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The Cosmic Microwave Background/Le rayonnement fossile à 3K

CMB: the isotropic part

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Presented by Guy Laval

Abstract

The Cosmic Microwave Background, or CMB, is the only truly diffuse background, whereas the other backgrounds come from the integrated light (along the line of sight) of various sources. The CMB is now known, thanks to the FIRAS experiment above the COBE satellite, to have a nearly perfect blackbody spectrum. This proves to be quite constraining on early energy releases. We review the average spectrum of the CMB with respect to other backgrounds and the consequences regarding the history of the early Universe. ***To cite this article: F.R. Bouchet, J.-L. Puget, C. R. Physique 4 (2003).***

Résumé

CMB : la partie isotrope. Le rayonnement fossile à 3K (CMB) est l'un des rares fonds extragalactiques de nature diffuse alors que la majorité des autres fonds provient de la lumière intégrée (le long de la ligne de visée) de sources variées. Le CMB est maintenant connu, grâce à l'expérience FIRAS à bord du satellite COBE, comme possédant un spectre indistinguable de celui d'un corps noir. Cela apporte de fortes contraintes sur des évenements énergétiques précoces. Nous présentons le spectre moyen du CMB par rapport aux autres fonds de rayonnement et les conséquences quant à l'histoire de l'Univers primordial. ***Pour citer cet article : F.R. Bouchet, J.-L. Puget, C. R. Physique 4 (2003).***

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Mots-clés : Anisotropies du fond de rayonnement cosmique ; Cosmologie ; Univers primordial

1. Introduction

The spectral energy distribution of the cosmic background (as shown in Fig. 1 of the presentation article by Bouchet, this volume) is dominated by a microwave component, the CMB, which contains 95% of the energy, is truly diffuse and has a spectrum very close to a Planck function. Before we move on, let us first note that other components of the cosmic background have been observed for a long time. Indeed, a background in the radio range, now known to originate from the sum of extragalactic radio sources, was the first component of the cosmic background to be observed. It contains only a very small fraction of the energy (1.1×10^{-6}, see Table 1).

Similarly, the X-ray background was discovered quite early by Giacconi et al. [1] and is now very well measured. The Gamma ray cosmic background is also detected in the range 0.1 MeV to more than 1 GeV. The X-ray background Spectral Energy Distribution (SED) peaks around 30 keV. At lower energies, Hasinger et al. [2] show that 75 to 80% of the intensity of the background was broken into individual sources and this fraction will probably significantly increase with observations carried

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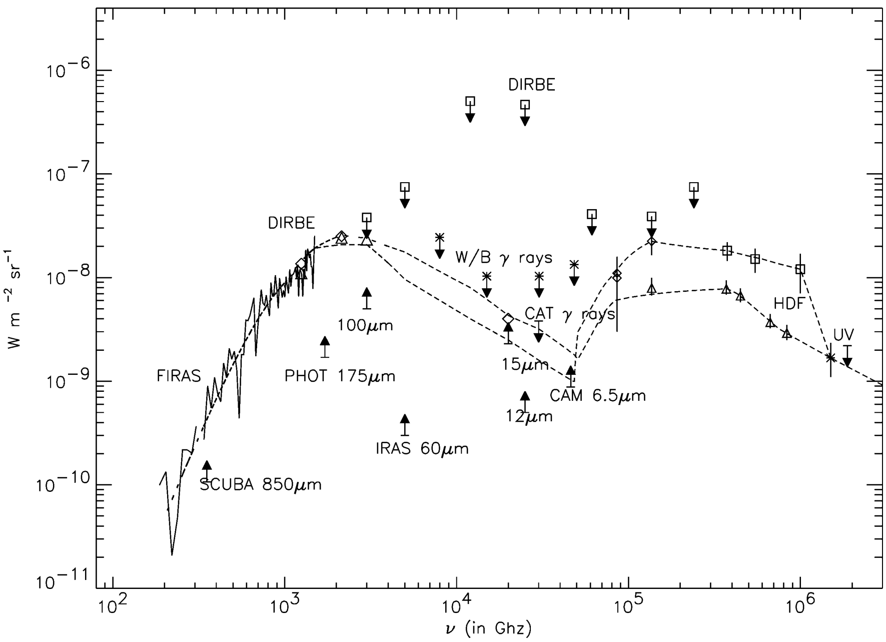


Fig. 1. The cosmic background spectrum (CMB excluded) from ultra-violet to submillimetre after Gispert et al. [17]. The two dotted lines connect upper and lower limits and show the range allowed by the observations. Reprinted from [17]. See also the discussion of infrared and radio sources by Lagache and Aghanim, this volume.

Table 1
The energy distribution in the various components of the cosmic background

Frequency range	Intensity $[\mathrm{W\,m^{-2}\,sr^{-1}}]$	Fraction of cosmic background
Radio	1.2×10^{-12}	1.1×10^{-6}
CMB	9.96×10^{-7}	0.93
Infrared	$4–5.2 \times 10^{-8}$	0.04–0.05
Optical	$2–4 \times 10^{-8}$	0.02–0.04
X-rays	2.7×10^{-10}	2.5×10^{-4}
Gamma rays	3×10^{-11}	2.5×10^{-5}

out with the Chandra observatory. Models of the X-ray background assume it is mostly made of the emission of extinguished Active Galactic Nuclei (AGNs). The high energy tail extending in the gamma ray range is likely to be of a similar nature.

Another component of the cosmic background made of the integrated radiation from all galaxies in the ultraviolet, optical and infrared, has been predicted for a long time [3]. In the optical and near infrared it contains the redshifted stellar radiation not absorbed by dust. The absorbed energy is re-radiated in the far infrared. The main energy source is expected to be the nucleosynthesis of heavy elements in stars.

It also contains the ultraviolet/optical radiation from the AGNs which probably draw their energy from accretion onto massive black holes in the centre of these galaxies. A large fraction of the energy radiated in the far ultraviolet and soft X-rays is very efficiently absorbed by dust and re-radiated in the far infrared. The fraction of the energy coming out in the hard X-rays escapes absorption and is seen directly as the cosmic background above about 30 keV.

The energy from these two processes is thus distributed between: (i) the optical and near infrared wavelength range which is dominated by stellar radiation; and (ii) the re-radiated part in the far infrared and submillimetre range which comes from nucleosynthesis in stars and from accretion onto black holes in AGNs; their relative contribution is currently unknown. For definiteness, we shall use 6×10^{13} Hz and 5 µm as the frequency and wavelength limits, respectively, between direct and dust re-radiated radiation.

These two components of the cosmic background were *still not detected until 8 years ago*. The combination of observations with the COSMIC BACKGROUND EXPLORER (COBE) satellite and of deep surveys in the optical and near infrared with the Hubble Space Telescope (HST), the Infrared Space Observatory (ISO) and large ground based telescopes has lead to a good measurement of the cosmic background in the far infrared and submillimetre ranges and lower limits in the mid infrared, near infrared and optical from deep surveys of extragalactic sources. These surveys have good enough sensitivities to lead to good estimates of the integrated brightness of these sources. In the ultraviolet and near infrared, upper limits of the integrated diffuse emission have been obtained from COBE and Rocket measurements. Finally, the propagation of ultra high energy gamma rays from Mkn 501 and Mkn 421 has allowed upper limits to be put on the mid infrared cosmic background about a factor of 2 above the lower limit obtained from the ISO cosmological counts at 15 µm. These limits constrain rather well the cosmic background in a spectral region where direct measurements are impossible due to the strong zodiacal cloud brightness.

It should be noted that the uncertainties in the cosmic background are at present larger in the optical range than in the infrared. Taking this into account the ratio of energy in the thermal infrared to the energy in the optical-UV is between 1 and 2.5.

The energy distribution of the cosmic background between the different wavelength ranges is given in Table 1.

2. Formation of the CMB, recombination

In the early universe, matter and radiation are in quasi-perfect thermal equilibrium. Two time scales are important in this respect. Elastic scattering of photons by free electrons through Thomson scattering has a mean free path given by

$$\lambda_{\mathrm{scatt}} = \frac{1}{n_o x_e (1+z)^3 \sigma_T} = \frac{7.5 \times 10^{30}}{x_e (1+z)^3}\ \mathrm{cm}, \tag{1}$$

where $n_o x_e$ is the density of free electrons, and σ_T stands for the Thomson cross-section. The second important one is the probability for absorption (or emission) of photons through free-free interactions which provides full thermalization to a Planckian spectrum for $z > 3 \times 10^7$. Comparing the Thomson mean free path with the horizon $H(z)$ as a function of redshift:

$$\frac{\lambda_{\mathrm{scatt}}}{H(z)} = \frac{8.3}{x_e(1+z)} \tag{2}$$

it is clear that the universe, which is fully ionised at $z = 1100$, is opaque in this redshift range. When the temperature in the universe becomes smaller than about 3000 K, the cosmic plasma recombines and the ionisation rate x_e falls from 1 at $z > 1000$ down to $x_e < 10^{-2}$ at $z < 1000$. The universe becomes thus transparent to background photons over a narrow redshift range of $\Delta z \simeq 100$. Photons will then propagate freely as long as galaxies and quasars do not reionise the universe. The Thomson optical depth between this reionization redshift z_{reion} and the present time is for the Euclidean case:

$$\tau_i = 0.01 \times (1 + z_{\mathrm{reion}})^{3/2}. \tag{3}$$

For the standard cosmological model, $z_{\mathrm{reion}} \simeq 10$; it is thus clear that the cosmic background at redshift 1000 can be observed with only small secondary distortions.

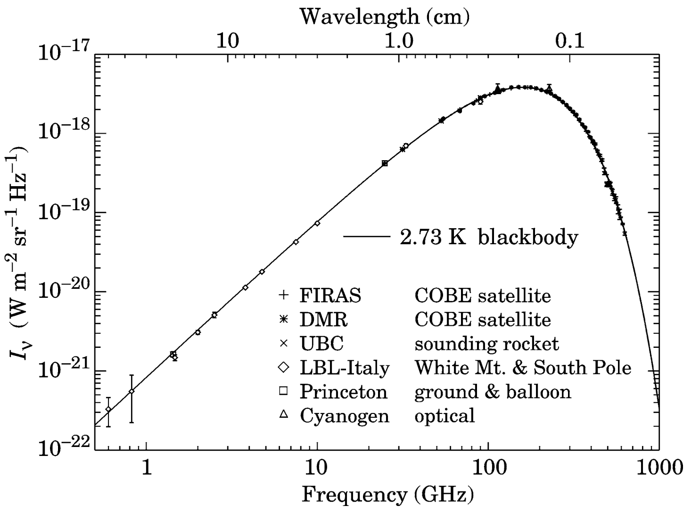
3. The CMB spectrum

It is rather remarkable that the temperature of the main component of the cosmic background can be computed from basics physics using only two cosmological observables. Alpher, Bethe and Gamow [4] showed that the chemical elements other than hydrogen, which cannot be explained by nucleosynthesis in stars, could have been formed in a hot big bang. Nevertheless they did not take into account the fact that radiation dominates over matter at that time. This was taken into account by Gamow [5,6], but the first correct calculation is given by Alpher and Herman [7]; they predicted a value around 5 K for the cosmic background radiation temperature.

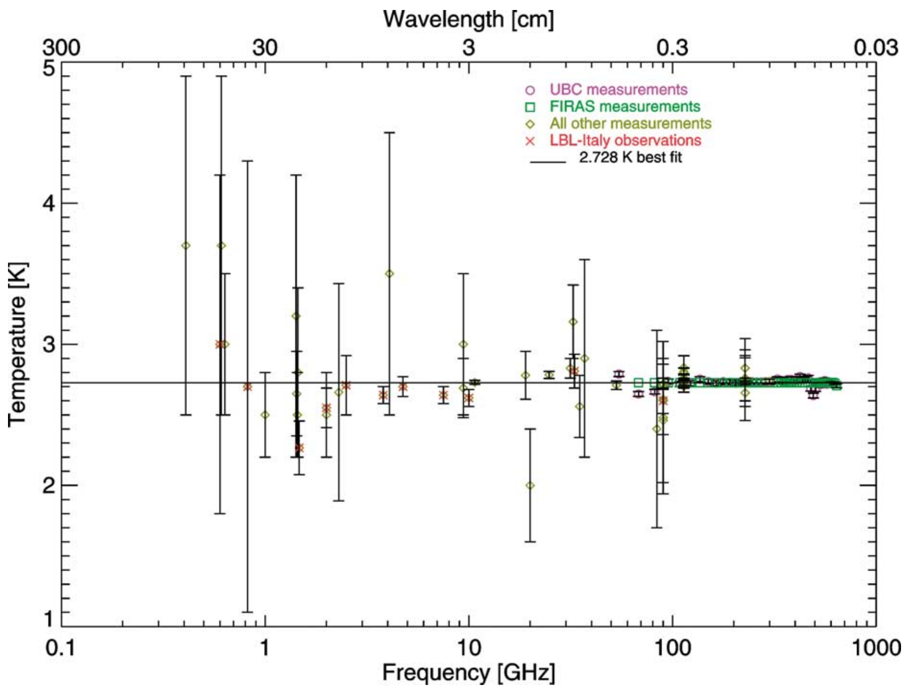
The argument goes as follows. To explain the large amount of Helium observed today (about 25%) Deuterium should be synthesised first. This can take place only when the cosmic plasma is in a rather narrow range of temperatures, high enough for the fusion reaction to take place, and low enough so Deuterium nuclei are not photo-dissociated. This temperature is $T \simeq 10^9$ K. The dynamics of the universe being dominated by radiation at this temperature, its expansion rate is then fixed by general relativity and the expansion time is 200 seconds. It is thus easy to compute the baryon density needed at this time which would lead to the synthesis of a substantial fraction of the mass into Deuterium (thus then into Helium),

$$t_{\mathrm{exp}}(T = 10^9) \times n_B \times (\sigma_{pn-D} \times v) \simeq 1, \tag{4}$$

where σ_{pn-D} stands for the Deuterium production cross-section which is at this temperature of the order of 10^{-2} mb, and v is the baryon velocity dispersion at $T \simeq 10^9$ K; this implies a baryon density $n_B \simeq 10^{18}\ \mathrm{cm}^{-3}$.



(a)



(b)

Fig. 2. (a) Experimental determinations of the spectrum of the CMB compared with a Planck function at 2.728 K shown as a thin line. (b) Deviations of the data from the best fit. This tightly constrains allowed energy releases at redshift below the thermalization epoch at $z \sim 10^7$; see text and Fig. 4. Reprinted from Smoot and Scott [18].

Knowing the present density in the universe ($\simeq 10^{-7}$ cm^{-3}) the expansion factor since primordial nucleosynthesis $1 + z_{NS}$ is then given by

$$1 + z_{NS} = \left(\frac{\rho_{NS}}{\rho_o}\right)^{1/3} \simeq 2 \times 10^8. \tag{5}$$

This lead to a prediction of the temperature of the black body radiation content of the universe today:

$$T_{BB} = \frac{10^9}{1 + z_{NS}} \simeq 5\ \mathrm{K}. \tag{6}$$

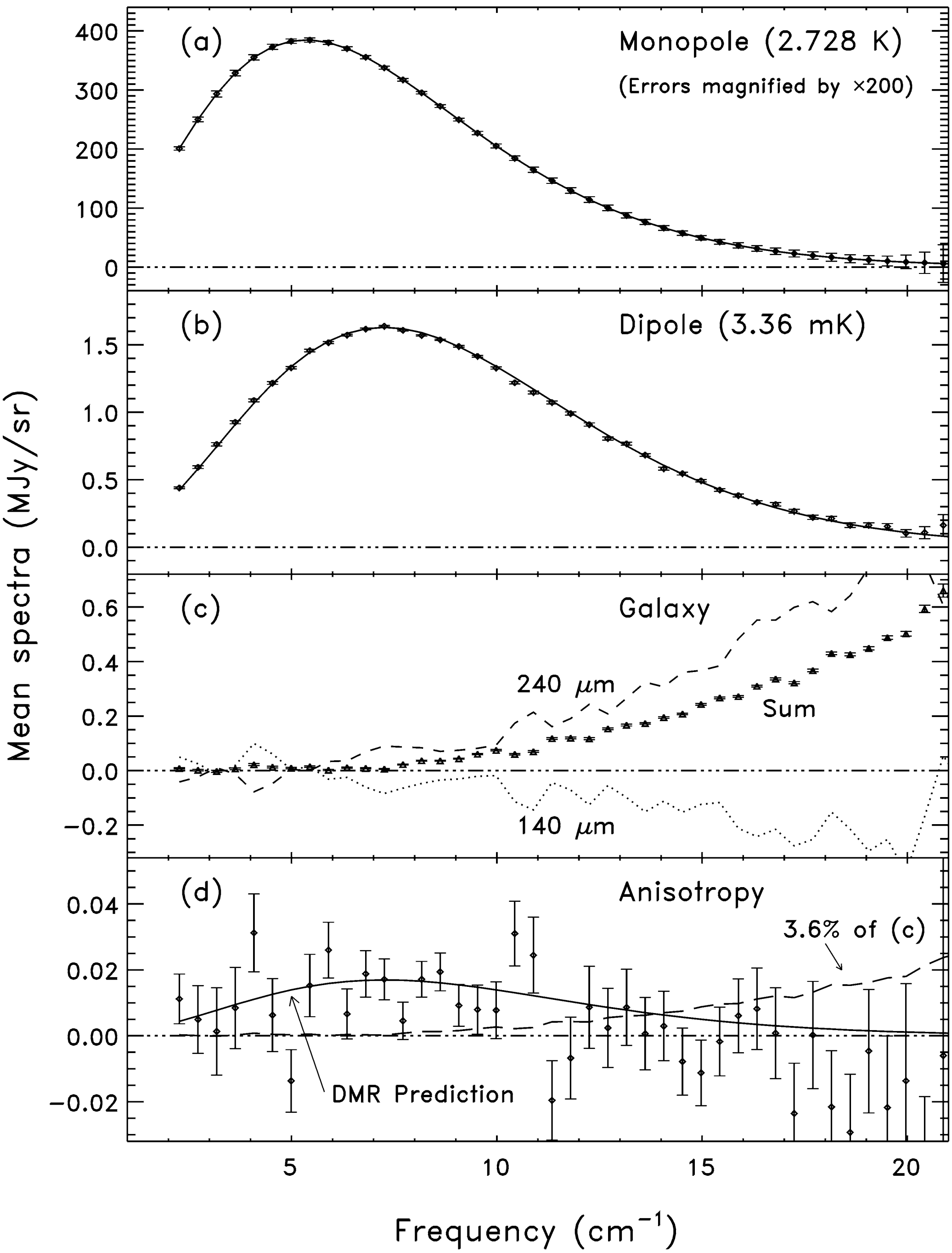


Fig. 3. (a) FIRAS data points with 200σ error bars (!), together with a 2.728 K Planck spectrum (solid line). (b) FIRAS dipole spectrum together with a curve representing a 3.36 mK differential Planck spectrum. (c) Spectra of the correlated part with Galactic templates given by DIRBE at 240 and 140 µm. The discrete points show the sum of the Galactic components in FIRAS. (d) Spectrum of the residual (dipole and galaxy subtracted) FIRAS fluctuations correlated with the DMR ones. The curve is the 35 µK differential spectrum predicted by DMR, and the dashed line is 3.6% of the Galactic spectrum in (c). Reprinted from [15].

This remarkable prediction based only on the helium fraction and a rough estimate of the present baryon density, was spectacularly confirmed in 1965 when Penzias and Wilson [8] announced "A Measurement of Excess Antenna Temperature at 4080 Mc/s" which was interpreted in the same journal issue by Dicke et al. [9] as the CMB with a temperature of 3.5 ± 1 K.

In the simplest hot big bang model, there is no energy released in the radiation between $z \simeq 10^9$ (electron–positron annihilation) and $z \simeq 10$ (first galaxies and quasars). Thus the background radiation which decouples at $z = 1000$ should be very close to a Planck function. This prediction was much more difficult to test observationally than the existence of the background. It took several decades before balloon borne experiments by Woody and Richards [10–12] could show that the spectrum of the CMB had a maximum at a frequency around 3×10^{11} Hz as it should be if the intensity measured at centimetre wavelengths was the Rayleigh Jeans part of a Planck function with a temperature around 3 K. This was a very important result but, in such a balloon borne experiment, systematic effects were such that deviations from a Planck function could not be assessed with an accuracy better than about 30%.

This situation is very reminiscent of the present one with respect to the measurements of the anisotropies of the CMB on small scale as will be seen below.

It took another 12 years before the COBE satellite made an extremely accurate check of the Planckian nature of the CMB spectrum as shown in Fig. 2. The refined calibration of FIRAS gives the final accurate absolute temperature of $T_{\mathrm{CMB}} = 2.725 \pm 0.001$ K [13].

Two types of distortions can affect the CMB. Energy released in the cosmic plasma at rather low redshifts (typically after recombination) heats the plasma at a temperature higher than the background radiation temperature. Compton scattering of photons on the hot electrons tends to shift, on average, the photon spectrum towards higher energies without changing the photon number. This distortion is referred to as a Compton distortion. With respect to the initial Planck spectrum, the spectrum is depleted in the Rayleigh Jeans part and boosted in the Wien part. For a non relativistic plasma, it is characterised by a single parameter y which is the integrated Compton optical depth

$$y = \int n_e \sigma_T^{\mathrm{d}} l. \tag{7}$$

A second type of distortion appears for energy released before re-ionisation but at times such that thermalization of the energy between plasma and radiation takes place but too late for photons to be produced to lead to a Planckian spectrum. This leaves a Bose–Einstein spectrum characterised by a non zero chemical potential μ.

The FIRAS sky spectra which are a function of frequency and position, have been separated by Fixsen et al. [14] into a Planckian monopole spectrum, a dipole (associated with the motion of our Galaxy with respect to the CMB) of known spectrum but for which the amplitude and the direction were obtained from the FIRAS data, and a galactic component of unknown spectrum but assumed spatial distribution (two templates were used without changing significantly the CMB results). The results are displayed in Fig. 3. Furthermore, the residual anisotropies were correlated with the DMR anisotropies and their spectrum is also displayed in Fig. 3. This spectrum is in good agreement with the one expected if the DMR anisotropies

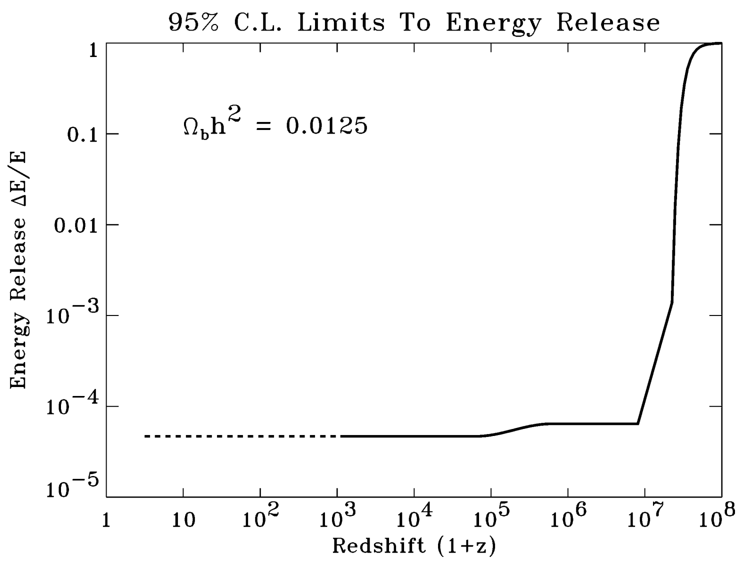


Fig. 4. Upper limit (from Smoot and Scott [18]) to the energy release allowed by the FIRAS spectrum as a function of redshift. Reprinted from [18].

are $\delta T/T$ fluctuations. As concluded by Fixsen et al. [15]: "*This strongly suggests that the anisotropy observed by DMR, and corroborated by* FIRAS*, is due to temperature variations in the CMB*." These results have just been improved with the comparison of FIRAS with WMAP [16].

The analysis of the spectrum of the residuals averaged over the good sky gives very tight upper limits for these two parameters measuring the expected deviations from a Planck spectrum:

$$y < 2.5 \times 10^{-5}, \tag{8}$$

$$\mu < 3.3 \times 10^{-4}. \tag{9}$$

These (3σ) limits constrain very strongly the maximum energy released in the universe around recombination: $\Delta E/E < 1 \times 10^{-4}$. This is shown in Fig. 4.

We have seen that the components of the cosmic background outside the microwave range contain less than 7% of the energy and is likely to be dominated by sources produced at rather low redshifts. The Planckian nature of the bulk of the diffuse part of the cosmic background, which is the CMB, has important implications. It tells us that very little energy release took place in the universe between $z = 10^7$ and the formation of the first extragalactic sources we see today. Thus the CMB we observe today is simply the redshifted background which was present after recombination at $z = 1000$ with a very small amount of secondary distortions. Furthermore, the background at this time resulted from well understood interactions with the other constituents of the universe (baryonic matter through free-free and Compton interactions and dark matter and neutrinos through gravity).

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