Strong Limits on the Possible Decay of the Vacuum Energy into CDM or CMB Photons

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We investigate models that suggest that the vacuum energy could decay into cold dark matter (CDM) or into a homogeneous distribution of thermalized cosmic microwave background (CMB) photons. We show that the agreement of the density fluctuation spectra obtained from the CMB and galaxy distribution data puts strong limits on the rate of vacuum energy decay. A vacuum energy decaying into CDM increases the density of the CDM ρ, diluting the CDM density fluctuations $(\delta\rho/\rho)^2$. The temperature fluctuations of the CMB photons $(\delta T/T)^2$ are approximately proportional to $(\delta\rho/\rho)^2$, at the recombination epoch. We define F as the predicted increase of $(\delta\rho/\rho)^2$ (or $(\delta T/T)^2$) at the recombination epoch. Since the present observed $(\delta\rho/\rho)^2$ derived from the CMB and galaxy distribution data agree to $\sim 10\%$, the maximum value for F is $F_{\rm max} \cong 1.1$. Our results indicate that the rate of decay of the vacuum energy into CDM or CMB photons is extremely small.

I. INTRODUCTION

Recent observations indicate that the universe is spatially flat and undergoing a late time acceleration. This acceleration has been attributed to a dark energy component with negative pressure which can induce repulsive gravity. The simplest and most obvious candidate for this dark energy is the cosmological constant Λ (which can be interpreted as vacuum energy) with the equation of state $w = p/\rho = -1$, where p is the pressure and ρ is the energy density. A decaying vacuum energy is very attractive since it may link the present vacuum energy that is accelerating the universe today, with perhaps the large vacuum energy that created the inflation epoch in the past.

We analyze how the observed cosmic microwave background (CMB) and large galaxy survey data constrain the decaying vacuum energy models into cold dark matter (CDM) from the recombination era (redshift $z \sim 1070$) to the present ($z \sim 0$) [1]. A vacuum energy decaying into CDM increases the CDM density, diluting its $(\delta\rho/\rho)^2$. In order to evaluate $(\delta\rho/\rho)^2$ at the recombination era, when it created the $\delta T/T$ of the CMB, its present measured value obtained from the galaxy distribution data, extrapolated back to the recombination era, must be increased by a factor F. The density fluctuations derived from the CMB data were compared with those derived from the 2dF Galaxy Redshift Survey (2dFGRS) [2, 3]. Since the present $(\delta\rho/\rho)^2$ derived from the CMB and galaxy distribution data agree to ~ 10 per cent, the maximum value for F is $F_{\rm max} \cong 1.1$ (see [4] for the final data set of the 2dFGRS).

We made a similar analysis for the possible decay of the vacuum energy into CMB photons [5]. In this scenario, the temperature fluctuations, created at the recombination epoch $(\delta T/T)_{\rm rec}$, were diluted by the photons created by the vacuum energy decay making the temperature fluctuations at present smaller.

II. VACUUM ENERGY DECAYING INTO CDM

A vacuum energy decaying into CDM increases the CDM density, diluting the CDM fluctuations $(\delta\rho/\rho)^2$. Consequently, a larger density fluctuation spectrum $(\delta\rho/\rho)^2$ is predicted at the recombination era ($z_{\rm rec} = 1070$) by the factor

$$F \equiv \left[\frac{\overline{\rho}_M(z)}{\overline{\rho}_M(z) - \Delta\rho(z)}\right]^2 \Big|_{z=z_{\rm rec}}, \tag{1}$$

where

$$\overline{\rho}_M(z) = \rho_c^0\,(1+z)^3\,\Omega_M^0 \tag{2}$$

is the matter density for a constant vacuum energy density, where $\rho_c^0 \equiv 3H_0^2/(8\pi G) \simeq 1.88\,h_0^2 \times 10^{-29}\,g\,cm^{-3}$ is the critical density, and Ω_M^0 is the normalized matter density, $\Omega_M^0 = \rho_M^0/\rho_c^0$ (~ 0.3). The difference between the matter density $\overline{\rho}_M$ and the matter density predicted by the model in which the vacuum energy decays into matter, $\rho_{M\nu}$, is

$$\Delta\rho(z) = \overline{\rho}_M(z) - \rho_{M\nu}(z)\,. \tag{3}$$

The density $\rho_{M\nu}(z)$ is normalized at redshift $z = 0$ $\left[\rho_{M\nu}(z=0) \equiv \rho^0{}_M\right]$. In order to describe the transfer of the vacuum energy density, ρ_Λ, into matter $\rho_{M\nu}$ [6], we use the conservation of energy equation,

$$\dot{\rho}_\Lambda + \dot{\rho}_{M\nu} + 3H\,(\rho_{M\nu} + P_{M\nu}) = 0\,, \tag{4}$$

where $P_{M\nu}$ is the pressure due to $\rho_{M\nu}$. For CDM, we have $P_{M\nu} = 0$.

There exists an extensive list of phenomenological Λ-decay laws. Several models in the literature are described by a power law dependence

$$\rho_\Lambda(z) = \rho_\Lambda^0\,(1+z)^n\,, \tag{5}$$

where $\rho_\Lambda^0 \equiv \rho_\Lambda(z=0)$, which we investigate here.

The solution for the matter density has the form [6, 7]

$$\rho_{Mv}(z) = A\,(1+z)^3 + B\,\rho_\Lambda(z)\,, \tag{6}$$

where A and B are unknown constants. Using Eqs.(6) and (5) in Eq.(4), the dependence of ρ_{Mv} as a function of n is

$$\rho_{Mv}(z) = \rho^0_{Mv}(1+z)^3 - \frac{n\,\rho^0_\Lambda}{3-n}\left[(1+z)^3 - (1+z)^n\right]. \tag{7}$$

Using Eqs.(2) and (7) in Eq.(3), we find from Eq.(1) that

$$F = \left[1 - \left(\frac{n}{3-n}\right)\left(\frac{\rho^0_\Lambda}{\rho^0_{Mv}}\right)\left[1-(1+z)^{n-3}\right]\right]^{-2}. \tag{8}$$

If, as discussed in section I, the density power spectrum from observations can be increased by no more than approximately 10% due to the decay of the vacuum energy, we then have a maximum value for the F factor $F_{\rm max} \cong 1.1$. This maximum value gives $n_{\rm max} \cong 0.06$.

We also considered a recent model suggested by the renormalization group equation of the effective quantum field theory which has a Λ-decay dependence [8]

$$\rho_\Lambda(z;\nu) = \rho^0_\Lambda + \rho^0_c\, f(z,\nu)\,, \tag{9}$$

where $\rho_\Lambda(z=0) \equiv \rho^0_\Lambda$, $k=0$, and

$$f(z) = \frac{\nu}{1-\nu}\left[(1+z)^{3(1-\nu)} - 1\right]. \tag{10}$$

The dimensionless parameter ν comes from the renormalization group

$$\nu \equiv \frac{\sigma}{12\pi}\,\frac{M^2}{M_P^2}\,, \tag{11}$$

where σM^2 is the sum of all existing particles (fermions with $\sigma=-1$ and bosons with $\sigma=+1$). The range of ν is $\nu \in (0,1)$ [9].

Using Eqs.(9) and (10), the matter density as a function of z and ν, in the matter era, is

$$\rho_{Mv}(z;\nu) \;=\; \rho^0_{Mv}\,(1+z)^{3(1-\nu)}\,. \tag{12}$$

Using Eqs.(12) and (2) in Eq.(3), we find from Eq.(1), the factor F modifying the density power spectrum:

$$F = (1+z_{\rm rec})^{6\nu}\,. \tag{13}$$

Using $F_{\rm max} \cong 1.1$ we place an upper limit on the ν parameter: $\nu_{\rm max} \cong 2.3\times10^{-3}$.

III. VACUUM ENERGY DECAYING INTO CMB PHOTONS

According to the standard model, the temperature fluctuations observed today are given by the expression

$$\left(\frac{\delta T}{T}\right)\Big|_{z\sim0} = \mathcal{K}\,\frac{\delta\rho}{\rho}\Big|_{z_{\rm rec}}\,, \tag{14}$$

where $\mathcal{K}$ is approximately constant and the temperature dependence of $T(z)$ is

$$T(z) = T_0\,(1+z)\,, \tag{15}$$

where $T_0 \simeq 2.75\,$K is the present CMB temperature [10]. The present value of $(\delta\rho/\rho)^2$ is gotten from the relation

$$\left(\frac{\delta\rho}{\rho}\right)\Big|_{z\sim0} = \mathcal{D}(z_{\rm rec}\to z=0)\;\frac{\delta\rho}{\rho}\Big|_{z_{\rm rec}}\,, \tag{16}$$

where $\mathcal{D}(z_{\rm rec}\to z=0)$ is the growth factor from the recombination era until the present time.

When we assume that the decay is adiabatic, the vacuum energy decays into a homogeneous distribution of thermalized black body CMB photons and the standard linear temperature dependence becomes modified [11]. The decay can be described by a generic temperature dependence,

$$T(z) = T_0\,(1+z)^{1-\beta}\,, \tag{17}$$

of the CMB photons. In principle, the possible range of β is $\beta\in[0,1]$ [11].

There are two effects due to the decaying vacuum energy into CMB photons:

1) Since the temperature fluctuations at the recombination epoch $(\delta T/T)_{\rm rec}$ should be diluted by the photons created, the temperature fluctuations at present become smaller; and

2) The value of the recombination redshift $\overline{z}_{\rm rec}$ is higher than that of the standard model $z_{\rm rec}$ since the universe is cooler at any given redshift.

Due to the dilution of $\delta T/T$, instead of Eq.(14) of the standard model, we must use the relation

$$F_1\left(\frac{\delta T}{T}\right)\Big|_{z_{\rm rec}} = \mathcal{K}\,\frac{\delta\rho}{\rho}\Big|_{z_{\rm rec}}\,, \tag{18}$$

where F_1 is defined by

$$F_1(z) \equiv \left[\frac{T\,(z)}{T\,(z)-\Delta T(z)}\right]\Big|_{z_{\rm rec}}\,. \tag{19}$$

$\Delta T(z)$ is the difference between the recombination temperature $T(z_{\rm rec})$ predicted by the standard model and that of the model in which the vacuum energy decays into photons at temperature $\overline{T}(z_{\rm rec})$:

$$\Delta T(z_{\rm rec}) = T\,(z_{\rm rec}) - \overline{T}(z_{\rm rec})\,. \tag{20}$$

Using Eqs.(17), (19), and (20), we obtain

$$F_1 = (1+z_{\rm rec})^{\beta}\,. \tag{21}$$

From Eqs.(17) and (20), $\overline{T}(z)$ was lower than $T\,(z)$ by ΔT at $z_{\rm rec}$. Thus, the resultant recombination redshift $\overline{z}_{\rm rec}$ was higher than that of the standard model $z_{\rm rec}$. Instead of Eq.(16), $(\delta\rho/\rho)$ at $z\sim0$ is now given by

$$\left(\frac{\delta\rho}{\rho}\right)\Big|_{z\sim0} = \mathcal{D}(\overline{z}_{\rm rec}\to z=0)\;\frac{\delta\rho}{\rho}\Big|_{z=\overline{z}_{\rm rec}}\,, \tag{22}$$

where $\mathcal{D}(\bar{z}_{\rm rec} \to z = 0)$ is the density fluctuation growth factor from the recombination era at $\bar{z}_{\rm rec}$ until the present epoch. Therefore, instead of Eq.(14), we have

$$\left(\frac{\delta T}{T}\right)\Big|_{z\sim 0} = \mathcal{K}\,\frac{\delta\rho}{\rho}\Big|_{z=\bar{z}_{\rm rec}} . \tag{23}$$

Using Eqs.(16) and (18), we have

$$\left(\frac{\delta\rho}{\rho}\right)\Big|_{z\sim 0} = \frac{F_1}{\mathcal{K}}\,\mathcal{D}(z_{\rm rec} \to z = 0)\left(\frac{\delta T}{T}\right)\Big|_{z_{\rm rec}} \tag{24}$$

and from Eqs.(22) and (23),

$$\left(\frac{\delta\rho}{\rho}\right)\Big|_{z\sim 0} = \frac{F_1}{\mathcal{K}}\,\mathcal{D}(\bar{z}_{\rm rec} \to z = 0)\left(\frac{\delta T}{T}\right)\Big|_{z_{\rm rec}} . \tag{25}$$

Equations (24) and (25) give the correction factor F_2 due to the change in the value of the recombination redshift,

$$F_2 = \frac{\mathcal{D}(\bar{z}_{\rm rec} \to z = 0)}{\mathcal{D}(z_{\rm rec} \to z = 0)} . \tag{26}$$

The growth of a perturbation in a matter-dominated Einstein-de Sitter universe is $\delta\rho/\rho \propto a = (1+z)^{-1}$, where a is the cosmic scale factor [12]. Thus, the growth factor $\mathcal{D}$ is

$$\mathcal{D} \simeq (1+z) .$$

We then find from Eq.(26)

$$F_2 \simeq \left(\frac{1+\bar{z}_{\rm rec}}{1+z_{\rm rec}}\right) . \tag{27}$$

The temperature at $z_{\rm rec}$ in the standard model is

$$T\,(z_{\rm rec}) = T_0\,(1+z_{\rm rec}) . \tag{28}$$

In order for the temperature at the recombination epoch $\bar{z}_{\rm rec}$ to be the same as the standard model $T(z_{\rm rec})$, when the vacuum energy is decaying into CMB photons, we must have, from Eq.(17),

$$\bar{z}_{\rm rec} = (1+z_{\rm rec})^{1/(1-\beta)} - 1 . \tag{29}$$

From Eq.(27), we then have

$$F_2 \simeq (1+z_{\rm rec})^{\beta/(1-\beta)} . \tag{30}$$

The total factor F is composed of F_1, due to the dilution of the CMB as a result of vacuum energy decay, and F_2, due to the change in the redshift of the recombination epoch. Assuming that the effects described by F_1^2 and F_2^2 are independent and that the total factor F is the product of F_1^2 and F_2^2, we have

$$F = F_1^2 F_2^2 . \tag{31}$$

Thus, from Eqs.(21), (30) and (31), the condition for the maximum value of $\beta \in [0,1]$ is

$$\beta_{\rm max} = \alpha\left[1 - \sqrt{1 - \frac{\ln(F_{\rm max})}{2\alpha^2 \ln(1+z_{\rm rec})}}\,\right] , \tag{32}$$

where

$$\alpha = 1 + \frac{\ln(F_{\rm max})}{4\ln(1+z_{\rm rec})} . \tag{33}$$

As noted above, the maximum value of F from observations is $F_{\rm max} \cong 1.1$. For $z_{\rm rec} \simeq 1070$, we find a very small maximum value of the β parameter, $\beta_{\rm max} \cong 3.4\times 10^{-3}$.

IV. CONCLUSIONS

We showed that the CMB and large galaxy survey data agreement puts strong limits on the rate of a possible decay of the vacuum energy into CDM and CMB photons.

When the vacuum energy decays into CDM, $\delta\rho/\rho$ is diluted and the density fluctuation spectrum is amplified by a factor F at the recombination era. The $(\delta\rho/\rho)^2$ derived from the CMB and galaxy distribution data agree to $\sim 10\%$, implying a maximum value for F: $F_{\rm max} \cong 1.1$.

We found that the decay of the vacuum energy into CDM as a scale factor power law $\rho_\Lambda \propto (1+z)^n$, gives a maximum value for the exponent $n_{\rm max} \cong 0.06$. For a parametrized vacuum decay into a CDM model with the form $\rho_\Lambda(z,\nu) = \rho_\Lambda(z=0) + \rho_c^0\,[\nu/(1-\nu)]\,[(1+z)^{3(1-\nu)} - 1]$, where ρ_c^0 is the present critical density, an upper limit on the ν parameter was found to be $\nu_{\rm max} \cong 2.3\times 10^{-3}$.

We made a similar analysis for the possibility of the decay of the vacuum energy into CMB photons. When photon creation due to the vacuum energy decay takes place, the standard linear temperature dependence, $T(z) = T_0\,(1+z)$, where T_0 is the present CMB temperature, is modified. We can place an upper limit on the β parameter for the decay of the vacuum energy into CMB photons, parametrized by a change in the CMB temperature at a given redshift z: $\overline{T}(z) = T_0(1+z)^{1-\beta}$. We find that $\beta_{\rm max} \cong 3.4\times 10^{-3}$.

Our results indicate that the rate of decay of the vacuum energy into CDM or CMB photons is extremely small. Since the results show that the vacuum energy can only decay to a negligible extent into cold dark matter or CMB photons, we conclude that if the vacuum energy is decaying, it is probably decaying, for example, into hot dark matter (e.g., high energy neutrinos) or exotic matter (e.g., scalar fields), since they do not affect the $(\delta\rho/\rho)^2$ or the $\delta T/T$ CMB spectra.

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