How I got excited about CMB B-mode
- a particle physicist’s experience

1. Quantum fluctuation of the metric

\[ \langle \hat{h} (\mathbf{k}, \eta) \hat{h}(\mathbf{k}', \eta) \rangle = |v(\mathbf{k}, \eta)|^2 (2\pi)^3 \delta^3(\mathbf{k} - \mathbf{k}'). \]

e.g. Dodelson “Modern Cosmology” Eq.(6.52)

2. Physics at GUT scale

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

3. Amazing technology matching w/ HEP
Simons Array  Ongoing

First receiver system “POLARBEAR-2” in preparation at KEK.

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

Outline
1. Mission
2. System
3. Project
4. Outcome

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) Graduate School for Advanced Studies (SOKENDAI)
4) Institute of Space and Astronautical Science (ISAS), Japan Aerospace Exploration Agency (JAXA)
LiteBIRD Joint Study Group Member List

as of Dec. 2017


1 Aoyama Gakuin University, Japan; 2Tohoku University, Japan; 3APC, France; 4University of Colorado, Boulder, USA; 5CNRS, IRAP, Toulouse, France; 6Lawrence Berkeley National Laboratory, Berkeley, USA; 7DAMTP, University of Cambridge, UK; 8The University of Tokyo, Japan; 9University of Colorado, Boulder, USA; 10Princeton University, USA; 11Amrita University, Kerala, India; 12Okayama University, Japan; 13Stanford University, USA; 14University of Tokyo, Japan; 15University of California, Berkeley, USA; 16University of California, San Diego, USA; 17University of Colorado, Boulder, USA; 18CEA, Grenoble, France; 19KEK, Tsukuba, Japan; 20IAS, Orsay, France; 21Academia Sinica, Taiwan; 22ISAS, JAXA, Japan; 23JAXA, Tsukuba, Japan; 24University of Oslo, Norway; 25SISSA, Trieste, Italy; 26Kansai Gakuin University, Japan; 27Kavli Institute for Cosmology Cambridge, UK; 28KIPAC, SLAC, USA; 29Kavli IPMU, Japan; 30Kakato University, Japan; 31Kakato University, Japan; 32Nagoya University, Japan; 33LAL, Univ. Paris-Sud, France; 34Max-Planck-Institut for Astrophysics, Garching, Germany; 35NAOJ, Japan; 36NIFS, Japan; 37AIST, Japan; 38NICT, Japan; 39NIST, Boulder, Colorado USA; 40Osaka Prefecture University, Japan; 41Osaka University, Japan; 42Oxford Astrophysics, United Kingdom; 43McGill University, Montreal, Canada; 44Lawrence Berkeley National Laboratory, USA; 45Radio Astronomy Laboratory, Berkeley, USA; 46RIKEN, Japan; 47Saitama University, Japan; 48Cardiff University, United Kingdom; 49Space Sciences Laboratory, Berkeley, USA; 50SOKENDAI, Japan; 51University of Manchester, United Kingdom; 52University of Tsukuba, Japan; 53University of Wisconsin-Madison, USA; 54Yokohama National University, Japan
1. Mission
Cosmic Microwave Background (CMB) = the oldest radiation you can see

~400 thousand years

13.8 Billion years

image credit NASA/WMAP team
Inflation

Quantum fluctuation of spacetime

$\sim 10^{-36} \text{sec}$

Hot Big Bang

CMB

$\sim 400 \text{ thousand years}$
Big leap from
LIGO to LiteBIRD

within
Einstein’s theory
of general relativity

beyond Einstein

LIGO: gravitational waves with classical origin
LiteBIRD: gravitational waves with quantum origin
“Detecting primordial gravitational waves would be one of the most significant scientific discoveries of all time.”

Cosmic inflation predicts generation of primordial gravitational waves due to quantum fluctuation of spacetime.
Test pattern on TV screen
“Test pattern” of inflation

Expected CMB Polarization Sky Map

Theoretical prediction: large-scale curl patterns (vortexes called “B-mode”)
B-mode power spectrum (2016)

- Inflation
  - $r < 0.07$ (95% C.L.)

- Secondary effect
  - (Gravitational lensing)

- Multipole Moment $\ell$

- Power spectrum $l(l+1)C_{ll}/(2\pi)$ ($\mu K^2$)
LiteBIRD expectation

Inflation

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

- B-mode from primordial gravitational waves proportional to $r$ (=“tensor-to-scalar ratio”).
- $r$ is proportional to the energy potential of the inflaton, a new hypothetical particle responsible for inflation.
- The expected energy potential is around the scale of Grand Unification of three fundamental forces.
- Measurement of B-mode is thus one of the most important topics in cosmology and particle physics.
- Current experimental limit ($r < 0.07$ at 95% C.L.) is weak. An order-of-magnitude improvement required.
LiteBIRD

Full success of LiteBIRD

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

Remarks

1. $\sigma(r)$ is the total uncertainty on the $r$ measurement that includes the following uncertainties**
   - statistical uncertainties
   - instrumental systematic uncertainties
   - uncertainties due to residual foregrounds and bias
   - uncertainties due to lensing B-mode
   - cosmic variance (for $r > 0$)
   - observer bias

2. The above should be achieved without delensing.

* More precise (i.e. long) definition ensures $>5$sigma $r$ detection from each bump for $r > 0.01$.

** We also use an expression $\delta r = \sigma(r=0)$, which has no cosmic variance.
**Extra success**

**Improve $\sigma(r)$ with external observations**

<table>
<thead>
<tr>
<th>Topic</th>
<th>Example Method</th>
<th>Example Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Delensing</td>
<td>Large CMB telescope array</td>
<td>CMB-S4 data</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Namikawa and Nagata, JCAP 1409 (2014) 009</td>
</tr>
<tr>
<td></td>
<td>Cosmic infrared background</td>
<td>Herschel data</td>
</tr>
<tr>
<td></td>
<td>Radio continuum survey</td>
<td>SKA data</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Namikawa, Yamauchi, Sherwin, Nagata, Phys. Rev. D 93, 043527 (2016)</td>
</tr>
<tr>
<td>Foreground removal</td>
<td>Lower frequency survey</td>
<td>C-BASS upgrade</td>
</tr>
</tbody>
</table>

- Delensing improvement to $\sigma(r)$ can be factor $\sim 2$ or more.
- *e.g. $\sim 6\sigma$ observation in case of Starobinsky model*
- Need to make sure systematic uncertainties are under control.
2. System
## Main Specifications

**Phase-A1 2016 Baseline**

<table>
<thead>
<tr>
<th>Item</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Launch year</td>
<td>2026-2027</td>
</tr>
<tr>
<td>Launch vehicle</td>
<td>JAXA H3</td>
</tr>
<tr>
<td>Observation type</td>
<td>All-sky CMB surveys</td>
</tr>
<tr>
<td>Observation time</td>
<td>3 years</td>
</tr>
<tr>
<td>Orbit</td>
<td>L2 Lissajous orbit</td>
</tr>
<tr>
<td>Scan strategy</td>
<td>Spin and precession ($\alpha = 45^\circ$, $\beta = 50^\circ$)</td>
</tr>
<tr>
<td>Observing frequencies</td>
<td>34 – 448 GHz</td>
</tr>
<tr>
<td>Number of bands</td>
<td>15</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>2.5 $\mu$K $^\prime$ (3 years)</td>
</tr>
<tr>
<td>Angular resolution</td>
<td>0.5° at 100 GHz (FWHM)</td>
</tr>
</tbody>
</table>
| Mission instruments | · Superconducting detector arrays  
· Polarization modulator with continuously-rotating half-wave plate (HWP)  
· Crossed-Dragone mirrors (LFT) + small refractive telescope (HFT)  
· 0.1K cooling chain (ST/JT/ADR)                                        |
| Data size           | 4 GB/day                                                                      |
| Mass                | 2.2 t                                                                         |
| Power               | 2.5 kW                                                                        |
**Payload Module**

- TES arrays
- Polarization modulators
- LFT + HFT
- 0.1 cooling system (ST/JT/ADR)

**Phase-A1 2016 Baseline**

- POLARBEAR-2 focal plane as a proof of principle
Five uncertainty components

Goal \( \delta r < 0.001 \)

- Statistics
- Systematics
- Observer bias
- Lensing
- Foreground
Error budget assignment toward full success

- Statistical error after foreground separation, including lensing B-mode contribution ($\sigma_{\text{stat}}$)
- Systematic error ($\sigma_{\text{sys}}$)
- Margin ($\sigma_{\text{mgn}}$)
- Requirement: $\sigma_{\text{stat}}^2 + \sigma_{\text{sys}}^2 + \sigma_{\text{mgn}}^2 < 0.001^2$
- We assign $\sigma_{\text{stat}} = \sigma_{\text{sys}} = \sigma_{\text{mgn}}$
- Therefore we require
  - $\sigma_{\text{stat}} < 0.57 \times 10^{-3}$
  - $\sigma_{\text{sys}} < 0.57 \times 10^{-3}$

  - At the moment an effect of each sys. error item is required to be less than 1% of lensing BB power.
  - Error budget management in the next step will allow less stringent requirements on outstanding items (e.g. Sidelobe, absolute angle error)
LiteBIRD: 15 Frequency Bands (Phase-A1 2016 Baseline)

Planck 2015

- Synchrotron
- Dust
- CMB
- CO J10
- CO J21
- CO J32
- CO J43

Frequency bands and associated sensitivities are shown in the graph.
Scan Strategy

Orbit: L2 Lissajous

Precession angle $\alpha = 45$ degrees
Spin angle $\beta = 50$ degrees
# of observations for each sky pixel

w/ a single detector

Mollweide view

1 year
Current baseline is extendable

• New launch vehicle: H-II $\Rightarrow$ H3
• New ground station: GREAT
• New mirror design
Launch Vehicle: H3

- To be replaced with H-III in 2020
- First test launch in 2020
- ½ cost w/ same capability (comparison w/ H-II B)
- Larger envelope

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

H-II B
- First Flight in 2009
- 4 successful flights/4 of 16.5 ton HTV to ISS
- GTO 8 ton class capability
### SUMMARY OF GROUND STATIONS

<table>
<thead>
<tr>
<th>station</th>
<th>Antenna diameter</th>
<th>Bands</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>GN (Ground Network)</td>
<td>10m</td>
<td>S up/down/range</td>
<td>3 stations in Japan, 4 outside Japan</td>
</tr>
<tr>
<td>USC</td>
<td>34m</td>
<td>S up/down/range, X up/down, Ka down</td>
<td></td>
</tr>
<tr>
<td>KTU4</td>
<td>20m</td>
<td>S up/down/range, X down</td>
<td></td>
</tr>
<tr>
<td>UDSC</td>
<td>64m</td>
<td>S up/down/range, X up/down/range</td>
<td>Will be replaced with the 54m antenna.</td>
</tr>
<tr>
<td>GREAT</td>
<td>54m</td>
<td>X up/down/range, Ka down</td>
<td>Under construction. Operational from 2019.</td>
</tr>
</tbody>
</table>

**GREAT**

Antenna available for L2 mission in 2020s. Only the limited data transfer is possible at L2.

Larger datalink capability
New Mirror Design for LFT

Paper submitted

SCS: Simple off-axis conic surface

ACS: Anamorphic conic surfaces without higher-order terms

AAS: Anamorphic aspherical surfaces with terms up to the 10\textsuperscript{th} order

Strehl Ratio > 0.95 over 32 x 18 degrees\textsuperscript{2}
Enhanced design example

LFT

<table>
<thead>
<tr>
<th>Center Freq [GHz]</th>
<th>Frac BW</th>
<th>Pixel Diameter [mm]</th>
<th>Num Pix</th>
<th>Num Det</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>0.30</td>
<td>30</td>
<td>21</td>
<td>42</td>
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<tr>
<td>60</td>
<td>0.23</td>
<td>30</td>
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<td>42</td>
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<tr>
<td>78</td>
<td>0.23</td>
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<td>50</td>
<td>0.30</td>
<td>30</td>
<td>28</td>
<td>56</td>
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<td>68</td>
<td>0.23</td>
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<td>89</td>
<td>0.23</td>
<td>30</td>
<td>28</td>
<td>56</td>
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<tr>
<td>68</td>
<td>0.23</td>
<td>18</td>
<td>57</td>
<td>114</td>
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<tr>
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<td>0.23</td>
<td>18</td>
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<td>114</td>
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<td>119</td>
<td>0.30</td>
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<tr>
<td>140</td>
<td>0.30</td>
<td>18</td>
<td>57</td>
<td>114</td>
</tr>
</tbody>
</table>

HFT

Reflective option is also considered (see Yutaro’s talk)
Enhanced HFT example

Reflective option is also considered

European consortium takes lead to make a decision.
Enhanced HFT* and foreground removal

- 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 $r \sim 0.0004 \pm 0.0005$ (ell $\geq 2$)
- Complicating the sky (spatial variations on nside=32 with synchrotron curvature) leads to $r = 0.0007 \pm 0.0007$ (ell $\geq 2$)
  - Synchrotron curvature leads to a larger bias if not fitted for in the modeling

*The design used in this study is different from the example I showed in this talk, though the performance should be similar.
3. Project
Basic Japanese Vision for 2020’s

Essentially the same vision I had in 2008, when Europe was focusing on Planck.

** Powerful Duo

JAXA-led focused mission

\[ \sigma(r) < 0.001 \]
\[ 2 \leq \ell \leq 200 \]

focused but still with many byproducts

US-led telescopes on ground

\[ 30 \leq \ell \leq 3000\text{-}10000 \]
e.g. Simons Observatory and CMB-S4

- This powerful duo is the best cost-effective way.
- Great synergy with two projects
  - Foreground data from LiteBIRD, Delensing with CMB-S4 data
Past and Near Future

Japanese fiscal year (JFY, April 1 – Mar 31)

FY2014

Feb. 2015: Applied to the strategic L-class mission. MDR (by the Advisory Committee for Space Science).

FY2015

June 2015: Recommendation to ISAS by ACSS in the 2nd priority.
Sep. 2015: Planning review was recommended by the ISAS selection committee.

May 2016: International review
Aug. 2016: ISAS planning review

FY2016

A1a
A1b
A1c

Phase A1: Sep 2016 – Aug. 2018
Phase A1a: Sep 2016 – Mar. 2017
Phase A1c: Sep. 2017 – Aug. 2018

FY2017

Down-selection (Solar power sail, new candidate)

FY2018

Project Readiness Review (ISAS level & JAXA level)

FY2019

System Requirement Review
Current Status

• A serious candidate for the Strategic L-class slot in middle 2020’s.
  – One of the two missions selected for Phase-A1 study (The other is Solar-Power-Sail Trojan mission).
  – Phase-A1 studies started in September 2016 and will continue to August 2018 (24 months). Down-selection for the slot is then expected after that.
  – Progress in key technology development was shown in the LB phase A1 Interim review in April, 2017.
“Current Status of LiteBIRD in JAXA” by Toru Yamada
(Former ISAS Director of International Strategy and Coordination)
Endorsements for LiteBIRD in Japan

• MEXT roadmap 2017 (August 2017)
  – proposed by Japanese Radio Astronomy community
  – endorsed by Japanese HEP community
  – LiteBIRD is selected as one of 7 new large-scale projects

• JAXA roadmap
  – Probing inflation from B-mode listed as one of top scientific objectives

• JAXA prefers focused missions for strategic large mission program. LiteBIRD is exactly a focused mission.

LiteBIRD is very well endorsed!
ISAS/JAXA Phase-A1

Purpose: Risk mitigation through front-loading

Traded mission instruments should be raised to 4 or 5.
- **TRL4**: Breadboard model validation (in laboratory environment)
- **TRL5**: Engineering model validation (in relevant environment)

Study Items in phase A1

- **Mission Requirements**
  - Revision of the requirements to the mission instruments
- **Mission Instruments** (TRL increase, conceptual design)
  - Polarization Modulator
  - Thermal and mechanical studies
  - Heat load to the mechanical coolers
- **System requirements**
  - Requirements to the service module and conceptual design of the satellite
- **Test and calibration plan**
- **Task share and interfaces among the international partners.**
# ISAS/JAXA Phase-A1 Plan

**LiteBIRD**

<table>
<thead>
<tr>
<th>Phase</th>
<th>FY2016</th>
<th>FY2017</th>
<th>FY2018</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1a</td>
<td>Q3</td>
<td>Q1</td>
<td>Q1</td>
</tr>
<tr>
<td></td>
<td>Q4</td>
<td>Q2</td>
<td>Q2</td>
</tr>
<tr>
<td>A1b</td>
<td></td>
<td>Q3</td>
<td>Q4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Q1</td>
<td>Q1</td>
</tr>
<tr>
<td>A1c</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Development of the half wave plate**

- Design BBM PM
  - PM trade-off
  - Freq. assignment LFT & HFT
  - Mirror & optical bench material
  - Cooling system
  - Scan strategy

- Test plan of the mission instruments

**“FY” = Japanese Fiscal Year (April – March)**

- Produce a real-size BBM PM (polarization modulator), perform mechanical and thermal performance tests
- Conceptual design of the mission instr.
- Define the requirements to the bus system
- Conceptual design of the bus system
- Design test facilities
- Room-temp electronics
- Draft ICD

T. Dotani
**LiteBIRD** Development in Japan

### Keys to the success and Phase-A1 goals
- Successful R&D on critical payload components
  - Polarization modulator (achieving TRL5)
  - Thermal design
- Sufficient systematics and foreground mitigations
  - Thorough studies by Joint Study Group
- Sufficient calibration strategy and AIV plan
- Reliable cost estimation
- Clear international interfaces

### Thermal design
- Passive cooling
  - 200K shield
  - 100K shield
  - 30K shield
  - 100K shield

### AIV plan
- JAXA 6-m diameter space chamber

### Polarization modulator
- \( \Phi 400 \text{mm} \) flight representative demonstration model
- \( \Phi \sim 1 \text{m} \) 4K cryostat
- Gripper Mechanism
- Cryogenic Synchronous Motor
  - Encoding System

### Anti-Reflection (AR)
- Achromatic HWP (AHWP)

### Mitigation of 1/f noise differential systematics

### JAXA ST/JT coolers
- Passive cooling
  - 4.8K JT
  - 4.8K JT
  - sub-K
  - LF-FP
  - HFT
  - LFT

### JAXA ST/JT coolers
- \( \Phi 2.4 \text{m} \)
International collaboration for LiteBIRD

Provisional task sharing

- Japan: LFT, HWP, precoolers, spacecraft, launch, operation
- US: Focal-plane units for LFT and HFT, cold readout
- Canada: warm readout (DfMUX)
- **Europe:** HFT, Sub-K cooler
- All: Data analysis and scientific exploitation

Teams and supports from space agencies

- US team (led by A. Lee) is supported by NASA for technology development.
- Canadian Space Agency (CSA) supported warm readout technology development by McGill group. CSA issued (July 17, 2017) a Request for Proposals (RFP) to conduct a (Canadian) contribution study for the LiteBIRD mission.
- European LiteBIRD consortium is organized. Some of members are already registered as LiteBIRD external collaborators.

Joint Study Group has been formed between LiteBIRD Phase A team and external collaborators. Studies on foreground, systematics, calibration and HFT ongoing.
The Japanese LiteBIRD team members have 10 years of collaboration with the US team members on ground-based telescopes and LiteBIRD.

Expected U.S. deliverables:
- Focal Plane Units (FPUs)
- Cryogenic readout

U.S. status.plan:
- Technology development supported by NAXA explorer
- Goal: Advance TRL of focal-plane and cryogenic readout
- 2018 Mission of Opportunity preproposal
- 2020 Concept Study Report (CSR)
- 2021 Phase B Start

HF-FPU:
- Sky side
- Launch lock
- 260 mm

HF Module:
- 120 mm
- Sky side
- Readout side

LF Module:
- Readout side
- Sky side
- 100 mm

MF Module:
- Readout side
- Sky side
- 100 mm

SQUID Amplifiers:
- 150 mm

HF = High Frequency, MF = Mid Frequency, LF = Low Frequency
Canadian group formation

Mission Contribution Study

Canadian Space Agency Mission Contribution Study for LiteBIRD submitted Sept 21, 2017
• Collaboration with Honeywell/COM DEV
• 7 month study started Jan 2018
• Develop plan for DSP motherboard: FPGA or ASIC
• Study and cost complete Canadian LiteBIRD contribution.
• Interface definition.
  • Plan two trips to Japan.
• Requirements flow down to readout system.

Proposal for development of Canadian Science Team also submitted recently
Expected major deliverables:
• High-Frequency Telescope (HFT)
• Sub-K cooling system

And strong role in data analysis

Discussions b/w JAXA and space agencies in Europe are ongoing

ASI: committed to Phase A
ESA: starting joint studies on mission payload
Baseline 2016

- **CEA Sub-Kelvin Cooler**
  - Experience from SPICA-SAFARI instrument
- **Two temperature stages**
  - 300 mK He-3 sorption stage
  - 100 mK ADR (CPA) stage
- 25 hour hold time, 89% duty cycle
- Vibration: 21g rms 120g static

European consortium will carry out tradeoff studies b/w Baseline 2016 system and Closed-Cycle Dilution Refrigerator (CCDR)
4. Outcome
Outcome of LiteBIRD

• System requirements are determined from the focused mission of LiteBIRD.

• LiteBIRD will produce lots of science results (collectively called “outcome”) thanks to its great precision.

• These science results however should have no influence on system requirements.

• In this way, LiteBIRD will keep system requirements simple, and make great outcome at the same time.

Success Criteria

• $\sigma(r) < 0.001$ (for $r=0$)
• $2 \leq \ell \leq 200$

System Requirements

Outcome

• Full & Extra Success
• Lots of other science results ($\tau$, neutrino mass, pol. non-Gaussianity/bispectra, foreground science, etc.)
Scientific outcome examples (1)

1) $C_l^{BB}$
   - inflation and quantum gravity $(r, n_t)$
   - improvement w/ delensing
   - lensing B-mode to very low $l$

2) $C_l^{EE}$
   - reionization history
   - better $\tau$ and sum of neutrino masses

Error on $n_t \sim 0.04$ is possible
Scientific outcome examples (2)

3) Power spectrum deviation from $\Lambda$CDM
   - parity violation in gravity
   - quantum loop gravity
   - primordial magnetic field
   - new source fields for gravitational waves

4) Bi-spectrum (BBB etc.)
   - tensor non-Gaussianity
   - origin of gravitational waves
Scientific shopping list (3)

5) Non-standard patterns (e.g. bubbles) in the maps
   → e.g. multiverse

6) Foreground science

7) Galactic magnetic field (in particular at large galactic attitudes)

8) Legacy all-sky multi-frequency maps of E-mode/B-mode/Foregrounds
   → various astronomical studies
Discovery impact on cosmology and fundamental physics

• Direct evidence for cosmic inflation

• GUT-scale physics

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

V: Inflaton potential
r: tensor-to-scalar ratio \( \leftrightarrow \) proportional to the B-mode power

• Arguably the first observation of quantum fluctuation of space-time!
  • Observational tests of quantum gravity!
In case of discovery, what can happen?

1. Find a correct inflation model in the \((r, n_s)\) plane
2. Find no inflation model in the \((r, n_s)\) plane
3. Establish Large field variation \((\Delta \phi > m_P)\) and significantly constrain theories of quantum gravity such as superstring theories

Any of the cases above is extremely exciting!


About predictions on $r$

- Many models predict $r > 0.01 \rightarrow >10\sigma$ discovery if $\sigma(r) < 0.001$

- More general (less model-dependent) prediction
  - Focus on the simplest models based on Occam’s razor principle.
  - Single field models that satisfy slow-roll conditions give
    
    \[
    r \simeq 0.002 \left( \frac{60}{N} \right)^2 \left( \frac{\Delta \phi}{m_{pl}} \right)^2
    \]
    
    Lyth relation $r \simeq 0.002 \left( \frac{60}{N} \right)^2 \left( \frac{\Delta \phi}{m_{pl}} \right)^2 \quad N$: e-folding
    
    $m_{pl}$: reduced Planck mass

  - Thus, large-field variation ($\Delta \phi > m_{pl}$), which is well-motivated phenomenologically, leads to $r > 0.002$.
    - Model-dependent exercises come to the same conclusion (w/ very small exceptions).
  - Detection of $r > 0.002$ establishes large-field variation (Lyth bound).
    - Significant impact on superstring theory that faces difficulty in dealing with $\Delta \phi > m_{pl}$
  - Ruling out large-field variation is also a significant contribution to cosmology and fundamental physics.

\[ \rightarrow \sigma(r) < 0.001 \text{ is needed to rule out large field models that satisfy the Lyth relation with >95\%C.L.} \]
If evidence is found before launch

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

$$\sigma(r) < 0.001 \text{ for } 2 \leq \ell \leq 200$$ is what we need to achieve in any case to set the future course of cosmology.

No-Lose Theorem of LiteBIRD
Delensing: Synergy w/ SKA radio galaxy survey

Namikawa, Yamauchi, Sherwin, Nagata, Phys. Rev. D93 (2016) 043527

![Graph showing improvement factor vs. sensitivity for different SKA configurations](image-url)
Gravitational lensing potential reconstruction w/ radio galaxies as mass tracer

SKA radio continuum survey

- Number density of galaxies from diffuse (continuum) radio survey using synchrotron radiation from galaxies
- Mapping over 30000 deg^2 up to high z (z ≤ 3~6) w/o effects of foregrounds (dust etc.). 10^8~9 galaxies expected to be detected

CMB gravitational lensing

Galaxy distribution for each z ⇒ matter density fluctuation at each z ⇒ Gravitational potential responsible for lensing at each z

- Most of lensing CMB B-mode reconstructable thanks to the capability of accessing high z
- Efficient delensing leads to better sensitivity on primordial B-mode
τ (optical depth) and neutrino mass

- Better E-mode measurement for $\ell < 20$ improves $\tau$
- Better $\tau$ improves $\Sigma m_\nu$
- $\Sigma m_\nu > 58 \text{meV}$ from oscillation measurements

Low $\ell$ measurements contribute to $\Sigma m_\nu$!
Origin of gravitational waves


Vacuum fluctuation vs. Source fields

Observation of $l < 10$ is required to distinguish between two. At LiteBIRD, this can be done easily.

Moreover, B-mode bi-spectrum ("BBB") is also used to detect source-field-originating non-Gaussianity at $>3\sigma$.

"Pseudoscalar model" from Namba, Peloso, Shiraishi, Sorbo, Unal, arXiv1509.07521 as an "evil example model"; indistinguishable w/ BB for $ell > 10$ alone.
Separation power w/ “BB”

\[
\chi^2_{BB}(r) = \sum_{\ell=\ell_{\text{min}}}^{\ell_{\text{max}}} \frac{2\ell + 1}{2} \left( \frac{C^{BB}_\ell(r) - C^{BB}_\ell(P)}{C^{BB}_\ell(r) + N^{BB}_\ell} \right)^2
\]

reduced \(\chi^2\)

\[
\chi^2_{BB}/(l_{\text{max}} - l_{\text{min}}) = 1.1
\]

Simple-minded \(\chi^2\) does not work.
Separation w/ B-mode bispectrum
“BBB”

Parity-violating B-mode non-Gaussianity arises in the pseudoscalar model we consider here. ⇒ sizable BBB signal

If the pseudoscalar model is the correct model, can the vacuum fluctuation hypothesis be ruled out?

\[
\chi^2_{BBB}(r) = \sum_{\ell_1, \ell_2, \ell_3 = \ell_{\text{min}}}^{\ell_{\text{max}}} \frac{\left| B_{\ell_1 \ell_2 \ell_3}(P) \right|^2}{6 \prod_{n=1}^{3} \left( C_{\ell_n}(V)(r) + N_{\ell_n}^{BBB} \right)}
\]

\[
= \frac{13}{\text{LiteBIRD}} \Rightarrow 3.6\sigma \text{ rejection!}
\]

Checking “BBB” is MUST-DO when the primordial B-mode is discovered.
Remarks

• $l_{\text{max}} = 100$ saturates the BBB sensitivity
• $l_{\text{min}} = 30 \rightarrow$ rejection significance is $1.9\sigma$, which is not sufficient.

\[ \rightarrow \text{LiteBIRD is an ideal tool to investigate B-mode bispectrum, in particular BBB.} \]

• The pseudoscalar model we consider here also produce TB, EB signals. Sensitivity is however reduced due to cosmic variance. Angle calibration w/ EB also complicates the analysis.
Spectral distortion derivatives?

Assessment at LiteBIRD in preparation

arXiv:1801.05120
**Summary**

**Scientific objectives**

- A definitive search for the CMB B-mode polarization from cosmic inflation
  - Either making a discovery or ruling out well-motivated large-field models
  - The discovery will be the first compelling evidence for gravitational waves from quantum origin
  - Full success: \( \delta r < 0.001 \) (\( \delta r \): the total uncertainty on the tensor-to-scalar ratio, which is a fundamental cosmology parameter related to the power of primordial gravitational waves)
  - Giving insight into the quantum nature of gravity and other new physics

**Observations**

- 3-year surveys in L2 at deg. scales (~30’ @ 150 GHz)
- 15 bands b/w 34 GHz and 448 GHz

**System overview**

- Two telescopes (LFT and HFT)
  - Polarization modulator on each telescope
  - Powerful foreground removal w/ 15 bands
  - Cooling chain to provide 0.1K base temp.

**International collaboration**

- Japan: LFT, HWP, precoolers, spacecraft, launch, operation
- US: Focal-plane units for LFT and HFT, cryogenic readout
- Canada: warm readout (DfMUX)
- Europe: HFT, Sub-K cooler
- All: Data analysis and scientific exploitation

**Project status/plan**

- Final selection in JFY 2018
- Launch in mid. 2020’s w/ JAXA H3