Studying the decay of the vacuum energy into CDM and CMB photons

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Vacuum energy decaying into CDM

We investigate models that suggest that the vacuum energy decays into cold dark matter (CDM) in [1].

The **CDM produced by a decaying vacuum energy** would **dilute the density fluctuation spectrum** created in the primordial universe and observed with large galaxy surveys at low redshifts.

We show that the **density fluctuation spectrum** obtained from the cosmic microwave background **(CMB) data together with large galaxy surveys** (e.g., the 2dF galaxy redshift survey) **puts strong limits on the rate of decay** of the vacuum energy.

The density fluctuation spectrum

Measurements of the CMB temperature fluctuations, $\delta T/T$, provides information on the density fluctuation spectrum **at the recombination era (redshift $z_{rec} \approx 1070$).**

Galaxy distribution data measures the density fluctuations $\delta\rho/\rho$ **at low redshifts, $z \lesssim 1$.**

The density fluctuations obtained by the **2dF galaxy redshift survey (2dFGRS) were compared with the CMB anisotropies data** by Peacock et al. [2].

The matter power spectrum, derived from the galaxy distribution data, differs from that derived from the CMB data by no more than 10%.

A larger density fluctuation spectrum

The relation between the density fluctuations $(\delta\rho/\rho)^2$ **over a distance** λ **and the power spectrum** $P(k)$ for the wave number $k = 2\pi/\lambda$, is

$$\left(\frac{\delta\rho}{\rho}\right)^2_\lambda \simeq \left[k^3 P(k)\right]_{k=2\pi/\lambda} .$$

If the vacuum energy decays into CDM, increasing ρ**, the** $(\delta\rho/\rho)$ **spectrum observed at low redshifts would have been diluted and the** $\delta\rho/\rho$ **would have been bigger at the recombination era.**

The amplifying factor:

A larger density fluctuation spectrum $(\delta\rho/\rho)^2$ **is predicted at the recombination era** $(z_{rec} = 1070)$ **by the factor**

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

where

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

is the matter density for a constant vacuum energy density,
$\rho_c^0 \equiv 3\,H_0^2/(8\,\pi\,G) \simeq 1.88\,h_0^2 \times 10^{-29}\,g\,cm^{-3}$ 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 $\bar{\rho}_M$ and the matter density ρ_{Mv} predicted by the model in which the vacuum energy decays into matter is

$$\Delta\rho(z) = \overline{\rho}_M(z) - \rho_{Mv}(z)\,.$$

The density $\rho_{Mv}(z)$ is normalized at redshift $z = 0$ $\left(\rho_{Mv}(z=0) \equiv \rho^0{}_M\right)$. **In order to describe the transfer of the vacuum energy ρ_Λ into matter ρ_{Mv} [3], we use the conservation of energy equation,**

$$\dot{\rho}_\Lambda + \dot{\rho}_{Mv} + 3\,H\,(\rho_{Mv} + P_{Mv}) = 0\,,$$

where P_{Mv} is the pressure due to ρ_{Mv}.

For CDM, we have $P_{Mv} = 0$.

A decaying scale factor power law

We consider the vacuum energy density ρ_Λ decaying as

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

where $\rho_\Lambda(z=0) \equiv \rho_\Lambda^0$.

The solution for the matter density has the form

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

where A and B are unknown constants.

The dependence of ρ_{Mv} as a function of n is

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

For this model we find

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

If the density power spectrum, from recent data, can be increased by no more than 10% due to the decay of the vacuum energy, the maximum value for the F factor is $F_{max} = 1.1$. This maximum value gives $n_{max} \approx 0.06$.

A recent parametrised Λ model

is suggested by the renormalization group equation [4]

$$\Lambda(z;\nu) = \Lambda_0 + \rho_c^0\ f(z,\nu)\,,$$

where $\Lambda(z=0) = \Lambda_0$, $k=0$, and

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

The parameter ν **is dimensionless** and comes from the **renormalization group**

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

σM^2 **is the sum of all particles** ($\sigma = \pm 1$ for fermions and bosons).

The matter density can be obtained as a function of z **and** ν in the matter era $(P_{Mv} = 0)$:

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

The factor F **modifying the density power spectrum is**

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

From the observational data $F_{max} = 1.1$ **and we predict**

$$\nu_{max} \approx 2.3\times 10^{-3}\,.$$

Due to the small values of n_{max} **and** ν_{max} **our results indicate that if the vacuum energy is decaying into CDM, the rate of decay is extremely small.**

Vacuum energy decaying into CMB photons

We analyze a model assuming that the vacuum energy decays into CMB photons in [5].

The $\delta T/T$ are proportional to the cold dark matter (CDM) density fluctuations [6].

The $\delta T/T$ **should be diluted at the recombination epoch** $(\delta T/T)_{rec}$ **by the photons created** by the vacuum energy decay.

We then have today smaller temperature fluctuations then existed at the recombination era.

This implies bigger density fluctuations $\delta\rho/\rho$ at the recombination era.

We observe the $\delta\rho/\rho$ at the present epoch $(z \sim 0)$ from GDD as well as from the CMB temperature fluctuation data.

The temperature fluctuations $\delta T/T$ were created by the density fluctuations at $z_{rec} \sim 1070$ [6].

The expected $\delta T/T$ observed today can be given by the expression

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

where $\mathcal{K}$ is approximately constant, $\bar{z}_{rec}$ **is the redshift for the standard model** at the recombination epoch, and

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

is the **temperature-redshift relation of the standard model**, where $T_0 \simeq 2.75K$ is the present CMB temperature.

We obtain **the present density fluctuation spectrum** $\delta\rho/\rho$ $(z \sim 0)$ **from the relation**

(2) $$\left(\frac{\delta\rho}{\rho}\right)_{\rm CMB}\Big|_{z\sim 0} = \mathcal{D}\left(\bar{z}_{rec} \to z = 0\right)\, \frac{\delta\rho}{\rho}\Big|_{\bar{z}_{rec}},$$

where $\mathcal{D}$ is **the density fluctuation growth factor between the recombination era and the present.**

We study **a generic model where the vacuum energy decays into CMB photons** with

$$T_{ph}(z) = T_0\,(1+z)^{1-\beta}\ .$$

A possible range for β is $\beta \in (0,1)$ [7].

The decay of the vacuum energy into CMB photons has two effects

1) The decay into CMB photons decreases the observed $\delta T/\bar{T}$.

Instead of Eq. (1), we have the relation

$$F_1 \left(\frac{\delta T}{\bar{T}}\right) \Big|_{\bar{z}_{rec}} = \mathcal{K}\, \frac{\delta\rho}{\rho}\Big|_{\bar{z}_{rec}} ,$$

where

$$F_1(z) \equiv \left[\frac{\overline{T}\,(z)}{\overline{T}\,(z) - \Delta T(z)}\right]\Big|_{\bar{z}_{rec}}$$

with

$$\Delta T(\bar{z}_{rec}) = \overline{T}\,(\bar{z}_{rec}) - T_{ph}(\bar{z}_{rec}) \,.$$

For the parametrized model T_{ph}, we have

$$F_1 = (1+\bar{z}_{rec})^{\beta} \;.$$

2) The recombination redshift, in the vacuum energy decay model, z_{rec}, occurs at a higher value than the recombination redshift $\bar{z}_{rec}$ of the standard model.

Instead of Eq.(2), we have

$$\left(\frac{\delta\rho}{\rho}\right)_{\rm CMB}\Big|_{z\sim 0} = \mathcal{D}_{ph}\left(z_{rec} \rightarrow z = 0\right)\ \frac{\delta\rho}{\rho}\Big|_{z=z_{rec}},$$

where $\mathcal{D}_{ph}$ **is the density fluctuation growth factor between the recombination era at z_{rec} until the present epoch.**

Consequently, instead of Eq.(1), we have

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

The correction factor due to the change of the recombination redshift is

$$F_2 = \frac{\mathcal{D}_{ph}(z_{rec} \to z = 0)}{\mathcal{D}(\bar{z}_{rec} \to z = 0)} \,,$$

where the growth factor $\mathcal{D}$ is approximately given by

$$\mathcal{D}(z \to 0) \simeq (1 + z) \,.$$

For the parametrized model T_{ph}, we find

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

In order to have the same temperature of the standard model

$$T\left(\bar{z}_{rec}\right) = T_0\left(1+\bar{z}_{rec}\right),$$

the redshift z_{rec} for the considered model with **the vacuum energy decaying into CMB photons** (T_{ph}) **is**

$$z_{rec} = \left(1+\bar{z}_{rec}\right)^{1/(1-\beta)} - 1\,.$$

Then

$$F_2 \simeq \left(1+\bar{z}_{rec}\right)^{\beta/(1-\beta)}\,.$$

Assuming that the effects F_1 **and** F_2 **are independent and taking into account the uncertainty of** 10% **:** $F = F_1^2\,F_2^2 = 1.1,$ **the maximum value of** $\beta,$ **using** $\bar{z}_{rec} \simeq 1100,$ **is then**

$$\beta_{max} \approx 3\times 10^{-3}\,.$$

Conclusions

The density fluctuation spectrum obtained from the CMB data together with large galaxy surveys **puts strong limits on the rate of decay of the vacuum energy.**

Due to the small values of the parameters our results indicate that if the vacuum energy is decaying into CDM or into CMB photons the rate of decay is extremely small.

We can conclude that, **if the vacuum energy is decaying**, it can only decay into hot dark matter (e.g., high energy neutrinos) or exotic matter (e.g., scalar fields) which **do not effect the** $(\delta\rho/\rho)^2$ **or the** $\delta T/T$ **CMB spectrum.**

References

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