Spectral distortions of the cosmic microwave background: a new window to early Universe physics

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Cosmology is now a precise scientific discipline, with detailed theoretical models that fit a wealth of very accurate measurements. Of the many cosmological data sets, the cosmic microwave background (CMB) temperature and polarization *anisotropies* provide the most stringent and robust constraints to theoretical models, allowing us to address fundamental questions about inflation, the nature of dark matter and dark energy, and particle physics [1, 2, 3]. But the CMB holds another, complementary piece of information: its *frequency spectrum*. Since COBE/FIRAS the average CMB spectrum is known to be extremely close to a perfect blackbody, with possible spectral distortions limited to $\Delta I_\nu / I_\nu \lesssim 10^{-5}$ [4, 5]. Although no distortion was detected, this measurement already places tight constraints on the thermal history of our Universe, ruling out cosmologies with extended periods of significant energy release, disturbing the equilibrium between matter and radiation. More than 20 years have past since the launch of COBE and from the technological point of view already today it should be possible to improve the sensitivity by *at least three orders of magnitude* [6]. This opens a new window to the early Universe, on one hand allowing us to directly probe processes that are present within the standard cosmological paradigm, but also opening up a huge discovery space for non-standard physics.

The CMB spectrum constrains energy release occurring at redshift $z \lesssim \text{few} \times 10^6$. A large number of astrophysical or cosmological processes in this range exist, leading to predictions of observable distortions. A small sample of processes follows.

- Reionization and structure formation: the first sources of radiation, supernova feedback [7] and structure formation shocks [8, 9, 10] heat the intergalactic medium at low redshifts ($z \lesssim 10$), leading to up-scattering of CMB photons characterized by a Compton y-distortion [11]. The distortion is expected to reach $\Delta I_\nu / I_\nu \simeq 10^{-7} - 10^{-6}$ and thus could be measured at $\simeq 100\,\sigma$ using present-day technology, teaching us about the average temperature of the intergalactic medium [12], and promising way to find the missing baryons in the local Universe which otherwise are hard to observe [9].
- Inflation: the Silk-damping of small-scale perturbations gives rise to a chemical potential (or μ-distortion) and y-type distortion [13, 14, 15, 16], which directly depends on the shape and amplitude of the primordial power spectrum at scales $0.1\,\text{kpc} \lesssim \lambda \lesssim 1\,\text{Mpc}$ [17, 18]. This allows constraining the trajectory of the inflaton at stages unexplored by CMB anisotropies and other ongoing or planned experiments [19]. The distortion is also sensitive to the difference between adiabatic and isocurvature perturbations [15, 20, 21], as well as primordial non-Gaussianity in the squeezed-limit [22, 23].
- Cosmological recombination radiation: the cosmological recombination process of hydrogen and helium introduces distortions at high redshifts ($z \simeq 10^3 - 10^4$), corresponding to $\simeq 260\,\text{kyr}$, $\simeq 130\,\text{kyr}$, and $\simeq 18\,\text{kyr}$ after the big bang. The overall distortions is very small ($\Delta I_\nu / I_\nu \simeq 10^{-9}$) but it has a unique frequency-dependence which opens an independent path to determination of cosmological parameters (like the baryon density and *pre-stellar* helium abundance) and direct measurements of the recombination dynamics, probing the Universe at stages well before the last scattering surface [24].
- cooling of matter: the adiabatic cooling of ordinary matter continuously extracts energy from the CMB photon bath leading to another small but indisputable distortion that directly depends on the baryon density and is characterized by a *negative* μ- and y-parameter [25, 26].

All these examples demonstrate that the CMB spectrum provides a rich and unique source of complementary information about the early Universe, with the certainty for the detection of spectral distortions at a level within reach of present day and future instrumentation. The CMB spectrum could also place interesting constraints on decaying and annihilating particles [27, 28, 29, 25], the power spectrum of small-scale magnetic fields [30], primordial black holes [31], and cosmic strings [32, 33, 34], to mention a few more exotic cases. Deciphering all these signals will be a big challenge for the future, but it holds the potential for new discoveries, providing additional, independent constraints on processes that otherwise will remain a secret of our Universe.

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