Funded by
the European Union

GroundBIRD

LSPE
Large Scale Polarization Explorer

LiteBIRD

CMB studies at the IAC: GroundBIRD, LSPE-Strip and LiteBIRD

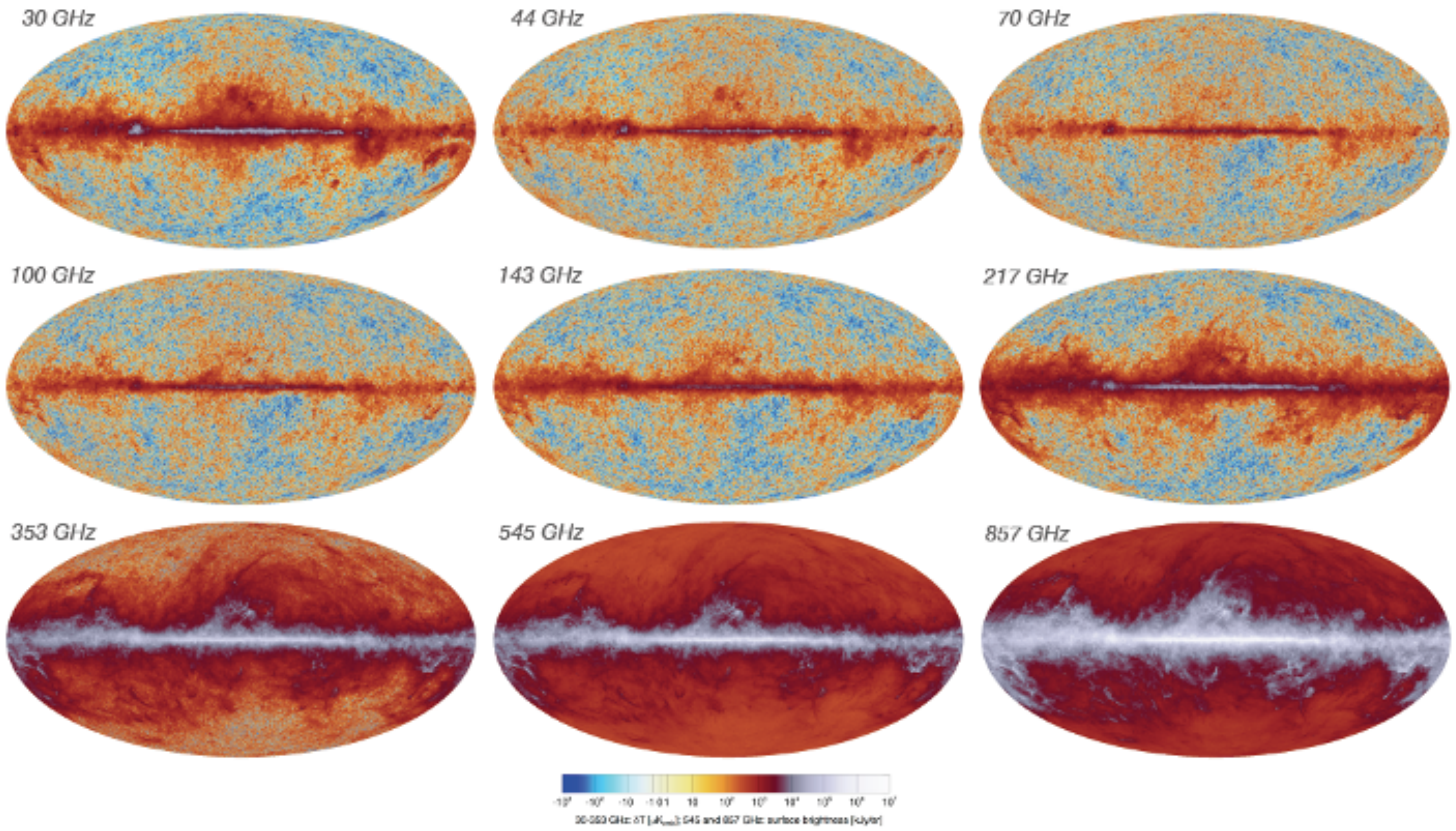
INSTITUTO DE ASTROFISICA DE CANARIAS · IAC ·

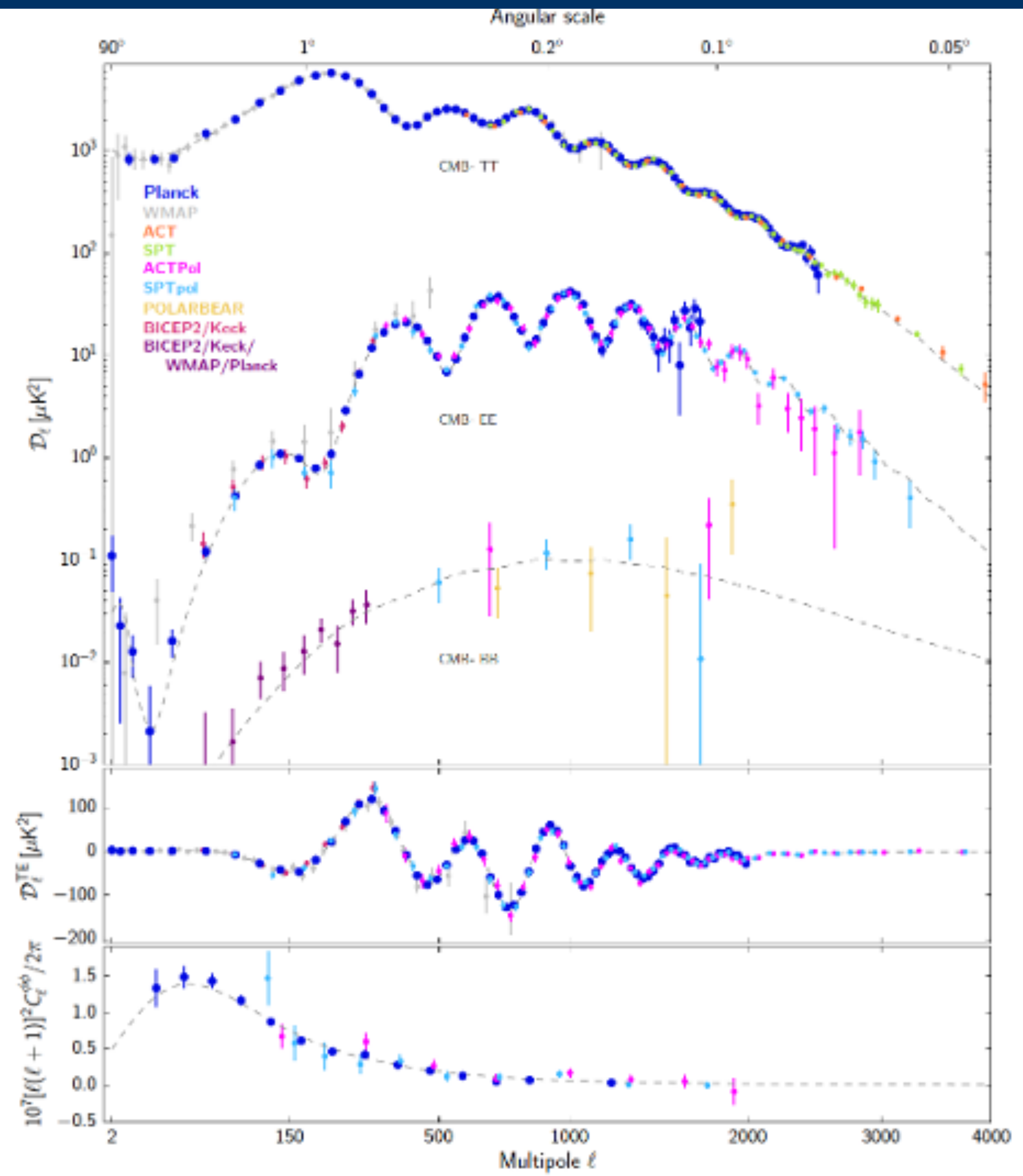
R.T. Génova-Santos
(IAC CMB-Cosmology groups)

Cosmology with the CMB

Planck results

- Temperature anisotropies measured to great precision by **Planck** (cosmic-variance limited up to $l \approx 1600$) and previous experiments





📖 Planck 2018 results I (A&A, 641, A1, 2020)

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LSPE Large Scale Polarization Explorer

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Planck results

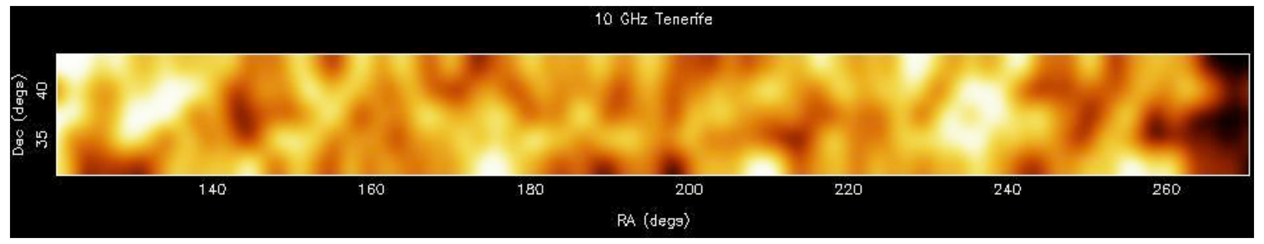
- **ΛCDM 6-parameter model** provides an excellent fit to the data!
- Sub-percent accuracy in the determination of all cosmological parameters except τ
  - **CDM** detected at ≳100σ
  - **Sound horizon** measured with 0.03% precision
  - **n_S** 8σ away from scale invariance
- Beyond ΛCDM:
  - No evidence for $dn_s/d(\ln k) \neq 0$
  - **Tensor modes**: $r < 0.1$
  - Marginal preference for an open universe: Ω_k = -0.0106 ± 0.0065
  - **Dark energy** equation of state consistent with $w_0 = -1$ and $w_a = 0$
  - **Neutrinos**: $\sum m_\nu < 0.17$ eV , $N_{eff} = 2.92 \pm 0.37$
  - …. and more

Parameter	*Planck* alone
$\Omega_b h^2$	0.02237 ± 0.00015
$\Omega_c h^2$	0.1200 ± 0.0012
$100\theta_{MC}$	1.04092 ± 0.00031
τ	0.0544 ± 0.0073
$\ln(10^{10} A_s)$	3.044 ± 0.014
n_s	0.9649 ± 0.0042
H_0	67.36 ± 0.54
Ω_Λ	0.6847 ± 0.0073
Ω_m	0.3153 ± 0.0073
$\Omega_m h^2$	0.1430 ± 0.0011
$\Omega_m h^3$	0.09633 ± 0.00030
σ_8	0.8111 ± 0.0060
$\sigma_8(\Omega_m/0.3)^{0.5}$	0.832 ± 0.013
z_{re}	7.67 ± 0.73
Age [Gyr]	13.797 ± 0.023
r_* [Mpc]	144.43 ± 0.26
$100\theta_*$	1.04110 ± 0.00031
r_{drag} [Mpc]	147.09 ± 0.26
z_{eq}	3402 ± 26
k_{eq} [Mpc^{-1}]	0.010384 ± 0.000081
Ω_K	-0.0096 ± 0.0061
Σm_ν [eV]	< 0.241
N_{eff}	$2.89^{+0.36}_{-0.38}$
$r_{0.002}$	< 0.101

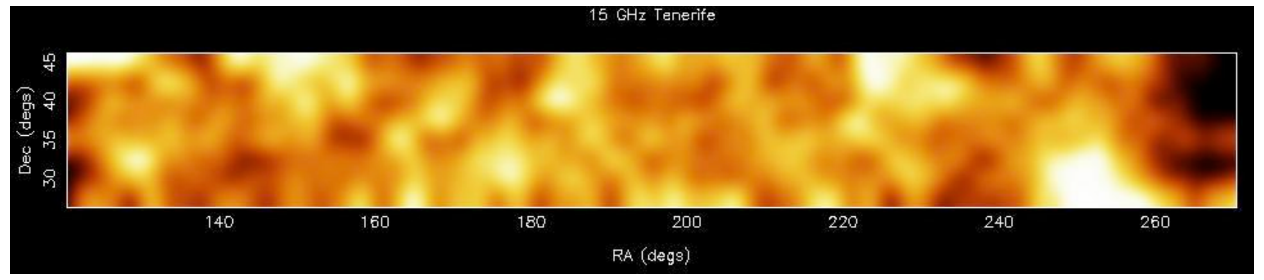
📖 Planck 2018 results I (A&A, 641, A1, 2020)

CMB studies from the TO

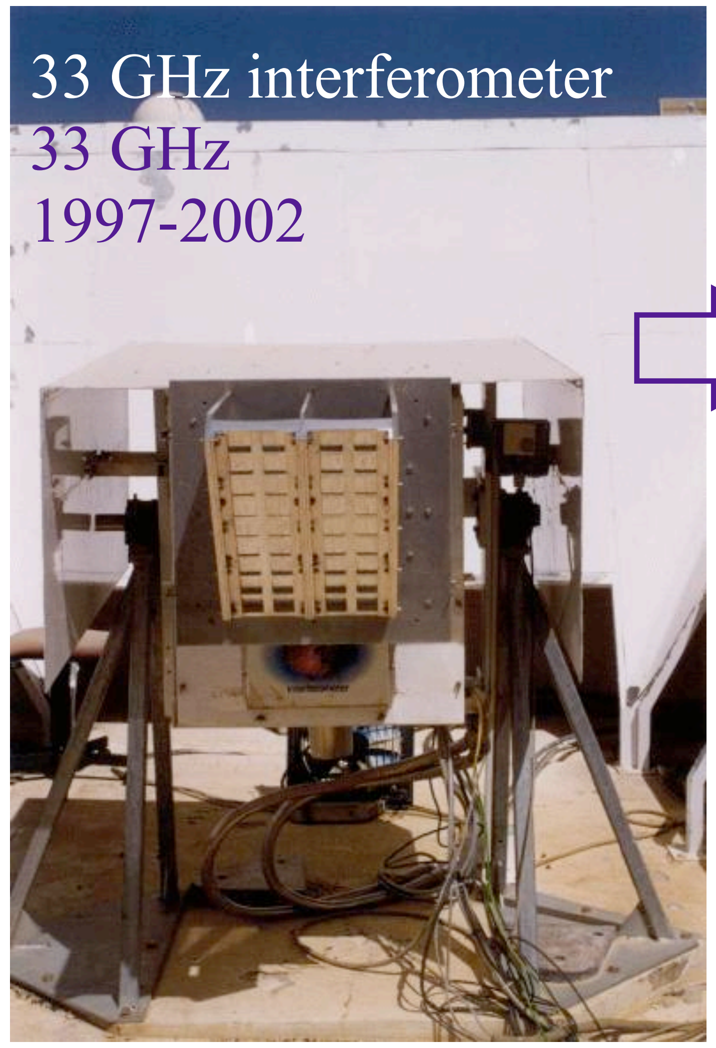
10 GHz Tenerife



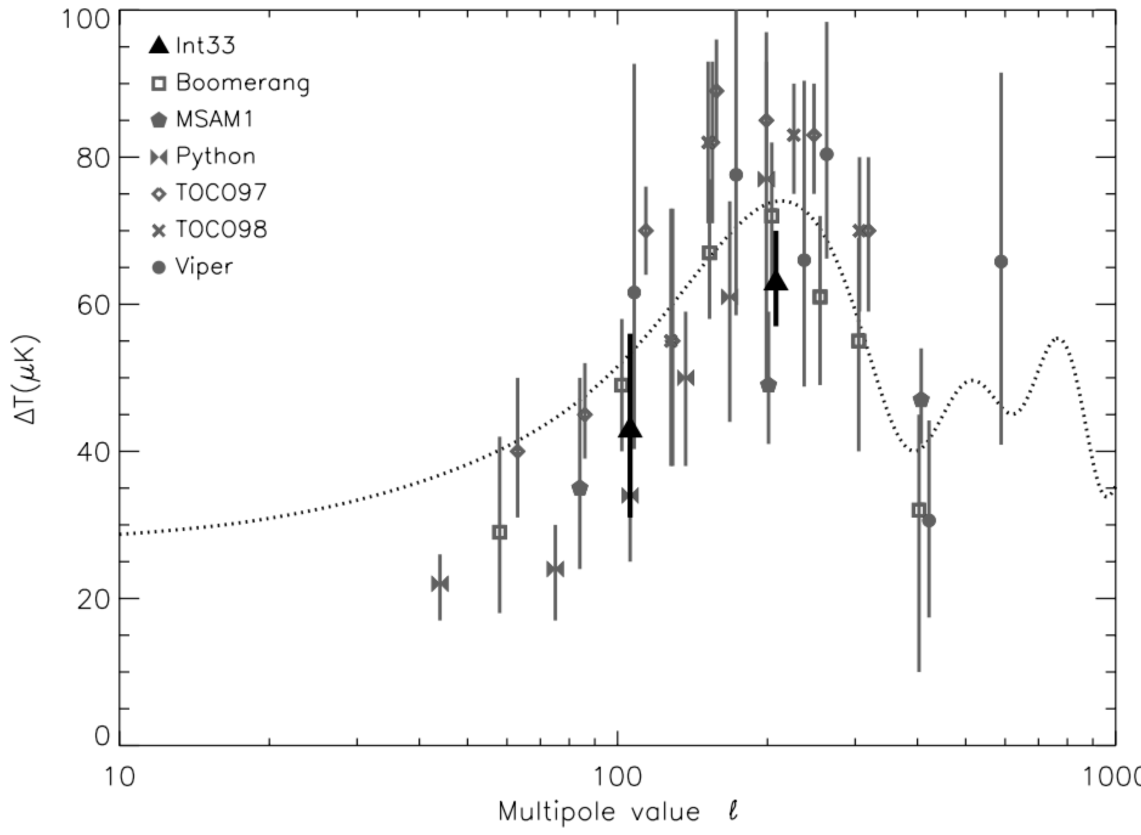
15 GHz Tenerife



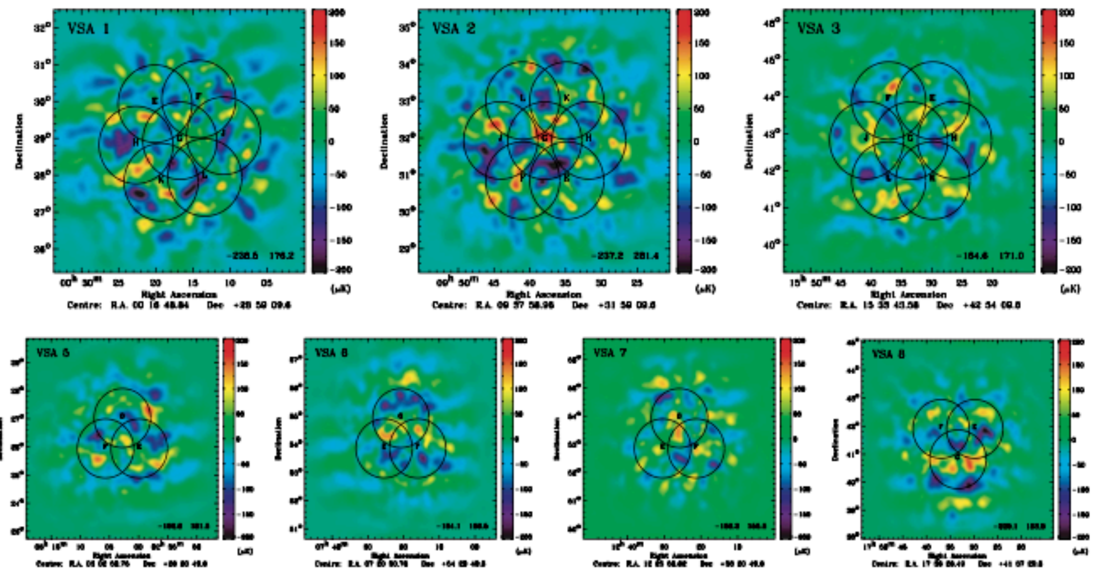
📖 Gutiérrez et al. (2000)

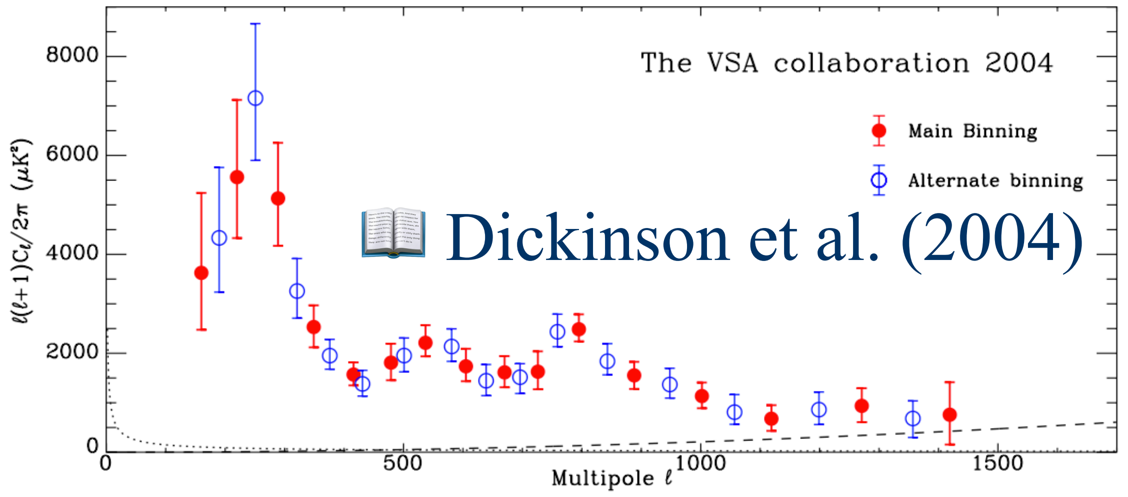


📖 Harrison et al. (2000)

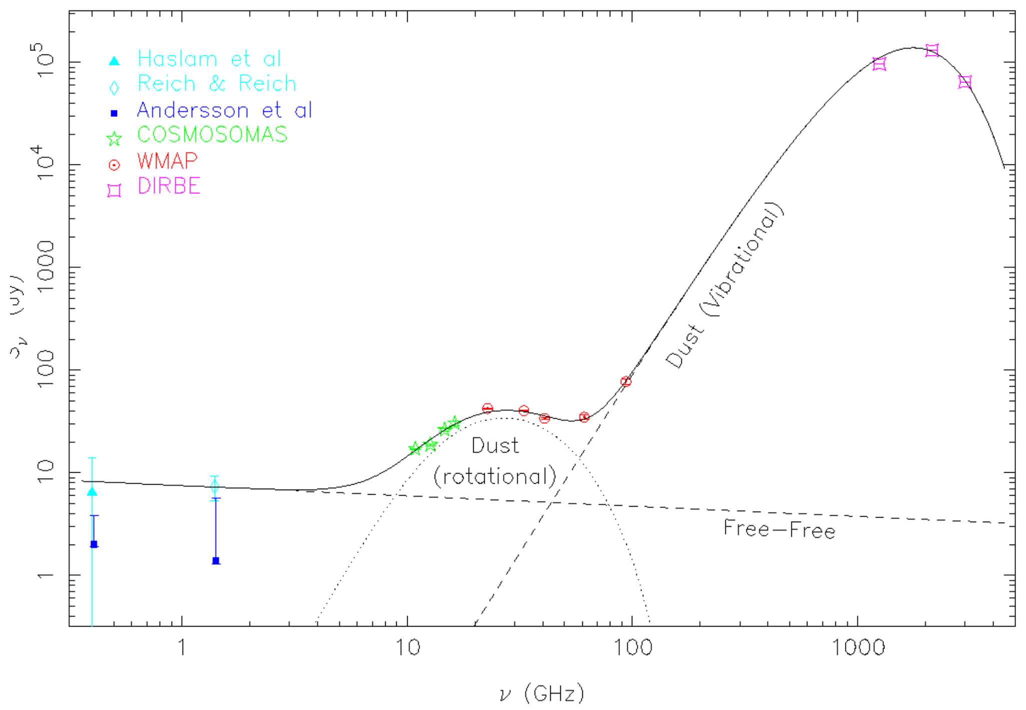


VSA 33 GHz





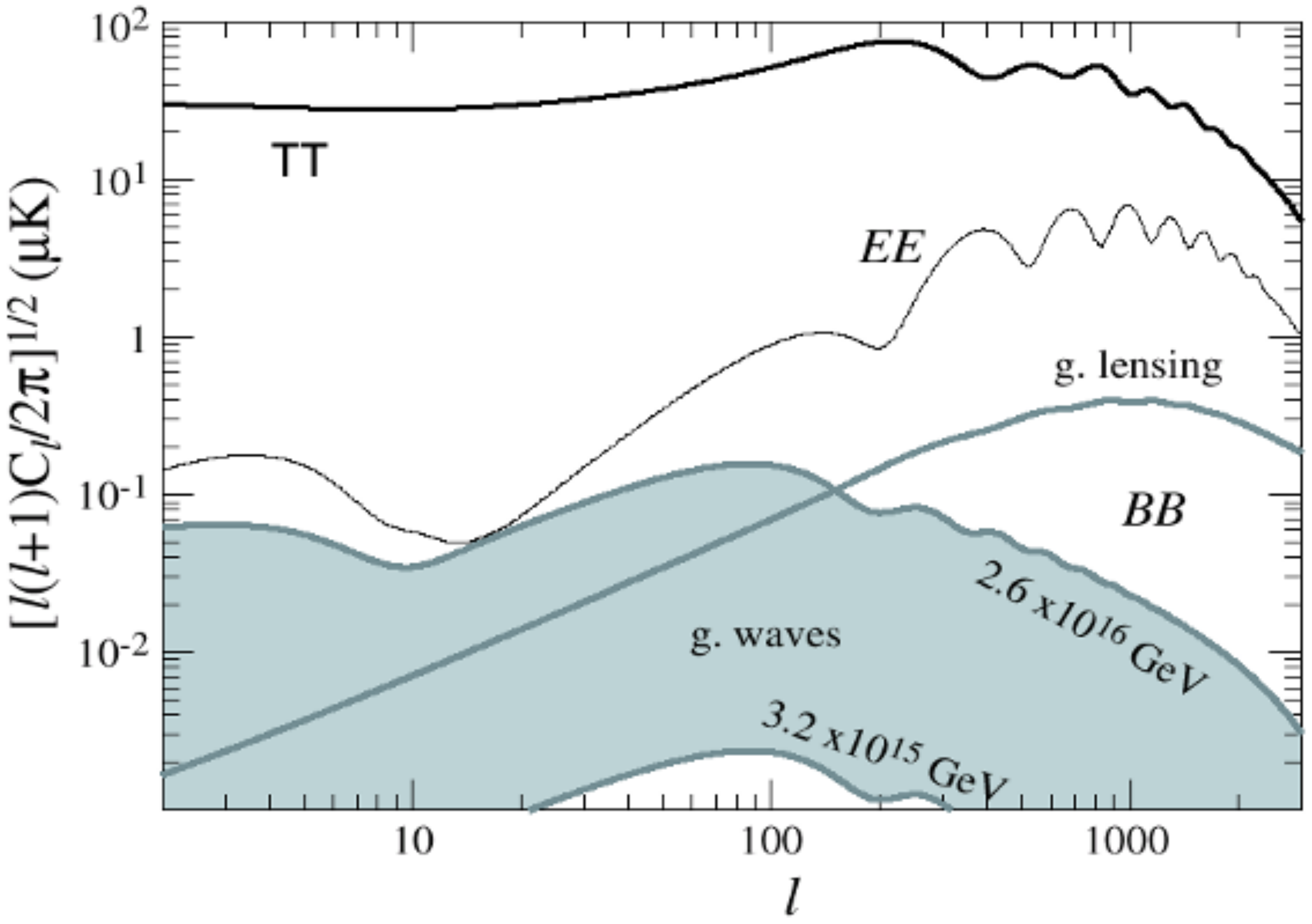
📖 Dickinson et al. (2004)



📖 Watson et al. (2005)

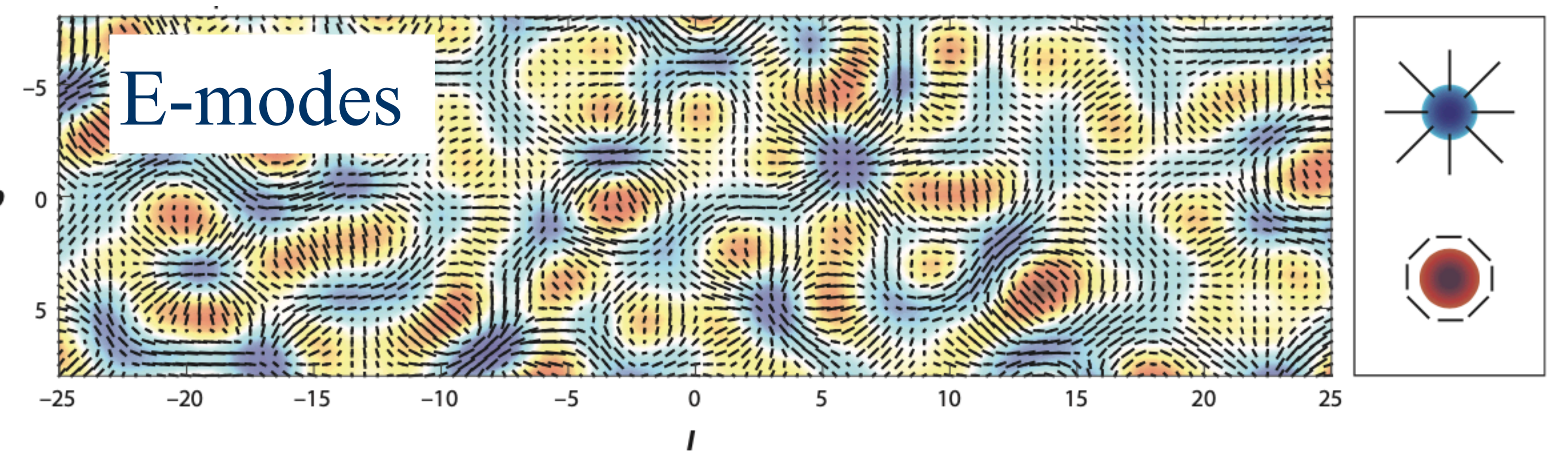
CMB polarization

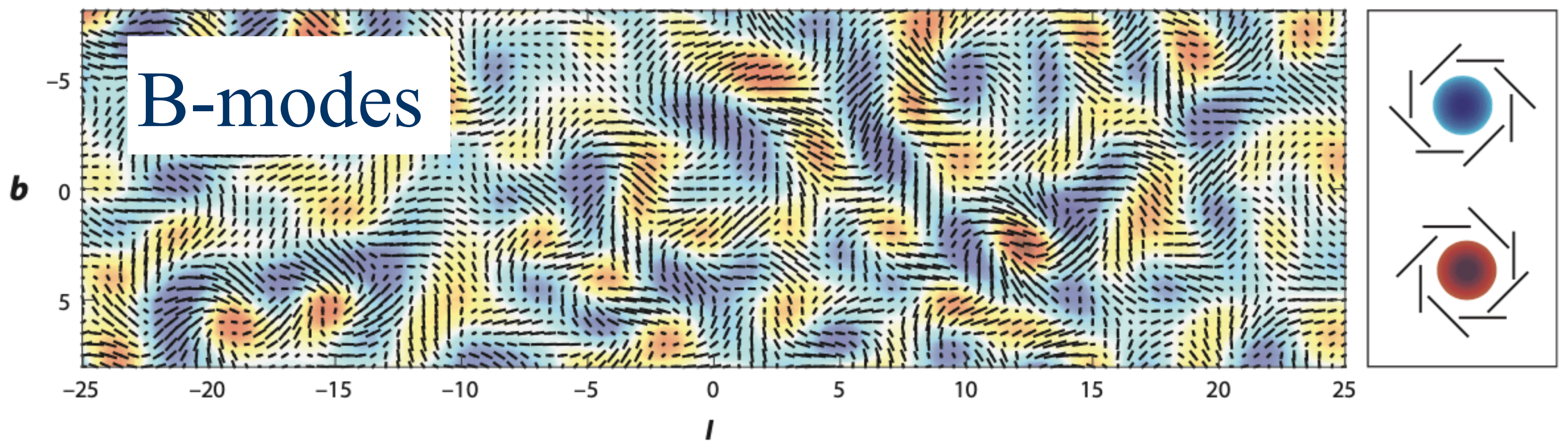
- Precise measurements **CMB polarization** helps to improve the precision on cosmological parameters, and are key for:
  - Indirect detection of **primordial gravitational waves** (tensor modes) from **inflation** (*B*-modes, *r* parameter)
  - Improve the sensitivity on τ (**reionization** history)
  - Constrain the sum of **neutrino masses**
  - Constrain parity-violation processes in the early Universe (**cosmic birefringence**)
  - … and more



$$r = 0.1 \left[\frac{V}{(2 \times 10^{16}\ \mathrm{GeV})^4} \right]$$

Energy levels close to GUT scale!

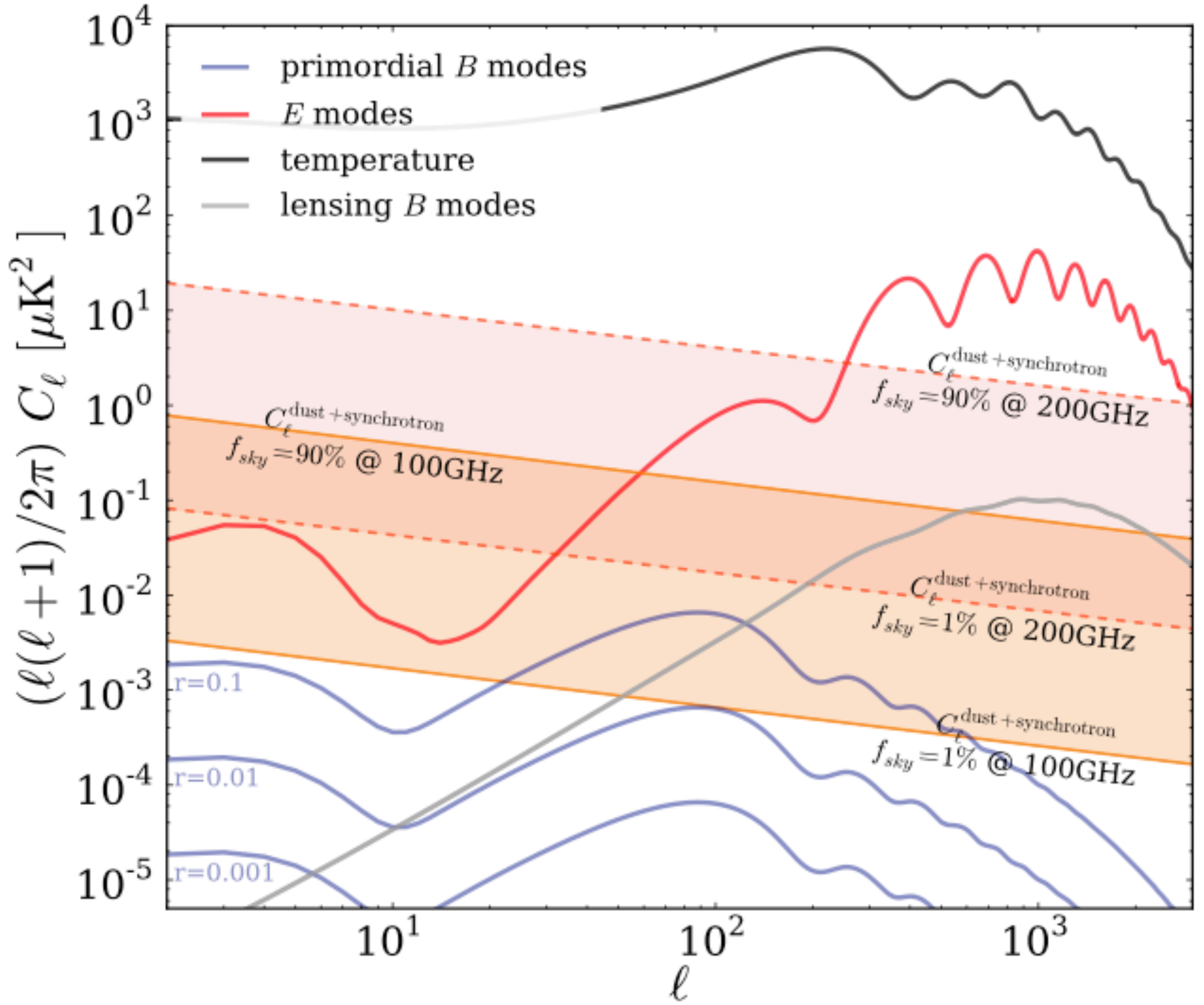




📖 Kamionkowski & Kovetz (2016)

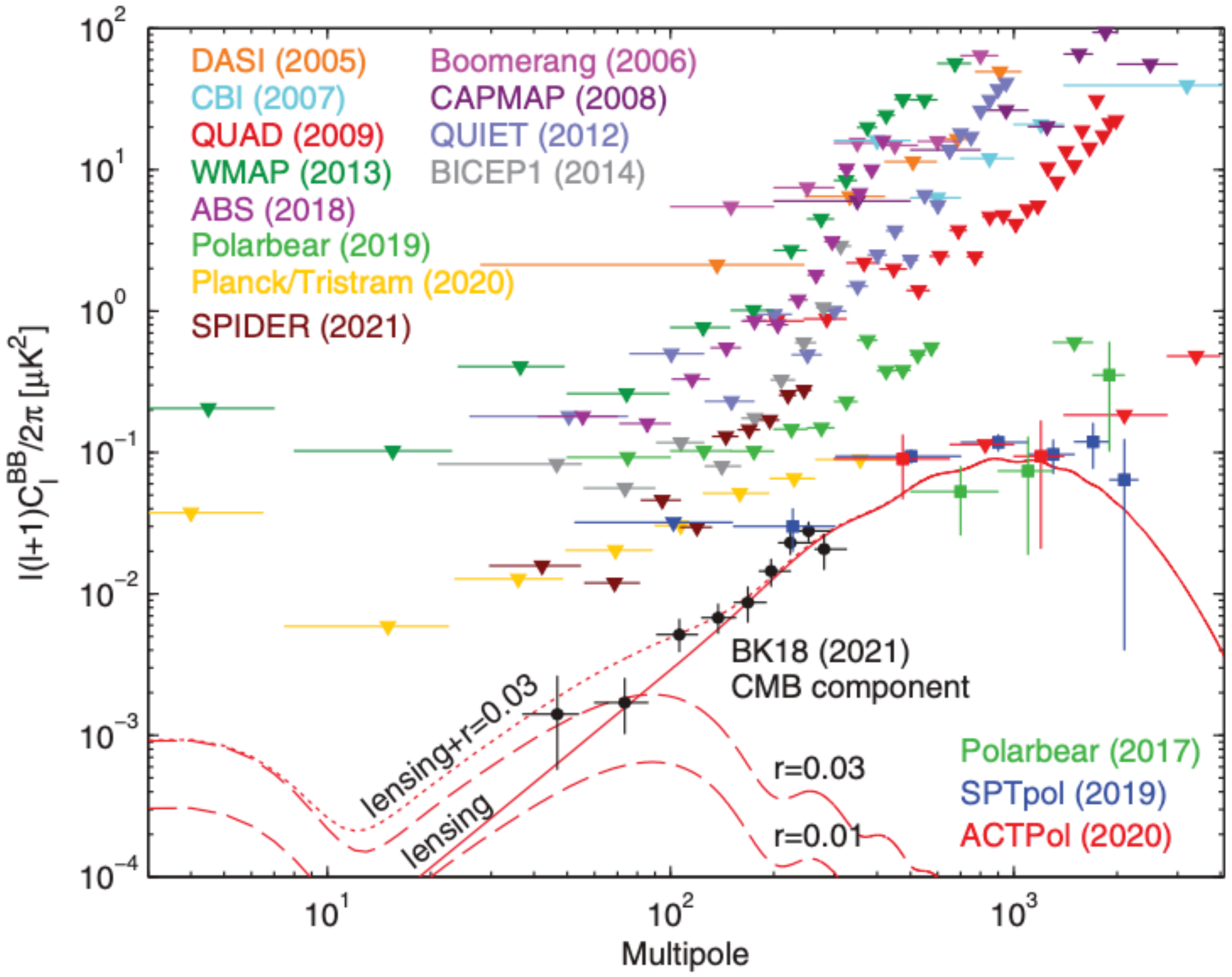
CMB polarization

- The *B*-mode signal is expected to have an amplitude at least 3 orders of magnitude below the CMB temperature anisotropies
- Faint compared with Galactic foregrounds



📖 Errard, Feeney et al. (2016)

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



📖 BICEP/Keck Collaboration (2021)

The challenge of B-modes detection

- Need **very high sensitivity** (⇒ large focal planes) and **exquisite control of systematics**, in particular:
  1. **Instrument systematic** uncertainties
  2. **Galactic foreground** contamination (⇒ wide spectral coverage)
  3. **"Lensing B-mode signal"** induced by gravitational lensing (⇒ high angular resolution)
  4. Observer biases

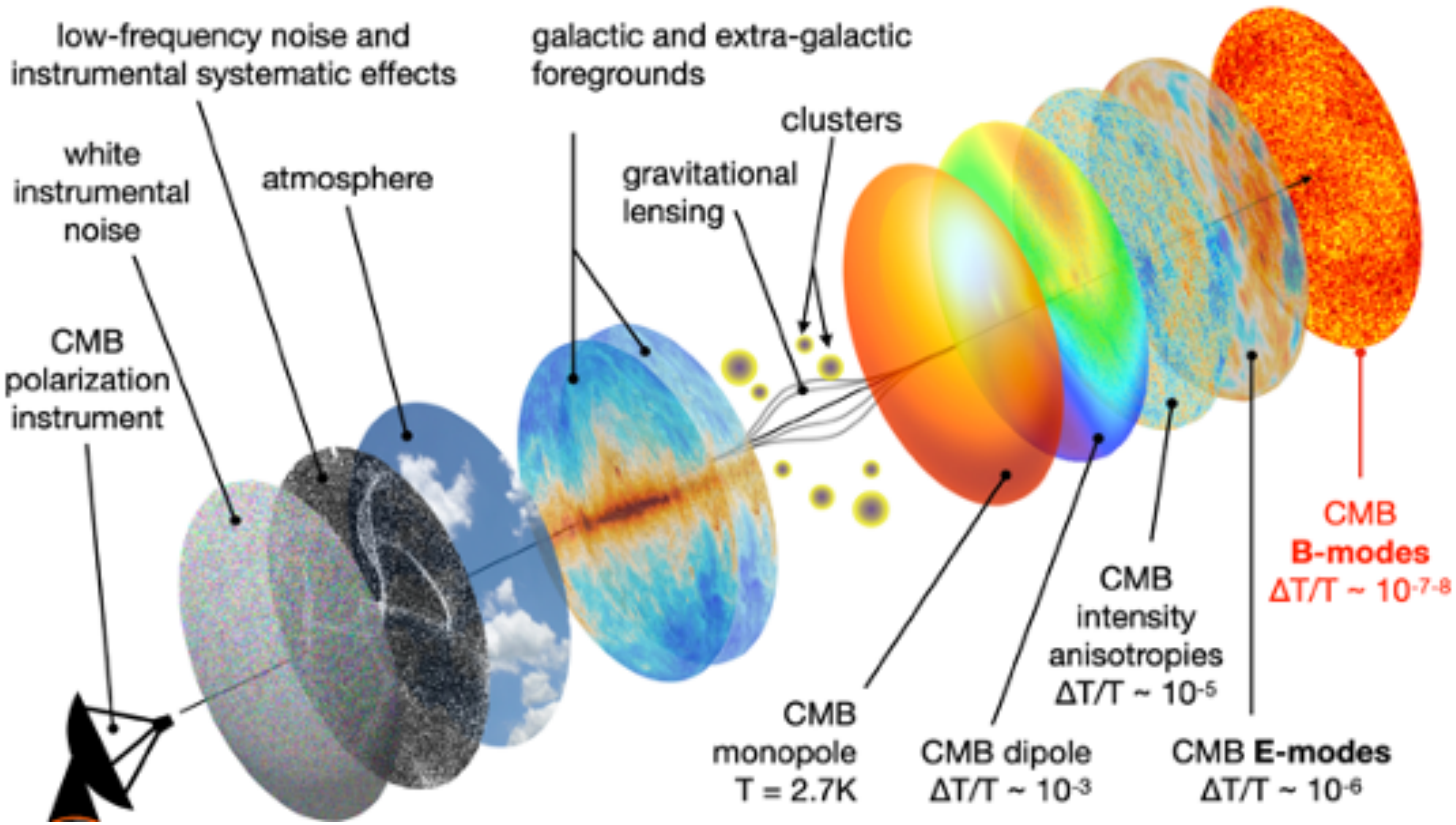
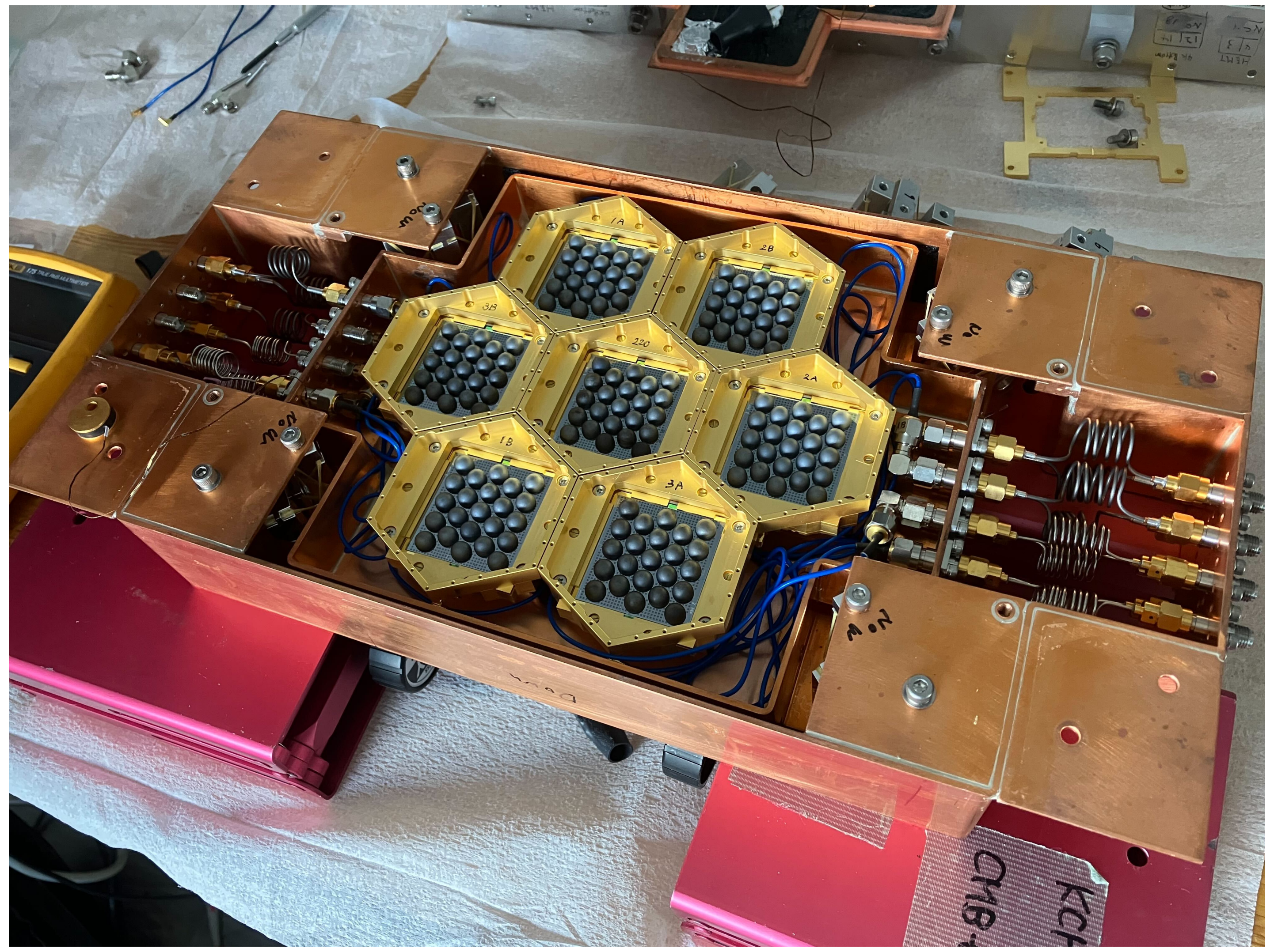
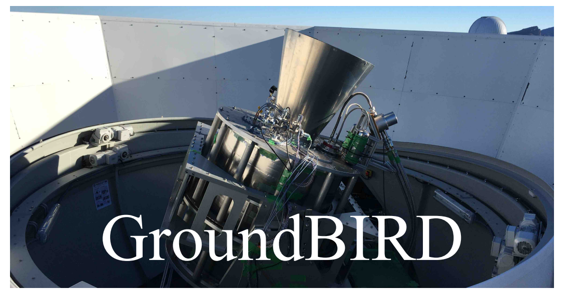


Image credit: Josquin Errard

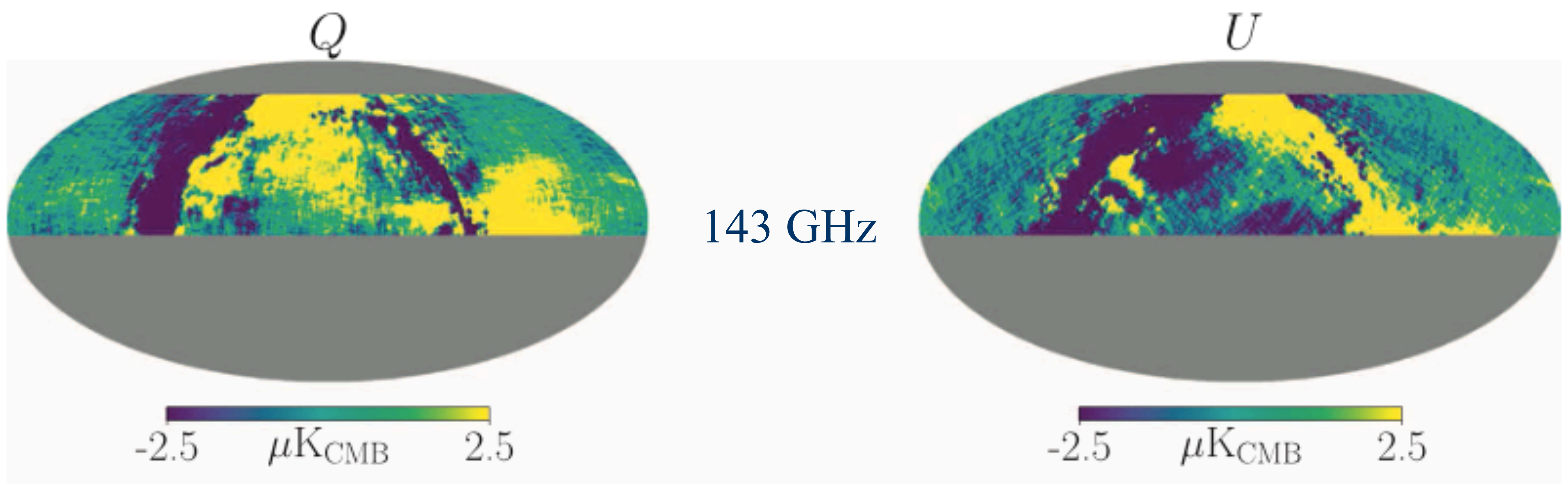
GroundBIRD

- Japan/Korea/Spain collaboration (lead: RIKEN Center for Advanced Photonics)
- Site: **Teide Observatory**
- Two frequencies: **145 GHz** and **220 GHz**
- Angular resolution: **0.5º** @ 145 GHz, **0.3º** @ 220 GHz
- Optics: cross-Dragone, FOV = ±10°
- Detectors: lens-antenna-filter couple **mKIDs** (**138** @ 145 GHz and **23** @ 220 GHz)
- Temperature **250 mK**, with cold optics at 4 K
- Scan speed: **120º/sec** (20 rpm)
- Sky coverage: **fsky ~0.45**
- Goals: large angular scales ⇒ **reionization** and **recombination bumps**

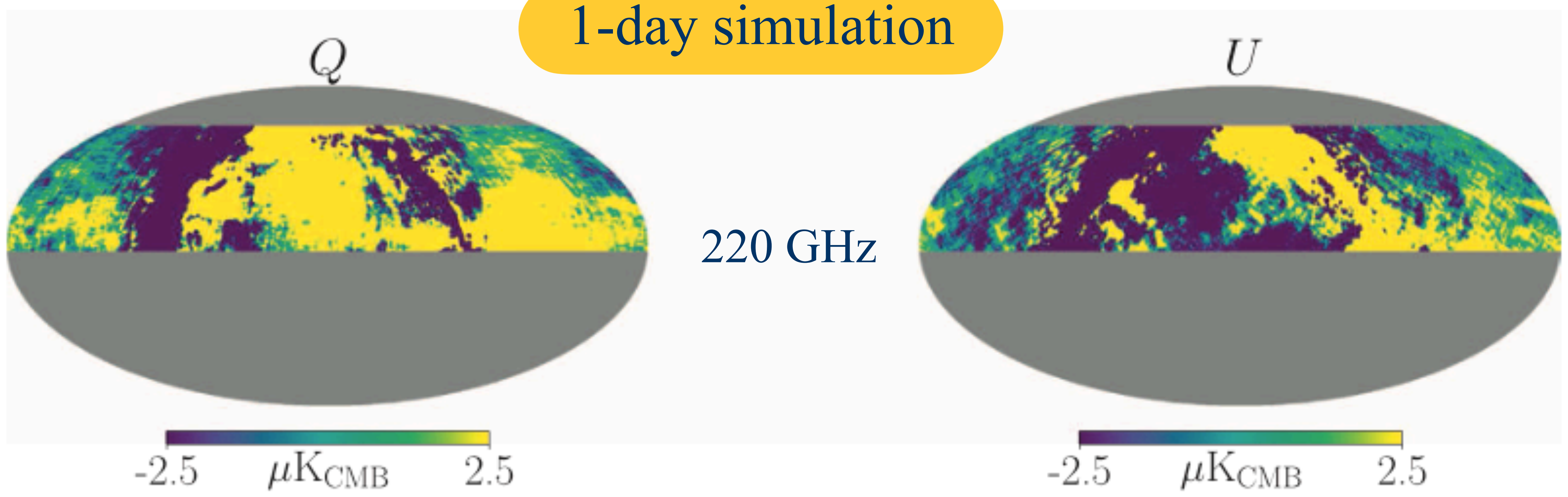




- A **3-year survey** with the current configuration will allow reaching **$\sigma(\tau) = 0.012$**

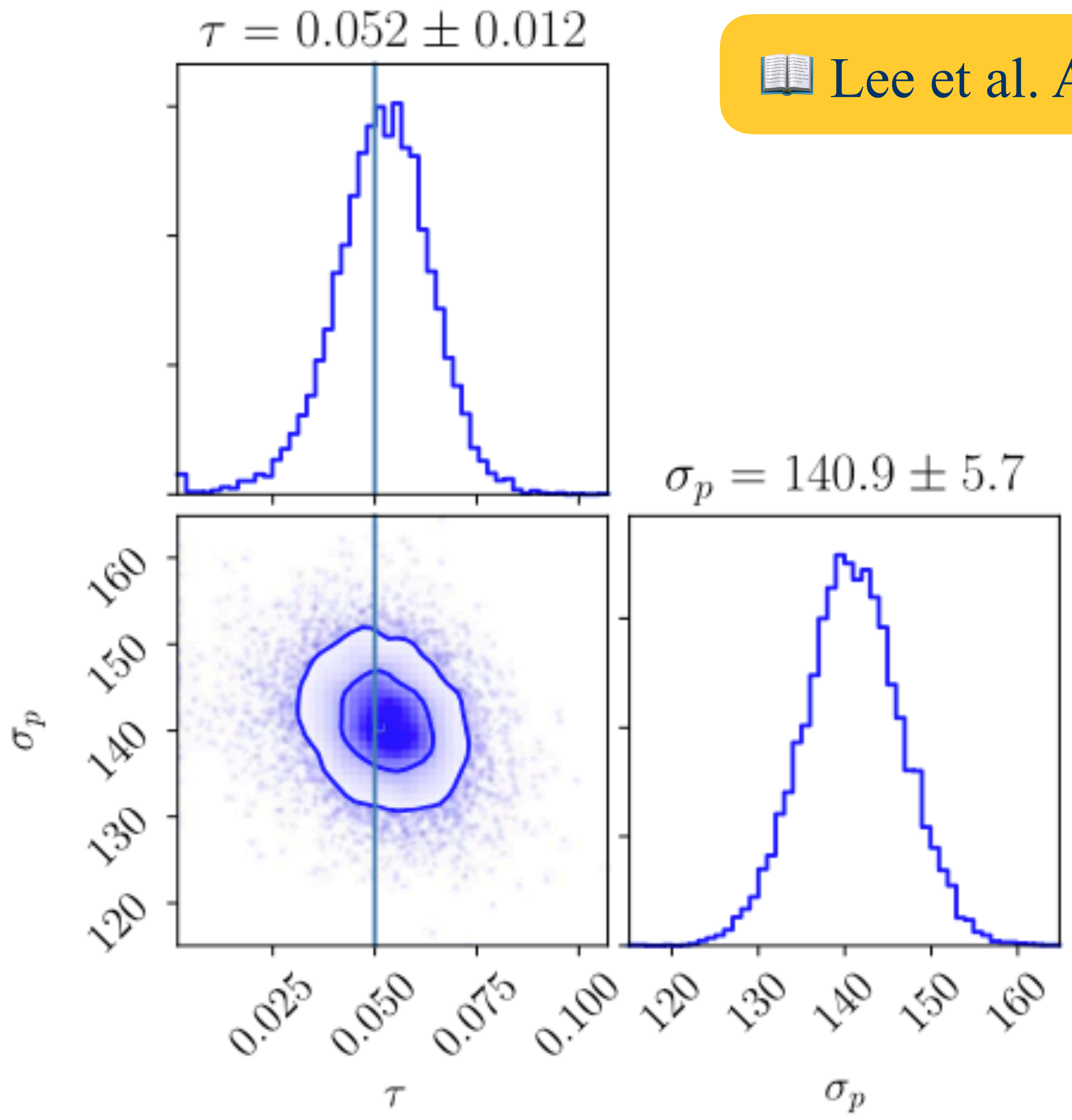


1-day simulation



Noise sensitivities for a 3-year survey

	145 GHz	220 GHz
Number of detectors	138	23
Sky coverage	0.537	0.462
Mean observation time (s arcmin^{-2})	**0.83**	**0.97**
NET (μK $\sqrt{s}$)	**820**	**2600**
Pixel noise level (μK arcmin)	**110**	**780**



📖 Lee et al. ApJ, 915, 2021

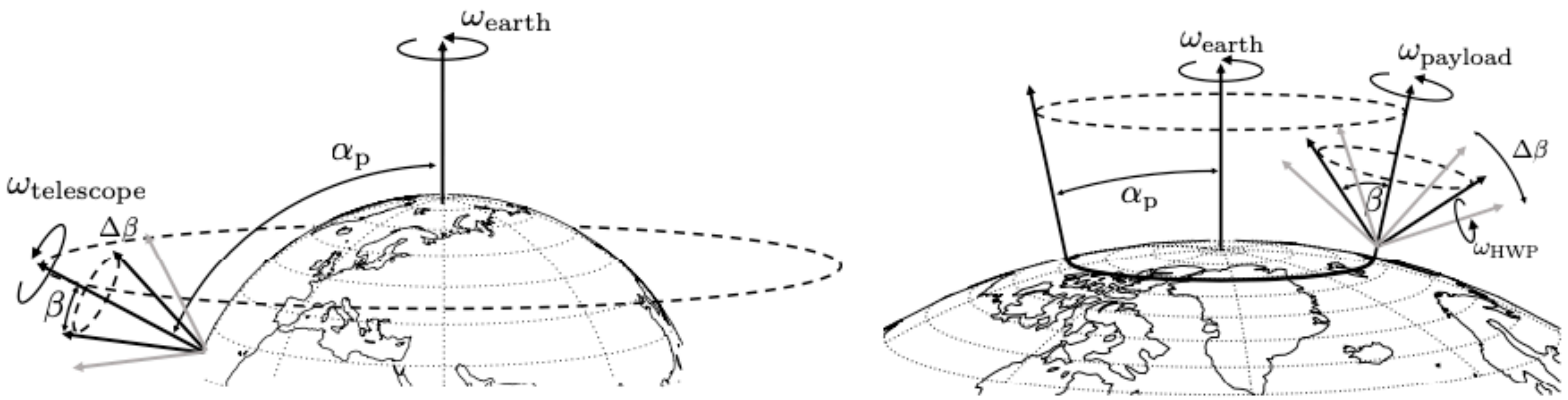
LSPE-Strip

📖 LSPE collaboration, JCAP008, 2021

- Large Scale Polarization Explorer (**LSPE**):
  - Ground-based observations at low-frequencies (**Strip**)
  - Stratospheric flight to cover the highest frequencies (**SWIPE**)

- **Strip**:
  - Site: **Teide Observatory**
  - Frequencies: 49 polarimeters @ **43 GHz** and 6 polarimeters @ **95 GHz**
  - HEMT technology
  - $f_{sky} \approx 0.3$
  - Operation plan: 2025-2027

Instrument	Strip		SWIPE		
Site	Tenerife		balloon		
Freq (GHz)	43	95	145	210	240
Bandwidth	17%	8%	30%	20%	10%
Angular resolution FWHM	20′	10′	85′		
Field of view	±5°		±11°		
Detector technology	HEMT		Multi-moded TES		
Number of polarimeters (Strip)/detectors (SWIPE)	49	6	162	82	82
NET ($\mu K_{CMB}\, s^{1/2}$)	515	1139	12.6	15.6	31.4
Observation time	2 years		8–15 days		
Observing efficiency	50%,[1]		90%		
Sky coverage[2] (nominal) $f_{sky,0}$	28%		38%		
Sky coverage[2] (this paper) f_{sky}	50%		38%		
Masked sky coverage for CMB analysis $f_{sky,cmb}$	25%		25%		
Map sensitivity (nominal) $\sigma_{Q,U,0}$ (μK_{CMB} arcmin)	102	777	10	17	34
Map sensitivity (this paper) $\sigma_{Q,U}$ (μK_{CMB} arcmin)	130	990	10	17	34
Noise power spectrum $(\mathcal{N}_\ell^{E,B})^{1/2}$ (μK_{CMB} arcmin)	260	1980	20	34	68

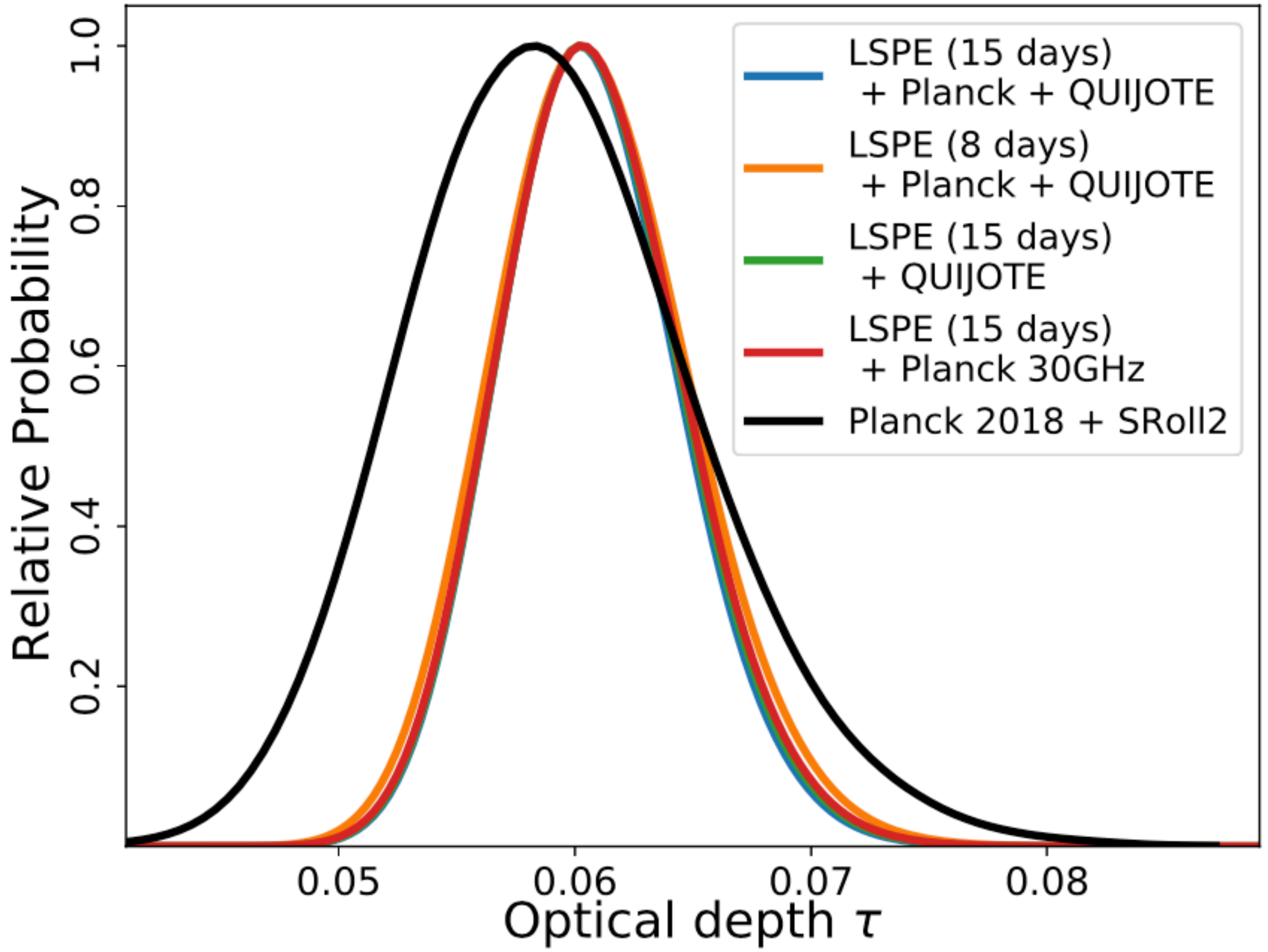


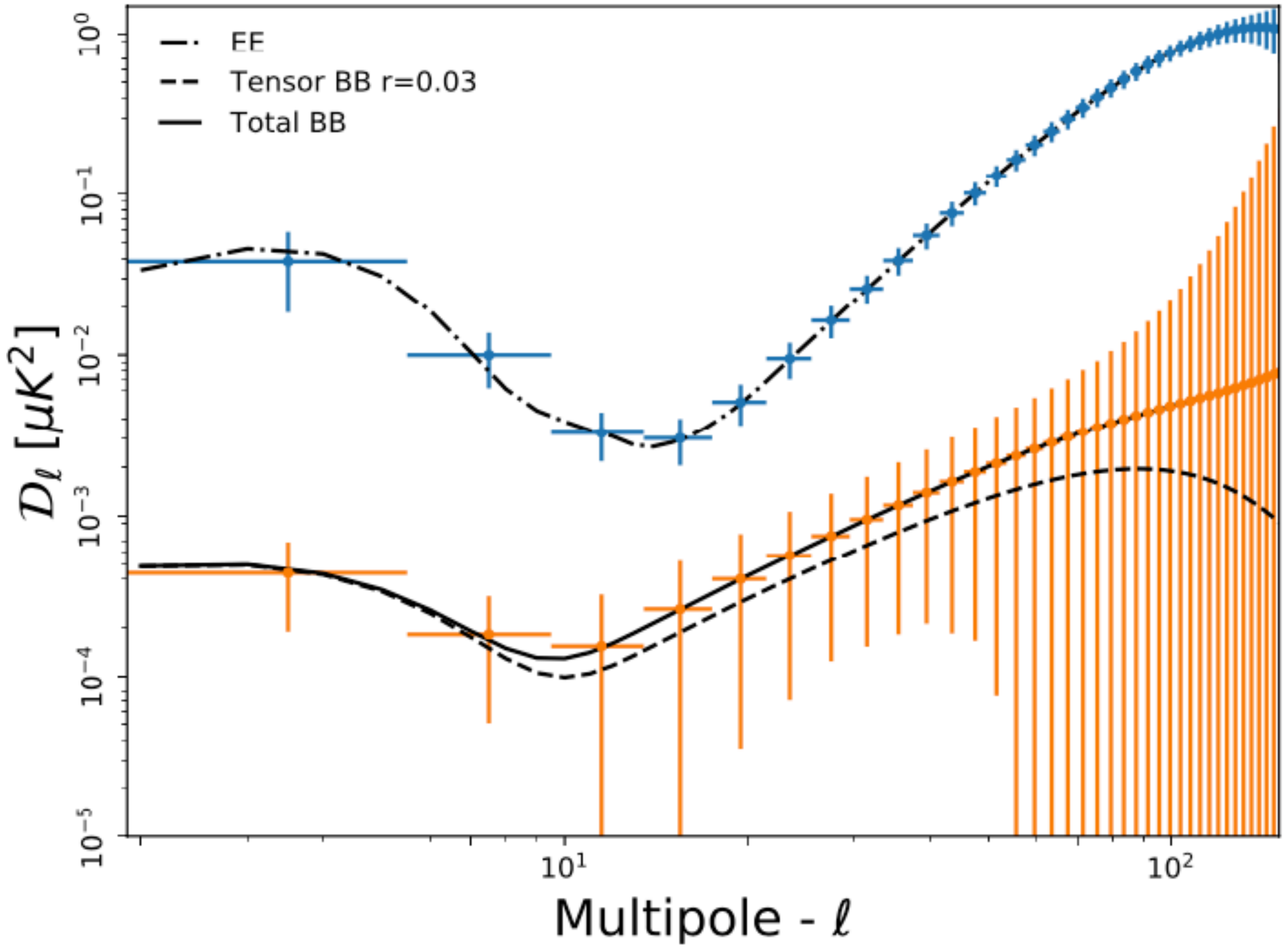
LSPE-Strip

Large Scale Polarization Explorer

Expected sensitivity on the optical depth to reionization: $\sigma(\tau) \approx 0.004$

Expected sensitivity on the *B*-mode amplitude: $\sigma(r) \approx 0.015$



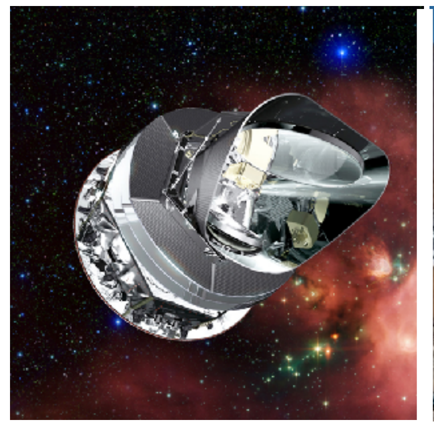


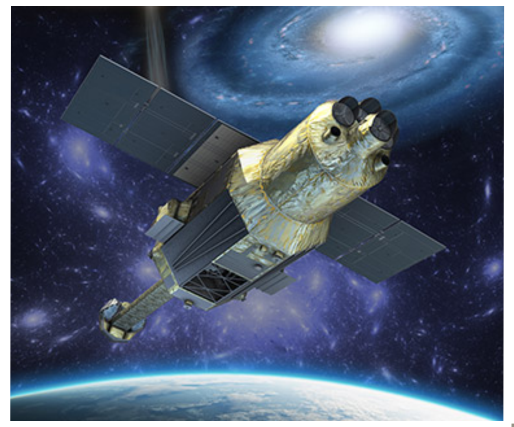
📖 LSPE collaboration, JCAP008, 2021

LiteBIRD Joint Study Group

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

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



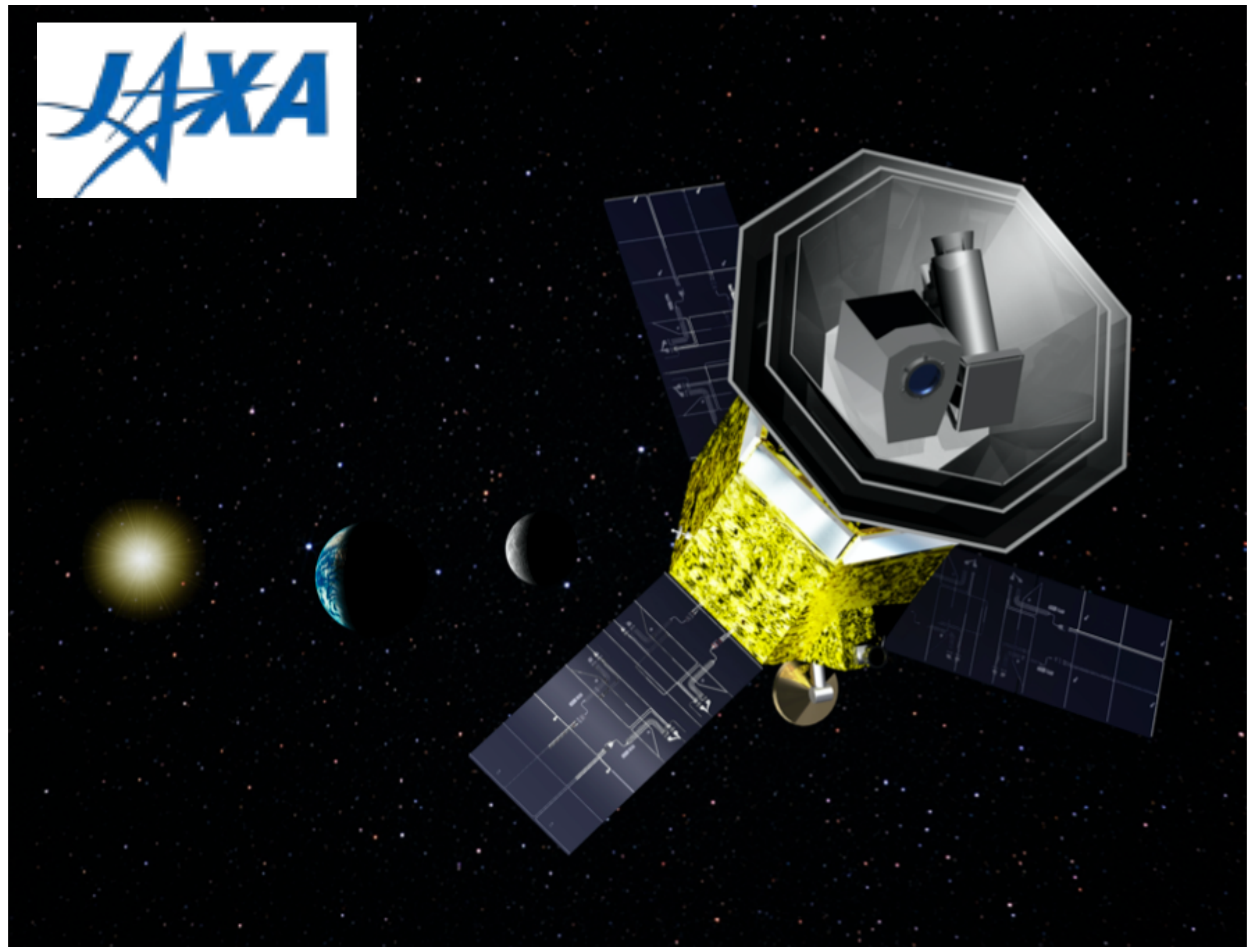


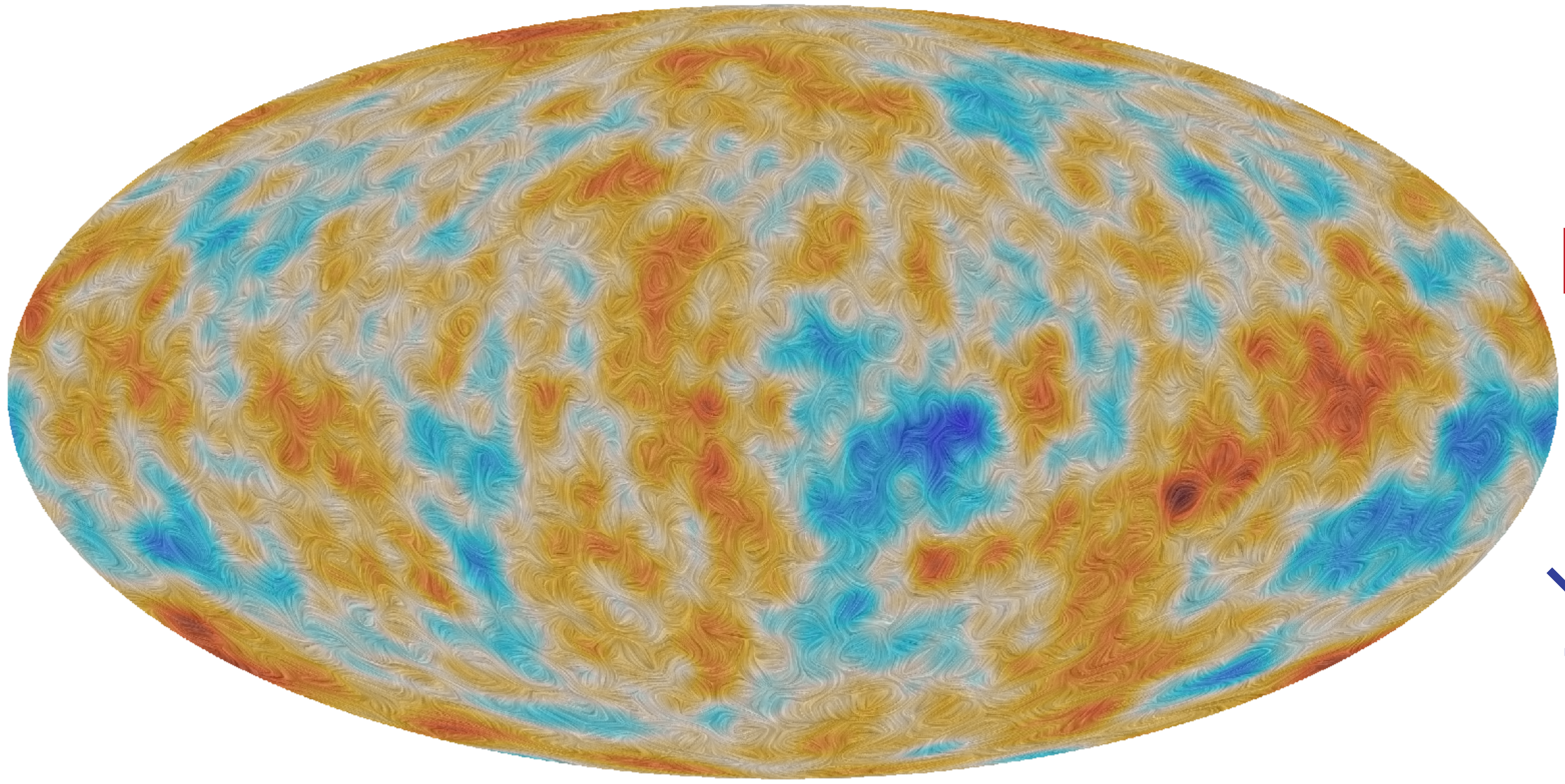
LiteBIRD Global F2F meeting
Sep 28 - Oct 1, 2023 at Elba

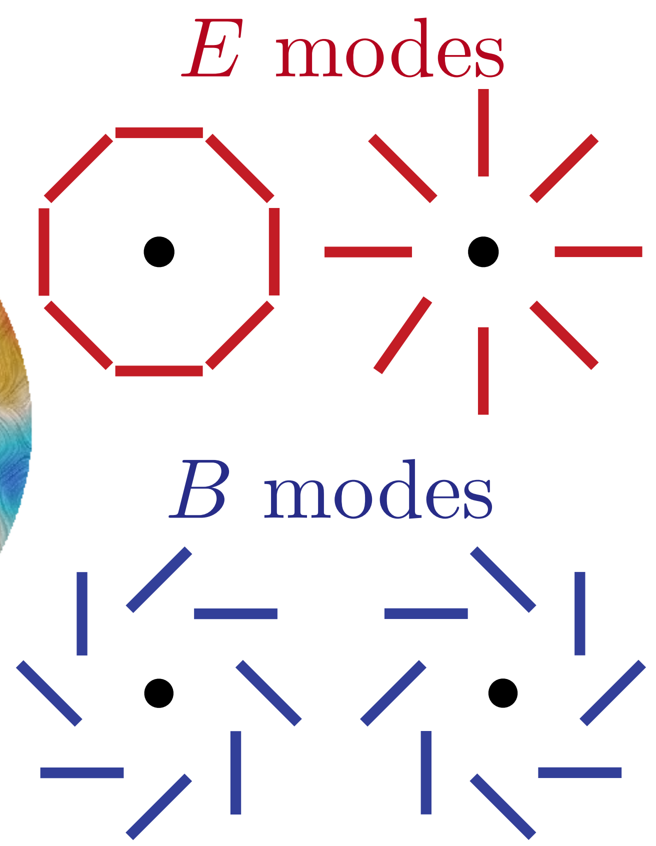
LiteBIRD overview

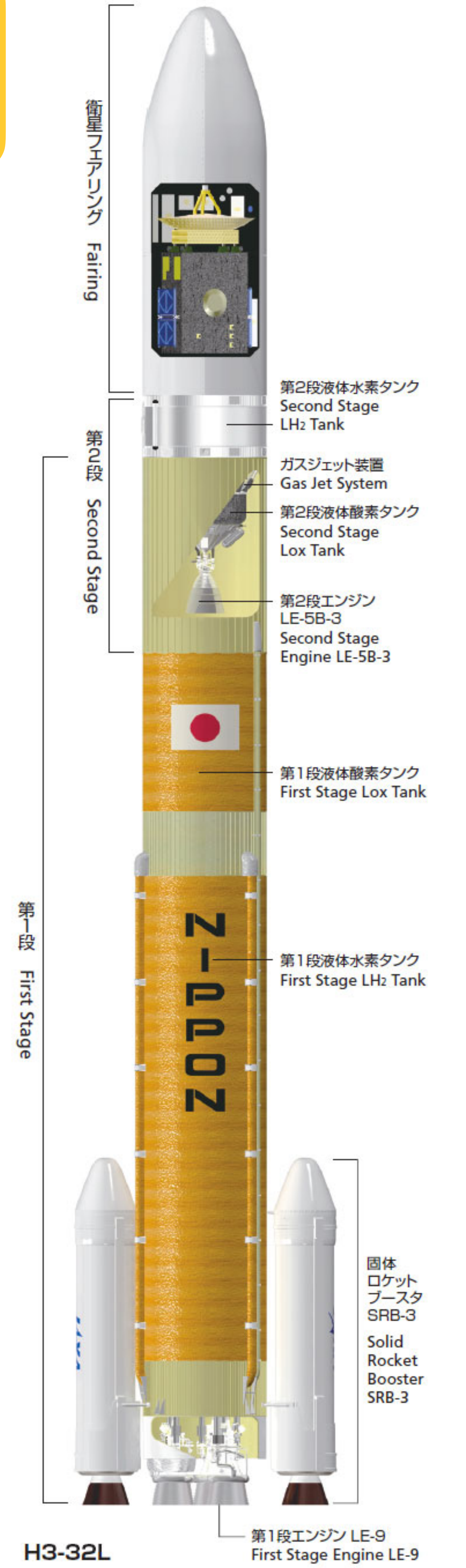
- Lite (Light) satellite for the study of *B*-mode polarization and Inflation from cosmic background Radiation Detection
- JAXA’s L-class mission selected in May 2019
- Expected launch in **JFY 2032** with JAXA’s H3 rocket
- **All-sky 3-year survey**, from Sun-Earth Lagrangian point L2
- Large frequency 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 collaboration PTEP 2023





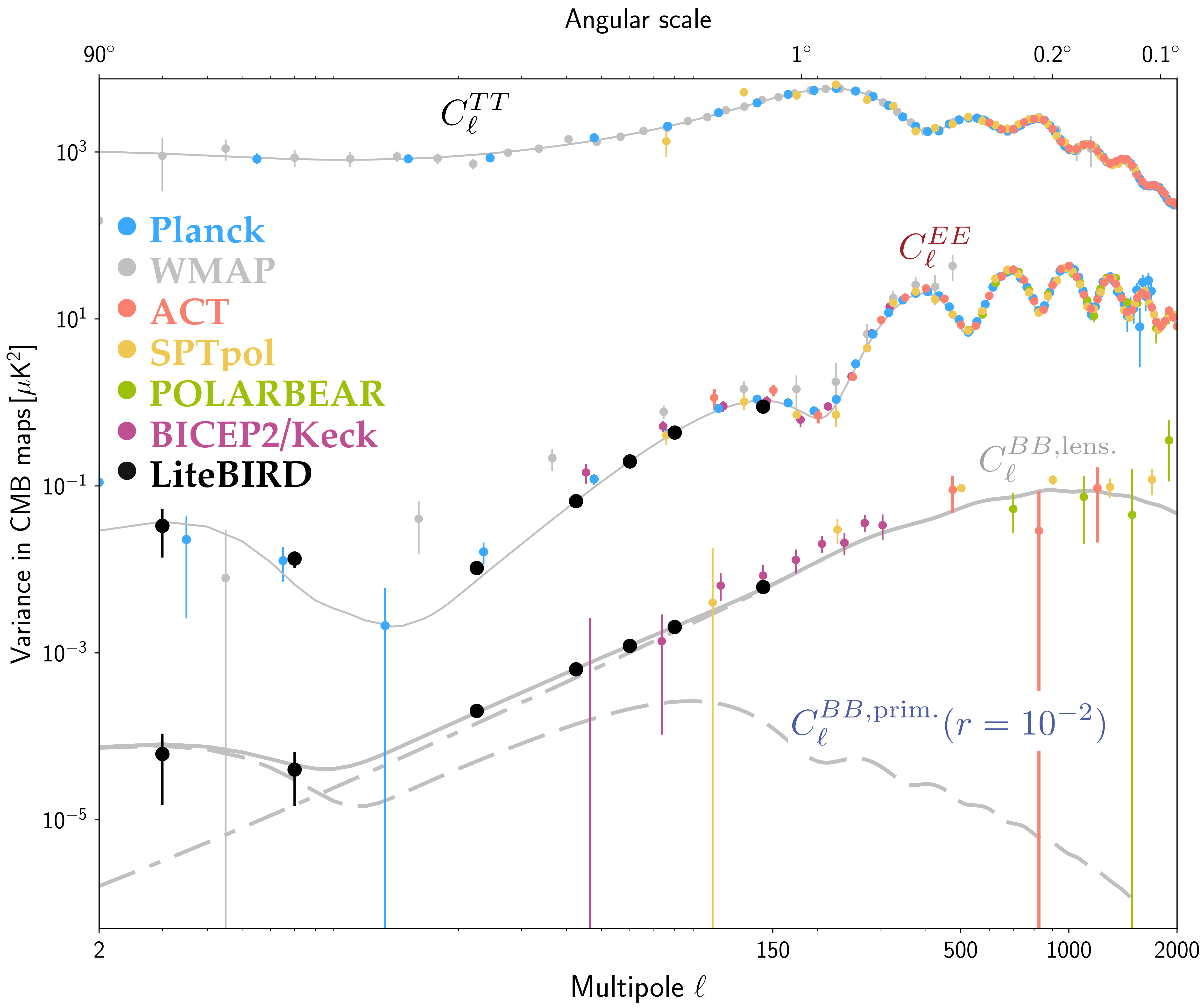




LiteBIRD main scientific objectives

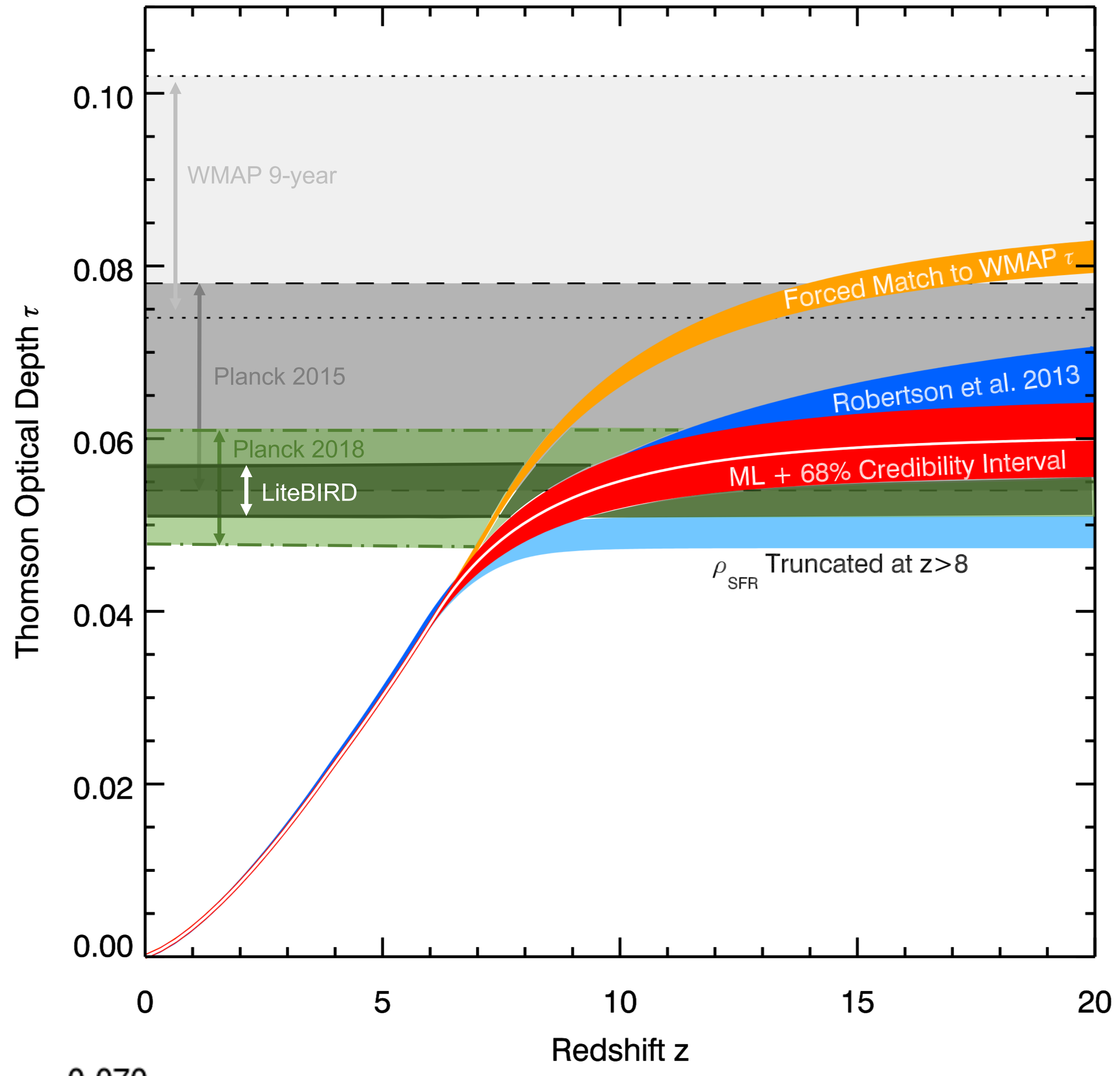
- Definitive search for the ***B*-mode signal** from **cosmic inflation** in the CMB polarization
  - Making a discovery or ruling out well-motivated inflationary models
  - Insight into the quantum nature of gravity
- The inflationary (i.e. primordial) B-mode power is proportional to the **tensor-to-scalar 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 ~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
- L2-requirements:
  - $\sigma_{stat} < 6\times10^{-4}$ and $\sigma_{sys} < 6\times10^{-4}$
  - Additional security margin of $\sigma_{margin} < 6\times10^{-4}$

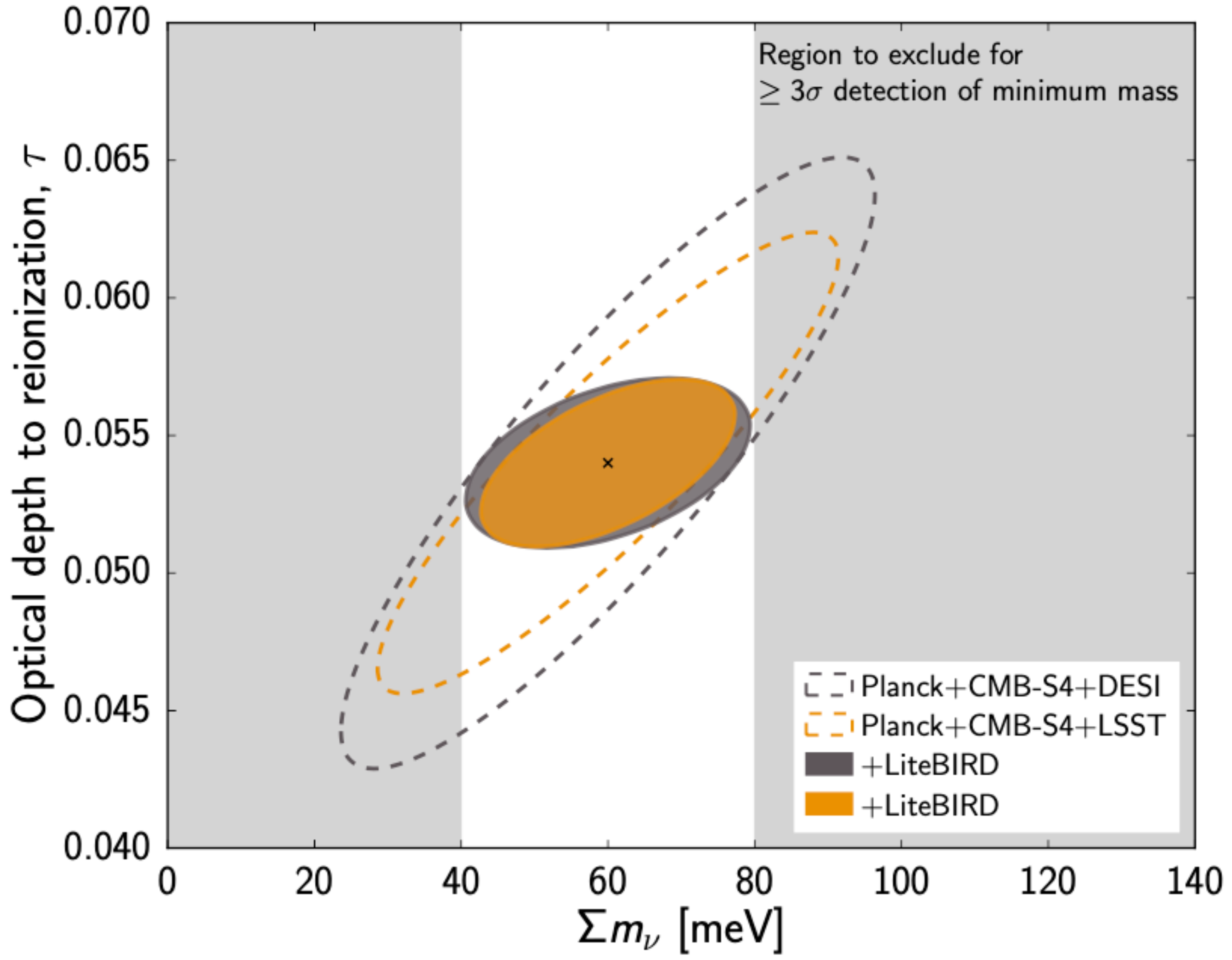


LiteBIRD other science outcomes

- 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



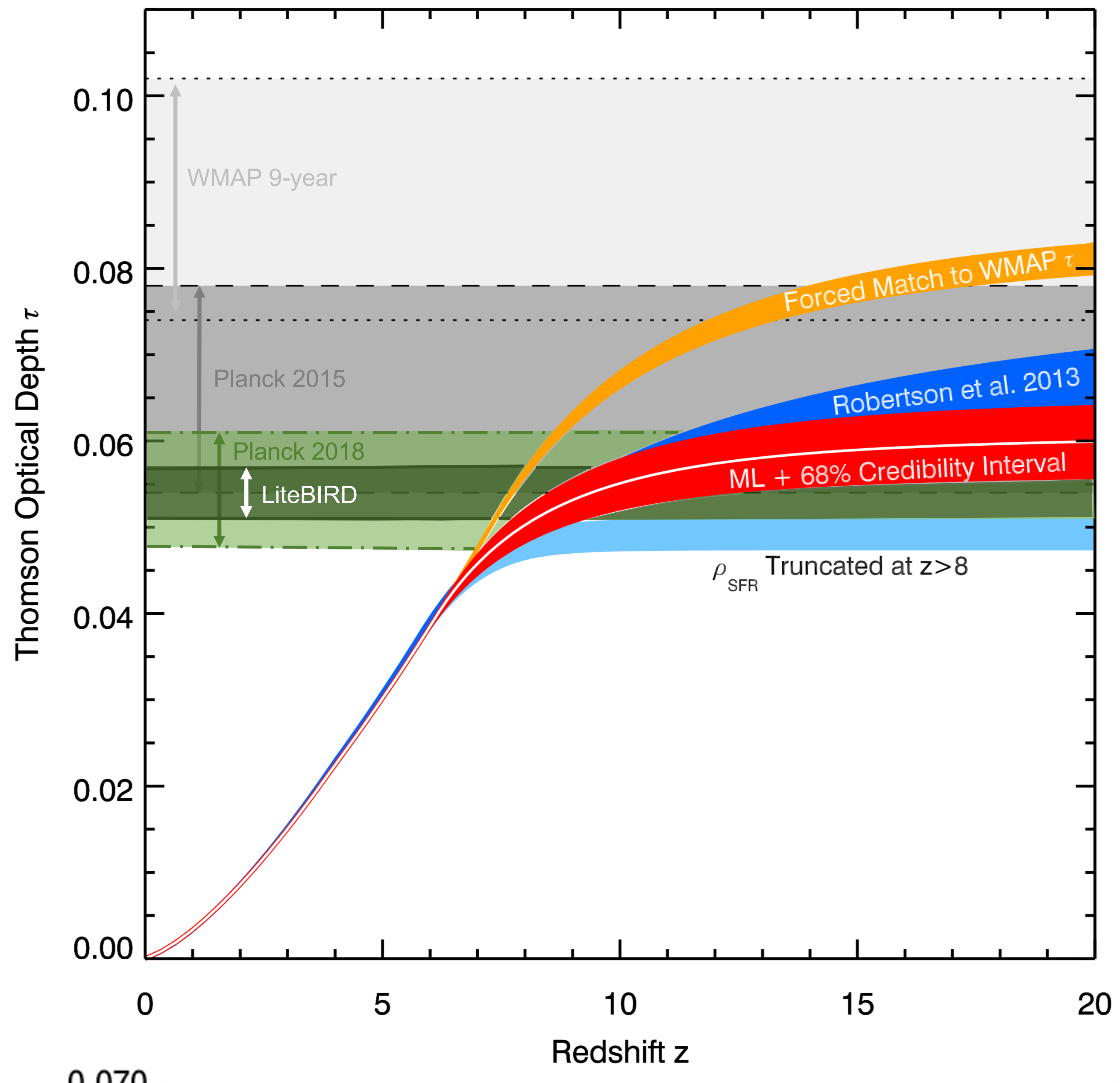
adapted from Robertson+2015



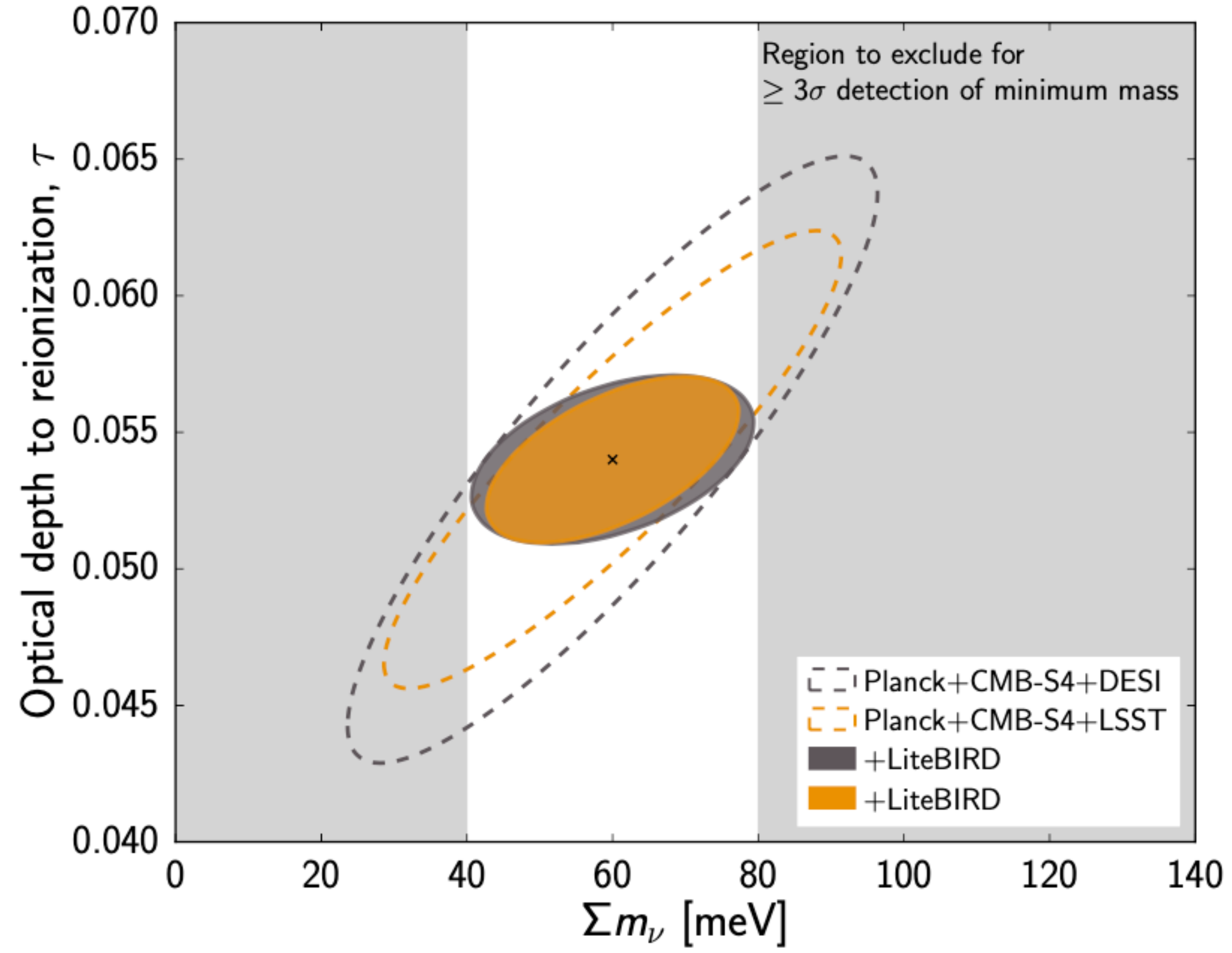
adapted from Calabrese+2017

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 $\Delta(z_{\text{reion}})$
  - **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



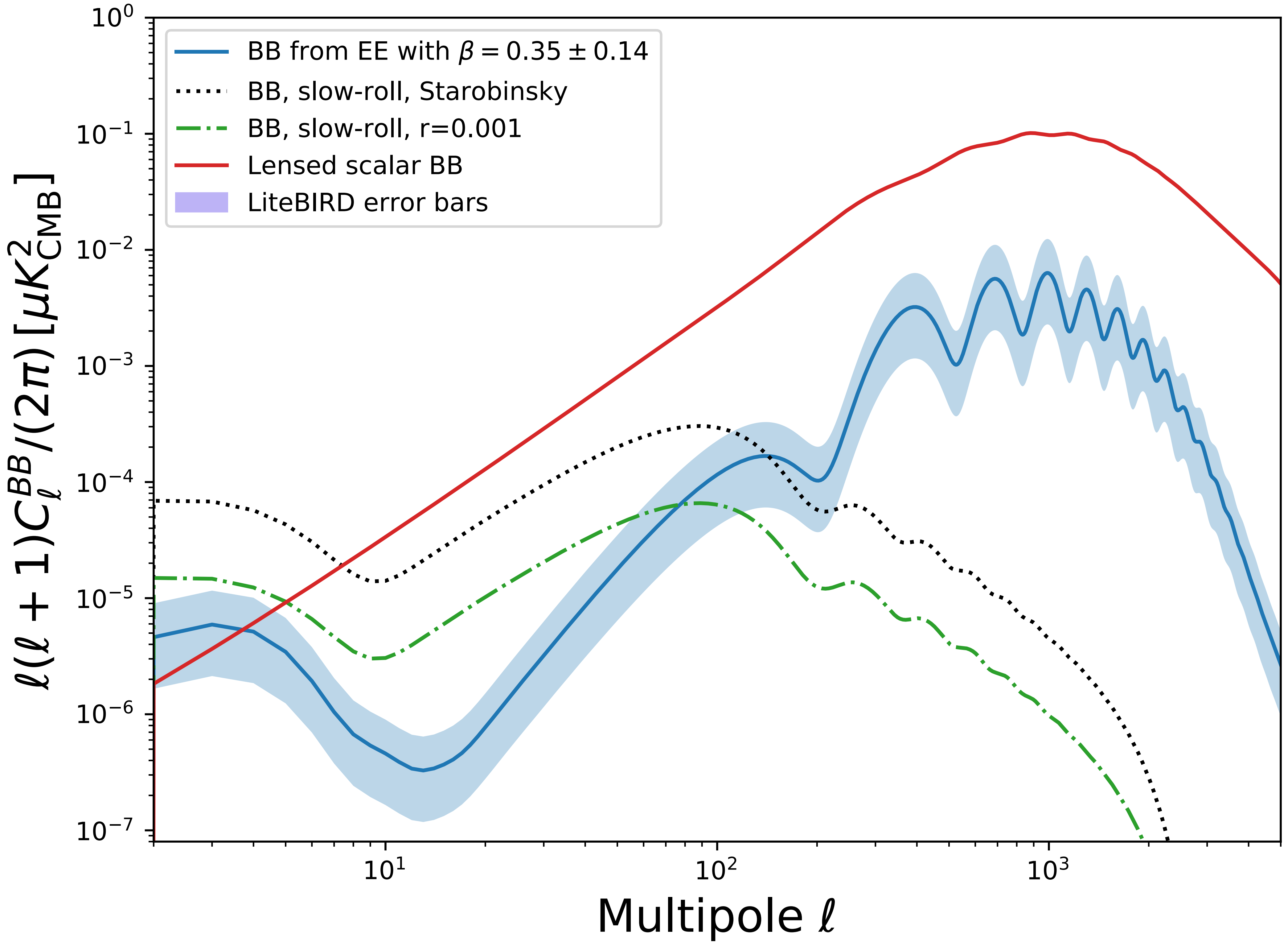
📖 adapted from Robertson+2015



📖 adapted from Calabrese+2017

Constraints on cosmic birefringence

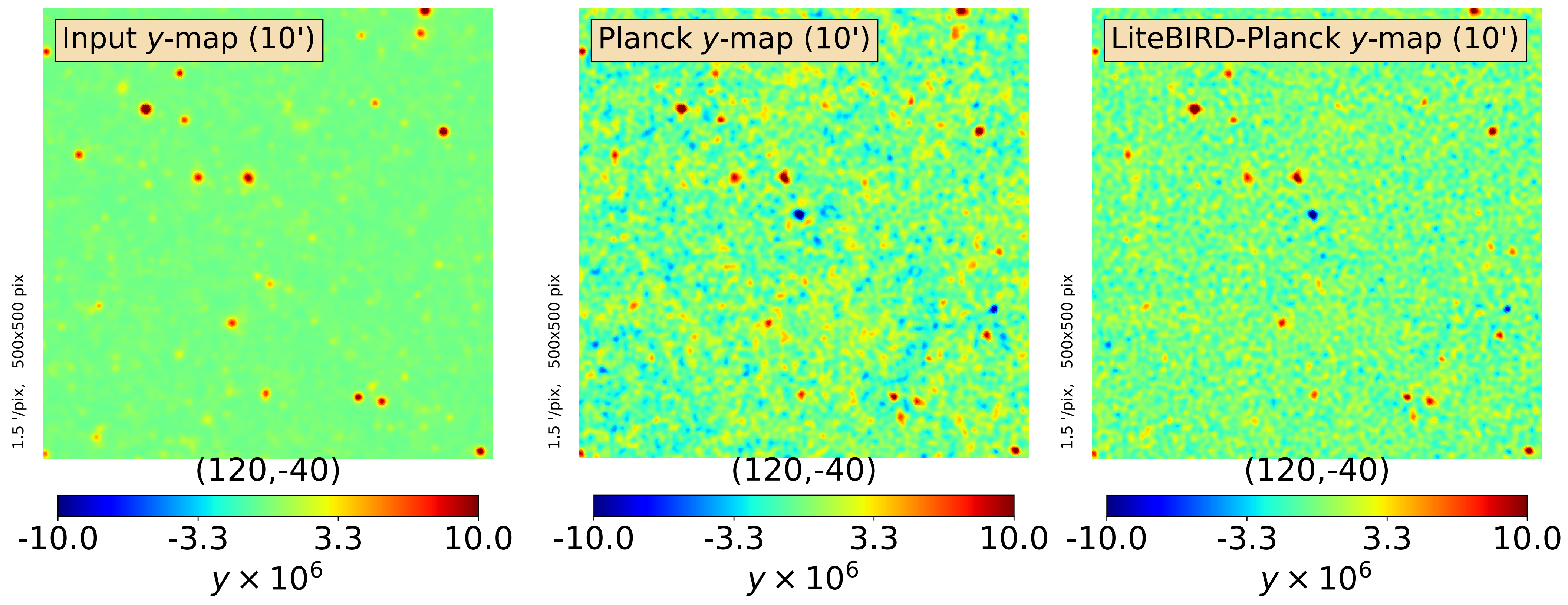
- **Cosmic birefringence** could be seeded by parity-violating processes in Universe
- Could occur if dark matter or dark energy are a pseudo-scalar field coupled to electromagnetism that changes sign under inversion of spatial coordinates
- Induces non-zero *TB* and *EB* and also a *B*-mode signal
- 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**

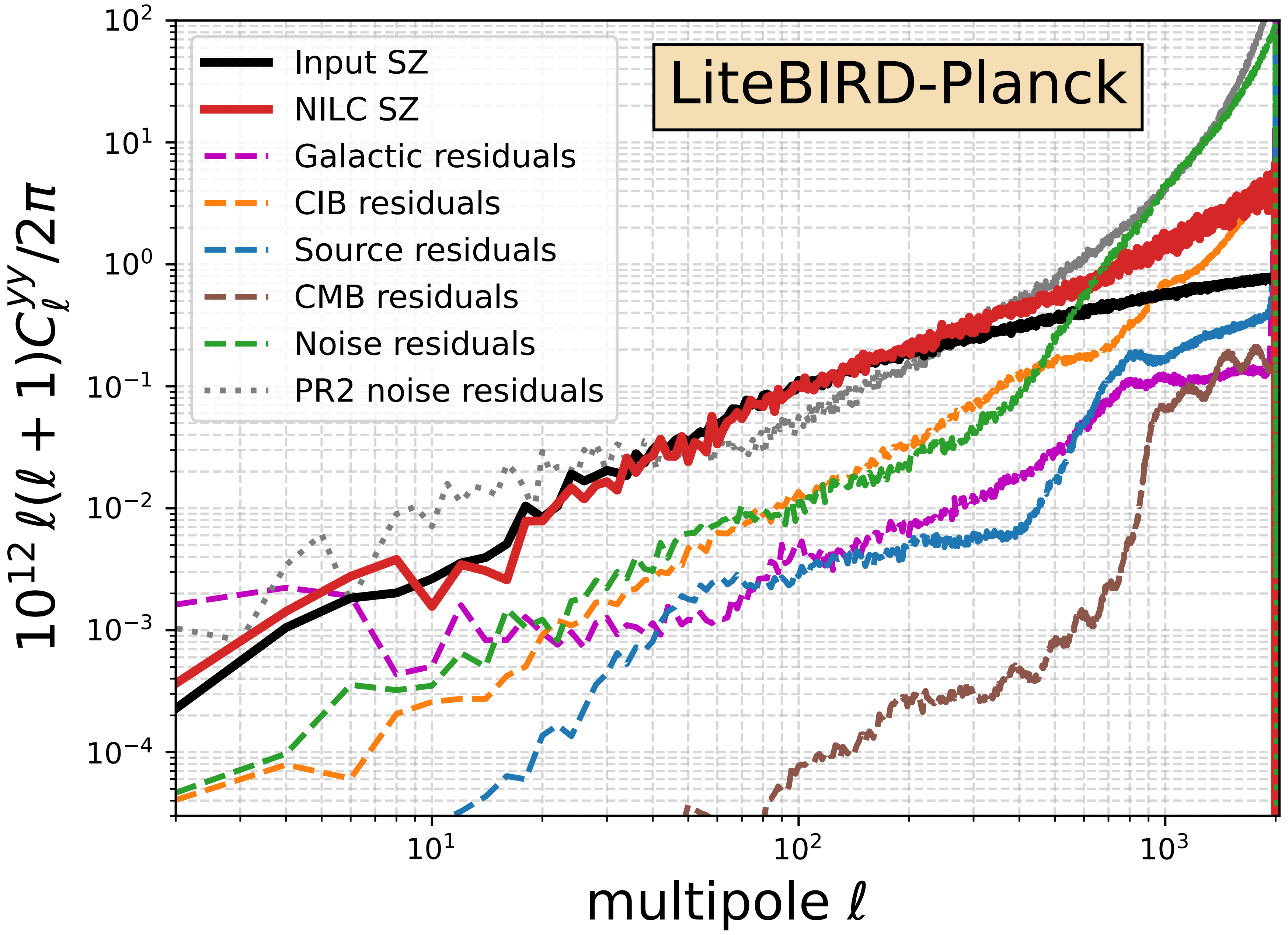


📖 LiteBIRD collaboration PTEP 2023

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%

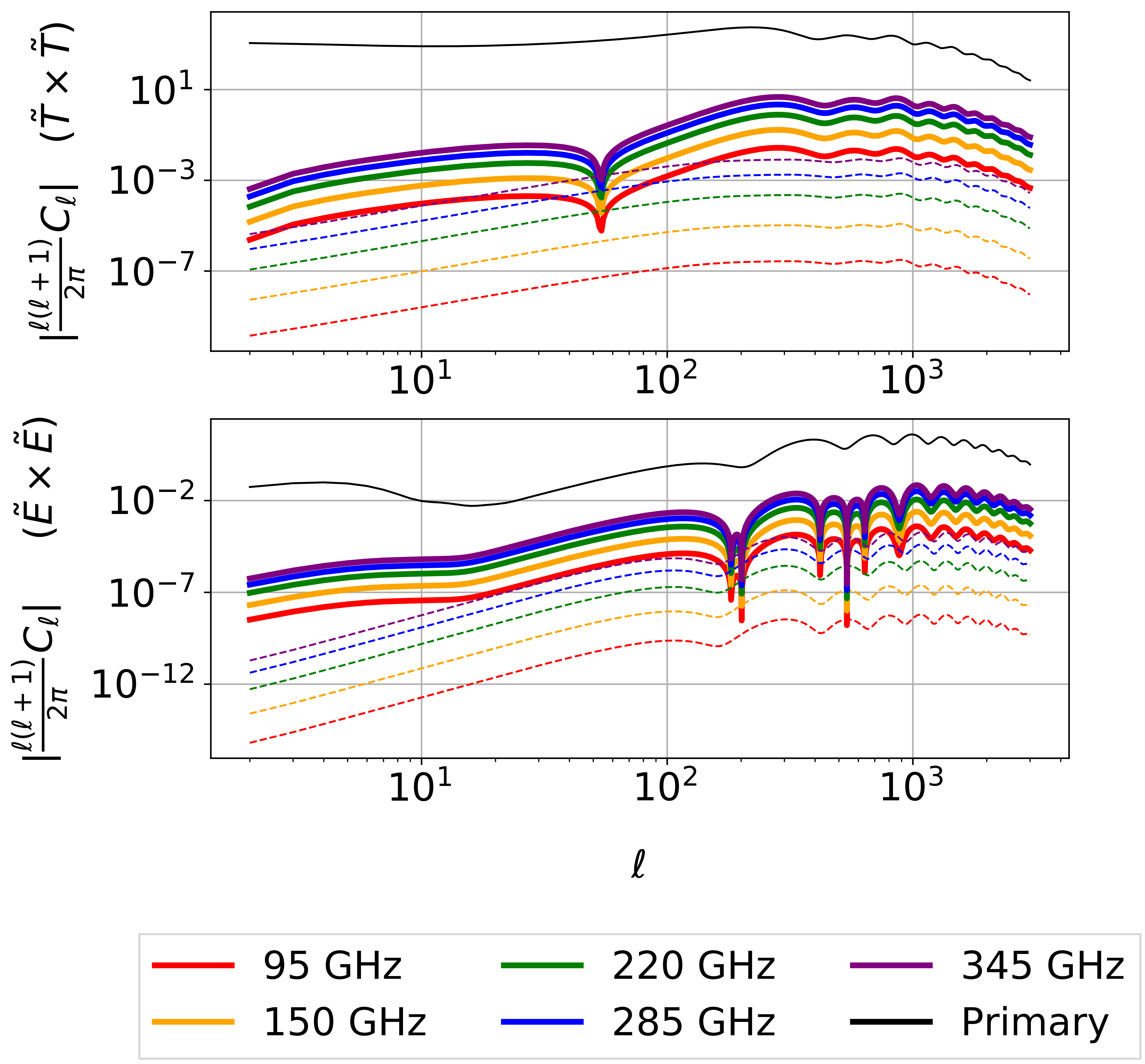




📖 Remazeilles+ JCAP 2024

Anisotropic CMB spectral distortions

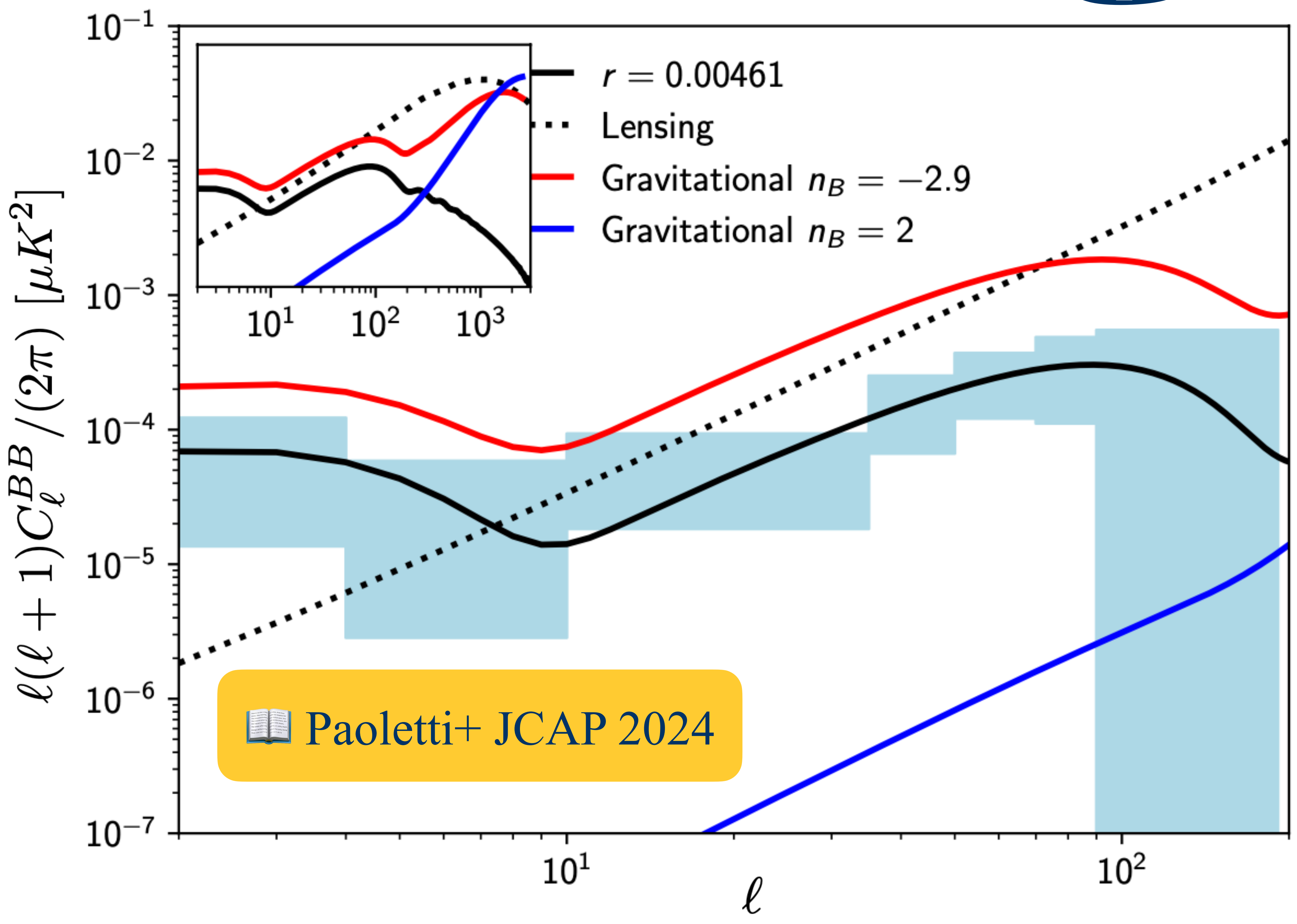
- LiteBIRD will be sensitive to any **spatially-varying CMB spectral distortion**, beyond the SZ effect
  - **Rayleigh scattering**. LiteBIRD will have sensitivity to measure at **25-sigma** (📖 Beringue et al. 2021) the frequency-dependent CMB anisotropies due to Rayleigh scattering by HI at the LSS
    - ➡ 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

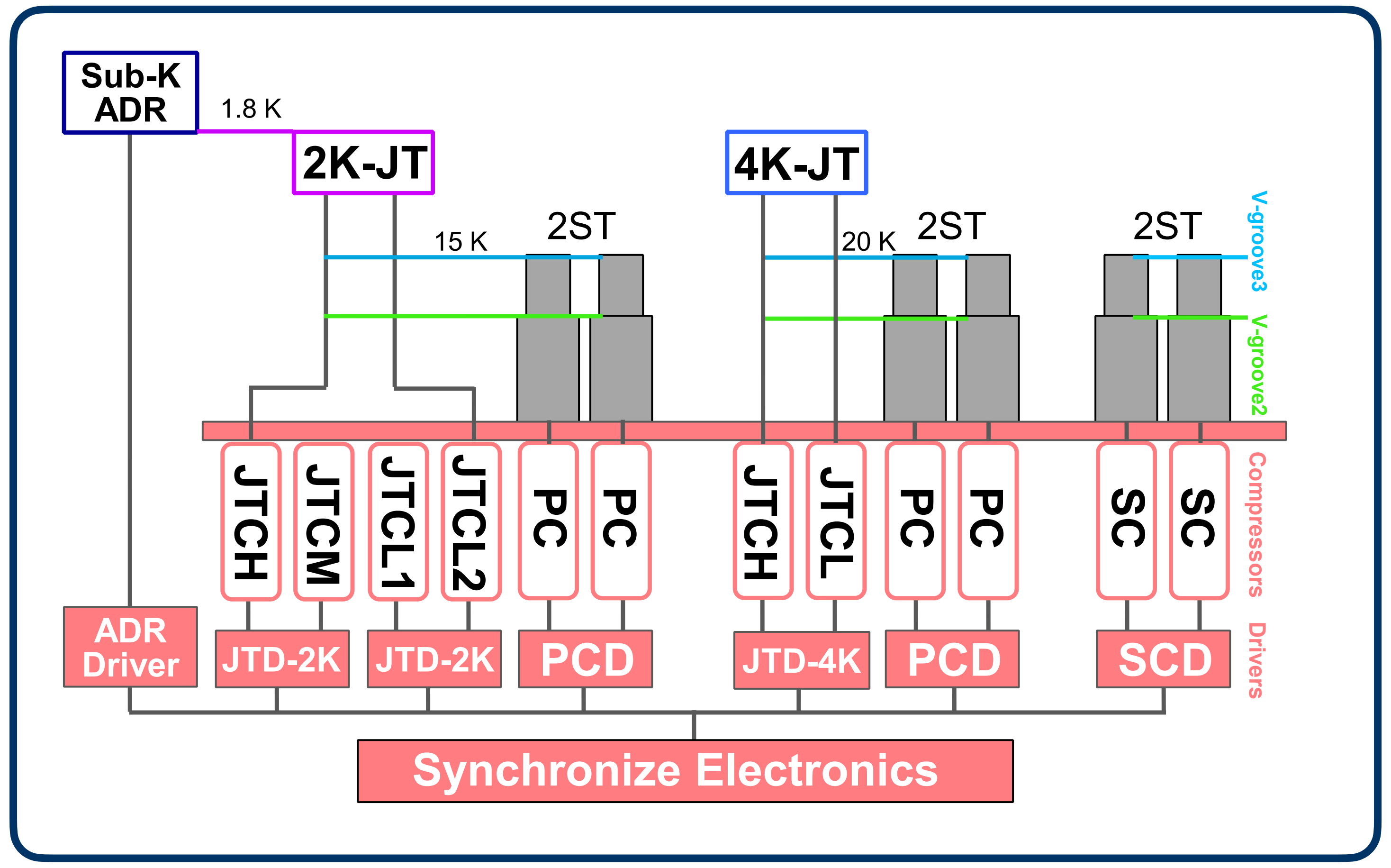
- Primordial magnetic fields (PMFs) affect the CMB via different effects:
  - **Gravitational effects** with magnetically-induced perturbations
  - Impact on the **ionization history** of the Universe due to their post-recombination dissipation
  - Induce a **Faraday rotation** of the CMB polarization
  - **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

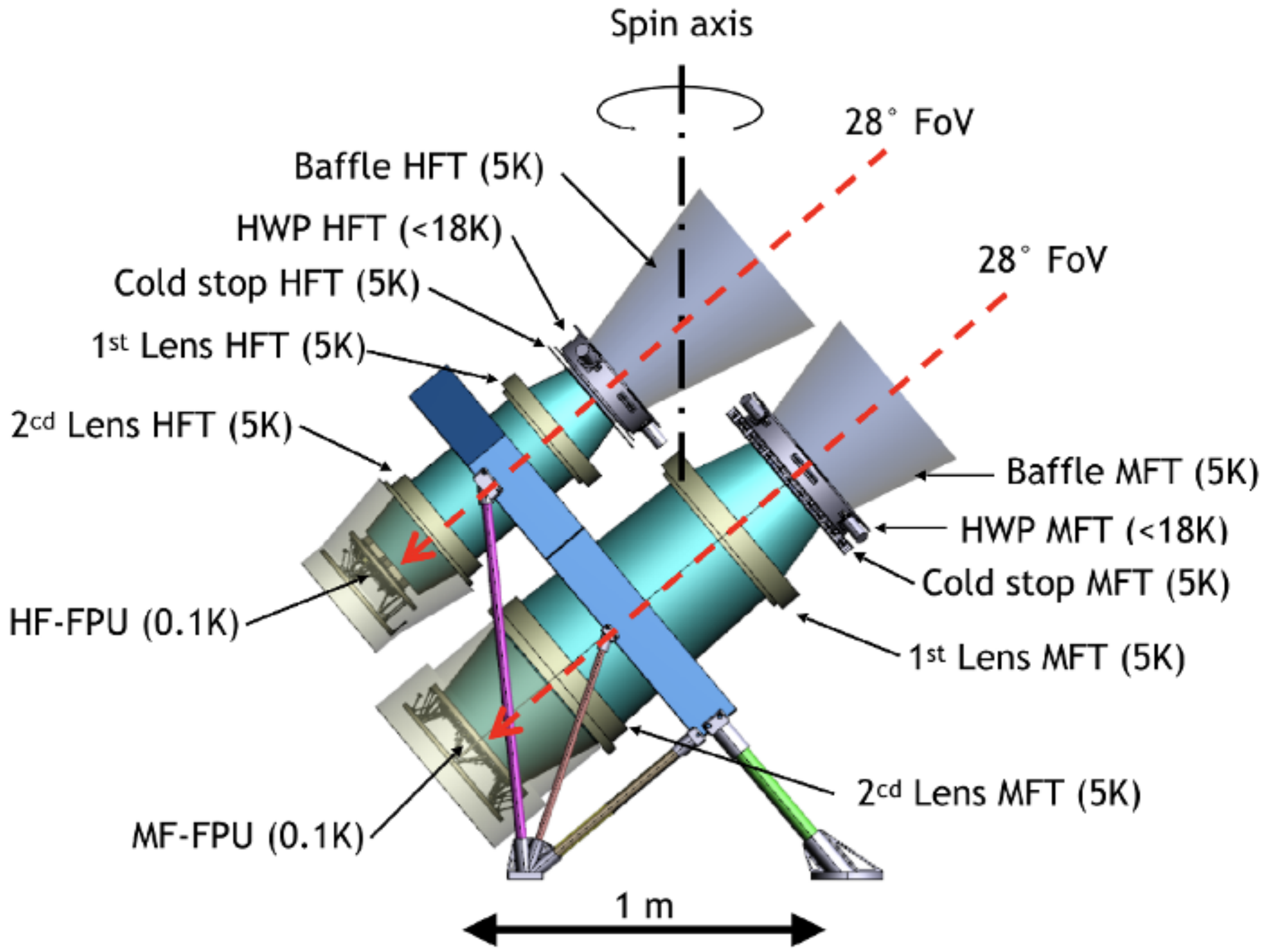


Upper limits on PMF amplitude for n_B = -2.9	
Gravitational effect	$B_{1\mathrm{Mpc}} < 0.8$ nG
Ionization history	$\sqrt{\langle B^2 \rangle} < 0.7$ nG
Faraday rotation	$B_{1\mathrm{Mpc}} < 3.2$ nG
Non-Gaussianities	$B_{1\mathrm{Mpc}} \lesssim 1$ nG

IAC contributions to LiteBIRD

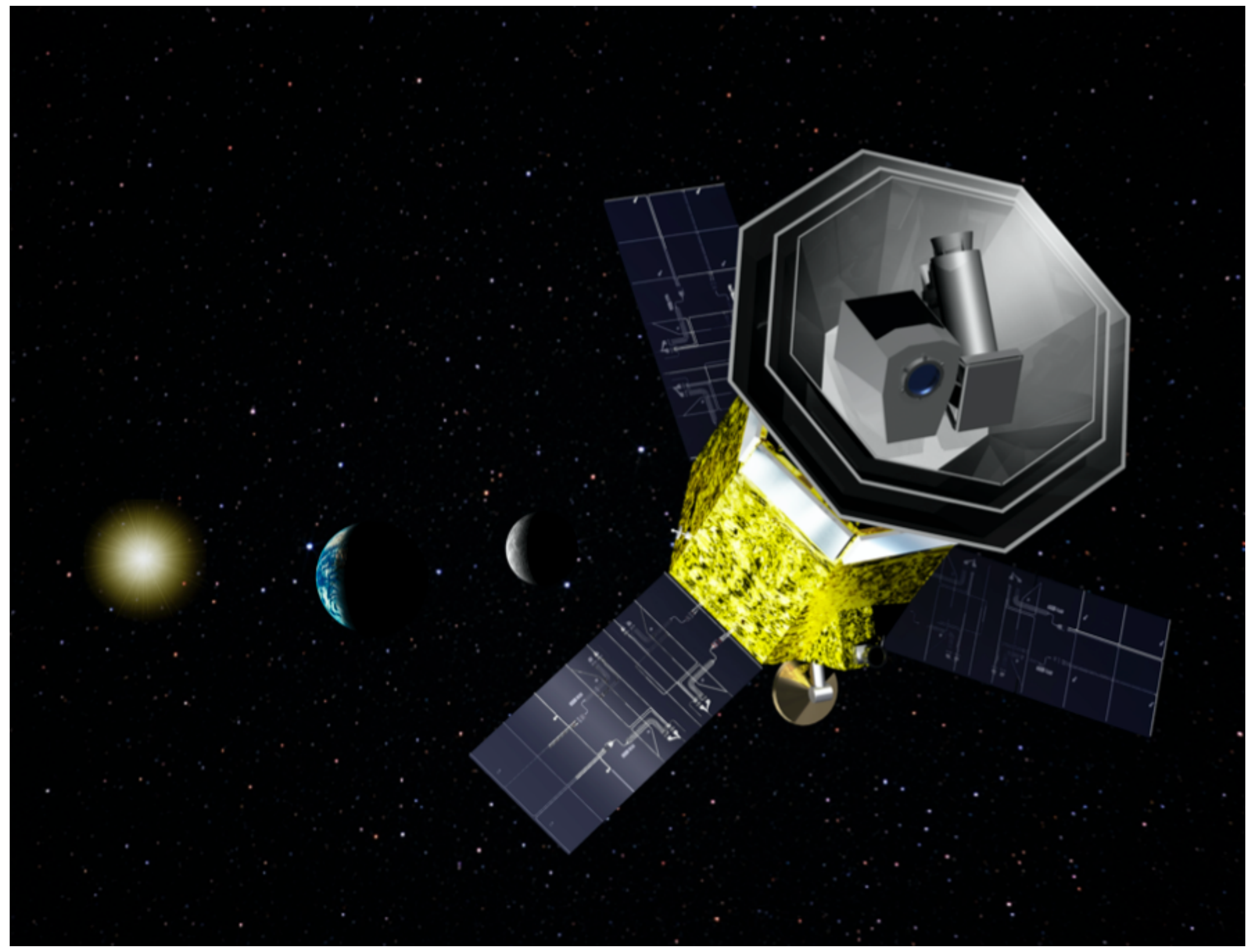
- Members: D. Adak, J.J. Díaz-García, R.T. Génova-Santos, R. González, C. Hernández-Monteagudo, J.A. Rubiño-Martín
- **Scientific preparation**:
  - Active participation in the **Calibration** (beams characterization) and **Foregrounds** (modelling of synchrotron emission) Joint Study Groups
  - Active participation in different forecast studies: **SZ effect**, **primordial magnetic fields**, **LSS/CMB** cross-correlations, sky models and component separation…
- Hardware development/implementation:
  - Design and implementation of the **Temperature Monitoring and Control System** (TMCS) for the Medium and High Frequency Telescopes (MHFT)
  - Responsibility of the Spanish LiteBIRD consortium (**IAC**, **IFCA**, **IDR/UPM**)
  - Goals:
    - Monitor the temperature of the MFHT 5, 2, 0.4 and 0.1 K stages
    - Compensate low-frequency thermal fluctuations in the 100 mK focal plane

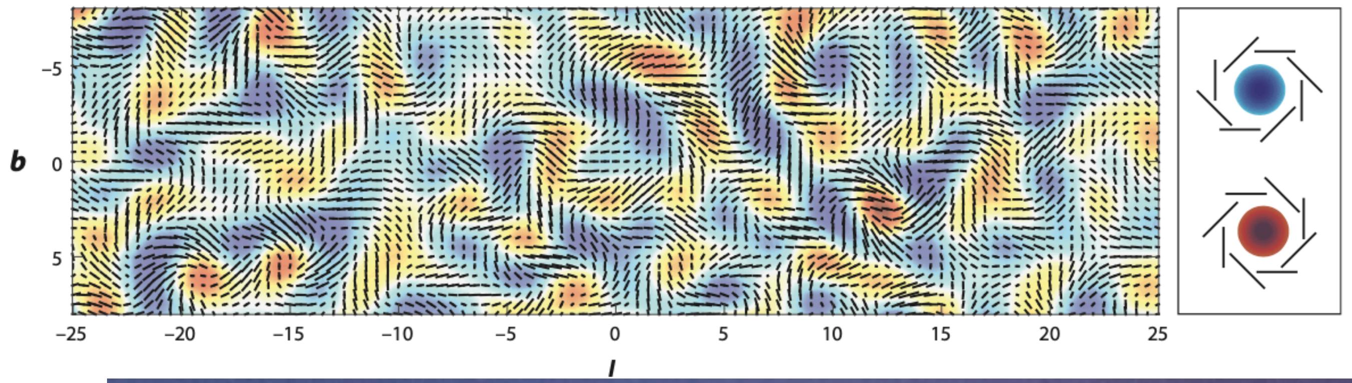




Conclusions

- **CMB temperature anisotropies** have played a key role in establishing the **ΛCDM** model, providing insights into **structure formation**, density of **baryons**, **DM**, **DE**, **Neff**, and the global properties of space-time.
- Future CMB polarization observations with improved sensitivity will allow to constrain **B-modes** and in turn shed information about the physical properties of the mechanism seeded the initial density perturbations (**cosmic inflation**)
- Reaching the required sensitivities is a major technological challenge (**sensitivity**, **systematics**, **foregrounds**)
- Current best upper limit: **$r < 0.032$** (📖 Tristram et al. 2022)
- The future **LiteBIRD** mission, to be launched in 2032, will reach **$\sigma(r) = 0.001$**
- In the interim, ground-based experiments (or even balloon-borne), like **GroundBIRD** and **LSPE** will aim to reach **$\sigma(r)$ = 0.005-0.01**
- Beyond gravitational waves (tensor modes):
    - **Reionization history**
    - **Neutrino masses**
    - **Cosmic birefringence**
    - **Primordial Magnetic Fields**
    - **Galactic science**…





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NÉEL institut

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HK
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OAC

岡山大学
OKAYAMA UNIVERSITY

QUP
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