PHYSICAL REVIEW D **78,** 123003 (2008)

Thermodynamics of the early Universe with mirror dark matter

Paolo Ciarcelluti*
Département AGO-IFPA, Université de Liège, B-4000 Liège, Belgium

Angela Lepidi†
Dipartimento di Fisica, Università di Ferrara, and INFN, sezione di Ferrara, I-44100 Ferrara, Italy
(Received 30 July 2008; published 10 December 2008)

Mirror matter is a promising self-collisional dark matter candidate. Here we study the evolution of thermodynamical quantities in the early Universe for temperatures below ~100 MeV in presence of a hidden mirror sector with unbroken parity symmetry and only with gravitational interactions. This range of temperatures is interesting for primordial nucleosynthesis analyses, therefore we focus on the temporal evolution of number of degrees of freedom in both sectors. Numerically solving the equations, we obtain the interesting prediction that the effective number of extra-neutrino families raises for decreasing temperatures before and after big bang nucleosynthesis; this could help solving the discrepancy in this number computed at nucleosynthesis and cosmic microwave background formation epochs.

DOI: 10.1103/PhysRevD.78.123003 PACS numbers: 95.30.Cq, 95.35.+d, 98.80.−k

I. INTRODUCTION

In the 1950s Lee and Yang [1] suggested that the existence of a hidden sector of particles and interactions with exactly the same properties as our visible world (except for right-handed, instead of left-handed, weak interactions) could restore the total symmetry of physical laws. Many years later Foot *et al.* [2] proposed a model with exact parity (mirror) symmetry between the two sectors, that are described by the same Lagrangian and coupling constants, and consequently have the same microphysics. Since the only interaction linking the two worlds is gravity [3], mirror baryons constitute a dark matter candidate in a natural way, as they interact with mirror photons, but not with the ordinary ones.

The phenomenology of mirror matter was studied in several papers (for an extended list see the bibliography of Ref. [4]), in particular, the implications for big bang nucleosynthesis (BBN) [5,6], primordial structure formation and cosmic microwave background [6–11], large scale structure of the Universe [6–9,11,12], microlensing events (MACHOs) [13–16], interpretation of DAMA experiment [17,18] are related to this study.

If the mirror (M) sector exists, then the Universe along with the ordinary (O) particles should contain their mirror partners, but their densities are not the same in both sectors. Indeed, the BBN bound on the effective number of extra-neutrino families implies that the M sector has a temperature lower than the O one, as naturally obtained in some inflationary models [19]. Then, two sectors have different initial conditions, they do not come into thermal equilibrium at later epoch and they evolve independently, conserving their entropies separately and maintaining the ratio between their temperatures approximately constant.

All the differences with respect to the O world can be described in terms of only two free parameters, defined as

$$x \equiv \left(\frac{s'}{s}\right)^{1/3}; \qquad \beta \equiv \Omega'_b/\Omega_b, \tag{1}$$

where T (T'), Ω_b (Ω'_b), and s (s') are, respectively, the O (M) photon temperature, cosmological baryon density, and entropy density. [20] The bounds on the mirror parameters are $x < 0.7$ and $\beta > 1$, the first one coming from the previously mentioned BBN limit and the second one from the hypothesis that a relevant fraction of dark matter is made of M baryons. In general, during most history of the Universe, we can approximate

$$x \equiv \left(\frac{s'}{s}\right)^{1/3} = \left[\frac{q'(T')}{q(T)}\right]^{1/3} \frac{T'}{T} \approx \frac{T'}{T}, \tag{2}$$

where now $q(T)$ and $q'(T)$ are, respectively, the O and M entropic degrees of freedom, and the M photon temperature $T'(T)$ is a function of the O one. This approximation is valid only if the temperatures of the two sectors are not too different, or otherwise if we are far enough from crucial epochs, like e^+-e^- annihilation [5]. But we are just investigating the range of temperatures interested by this phenomenon, and in fact one of the aims of this paper is to compute the trends of these thermodynamical quantities exactly, when the previous approximation is no longer valid.

The present study is required for different reasons. First of all, we need a detailed study of thermodynamical evolution of the early Universe in order to obtain a reliable description of the thermal cosmic history in presence of M dark matter. Second, an accurate study of the trend of number of degrees of freedom is necessary for any future simulation of nucleosynthesis of primordial elements in

*paolo.ciarcelluti@ulg.ac.be
†lepidi@fe.infn.it

 © 2008 The American Physical Society

both sectors, that may be compared with observations. In particular, it becomes even more important in view of the recent proposed interpretation of the DAMA/LIBRA experiment in terms of interactions with M heavy elements [17,18]. Third, claims for variations of the effective number of extra-neutrino families computed at BBN (~ 1 MeV) and cosmic microwave background (CMB) formation ($\lesssim 1$ eV) epochs require investigations for possible variations of these numbers as consequences of physics beyond the standard model (see the recent Ref. [21] and references therein for previous works).

The plan of the paper is as follows. In the next section we introduce the thermodynamical equilibrium in the early mirror Universe and the equations governing its evolution. In Sec. III we present the numerical solutions of these equations and discuss the results. Finally, our main conclusions are summarized in Sec. IV.

II. THERMODYNAMICAL EQUILIBRIUM

We extend the standard theory of thermodynamics in the early Universe in order to take the existence of M particles into account.

We consider the Universe as a thermodynamical system composed of different species (O and M electrons, photons, neutrinos, nucleons, etc.) which, in the early phases, were to a good approximation in thermodynamical equilibrium, established through rapid interactions, in the two sectors separately.

We assume, as usual, that the Universe is homogeneous, and the chemical potentials of all particle species A are negligible, i.e. $\mu_A \ll T$ [22,23]. The latter assumption implies the conservation of the total entropy of the Universe S. Therefore we can use the equilibrium Bose-Einstein or Fermi-Dirac distribution functions and calculate the energy density ρ, the pressure p, and the entropy density s for every particle species in thermal equilibrium:

$$\rho_A(T) = \frac{g_A}{2\pi^2} \int_{m_A}^{\infty} \frac{(E^2 - m_A^2)^{1/2} E^2}{\exp[\frac{E}{T}] \pm 1} dE, \tag{3}$$

$$p_A(T) = \frac{g_A}{6\pi^2} \int_{m_A}^{\infty} \frac{(E^2 - m_A^2)^{3/2}}{\exp[\frac{E}{T}] \pm 1} dE, \tag{4}$$

$$s_A(T) = \frac{p_A(T) + \rho_A(T)}{T}, \tag{5}$$

where g_A is the spin-degeneracy factor of the species A, the signs $+$ and $-$ correspond, respectively, to fermions and bosons, and $E = \sqrt{\mathbf{p}^2 + m^2}$, with $\mathbf{p}$ the momentum. We can use the usual parametrization of the entropy density:

$$s(T) = \frac{2\pi^2}{45} q(T) T^3, \tag{6}$$

where

$$q(T) \equiv \sum_{\text{bosons}} g_b(T) \left(\frac{T_b}{T}\right)^3 + \frac{7}{8} \sum_{\text{fermions}} g_f(T) \left(\frac{T_f}{T}\right)^3 \tag{7}$$

is the number of *effective entropic* degrees of freedom (d.o.f.), that group together the d.o.f. for all bosons (g_b) and fermions (g_f). An analogous formalism can be used for the total energy density ρ, which can be parametrized as

$$\rho(T) = \frac{\pi^2}{30} g(T) T^4, \tag{8}$$

where

$$g(T) \equiv \sum_{\text{bosons}} g_b(T) \left(\frac{T_b}{T}\right)^4 + \frac{7}{8} \sum_{\text{fermions}} g_f(T) \left(\frac{T_f}{T}\right)^4 \tag{9}$$

is the number of *effective energetic* degrees of freedom.

A. Equations

We calculate the equations which link the O and M sector temperatures and thermodynamical quantities; then we solve these equations numerically. Once the temperatures are known, it is possible to obtain the exact total number of d.o.f. in both sectors, which, as it is common in literature, can be expressed in terms of extra-neutrino number. We report in Sec. III the results of these calculations.

The presence of the other sector leads in both sectors to the same effects of having more particles. As already stated, we do not take interactions between the two sectors besides gravity into account. This implies that the entropies of the two sectors are conserved separately, and the parameter x is constant during the cosmic evolution:

$$x = \left(\frac{s'}{s}\right)^{1/3} = \left(\frac{s' \cdot a^3}{s \cdot a^3}\right)^{1/3} = \left(\frac{S'}{S}\right)^{1/3} = \text{const}, \tag{10}$$

where a is the scale factor.

As already stressed, O and M sectors have the same microphysics; therefore we can assume, to a first approximation, that the neutrino decoupling temperature [24] $T_{D\nu}$ is the same in both of them, that is $T_{D\nu} = T'_{D\nu'}$. But the temperatures in the O sector when the O and M neutrino decouplings take place are different, $T_{D\nu} \neq T_{D\nu'}$, with $T_{D\nu} < T_{D\nu'}$ since $x < 1$. Therefore, at $T \gg T_{D\nu}$ ($T'_{D\nu}$), O (M) neutrinos are in thermal equilibrium with the O (M) plasma and their temperature is $T_\nu = T$ ($T'_\nu = T'$), while after decoupling it scales as a^{-1}.

In each sector, shortly after the ν decoupling, the e^+-e^- annihilate because the temperature becomes lower than $2m_e$, which is the threshold for the reaction $\gamma \leftrightarrow e^+ e^-$ in both O and M worlds. Thus electrons and positrons transfer their entropy to the corresponding photons, which become hotter than neutrinos.

This fact will be used together with the entropy conservations (total and in each sector separately) to find the equations that govern the evolution of the M photon temperature T' as a function of the O one T. In fact, O and

M neutrino decouplings are key events, together with both e^+-e^- annihilation processes, for the thermodynamics in this range of temperatures. Once we call $T_{D\nu'}$ the O world temperature when the M neutrino decoupling takes place, we can split the early Universe evolution for temperatures $T \lesssim 100$ MeV into three phases.

1. *Phase* $T > T_{D\nu'}$

Photons, electrons, positrons and neutrinos are in thermal equilibrium in each sector separately, that is $T_\nu = T_e = T$, $T'_\nu = T'_e = T'$ [25]. Using equations from (3) to (9) for particles in both sectors we are able to calculate only the d.o.f. number in O or M worlds; but to work the *total* d.o.f. number out, we need the M temperature T' as a function of the O one T or vice versa.

As we neglect the entropy exchanges between the sectors (valid since there are only gravitational interactions between them), we can obtain both these functions using Eq. (1) and imposing $x = \text{const}$ in

$$x^3 = \frac{s'_e + s'_\gamma + s'_\nu}{s_e + s_\gamma + s_\nu} = \frac{[\frac{7}{8} q_e(T') + q_\gamma + \frac{7}{8} q_\nu] T'^3}{[\frac{7}{8} q_e(T) + q_\gamma + \frac{7}{8} q_\nu] T^3}, \tag{11}$$

where $q_\nu = 6$ and $q_\gamma = 2$, while $q_e(T)$ stands for

$$q_e(T) = \frac{8}{7} \frac{s_e(T)}{\frac{2\pi^2}{45} T^3}, \tag{12}$$

with $s_e(T)$ defined in (5), and we have used $T'_e = T'_\nu = T'_\gamma = T'$, $T_e = T_\nu = T_\gamma = T$. We have used also that, since particles and physics are the same in both sectors, the equilibrium distribution functions, and thus the spin-degeneracy factors, are the same: $q_e = q'_e$, $q_\gamma = q'_\gamma$, $q_\nu = q'_\nu$. Equation (11) can be solved numerically in order to obtain the function $T'(T)$ for every $T > T_{D\nu'}$

2. *Phase* $T_{D\nu} < T \leq T_{D\nu'}$

At $T \simeq T_{D\nu'}$ M neutrinos decouple and right after M electrons and positrons annihilate, transferring their entropy only to the M photons, and hence raising their temperature. In the M sector the entropies of the system $(e'^{\pm}, \gamma')$ and of ν' are conserved separately. Nevertheless, O photons and neutrinos have still the same temperature T. Therefore we have two equations. The first one comes from the conservation of entropies in the M sector, so that their ratio is equal to the asymptotic value computed at high temperatures, when the e'^+-e'^- annihilation process had not begun yet:

$$\frac{S'_e + S'_\gamma}{S'_\nu} = \frac{s'_e + s'_\gamma}{s'_\nu} = \frac{\frac{7}{8} q_e(T') + q_\gamma}{\frac{7}{8} q_\nu} \left(\frac{T'}{T'_\nu}\right)^3 = \frac{\frac{7}{8} \cdot 4 + 2}{\frac{7}{8} \cdot 6} = \frac{22}{21}, \tag{13}$$

and its solution gives T'_ν as a function of T'. The second one is the conservation of ratio of entropies in the two sectors:

$$x^3 = \frac{[\frac{7}{8} q_e(T') + q_\gamma] T'^3 + \frac{7}{8} q_\nu T'^3_\nu}{[\frac{7}{8} q_e(T) + q_\gamma + \frac{7}{8} q_\nu] T^3}, \tag{14}$$

and its solution, obtained using Eq. (13), gives T' as a function of T. Equation (14) is the same as Eq. (11) but with $T'_e = T'_\gamma = T' \neq T'_\nu$.

3. *Phase* $T \leq T_{D\nu}$

At $T \simeq T_{D\nu}$ O neutrinos decouple and right after O electrons and positrons annihilate. Now also in the O sector the entropies of the system $(e^{\pm}, \gamma)$ and ν are conserved separately; therefore we need one more equation to calculate the O neutrino temperature T_ν as a function of the O photon one T:

$$\frac{S_e + S_\gamma}{S_\nu} = \frac{\frac{7}{8} q_e(T) + q_\gamma}{\frac{7}{8} q_\nu} \left(\frac{T}{T_\nu}\right)^3 = \frac{22}{21}, \tag{15}$$

$$\frac{S'_e + S'_\gamma}{S'_\nu} = \frac{\frac{7}{8} q_e(T') + q_\gamma}{\frac{7}{8} q_\nu} \left(\frac{T'}{T'_\nu}\right)^3 = \frac{22}{21}, \tag{16}$$

$$x^3 = \frac{[\frac{7}{8} q_e(T') + q_\gamma] T'^3 + \frac{7}{8} q_\nu T'^3_\nu}{[\frac{7}{8} q_e(T) + q_\gamma] T^3 + \frac{7}{8} q_\nu T^3_\nu}. \tag{17}$$

Equation (17) is the same as Eq. (14) but with $T_e = T_\gamma = T \neq T_\nu$.

Once both O and M photon temperatures are known, it is straightforward to calculate the total energy and entropy densities; then, reversing Eqs. (6) and (8), we can obtain the entropic (q) and energetic (g) number of d.o.f. Calculations have been made for several different values of x, as reported in the following section.

III. NUMERICAL CALCULATIONS

The equations we introduced in the previous section have been solved numerically. Since x is a free parameter in our theory, several values have been used for it—from 0.1 to 0.7 with step 0.1 or less. In the extreme asymptotic cases $T \gg T_{D\nu'} \simeq \frac{T_{D\nu}}{x}$ or $T \ll T_{\text{ann}\, e^\pm} \simeq 1$ MeV we expect $q(T) \simeq q'[T'(T)]$; therefore, using Eq. (2), in these limits the ratio of M and O photon temperatures should be x, that is $\frac{T'}{xT} \simeq 1$. Instead, when $T_{D\nu'} \gtrsim T \gtrsim T_{\text{ann}\, e^\pm}$ we expect $q'[T'(T)] \leq q(T)$ because the e^+-e^- annihilation takes place before in the M world, leading to a decrease of $q'(T')$ and a corresponding increase of T' in order to keep the entropy densities ratio constant; thus we expect $\frac{T'}{xT} > 1$. Later on, when the O electrons and positrons annihilate, they make even T increase and thus the ratio $\frac{T'}{xT}$ decreases to the asymptotic value 1. These remarks have been verified numerically; the ratio $\frac{T'}{xT}$ is plotted in Fig. 1 for different values of x.

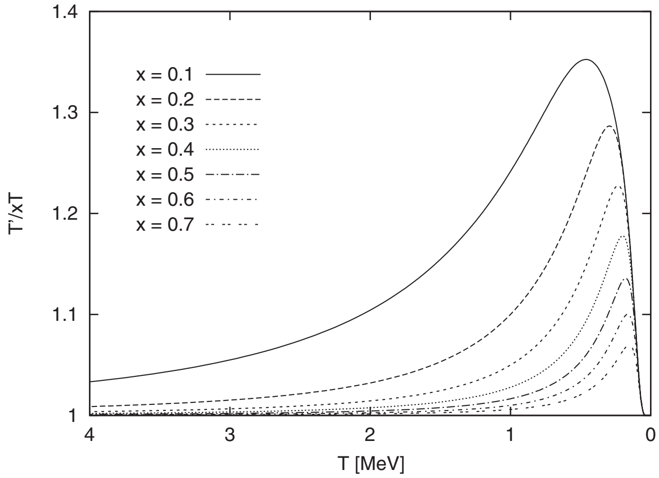

FIG. 1. The ratio $\frac{T'}{xT}$ for several values of x. The asymptotic values of this ratio are 1 both for high and low temperatures, as expected.

M e^+-e^- annihilation happens at higher O temperatures for lower x values, raising before the temperature of M photons; this results in a shift of the peaks of Fig. 1 towards higher T. In addition, for lower x the difference in T between the two annihilation processes is higher, so M photons have more time to raise their temperatures before the O ones start to do the same. This leads to the change of the shape of the curves.

A. Number of degrees of freedom

Using equations from (3) to (5) to reverse (6) and (8), we can obtain the total number of O entropic ($\bar{q}$) and energetic ($\bar{g}$) d.o.f. at any temperatures T. We can apply the same procedure to calculate the *standard* values $q_{\rm std}$ and $g_{\rm std}$, as well as the M ones $\bar{q}'$ and $\bar{g}'$, and the influence of a sector on the other one.

To a first approximation, we expect $\bar{q}$ ($\bar{g}$) to have a cubic (quartic) dependence on x when the temperature is not close to the ν decoupling and the e^+-e^- annihilation phases: $\bar{q} = q_{\rm std}(1 + x^3)$, $\bar{q}' = q_{\rm std}(1 + x^{-3})$, $\bar{g} = g_{\rm std}(1 + x^4)$, $\bar{g}' = g_{\rm std}(1 + x^{-4})$ (for an explanation see Ref. [5]).

In the continuation we present the results of accurate numerical calculations. In Table I some values are reported for special temperatures and several values of x. As expected, the total d.o.f. numbers are always higher than the standard and increase with x. Moreover, the M sector values are higher than the O ones by a factor of order x^{-3} (for $\bar{q}$) or x^{-4} (for $\bar{g}$).

In Fig. 2, panel (a) $q_{\rm std}$, $\bar{q}$, $\bar{q}'$ are plotted for the intermediate value $x = 0.5$; panel (b) of the same figure shows the corresponding values of g. In the figure $\bar{q}'$ ($\bar{g}'$) has been scaled by a factor x^3 (x^4); in this way the asymptotic values are the same than the O sector ones because at the extremes $\frac{T'}{T} = x$ (see Fig. 1). We can see that $\bar{q}$, $\bar{g}$, $\bar{q}'$ and $\bar{g}'$ have similar trends, but, due to $T' < T$, the d.o.f. number in the M sector begins to decrease before (at higher T).

TABLE I. Standard and nonstandard total d.o.f. numbers for several x values in both O and M sectors. Temperatures are in MeV.

T	0.005	0.1	0.5	1	5
$q_{\rm std}$	3.91	4.78	10.0	10.6	10.75
$g_{\rm std}$	3.36	4.30	10.0	10.6	10.75
			x = 0.1		
T'	0.0005	0.0107	0.0675	0.124	0.511
$\bar{q}$	3.91	4.78	10.0	10.6	10.75
$\bar{q}'$	3913	3913	4072	5522	10 070
$\bar{g}$	3.36	4.30	10.0	10.6	10.75
$\bar{g}'$	33 629	32 894	30 032	44 430	98 436
			x = 0.3		
T'	0.0015	0.0321	0.170	0.315	1.50
$\bar{q}$	4.015	4.91	10.3	10.8	11.0
$\bar{q}'$	149	149	261	347	406
$\bar{g}$	3.39	4.34	10.1	10.6	10.8
$\bar{g}'$	418.5	409	750	1082	1325
			x = 0.5		
T'	0.0025	0.0533	0.263	0.508	2.50
$\bar{q}$	4.40	5.38	11.3	11.9	12.1
$\bar{q}'$	35.2	35.5	77.3	90.5	96.5
$\bar{g}$	3.57	4.58	10.7	11.2	11.4
$\bar{g}'$	57.2	56.6	138	168	182
			x = 0.7		
T'	0.0035	0.0733	0.357	0.704	3.50
$\bar{q}$	5.25	6.42	13.5	14.2	14.4
$\bar{q}'$	15.3	16.3	36.9	40.6	42.0
$\bar{g}$	4.17	5.35	12.4	13.1	13.3
$\bar{g}'$	17.4	18.5	47.8	53.3	55.5

In Fig. 3 the values of $\bar{g}$ in O and M sectors are plotted in comparison with the standard for several x values (from 0.1 to 0.7 with step 0.1). As in Fig. 2 the mirror values $\bar{g}'$ have been multiplied by x^4. The predicted quartic dependence of g on x at the extremes is proved correct. In panel (a) we note that ordinary d.o.f. with $x < 0.3$ are practically identical to the standard case. In addition, the plot shape does not change with x in the O sector, while it does in the M one. This sector evolves with temperature $T' \sim xT < T$; therefore, for lower x the number of d.o.f. starts decreasing before below the asymptotic value at high T. The change of the shape of the plots in panel (b) is related to the same physical processes responsible for the analogous effect present in Fig. 1, that is due to the e^+-e^- annihilation in the M sector.

B. Number of neutrino families

We know that the SM contains three neutrino species; the possible existence of a fourth neutrino has been investigated for a long time, also using BBN constraints. This is why in literature one can often find bounds on the number

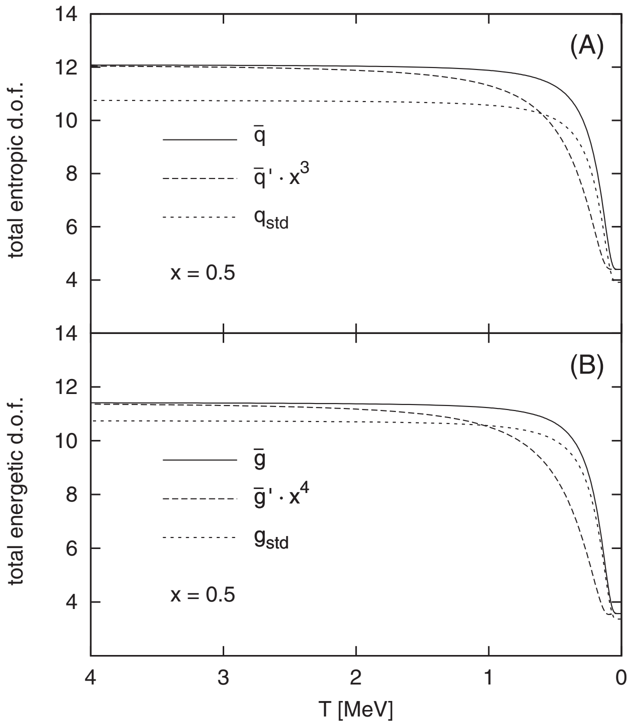

FIG. 2. Total entropic panel (a) and energetic panel (b) degrees of freedom computed in ordinary and mirror sectors and for the standard. The mirror values have been multiplied by x^3 (q) and x^4 (g) to make them comparable with the ordinary ones, since $\frac{T'}{xT} \sim 1$.

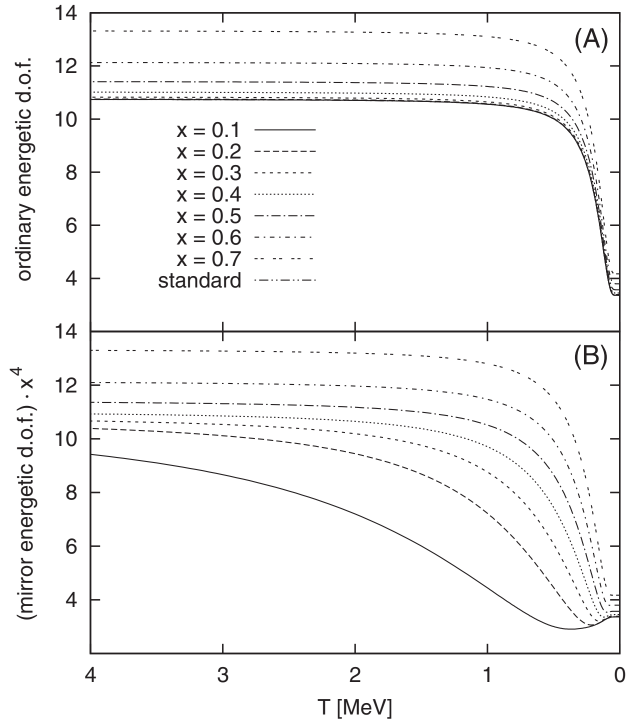

FIG. 3. Total energetic degrees of freedom in the ordinary panel (a) and mirror panel (b) sectors computed for several values of x. In panel (a) the standard is shown for comparison. In panel (b) the mirror values have been multiplied by x^4 to make them comparable with the ordinary ones, since $\frac{T'}{xT} \sim 1$.

of d.o.f. in terms of *effective* extra-neutrino number $\Delta N_\nu = N_\nu - 3$. In general, the effective number of neutrinos N_ν is found assuming that all particles contributing to the Universe energy density, except electrons, positrons and photons, are neutrinos; in formula that means:

$$\bar{g}(T) = g_e(T) + g_\gamma + \frac{7}{8} \cdot 2N_\nu \cdot \left(\frac{T_\nu}{T}\right)^4$$
$$\Rightarrow N_\nu = \frac{\bar{g}(T) - g_e(T) - g_\gamma}{\frac{7}{8} \cdot 2} \cdot \left(\frac{T}{T_\nu}\right)^4. \qquad (18)$$

N_ν has been worked out using Eq. (18) together with the results of previous numerical simulations; some data are reported in Table II, while plots for several x values and any temperatures from 0 to 3 MeV are shown in Fig. 4. We stress that the standard values $N_\nu = 3$ is the same at any temperatures, while *a distinctive feature of mirror scenario is that the number of neutrinos raises for decreasing temperatures*. Anyway, this effect is not a problem; on the contrary it may be useful since recent cosmological data fits give indications for a number of neutrinos at recent times higher than at BBN epoch. In Ref. [21] the authors found $N_\nu = 5.2^{+2.7}_{-2.2}$ using recent cosmic microwave background and large scale structure (LSS) data. We can use the aforementioned mirror feature together with the results of a previous work on CMB and LSS power spectra [7,11], where the author studied the dependence of the spectra on the parameters x and N_ν for a flat Universe with mirror dark matter. As can be easily evinced from Figs. 11, 12, 14, and 15 of Ref. [11], an increase of the effective number of neutrinos is well mimicked by an increase of the parameter x, and the amounts of the respective increases are in accordance with what is required to justify the data of CMB and LSS. Thus, considering the sum of these effects, i.e. the raise in N_ν before and after BBN, and the similarity of CMB and LSS spectra of mirror models and standard N_ν with the ones obtained without mirror sector but with larger N_ν, the mentioned discrepancy disappears naturally.

Similarly, the effective number of neutrinos in the M sector can be worked out as

$$N'_\nu = \frac{\bar{g}' - g'_e(T') - g'_\gamma}{\frac{7}{8} \cdot 2} \cdot \left(\frac{T'}{T'_\nu}\right)^4. \qquad (19)$$

Once again these values are higher than the O ones, but now by a factor x^{-4}; they have been computed numerically and some special values are reported in Table III. For lower x this number can become very high, inducing relevant consequences on the primordial nucleosynthesis in the M sector, that is highly dependent on this parameter.

a. Predictions for special temperatures It is possible to obtain the asymptotic values of N_ν at $T \gg T_{D\nu}$ and $T \ll T_{\text{ann } e^\pm}$ in a simple way starting from the standard values:

TABLE II. Effective number of neutrinos in the ordinary sector for some special cases. Temperatures are in MeV.

T	$x = 0.1$	$x = 0.3$	$x = 0.5$	$x = 0.7$
		ordinary sector		
0.005	3.000 74	3.059 97	3.462 70	4.777 51
0.1	3.000 74	3.059 97	3.462 44	4.768 29
0.5	3.000 74	3.059 97	3.407 06	4.529 42
1	3.000 71	3.052 02	3.391 66	4.491 33
5	3.000 63	3.049 89	3.384 30	4.475 63

TABLE III. Effective number of neutrinos in the mirror sector for some special cases. Temperatures are in MeV.

T'	$x = 0.1$	$x = 0.3$	$x = 0.5$	$x = 0.7$
		mirror sector		
0.005	74 011	917.0	121.4	33.83
0.1	62 007	805.0	111.6	32.21
0.5	61 447	763.1	101.9	28.86
1	61 435	761.8	101.4	28.66
5	61 432	761.4	101.3	28.59

$$g_{\rm std}(T \gg T_{D\nu}) = 10.75; \qquad g_{\rm std}(T \ll T_{{\rm ann}\, e^\pm}) \simeq 3.36. \tag{20}$$

Without the M sector, we have, as expected:

$$\begin{aligned} N_\nu(T \gg T_{D\nu}) &= \frac{10.75 - 2 - \frac{7}{8}\cdot 4}{\frac{7}{8}\cdot 2} = 3; \\ N_\nu(T \ll T_{{\rm ann}\, e^\pm}) &= \frac{3.36 - 2}{\frac{7}{8}\cdot 2}\cdot\left(\frac{11}{4}\right)^{4/3} = 3. \end{aligned} \tag{21}$$

While, when the M sector is present, we can use the previously mentioned quadratic approximation $\bar{g} = g_{\rm std}(1 + x^4)$ at the special temperatures we are considering; hence

$$\begin{aligned} N_\nu(T \gg T_{D\nu}) &= \frac{10.75(1 + x^4) - 2 - \frac{7}{8}\cdot 4}{\frac{7}{8}\cdot 2} \\ &= 3 + 6.14x^4; \\ N_\nu(T \ll T_{{\rm ann}\, e^\pm}) &= \frac{3.36(1 + x^4) - 2}{\frac{7}{8}\cdot 2}\cdot\left(\frac{11}{4}\right)^{4/3} \\ &\simeq 3 + 7.40x^4. \end{aligned} \tag{22}$$

From the above equations we can see that the increase ΔN_ν is

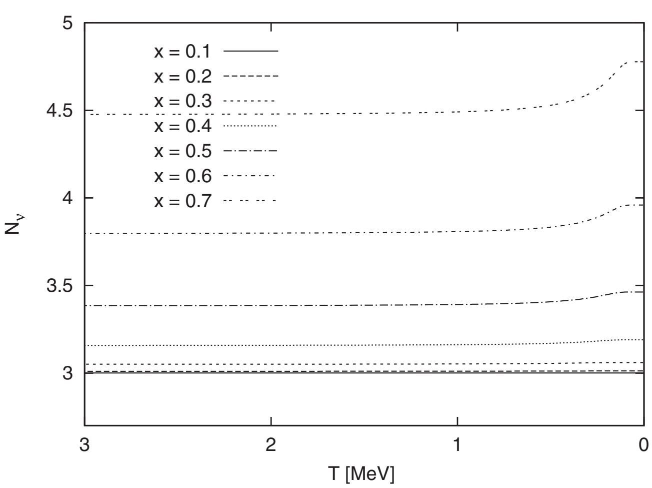

FIG. 4. Effective number of neutrino families N_ν in the ordinary sector for several x values.

$$\begin{aligned} \Delta N_\nu &= N_\nu(T \ll T_{{\rm ann}\, e^\pm}) - N_\nu(T \gg T_{D\nu}) \\ &= x^4 \cdot \frac{1}{\frac{7}{8}\cdot 2}\left[3.36\left(\frac{11}{4}\right)^{4/3} - 10.75\right] \simeq 1.255 \cdot x^4. \end{aligned} \tag{23}$$

This leads to N_ν higher than the standard in presence of the M world and to a further growth of this parameter at low temperatures. If we assume a conservative limit on the effective number of neutrino families $N_\nu(T \gg T_{D\nu}) \le 4$, this implies $x \le 0.635$ and $N_\nu(T \ll T_{{\rm ann}\, e^\pm}) \le 4.26$. For some interesting values of the parameter x we obtain

$$\begin{aligned} x = 0.7 &\Rightarrow N_\nu(T \gg T_{D\nu}) \simeq 4.5 \quad \text{and} \\ &\quad N_\nu(T \ll T_{{\rm ann}\, e^\pm}) \simeq 4.8; \\ x = 0.6 &\Rightarrow N_\nu(T \gg T_{D\nu}) \simeq 3.8 \quad \text{and} \\ &\quad N_\nu(T \ll T_{{\rm ann}\, e^\pm}) \simeq 3.96; \\ x = 0.3 &\Rightarrow N_\nu(T \gg T_{D\nu}) \simeq 3.05 \quad \text{and} \\ &\quad N_\nu(T \ll T_{{\rm ann}\, e^\pm}) \simeq 3.06. \end{aligned} \tag{24}$$

These rough estimates are in agreement with the asymptotic numerical values computed before and after BBN; nevertheless, the previous detailed analysis of the evolution of this quantity is crucial for future studies of the nucleosynthesis in both sectors.

IV. CONCLUSIONS

In this paper we have investigated the consequences of the existence of a mirror sector of particles and interactions with exact parity symmetry on the thermodynamics of the early Universe for temperatures below ~100 MeV. In particular we have studied in detail the evolution of the entropic and energetic degrees of freedom in both sectors.

To perform these calculations first we have found the system of equations governing the thermodynamical equilibria in the two sectors, and then we have solved them numerically in order to obtain the mirror temperature T' corresponding to any ordinary temperature T; once these temperatures have been known, we have been able to obtain the entropic and energetic densities, and thus the numbers of degrees of freedom and the effective numbers of neutrino families in both sectors. We have found that the evolution of the ordinary sector is influenced by the mirror particles, that provide extra degrees of freedom, and, due to the electron-positron annihilation process happening in the mirror sector, changes in time for temperatures around the BBN epoch. This makes crucial the present investigation in order to study in detail the BBN process in presence of mirror dark matter. Furthermore, the special feature that models containing the mirror sector change the number of equivalent neutrinos during the Universe evolution, if considered together with preexisting models of cosmic microwave background and large scale structure power spectra with mirror dark matter, supplies a possible interpretation of the discrepancy in the effective number of neutrino families "observed" indirectly at BBN and CMB epochs.

In the mirror sector we have obtained very high values of degrees of freedom, as predicted, and, similarly to the other sector, they are variable for temperatures below some MeV. These data provide the necessary input for a detailed study of BBN in the mirror sector. This is required in order to obtain the exact amounts of primordial heavy mirror elements, that are necessary for a correct interpretation of nonlinear processes of structure formation and of the new DAMA/LIBRA results.

ACKNOWLEDGMENTS

We thank Zurab Berezhiani for interesting discussions and comments, and Serena Fermo for patiently improving our English. P. C. acknowledges support from the Belgian fund for scientific research (FNRS).

[1] T. D. Lee and C.-N. Yang, Phys. Rev. **104**, 254 (1956).
[2] R. Foot, H. Lew, and R. R. Volkas, Phys. Lett. B **272**, 67 (1991).
[3] There could be other interactions, as, for example, the kinetic mixing between ordinary and mirror photons [26], but they are very low, and are neglected in the present study.
[4] L. B. Okun, Phys. Usp. **50**, 380 (2007).
[5] Z. Berezhiani, D. Comelli, and F. L. Villante, Phys. Lett. B **503**, 362 (2001).
[6] P. Ciarcelluti, AIP Conf. Proc. **1038**, 202 (2008).
[7] P. Ciarcelluti, Ph.D. thesis, University of Roma "Tor Vergata," Italy, 2003, arXiv:astro-ph/0312607.
[8] Z. Berezhiani, P. Ciarcelluti, D. Comelli, and F. L. Villante, Int. J. Mod. Phys. D **14**, 107 (2005).
[9] P. Ciarcelluti, Frascati Phys. Ser. **555**, 1 (2004).
[10] P. Ciarcelluti, Int. J. Mod. Phys. D **14**, 187 (2005).
[11] P. Ciarcelluti, Int. J. Mod. Phys. D **14**, 223 (2005).
[12] A. Y. Ignatiev and R. R. Volkas, Phys. Rev. D **68**, 023518 (2003).
[13] S. I. Blinnikov, arXiv:astro-ph/9801015.
[14] R. Foot, Phys. Lett. B **452**, 83 (1999).
[15] R. N. Mohapatra and V. L. Teplitz, Phys. Lett. B **462**, 302 (1999).
[16] Z. Berezhiani, S. Cassisi, P. Ciarcelluti, and A. Pietrinferni, Astropart. Phys. **24**, 495 (2006).
[17] R. Foot, Phys. Rev. D **78**, 043529 (2008).
[18] R. Bernabei *et al.* (DAMA), Eur. Phys. J. C **56**, 333 (2008).
[19] Z. G. Berezhiani, A. D. Dolgov, and R. N. Mohapatra, Phys. Lett. B **375**, 26 (1996).
[20] From now on all particles and parameters of the mirror sector will be marked by $'$ to distinguish them from the ones related to the observable or ordinary world.
[21] G. Mangano, A. Melchiorri, O. Mena, G. Miele, and A. Slosar, J. Cosmol. Astropart. Phys. 03 (2007) 006.
[22] E. W. Kolb and M. S. Turner, *The Early Universe*, Frontiers in Physics Vol. 69 (Addison-Wesley, Redwood City, CA, 1990).
[23] T. Padmanabhan, *Theoretical Astrophysics, Volume III: Galaxies and Cosmology* (Cambridge University, Cambridge, England, 2002).
[24] The assumption that the neutrino decoupling is an instantaneous process taking place when photons have the temperature $T = T_{D\nu}$ introduces just a small error ($< 1\%$), that is negligible for the precision required in this work.
[25] For simplicity we write $T'_{\nu'} = T'_{\nu}$, $T'_{e'} = T'_{e}$, $T'_{\gamma'} = T'_{\gamma} = T'$, and $T_{\gamma} = T$.
[26] R. Foot, A. Y. Ignatiev, and R. R. Volkas, Phys. Lett. B **503**, 355 (2001).