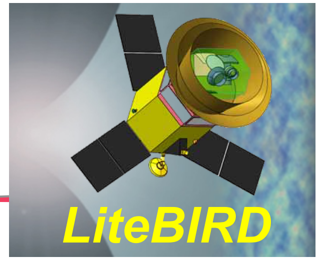
Large-scale E-mode

A cosmic variance limited measurement of EE on large angular scales will be an important, and guaranteed, legacy for LiteBIRD!



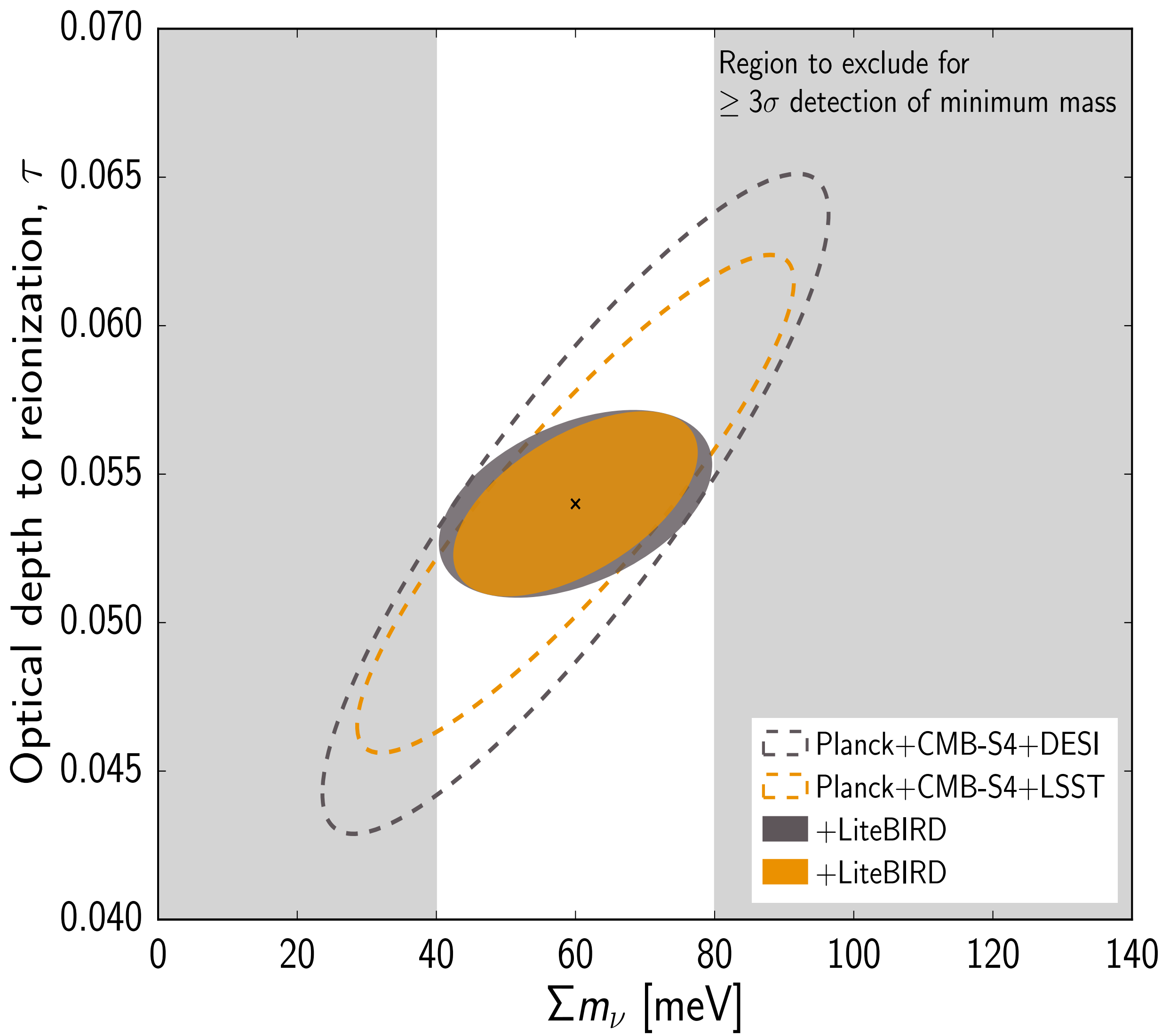


Σm_ν w/ improved τ

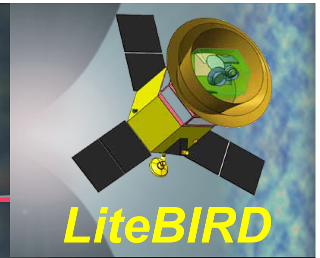


- $\sigma(\Sigma m_\nu)$ =15 meV
- $\geq 3\sigma$ detection of minimum mass for normal hierarchy
- $\geq 5\sigma$ detection of minimum mass for inverted hierarchy

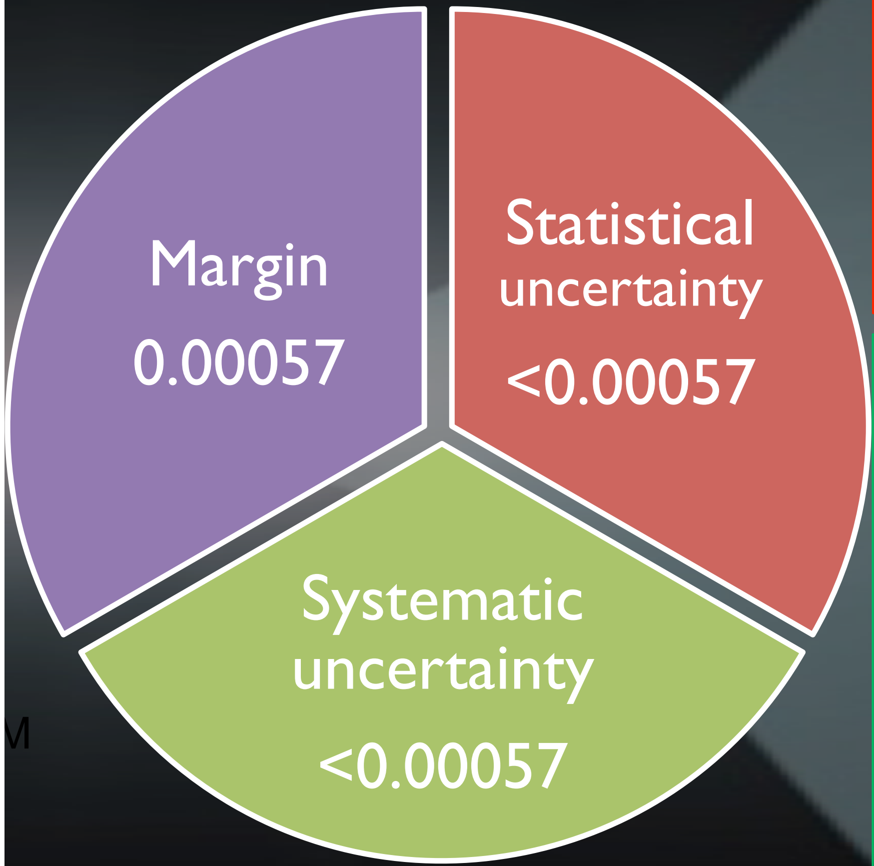
Caveat:
No systematic error included yet.



Design drivers toward full success



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



Statistical uncertainty includes

- foreground cleaning
- lensing B-mode
- 1/f noise

→ Broadband 34 – 448 GHz (15 bands)

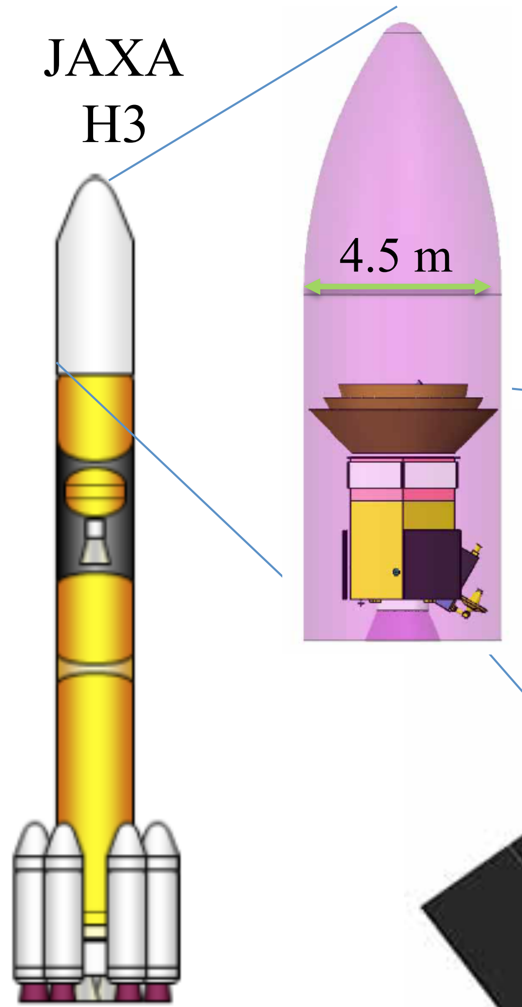
Systematic uncertainty includes

- 1/f noise
- Polarization efficiency & knowledge
- Disturbance to instrument
- Off-boresight pick up
- Calibration accuracy

→ Polarization Modulation Unit (PMU)

Our simulations tell that both criteria are satisfied!

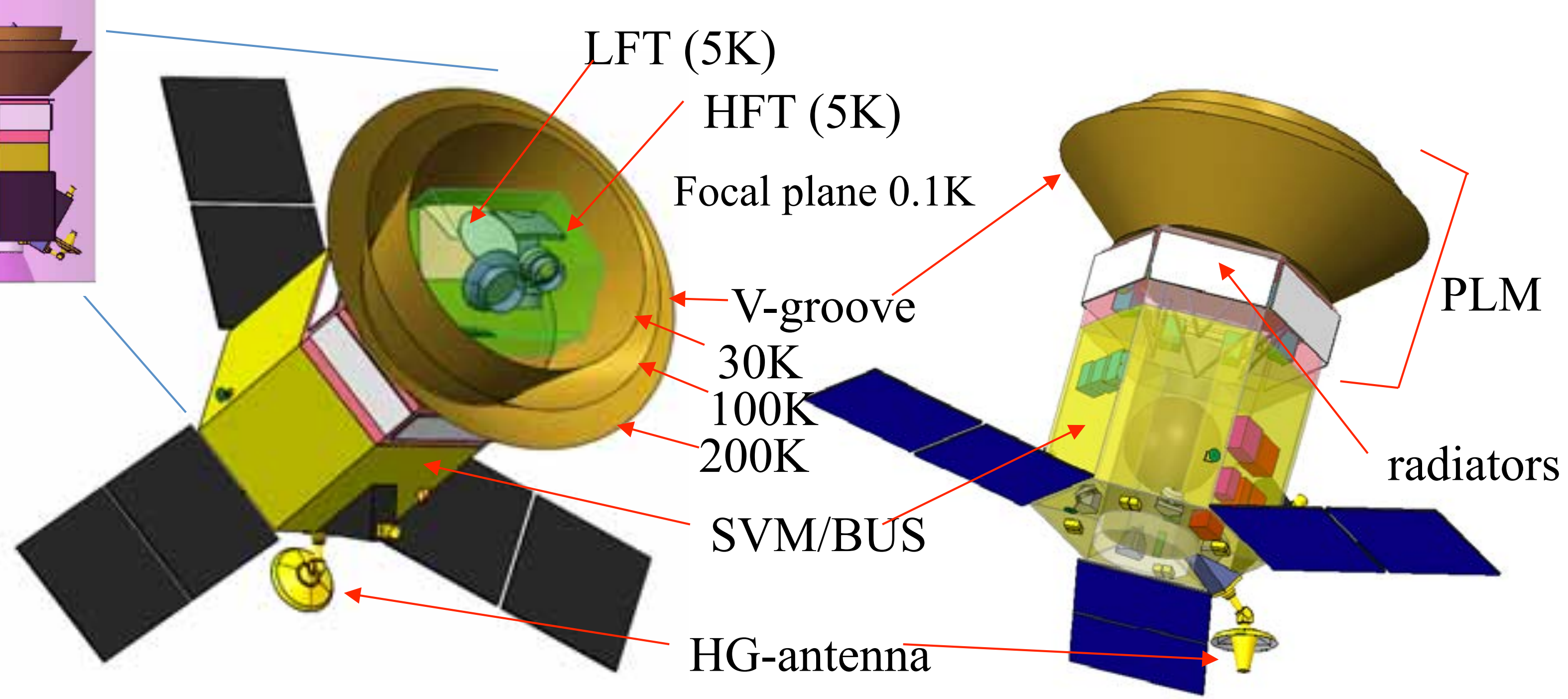
LiteBIRD spacecraft



Two telescopes

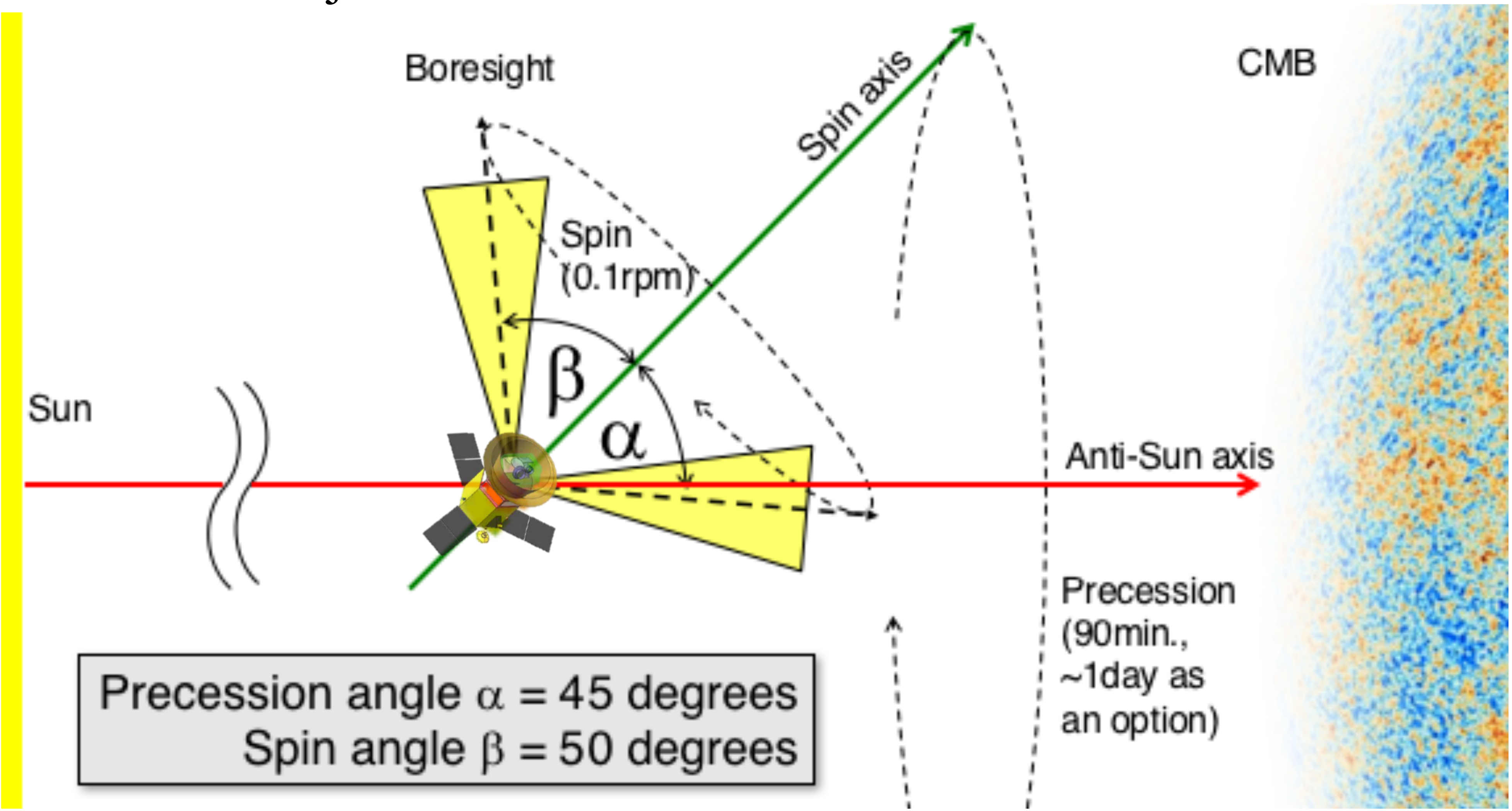
LFT (Low frequency telescope) 34 – 161 GHz : Synchrotron + CMB

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



Scan strategy

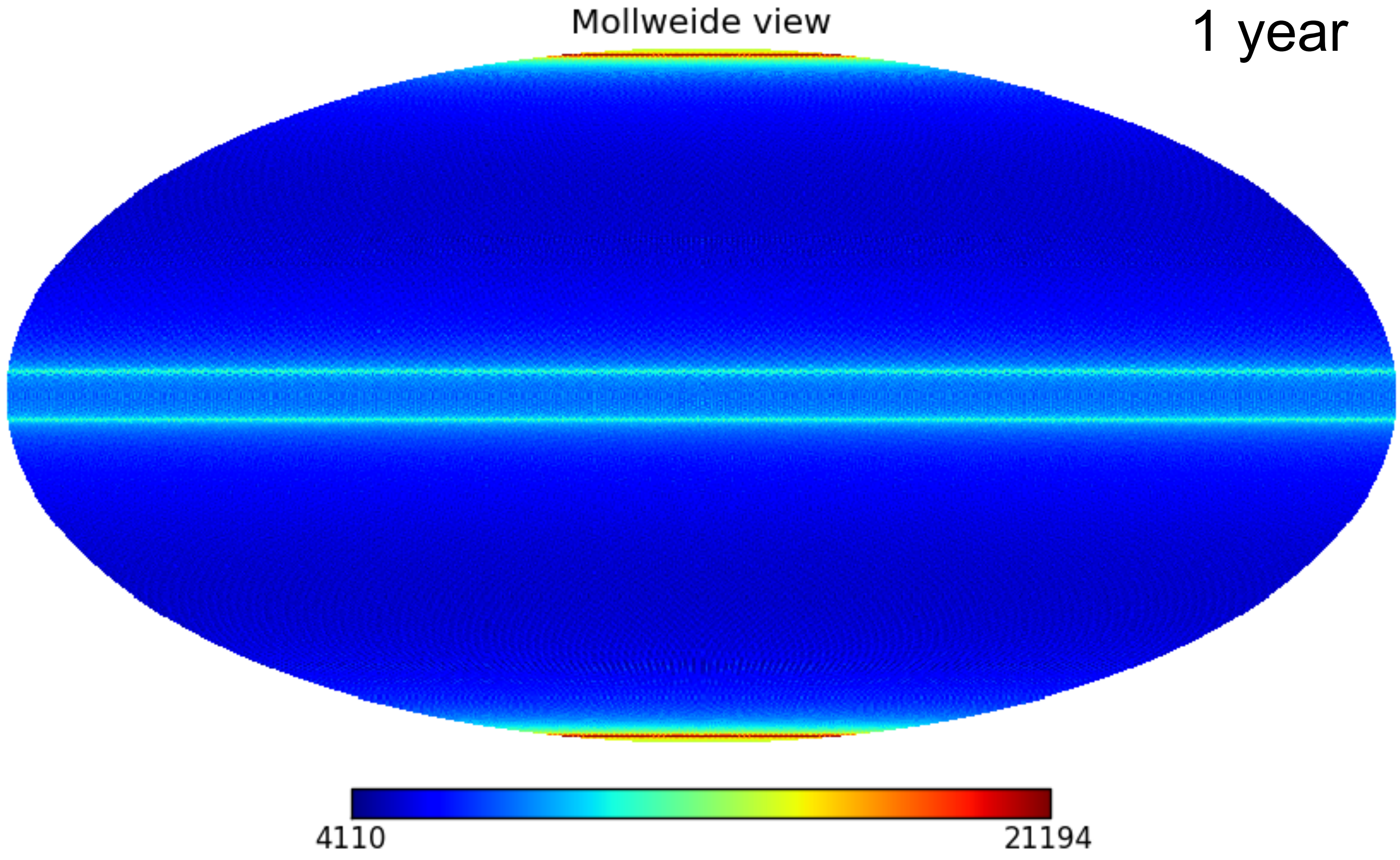
Orbit: L2 Lissajous



of observations for each sky pixel

w/ a single detector

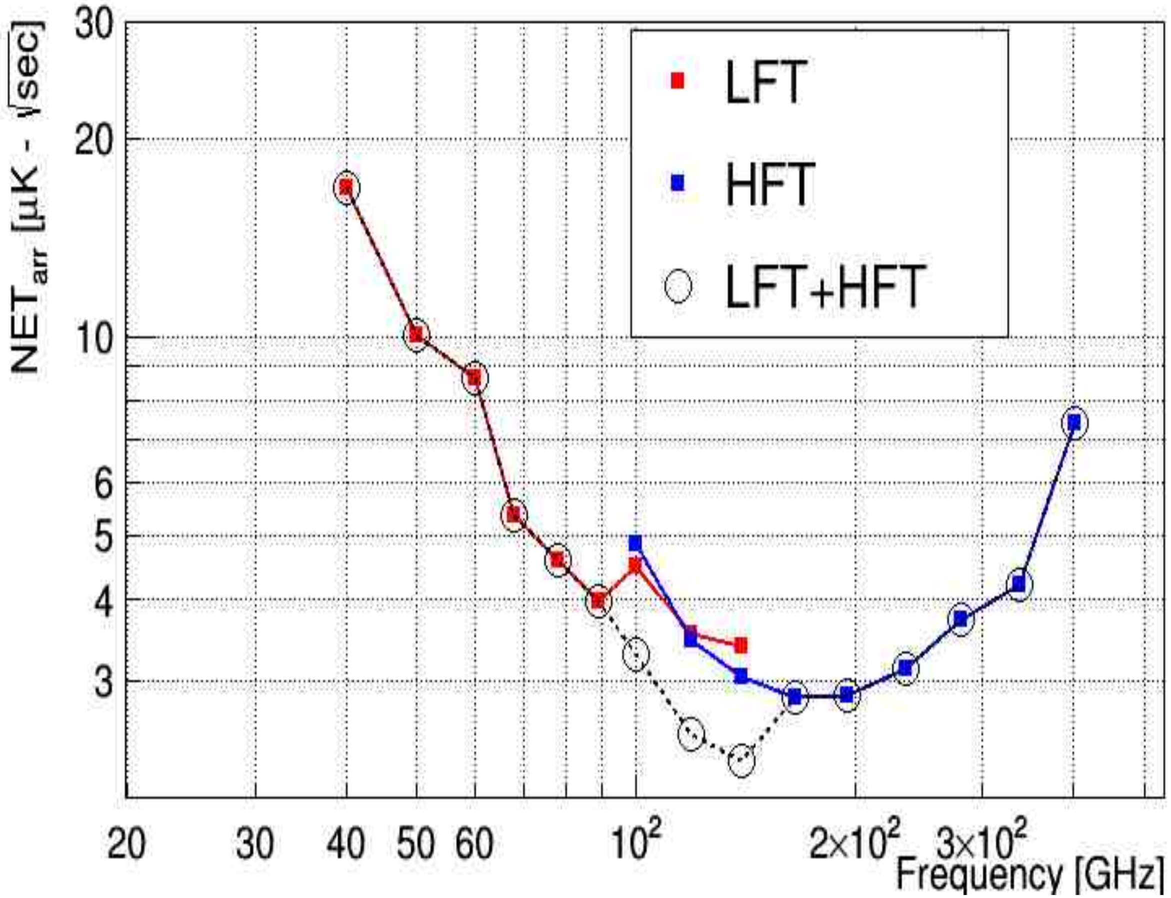
1 year



Sensitivity

- Good sensitivities under available focal planes
- Further optimization possible w/ minor design impact

Detector array sensitivity (NET_{arr})

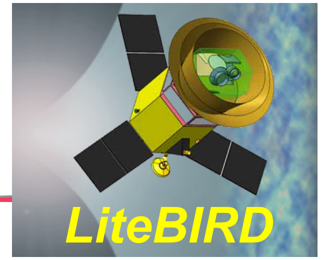


NET_{arr} → Sky sensitivity

Frequency [GHz]	$NET_{CMB,Arr}$ [$\mu K \cdot \sqrt{s}$]	Sensitivity [μK – arcmin]
40	16.76	34.99
50	10.04	20.96
60	8.67	18.09
68	5.37	11.21
78	4.57	9.54
89	3.97	8.29
100	3.39	6.88
119	2.49	5.19
140	2.27	4.75
166	2.85	5.96
195	2.86	5.97
235	3.13	6.52
280	3.73	7.79
337	4.22	8.82
402	7.40	15.44

(3yr obs.)

Foreground cleaning



Methodology

Synchrotron: $[Q_s, U_s](\hat{n}, \nu) = [Q_s, U_s](\hat{n}, \nu_*)\left(\frac{\nu}{\nu_*}\right)^{\beta_s(\hat{n})+C_s(\hat{n})\ln(\nu/\nu_*^C)}$

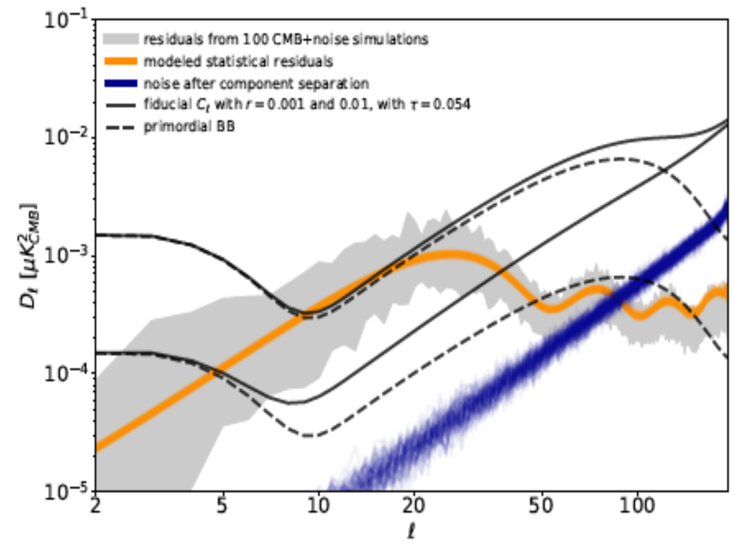
- AME is effectively absorbed by synchrotron curvature

Dust: $[Q_d, U_d](\hat{n}, \nu) = [Q_d, U_d](\hat{n}, \nu_*)\left(\frac{\nu}{\nu_*}\right)^{\beta_d(\hat{n})-2}\frac{B[\nu, T_d(\hat{n})]}{B[\nu_*, T_d(\hat{n})]}$

(8 parameters in each sky region) x (12 x N_{side}^2)

= 6144 parameters w/ $N_{\mathrm{side}} = 8$

to take spatial variations into account

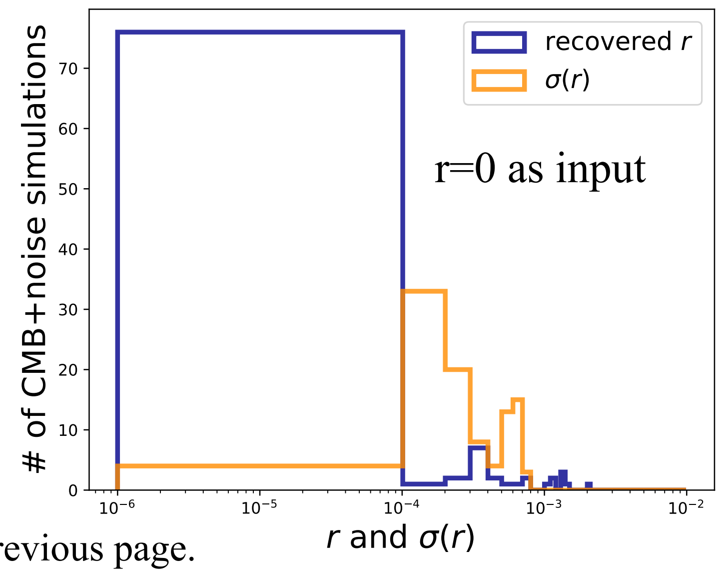


Results*

"Multipatch technique" (extension of xForecast)

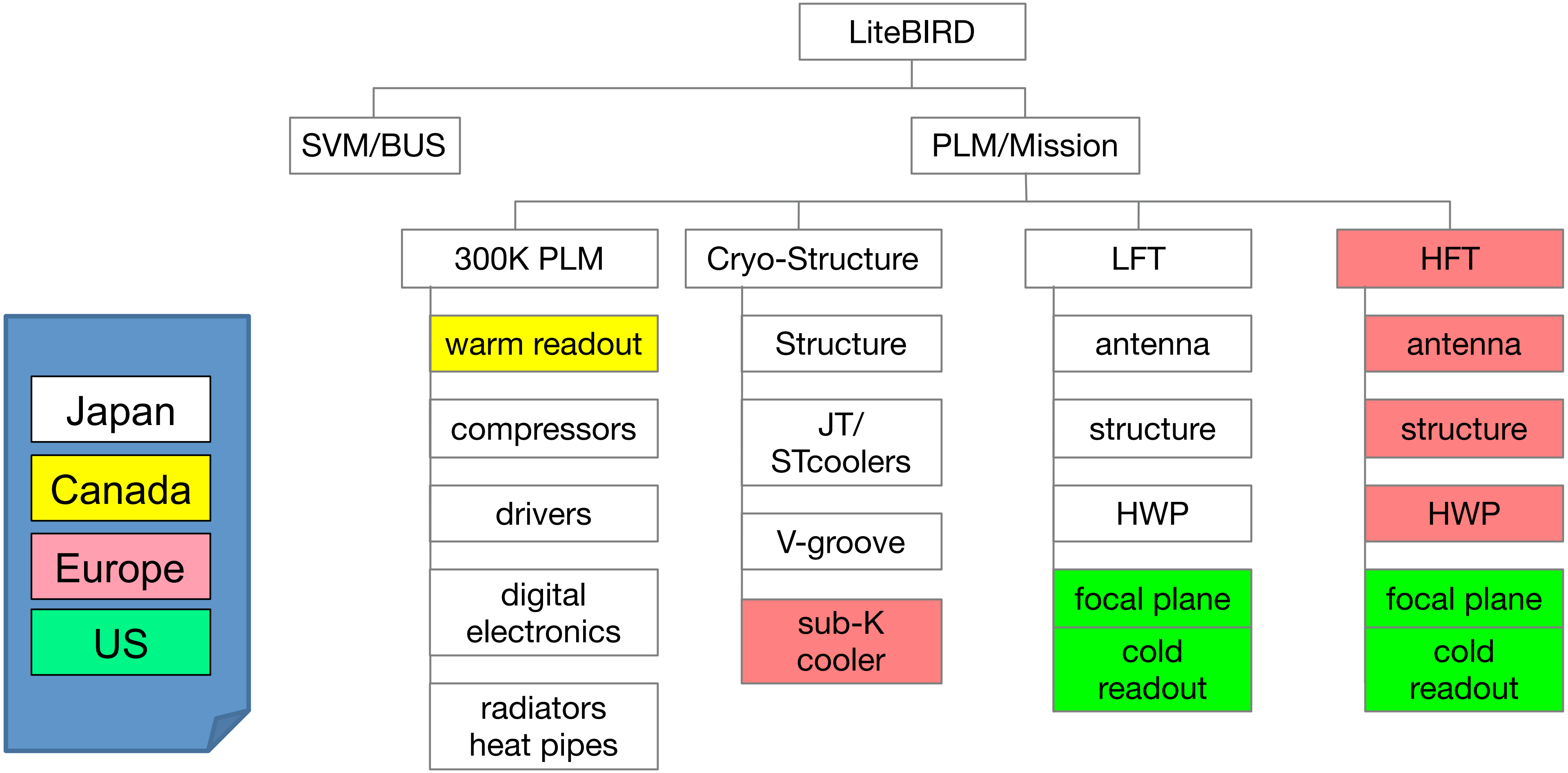
- σ(r=0) = 0.0005 ☺
- Negligibly small bias ☺

Consistent results from COMMANDER! ☺



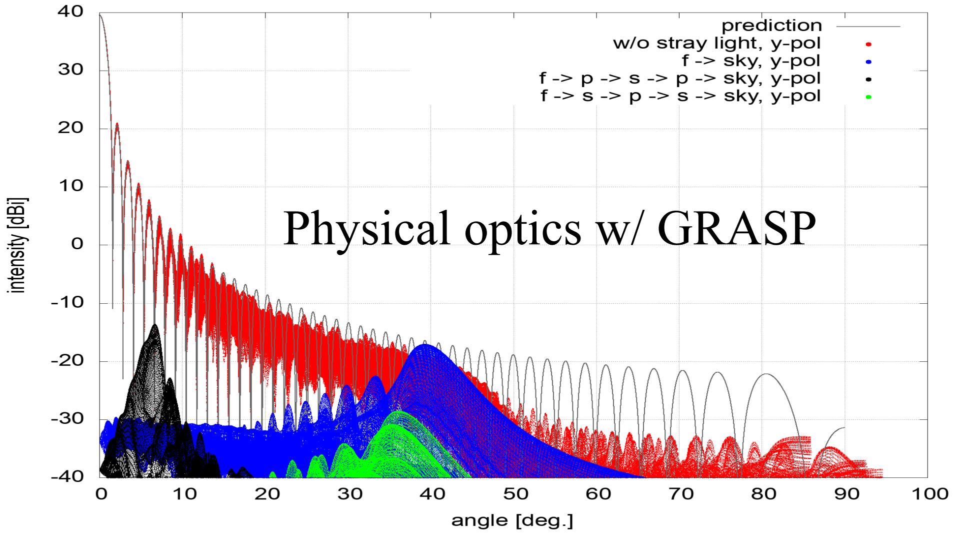
* Assumed time loss of ADR cycles. Detector config. slightly different from previous page.

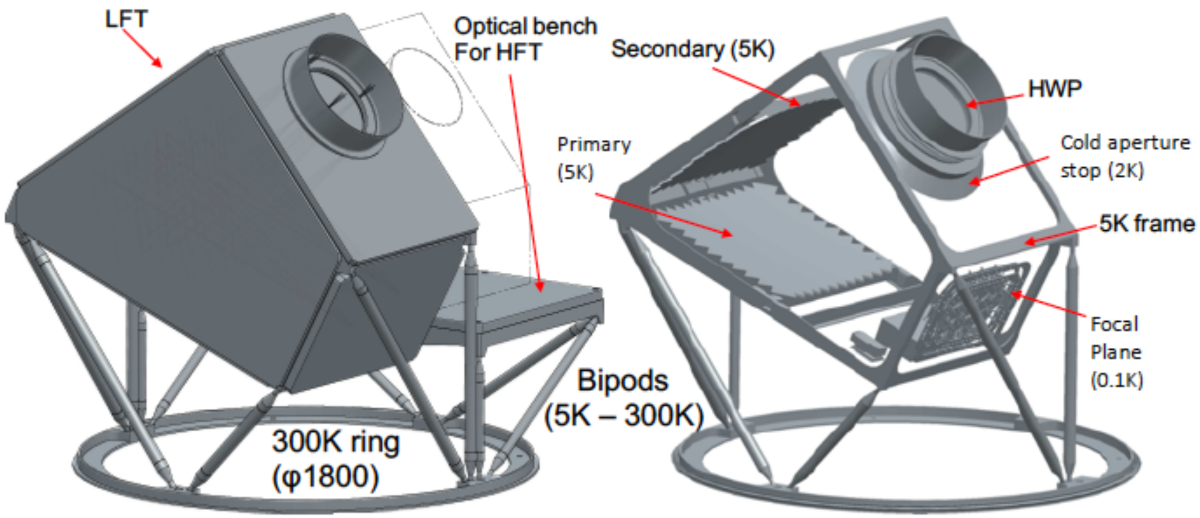
LiteBIRD component tree

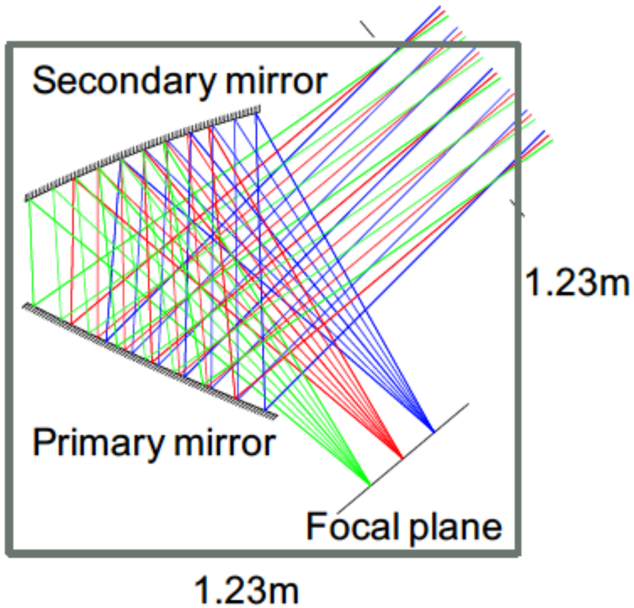


LFT optics

- Crossed Dragone
- Aperture diameter 400 mm
- Angular resolution 20 – 70 arcmin.
- 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
- New mirror design (anamorphic aspherical surfaces) S. Kashima et al. 2018 Appl. Opt.





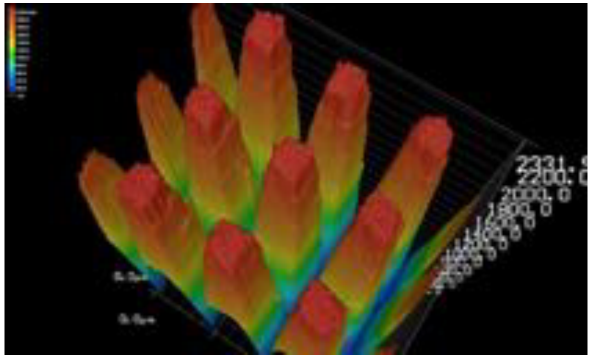


LFT polarization modulator

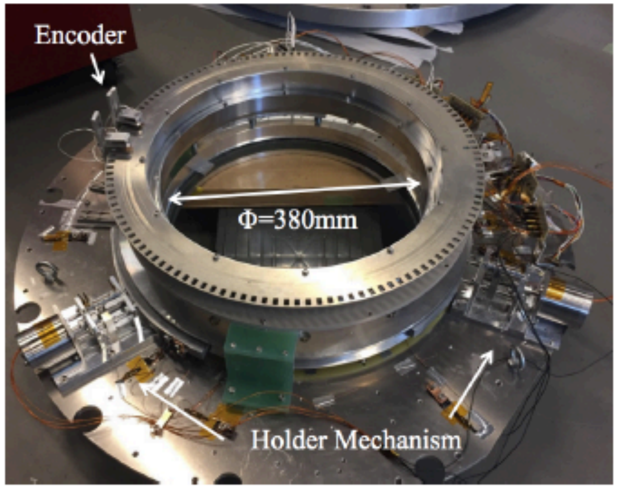
Continuously-rotating half-wave plate (HWP)

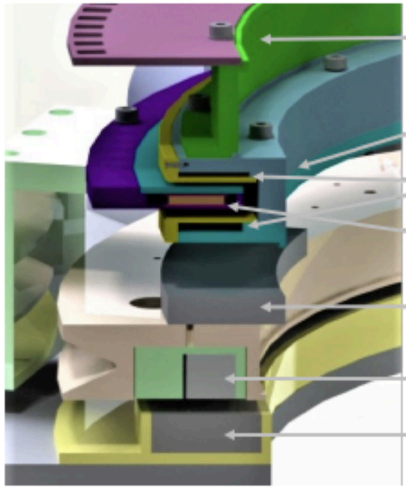
- Mitigation of 1/f noise
- Mitigation of differential systematics
- Baseline is to rotate HWP continuously throughout the mission

Bell-shaped anti-reflection on sapphire HWP

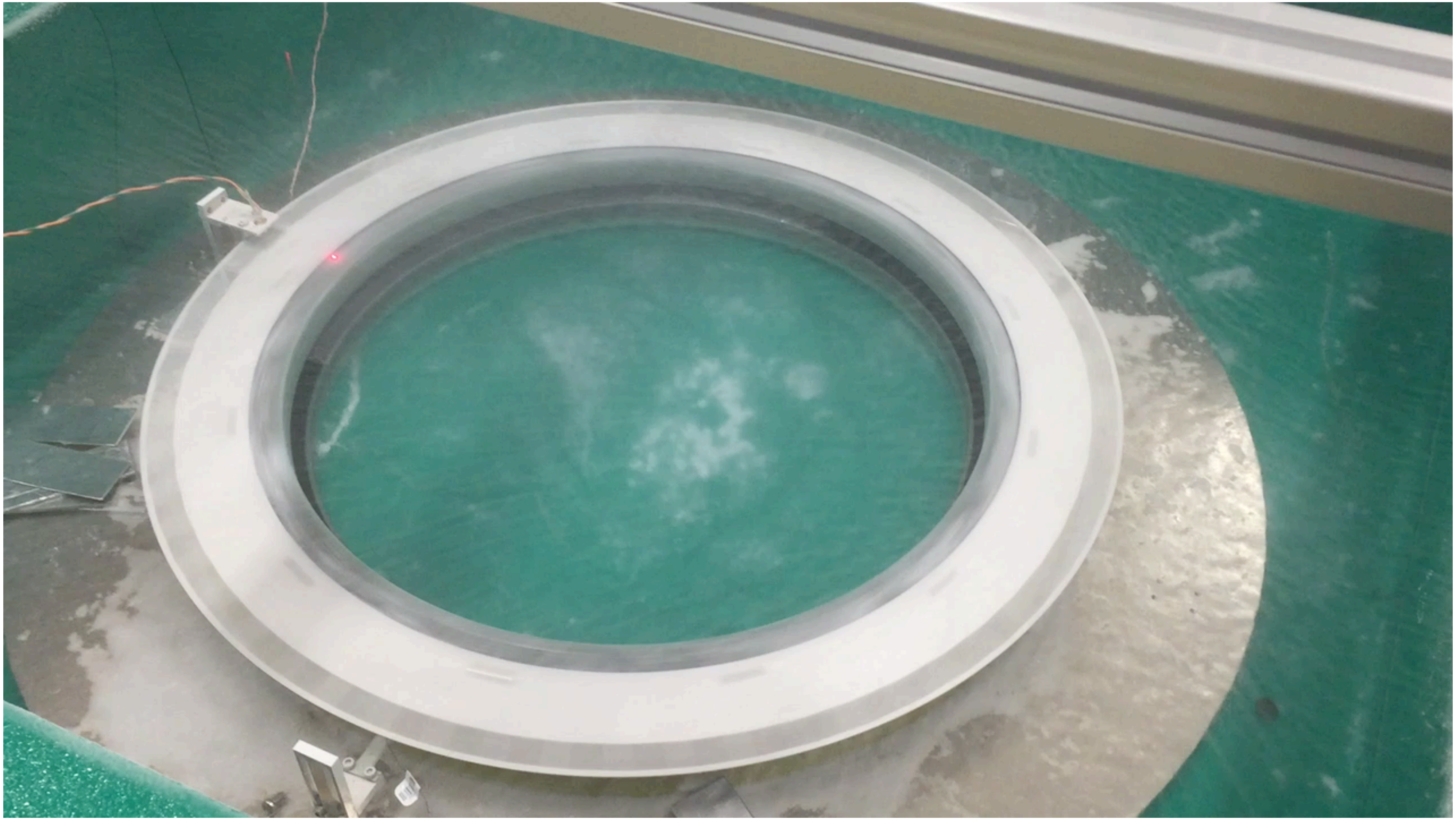


Superconducting magnetic rotator BBM developed in Phase A1.
Mechanical and thermal feasibilities are being evaluated.





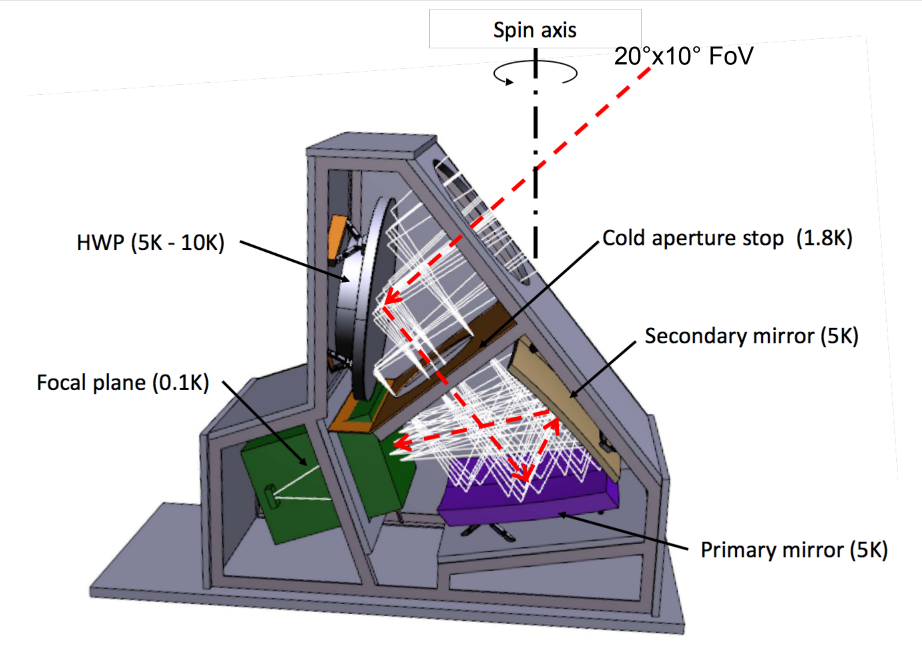
[SPIE 10708-12] Y. Sakurai et al. "Design and development of a polarization modulator unit based on a continuous rotating half-wave plate for LiteBIRD"
[SPIE 10708-142] K. Komatsu et al. "Prototype design and evaluation of the nine-layer achromatic half-wave plate for the LiteBIRD low frequency telescope"



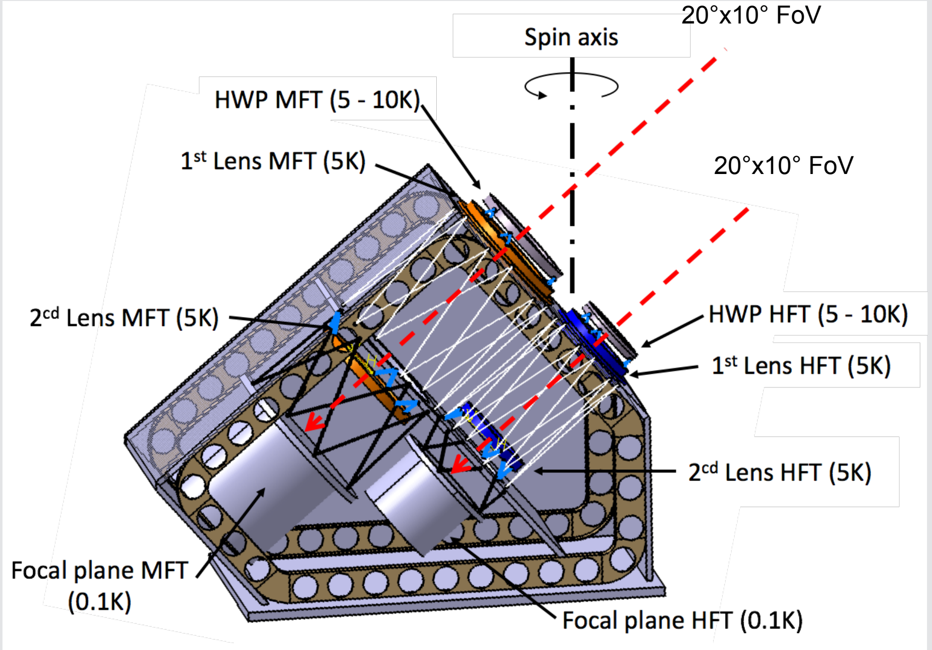
HFT design status

Two concepts under study by the European consortium

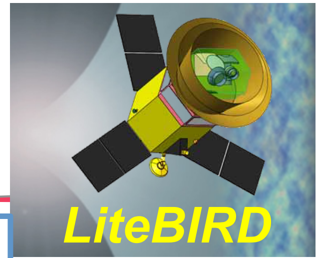
Reflective solution
- Crossed Dragone telescope - F/3.5
- Frequency coverage: 89 - 448 GHz
- Continuous rotating HWP mechanism
- Reflective Embedded Metal-mesh HWP tilted at 45°



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 w/ TES bolometers

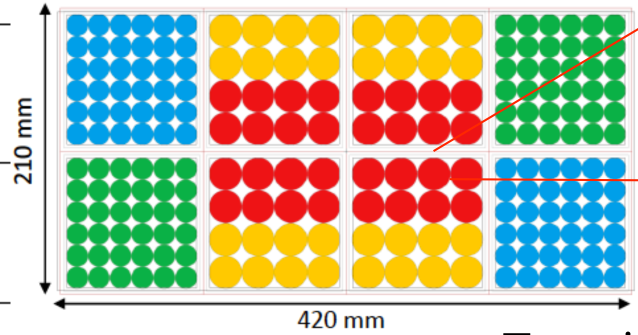


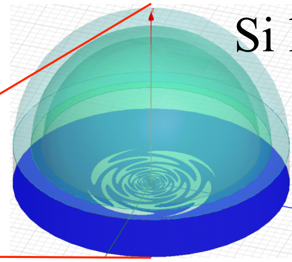
Pixel Type	Frequency [GHz]	Frac BW	Num Pix
LFT-1	40	0.30	32
LFT-1	60	0.23	32
LFT-1	78	0.23	32
LFT-2	50	0.30	32
LFT-2	68	0.23	32
LFT-2	89	0.23	32
LFT-3	68	0.23	72
LFT-3	89	0.23	72
LFT-3	119	0.30	72
LFT-4	78	0.23	72
LFT-4	100	0.23	72
LFT-4	140	0.30	72
HFT-1	100	0.23	108
HFT-1	140	0.30	108
HFT-1	195	0.30	108
HFT-2	119	0.30	108
HFT-2	166	0.30	108
HFT-2	235	0.30	108
HFT-3	280	0.30	161
HFT-3	402	0.23	161
HFT-4	337	0.30	161

total: 3,510 TESes

US team (PI Adrian Lee)
Berkeley, Colorado, LBNL, NIST, Stanford, UCSD

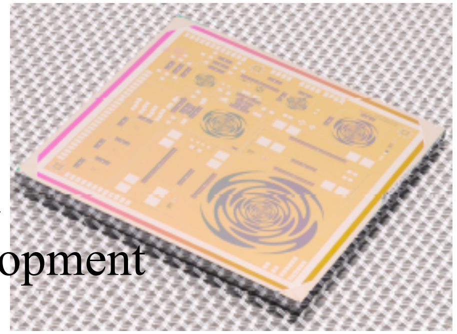
LFT f/3.0 design





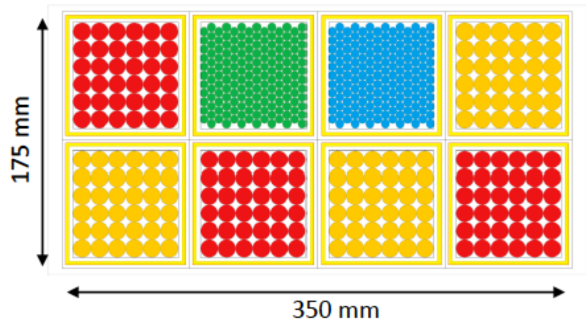
Si lenslet

Sinuous Antenna for broadband trichroic pixels

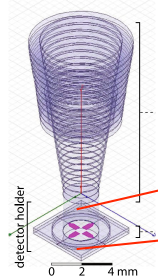


Test pixel for space-optimized bolometer development

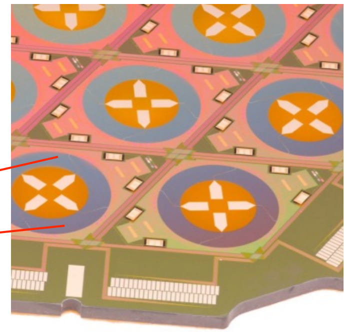
HFT f/3.5 design



(reflective case)



Si platelet corrugated horn



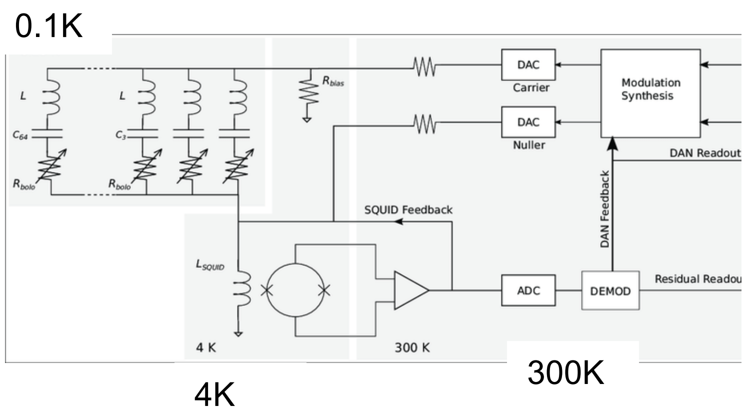
OMT

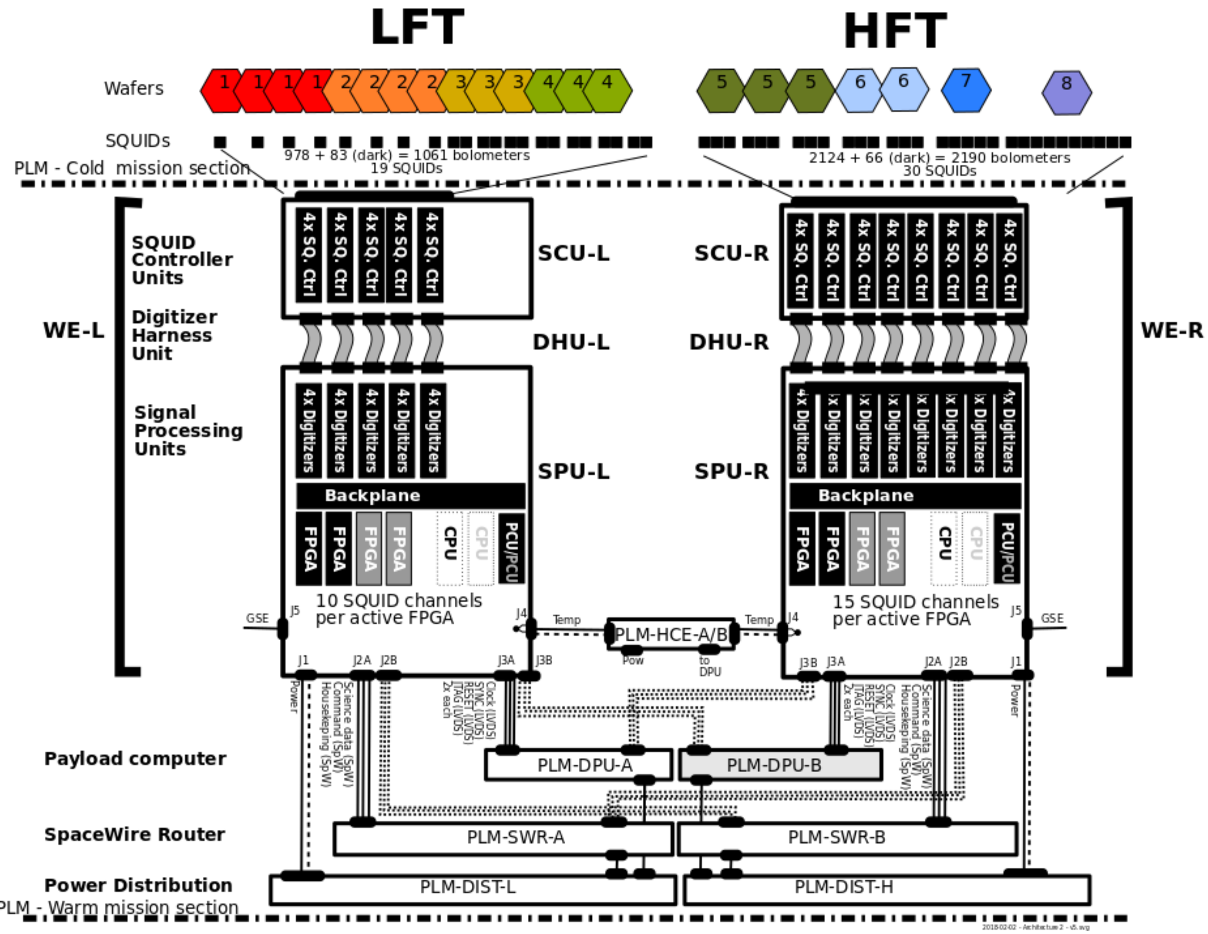
DfMUX readout

Canadian Space Agency / Agence spatiale canadienne

LiteBIRD

- Frequency Multiplexed Readout
  - USA: Cold components (SQUID)
  - Canada: warm electronics
- Based on system deployed for South Pole Telescope and POLARBEAR.





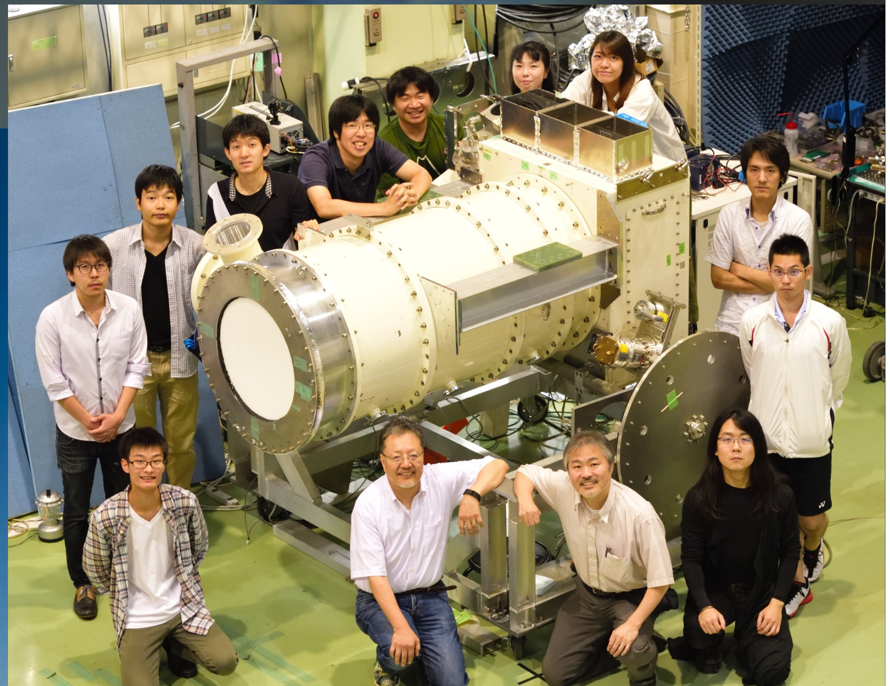
McGill University

POLARBEAR/Simons Array: Commonalities w/ LiteBIRD

→ Talk by Davide Poleti (Monday)

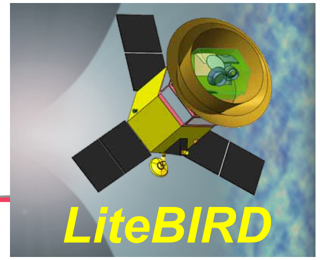
- Multi-chroic Al-Mn TES w/ sinuous antenna
- DfMUX readout w/ DAN
- (Continuously-rotating HWP)

First receiver system "POLARBEAR-2" just shipped from KEK Japan to Chile!

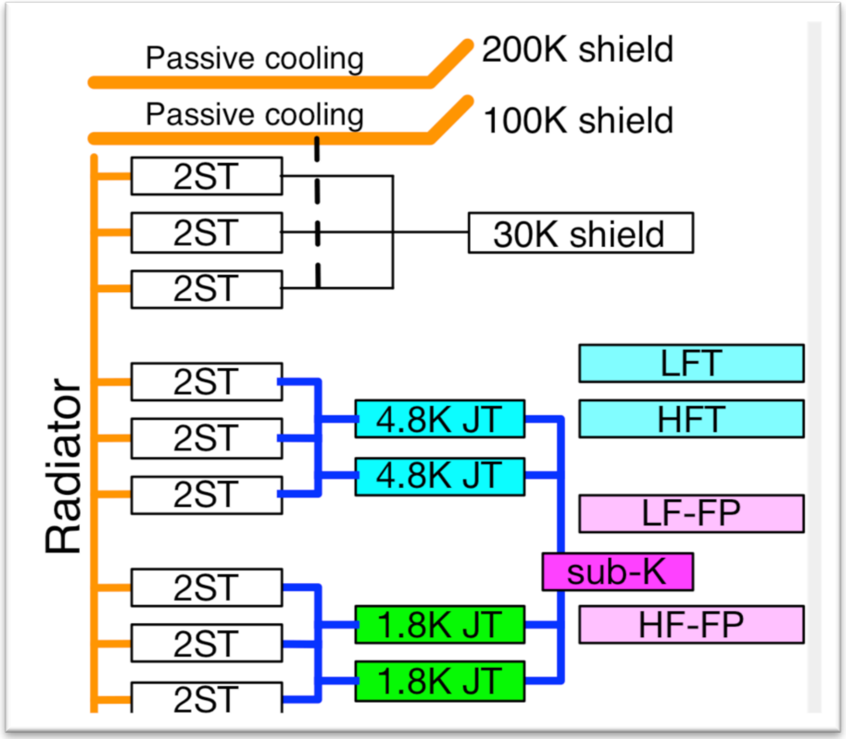


Ground-based project carried out by CMB experimenters on LiteBIRD. 10 years of collaboration b/w Japan, US, Canada, Europe. Stepping-stone for LiteBIRD.

Cooling system and thermal design



- Based on SPICA design study
  1. Passive cooling with V-grooves
  2. Redundant for mechanical coolers (1.8KJT, 4.8KJT, 2ST)
  3. Sub-K cooler: CCDR or ADR



	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

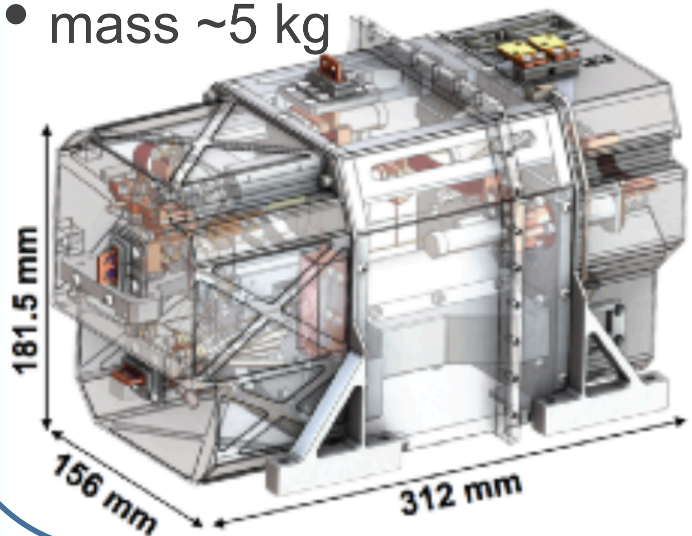
[SPIE 10698-219] T. Hasebe et al. "Thermal design utilizing radiative cooling for the payload module of LiteBIRD"

Sub-Kelvin cooler

Two technologies available in France

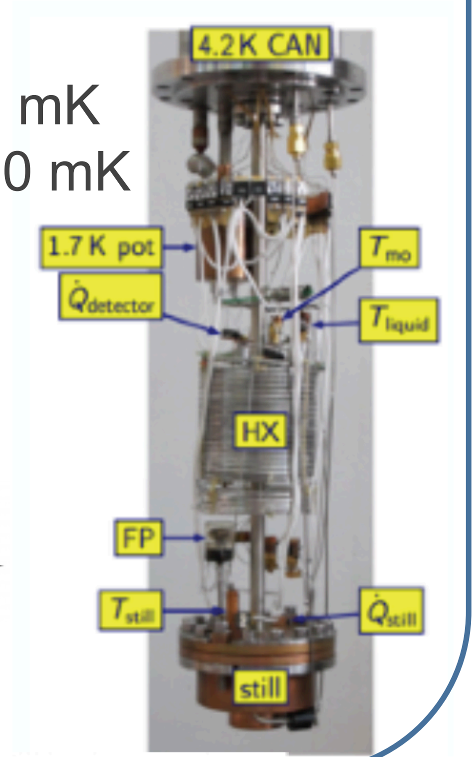
Hybrid Adiabatic Demagnetization Refrigerator (ADR)

- 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 (CCDR)

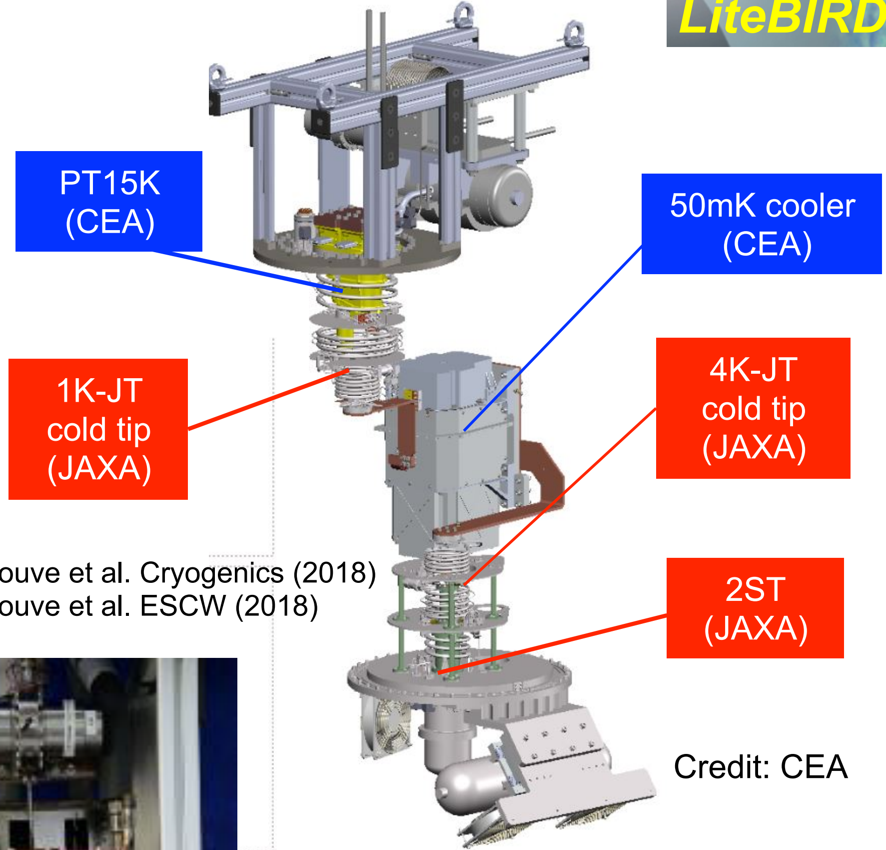
- NEEL / IAS / CNES
- Continuous - Duty Cycle: 100%
- TRL - 4
- Heat lifts
    - 3µW @ 100 mK
    - 10µW @ 300 mK



End-to-end cooling chain verification

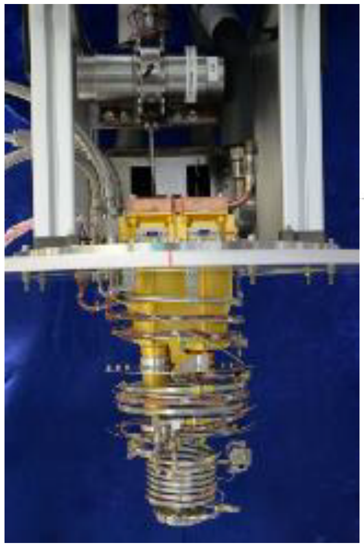
- In the framework of ESA Core Technology Program, Cryo-Chain CTP (CC-CTP) project has been promoted during 2016-2018, in the international collaboration led by CNES, with JAXA and CEA.

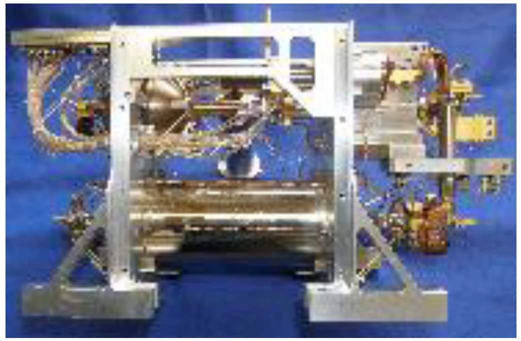
- Thermal interface from 300K to 100mK/ 50mK (end-to-end) has been demonstrated for Athena , LiteBIRD and SPICA.



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

Credit: CEA



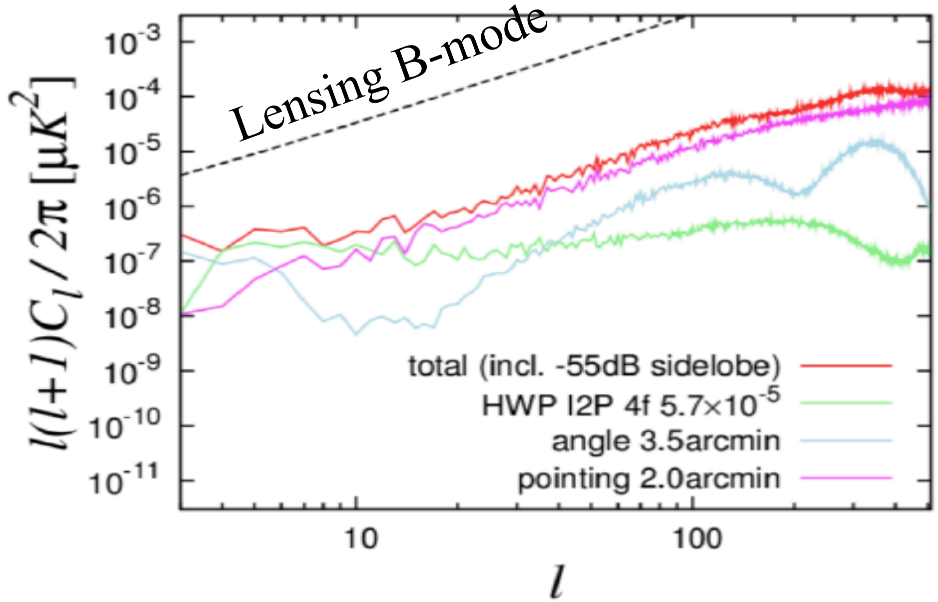


LiteBIRD basic parameters

	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	1248	2262
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	

Systematics and calibration

- One of the largest study groups at LiteBIRD
- Systematic approach for systematic uncertainties
  - List systematic error items → ~10 categories, ~70 items listed
  - Assign each item $\sigma(r)_{sys} < 5.7 \times 10^{-6}$ as the budget (1% of total budget for systematic error)
  - Derive a requirement for each item, define method (incl. calibration methods) and estimate $\sigma(r)_{sys}$
  - Assign special budget allocations for outstanding items
  - Sum each contribution on map base to estimate total $\sigma(r)_{sys}$ (some studies even on TOD basis) to take positive correlations into account
  - Iterate procedure
- Example: studies of systematic errors due to HWP imperfection
  - Mueller matrix from RCWA simulations of electromagnetic wave propagation through realistic HWP for different frequencies and incident angles
  - 4f component from M_{IQ}, M_{IU} ~10^{-4} in the worst case
  - Obtain leakage maps and BB power to estimate $\sigma(r)_{sys}$



All known systematics will be mitigated enough!

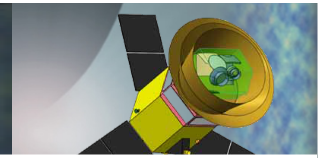
Development model philosophy

- 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) :

JAXA ϕ6m space chamber

JFY	2019	2020	2021	2022	2023	2024	2025	2026	2027
JAXA phase	phase A		phase B		phase C		phase D		
LFT-DM									
PLM-STM									
PLM-EM									Launch
FM									

LiteBIRD summary



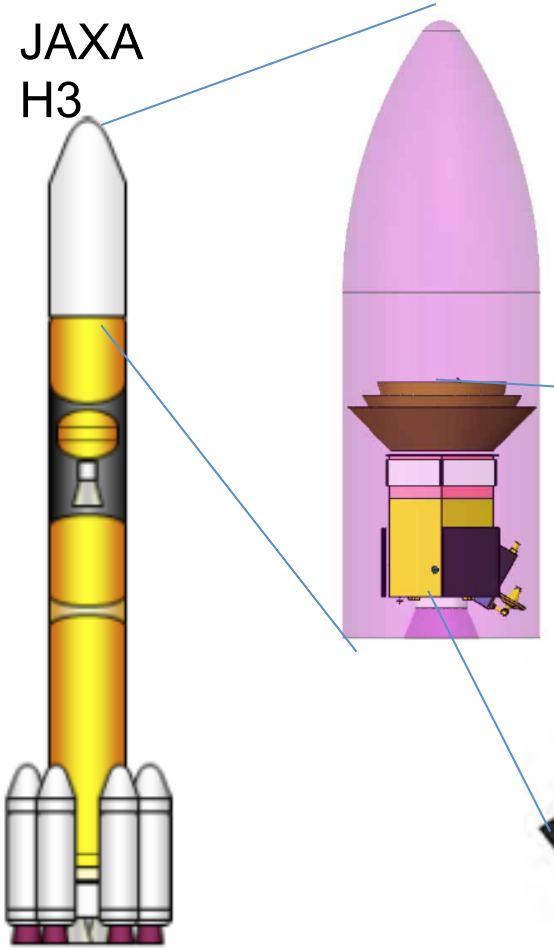
- JAXA-led international mission proposal (12 countries)
- Status: Phase A (concept development)
- 3yr observations at L2

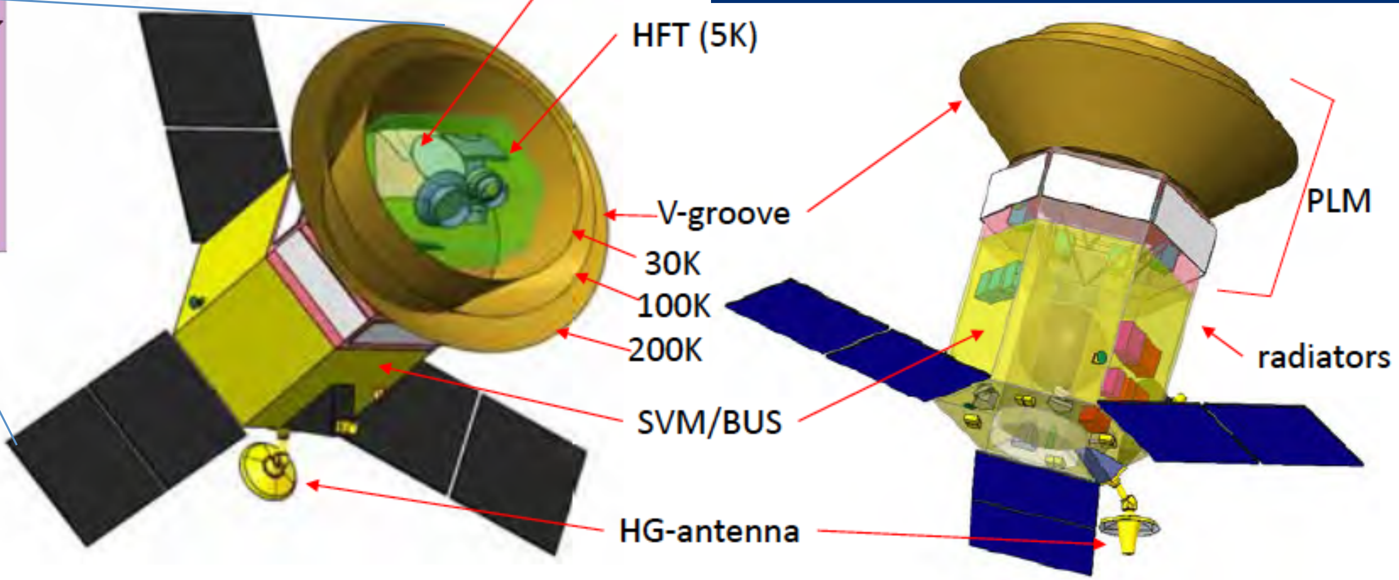
Full Success:
$\delta r < 1 \times 10^{-3}$ (for r=0)
$2 \leq \ell \leq 200$

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

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

15 bands (34 – 448 GHz)





Backup slides

Rationale for mission requirements

LiteBIRD

- Many models predict r > 0.01
- More general (less model-dependent) prediction
  - Focus on the simplest models based on Occam's razor principle → Single-field slow-roll (SFSR) models:
  - Detection of r > 0.002 establishes large-field variation (Lyth bound).
    - Significant impact on superstring theory that faces difficulty in dealing with $\Delta\phi > m_{pl}$
  - Obtaining r < 0.002 also has a significant impact on inflationary models and quantum gravity behind it.

Measurements w/ σ(r) < 0.001 would provide a fairly definitive statement about the validity of the most important class of inflationary models, i.e. single field slow-roll models with Δϕ exceeding the Planck scale, which would constitute a milestone in cosmology.

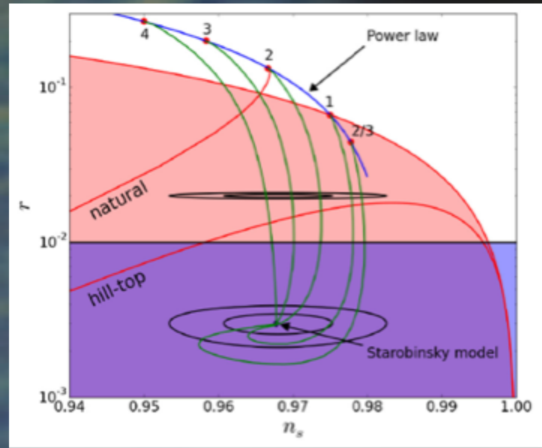
If evidence is found before launch

- 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

Impacts of discovery

- Direct evidence for cosmic inflation in case power spectrum agrees w/ prediction
  - Many models predict $0.003 < r < 0.05$
  - 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 quantum gravity
  - 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)
- Unexpected discovery (e.g. non-standard power spectrum) may rule out standard inflation paradigm
- Sense of wonder beyond science!

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 "Usuda Deep Space Center"	64m	S up/down/range X up/down/range	Will be replaced with the 54m antenna.
	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