Continuous matter creation and the acceleration of the universe: the growth of density fluctuations

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Abstract   Cosmologies including continuous matter creation are able to reproduce the main properties of the standard ΛCDM model, in particular in cases where the particle and entropy production rates are equal. These specific models, characterized by a mass density equal to the critical value, behave like the standard ΛCDM model at early times whereas their late evolution is similar to the steady-state cosmology. The maximum amplitude of density fluctuations in these models depends on the adopted creation rate, related here to the parameter Ω_v and this limitation could be a difficulty for the formation of galaxies and large-scale structure in this class of universe. Additional problems are related with predictions either of the random peculiar velocities of galaxies or the present density of massive clusters of galaxies, both being largely overestimated with respect to observational data.

1 Introduction

The standard model in cosmology, the so-called ΛCDM model, assumes the presence of a constant cosmological term in Einstein's equations and that the universe is constituted, besides baryons, photons and neutrinos, by a dominant weakly interacting component of unknown nature dubbed dark matter. This model gives the best

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description of the present data as, for instance, those resulting from the analysis of the 7 years operation of the WMAP satellite [1] and supernova distances [2].

The inclusion of the cosmological term in Einstein's equations represents the most simple and natural explanation for the observed acceleration of the expansion of the universe detected through supernova data. However, arguments against the inclusion of such a cosmological term are often found in the literature. The first one is the so-called "coincidence" problem, which can be stated in the following way: why do we observe presently an almost equal contribution of matter and the cosmological term to the total energy budget of the universe, considering that these components evolve differently with time? Such a "coincidence" would suggest that we are living in a particular moment of the history of the universe, contrary to a "cosmological principle" stating that we are not in a special place in the universe either in space or in time. Notice that if the accelerated phase started around $z \approx 0.75$, such a phase covers about 48% of the existence of our universe! The second argument is related to the interpretation of the cosmological constant as the vacuum energy density. As it is well known, formal quantization of classical fields leads to a divergent energy density for the vacuum state, which can be avoided by imposing a physical cut-off [3]. If we adopt as a cut-off the Planck scale, then the theory predicts an effective cosmological constant corresponding to an energy density that is about 120 orders of magnitude higher than the observed value. Convincing arguments against these difficulties were recently given by Bianchi and Rovelli [4], who concluded that the "coincidence problem" is ill defined and that the identification of the cosmological constant with the vacuum energy density is probably a mistake.

Face to this debate on the existence (or not) of the cosmological term, alternative models have been discussed in the literature [5–9]. In some of these models, the acceleration of the expansion is driven by a negative pressure term associated to particle creation at the expense of the gravitational field, an original idea proposed by Zeldovich [10] almost 40 years ago. Particular cases in which the particle production rate is proportional to the Hubble parameter give results similar to the canonical ΛCDM model [11,12]. From a thermodynamic point of view, particle production from the gravitational field can be considered in the context of open systems, where the "heat" received by the system is due entirely to the change in the number of particles [13]. In the standard model, matter is produced suddenly at the initial singularity and during the re-heating at the end of the inflationary phase. After that the universe evolves adiabatically, i.e., both the entropy per unit of comoving volume and the entropy per particle remain constant during the expansion.

In the present paper we review the properties of specific models including particle creation, emphasizing some particular aspects not previously noticed. We investigate also the linear growth of density perturbations in this class of cosmological models and we will show that, depending on the creation rate, the amplitude of the density contrast is unable to grow beyond a certain limit. The critical creation rate below which density fluctuations are able to grow continuously up to present time is marginally compatible with the parameters of the ΛCDM moldel. This could represent a difficulty for the formation of galaxies and the large-scale structure, condemning this particular class of cosmology. This paper is organized as follows: in Sect. 2 the principal physical

aspects of the model are revisited; in Sect. 3 the growth of density perturbations is examined and finally, in Sect. 4 the main conclusions are given.

2 The cosmological model

In the present investigation, for simplicity, we will neglect the evolution of the baryonic component and we will focus our attention on the dominant (dark matter) component only. The number of baryons per unit of comoving volume remains conserved during the expansion, i.e., $n_b a^3 = $ constant, where n_b is the comoving baryon number density and $a = a(t)$ is the scale factor. On the other hand, the bulk of the dominant component is produced as in the standard scenario but now the possibility of a continuous creation of dark matter particles is included. This implies that we renounce to the common idea that the expansion of the universe could be described by "closed" system and we assume, following Prigogine et al. [13] that, in fact, the expansion is described by an "open" thermodynamic system. Under these conditions, the first law can be written as

$$T\mathrm{d}S = \mathrm{d}E + P\mathrm{d}V - \mu\mathrm{d}N \tag{1}$$

where the chemical potential μ is here associated to the non conservation of the particle number. Introducing, respectively, the entropy density s, the energy density ρ, the particle number density n, the enthalpy density $h = (P + \rho)$, replacing into Eq. 1, developing and using the Euler's relation

$$n\mu = (P + \rho) - Ts = h - Ts \tag{2}$$

one obtains after some algebra

$$\left(\frac{\mathrm{d}\rho}{\mathrm{d}t} - \frac{h}{n}\frac{\mathrm{d}n}{\mathrm{d}t}\right) = sT\left(\frac{\mathrm{d}\lg s}{\mathrm{d}t} - \frac{\mathrm{d}\lg n}{\mathrm{d}t}\right) \tag{3}$$

which is essentially the Gibbs relation for the system (see [14] for a covariant derivation of this relation).

Solutions of Eq. 3 permit the study of different particle production scenarios but relations either between the state variables s and n or for their production rates are required, since they define the model. The simplest possibility, considered either by [11] or [12] , corresponds to the case where the entropy per particle remains constant during the expansion process, i.e., $s/n = $ constant. This hypothesis implies that the energy density is a function of the particle number density only and not of the temperature also. Moreover, it is worth mentioning that such a condition is not equivalent to an adiabatic expansion as it occurs in the standard model since, as we shall see later, there is entropy production and the aforementioned condition expresses only the fact that the relative rates of particle and entropy production are equal. In this case, the right side of Eq. 3 is zero and the particle production rate is related to the energy

density variation rate by

$$\frac{d\rho}{dt} = \frac{h}{n}\frac{dn}{dt} \tag{4}$$

Let the stress-energy tensor of the dark matter fluid be

$$T_{ab} = (\rho + \Pi)u_a u_b - \Pi g_{ab} \tag{5}$$

where $\Pi = P(\rho) + P_c$ is the effective pressure acting on the fluid, with the first term on the right side representing the pressure due to kinetic motions and interactions between particles and the second, P_c, being a new term associated to the particle production. Considering a Friedman–Robertson–Walker (FRW) metric for a spatially flat spacetime, i.e.,

$$ds^2 = -dt^2 + a^2(t)\left(dr^2 + r^2 d\Omega^2\right) \tag{6}$$

from the equation $T^k_{0;k} = 0$, one obtains for the variation rate of the energy density

$$\frac{d\rho}{dt} + 3\frac{\dot{a}}{a}(h + P_c) = 0 \tag{7}$$

Then, from Eqs. 4 and 7, one obtains immediately an expression for the pressure associated to particle production

$$P_c = -\frac{h}{3H}\left(3H + \frac{d\lg n}{dt}\right) \tag{8}$$

where the Hubble parameter H was defined as usually, namely, $H = \dot{a}/a$. It should be emphasized again that the above relation is valid only if the ratio s/n remains constant in the process. As expected, the relation above indicates that if the particle production rate is positive in a expanding universe ($H > 0$), the pressure P_c is negative, contributing to accelerate the expansion. The simplest world model without a cosmological constant, but including a negative pressure term due to particle production is obtained from the *ansatz* $P_c = -\lambda$, where λ is a positive constant having the dimension of an energy density. This *ansatz* is equivalent, as we shall see below, to the usual assumption that the particle production rate is proportional to the Hubble parameter if the created particles are "cold" and interact "weakly". Consequently, the enthalpy density is simply $h = \rho$ and the relation between the particle and the energy densities is given by $\rho = nmc^2$, where m is the rest mass of the created particles (supposed to be uncharged). Under these conditions, Eq. 8 can be recast as

$$\frac{dn}{dt} + 3Hn = \frac{3\lambda}{mc^2}H \tag{9}$$

Notice that now the particle conservation equation has a (positive) source term proportional to the Hubble parameter as mentioned above. Using the scale parameter a as the independent variable instead of time, the equation above can be rewritten as

$$\frac{\mathrm{d}n}{\mathrm{d}\lg a} + 3n = \frac{3\lambda}{mc^2} \tag{10}$$

and similarly for the energy density

$$\frac{\mathrm{d}\rho}{\mathrm{d}\lg a} + 3\rho = 3\lambda \tag{11}$$

Integration of Eq. 11 is trivial and is given by

$$\rho = \lambda + \frac{(\rho_* - \lambda)}{a^3} \tag{12}$$

where ρ_* is the energy density when $a = 1$ (the present time). The equation above can be recast as

$$\rho = \rho_* \left(\Omega_v + \Omega_m a^{-3} \right) \tag{13}$$

which is formally identical to the expression of the energy density in the case of the standard ΛCDM model, if one identifies $\Omega_v = \lambda/\rho_*$ and $\Omega_m = 1 - \Omega_v$. However, in the present case Ω_v is not the density parameter associated to the cosmological term but to the creation rate. Similarly, Ω_m in the present case is not equivalent to the matter parameter density as in the standard model, since here the present matter density is equal to the critical density. Integration of Eq. 10 is also trivial and gives for the evolution of the particle number density

$$n = n_* \left(\Omega_v + \Omega_m a^{-3} \right) \tag{14}$$

where n_* is the present particle number density. For high redshifts or $a \ll 1$, the particle number density satisfies the condition $na^3 = n_* \Omega_m = $ constant, similar to the standard model. However, in the future, when $a \gg 1$, the standard model predicts that either for baryons or for dark matter, the particle number density goes to zero due to the expansion of the universe while the present model predicts a constant density equal to $n = n_* \Omega_v$ for dark matter particles. In other words, the present model predicts a future state of the universe constituted by dark matter only since the density ratio n_b/n goes to zero. This future behaviour of dark matter is identical to that of the steady-state cosmology, since when $a \gg 1$ the creation rate will be equal to the expansion rate. It worth mentioning that the present matter density in this model is higher than the standard ΛCDM by a factor of $1/\Omega_m$, a fact with observable consequences, as we shall see later. In reality, these are not the only differences with the standard model. Since the ratio s/n remains constant during the expansion, the evolution of the entropy density is given by

$$s = s_* \left(\Omega_v + \Omega_m a^{-3} \right) \tag{15}$$

where s_* is the present entropy density of dark matter. The equation above says that the evolution of the entropy density also differs from the standard model, with a temporal behaviour similar to that of the particle density or, in other words, in the future the entropy of the universe will essentially dominated by that of dark matter. Notice also that in the standard model, the entropy in a proper volume corresponding to a unit comoving volume (sa^3) is constant but in the present model there is entropy production at a rate

$$\frac{d(sa^3)}{dt} = 3s_* \Omega_v a^3 H \tag{16}$$

Once the past behaviour of the present model is similar to that of the standard model, both models satisfy the different tests (supernova distances, baryon acoustic peak, "shift" parameter associated to the CMB, age of the universe) if the parameters of both models are conveniently interpreted (see for instance, Ref. [12]).

The particular cosmology here considered has a deceleration parameter q formally similar to the standard model, i.e.,

$$q = -\frac{\ddot{a}a}{\dot{a}^2} = \frac{1}{2} \frac{\left(\Omega_m a^{-3} - 2\Omega_v \right)}{\left(\Omega_v + \Omega_m a^{-3} \right)} \tag{17}$$

Thus, the present value of this parameter is simply

$$q_* = \frac{1}{2}(1 - 3\Omega_v) \tag{18}$$

Since observations of supernova distances indicate $\Omega_v = 0.7 \pm 0.1$ ([15]), from the equation above it results that $q_* = -0.55 \pm 0.15$.

3 The evolution of density perturbations

In the present study, in order to obtain the linearized equations, the Newtonian approximation will be used. This approximation is justified in the weak field limit, i.e., when the velocity of peculiar motions satisfies the condition $V_p \ll c$ and the scale of the perturbations is much less than the Hubble radius (see Ref. [16]). Notice that in the case of the "standard" model, a fully relativistic treatment leads essentially to same results obtained through the weak field approximation.

The first equation is the particle number conservation (Eq. 9), which can be recast as

$$\frac{dn}{dt} + \nabla \cdot (n\mathbf{U}) = \alpha H \tag{19}$$

where $\alpha = 3\lambda/mc^2 = 3\Omega_v n_*$. The velocity field $\mathbf{U}$ includes the Hubble flow and peculiar velocities resulting from gravitational interactions between density peaks. The second equation expresses the gravitational aceleration in terms of the mass distribution, i.e.,

$$\nabla \cdot \mathbf{g} = 4\pi Gmn \tag{20}$$

Finally, the equation of motion, which in absence of pressure gradient terms can be simply written as

$$\frac{\partial \mathbf{U}}{\partial t} + \mathbf{U} \cdot \frac{\partial \mathbf{U}}{\partial r} + \mathbf{g} = 0 \tag{21}$$

These equations are similar to those in the usual Newtonian approximation except by the fact that now a source term is present in the continuity equation. Defining the perturbed quantities n_1, $\mathbf{g}_1$ and $\mathbf{V}_p$ by the relations,

$$n(\mathbf{r}, t) = n_0(t) + n_1(\mathbf{r}, t) \tag{22}$$

$$\mathbf{g}(\mathbf{r}, t) = \mathbf{g}_0(\mathbf{r}, t) + \mathbf{g}_1(\mathbf{r}, t) \tag{23}$$

$$\mathbf{U}(\mathbf{r}, t) = H\mathbf{r} + \mathbf{V}_p(\mathbf{r}, t) \tag{24}$$

introducing the density contrast $\delta = n_1/n_0$, replacing the perturbed quantities into Eqs. 19, 20, 21, expanding and retaining only first order terms, one obtains respectively for the linearized continuity, force and motion equations

$$\dot{\delta} + \nabla \cdot \mathbf{V}_p = -\frac{4\pi Gm}{3H_0}\alpha\delta \tag{25}$$

$$\nabla \cdot \mathbf{g}_1 = 4\pi Gmn_0\delta \tag{26}$$

and

$$\frac{\partial \mathbf{V}_p}{\partial t} + H_0\mathbf{V}_p + \mathbf{g}_1 = 0 \tag{27}$$

It should be emphasized that here the subscript "0" denotes unperturbed values while quantities taken at present time ($z = 0$) are denoted by the subscript "*". Writing the perturbed quantities in terms of the Fourier components, the system of linear equations above becomes

$$\dot{\delta}_k + \frac{i\mathbf{k} \cdot \mathbf{V}_k}{a} = -\frac{4\pi Gm\alpha}{3H_0}\delta_k \tag{28}$$

$$\frac{i\mathbf{k} \cdot \mathbf{g}_k}{a} = 4\pi Gmn_0\delta_k \tag{29}$$

$$\frac{\partial \mathbf{V}_k}{\partial t} + H_0\mathbf{V}_k + \mathbf{g}_k = 0 \tag{30}$$

After some lengthy but trivial algebra with these equations, one obtains finally for the evolution of the density contrast in the linear approximation

$$\ddot{\delta}_k + \left(2H_0 + \frac{4\pi G m \alpha}{3H_0}\right)\dot{\delta}_k + 4\pi G m\left[\alpha\left(1 - \frac{\ddot{a}a}{3\dot{a}^2}\right) - n_0\right]\delta_k = 0 \qquad (31)$$

Notice if there is no particle creation ($\alpha = 0$) the usual equation describing the evolution of the density contrast in absence of pressure gradients is recovered (see for instance [17]).

In order to solve numerically Eq. 31, it is convenient to introduce a dimensionless time variable $\tau = t/t_*$, where t_* is the present age of the universe. Using now the notation $\partial\delta_k/\partial\tau = \delta_k'$ and $\partial^2\delta_k/\partial\tau^2 = \delta_k''$, Eq. 31 can be written in a general form

$$\delta_k''(\tau) + g_1(\tau)\delta_k'(\tau) + g_2(\tau)\delta_k(\tau) = 0 \qquad (32)$$

where explicit expressions for the functions $g_1(\tau)$ and $g_2(\tau)$ depend on the adopted cosmological model. For the standard ΛCDM model, these functions are given, respectively, by

$$g_1(\tau) = 2\beta_* f(a(\tau)) = 2\beta_*\sqrt{1 + \chi a^{-3}(\tau)} \qquad (33)$$

and

$$g_2(\tau) = -\frac{3}{2}\beta_*^2\chi a^{-3}(\tau) \qquad (34)$$

In these equations, $\beta_* = H_* t_* \sqrt{\Omega_v}$, $\chi = \Omega_m/\Omega_v$ and the scale factor as a function of the dimensionless time is

$$a(\tau) = \chi^{1/3} Sinh^{2/3}(3\beta_*\tau/2) \qquad (35)$$

When particle creation is included ($\alpha \neq 0$), the functions $g_1(\tau)$ and $g_2(\tau)$ become

$$g_1(\tau) = 2\beta_* f(a(\tau))\left[1 + \frac{3}{4}\frac{1}{f^2(a(\tau))}\right] \qquad (36)$$

and

$$g_2(\tau) = \frac{3}{2}\beta_*^2\left[\frac{(4 + 7\chi a^{-3}(\tau))}{2(1 + \chi a^{-3}(\tau))} - f^2(a(\tau))\right] \qquad (37)$$

In both cases the parameter β_* can be estimated from Eq. 35, using the condition $a(1) = 1$. Thus, $\beta_* = 2ArcSinh(\chi^{-1/2})/3$, implying that the only free parameter in these equations is Ω_v.

Numerical solutions of these equations were obtained by adopting initial conditions appropriate to the decoupling between matter and radiation at $z \sim 1{,}100$ and using
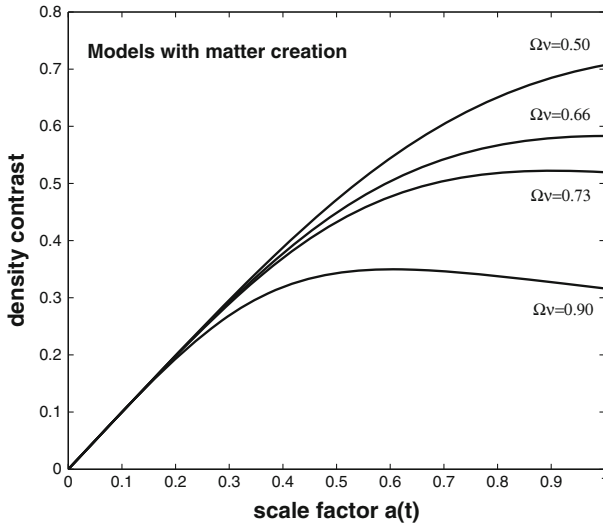
Fig. 1 Density contrast evolution as a function of the scale parameter. Labels indicate different values of the parameter Ω_v

the fact that at these high redshifts both models are similar to the Einstein-de Sitter cosmology. Moreover, since there is no continuous production of baryons, the transition from an "opaque" to a "transparent" universe should occur at the same redshift as in the canonical model. Thus, the evolution of the density contrast when $a \ll 1$ is $\delta(t) \propto a(t)$.

Our results indicate that for models with $\alpha \neq 0$, i.e., including particle creation, the density contrast increases, reaches a maximum before the present time and then decreases if the parameter Ω_v is higher than a critical value equal to $\Omega_{v,crit} = 0.666$. For this particular value, the maximum occurs at the present time and for lower values, the maximum occurs in the future, i.e., when $a > 1$. This behaviour is illustrated in Fig. 1 where the evolution of the density contrast as a function of the scale factor and for different values of the parameter Ω_v is shown. For $a < 0.03$ or $z > 35$, as expected, all models coincide since they follow the same behaviour of the Einstein-de Sitter solution.

The existence of a maximum in the evolution of the density contrast is a consequence of a fundamental difference between models including particle creation and the standard ΛCDM cosmology. These differences are clearly seen in a close inspection of the coefficients appearing in Eq. 31 either when $\alpha = 0$ (ΛCDM model) or when $\alpha \neq 0$, particle creation model. The first coefficient, corresponding to the second term on the left (or the coefficient of the first derivative of the density contrast) is simply equal to $2H = 2\dot{a}/a$ in the case of the standard model. This is a damping mechanism related to the expansion of the universe. When particle creation is included, this damping coefficient increases from $2H$ up to $2.36H$ for $a = 1$ and $\Omega_v = 0.73$. Such a variation is a small effect not responsible for the existence of a maximum, although it contributes to decrease slightly the amplitude of the density contrast. The second
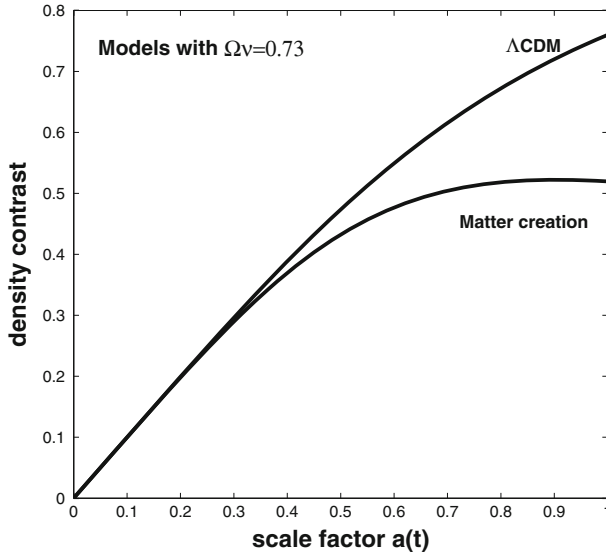
Fig. 2 Comparison between the density contrast evolution resulting from the standard ΛCDM model and the present cosmology including matter creation

coefficient, corresponding to the third term on the left of Eq. 31, can be recast as

$$4\pi Gm\left[\alpha\left(1+\frac{q}{3}\right)-n_0\right]$$ (38)

where q is the deceleration parameter. In the standard model ($\alpha = 0$) the coefficient above is negative, representing the well known gravitational instability. When particle production is included, an extra term counterbalancing gravity appears and the amplitude of the density contrast increases as far as the condition

$$\frac{2(1+\chi a^{-3})^2}{(4+7\chi a^{-3})} > 1$$ (39)

is satisfied which, for adequate values of $\chi = \Omega_m/\Omega_v$, is equivalent to the condition $a < 0.5$. Consequently, depending on the value of Ω_v, a maximum amplitude is attained in the late evolution of the density contrast, whose value depends on the particle creation rate.

In Fig. 2, the density contrast evolution for $\Omega_v = 0.73$ is shown for both the standard and the particle creation model. The density contrast of the later at the present time is about 30% lower than that derived for the standard model, with the maximum occurring at $z \sim 0.2$.

The effective damping of the density contrast induced by particle production poses some difficulties to the process of galaxy and large-scale structure formation by gravitational instability. However, other problems related with the growth of the density contrast exist in this model. For instance, the present root mean square value of the

peculiar velocity of galaxies in the linear theory when particle creation is absent is given by [17]

$$\langle V_p^2 \rangle^{1/2} = Ha \left(\frac{\mathrm{d} lg\, \delta(a)}{\mathrm{d} lga} \right) \sqrt{J_2} \tag{40}$$

where $J_2 = 150h^{-2}Mpc^2$ is the second moment of the two-point correlation function of galaxies [18]. The introduction of the particle creation process modifies the continuity equation, as we have seen previously, since a source term is now present. Consequently, the resulting equation for the root mean square velocity of galaxies in the linear theory is now given by

$$\langle V_p^2 \rangle^{1/2} = Hf(a)a \left[1 + \frac{3}{2}\frac{n_*}{n_0}\frac{\Omega_v}{f(a)} \right] \sqrt{J_2} \tag{41}$$

where we have defined as in Ref. [17] $f(a) = \mathrm{d} \lg \delta / \mathrm{d} \lg a$. Numerical solutions of the equation above indicate that the present root mean square velocity practically independs on the parameter Ω_v, being equal to $\simeq 1,200 km/s$. This is considerably higher than the value derived from observational data, i.e., 325 km/s [19]. Moreover, as mentioned before, the present matter density is greater than that of the standard ΛCDM model by a factor of Ω_m^{-1}. As a consequence, the predicted density of clusters of galaxies above a given mass is higher either than predictions of the standard model or observational data. For clusters with masses higher than $10^{15}M_\odot$, data by Bahcall and Cen [20] indicate that the density is about $7.2 \times 10^{-8}Mpc^{-3}$ while from the creation model a density of about $3.8 \times 10^{-6}Mpc^{-3}$ is predicted.

4 Conclusions

Cosmological models described by "open" thermodynamic systems, i.e., including particle creation at the expense the gravitation field can reproduce formally the past evolution of matter, mimicking the presence of a cosmological constant in Friedman equations. This class of models results from the assumption that entropy and particle production rates are equal and that the negative pressure resulting from the particle creation process is a constant. This last hypothesis is equivalent to the assumption of a production rate proportional to the Hubble constant. It is worth mentioning that in the steady-state cosmology the creation rate required to compensate the expansion and to maintain a constant particle density is $\dot{r}_{ss} = 3H_*n_*$, which should be compared with the rate of the present model, given by $\dot{r}_{cre} = 3\Omega_v H_*n_*$. Thus, the present model has two asymptotic behaviours: in earlier times behaves as the standard model or the Einstein-de Sitter solution and in late times behaves as the steady-state cosmology, except by the fact that the baryon-to-dark matter particle density ratio goes to zero.

Difficulties appear for the creation model when the evolution of density fluctuations is regarded closely. In this model, the particle production mechanism mimics also a damping mechanism that limits the growth of the density contrast, constraining the process of galaxy and large-scale structure formation. Moreover, the predicted root

mean square peculiar velocity of galaxies in the linear theory is about four times higher than observations. The creation model has also difficulties to explain the observed density of massive clusters of galaxies, predicting presently ($z = 0$) an excess of objects by a factor of fifty with respect to observations, consequence of the fact that the present matter density in this cosmology is equal to the critical value. Nevertheless it is important to mention that the present analysis is based on a linear approach and that the inclusion of non-linear terms, affecting the late evolution of the density contrast may eventually change our conclusions. Cosmological simulations including particle creation will be the next step to investigate these non-linear effects, that will be able to corroborate or not the present study.

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