LiteBIRD

for testing Cosmic Inflation from CMB polarization measurements from space

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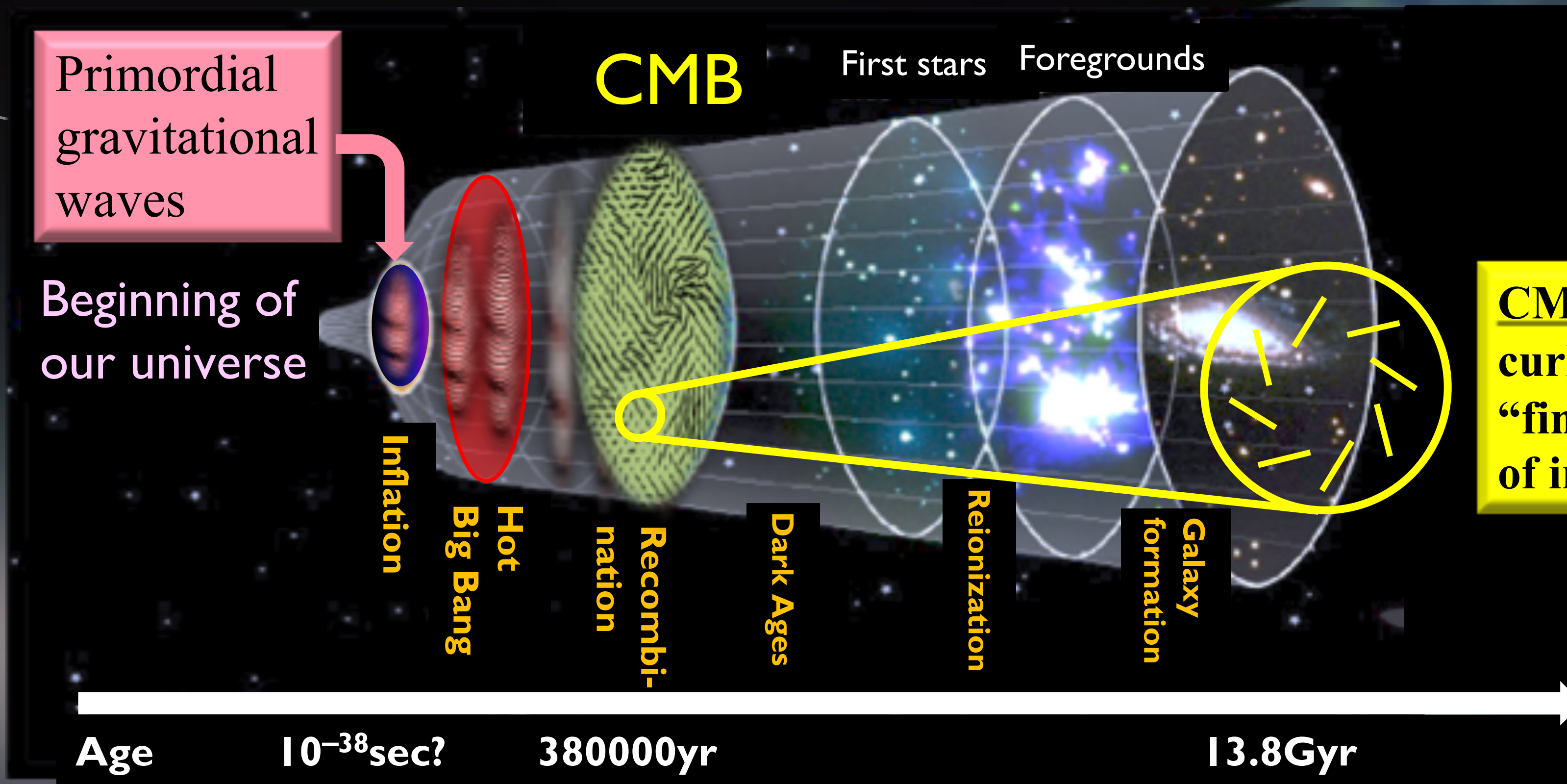
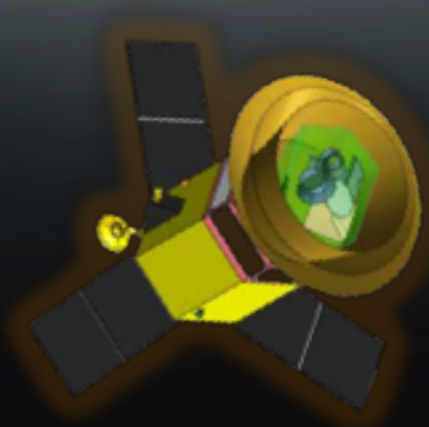
4) Graduate School for Advanced Studies (SOKENDAI)

for LiteBIRD Joint Study Group





- LiteBIRD is a satellite to observe polarization of the CMB.
- Its primary mission is to search for the signal of primordial gravitational waves, imprinted as the CMB B-mode polarization.

Huge discovery impacts

LiteBIRD

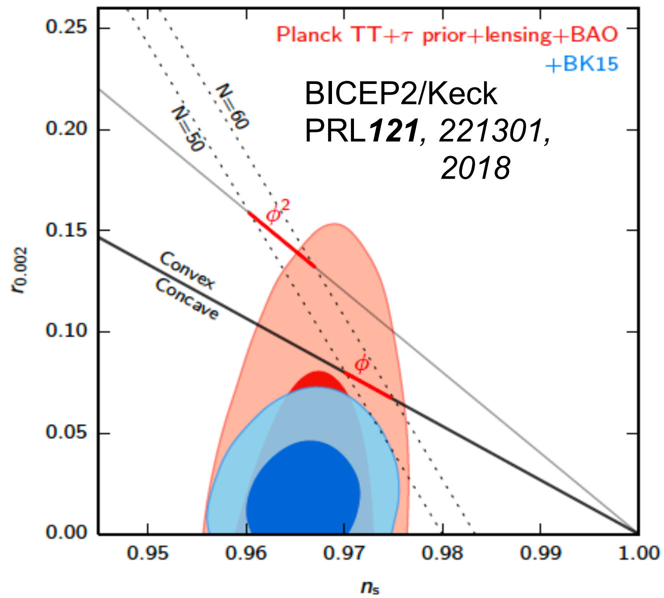
- Direct evidence for Cosmic Inflation, and knowledge on when it happened
- (Arguably) First evidence for quantum fluctuation of space-time
- Knowledge on the Inflation energy scale

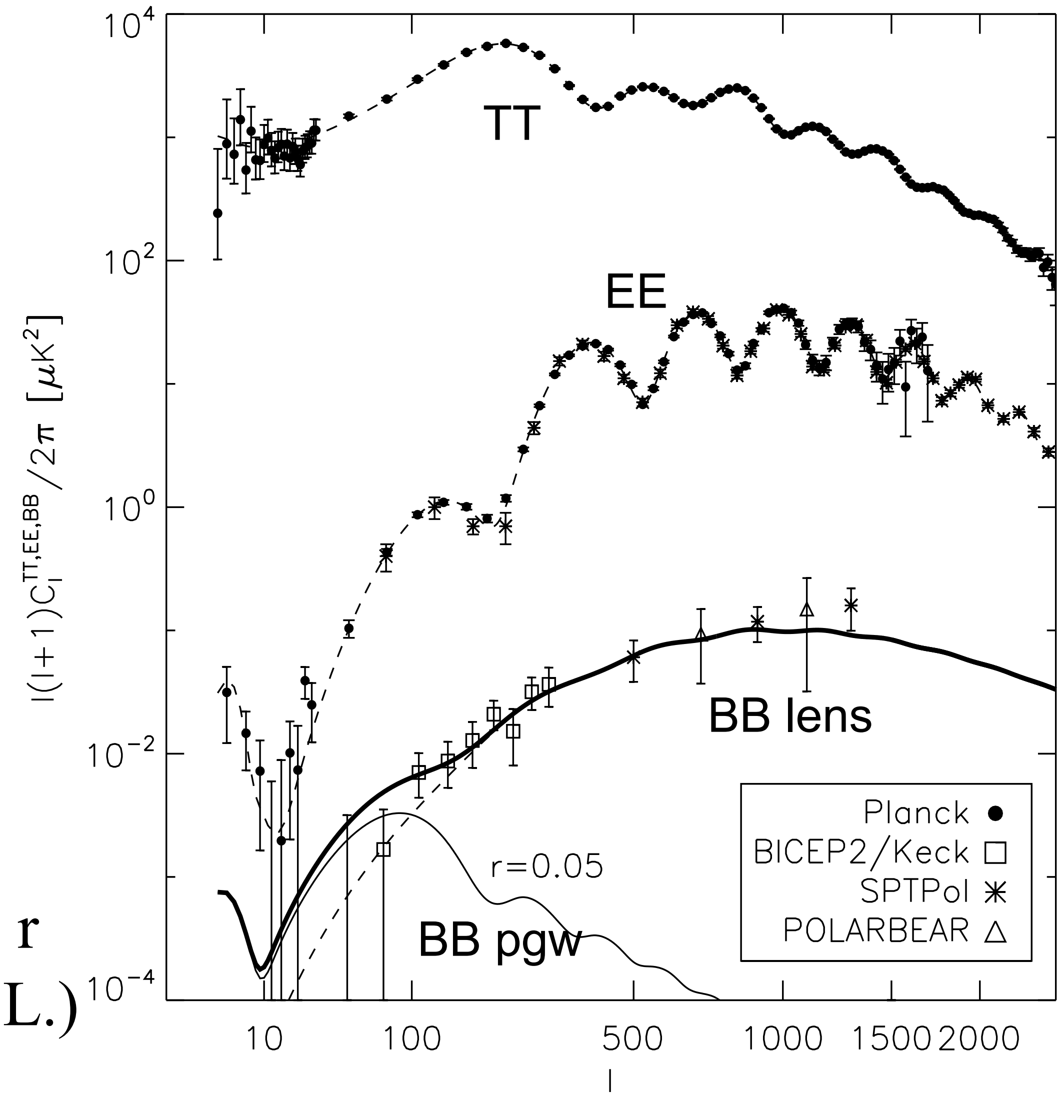
“Detecting primordial gravitational waves would be one of the most significant scientific discoveries of all time.”

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

CMB power spectra

BB from primordial gravitational waves (pgw) has not been discovered yet.





$C_l^{BB}{}_{pgw} \propto$ tensor-to-scalar ratio, r

<u>Current limit</u>: r < 0.06 (95% C.L.)

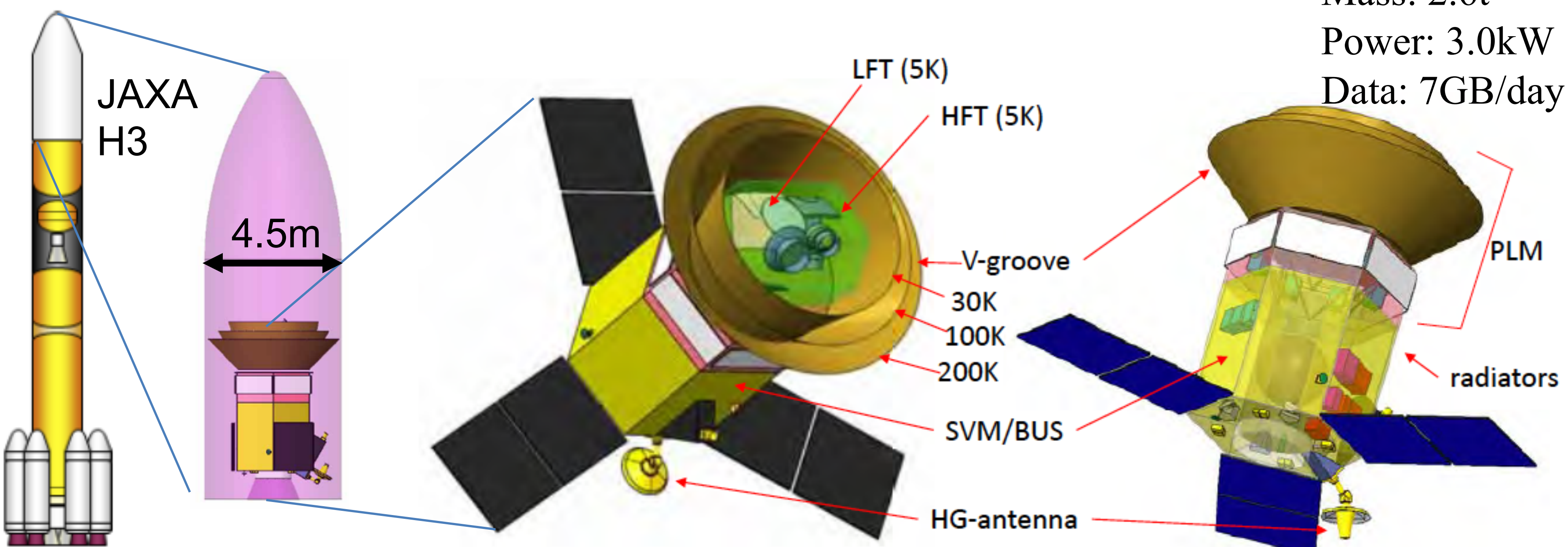
Large field models (i.e. large B-mode signals) only in the Swampland ?

We will see.

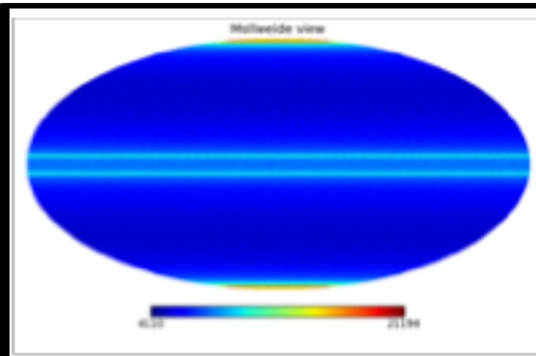
LiteBIRD project overview

- JAXA's L-class mission candidate
- Expected launch in 2027
- Observations for 3 years (baseline) around Sun-Earth Lagrangian point L2
- Millimeter-wave all sky surveys (34–448 GHz, 15 bands) at 70–20 arcmin.
- Mission: $\delta r < 0.001$ in $2 \leq \ell \leq 200$ w/ CMB B-mode observation

Mass: 2.6t
Power: 3.0kW
Data: 7GB/day

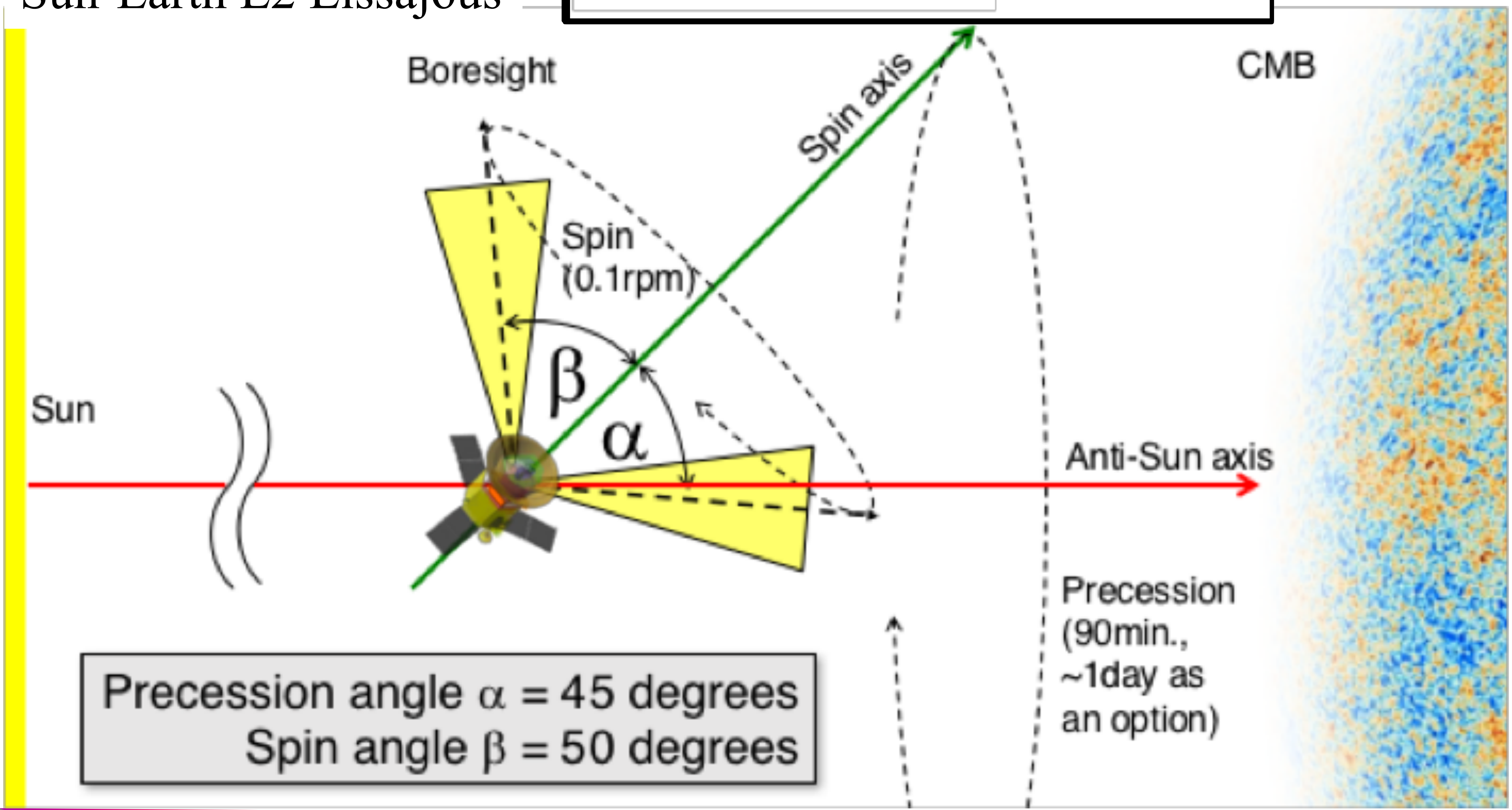


Operation



1 year

Orbit:
Sun-Earth L2 Lissajous



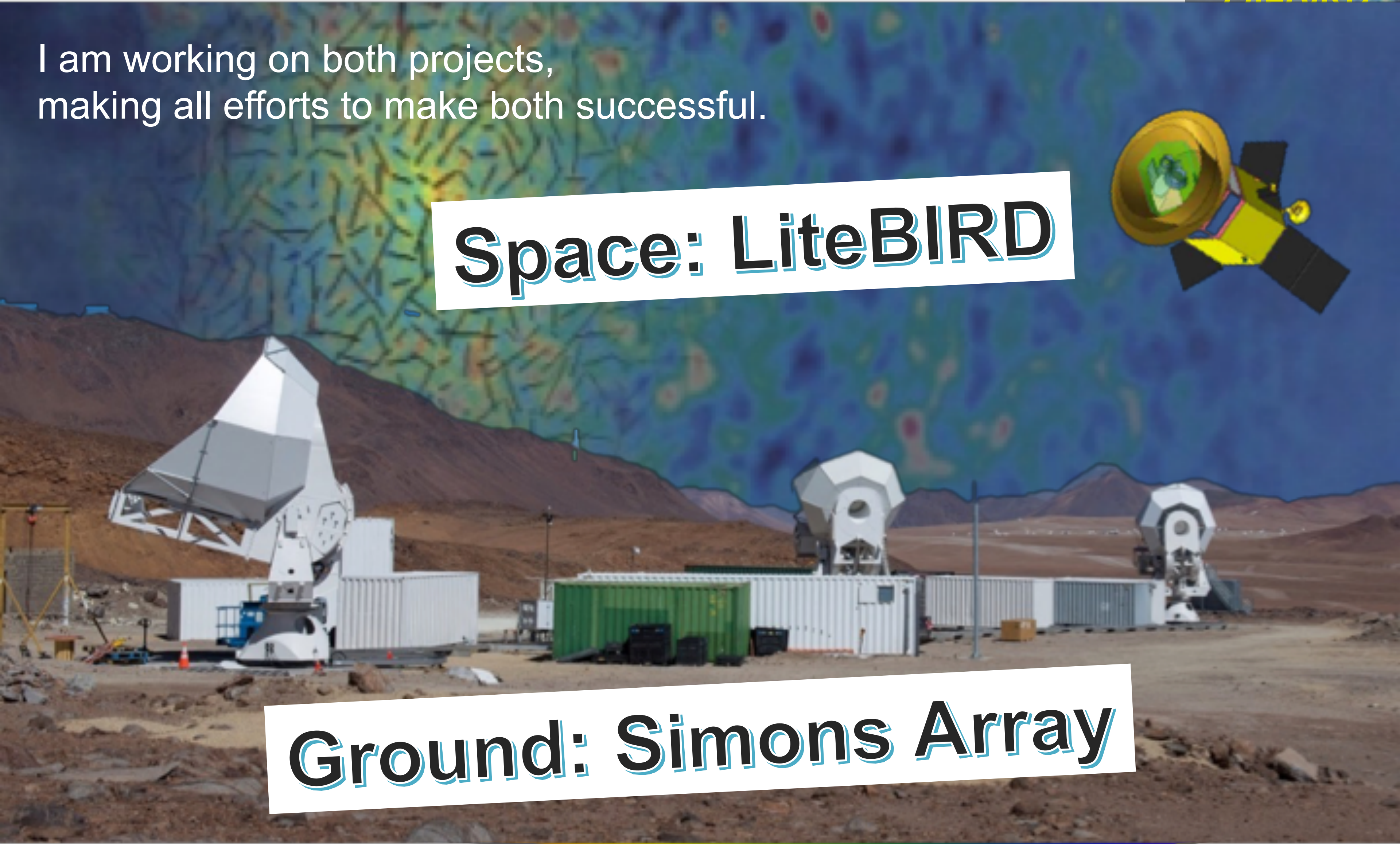
LiteBIRD Joint Study Group

About 200 researchers from Japan, North America & Europe

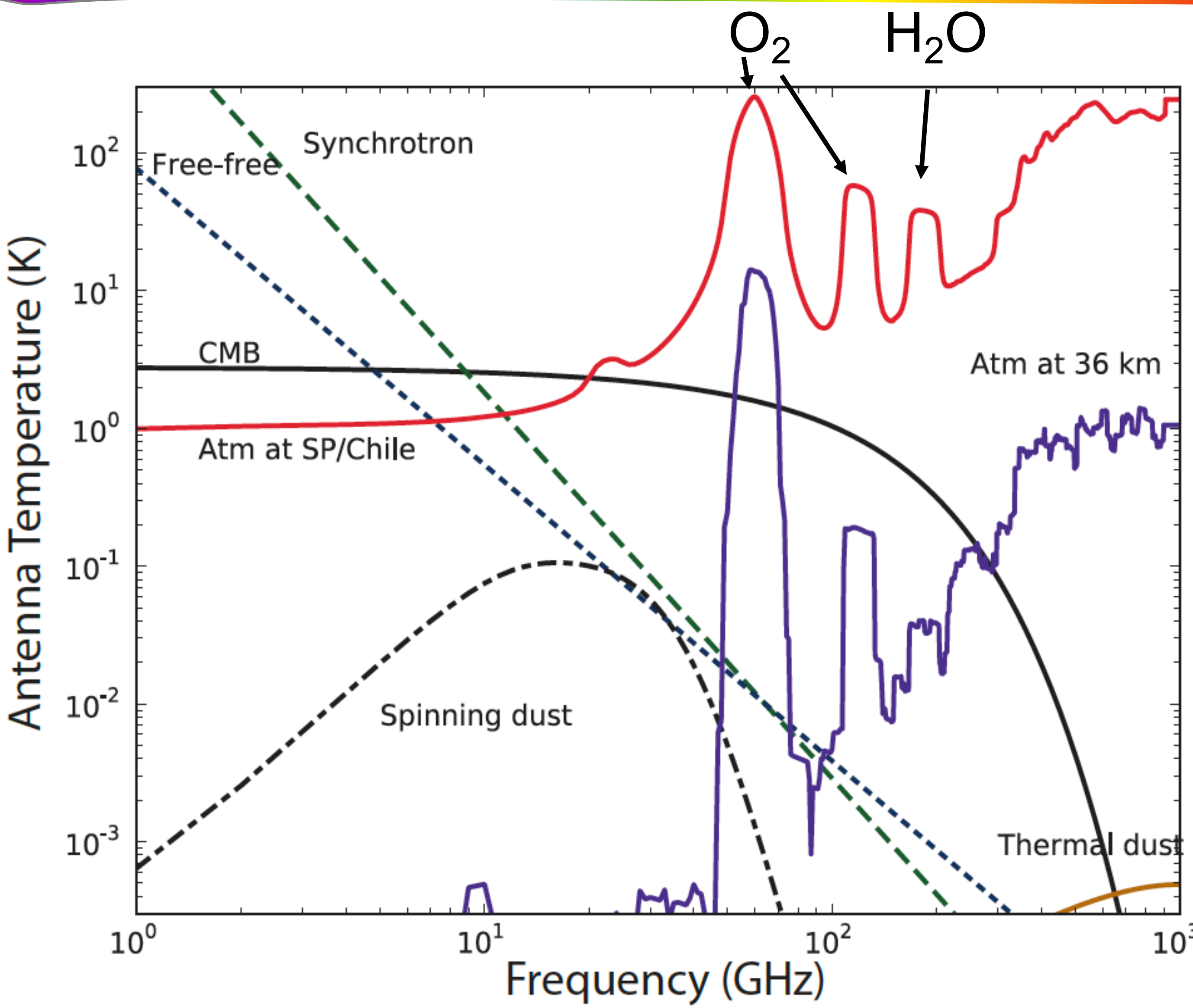
Team experiences: CMB exp., X-ray satellites, other large proj. (HEP, ALMA etc.)

Why measure from space?

I am working on both projects,
making all efforts to make both successful.



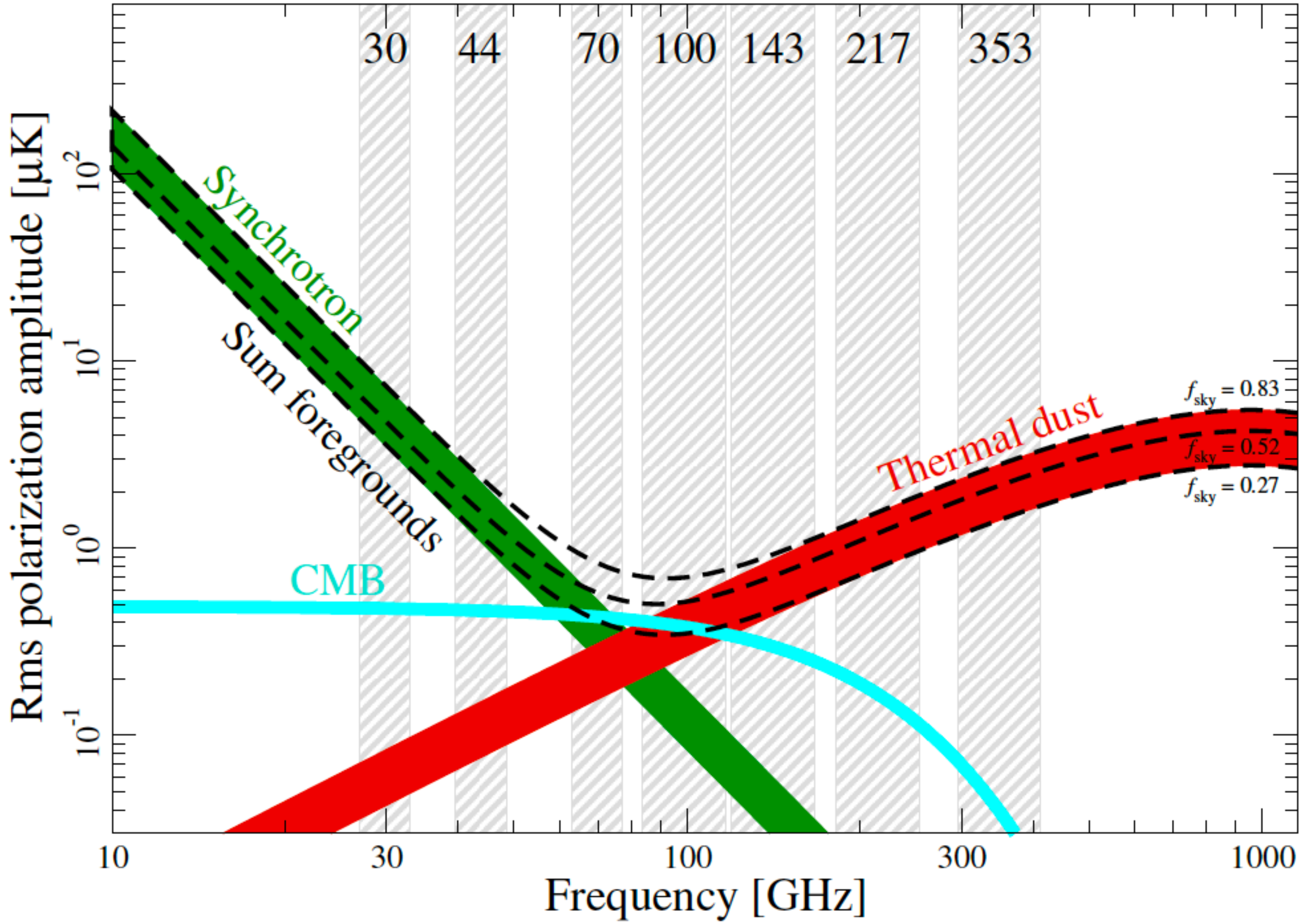
Why measure from space?



<u>Sky emission:</u>
Galactic latitude ~20deg.

Hanany, Niemack, Page arXiv:1206.2402

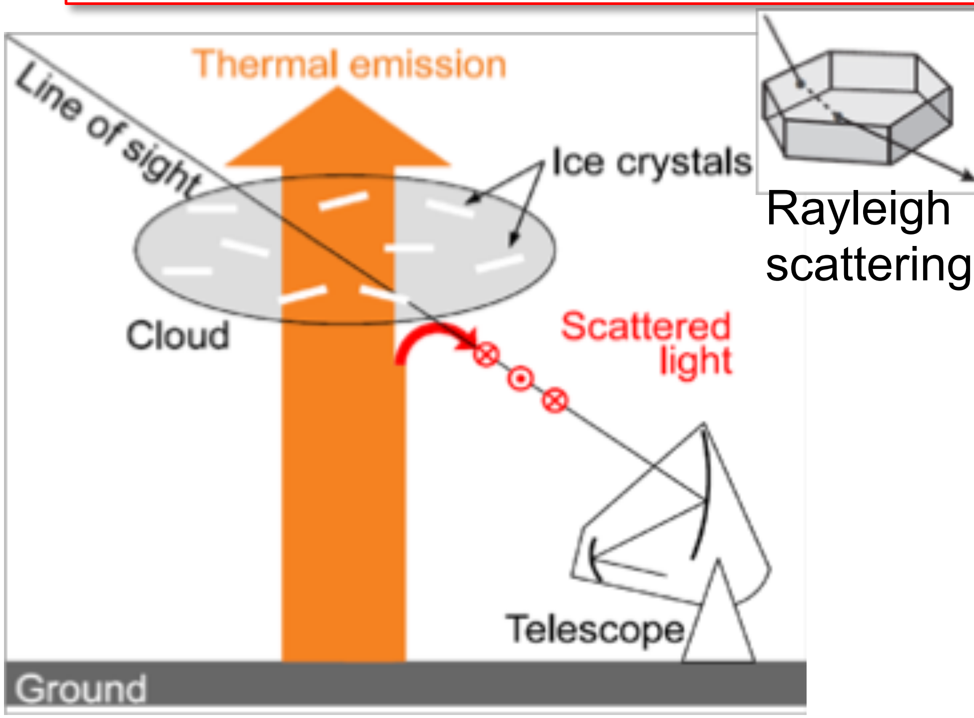
Why measure from space?



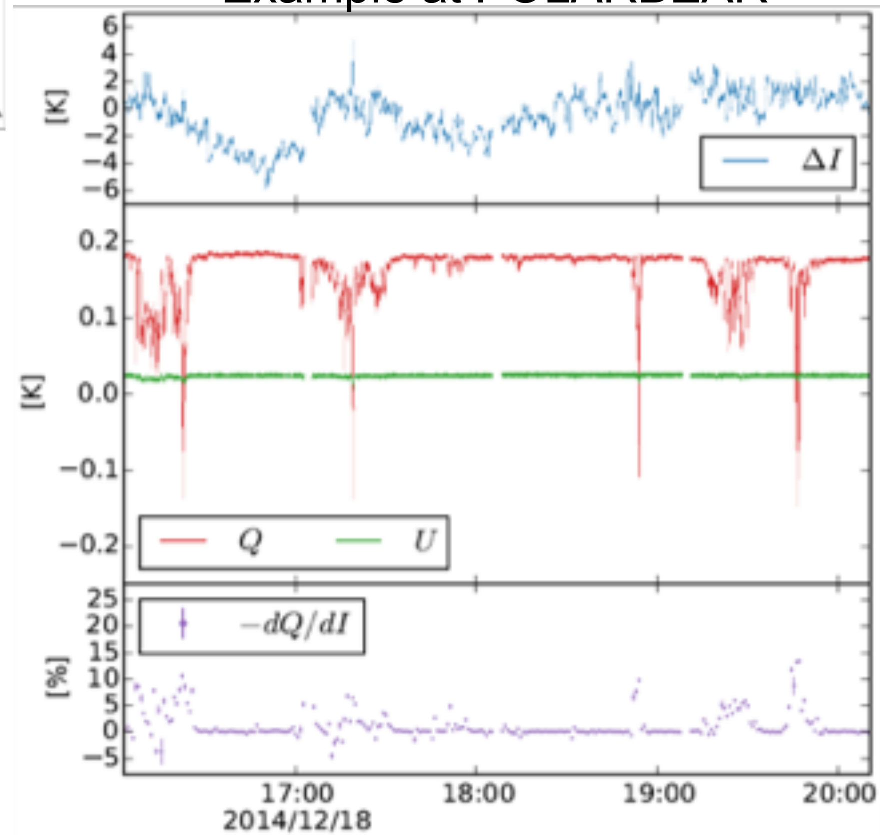
Planck
2018

Why measure from space?

A new problem on ground: Polarization from icy clouds



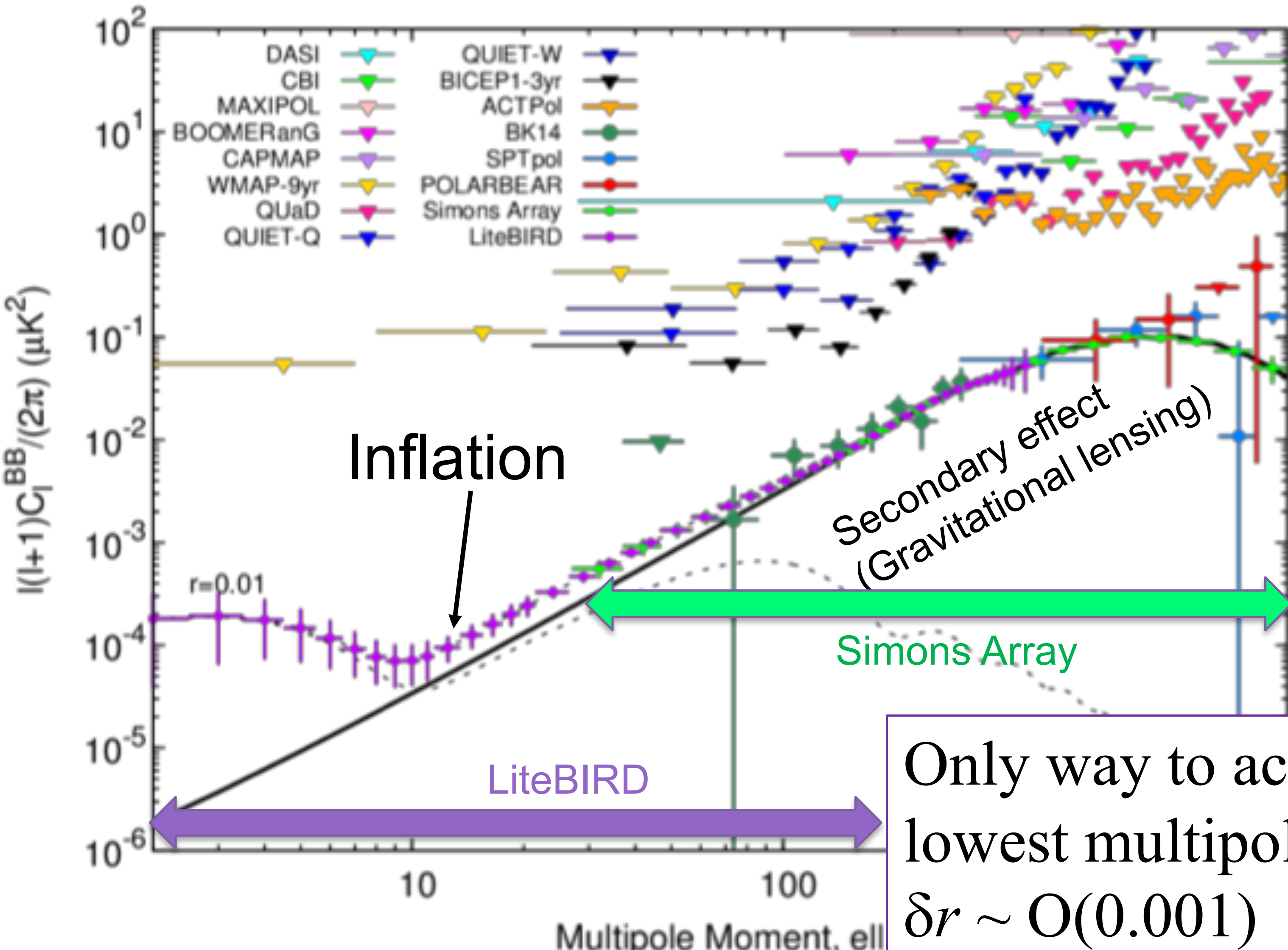
Example at POLARBEAR



All ground proposals (Simons Array, Simons Observatory, CMB-S4 etc.) need to address this "super foreground" issue.

Satoru Takakura *et al* 2019 *ApJ* **870** 102 (arXiv:1809.06556)

Why measure from space?



Only way to access lowest multipoles w/ $\delta r \sim O(0.001)$

Why measure from space?

- Superb environment !
  - No statistical/systematic uncertainty due to atmosphere (cf. polarization due to icy clouds in POLARBEAR obs., S. Takakura et al. 2018)
  - No limitation on the choice of observing bands (except CO lines)
  - No ground pickup

  Rule of thumb: 1,000 detectors in space ~ 100,000 detectors on ground

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

LiteBIRD status and near-term schedule

- ISAS/JAXA Phase-A1* concept development completed (Sep. 2016 – Aug. 2018)
  - The most advanced status among all CMB space mission proposals in the world
  - Phase A committment from ASI, CNES, CSA, NASA (tech. development), ESA also conducted CDF studies on HFT w/ JAXA and European consortium
- Phase-A1 exit review (Nov.-Dec. 2018) ended successfully
  - **About 950 pages of study reports**
- Cost reduction & review (Jan.-Mar. 2019) ⟸ We are here.
- Final down selection (April 2019?)
  - LiteBIRD or OKEANOS (solar-sail mission to Jupiter's Trojans)

*After JAXA's operational reforms in 2017, it is now called pre-Phase-A2.

Advantages of LiteBIRD

- In 2017, the funding agency (MEXT) selected LiteBIRD as one of seven most important new large-scale projects in Japan among all areas of research !
- JAXA roadmap chose probing Cosmic Inflation from B-mode as one of top scientific objectives.

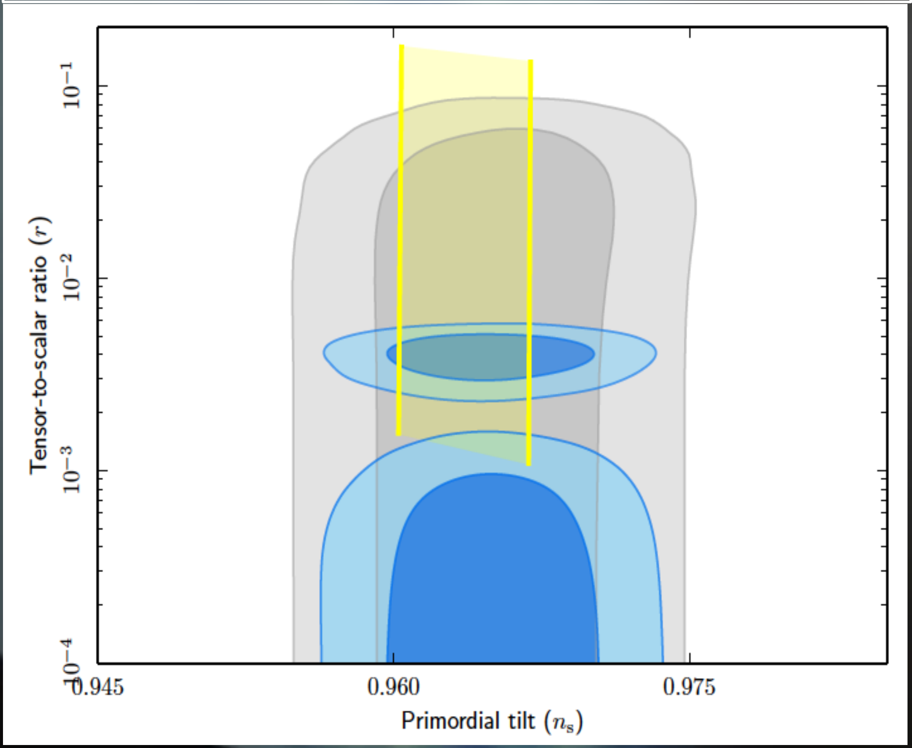
LiteBIRD has a clear goal and can achieve it!

Full Success：
$\delta r < 1 \times 10^{-3}$ (for r=0)
$2 \leq \ell \leq 200$

(Rationale)

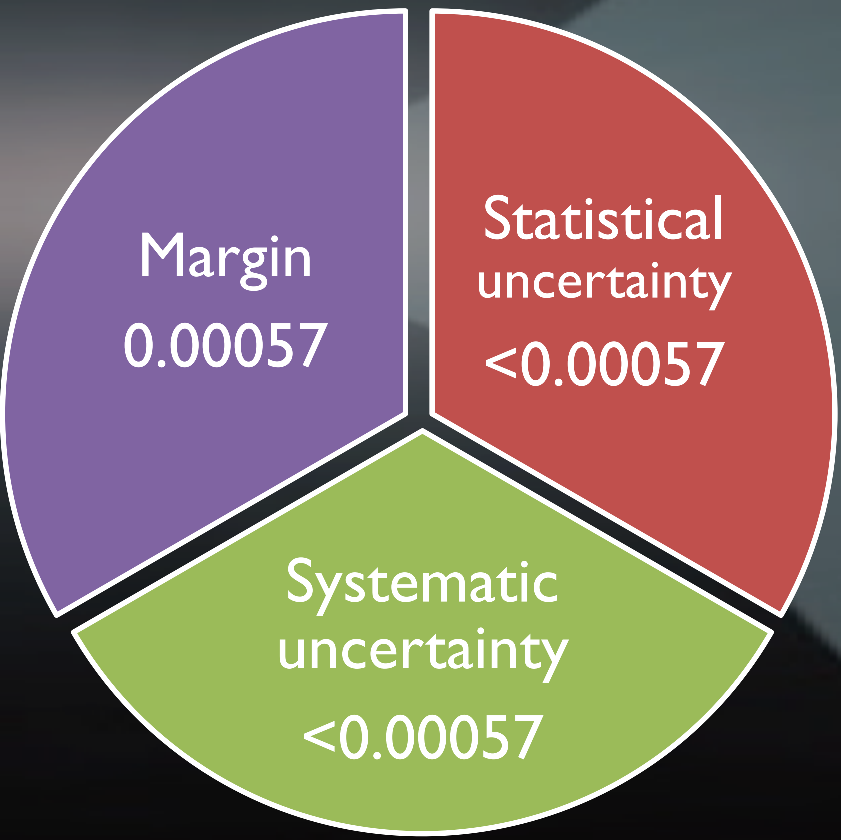
- Simplest and well-motivated $R+R^2$ "Starobinsky" model will be tested.
- Clean sweep of single-field models w/ characteristic scale of inflaton field > m_{pl}

- Detailed foreground cleaning studies yield $\sigma(r=0) = 0.5 \times 10^{-3}$
- Thorough systematic error studies yield total uncertainty $\delta r < 1.0 \times 10^{-3}$ w/o delensing



Scientific goal and challenges

Full Success :
$\delta r < 1 \times 10^{-3}$ (for r=0)
$2 \leq \ell \leq 200$



Statistical uncertainty includes

- foreground cleaning residuals
- lensing B-mode power
- 1/f noise

Systematic uncertainty includes

- Bias from 1/f noise
- Polarization efficiency & knowledge
- Disturbance to instrument
- Off-boresight pick up
- Calibration accuracy

Foreground cleaning

Methodology

Synchrotron: $[Q_s, U_s](\hat{n}, \nu) = [Q_s, U_s](\hat{n}, \nu_*) \left(\frac{\nu}{\nu_*}\right)^{\beta_s(\hat{n}) + C_s(\hat{n}) \ln(\nu/\nu_*^C)}$

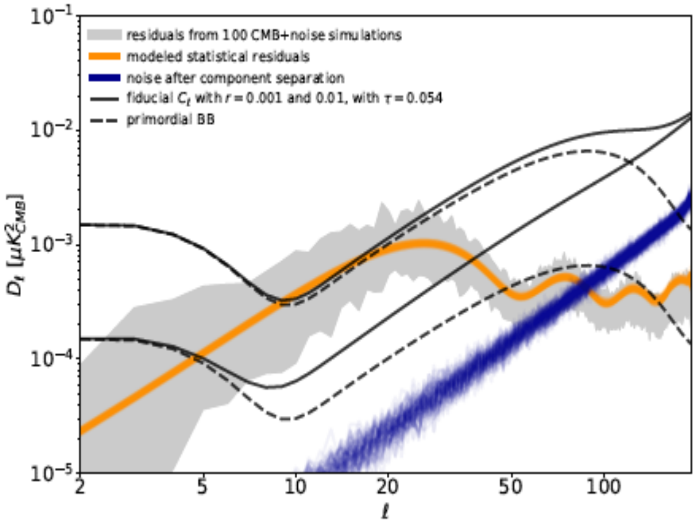
- AME is effectively absorbed by synchrotron curvature

Dust: $[Q_d, U_d](\hat{n}, \nu) = [Q_d, U_d](\hat{n}, \nu_*) \left(\frac{\nu}{\nu_*}\right)^{\beta_d(\hat{n}) - 2} \frac{B[\nu, T_d(\hat{n})]}{B[\nu_*, T_d(\hat{n})]}$

(8 parameters in each sky region) x (12 x N_{side}^2)

= 6144 parameters w/ $N_{\mathrm{side}} = 8$

to take spatial variations into account

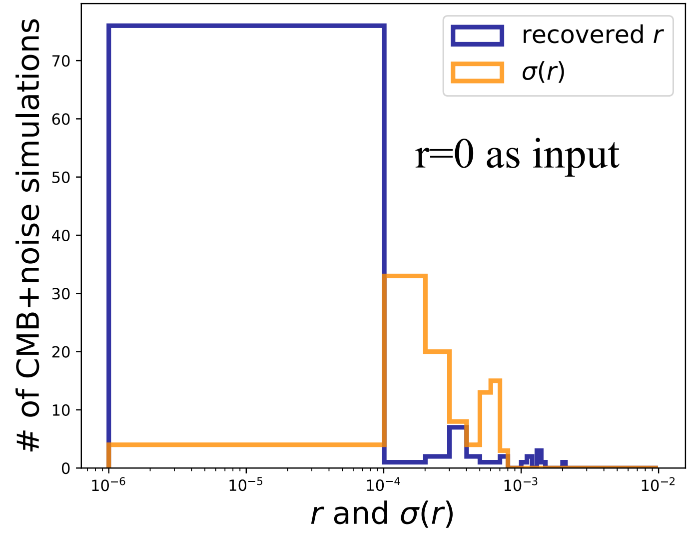


Results

"Multipatch technique" (extension of xForecast)*

- σ(r=0) = 0.0005
- Negligibly small bias

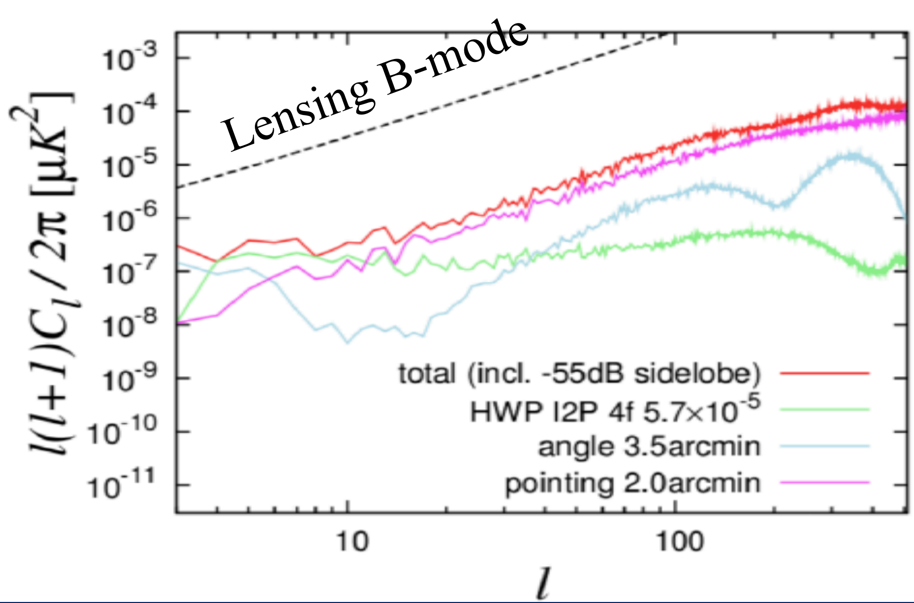
Consistent results from COMMANDER!



* Errard and Stompor, Phys.Rev. D99 (2019) no.4, 043529

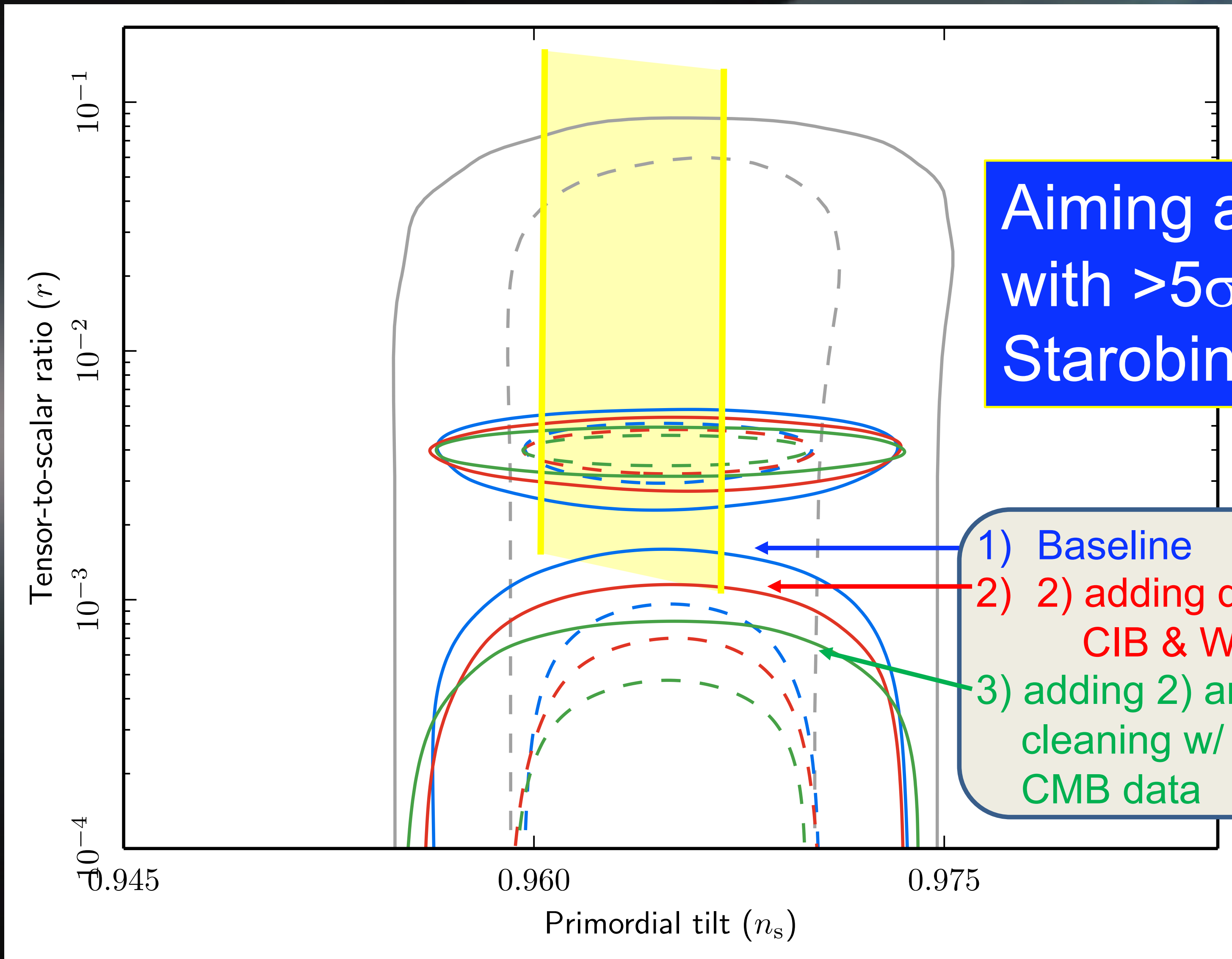
Systematics and calibration

- One of the largest study groups at LiteBIRD
- Systematic approach for systematic uncertainties
  - List systematic error items → 14 categories, 70 items listed
  - Assign each item $\sigma(r)_{sys} < 5.7 \times 10^{-6}$ as the budget (1% of total budget for systematic error)
  - Derive a requirement for each item, define method (incl. calibration methods) and estimate $\sigma(r)_{sys}$
  - Assign special budget allocations for outstanding items
  - Sum each contribution on map base to estimate total $\sigma(r)_{sys}$ (some studies even on TOD basis) to take positive correlations into account
  - Iterate procedure
- Example: studies of systematic errors due to HWP imperfection
  - Mueller matrix from RCWA simulations of electromagnetic wave propagation through realistic HWP for different frequencies and incident angles
  - 4f component from M_{IQ}, M_{IU} ~10^{-4} in the worst case
  - Obtain leakage maps and BB power to estimate $\sigma(r)_{sys}$



All known systematics will be adequately mitigated!

Further improvement with external data (extra success)



Aiming at detection with >5σ in case of Starobinsky model

1) Baseline
2) 2) adding delensing w/ Planck CIB & WISE
3) adding 2) and extra foreground cleaning w/ high-resol. ground CMB data

LiteBIRD science outcomes

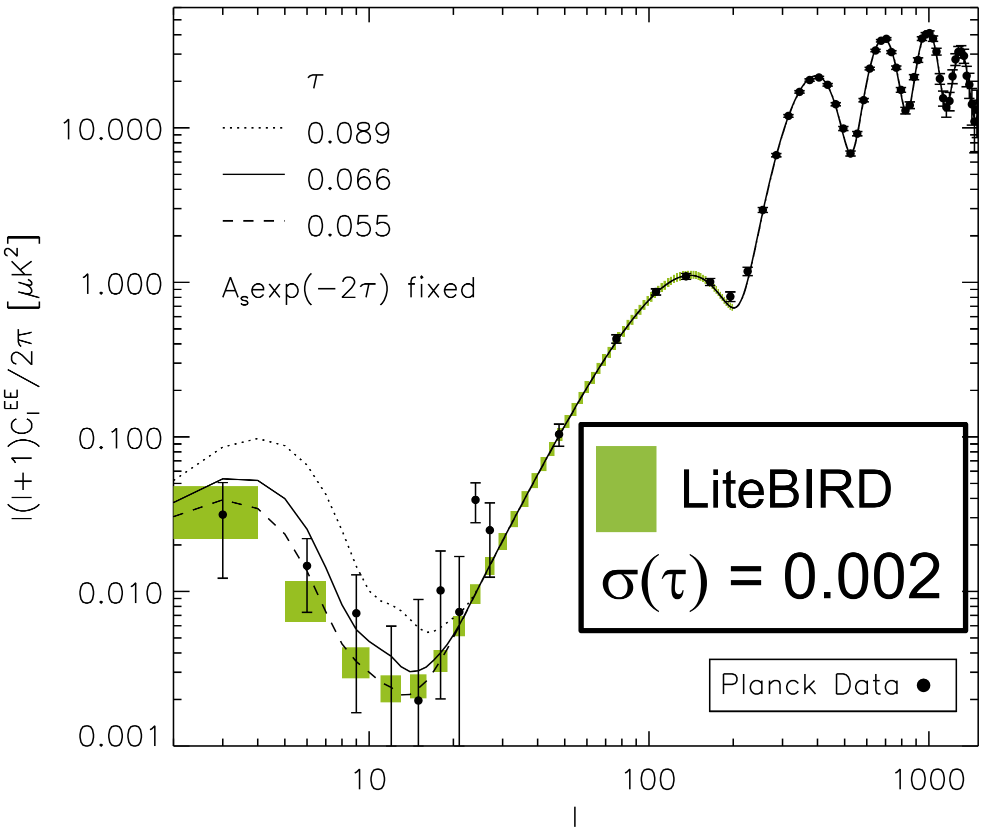
System requirements from 1. only

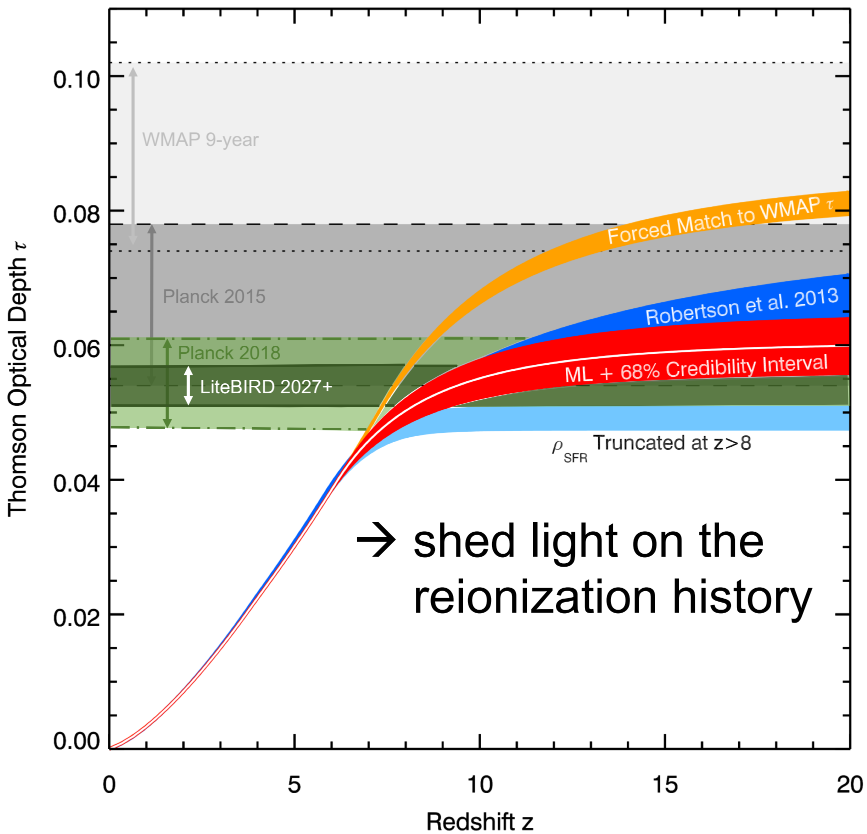
1. Full success
2. Extra success (see previous page)
3. Characterization of B-mode
   (e.g scale-invariance, non-Gaussianity, and parity violation)
4. Large-scale E mode and its implications
   for reionization history and the neutrino mass
5. Birefringence
6. Power spectrum features in polarization
7. SZ effect (thermal and relativistic correction)
8. Anomaly
9. Cross-correlation science
10. Galactic science

3. – 10. almost guaranteed if full success is achieved.

Large-scale E-mode

A cosmic variance limited measurement of EE on large angular scales will be an important, and guaranteed, legacy for LiteBIRD!

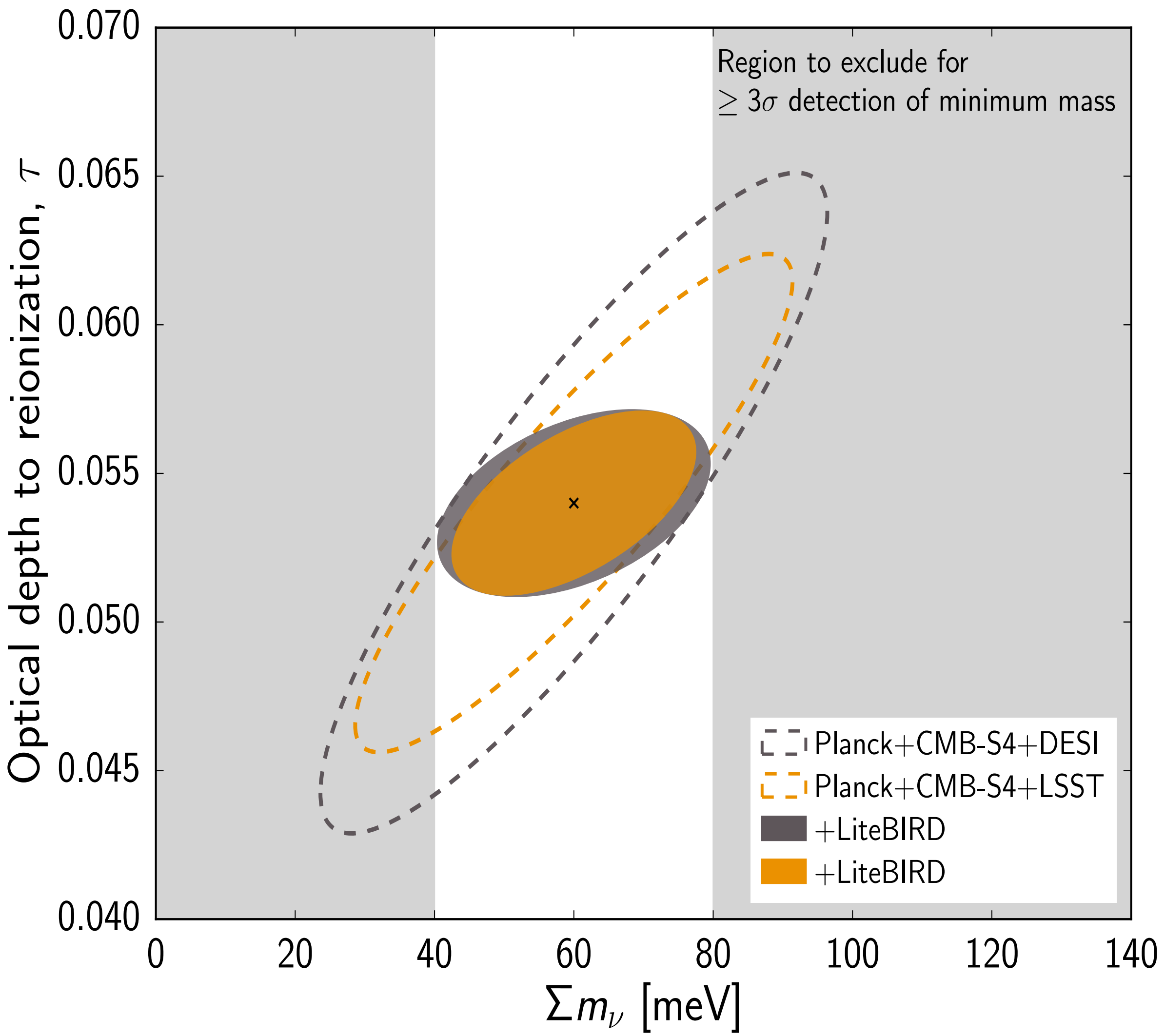




Σm_ν w/ improved τ

- $\sigma(\Sigma m_\nu)$ = 15 meV
- $\geq$ 3σ detection of minimum mass for normal hierarchy
- $\geq$ 5σ detection of minimum mass for inverted hierarchy

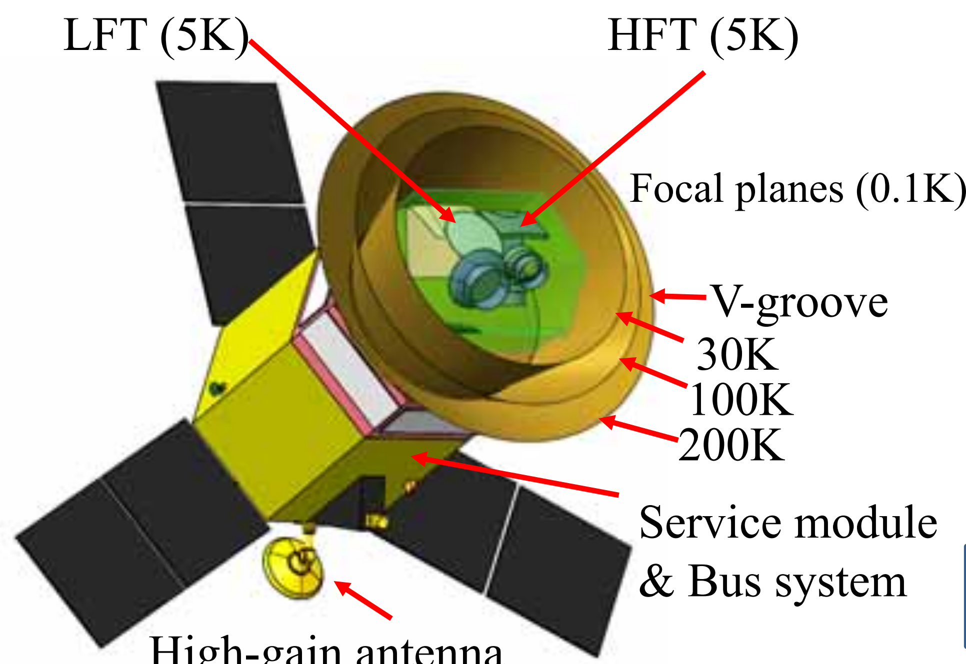
Caveat:
No systematic error included yet.



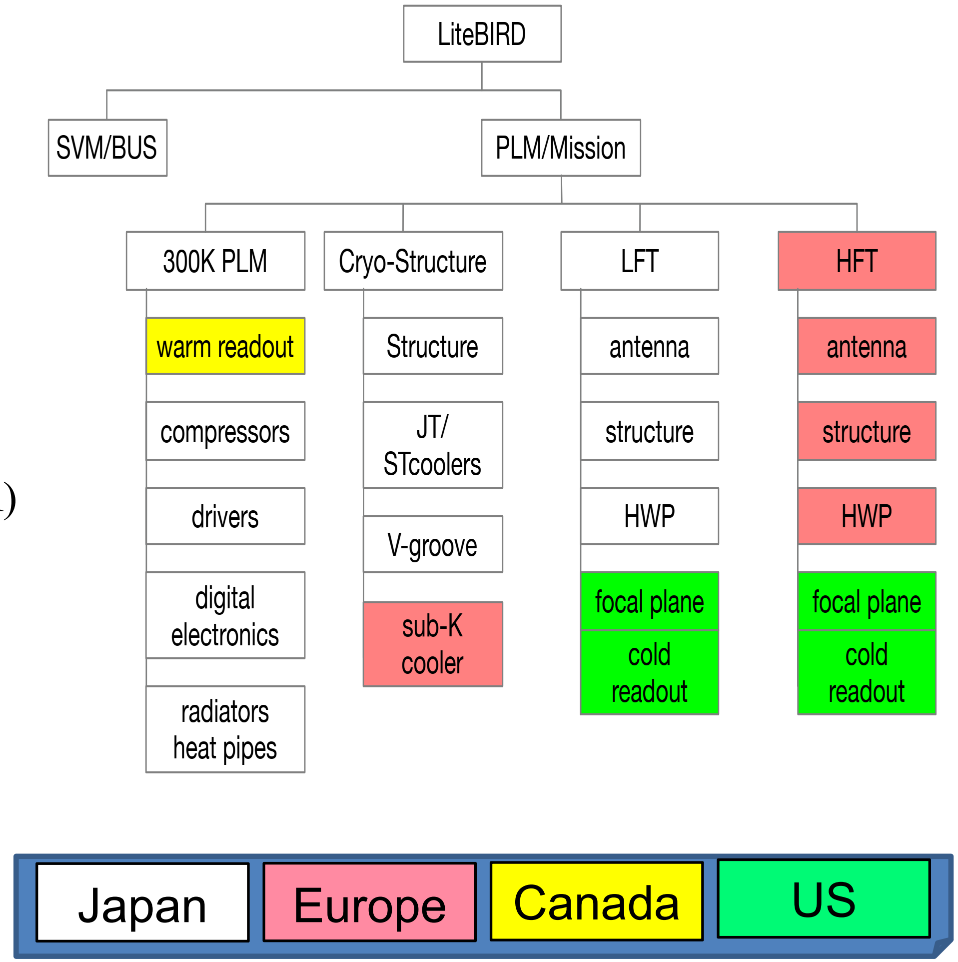
LiteBIRD mission instrument

Three features

1. Two telescopes w/ TES arrays
2. Polarization modulator for 1/f noise & systematics reduction
3. Cryogenic system for 0.1K base temperature

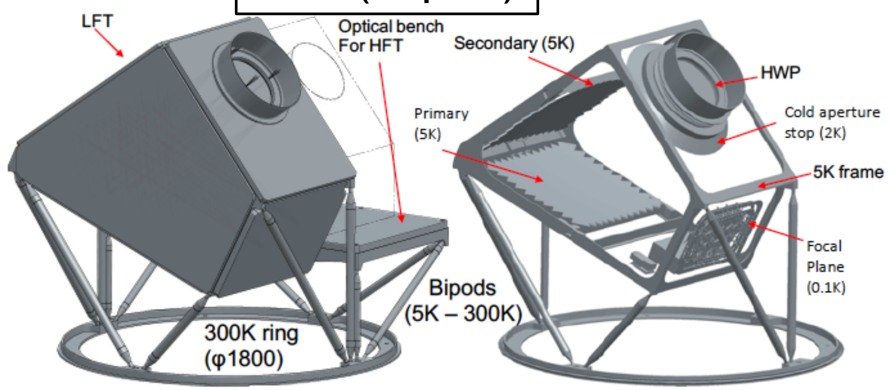


Component tree

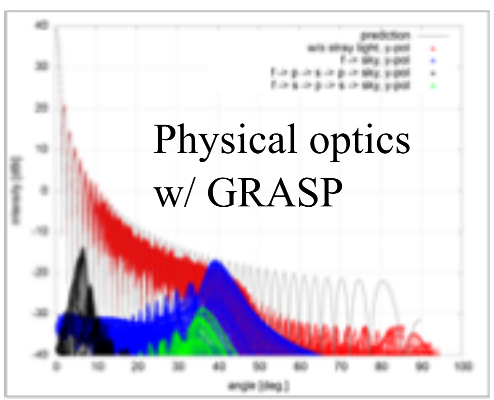


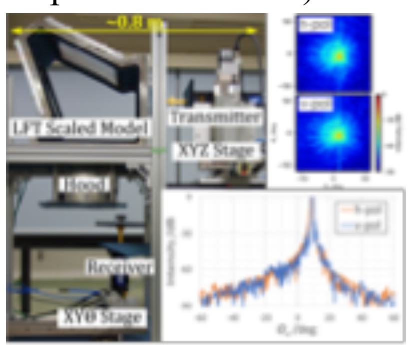
1. Two telescopes w/ TES arrays

LFT (Japan)



- Crossed Dragone with aperture diameter 400 mm, angular resolution 20 – 70 arcmin., field of view 20 deg x 10 deg, F#3.0 & crossed angle of 90 degree
- All 5K parts are made of Aluminum, less than 150 kg
- New mirror design (anamorphic aspherical surfaces) S. Kashima et al. 2018 Appl. Opt.



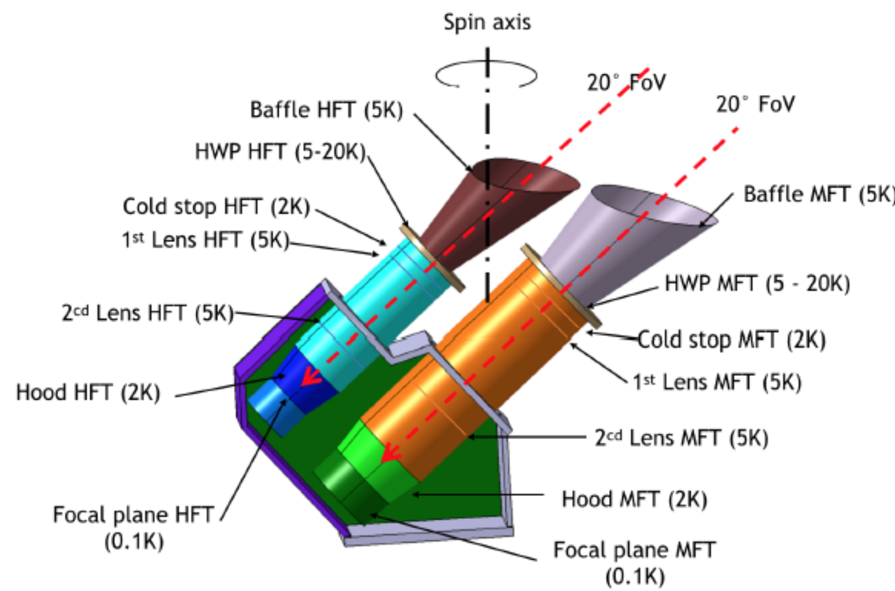


far sidelobe meas.
for LFT scale model

HFT (Europe)

<u>Refractive solution (Baseline)</u>

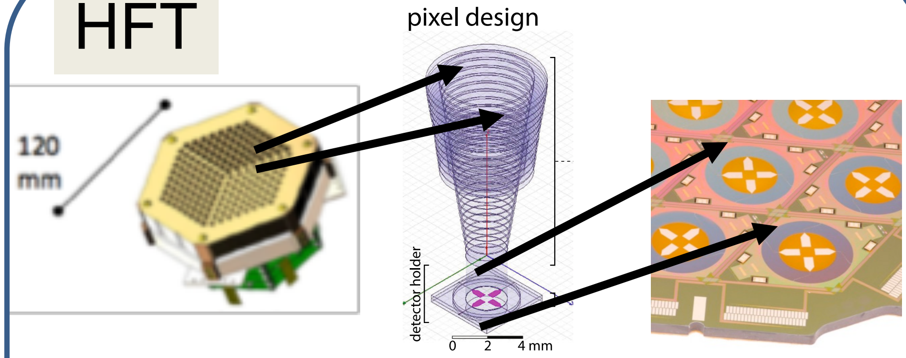
- Two F/2.3 telescopes:
  - 89-270 GHz
  - 238-448 GHz
- Transmissive metal-mesh HWP
- Silicon lenses



US

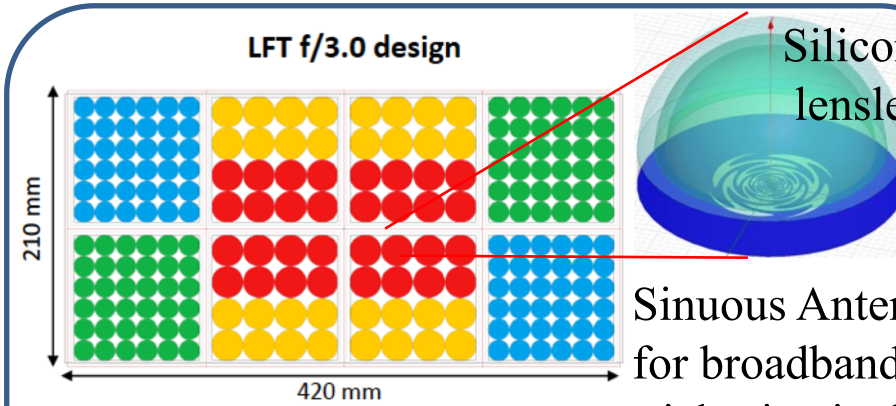
TES arrays

HFT



Silicon platelet
Corrugated horn

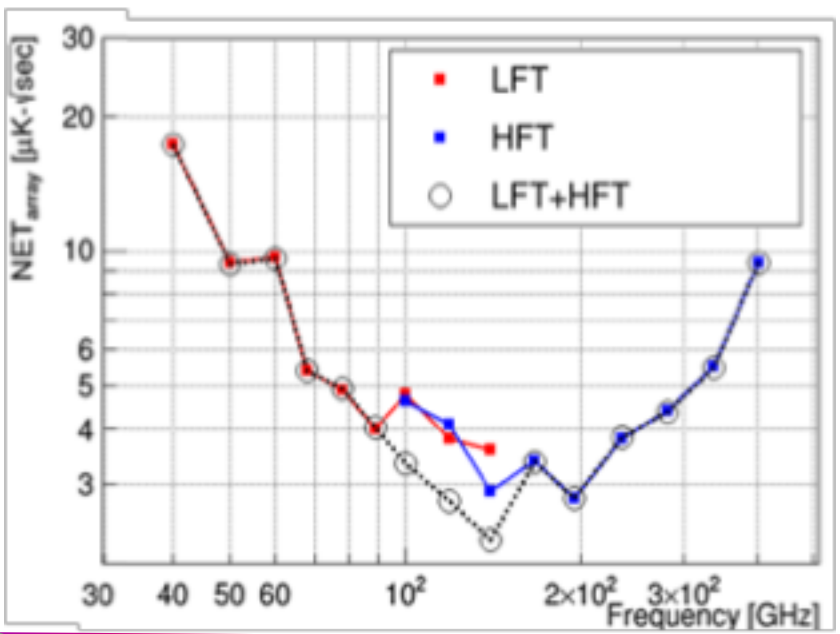
OMT



Silicon lenslet

Sinuous Antenna for broadband trichroic pixels

LFT



Proof of principle at Simons Array

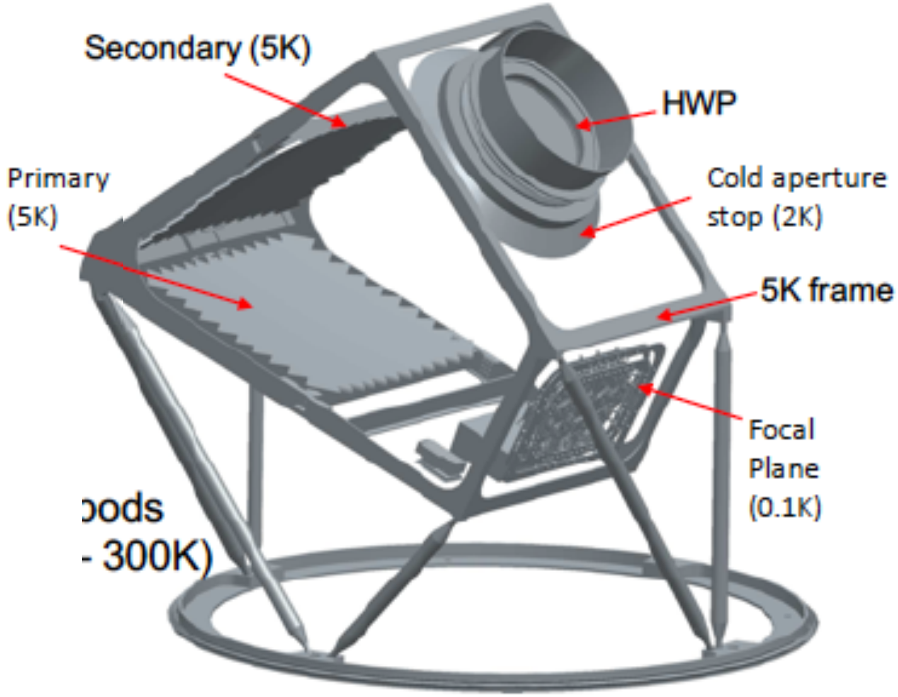
We got the first light in Jan 2019!

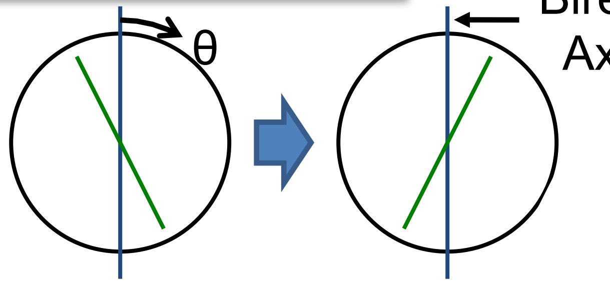
2. Polarization modulator for 1/f noise & systematics reduction

Continuously-rotating half-wave plate (HWP)

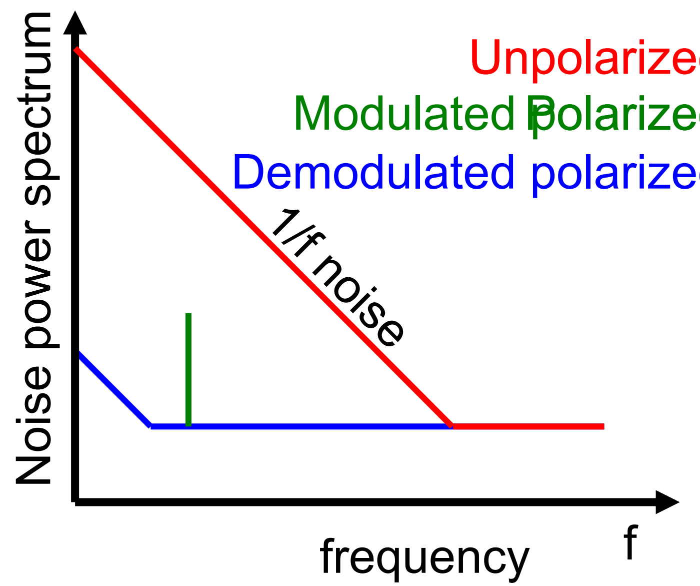
LFT

HWP at the most sky side





$$\updownarrow = I + P\cos 4\theta_{\mathrm{HWP}}$$



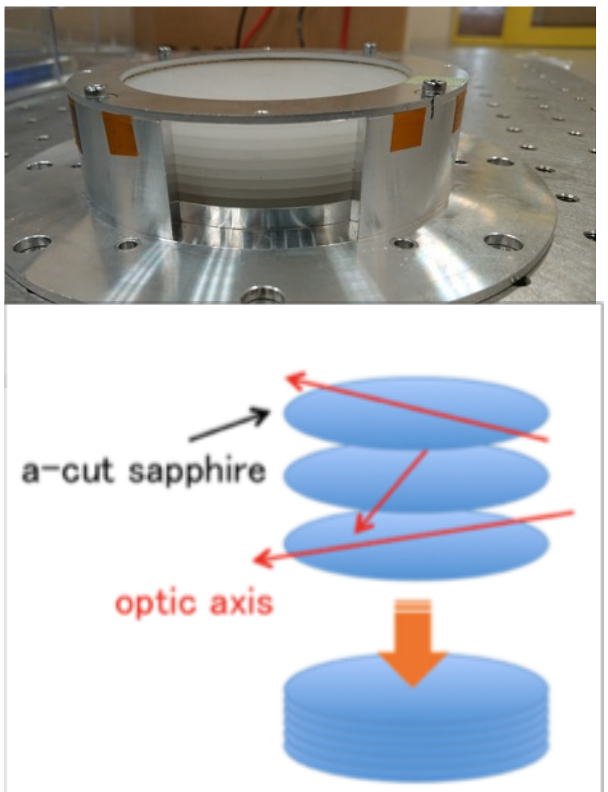
2. Polarization modulator for 1/f noise & systematics reduction

Developed
Kavli IPMU, U. Tokyo

Two techniques for broadband system

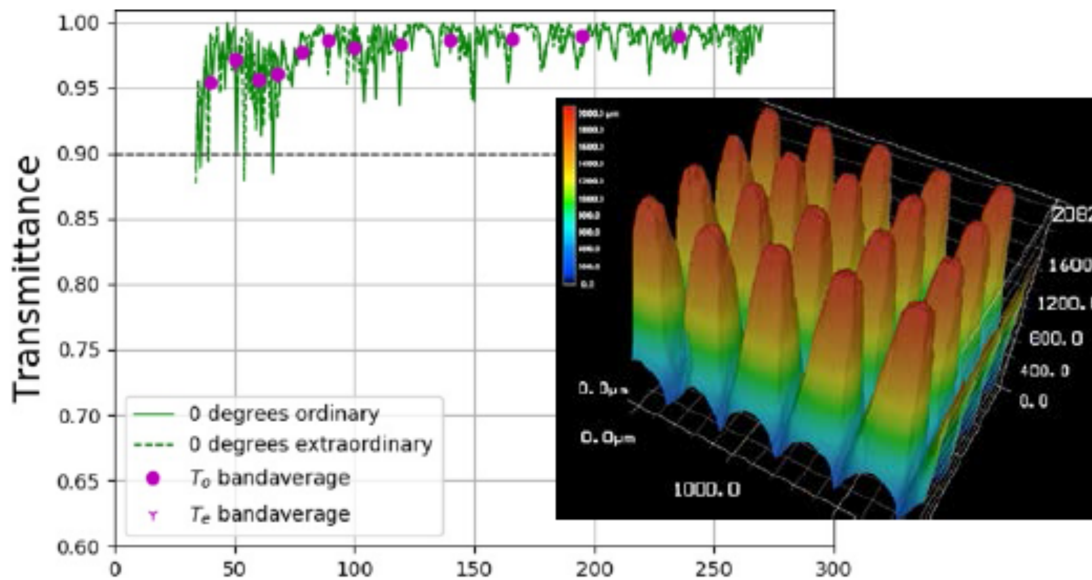
1. Stack of sapphire plates

(Pancharatnam Achromatic HWP)



2. Moth eye structure on a sapphire surface

World's most broadband sapphire HWP for CMB!



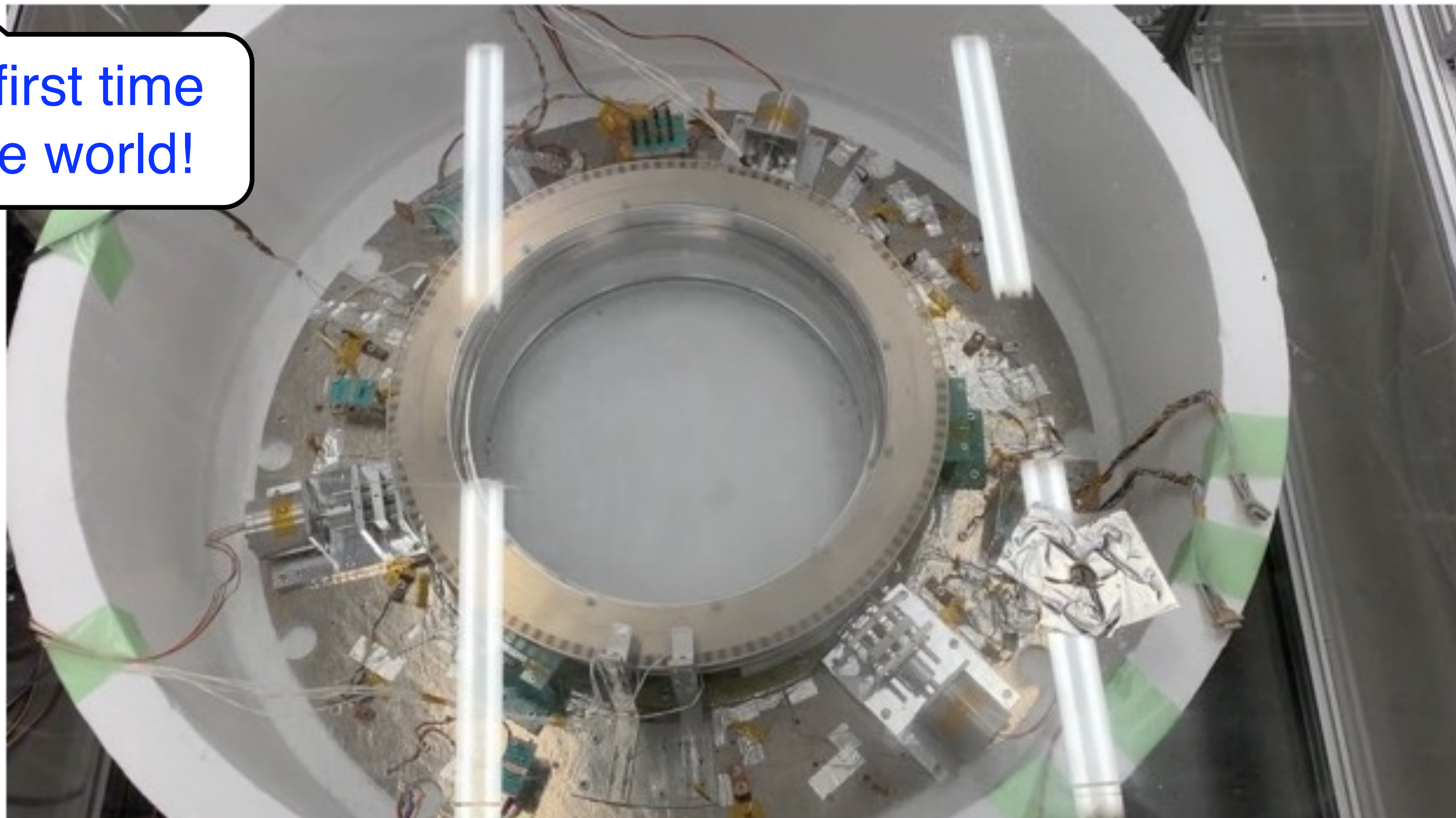
Large (~450mmϕ) LFT polarization modulator

Developed at Kavli IPMU

Superconducting magnetic bearing system operational in a 4K cryostat.

We observed the stable rotation at cryogenic temperature (<10K).

The first time in the world!

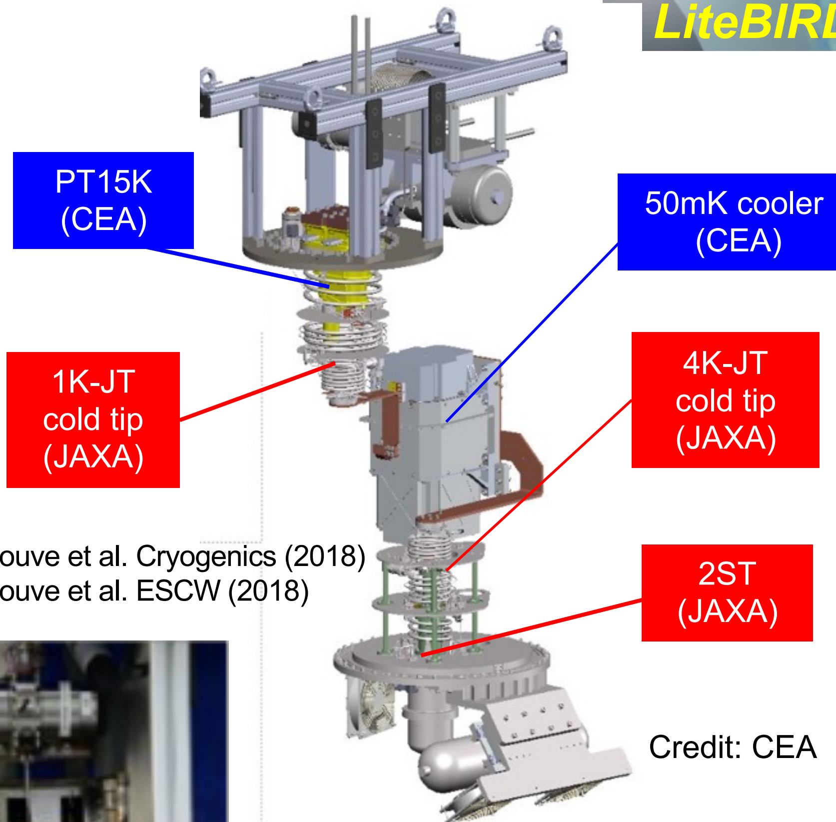


Europe

Japan

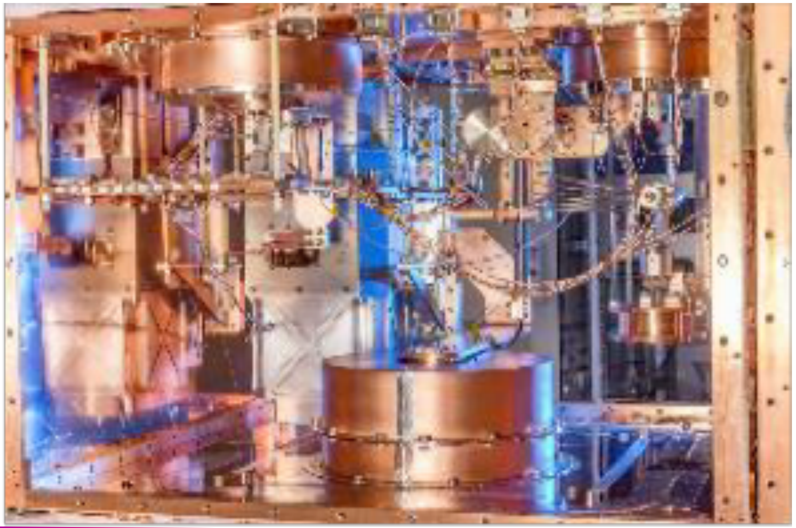
3. Cryogenic system for 0.1K base temperature

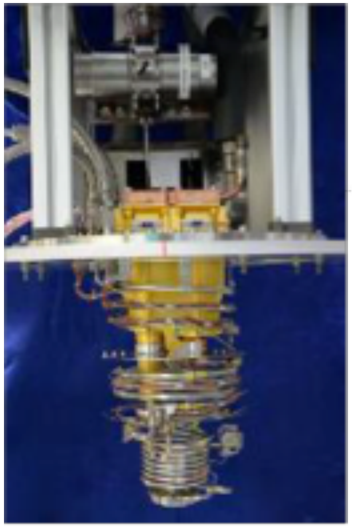
- In the framework of ESA Core Technology Program (CTP), Cryo-Chain CTP (CC-CTP) project has been promoted during 2016-2018, in the international collaboration led by CNES, with JAXA and CEA.
- Thermal interface from 300K to 100mK/50mK (end-to-end) has been demonstrated for Athena, LiteBIRD and SPICA.

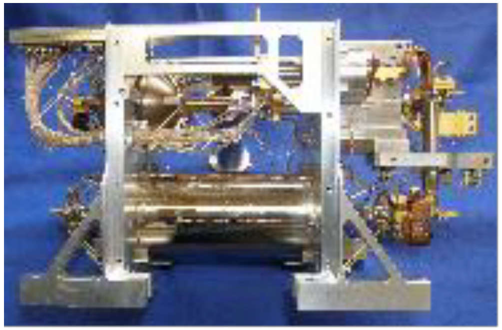


T.Prouve et al. Cryogenics (2018)
T.Prouve et al. ESCW (2018)

Credit: CEA







LiteBIRD Summary

- JAXA's L-class mission candidate
- Expected launch in 2027. Final down selection this year!
- Observations for 3 years around Sun-Earth Lagrangian point L2
- Millimeter-wave all sky surveys (34–448 GHz, 15 bands) at degree scales

Full Success:
$\delta r < 1 \times 10^{-3}$ (for r=0)
$2 \leq \ell \leq 200$

➢ Detailed foreground cleaning studies yield $\sigma(r=0) = 0.5 \times 10^{-3}$
➢ Thorough systematic error studies yield total uncertainty $\delta r < 1.0 \times 10^{-3}$

<u>CMB B-mode from primordial gravitational waves generated during Inflation would provide</u>

- Direct evidence for Inflation, and knowledge on when it happened
- (Arguably) First evidence for quantum fluctuation of space-time
- Knowledge on the Inflation energy scale