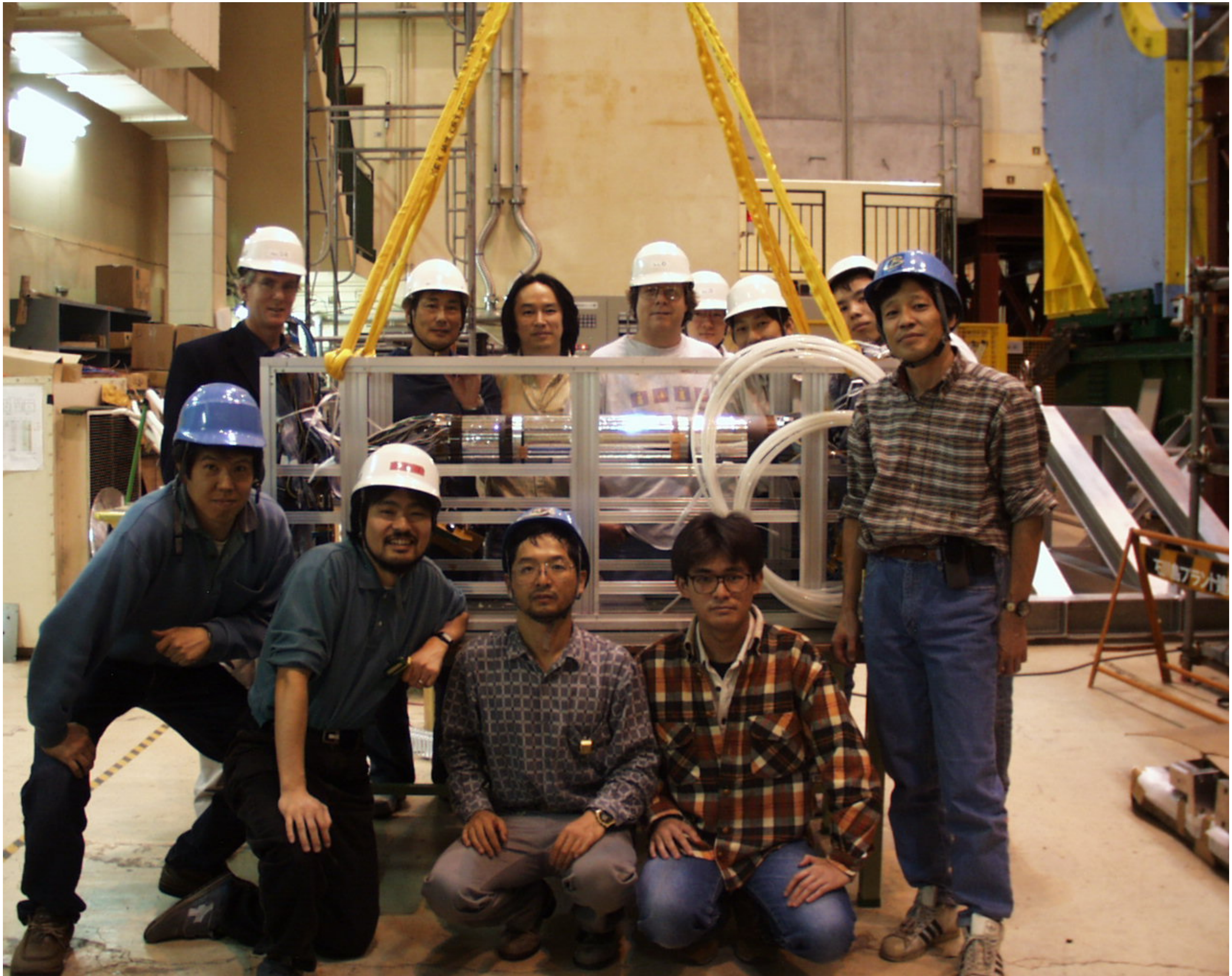


How I got excited about CMB B-mode
- a particle physicist's experience

1. Quantum fluctuation of the metric

$$\langle \hat{\tilde{h}}^{\dagger}(\vec{k},\eta)\hat{\tilde{h}}(\vec{k}',\eta)\rangle = |v(\vec{k},\eta)|^2(2\pi)^3\delta^3(\vec{k}-\vec{k}').$$

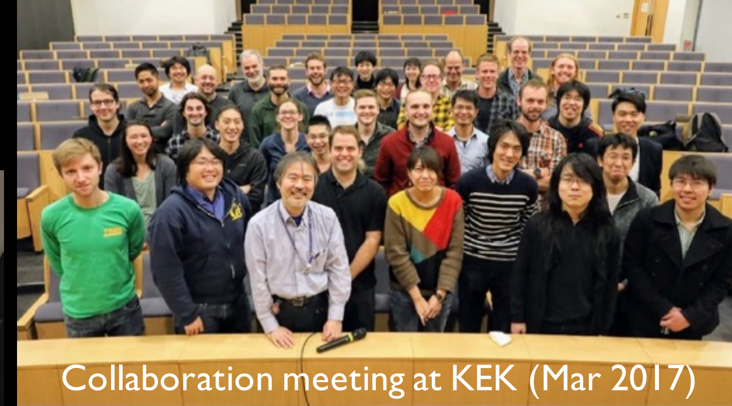
e.g. Dodelson "Modern Cosmology" Eq.(6.52)

2. Physics at GUT scale

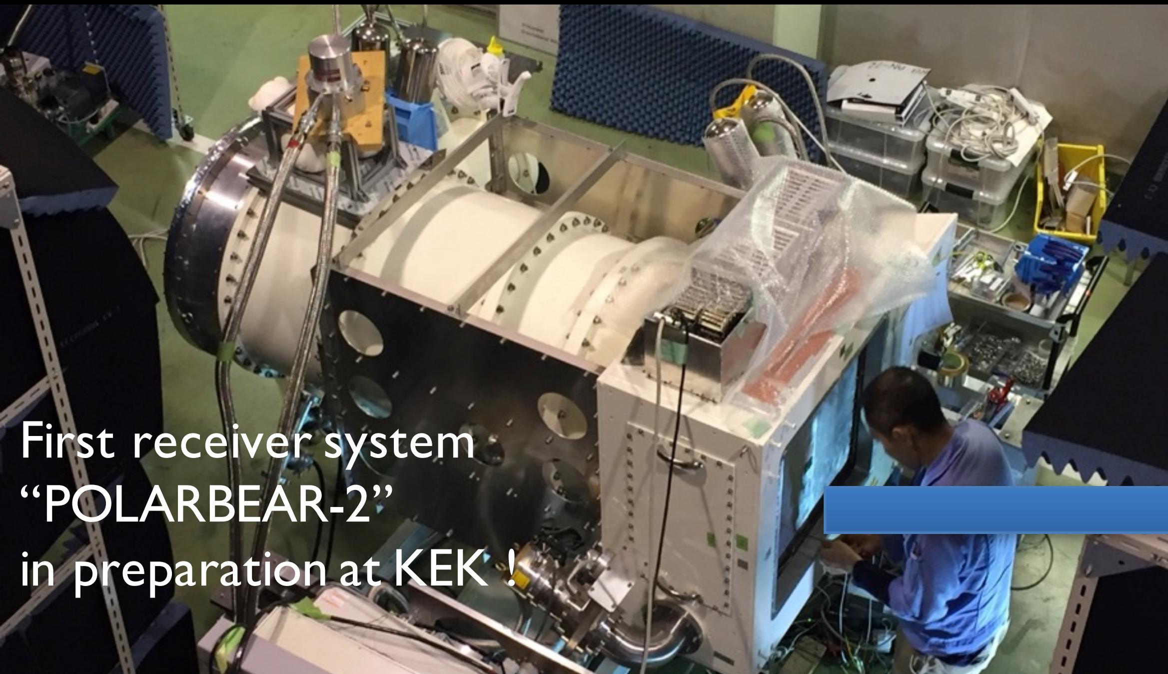
$$V^{1/4} = 1.06 \times 10^{16} \times \left(\frac{r}{0.01}\right)^{1/4} \text{[GeV]}$$

3. Amazing technology matching w/ HEP

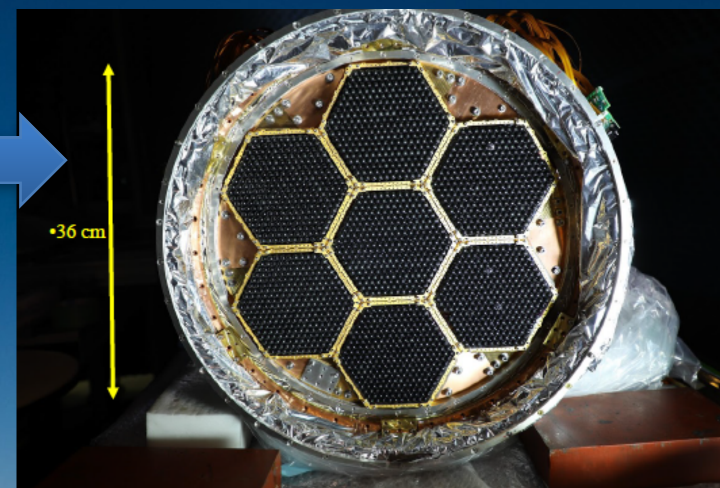
Simons Array Ongoing



Collaboration meeting at KEK (Mar 2017)



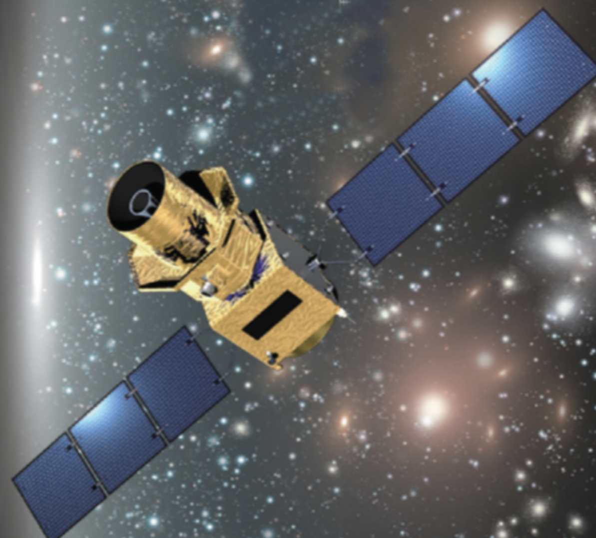
First receiver system
“POLARBEAR-2”
in preparation at KEK !



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)

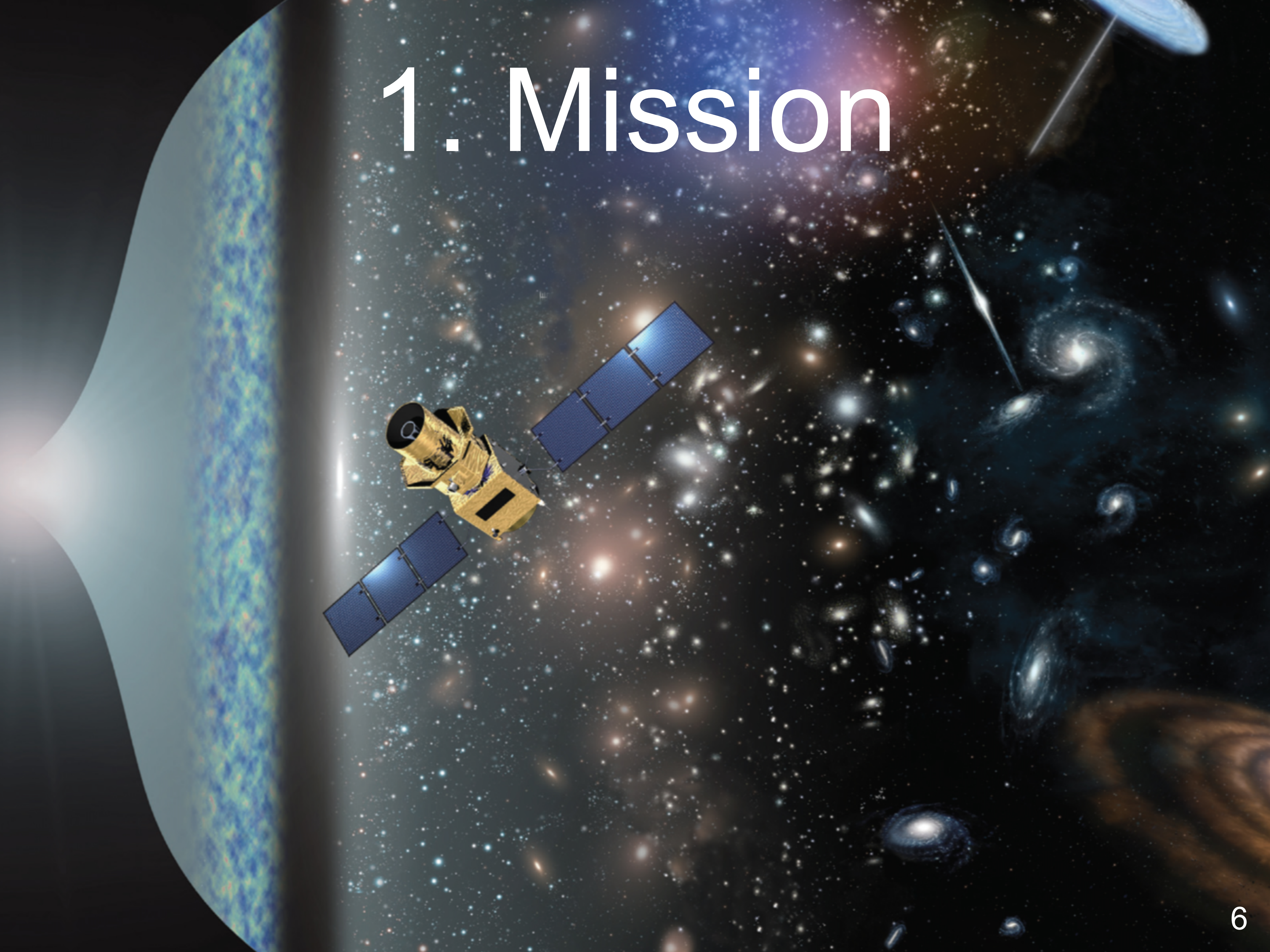
LiteBIRD Joint Study Group Member List

as of Dec. 2017

M. Hazumi[19,22,30,50]· P.A.R. Ade[48]· Y. Akiba[19,50]· D. Alonso[42]· K. Arnold[16]· J. Aumont[20]· C. Baccigalupi[25]· D. Barron[49]· S. Basak[11,25]· S. Beckman[15]· J. Borrill[6,49]· F. Boulanger[20]· M. Bucher[3]· E. Calabrese[48]· Y. Chinone[15,30]· S. Cho[13]· A. Cukierman[15]· D.W. Curtis[49]· T. de Haan[44]· M. Dobbs[43]· A. Dominjon[35]· T. Dotani[22]· L. Dubandd[18]· A. Ducout[30]· J. Dunkley[10,42]· J.M. Duval[18]· T. Elleflot[16]· H.K. Eriksen[24]· J. Errard[3]· J. Fischer[49]· T. Fujino[54]· T. Funaki[12]· U. Fuskelandd[24]· K. Ganga[3]· N. Goeckner-Wald[15]· J. Grain[20]· N.W. Halverson[4,9,17]· T. Hamada[2,19]· T. Hasebe[22]· M. Hasegawa[19,50]· K. Hattori[37]· M. Hattori[2]· L. Hayes[49]· N. Hidehira[12]· C.A. Hill[15,44]· G. Hilton[39]· J. Hubmayr[39]· K. Ichiki[32]· T. Iida[30]· H. Imada[22]· M. Inoue[40]· Y. Inoue[19,21]· K.D. Irwin[13,29]· H. Ishino[12]· O. Jeong[15] · H. Kanai[54]· D. Kaneko[30]· S. Kashima[35]· N. Katayama[30]· T. Kawasaki[31]· S.A. Kernasovskiy[13]· R. Keskitalo[6,49]· A. Kibayashi[12]· Y. Kida[12]· K. Kimura[40] · T. Kisner[6,49] · K. Kohri[19] · E. Komatsu[34]· K. Komatsu[12]· C.L. Kuo[13,29]· N.A. Kurinsky[13,29]· A. Kusaka[14,44]· A. Lazarian[53]· A.T. Lee[15,44,45]· D. Li[13]· E. Linder[44,49]· B. Maffei[20]· A. Mangilli[20]· M. Maki[19]· T. Matsumura[30]· S. Matsuura[27]· D. Meilhan[49]· S. Mima[46]· Y. Minami[19]· K. Mitsuda[22]· L. Montier[5]· M. Nagai[35]· T. Nagasaki[19]· R. Nagata[19]· M. Nakajima[40]· S. Nakamura[54]· T. Namikawa[13]· M. Naruse[47]· H. Nishino[19]· T. Nitta[52]· T. Noguchi[35]· H. Ogawa[40]· S. Oguri[46]· N. Okada[23]· A. Okamoto[23]· T. Okamura[19]· C. Otani[46]· G. Patanchon[3]· G. Pisano[48]· G. Rebeiz[16]· M. Remazeilles[51]· P.L. Richards[15]· S. Sakai[22]· Y. Sakurai[30]· Y. Sato[23]· N. Sato[19]· M. Sawada[1]· Y. Segawa[19,50]· Y. Sekimoto[8,22,50]· U. Seljak[15]· B.D. Sherwin[7,28,44]· T. Shimizu[8]· K. Shinozaki[23]· R. Stompor[3]· H. Sugai[30]· H. Sugita[23]· A. Suzuki[15,45]· J. Suzuki[19]· O. Tajima[19,50]· S. Takada[36]· R. Takaku[54]· S. Takakura[19,41]· S. Takatori[19,50]· D. Tanabe[19,50]· E. Taylor[49]· K.L. Thompson[13,29]· B. Thorne[30,42]· T. Tomaru[19]· T. Tomida[22]· N. Tomita[1]· M. Tristram[33]· C. Tucker[16]· P. Turin[49]· M. Tsujimoto[22]· S. Uozumi[12]· S. Utsunomiya[30]· Y. Uzawa[38]· F. Vansyngel[20]· I.K. Wehus[24]· B. Westbrook[15]· M. Willer[49]· N. Whitehorn[15]· Y. Yamada[12]· R. Yamamoto[22]· N. Yamasaki[22]· T. Yamashita[54]· M. Yoshida[19]

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

1. Mission



Cosmic Microwave Background (CMB)

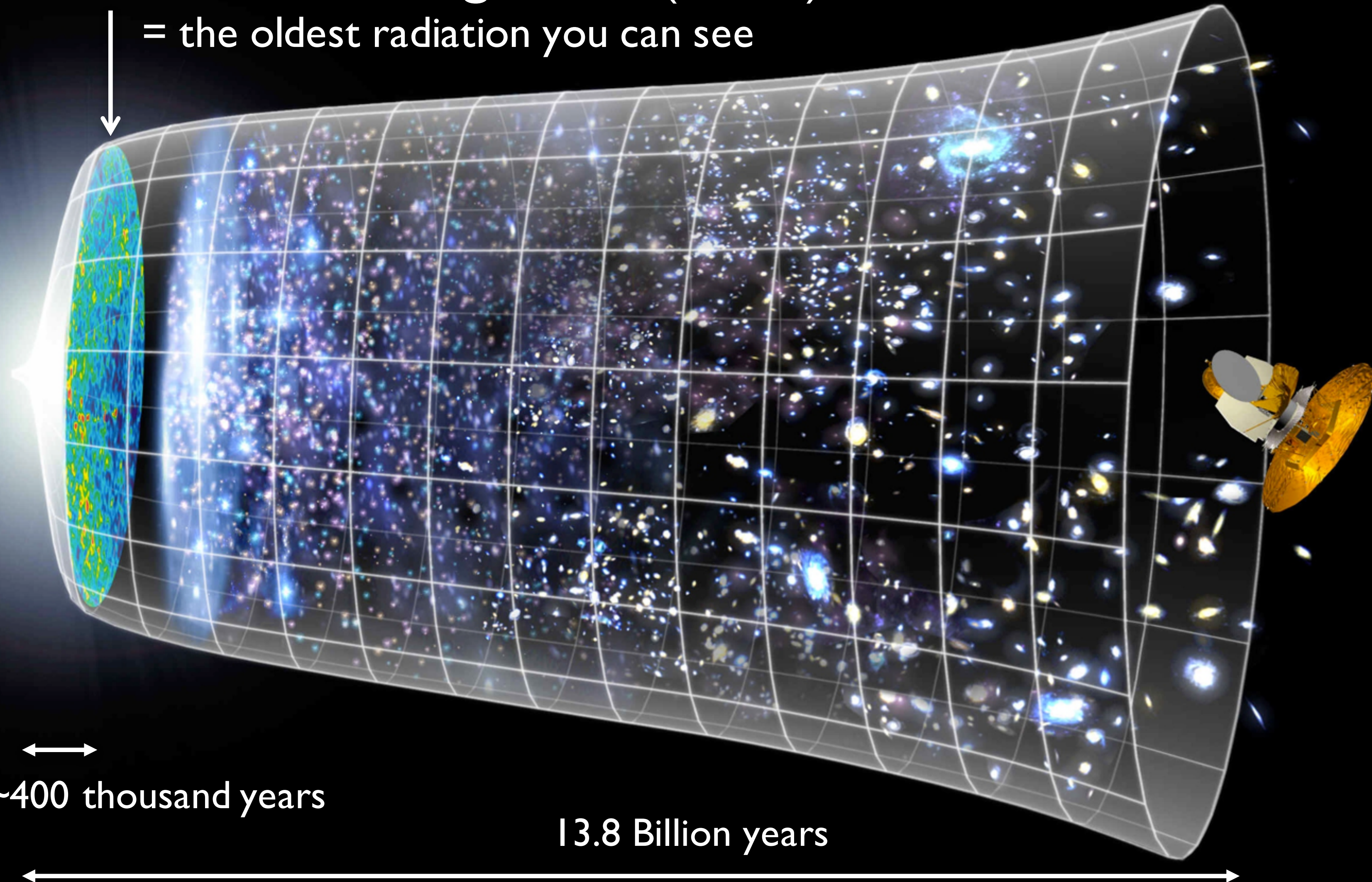
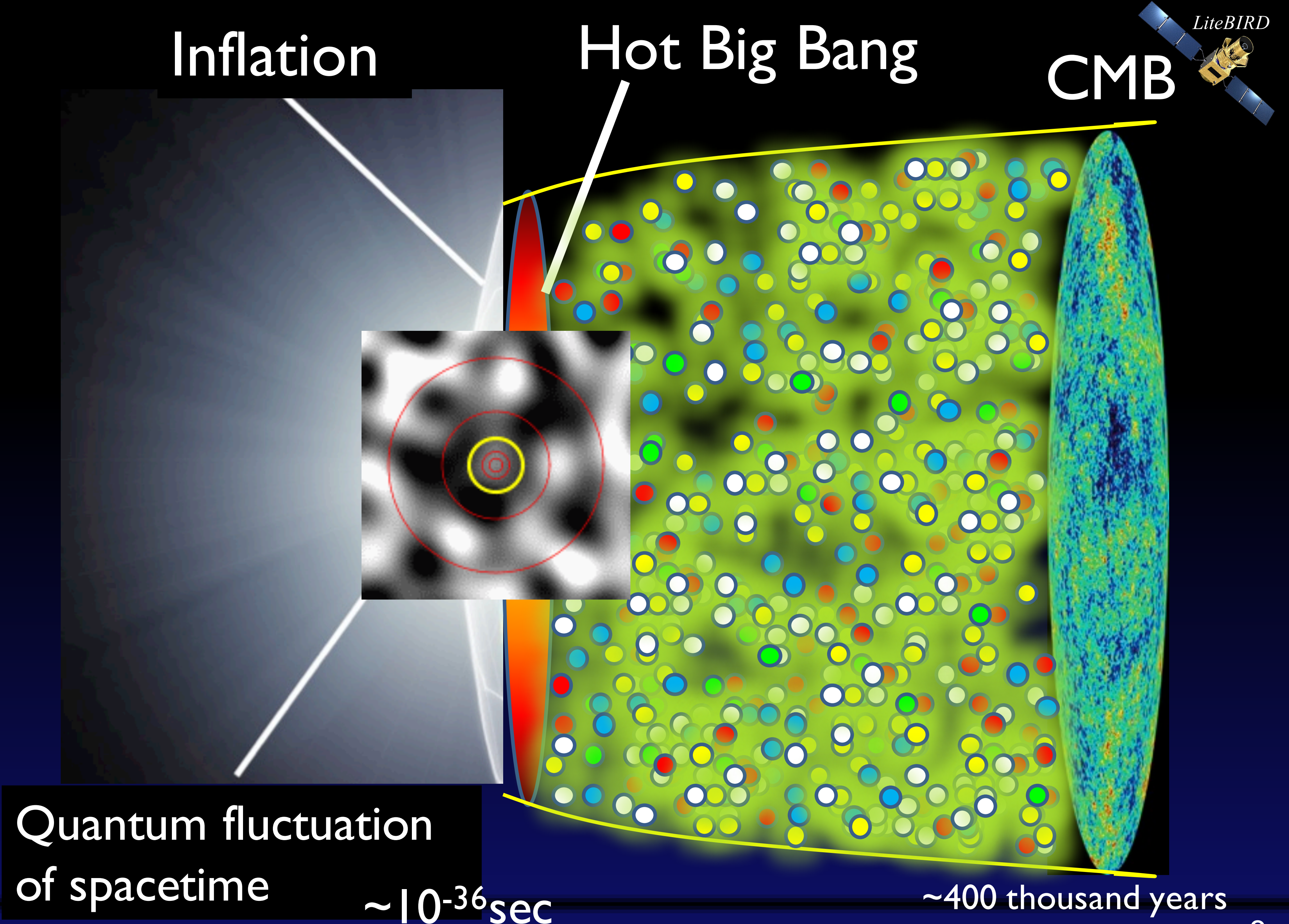


image credit NASA/WMAP team

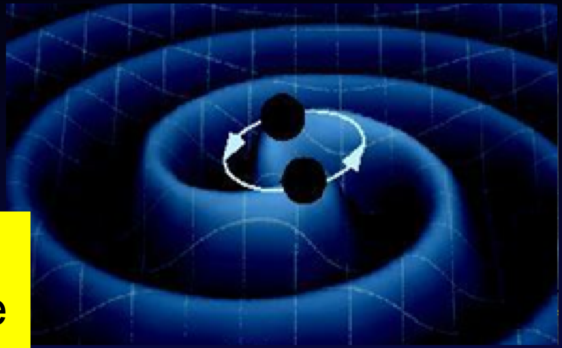

Inflation
Hot Big Bang
CMB
LiteBIRD
Quantum fluctuation of spacetime
~10-36sec
~400 thousand years

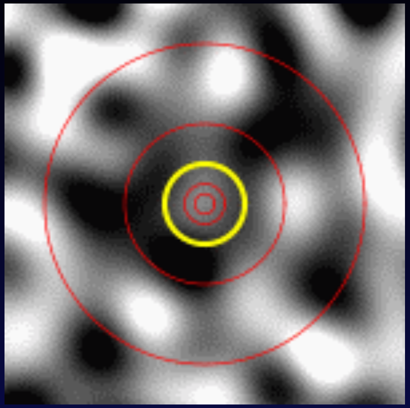
Big leap from LIGO to LiteBIRD

within
Einstein's theory
of general relativity

beyond Einstein

The 2017
Nobel Prize
in Physics





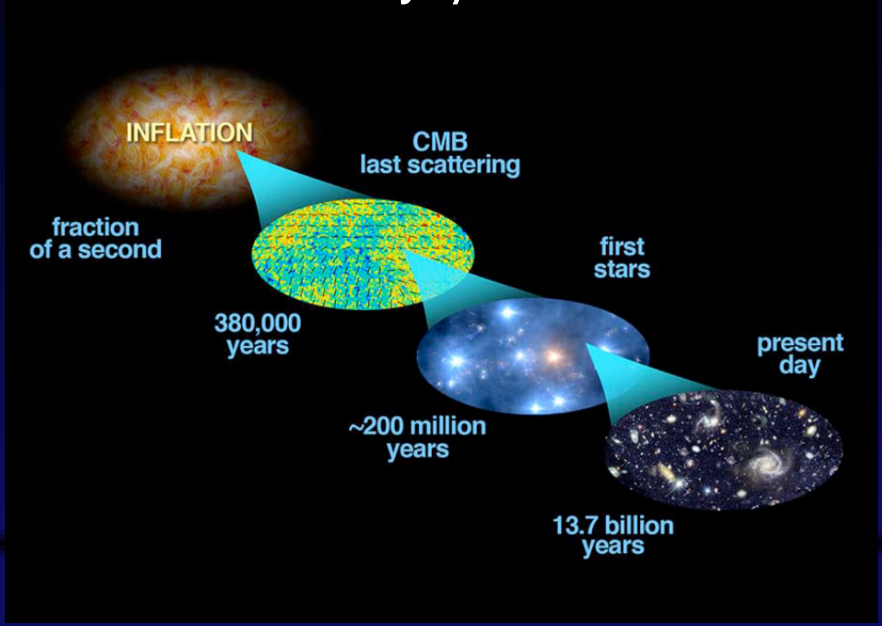
LIGO: gravitational waves with classical origin
LiteBIRD: gravitational waves with quantum origin

LiteBIRD

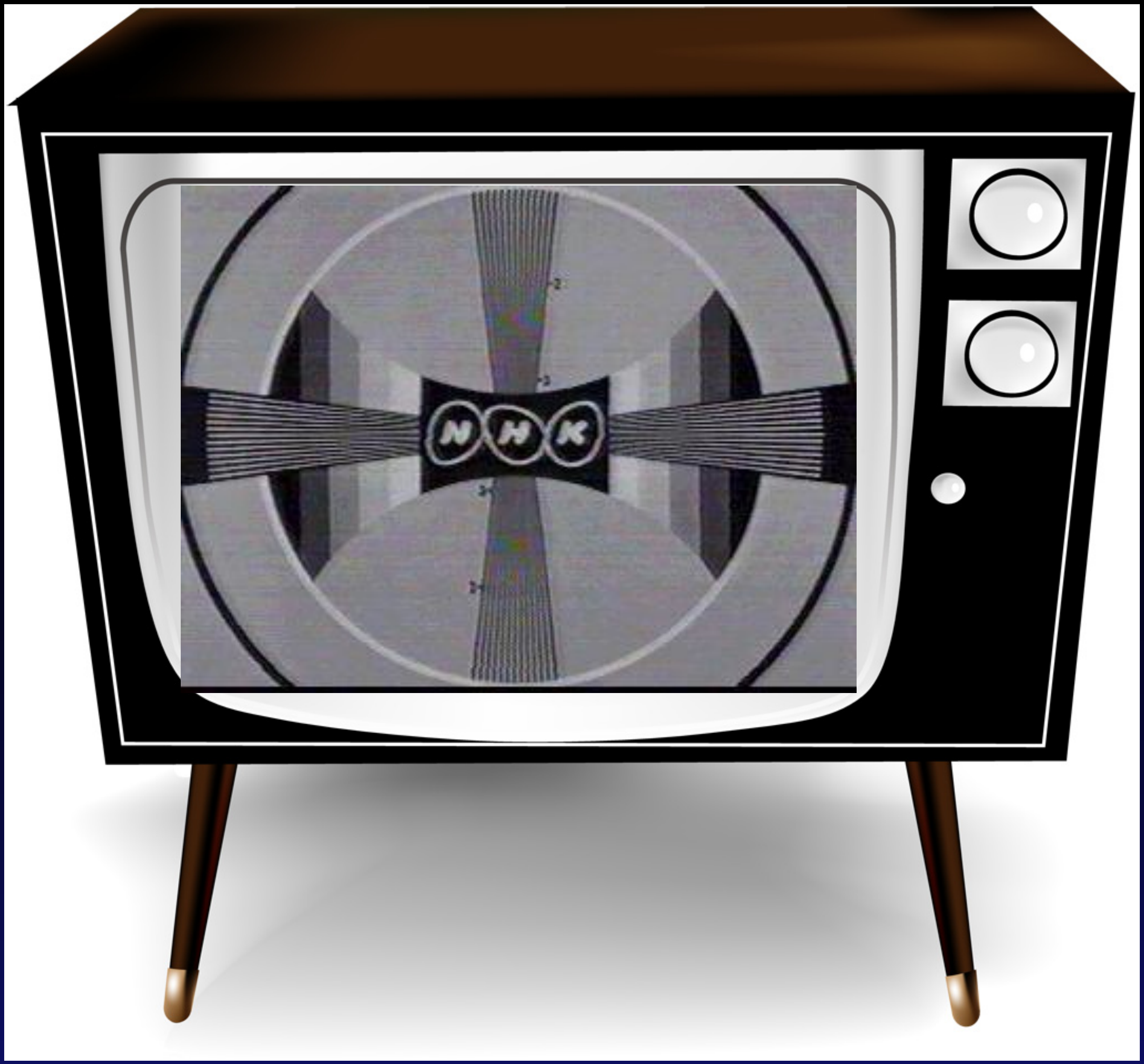
"Detecting primordial gravitational waves would be one of the most significant scientific discoveries of all time."

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

Cosmic inflation predicts generation of primordial gravitational waves due to quantum fluctuation of spacetime



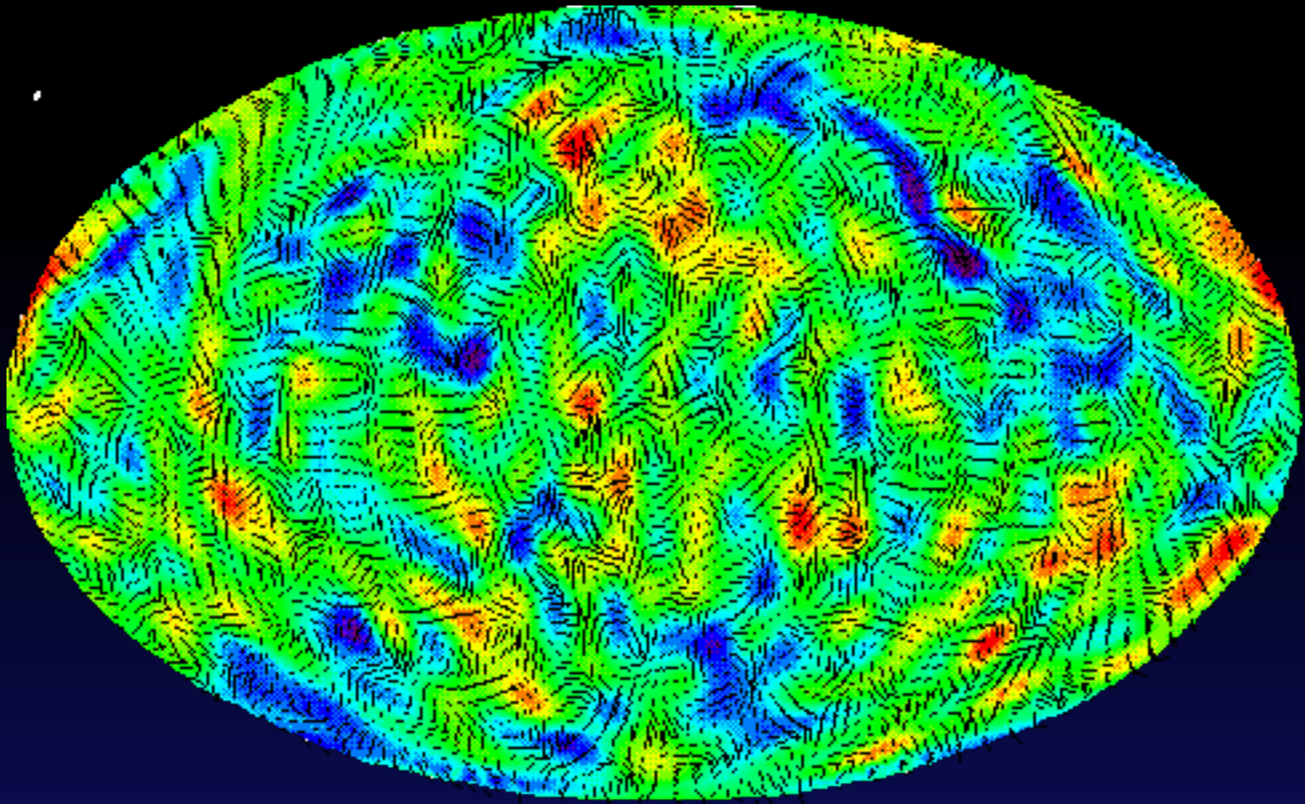
Test pattern on TV screen



“Test pattern” of inflation

LiteBIRD

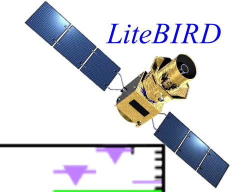
Expected CMB Polarization Sky Map

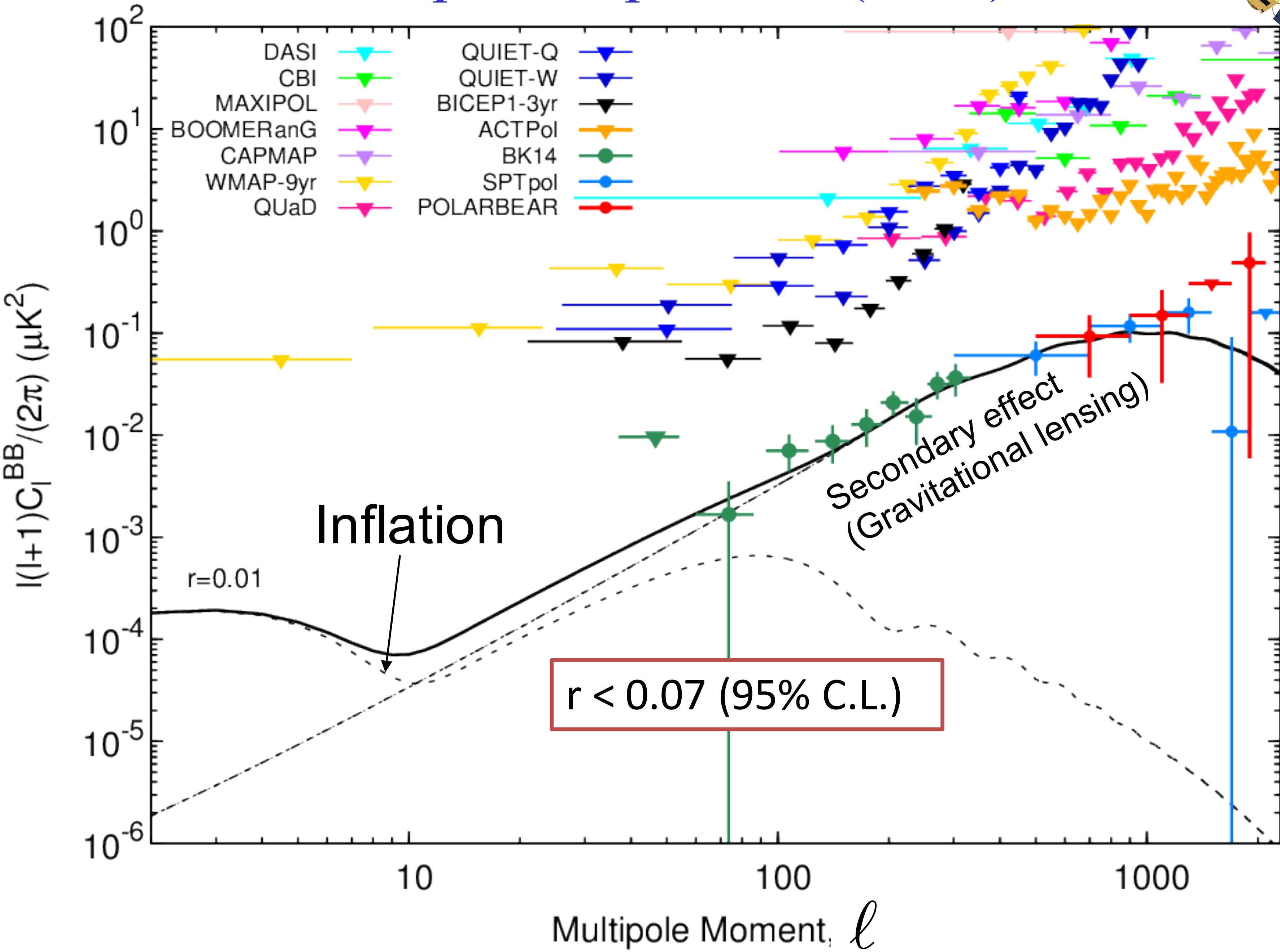


Simulation

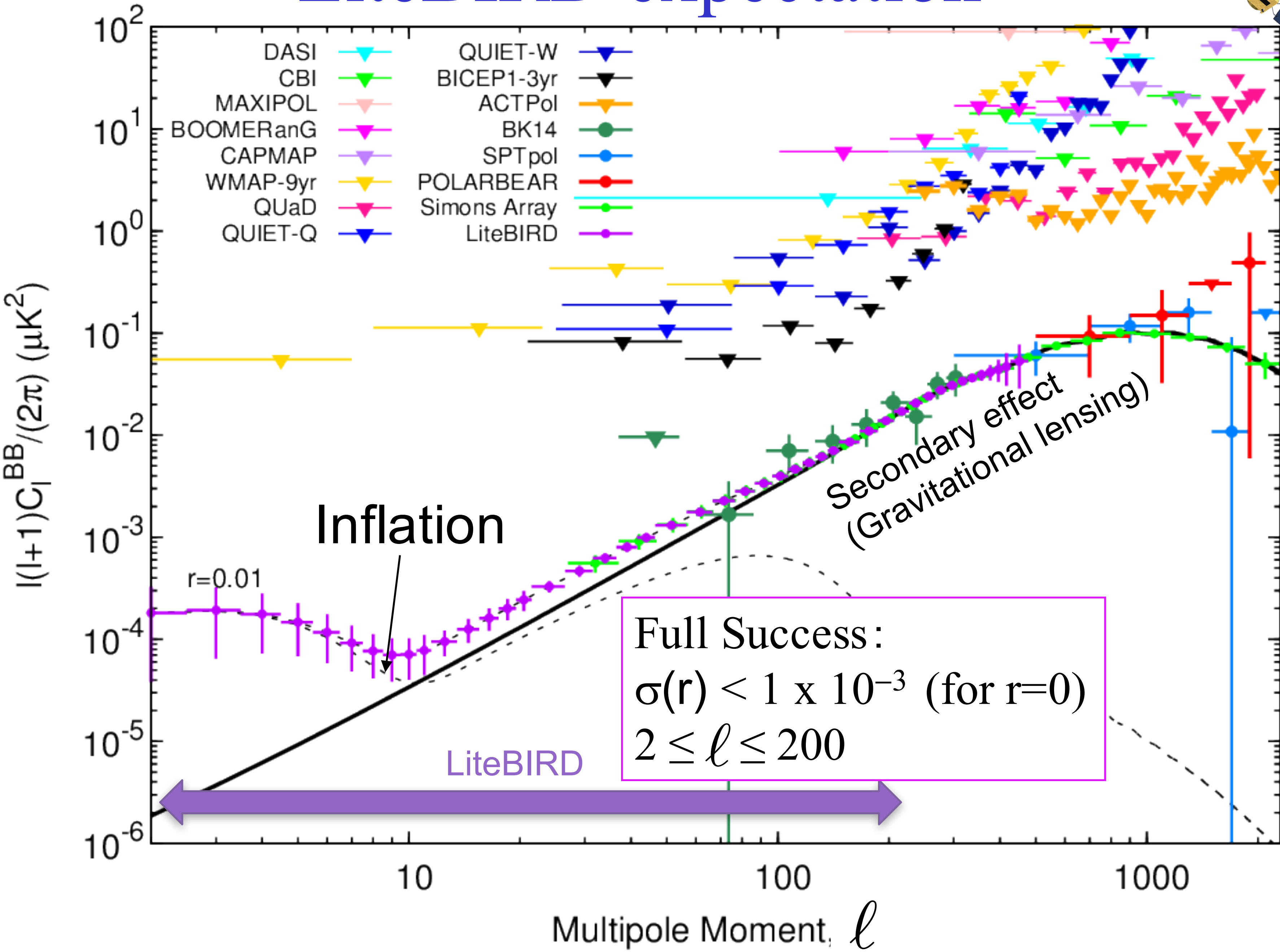
Theoretical prediction: large-scale curl patterns (vortexes called “B-mode”)

B-mode power spectrum (2016)





LiteBIRD expectation



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.

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 >5sigma r detection from each bump for r > 0.01.**

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

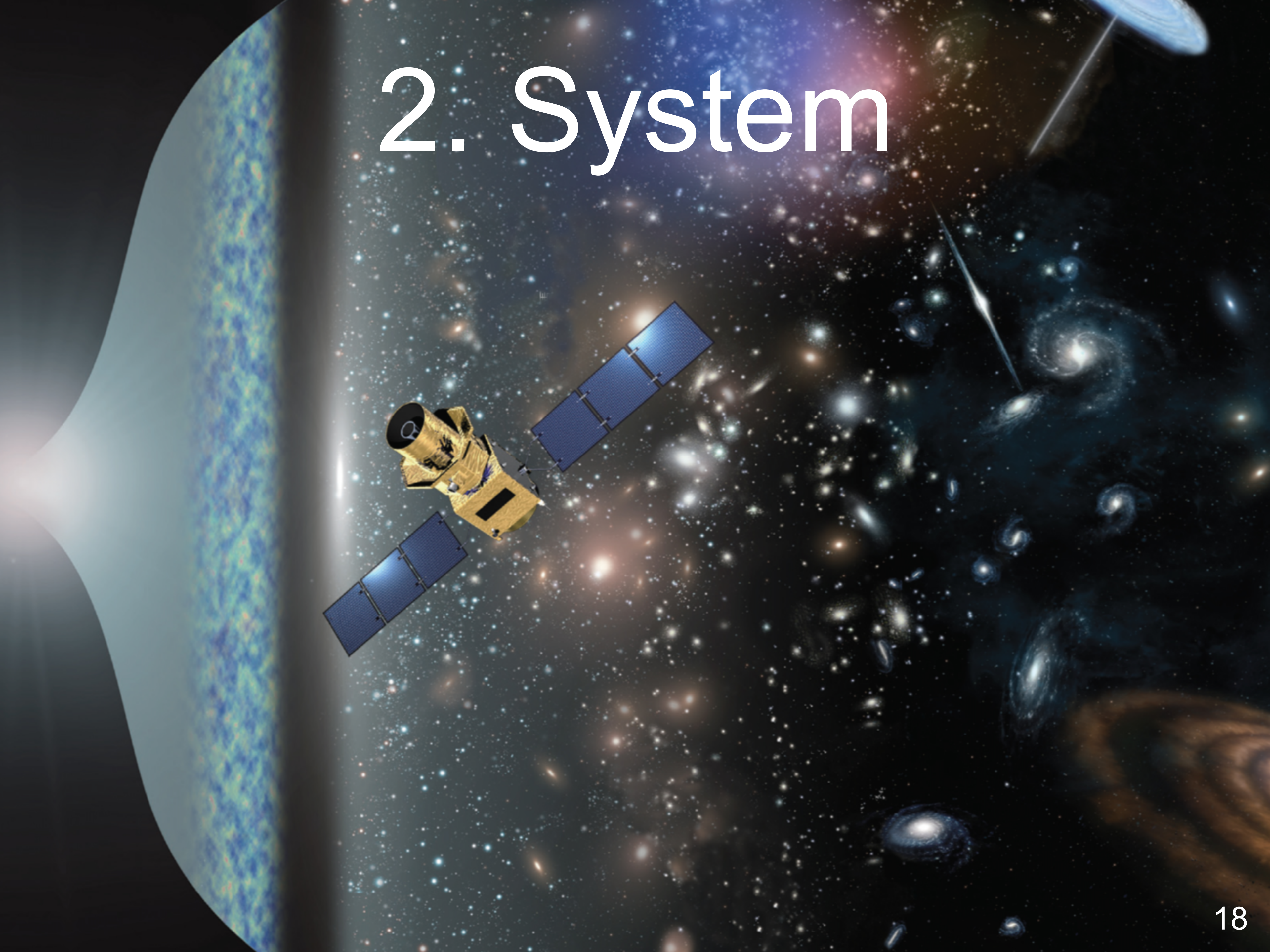
Extra success

Improve σ(r) with external observations

Topic	Example Method	Example Data
Delensing	Large CMB telescope array	CMB-S4 data Namikawa and Nagata, JCAP 1409 (2014) 009
	Cosmic infrared background	Herschel data Sherwin and Schmittfull, Phys. Rev. D 92, 043005 (2015)
	Radio continuum survey	SKA data Namikawa, Yamauchi, Sherwin, Nagata, Phys. Rev. D 93, 043527 (2016)
Foreground removal	Lower frequency survey	C-BASS upgrade

- Delensing improvement to σ(r) can be factor ~2 or more.
  - **e.g. ~6sigma observation in case of Starobinsky model**
  - Need to make sure systematic uncertainties are under control.

2. System



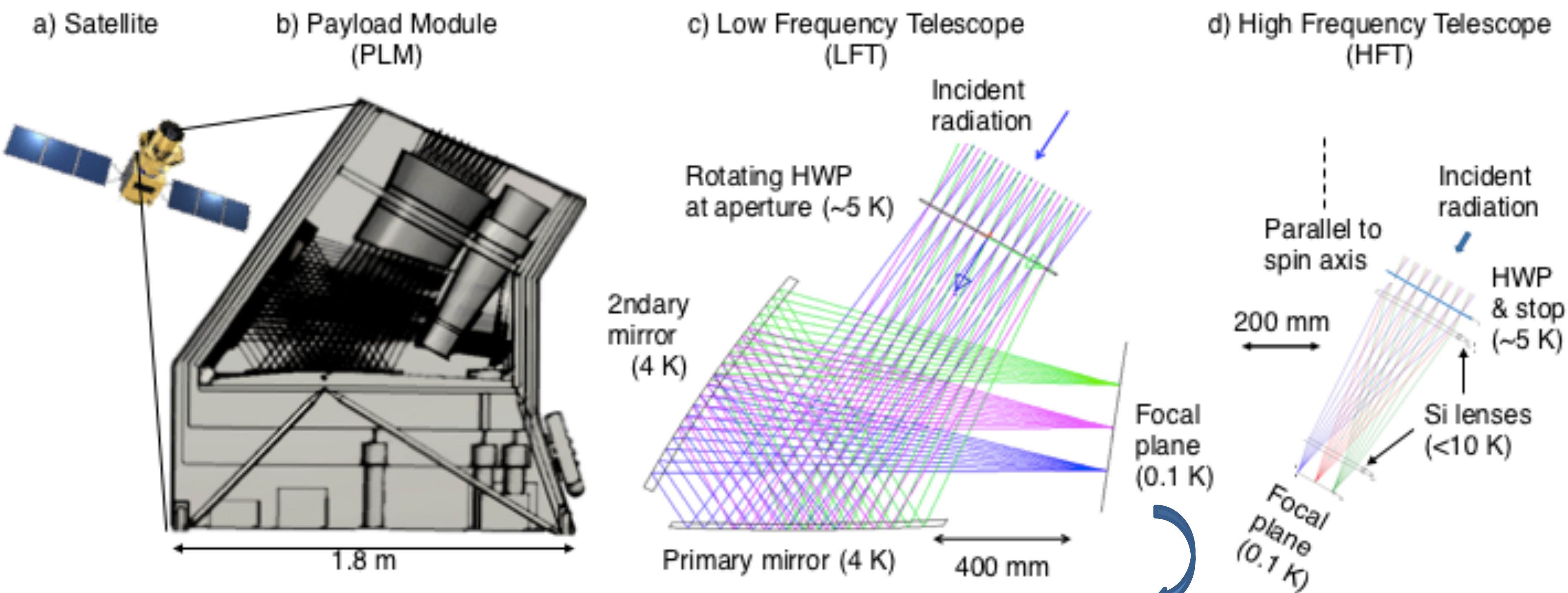
Main Specifications

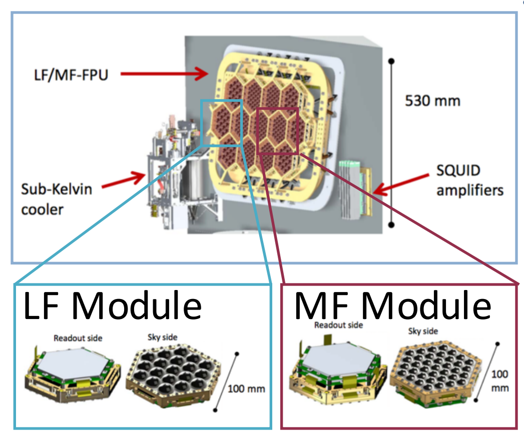
Phase-A1 2016 Baseline

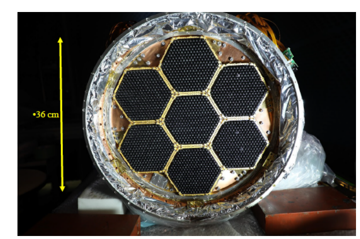
Item	Specification
Launch year	2026-2027
Launch vehicle	JAXA H3
Observation type	All-sky CMB surveys
Observation time	3 years
Orbit	L2 Lissajous orbit
Scan strategy	Spin and precession ($\alpha = 45°$, $\beta = 50°$)
Observing frequencies	34 – 448 GHz
Number of bands	15
Sensitivity	2.5 μK′ (3 years)
Angular resolution	0.5° at 100 GHz (FWHM)
Mission instruments	· Superconducting detector arrays · Polarization modulator with continously-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

Phase-A1 2016 Baseline



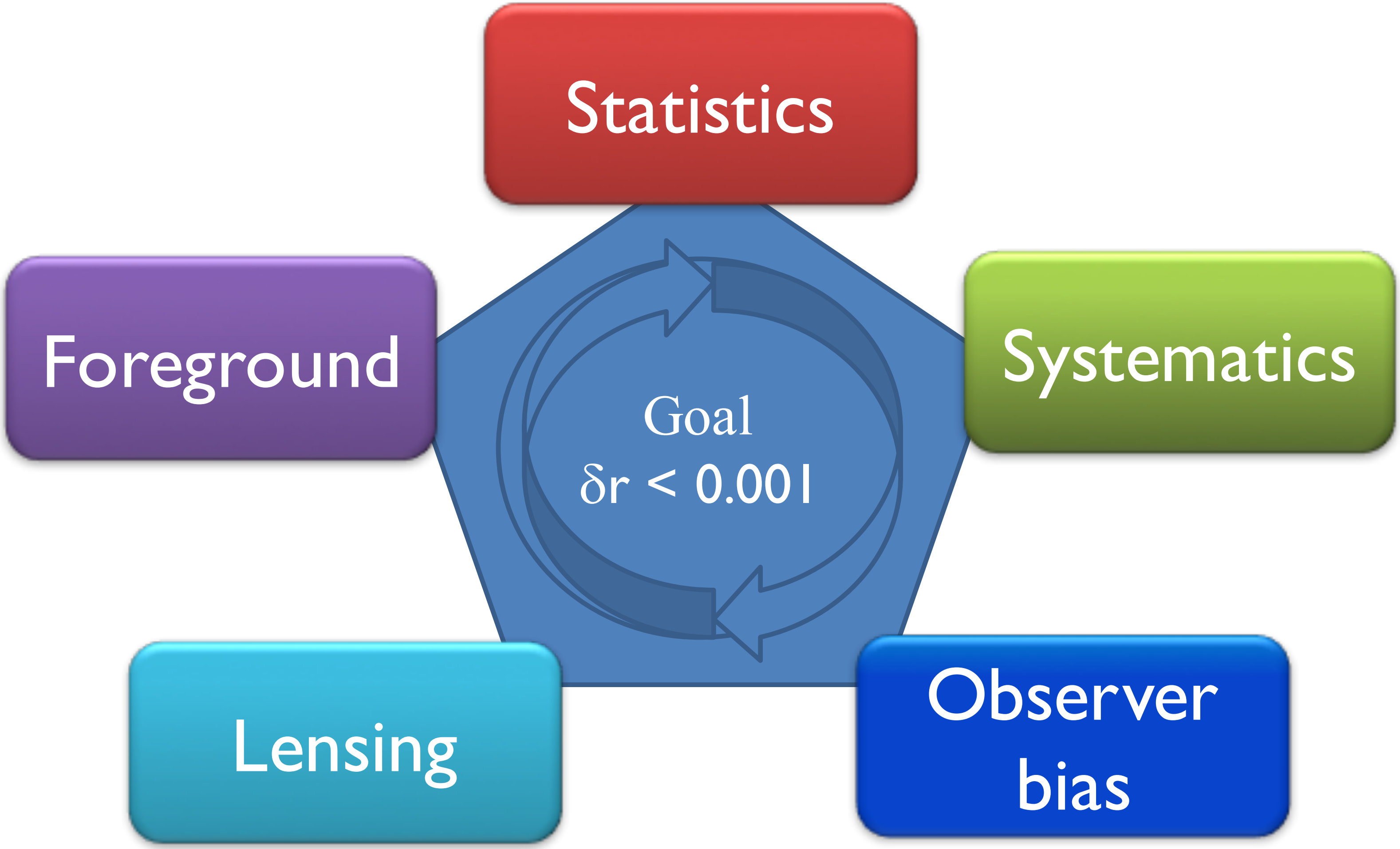




POLARBEAR-2
focal plane
as a proof
of principle

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

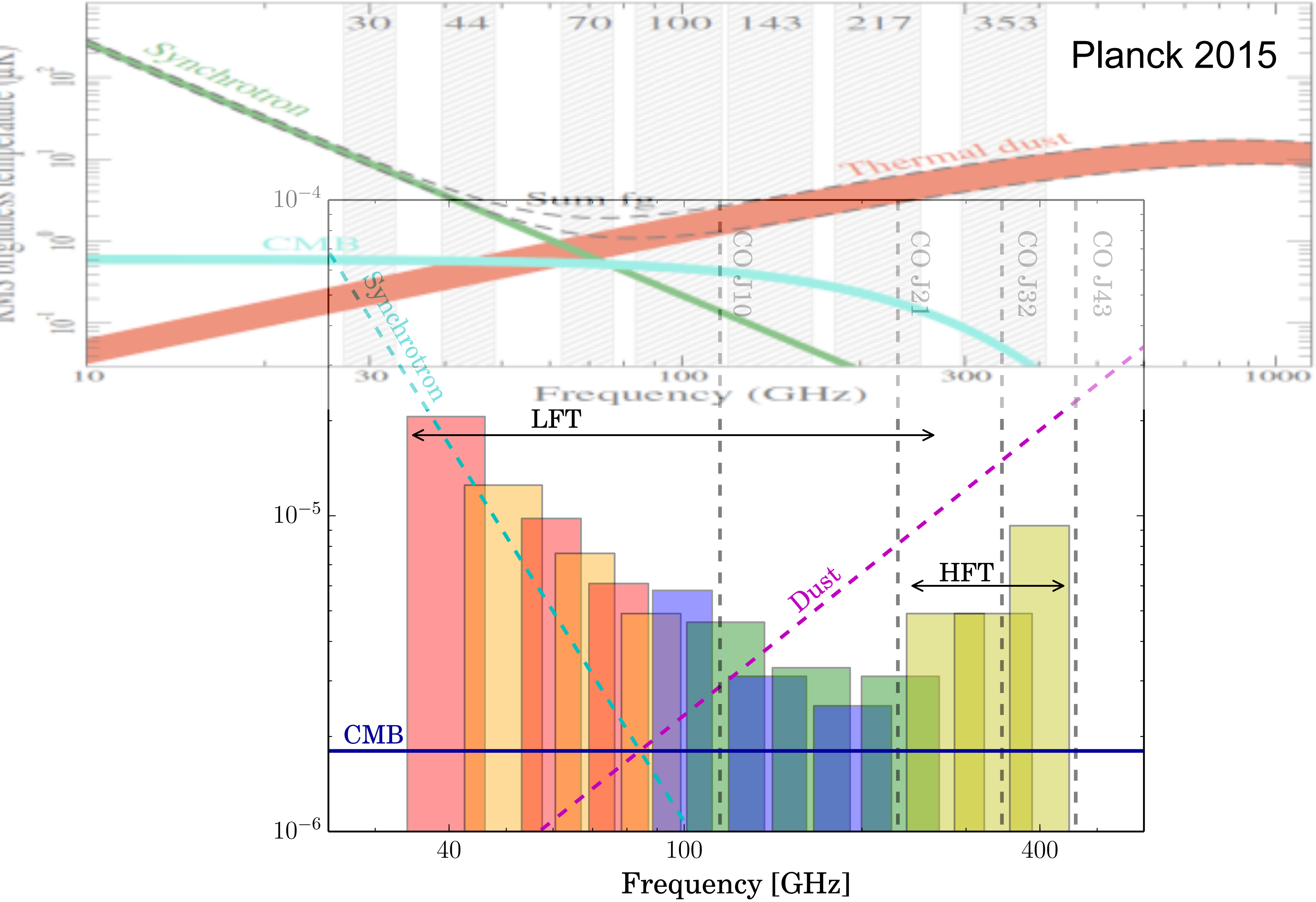
Five uncertainty components



Error budget assignment toward full success

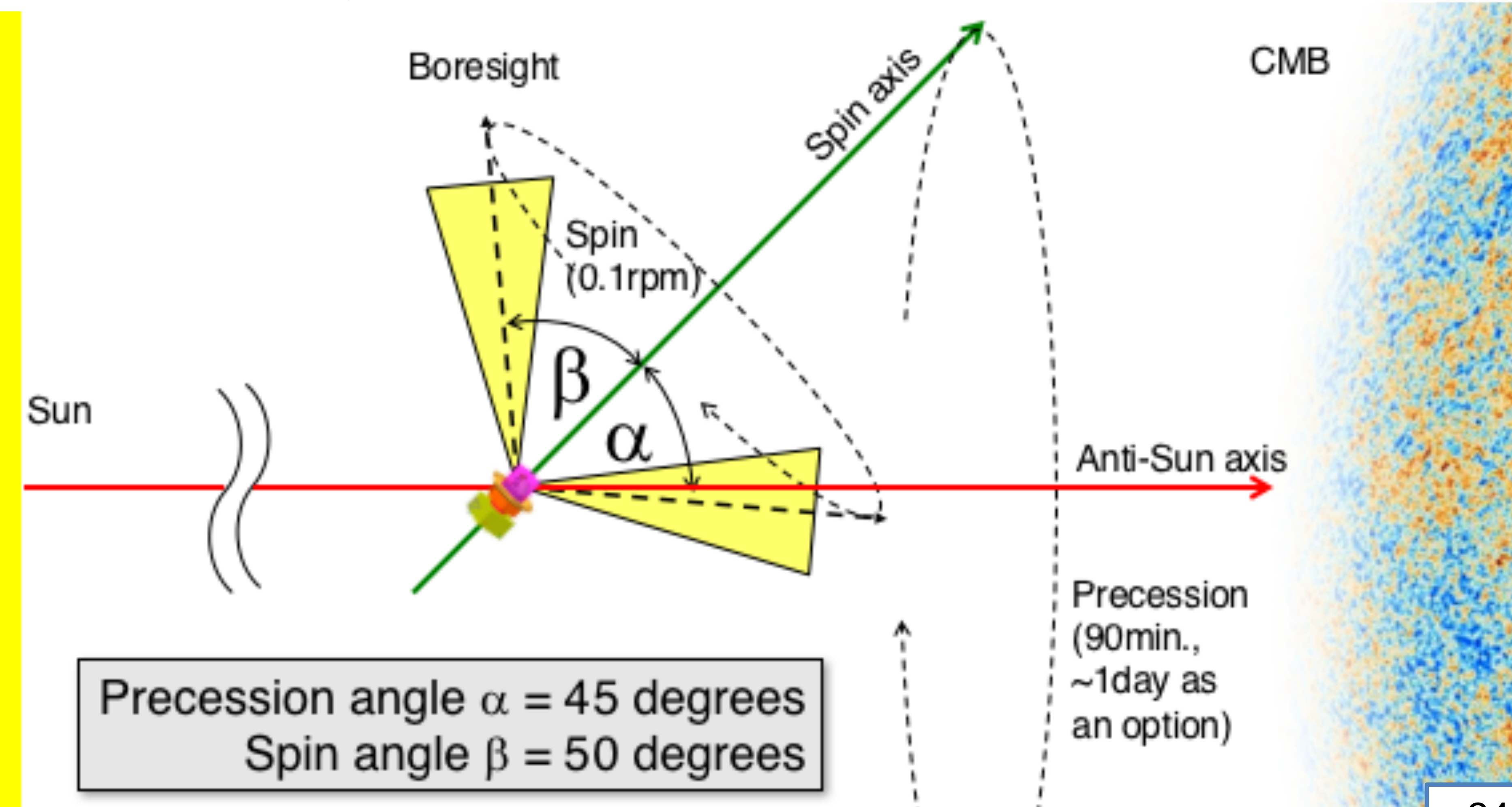
- Statistical error after foreground separation, including lensing B-mode contribution (σ_{stat})
- Systematic error (σ_{sys})
- Margin (σ_{mgn})
- Requirement: $\sigma_{stat}^2 + \sigma_{sys}^2 + \sigma_{mgn}^2 < 0.001^2$
- We assign $\sigma_{stat} = \sigma_{sys} = \sigma_{mgn}$
- Therefore we require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



Scan Strategy

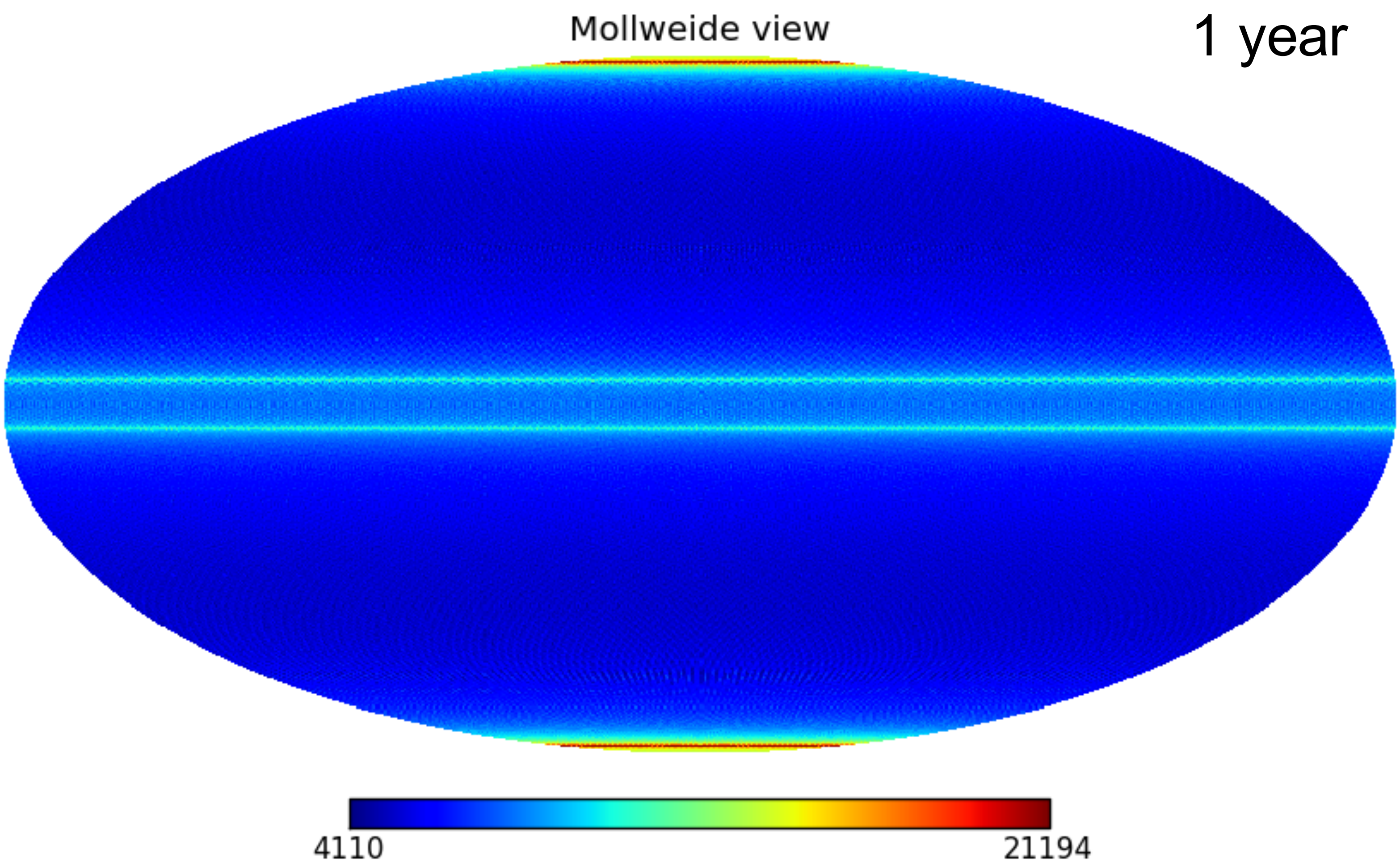
Orbit: L2 Lissajous



of observations for each sky pixel

w/ a single detector

1 year

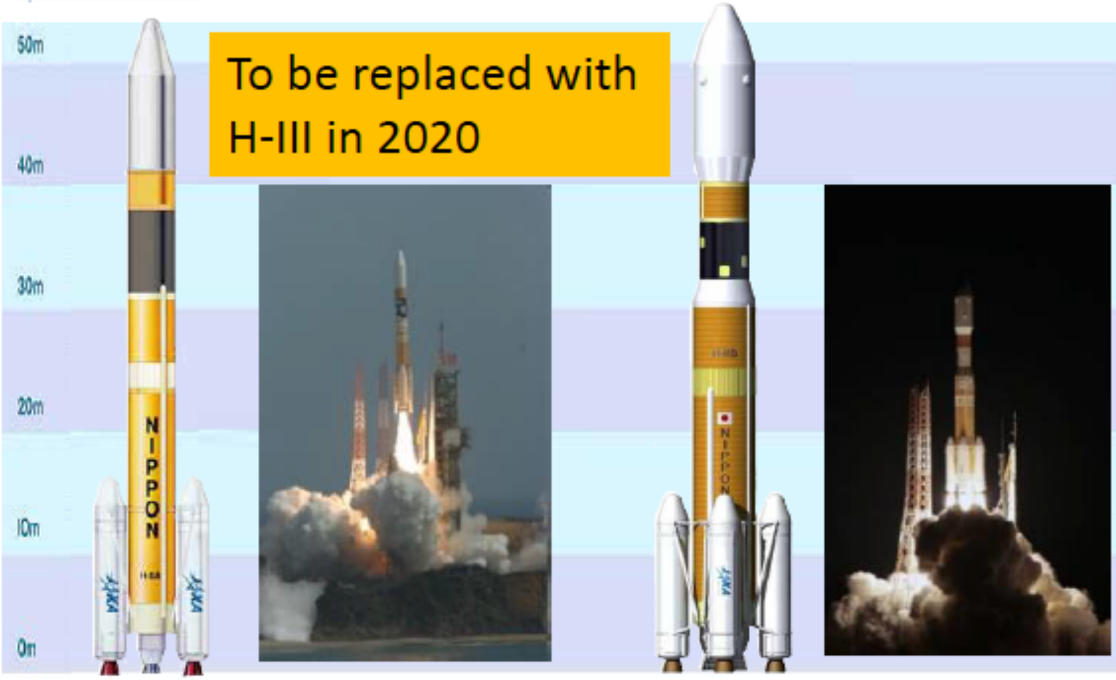


Current baseline is extendable

- New launch vehicle: H-II → H3
- New ground station: GREAT
- New mirror design

Launch Vehicle: H3

To be replaced with H-III in 2020

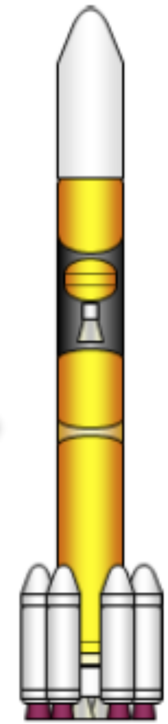


H-II A

- 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

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

Ground Station for Deep Space Exploration and Telecommunication (GREAT)

Summary of Ground Stations

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

Antenna available for L2 mission in 2020s.

Only the limited data transfer is possible at L2.

Larger datalink capability

New Mirror Design for LFT

S. Kashima

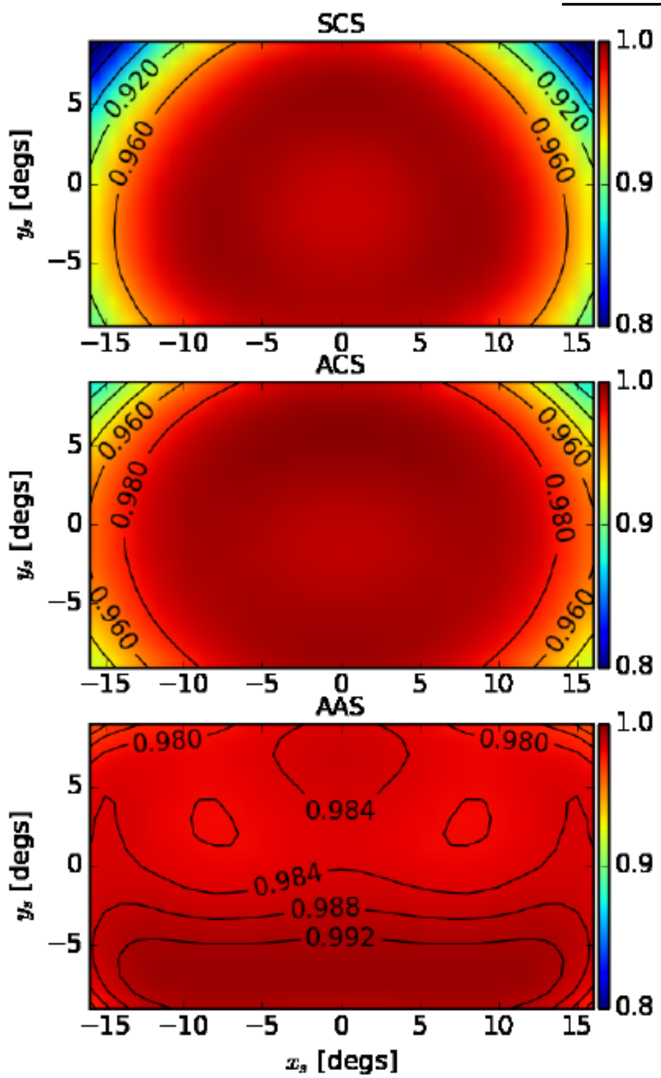
Paper submitted

SCS: Simple off-axis conic surface

ACS: Anamorphic conic surfaces without higher-order terms

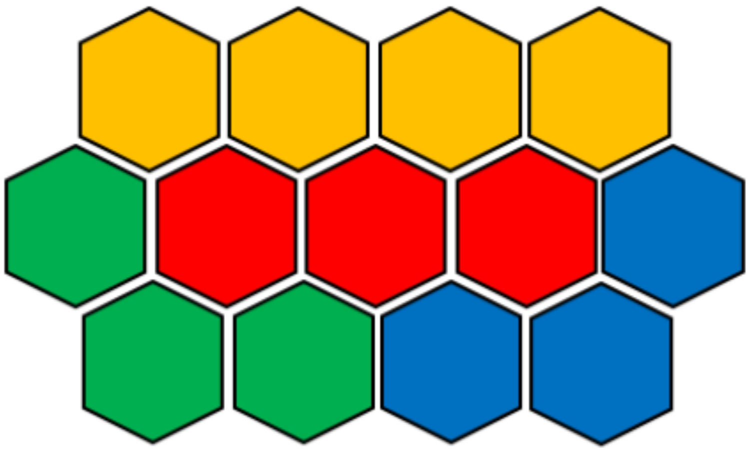
AAS: Anamorphic aspherical surfaces with terms up to the 10th order

Strehl Ratio > 0.95 over 32 x 18 degrees²



Enhanced design example

LFT



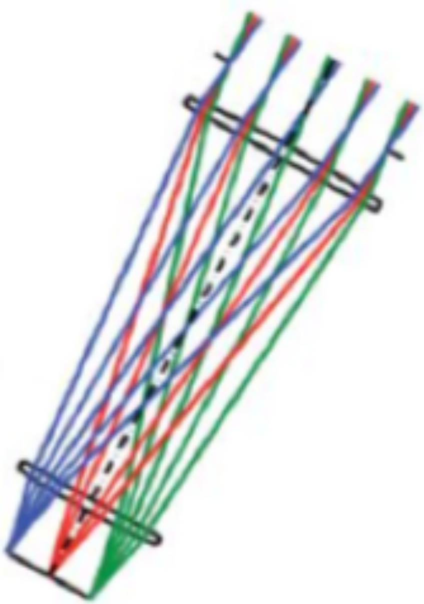
Center Freq GHz	Frac BW	Pixel Diameter [mm]	Num Pix	Num Det
40	0.30	30	21	42
60	0.23	30	21	42
78	0.23	30	21	42
50	0.30	30	28	56
68	0.23	30	28	56
89	0.23	30	28	56
68	0.23	18	57	114
89	0.23	18	57	114
119	0.30	18	57	114
78	0.23	18	57	114
100	0.23	18	57	114
140	0.30	18	57	114

HFT

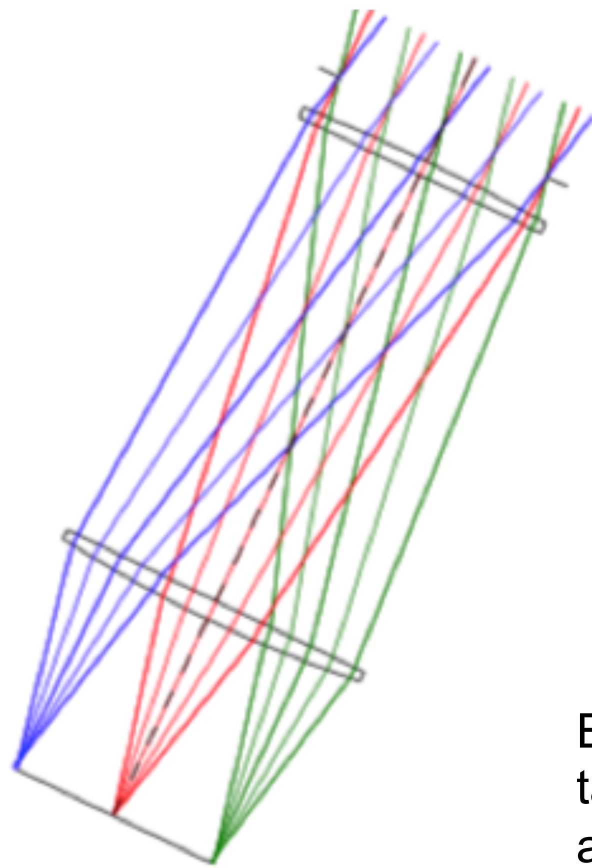
Reflective option is also considered (see Yutaro's talk)

Center Freq GHz	Frac BW	Pixel Diameter [mm]	Num Pix	Num Det
100	0.23	12	111	222
140	0.30	12	111	222
195	0.30	12	111	222
119	0.30	12	74	148
166	0.30	12	74	148
235	0.30	12	74	148
337	0.30	5.2	169	338
280	0.30	5.2	169	338
402	0.23	5.2	169	338

Enhanced HFT example



Baseline design
(LO-HFT200)



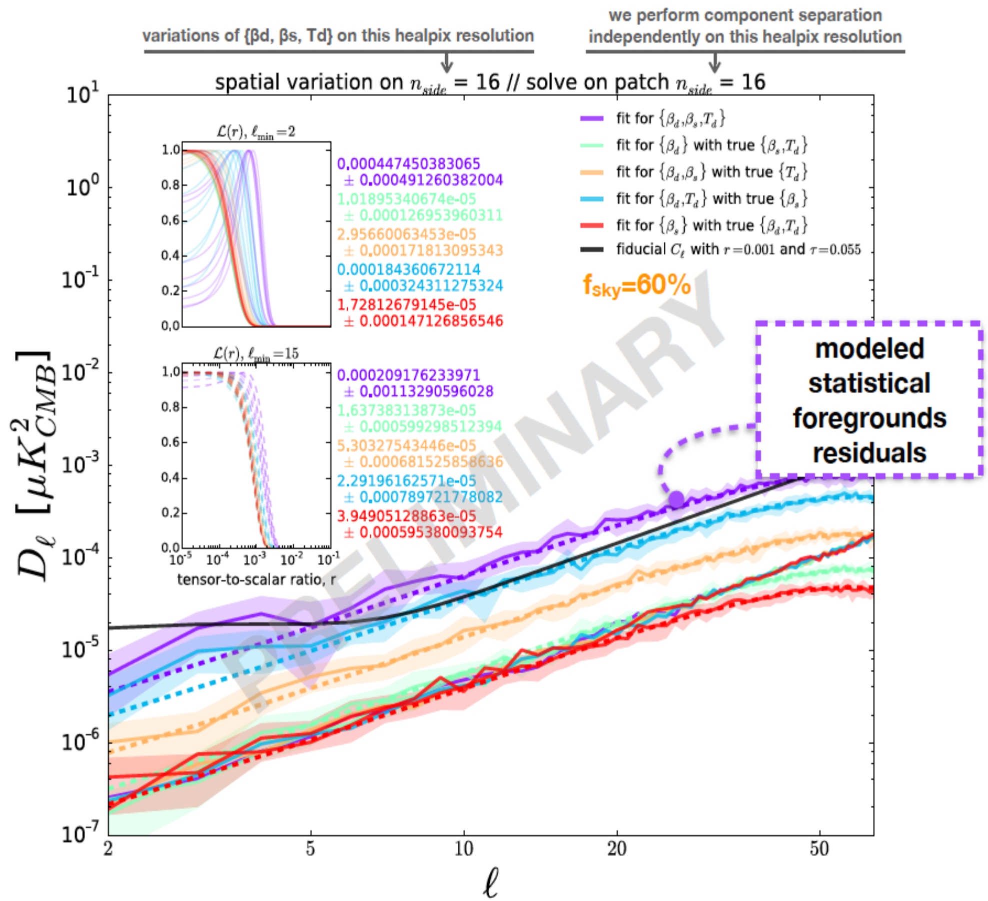
Large HFT
(LO-HFT300)

Reflective option
is also considered

European consortium
takes lead to make
a decision.

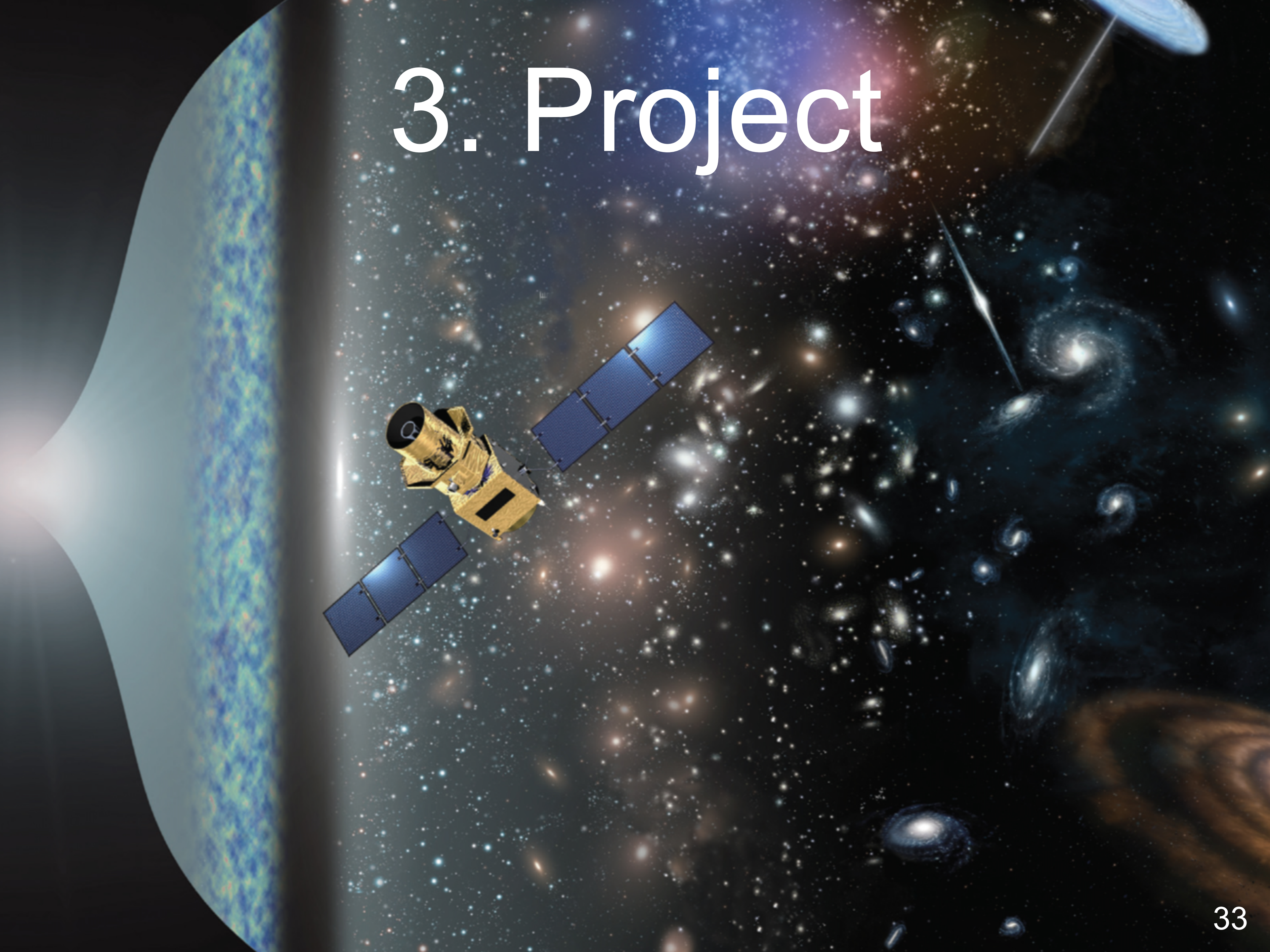
Enhanced HFT* and foreground removal

- 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 ~ 0.0004 +/- 0.0005 (ell >= 2)
- Complicating the sky (spatial variations on nside=32 with synchrotron curvature) leads to r = 0.0007 +/- 0.0007 (ell >= 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.

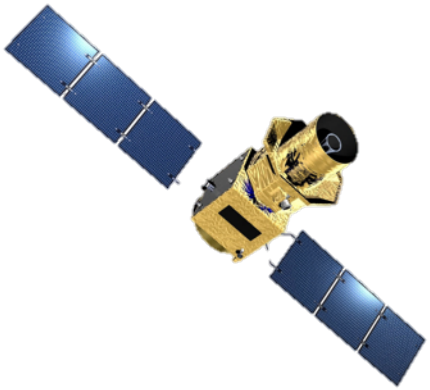
3. Project



Basic Japanese Vision for 2020's

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

Powerful Duo



X

JAXA-led focused mission

$\sigma(r)<0.001$

$2 \leq \ell \leq 200$

focused but still with many byproducts

US-led telescopes on ground

$30 \leq \ell \leq 3000\sim10000$

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.

FY2016

May 2016: International review

Aug. 2016: ISAS planning review

A1a

FY2017

A1b

A1c

Phase A1: Sep 2016 – Aug. 2018
- Phase A1a: Sep 2016 – Mar. 2017
- Phase A1b: Apr. 2017 – Aug. 2017
- Phase A1c: Sep. 2017 – Aug. 2018

FY2018

Down-selection (Solar power sail, new candidate)

Project Readiness Review (ISAS level & JAXA level)

FY2019

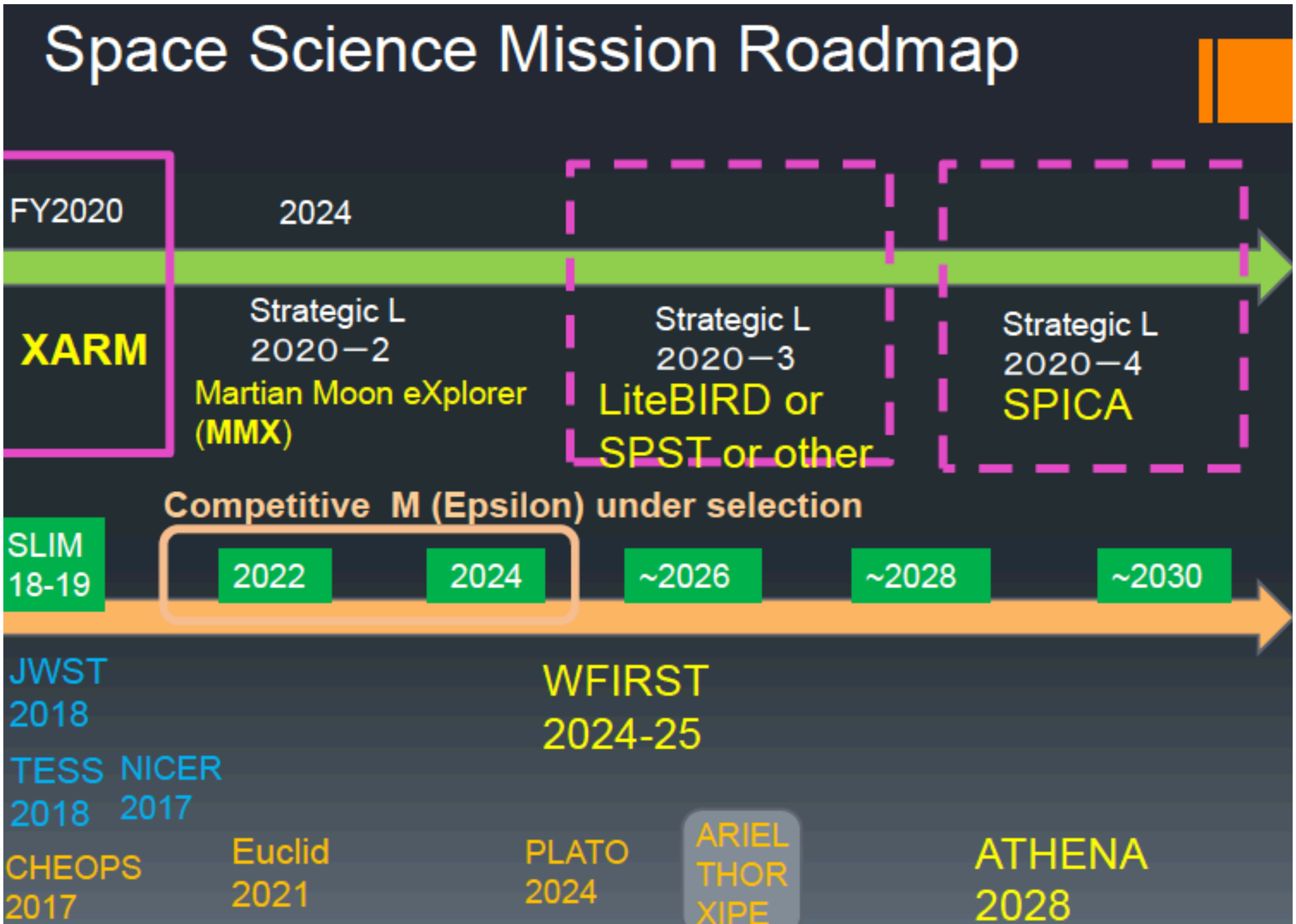
System Requirement Review

"Current Status of LiteBIRD in JAXA" by Toru Yamada

Current Status

- A serious candidate for the Strategic L-class slot in middle 2020's.
  - Proposal submitted to ISAS in response to a call for a strategic large mission in 2015.
  - 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

T. Dotani

Purpose : Risk mitigation through front-loading

TRL of mission instruments should be raised to 4 or 5.

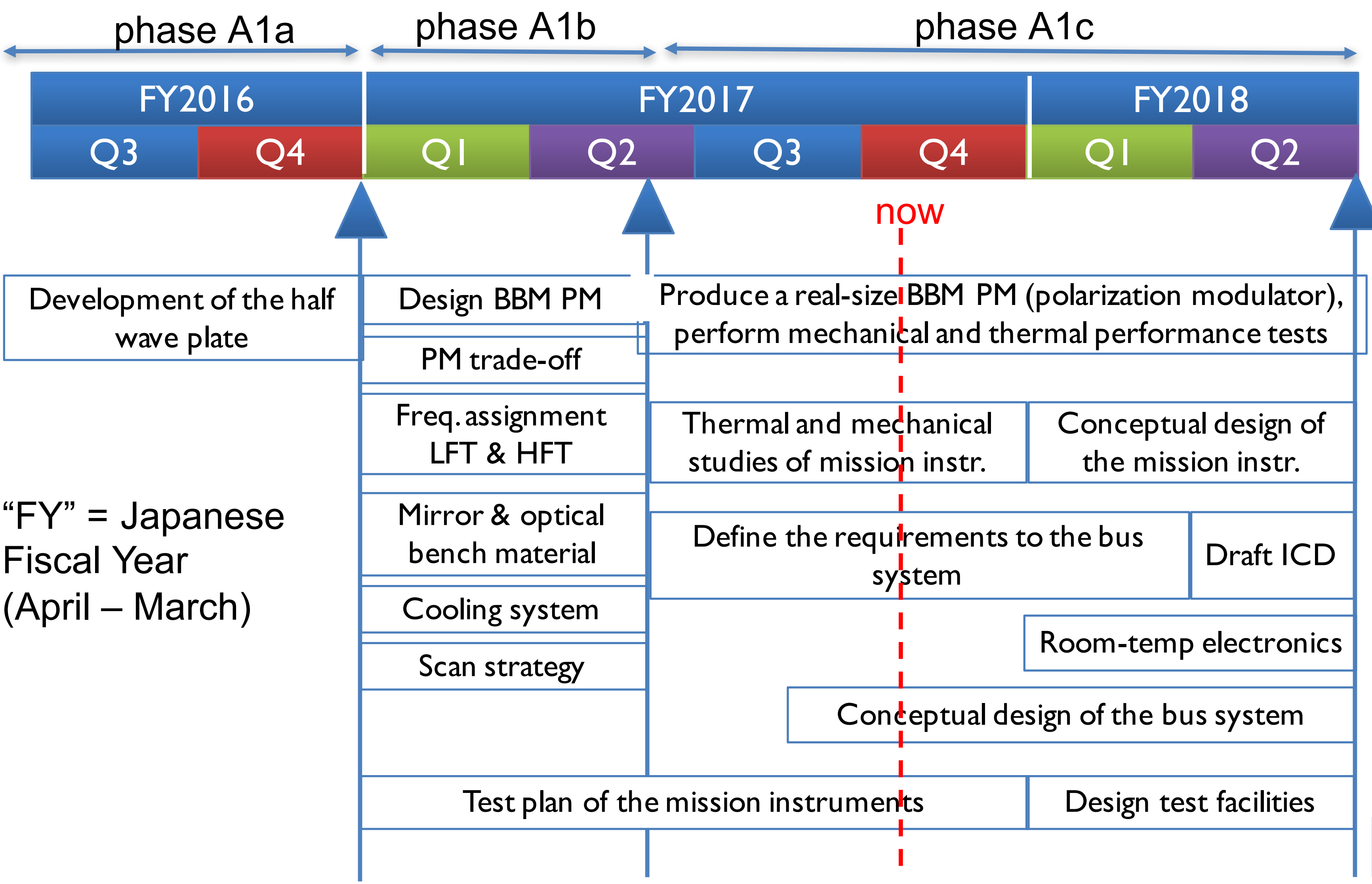
TRL4 : Breadboard model validation (in laboratory environment)
TRL5 : Engineering model validation (in relevant environment)

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

T. Dotani



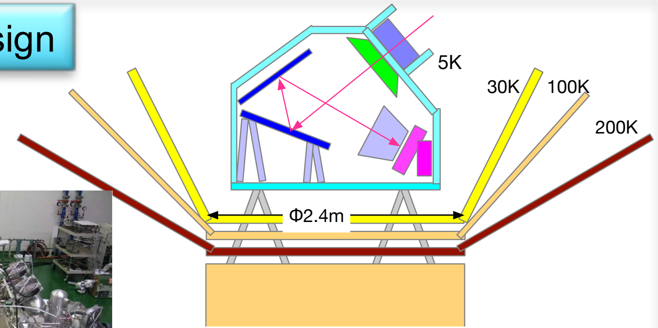
“FY” = Japanese Fiscal Year (April – March)

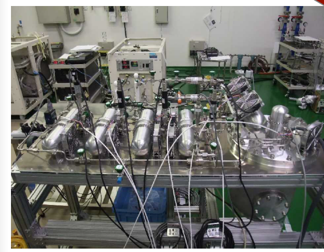
LiteBIRD Development in Japan

Keys to the success and Phase-A1 goals

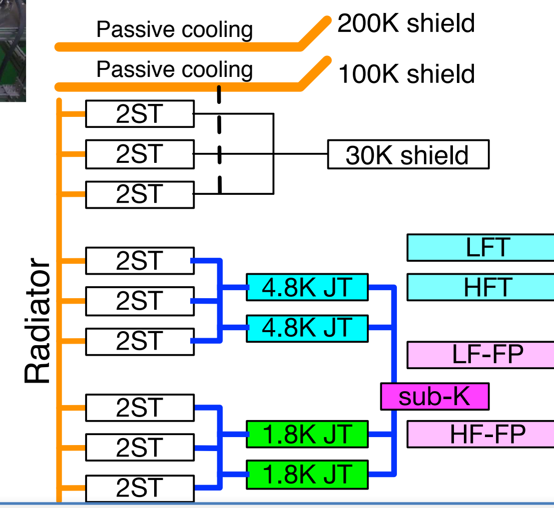
- Successful R&D on critical payload components
  - Polarization modulator (achieving TRL5)
  - Thermal design
- Sufficient systematics and foreground mitigations
  - Thorough studies by Joint Study Group
- Sufficient calibration strategy and AIV plan
- Reliable cost estimation
- Clear international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

Thermal design





JAXA ST/JT coolers

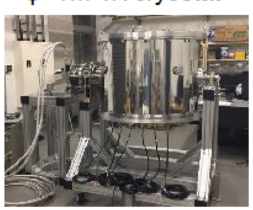


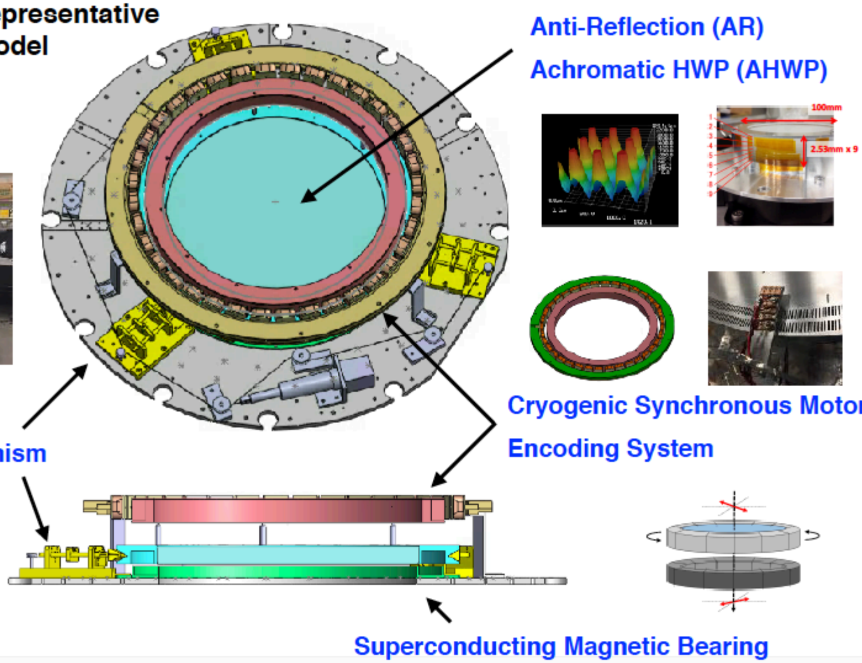
Polarization modulator

mitigation of 1/f noise differential systematics

ϕ 400mm flight representative demonstration model

ϕ~1m 4K cryostat





AIV plan

JAXA 6-m diameter space chamber

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.

LiteBIRD U.S. team

UC BERKELEY | STANFORD UNIVERSITY | CU BOULDER | UC SAN DIEGO | NIST

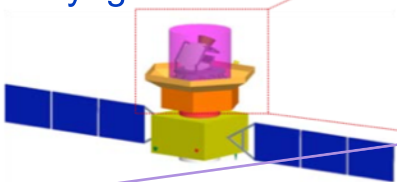
The Japanese LiteBIRD team members have 10 years of collaboration with the US team members on ground-based telescopes and LiteBIRD.

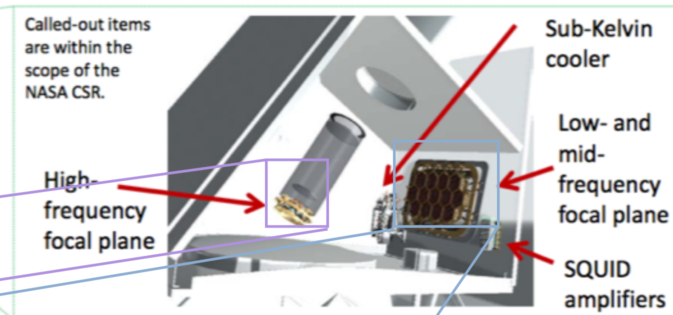
U.S. status/plan

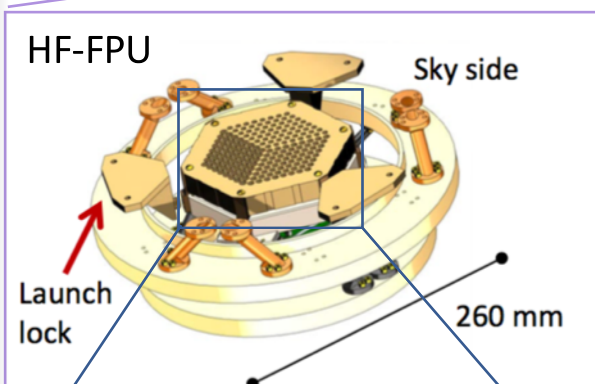
- Technology development supported by NAXA explorer
  - Goal: Advance TRL of focal-plane and cryogenic readout
- 2018 Mission of Opportunity preproposal
- 2020 Concept Study Report (CSR)
- 2021 Phase B Start

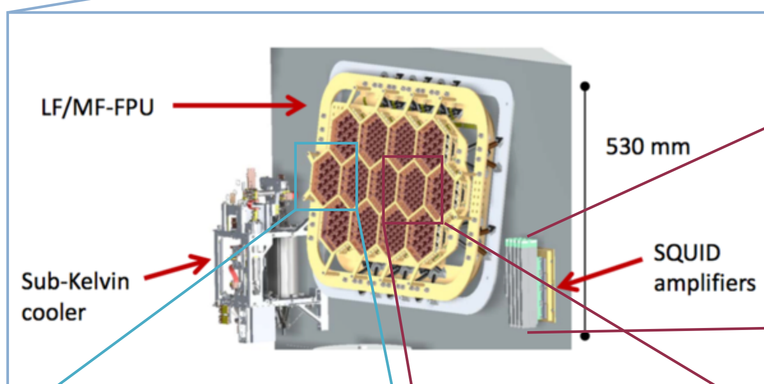
Expected U.S. deliverables

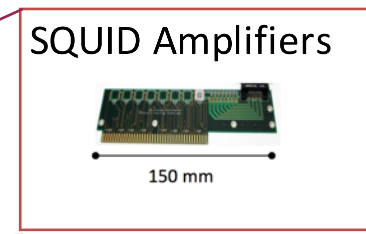
- Focal Plane Units (FPUs)
- Cryogenic readout

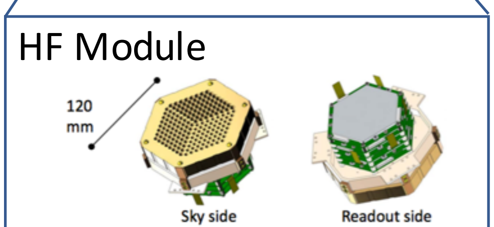


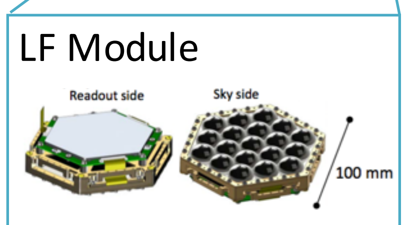


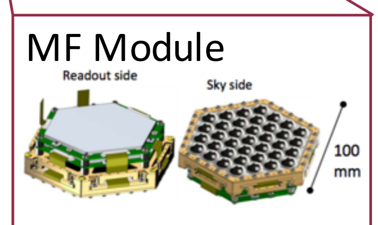










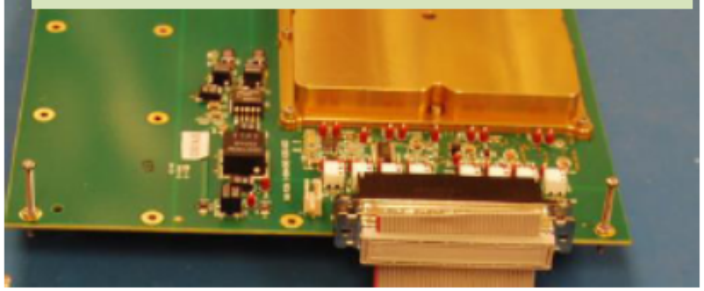


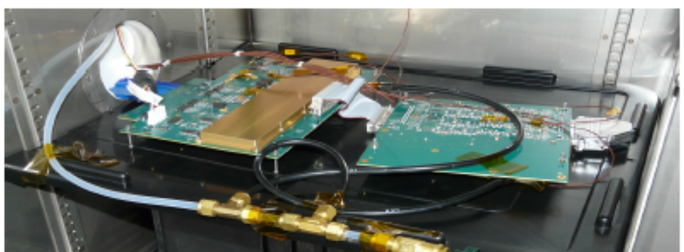
HF = High Frequency,
MF = Mid Frequency,
LF = Low Frequency

M. Dobbs

Canadian group formation

Design, construction and testing of **flight representative electronics** for the key analog circuits—the SQUID electronics and the digitizer/synthesizer (Mezzanine) boards in collab with experienced satellite builder (COM DEV).





Environmental testing of the Flight Representative hardware, and cryogenic **end-to-end testing** of the Flight representative hardware with the 64x DAN firmware to provide a TRL5 implementation of the readout system components.

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

European LiteBIRD Consortium

1st Meeting in Cardiff (Aug 2-3, 2017)

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

2nd Meeting in Paris (Oct 23-24, 2017)

ASI: committed to Phase A
ESA: starting joint studies on misshion payload

3rd Meeting in Turin (Feb 8-9, 2018)

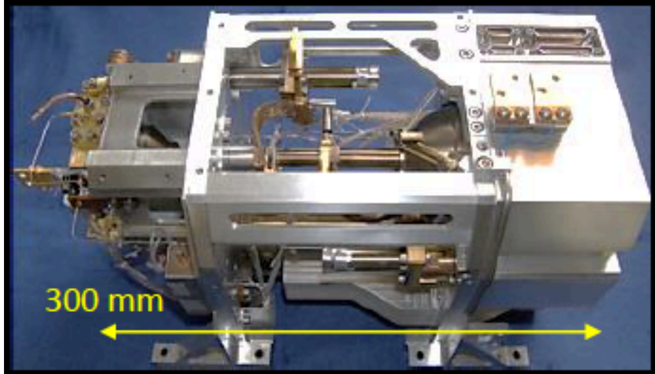
Expected major deliverables:

- High-Frequency Telescope (HFT)
- Sub-K cooling system

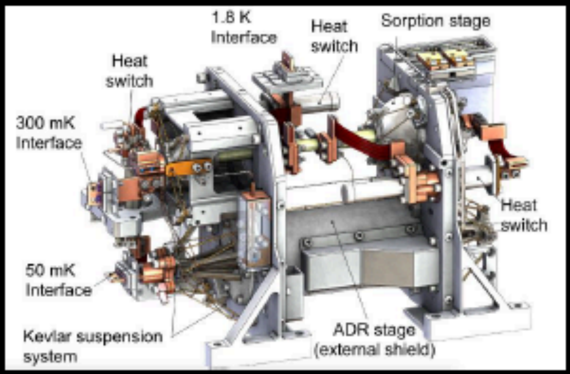
And strong role in data analysis

Sub-Kelvin Cooler

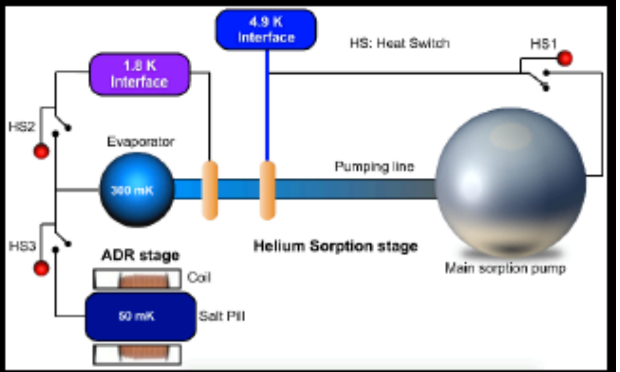
from LTD17 presentation by A. Suzuki



Sub-Kelvin Cooler without a cover



CAD drawing with parts call out



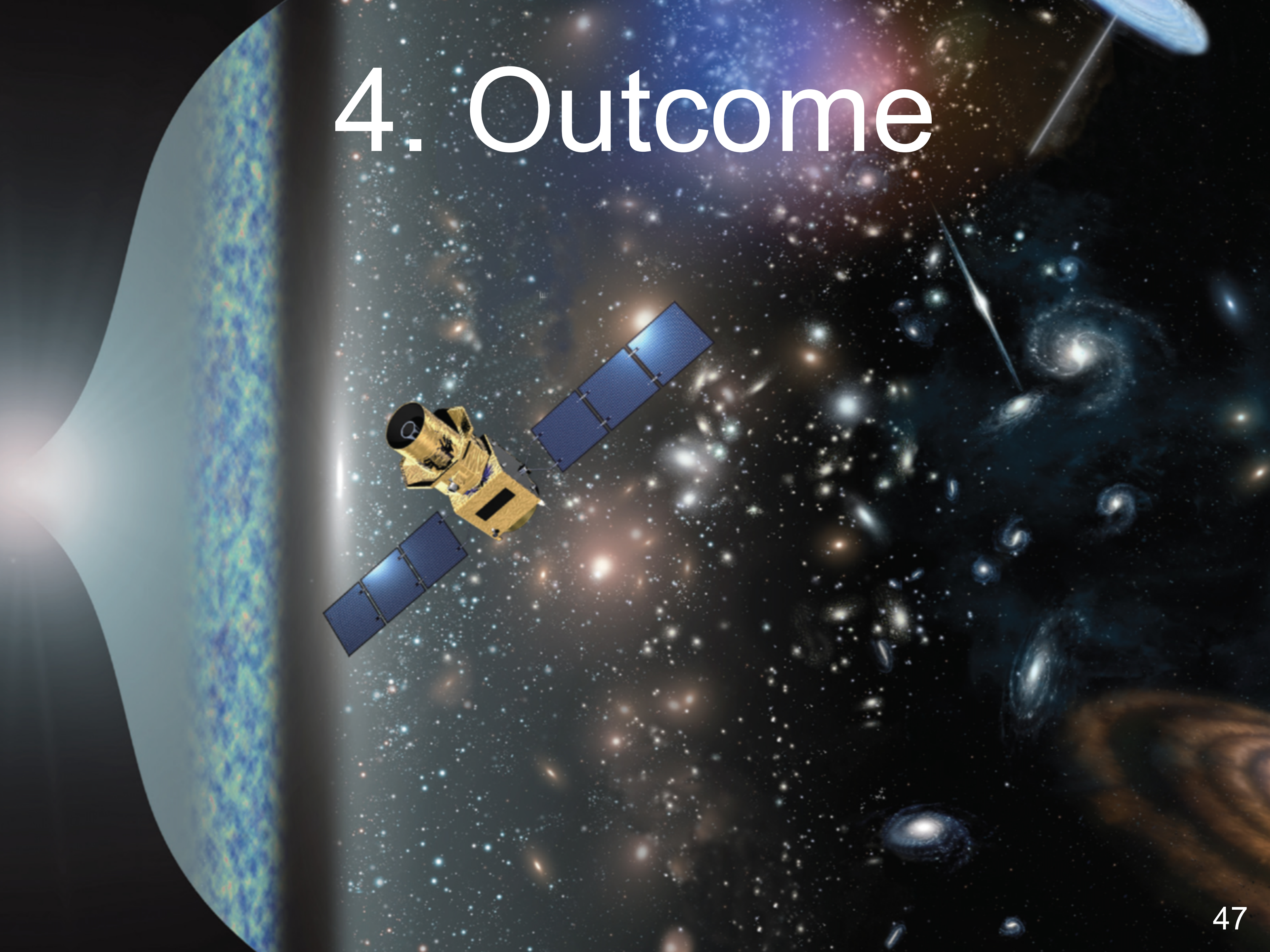
Schematic of the ADR

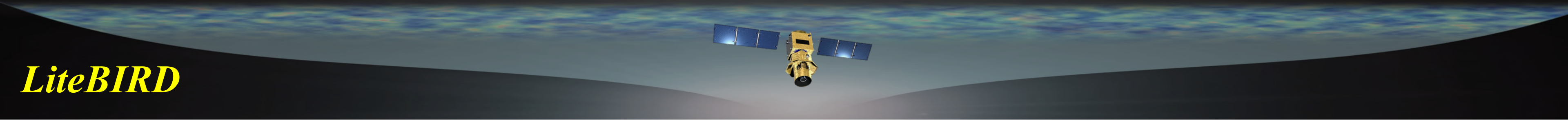
Baseline 2016

- 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 (τ, neutrino mass, pol. non-Gaussianity/bispectra, foreground science, etc.)

Scientific outcome examples (1)

LiteBIRD

1) C_l^{BB}

Error on n_t ~0.04 is possible

- inflation and quantum gravity (r, n_t)
- improvement w/ delensing
- lensing B-mode to very low ℓ

2) C_l^{EE}

- reionization history
- better τ and sum of neutrino masses

Scientific outcome examples (2)

3) Power spectrum deviation from ΛCDM
   - 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

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

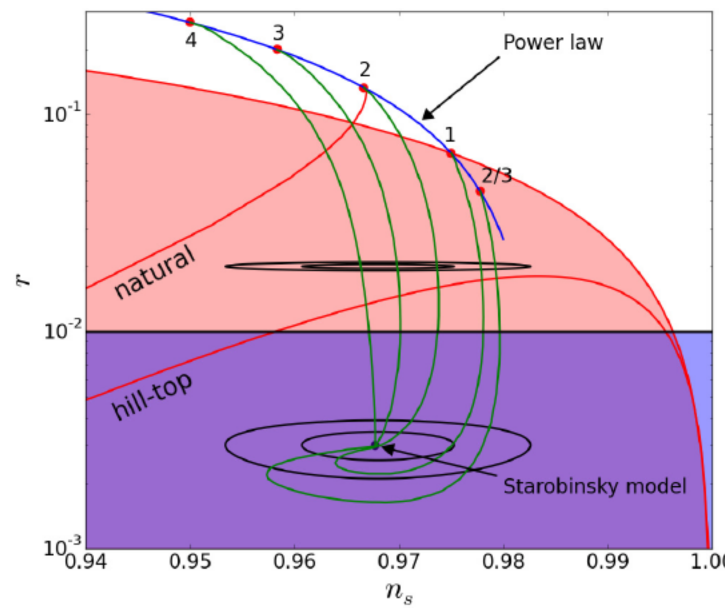
V: Inflaton potential
r: tensor-to-scalar ratio ← proportional to the B-mode power

- 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 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 → >10sigma 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

Lyth relation

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

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.

→ $\sigma(r) < 0.001$ is needed to rule out large field models that satisfy the Lyth relation with >95%C.L.

If evidence is found before launch

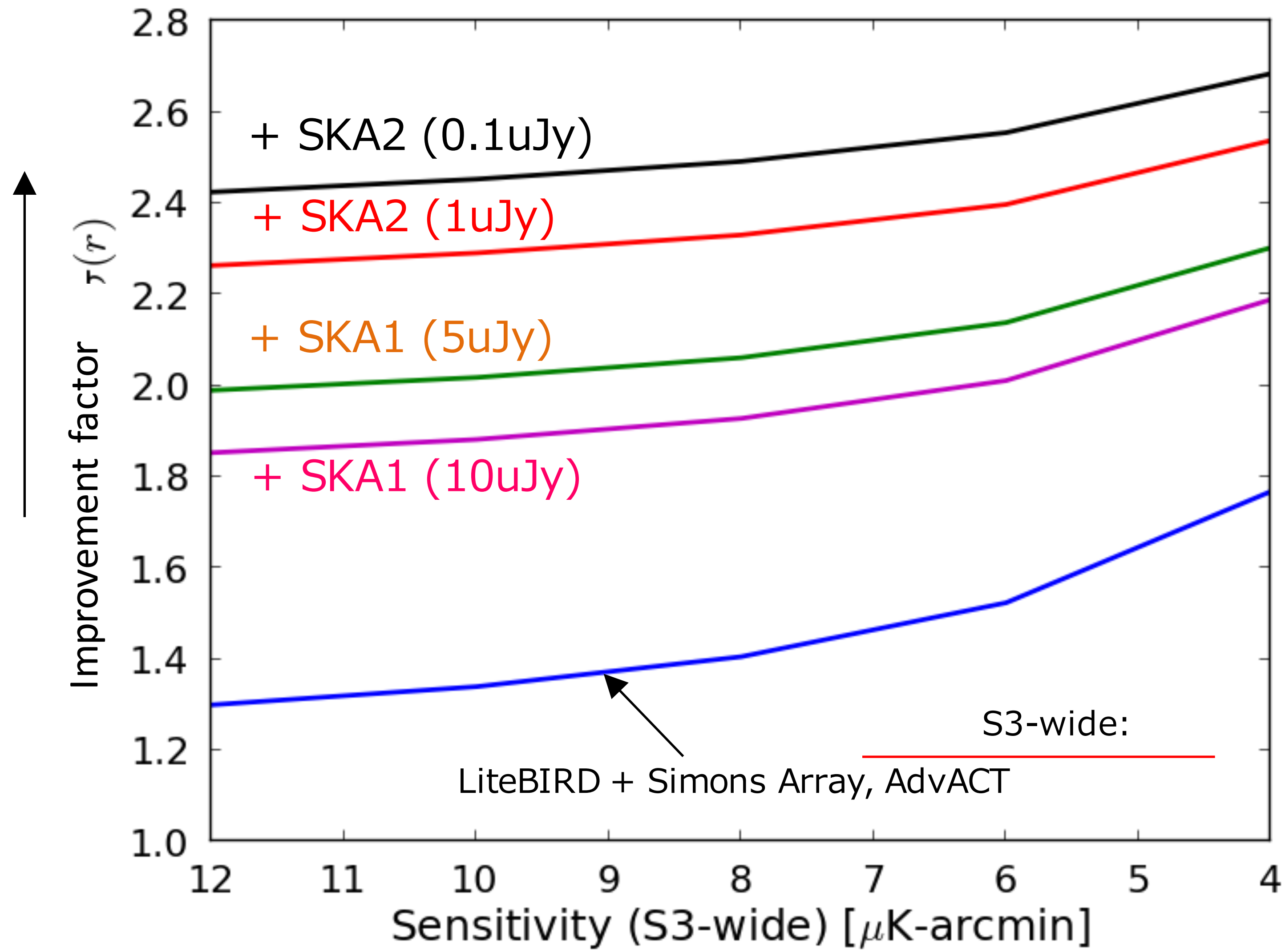
- r is fairly large → Comprehensive studies by LiteBIRD !
- Much more precise measurement of r from LiteBIRD will play a vital role in identifying the correct inflationary model.
- LiteBIRD will measure the B-mode power spectrum w/ high significance for each bump if $r>0.01$.
  - Deeper level of fundamental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

$\sigma(r) < 0.001$ for $2 \le \ell \le 200$ 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



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

LiteBIRD

Gravitational lensing potential reconstruction w/ radio galaxies as mass tracer

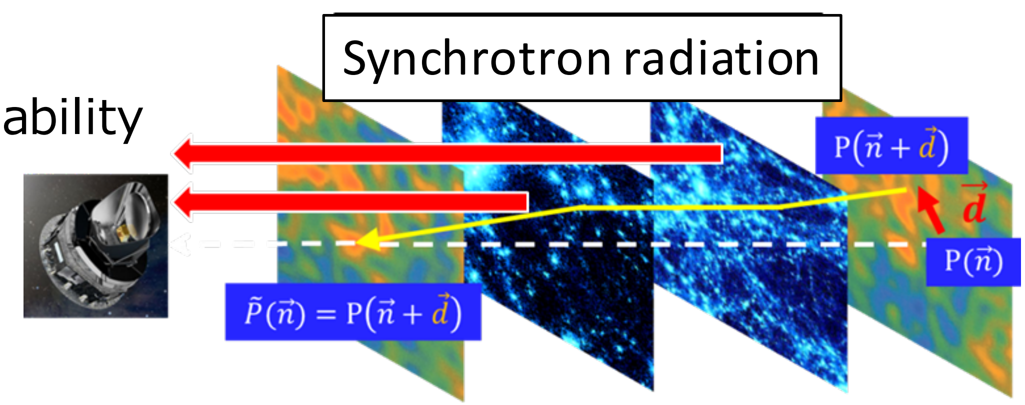
SKA radio continuum survey

- Number density of galaxies from difuse (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

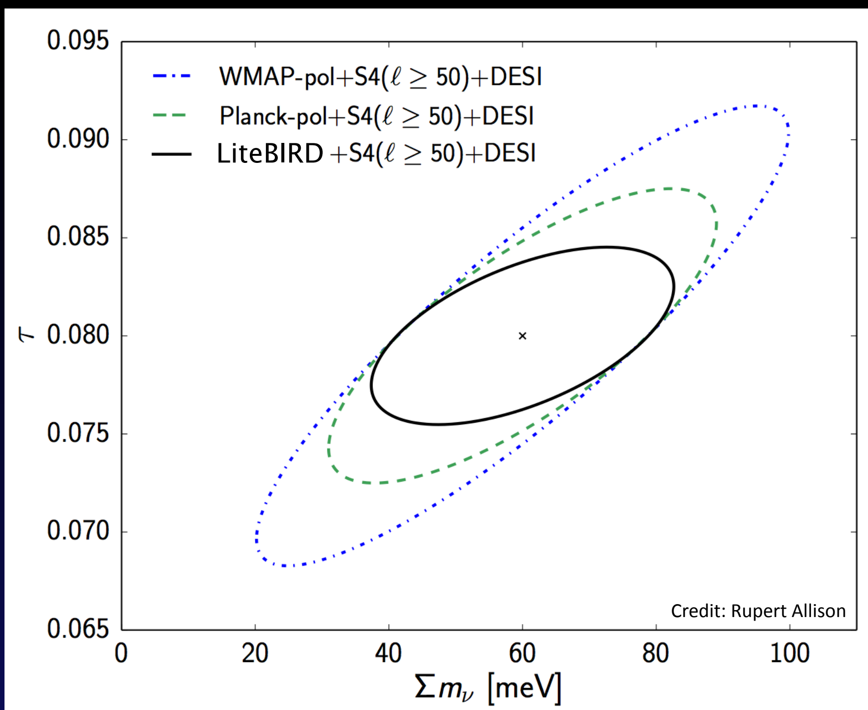
Galaxy distribution for each z ⇒ matter density fluctuation at each z
⇒ Gravitational potential responsible for lensing at each z

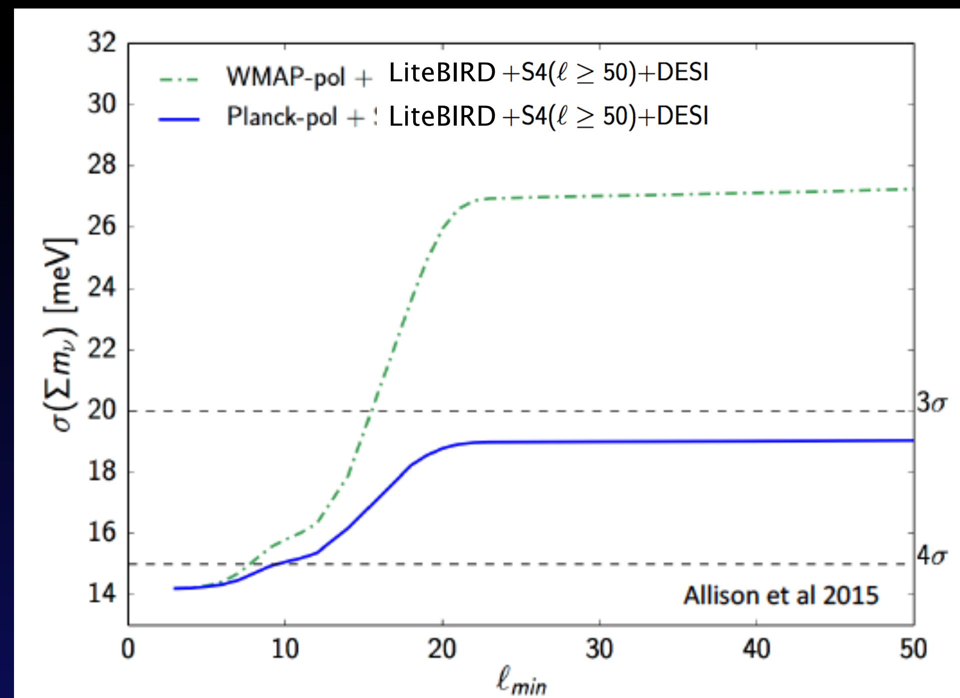
- Most of lensing CMB B-mode reconstructable thanks to the capability of accessing high z
- Efficient delensing leads to better sensitivity on primordial B-mode



τ(optical depth) and neutrino mass

- Better E-mode measurement for < 20 improves τ
- Better τ improves Σm_ν
- Σm_ν > 58meV from oscillation measurements





Low ℓ measurements contribute to Σm_ν !

Origin of gravitational waves

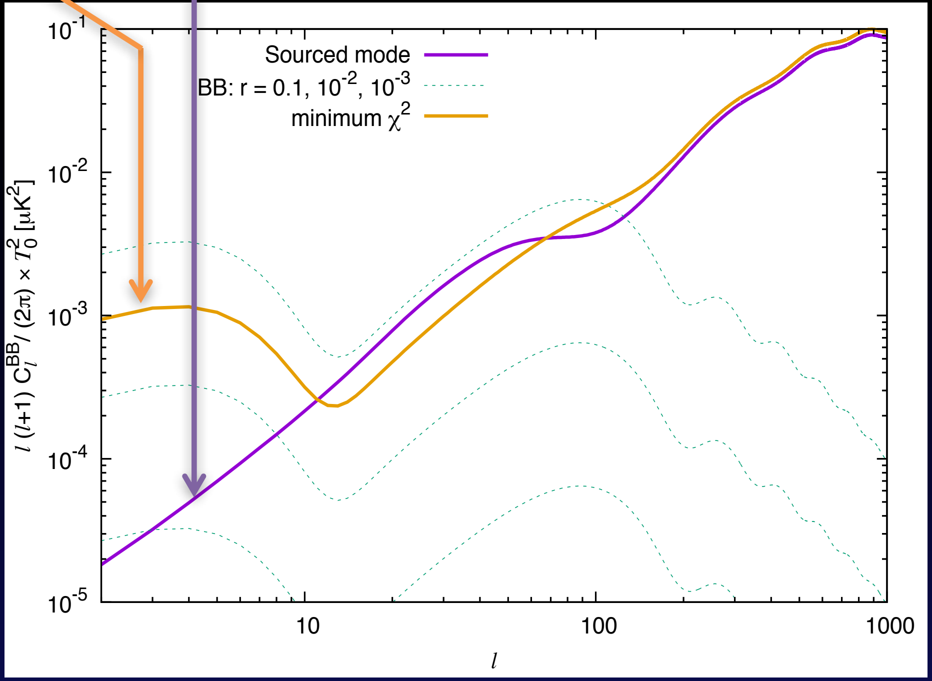
M. Shiraishi, C. Hikage, T. Namikawa, R. Namba, MH, Phys. Rev. D 94, 043506 (2016)

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 >3σ

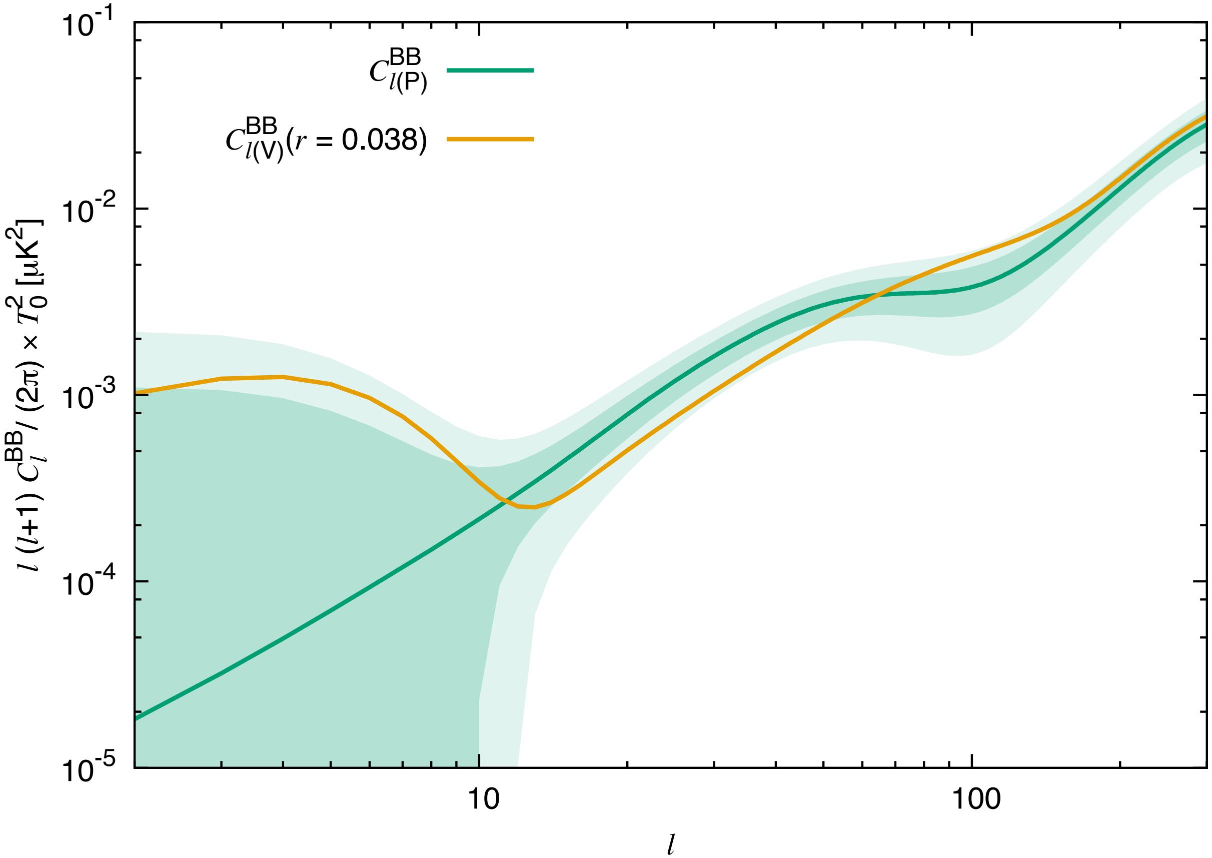


"Pseudoscalar model" from Namba, Peloso, Shiraishi, Sorbo, Unal, arXiv1509.07521 as an "evil example model"; indistinguishable w/ BB for ell > 10 alone.

Separation power w/ "BB"

LiteBIRD

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



reduced chi^2

$\chi^2_{BB}/(l_{max}-l_{min})$

= 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 vaccum fluctuation hypothesis be ruled out ?

$$\chi^2_{BBB}(r) = \sum_{\substack{\ell_1,\ell_2,\ell_3=\ell_{\min} \\ \ell_1+\ell_2+\ell_3=\mathrm{even}}}^{\ell_{\max}} \frac{\left|B^{BBB}_{\ell_1\ell_2\ell_3(\mathrm{P})}\right|^2}{6\prod_{n=1}^{3}\left(C^{BB}_{\ell_n(\mathrm{V})}(r) + N^{BB}_{\ell_n}\right)}$$

<u>= 13 @ LiteBIRD → 3.6σ rejection !</u>

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

Remarks

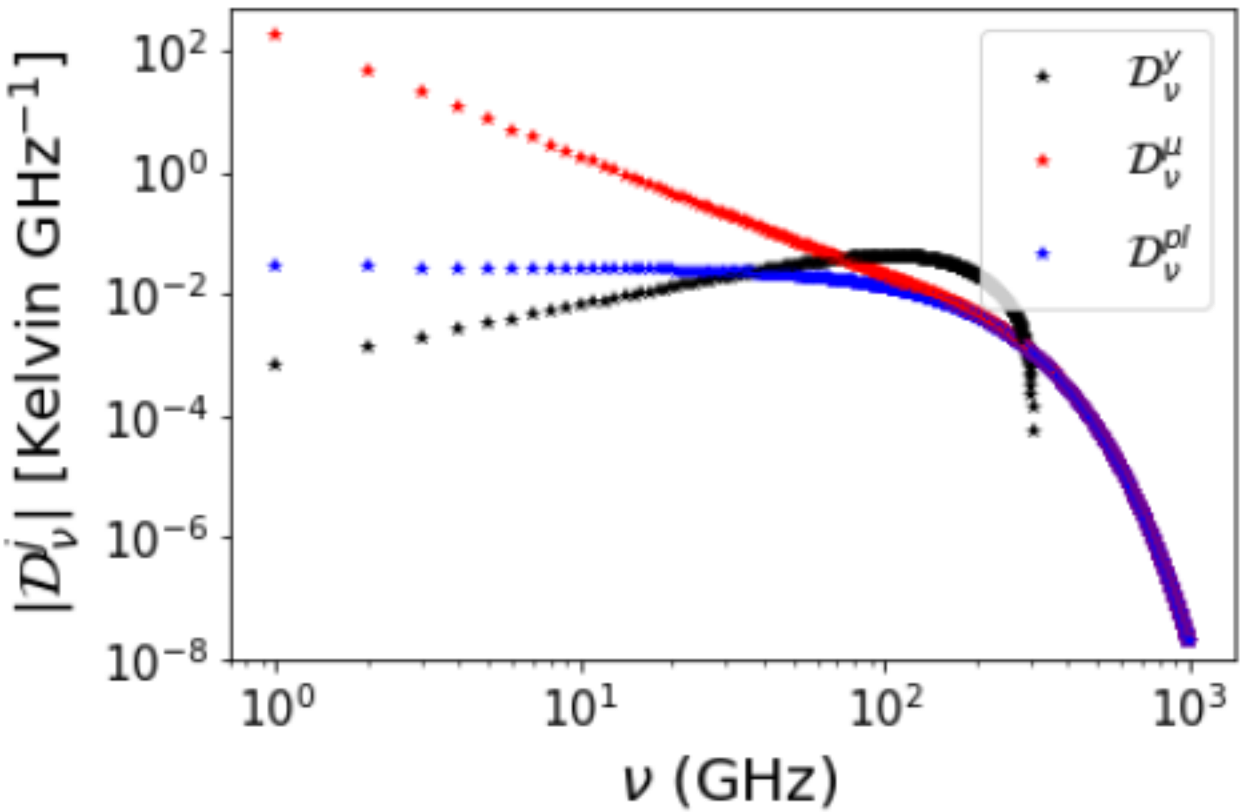
- l_{max} = 100 saturates the BBB sensitivity
- lmin = 30 → rejection significance is 1.9σ, which is not sufficient.

→ 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 ?

4 *Mukherjee, Silk & Wandelt* arXiv:1801.05120



Assesment at LiteBIRD in preparation

LiteBIRD Summary

Probing the Universe before the hot Big Bang

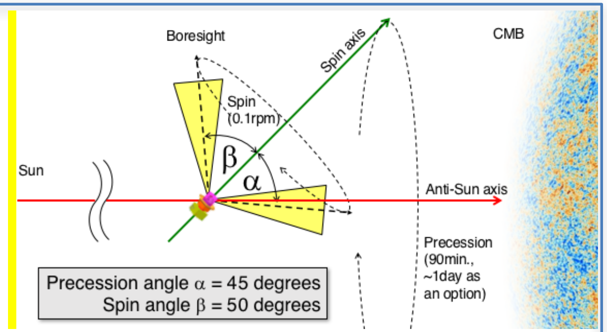
Scientific objectives

Mission for Fundamental Physics with High Priority in JAXA's Roadmap

- 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: **$\delta r < 0.001$** (δr: 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

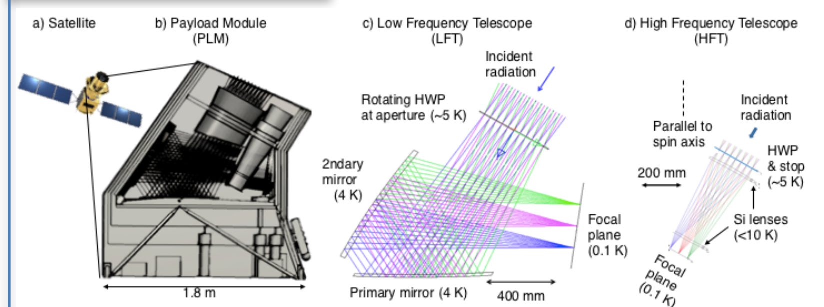
Observations

- 3year 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

- Phase A1 (Sep. 2016 – Aug. 2018)
- Final selection in JFY 2018
- Launch in mid. 2020's w/ JAXA H3