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
IAP
IAS Institut d'Astrophysique Spatiale Orsay
LiteBIRD
IFCA Instituto de Física de Cantabria
ifpU
IJCLab Irène Joliot-Curie Laboratoire de Physique des 2 Infinis
INFN
INAF ISTITUTO NAZIONALE DI ASTROFISICA
IPMU
iPNS 素粒子原子核研究所 Institute of Particle and Nuclear Studies
irap astrophysique & planétologie
JAXA
NASA Jet Propulsion Laboratory California Institute of Technology
NATIONAL INSTITUTE OF TECHNOLOGY KAGAWA COLLEGE 香川高専
KEK
KIPAC KAVLI INSTITUTE FOR PARTICLE ASTROPHYSICS & COSMOLOGY
KMI Kobayashi-Maskawa Institute Nagoya University
LMU
LPSC GRENOBLE | MODANE
MAX-PLANCK-INSTITUT FÜR ASTROPHYSIK
McGill
Maynooth University National University of Ireland Maynooth
名古屋大学 NAGOYA UNIVERSITY
NÉEL institut
NIST
HK Norwegian Directorate for Higher Education and Skills
OAC
岡山大学 OKAYAMA UNIVERSITY
QUP International Center for Quantum-field Measurement Systems for Studies of the Universe and Particles
POLITÉCNICA
idr
RWTH AACHEN UNIVERSITY
SAPIENZA UNIVERSITÀ DI ROMA
SISSA
SORBONNE UNIVERSITÉ
SRON
SSDC SPACE SCIENCE DATA CENTER
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Stockholm University
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The LiteBIRD space mission and the Galactic foreground challenge

Arianna Rizzieri
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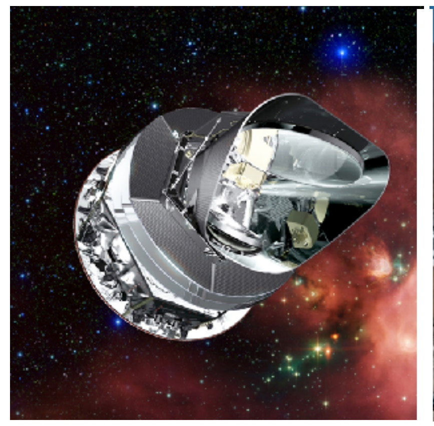
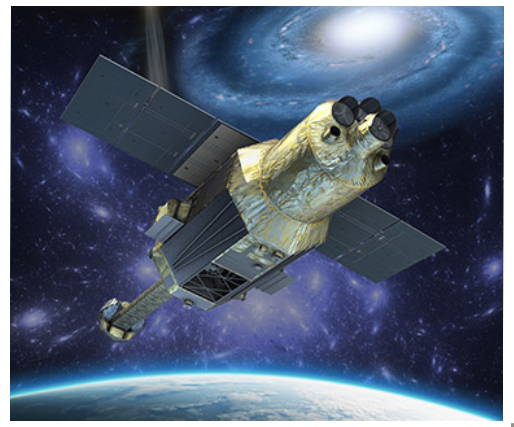
LiteBIRD Joint Study Group

Around 400 researchers from **Japan**, **North America** and **Europe**

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

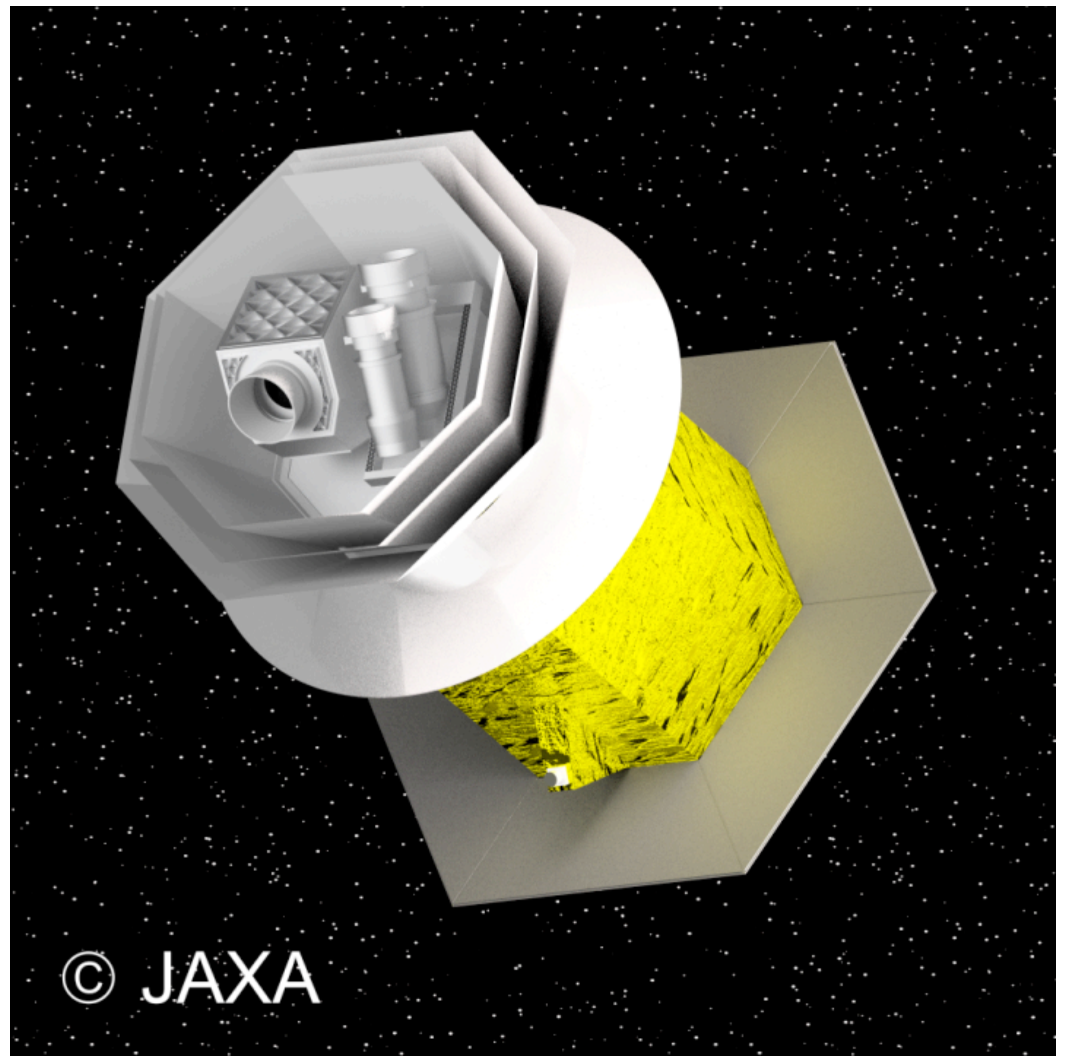


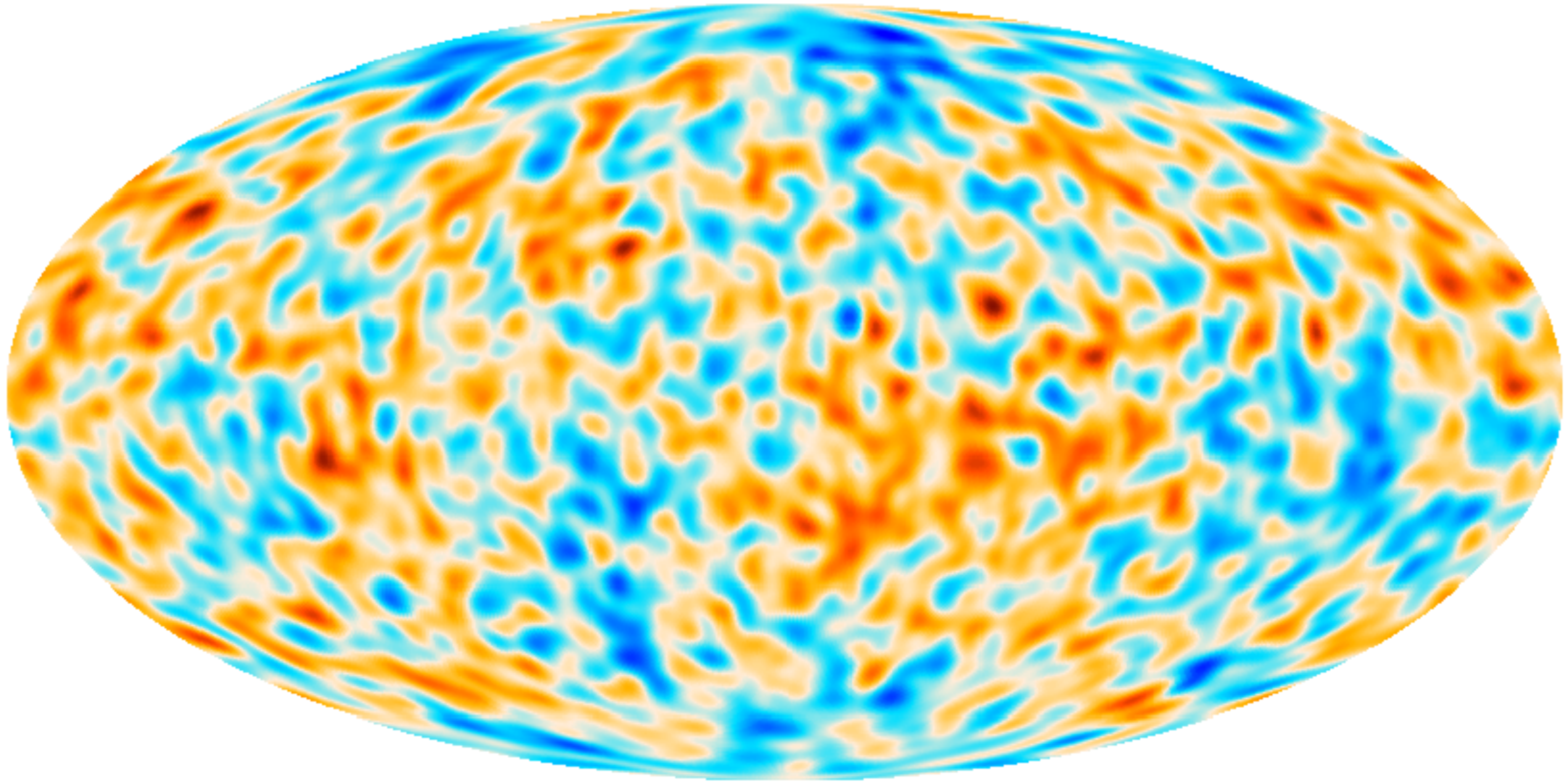


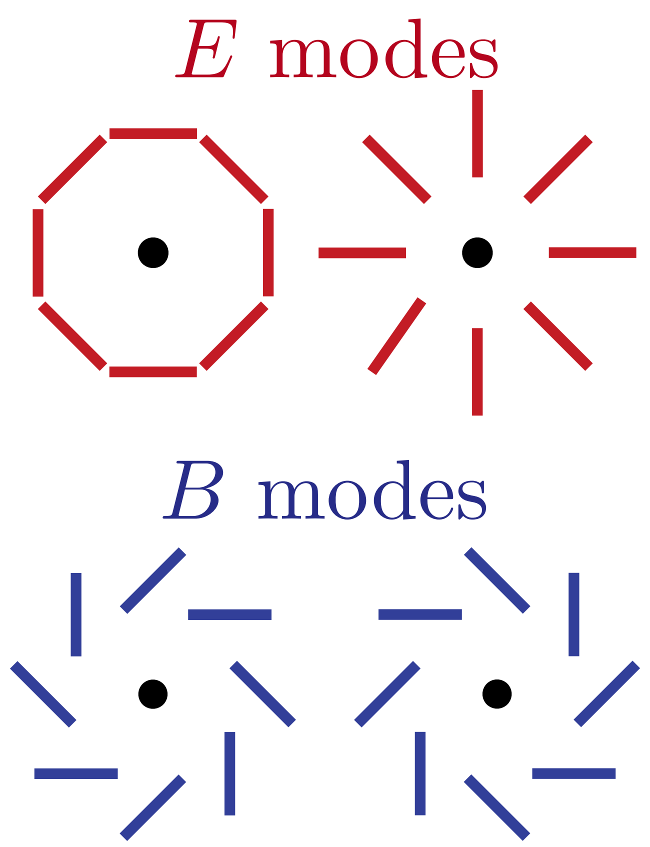
LiteBIRD overview

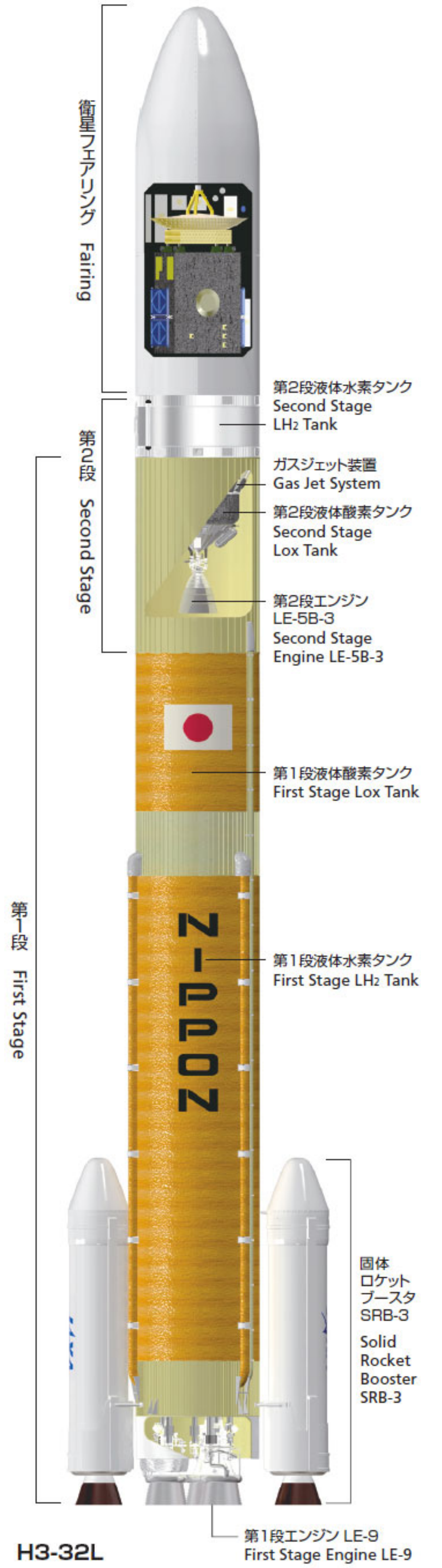
- Lite (Light) spacecraft for the study of *B*-mode polarization and Inflation from cosmic background Radiation Detection
- JAXA's L-class mission was selected in May 2019 to be launched by JAXA's H3 rocket.
- **All-sky 3-year survey**, from Sun-Earth Lagrangian point L2
- Large frequency coverage (**40–402 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 collaboration PTEP 2023

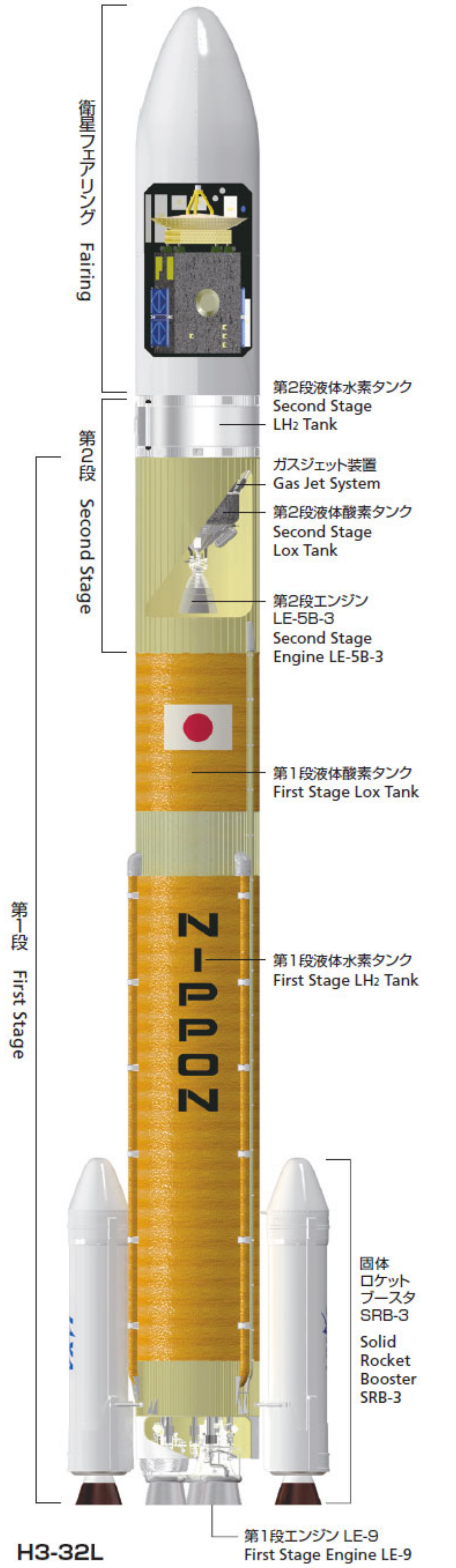








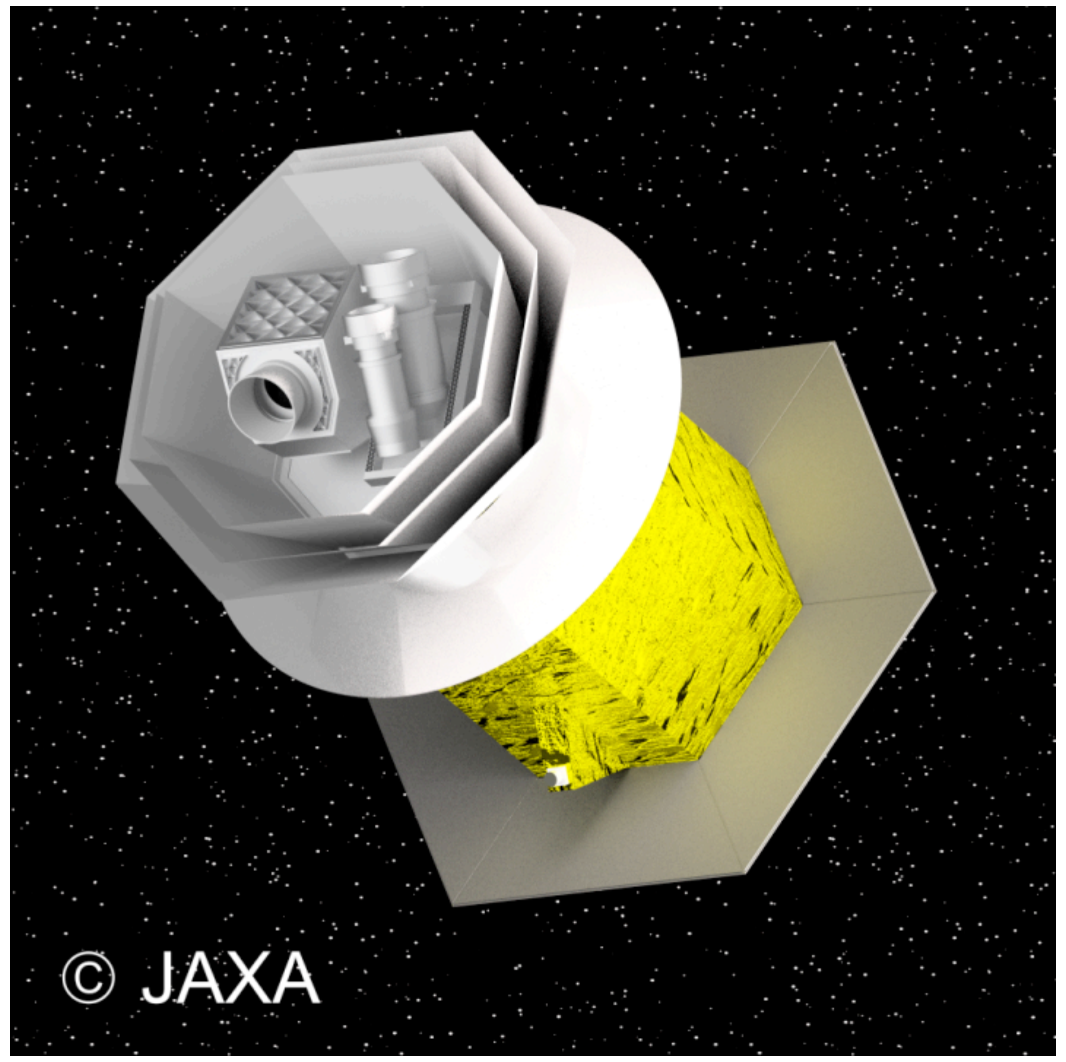
LiteBIRD overview

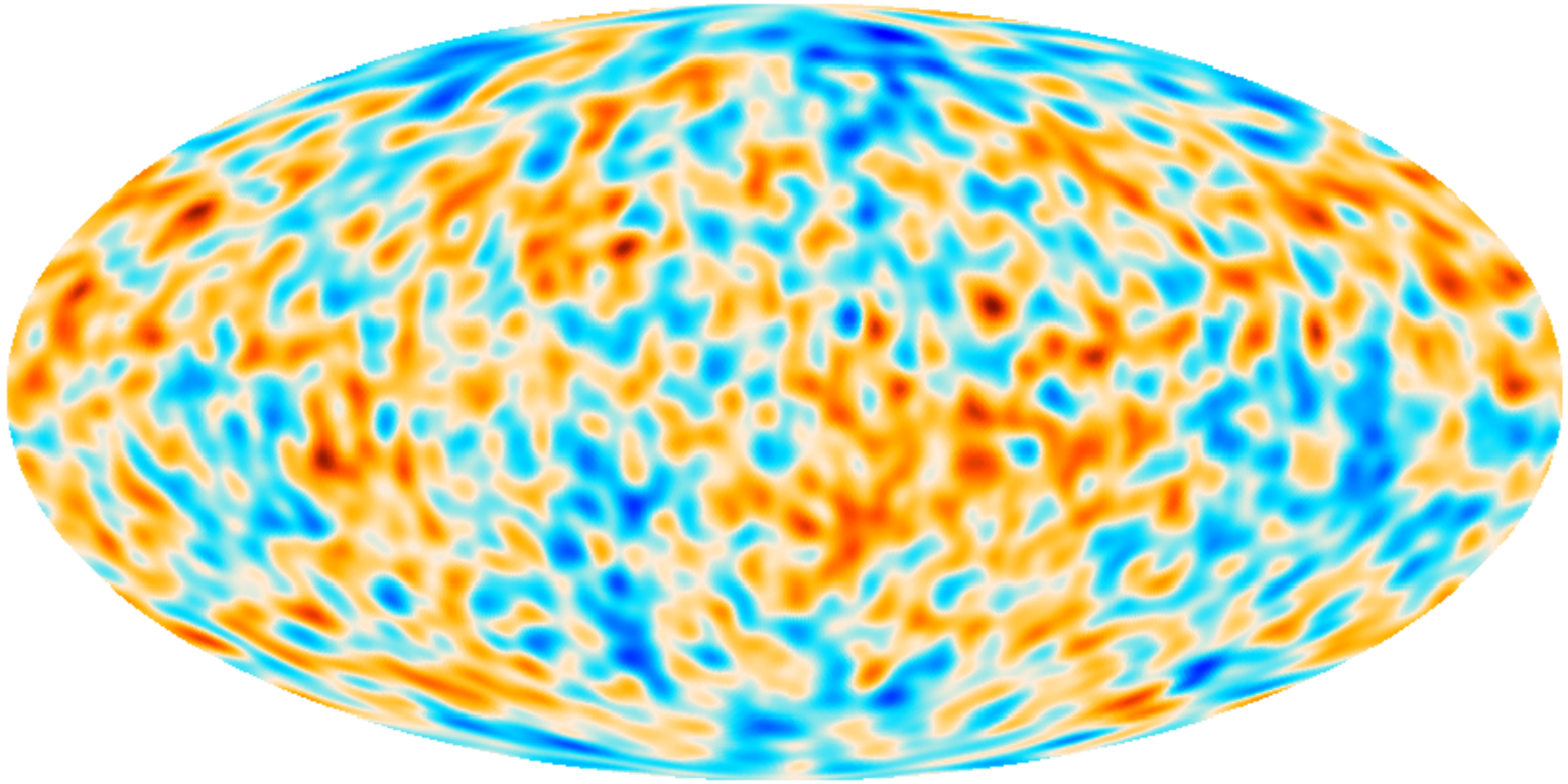


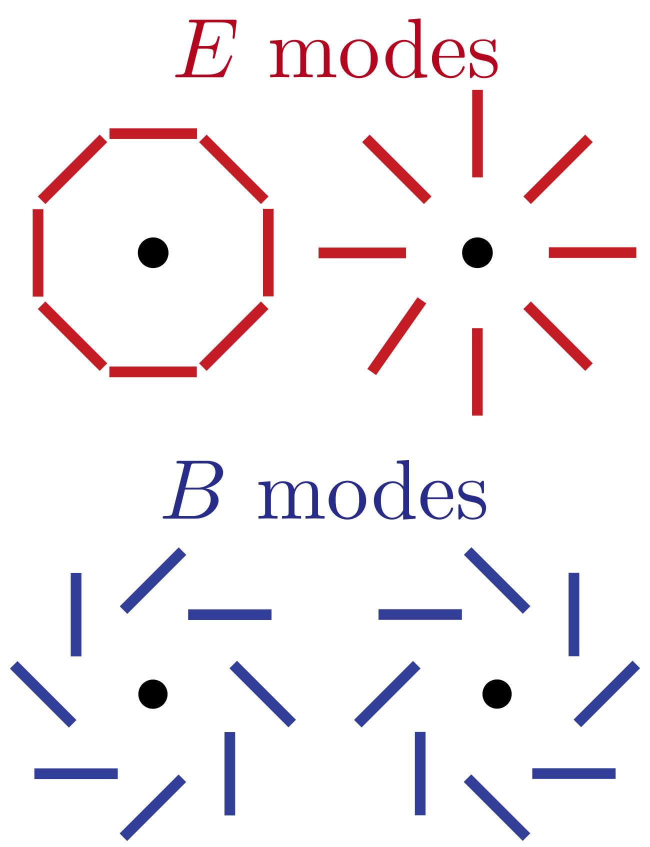
LiteBIRD reformation phase

📖 LiteBIRD collaboration PTEP 2023

- After the ISAS/JAXA mission definition review, LiteBIRD is under rescope studies to consolidate the mission's feasibility with the same scientific objectives.
- The LiteBIRD collaboration will spend approximately one year (~ late 2025) on the studies of the reformation plan.







The challenge of B-modes detection

- The *B*-mode signal is expected to have an amplitude at least 3 orders of magnitude below the CMB temperature anisotropies
- LiteBIRD is targeting a sensitivity level in polarization ~30 times better than Planck
- This extremely good statistical uncertainty must go in parallel with exquisite control of:
  1. **Instrument systematic** uncertainties
  2. **Galactic foreground** contamination
  3. **"Lensing B-mode signal"** induced by gravitational lensing
  4. Observer biases

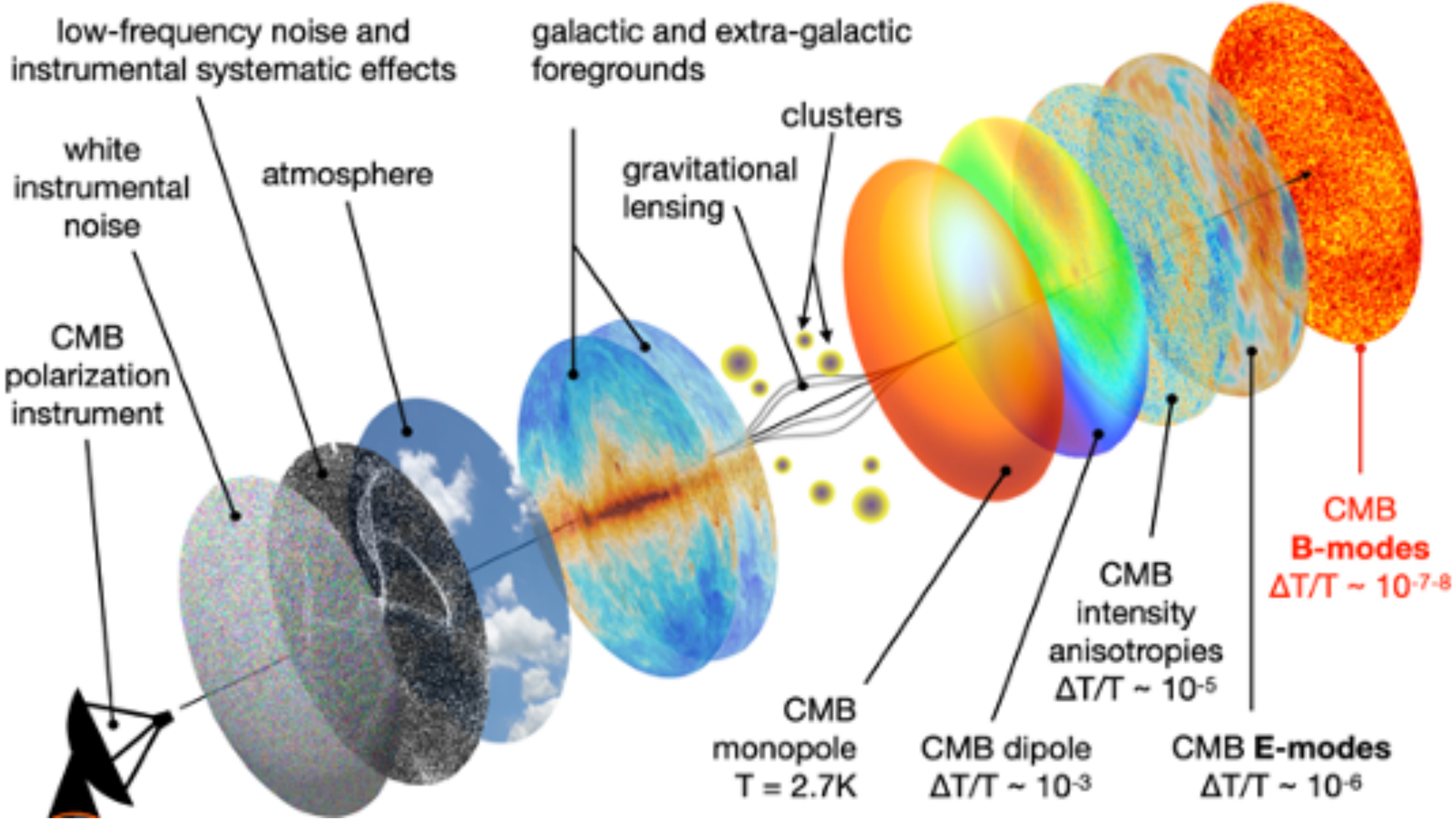


Image credit: Josquin Errard

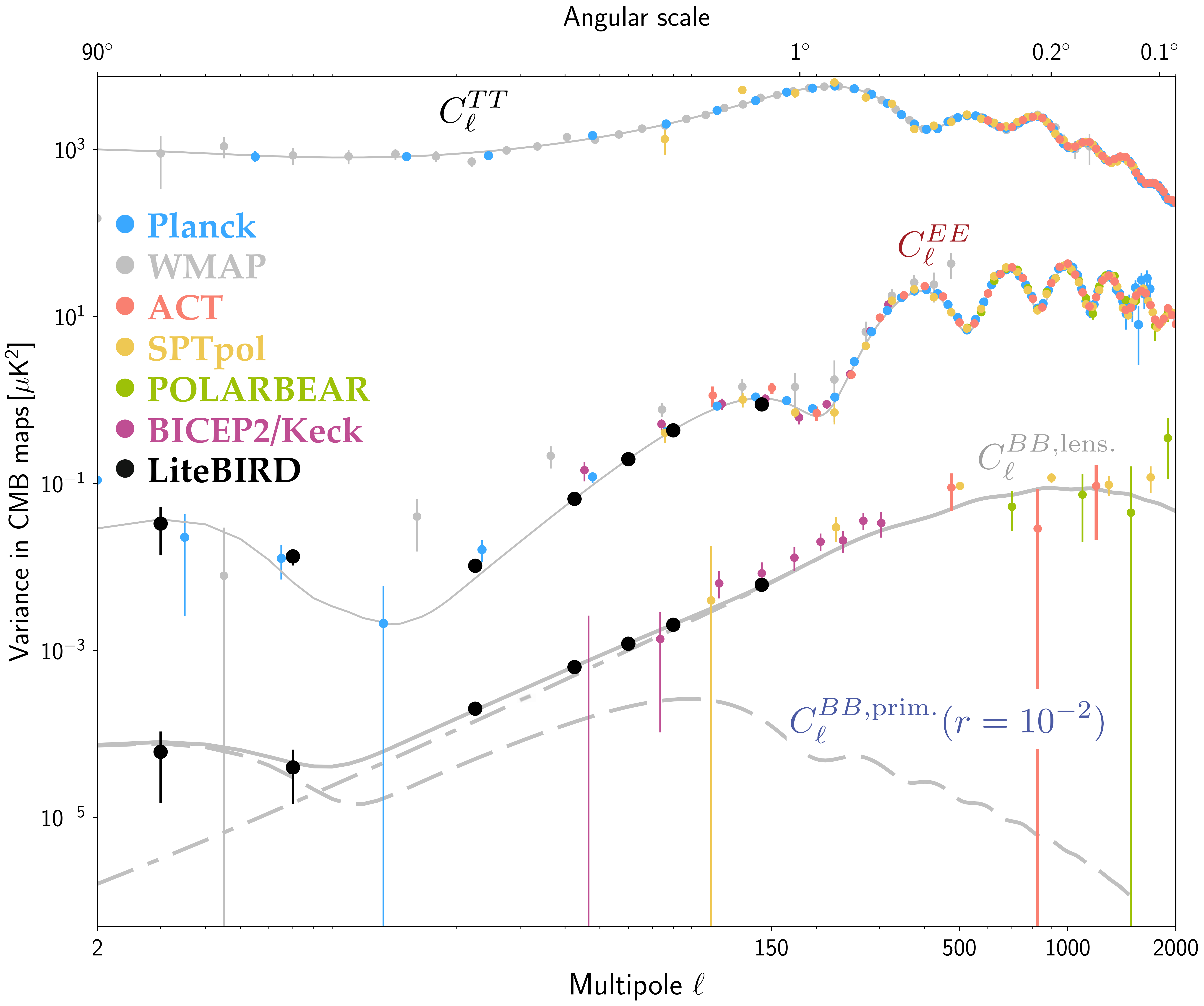
LiteBIRD main scientific objectives

- 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**

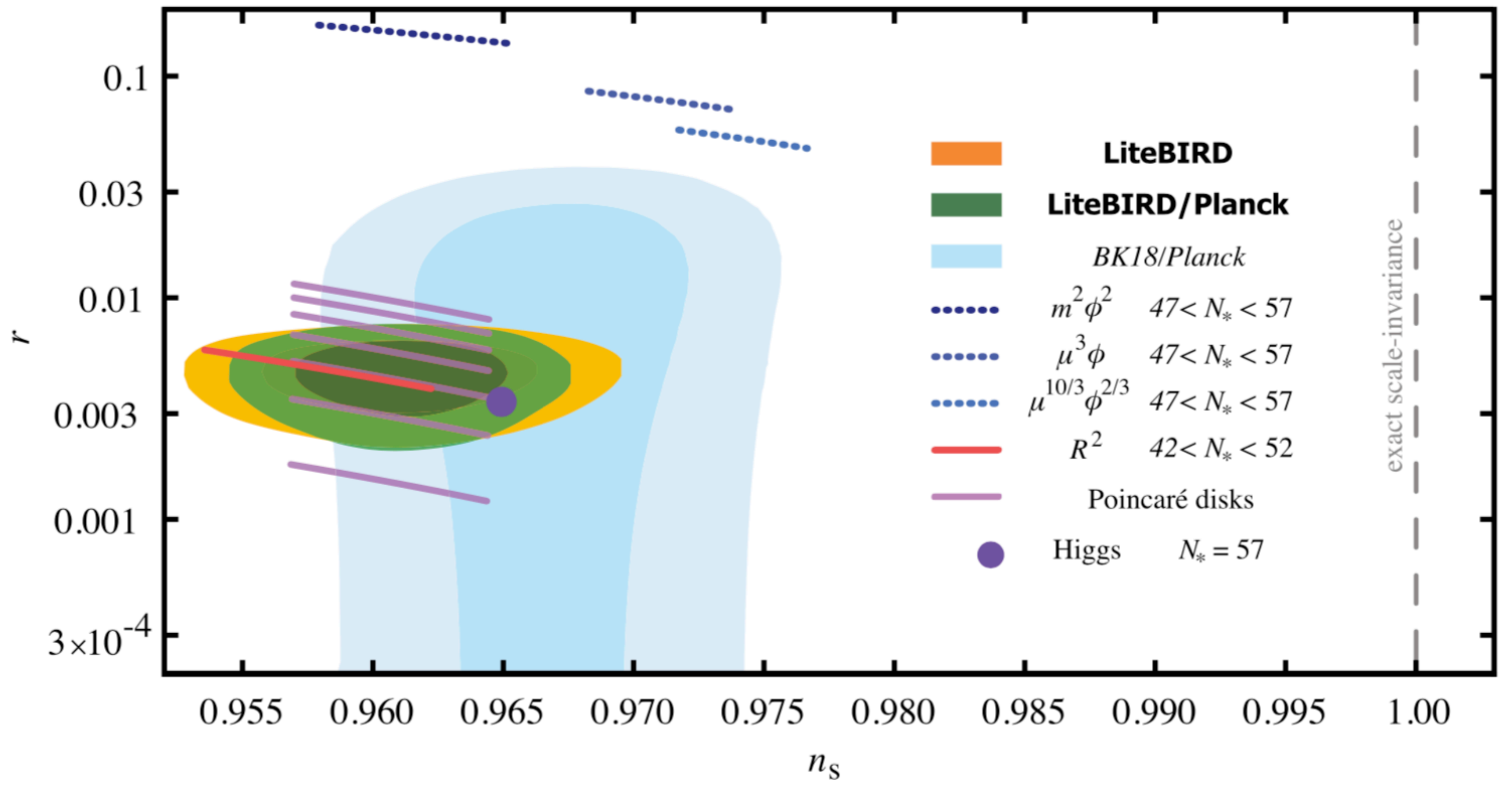
- Current best constraint: $r < 0.032$ (95% C.L.)
(📖 Tristram et al. 2022, combining BK18 and Planck PR4)

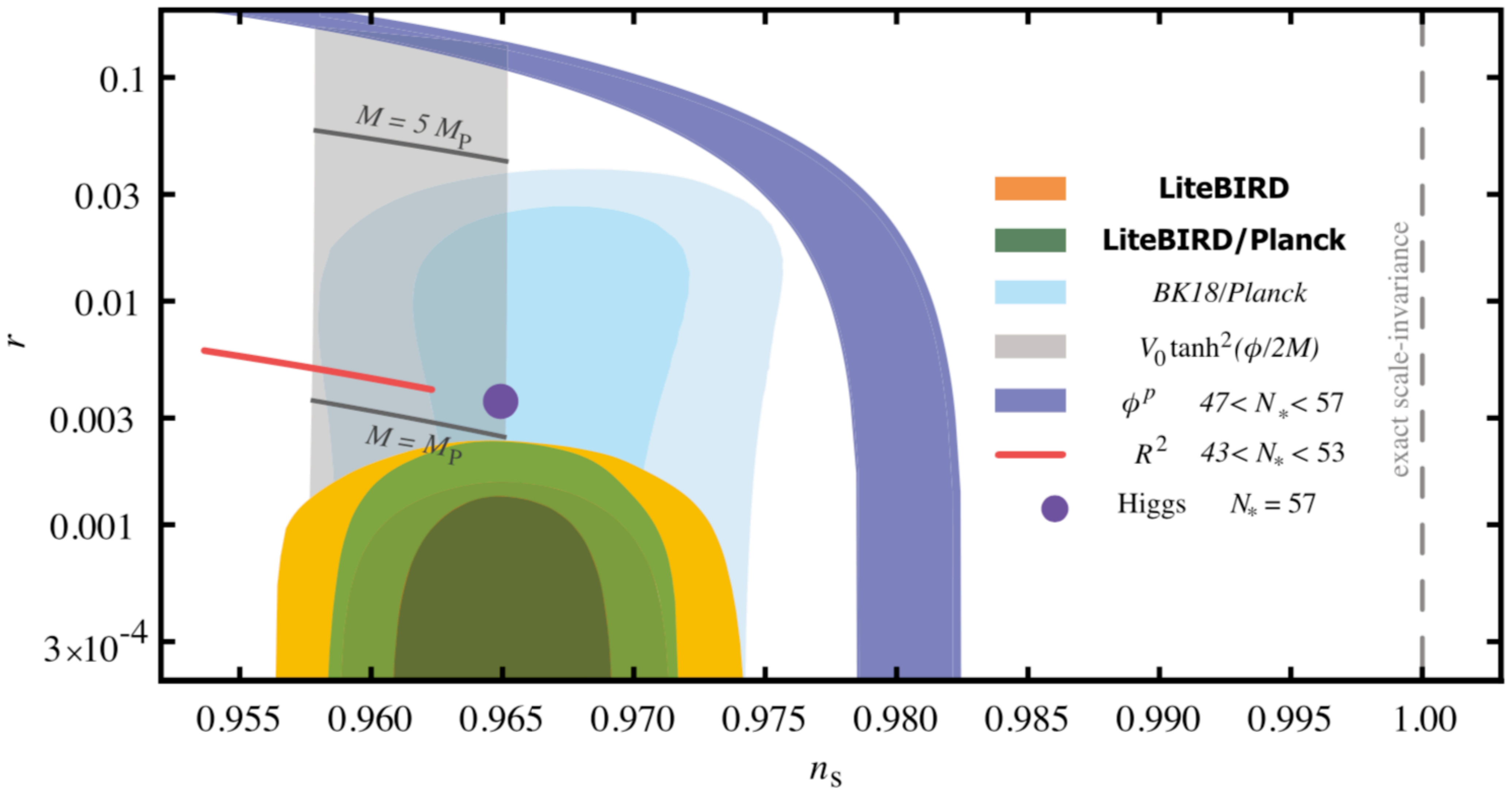
- LiteBIRD will improve current sensitivity on r by a factor ~30
  - For $r = 0$, **total uncertainty of $\delta r < 0.001$**



LiteBIRD constraints on inflation

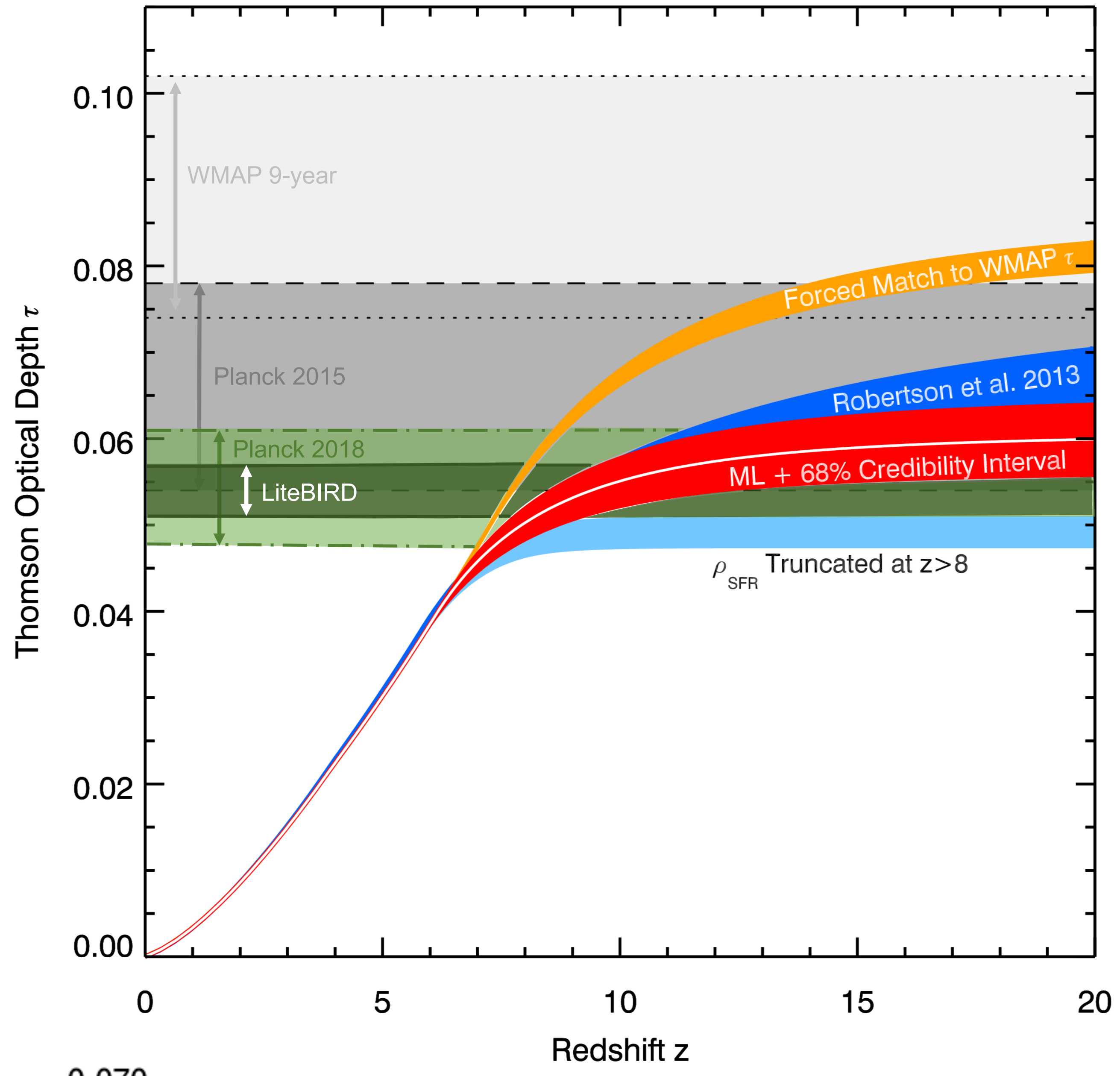
- Huge discovery impact (evidence for inflation, knowledge of its energy scale, and distance traveled by the inflaton…)
- A detection of B-modes by LiteBIRD with $r > 0.01$ would imply an excursion of the inflation field that exceeds the Planck mass
  - Such a detection would **constrain theories of quantum gravity** such as superstring theories
- An upper limit from LiteBIRD would disfavour the simplest inflationary models, with $\mathcal{M} > M_{\rm p}$
  - This includes the monomial models, α-attractors with a super-Planckian characteristic scale, including the **Starobinsky model** and models that invoke the Higgs field as the inflaton



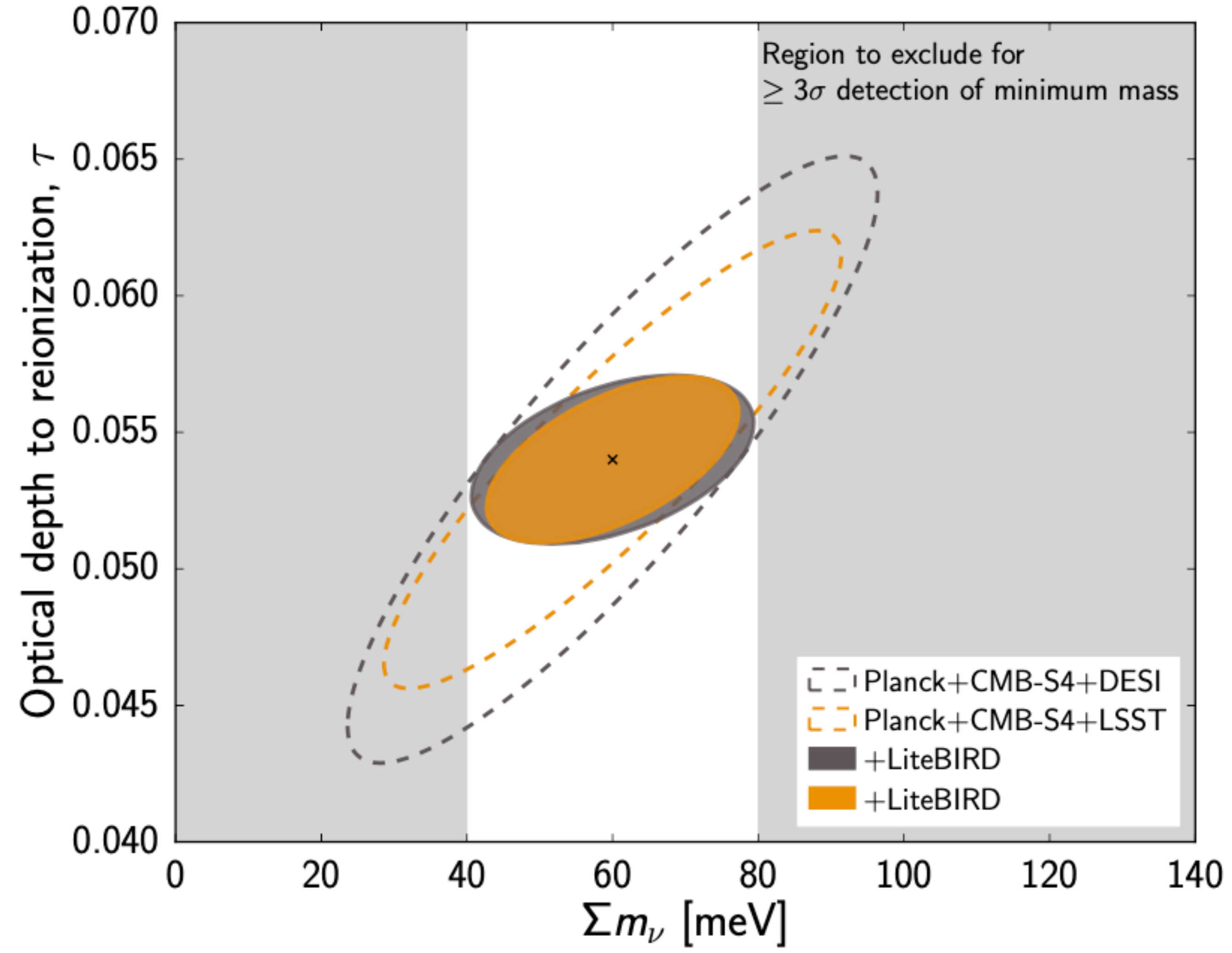


LiteBIRD other science outcomes

- 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 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** ($\sigma(\sum m_\nu) = 12$ meV)
  3. Constraints on **cosmic birefringence**
  4. **SZ effect** (thermal, diffuse, relativistic corrections)
  5. Constraints on **primordial magnetic fields**
  6. Elucidating **anomalies**
  7. **Galactic science**
     - Characterizing the foreground SED
     - Large-scale Galactic magnetic field
     - Models of dust polarization



adapted from Robertson+2015

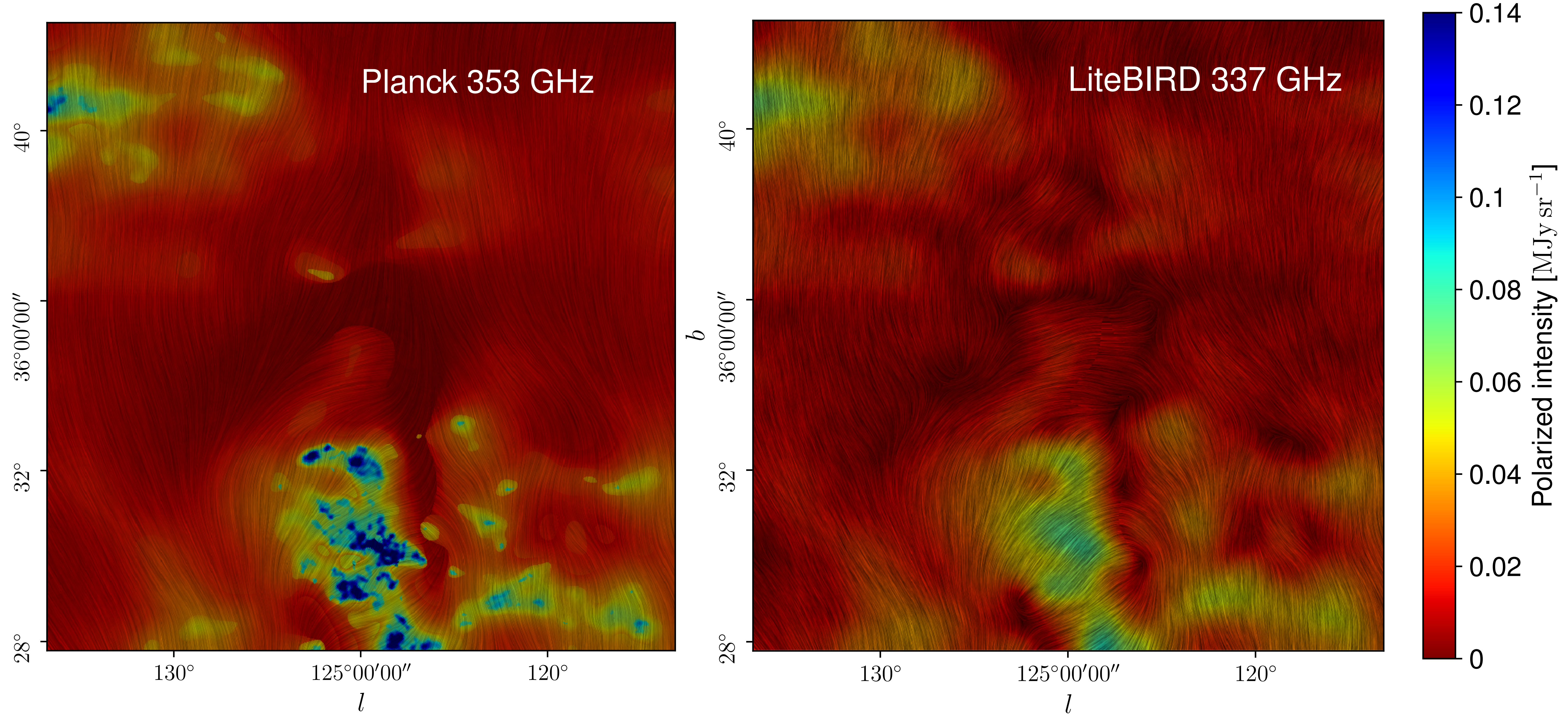


adapted from Calabrese+2017

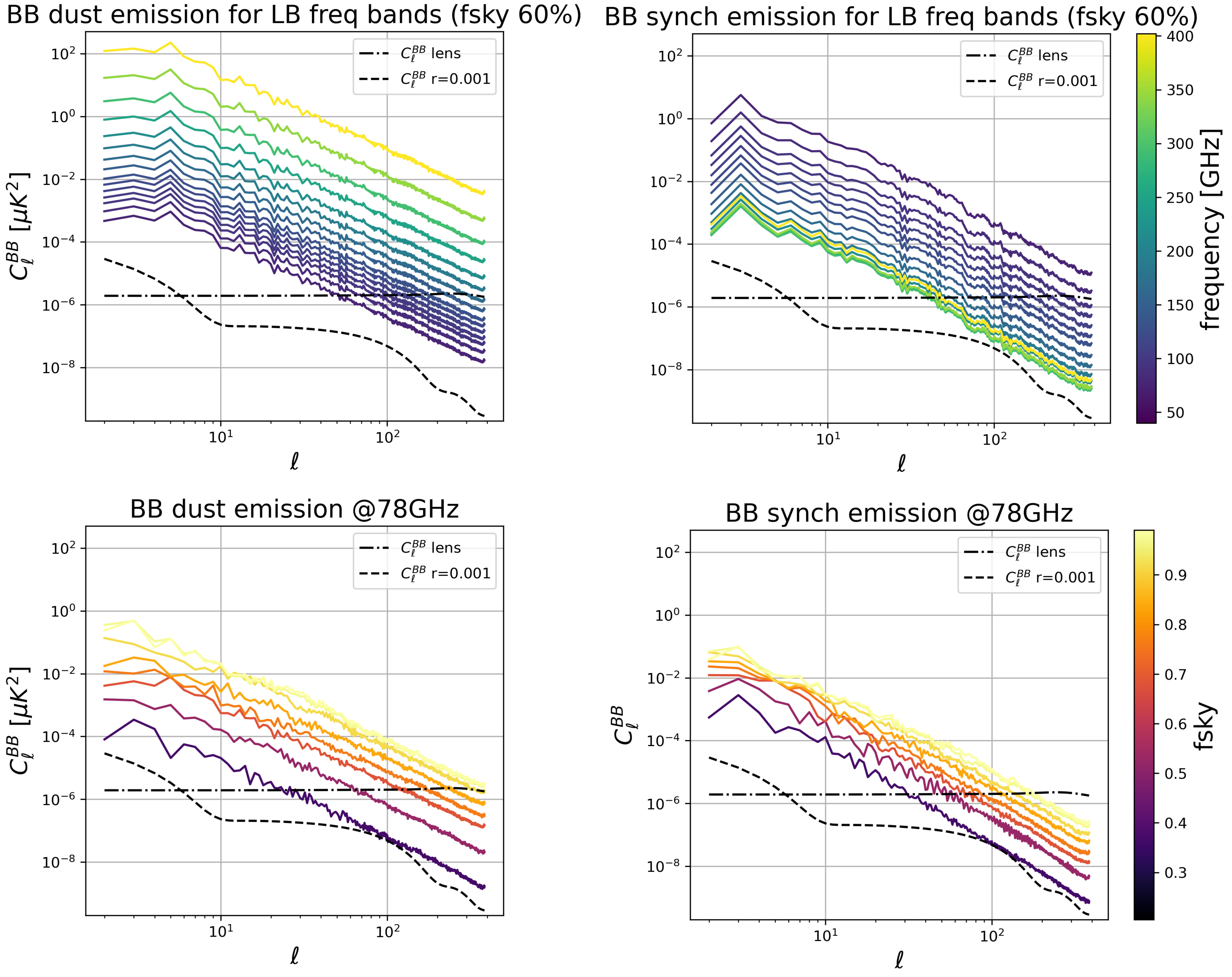
Galactic astrophysics

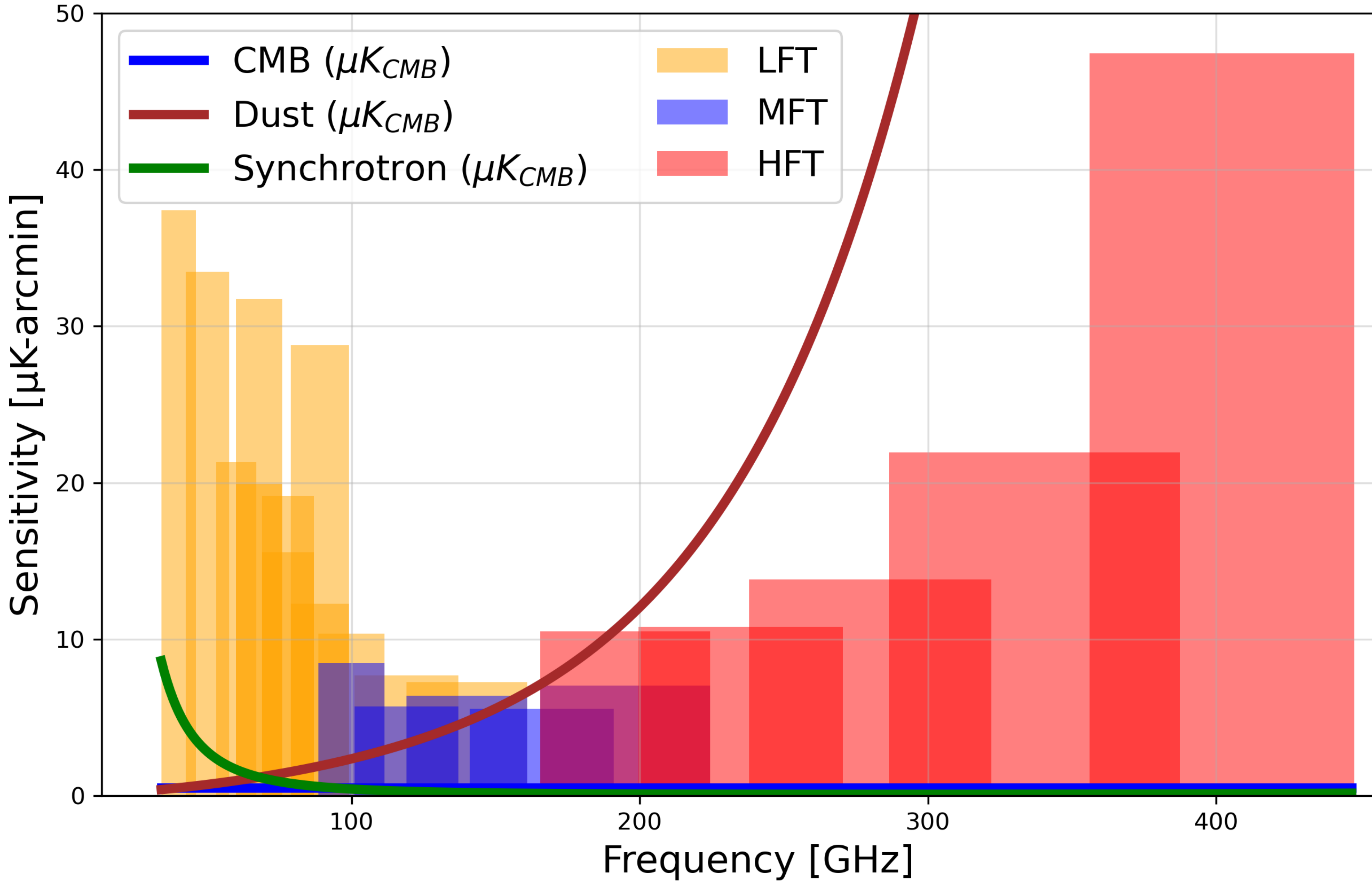
- LiteBIRD will provide 15 high-sensitivity polarization full-sky maps from 40 to 402 GHz
- Sensitivity improved by a factor of 5 at 40 GHz and 10 at 402 GHz, with respect to Planck
- Gain in spectral resolution

- **Wealth of Galactic science possible**:
  - Geometry of the Galactic magnetic field
  - Interstellar turbulence
  - Dust composition
  - Grain alignment
  - Cold clumps
  - Geometry of synchrotron-bright loops
  - SED of the synchrotron emission
  - SED for dust emission Q and U
  - Nature of AME and spectral variations...
  - … and many others!



Foreground cleaning





- Projected **polarization sensitivities** for a **3-year full-sky survey**: sensitivity both in CMB and foreground dominated channels
- Polarized diffuse Galactic foregrounds (thermal dust emission and synchrotron emission) dominating by orders of magnitude the signal we target

Foreground cleaning

Foreground modeling

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

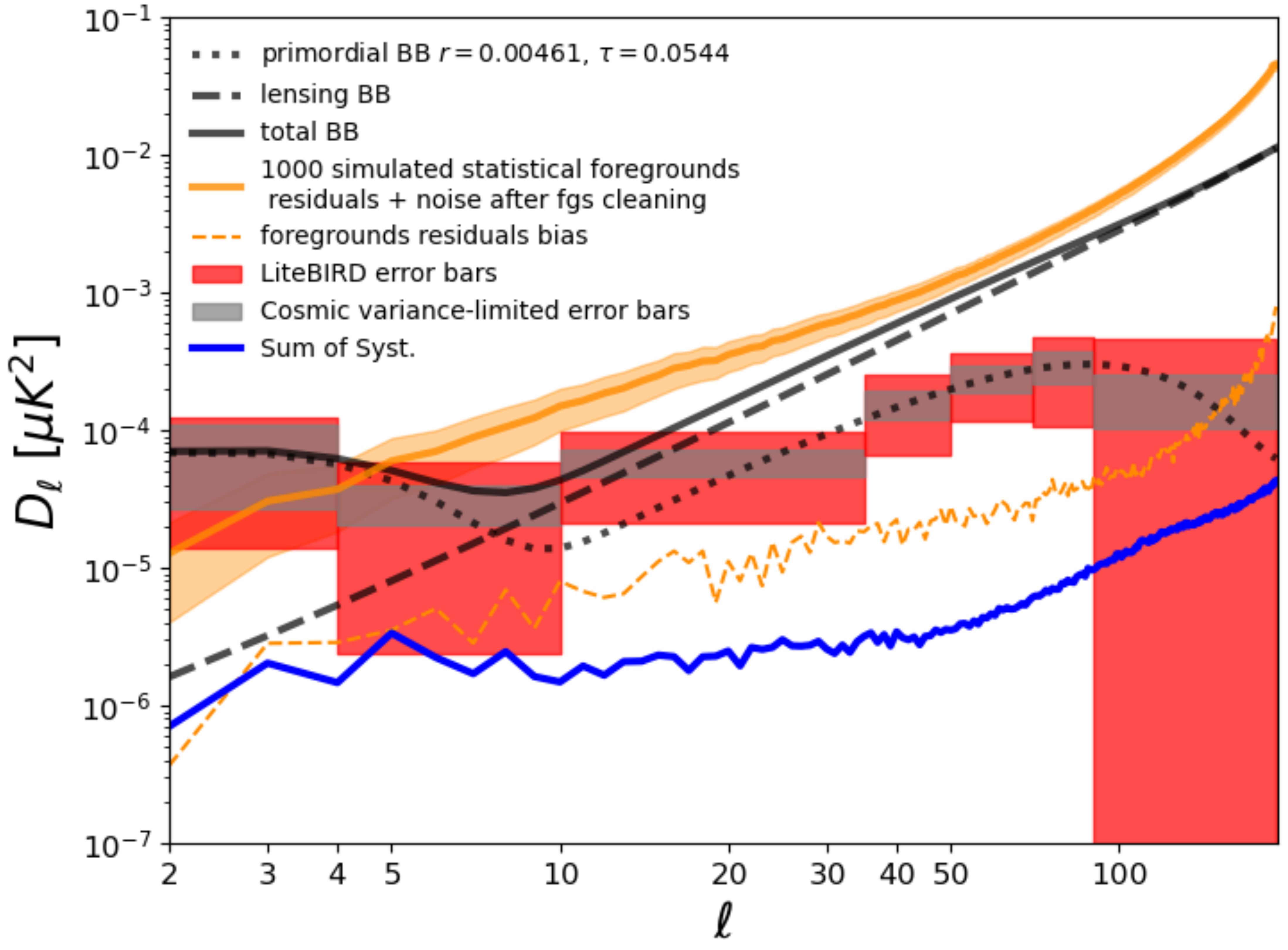
$$[Q_s, U_s](\hat{n}, \nu) = [Q_s, U_s](\hat{n}, \nu_\star) \cdot \left(\frac{\nu}{\nu_\star}\right)^{\beta_s(\hat{n})}$$

- **Dust**: modified blackbody

$$[Q_d, U_d](\hat{n}, \nu) = [Q_d, U_d](\hat{n}, \nu_\star) \cdot \left(\frac{\nu}{\nu_\star}\right)^{\beta_d(\hat{n})-2} \frac{B_\nu(T_d(\hat{n}))}{B_{\nu_\star}(T_d(\hat{n}))}$$

- **7 parameters** in each sky patch
- **Multi-Clustering** interface with foregrounds data to account for spatial variability (📖 Errard et al. 2020, Puglisi et al. 2022, Carones et al. 2023)
- Current baseline for fitting foregrounds: $12\times(N_{side})^2$ patches with N_{side} between 8 and 64, depending on the foreground parameter

Impact of foreground residuals

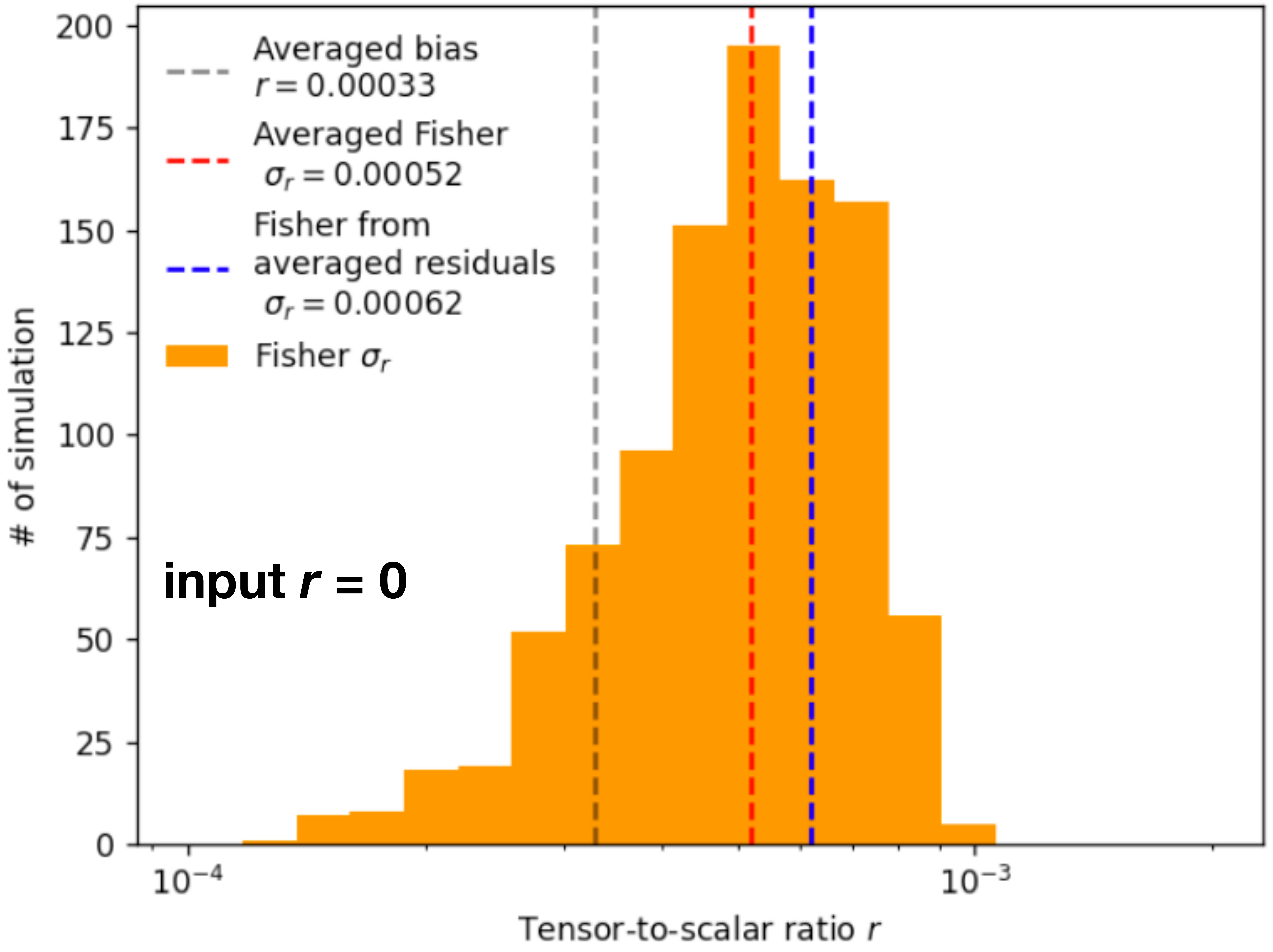


📖 LiteBIRD collaboration PTEP 2023

Foreground cleaning

From foreground residuals to *r*

- 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: $r = (3.3 \pm 6.2)\times10^{-4}$

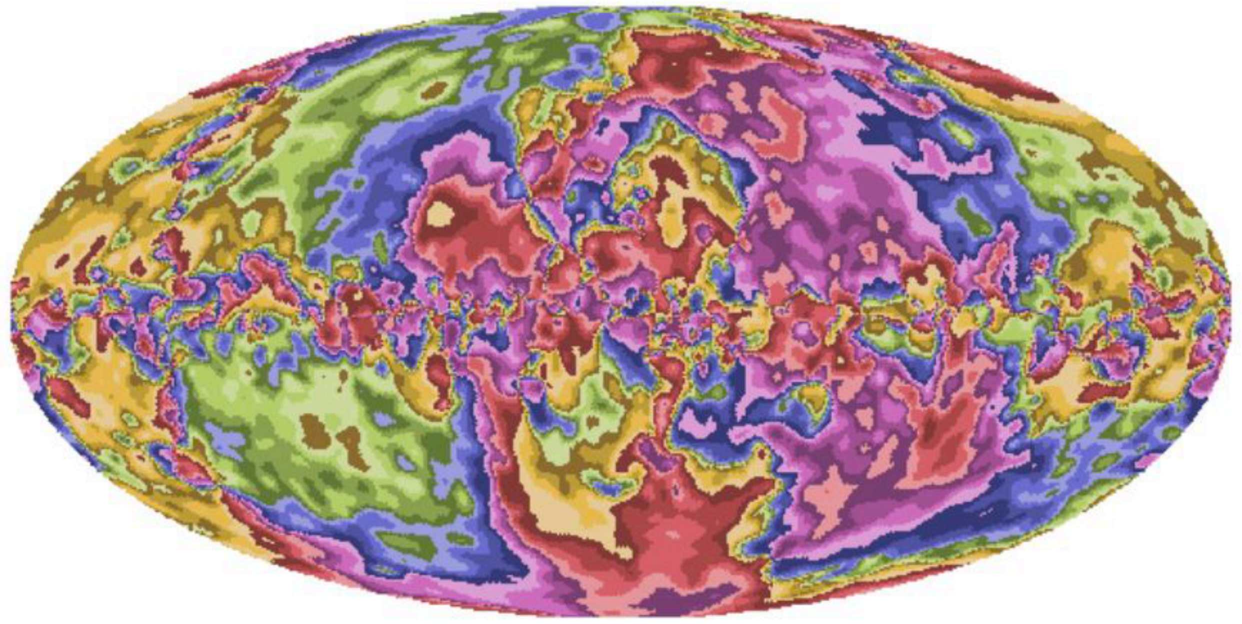


📖 LiteBIRD collaboration PTEP 2023

Foreground cleaning current studies

Need for robust component separation techniques to deal with complex foreground models:

- **Many component separation techniques explored** (parametric, minimum variance, SMICA, Delta-map, etc)
- Forecast against a variety of foreground models available in the literature. Common difficulty for the component separation techniques: spatial variability of the foreground SEDs.
  - **moment expansion** (Vacher+ 2022)
  - **clustering** (Puglisi+ 2022, Carones+ 2023)



Carones+ 2023

The ability to reconstruct these clusters impacts the performance of the component separation techniques.

Forecasts by building the clusters from the LiteBIRD frequency maps themselves, but eventually external data could help (see Puglisi + 2022)

- Upcoming forecasting papers on LiteBIRD ability to reconstruct both large scales B and E modes.

Conclusion

- Currently in reformation phase studies, aiming at consolidating the feasibility of the science target. Most mature CMB space mission to date, to be launched in the early 2030s!

- Expected sensitivity on r (without de-lensing!): δr **< 0.001 (r=0)**

- Other science goals:
  - B-mode power spectrum
  - Large-scale E modes
  - Reionization
  - Neutrino mass
  - Cosmic birefringence
  - SZ effect
  - Constraints on primordial magnetic field
  - Elucidating anomalies
  - **Galactic foregrounds**

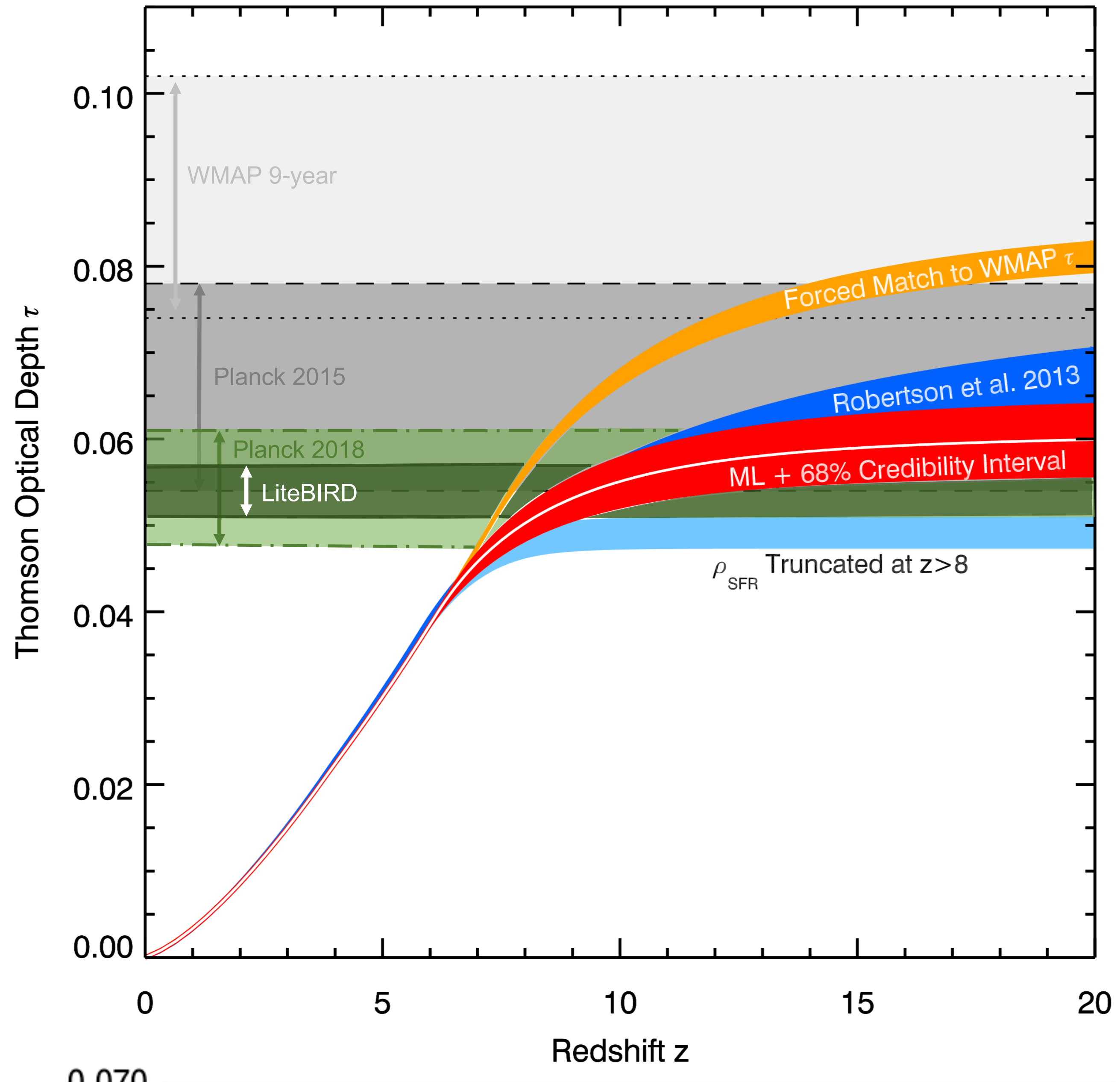
- Galactic foregrounds are the main **data analysis challenge** for LiteBIRD: need for robust component separation techniques

Thanks!

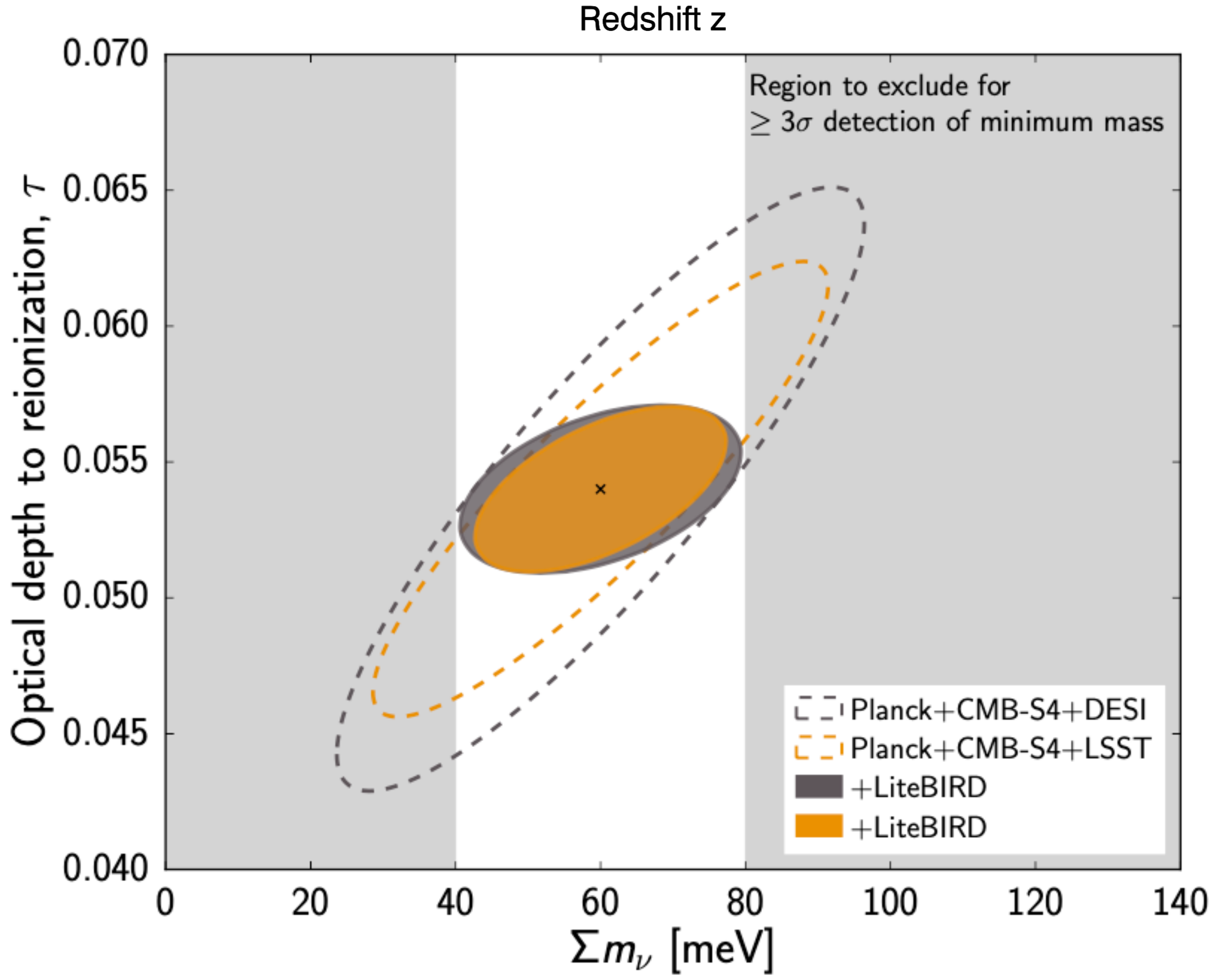
Back-up slides

Optical depth, reionization and neutrino masses

- LiteBIRD will provide a cosmic-variance limited measurement of the ***E*-mode** power spectrum at large scales ($2 < \ell < 200$)
- This will lead to improved constraints on:
  - **Reionization**
    - Cosmic-variance measurement of the **optical depth** to reionization ⇒ $\sigma(\tau) \approx 0.002$ ⇒ ×3 improvement with respect to Planck (📖 Planck Int.Res. LVII, 2020)
    - Improved constraints on reionization history models: 35% improvement on the uncertainty of $\Delta(z_{\mathrm{reion}})$
  - **Neutrino masses**
    - ×2 improvement on $\sigma(\sum m_\nu)$
    - $\sigma(\sum m_\nu) = 12$ meV ⇒ 5σ detection for a minimum value of $\sum m_\nu = 60$ meV (allowed by flavour-oscillation experiments) or larger
    - Potentially allow to distinguish between the inverted neutrino mass ordering and the normal ordering



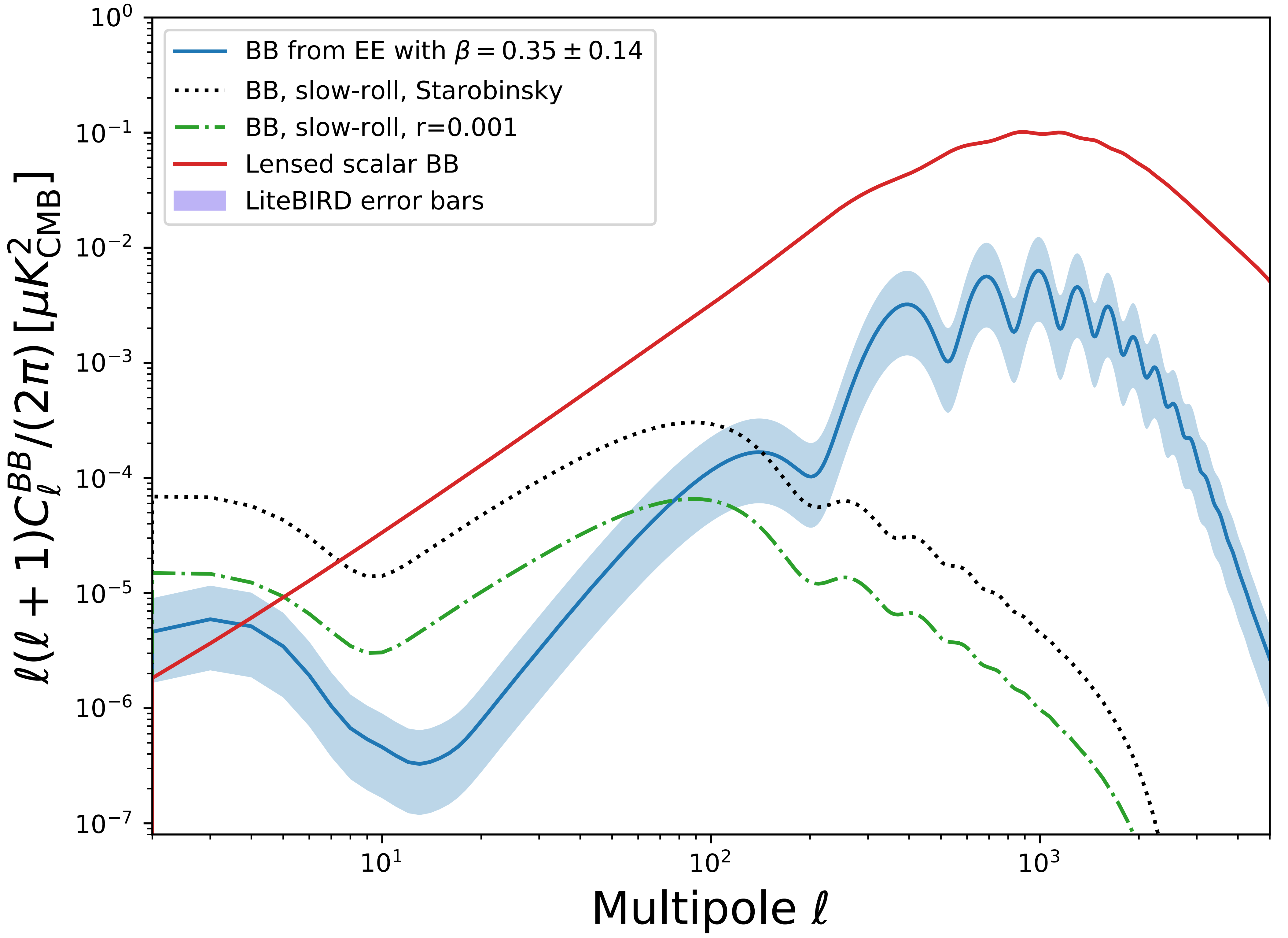
📖 adapted from Robertson+2015



📖 adapted from Calabrese+2017

Constraints on cosmic birefringence

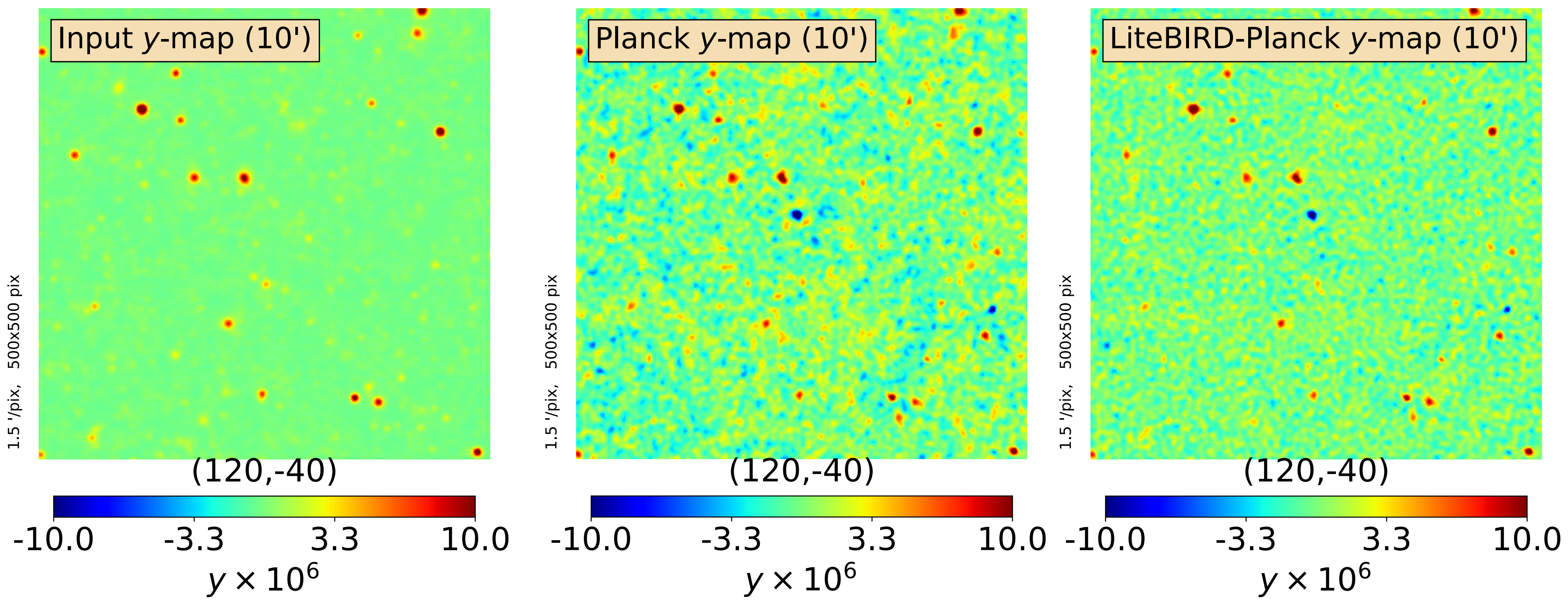
- **Cosmic birefringence** could be seeded by parity-violating processes in Universe
- Could occur if dark matter or dark energy are a pseudo-scalar field coupled to electromagnetism that changes sign under inversion of spatial coordinates
- Induces non-zero *TB* and *EB* and also a *B*-mode signal
- Constraints from the CMB must account jointly for i) a possible detector angle miscalibration (📖 Minami et al., 2019) and ii) a positive EB signal from Galactic foregrounds (📖 Diego-Palazuelos et al., 2022)
- Recent measurements show a tentative detection of a birefringence angle of **β = (0.34±0.09)°** (📖 Eskilt & Komatsu 2022, from a combination of WMAP and Planck PR4)
- LiteBIRD has the potential to:
  - Reduce the error bar on a global β leading to a **~10-sigma detection**
  - Produce a map of β to test for **cosmic-birefringence anisotropy**

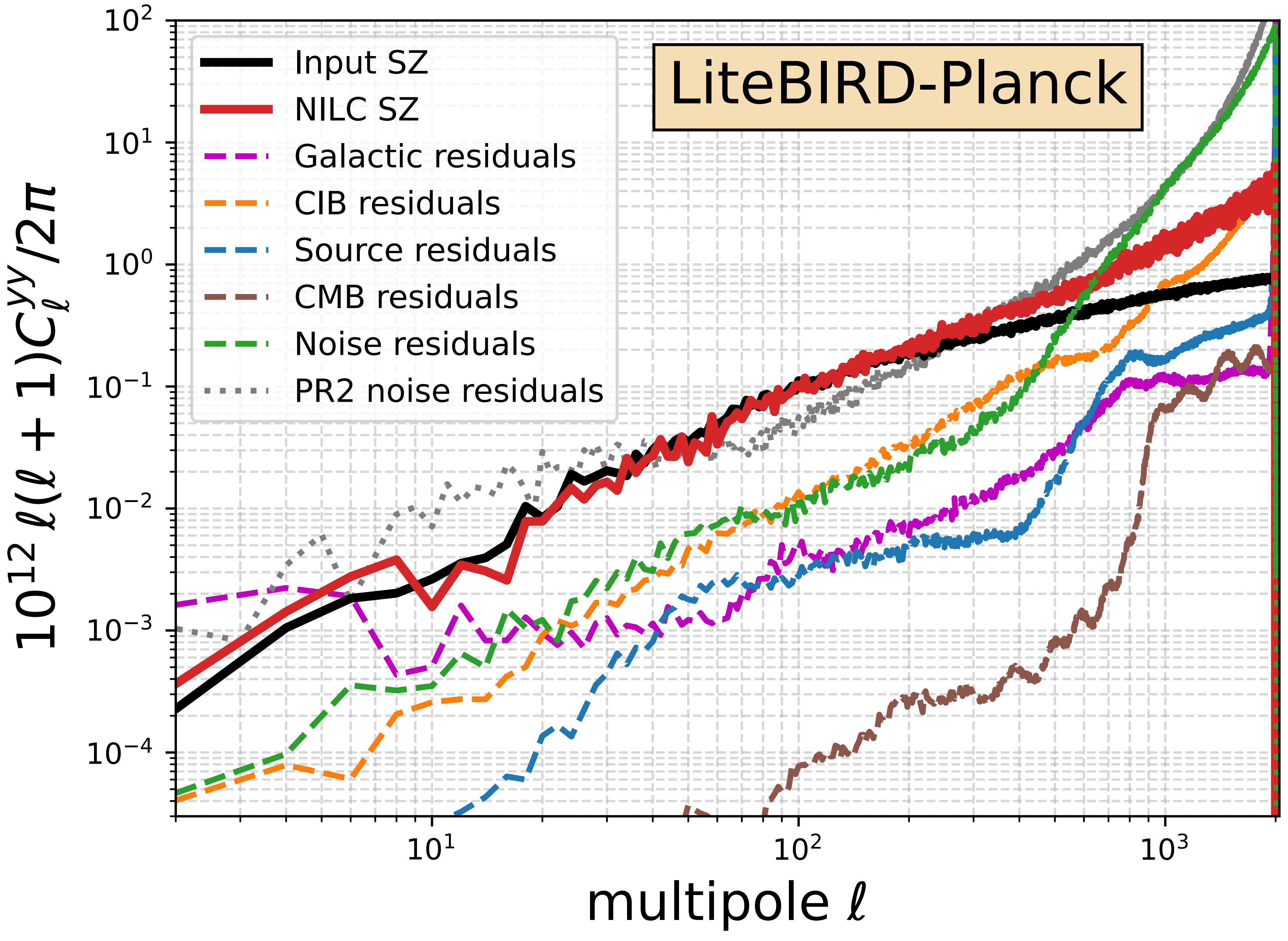


📖 LiteBIRD collaboration PTEP 2023

Mapping the hot gas in the Universe

- The **Sunyaev-Zel'dovich** effect provides a mean to map the distribution of hot electrons in the Universe
- Improved sensitivity and frequency coverage of LiteBIRD crucially contributes to improve these studies
- Combination with Planck adds the benefit of angular resolution
- LiteBIRD will **improve ×10 the noise in the SZ map** wrt Planck
- This will allow to:
  - Produce a high-fidelity SZ map over the full-sky essentially **free of contamination at $\ell < 200$**
  - Test theories of structure formation via **hot-gas tomography** from SZ × galaxy surveys correlations
  - Search form **WHIM** in filaments connecting clusters
  - Study an **inhomogeneous reionization** process via cross-correlations of SZ × CMB optical depth
  - Measure the mean gas T_e via the relativistic SZ
  - Improve constraints on $S_8 = \sigma_8(\Omega_m/0.3)^{0.5}$ by 15%

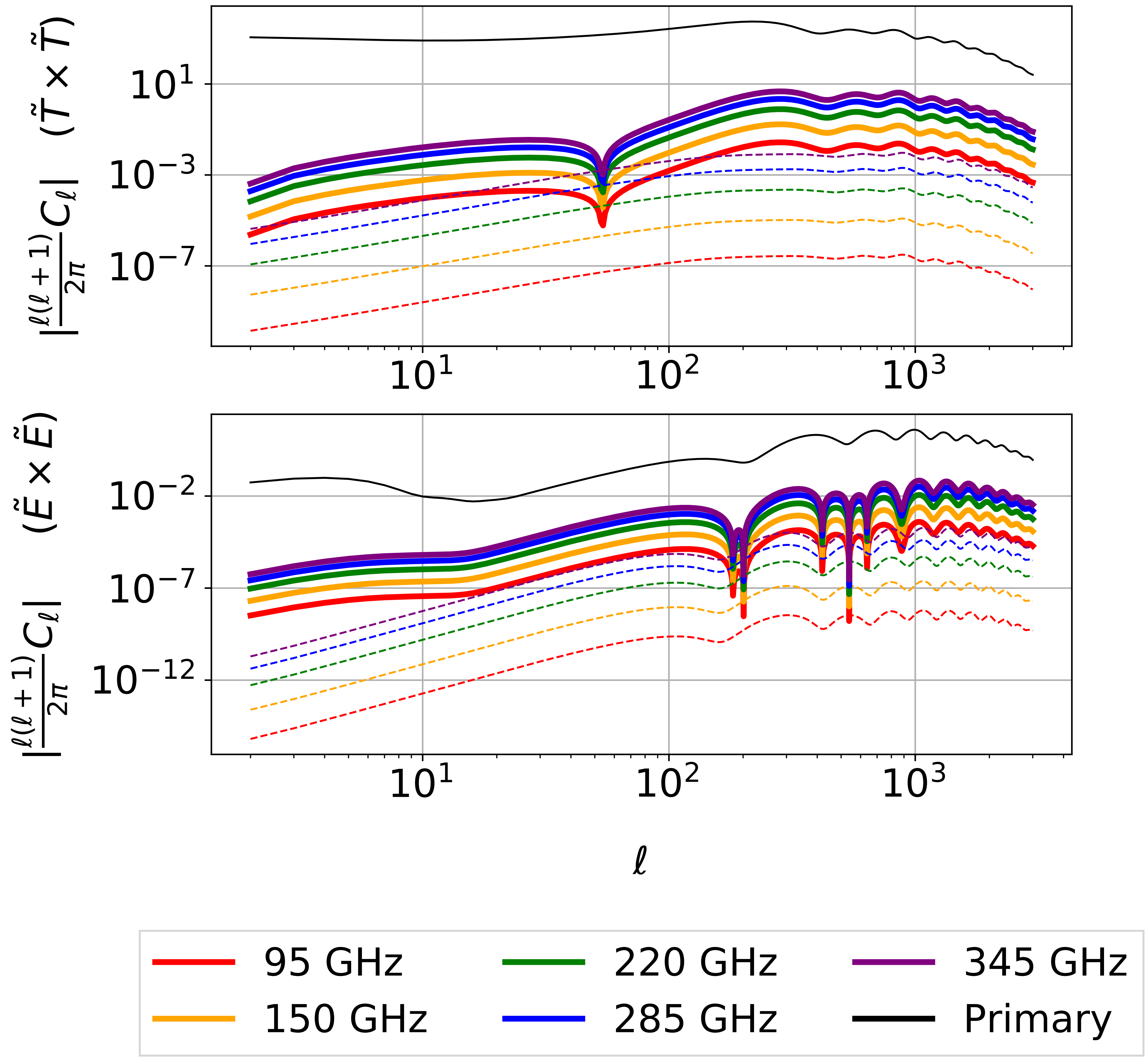




Remazeilles+ JCAP 2024

Anisotropic CMB spectral distortions

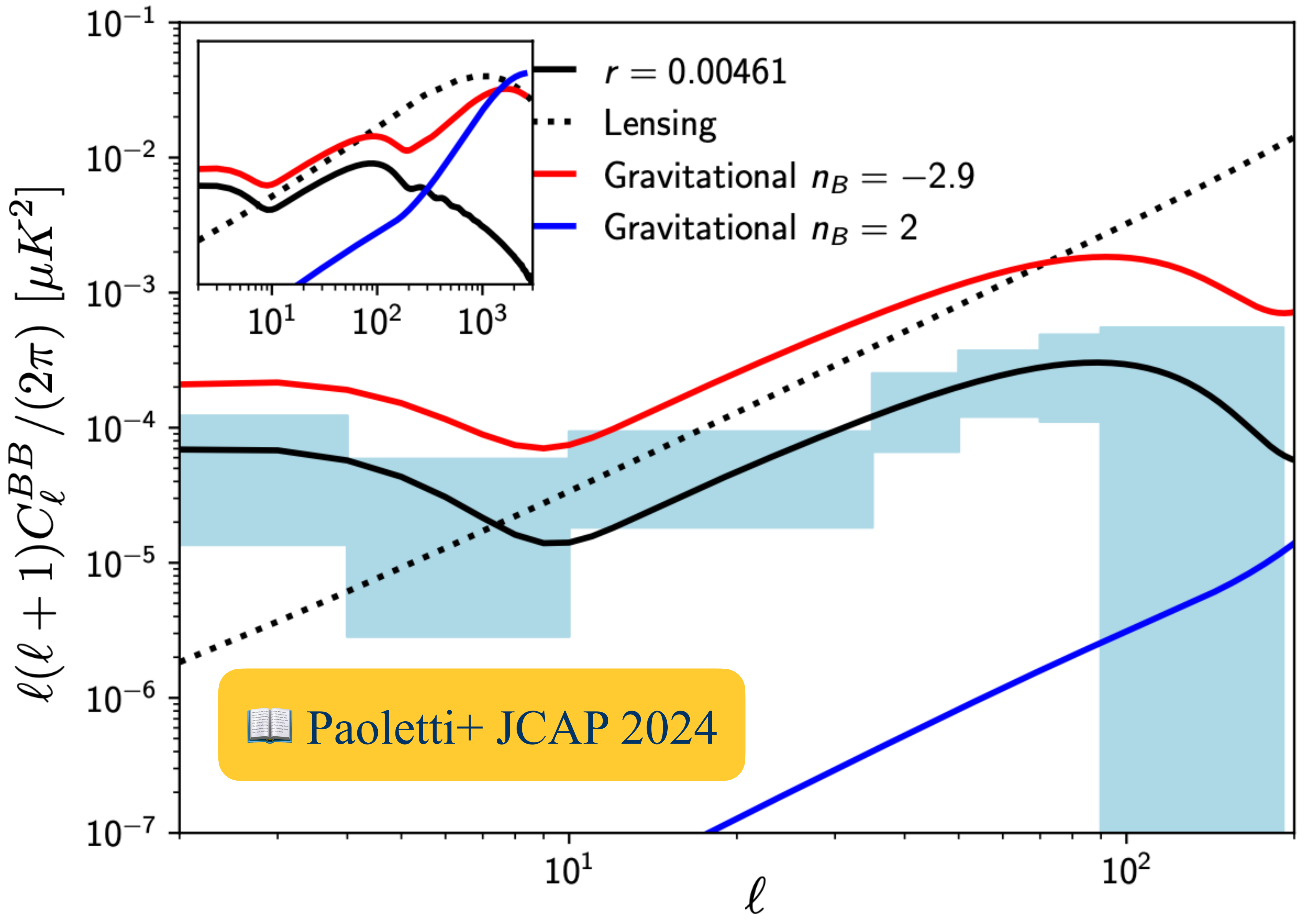
- LiteBIRD will be sensitive to any **spatially-varying CMB spectral distortion**, beyond the SZ effect
  - **Rayleigh scattering**. LiteBIRD will have sensitivity to measure at **25-sigma** (📖 Beringue et al. 2021) the frequency-dependent CMB anisotropies due to Rayleigh scattering by HI at the LSS
    - ➡ Such a detection would allow to derive improved constraints on N_{eff} and $\sum m_\nu$
  - **μ distortion**. LiteBIRD can detect an anisotropic μ distortion induced by non-Gaussian fluctuations induced during inflation
    - ➡ This would offer a power test of inflation at its onset
  - **Axion decay**. LiteBIRD can look for polarized spectral distortions produced by resonant conversion of axions into photons by the Galactic magnetic field



📖 Dibert+ PhysRevD 2022

Constraints on primordial magnetic fields

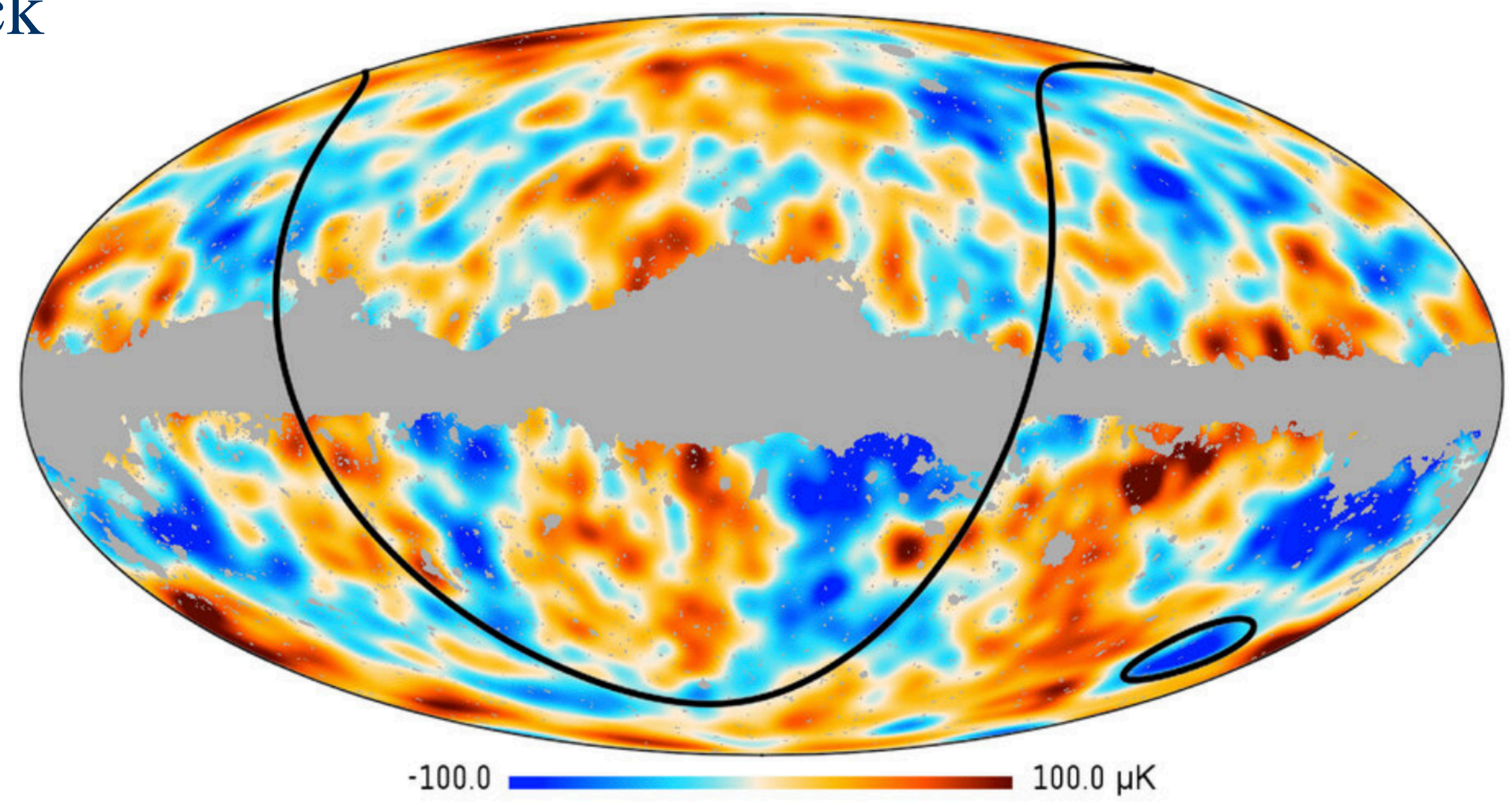
- Primordial magnetic fields (PMFs) affect the CMB via different effects:
  - **Gravitational effects** with magnetically-induced perturbations
  - Impact on the **ionization history** of the Universe due to their post-recombination dissipation
  - Induce a **Faraday rotation** of the CMB polarization
  - **Non-Gaussianity** induced in the CMB polarization anisotropies
- LiteBIRD:
  - Is a **sensitive probe** to PMFs through all these effects, thanks mainly to its remarkable sensitivity in polarization
  - Will **break the nG threshold** improving current upper limits by a factor of ~ 3
  - Will be able to **univocally identify the PFMs contribution to CMB** by joining all these effects together
  - Will allow a detection of **nG fields** with high significance



Upper limits on PMF amplitude for n_B = -2.9	
Gravitational effect	$B_{1\mathrm{Mpc}} < 0.8$ nG
Ionization history	$\sqrt{\langle B^2 \rangle} < 0.7$ nG
Faraday rotation	$B_{1\mathrm{Mpc}} < 3.2$ nG
Non-Gaussianities	$B_{1\mathrm{Mpc}} \lesssim 1$ nG

Elucidating spatial anomalies with polarization

- Various so-called anomalies have been found in WMAP and Planck temperature data that exert a mild tension against the ΛCDM cosmological model:
  - a lack of power on large angular scales
  - the alignment of the quadrupole and octopole moments
  - a hemispherical asymmetry in power on the sky
  - a lack of correlation at large angular scales
  - parity asymmetry in the power associated with even/odd mode
  - an anomalous "Cold Spot" on a scale of ~ 10°
  - anomalously low temperature variance

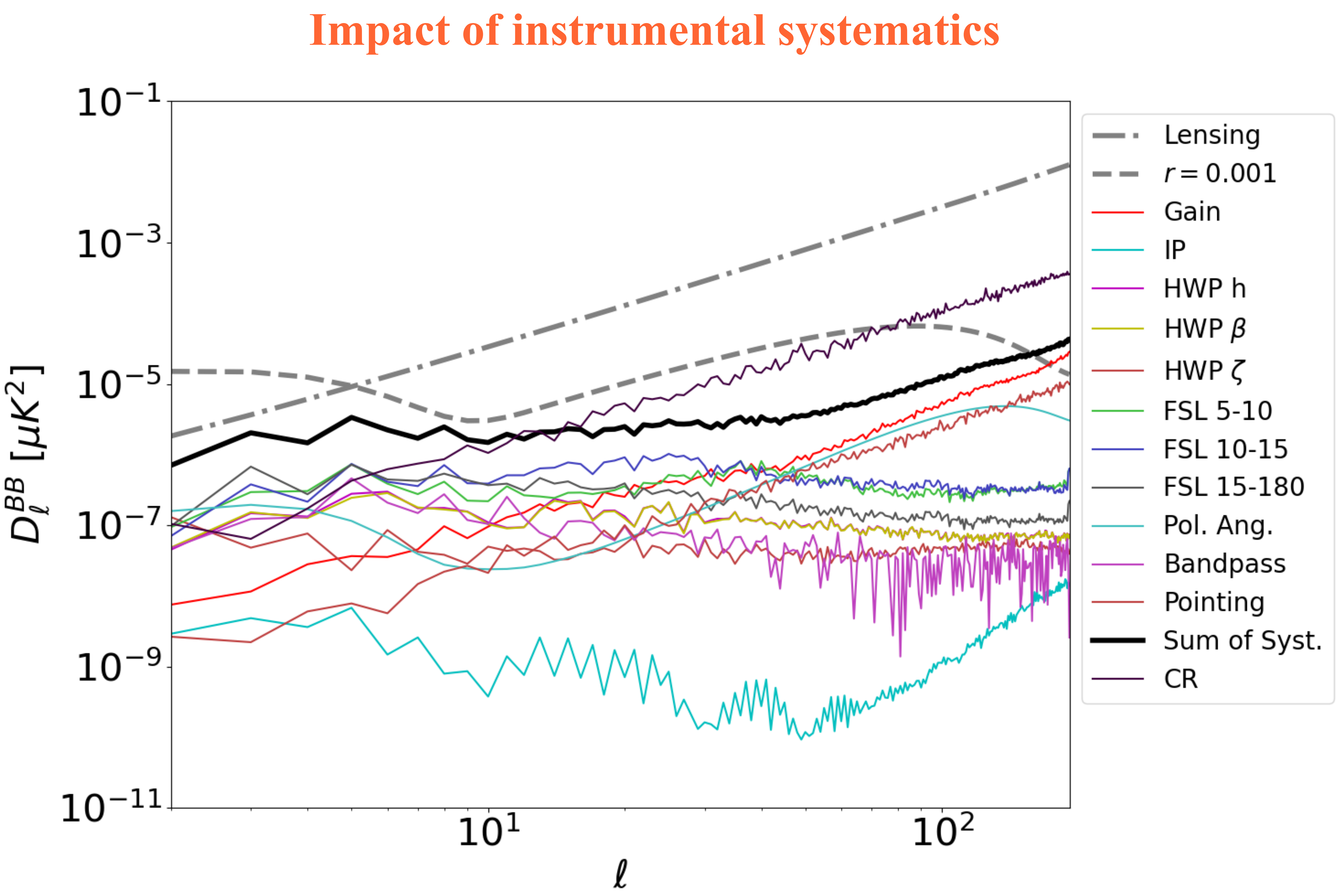


Credit ESA/Planck Collaboration

- Given their modest statistical significance, these could simply be statistical flukes
- However, they may also be hints of **new physics** beyond the standard model

- Polarized CMB anisotropies provide independent information on the fluctuations that source the temperature anisotropy
- **LiteBIRD E-mode polarization sky maps will allow further tests** on the nature of these spatial anomalies at close to the cosmic-variance level of sensitivity

Impact of instrumental systematics



Category	Systematic effect
Beam	Far sidelobes Near sidelobes Main lobe Ghost Polarization and shape in band
Cosmic ray	Cosmic-ray glitches
HWP	Instrumental polarization Transparency in band Polarization efficiency in band Polarization angle in band
Gain	Relative gain in time Relative gain in detectors Absolute gain
Polarization angle	Absolute angle Relative angle HWP position Time variation
Pol. efficiency	Efficiency
Pointing	Offset Time variation HWP wedge
Bandpass	Bandpass efficiency
Transfer function	Crosstalk Detector time constant knowledge