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BERKELEY LAB
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CARDIFF UNIVERSITY
PRIFYSGOL CAERDYD
cea
Centre Pierre Binétruy
CNRS • Berkeley
cnes
cnrs
CSA ASC
Canada

CSIC
CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS
CSL
CENTRE SPATIAL DE LIÈGE
ENS
PSL
erc
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IPMU
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MATHEMATICS OF THE UNIVERSE
iPNS
素粒子原子核研究所
Institute of Particle and Nuclear Studies

LiteBIRD

irap
astrophysique & planétologie
JAXA
KEK
KIPAC
KAVLI INSTITUTE FOR PARTICLE ASTROPHYSICS & COSMOLOGY
KMI
Kobayashi-Maskawa Institute
Nagoya University
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Quantum-field Measurement Systems for
Studies of the Universe and Particles
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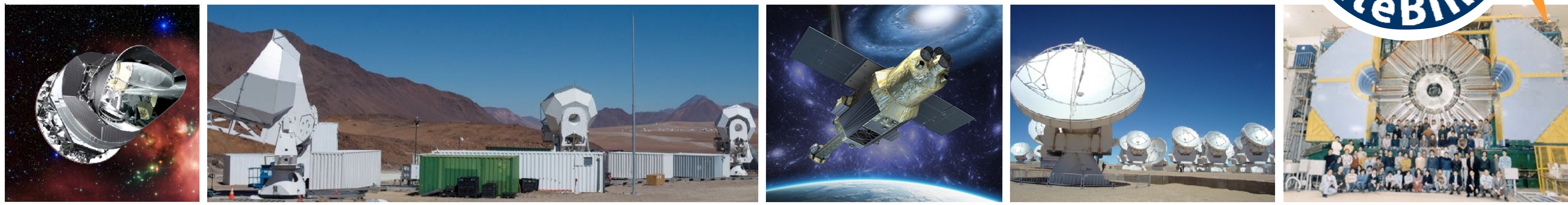
DI PADOVA
THE UNIVERSITY OF TOKYO
UNIVERSITY OF
TORONTO

LiteBIRD Joint Study Group

Over 300 researchers from **Japan**, **North America** and **Europe**

Team experience in CMB experiments, X-ray satellites and other large projects (ALMA, HEP experiments, …)

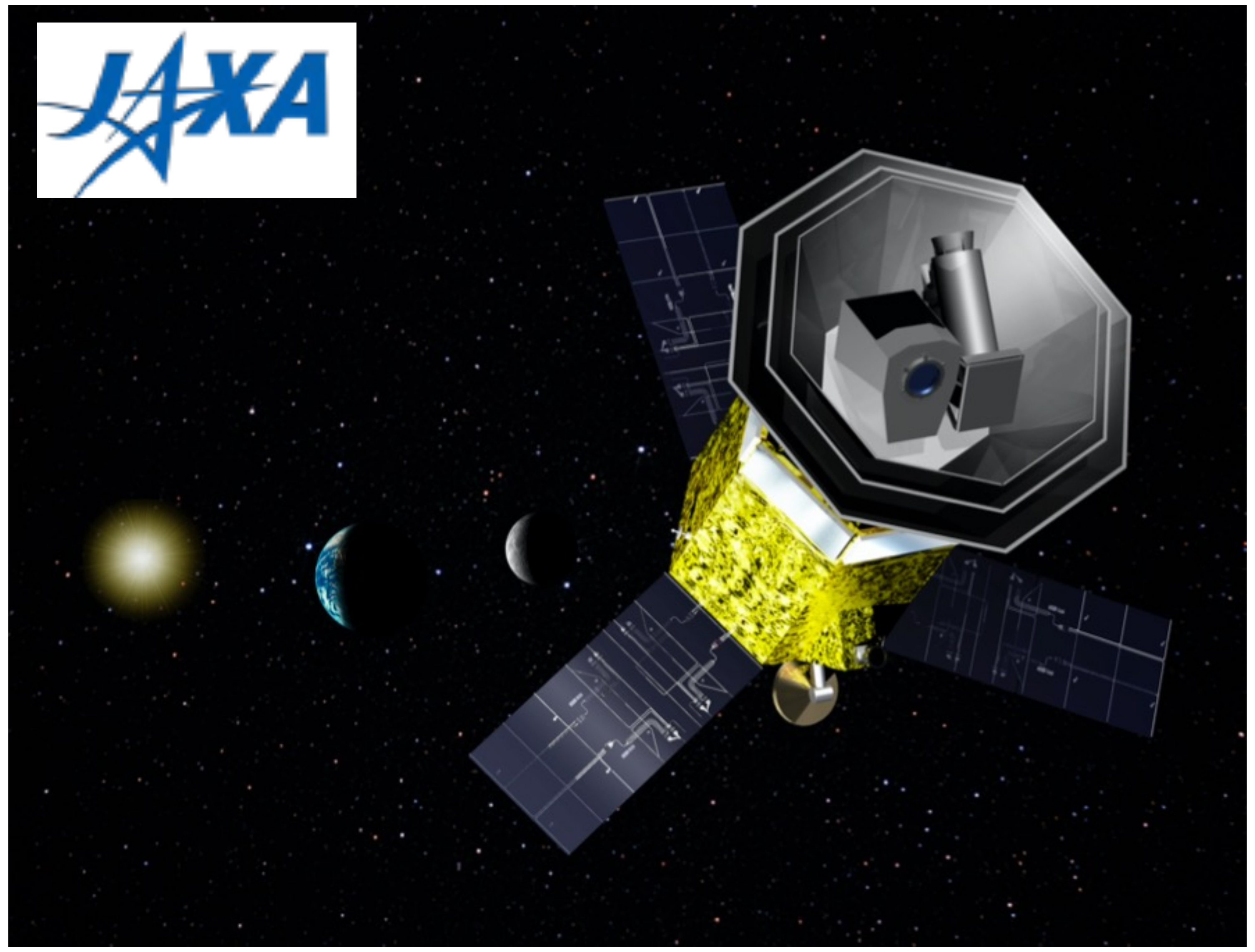


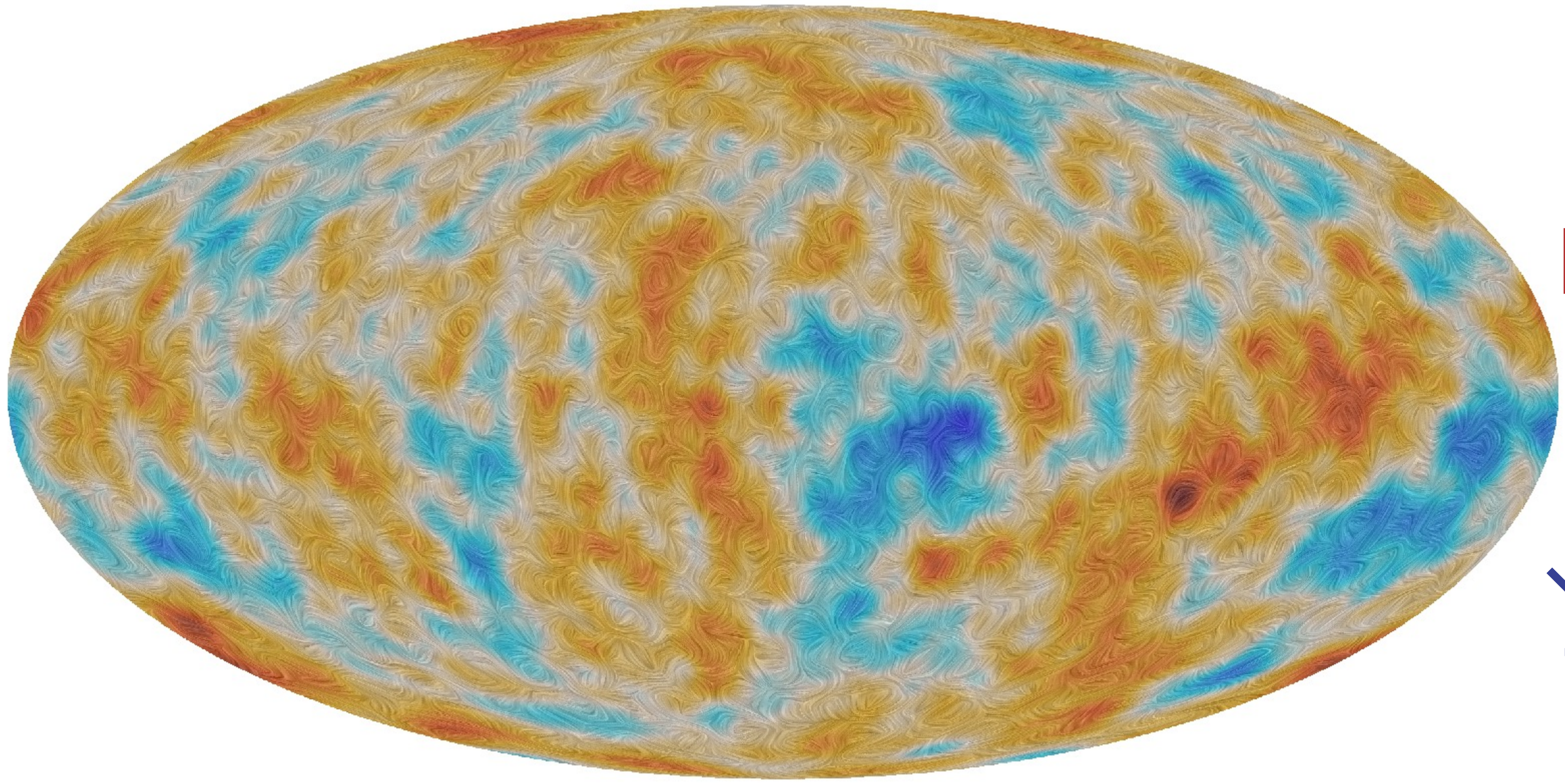
LiteBIRD Team at Okayama face-to-face meeting, December 2022

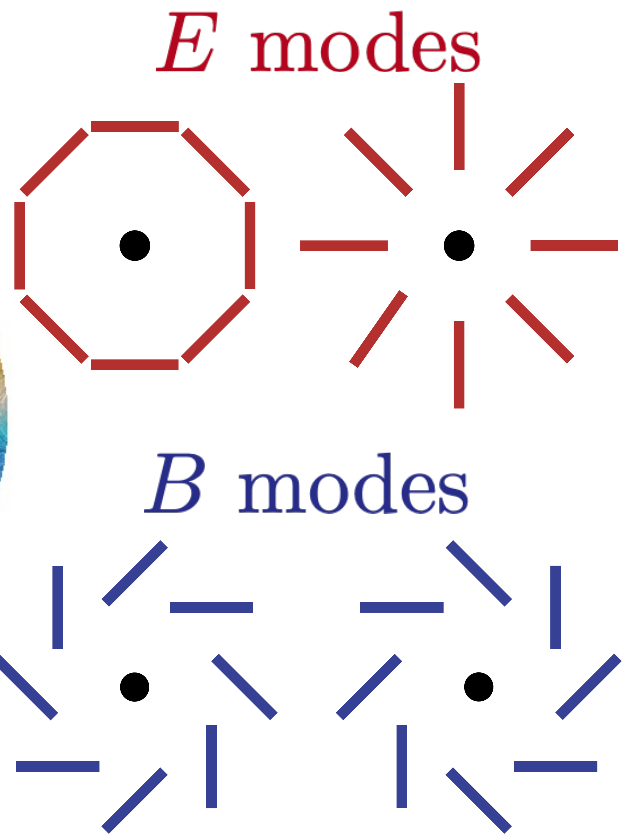
LiteBIRD overview

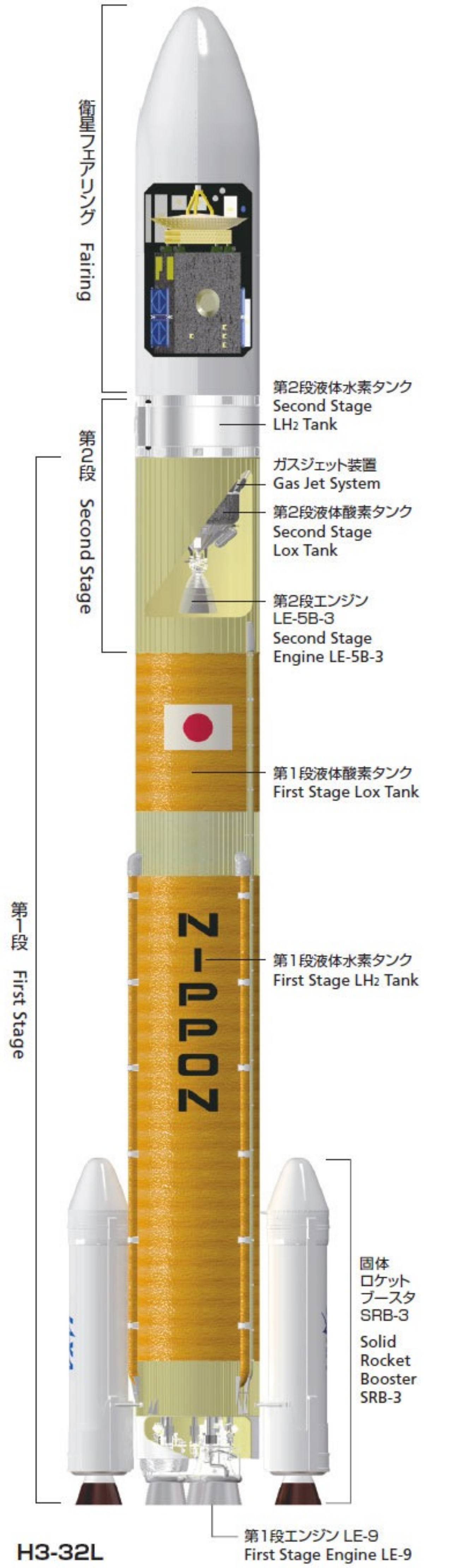
📖 Hazumi+ SPIE 2020

- Lite (Light) satellite for the study of *B*-mode polarization and Inflation from cosmic background Radiation Detection
- JAXA's L-class mission selected in May 2019
- Expected launch in late **2029** with JAXA's H3 rocket
- **All-sky 3-year survey**, from Sun-Earth Lagrangian point L2
- Large frequency coverage (**40–402 GHz**, 15 bands) at **70–18 arcmin** angular resolution for precision measurements of the **CMB *B*-modes**
- Final combined sensitivity: **2.2 μK·arcmin**







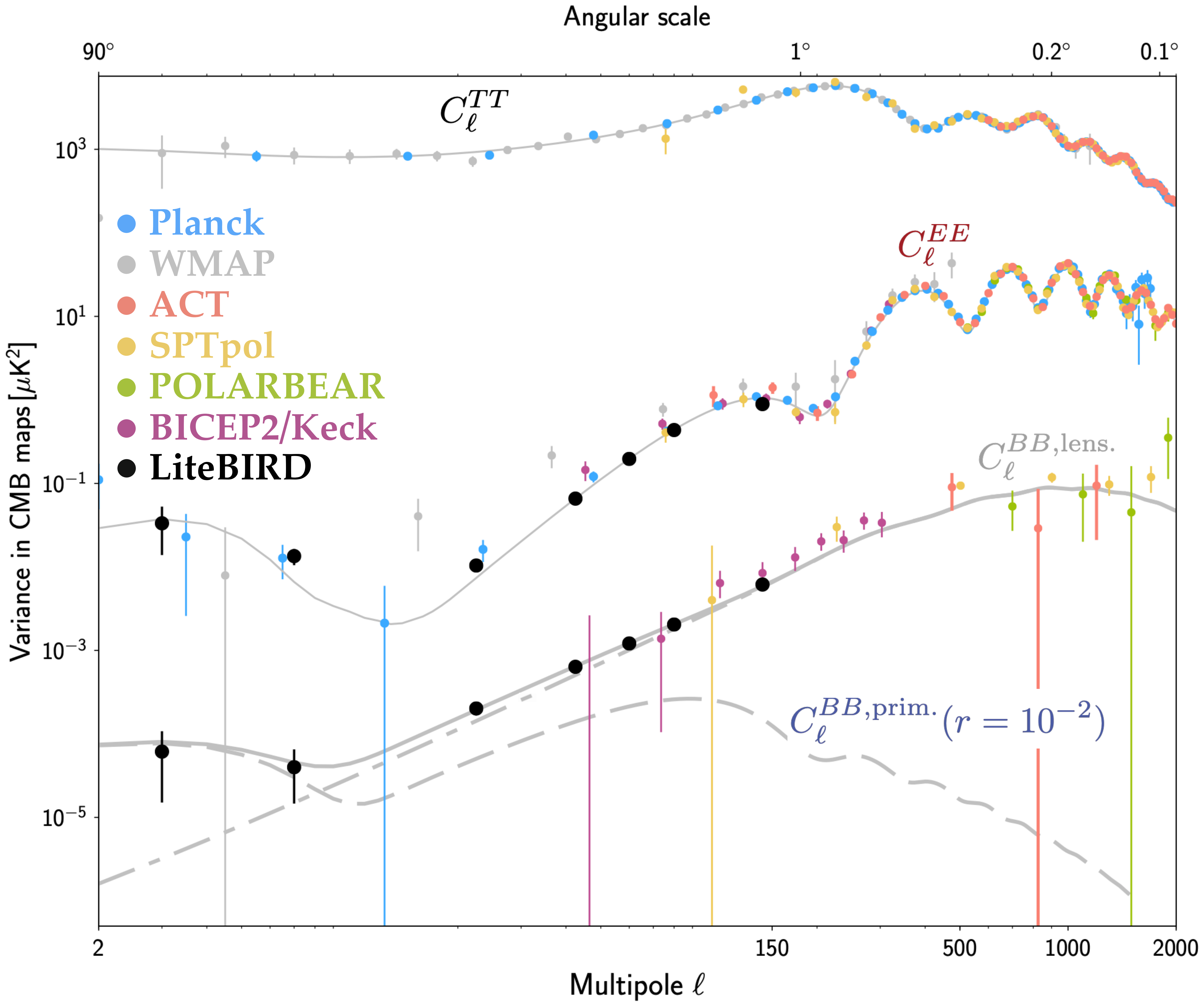


LiteBIRD main scientific objectives

- Definitive search for the ***B*-mode signal** from **cosmic inflation** in the CMB polarization
  - Making a discovery or ruling out well-motivated inflationary models
  - Insight into the quantum nature of gravity
- The inflationary (i.e. primordial) B-mode power is proportional to the **tensor-to-scalar ratio, *r***
- Current best constraint: $r < 0.032$ (95% C.L.)

(📖 Tristram et al. 2021, combining BK18 and Planck PR4)

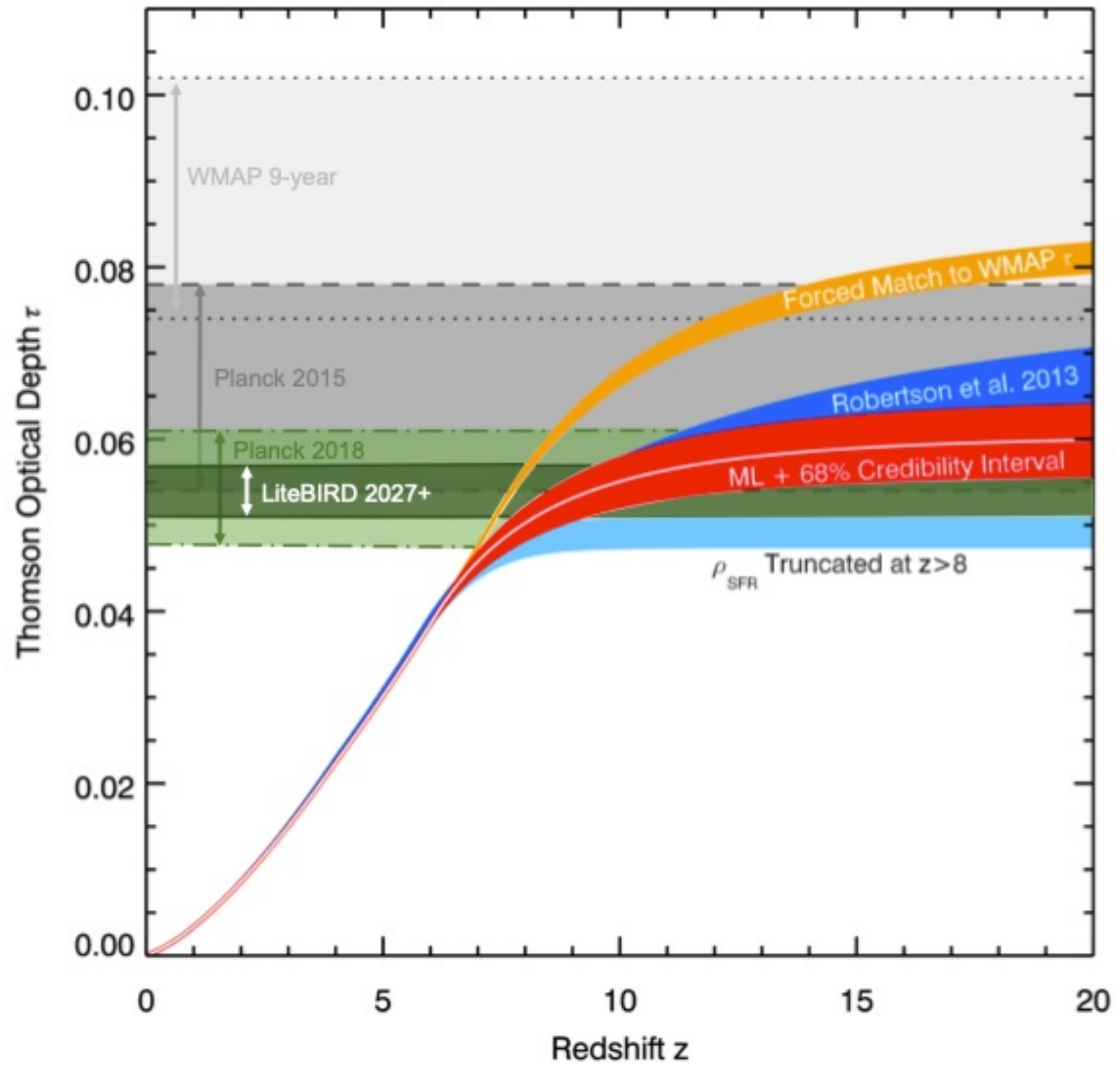
- LiteBIRD will improve current sensitivity on r by a factor ~50
- L1-requirements (no external data):
  - For $r = 0$, **total uncertainty of $\delta r < 0.001$**
  - For $r = 0.01$, 5-σ detection of the reionization ($2 < \ell < 10$) and recombination ($11 < \ell < 200$) peaks independently
- Huge discovery impact (evidence for inflation, knowledge of its energy scale, …)



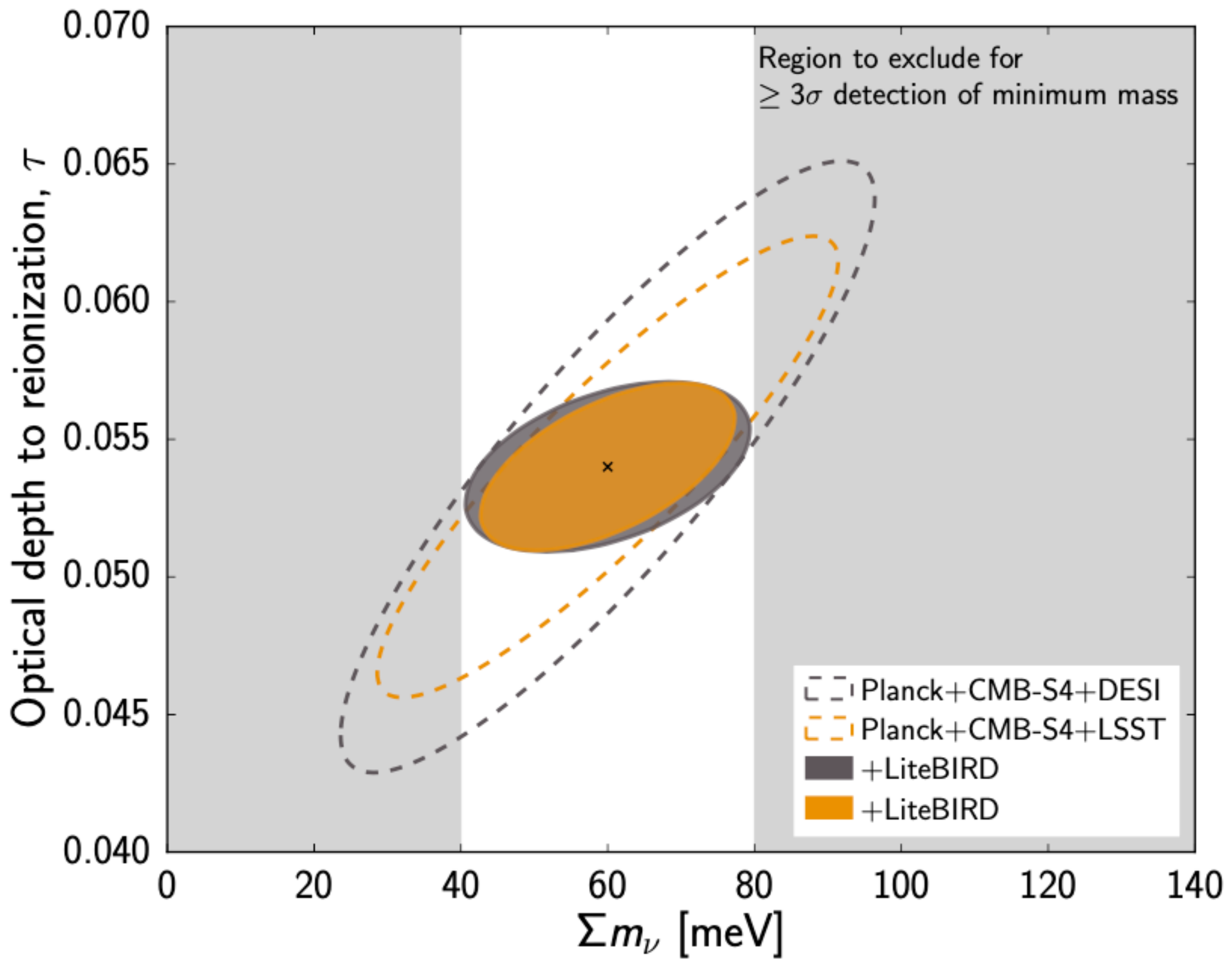
LiteBIRD other science outcomes

- The mission specifications are driven by the required sensitivity on *r*
- Meeting those sensitivity requirements would allow to address other important scientific topics, such as:

1. Characterize the *B*-mode power spectrum and search for source source fields (e.g. scale-invariance, non-Gaussianity, parity violation, …)
2. Power spectrum features in polarization
    - Large-scale ***E*-modes**
    - **Reionization** (improve $\sigma(\tau)$ by a factor of 3)
    - **Neutrino mass** ($\sigma(\sum m_\nu) = 15$ meV)
3. Constraints on **cosmic birefringence**
4. **SZ effect** (thermal, diffuse, relativistic corrections)
5. Elucidating **anomalies**
6. **Galactic science**
    - Characterizing the foreground SED
    - Large-scale Galactic magnetic field
    - Models of dust polarization



📖 adapted from Robertson+2015



📖 adapted from Calabrese+2017

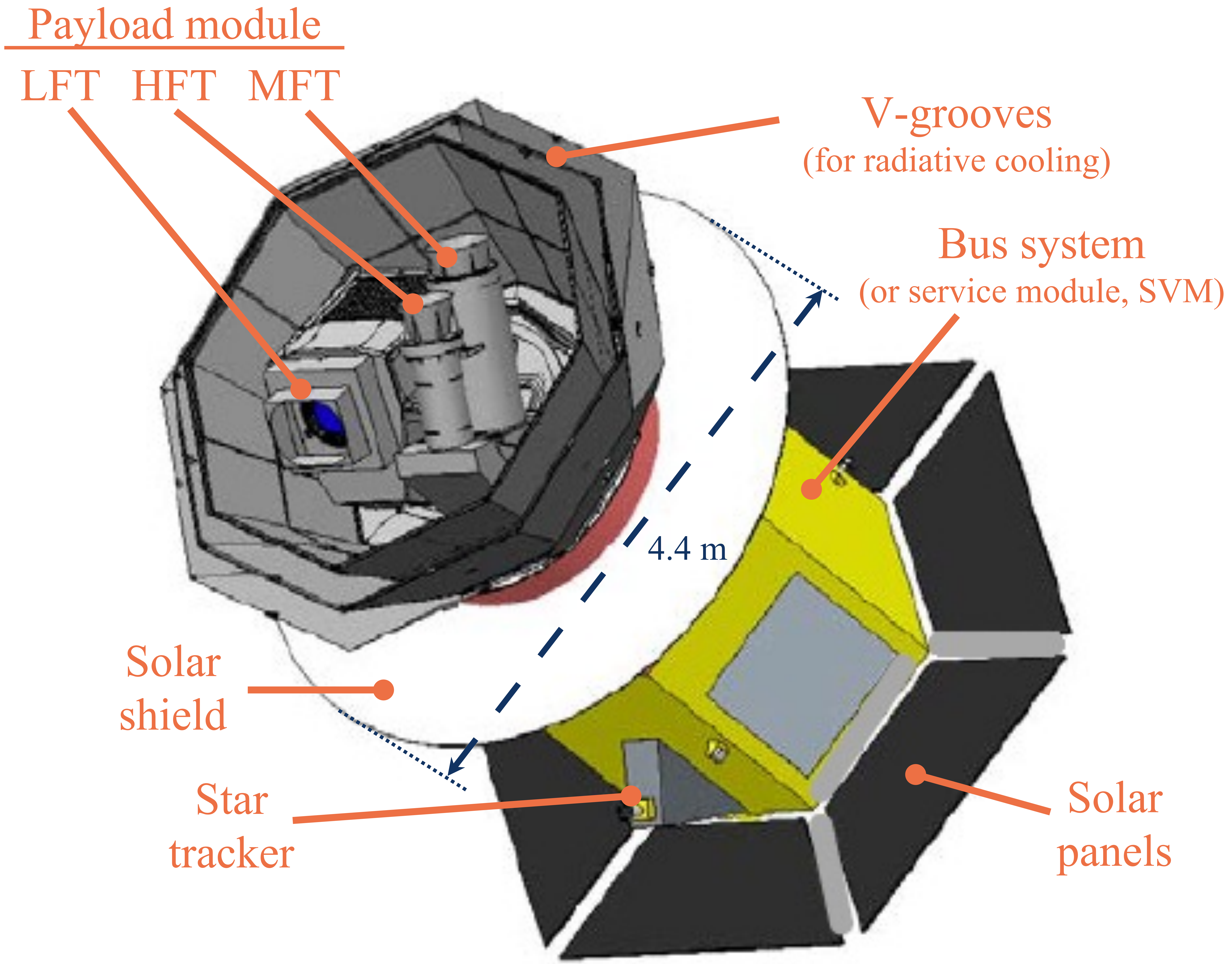
LiteBIRD scanning strategy

- 3-year survey, Sun-Earth L2 Lissajous orbit
- Precession angle: $\alpha = 45°$
- Spin angle: $\beta = 50°$

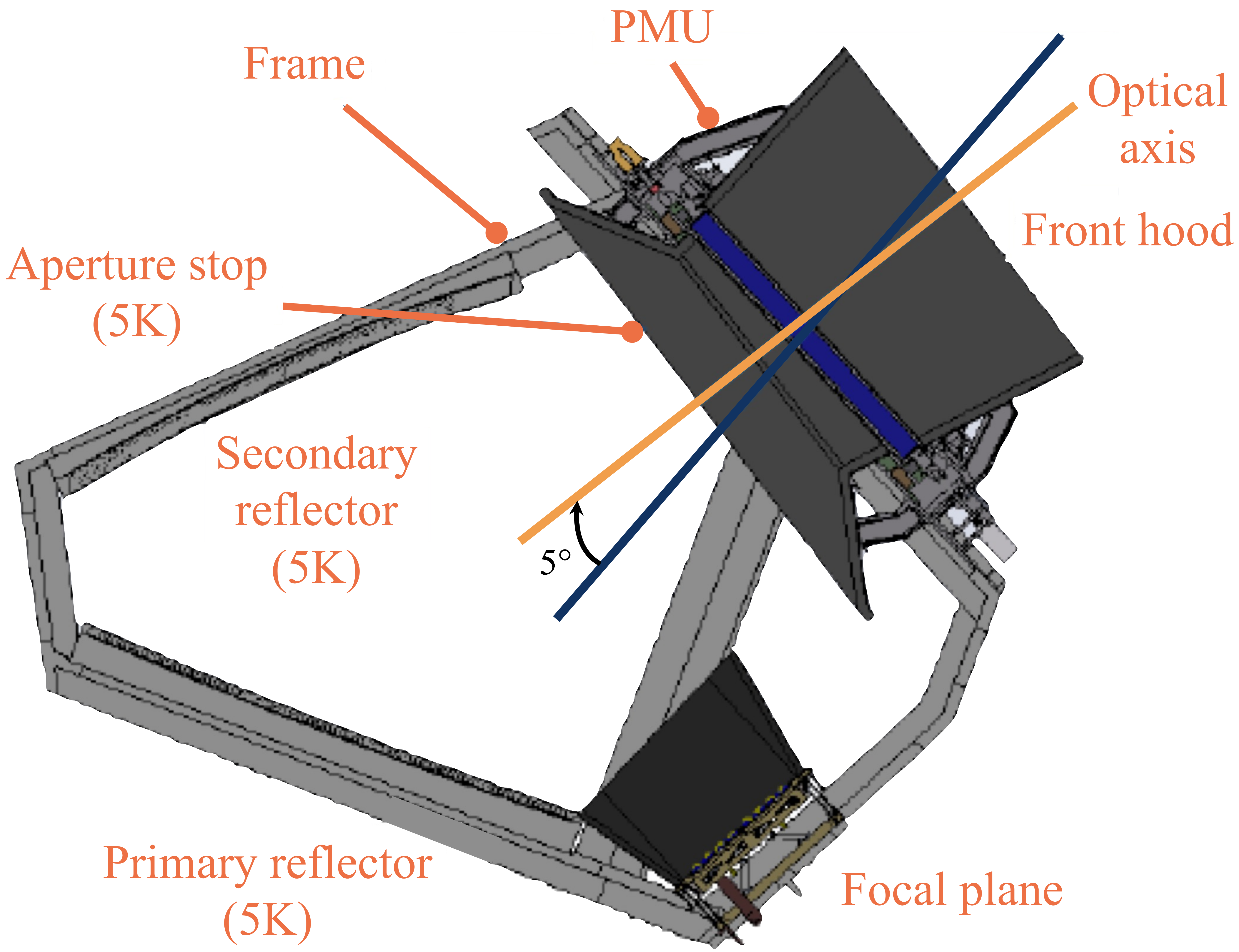
LiteBIRD spacecraft overview

- **3 telescopes** are used to provide the **40-402 GHz** frequency coverage
  1. **LFT** (low frequency telescope)
  2. **MFT** (middle frequency telescope)
  3. **HFT** (high frequency telescope)
- Multi-chroic transition-edge sensor (TES) **bolometer arrays** cooled to **100 mK**
- Polarization modulation unit (PMU) in each telescope with **rotating half-wave plate** (HWP), for 1/*f* noise and systematics reduction
- Optics cooled to **5 K**

- Mass: 2.6 t
- Power: 3.0 kW
- Data: 17.9 Gb/day



Low Frequency Telescope (LFT)



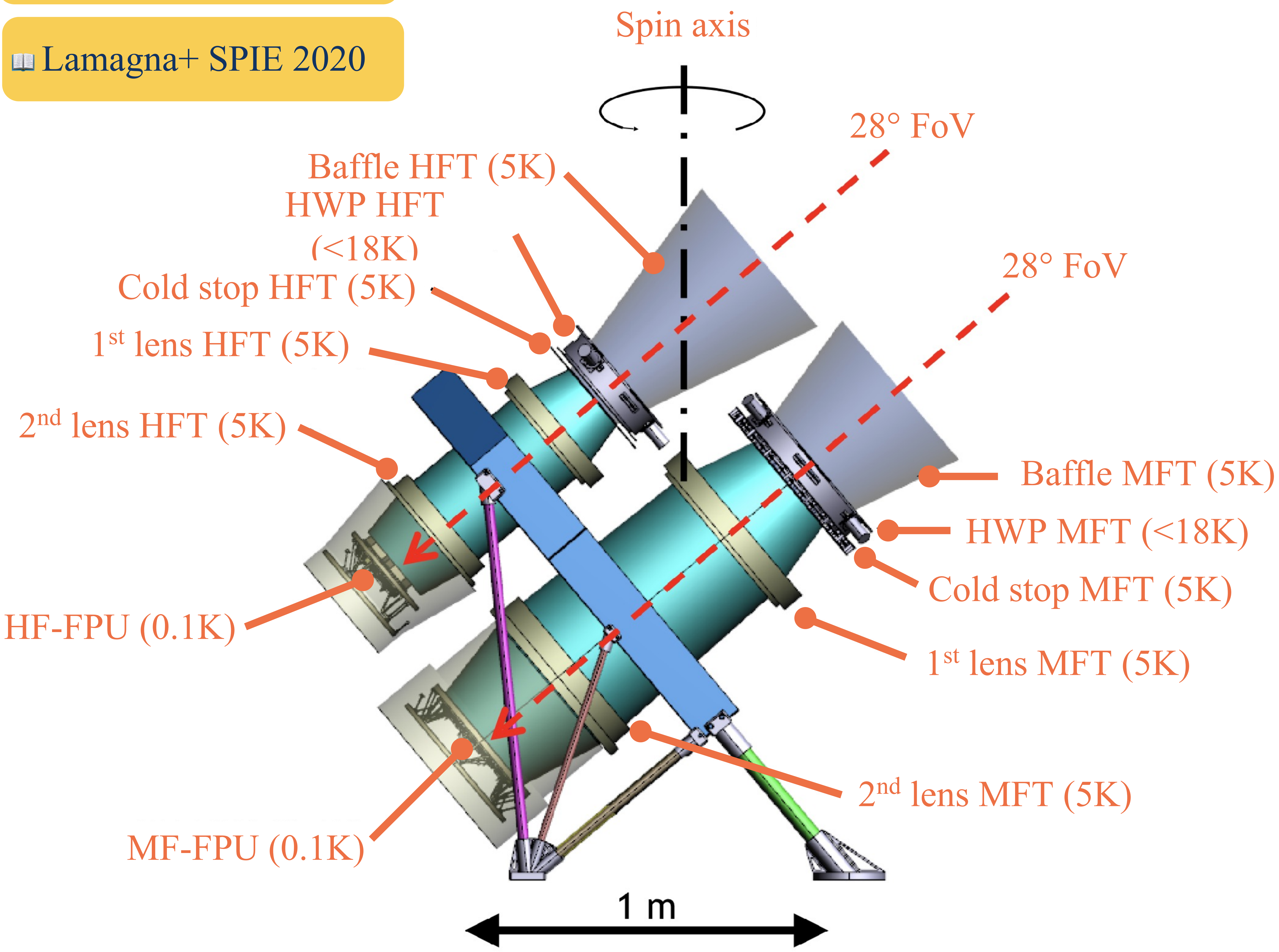
- Polarization Modulation Unit (PMU) as the first sky-side optical element
- **Crossed-Dragone** design
  - Mirrors and aperture stop at **5 K**
  - Made of aluminium
- Field of view: **18°×9°**
- Strehl ratio > 0.95 (@ 140 GHz)
- Aperture diameter: **400 mm**
- Frequency range: **40-140 GHz**
- Angular resolution: **70-24 arcmin**
- F#3.0 & cross angle of 90°
- Cross-polarization < **-30 dB**
- Rotation of the polarization angle across the FoV < ±1.5°
- Weight < 200 kg

📖 Sekimoto+ SPIE 2020

Middle-High Frequency Telescopes (MFT/HFT)

📖 Montier+ SPIE 2020

📖 Lamagna+ SPIE 2020



- Refractive optics
- Each telescope has PMU with a half-wave-plate (HWP)
- Optics at **5 K**
- Field of view: **28°**
- Simple and high heritage from ground experiments
- Compact (mass & volume)
- Simplified design for filtering scheme
- PP lenses + ARC
- Weight 180 kg

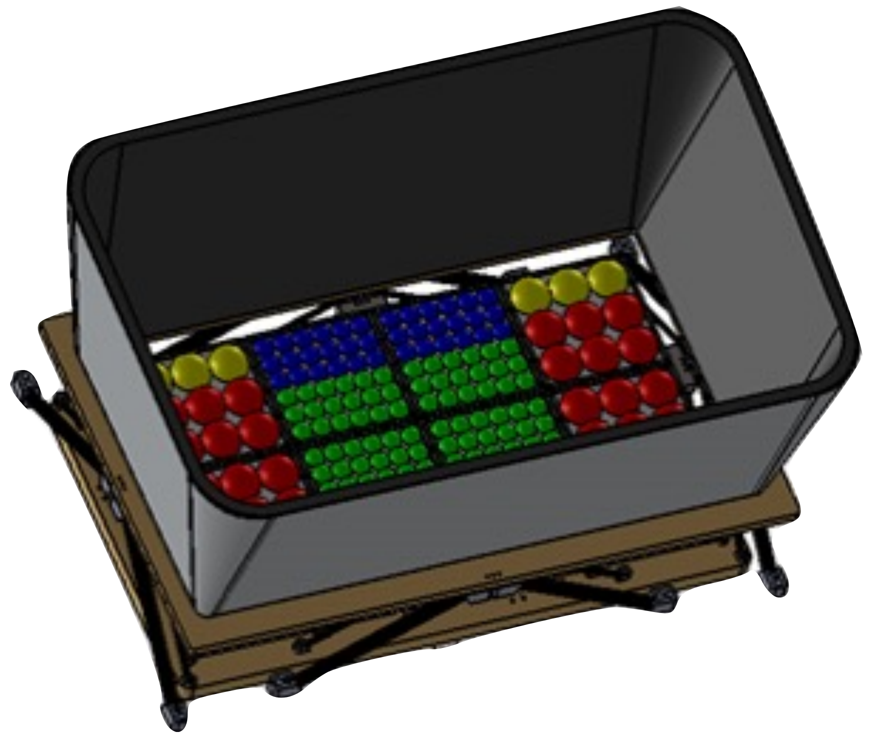
	MFT	HFT
ν (GHz)	**100-195**	**195-402**
Ap. diameter (mm)	**300**	**200**
Ang. res. (arcmin)	**38-28**	**29-18**

Focal plane configuration

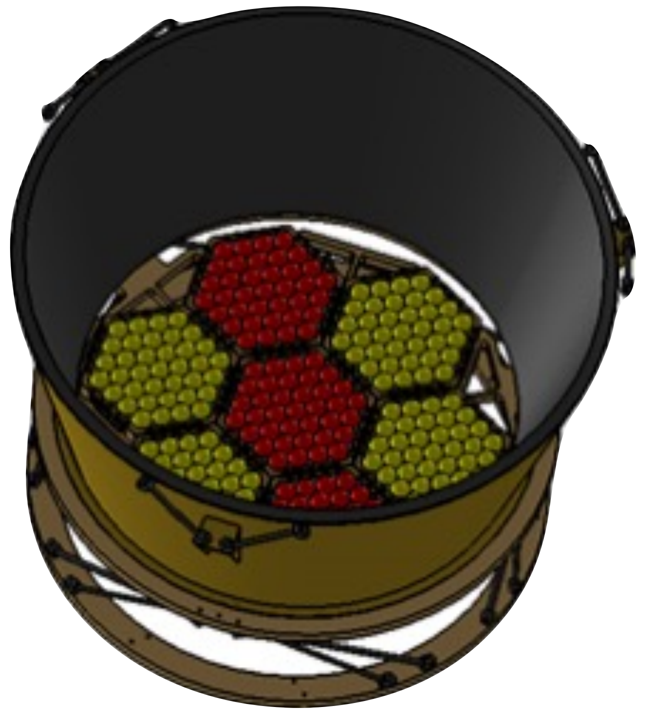
- Transition-Edge Sensor (TES) arrays
- Multichroic detectors
- Number of sensors: 4508
- 15 bands including overlap between instruments

Rule of thumb:
1000 detectors in space
= 100 000 detectors on ground

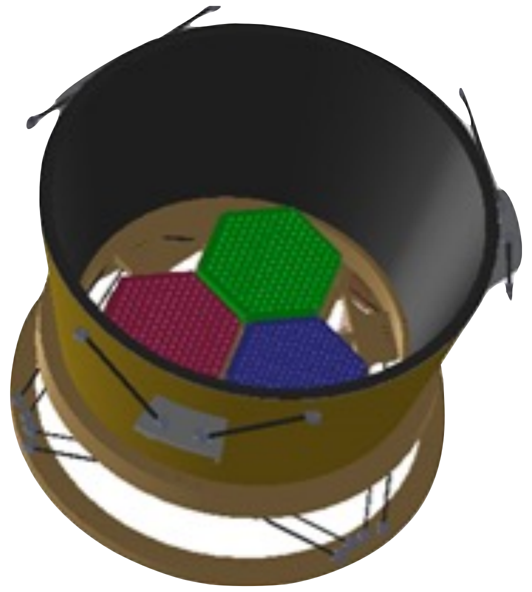
LFT



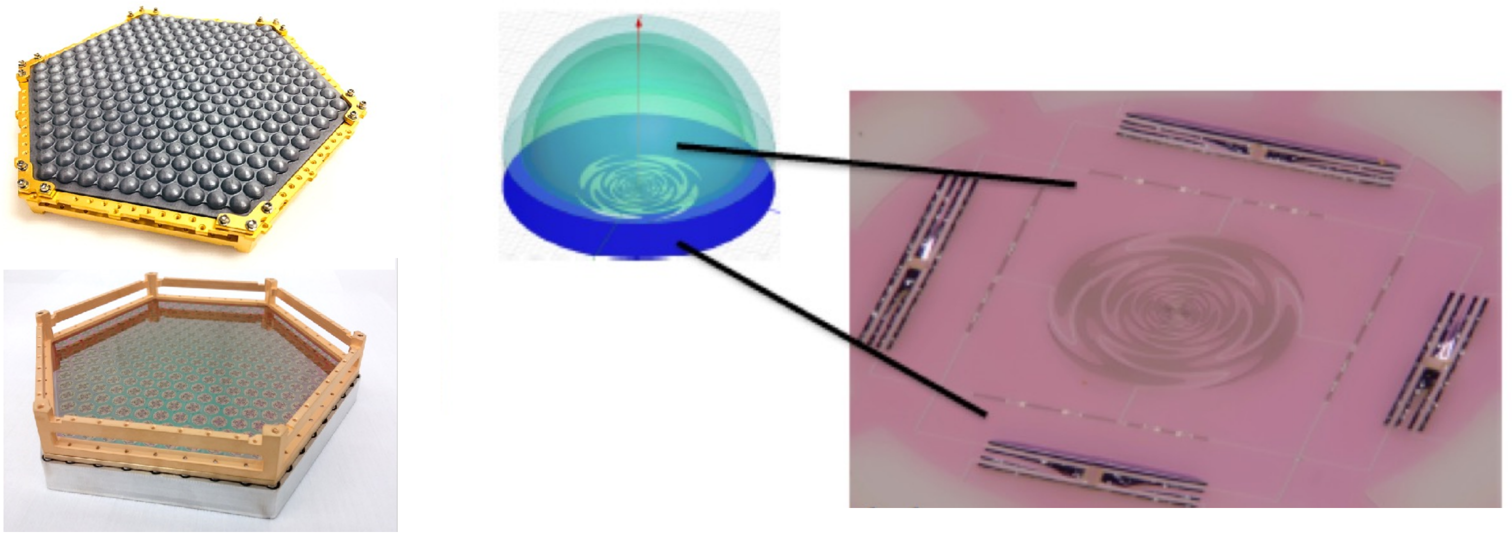
MFT



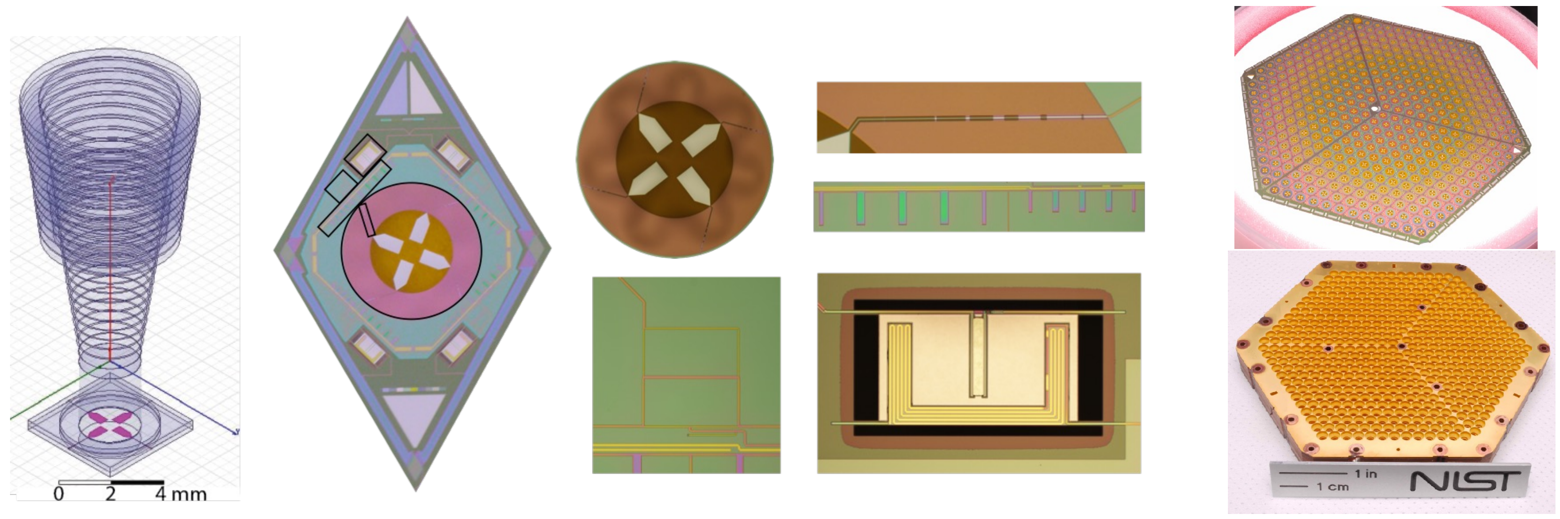
HFT



Lensed coupled detectors
Lenslets



Horn coupled detectors
Platelets



MFT (2.5:1)

89GHz — 225 GHz

2075 detectors
366 Trichroic TES
588 Dichroic TES

100 119 140 166 195

LFT (5.7:1)

34GHz — 161 GHz

40 50 60 68 78 89 100 119 140
68 78 89

1258 detectors
2 x (65 + 155) Trichroic TES

HFT (2.7:1)

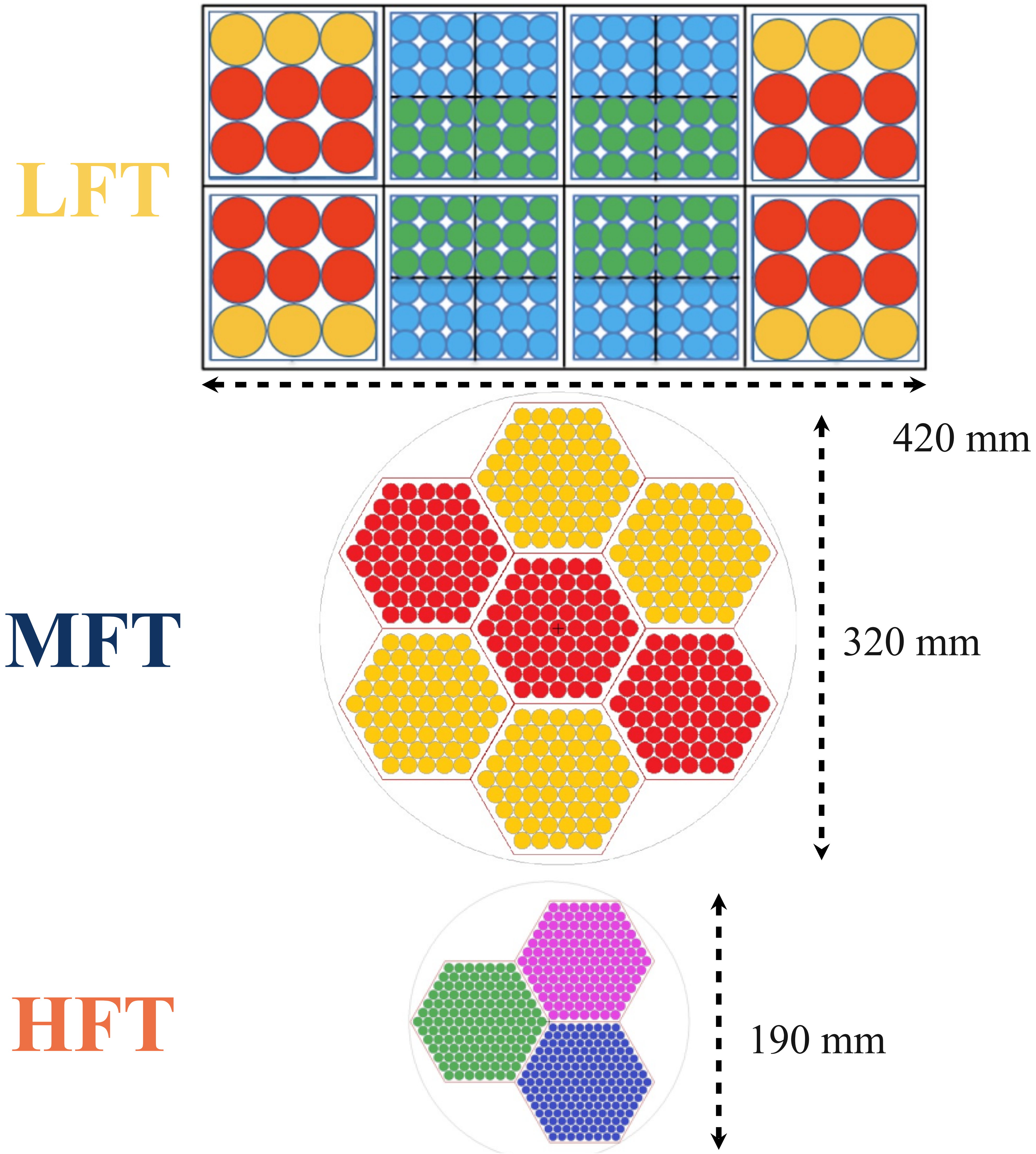
166 GHz — 448 GHz

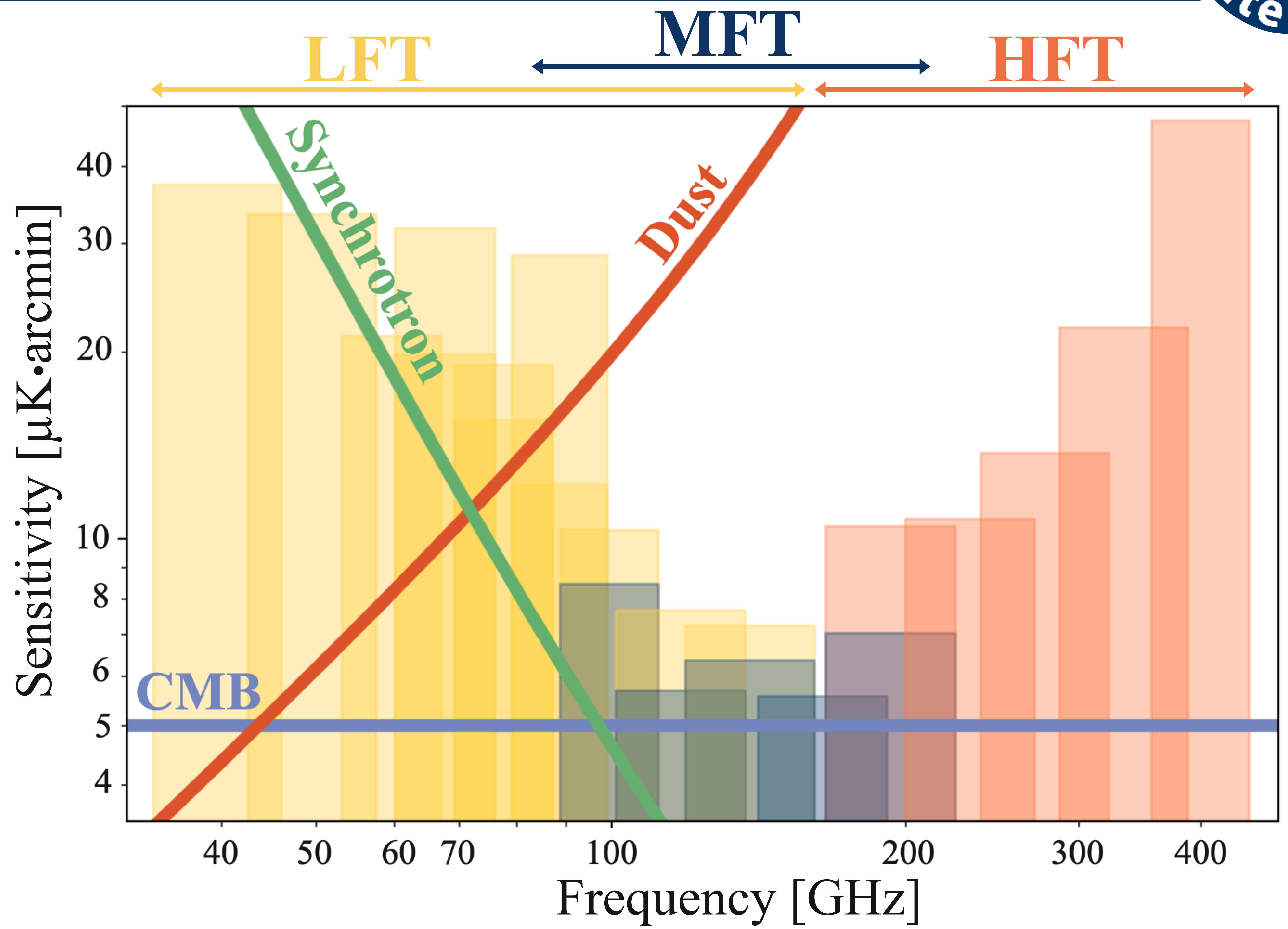
195 235 280 337 402

1355 detectors
2 x 255 Dichroic TES
338 Monochromatic TES

📖 Westbrook+ SPIE 2020

LiteBIRD sensitivities

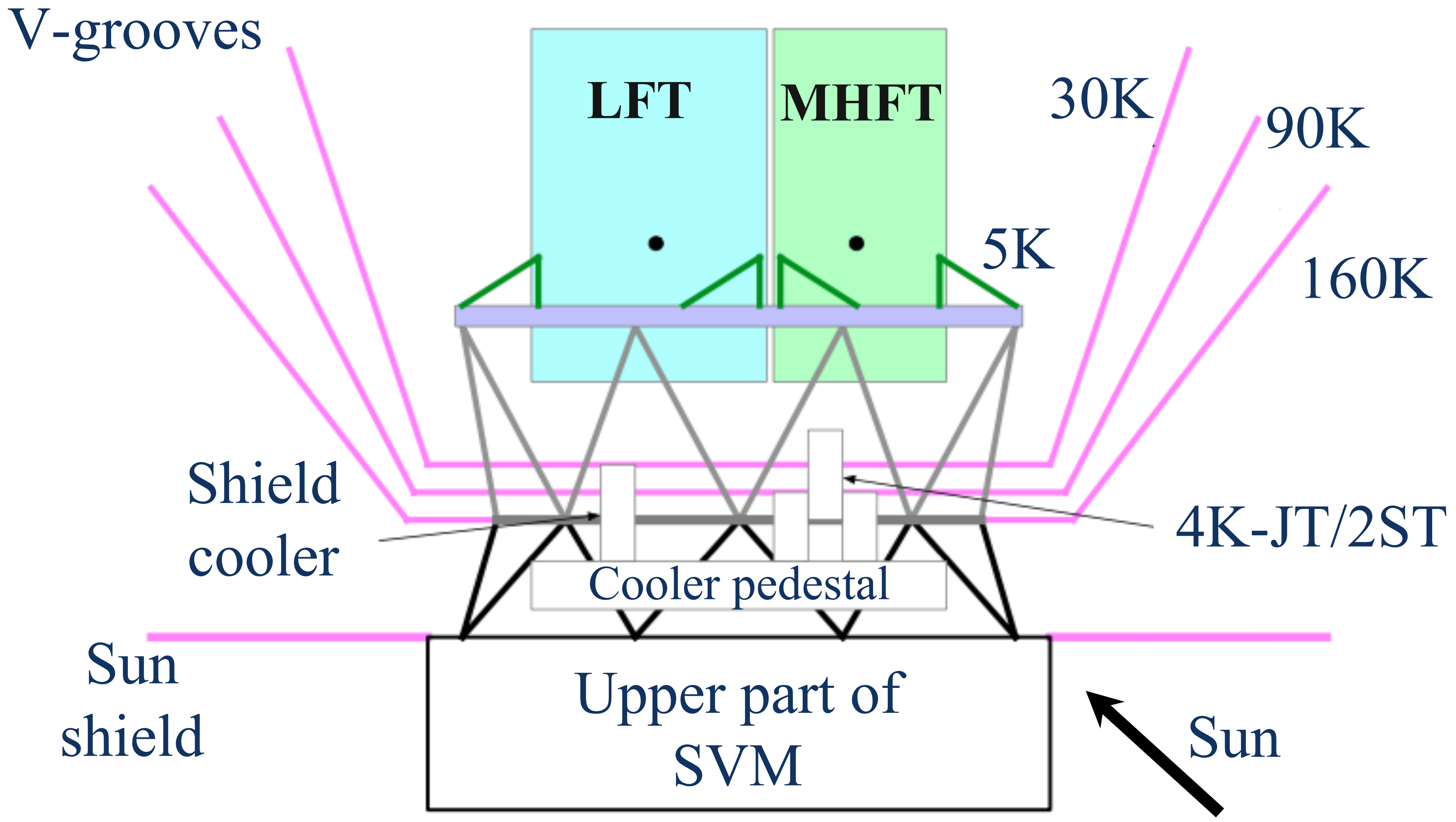


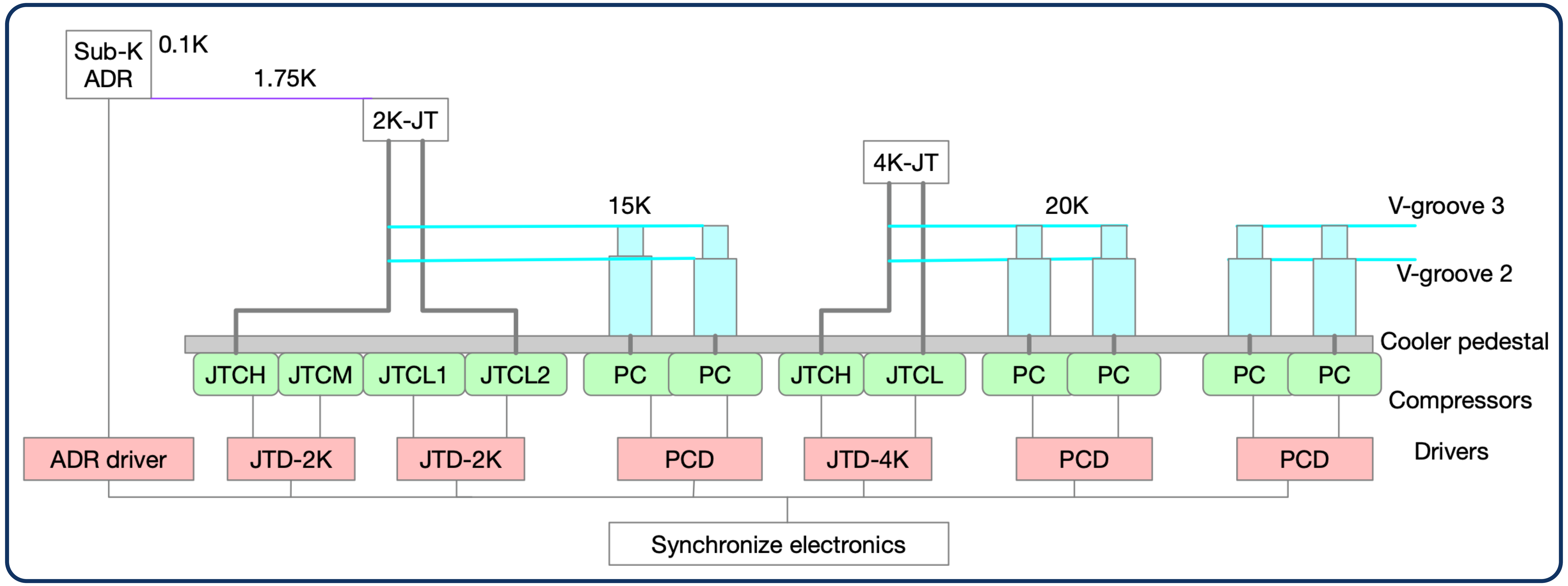


📖 Hazumi+ SPIE 2020

- Projected **polarization sensitivities** for a **3-year full-sky survey**
- Best of 4.3 μK·arcmin @ 119 GHz (Hazumi+ 2020)
- Combined sensitivity to primordial CMB anisotropies: **2.2 μK·arcmin**

LiteBIRD cryogenic system

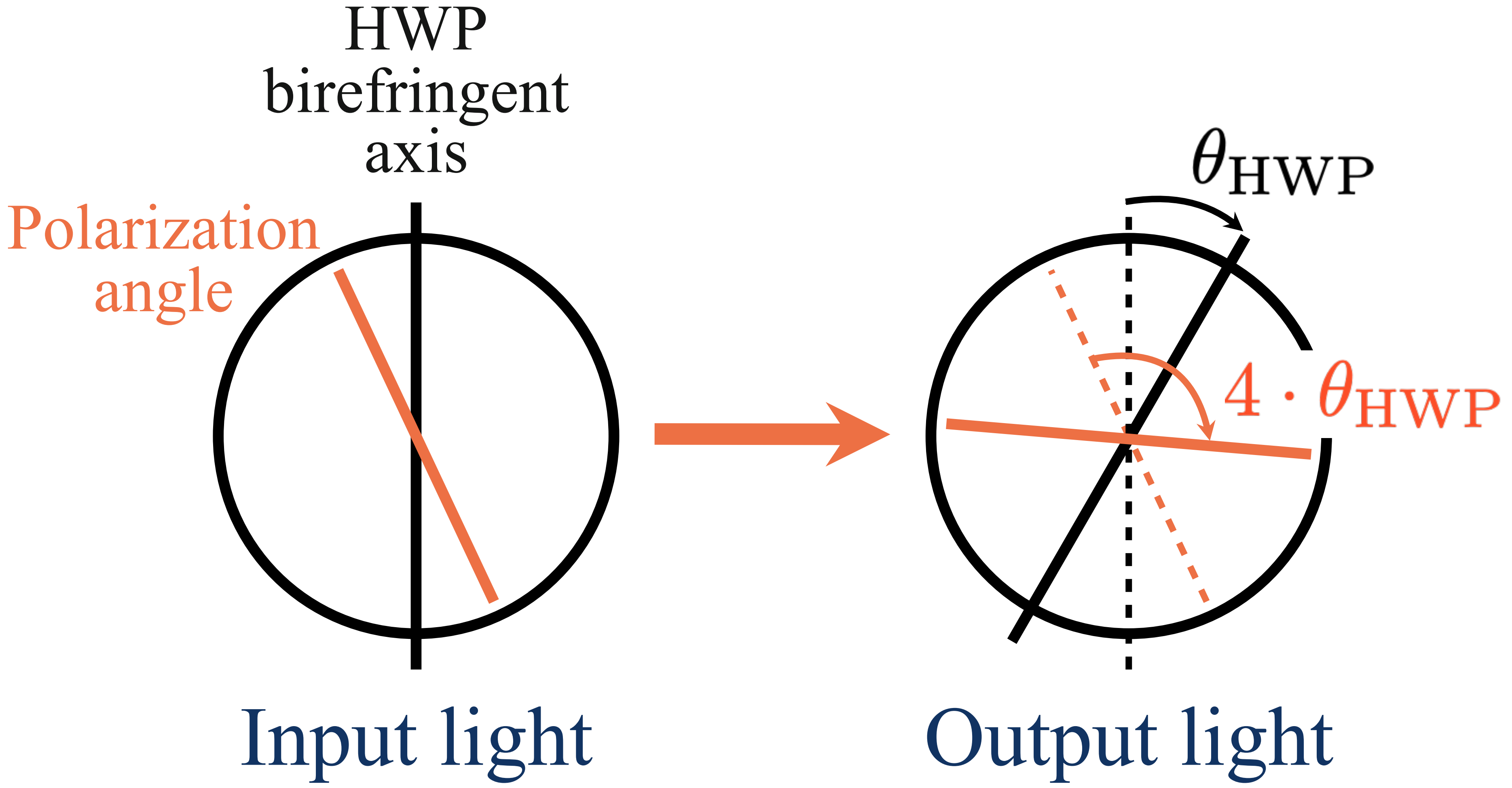


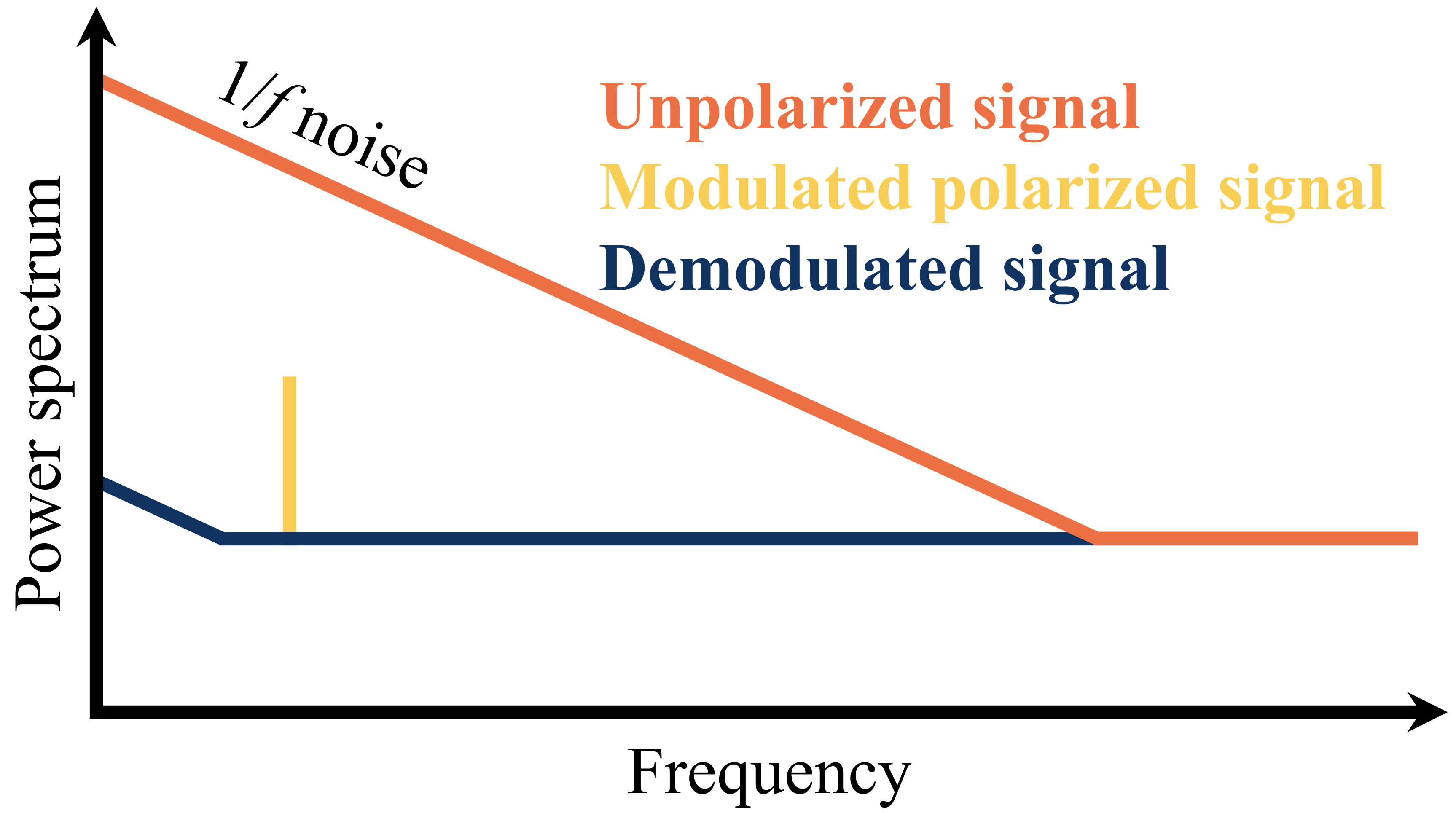


- Continuous cooling at 100 mK
- High stability on telescopes at all stages

Polarization Modulation Unit (PMU)

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

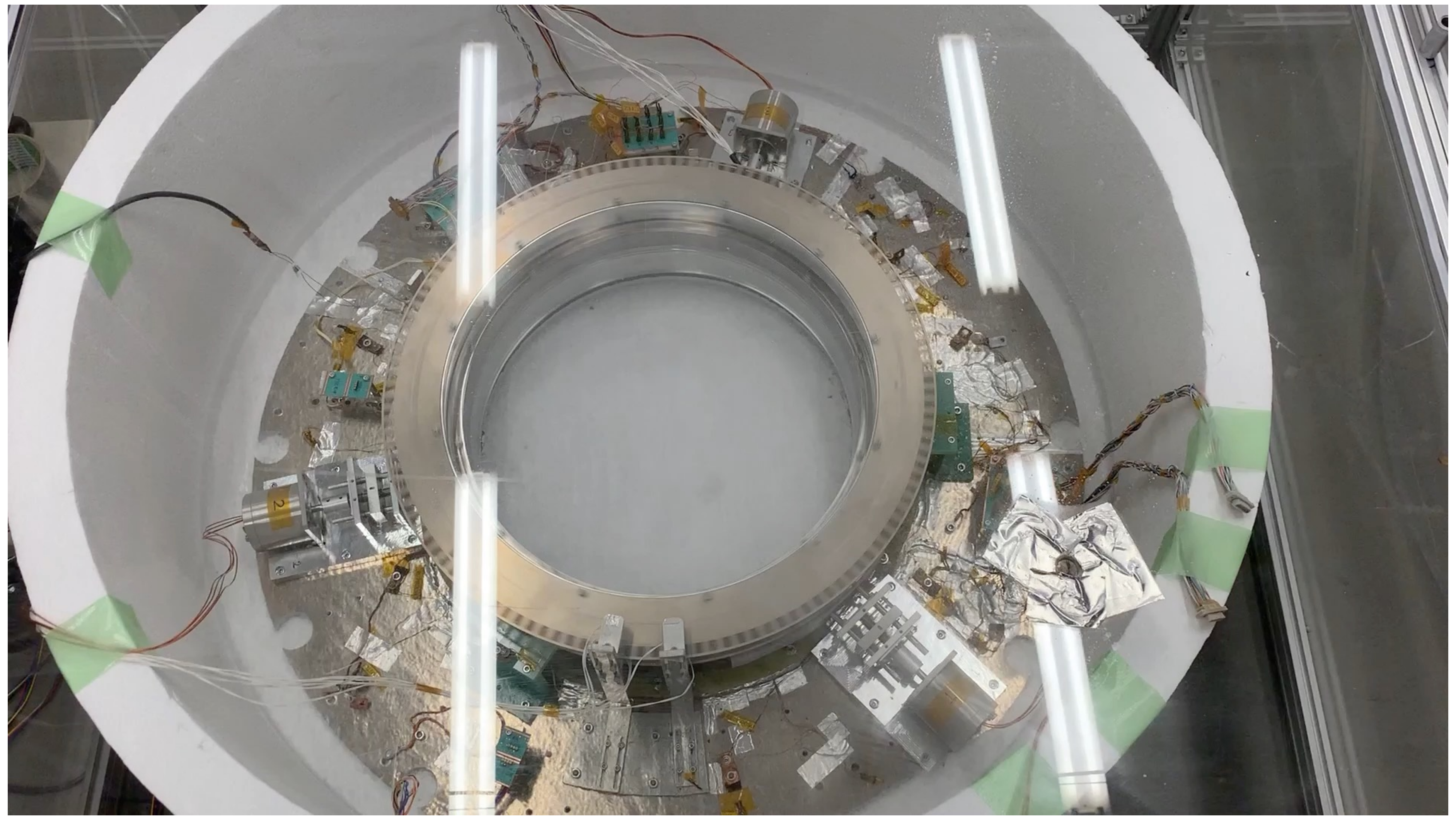




📖 Sakurai+2020 📖 Komatsu+2020

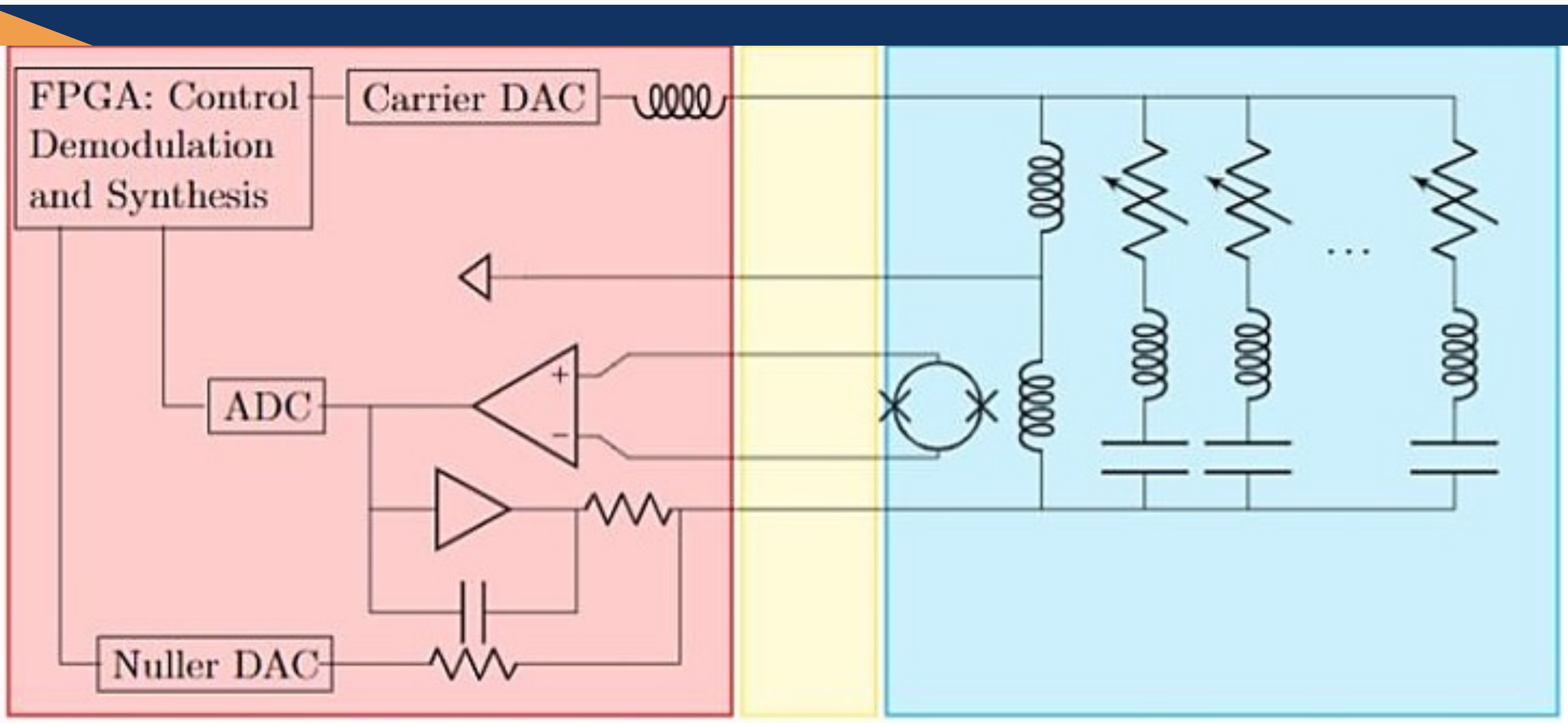
📖 Toda+2020 📖 Columbro+2020 📖 Sugiyama+2020

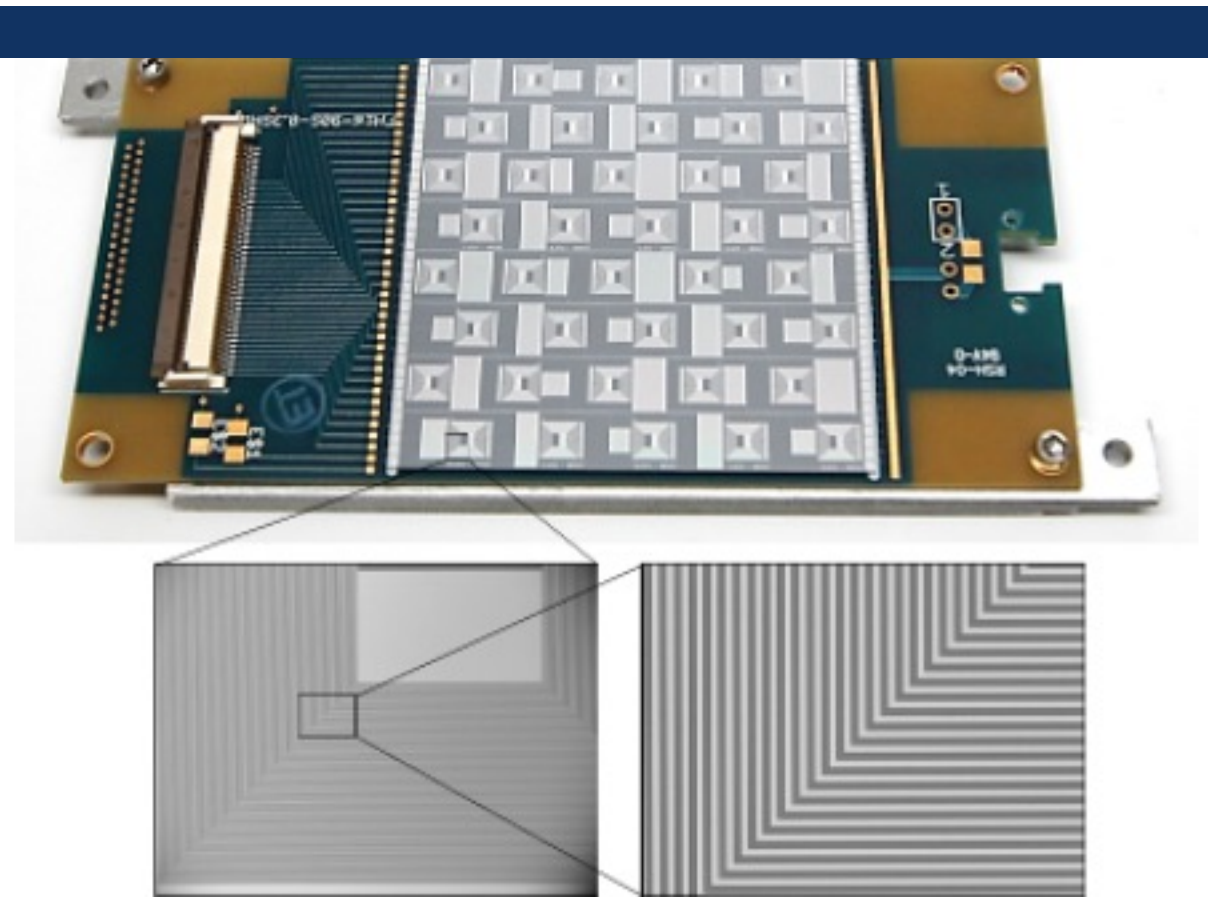
- LFT PMU BBM at Kavli IPMU:

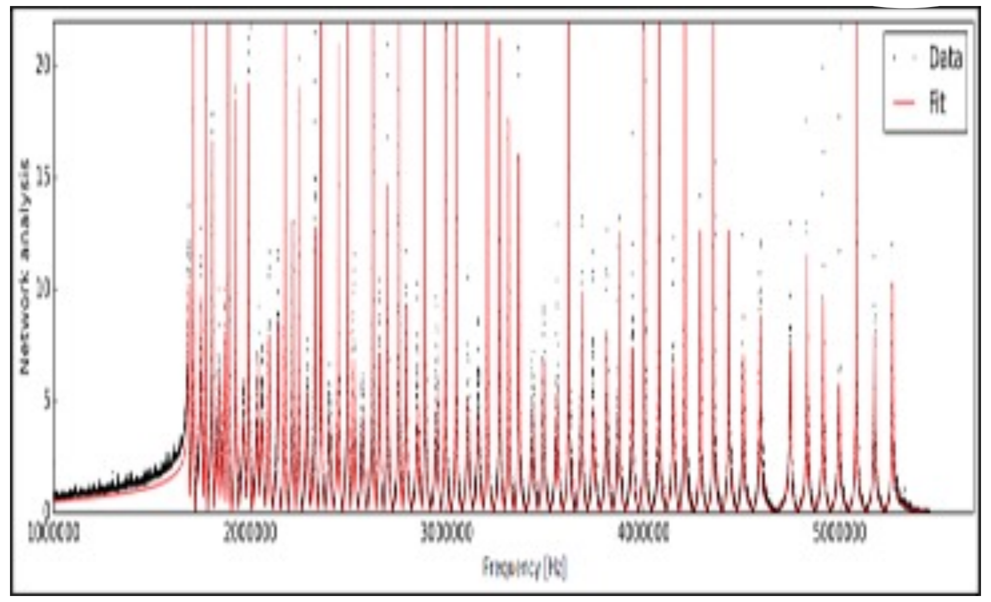


- Rotation test of superconducting magnetic bearing system in the 4K cryostat
- Stable rotation at cryogenic temperature (< 10 K)

LiteBIRD readout system



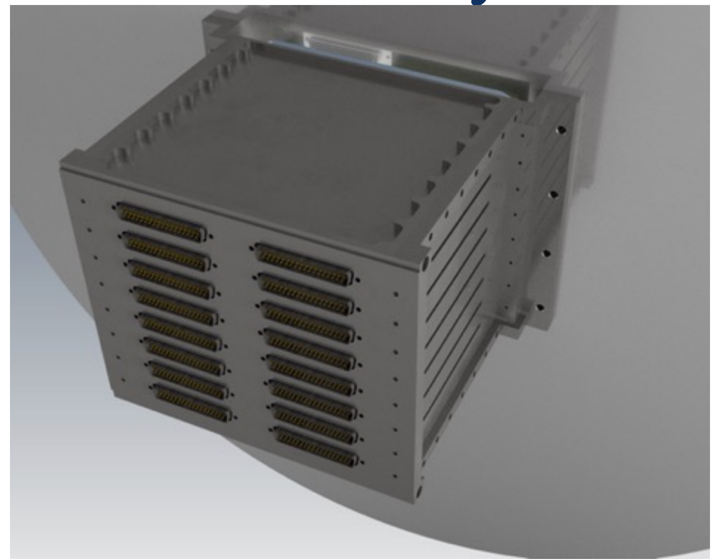




Cold Readout LC filters for MUX

- Digital frequency multiplexing (DfMux) readout technology enables the readout of many Transition Edge Sensors (TES) with fewer components and a low wire count.
- Superconducting resonators are used to assign unique frequency channels to the TES sensors.
- The signal is read out using a low-noise SQUID amplifier and an FPGA controller.
- This approach saves on mass, volume, power consumption, and cost.
- The technique draws its heritage from ground-based CMB experiments.

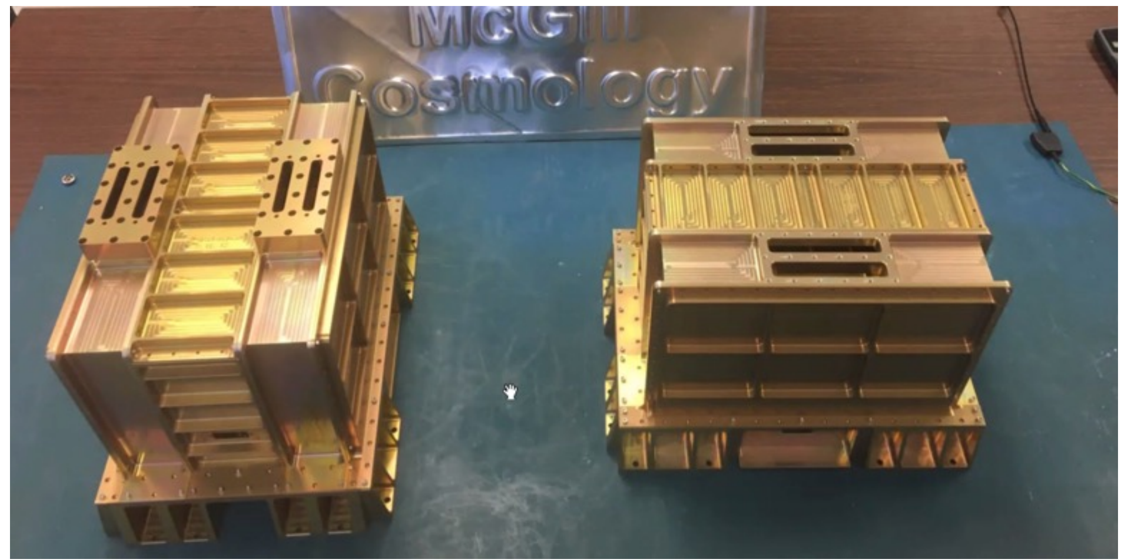
SQUID controller board



SQUID controller assembly

Digitizer assembly

Signal Processing Unit



Digitizer assembly

Foreground cleaning

Foreground modeling

- **Synchrotron**: curved spectrum (AME is absorbed in the curvature)

$$[Q_\mathrm{s}, U_\mathrm{s}](\hat{n},\nu) = [Q_\mathrm{s}, U_\mathrm{s}](\hat{n},\nu_\star)\cdot\left(\frac{\nu}{\nu_\star}\right)^{\beta_\mathrm{s}(\hat{n})+C_\mathrm{s}(\hat{n})\ln(\nu/\nu^\mathrm{c})}$$

- **Dust**: modified blackbody

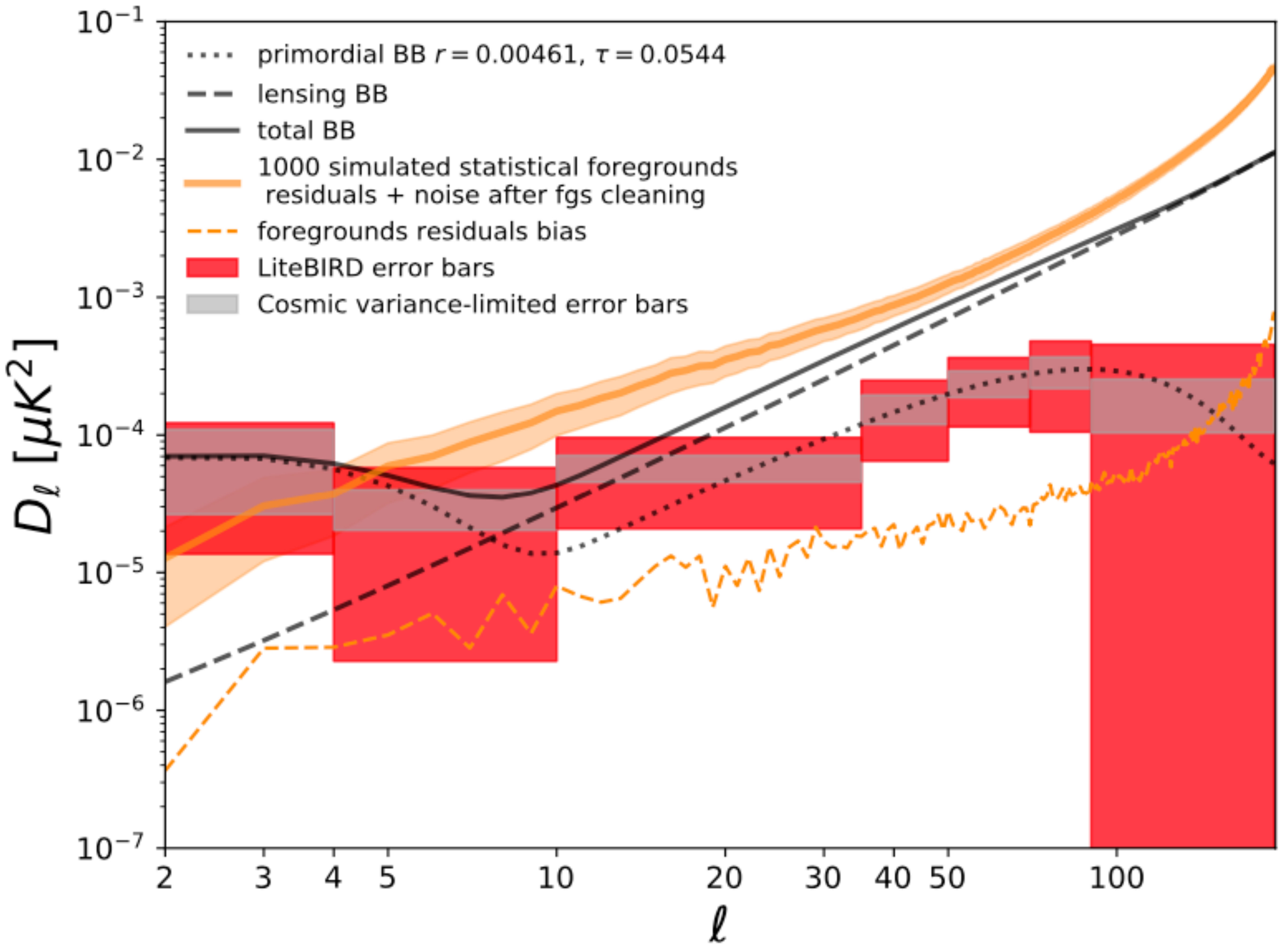
$$[Q_\mathrm{d}, U_\mathrm{d}](\hat{n},\nu) = [Q_\mathrm{d}, U_\mathrm{d}](\hat{n},\nu_\star)\cdot\left(\frac{\nu}{\nu_\star}\right)^{\beta_\mathrm{d}(\hat{n})-2}\frac{B_\nu\left(T_\mathrm{d}(\hat{n})\right)}{B_{\nu_\star}\left(T_\mathrm{d}(\hat{n})\right)}$$

↓

8 parameters in each sky patch

- "**Multipatch** technique" (extension of xForecast), to account for spatial variability. 12×(N_side)^2 patches ⇒ 6144 parameters with $N_\mathrm{side} = 8$

Impact of foregrounds residual



Foreground cleaning

- "Multipatch technique" (extension of xForecast)
- Distribution of the recovered *r* in 1000 simulations with input $r = 0$, with and without foreground residuals
- Bias from foreground (PySM `d1s1`) residuals is found to be small
- Final value: **$r = (3.3 \pm 6.2)\times10^{-4}$**