Instituto de Física de Cantabria

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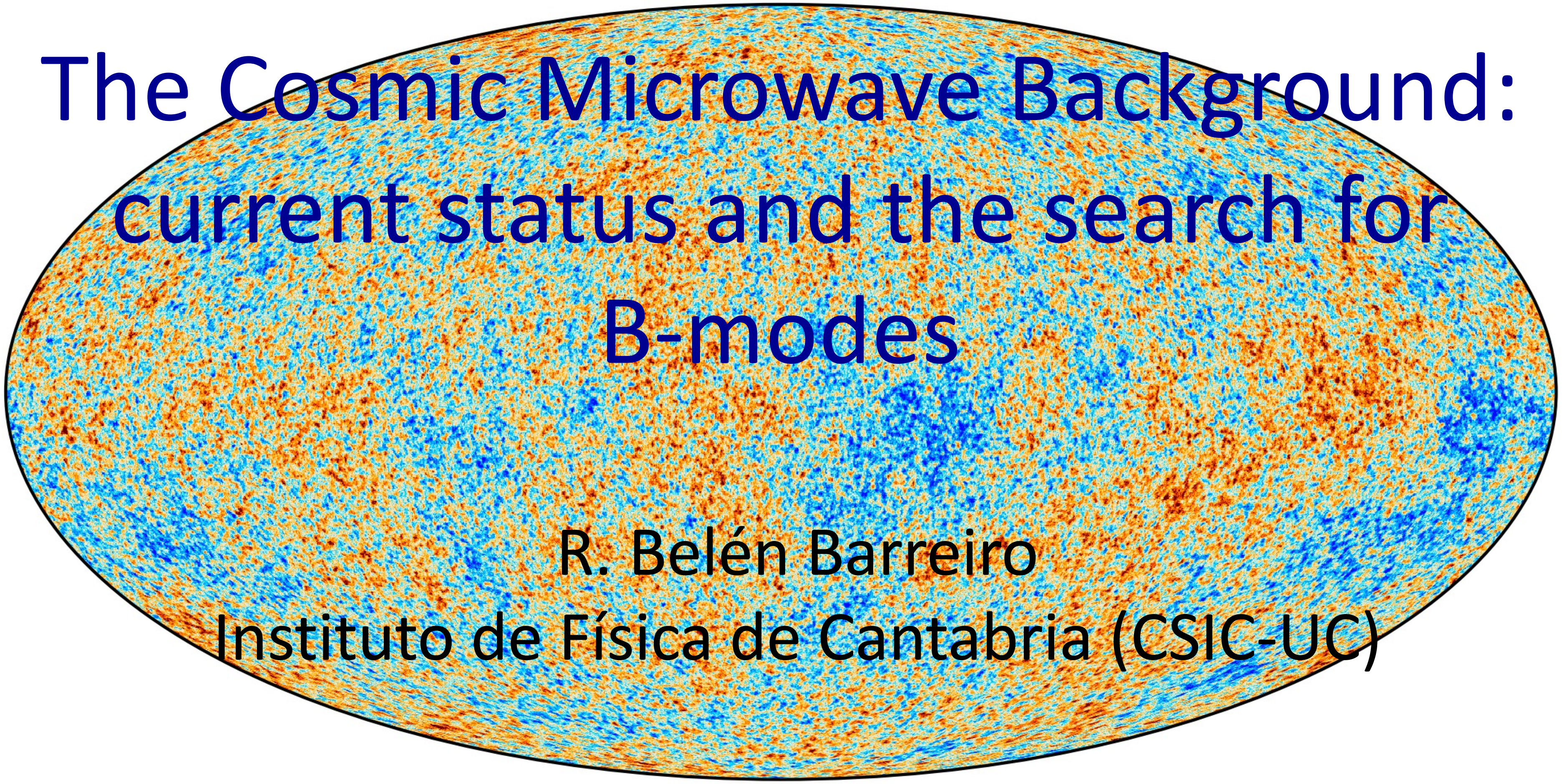


The Cosmic Microwave Background: current status and the search for B-modes

R. Belén Barreiro

Instituto de Física de Cantabria (CSIC-UC)

RENATA meeting 2025, Zaragoza, 22nd September

The Cosmic Microwave Background (CMB)

The **CMB** is a **homogenous and isotropic radiation** that has travelled to us from the last scattering surface since the universe **was 380,000** years-old. It has a blackbody spectrum with T_0=2.725K

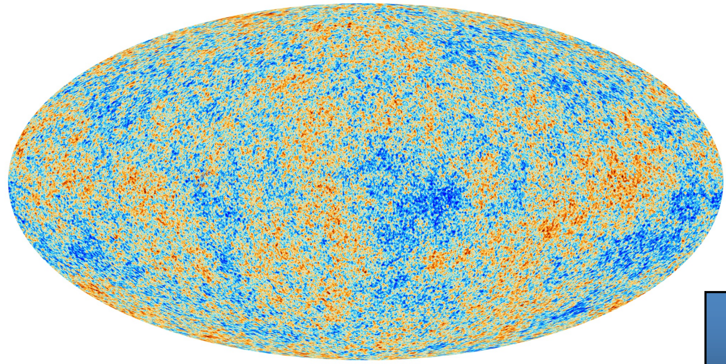
It presents small anisotropies at the level of ~10^{-5}, which encode a wealth of information about the early Universe, its content and evolution.

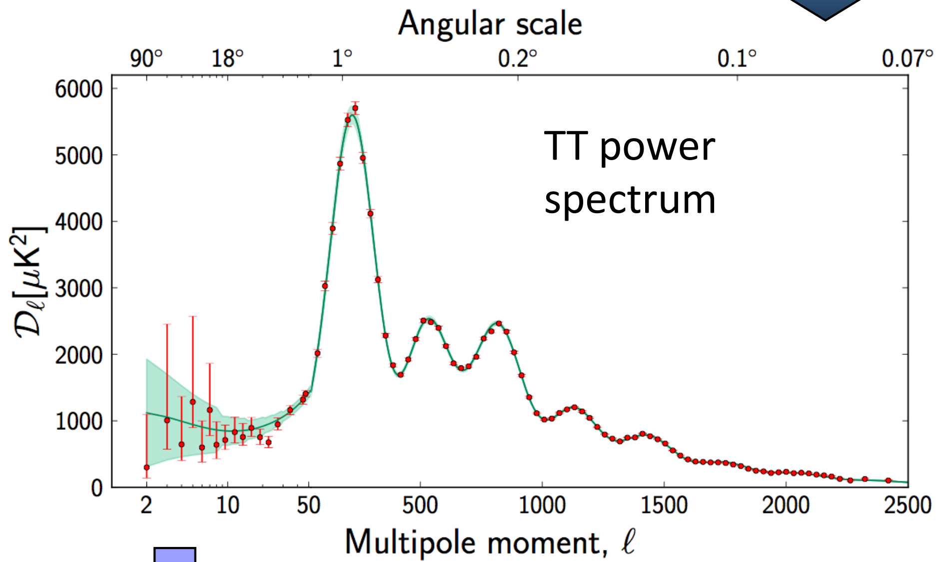
CMB fluctuations are described as a random field on the sphere:

$$\frac{\Delta T}{T}(\vec{n}) = \sum_{\ell=1}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell m} Y_{\ell m}(\vec{n})$$

$$\left\langle a_{\ell m} a^{*}_{\ell' m'} \right\rangle = C_\ell \delta_{\ell \ell'} \delta_{m m'}$$

The angular power spectrum (C_ℓ's), which depends on the cosmological model, is the key observable of the CMB



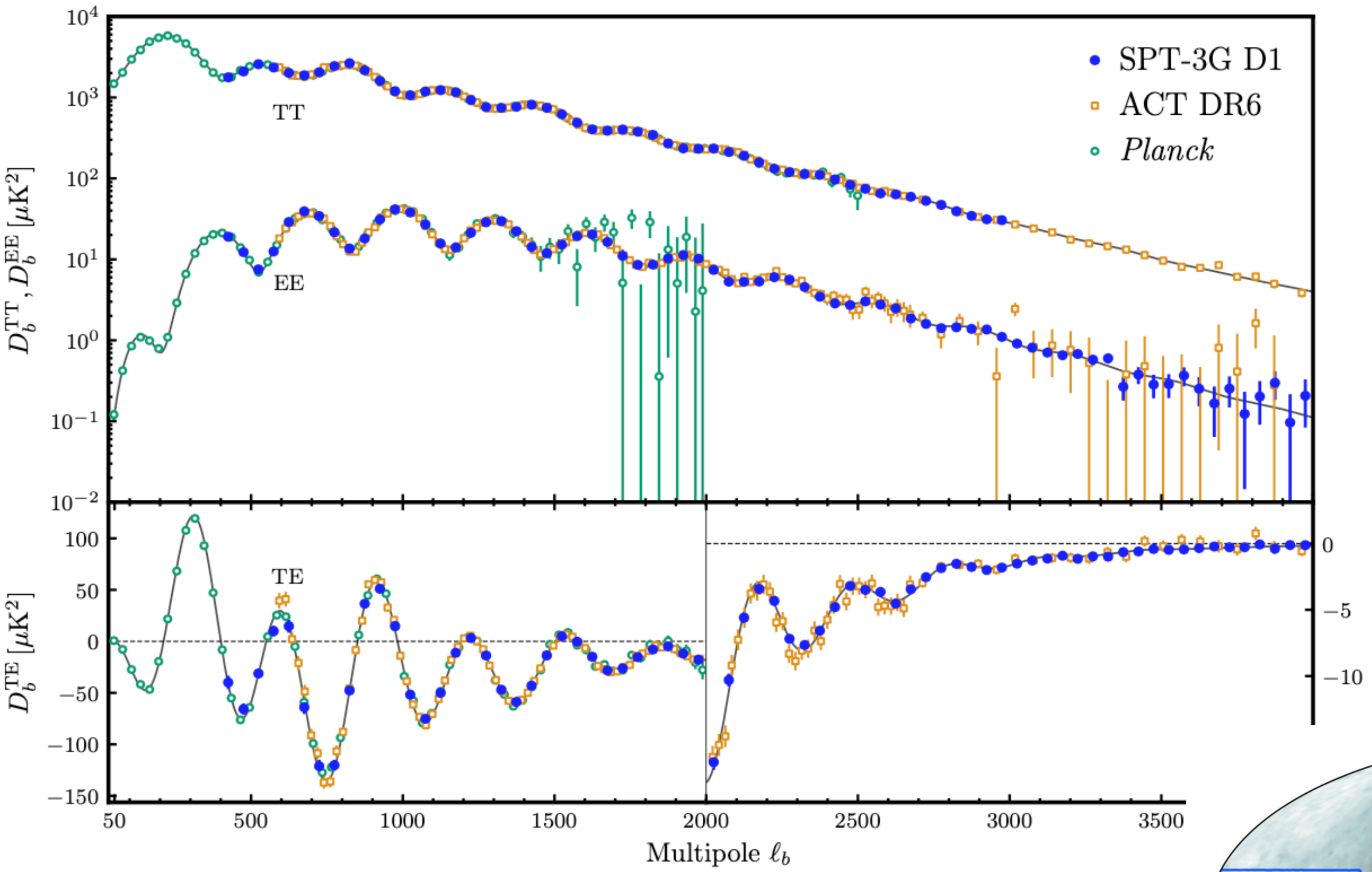


Cosmological Parameters

CMB polarization

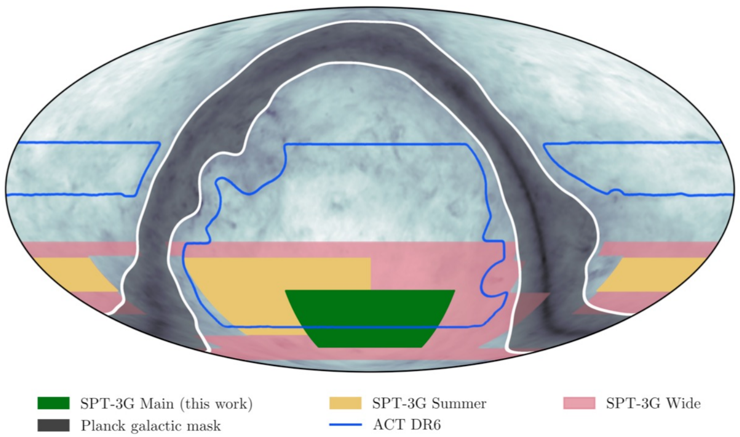
- CMB is partially and linearly polarised (polarization produced by Thomson scattering in the Last Scattering Surface)
- Linear **polarisation is defined locally**, in terms of the **Stokes parameters Q and U**
- Full-sky polarization maps can be decomposed into two components, the E-modes and the B-modes, (invariant under rotation) and are related to the Q and U Stokes parameters by a non-local transformation
- We can also measure auto- and cross-angular spectra for polarization, so we have: TT, EE, BB and TE (EB and TB are expected to be zero in standard cosmology)
- Scalar perturbations produce only E-mode of polarization
- Primordial gravitational waves (predicted by inflation) produce both E and B-mode polarization → **if we detect primordial B polarization, we have (indirect) proof of primordial gravitational waves !!**

CMB power spectra measurements: current status



Solid line corresponds to the Planck best fit ΛCDM model (Planck+SPT+ACT)

Very good agreement with ΛCDM model and between different data sets



SPT-3G: Camphuis+ 2025

ACT DR6: Louis+ 2025

Planck Collaboration VI, 2020

The flat ΛCDM cosmological model

- The Universe is highly homogenous and isotropic at large scales due to an early phase of cosmic inflation
- Its spatial geometry is flat
- Most of the energetic content of the Universe is in one of following forms:
  - Baryonic matter (around 5%)
  - Weakly interactive cold dark matter (around 27%)
  - Dark energy (around 68%), which is responsible of the current accelerated expansion of the Universe

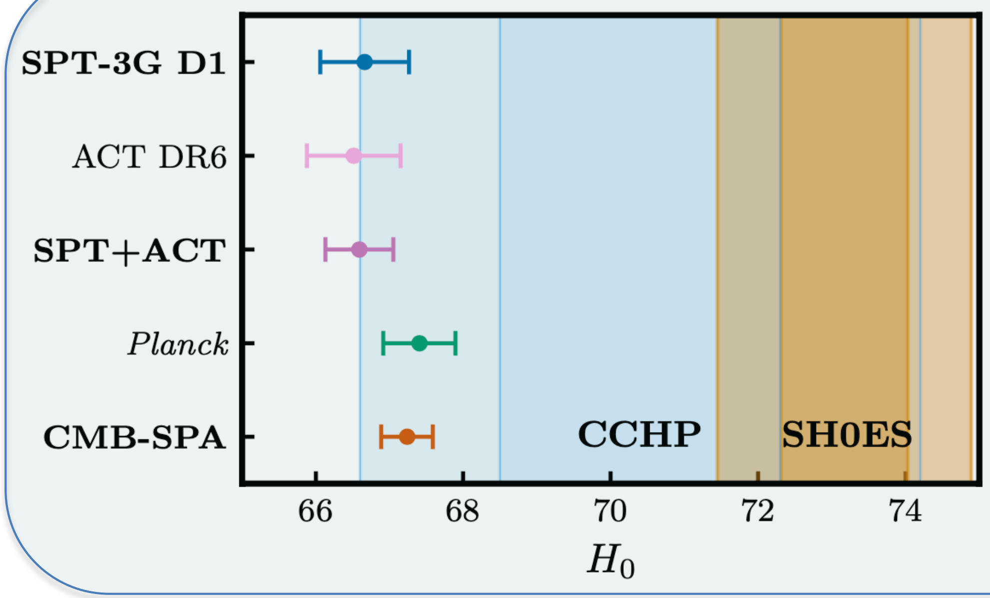
The flat ΛCDM model is defined with only 6 parameters: $\{\Omega_b, \Omega_c, H_0, n_s, \tau, A_s\}$

Best-fit from Planck + ACT + SPT

Parameter	Mean	68% CI
$100\Omega_b h^2$	2.2381	0.0093
$100\Omega_c h^2$	12.009	0.086
Ω_m	0.3166	0.0051
Ω_Λ	0.6833	0.0051
τ_{reion}	0.0559	0.0055
$\ln(10^{10}A_s)$	3.0479	0.0099
n_s	0.9684	0.0030
H_0	67.24	0.35

Camphuis+ 2025

Cosmic tensions



H_0 measurements

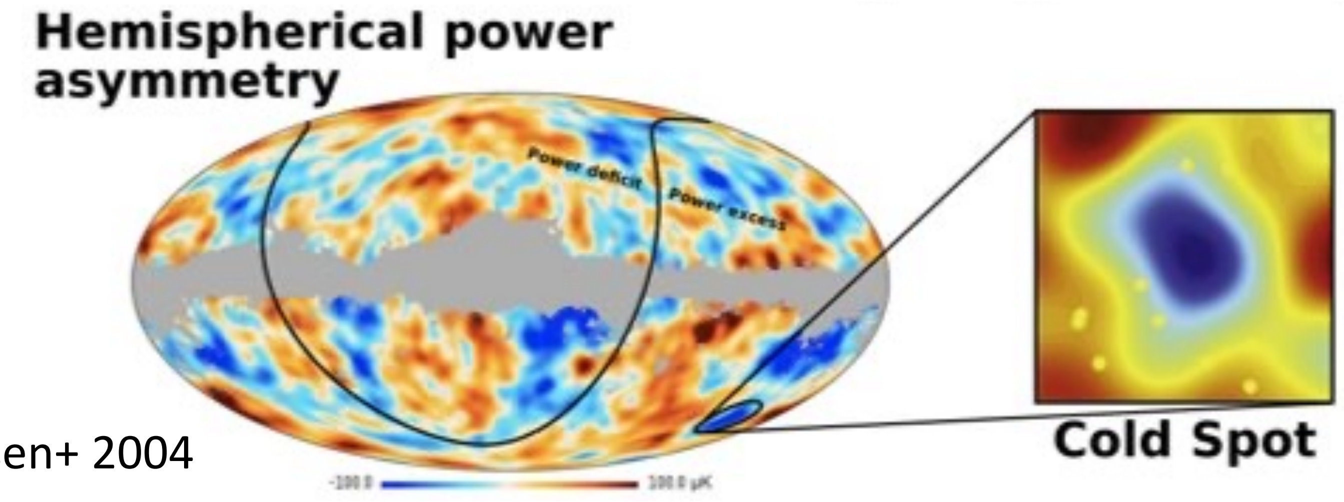
CMB: $H_0 = 67.24 \pm 0.35$ [Camphuis+ 2025]
CCHP: $H_0 = 70.4 \pm 1.9$ [$Freeman + 2024$]
SH0ES: $H_0 = 73.17 \pm 0.86$ [Breuval+ 2024]

6.4σ tension between CMB and SNs !!

- Preference for an excess of lensing in the CMB power spectrum in Planck PR3: no inconsistency in PR4, SPT or ACT
- Measurements of matter fluctuations σ_8: recent values from different probes (including e.g. data from DES-Y3, KiDS) more consistent with CMB (<2σ)
- Preference for a time-evolving dark energy when combining DESI + CMB + SNs
- A tension ~2-3σ between CMB and BAO from DESI-DR2 (assuming ΛCDM) has been reported [Camphius+ 2025, García-Quintero 2025]

CMB anomalies

- CMB maps reveal large-scale anomalies of moderate significance (~2-3σ) – such as deficit of power in large scales, hemispherical power asymmetry, a prominent cold spot -- that challenge the isotropy of the universe [Planck Collaboration VII, 2020]
- The fact that the anomalies have been seen by two independent experiments (WMAP and Planck) increases confidence of these detections as real sky signals
- Interestingly, there is a hint of power asymmetry in polarization with the same orientation as that in temperature, although at a moderate significance [Gimeno-Amo et al. 2024]



Eriksen+ 2004

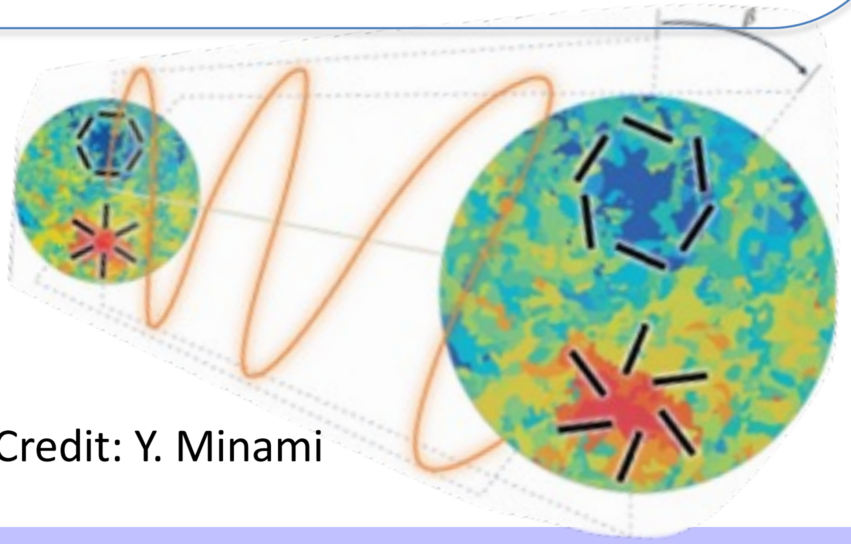
Vielva+ 2004

Cosmic birefringence

- Cosmic birefringence refers to the rotation of the plane of linear polarization of CMB photons as they travel through space, potentially induced by coupling to an axion-like field (possibly associated to dark matter or dark energy)
- This effect produces parity-violating signatures in the CMB, such as non-zero TB and EB correlations
- Miscalibration angle of the detectors can also mimic CB, mixing E and B modes.
- Spurious EB from astrophysical emissions can also be present in the data

Recent measurements show tentative detections of rotations:

- $\beta = 0.30° \pm 0.11°$ Planck [Diego-Palazuelos+2022]
- $\beta = 0.342° \pm 0.093°$ Planck+WMAP [Eskilt & Komatsu 2022]
- $\beta = 0.20° \pm 0.08°$ ACT DR6 [Louis+ 2025]
- $\beta = 0.32° \pm 0.12°$ Planck [Remazeilles 2025]
- $\beta = 0.215° \pm 0.074°$ ACT DR6 [Diego-Palazuelos & Komatsu 2025]



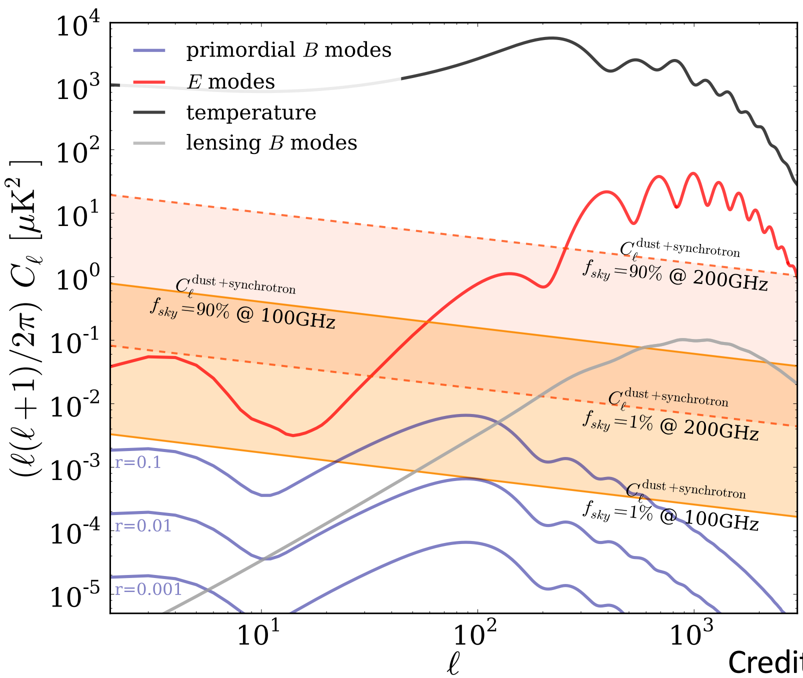
Credit: Y. Minami

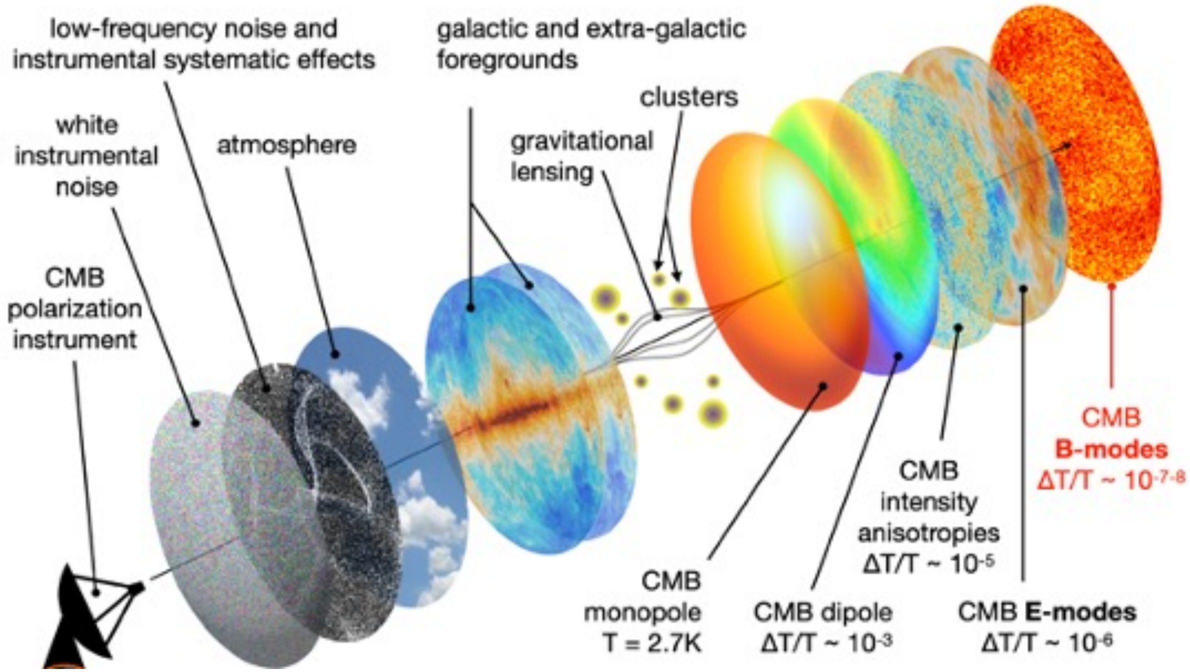
The challenge of B-mode detection

B-mode not detected yet, best constraint r < 0.032 (r → tensor-to-scalar ratio amplitude) [Tristram et al. 2022]

Its detecion is extremely challenging, since it is a very weak signal. It requires:

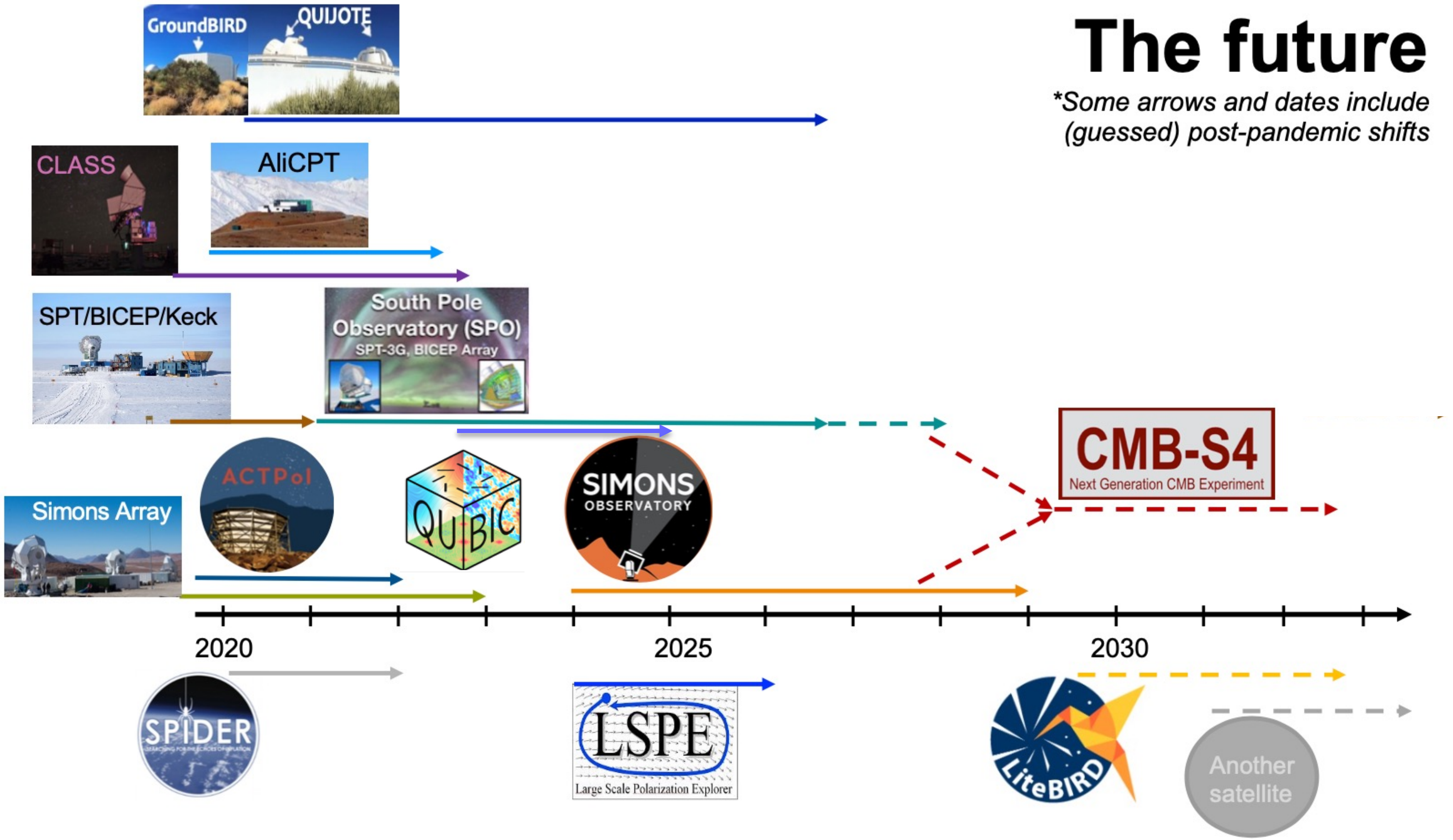
- Exquisite control of systematics (many systematics can produce E→B leakage)
- Remove Galactic foreground contamination (mainly synchrotron at low frequencies and thermal dust at high frequencies)
- Remove spurious B-mode signal induced by gravitational lensing





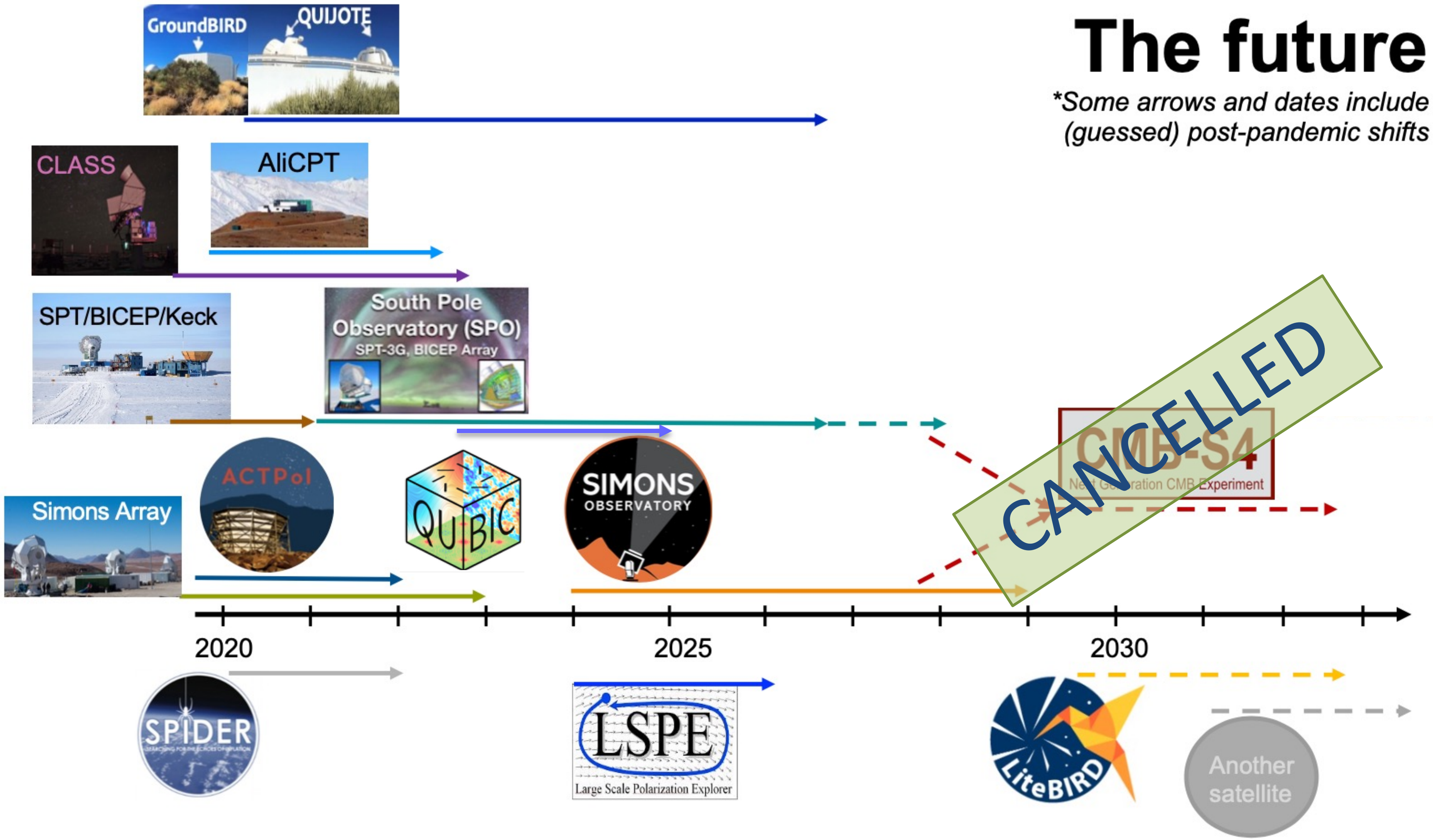
Credit: J. Errard

The quest for the B-mode of CMB polarization



Credit: in original form, from E. Calabrese

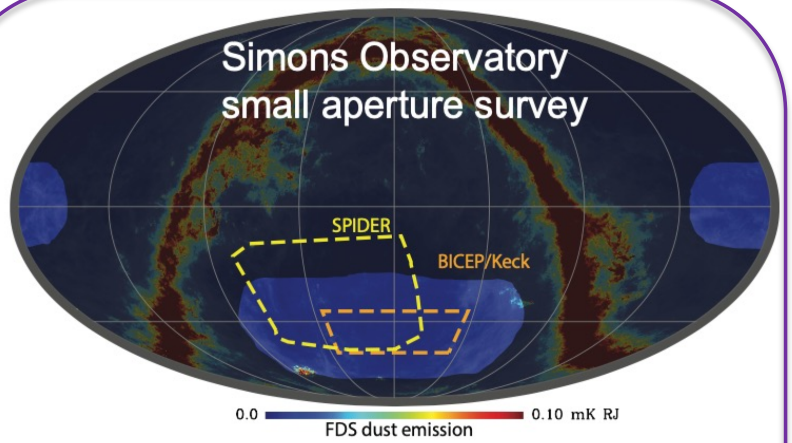
The quest for the B-mode of CMB polarization



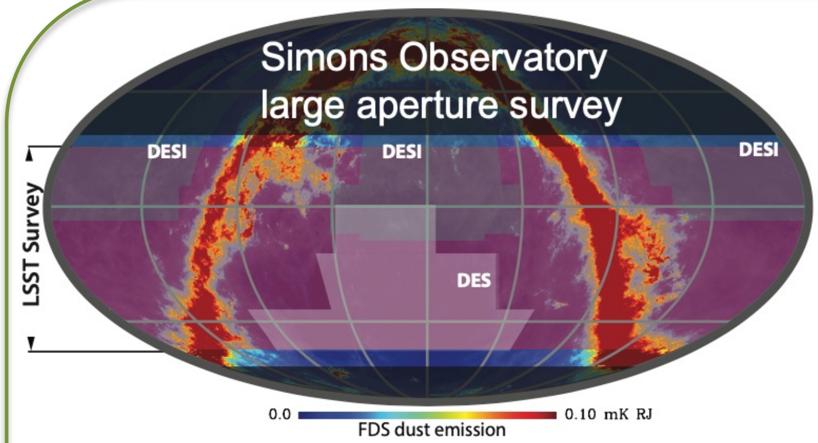
Credit: in original form, from E. Calabrese

The Simons Observatory

- Site: Atacama desert (Chile)
- 3 Small Aperture Telescope (SAT) + 1 Large Aperture Telescope (LAT), ~80000 detectors
- Covering 6 frequency bands from 27 to 280 GHz
- 5-years observations
- Large international collaboration (12 countries, ~300 membrers) led by US



- f_{sky} ~10%, resolution ~ 0.5°
- Sensitivity ~ 2μk-arcmin
- Focus on primordial B-modes
- σ_r ~0.003



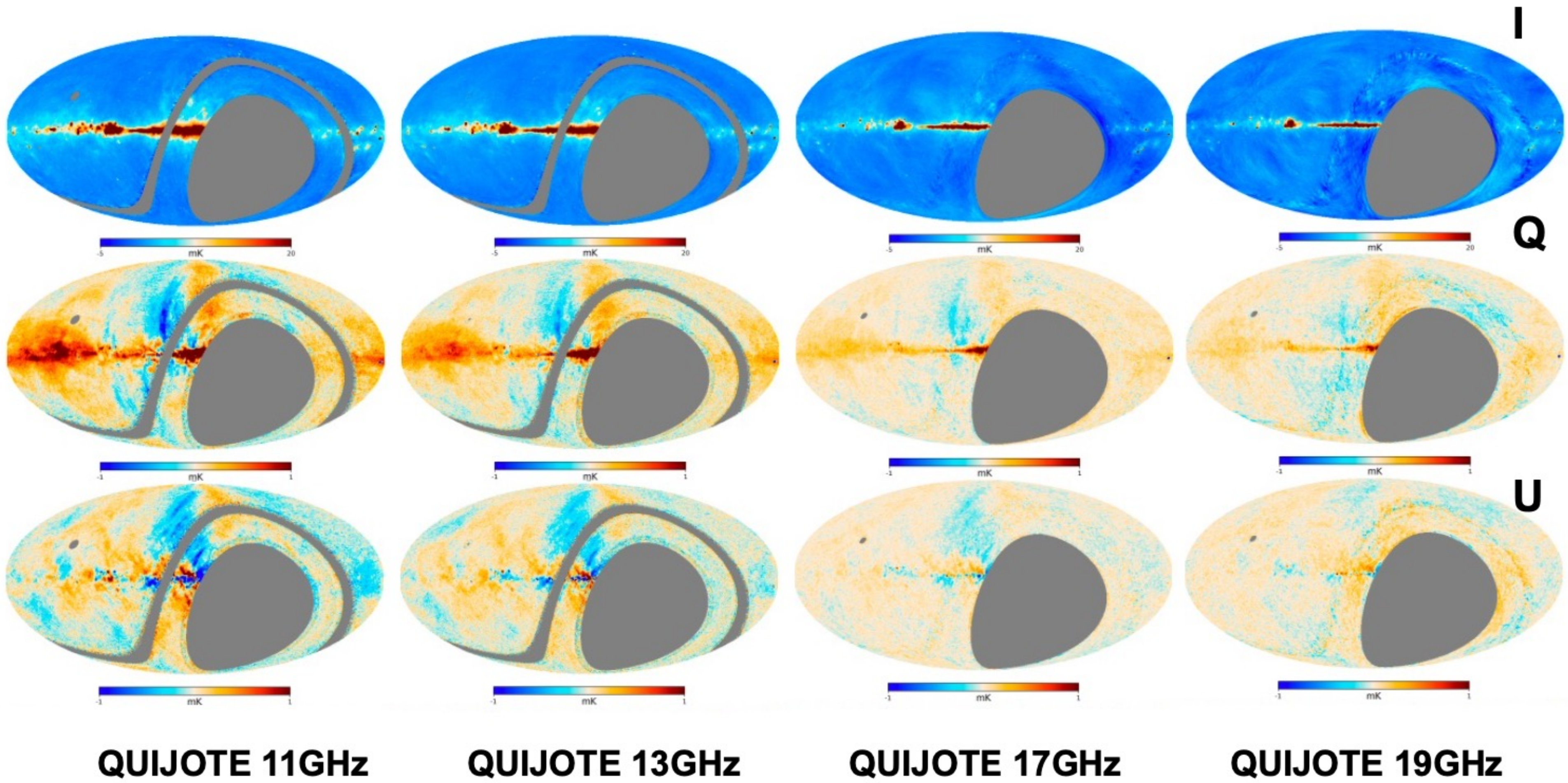
- f_{sky} ~40%, resolution ~ 1’
- Sensitivity ~ 6μk-arcmin
- Overlap with Galaxy surveys
- Neutrino mass, effective number of relativistic species, duration of reionization…

Astro2020 APC White Paper, SO Collaboration, 2019

The QUIJOTE Experiment

- Site: Teide Observatory (altitude 2400 m, 28.3º N, 16.5 W)
- Angular resolution: 0.92º to 0.26º
- Sky coverage: -32º < Dec. < 88º (f_{sky}=0.65).
- Instruments
  - MFI, at 11, 13, 17 and 19 GHz (to be updated with MFI2)
  - TGI/FGI joint instrument at 30 and 40 GHz
- Main goals:
  - To improve our knowledge of Galactic polarized foregrounds at low frequency
  - To constrain primordial B-mode using different technology, frequency range and sky region than usual experiments
- Wide survey with MFI completed, main results and products published in 2023
- Unique frequency coverage
- Complementary to CMB experiments observing at higher frequencies

The QUIJOTE Experiment: wide survey with MFI (10-20 GHz)



RADIO FOREGROUNDS+

Maps smoothed at 1 degree. Sky coverage ~ 29,000 deg^2 .

Rubiño-Martín et al. 2023

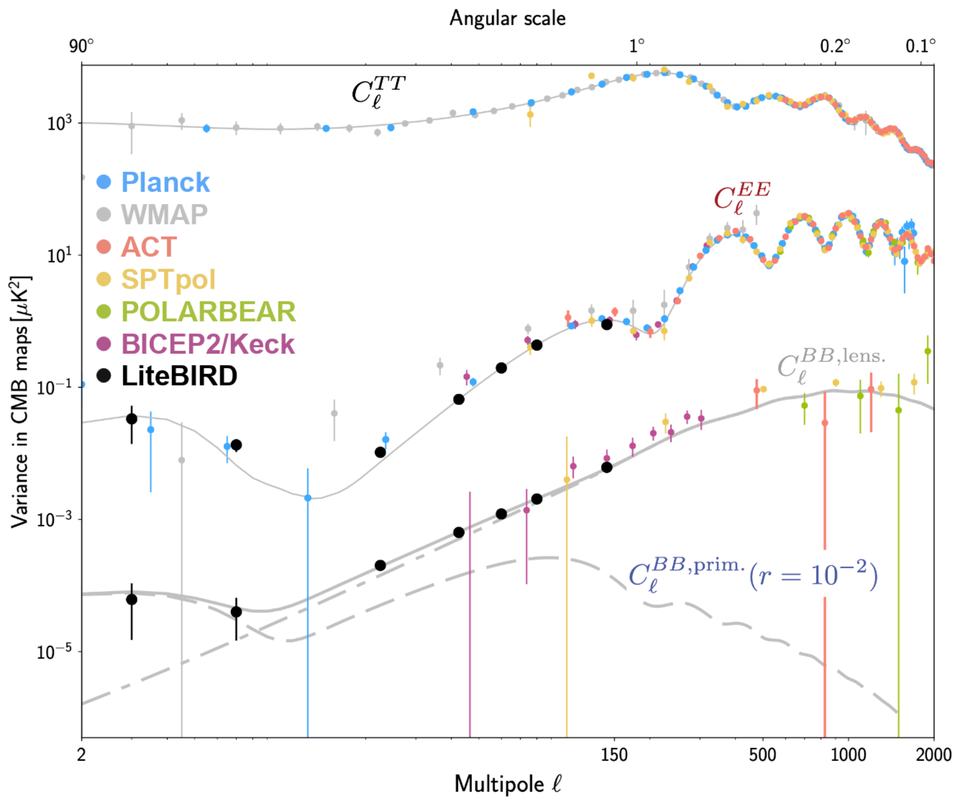
LiteBIRD Collaboration

LiteBIRD: JAXA's L-class mission selected in May 2019

Aournd 400 researchers from Japan, North America and Europe

LiteBIRD: Lite spacecraft for the study of B-mode polarization and inflation from cosmic background radiation detection

- JAXA's L-class mission selected in May 2019
- All-sky 3-year survey, from Sun-Earth Lagrangian point L2
- Large frequency coverage (40–402 GHz) at 70–18 arcmin angular resolution
- Final combined sensitivity: 2.2 μK·arcmin
- Definitive search for B-model signal from cosmic inflation: making a discovery or ruling out inflationary models
- Many other science outcomes: cosmic birefringence, reionization, neutrino mass, elucidating anomalies, Galactic astrophysics…



LiteBIRD Collaboration, PTEP, 2023, 042F01

Other projects of the Spanish CMB community

- A 90 GHz instrument is under development to be installed at the Teide Observatory [IAC, IFCA, U. Roma, IPMU]

- European Low Frequency Survey (ELFS) [U. Milan, IFCA, IAC, U.Oxford, IRAP, SISSA]
  - aim to detect the B-mode using frequencies from 5-120 GHz
  - First step: installing a 5 – 10 GHz instrument in Atacama, followed by a 10-20 GHz one (that could complement other experiments as SO)

- Tenerife Microwave Spectrometer (TMS) [IAC, INAF, U.Milan, UPCT, IDOM company]
  - Absolute spectrometer in the 10-20 GHz range that will be installed at the Teide Observatory
  - Main goal to characterize the absolute monopole from our Galaxy and to probe possible deviations of the CMB spectrum from a blackbody

Final remarks

- Current observations show that the base-ΛCDM model fits well CMB data (temperature, polarization, lensing).
- Density fluctuations consistent with predictions from the simplest models of inflation. No primordial gravitational waves detected yet.
- However, some tensions remain, mainly with direct measurements of H_0.
- Origin of CMB anomalies is not clear yet.
- Tentative detections of the rotation of CMB polarization that could point towards Cosmic Birefringence.
- Many efforts on the way to detect the intrinsic B-mode of polarization, that would test $r \sim 10^{-3}$.
- Exciting results to come in the next years…