State of the art of CMB observations: Activities at Unimi and INFN-MI

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The Cosmic Microwave Background

- The Cosmic Microwave Background (CMB) is blackbody radiation of primordial origin, with an average temperature of ~ 2.7 K, with tiny anisotropies in temperature and polarization

- It is one of the most powerful cosmological probes, providing key information on both the early stages of the Universe and its evolution.

- From its existence and properties we have learned that:
  - In the far past, the Universe was very hot and dense: **Big Bang**
  - The Universe is very uniform on the largest scales, due to an early phase of very rapid expansion: **Inflation**
  - Most matter in the Universe has no electromagnetic interaction: **Dark Matter**

Origin of the CMB

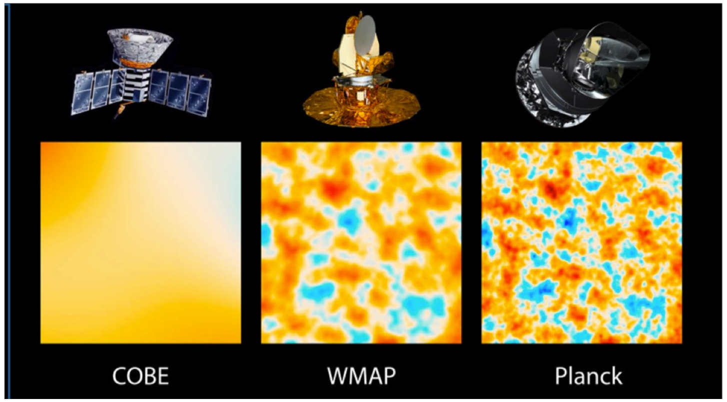
- It was emitted ~ 380 000 years after the Big Bang, when the Universe was:
  - Simple: photons, barions (73% H^+, 27% $^4He^{++}$, traces of D^+, T^+, $^3He^{++}$, Li^{+++}, n), neutrinos and Dark Matter
  - Low-density (~ 10^9 nucleons/m^3)
  - Opaque and in thermal equilibrium at a T ~ 3000 K
  - Characterized by small inhomogeneities (1 part in 10^4~10^5), propagating as sound waves in the baryon-photon plasma
- As the Universe expands it cools and at the Epoch of **Recombination** the photons no longer have enough energy to keep H and He atoms ionized
- The Universe become transparent to radiation, and photons free stream for ~ 13.8 B years and today the CMB appears as a highly uniform blackbody with T ~ 2.7K, with small fluctuations

Anisotropies

- Around Recombination, gravity acts to compress the baryons in the potential wells dominated by dark matter, but it is opposed by photon pressure via Thomson scattering
- Before matter-radiation decoupling, perturbation in matter density/CMB temperature display an oscillatory behaviour
- The pattern of anisotropies at recombination ($O(10^{-4})$ in T) is frozen into the CMB photons distribution (some additional perturbations are introduced by the subsequent free streaming through the expanding Universe)
- The Thomson cross section in the electron restframe depends on the angle between the incoming and outgoing photons directions. If the incoming radiation field has a quadrupole moment, the outgoing radiation has a net linear polarization
- CMB polarization can be decomposed in a gradient pattern (E-mode, $O(10^{-6} – 10^{-5})$), and a still undetected curl type pattern (B-mode, $< 10^{-7}$), which can only be produced by gravitational waves

Anisotropy observational history

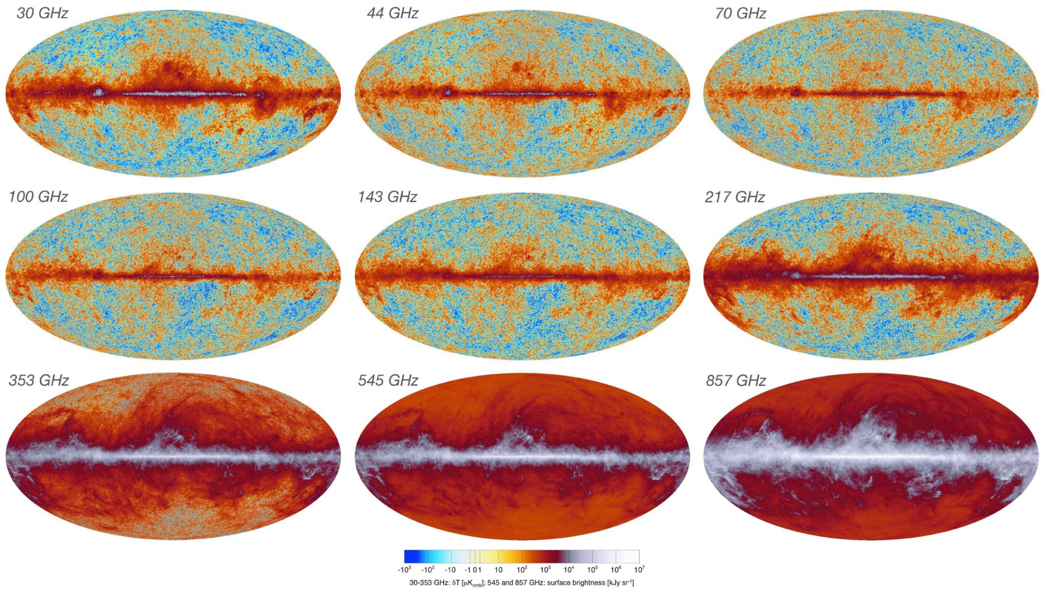
- Over the last 60 years, a significant effort has been dedicated to observing the CMB from ground, high-altitude balloons, and space, with different trade-offs
- The three major observational milestones were the space observatories: COBE (NASA, T), WMAP (NASA, T+P), Planck (ESA, T+P)



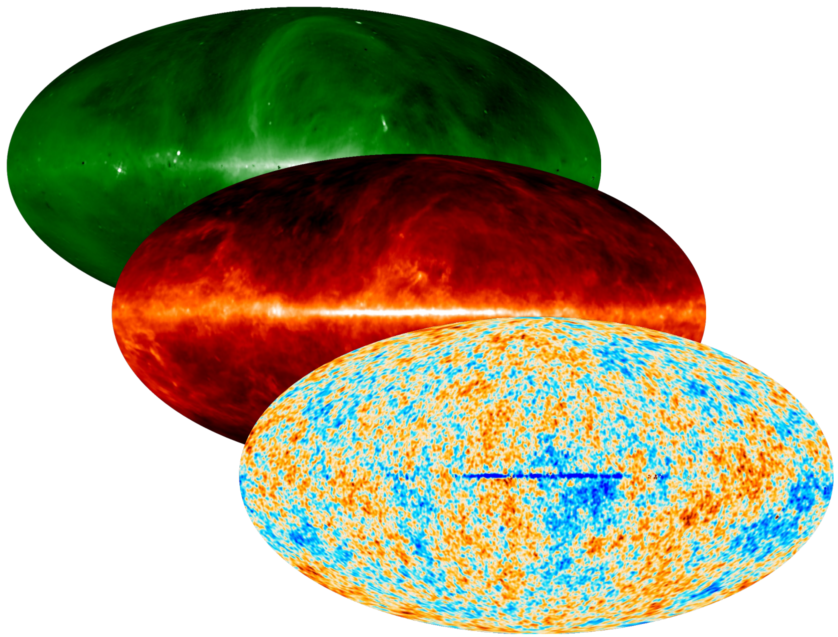
- Their full-sky observations have been complemented by ground and ballon measurements providing high sensitivity measurements of small portions of the sky

Credit: NASA

Planck results/1

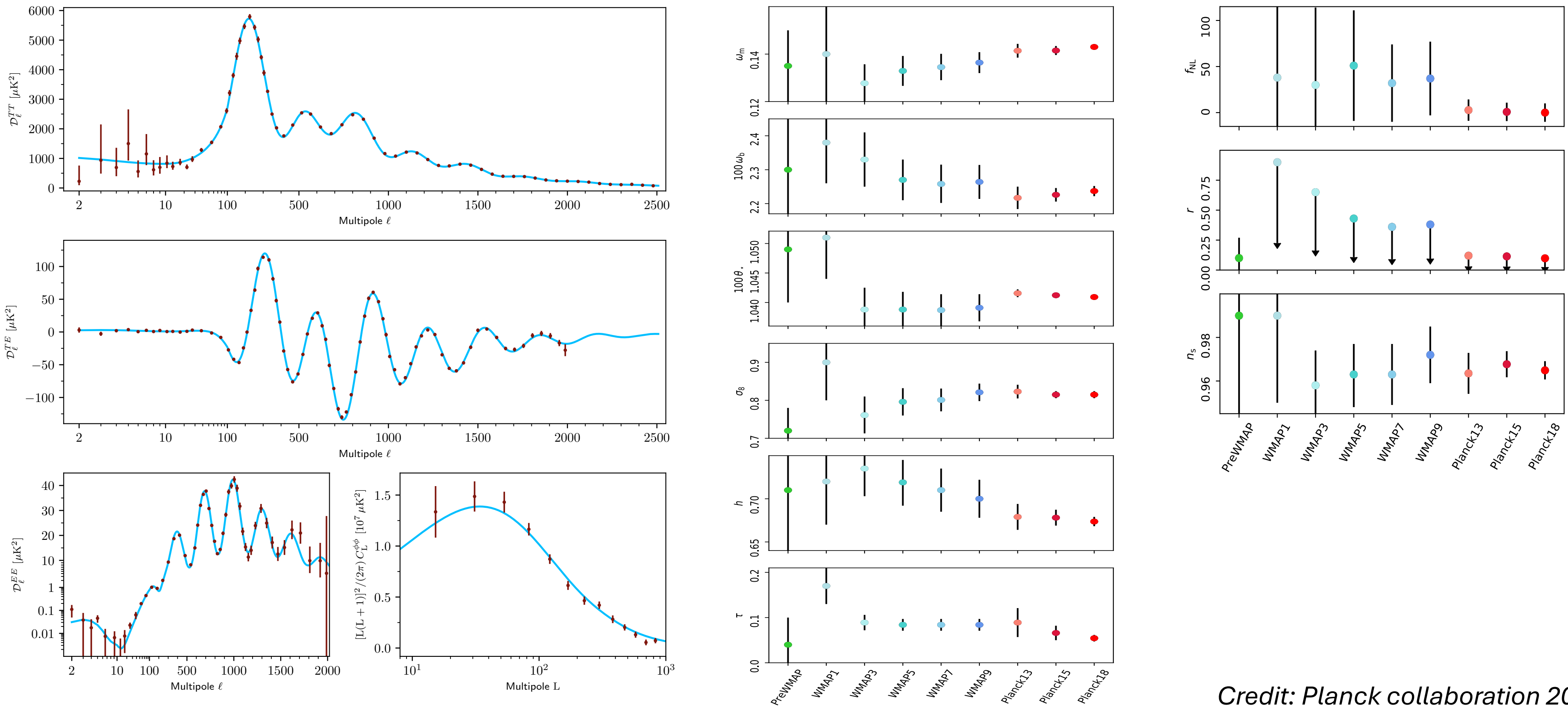


Credit: Planck collaboration 2020



Full sky maps of microwave emission in T and P in 9 frequencies from 30 to 857 GHz, allowing to isolate the CMB signal from the astrophysical foregrounds.

Planck results/2



Credit: Planck collaboration 2020

Planck Legacy

- Planck provided the definitive* CMB temperature anisotropies measurements on angular scales larger than ~ 10' which, together with Planck polarziation measurements, allowed us to characterize most of the main cosmological parameters with percent level accuracy
- It marked the point where CMB temperature measurements transitioned from being noise dominated to being limited by our knowledge of instrumental systematics and astrophysical foregrounds
- Lessons learned from Planck are now been applied to the current and future generations of CMB experiments
- These experiments focus on detection of primordial polarization B-modes, improved E-mode characterization, and high-resolution temperature measurements

Future CMB science: cosmology and particle physics

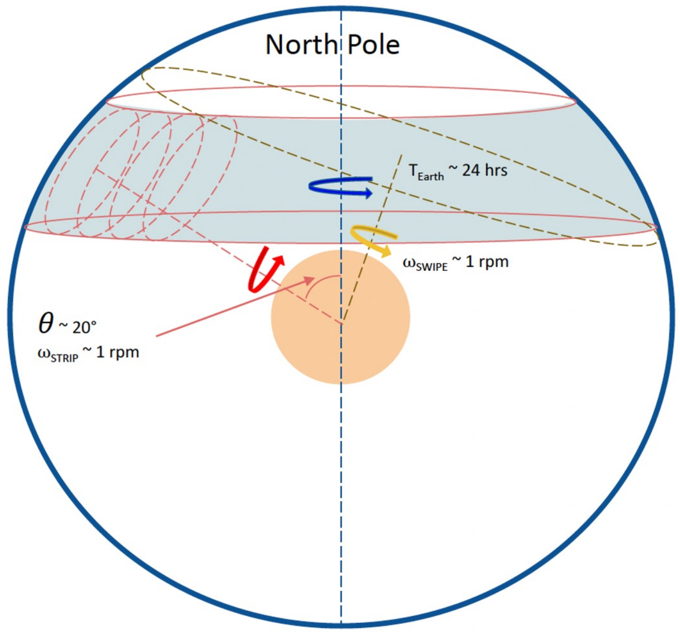
- Detection of primordial B-mode polarization on angular scales > 1º
  - primordial B-modes are produced by gravitational waves, which in turn are a natural prediction of Inflation. Detecting and characterizing primordial B-modes will allow to close the loop on Inflation, but the expected signal is tiny, O(10) nK or below, i.e. **$r \lesssim 0.01$**
- Neutrino properties and additional relativistic degrees of freedom
  - Neutrinos become non-relativistic between Recombination and today. The CMB primary temperature anisotropy spectrum probe Recombintion physics, while the distorsion of that spectrum due to gravitational lensing probe υ impact on the growth of cosmic structures, allowing to constrain their total mass
  - Additional light particles would affect the background expansion rate and the suppressions of small scale CMB anisotropies
- Dark Matter
  - CMB allows to probe the total DM content, but also possible types of DM interaction, like DM annihilation or DM-baryon scattering
- Reconstruction of the reionization history
  - at late times, intergalactic H and He are ionized again due to the action of the first sources of light, leading to additional CMB photons scattering on free electrons, allowing to reconstruct the properties of these sources. Due to internal CMB degeneracies, accurate measurements of reionization are necessary to properly constrain neutrinos masses

Local activity

- Our group is strongly involved in all aspects of CMB experiment design, realization, and analysis
- Detector design and characterization (Planck, LSPE-Strip)
- Optics and beam characterization, both in the lab and with simulations (Planck, LSPE-Strip, LiteBIRD)
- Calibration (LSPE-Strip, LiteBIRD)
- Atmosphere modeling (LSPE-Strip, QUBIC)
- Mapmaking (Planck, LSPE-Strip, LiteBIRD)
- Component separation (Planck, LSPE, QUBIC)
- Power spectrum, likelihood and parameter estimation (Planck, LSPE-Strip, LiteBIRD)

Large Scale Polarization Explorer

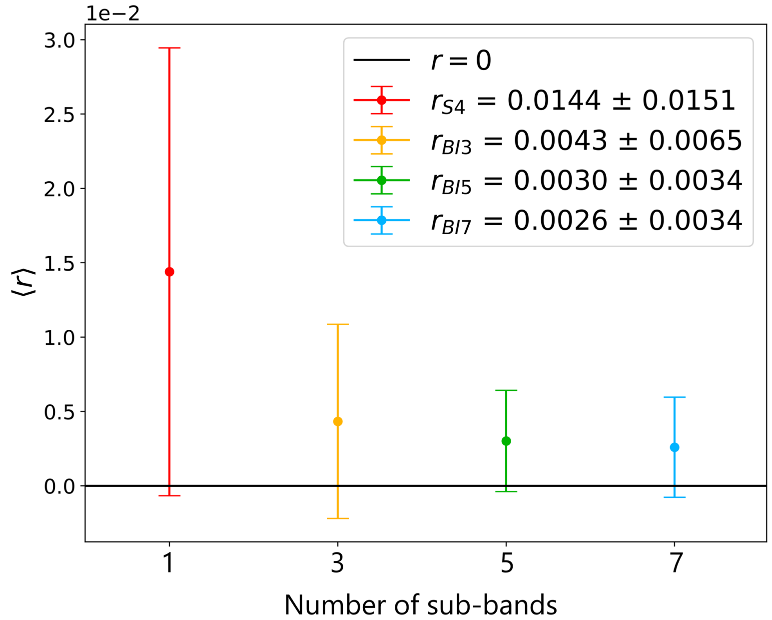
- LSPE is an ASI and INFN funded project, consisting of two instruments: a ground telescope under construction at the Pico del Teide Observatory in Tenerife (STRIP) and a high-altitude balloon for a long duration circumpolar flight (SWIPE)
- STRIP will observe ~ 30-40% of the sky at 44 and 95GHz, allowing an accurate characterization of the synchrotron emission by the Galaxy and of the atmosphere emission at the site
- Together with SWIPE, STRIP aims at a sensitivity on the tensor-to-scalar ratio $\sigma_r = 0.01$ and to a sample-variance limited measurement of reionization
- STRIP activities are headquartered here in Milan, and we are deeply involved in all the aspects of the project



Credit: LSPE collaboration

Q-U Bolometric Interferometer for Cosmology

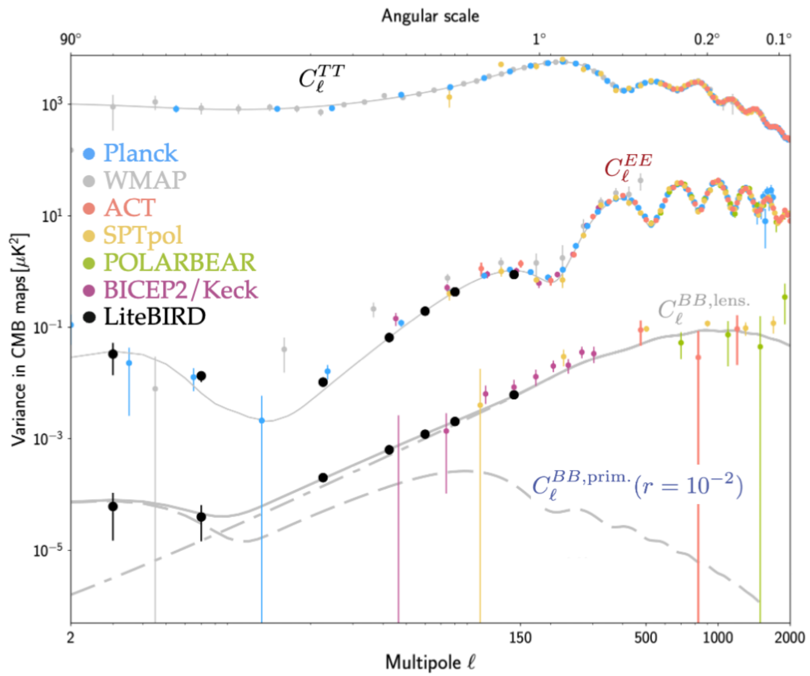
- QUBIC is a ground-based experiment for the measurement of CMB polarization on ~ degree scales, under construction at Alto Chorillo in Argentina
- A technology-demostrator has been deployed, observing the sky at 150GHz, while the full instrument, covering also the 250GHz band, is under development
- The interferometric approach allows for a better reconstruction of the frequency dependence of foreground emission, in turn reducing residual foreground contamination in CMB maps and increasing the robustness of r measurements
- We are involved in the analysis of TD data, atmosphere modeling, and componet separation



Credit: Regnier et al. 2024

Lite satellite for the studies of B-mode polarization and Inflation from cosmic background Radiation Detection

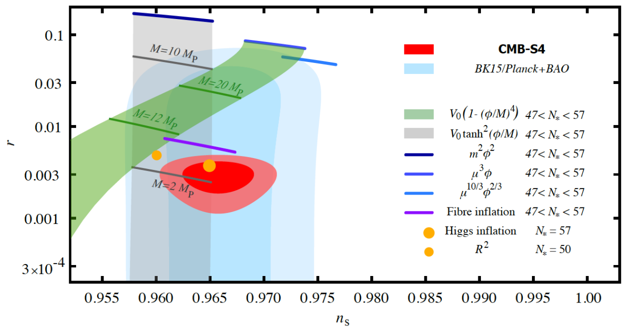
- LiteBIRD is a space observatory under development by an international collaboration led by JAXA (with ASI and INFN funding), aiming for an early ‘30s launch
- It will provide full-sky maps of the polarized emission on scales ≳ 0.5 - 1º, in 15 frequencies band covering the 40-400 GHz range
- Its main science goal is a sensitivity σ_r = 0.001, and separate 5 detection of r = 0.01 from both scales larger than ~ 20º and scales in 1º-20º
  - A byproduct of this goal will be the definitive* measurements of E-mode polarization over those angular scales
- Our group is leading the activites in beam modeling, calibration, mapmaking, and the development of the simulation pipeline, and we are also involved in the power spectrum and likelihood activities

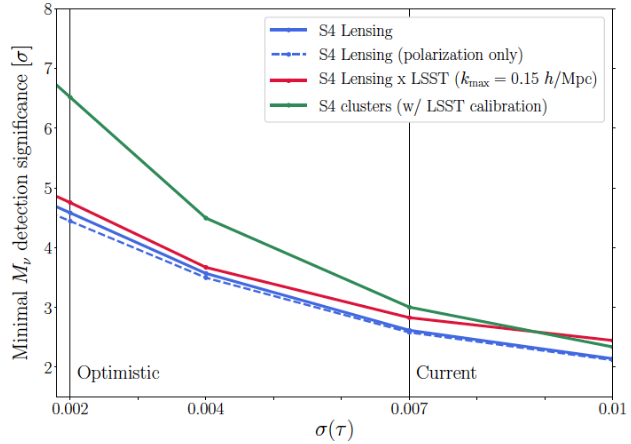


Credit: LiteBIRD collaboration 2024

CMB-S4

- CMB-S4 are two sets of ground based observatory encompassing O(5 10^5) detectors, under development for deployment in the Atacama desert in Chile and at the South Pole in the early 2030s
- With a combined coverage of ~ 70% in the 30-250GHz frequency range, CMB-S4 main cosmology goals are a 5σ detection of r = 0.003, a limit $\Delta N_{eff} < 0.06$ on the number of extra relativistic degrees of freedom, and a robust detection of the minimum total neutrino mass
- Our group is not currently involved in CMB-S4, but there is an ongoing effort aimed at defining a joint contribution to the project by the entire Italian CMB community





Credit: CMB-S4 collaboration 2019

Summary

- There is still a wealth of information to be gained by CMB measurements for cosmology, fundamental physics, and astrophysics
- The next 10-15 years will bring significant progress in understanding the early phases of the Universe, the nature of Dark Matter and Dark Energy, the properties of neutrinos and other possible light particles, the evolution of cosmic structure, the formation of the first sources of light, the structure of our Galaxy, and more
- Even more information can be gained by combining CMB observation with other cosmologial probes, like gravitational lensing and large scale structure measurements
- Our group is directly involved in many of the CMB ongoing efforts, with leading roles into all aspects of CMB data analysis, from instrumental design, to the final science analysis