Future missions on CMB polarization: LiteBIRD

Masashi Hazumi
(KEK / Kavli IPMU / SOKENDAI)

Xith Rencontres Du Vietnam
Cosmology
50 Years After CMB Discovery
Physics of primordial CMB B-mode

• 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

• Arguably the first observation of quantum fluctuation of space-time!
Limits on $r$ as of August 20, 2015

- Planck Temperature: $r < 0.11$ (95\% C.L.)
- "BKP" Polarization: $r < 0.12$ (95\% C.L.)
- Combined: $r < 0.09$ (95\% C.L.)
Yuji Chinone

$\frac{l(l+1)C_{\ell}BB}{2\pi} (\mu K^2)$

$r=0.01$

Multipole Moment, $\ell$

2015/08/20

50 Years After CMB Discovery

Qui Nhon, Vietnam

Masashi Hazumi (KEK/Kavli IPMU)
What do we need next?

1. Larger sky area  
   (BICEP2 already sample-variance limited)
2. More frequencies for foreground separation
3. More precise measurements of lensing B mode

Good News:  
Powerful ground-based and balloon projects in next ~5 years  
\( \Rightarrow \) Error on \( r \sim 0.01 \) is the goal
B-mode projects in next 5 years

**Ground**
- ACTPol → Advanced ACTPol
- POLARBEAR → Simons Array
- In addition, ABS, CLASS
- SPTPol → SPT3G
- BICEP1, BICEP2, BICEP3
- DASI QUAD KECK
- In addition, QUIJOTE in Canary island, GroundBIRD in Chile or Canary island, AMiBA in Hawaii
- Atacama, Chile

**Balloon**
- EBEX → EBEX6K
- SPIDER
- LSPE
- PIPER
- In addition, QUBIC at Dome C
In 2020s

Space!
Why in space? - Clear limitations on ground

- Frequency bands are limited → foreground rejection capability is limited
  - Lines due to $\text{O}_2$ and $\text{H}_2\text{O}$ need to be avoided
  - High frequencies (e.g. 353GHz that Planck relies on for foreground removal) are hard to access
- Atmosphere is nuisance. Not only giving additional noise but may produce polarized signals at the level we want to reach.
- Hard to access very low multipoles

All the issues above do not exist in space.
John Ruhl
(CM@50 Princeton, June 2015)
Balloon experiments also suffer from O2 in 60GHz region
Why targeting $\sigma(r) < 0.001$ ?

• Many models predict $r > 0.01 \Rightarrow >10\sigma$ discovery. What if we do not see the signal?

• Single field models that satisfy slow-roll conditions give

$$r \approx 0.002 \left( \frac{60}{N} \right)^2 \left( \frac{\Delta \phi}{m_{pl}} \right)^2$$

$N$: e-folding, $m_{pl}$: reduced Planck mass

• Establishing a bound $r < 0.002$ (95\%C.L.) will rule out large field models
  – More model-dependent studies come to the same conclusion
Past Proposals

- **EPIC-IM (2010)**
  - Proposed for Astro2010: US Astronomy and Astrophysics Decadal Survey

- **PRISM (2013)**
  - Proposed as an ESA L-class (L2/L3) mission

- **COrE+ (2015)**
  - Proposed as an ESA M-class (M4) mission

Science was rated very high. Not selected mainly from program-level considerations
Current Situation

• **LiteBIRD**
  • Proposal submitted to JAXA for JFY2022 launch
  • Passed initial down-selection by JAXA/ISAS (June 2015), in transition to phase-A studies
  • US participation proposal for NASA MO also passed initial down-selection (July 2015), starting phase-A studies

• **PIXIE**
  • NASA small PI-led mission proposal Feb 2011, not selected
  • Re-propose to next MIDEX AO (2017?)

• **Mission for ESA M5**
  • Proposal due next year
  • Planned launch date of 2029-2030
**PIXIE: Primordial Inflation Explorer**

**PI: Al Kogut (GSFC)**

Cryogenic instrument in low-Earth orbit
- 4 multi-moded detectors
- Entire instrument at 2.725 K
- Spin at 4 RPM to sample Stokes Q/U

**Scientific goals:**

- **B-mode:** $\sigma(r) < 2 \times 10^{-4}$
- **Distortion:** $|\mu| < 10^{-8}$, $|y| < 2 \times 10^{-9}$

Full-Sky Spectro-Polarimetric Survey
- 400 frequency channels, 30 GHz to 6 THz
  - 60 – 600 GHz for CMB w/ FG removal
- Stokes I, Q, U parameters
- 49152 sky pixels each $0.9^\circ \times 0.9^\circ$
- Pixel sensitivity $6 \times 10^{-26}$ W m$^{-2}$ sr$^{-1}$ Hz$^{-1}$
- CMB sensitivity 70 nk RMS per pixel

arXiv:1105.2044
Lite (Light) Satellite for the Studies of B-mode Polarization and Inflation from Cosmic Background Radiation Detection

• JAXA-based CMB B-mode satellite
• Target launch year: early 2020s
• Full success criteria
  – Total uncertainty on $r$: $\sigma(r) < 0.001^*$
  – Multipole coverage: $2 \leq \ell \leq 200$
• Orbit: L2
• Observing time: $\geq 3$ years

*Studies with our current design indicate better performance
LiteBIRD working group

121 members, international and interdisciplinary (as of June 20)

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

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

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

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

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

Saitama U.
M. Naruse

Nagoya U.
K. Ichiki

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

NICT
Y. Uzawa

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

Kansei Gakuin U.
S. Matsuura

RIKEN
S. Mima
C. Otani

APC Paris
U. Tsukuba
M. Nagai

TIT
S. Matsuoka
R. Chendra

CU Boulder
N. Halverson

McGill U.
M. Dobbs

MPA
E. Komatsu

NIST
G. Hilton
J. Hubmayr

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

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

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

JAXA engineers

IR astronomers

X-ray astrophysicists

CMB experimenters

Supercconducting detector developers

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LiteBIRD Instrument

- Mission module benefits from heritages of other missions (e.g. ASTRO-H) and proof-of-principle ground-based experiments (e.g. POLARBEAR).
- Bus module based on high TRL components

Multi-chroic focal plane detectors

<table>
<thead>
<tr>
<th>Solar array paddle</th>
<th>Bus module</th>
</tr>
</thead>
<tbody>
<tr>
<td>HGA: X band data transfer to the ground</td>
<td></td>
</tr>
</tbody>
</table>

Mission module

- Line of sight
- FOV 10 x 20 deg.
- 0.1 rpm spin rate
- 30 deg.

Cryogenics
- JT/ST and ADR (Astro-H heritage)

- Continuously-rotating half wave plate (HWP)

- Mirrors at 4K

Mission module benefits from heritages of other missions (e.g. ASTRO-H) and proof-of-principle ground-based experiments (e.g. POLARBEAR).

Bus module based on high TRL components

Cryogenics
- JT/ST and ADR (Astro-H heritage)
LiteBIRD focal plane baseline configuration

2022 TES bolometers
UC Berkeley TES option

tri-chroic (140/195/280GHz)

tri-chroic (60/78/100GHz)

6-band baseline design
→ 12 bands can be accommodated (with frequency overlap & w/ notch filters for CO-line rejection)

<table>
<thead>
<tr>
<th>Band (GHz)</th>
<th>Beam (arcmin)</th>
<th>NET (µK√s)</th>
<th>Pixels per wafer</th>
<th>Nwf</th>
<th>N_bolo</th>
<th>NET_arr (µK√s)</th>
<th>Sens. (µK/arcmin)</th>
<th>Sens. with Band margin (µK/arcmin)</th>
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</thead>
<tbody>
<tr>
<td>60</td>
<td>54.1</td>
<td>94</td>
<td>19</td>
<td>8</td>
<td>304</td>
<td>5.4</td>
<td>9.6</td>
<td>15.7</td>
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<tr>
<td>78</td>
<td>55.5</td>
<td>59</td>
<td>19</td>
<td>8</td>
<td>304</td>
<td>3.4</td>
<td>6.0</td>
<td>9.9</td>
</tr>
<tr>
<td>100</td>
<td>56.8</td>
<td>42</td>
<td>19</td>
<td>8</td>
<td>304</td>
<td>2.4</td>
<td>4.3</td>
<td>7.1</td>
</tr>
<tr>
<td>140</td>
<td>40.5</td>
<td>37</td>
<td>37</td>
<td>5</td>
<td>370</td>
<td>1.9</td>
<td>3.4</td>
<td>5.6</td>
</tr>
<tr>
<td>195</td>
<td>38.4</td>
<td>31</td>
<td>37</td>
<td>5</td>
<td>370</td>
<td>1.6</td>
<td>2.9</td>
<td>4.7</td>
</tr>
<tr>
<td>280</td>
<td>37.7</td>
<td>38</td>
<td>37</td>
<td>5</td>
<td>370</td>
<td>2.0</td>
<td>3.5</td>
<td>5.7</td>
</tr>
<tr>
<td>total</td>
<td>37.7</td>
<td>38</td>
<td>37</td>
<td>5</td>
<td>370</td>
<td>2.0</td>
<td>3.5</td>
<td>5.7</td>
</tr>
</tbody>
</table>

\( T_{bath} = 100 \text{mK} \)

Sinuous antenna

TESes

Triplexers
15 frequency bands can be accommodated with an additional horn-coupled array.
Scan strategy at L2

Precession angle $\alpha = 65^\circ$
~90 min.

Spin axis
Spin angle $\beta = 30^\circ$
0.1rpm

Anti-sun direction
Road to achieve the full success

\[ \sigma(r) < 0.001 \]

Observer bias as the 5th element \(\rightarrow\) mitigation by e.g. blind analyses
LiteBIRD systematic uncertainties

Requirements on major sources of uncertainties

<table>
<thead>
<tr>
<th></th>
<th>Diff. gain calibration</th>
<th>Diff. beam width</th>
<th>Diff. beam pointing</th>
<th>Diff. beam ellipticity</th>
<th>Pointing knowledge</th>
<th>Angle calibration</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\ell = 4$</td>
<td>0.003%</td>
<td>0.8%</td>
<td>4''</td>
<td>3%</td>
<td>8'</td>
<td>1'</td>
</tr>
<tr>
<td>$\ell = 80$</td>
<td>0.03%</td>
<td>0.6%</td>
<td>3''</td>
<td>0.1%</td>
<td>30'</td>
<td>10'</td>
</tr>
</tbody>
</table>

- L2 provides superior conditions for measuring faint B-mode fluctuations.
- HWP mitigates differential systematics greatly.
  - ABS experience $\rightarrow$ LiteBIRD requirements on systematic leakage are met except monopole. A constant and small monopole leakage can be compensated for during map making.
- E to B leakage due to satellite pointing is not mitigated by HWP, but it is not a problem. Expected pointing accuracy of 0.7’ is much better than the requirement.
- Absolute polarization angle is calibrated with E-B correlations with an expected accuracy of 1’.
σ(r) = 0.45 × 10^{-3}
for r = 0.01, including foreground removal*, cosmic variance and delensing w/ CIB**

r < 0.4 × 10^{-3}
(95% C.L.)
for undetectably small r

* Foreground residual estimation with Errard et al. 2011, Phys. Rev. D 84, 063005
  plus a new method (this proposal, another paper in preparation)

** "Delensing the CMB with the Cosmic Infrared Background", B. D. Sherwin, M. Schmittfull arXiv:1502.05356
LiteBIRD constraints on $r$ vs. $n_s$ plane
Three additional comments
(1) If evidence is found before launch

• $r$ is fairly large!
• 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 with high significance for each bump!
  – Deeper level of fundamental physics

$\sigma(r) < 0.001$ is what we need to achieve in any case to set the future course of cosmology

No-Lose Theorem of LiteBIRD
(2) Synergy

Satellite for ultimate $r$ meas.

$\sigma(r) < 0.001$

$2 \leq \ell \leq 200$

Telescope arrays on ground

$30 \leq \ell \leq \sim 3000$ e.g. CMB-S4

Powerful Duo
Complementarity of Observations

Frequency

Space

Balloon

Ground

300 GHz

30 GHz

10

1,000

\ell

10,000
(3) Beyond inflation

- LiteBIRD will provide the most precise whole-sky maps of B-mode and E-mode.
  - $C_l^{BB}$, $r$, $n_t$, ...
  - $C_l^{EE}$, bi-spectrum, tri-spectrum, ..
  - Deviations from standard power spectra (incl. $C_l^{EB}$)
  - Non-standard patterns (e.g. bubbles) in the maps
  - etc.

Bounce, Multiverse, Universe from Nothing

**Bold ideas from theorists are welcome!**
Summary

• CMB B-mode is the key to the direct confirmation of cosmic inflation and will shed light on quantum gravity

• Missions in 2020s are designed to achieve $\sigma(r) < 0.001$, 100 times better than the present limit.

• LiteBIRD passed initial down-selections of both JAXA and NASA, targeting launch in early 2020s.

• PIXIE proposal anticipated in 2017

• ESA M5 call is in consideration

Stay tuned!
From ground to space
LiteBIRD Roadmap

Predictions by representative inflationary models

r=0.001
r=0.01
r=0.1
r=1

2005  2010  2015  2020

Simons Array

GroundBIRD
QUIET
POLARBEAR

LiteBIRD

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ISAS/JAXA mission categories

*Space Policy Commission* under cabinet office intends to guarantee predetermined *steady annual budget* for space science and exploration for ISAS/JAXA to maintain its excellent scientific activities.

- **Strategic Large Missions (300M$ class)** for JAXA-led flagship science mission with HIIA vehicle (3 in ten years)

- **Competitively-chosen medium-sized focused missions (<150M$ class)** with Epsilon rocket (every 2 years)

- **Missions of opportunity (10M$ per year)** for foreign agency-led mission, sounding rocket, ISS

- **LiteBIRD**

  ✓

  ~2022

#3 Under selection

2016

ASTRO-H

ERG

JUICE
Project Timeline after MDR

5~6 years to launch

~1year

Down selection

New participants (e.g. from Asia, Europe)

Formal agreements with foreign agencies at this point

How do we have commitment and synchronization from international partners?

ISAS support

SE office’s project incubation function

ISAS reviews with steering committees of space science/engineering

Project life cycle review by ISAS

JAXA key decision points

SCSS

MDR

SRR

SDR

PDR

SCSS
LiteBIRD foreground subtraction exercise using a template method with 6 bands

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

<table>
<thead>
<tr>
<th>Band (GHz)</th>
<th>Sensitivity ($\mu K$ arcmin)</th>
</tr>
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<tbody>
<tr>
<td>60</td>
<td>10.3</td>
</tr>
<tr>
<td>78</td>
<td>6.5</td>
</tr>
<tr>
<td>100</td>
<td>4.7</td>
</tr>
<tr>
<td>140</td>
<td>3.7</td>
</tr>
<tr>
<td>195</td>
<td>3.1</td>
</tr>
<tr>
<td>280</td>
<td>3.8</td>
</tr>
<tr>
<td>Total</td>
<td>1.8 (2.9$^b$)</td>
</tr>
</tbody>
</table>

Method II: $\Delta$-template with uniform $\beta$ distribution
Method II': $\Delta$-template with a prior in $\beta$ distribution
Method III: iterative $\Delta$-template

Offset $0.3 \times 10^{-3}$ small enough

Katayama, Komatsu et al. in prep.
Expected sensitivity on $r$

with 2 effective years

Foreground residual

$\sigma_{fg}$

$\sum_{fg=S,D} C_{\ell}^{f_X Y} (\nu, \nu) + N_{fg,XY} (\nu, \nu_{sp})$

Expected sensitivity on $r$

Cosmic variance limited

Foreground residual

Lensing limited

katayama - komatsu

Cosmic variance limited

1$\sigma$

3$\sigma$

5$\sigma$

10$\sigma$

20$\sigma$

$F_{\ell} (\nu) = \sum_{fg=S,D}$
Launch Vehicle

LiteBIRD’s target launch year = 2021-2022

- 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

- H3
  - will be ready in 2020
  - ½ cost w/ same capability
    (comparison w/ H-II B)
Scan strategy

\[ \alpha + \beta \geq 90^\circ \text{ for full sky} \]

\[ \alpha + \beta \leq 95^\circ \text{ from thermal/optical requirements} \]

\( (\alpha, \beta) = (65^\circ, 30^\circ) \) chosen to minimize the effect of E to B leakage due to pointing bias

Good crosslink reduces pointing bias w/ multiple measurements
The cross-Dragone telescope provides the diffraction limited focal plane size of D=300mm. We employed the tri-chroic pixel using TES to optimize the focal plane configurations.

<table>
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</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>304</td>
<td>0.296</td>
<td>6.49</td>
<td>8.28</td>
<td>94.07</td>
<td>15.72</td>
</tr>
<tr>
<td>78</td>
<td>304</td>
<td>0.301</td>
<td>6.61</td>
<td>8.61</td>
<td>58.97</td>
<td>9.86</td>
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<tr>
<td>100</td>
<td>304</td>
<td>0.286</td>
<td>6.27</td>
<td>8.72</td>
<td>42.26</td>
<td>7.06</td>
</tr>
<tr>
<td>140</td>
<td>370</td>
<td>0.361</td>
<td>7.92</td>
<td>10.56</td>
<td>36.89</td>
<td>5.59</td>
</tr>
<tr>
<td>195</td>
<td>370</td>
<td>0.243</td>
<td>5.32</td>
<td>9.45</td>
<td>31.00</td>
<td>4.70</td>
</tr>
<tr>
<td>280</td>
<td>370</td>
<td>0.123</td>
<td>2.70</td>
<td>7.57</td>
<td>37.54</td>
<td>5.69</td>
</tr>
<tr>
<td>Combined</td>
<td>2022</td>
<td>2.70</td>
<td>2.70</td>
<td>7.57</td>
<td>37.54</td>
<td>5.69</td>
</tr>
</tbody>
</table>

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

- Sensitivity: Optical NEP = $2 \times 10^{-18}$ W/√Hz
- Broad frequency coverage: ~50 – 320 GHz
- Multi-pixel array: ~2000
- Low power consumption (< 100W total)
- Controlled sidelobe at a feed

Transition edge sensor (TES) bolometer
Example from POLARBEAR focal plane

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

PB-2
2 bands/pixel (95,150GHz)
7588 TESs (1897×2pol×2band)
Readout is DfMUX with MUX=40 by McGill Univ.

Microwave kinetic inductance detector (MKID)
Example of MKID from NAOJ.

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

More examples from JPL, SRON and others.

Z. Kermish Ph.D. thesis
UC Berkeley

High TRL by the use in various CMB experiments.
Need space qualified low loading TES and low power consumption readout.

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

Both TES and MKID are exposed to the proton beams (10 years eq. at L2). They are in the process of measuring the effect.