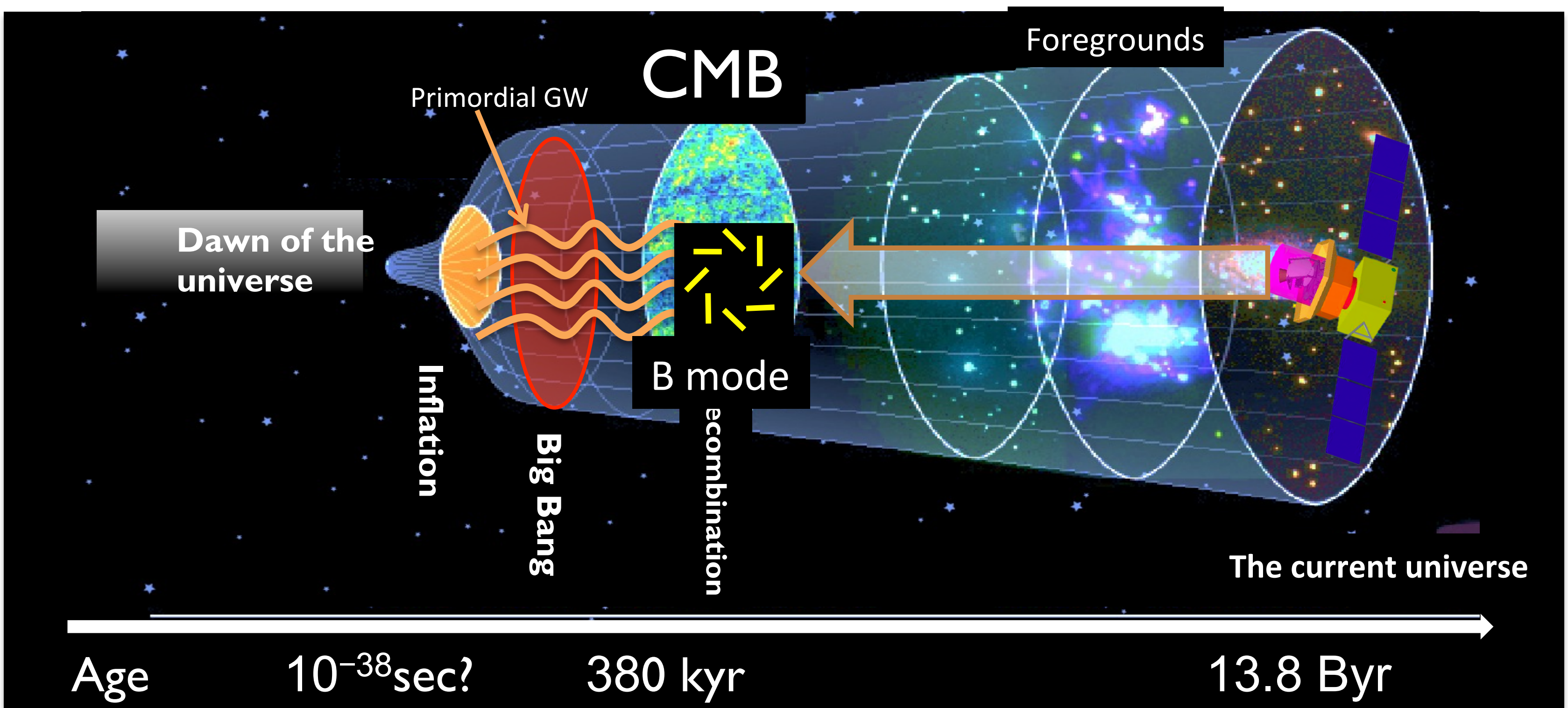
LiteBIRD 計画における系統誤差の研究

魚住聖, 石野宏和, 松村知岳[A], 羽澄昌史[B], 永田竜[B], 片山伸彦[C], 菅井肇[C], 岡山大理, JAXA/ISAS[A], 高工研[B], Kavli IPMU[C] 他LiteBIRD Working Group

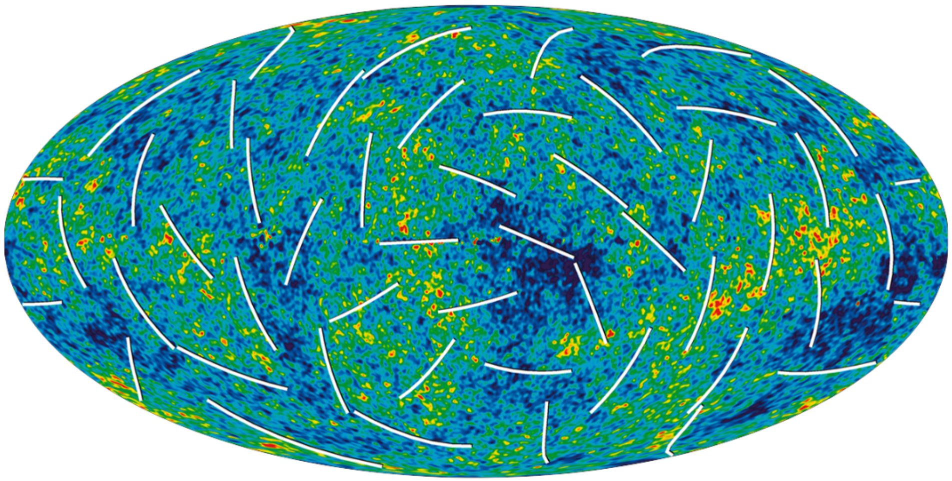
- インフレーションモデルと原始重力波からのBモードCMB偏光
- LiteBIRD計画の概要
- 測定系統誤差を抑えるためのscan strategyの研究

Goal： Verification of inflation using CMB

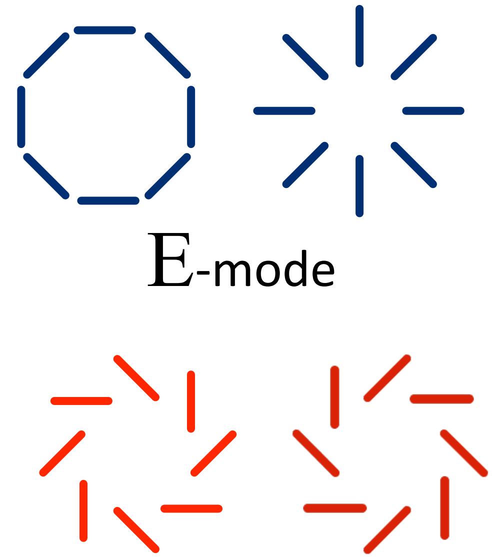
- Inflationary universe theory predicts generation of primordial gravitational waves.
- Primordial gravitational waves leave a large vortex-like patterns “inflation fingerprint” called B-mode on the CMB polarization map.
- LiteBIRD observes the CMB polarization by precisely scanning all sky in space.



Why the B-mode polarization?



Decompose the all-sky CMB polarization into two patterns



E-mode

B-mode

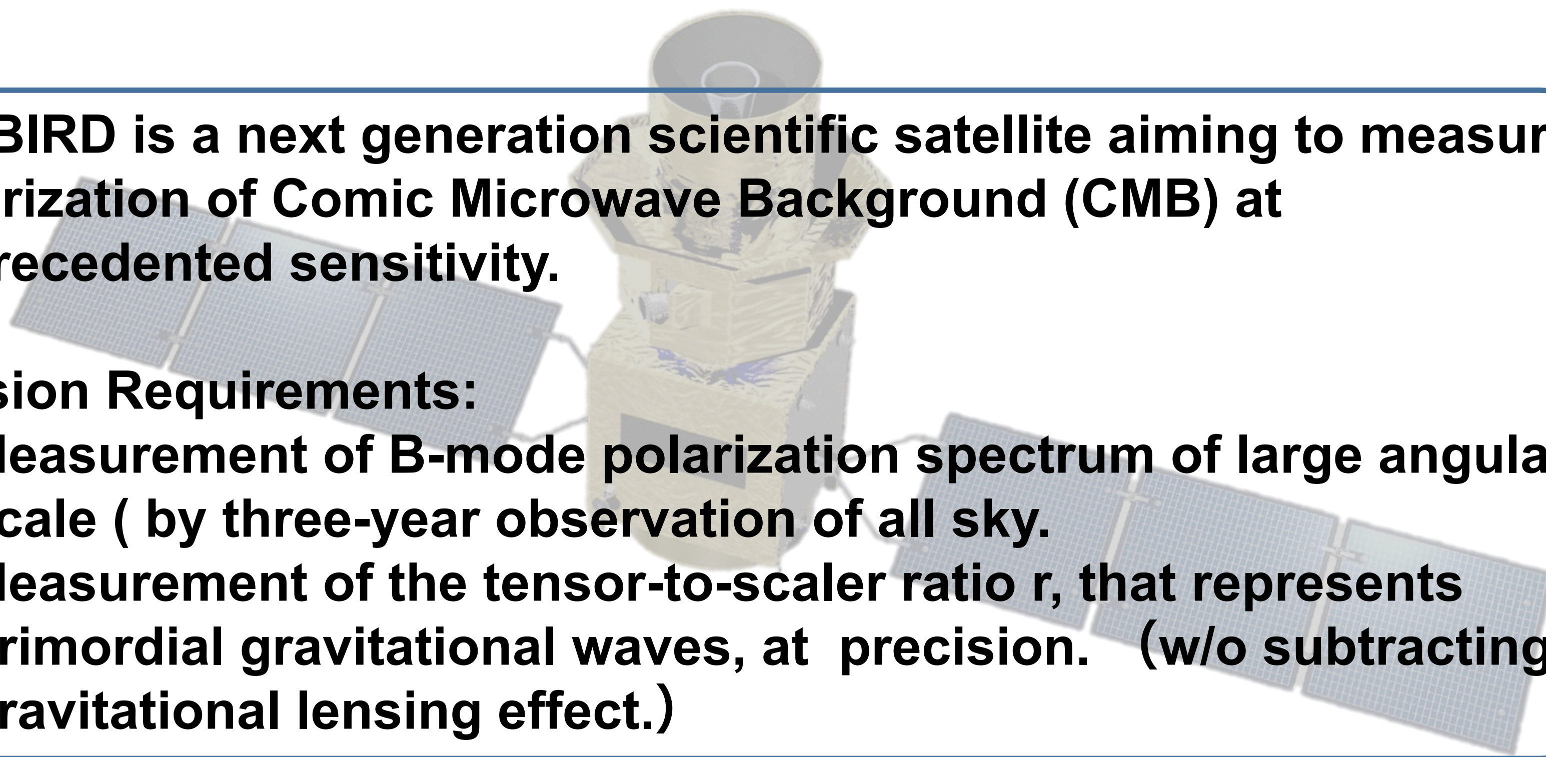
Density Fluctuations → E-mode (Dominant, discovered)

Primordial Gravitational Waves → E-mode + B-mode (Faint, undetected)

B-mode polarization makes it possible to probe primordial gravitational waves!

LiteBIRD

Lite (Light) Satellite for the studies of B-mode polarization and Inflation from cosmic background Radiation Detection (http://litebird.jp/)



LiteBIRD is a next generation scientific satellite aiming to measure polarization of Comic Microwave Background (CMB) at unprecedented sensitivity.

Mission Requirements:

- **Measurement of B-mode polarization spectrum of large angular scale (by three-year observation of all sky.**
- **Measurement of the tensor-to-scaler ratio r, that represents primordial gravitational waves, at precision.（w/o subtracting the gravitational lensing effect.）**

LiteBIRD working group

JAXA
T. Dotani
H. Fuke
H. Imada
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
S. Utsunomiya
T. Wada
R. Yamamoto
N. Yamasaki
T. Yoshida
K. Yotsumoto

Osaka U.
S. Kuromiya
M. Nakajima
S. Takakura
K. Takano

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

Okayama U.
T. Funaki
N. Hidehira
H. Ishino
A. Kibayashi
Y. Kida
K. Komatsu
S. Uozumi
Y. Yamada

NIFS
S. Takada

Kavli IPMU
K. Hattori
N. Katayama
Y. Sakurai
H. Sugai

KEK
M. Hazumi (PI)
M. Hasegawa
N. Kimura
K. Kohri
M. Maki
Y. Minami
T. Nagasaki
R. Nagata
H. Nishino
S. Oguri
T. Okamura
N. Sato
J. Suzuki
T. Suzuki
O. Tajima
T. Tomaru
M. Yoshida

Kansei Gakuin U.
S. Matsuura

Kitazato U.
T. Kawasaki

Konan U.
I. Ohta

NAOJ
A. Dominjon
T. Hasebe
J. Inatani
K. Karatsu
S. Kashima
T. Noguchi
Y. Sekimoto
M. Sekine

Saitama U.
M. Naruse

NICT
Y. Uzawa

SOKENDAI
Y. Akiba
Y. Inoue
H. Ishitsuka
Y. Segawa
S. Takatori
D. Tanabe
H. Watanabe

U. Tsukuba
M. Nagai

TIT
S. Matsuoka
R. Chendra

U. Tokyo
S. Sekiguchi
T. Shimizu
S. Shu
N. Tomita

Tohoku U.
M. Hattori

Nagoya U.
K. Ichiki

Yokohama Natl. U.
T. Fujino
F. Irie
H. Kanai
S. Nakamura
T. Yamashita

RIKEN
S. Mima
C. Otani

APC Paris
R. Stompor

Cardiff U.
G. Pisano

Paris ILP
J. Errard

CU Boulder
N. Halverson

McGill U.
M. Dobbs

MPA
E. Komatsu

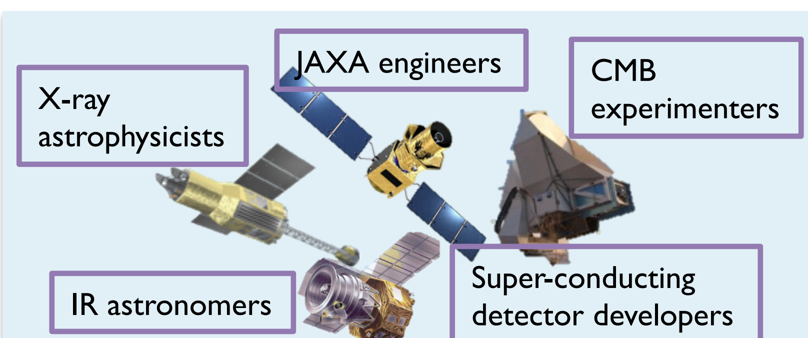
NIST
G. Hilton
J. Hubmayr

Stanford U.
S. Cho
K. Irwin
S. Kernasovskiy
C.-L. Kuo
D. Li
T. Namikawa
W. Ogburn
K. L. Thompson

U. Wisconsin
K. Arnold

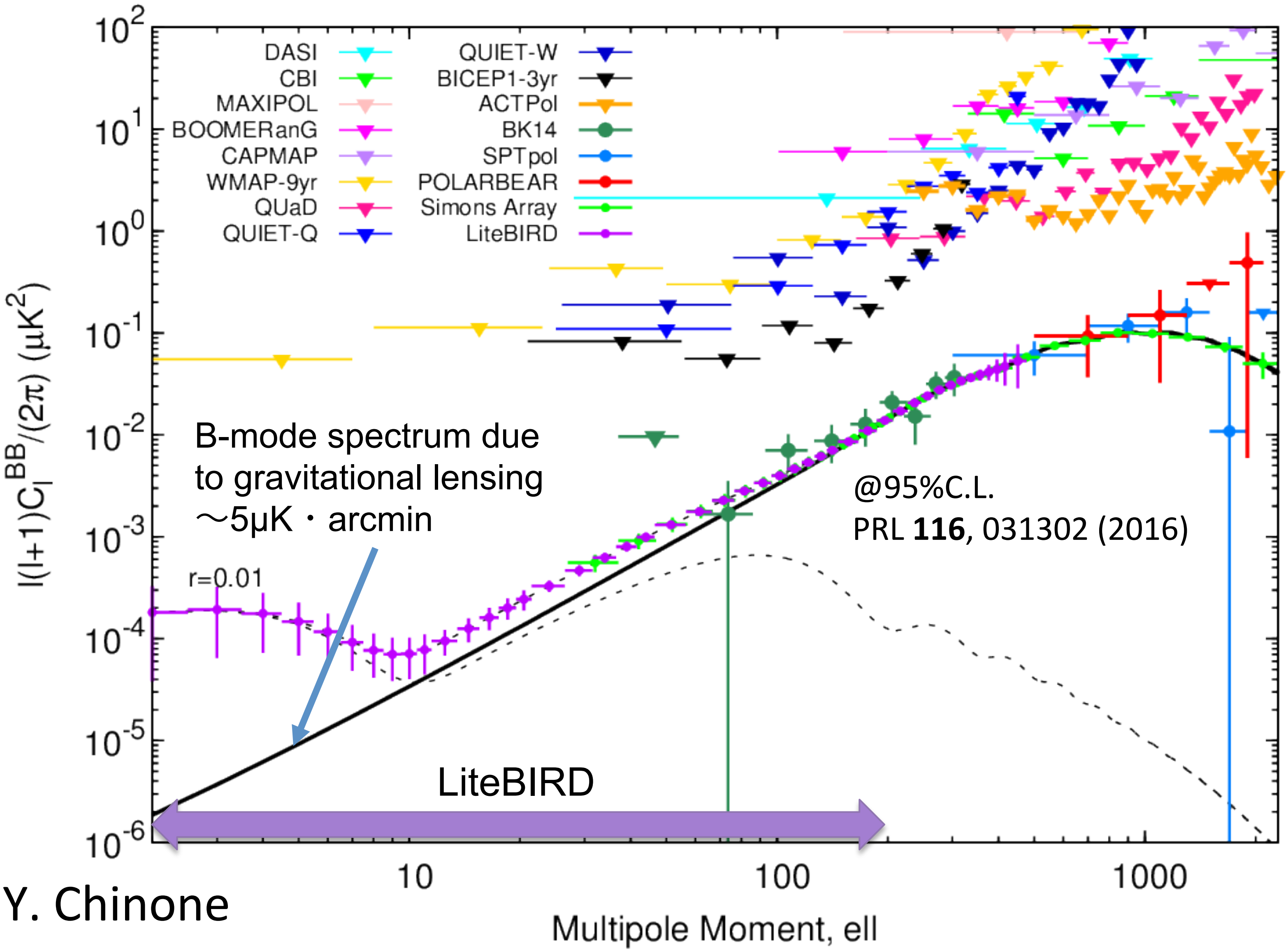
UC Berkeley / LBNL
D. Barron
J. Borrill
Y. Chinone
A. Cukierman
T. de Haan
N. Goeckner-wald
P. Harvey
C. Hill
W. Holzapfel
Y. Hori
O. Jeong
R. Keskitalo
T. Kisner
A. Kusaka
A. Lee(US PI)
E. Linder
P. Richards
U. Seljak
B. Sherwin
A. Suzuki
P. Turin
B. Westbrook
N. Whitehorn

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



139 members, international and interdisciplinary (as of Jun 27, 2016)

LiteBIRD Measurement Precision (at r=0.01)



Y. Chinone

Why the δr < 0.001 goal?

- Many models predict r>0.01. → Discovery at >10σ.
- In case primordial gravitational waves are not seen:
  - Focus on models with less parameters（Occam's Razor）
  - Most single field slow-roll says

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

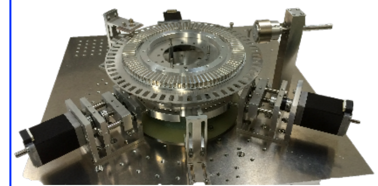
Lyth relation

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

  - If LiteBIRD achieves δr < 0.002 (95%C.L.), those that satisfy $\Delta\phi > m_{pl}$ in the typical inflation models are rejected.
    - Important milestone in the goal to identify the correct models.
    - Possible to obtain similar results in more model-dependent analyses.

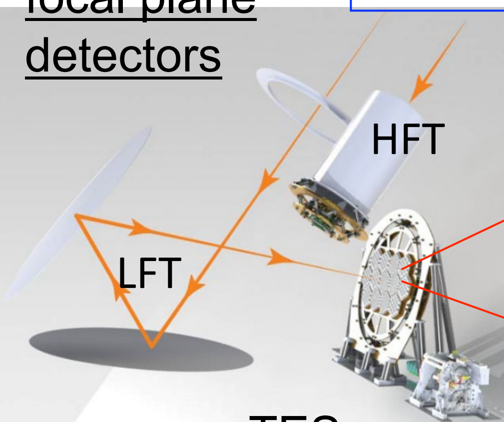
Observation Apparatus Overview

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



Continuously-rotating half wave plate (HWPs) for LFT and HFT

Multi-chroic focal plane detectors

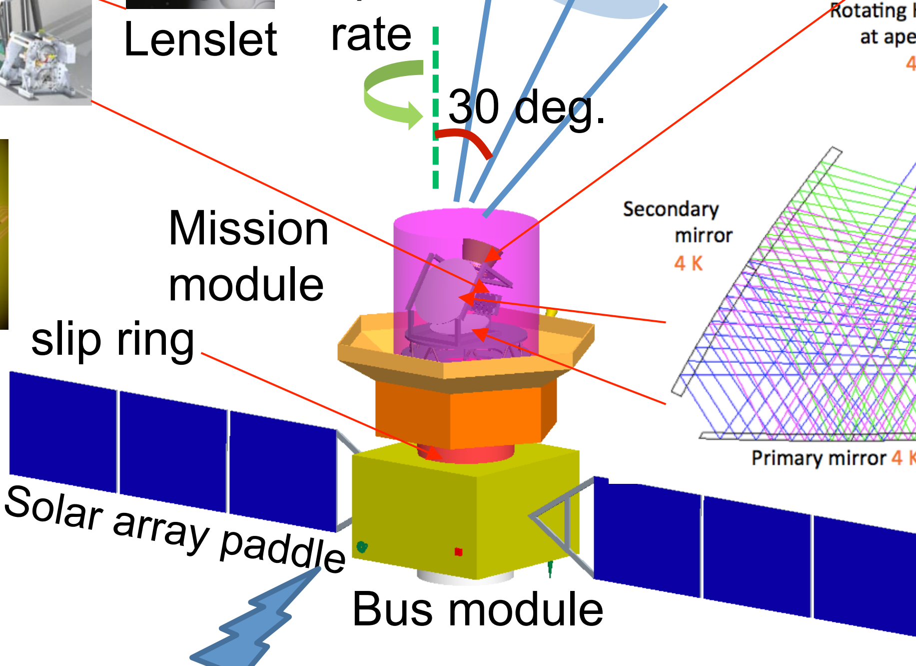


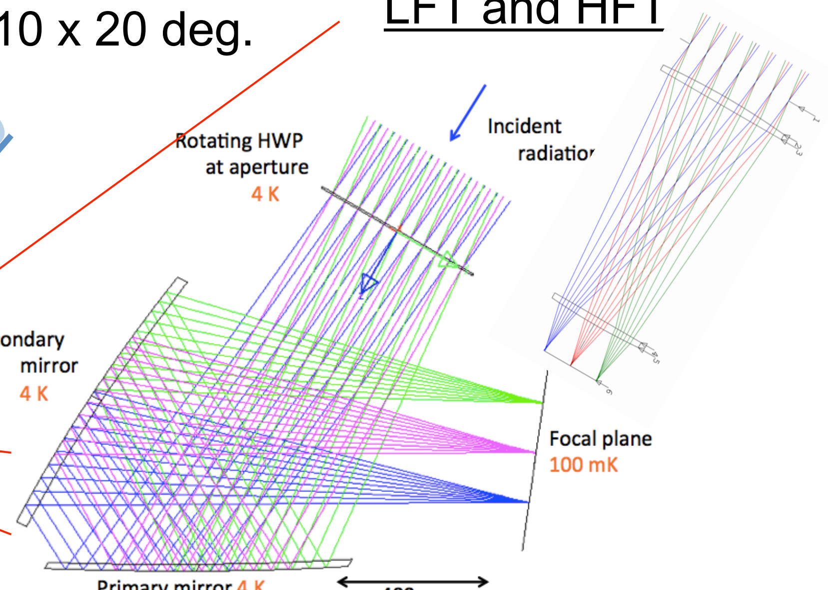
Lenslet

TES

Cryogenics

- JT/ST and ADR

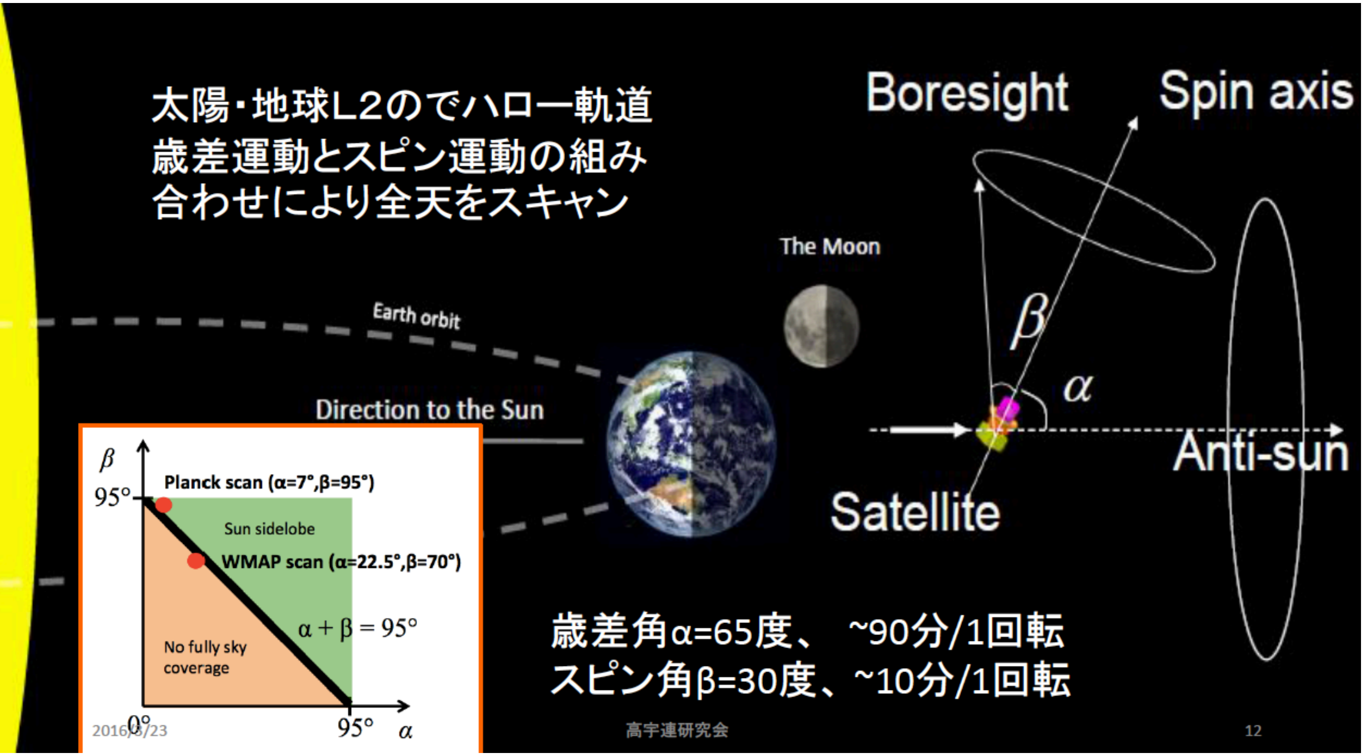




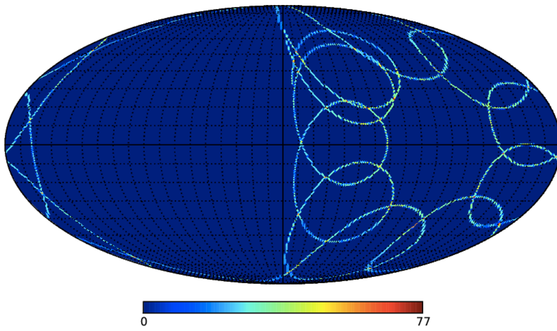
Mirrors at 4K

HGA: X band data transfer to the ground

Scan Strategy



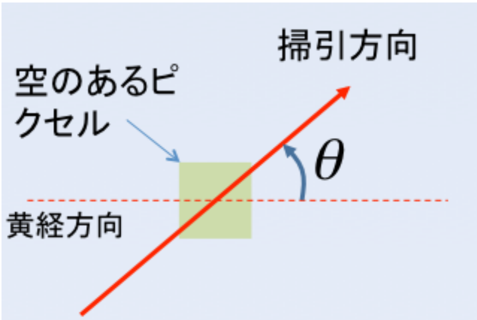
Scheme of the sky scan



- 地球-太陽軸に対して、歳差角α, スピン角βで回転する
- 全天スキャンからの条件：$\alpha+\beta>90^\circ$
- 太陽からの光流入を避けるための条件：$\alpha+\beta<95^\circ$
- 歳差時間・スピン回転数もある程度の自由度がある
- 半波長板無し（最悪のケース含む）を仮定して、Bモード偏光測定を最も有利にするパラメータセットは何か？

First important parameter :Cross-link

Vary α, β under condition $\alpha+\beta=95^o$, precession time=1.51 hrs, spin revolution rate=0.3 rpm



"Cross-link"

h_n = $<\cos n\theta>^2+<\sin n\theta>^2$

Relates to many systematic Uncertainties

Smaller h_n is Better!

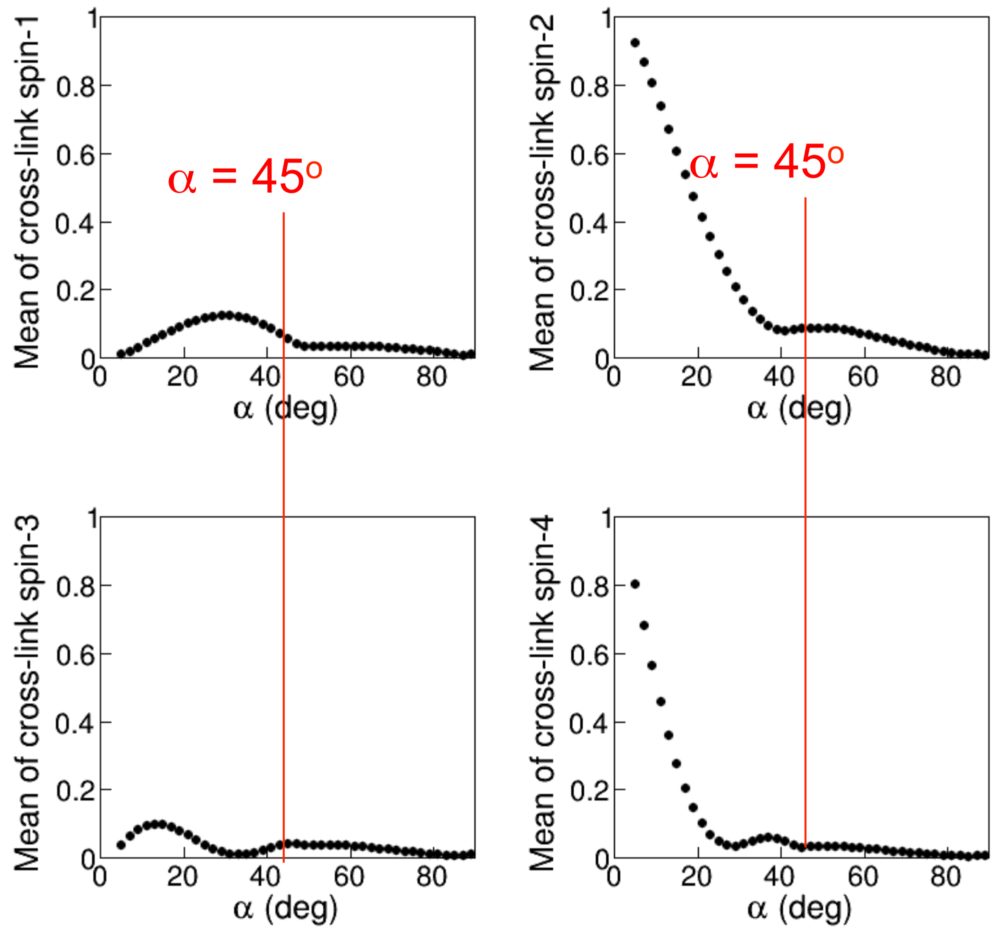
Temperature-to-Bmode leakage :

$$\Delta C_\ell^{BBg} = \frac{1}{8}\langle|\tilde{h}_2|^2\rangle\,|\delta g_1 + i\delta g_2|^2\, C_\ell^{TT}, \quad (26)$$

$$\Delta C_\ell^{BBp} = \frac{1}{32}\langle|\tilde{h}_1|^2\rangle\left|\rho_1 e^{i\chi_1} + \rho_2 e^{i(\chi_2+\pi/4)}\right|^2 \ell^2 C_\ell^{TT}, \quad (27)$$
$$+ \frac{1}{32}\langle|\tilde{h}_3|^2\rangle\left|\rho_1 e^{-i\chi_1} + \rho_2 e^{-i(\chi_2-3\pi/4)}\right|^2 \ell^2 C_\ell^{TT}$$

$$\Delta C_\ell^{BBe} = \frac{1}{4}\left|\Im\left[\frac{\delta b_{\ell 2}^1 + \delta b_{\ell 2}^2}{b_{\ell 0}}\right]\right|^2 C_\ell^{TT} \quad (28)$$
$$+\frac{1}{8}\langle|\tilde{h}_4|^2\rangle\left|\frac{\delta b_{\ell 2}^1 - \delta b_{\ell 2}^2}{b_{\ell 0}}\right|^2 C_\ell^{TT},$$

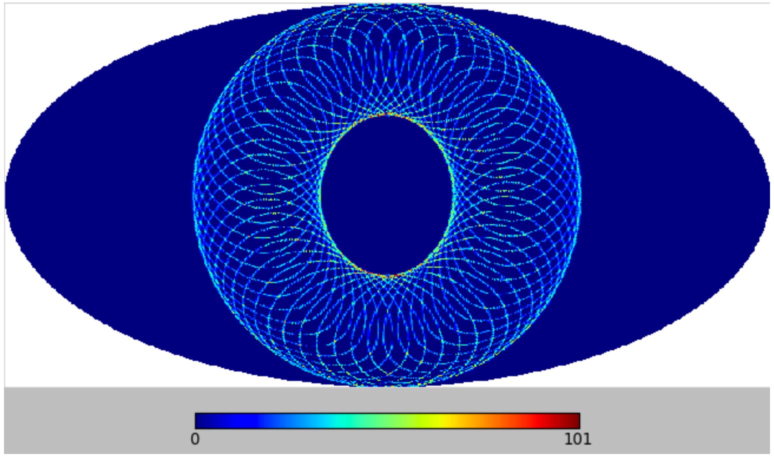
arXiv:1604.02290v1



$\alpha > 45^o$ seems to be OK concerning the cross-link.

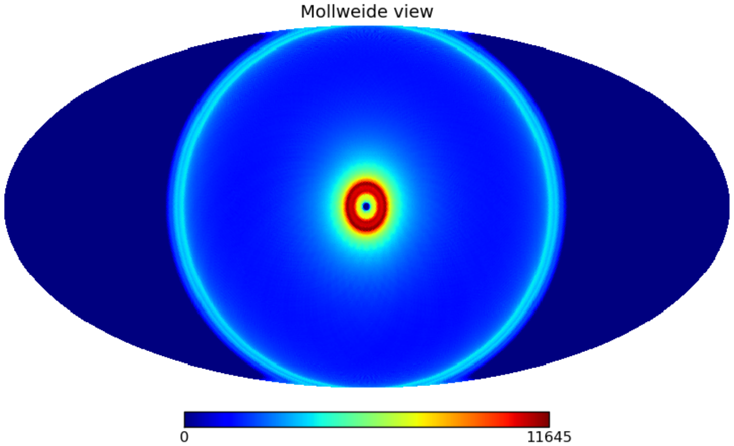
Two current candidates of (α,β)

Large-α (α>β) option
(current LiteBIRD nominal): hitmap



α=65°, β=30°, α+β=95°,
precession time=1.51 hrs,
spin revolution rate=0.1 rpm

Small-α (α<β) option :
hitmap



α=45°, β=50°, α+β=95°,
precession time=1.51 hrs,
spin revolution rate=0.1 rpm
Smaller hole (α~β)

- It is also important to consider "re-visit" to remove possible time-dependent effect
- Studies to decide the scan parameter is currently ongoing using realistic simulation & data analysis tools.

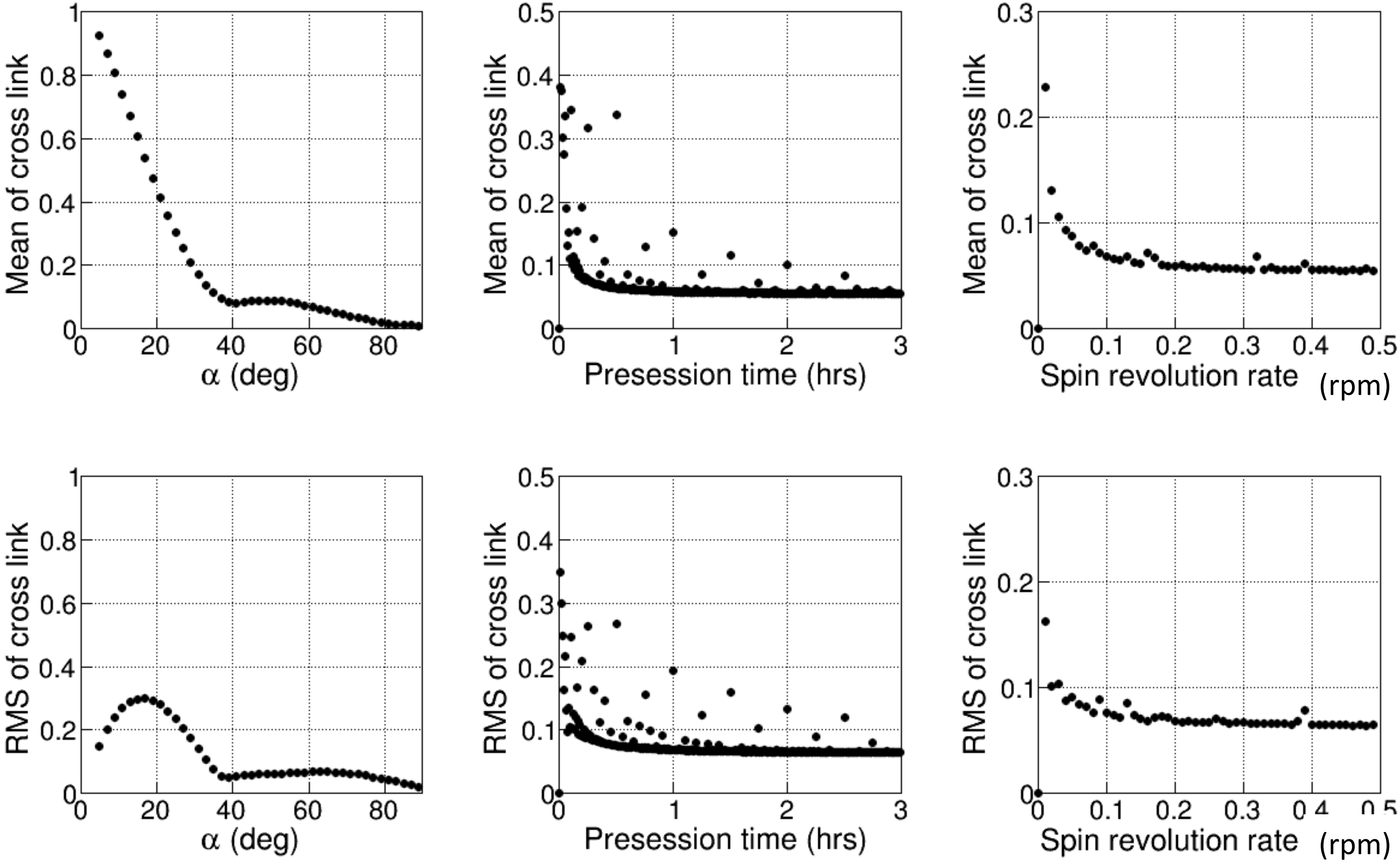
Summary

- The LiteBIRD is next-generation satellite project aiming to probe very early stage of the universe through measurement of the CMB B-mode polarization.
- It has sensitivity to scalar-tensor ratio of $\delta r<0.001$ which proves inflation scenario, and even identify right model in many inflation models.
- To eliminate systematic uncertainties, definition of certain scan strategy to suppress cross-link is important.
- There are also many factors (e.g. revisiting, satellite structure) which are affected by the scan strategy.
- Considering those factors, study for determination of scan strategy parameters is extensively ongoing.
- The scan strategy parameter will be settled soon (Sep~Oct).

Backups

spin-2 cross-link

(Nominal values : α=65°, β=30°, $\alpha+\beta$=95°, precession time=1.51 hrs, spin revolution rate=0.3r pm)



Symbol	Description	Value set to in relevant simulation
ψ	The orientation of the scan direction with respect to North	Varies with scan strategy, position and time
$\tilde{h}_n$	The average of the complex exponential of the orientations for a pixel, $\langle e^{in\psi}\rangle_{\rm hits}$	Varies with scan and pixel
FWHM	the full width at half the maximum of the beam	7 arcmin for all the simulations
δg_i	The differential gain between the two detectors in pair i	0.01 for both detector pairs
ρ_i	The angle between the two beam centres in pair i	0.1 arcmin for both (1.5% of the FWHM)
χ_i	The orientation of the second beam from the first in a detector pair i relative to the direction of the scan	0 and $\pi/4$
$b_{\ell m}$	The spherical harmonic decomposition of the temperature beam	That of an elliptical Gaussian — see equation (29)
$\delta b^i_{\ell m}$	The spherical harmonic decomposition of the difference of the temperature beams of pair i	That of an elliptical Gaussian — see equation (29)
q	Ellipticity parameter for the elliptical Gaussian beam. Note that $q = 1$ is axisymmetric (see equation 29). q is also the ratio of the major and minor axes of the ellipse.	1.05 and 1

Table 1. Description of the variables used in the analysis (see Sections 2 & 3 in the main text) and the values adopted for the simulations.

Scan	Boresight angle (β)	Precession angle (α)	Spin period ($T_{\rm spin}$)	Precession period ($T_{\rm prec}$)
Planck	85°	7.5°	1 min	6 months
WMAP	70°	22.5°	129 s	1 hr
EPIC	50°	45°	1 min	3 hrs

Table 2. Observational parameters used to generate the scan strategies for the simulations described in Section 3.

arXiv:1604.02290v1

Parameters/strategies which (may) need to be considered for the scan optimization

- All-sky scan($\alpha+\beta=95^{o}$)
- Cross-link
- Hit uniformity

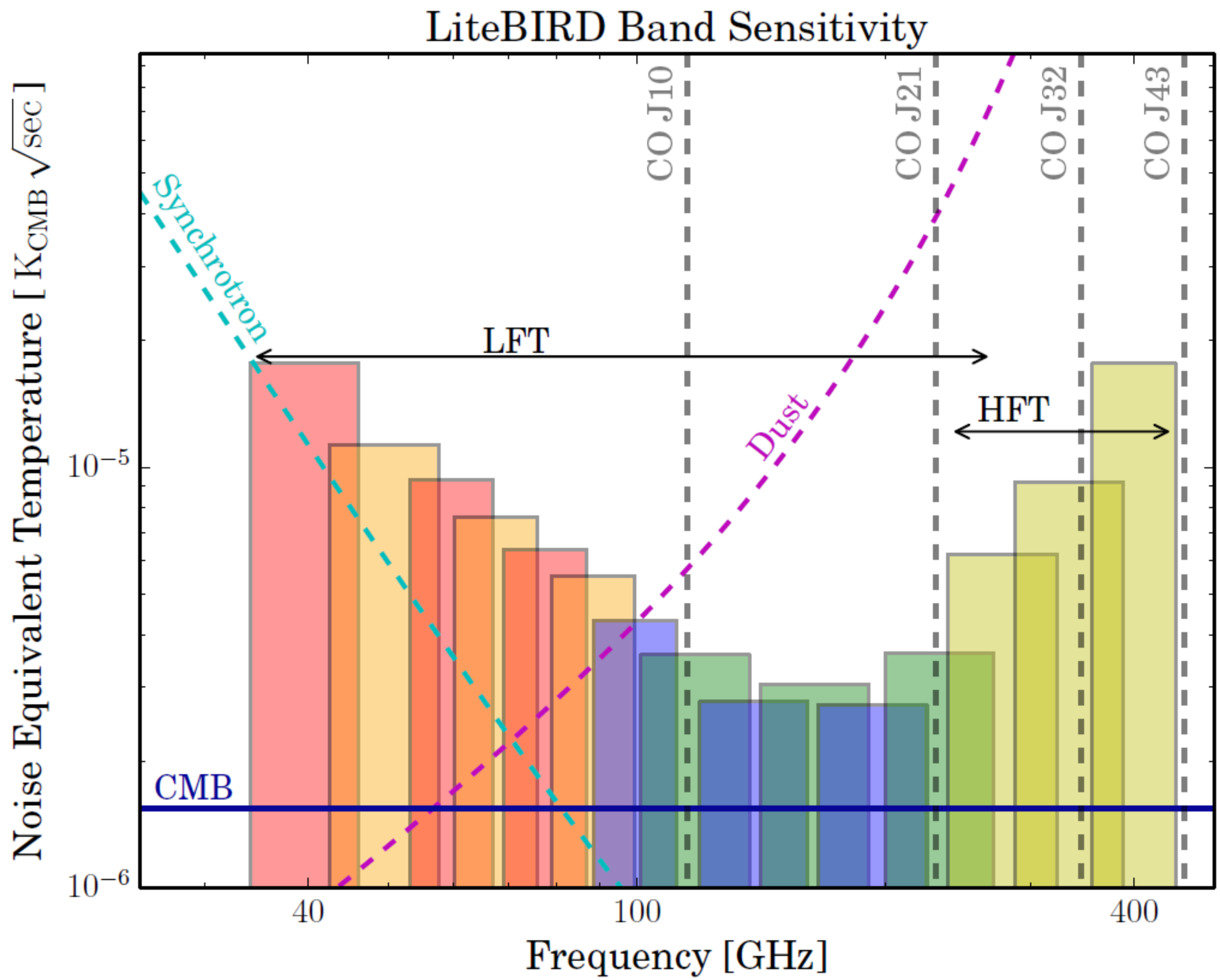
those had been dominant targets so far

- How useful is it for destriping?
- Stepped/continuous precession?
- Jack-knife availability

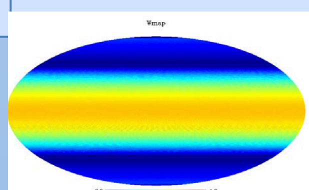
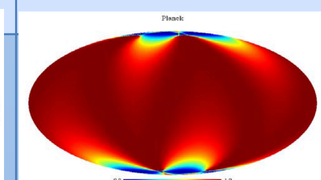
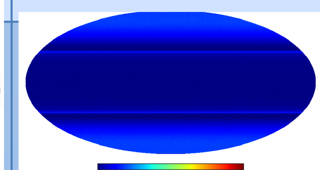
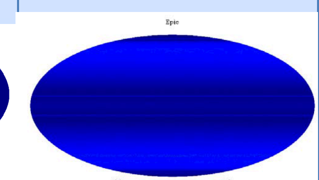
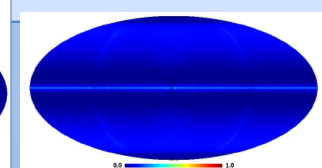
Revisit time optimization

- ADR cycling (30 hrs) and its dead-time (15%)
- Galaxy masking (f_{sky}~0.5)
- Heat issues, mission-part structure … need assesment from optical / structure viewpoint
- Any synchronous effect with other devices
- Any others (e.g. data transfer rate)?

Foreground separation by multi-band measurement



Scan strategy comparison

	WMAP	Planck	Litebird (fast spin)	EPIC	ESA M5 (arXiv:1604.02290)
Concept& Priority	Scan a pixel with many azimth angle, Comparison with COBE	Simplicity : Sun aspect angle constant to minimize thermal variation	Cross-link & Hit uniformity (+Jack-knife test?)	Cross-link & Jack-knife test	Cross-link (multi-spin)
Scan parameters	$\alpha=22.5^{o}$ $\beta=70^{o}$ Prec = 1 hr Spin = 0.45 rpm	$\alpha=7.5^{o}$ $\beta=85^{o}$ Prec = 6 months Spin = 1 rpm	$\alpha=65^{o}$ $\beta=30^{o}$ Prec = 1.51 hrs Spin = 0.3 rpm	$\alpha=45^{o}$ $\beta=55^{o}$ Prec = 3.2 hrs Spin = 1 rpm (option-?)	$\alpha=45^{o}$ $\beta=50^{o}$ Prec = 40 hrs Spin = 0.4 rpm etc.
Cross-link map					
References/notes	http://map.gsfc.nasa.gov/mission/observatory_scan.html	https://wiki.cosmos.esa.int/planckpla/index.php/Survey_scanning_and_performance et al.	ADR heat cycle ~ 30 hrs	arXiv:0805.4207 0906.1188	arXiv:1604.02290

αに関連するハードウェアなどの事項

- 衛星の構造。特に熱的なもの。基本的に衛星と外部とのインターフェース
  - 太陽光からの照射
  - 排熱板
  - 開口近辺の影
- 光学系
  - サイドローブへの太陽・地球・月からの漏れ込み
- 太陽電池パネルのサイジング
- テレメトリーアンテナ
  - X/S バンド両方
- スラスターの位置・推薬の量
- RWへの要求

βに関連するハードウェアなどの事項

- HWPの設置位置･角度
- 光学系とその支持構造の設置位置･角度
  - 衛星の筐体の大きさ
  - シェル内部熱構造
  - シェル内部迷光･反射
- サブK冷凍機の配置
  - JT/ST冷凍機の配置･配線
- 焦点面検出器配置
  - ハーネスの長さ
  - 熱流入