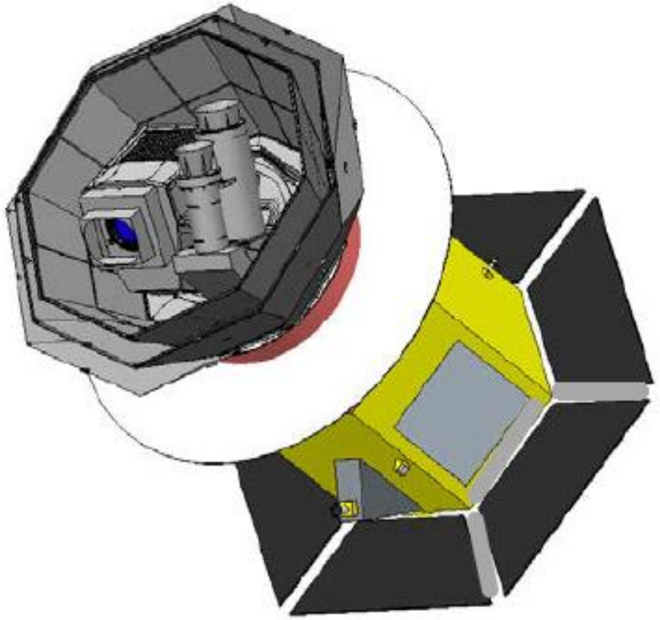
LiteBIRD satellite

JAXA's new strategic L-class mission for all-sky surveys of cosmic microwave background (CMB) polarization



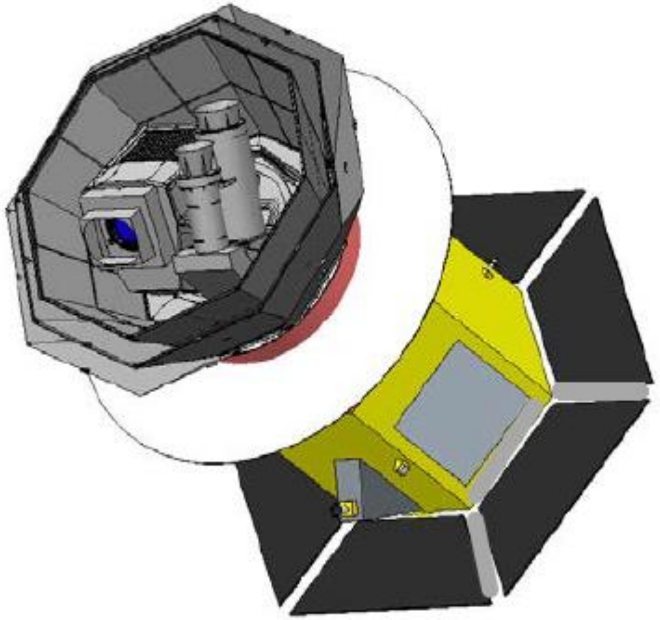
Masashi Hazumi

1. Director, International Center for Quantum-field Measurement Systems for Studies of the Universe and Particles (QUP), High Energy Accelerator Research Organization (KEK)
2. Professor, Institute of Particle and Nuclear Studies (IPNS), High Energy Accelerator Research Organization (KEK)
3. Specially-appointed Professor, Institute of Space and Astronautical Science (ISAS), Japan Aerospace Exploration Agency (JAXA)
4. Project professor, Kavli Institute for Mathematics and Physics of the Universe (Kavli IPMU), The University of Tokyo
5. Professor, Graduate School for Advanced Studies (SOKENDAI)

On behalf of the LiteBIRD Collaboration

LiteBIRD satellite

JAXA's new strategic L-class mission for all-sky surveys of cosmic microwave background (CMB) polarization



Tomotake Matsumura

1. Director, International Center for Quantum-field Measurement Systems for Studies of the Universe and Particles (QUP), High Energy Accelerator Research Organization (KEK)
2. Professor, Institute of Particle and Nuclear Studies (IPNS), High Energy Accelerator Research Organization (KEK)
3. Specially-appointed Professor, Institute of Space and Astronautical Science (ISAS), Japan Aerospace Exploration Agency (JAXA)
4. Project professor, Kavli Institute for Mathematics and Physics of the Universe (Kavli IPMU), The University of Tokyo
5. Professor, Graduate School for Advanced Studies (SOKENDAI)

On behalf of the LiteBIRD Collaboration

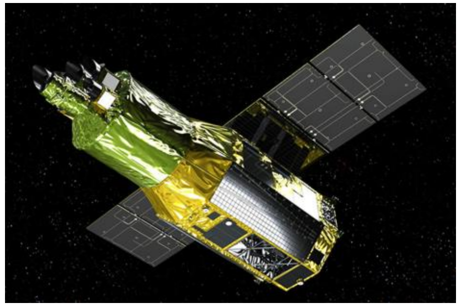
Strategic L-class missions at JAXA

- Flagship science mission with HIIA/H3 vehicle
- 30B yen cost cap (300M USD for 1 USD = 100 yen)

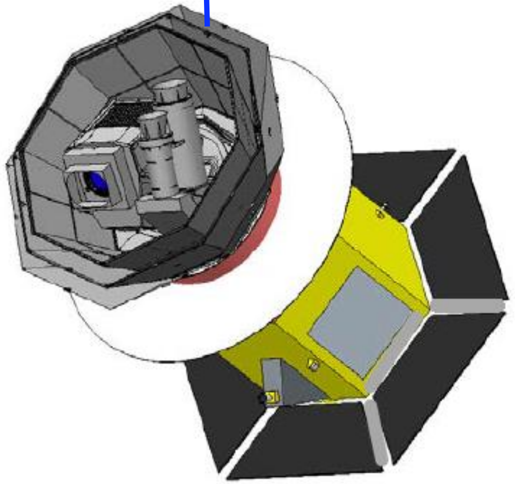
Japanese Fiscal Year

20	21	22	23	24	25	26	27	28	29	30	31	32

XRISM (recovery of Hitomi)



L-class #1 Martian Moons eXploration (MMX)

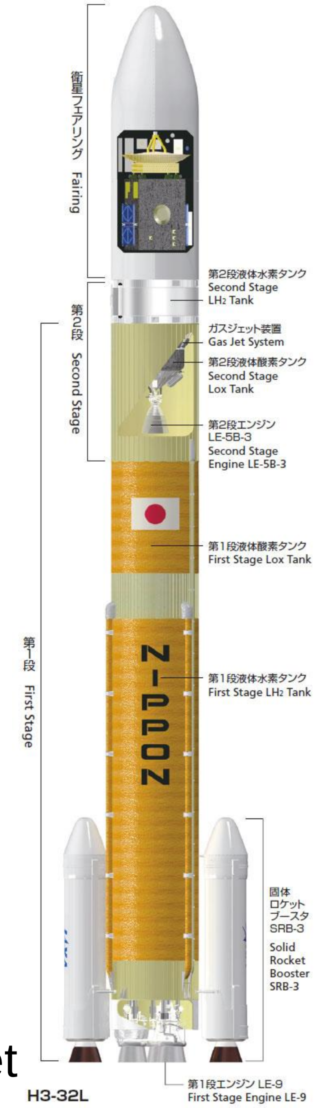


L-class #2 LiteBIRD (selected in May 2019)

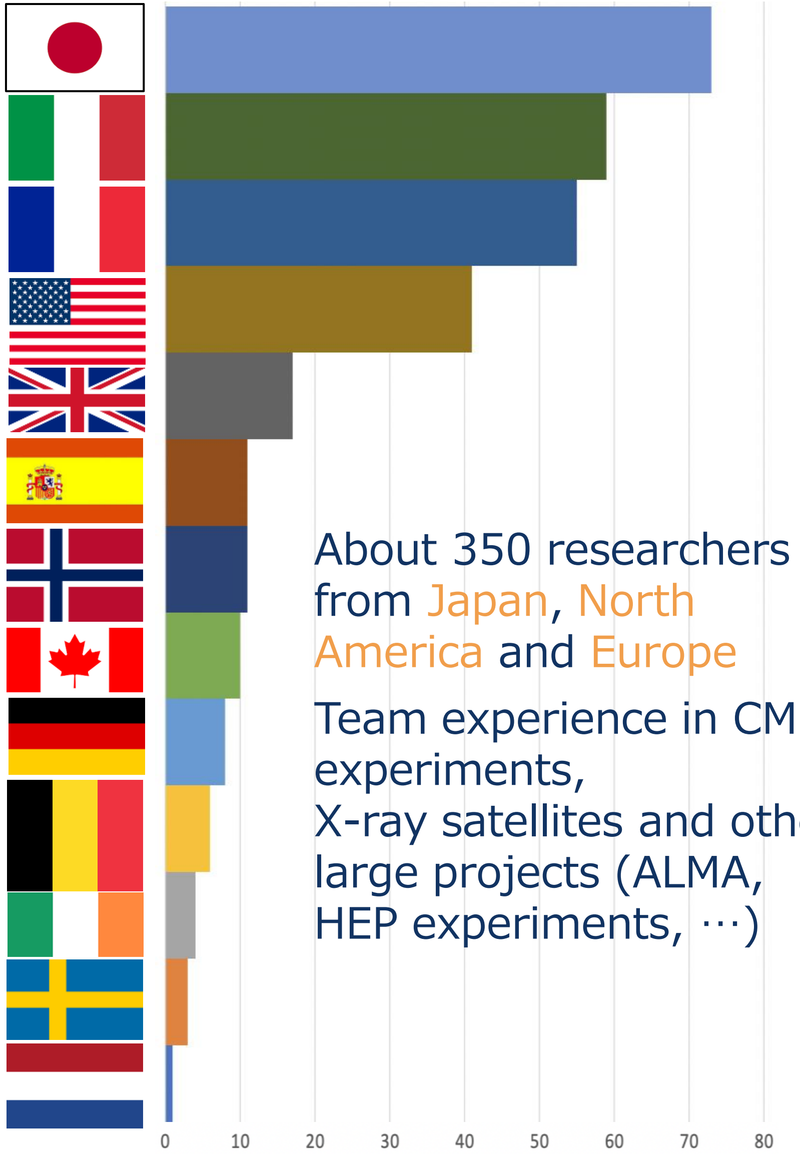
L-class #3 Is open

HIIA rocket

H3 rocket

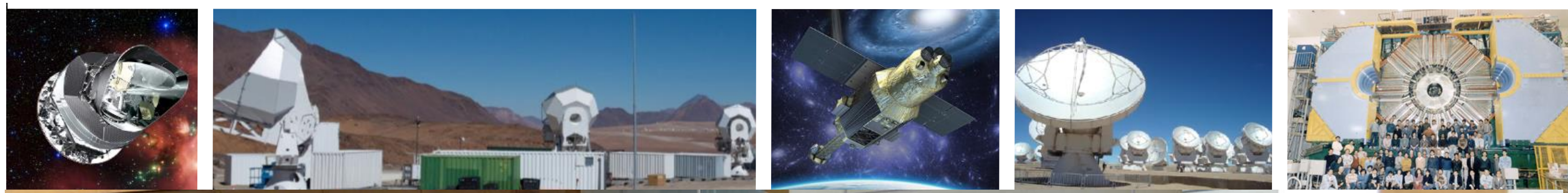


LiteBIRD Collaboration



About 350 researchers from Japan, North America and Europe

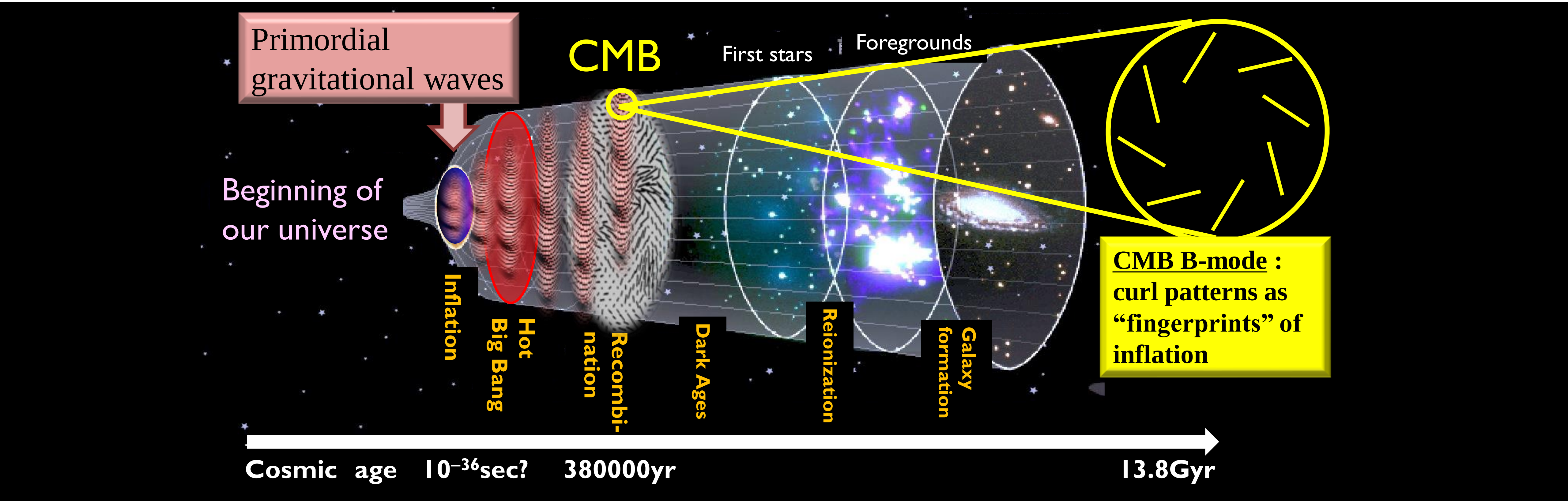
Team experience in CMB experiments,
X-ray satellites and other large projects (ALMA, HEP experiments, …)



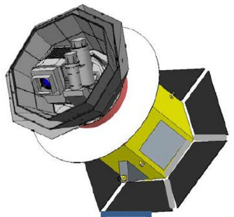
Main scientific objective: test of cosmic inflation

<u>Cosmic inflation</u>

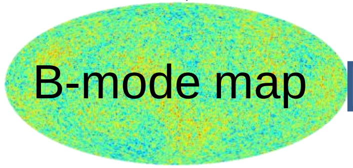
- Primordial accelerating expansion that successfully solves problems of the naïve big-bang model
- Particle physics idea: a new scalar field ϕ "Inflaton" with potential $V(\phi)$ as a source of acceleration.
- In case of single-field slow-roll inflation → $V^{1/4} = 1.04 \times 10^{16}\mathrm{GeV}\left(\frac{r}{0.01}\right)^{1/4}$
- Tensor-to-scalar ratio, ***r***, is a key parameter. → **need an order of magnitude better sensitivity than before**



CMB Power Spectra



Foreground Removal
Extraction of B-mode

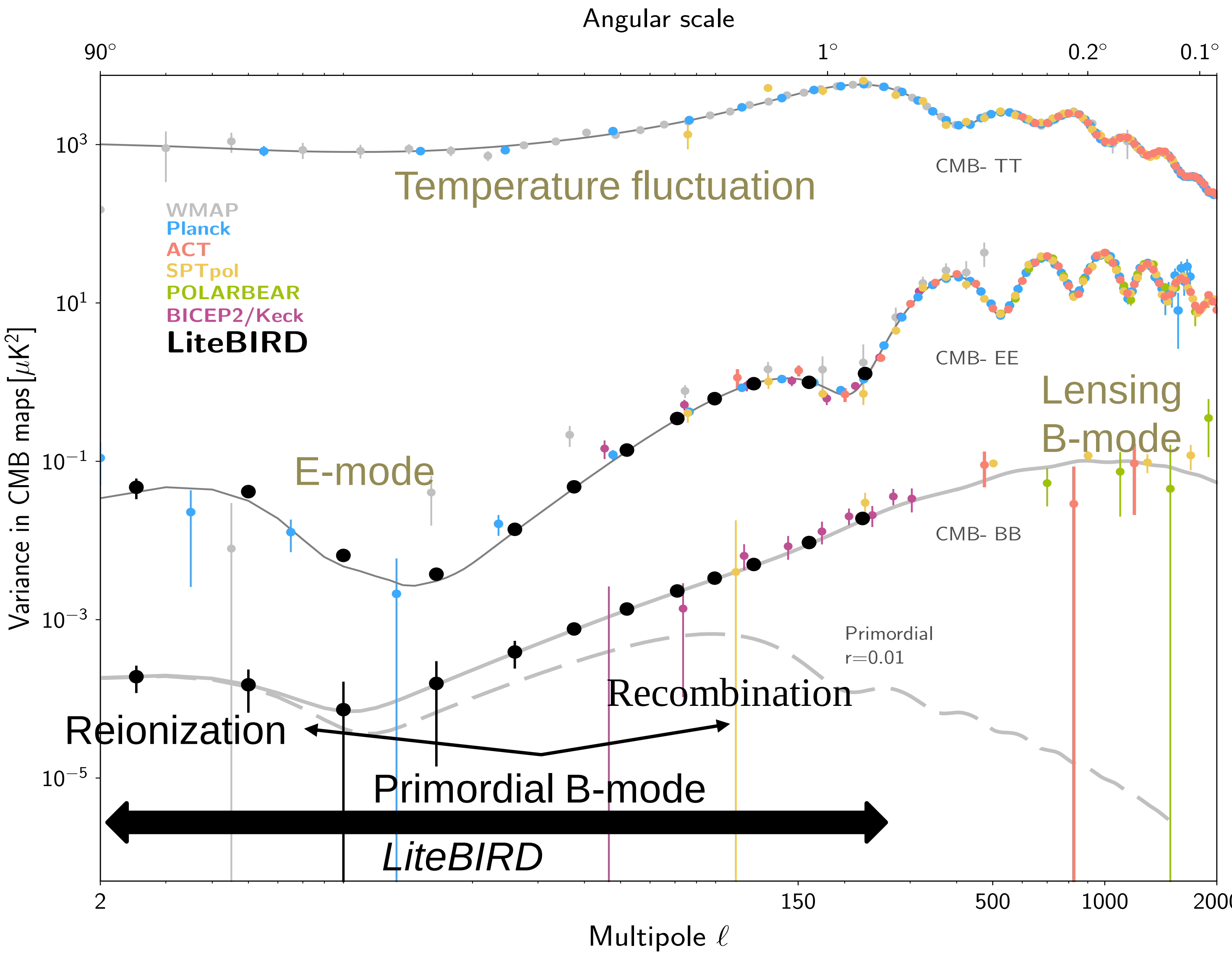


Spectrum analysis

The primordial B-mode power is proportional to the tensor-to-scalar ratio "*r*".

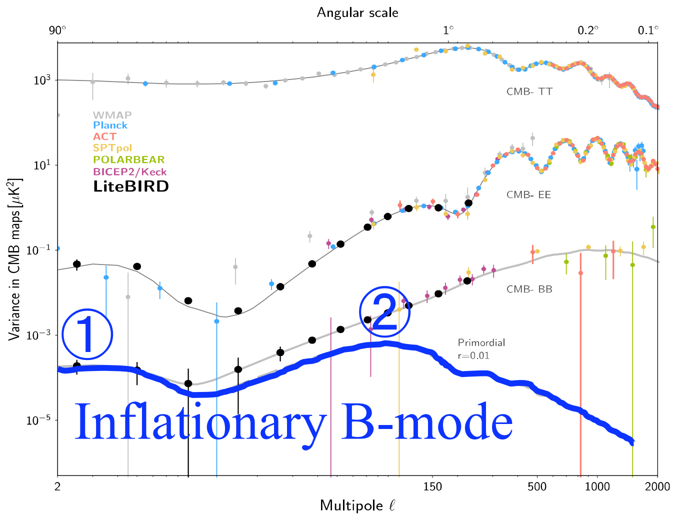
r < 0.032 (95% C.L.) (M. Tristram et al. 2021, combining Bicep2/Keck 2018 and Planck PR4 data set)

LiteBIRD will improve the sensitivity by more than the order of magnitude (see the next page.)



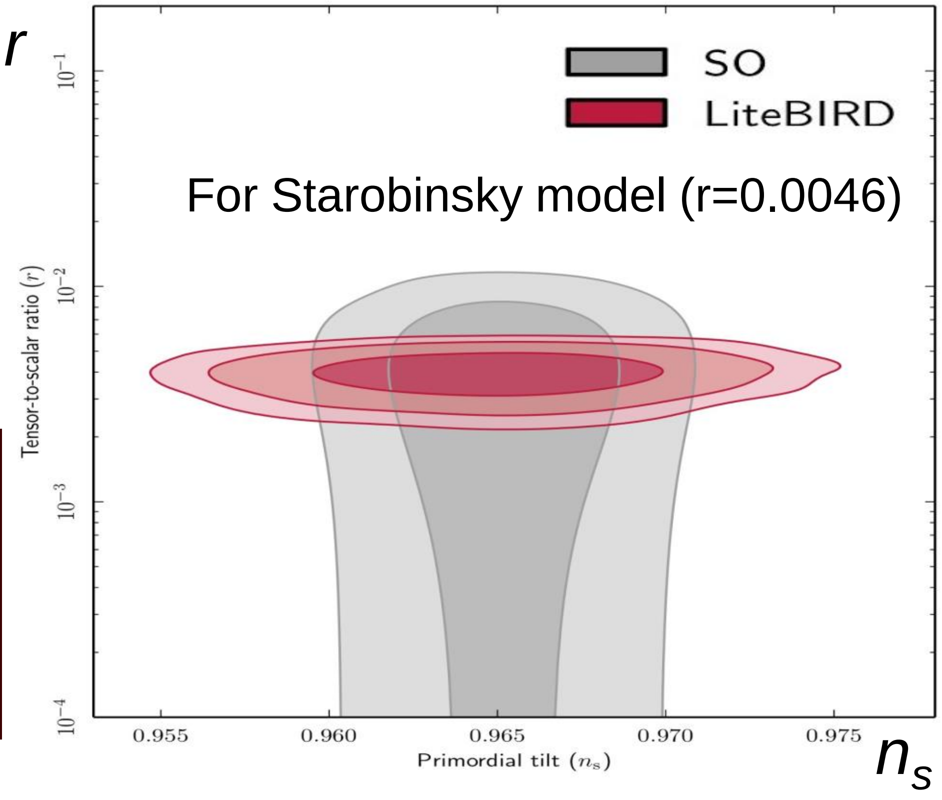
Top-level mission requirements will be satisfied!

- $\delta r < 1 \times 10^{-3}$ (for $r = 0$)
- $>5\sigma$ observation for each bump (for $r \geq 0.01$)



① Reionization bump
② Recombination bump

- Detailed foreground cleaning studies yield $\sigma(r = 0) = 0.6 \times 10^{-3}$
- Thorough systematic error studies yield total uncertainty $\delta r < 1.0 \times 10^{-3}$
- Achieved without delensing



Rationale

- Large discovery potential for $0.003 < r < 0.03$
- Clean sweep of single-field models with characteristic field-variation-scale of inflaton potential greater than m_{pl} (A. Linde, JCAP 1702 (2017) no.02, 006)
  - Simplest and well-motivated $R+R^2$ "Starobinsky" model will be tested.

Why measure from 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 on the choice of observing bands (except CO lines); important for foreground separation
  - No ground pickup

Rule of thumb: 1 detector in space ~ 100 detectors on the ground

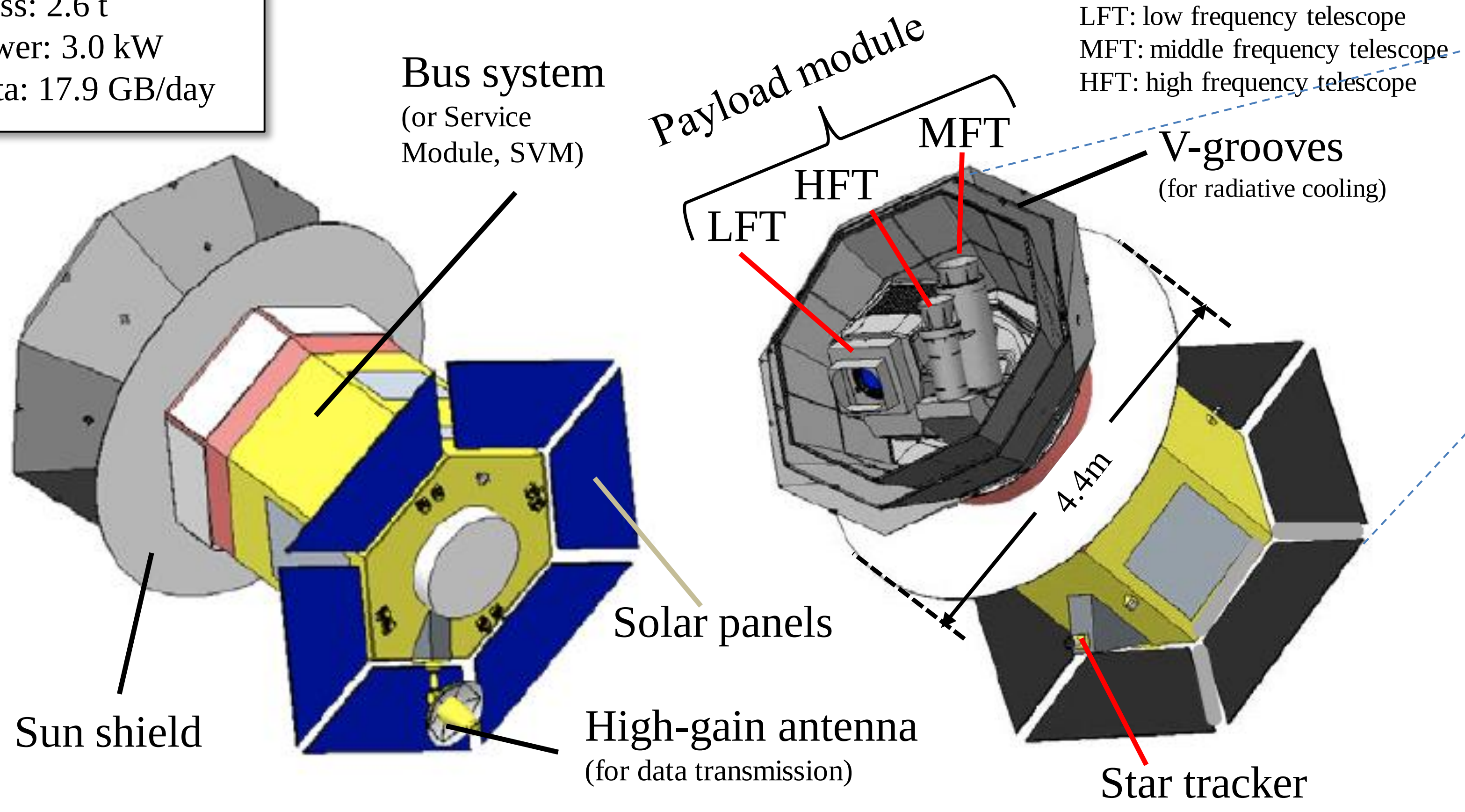
- Only way to access lowest multipoles w/ dr ~ O(0.001)
  - Both B-mode bumps need to be observed for the firm confirmation of Cosmic Inflation → We need measurements from space.
- Complementarity with ground-based CMB projects
  - Foreground information from space will help foreground cleaning for ground CMB data
  - High multipole information from ground will help “delens” space CMB data

LiteBIRD Spacecraft Overview

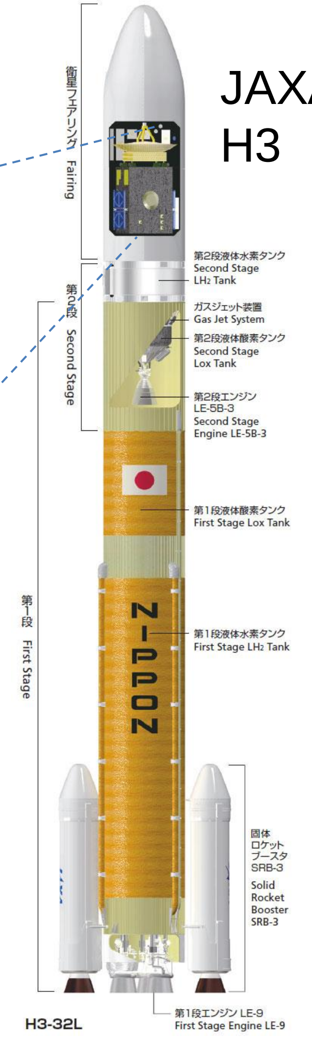
- JAXA's L-class mission selected in May 2019, with expected launch in late 2020s with JAXA's H3 rocket
- Observations for 3 years (baseline) around Sun-Earth Lagrangian point L2
- Millimeter-wave all sky surveys (<u>34–448 GHz, 15 bands</u>) at 71–18 arcmin angular resolution

Mass: 2.6 t
Power: 3.0 kW
Data: 17.9 GB/day

LFT: low frequency telescope
MFT: middle frequency telescope
HFT: high frequency telescope

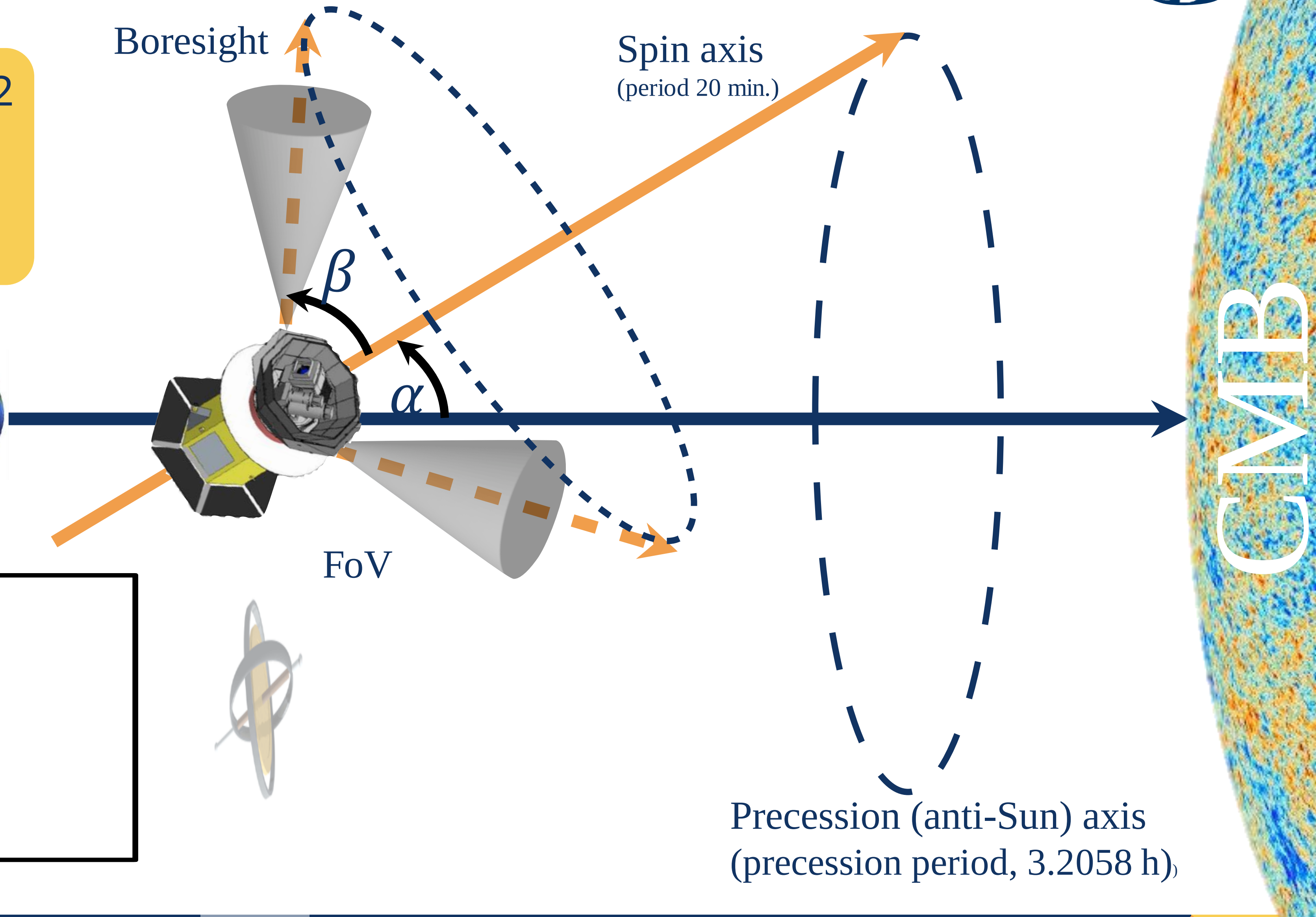


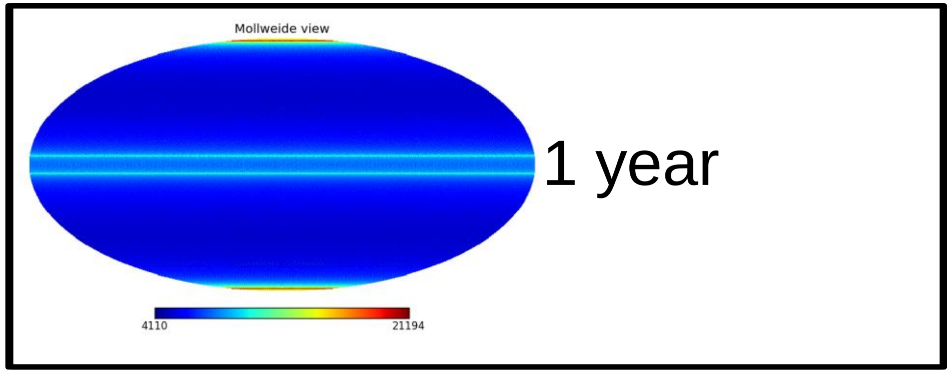
JAXA H3



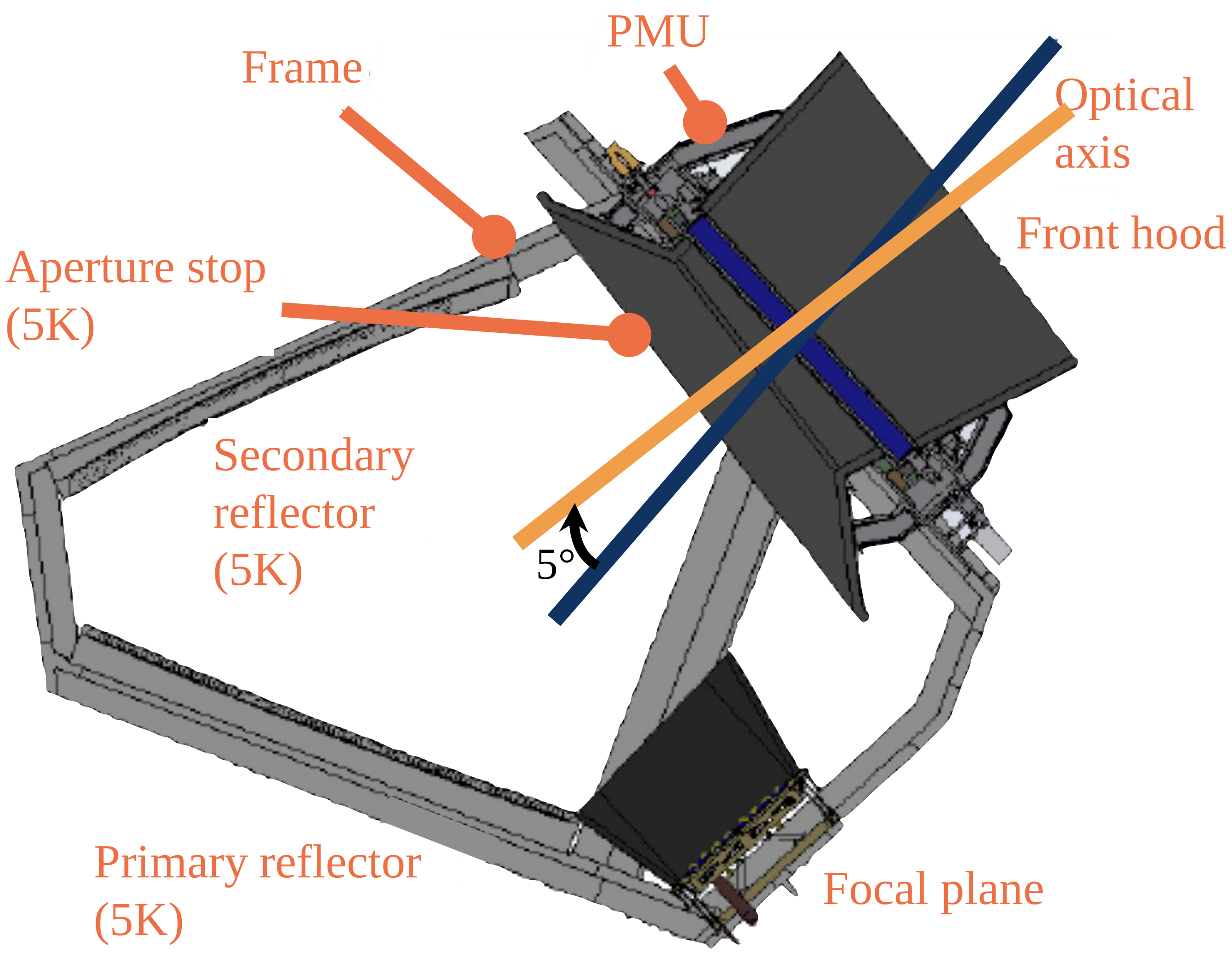
LiteBIRD scanning strategy

- 3-year survey, Sun-Earth L2 Lissajous orbit
- Precession angle: α = 45°
- Spin angle: β = 50°





Low Frequency Telescope (LFT)



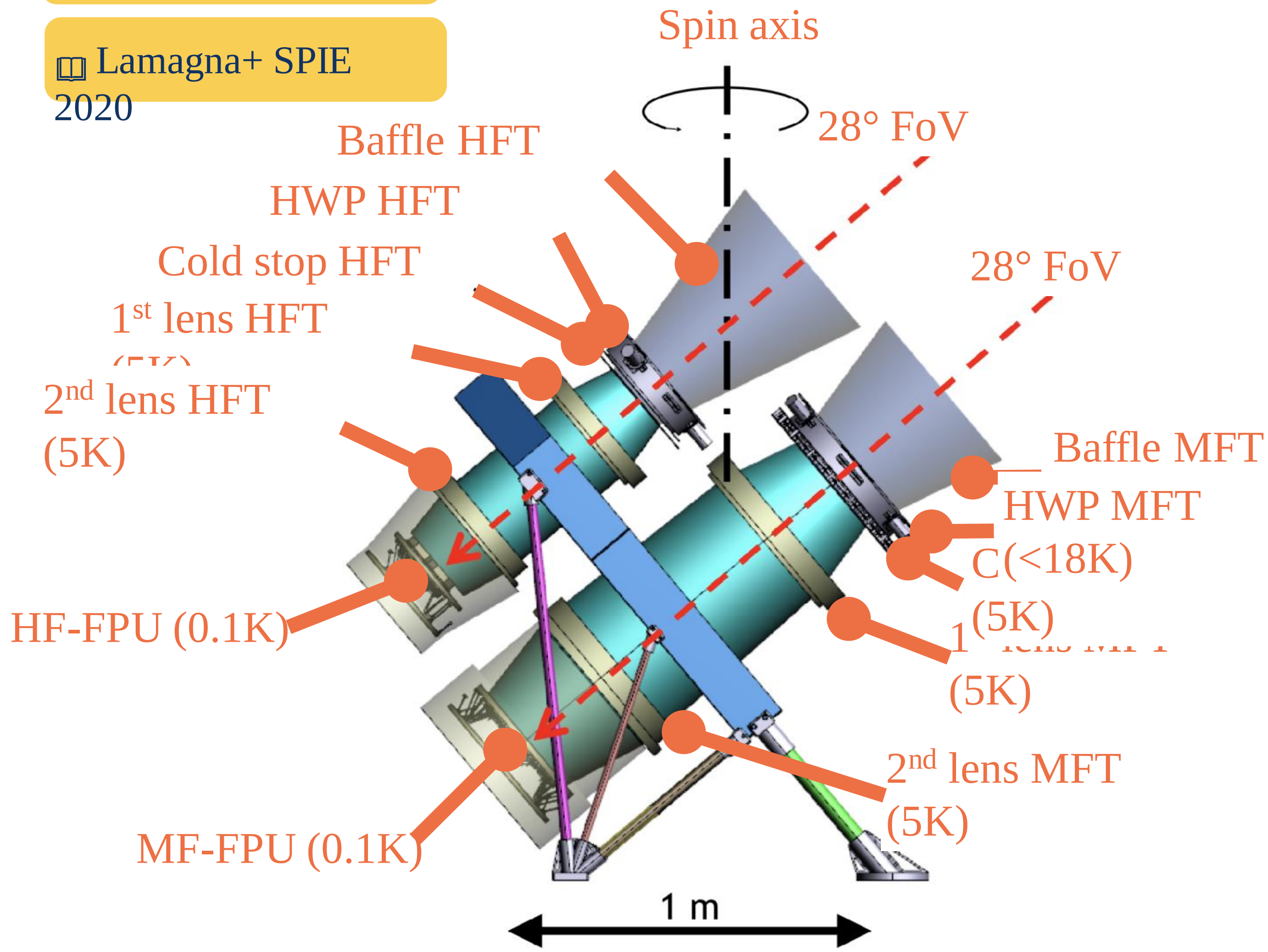
- Polarization Modulation Unit (PMU) as the first sky-side optical element
- **Crossed-Dragone** design
  - Mirrors and aperture stop at **5 K**
  - Made of aluminium
- Field of view: **18°╳9°**
- Strehl ratio > 0.95 (@ 140 GHz)
- Aperture diameter: **400 mm**
- Frequency range: **40-140 GHz**
- Angular resolution: **70-24 arcmin**
- F#3.0 & cross angle of 90°
- Cross-polarization < **-30 dB**
- Rotation of the polarization angle across the FoV < ±1.5°
- Weight < 200 kg

📖 Sekimoto+ SPIE 2020

Middle-High Frequency Telescopes (MFT/HFT)

📖 Montier+ SPIE 2020

📖 Lamagna+ SPIE 2020



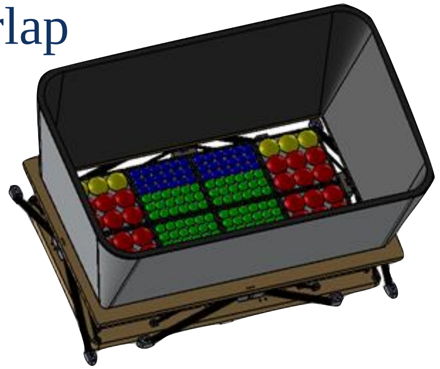
- Refractive optics
- Each telescope has PMU with a half-wave-plate (HWP)
- Optics at **5 K**
- Field of view: **28°**
- Simple and high heritage from ground experiments
- Compact (mass & volume)
- Simplified design for filtering scheme
- PP lenses + ARC
- Weight 180 kg

	MFT	HFT
ν (GHz)	**100-195**	**195-402**
Ap. diameter (mm)	**300**	**200**
Ang. res. (arcmin)	**38-28**	**29-18**

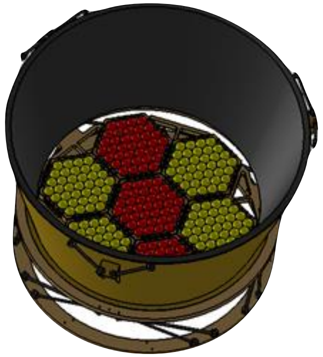
Focal plane configuration

- Transition-Edge Sensor (TES) arrays: [“variable registers” sensitive to input power]
- Multichroic detectors
- Number of sensors: 4508
- 15 bands including overlap between instruments

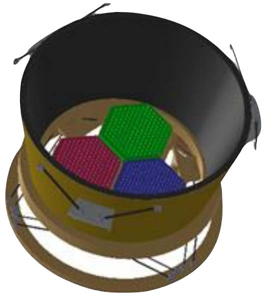
LFT



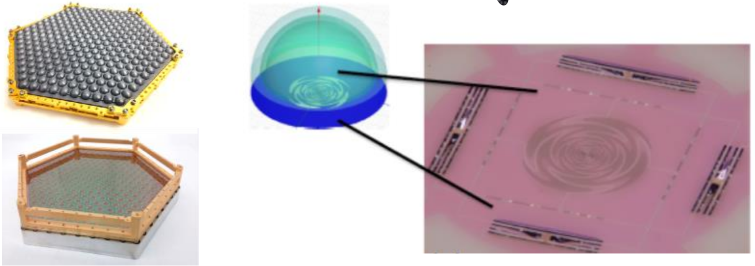
MFT



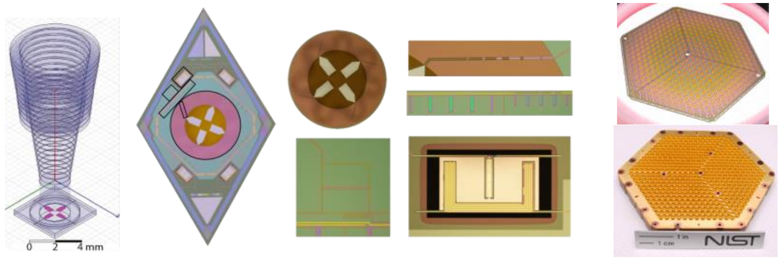
HFT



Lensed coupled detectors
Lenslets



Horn coupled detectors
Platelets



MFT (2.5:1) 89GHz – 225 GHz

2075 detectors
366 Trichroic TES
588 Dichroic TES

Bands: 100, 119, 140, 166, 195

LFT (5.7:1) 34GHz – 161 GHz

Bands: 40, 50, 60, 68, 78, 89, 100, 119, 140
68, 78, 89

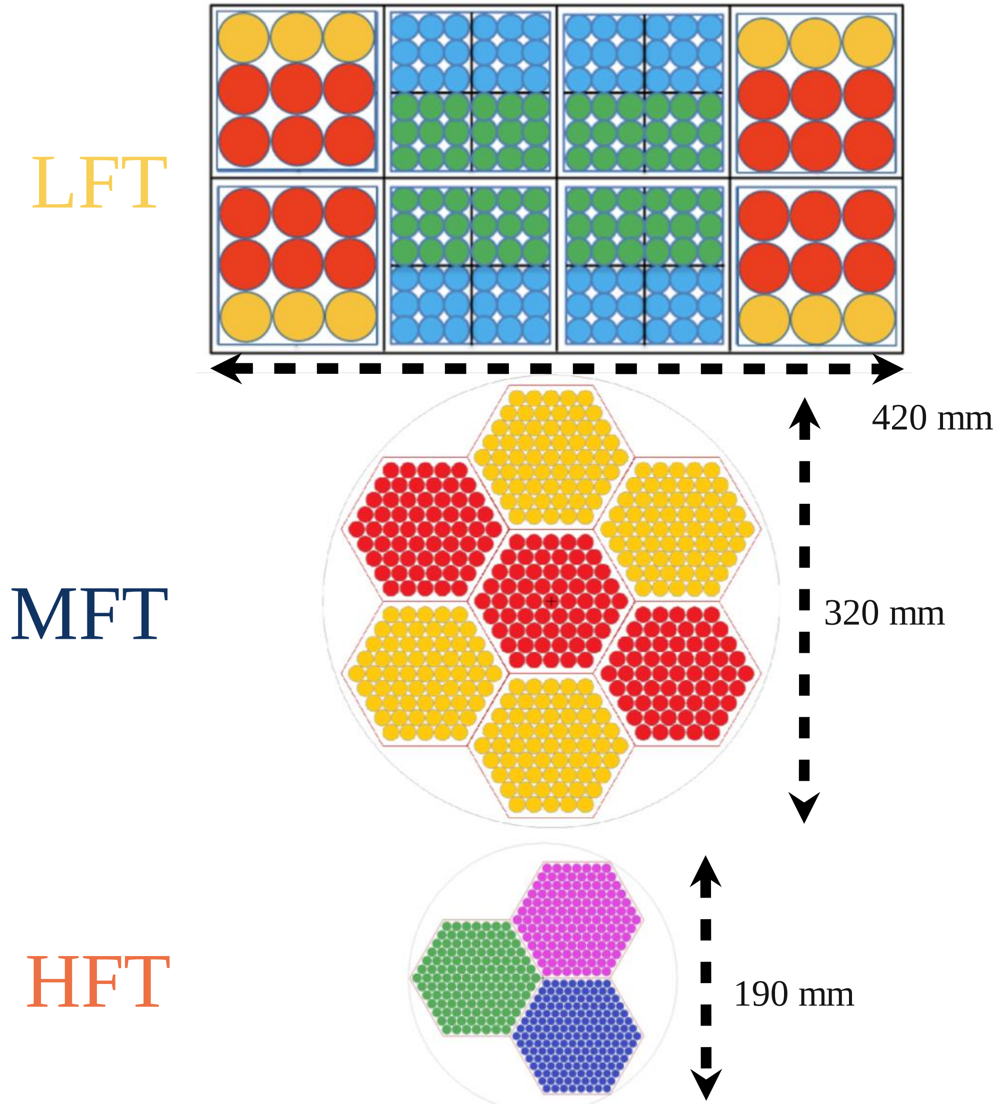
1258 detectors
2 x (65 + 155) Trichroic TES

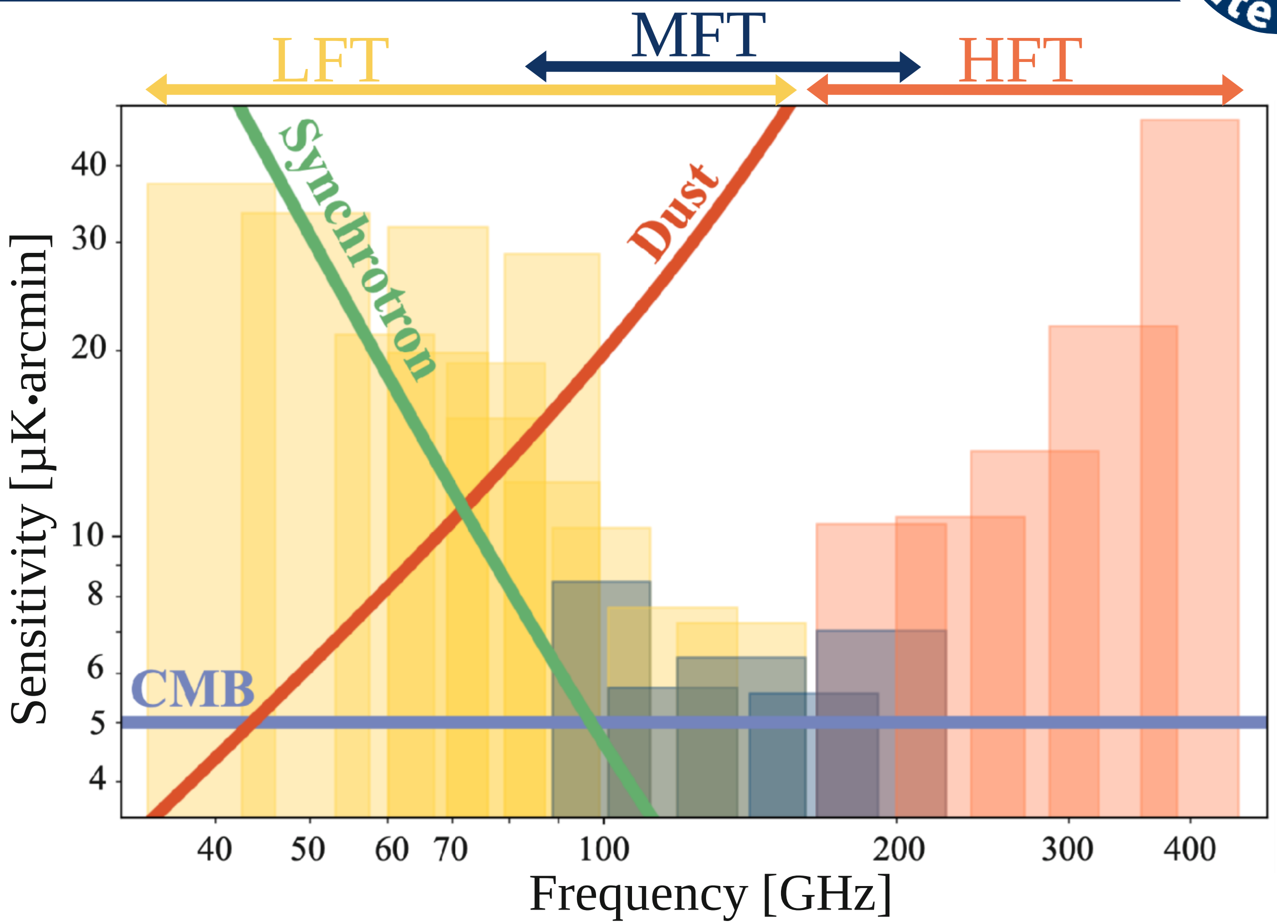
HFT (2.7:1) 166 GHz – 448 GHz

Bands: 195, 235, 280, 337, 402

1355 detectors
2 x 255 Dichroic TES
338 Monochromatic TES

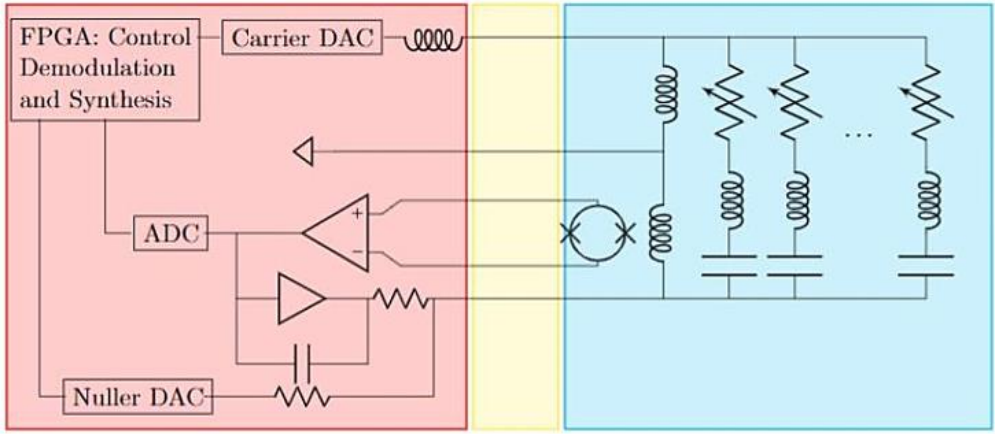
LiteBIRD frequency bands and sensitivities

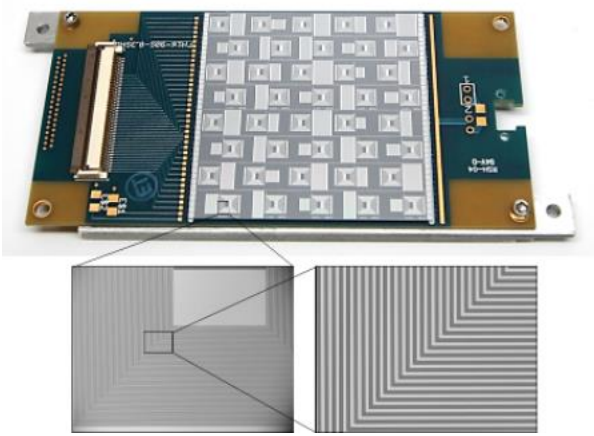


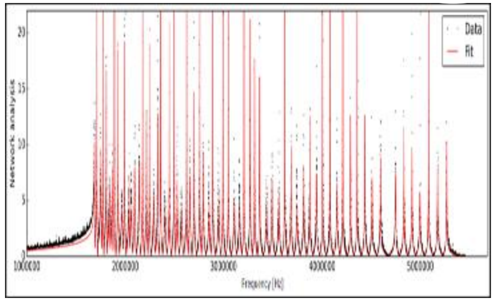


- Projected polarization sensitivities for a 3-year full-sky survey
- Best of 4.3 μK·arcmin @ 119 GHz (Hazumi+ 2020)
- Combined sensitivity to primordial CMB anisotropies: 2.2 μK·arcmin

LiteBIRD readout system





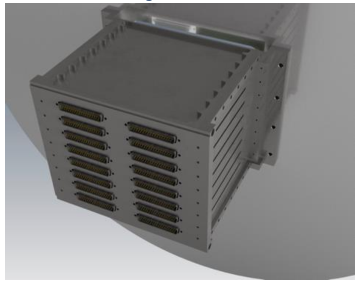


Cold Readout LC filters for MUX

- Frequency multiplexing readout technology to readout multiple TES with less components
- Assign unique frequency channel to TES sensors via superconducting resonators
- Low noise SQUID amplifier and FPGA controller readout the signal
- Saves mass, volume, power consumption and cost
- Heritage from ground based CMB experiments

SQUID controller board

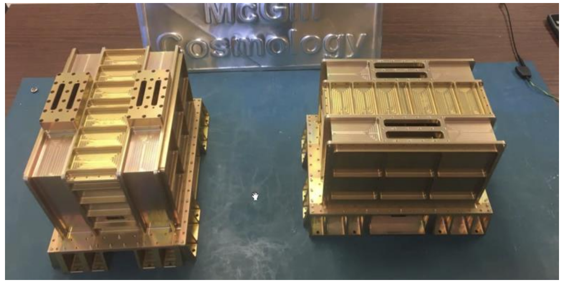
SQUID controller assembly



Digitizer assembly

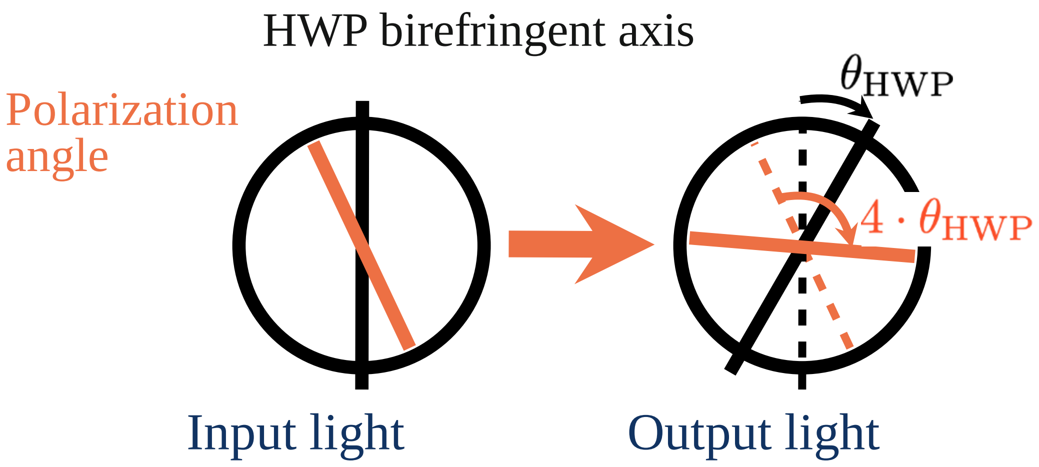
Signal Processing Unit

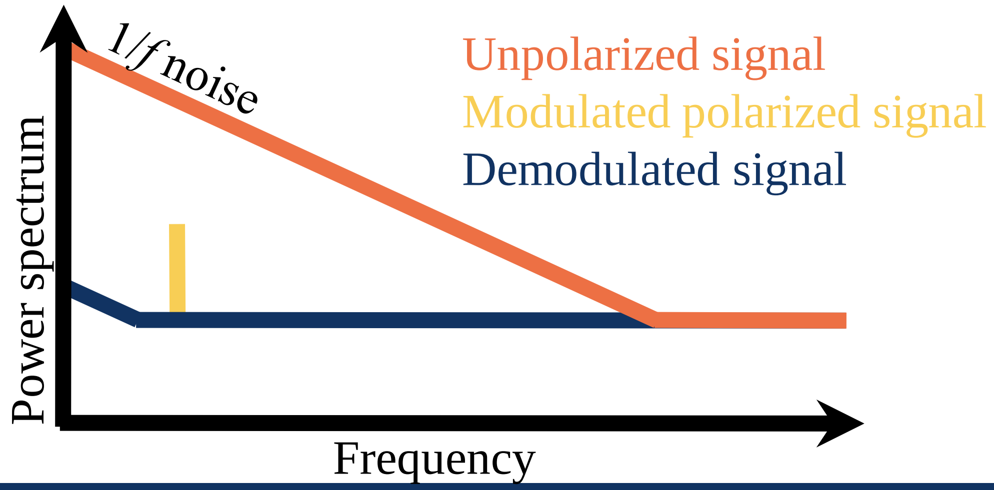
Digitizer assembly



Polarization Modulation Unit (PMU)

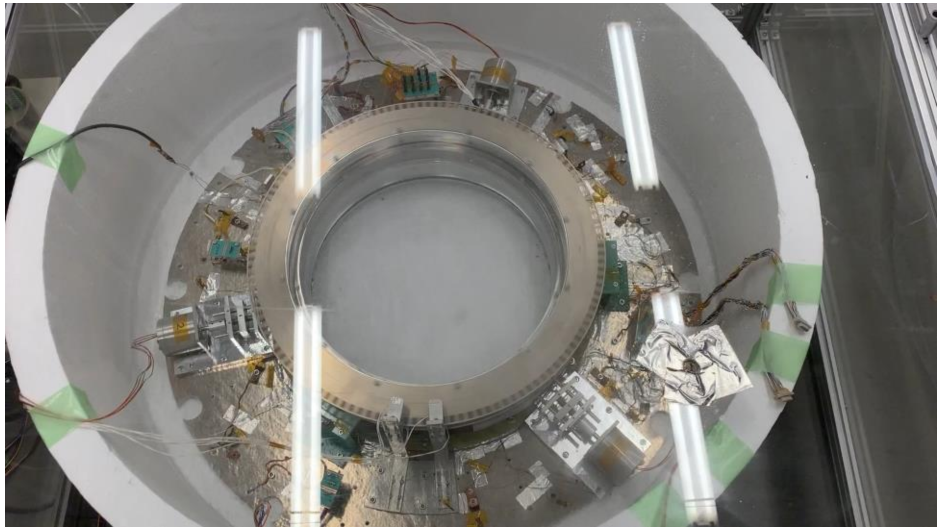
- Rotating a birefringent plate to modulate polarization
- The first sky-side optical element





📖 Sakurai+2020 📖 Komatsu+2020
📖 Toda+2020 📖 Columbro+2020 📖 Sugiyama+2020

- LFT PMU BBM at Kavli IPMU:



- Rotation test of superconducting magnetic bearing system in the 4K cryostat
- Stable rotation at cryogenic temperature (< 10 K)

Foreground cleaning

Foreground modeling

- **Synchrotron**: curved spectrum (AME is absorbed in the curvature)

$$[Q_\mathrm{s}, U_\mathrm{s}](\hat{n}, \nu) = [Q_\mathrm{s}, U_\mathrm{s}](\hat{n}, \nu_\star) \cdot \left(\frac{\nu}{\nu_\star}\right)^{\beta_\mathrm{s}(\hat{n}) + C_\mathrm{s}(\hat{n}) \ln(\nu/\nu^\mathrm{c})}$$

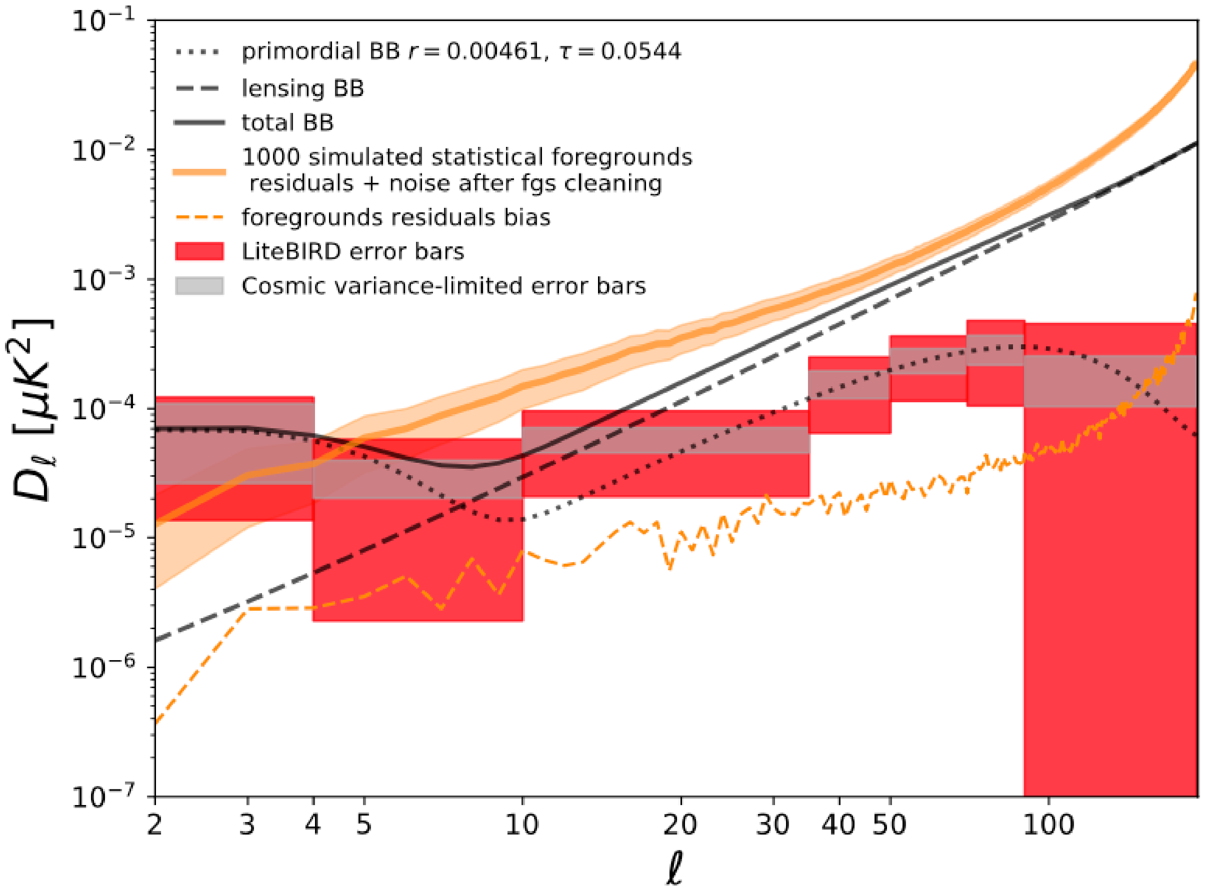
- **Dust**: modified blackbody

$$[Q_\mathrm{d}, U_\mathrm{d}](\hat{n}, \nu) = [Q_\mathrm{d}, U_\mathrm{d}](\hat{n}, \nu_\star) \cdot \left(\frac{\nu}{\nu_\star}\right)^{\beta_\mathrm{d}(\hat{n}) - 2} \frac{B_\nu(T_\mathrm{d}(\hat{n}))}{B_{\nu_\star}(T_\mathrm{d}(\hat{n}))}$$

8 parameters in each sky patch

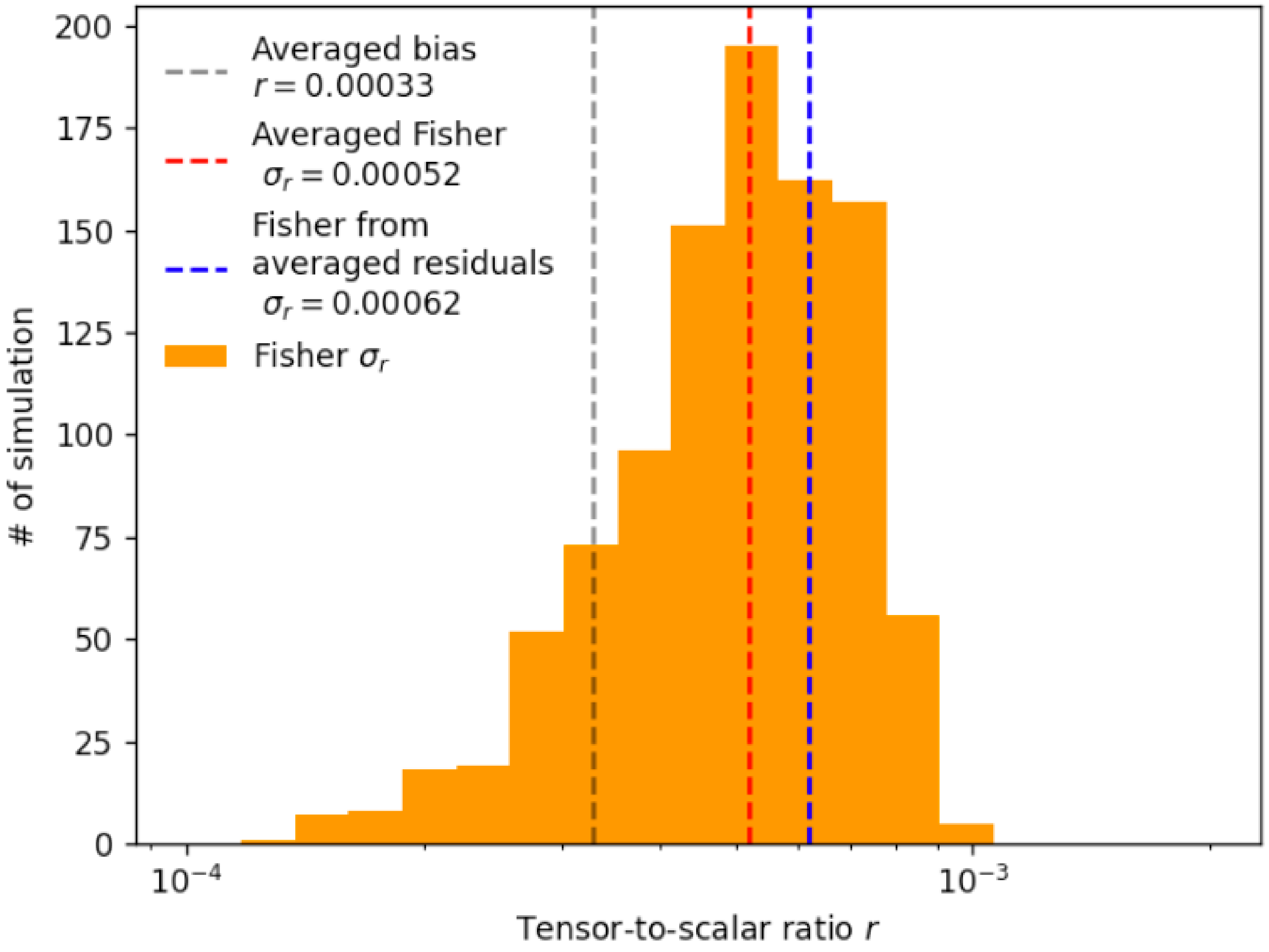
- "**Multipatch** technique" (extension of xForecast), to account for spatial variability. $12 \times (N_\mathrm{side})^2$ patches ⇒ 6144 parameters with $N_\mathrm{side} = 8$

Impact of foregrounds residual



Foreground cleaning

- "Multipatch technique" (extension of xForecast)
- Distribution of the recovered *r* in 1000 simulations with input *r* = 0, with and without foreground residuals
- Bias from foreground (PySM `d1s1`) residuals is found to be small
- Final value: ***r* = (3.3 ± 6.2)×10^{-4}**



PTEP Invited Paper

arXiv > astro-ph > arXiv:2202.02773

Search... All fields Search

Help | Advanced Search

Astrophysics > Instrumentation and Methods for Astrophysics

[Submitted on 6 Feb 2022]

Probing Cosmic Inflation with the LiteBIRD Cosmic Microwave Background Polarization Survey

LiteBIRD Collaboration: E. Allys, K. Arnold, J. Aumont, R. Aurlien, S. Azzoni, C. Baccigalupi, A. J. Banday, R. Banerji, R. B. Barreiro, N. Bartolo, L. Bautista, D. Beck, S. Beckman, M. Bersanelli, F. Boulanger, M. Brilenkov, M. Bucher, E. Calabrese, P. Campeti, A. Carones, F. J. Casas, A. Catalano, V. Chan, K. Cheung, Y. Chinone, S. E. Clark, F. Columbro, G. D'Alessandro, P. de Bernardis, T. de Haan, E. de la Hoz, M. De Petris, S. Della Torre, P. Diego-Palazuelos, T. Dotani, J. M. Duval, T. Elleflot, H. K. Eriksen, J. Errard, T. Essinger-Hileman, F. Finelli, R. Flauger, C. Franceschet, U. Fuskeland, M. Galloway, K. Ganga, M. Gerbino, M. Gervasi, R. T. Génova-Santos, T. Ghigna, S. Giardiello, E. Gjerløw, J. Grain, F. Grupp, A. Gruppuso, J. E. Gudmundsson, N. W. Halverson, P. Hargrave, T. Hasebe, M. Hasegawa, M. Hazumi, S. Henrot-Versillé, B. Hensley, L. T. Hergt, D. Herman, E. Hivon, R. A. Hlozek, A. L. Hornsby, Y. Hoshino, J. Hubmayr, K. Ichiki, T. Iida, H. Imada, H. Ishino, G. Jaehnig, N. Katayama, A. Kato, R. Keskitalo, T. Kisner, Y. Kobayashi, A. Kogut, K. Kohri, E. Komatsu, K. Komatsu, K. Konishi, N. Krachmalnicoff, C. L. Kuo, L. Lamagna, M. Lattanzi, A. T. Lee, C. Leloup, F. Levrier, E. Linder, G. Luzzi, J. Macias-Perez, B. Maffei, D. Maino, S. Mandelli, E. Martínez-González et al. (87 additional authors not shown)

LiteBIRD, the Lite (Light) satellite for the study of B-mode polarization and Inflation from cosmic background Radiation Detection, is a space mission for primordial cosmology and fundamental physics. The Japan Aerospace Exploration Agency (JAXA) selected LiteBIRD in May 2019 as a strategic large-class (L-class) mission, with an expected launch in the late 2020s using JAXA's H3 rocket. LiteBIRD is planned to orbit the Sun-Earth Lagrangian point L2, where it will map the cosmic microwave background (CMB) polarization over the entire sky for three years, with three telescopes in 15 frequency bands between 34 and 448 GHz, to achieve an unprecedented total sensitivity of 2.2μK-arcmin, with a typical angular resolution of 0.5° at 100 GHz. The primary scientific objective of LiteBIRD is to search for the signal from cosmic inflation, either making a discovery or ruling out well-motivated inflationary models. The measurements of LiteBIRD will also provide us with insight into the quantum nature of gravity and other new physics beyond the standard models of particle physics and cosmology. We provide an overview of the LiteBIRD project, including scientific objectives, mission and system requirements, operation concept, spacecraft and payload module design, expected scientific outcomes, potential design extensions and synergies with other projects.

Comments: 155 pages, submitted to PTEP
Subjects: **Instrumentation and Methods for Astrophysics (astro-ph.IM)**; Cosmology and Nongalactic Astrophysics (astro-ph.CO)
Cite as: arXiv:2202.02773 **[astro-ph.IM]**
(or arXiv:2202.02773v1 **[astro-ph.IM]** for this version)
https://doi.org/10.48550/arXiv.2202.02773

Submission history

From: Hirokazu Ishino [view email]
[v1] Sun, 6 Feb 2022 13:17:44 UTC (53,502 KB)

Download:

- PDF
- Other formats

(license)

Current browse context:
astro-ph.IM
< prev | next >
new | recent | 2202

Change to browse by:
astro-ph
astro-ph.CO

References & Citations
- INSPIRE HEP
- NASA ADS
- Google Scholar
- Semantic Scholar

Export Bibtex Citation

Bookmark

Overall schedule

Public document

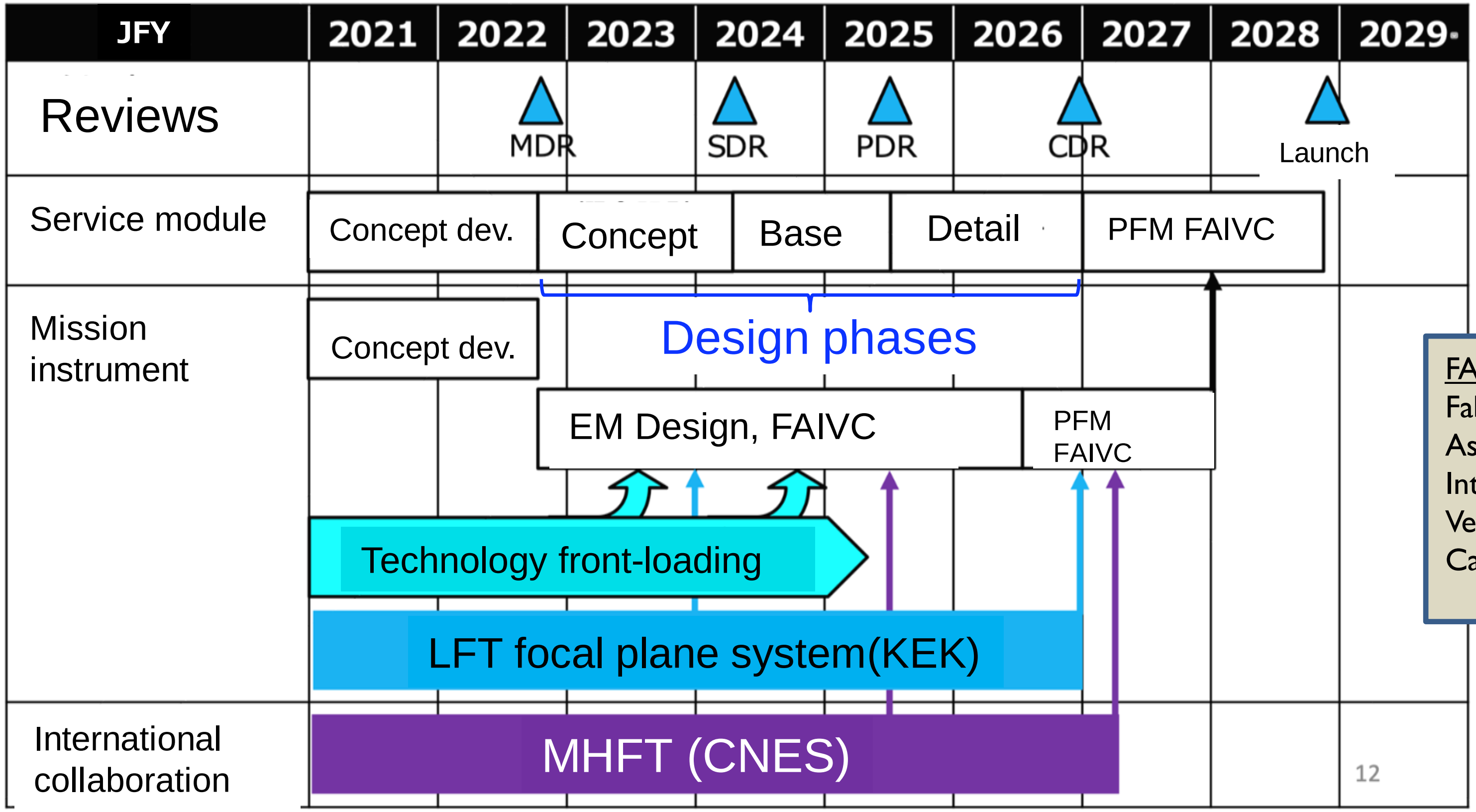
Cabinet Office
Committee on Space Policy
Subcommittee on Space Science and Exploration
48th Meeting

Nov 12 (Fri.), 2021
14:00 – 15:30

https://www8.cao.go.jp/space/comittee/27-kagaku/kagaku-dai48/siryou1_1.pdf

2. Cosmic Microwave Background Polarization Satellite "LiteBIRD"
2.7 Schedule

By reorganizing the procurement management plan and incorporating the results of the Technology Front-loading, we expect to be ready for development consistent with the Baseline Space Plan Process Chart.



FAIVC: Fabrication, Assembly, Integration, Verification, Calibration

Strong endorsements from communities and evaluations in the world

Japan

- Strong endorsement from radio astronomy community → one of flagship projects of Japan in SCJ Master Plan 2020 and MEXT roadmap 2020
- Strong endorsement from HEP community → reflected to KEK-PIP 2021

Canada

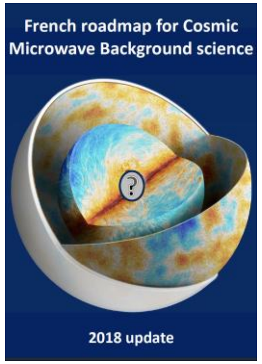
First-priority mission in Canadian Astronomy Long Range Plan 2020-2030

Priority	Mission	Anticipated cost to Canada	Estimated Launch Time Scale
1	LiteBIRD	$25-$40M	Late 2020s
2	….		

Recommended Space Astronomy Missions: Large ($25M-$100M) Investments

France

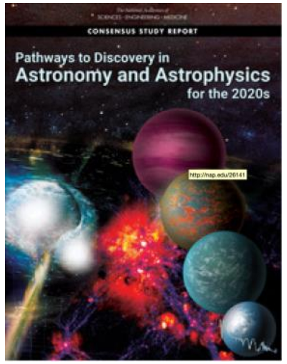
"LiteBIRD is the most advanced space mission proposal, … LiteBIRD represents a unique opportunity to take a lead on an imaging CMB instrument by CNES and the French community." in French roadmap on CMB science (2018 update)



USA

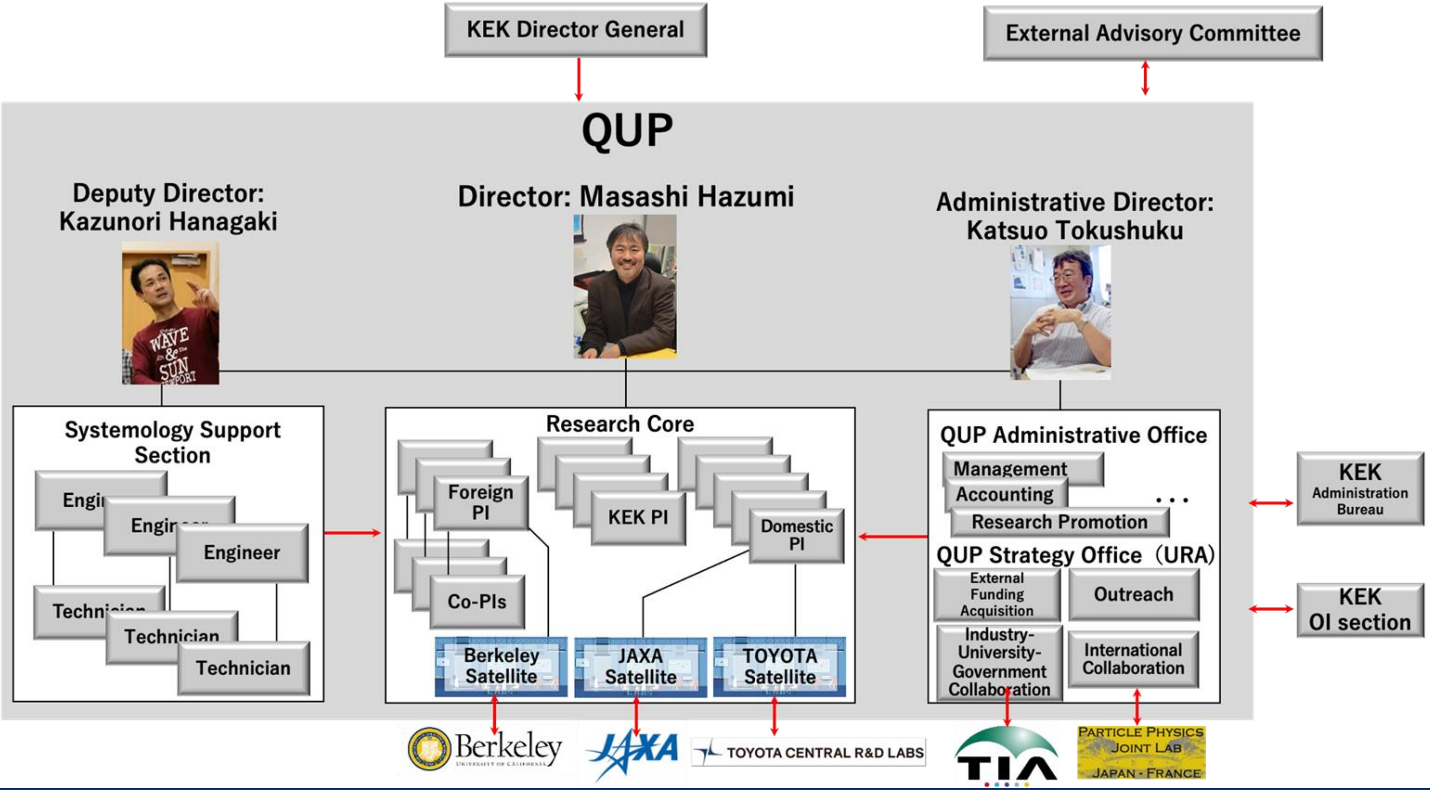
Decadal 2020 report

The US LiteBIRD contribution is too small in scale to be listed, but the need for satellite CMB observations is clearly stated.



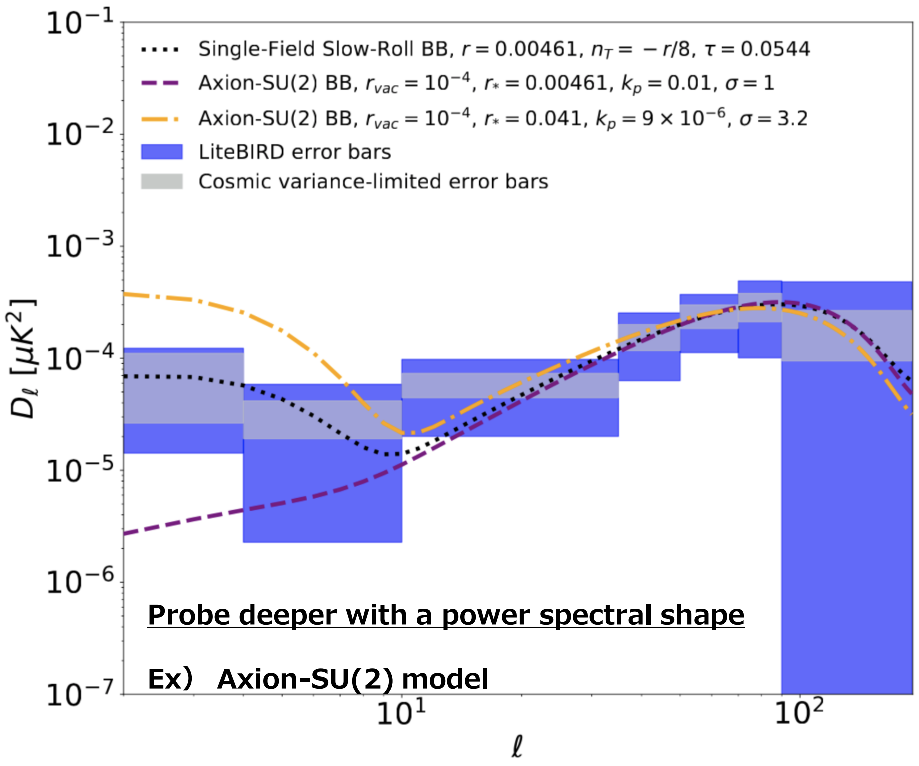
QUP from the context of LiteBIRD

- LiteBIRD focal plane detector system development is QUP's flagship project, with ~10 people (researchers and engineers) for LiteBIRD.
- QUP Director is the global PI of LiteBIRD.
- QUP will set up a satellite laboratory at UC Berkeley.



UC Berkeley Marvel Fabrication Lab.

Beyond *r*

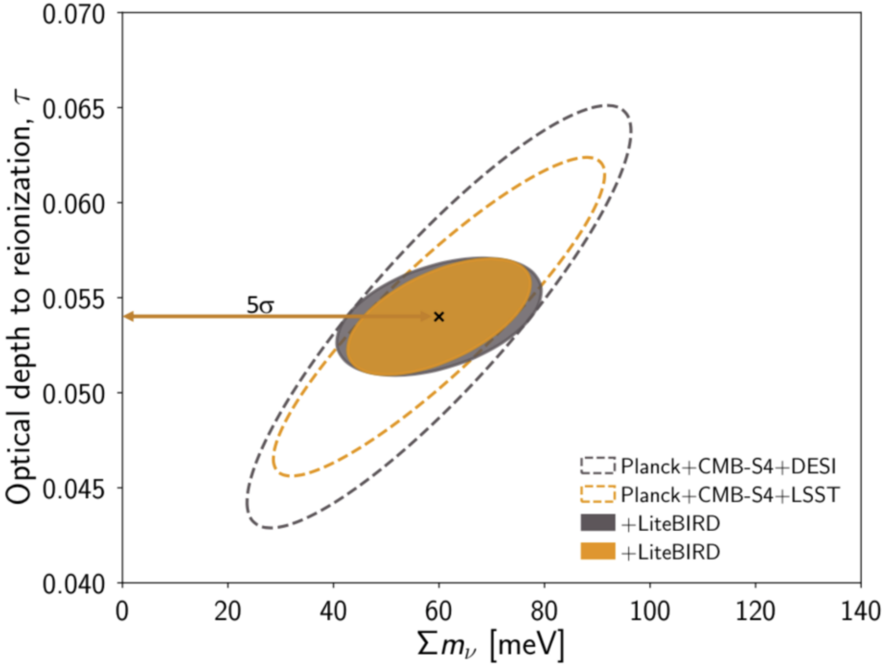


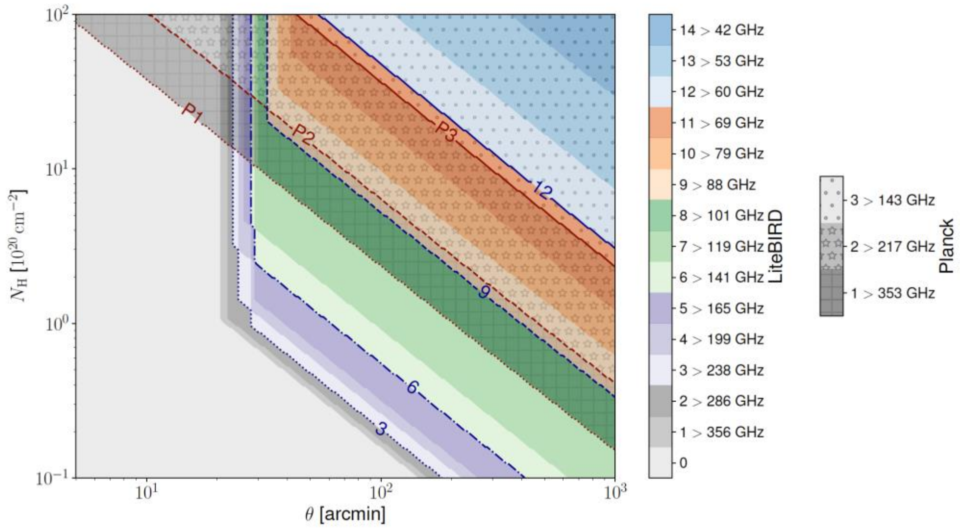
Probe deeper with a power spectral shape

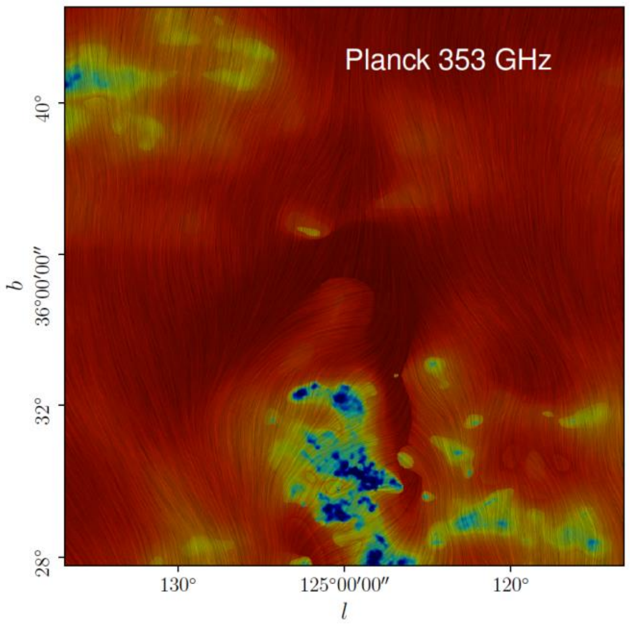
Ex） Axion-SU(2) model

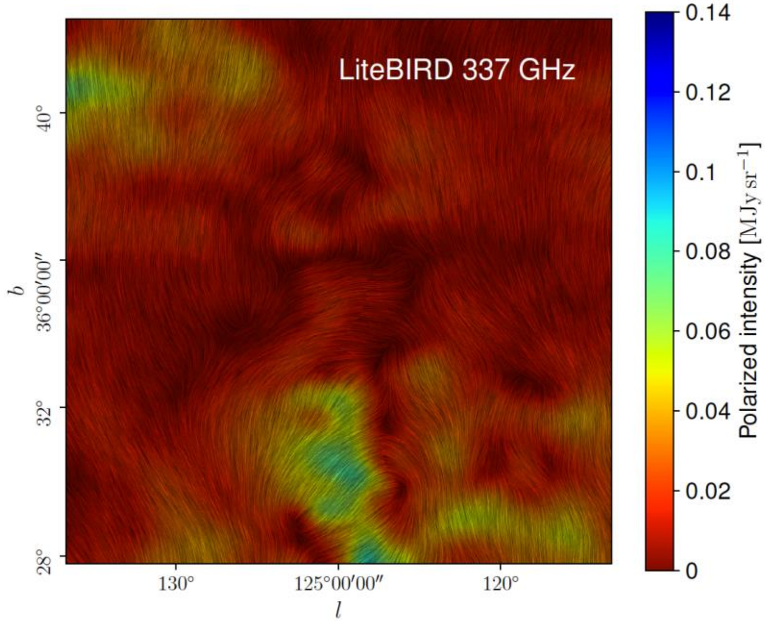
Sum of neutrino masses

- $\sigma(\Sigma m_\nu) = 12$ meV
- 5σ detection of minimum mass for normal hierarchy!









APC
ASI
Berkeley UNIVERSITY OF CALIFORNIA
BERKELEY LAB
UNIVERSITÀ DEGLI STUDI DI MILANO BICOCCA
CARDIFF UNIVERSITY PRIFYSGOL CAERDYD
cea
Centre Pierre Binétruy CNRS • Berkeley
cnes
cnrs
CSA ASC Canada
CSIC CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS
CSL CENTRE SPATIAL DE LIÈGE
ENS | PSL
erc European Research Council Established by the European Commission
EXCELENCIA MARÍA DE MAEZTU
EXCELENCIA SEVERO OCHOA
FAU FRIEDRICH-ALEXANDER UNIVERSITÄT ERLANGEN-NÜRNBERG
Forskningsrådet The Research Council of Norway
GOBIERNO DE ESPAÑA MINISTERIO DE CIENCIA E INNOVACIÓN
NASA Goddard Space Flight Center
G S S I GRAN SASSO SCIENCE INSTITUTE
INSTITUTO DE ASTROFISICA DE CANARIAS IAC
IAP
IAS Orsay
IFCA Instituto de Física de Cantabria
ifpU
IJCLab Irène Joliot-Curie Laboratoire de Physique des 2 Infinis
INFN
INAF ISTITUTO NAZIONALE DI ASTROFISICA
IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE
IPNS 素粒子原子核研究所 Institute of Particle and Nuclear Studies
irap astrophysique & planétologie
JAXA
KEK
KIPAC
KMI Kobayashi-Maskawa Institute Nagoya University
LMU USM
LPSC GRENOBLE | MODANE
MAX-PLANCK-INSTITUT FÜR ASTROPHYSIK
McGill
名古屋大学 NAGOYA UNIVERSITY
香川高専 NATIONAL INSTITUTE OF TECHNOLOGY KAGAWA COLLEGE
NÉEL institut
NIST
Norwegian Directorate for Higher Education and Skills
LiteBIRD
岡山大学 OKAYAMA UNIVERSITY
QUP International Center for Quantum-field Measurement Systems for Studies of the Universe and Particles
POLITÉCNICA | idr
PRINCETON UNIVERSITY
SAPIENZA UNIVERSITÀ DI ROMA
SISSA
SORBONNE UNIVERSITÉ
SSDC SPACE SCIENCE DATA CENTER
LELAND STANFORD JUNIOR UNIVERSITY 1891
Stockholm University
TOR VERGATA UNIVERSITÀ DEGLI STUDI DI ROMA
UCL
UBC THE UNIVERSITY OF BRITISH COLUMBIA
UC UNIVERSIDAD DE CANTABRIA
University of Colorado Boulder
UKRI Science and Technology Facilities Council
ULB UNIVERSITÉ LIBRE DE BRUXELLES
Universidad de La Laguna
MANCHESTER 1824 The University of Manchester
UiO University of Oslo
UNIVERSITÀ DI PISA
Università degli Studi di Ferrara
UNIVERSITÀ DEGLI STUDI DI MILANO
UNIVERSITÀ DEGLI STUDI DI PADOVA
THE UNIVERSITY OF TOKYO
UNIVERSITY OF TORONTO

Huge discovery impacts

- Direct evidence for inflation
- Knowledge on the inflation energy scale
- First evidence for quantum fluctuation of space-time

Insight on quantum gravity, including String Theory

“Detecting primordial gravitational waves would be one of the most significant scientific discoveries of all time.”

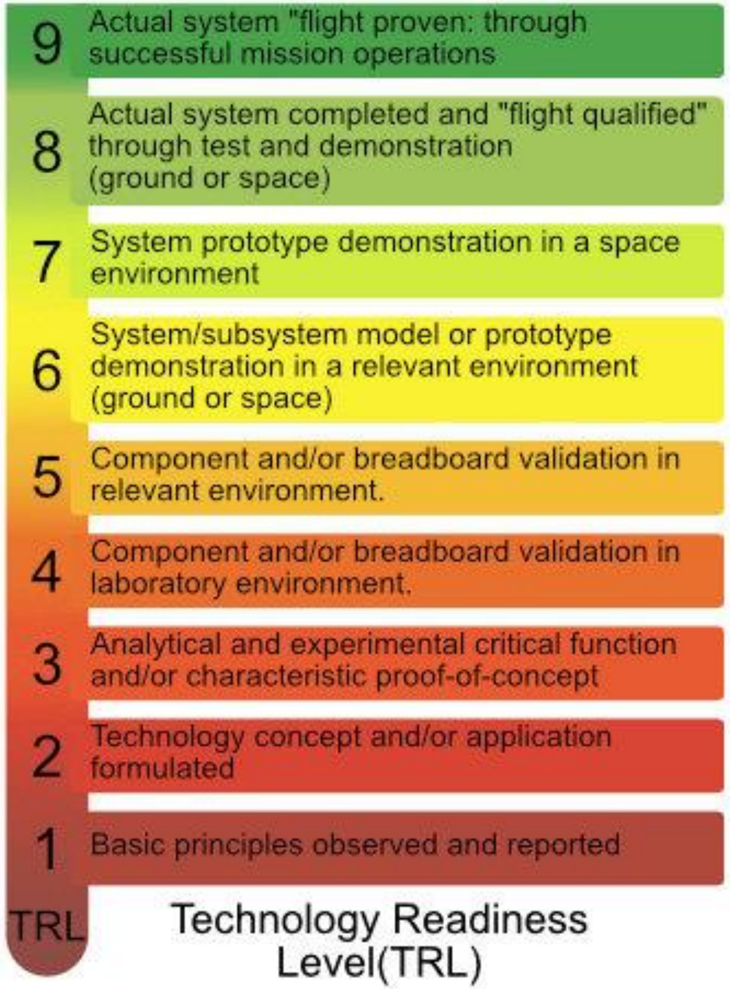
Final report of the task force on cosmic microwave background research “Weiss committee report” July 11, 2005, arXiv/0604101

Reviews and technology readiness levels (TRLs)

- **At the end of the mission definition phase*), the LiteBIRD team underwent a review by the Institute of Space and Astronautical Science (ISAS).**
- **The schedule, budget plan, personnel plan, and readiness (e.g., equipment development) were scrutinized by experts outside the LiteBIRD team. Our project was feasible enough to pass that rigorous review.**

***) In the mission definition phase, we constructed a requirements flow consisting of "science objectives," "observation requirements derived from science objectives,"
and "instrument (system) requirements derived from observation requirements." The ending review focuses on the higher-level requirements.**
We prepared approximately 1000 pages of documents.

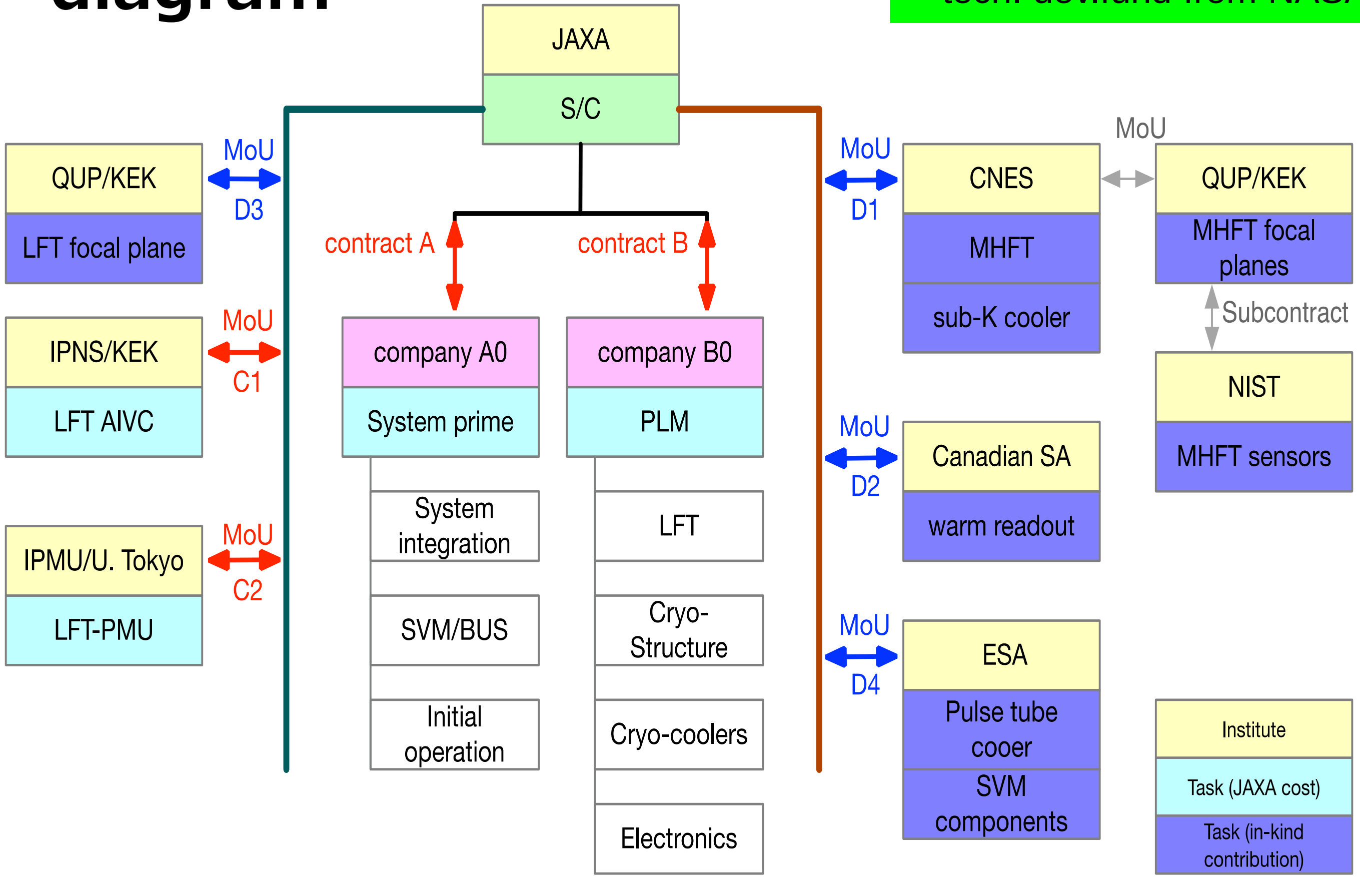
	Critical components	Others
Project Preparation Review	TRL ≥ 4	TRL ≥ 3
Project Transition Review	TRL ≥ 5	TRL ≥ 4



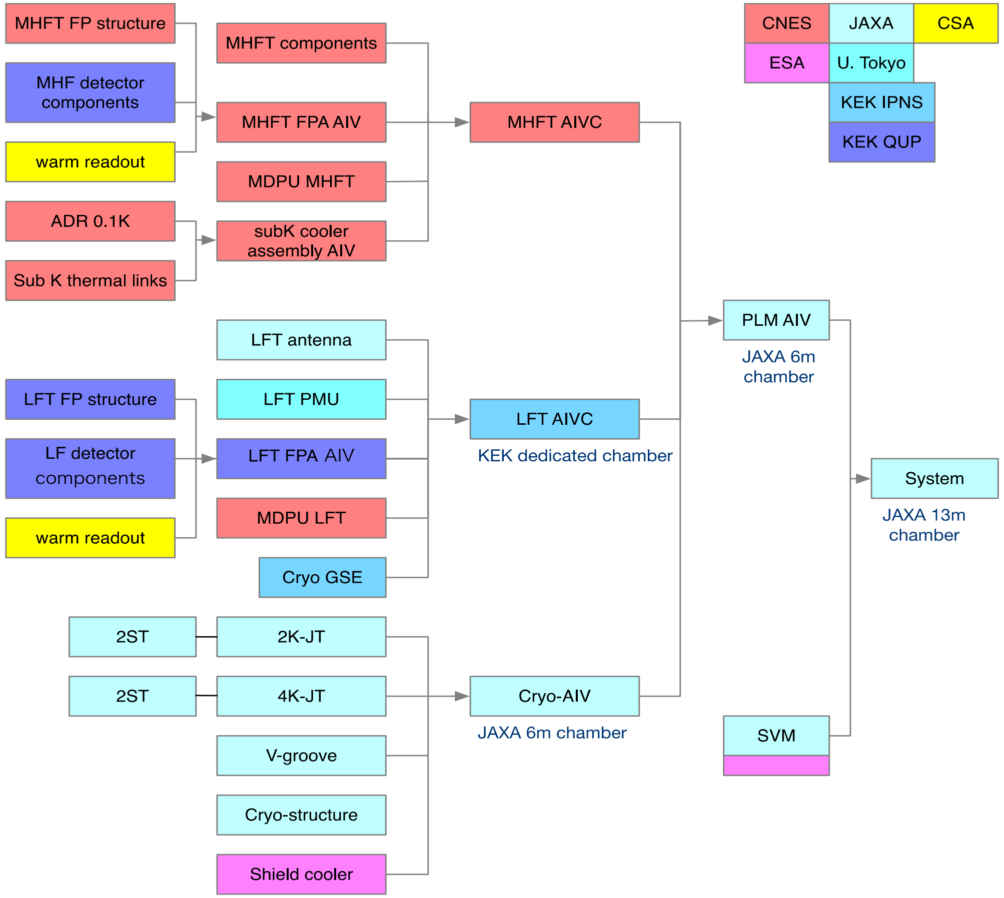
Global procurement management

Procurement Management diagram

Phase A commitment from space agencies in Canada, France, Italy, Spain.
+ tech. dev.fund from NASA



Integration Management diagram



Impact on Fundamental Physics (1)

Inflaton

Scalar particle responsible for inflation

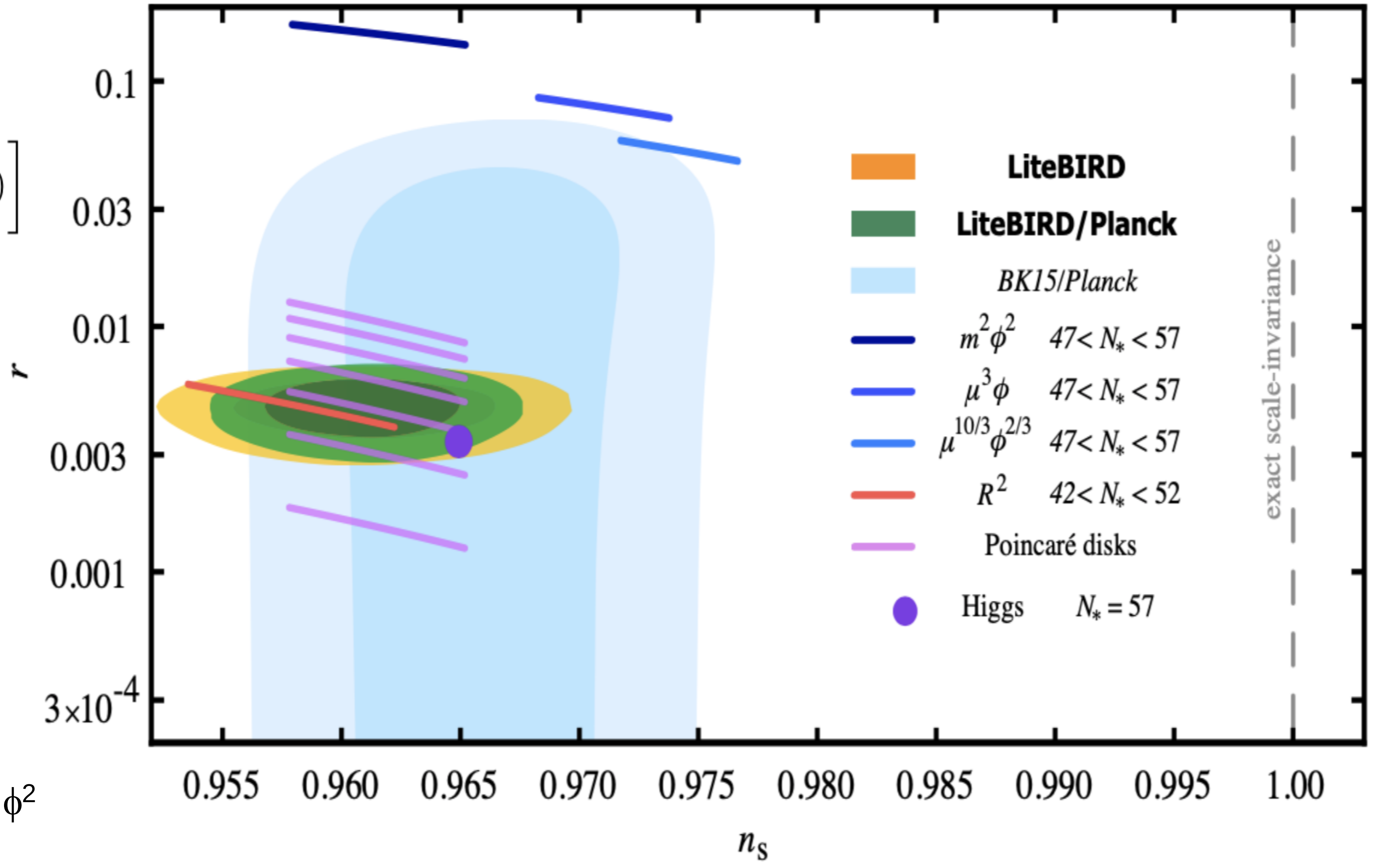
$$S \supset \int d^4x\sqrt{-g}\left[-\frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - V(\phi)\right]$$

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

GUT scale for no reason!
Measurement of r is GUT physics!

Higgs

The inflaton looks like the Higgs.
Are they the same?
→ Higgs inflation:
Higgs with a coupling to gravity ~Rϕ^2



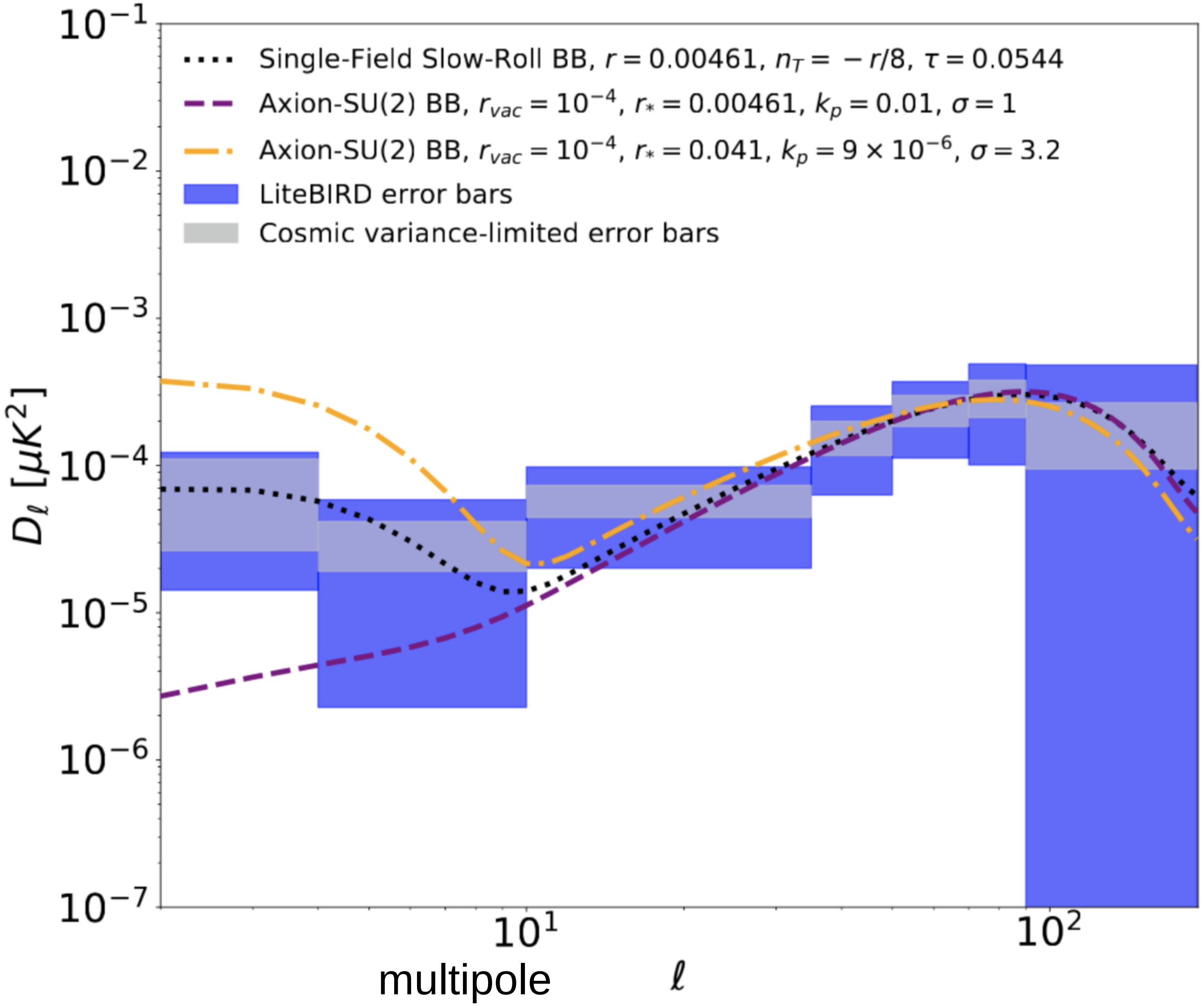
Impact on Fundamental Physics (2)

New particle(s) beyond SM

Ex) Axion-SU(2) model

The example on the right figure shows that the spectrum can change due to the new gauge field. Large-angle correlations with multipoles smaller than 10 are where LiteBIRD's all-sky surveys are most powerful.

If you see such a non-standard spectrum, it is a great discovery.

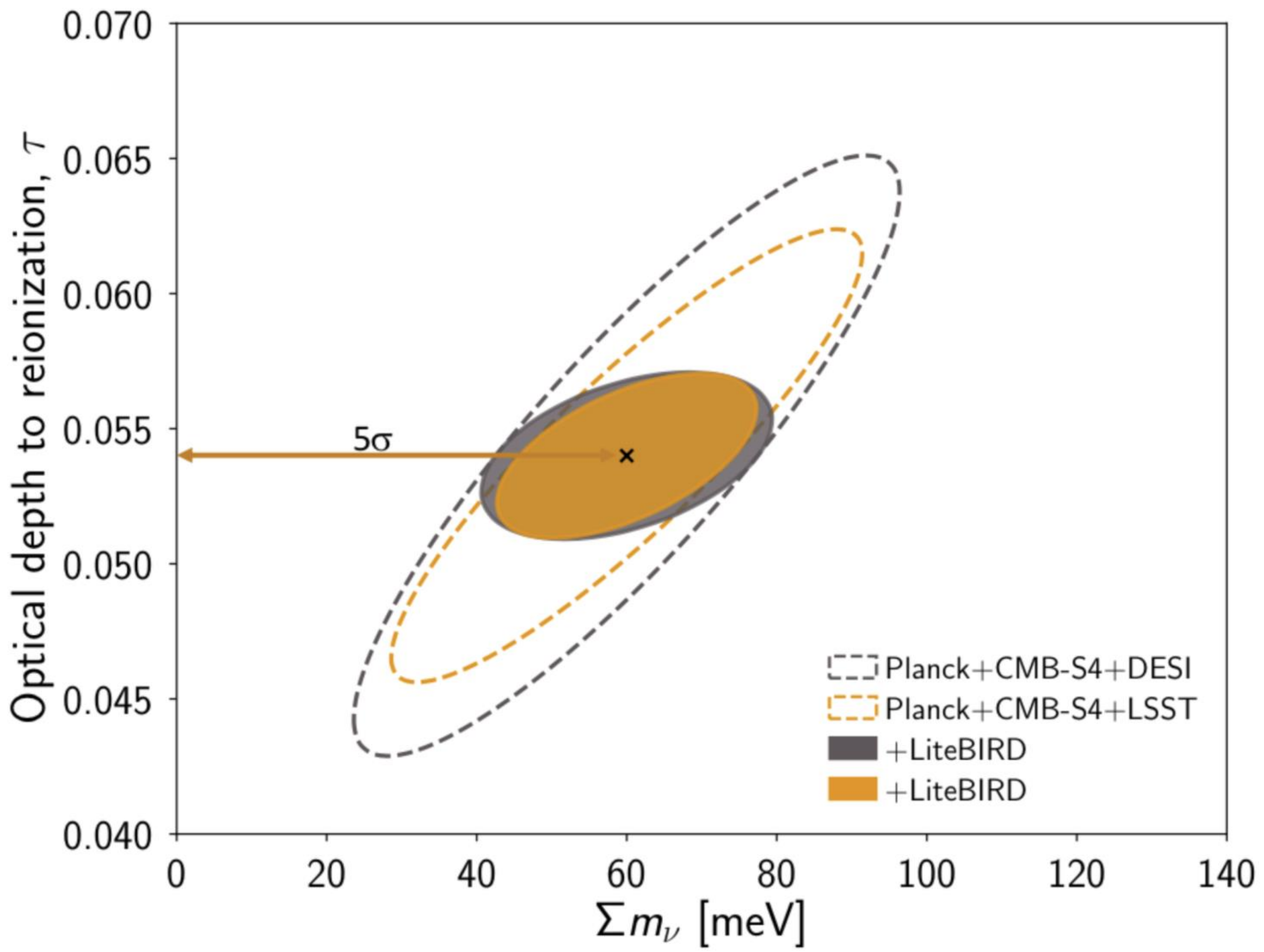


Impact on Fundamental Physics (3)

Sum of neutrino masses

- $\sigma(\Sigma m_\nu) = 12$ meV
- 5σ detection of minimum mass for normal hierarchy!

The heavier the neutrinos are, the slower the structure formation is. We can thus determine the sum of neutrino masses by comparing the fluctuations at recombination and in the late universe. However, there is a degeneracy between the fluctuations at recombination and the optical depth (τ), limiting the precision. LiteBIRD can determine τ precisely from the E-mode, and as a result can improve the precision of the sum of the neutrino masses.

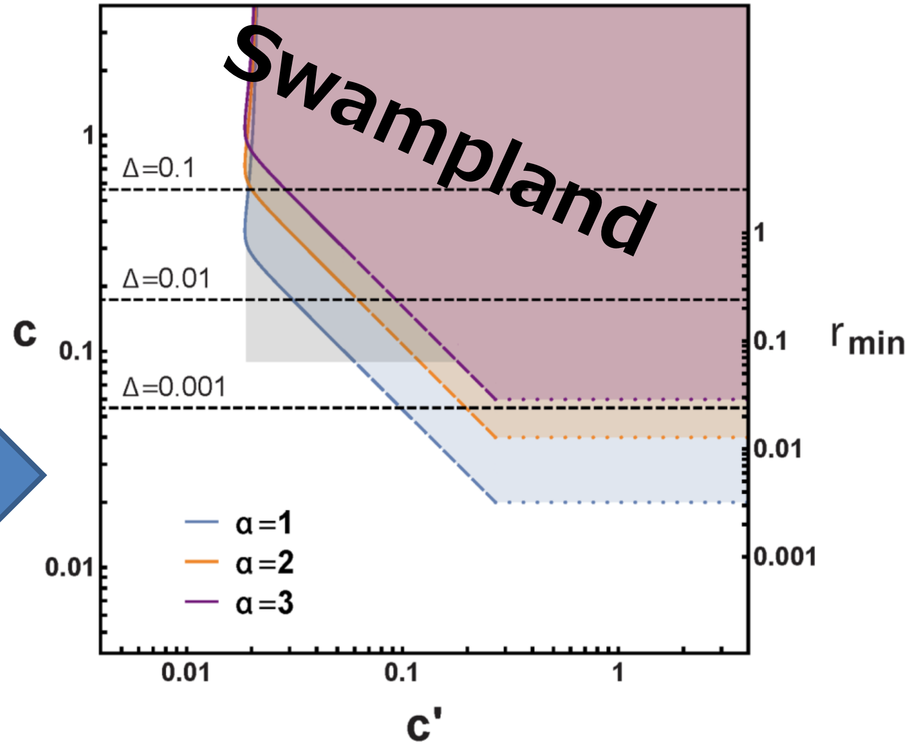


Impact on Fundamental Physics (4)

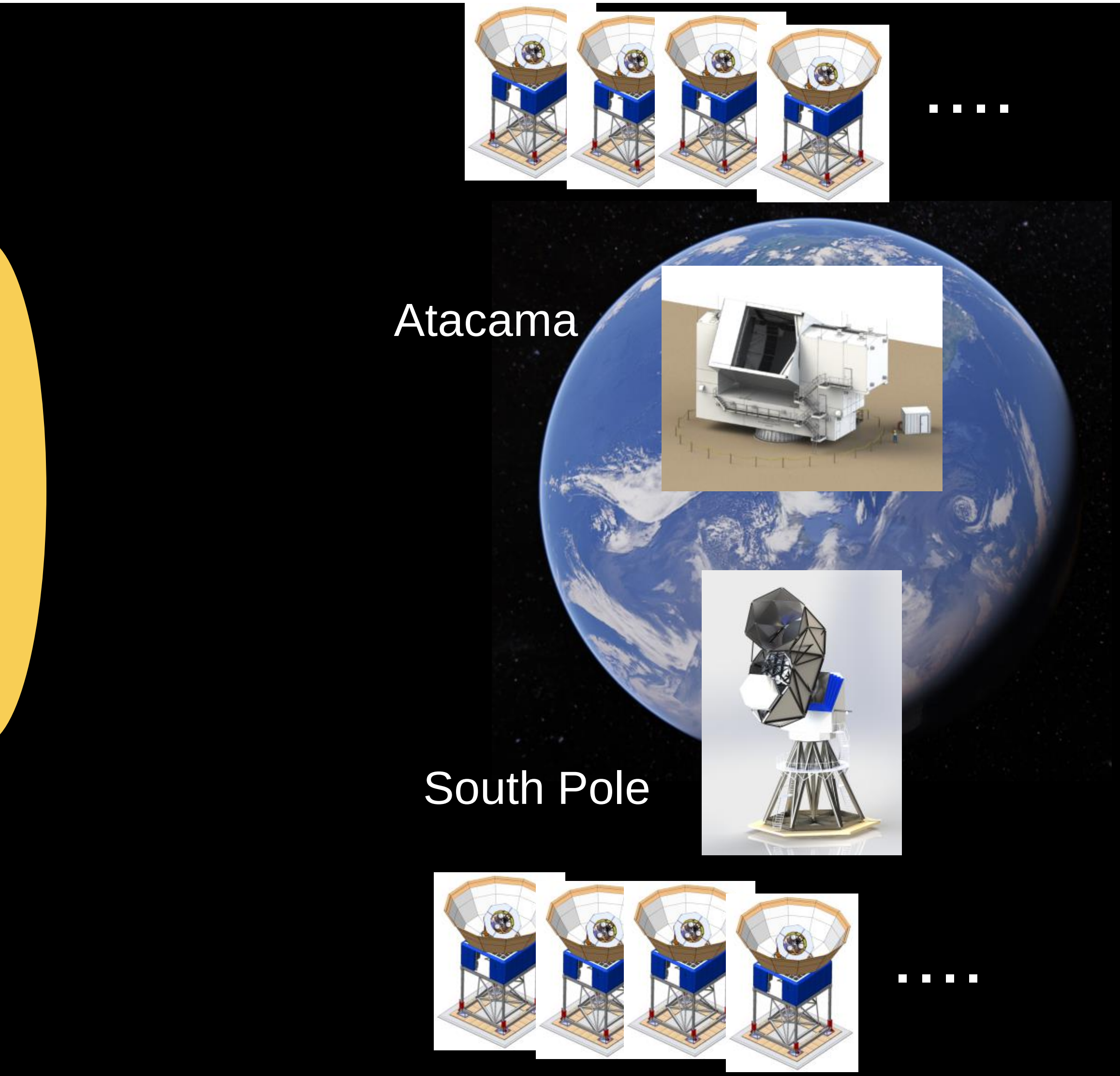
Tests of Quantum Gravity

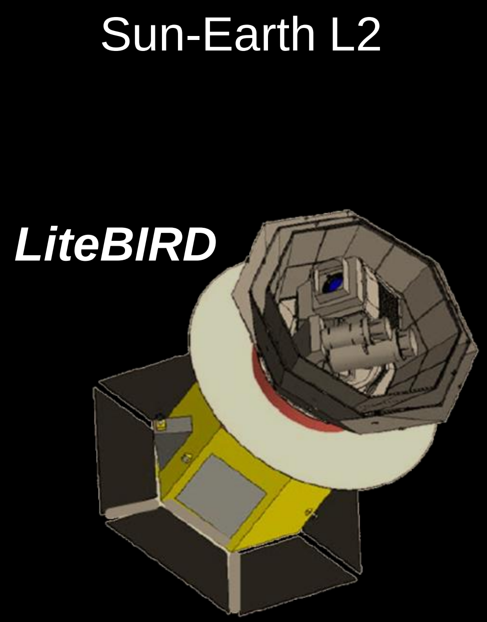
- **Example of recent progress "Swampland Hypothesis" (Obied-Oguri-Spodyneiko-Vafa 2018)**
  - **Swampland: a parameter region not allowed in superstring theory → restrict inflationary models → LiteBIRD can test the hypothesis**
- **A case study using the modified Swampland hypothesis (Chiang-Leedom-Murayama 2019)**
  - **Restrictions on the parameter c(c'), which is related to the first derivative (second derivative) of the inflation potential**
  - **Allowed region is in white in the right figure.**

Most cited papers published in 2018 particle theory (iNSPIRE)



Vision for the future

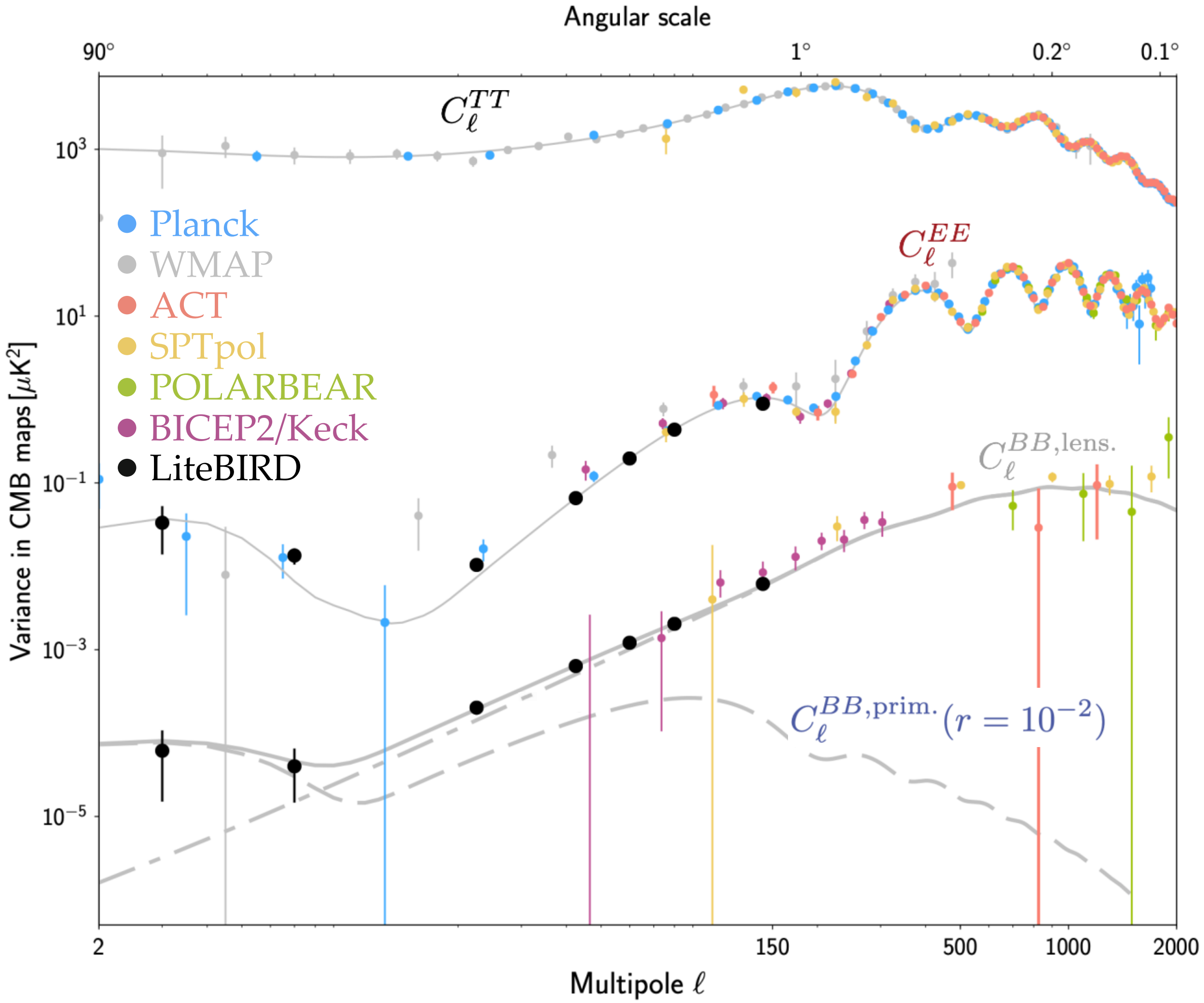




We need three locations!

LiteBIRD main scientific objectives

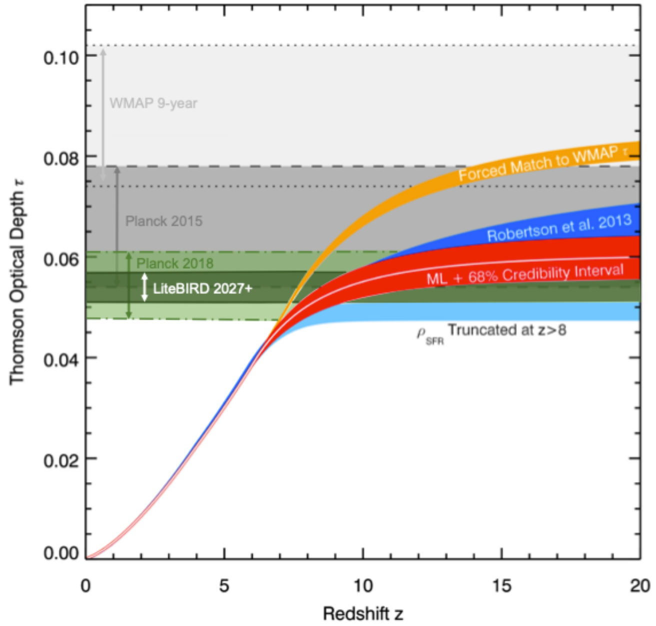
- Definitive search for the *B*-mode signal from cosmic inflation in the CMB polarization
  - Making a discovery or ruling out well-motivated inflationary models
  - Insight into the quantum nature of gravity
    The inflationary (i.e. primordial) *B*-mode power is proportional to the tensor-to-scalar ratio, r
- Current best constraint: $r < 0.032$ (95% C.L.) (M. Tristram 2021, combining BK18 and Planck PR4)



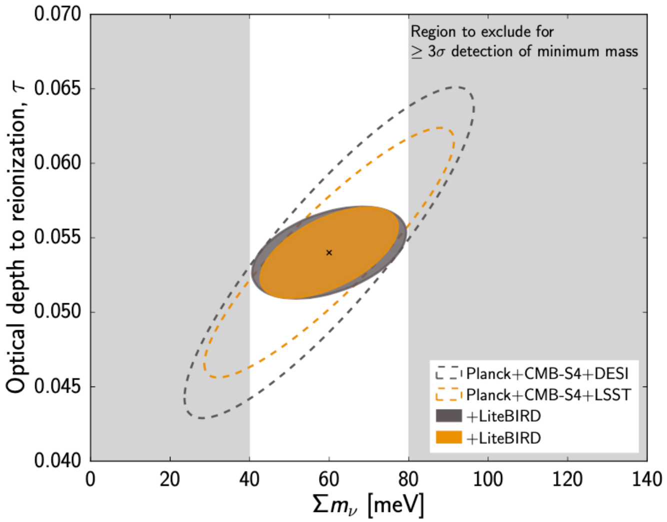
- LiteBIRD will improve current sensitivity on r by a factor ~50
- Top requirements (no external data):
  - For $r = 0$, total uncertainty of $\delta r < 0.001$
  - For $r = 0.01$, 5-σ detection of the reionization ($2 < \ell < 10$) and recombination ($11 < \ell < 200$) peaks independently

LiteBIRD other science outcomes

- The mission specifications are driven by the required sensitivity on *r*
- Meeting those sensitivity requirements would allow to address other important scientific topics, such as:
  1. Characterize the *B*-mode power spectrum and search for source source fields (e.g. scale-invariance, non-Gaussianity, paritiy violation, …)
  2. Power spectrum features in polarization
     - Large-scale *E*-modes
     - Reionization (improve $\sigma(\tau)$ by a factor of 3)
     - Neutrino mass ($\sigma(\sum m_\nu) = 15$ meV)
  3. Constraints on cosmic birefringence
  4. SZ effect (thermal, diffuse, relativistic corrections)
  5. Elucidating anomalies
  6. Galactic science
     - Characterizing the foreground SED
     - Large-scale Galactic magnetic field
     - Models of dust polarization



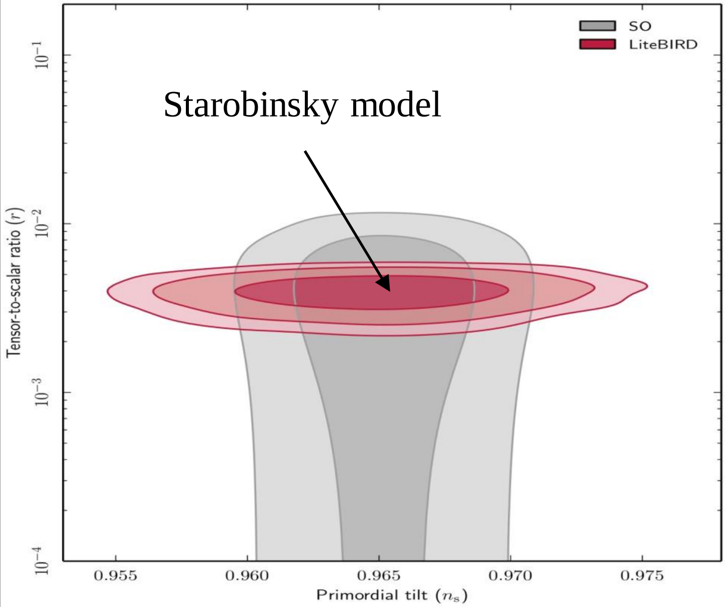
adapted from Robertson+2015



adapted from Calabrese+2017

Science at LiteBIRD: Summary

- Detailed foreground cleaning studies yield $\sigma(r=0) = 0.6 \times 10^{-3}$
- Thorough systematic error studies yield total uncertainty $\delta r < 1.0 \times 10^{-3}$
- Achieved without delensing

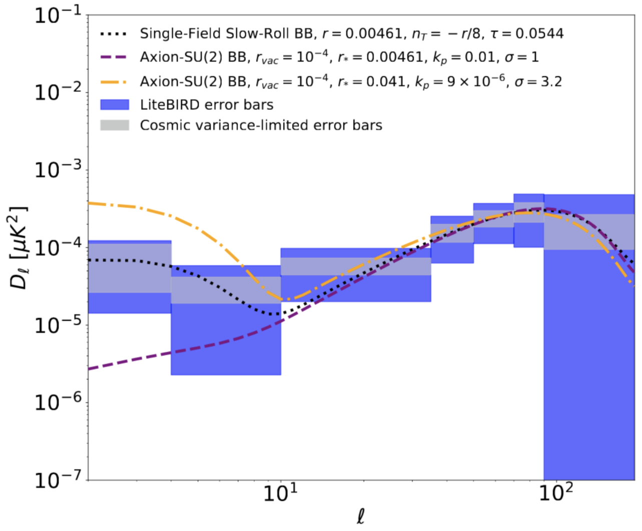


1. Tensor-to-scalar ratio, *r*, from top-level mission requirements

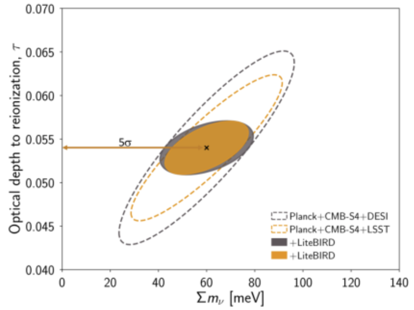
Items (2.-9.) have nothing to do with misson/system requirements, but will be guaranteed if 1. is achieved.

2. Further improving sensitivity on *r* with external data
3. Characterization of B-mode and search for source fields (e.g scale-invariance, non-Gaussianity, parity violation)
4. Power spectrum features in polarization
5. Large-scale E-modes - its implications for reionization history and the neutrino mass
6. Cosmic birefringence
7. SZ effect (thermal and relativistic correction)
8. Elucidating anomalies
9. Galactic science

- Non-standard B-mode power spectrum due to a new gauge particle (SU(2) example)



- Cosmic-variance limited measurements of the low-multipole E-mode → improve τ measurement → improve Σm_ν



Systematics and Calibration

- One of the largest study groups at LiteBIRD
- Systematic approach for systematic uncertainties

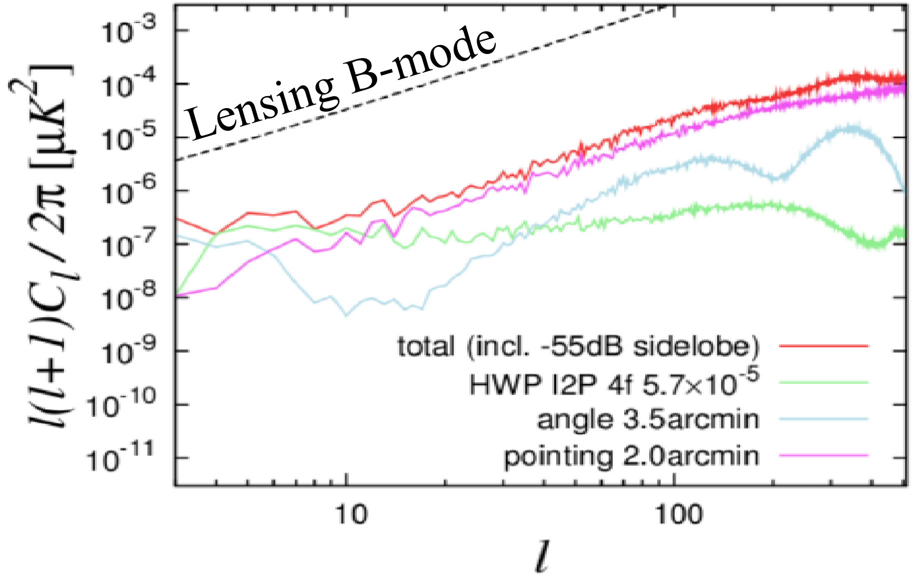
List sources
14 categories
70 items
→
Assign each 1% of total budget
$\sigma(r)_{sys} < 5.7 \times 10^{-6}$
→
Define method (incl. calib. meth.)
estimate of $\sigma(r)_{sys}$
→
Allocate special budget for outstanding items
→
Sum on map base
total $\sigma(r)_{sys}$

Iteration

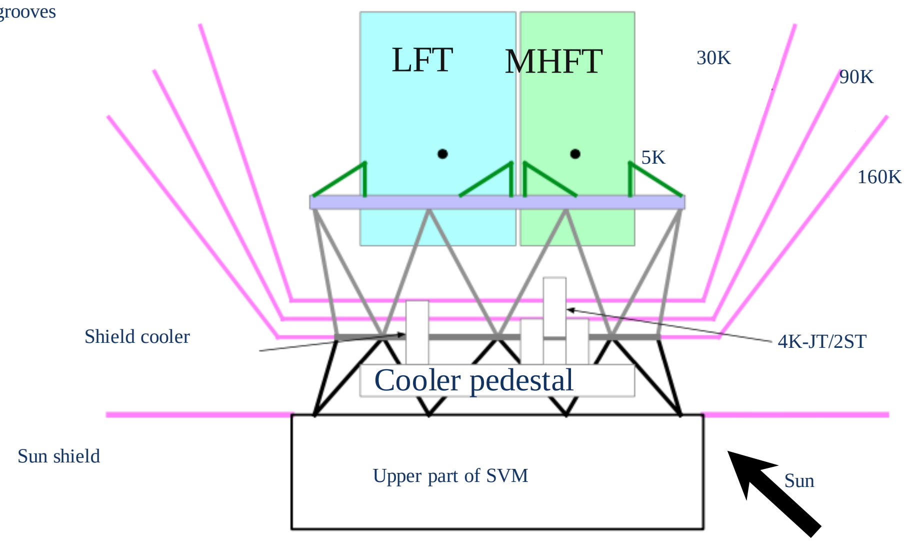
- Example: studies of systematic errors due to HWP imperfection

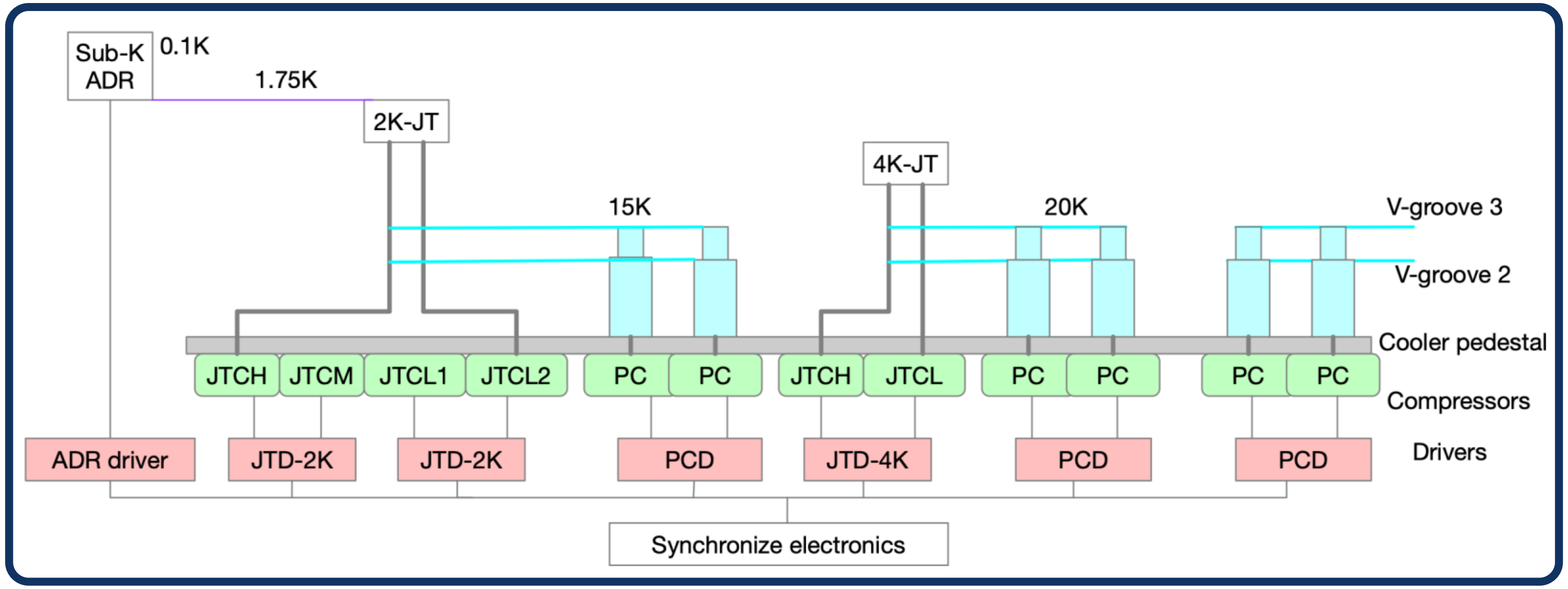
Realistic HWP for different frequencies and incident angles
→
Mueller matrix M from RCWA sim.
$1M_{IQ}$, $M_{IU} \sim 10^{-4}$ (worst case)
→
Obtain leakage Maps and BB power
$\sigma(r)_{sys}$

All known systematics will be adequately mitigated!



LiteBIRD cryogenic system





- Continuous cooling at 100 mK
- High stability on telescopes at all stages