LiteBIRD Vision and Overview

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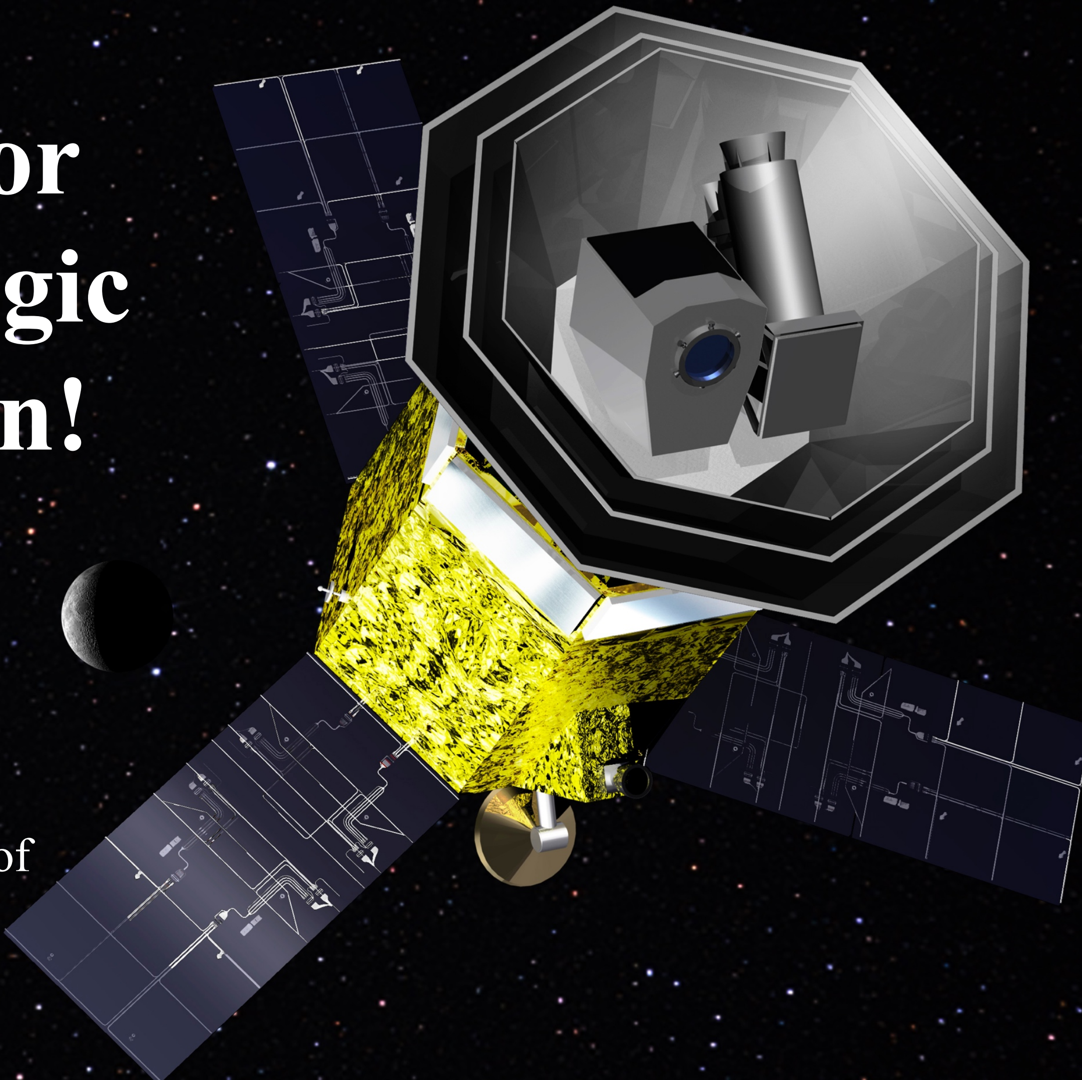
In May 2019, *LiteBIRD* was selected for JAXA's strategic L-class mission!

Official announcement
http://www.isas.jaxa.jp/home/rikou/godo/2019/0602/gbi7uzhxfxmz/misison_selection_announcement_may2019.pdf



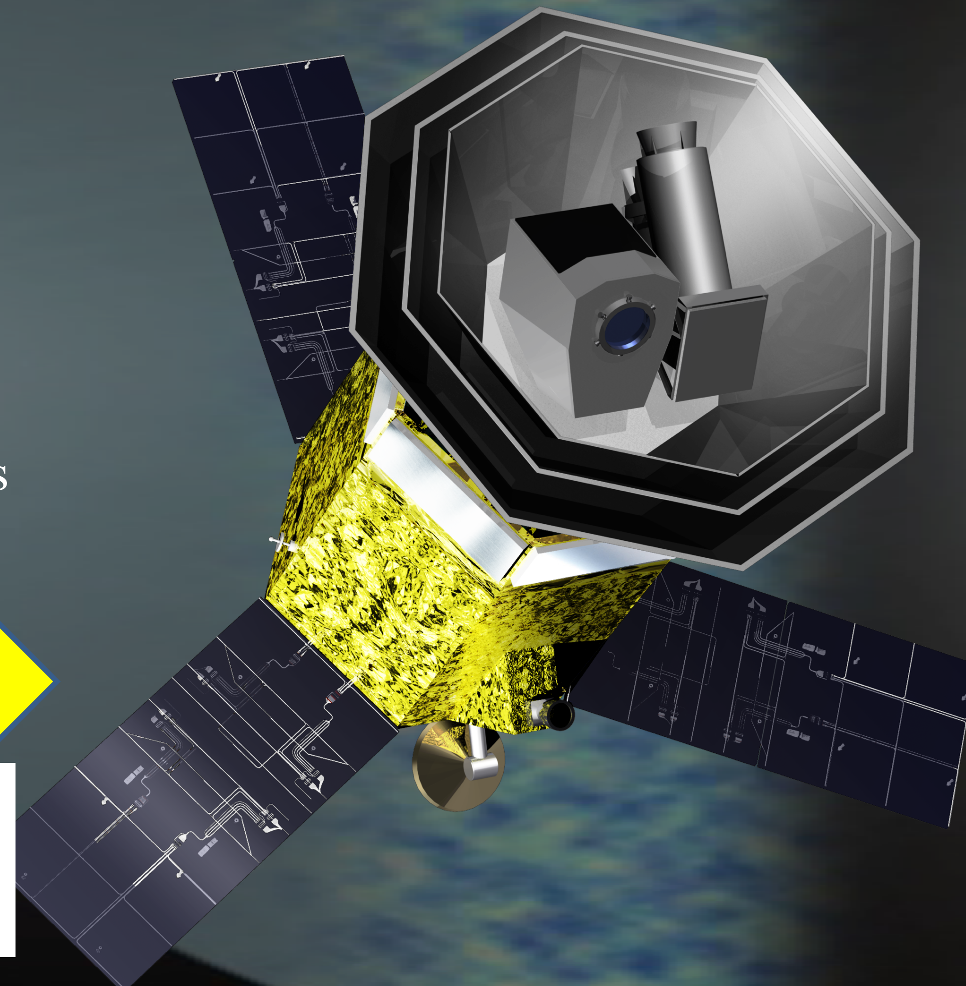
LiteBIRD:

Lite (light) satellite for the studies of
B-mode polarization and
Inflation from cosmic background
Radiation
Detection

How it started

- Original proposal in 2008
- Four key concept
  - Warm launch
  - Modest angular resolution but no compromise
  - Multi-chroic detectors
  - Focused mission
- Vision of "powerful duo"
  - Compact satellite + Large aperture ground telescopes

"Drawing" in the original proposal



Progress 2008-2019

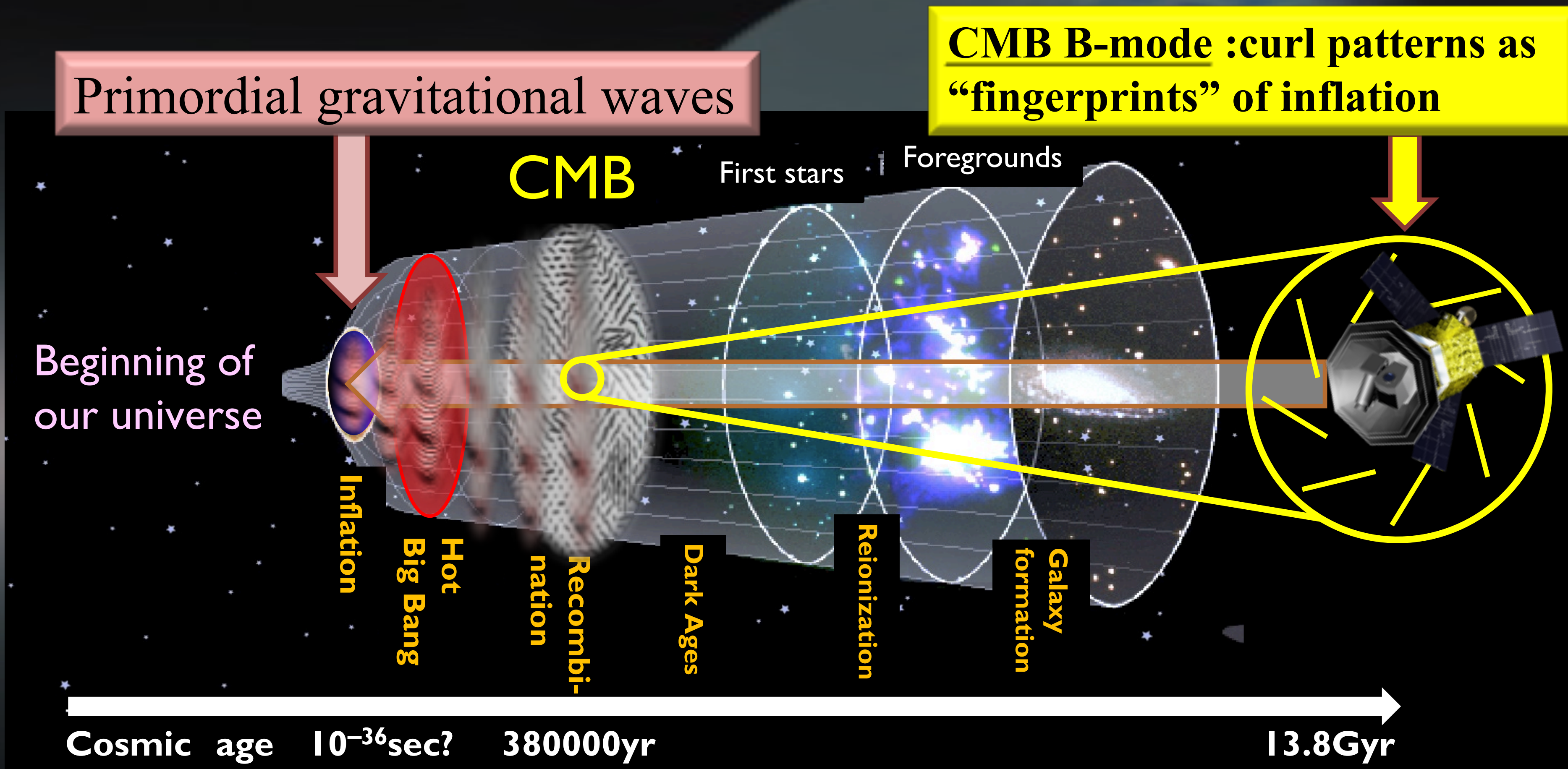
- 2008: Initial proposal by the KEK CMB group.
  LiteBIRD working group established (authorized by Steering Committee for Space Science (SCSS) in Japan
  - US and Canada joined the studies almost from the beginning based on POLARBEAR collaboration
- 2012: Fundamental physics mission recognized as a new category by SCSS
- 2013: Space Science/Exploration Roadmap describes tests of cosmic inflation with CMB B-mode as one of the top-priority science objectives
- 2014: Selected as one of important large projects in Master Plan 2014 by Science Council of Japan
- 2015: Formal proposal to ISAS/JAXA as a strategic L-class mission
  Letter from ISAS DG (Prof. Saku Tsuneta) to European community
- 2016: Pre-Phase A2 Start
  - European activities started and progressed rapidly.
- 2018: Pre-Phase A2 End
- 2019: Selected as the next strategic L-class mission (mission #2)

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.)

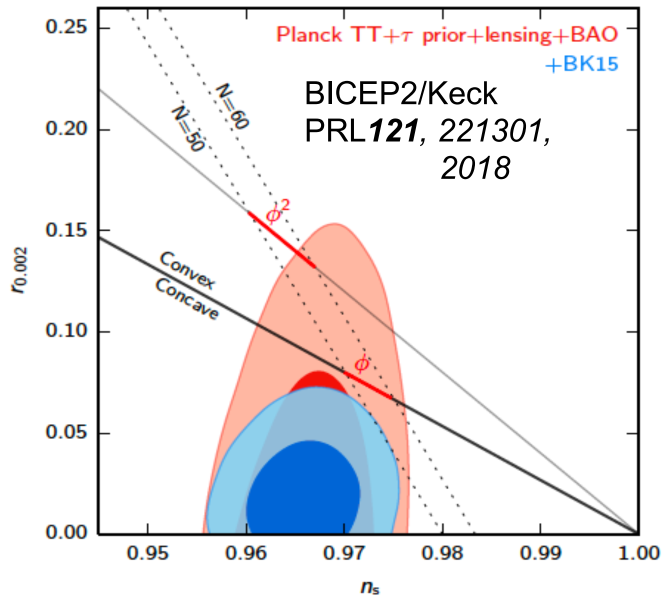
CMB B-mode as signal of inflation

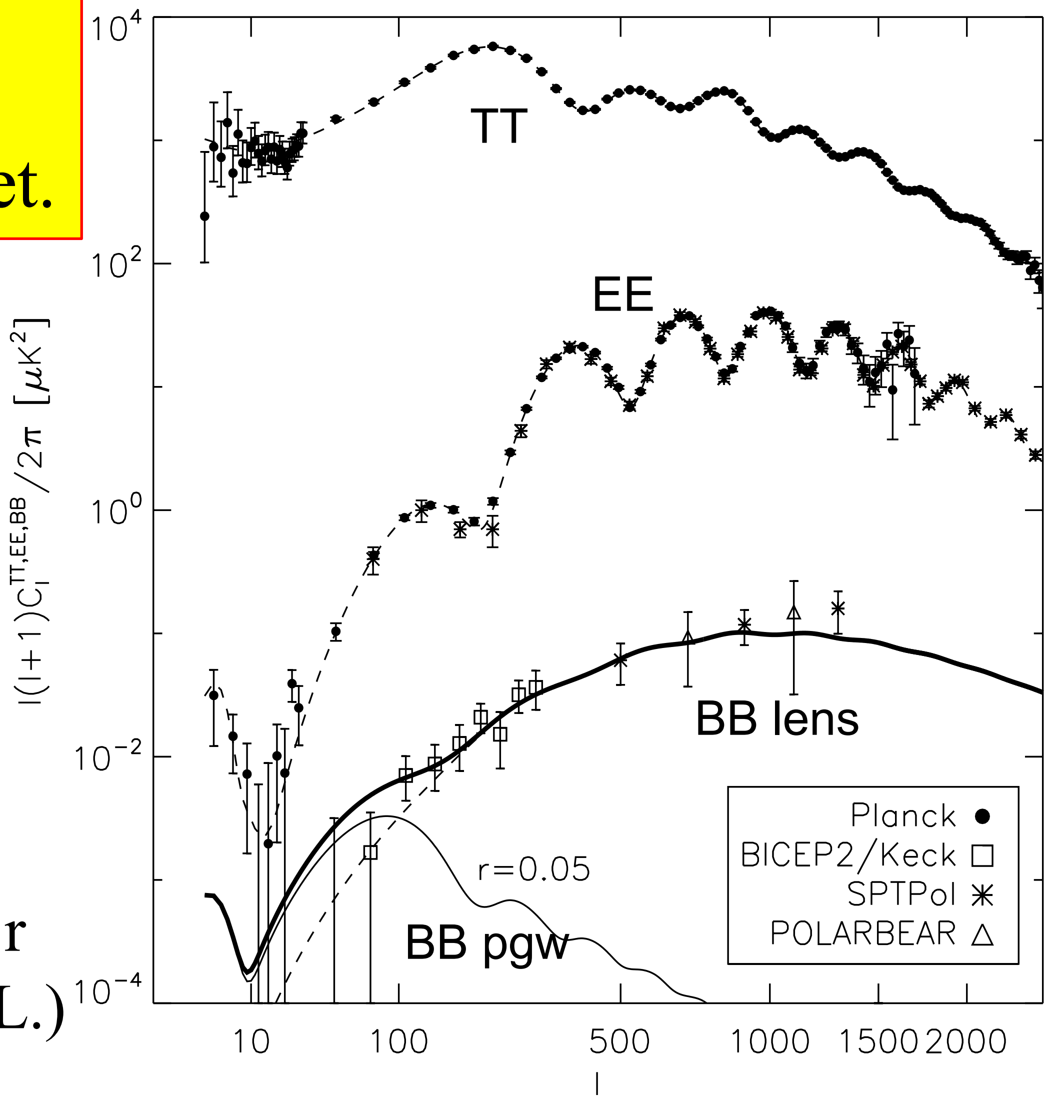


CMB B-mode is the best probe for primordial gravitational waves.
"Direct detection" of primordial GW w/ CMB as an experimental apparatus !

Basics (1): CMB Power Spectra

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

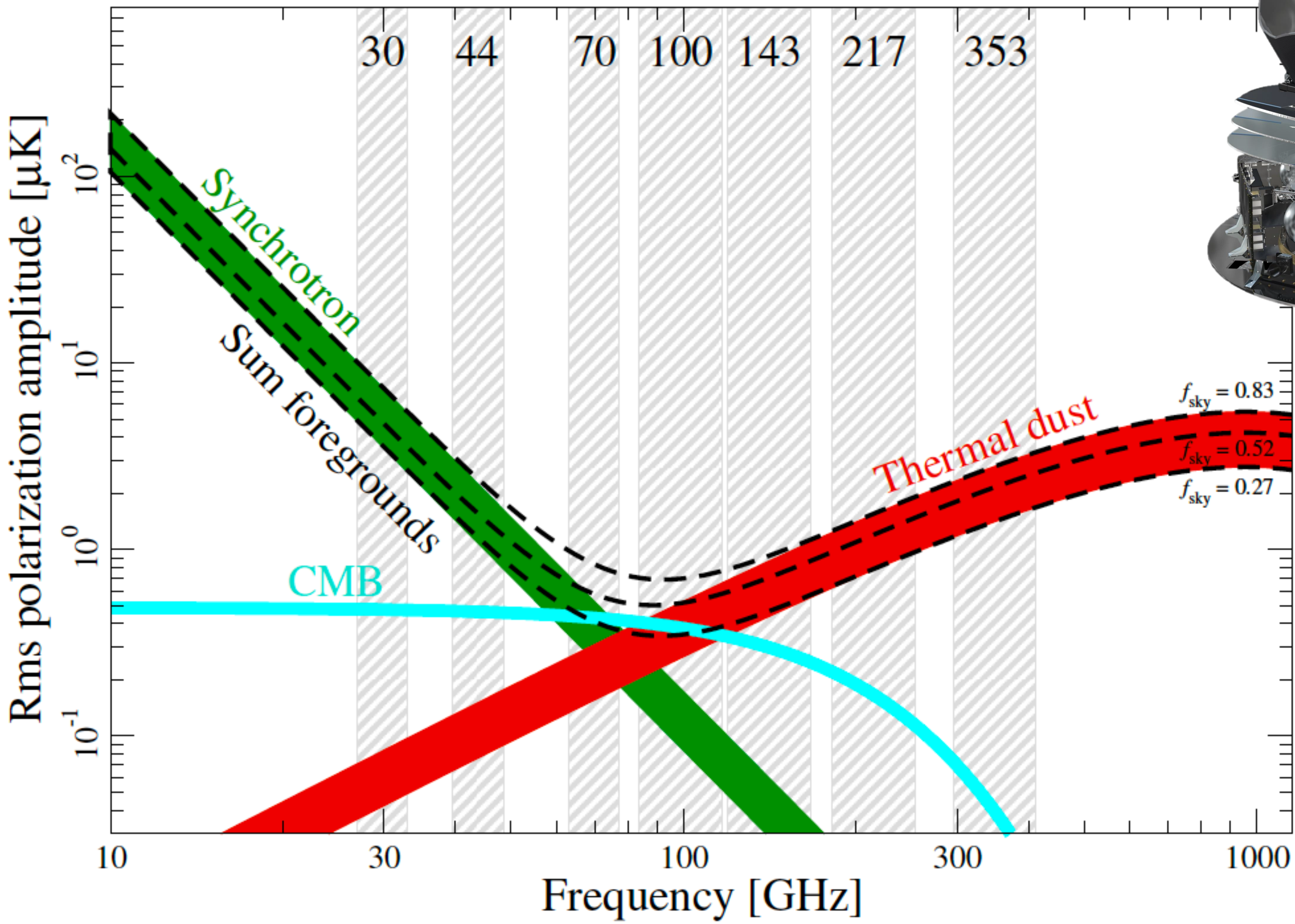


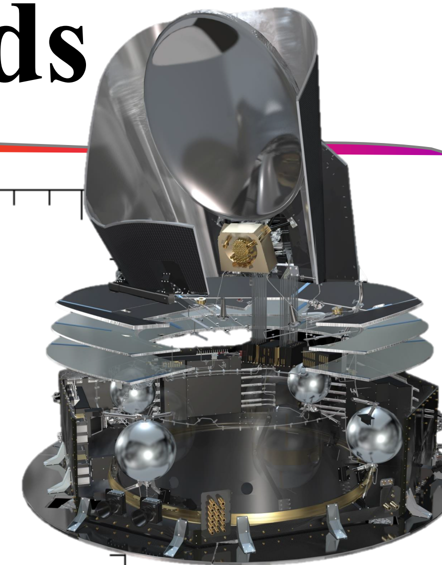


$C_{l\ pgw}^{BB} \propto$ tensor-to-scalar ratio, r

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

Basics (2): Foregrounds





Planck 2018

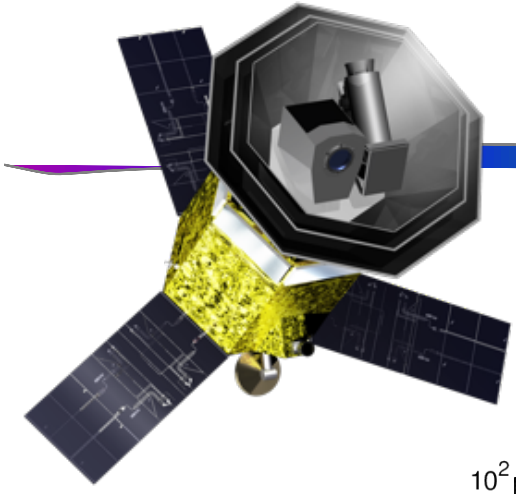
Why Measure from Space?

- 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), important for foreground separation
  - No ground pickup

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

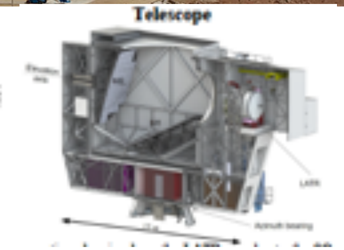
- Only way to access lowest multipoles w/ $\delta r \sim O(0.001)$
  - Both B-mode bumps need to be observed for the firm confirmation of Cosmic Inflation → We need measurements from space.
- Complementarity with ground-based CMB projects
  - Foreground information from space will help foreground cleaning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

Vision for 2020's



X

Powerful Duo



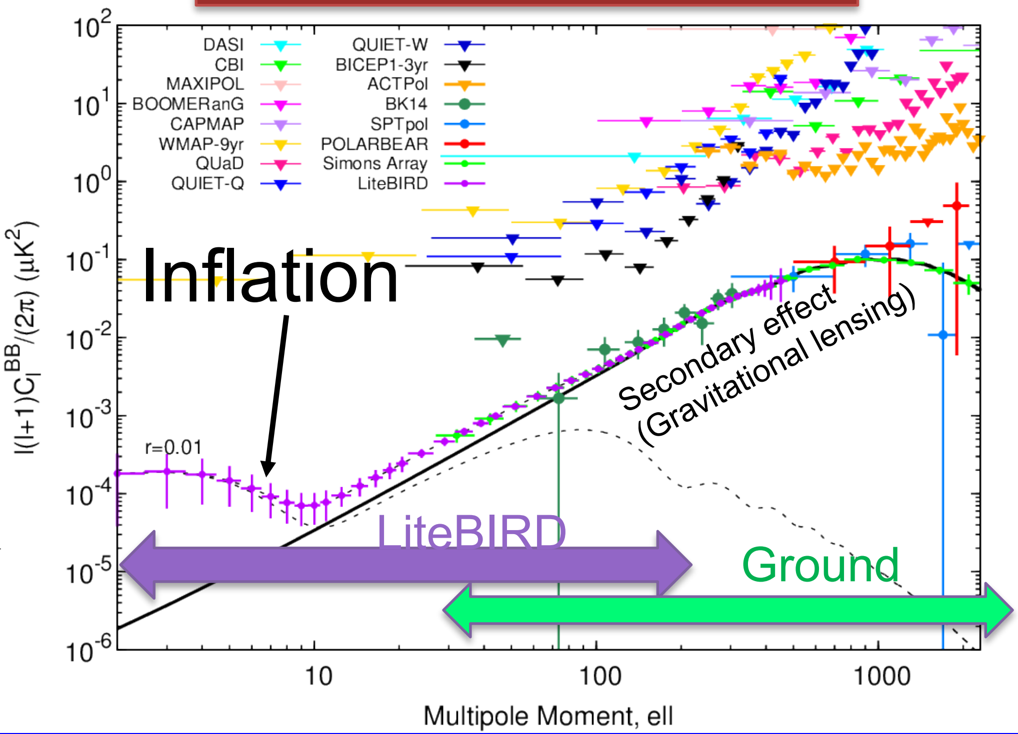
<u>LiteBIRD</u>

JAXA-led focused mission

σ(r)<0.001

$2 \leq \ell \leq 200$

focused but still with many byproducts



<u>Ground</u>

US-led telescopes on ground

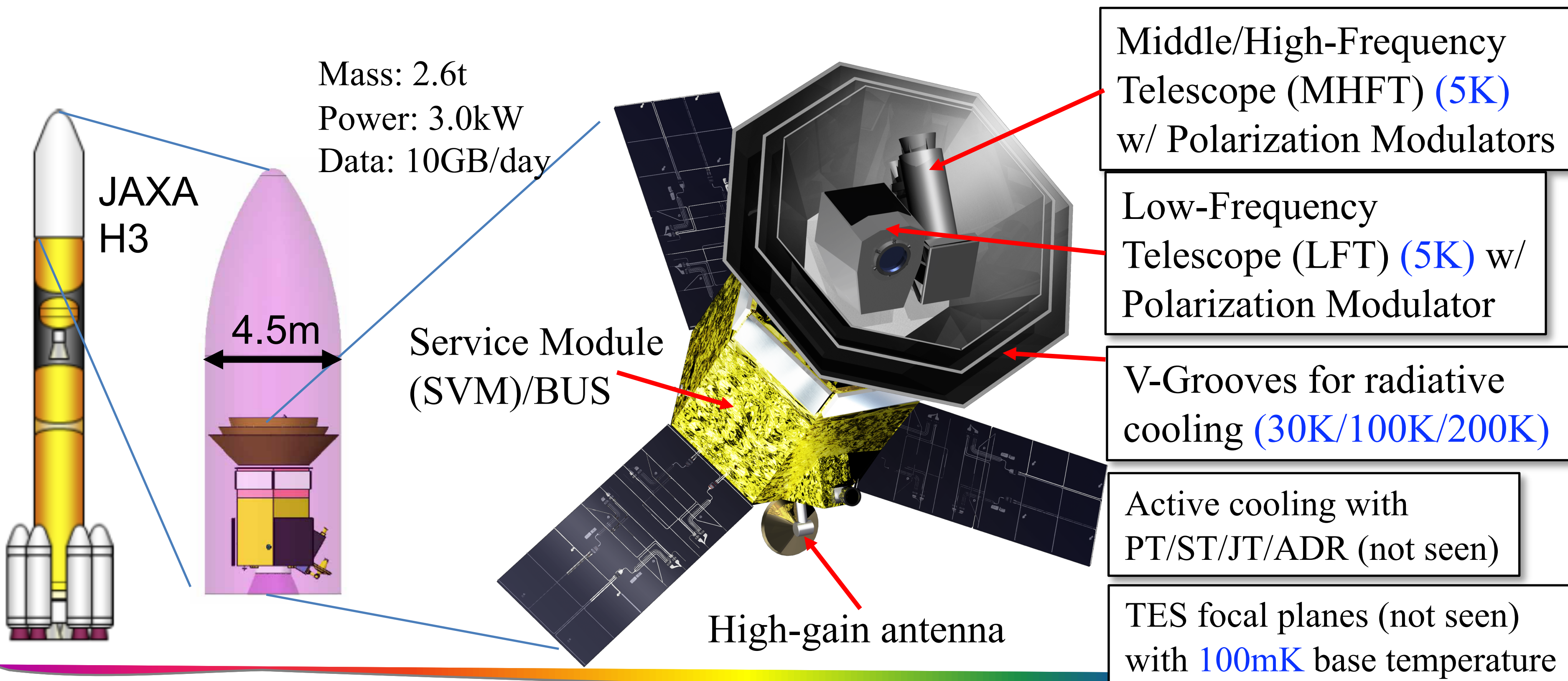
$30 \leq \ell \leq \sim 8000$

e.g. Simons Observatory and CMB-S4

- This powerful duo is the best cost-effective way.
- Great synergy with two projects

LiteBIRD Overview

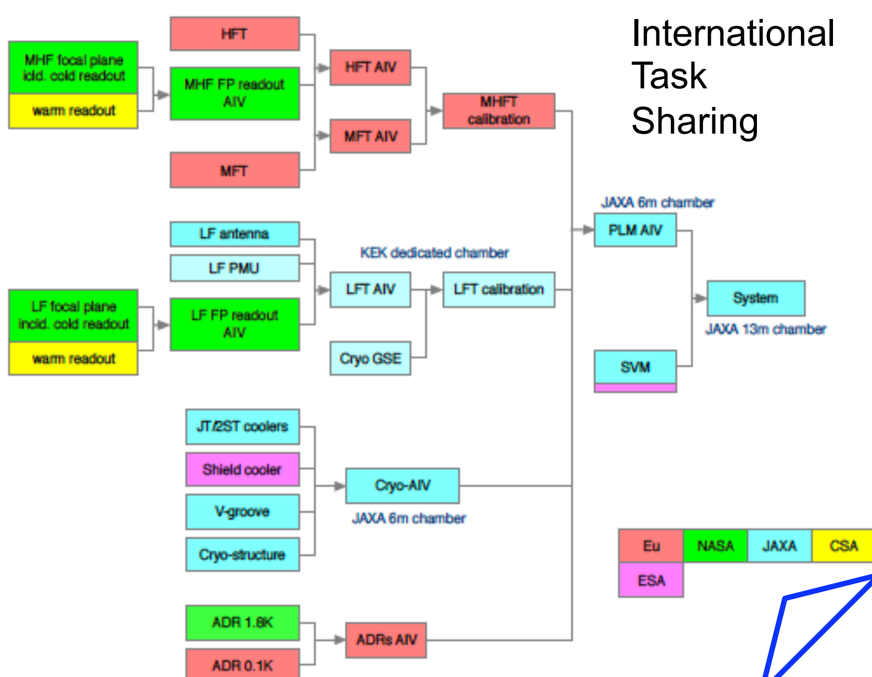
- JAXA's L-class mission selected in May 2019
- Expected launch in 2027 with JAXA's H3 rocket.
- Observations for 3 years (baseline) around Sun-Earth Lagrangian point L2
- Millimeter-wave all sky surveys (34–448 GHz, 15 bands) at 70–20 arcmin.
- Mission: δr (total uncertainty) < 0.001 (for r=0) with CMB B-mode observation



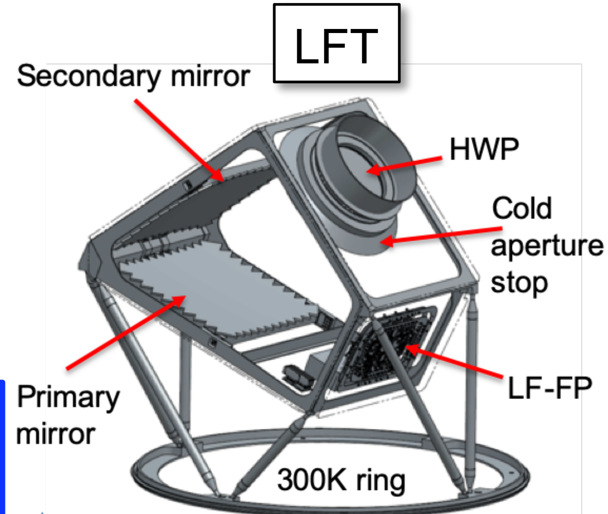
LiteBIRD Mission Instrument

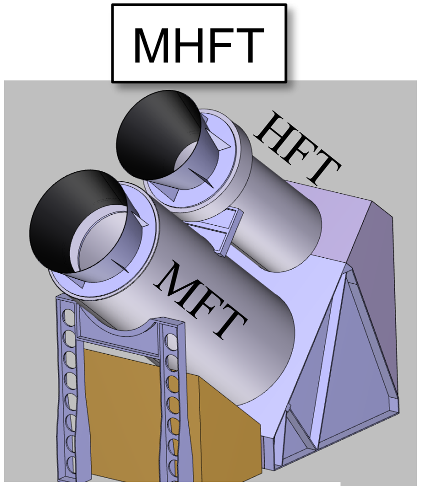
Three features

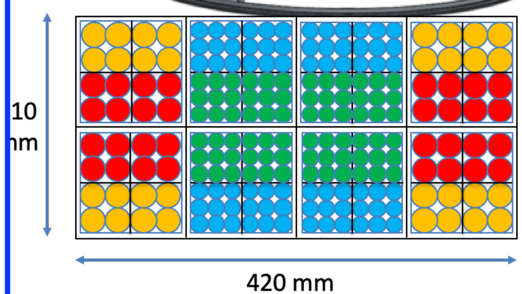
1. Two telescopes w/ TES arrays
2. Polarization modulator with a rotating half-wave plate (HWP) for 1/f noise & systematics reduction
3. Cryogenic system for 0.1K base temperature

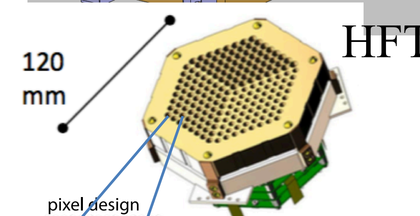


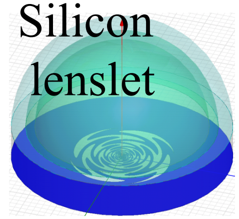
1. Two telescopes w/ TES arrays





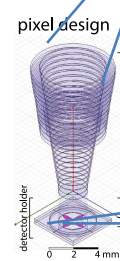






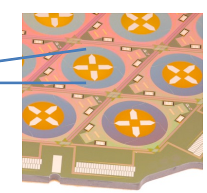
Silicon lenslet

Sinuous Antenna for broadband trichroic pixels



Silicon platelet Corrugated horn

OMT

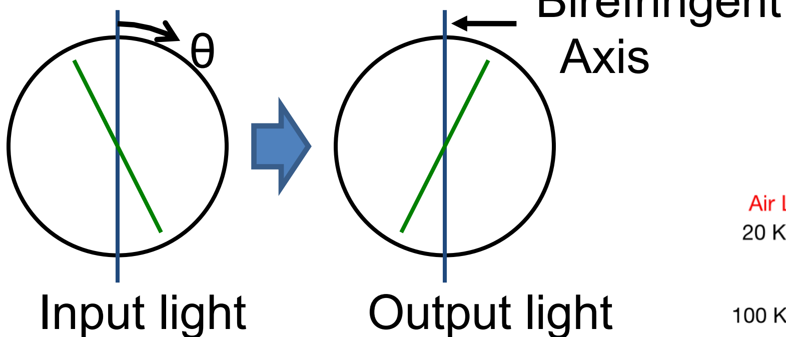


Developing TES bolometers more immune to cosmic rays

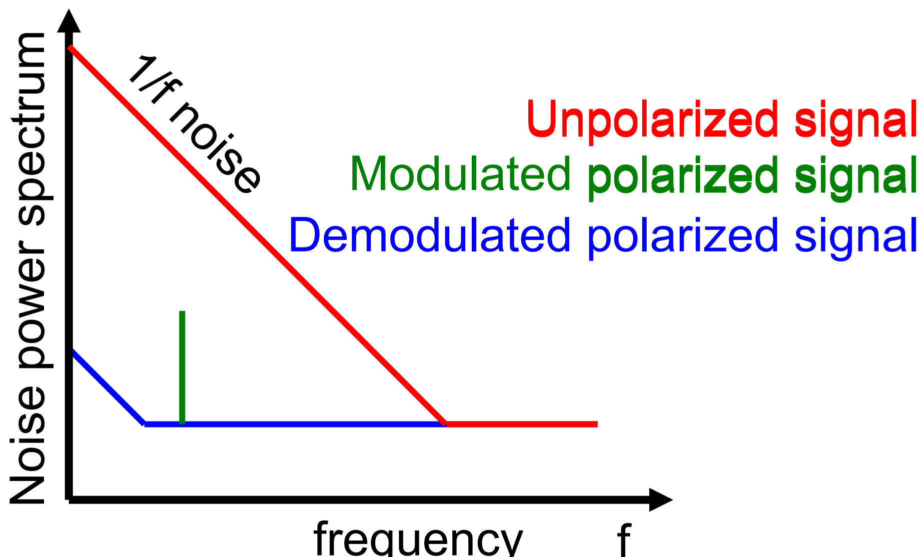
LiteBIRD Mission Instrument

2. Polarization modulator with a rotating half-wave plate (HWP) for 1/f noise & systematics reduction

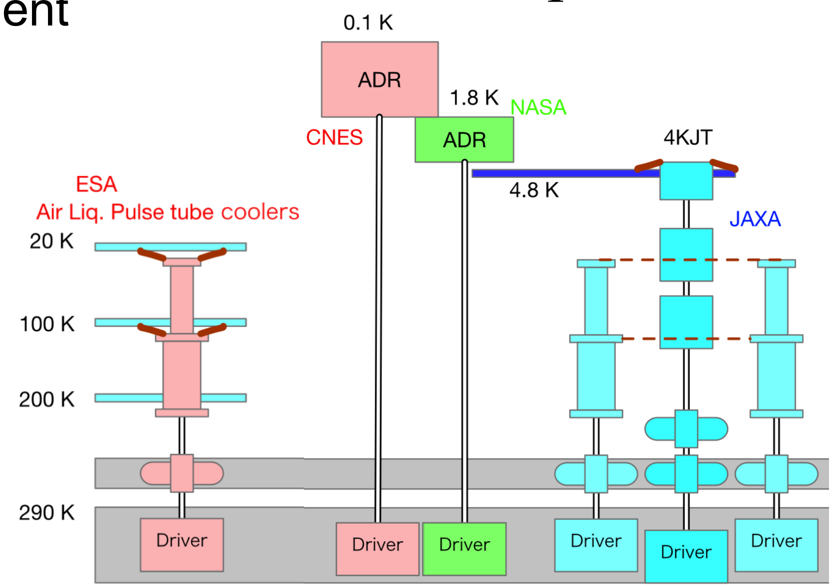
Rotating a birefringent plate at the most sky side

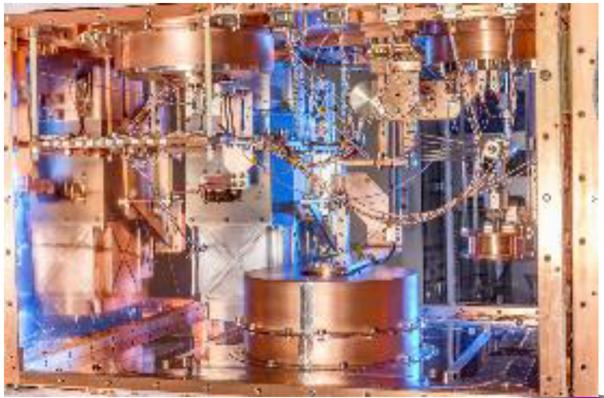


$$I + P\cos 4\theta_{\mathrm{HWP}}$$



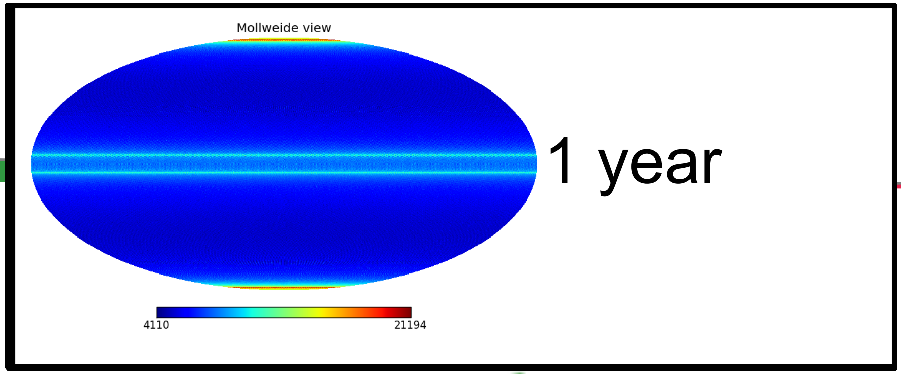
3. Cryogenic system for 0.1K base temperature

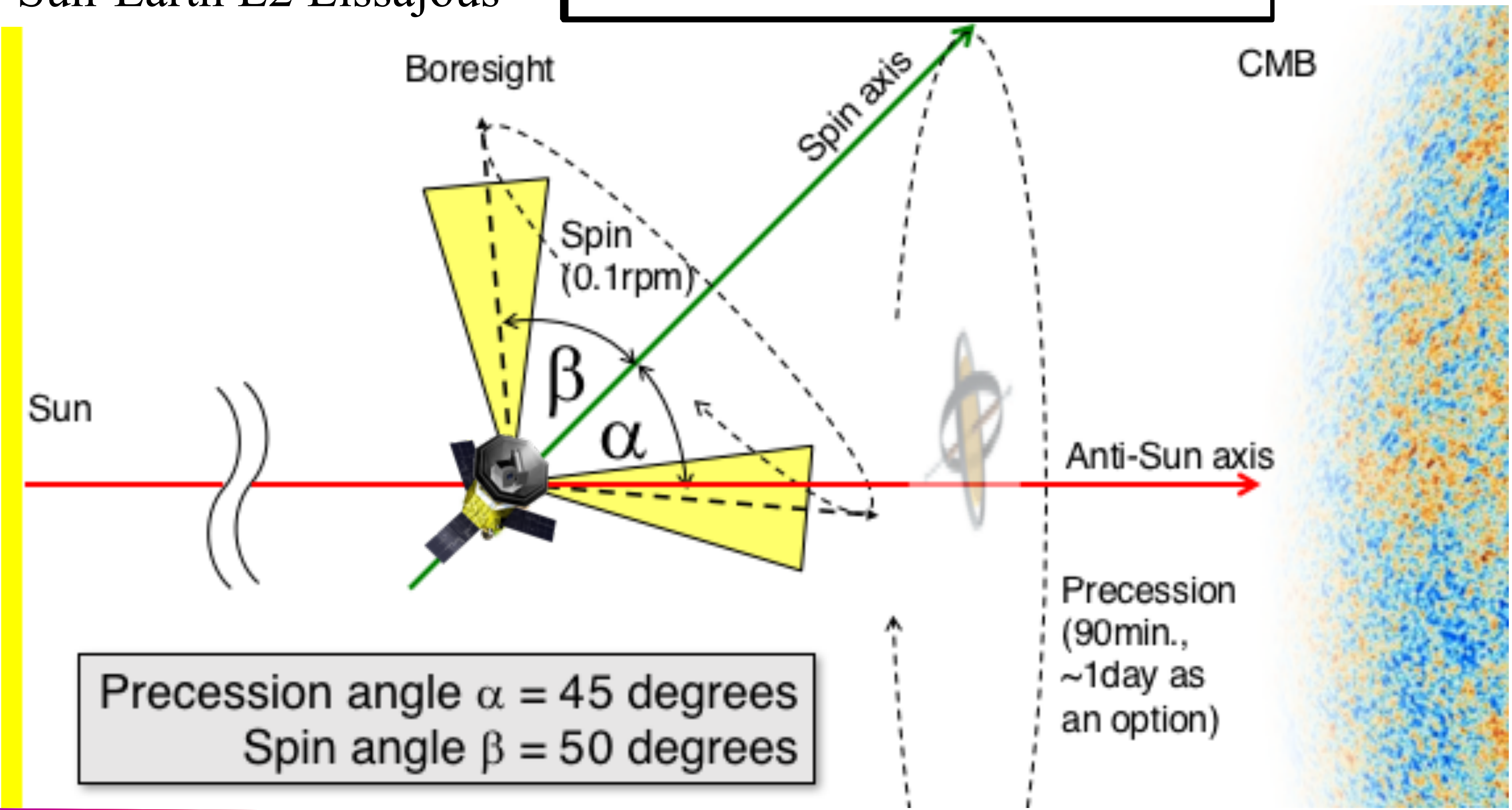




Operation

Orbit:
Sun-Earth L2 Lissajous





LiteBIRD has a clear goal and will achieve it!

Full Success：

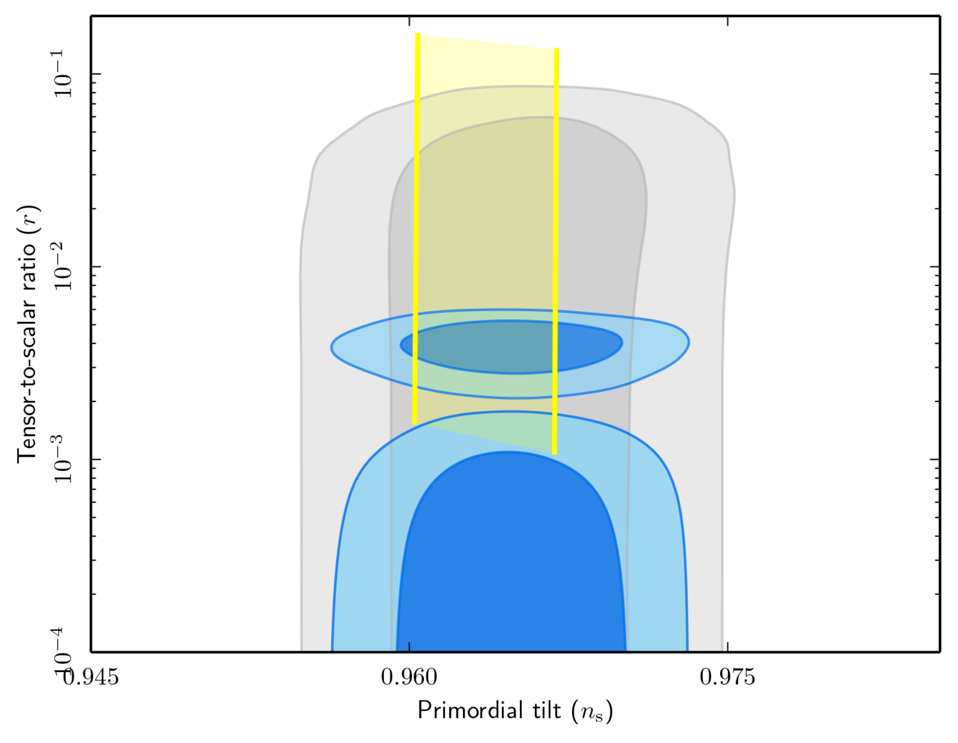
- $\delta r < 1 \times 10^{-3}$ (for r=0)
- >5σ observation for each bump (for $r \geq 0.01$)

Rationale

- Large discovery potential for $0.005 < r < 0.05$
- Simplest and well-motivated $R+R^2$ "Starobinsky" model will be tested.
- Clean sweep of single-field models with characteristic field variation scale of inflaton potential greater than m_{pl} (A. Linde, JCAP 1702 (2017) no.02, 006)

◆ Detailed foreground cleaning studies yield $\sigma(r=0) = 0.6 \times 10^{-3}$

◆ Thorough systematic error studies yield total uncertainty $\delta r < 1.0 \times 10^{-3}$ without delensing



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 $N_{\rm side}{}^2$)

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

to take spatial variations into account

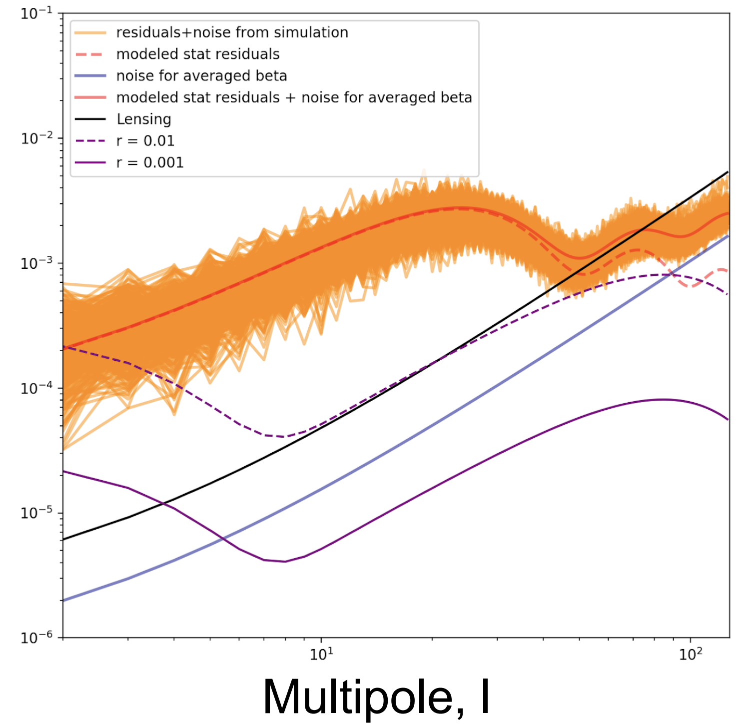
Results

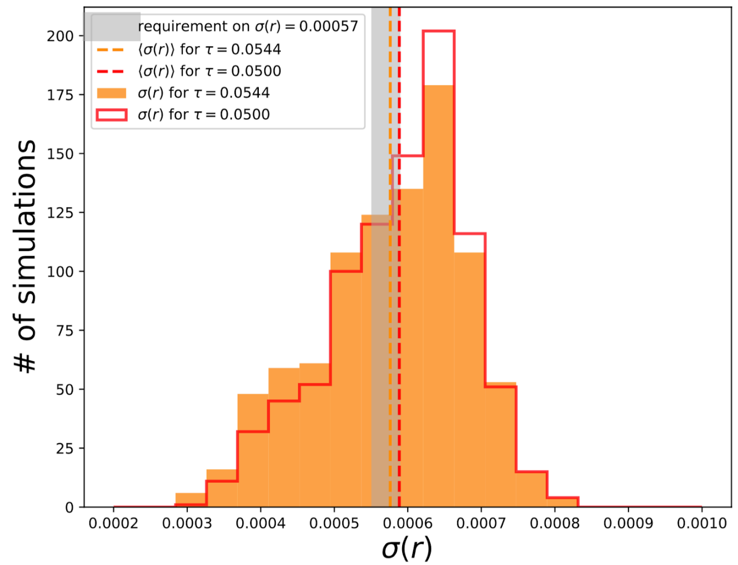
"Multipatch technique" (extension of xForecast)*

- $\sigma(r=0) = 0.0006$
- Negligibly small bias

Consistent results from COMMANDER-2!

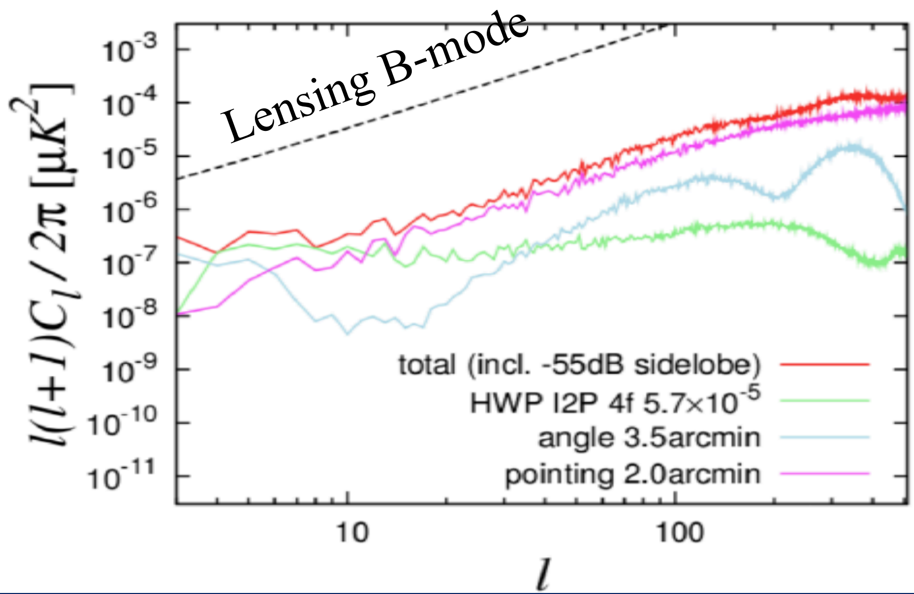
* Errard and Stompor, Phys.Rev. D99 (2019) no.4, 043529





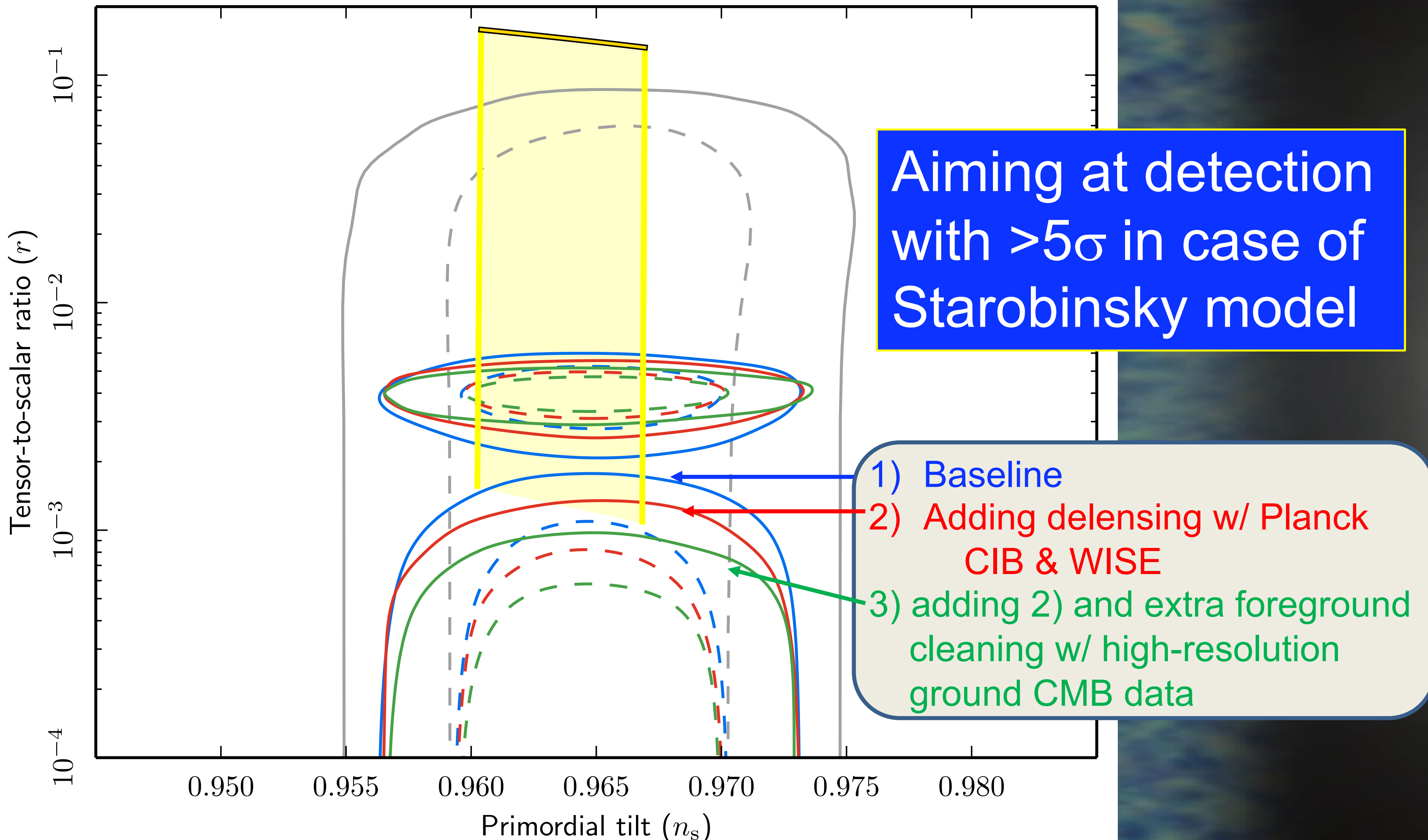
Systematics and Calibration

- 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}, $M_{IU} \sim 10^{-4}$ 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)



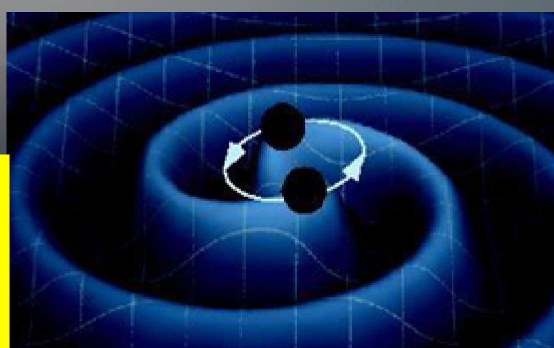
Aiming at detection with >5σ in case of Starobinsky model

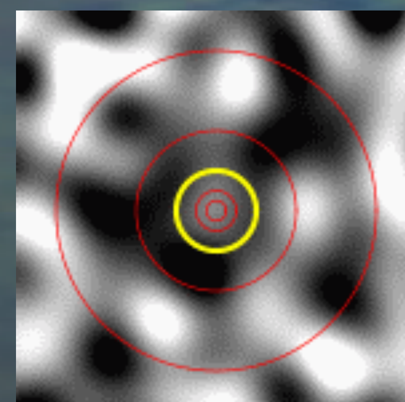
Big leap from
LIGO to CMB B-mode

within
Einstein's theory
of general relativity

beyond Einstein

The 2017
Nobel Prize
in Physics





- LIGO: gravitational waves with classical origin
- CMB B-mode: gravitational waves with quantum origin

Huge discovery impacts

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

"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

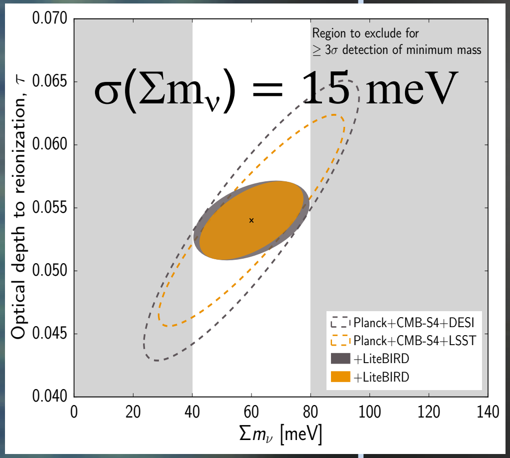
Last but no least, "origin of everything" evokes sense of wonder beyond science.

LiteBIRD Science Outcomes

1. Full success

System requirements from full success only

2. Extra success (already discussed)
3. Characterization of B-mode and search for sources fields (e.g scale-invariance, non-Gaussianity, parity violation)
4. Power spectrum features in polarization
5. Large-scale E mode and its implications for reionization history and the neutrino mass
6. Cosmic birefringence
7. SZ effect (thermal and relativistic correction)
8. Elucidating anomalies
9. Galactic science



3. – 9. in principle guaranteed if full success is achieved.

LiteBIRD Summary

- Selected for JAXA's L-class mission
- Expected launch in 2027
- 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)
- $>5\sigma$ observation for each bump (for $r \geq 0.01$)

➢ Detailed foreground cleaning studies yield $\sigma(r=0) = 0.6 \times 10^{-3}$
➢ 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
- Evoke sense of wonder beyond science

Backup

Physics of Cosmic Inflation

- Inflation: primordial accelerating expansion
  - successfully solve problems of naïve big-bang model
- Underlying physics is unknown but needs BSM
  - Leading hypothesis: new scalar field ϕ "Inflaton" with potential V(ϕ) → source of acceleration!
- In case of single-field slow-roll inflation (simplicity as guideline)

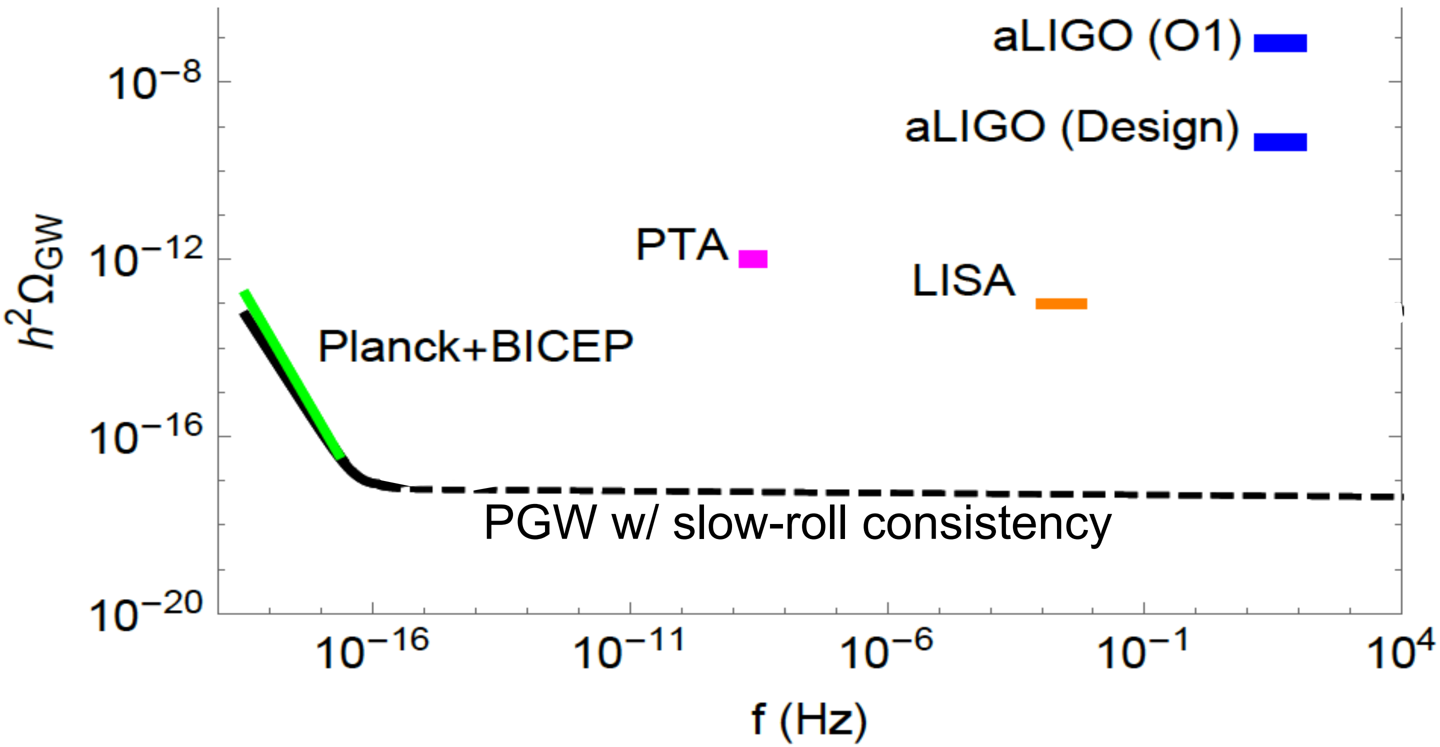
$$V^{1/4} = 1.04 \times 10^{16} \times \left(\frac{r}{0.01}\right)^{1/4} [GeV]$$

- r (tensor-to-scalar ratio) is a key parameter

CMB B-mode vs. interferometer

Caprini, Figueroa, arXiv1801.04268 (line w/ nt = 0.2 removed as it is irrelevant)

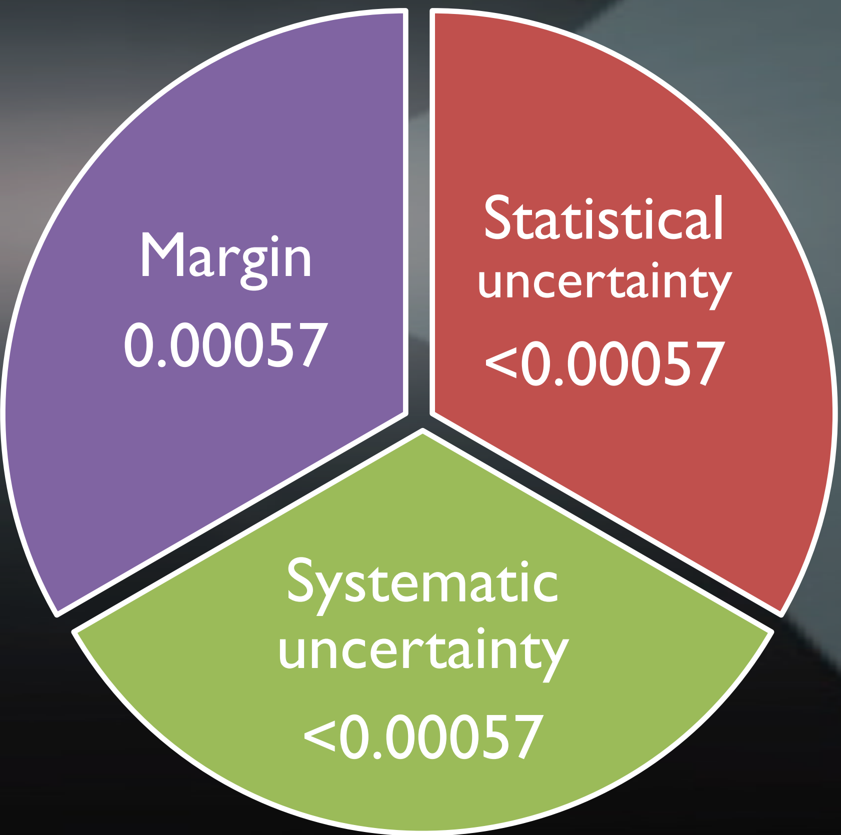
$$\Omega_{gw}(f) = \frac{3}{128}\Omega_{\rm rad}\, r\, A_s \left(\frac{f}{f_*}\right)^{n_t}\left[\frac{1}{2}\left(\frac{f_{\rm eq}}{f}\right)^2 + \frac{4}{9}(\sqrt{2}-1)\right]$$



Discovery with CMB B-mode will provide a clear target for a future space interferometer.

Scientific Goal and Challenges

Full Success :
- $\delta r < 1 \times 10^{-3}$ (for $r=0$)
- $>5\sigma$ observation for each bump (for $r \geq 0.01$)



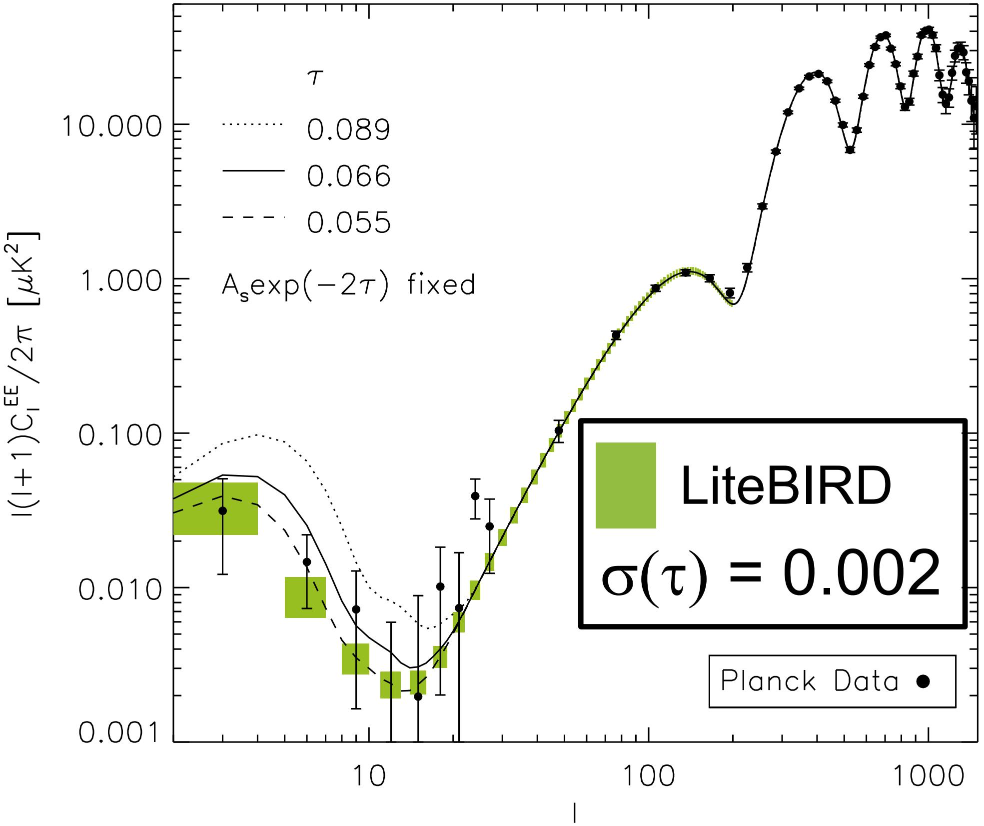
δr : Total uncertainty

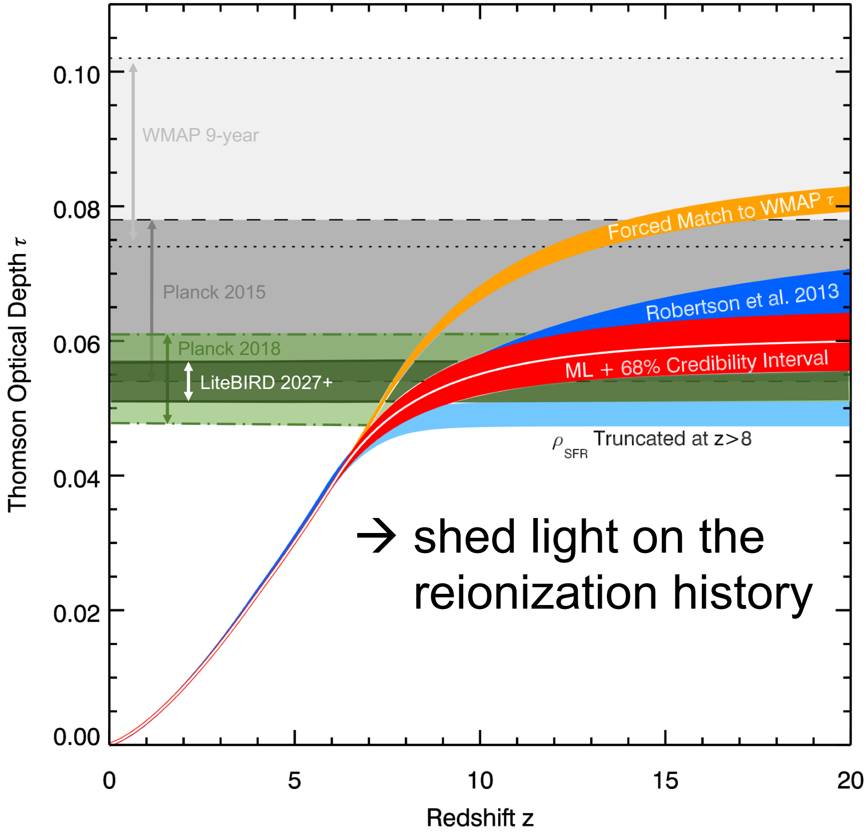
Statistical uncertainty includes
- foreground cleaning residuals
- lensing B-mode power
- 1/f noise

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

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 with improved τ

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

Caveat:
No systematic error included yet.