Giuseppe Puglisi
on behalf of the LiteBIRD Collaboration

The LiteBIRD Cosmic Microwave Background Polarization Survey

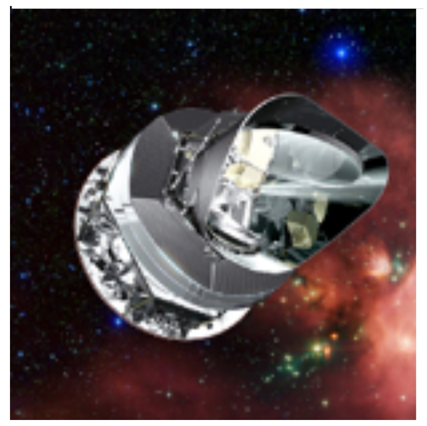
Cosmology 2023 in Miramare
29/08/2023

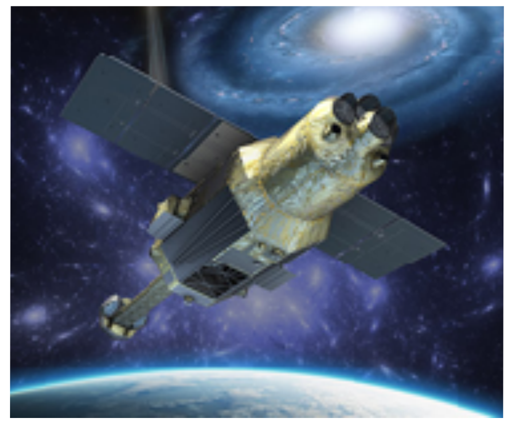
Università di Catania
INAF ISTITUTO NAZIONALE DI ASTROFISICA
INFN Istituto Nazionale di Fisica Nucleare

LiteBIRD Joint Study Group

Over 350 researchers from **Japan**, **North America** and **Europe**

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





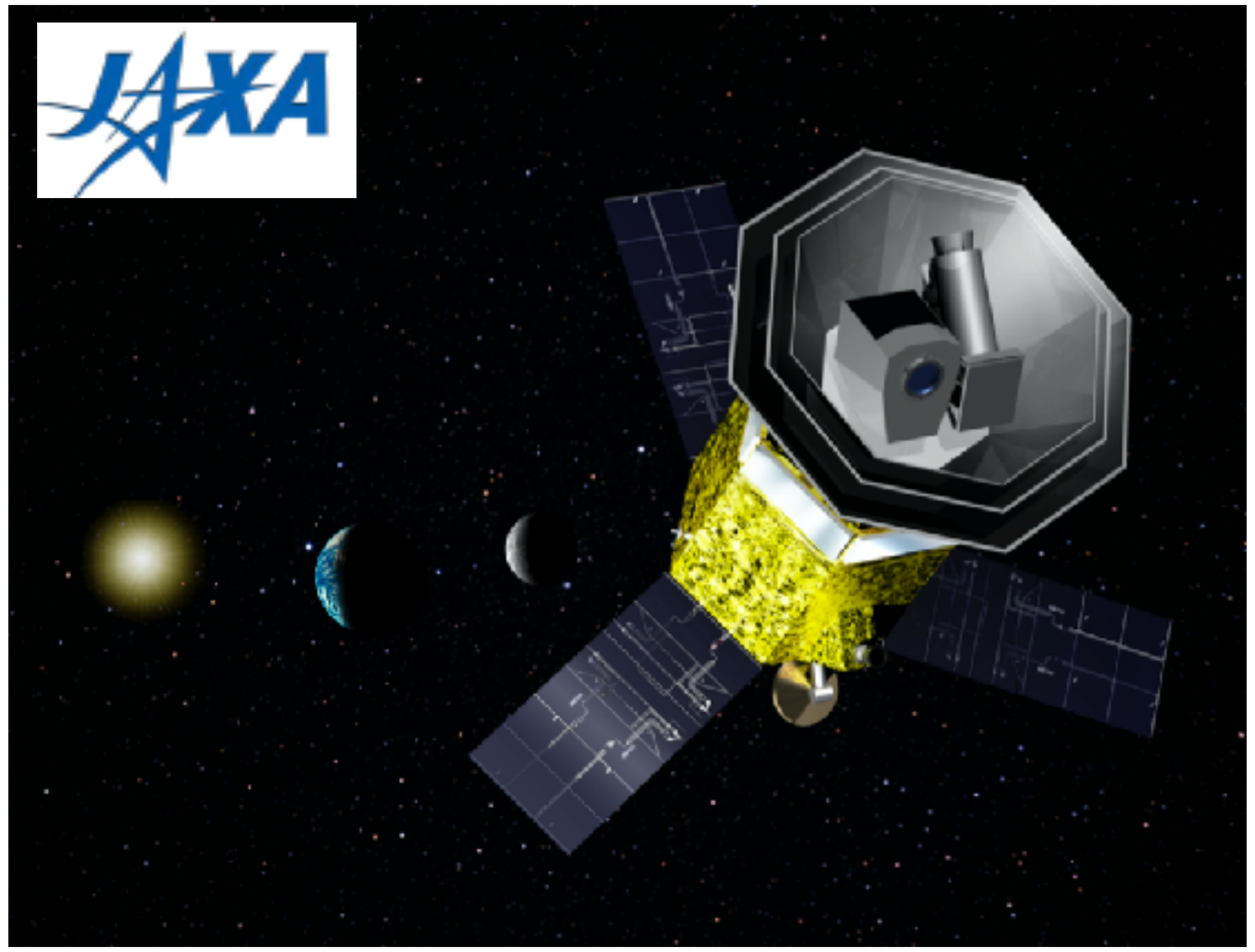
LiteBIRD Global F2F meeting
December 5-8, 2022 at Okayama

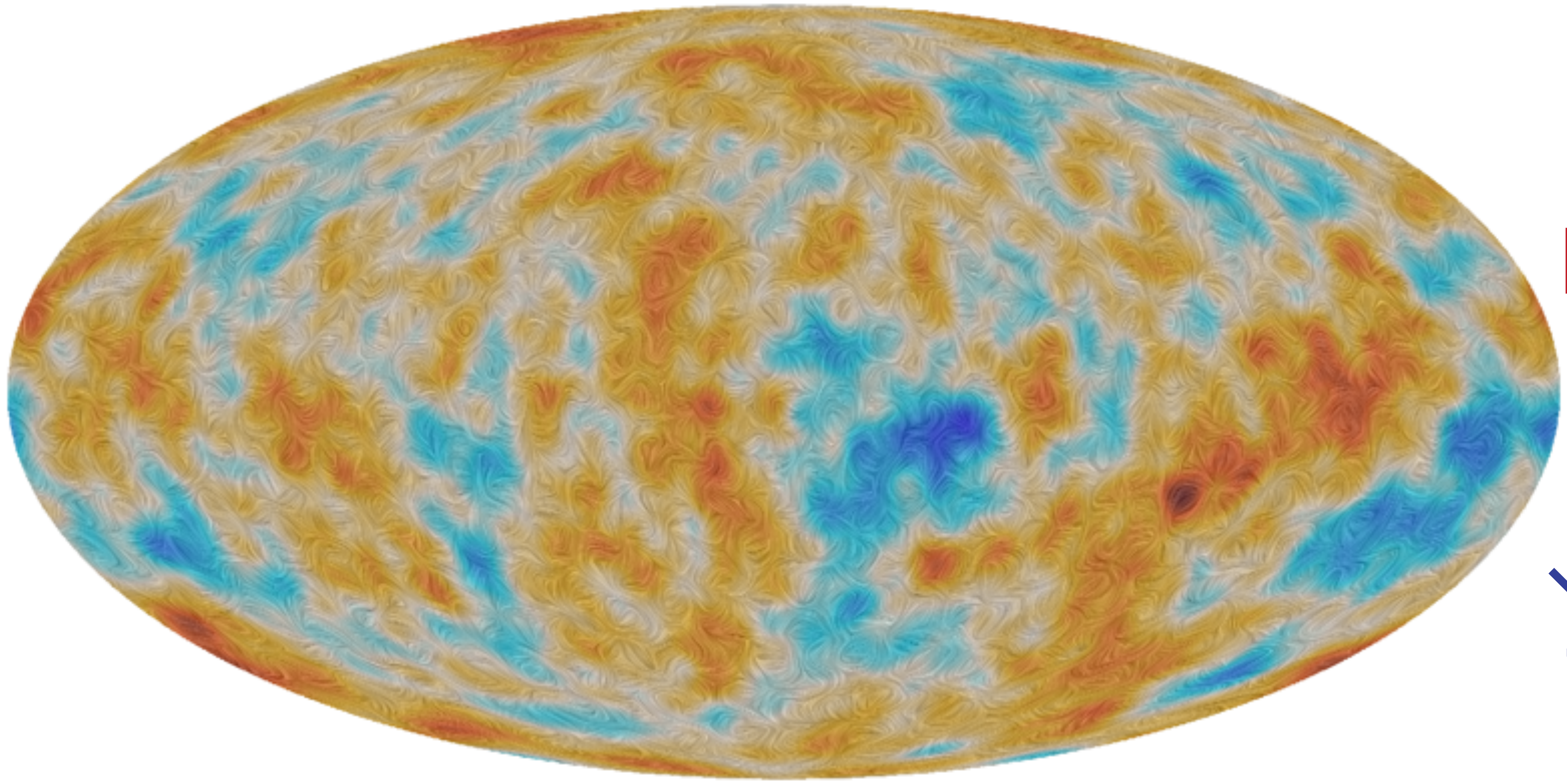
APC
ASI
Berkeley
UNIVERSITY OF CALIFORNIA
BERKELEY LAB
UNIVERSITÀ DEGLI STUDI DI MILANO BICOCCA
CARDIFF UNIVERSITY
PRIFYSGOL CAERDYDD
cea
Centre Pierre Binétruy
CNRS • Berkeley
cnes
cnrs
CSA ASC
Canada
CSIC
CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS
CSL
CENTRE SPATIAL DE LIÈGE
ENS
PSL
erc
European Research Council
EXCELENCIA MARÍA DE MAEZTU
EXCELENCIA SEVERO OCHOA
FAU
FRIEDRICH-ALEXANDER UNIVERSITÄT ERLANGEN-NÜRNBERG
Forskningsrådet
The Research Council of Norway
GOBIERNO DE ESPAÑA
MINISTERIO DE CIENCIA E INNOVACIÓN
NASA
Goddard Space Flight Center
GSSI
GRAN SASSO SCIENCE INSTITUTE
INSTITUTO DE ASTROFISICA DE CANARIAS
IAC
LiteBIRD
IAP
IAS
Orsay
IFCA
Instituto de Física de Cantabria
ifpU
IJCLab
Irène Joliot-Curie
Laboratoire de Physique des 2 Infinis
INFN
INAF
ISTITUTO NAZIONALE DI ASTROFISICA
IPMU
INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE
IPNS
素粒子原子核研究所
Institute of Particle and Nuclear Studies
irap
astrophysique & planétologie
JAXA
KEK
KIPAC
KMI
Kobayashi-Maskawa Institute
Nagoya University
LMU
USM
LPSC
GRENOBLE | MODANE
MAX-PLANCK-INSTITUT FÜR ASTROPHYSIK
McGill
名古屋大学
NAGOYA UNIVERSITY
NATIONAL INSTITUTE OF TECHNOLOGY KAGAWA COLLEGE
香川高専
NÉEL institut
NIST
Norwegian Directorate for Higher Education and Skills
岡山大学
OKAYAMA UNIVERSITY
QUP
International Center for Quantum-field Measurement Systems for Studies of the Universe and Particles
POLITÉCNICA
idr
PRINCETON UNIVERSITY
SAPIENZA
UNIVERSITÀ DI ROMA
SISSA
SORBONNE UNIVERSITÉ
SSDC
SPACE SCIENCE DATA CENTER
LELAND STANFORD JUNIOR UNIVERSITY
Stockholm University
公立諏訪東京理科大学
Suwa University of Science
TOR VERGATA
UNIVERSITÀ DEGLI STUDI DI ROMA
UCL
UBC
THE UNIVERSITY OF BRITISH COLUMBIA
UC
UNIVERSIDAD DE CANTABRIA
University of Colorado Boulder
UKRI
Science and Technology Facilities Council
ULB
UNIVERSITÉ LIBRE DE BRUXELLES
Universidad de La Laguna
MANCHESTER 1824
The University of Manchester
UiO University of Oslo
UNIVERSITÀ DI PISA
Università degli Studi di Ferrara
UNIVERSITÀ DEGLI STUDI DI MILANO
UNIVERSITÀ DEGLI STUDI DI PADOVA
THE UNIVERSITY OF TOKYO
UNIVERSITY OF TORONTO

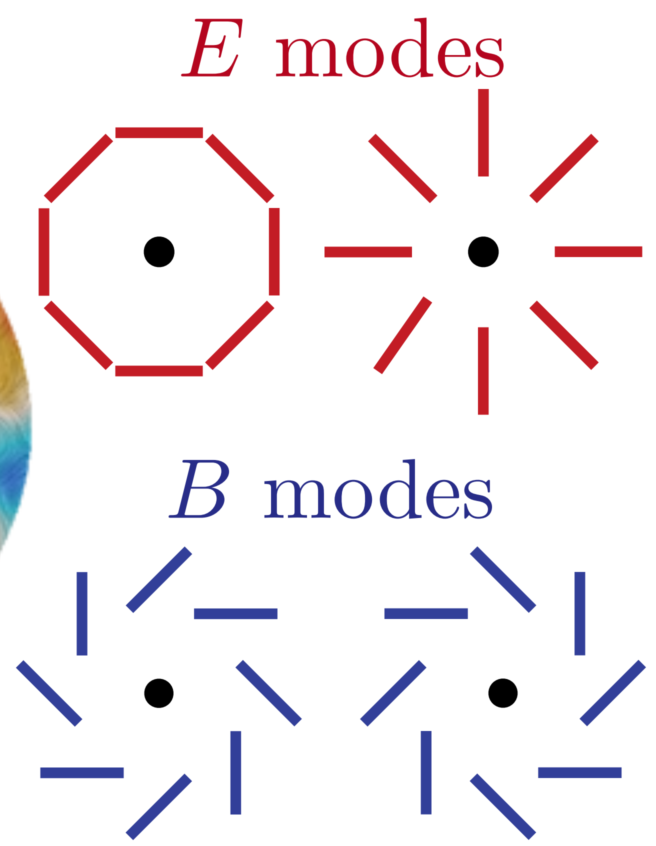
LiteBIRD overview

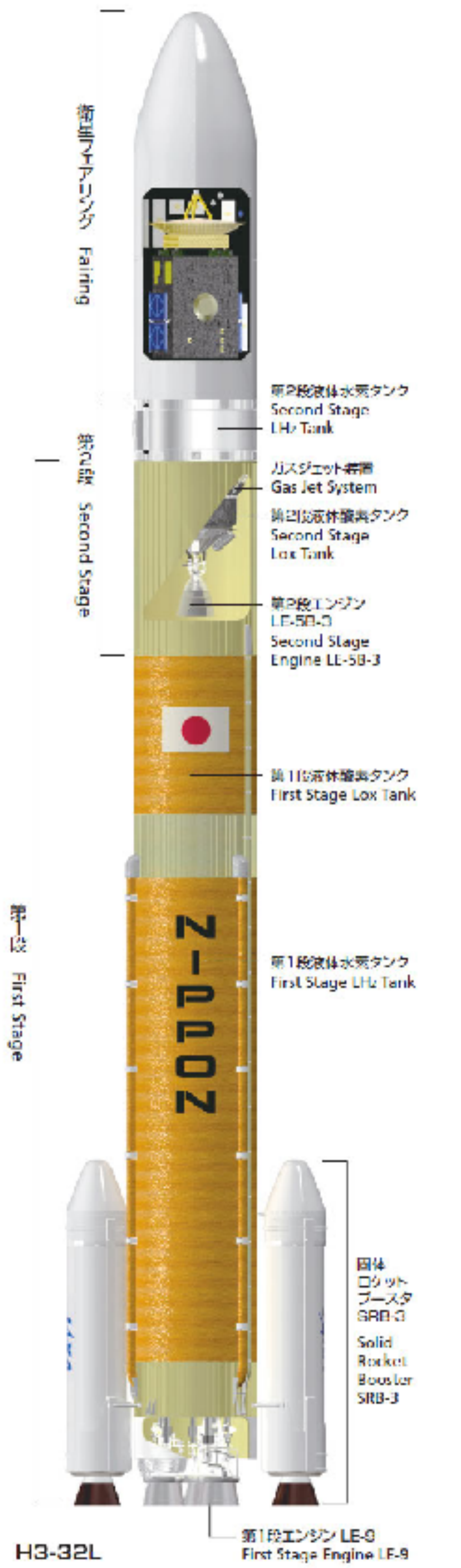
- Lite (Light) satellite for the study of *B*-mode polarization and Inflation from cosmic background Radiation Detection
- JAXA's L-class mission selected in May 2019
- Expected launch in late **2030** with JAXA's H3 rocket
- **All-sky 3-year survey**, from Sun-Earth Lagrangian point L2
- Large frequency coverage (**40–402 GHz**, 22 bands) at **70–18 arcmin** angular resolution for precision measurements of the **CMB *B*-modes**
- Final combined sensitivity: **2.2 μK·arcmin**

📖 LiteBIRD collaboration PTEP 2023



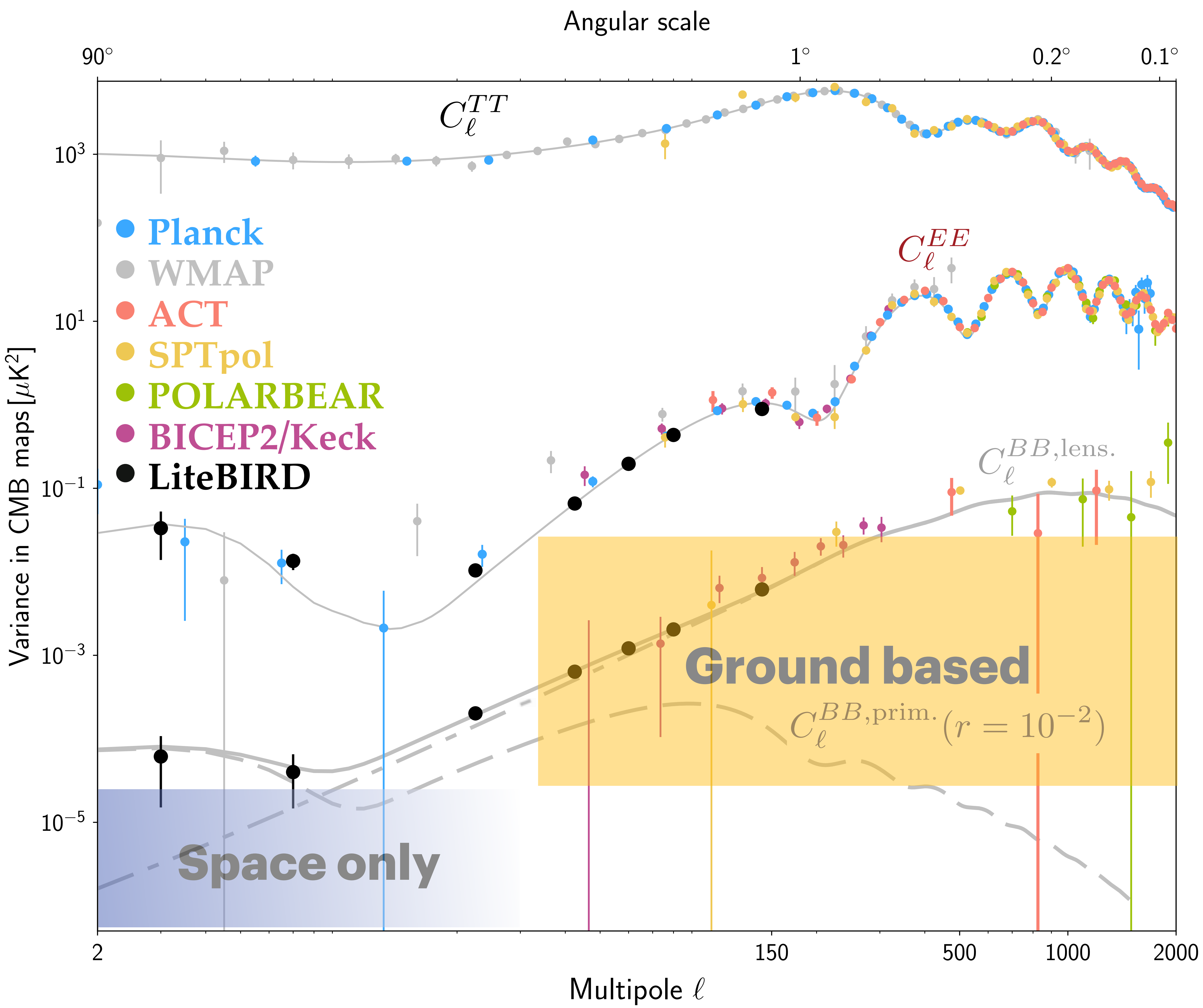






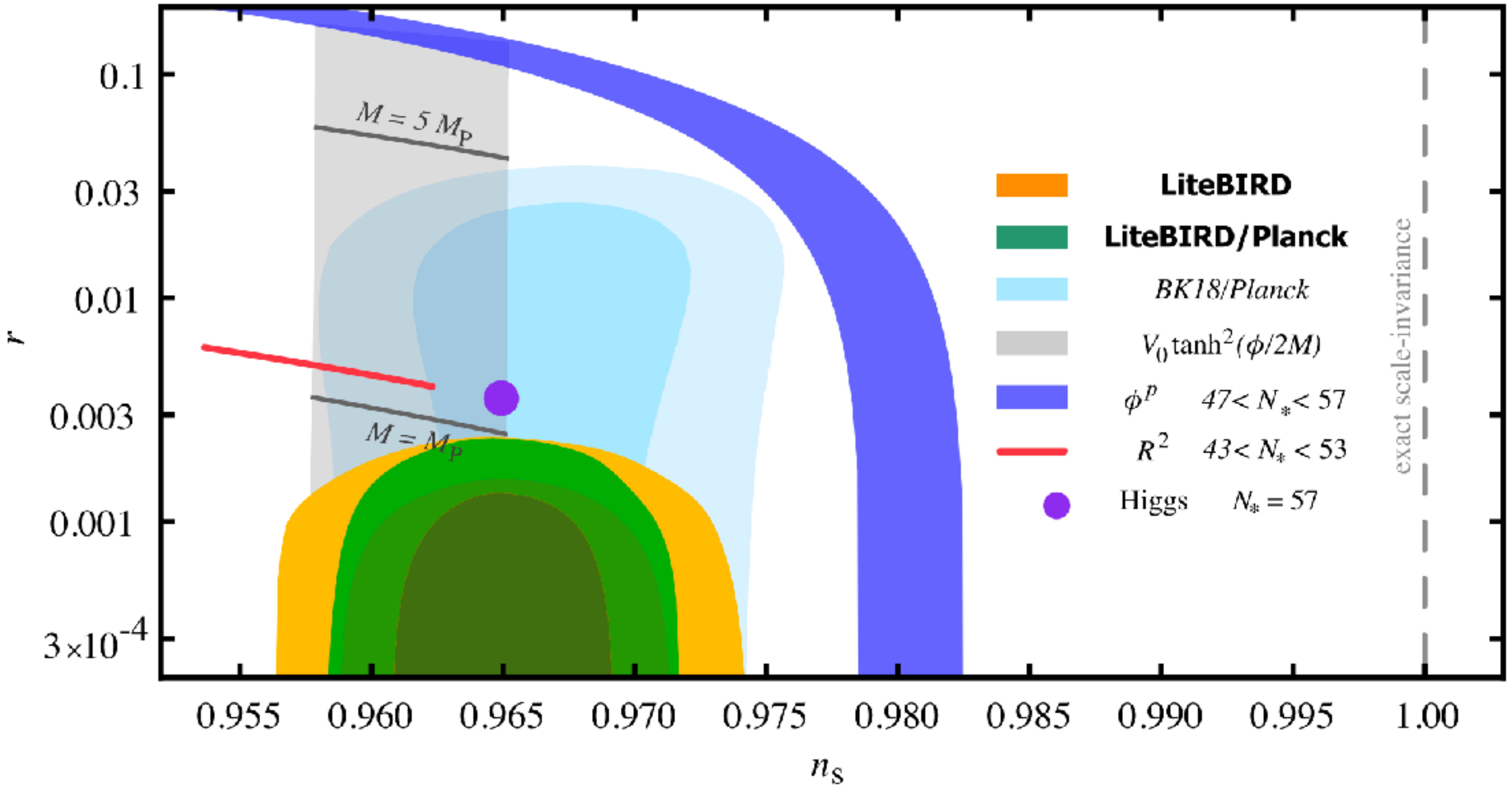
LiteBIRD main scientific objectives

- Definitive search for the ***B*-mode signal** from **cosmic inflation** in the CMB polarization
  - Making a discovery or ruling out well-motivated inflationary models
- The inflationary (i.e. primordial) *B*-mode power is proportional to the **tensor-to-scalar ratio, *r***
- **Reionization + Recombination bumps:** improve 50x current constraints: $r < 0.032$ (95% C.L.) 📖 Tristram et al. 2022, combining BK18 and Planck PR4



LiteBIRD main scientific objectives

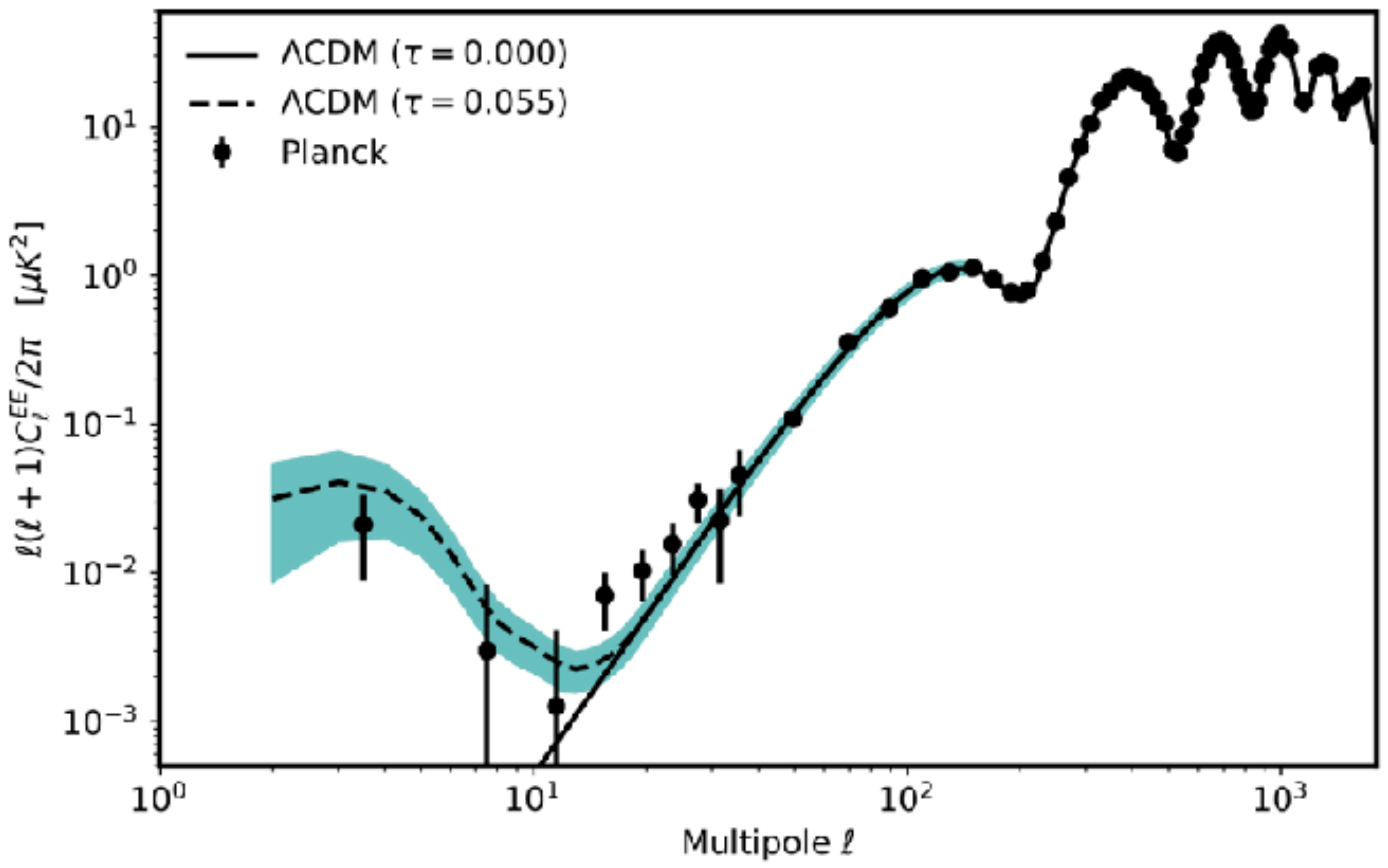
- Level 1-requirements (no external data):
  - For $r = 0$, **total uncertainty of $\delta r < 0.001$**
  - For $r = 0.01$, 5-σ detection of the reionization ($2 < \ell < 10$) and recombination ($11 < \ell < 200$) peaks independently

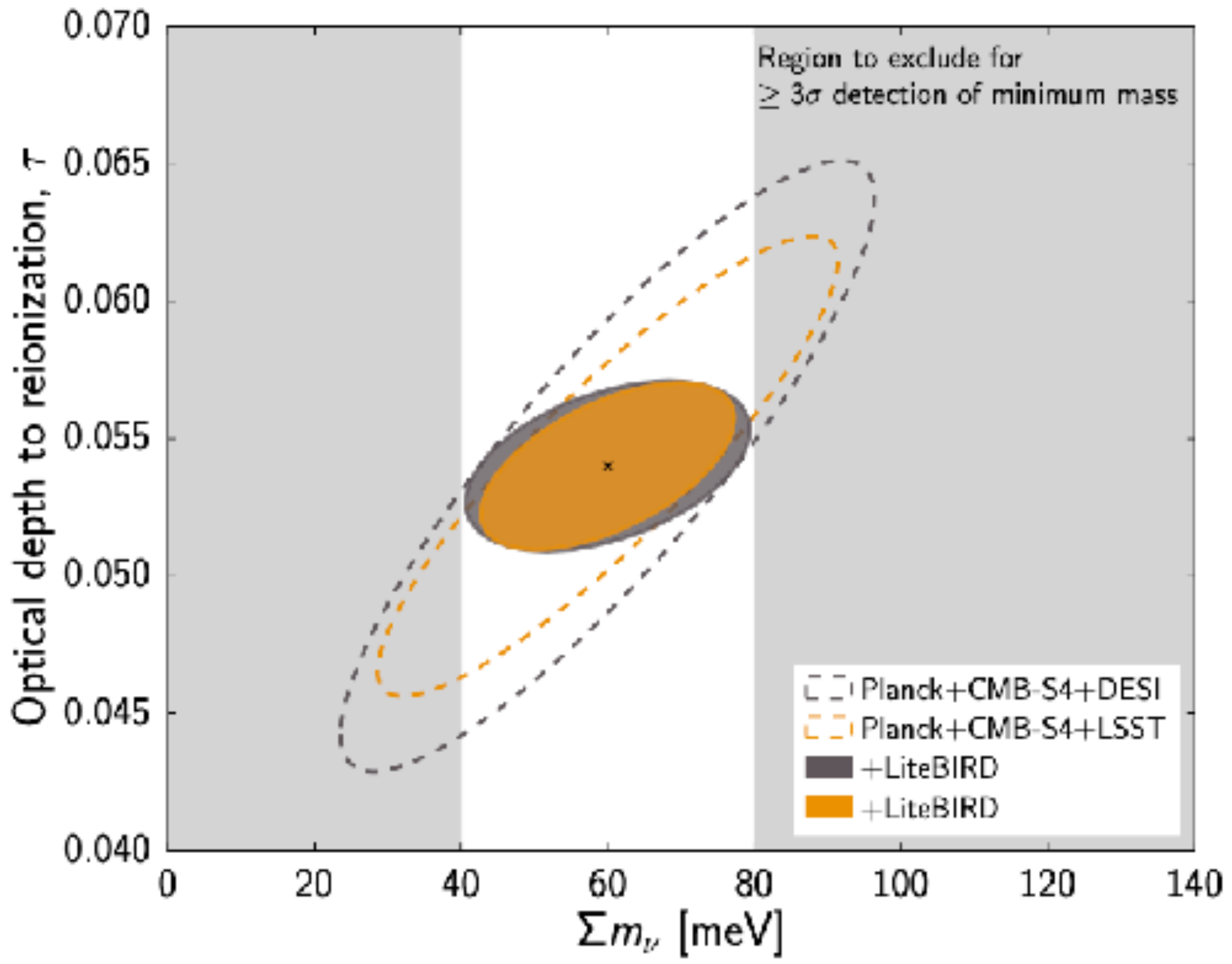


📖 LiteBIRD collaboration PTEP 2023

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. Power spectrum features in polarization
     - Large-scale ***E*-modes**
     - **Reionization** cosmic variance limited measurement of τ (3x improvement wrt *Planck)*
     - **Neutrino mass** ($\sigma(\sum m_\nu) = 12$ meV)
     - **Effective species** $\sigma(N_{eff}) = 0.15$
  2. Constraints on **cosmic birefringence**
  3. **SZ effect** (thermal, diffuse, relativistic corrections)
  4. Elucidating **anomalies**
  5. **Galactic science**

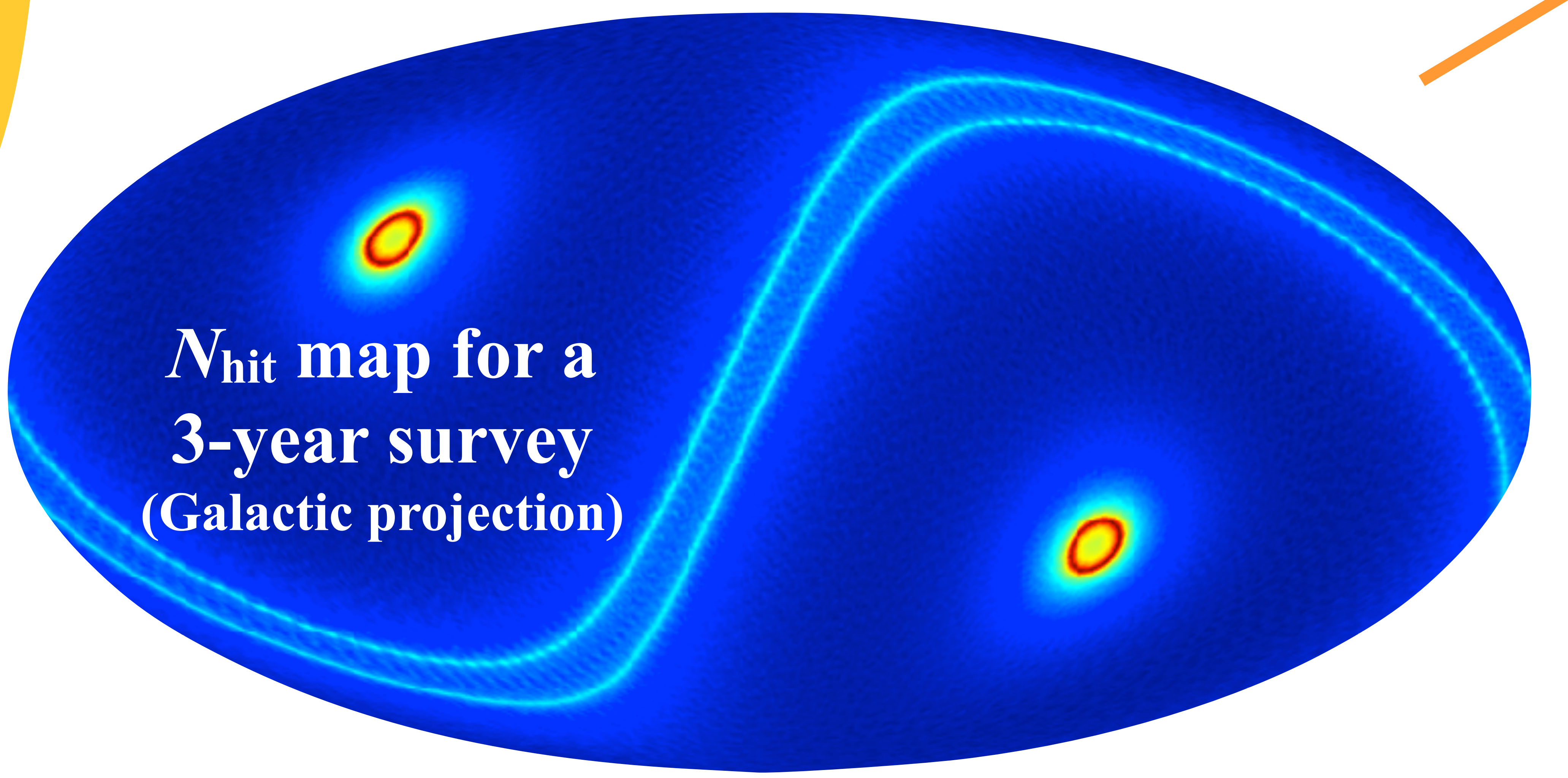




adapted from Calabrese+2017

LiteBIRD scanning strategy

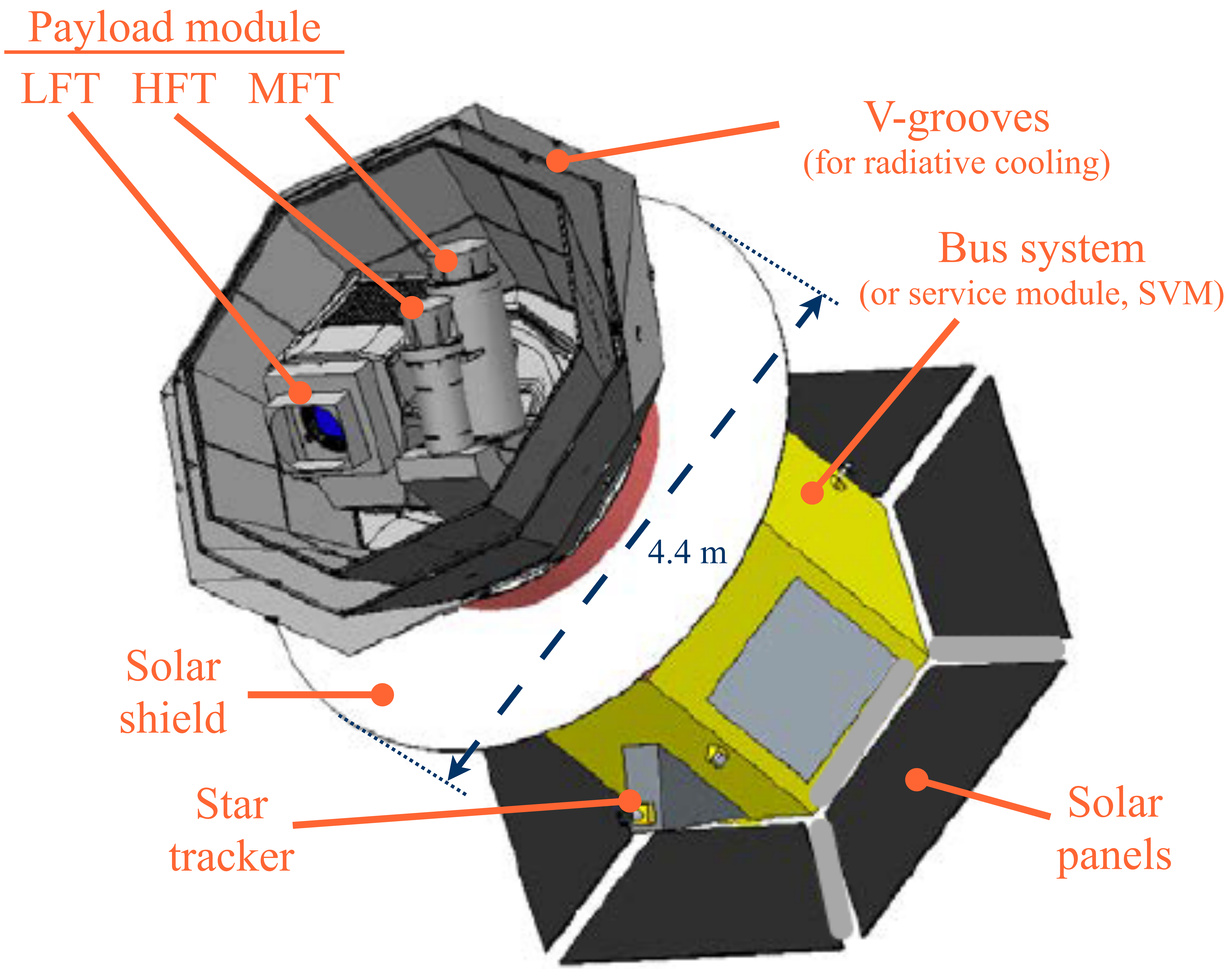
- 3-year survey, Sun-Earth L2 Lissajous orbit
- Precession angle: $\alpha = 45°$
- Spin angle: $\beta = 50°$



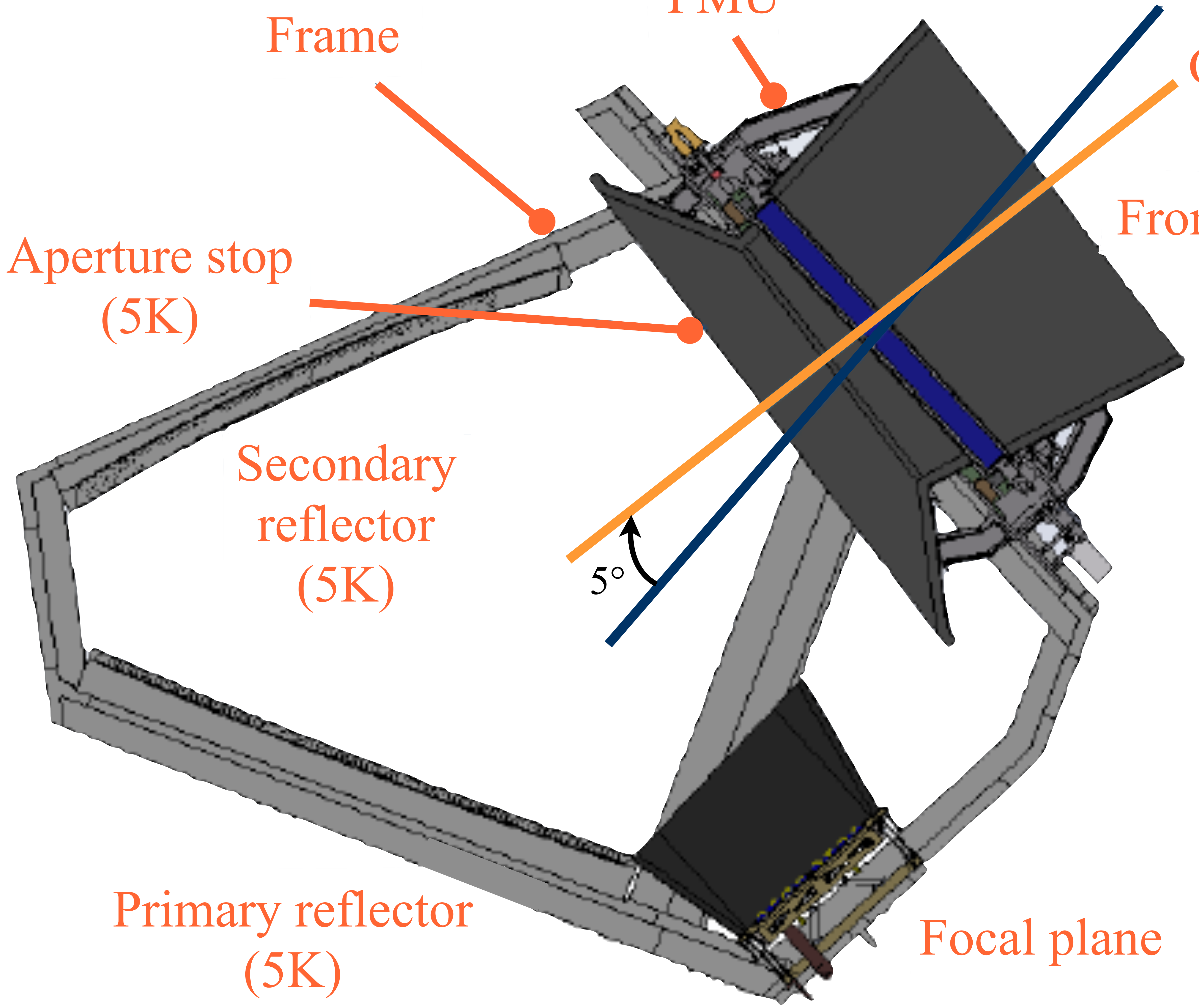
LiteBIRD spacecraft overview

- **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)



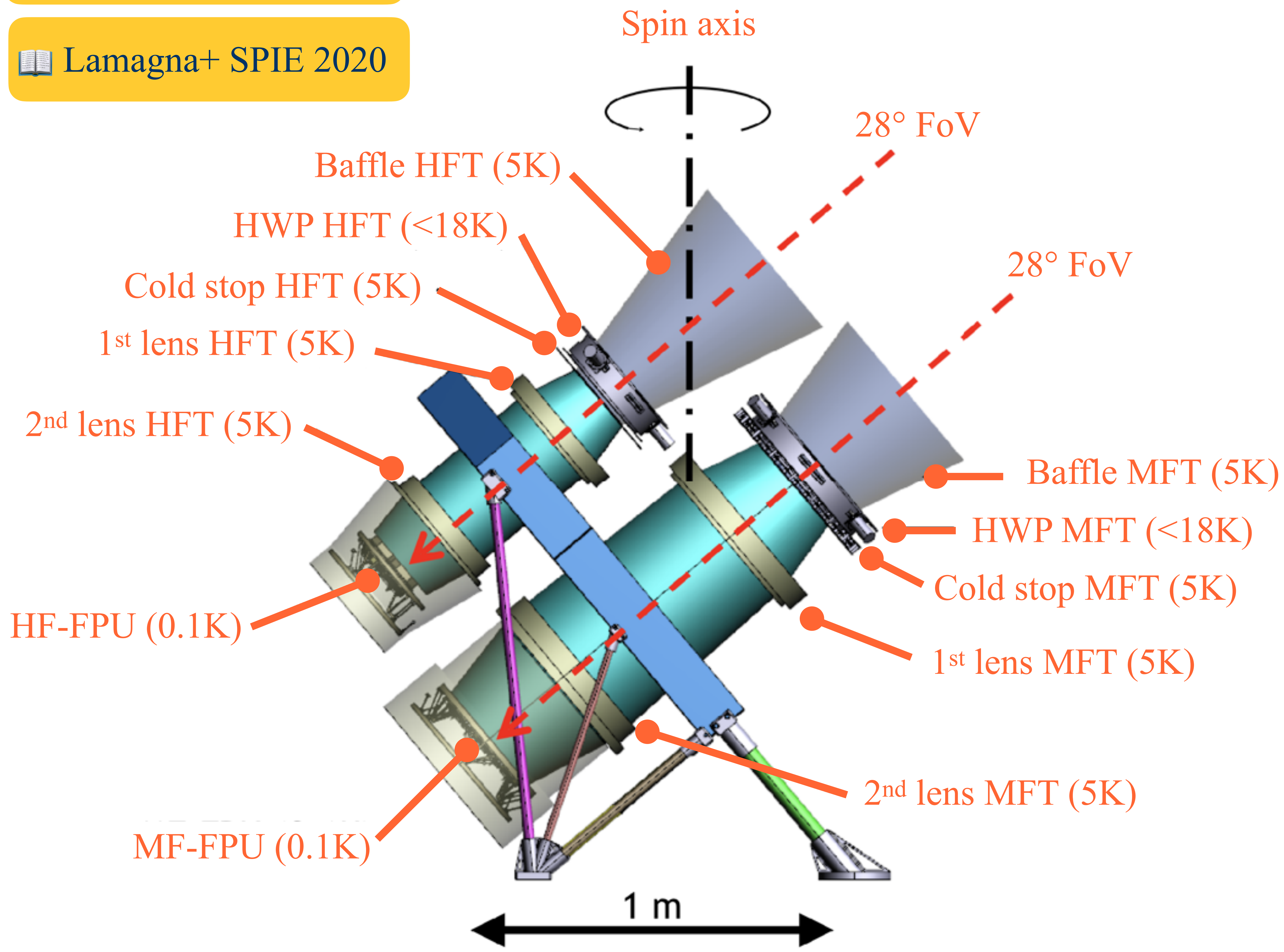
- Polarization Modulation Unit (PMU) as the first sky-side optical element
- **Crossed-Dragone** design
  - Mirrors and aperture stop at **5 K**
  - Made of aluminium
- Field of view: **18° × 9°**
- Strehl ratio > 0.95 (@ 161 GHz)
- Aperture diameter: **400 mm**
- Frequency range: **40-140 GHz**
- Angular 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

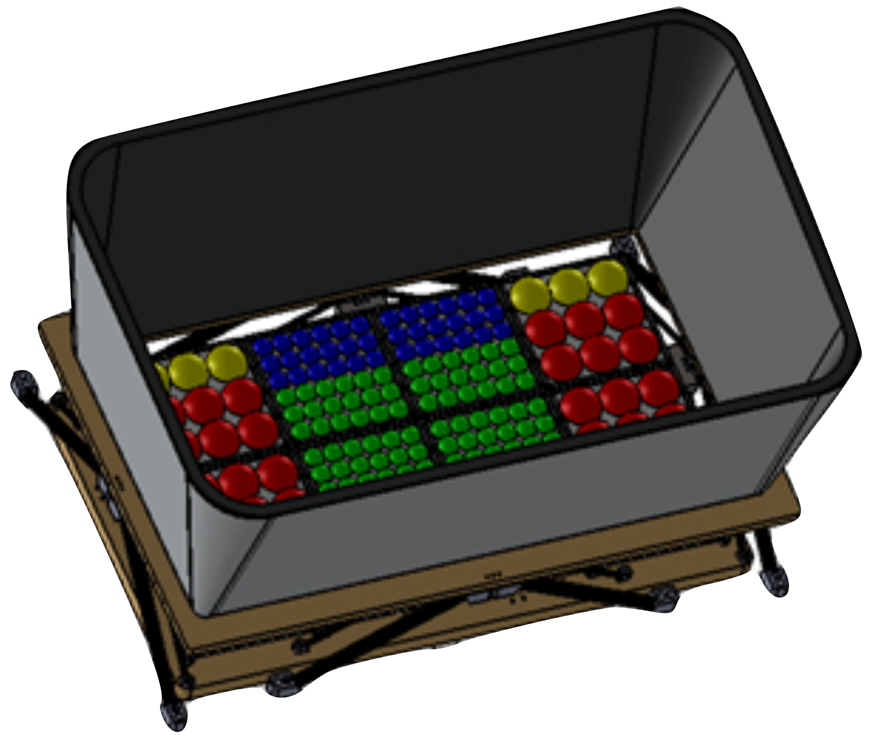
	MFT	HFT
ν (GHz)	**100-195**	**195-402**
Ap. diameter (mm)	**300**	**200**
Ang. res. (arcmin)	**38-28**	**29-18**

Focal plane configuration

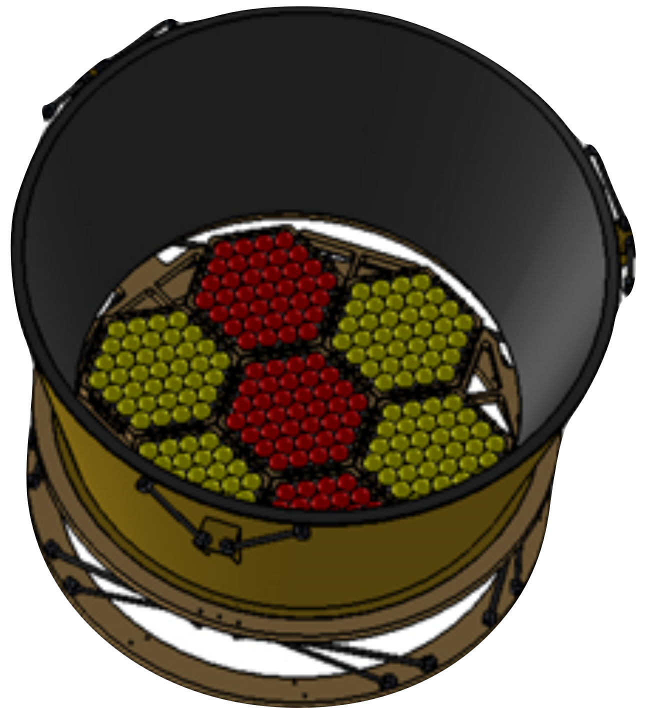
- Transition-Edge Sensor (TES) arrays
- Multichroic detectors
- Number of detectors: 4508
- 15 bands including overlap between instruments

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

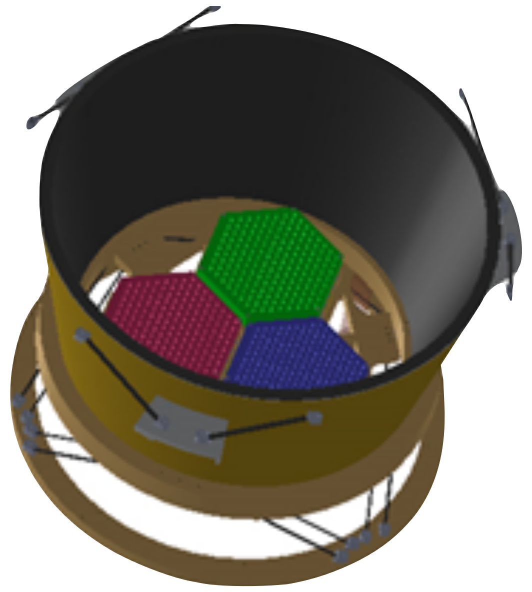
LFT



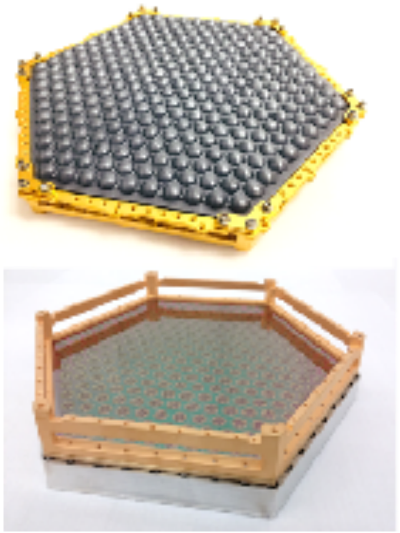
MFT

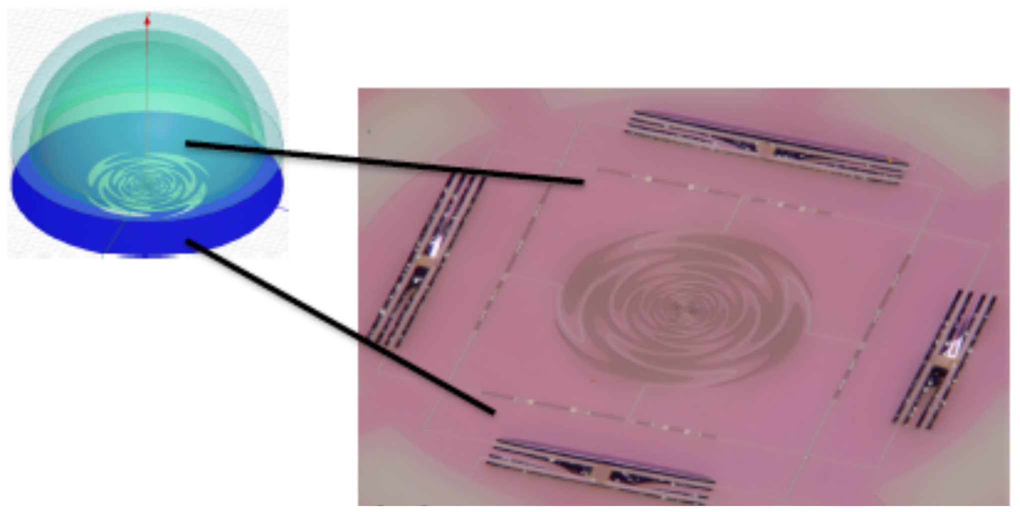


HFT

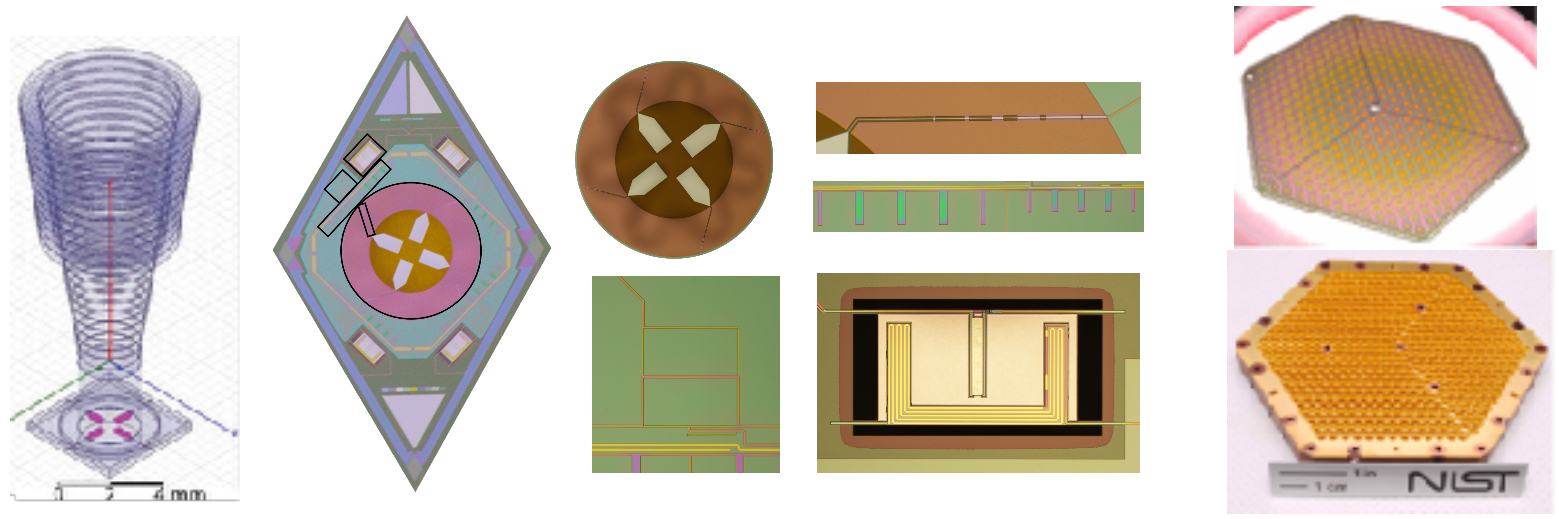


Lensed coupled detectors
Lenslets





Horn coupled detectors
Platelets



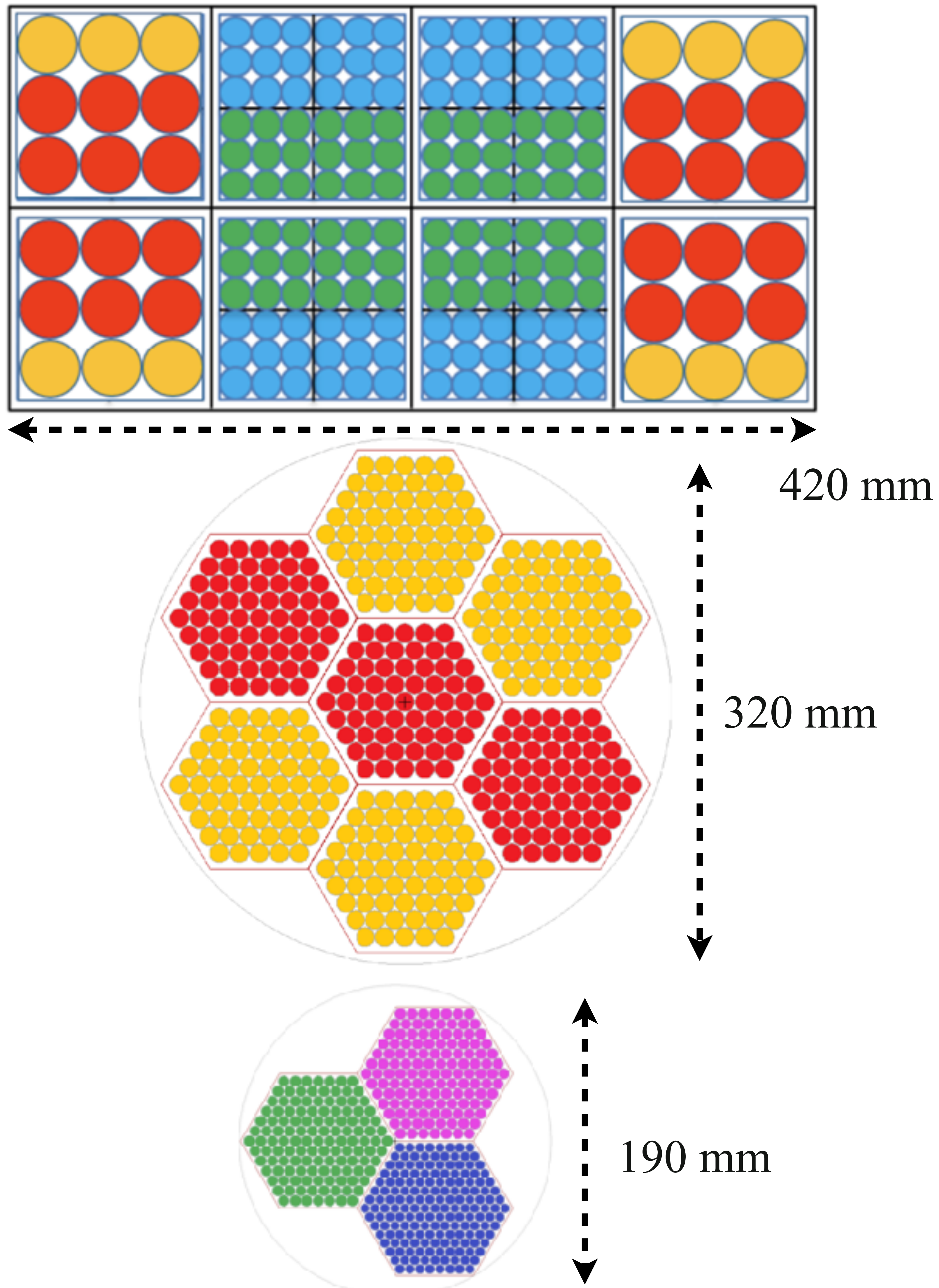
MFT (2.5:1)
89GHz — 225 GHz
2074 detectors
2 x 183 Trichroic TES
2 x 244 Dichroic TES
Bands: 100, 119, 140, 166, 195

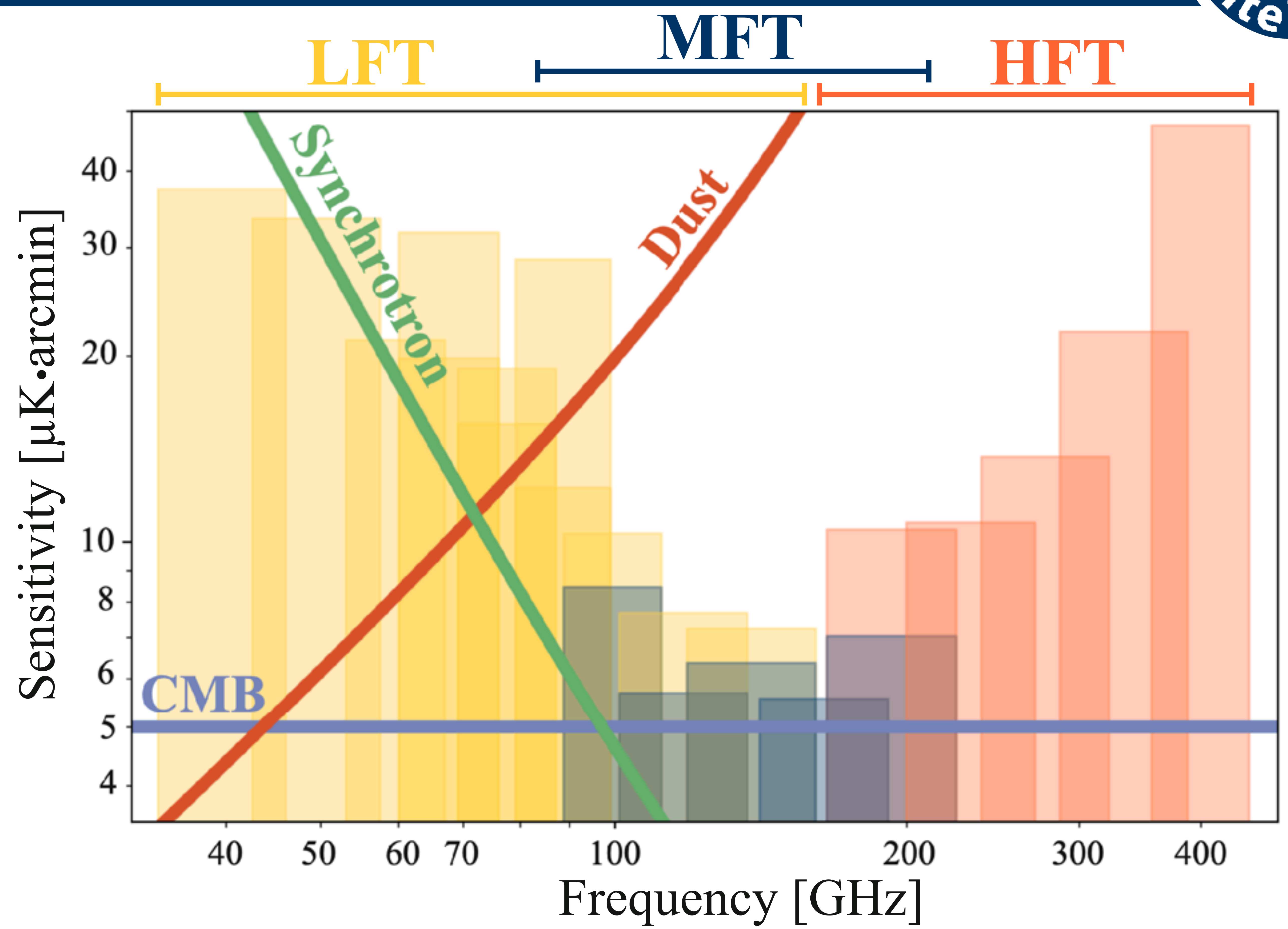
LFT (5.7:1)
34GHz — 161 GHz
Bands: 40, 50, 60, 68, 78, 89, 100, 119, 140
68, 78, 89
1080 detectors
2 x 180 Trichroic TES

HFT (2.7:1)
166 GHz — 448 GHz
Bands: 195, 235, 280, 337, 402
135 detectors
2 x 254 Dichroic TES
2 x 169 Monochromatic TES

📖 Westbrook+ SPIE 2020

LiteBIRD sensitivities





- Projected **polarization sensitivities** for a **3-year full-sky survey**
- Best of 4.6 μK·arcmin @ 119 GHz
- Combined sensitivity to primordial CMB anisotropies: **2.2 μK·arcmin**

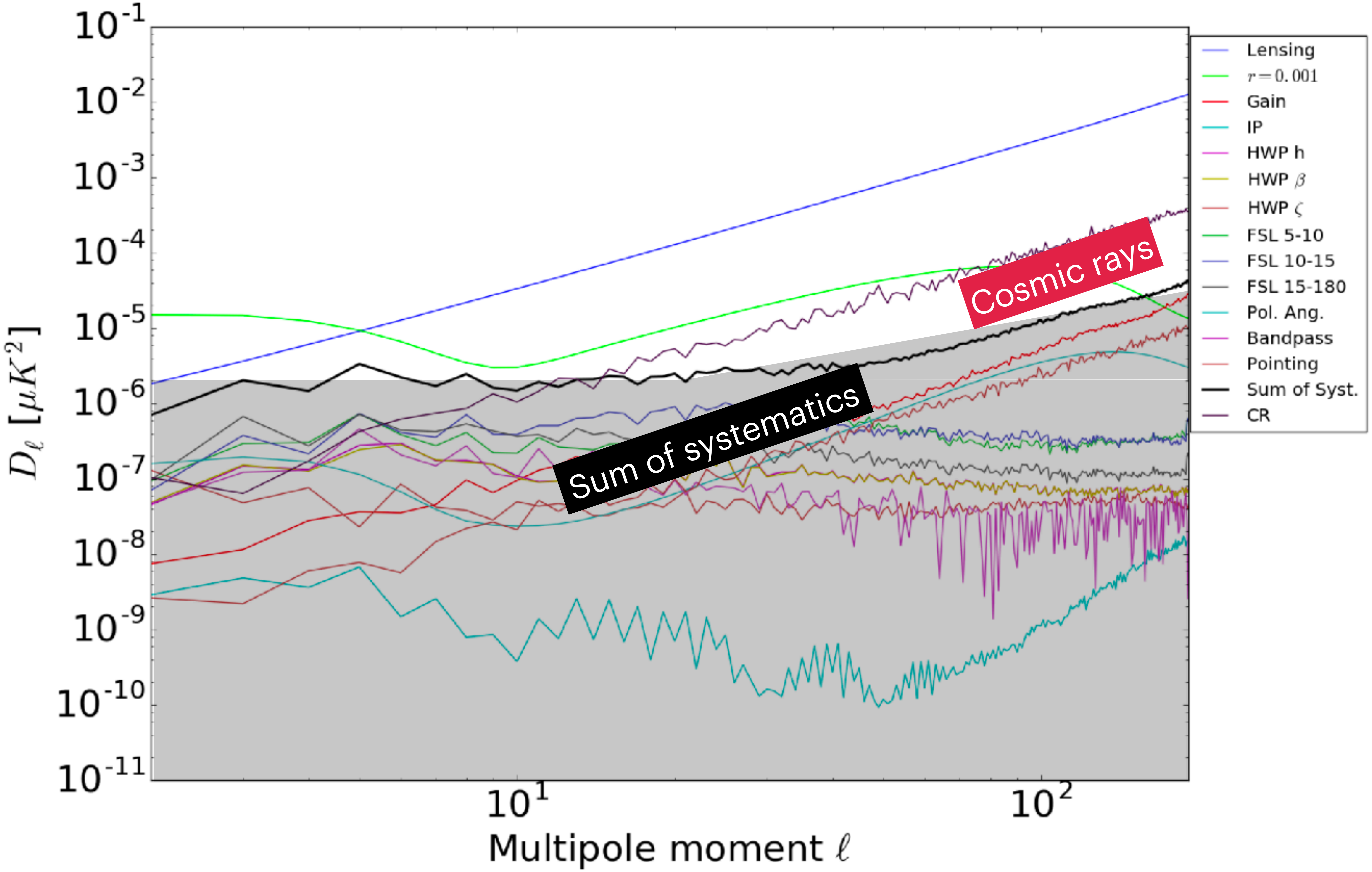
LiteBIRD collaboration PTEP 2023

Instrumental Systematics

1. Inject each instrum. Systematics into time ordered data simulations (w/o any B-mode signal)
2. Estimate how systematics leak into B-mode power spectrum
3. Accounting for all systematic effects, we get

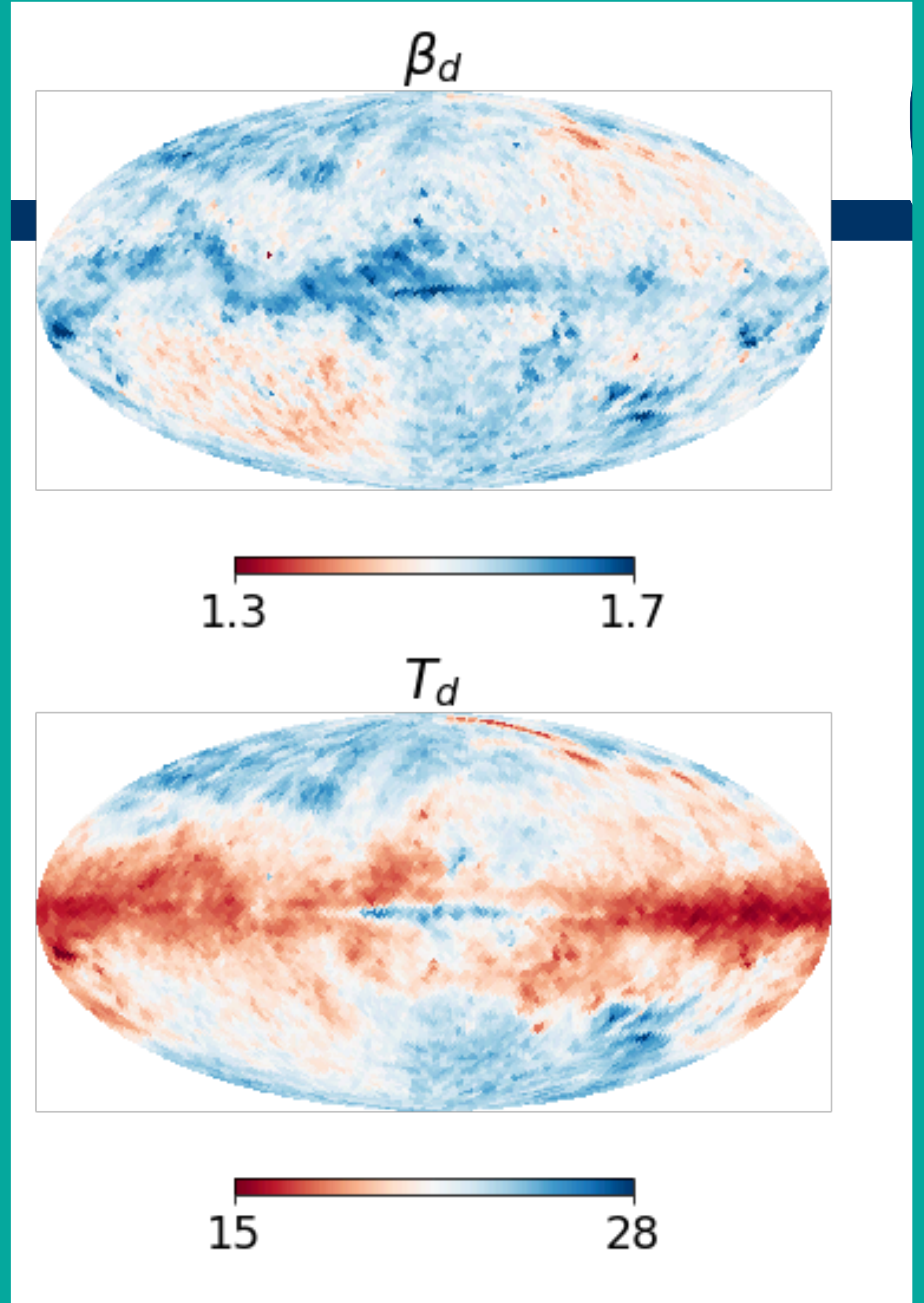
$$\Delta r_{\rm syst} = 1.7 \times 10^{-4}$$

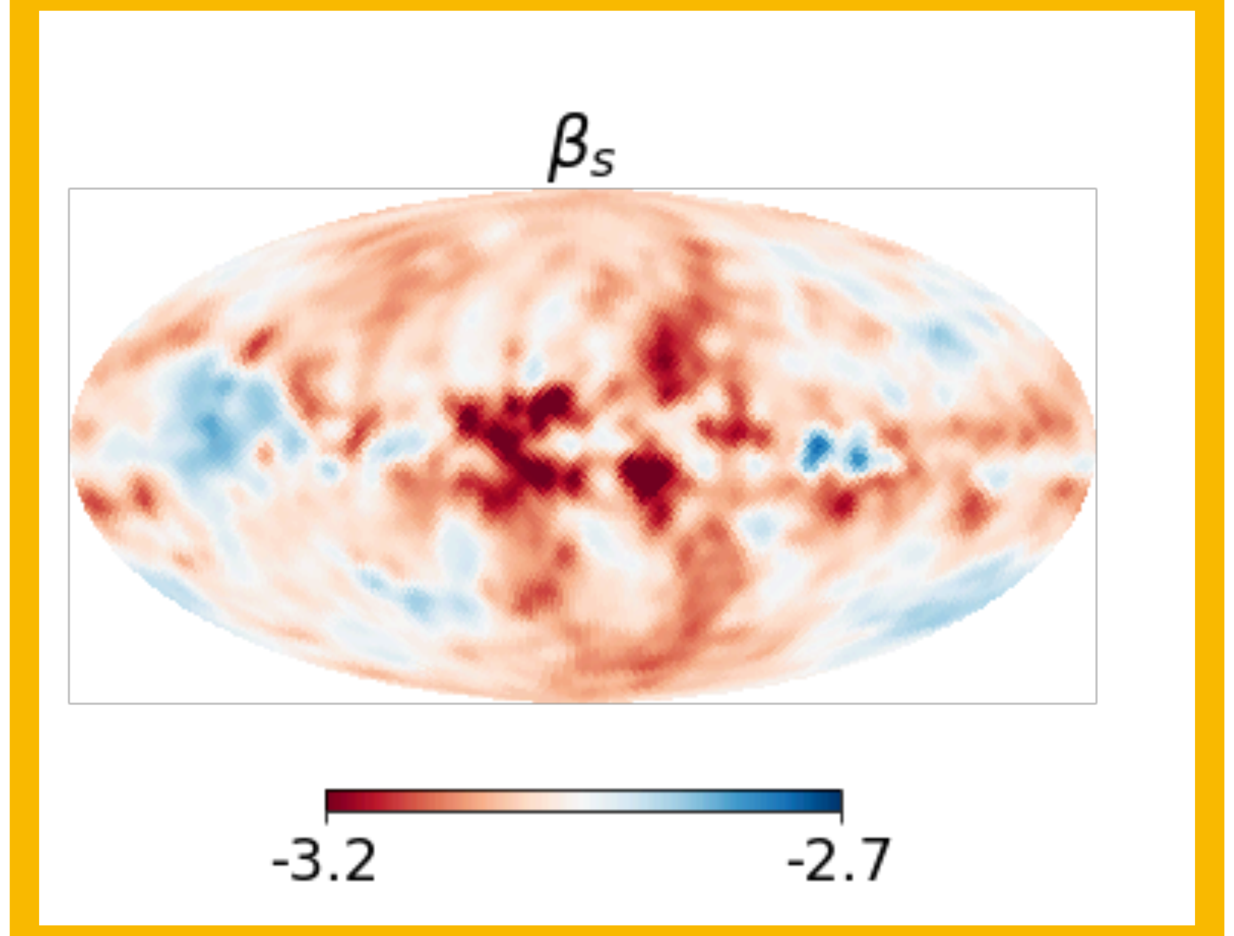
📖 LiteBIRD collaboration PTEP 2023



Galactic Foregrounds

- Galactic emission could vary along the l.o.s and at different l.o.s
- Spatial variability is hard to be tackled   in both blind and non -blind component separation methods
- Models are being built to account for spatial variability





Galactic Foregrounds

Foreground modeling

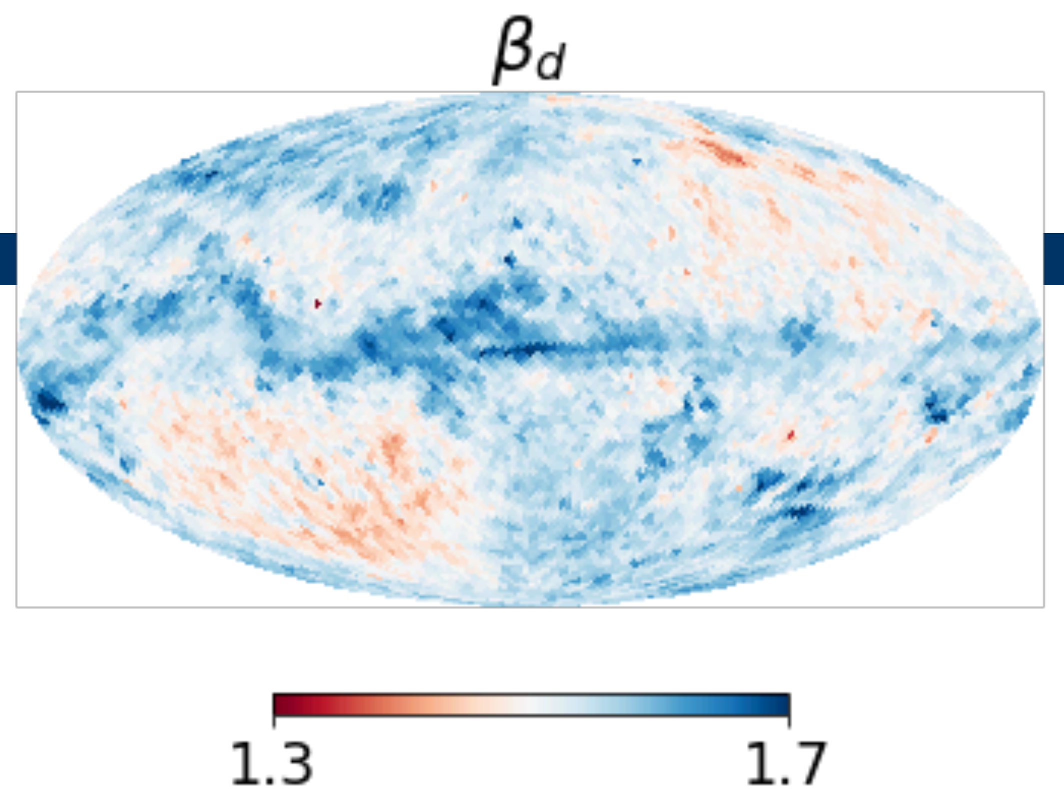
- **Synchrotron**: power law with spatially-varying index

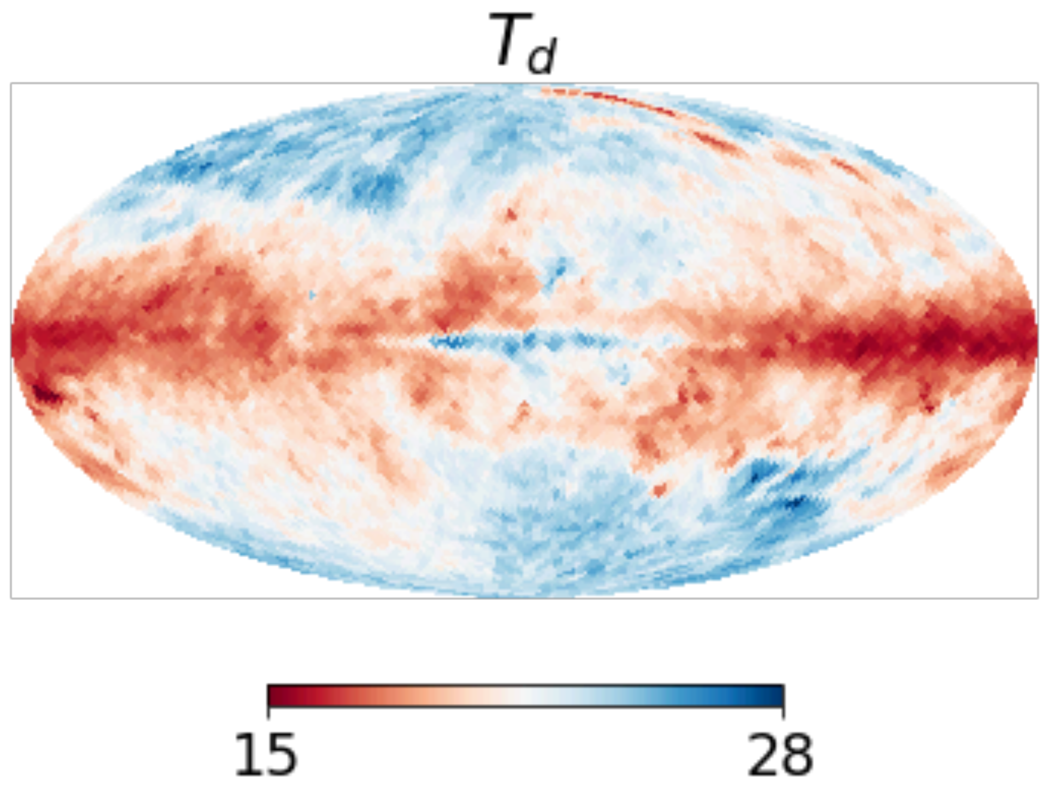
$$[Q_{\rm s}, U_{\rm s}]\,(\hat{n},\nu) = [Q_{\rm s}, U_{\rm s}]\,(\hat{n},\nu_\star)\cdot\left(\frac{\nu}{\nu_\star}\right)^{\beta_{\rm s}(\hat{n})}$$

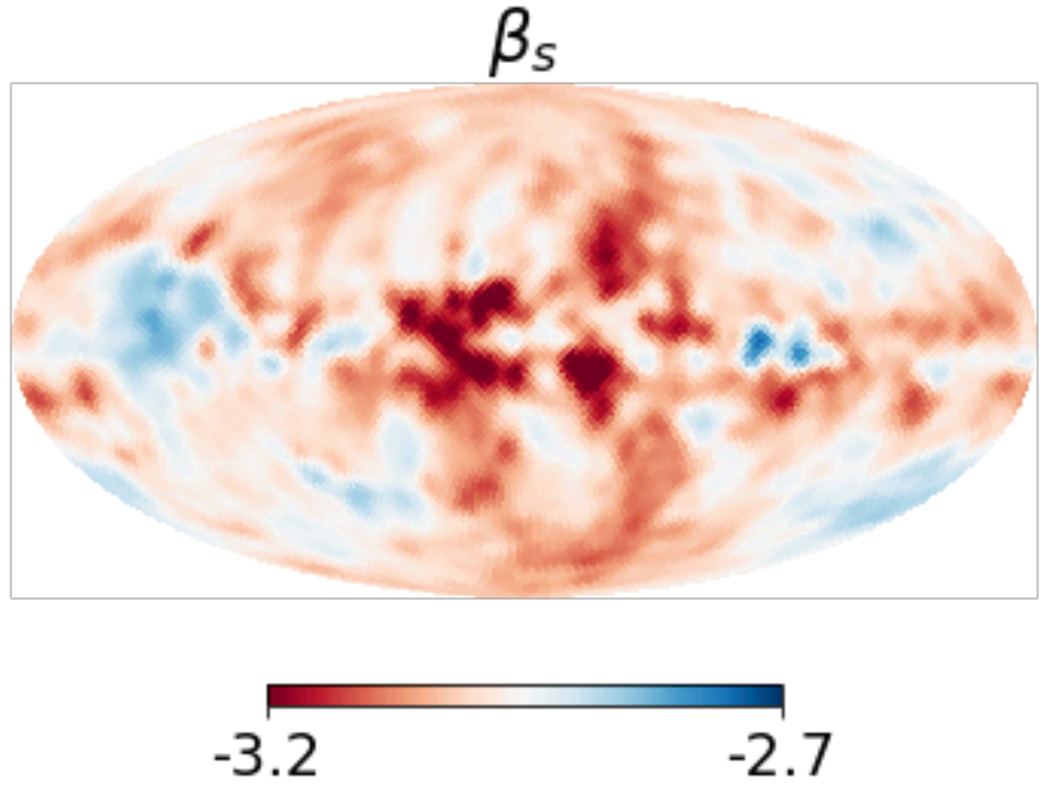
- **Dust**: modified blackbody

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

7 parameters

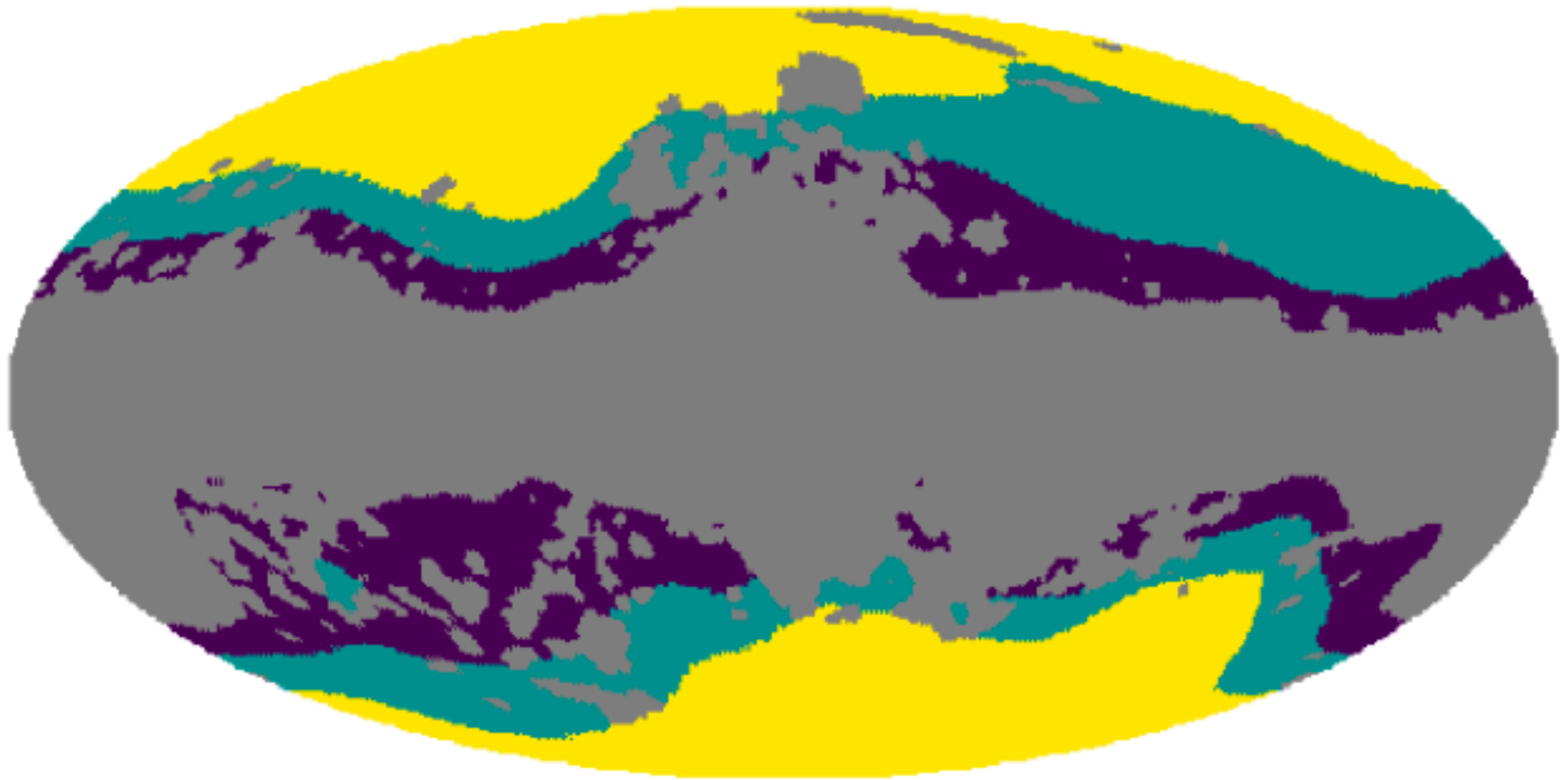






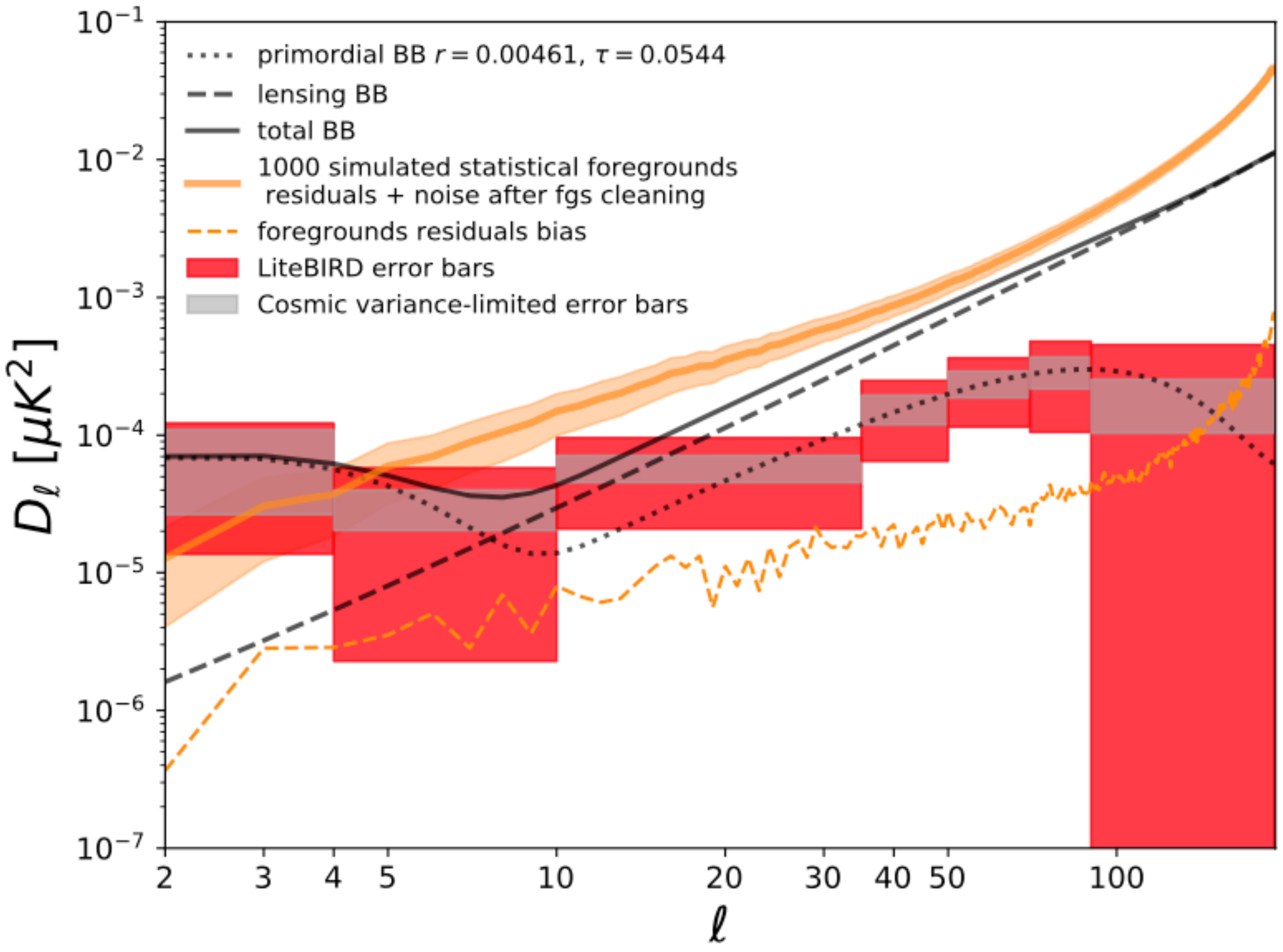
Foreground cleaning

- "**Multiresolution** technique" (extension of xForecast, Errard et al. 2013), to account for spatial variability
- $12\times(N_{side})^2$ patches with N_{side} =16,32,64 (changing with Galactic latitude)



$$r_{FG} = (3.3 \pm 6.2) \times 10^{-4}$$

Impact of foreground residuals



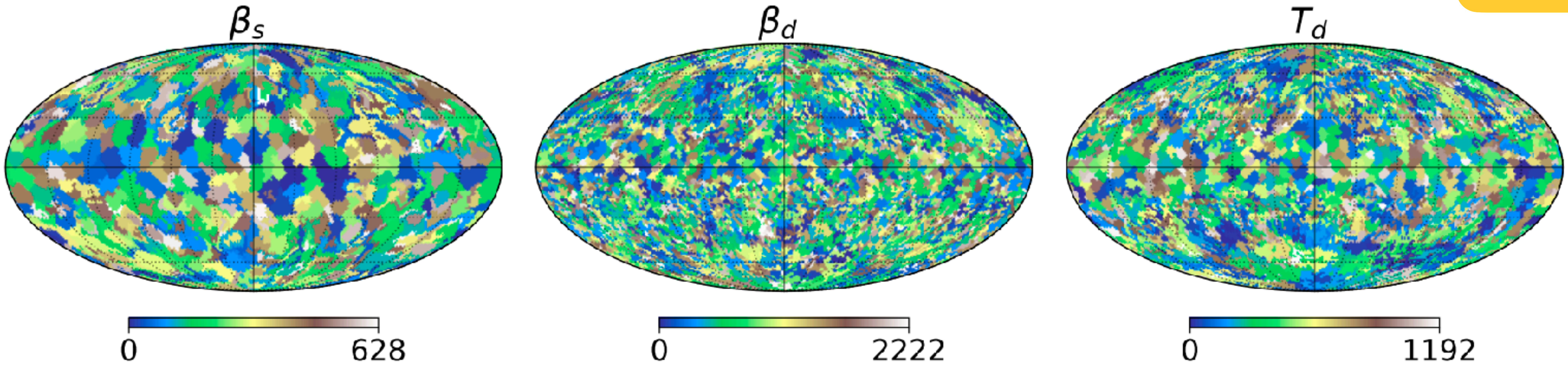
📖 LiteBIRD collaboration PTEP 2023

Clustering methods

- Use unsupervised clustering methods (hierarchical clustering) to identify an optimal partition of the sky
- Run **non-blind foreground cleaning** (FGBuster) on LiteBIRD simulated maps
- Estimate foreground parameters *locally*
- Residuals on the *foreground cleaned* CMB B-modes map:

$$r_{FG} = (2.2 \pm 6.3) \times 10^{-4}$$

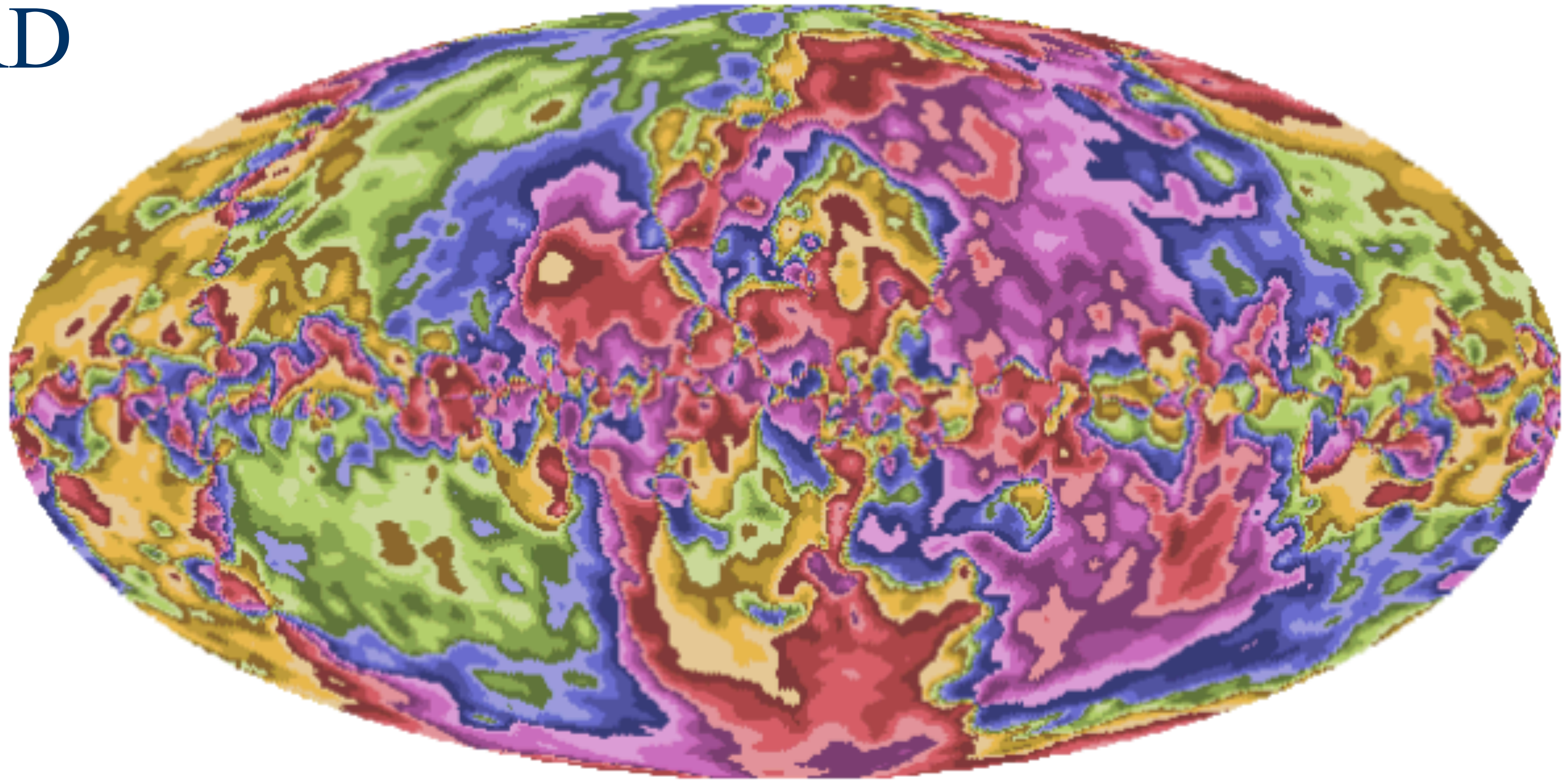
📖 Puglisi et al. 2022



Clustering methods (cont'd)

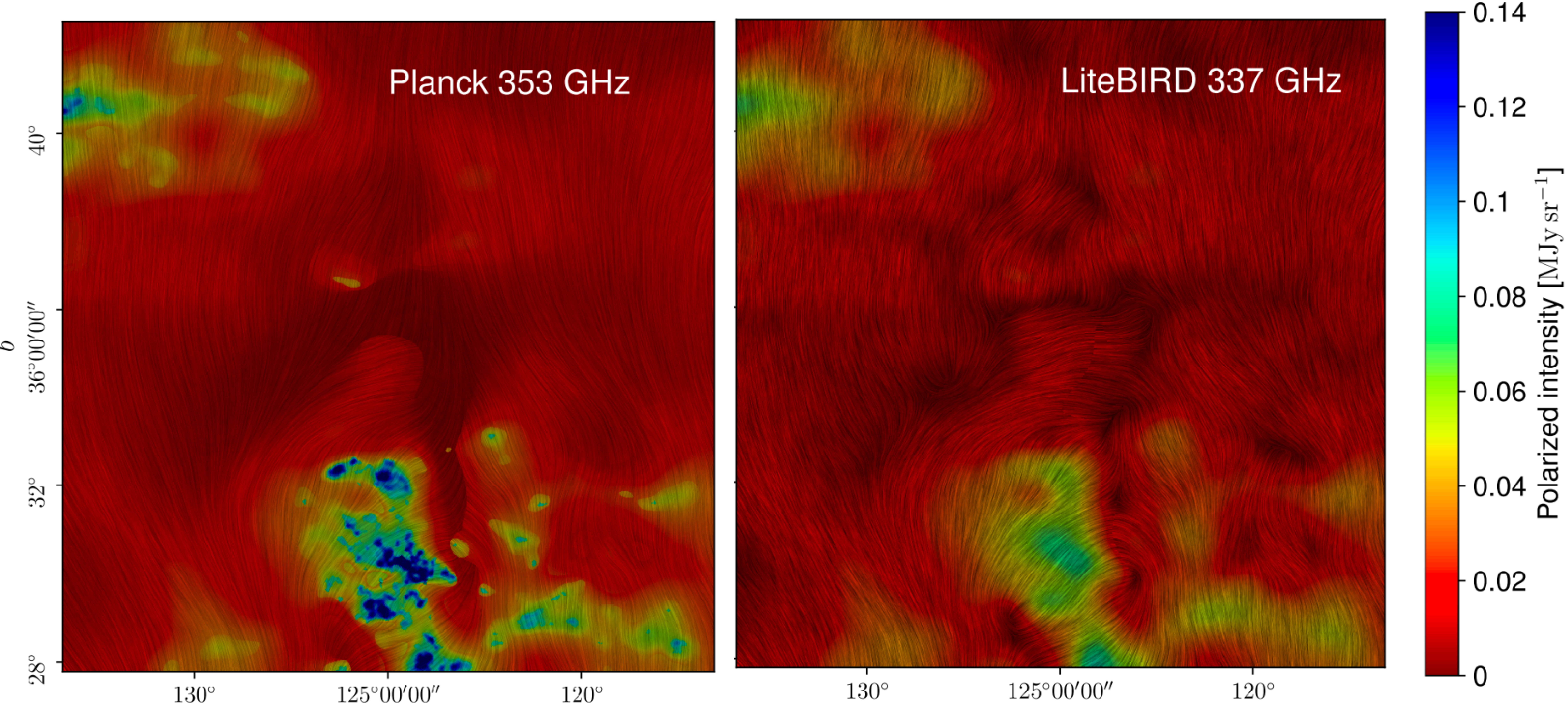
- Identify patches by combining low and high LiteBIRD frequency channels
- Run **blind foreground cleaning** (NILC) on LiteBIRD simulated maps
- Estimate foreground parameters *locally*
- Residuals on the *foreground cleaned* CMB B-modes map:

$$r_{FG} < 3.4 \times 10^{-4}$$

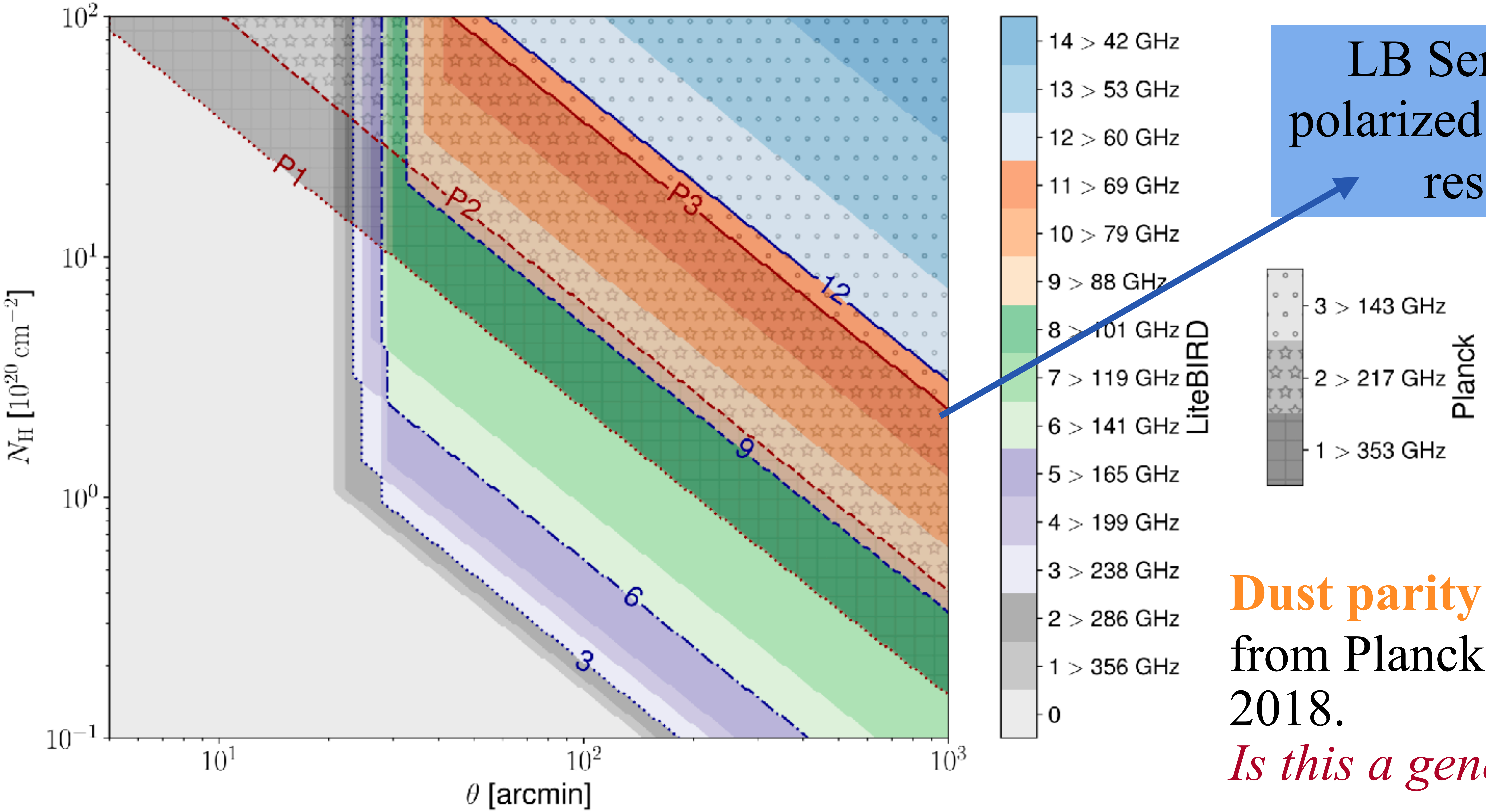


📖 Carones et al. 2023
See Carones talk on Friday

Galactic Science



Galactic Science



LB Sensitivity to SNR>1 polarized dust as a function of resolution and N_H

Dust parity violation $C_\ell^{TB} \neq 0$ from Planck Collaboration IX , 2018.

Is this a generic feature of ISM?

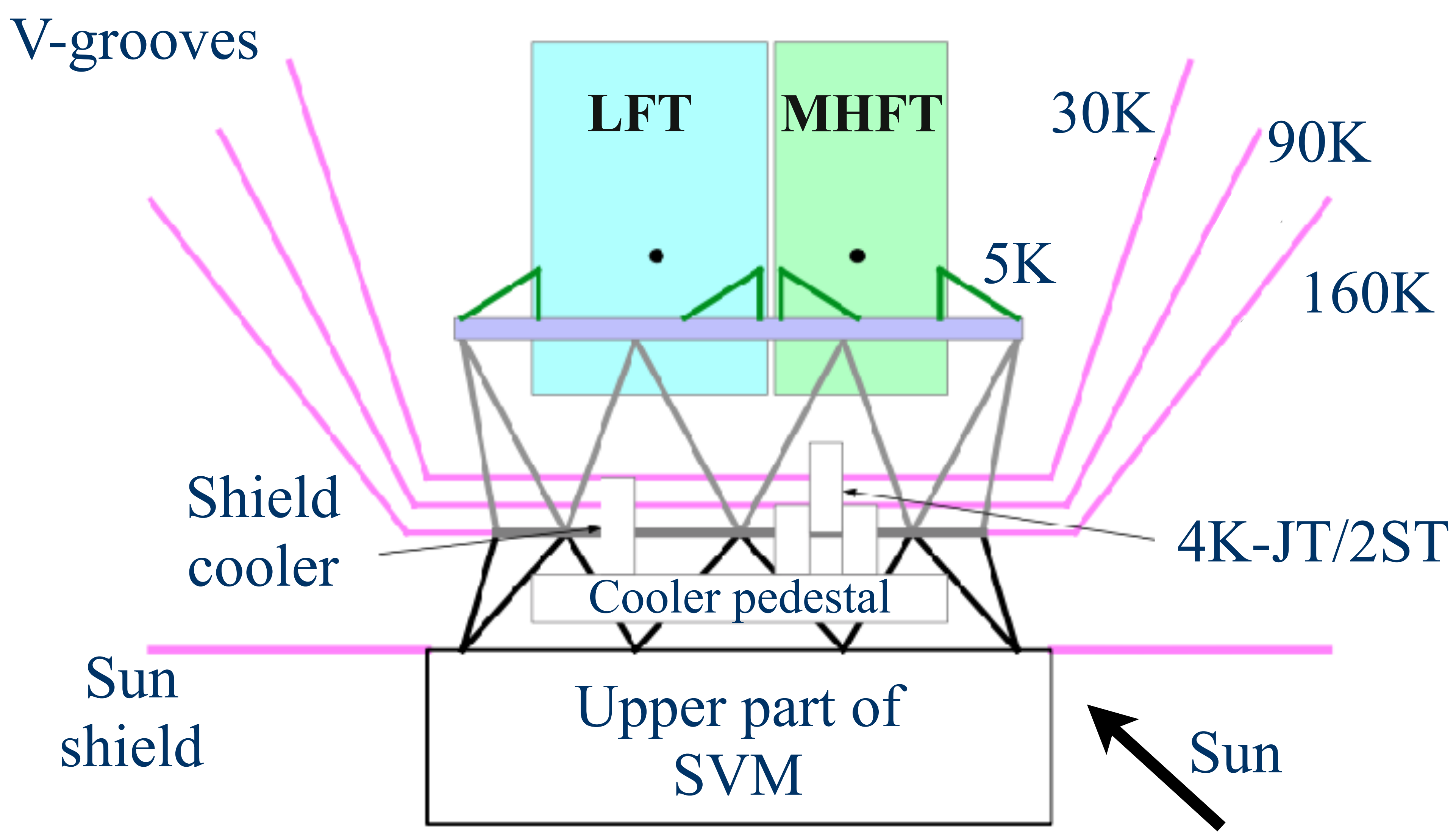
Concluding remarks

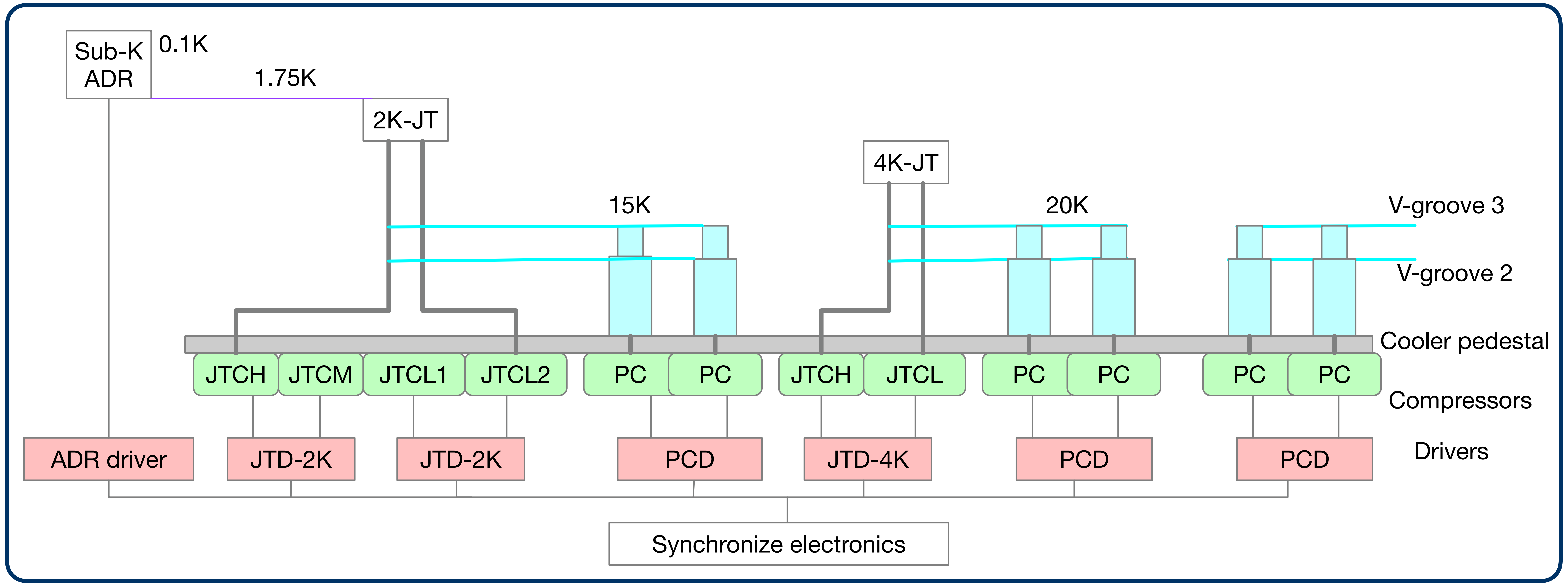
- LiteBIRD For $r = 0$, **total uncertainty of $\delta r < 0.001$**
- For $r = 0.01$, 5σ detection of the reionization ($2 < \ell < 10$) and recombination ($11 < \ell < 200$) peaks independently
- Partition of the sky into sub-patches have shown strong benefits for LiteBIRD component separation
- Unprecedented TRL simulation effort to inject **and mitigate** systematic effects
- CMB-S4 - LB joint simulations. **Ancillary data** LiteBIRD low and high frequency channels CMB-S4 component separation? How CMB-S4 LATs **would de-lens** LB data?


Thank you!

Backup

LiteBIRD cryogenic system

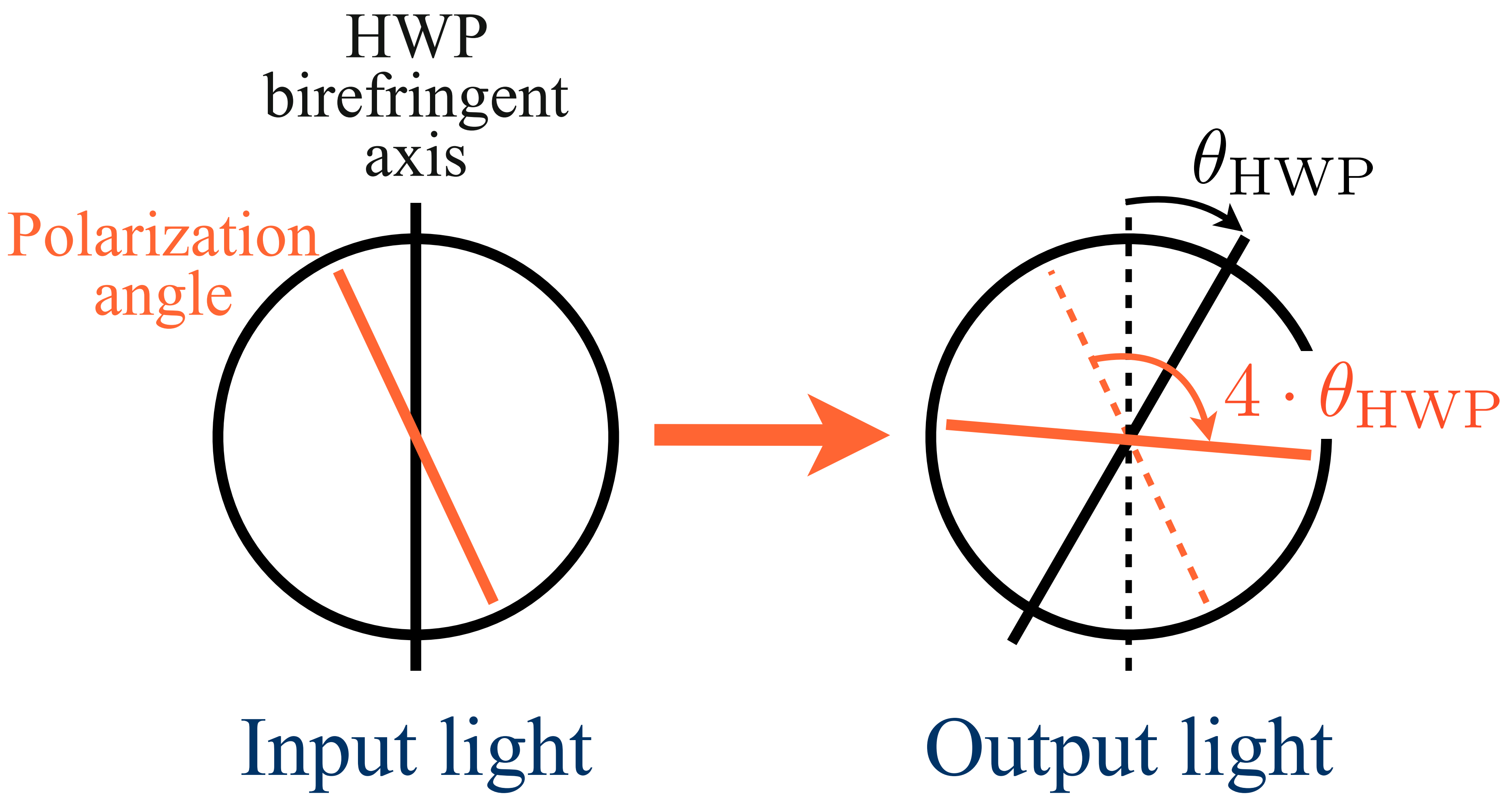


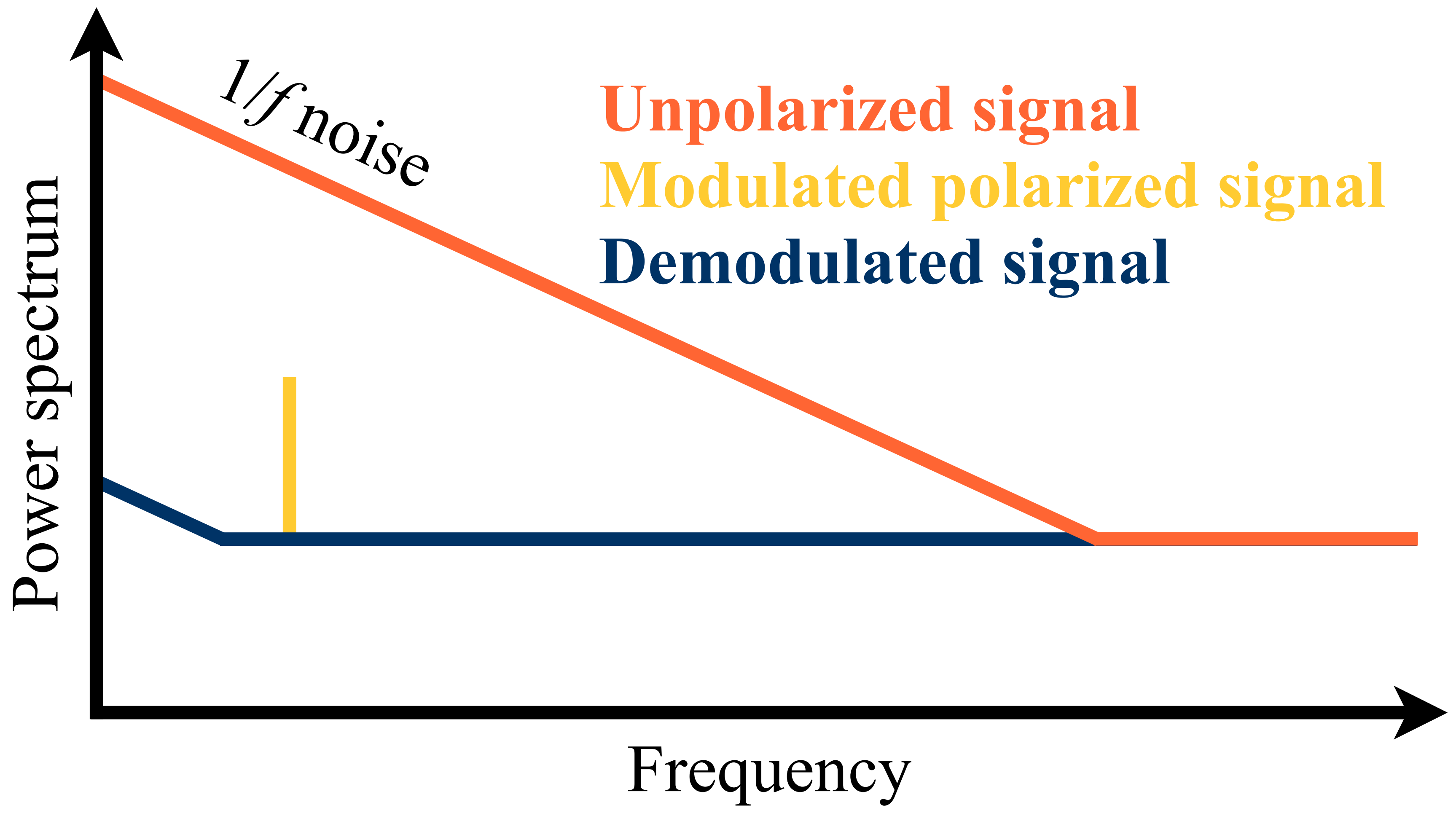


- Continuous cooling at 100 mK
- High stability on telescopes at all stages

Polarization Modulation Unit (PMU)

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

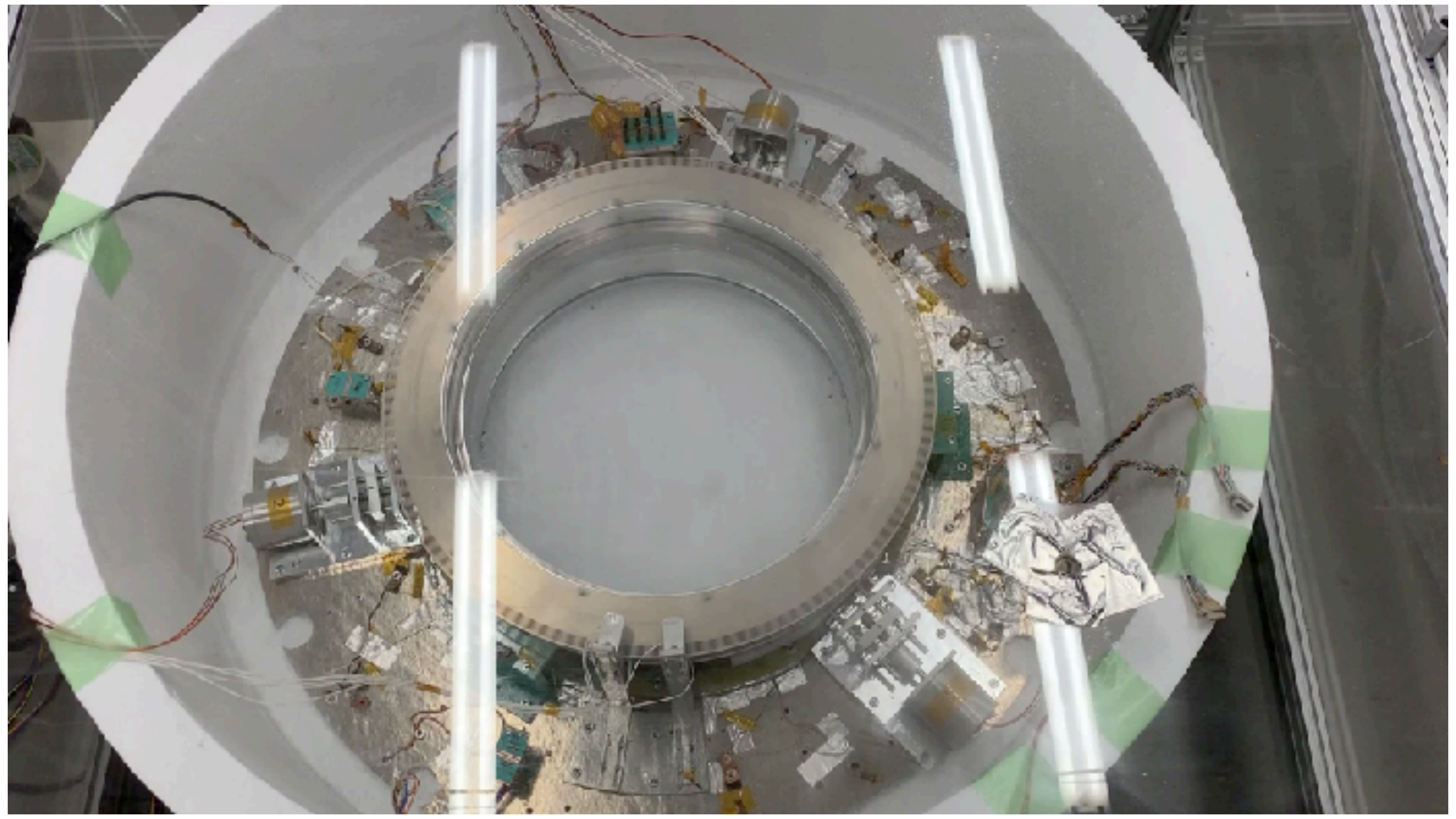




📖 Sakurai+2020 📖 Komatsu+2020

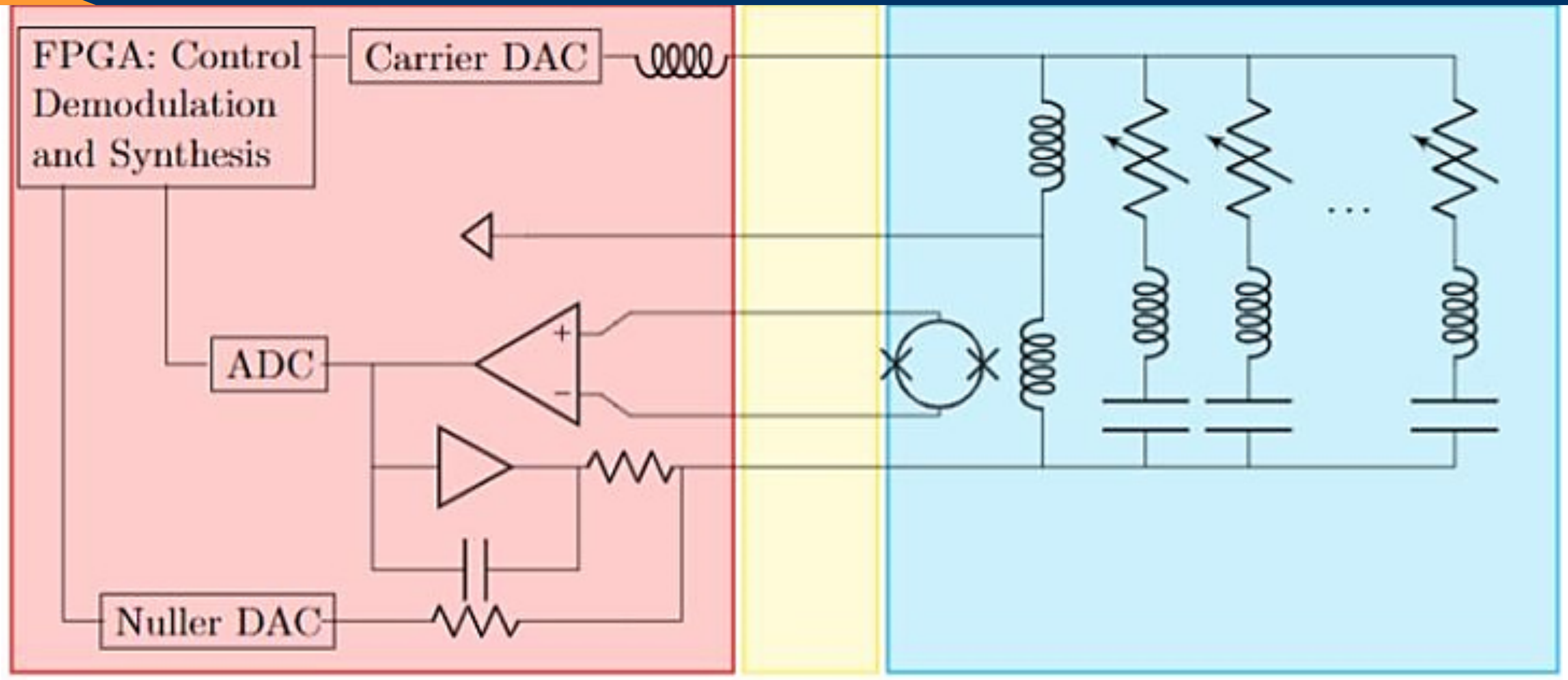
📖 Toda+2020 📖 Columbro+2020 📖 Sugiyama+2020

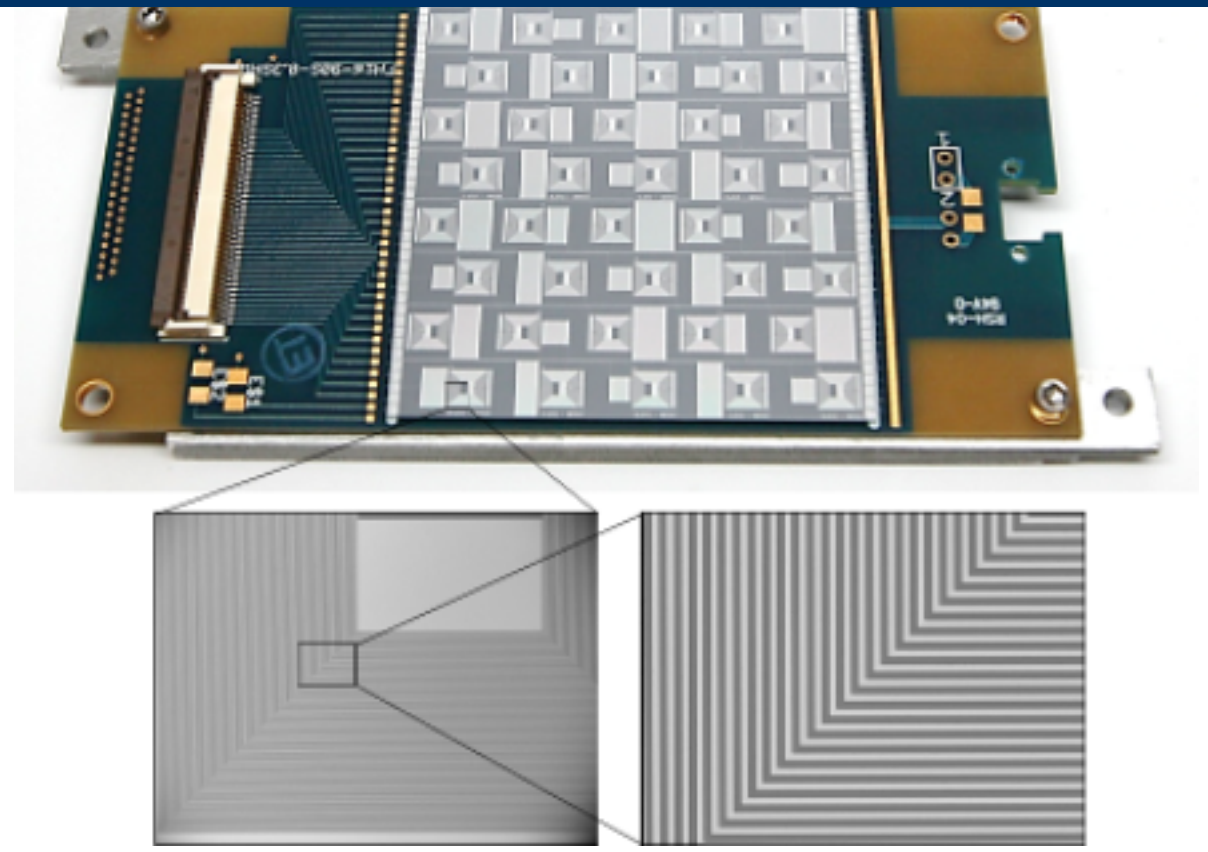
- LFT PMU BBM at Kavli IPMU:

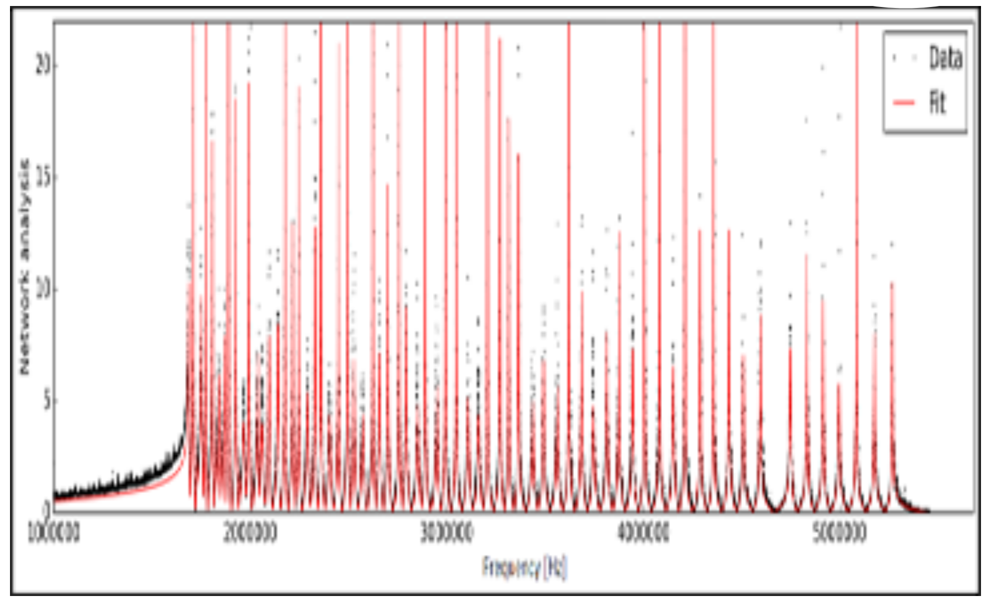


- Rotation test of superconducting magnetic bearing system in the 4K cryostat
- Stable rotation at cryogenic temperature (< 10 K)

LiteBIRD readout system



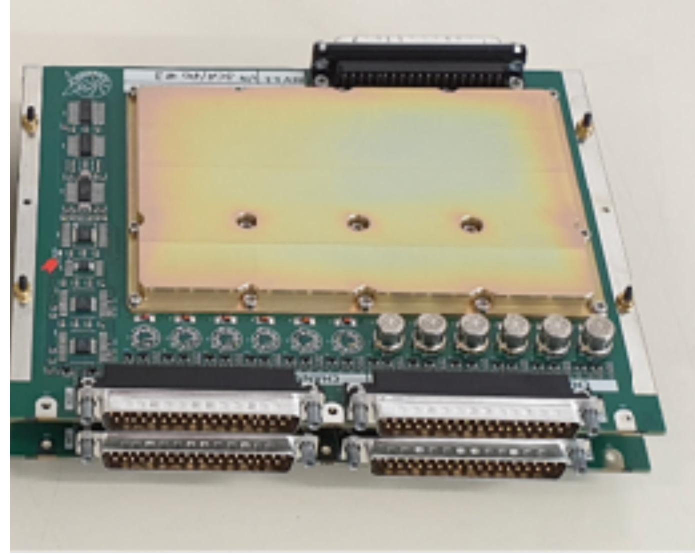




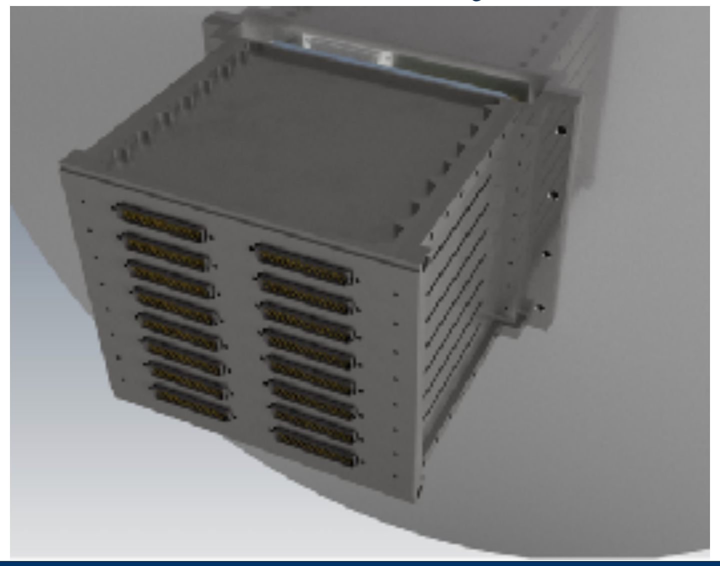
Cold Readout LC filters for MUX

- 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



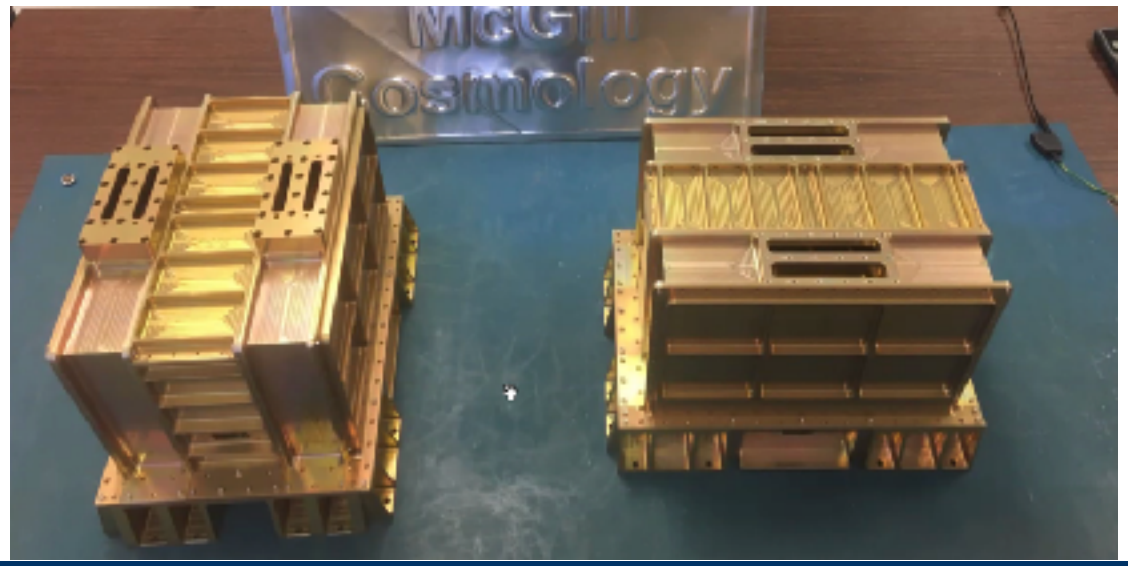
SQUID controller assembly



Digitizer assembly

Signal Processing Unit

Digitizer assembly



Foreground cleaning

- "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: **$r = (3.3 \pm 6.2)\times 10^{-4}$**