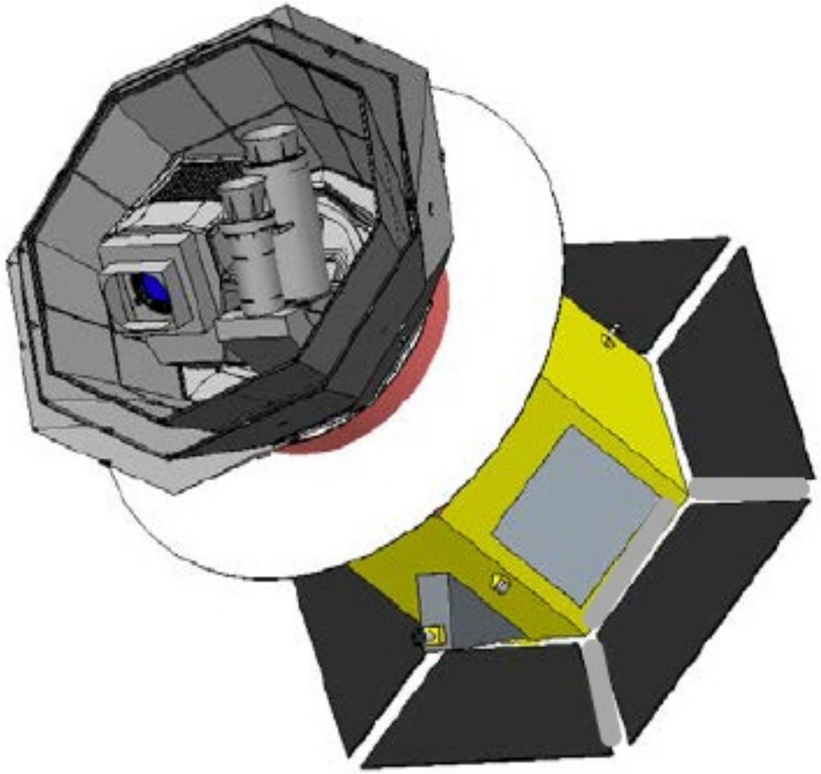
LiteBIRD Cosmic Microwave Background Polarization Mission



Adrian T. Lee

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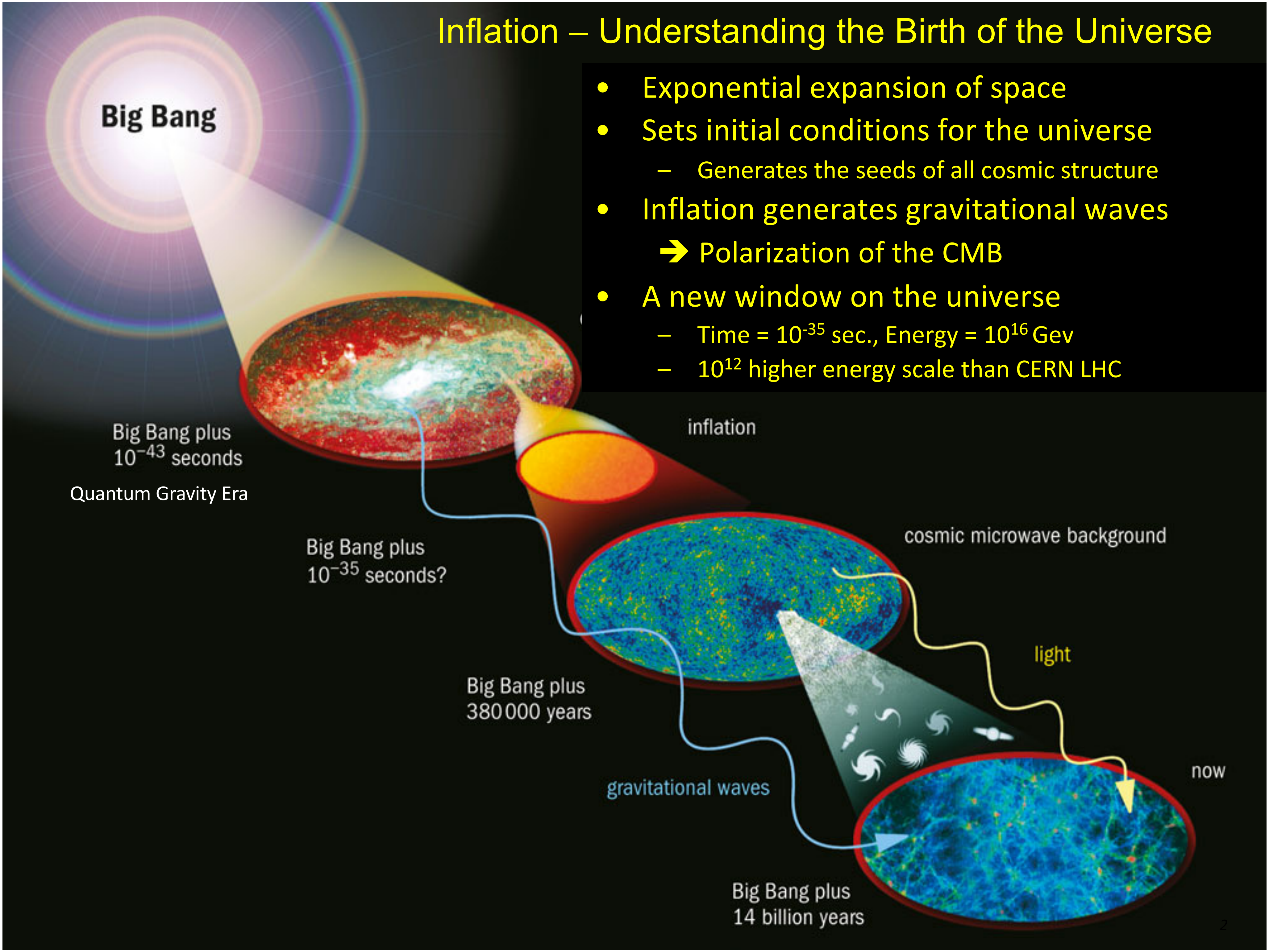
Physics Department and Space Sciences Laboratory

On behalf of the LiteBIRD Joint Study Group

Inflation – Understanding the Birth of the Universe

- Exponential expansion of space
- Sets initial conditions for the universe
  - Generates the seeds of all cosmic structure
- Inflation generates gravitational waves
  - ➔ Polarization of the CMB
- A new window on the universe
  - Time = 10^{-35} sec., Energy = 10^{16} Gev
  - 10^{12} higher energy scale than CERN LHC



LiteBIRD Joint Study Group

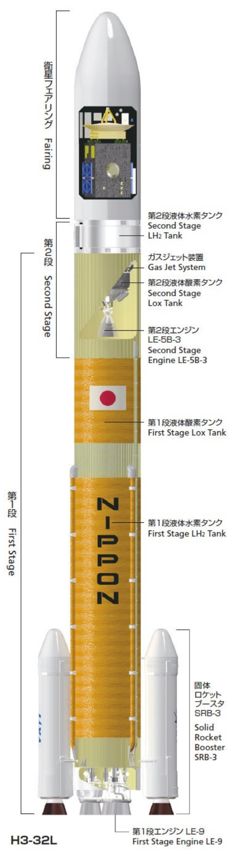
> 250 researchers from Japan, North America & Europe

M. Hazumi[1,2,3,4], P.A.R. Ade[5], A. Adler[6], E. Allys[7], K. Arnold[8], D. Auguste[9], J. Aumont[10], R. Aurlien[11], J. Austermann[12], C. Baccigalupi[13], A.J. Banday[10], R. Banerji[11], R.B. Barreiro[14], S. Basak[15], J. Beall[12], D. Beck[16], S. Beckman[17], J. Bermejo[18], P. de Bernardis[19], M. Bersanelli[20], J. Bonis[9], J. Borrill[21,22], F. Boulanger[7], S. Bounissou[23], M. Brilenkov[11], M. Brown[24], M. Bucher[25], E. Calabrese[5], P. Campeti[13], A. Carones[26], F.J. Casas[14], A. Challinor[27,28,29], V. Chan[30], K. Cheung[17], Y. Chinone[31], J.F. Cliche[32], L. Colombo[20], F. Columbro[19], J. Cubas[33], A. Cukierman[17,16], D. Curtis[22], G. D'Alessandro[19], N. Dachlythra[34], M. De Petris[19], C. Dickinson[24], P. Diego-Palazuelos[14], M. Dobbs[32], T. Dotani[2], L. Duband[35], S. Duff[12], J.M. Duval[35], K. Ebisawa[2], T. Elleflot[36], H.K. Eriksen[11], J. Errard[25], T. Essinger-Hileman[37], F. Finelli[38], R. Flauger[8], C. Franceschet[20], U. Fuskeland[11], M. Galloway[11], K. Ganga[25], J.R. Gao[39], R. Genova-Santos[40], M. Gerbino[41], M. Gervasi[42], T. Ghigna[3,43], E. Gjerløw[11], M.L. Gradziel[44], J. Grain[23], F. Grupp[45], A. Gruppuso[38], J.E. Gudmundsson[34], T. de Haan[1], N.W. Halverson[46], P. Hargrave[5], T. Hasebe[2], M. Hasegawa[1], M. Hattori[47], S. Henrot-Versillé[9], D. Herman[11], D. Herranz[14], C.A. Hill[36,17], G. Hilton[12], Y. Hirota[48], E. Hivon[49], R.A. Hlozek[30], Y. Hoshino[50], E. de la Hoz[14], J. Hubmayr[12], K. Ichiki[51], T. Iida[52], H. Imada[53], K. Ishimura[54], H. Ishino[55], G. Jaehnig[46], T. Kaga[2], S. Kashima[53], N. Katayama[3], A. Kato[1,4], T. Kawasaki[56], R. Keskitalo[21,22], T. Kisner[21,22], Y. Kobayashi[48], N. Kogiso[57], A. Kogut[37], K. Kohri[1], E. Komatsu[58], K. Komatsu[55], K. Konishi[48], N. Krachmalnicoff[13], I. Kreykenbohm[59], C.L. Kuo[60,16], A. Kushino[61], L. Lamagna[19], J.V. Lanen[12], M. Lattanzi[62], A.T. Lee[17,36], C. Leloup[25], F. Levrier[7], E. Linder[22,36], T. Louis[9], G. Luzzi[63], T. Maciaszek[64], B. Maffei[23], D. Maino[20], M. Maki[1], S. Mandelli[20], E. Martinez-Gonzalez[14], S. Masi[19], T. Matsumura[3], A. Mennella[20], M. Migliaccio[26], Y. Minami[1], K. Mitsuda[53], J. Montgomery[32], L. Montier[10], G. Morgante[38], B. Mot[10], Y. Murata[2], J.A. Murphy[44], M. Nagai[53], Y. Nagano[55], T. Nagasaki[1], R. Nagata[2], S. Nakamura[65], T. Namikawa[27], P. Natoli[41], S. Nerval[30], T. Nishibori[66], H. Nishino[31], F. Noviello[5], C. O'Sullivan[67], H. Ogawa[57], H. Ogawa[2], S. Oguri[2], H. Ohsaki[48], I.S. Ohta[68], N. Okada[2], N. Okada[57], L. Pagano[40], A. Paiella[19], D. Paoletti[38], G. Patanchon[25], J. Peloton[9], F. Piacentini[19], G. Pisano[19,5], G. Polenta[69], D. Poletti[13], T. Prouvé[35], G. Puglisi[16], D. Rambaud[10], C. Raum[17], S. Realini[20], M. Reinecke[58], M. Remazeilles[24], A. Ritacco[23,7], G. Roudil[10], J.A. Rubino-Martin[40], M. Russell[8], H. Sakurai[70], Y. Sakurai[3], M. Sandri[38], M. Sasaki[59], G. Savini[71], D. Scott[72], J. Seibert[8], Y. Sekimoto[2,73,1], B. Sherwin[27,29,36], K. Shinozaki[66], M. Shiraishi[74], P. Shirron[37], G. Signorelli[75], G. Smecher[76], S. Stever[55,3], R. Stompor[25], H. Sugai[3], S. Sugiyama[50], A. Suzuki[36], J. Suzuki[1], T.L. Svalheim[11], E. Switzer[37], R. Takaku[2,77], H. Takakura[73,2], S. Takakura[3], Y. Takase[55], Y. Takeda[2], A. Tartari[75], E. Taylor[17], Y. Terao[48], H. Thommesen[11], K.L. Thompson[60,16], B. Thorne[43], T. Toda[55], M. Tomasi[20], M. Tominaga[73,2], N. Trappe[67], M. Tristram[9], M. Tsuji[74], M. Tsujimoto[2], C. Tucker[5], J. Ullom[12], G. Vermeulen[78], P. Vielva[14], F. Villa[38], M. Vissers[12], N. Vittorio[26], I. Wehus[11], J. Weller[79,45], B. Westbrook[17], J. Wilms[59], B. Winter[71,80], E.J. Wollack[36], N.Y. Yamasaki[2], T. Yoshida[2], J. Yumoto[48], M. Zannoni[42], and A. Zonca[81]

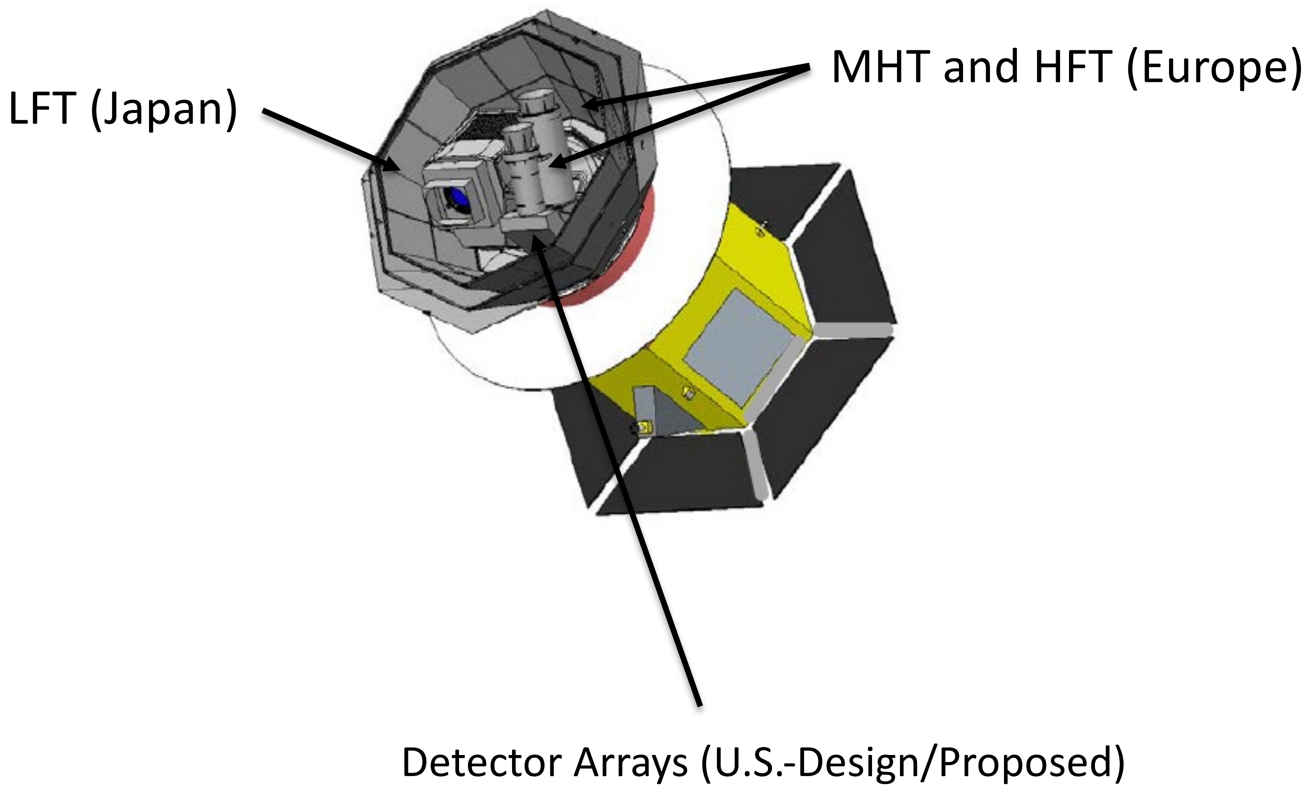
LiteBIRD Summary

- JAXA-led international mission proposal (12 countries)
- **L-Class Mission Selected by JAXA in 2019**
- Launch in late 2020s
- 3yr observation at Sun-Earth Lagrangian Point L2
- 15 Frequency Bands 34-448 GHz, 71-18 arc-min resolution

HIIA



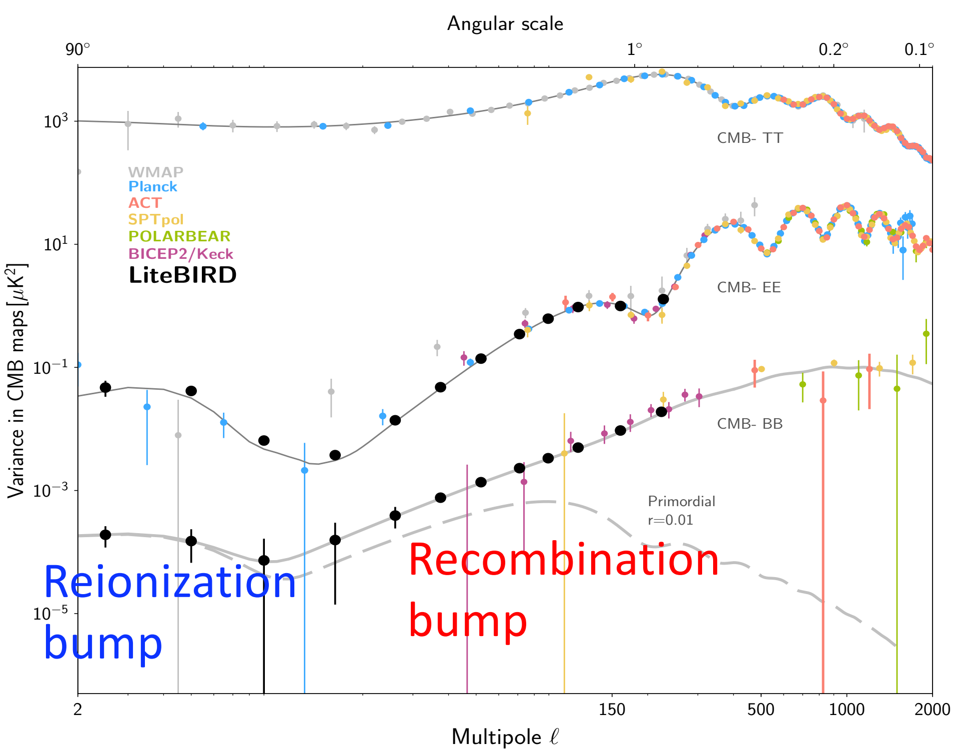
H3



U.S. team working under NASA "Technical Development" grant

Main scientific objectives

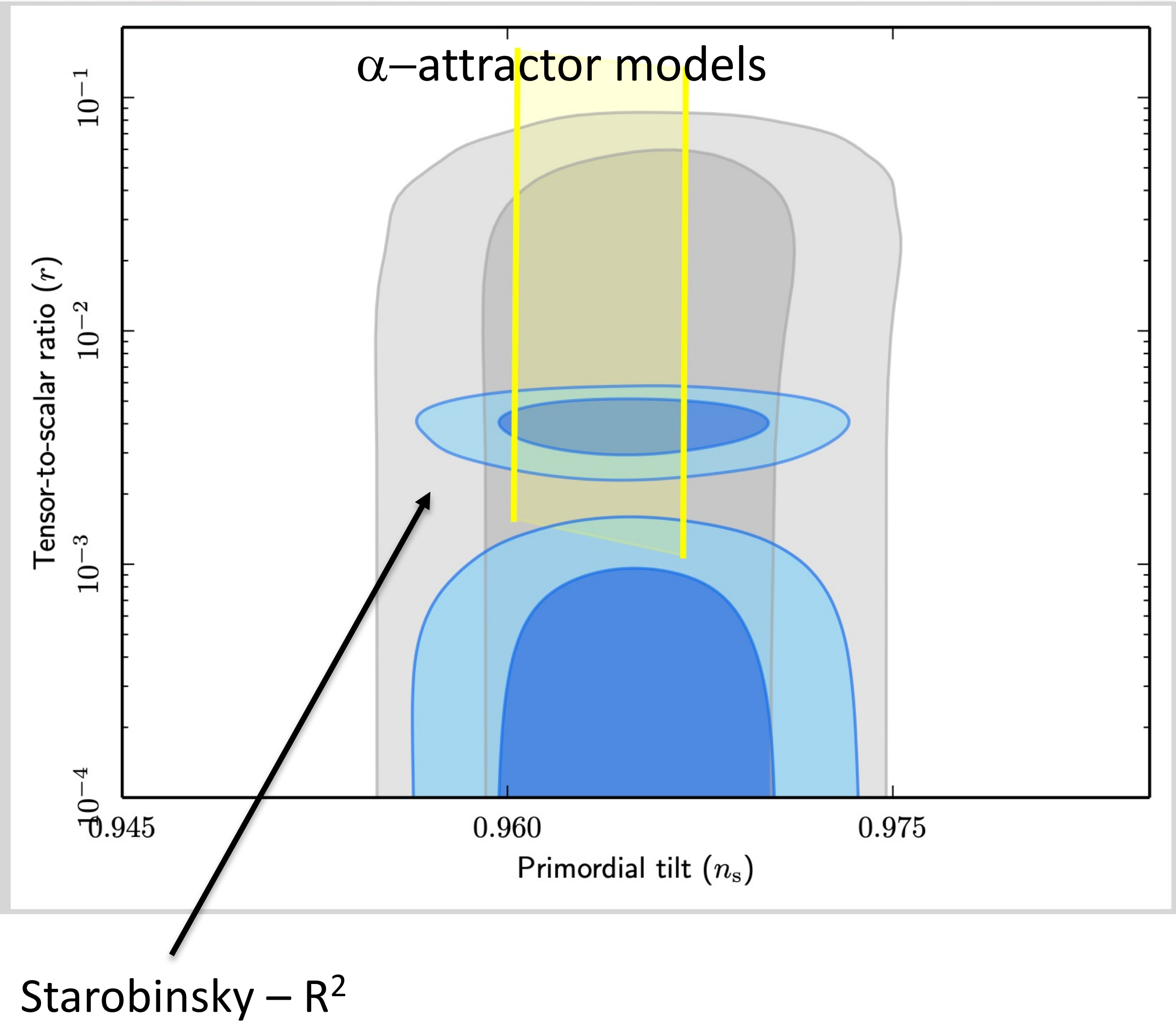
- **Primordial Cosmology**
  - Definitive search for a signal from cosmic inflation
    - Either making a discovery or ruling out well-motivated inflationary models
- **Fundamental Physics**
  - Energy Scale: Insight into quantum nature of gravity, other new physics



- Level-1 Requirement: $\delta r < 0.001$ total error
- This total error includes:
  - $\sigma_{stat} < 5.7 \times 10^{-4}$ inc. foreground removal
  - $\sigma_{syst} < 5.7 \times 10^{-4}$
  - Margin $= 5.7 \times 10^{-4}$
- There is no delensing assumed here

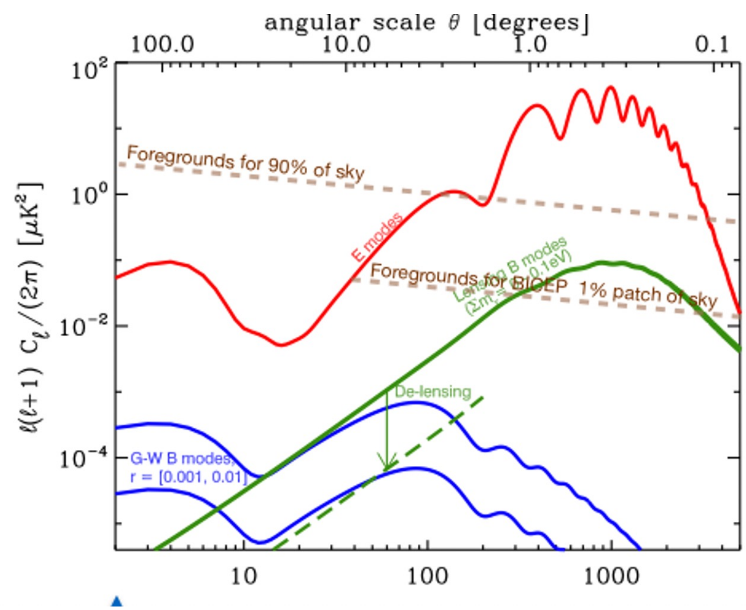
- 2nd Level-1 Requirement
  - > 5σ detection of both Reionization and Recombination bumps for r = 0.01 ($\tau = 0.05$)

LiteBIRD Inflation Constraints



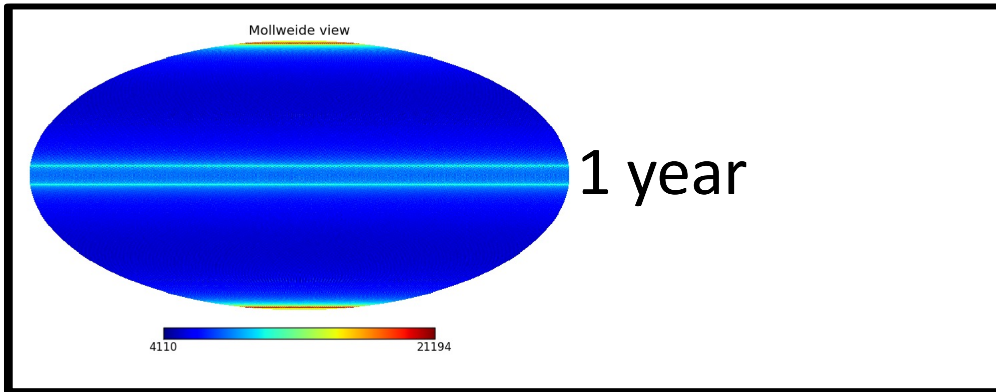
Why Space?

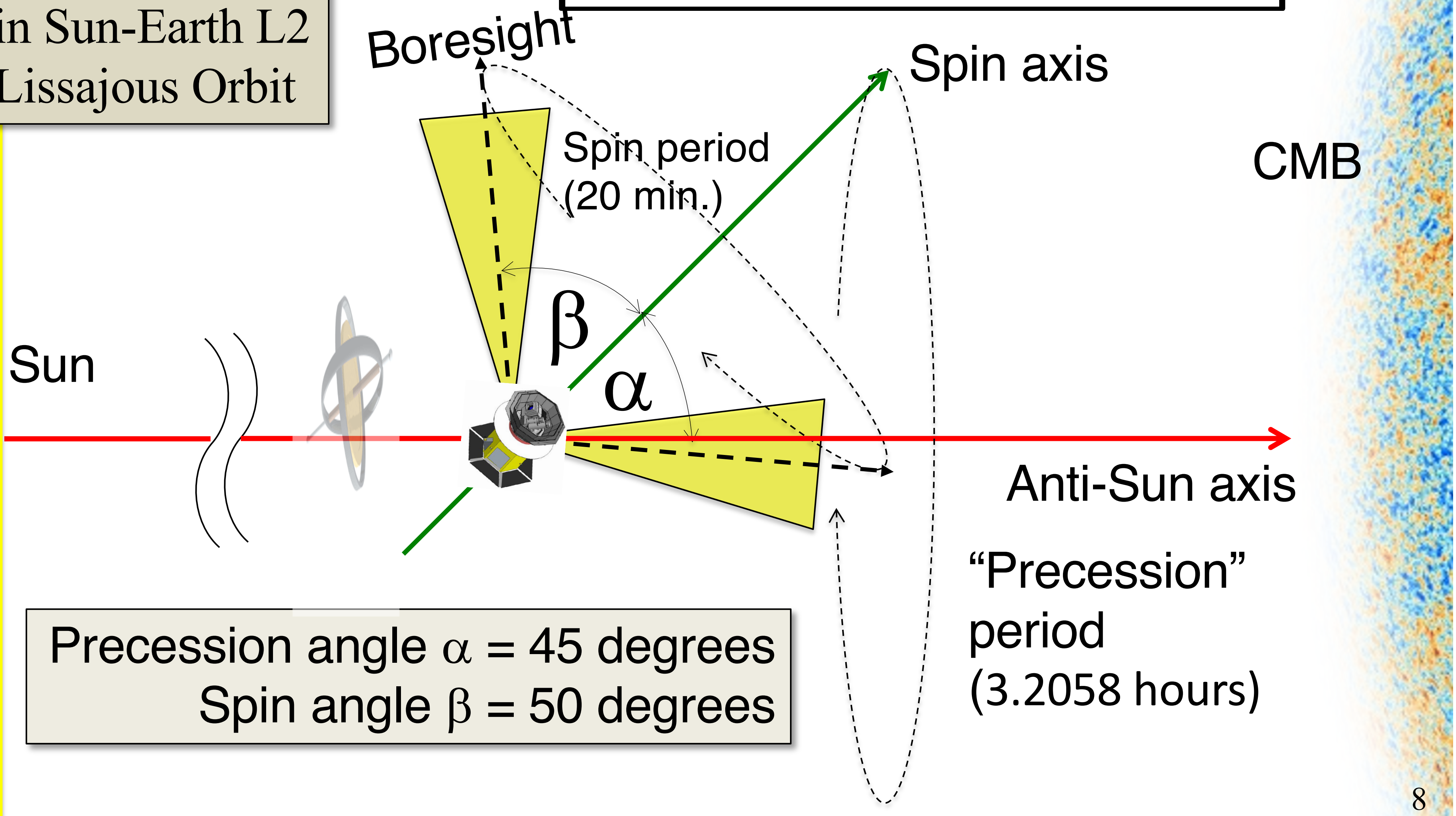
- History: COBE, WMAP, and Planck are reference experiments
- Advantages of Space:
  - Access to all frequencies
    - Important for foreground meas.
  - Absence of atmospheric fluctuations ➔ Access to lowest multipoles
    - Measure Reionization and Recombination bumps
  - L2 enables bright objects (sun/moon) to be behind spacecraft.
- Complementarity
  - Ground gives delensing data
  - LiteBIRD gives foreground information



Operation

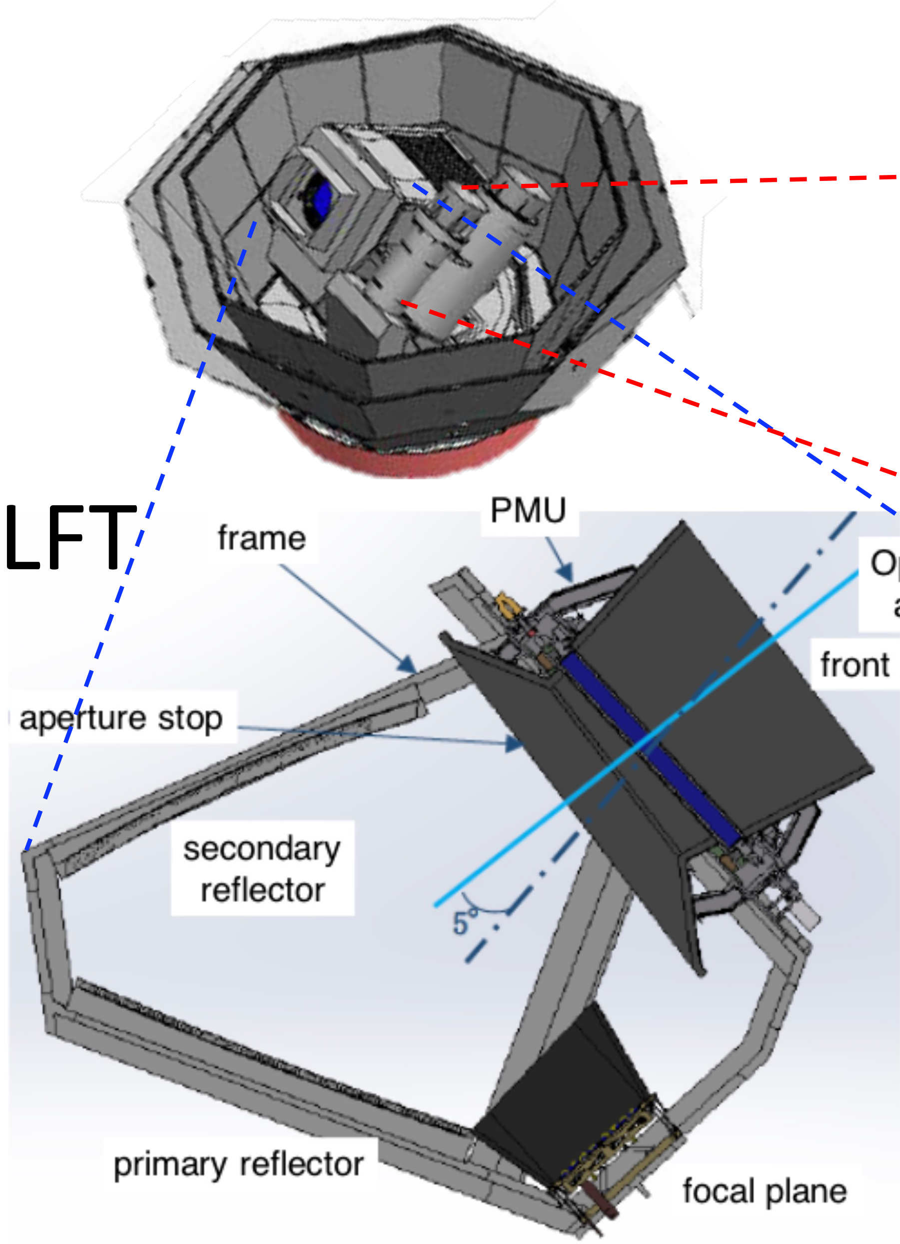
Observations
for 3 years
in Sun-Earth L2
Lissajous Orbit

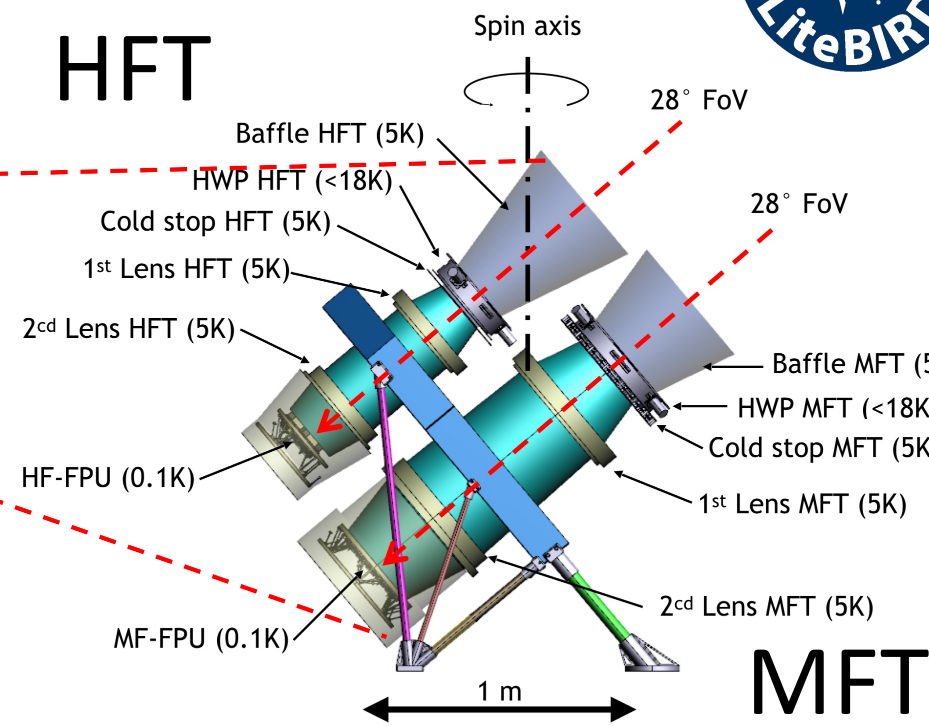




Precession angle α = 45 degrees
Spin angle β = 50 degrees

LiteBIRD Payload Module

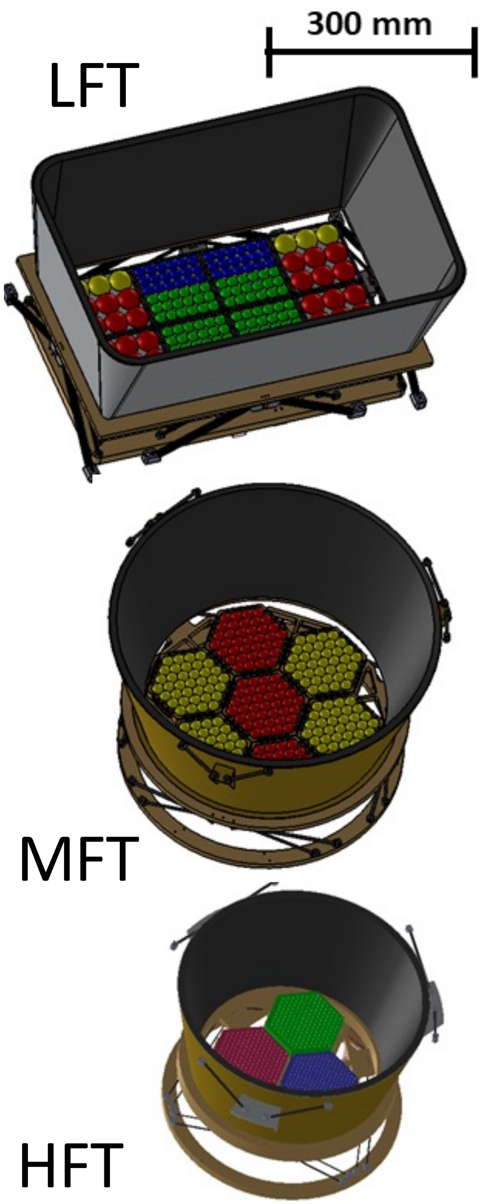


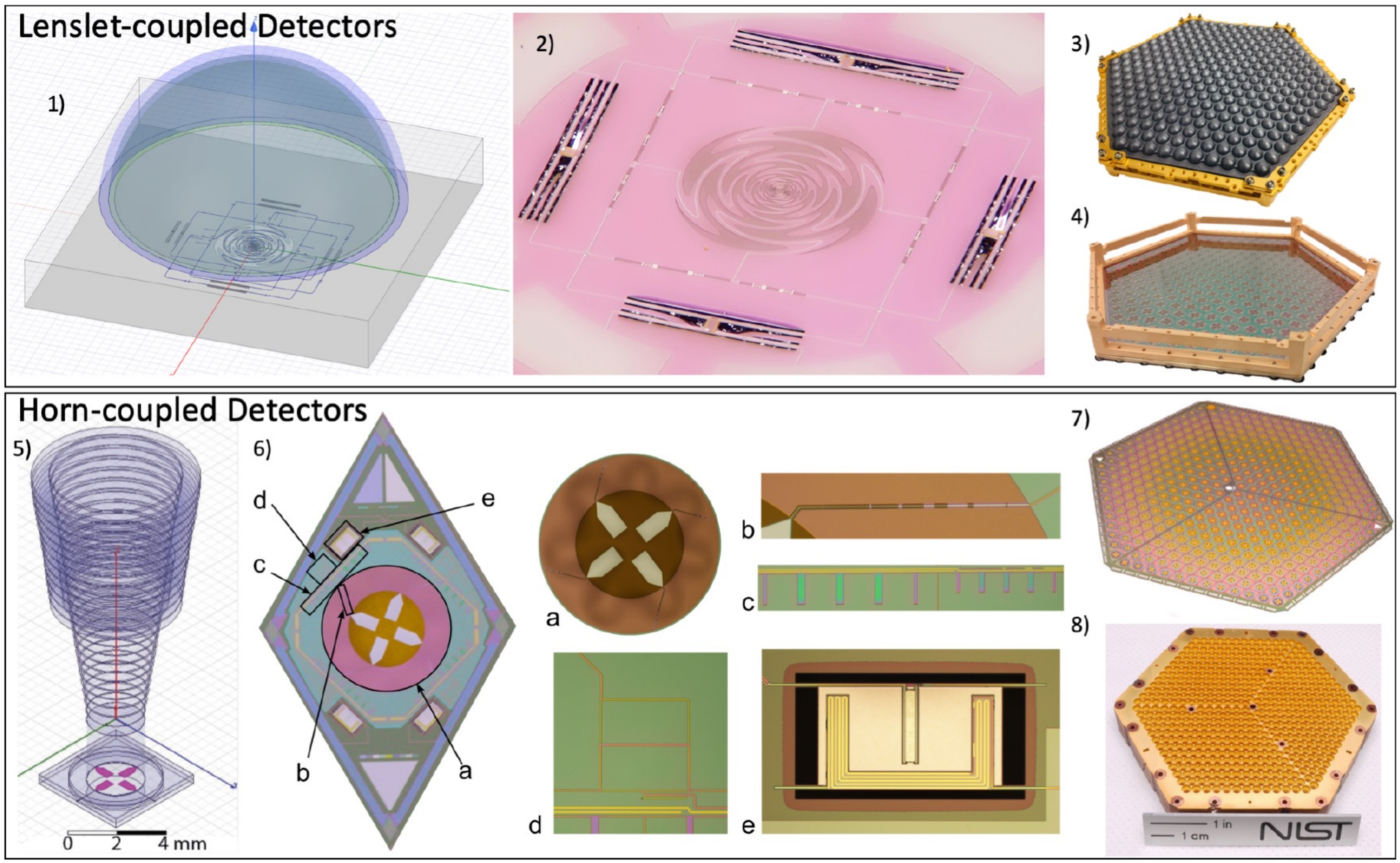


<u>Three features</u>

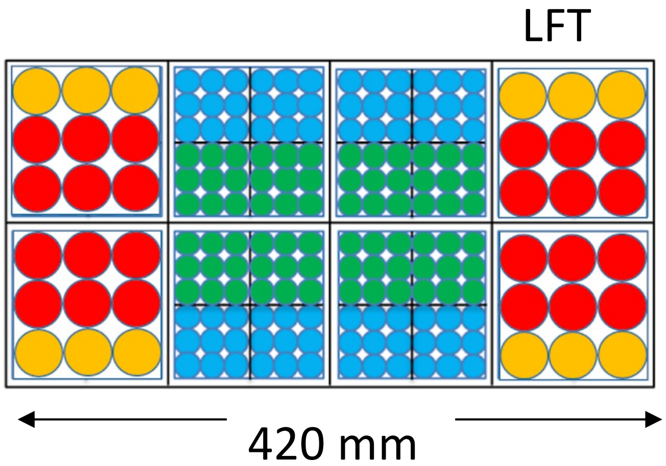
1. Three telescopes with multi-chroic transition-edge sensor (TES) bolometer arrays
2. Polarization modulation unit (PMU) in each telescope with rotating half-wave plate (HWP) for 1/f noise & systematics reduction
3. Cryogenic system for 0.1K base temperature

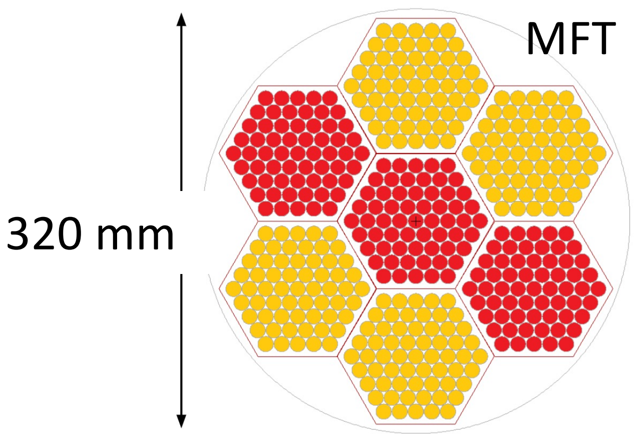
Transition Edge Sensor (TES) Arrays

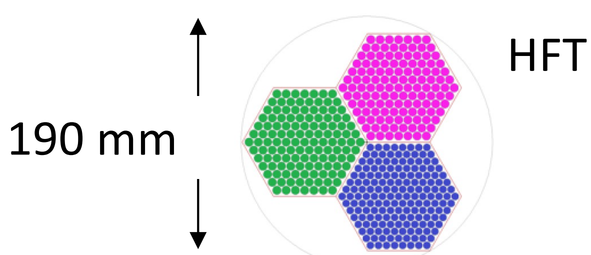


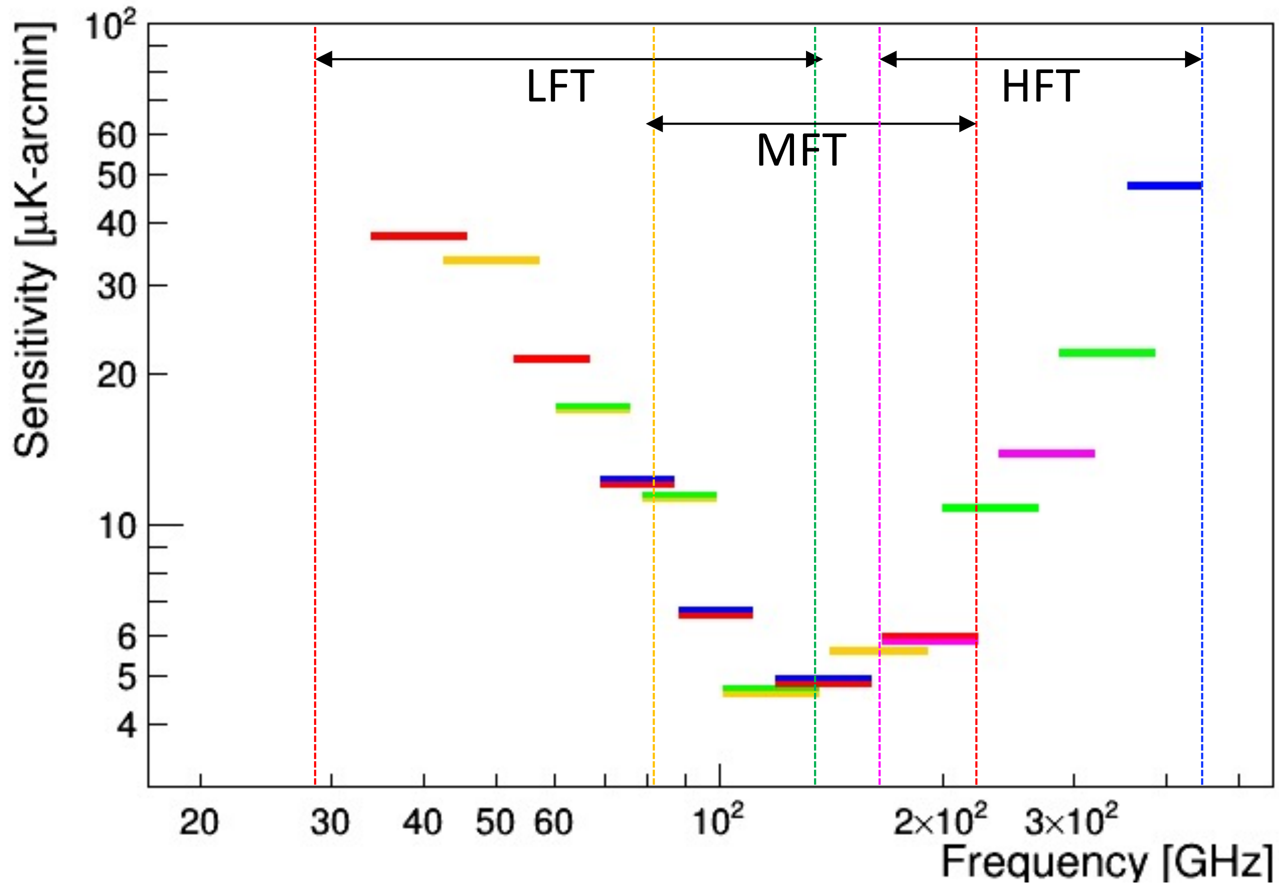


Map Noise









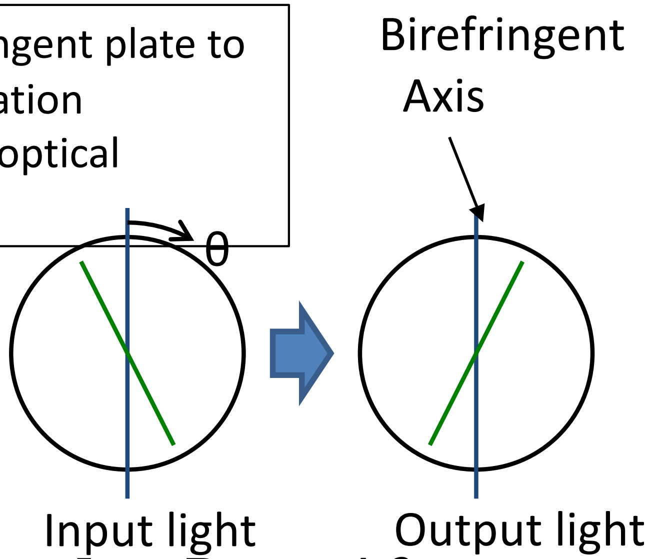
Total polarization sensitivity (observations for 3 years):

2.16μK-arcmin

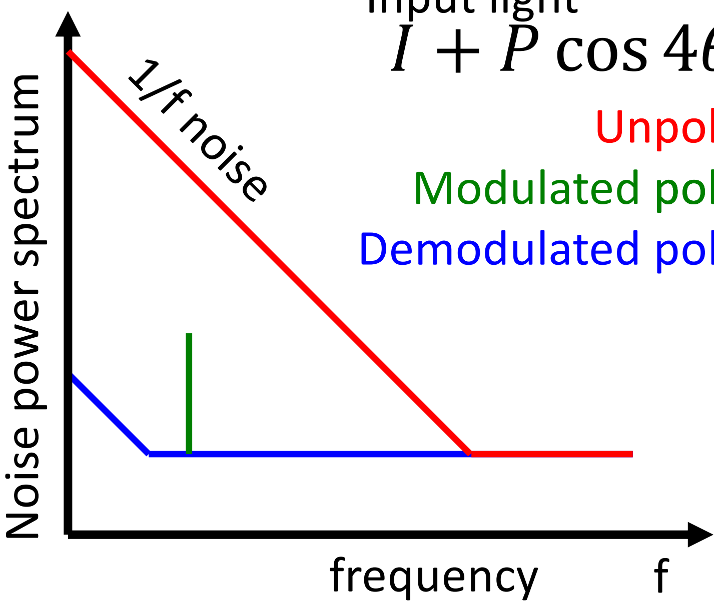
Polarization Modulation Unit (PMU)

Operation Principle

- Rotating a birefringent plate to modulate polarization
- The first sky-side optical element



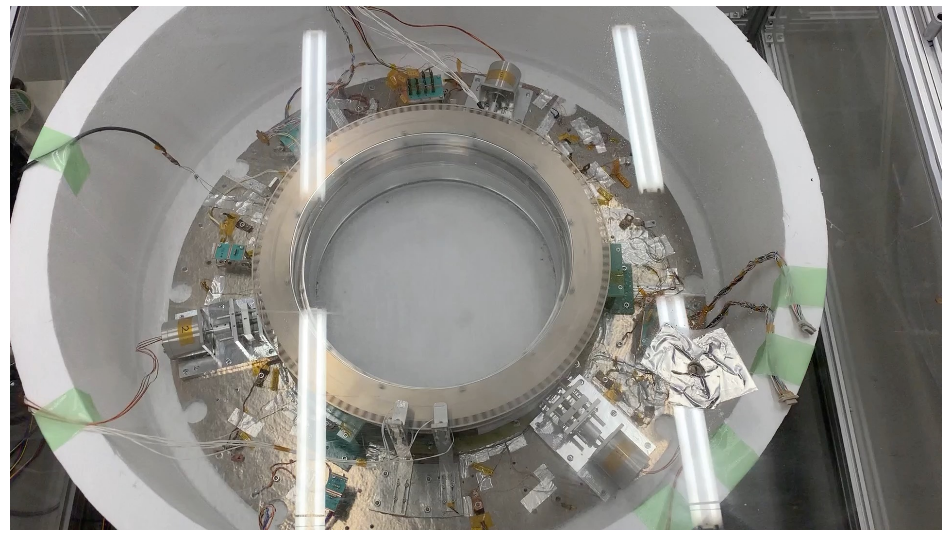
$$I + P\cos 4\theta_{\mathrm{HWP}}$$



Unpolarized signal

Modulated polarized signal

Demodulated polarized signal



Rotation test of superconducting magnetic bearing system in the 4K cryostat.

The stable rotation at cryogenic temperature (<10K).

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 (Ichiki-Kanai-Katayama-Komatsu 2019)

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

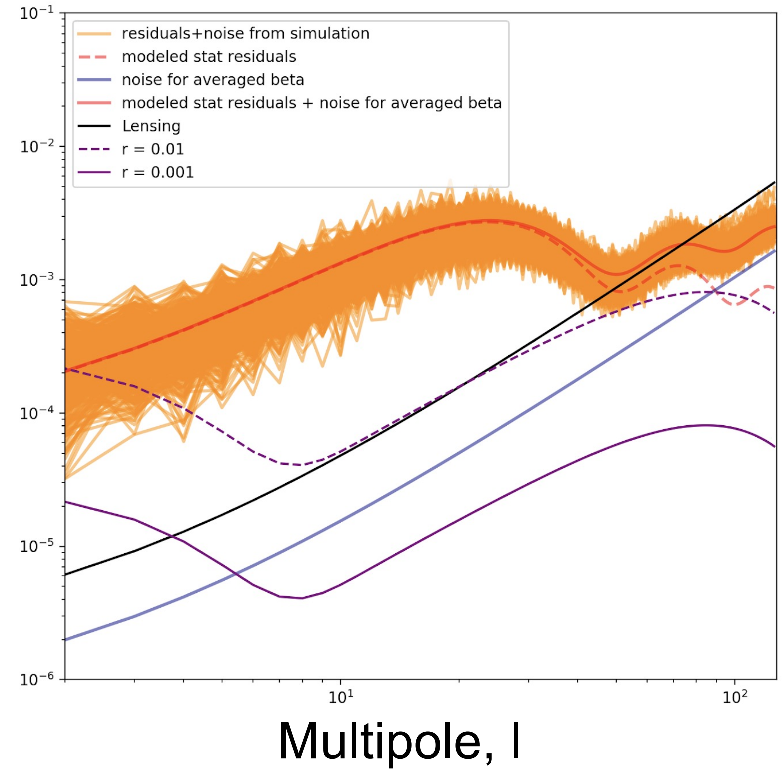
Results

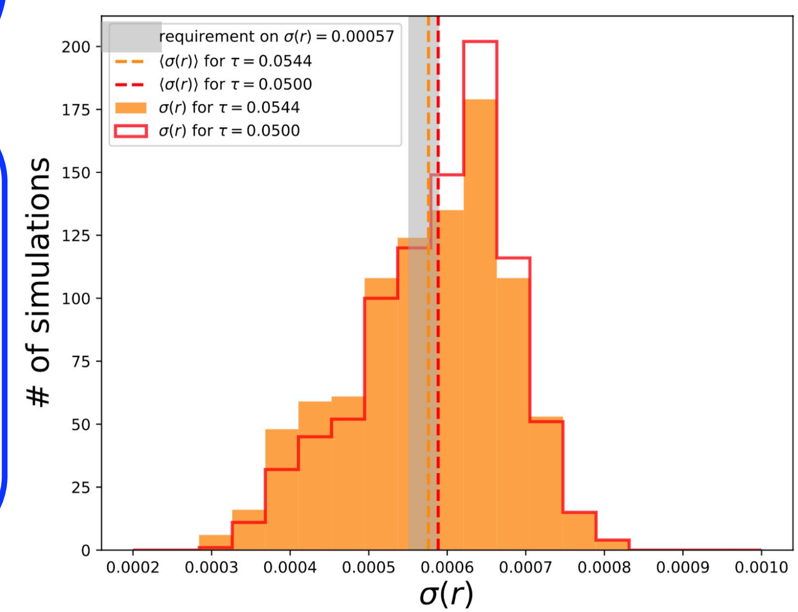
"Multipatch technique" (extension of x Forecast)*

- $\sigma(r=0) = 0.6 \times 10^{-3}$
- 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 sources
14 categories
70 items

Assign each 1% of total budget
$\sigma(r)_{sys} < 5.7 \times 10^{-6}$

Define method (incl. calib. meth.)
estimate of $\sigma(r)_{sys}$

Allocate special budget for outstanding items

Sum on map base
total $\sigma(r)_{sys}$

Iteration

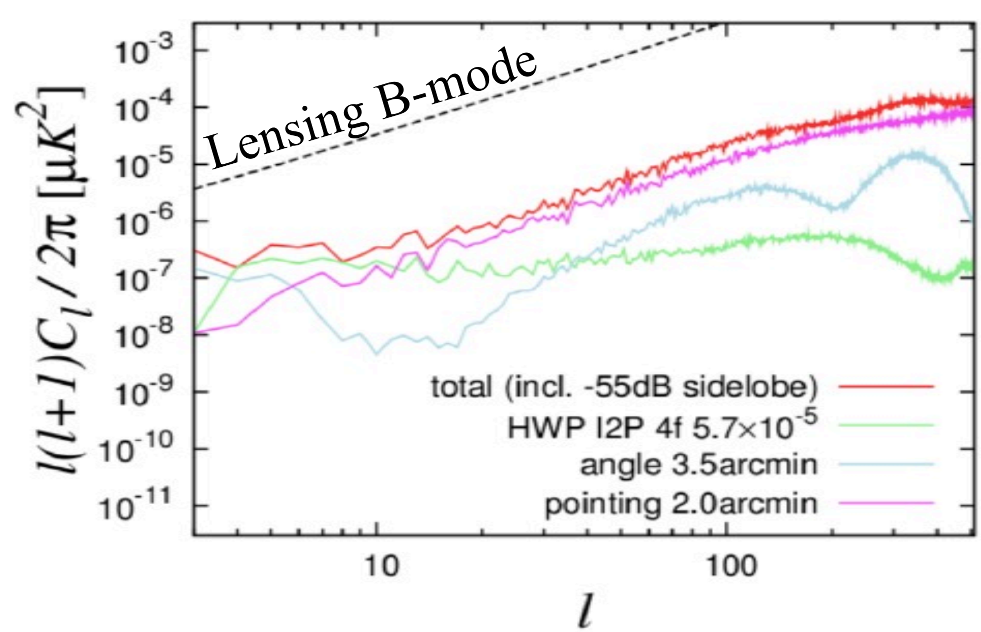
- **Example: studies of systematic errors due to HWP imperfection**

Realistic HWP for different frequencies and incident angles

Mueller matrix M from RCWA sim.
$1M_{IQ}$, $M_{IU} \sim 10^{-4}$ (worst case)

Obtain leakage Maps and BB power
$\sigma(r)_{sys}$

Known systematic errors within budget using current instrumental model and calibration requirements



LiteBIRD Science Outcomes

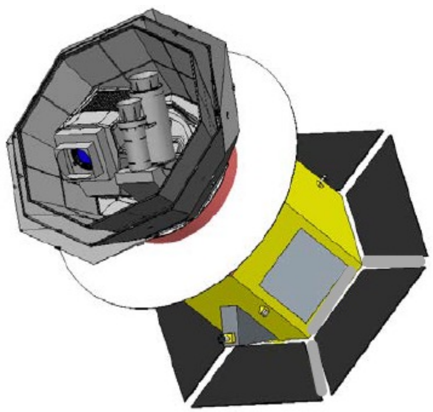
1. **Tensor-to-scalar ratio, *r*, from top-level mission requirements**

The following items (2-9) do not drive mission/system requirements,
but will be guaranteed if (1) is achieved.

2. **Further improving sensitivity on *r* with external data**
3. **Characterization of B-mode and search for source fields (e.g scale-invariance, non-Gaussianity, parity violation)**
4. **Power spectrum features in polarization**
5. **Large-scale E-modes**
   - 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**

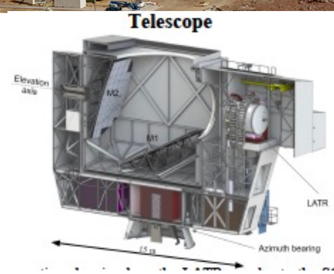
Targeted mission requirements
and rich scientific outcomes

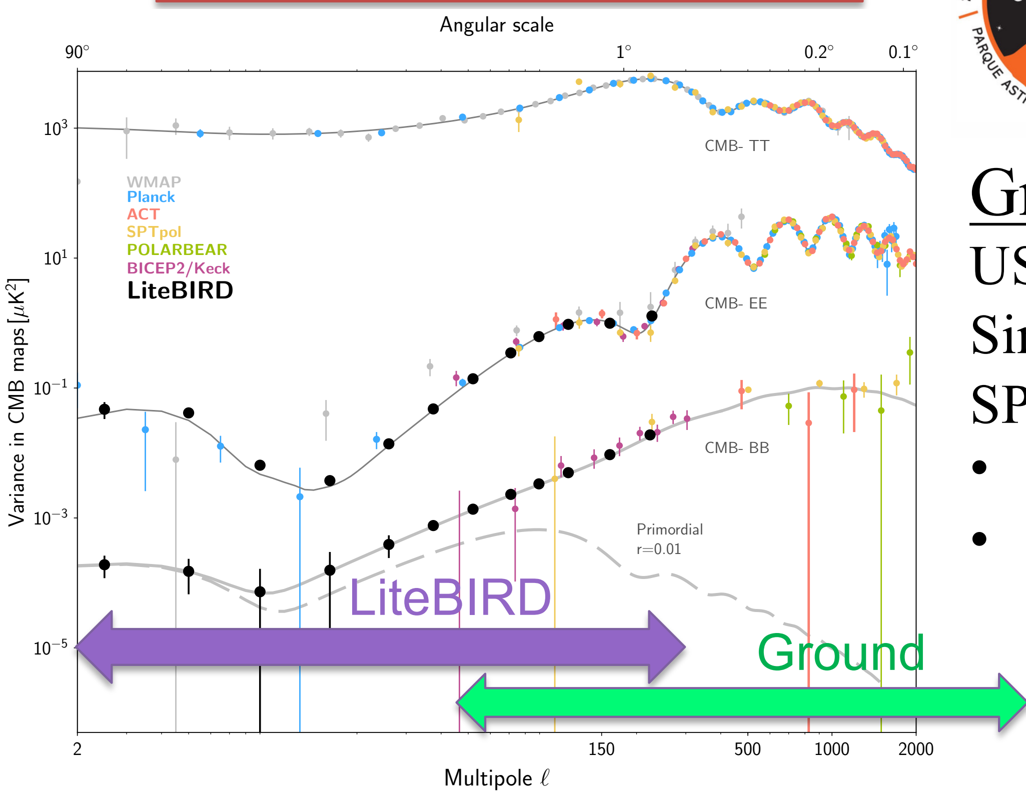
Vision for next 15 years



X

Powerful Duo





<u>LiteBIRD</u>

JAXA-led focused mission

- $\delta(r) < 0.001$
- $2 \leq \ell \leq 200$

focused but still with byproducts

<u>Ground-based</u>

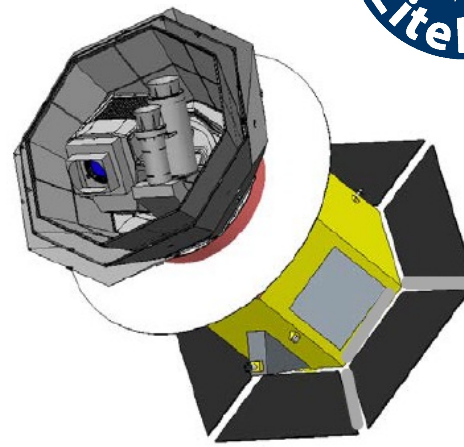
US-led telescopes (e.g. Simons Observatory, SPO, and CMB-S4)

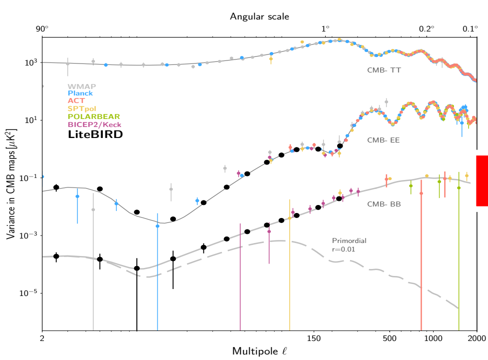
- $30 \leq \ell \leq \sim 8000$
- Including delensing

- This powerful duo is a cost-effective strategy with great synergy
- MoU between LiteBIRD and CMB-S4 for science and technology under discussion

LiteBIRD Summary

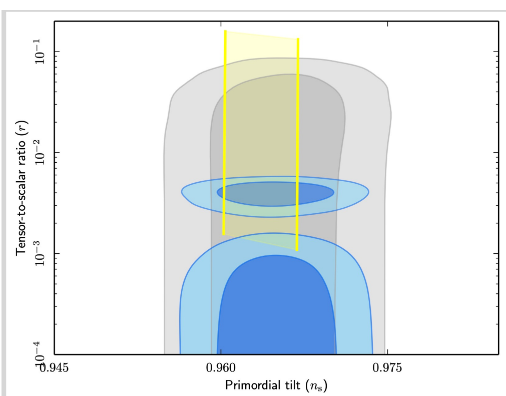
- **Selected for JAXA's L-class mission**
- **Expected launch in 2020s**
- **Observations for 3 years around Sun-Earth L2**
- **Full-sky degree-scale CMB polarization surveys**
- **Total polarization sensitivity: 2.16 μK-arcmin**





<u>Conclusion of the concept development studies</u>

Top-level mission requirements will be satisfied.



<u>Discovery by LiteBIRD has huge impacts and will provide</u>

- Direct evidence for inflation
- Knowledge on the inflation energy scale
- First evidence for quantum fluctuation of space-time
- Insight on quantum gravity, including String Theory

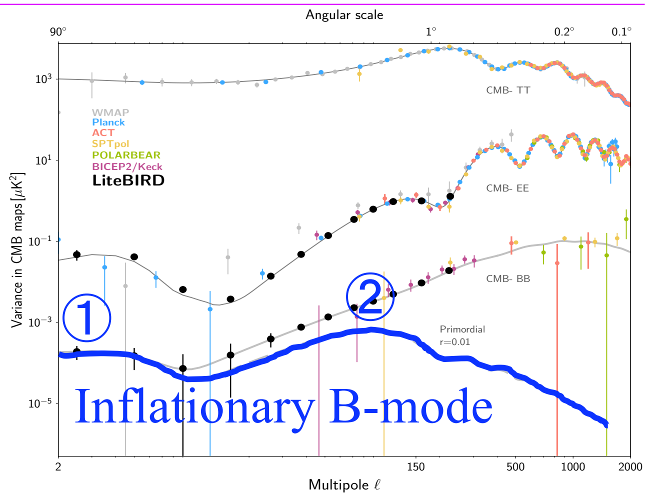
Backup Slides

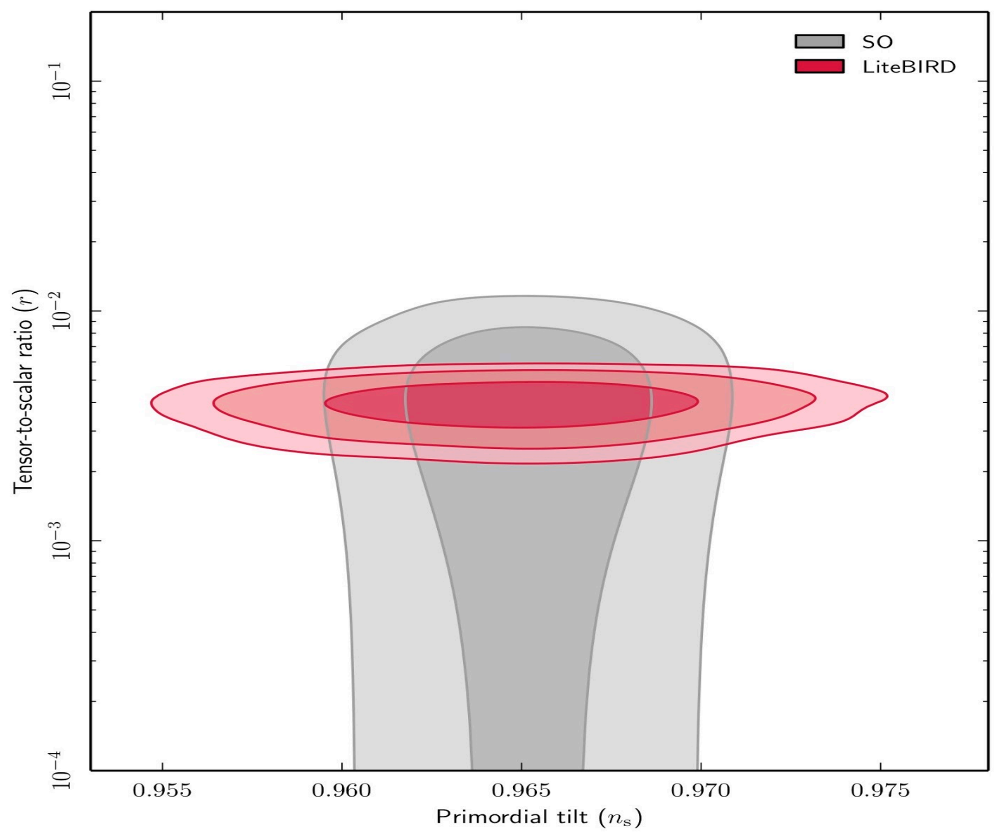
Top-level mission requirements will be satisfied!

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

$\sigma(r=0) = 0.6 \times 10^{-3}$

① Reionization bump
② Recombination bump

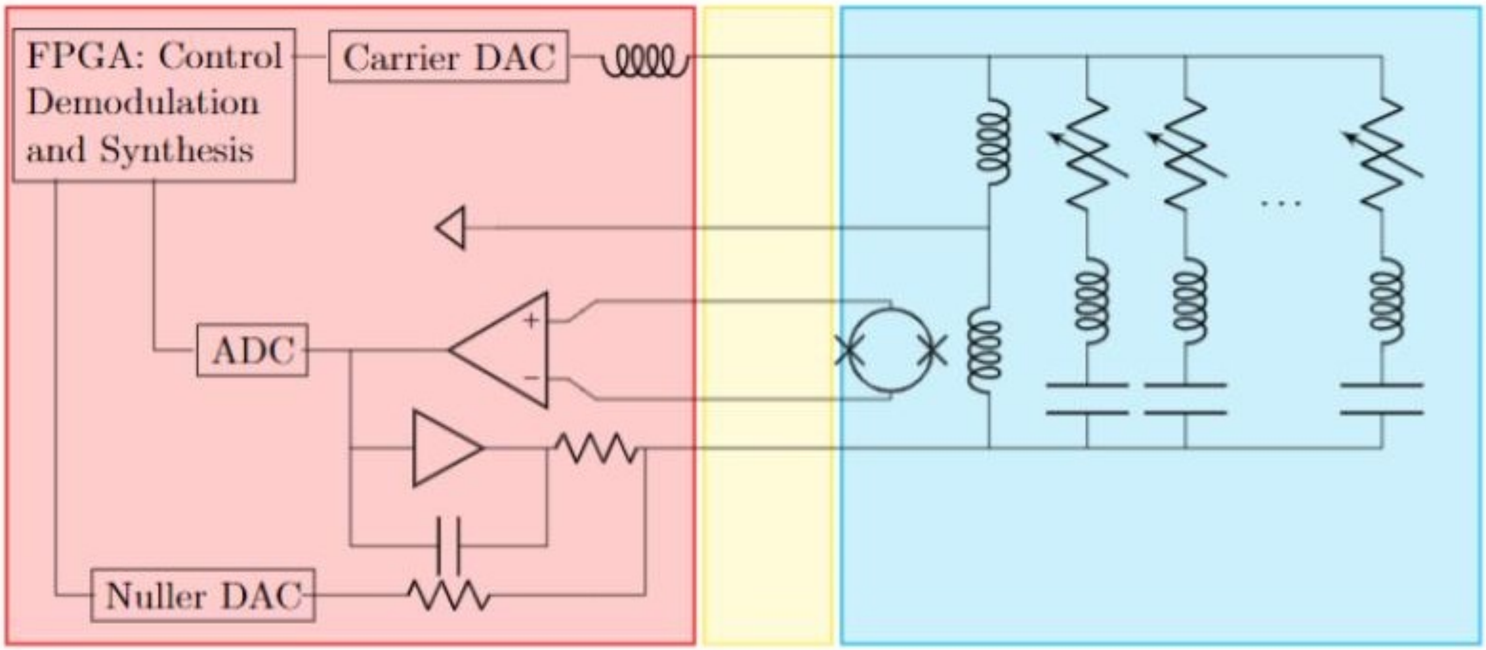


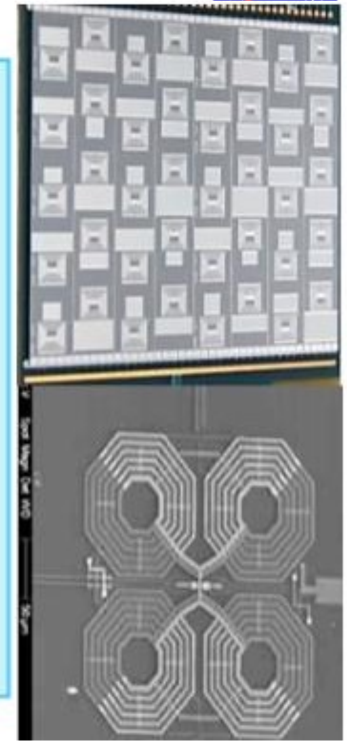


Rationale

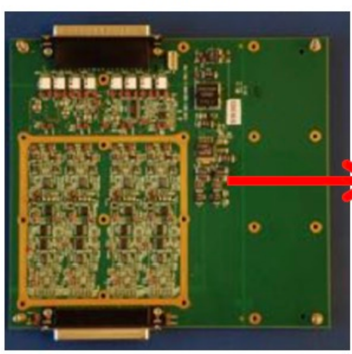
- ◆ Large discovery potential for $0.005 < r < 0.05$
- ◆ Clean sweep of single-field models with characteristic field-variation-scale of inflaton potential greater than m_{pl}
  (A. Linde, JCAP 1702 (2017) no.02, 006)
  - ◆ Simplest and well-motivated $R+R^2$ "Starobinsky" model will be tested.

Digital frequency-domain multiplexing (DfMUX) readout

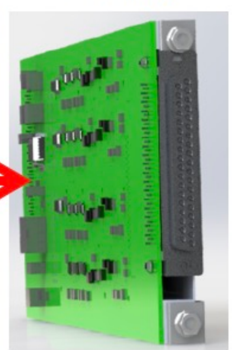




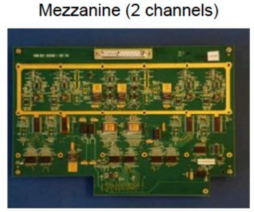
STDP SQUID Controller



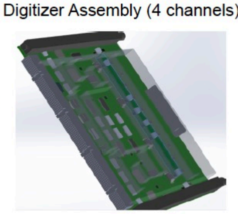
SQUID Controller Assembly

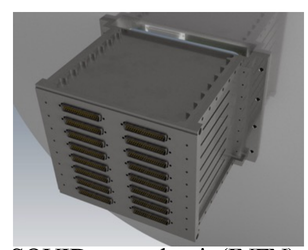


Mezzanine (2 channels)



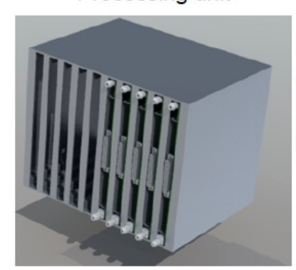
Digitizer Assembly (4 channels)



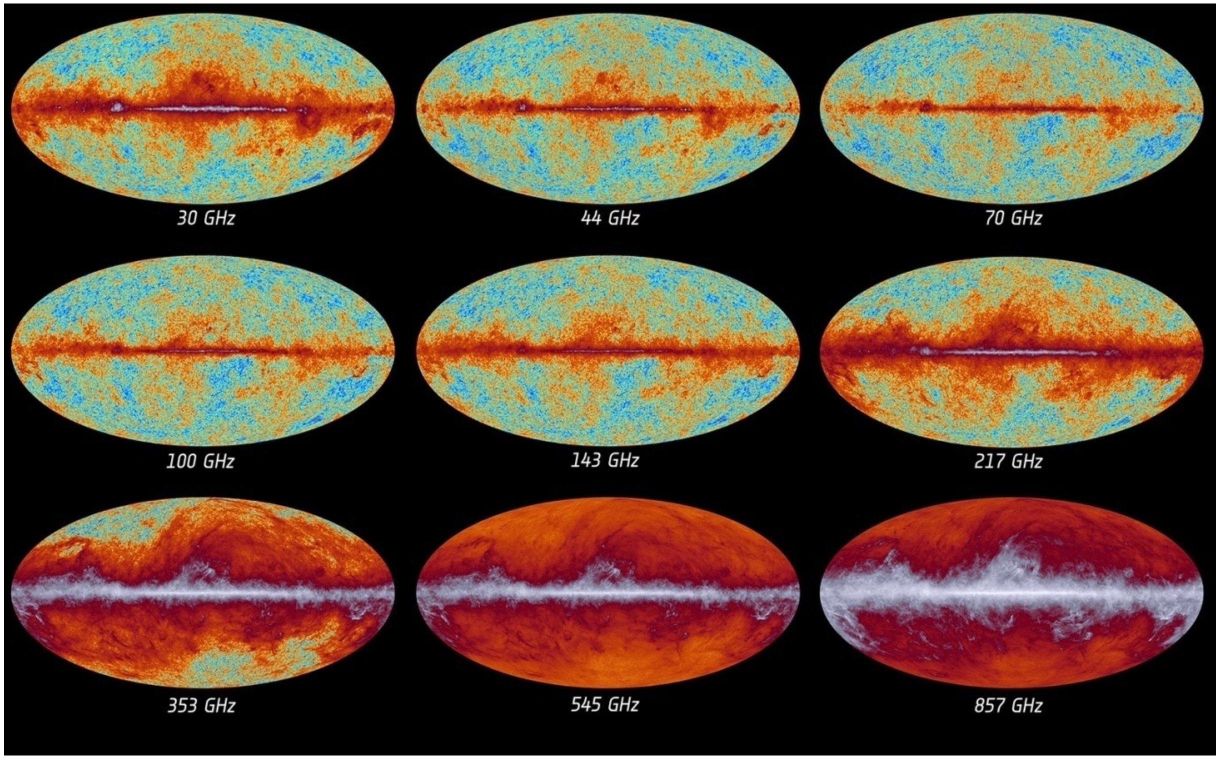


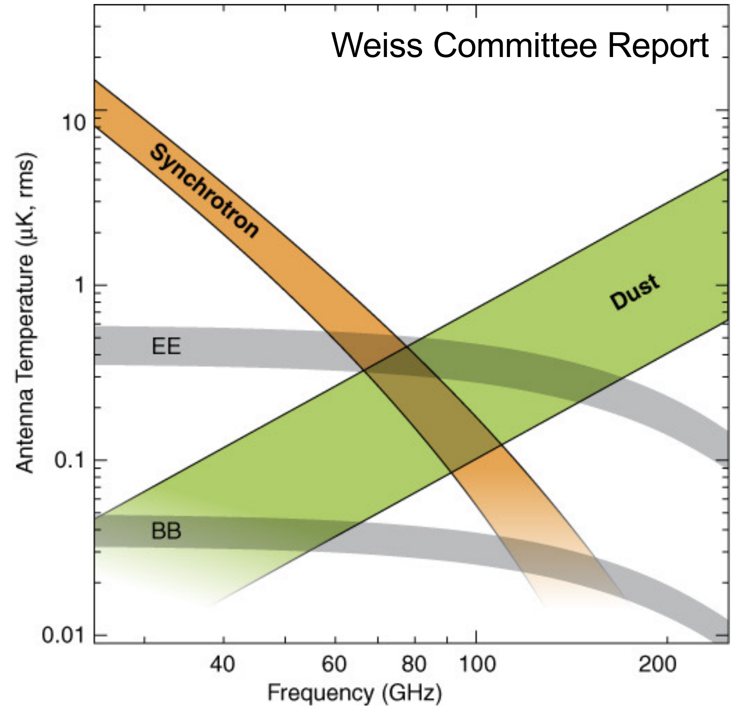
SQUID control unit (INFN)

LFT Signal Processing unit



Challenge: Galaxy brighter than CMB signal





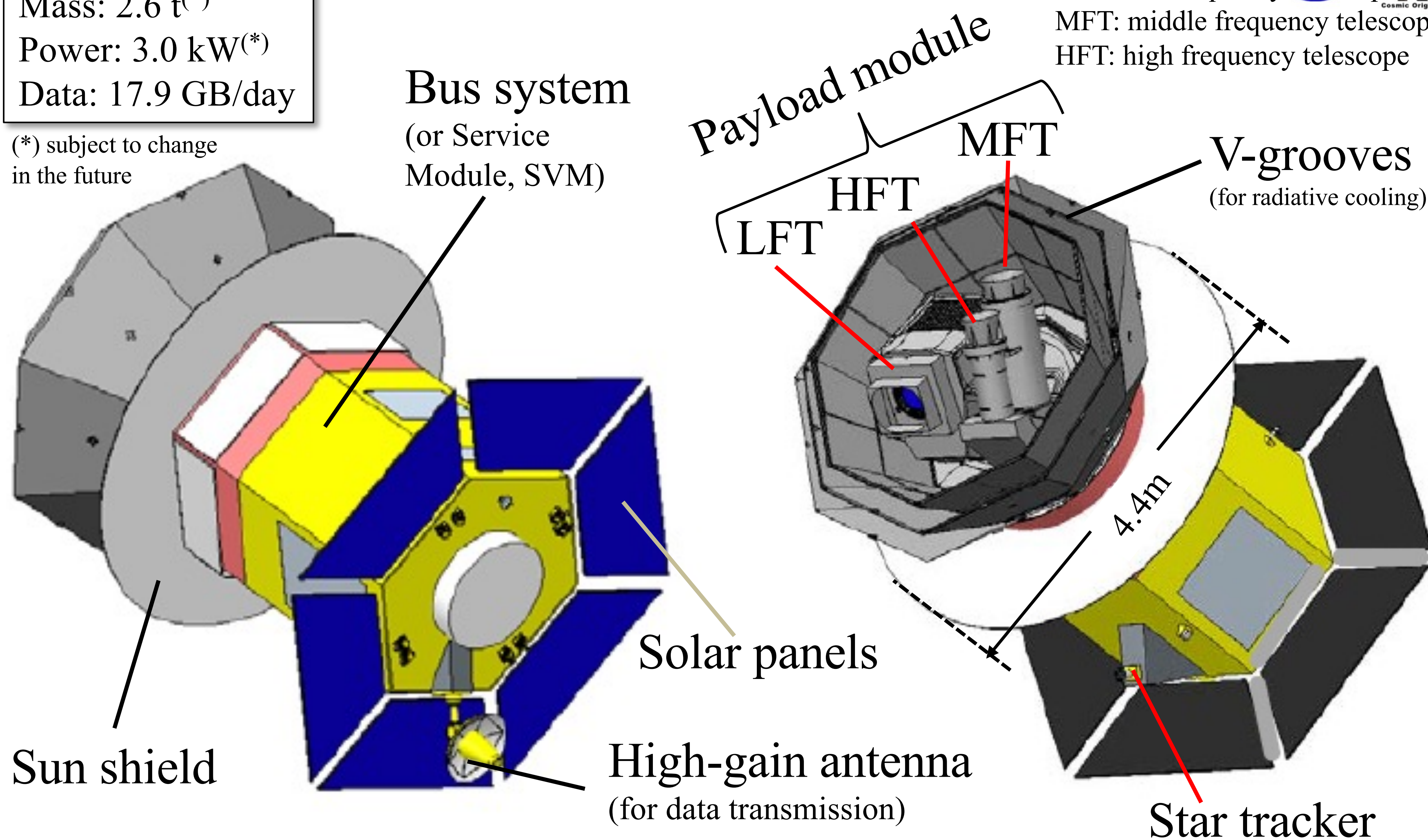
Planck: ESA

- Galactic foregrounds
  - Synchrotron Radiation and Dust Emission (plus others…)
  - Current Models Require 5-7 bands
- LiteBIRD
  - Separate foregrounds using 15 frequency bands 34-448 GHz (71-18 arcmin angular resolution)

LiteBIRD Spacecraft Overview

Mass: 2.6 t(*)
Power: 3.0 kW(*)
Data: 17.9 GB/day

(*) subject to change in the future



LFT: low frequency telescope
MFT: middle frequency telescope
HFT: high frequency telescope