Limits on decaying dark energy density models from the CMB temperature-redshift relation

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OUTLINE:

Consider a phenomenological model for dark energy decay into photons and/or particles as proposed by Lima (Phys. Rev. D 54, 2571 (1996)):

taking into account thermodynamic aspects of decaying dark energy models, in particular in the case of a continuous photon creation and/or disruption;

we derive a temperature redshift relation for the CMB which depends on the effective equation of state w_{eff} and on the "adiabatic index" γ.

We compare then our results with the data on the CMB temperature as a function of the redshift obtained from Sunyaev-Zel'dovich observations and at higher redshift from quasar absorption line spectra.

PJ, D.Puy, M.Signore and C.Tortora, GRG, **43**, 1083 (2011), PJ and C. Tortora, Phys. Rev. **D84**, 043517 (2011).

THEORETICAL FRAMEWORK

Photons created by dark energy decay could lead to distortions in the Planck spectrum of the CMB. If the dark energy is considered as a component transferring energy continuously to the radiation and/or matter component, the second law of thermodynamics constrains the whole process in such a way that the temperature law, that is how the temperature of the CMB changes with time, can be determined.

Lima discussed under which conditions the equilibrium relations are preserved ("adiabatic" vacuum decay) and derived a temperature redshift relation law

$$T = (1+z)^{1-\beta}$$

assuming a nonvanishing source term in the balance equation for particle number, which depends on a function β assumed to be constant.

Parameter can then be determined by fitting the temperature redshift relation to the data.

However, this way β cannot be related to more fundamental quantities (for instance w_{eff}).

TEMPERATURE-REDSHIFT RELATION

Consider FLRW cosmology and a Universe containing three different components:

- radiation

- matter (both baryonic and dark matter),

for which we have the law

$$p = (\gamma - 1)\rho \tag{1}$$

with γ for instance 4/3 and 1, respectively.

- a dark energy, quintessence-like x component, with pressure p_x and density ρ_x.

Einstein field equations:

$$8\pi G(\rho_m + \rho_\gamma + \rho_x) = 3\frac{\dot{R}^2}{R^2} + 3\frac{k}{R^2} \qquad (2)$$

$$8\pi G(p_\gamma + p_x) = -2\frac{\ddot{R}}{R} - \frac{\dot{R}^2}{R^2} - \frac{k}{R^2} \qquad (3)$$

Assume $k = 0$, and take the sum of eqs. (2) and (3):

$$8\pi G(\rho_{tot} + p_{tot}) = 2\frac{\dot{R}^2}{R^2} - 2\frac{\ddot{R}}{R} = -2\dot{H} \qquad (4)$$

with $\rho_{tot} = \rho_m + \rho_\gamma + \rho_x$, $p_{tot} = p_\gamma + p_x$

The energy conservation equation can be written as

$$\dot{\rho}_i + 3(\rho_i + p_i)H = C_i \tag{5}$$

$(i = m, \gamma, x)$ where $H = \dot{R}/R$ is the Hubble parameter and for $i = x$

$$C_x = -\dot{\rho}_x - 3(\rho_x + p_x)H \tag{6}$$

is a term which depends on the dark energy and acts as a source term for the other components.

Assuming for the dark energy $p_x = -\rho_x$ (thus setting $w_x = -1$): for instance quintessence models in the limit where the scalar field does not depend on time and thus its time derivative vanishes. The vacuum plays the role of a condensate with no entropy. Notice, that w_{eff} (the effectively measured quantity) can differ from -1.

Writing $\rho_x = \Lambda(t)/(8\pi G)$, we have

$$C_x = -\frac{\dot{\Lambda}(t)}{8\pi G} \tag{7}$$

Equation for the particle number density

$$\dot{n}_j + 3n_j H = \psi_j \tag{8}$$

n_j: particle number density (component j)

ψ_j: particle source term

Using Gibbs law and well-known thermodynamic identities (see paper by Lima et al.), one gets

$$\frac{\dot{T}}{T} = \left(\frac{\partial p_\gamma}{\partial \rho_\gamma}\right)_n \frac{\dot{n}_\gamma}{n_\gamma} - \frac{\psi_\gamma}{n_\gamma T \left(\frac{\partial \rho_\gamma}{\partial T}\right)_n} \left[p_\gamma + \rho_\gamma - \frac{n_\gamma C_x}{\psi_\gamma}\right] \tag{9}$$

To get a black-body spectrum the second term in brackets in eq.(9) has to vanish, thus

$$C_x = \frac{\psi_\gamma}{n_\gamma} \left[p_\gamma + \rho_\gamma\right] \tag{10}$$

Thus, using the equation for the particle number conservation, we get

$$\frac{\dot{T}}{T} = (\gamma - 1)\left[\frac{\dot{\Lambda}}{2\dot{H}} - 3H\right] \tag{11}$$

Integration of eq.(11) with change variable from t to z, accordingly $\frac{dt}{dz} = \frac{-1}{H(1+z)}$. This way we get (with z_1 corresponding to the time t_1 and $z_0 = 0$ corresponding to t_0 present time)

$$ln\frac{T(z=0)}{T(z_1)} + 3(\gamma - 1)ln\frac{R(z=0)}{R(z_1)} = \frac{(\gamma - 1)}{2}\int_0^{z_1}\frac{\Lambda'}{H'H(1+z)}dz \tag{12}$$

$'$ denotes derivative with respect to z.

Assume a power law model for the Λ term

$\Lambda = B(R/R_0)^{-m}$ or $\Lambda = B(1+z)^m$,

$B = 3H_0^2(1-\Omega_{m0})$

(see also Y. Ma, Nucl. Phys. B804, 262 (2008)).

The Hubble parameter as a function of m can be computed and leads to

$$H(z) = H_0 \left[\frac{(3\Omega_{m0} - m)}{3-m}(1+z)^3 + \frac{3(1-\Omega_{m0})}{3-m}(1+z)^m \right]^{1/2} \quad (13)$$

Ω_{m0} present value of the total matter density: $\rho_{m0} = 3H_0^2 M_{Pl}^2 \Omega_{m0}$, ($M_{Pl} = (8\pi G)^{-1/2}$)

(Due to the negligible energy density accounted for by the radiation, we neglected this term.)

As next we insert $H(z)$ and its derivative as taken from eq.(13) into eq.(12) and integrate it, to get (setting $z_1 = z$)

$$T(z) = T_0(1+z)^{3(\gamma-1)} \times \left(\frac{(m-3\Omega_{m0}) + m(1+z)^{m-3}(\Omega_{m0}-1)}{(m-3)\Omega_{m0}}\right)^{\gamma-1}$$

Notice that for $z = 0$: $T(0) = T_0$, whereas for $m = 0$ the expression in the parenthesis is equal to 1 and thus $T(z) = T_0(1+z)^{3(\gamma-1)}$, which for the canonical value of $\gamma = 4/3$ reduces to the standard expression.

If m is positive, then the dark energy slowly decreases as a function of the cosmic time, whereas if m is negative the inverse process happens.

Effective dark energy equation of state $p = w_{eff}\rho$ with $w_{eff} = \frac{m}{3} - 1$. If $m > 0$ then we have $w_{eff} > -1$, i.e. our model is quintessence-like, while we have a phantom-like model when m is negative and $w_{eff} < -1$.

Deceleration parameter

$$q(z) = -\frac{\ddot{R}R}{\dot{R}^2} = \frac{(1+z)^3(m-3\Omega_{m0}) + 3(m-2)(1+z)^m(\Omega_{m0}-1)}{2(1+z)^3(m-3\Omega_{m0}) + 6(1+z)^m(\Omega_{m0}-1)}$$

Imposing that $q(z) = 0$, we can determine the *transition redshift*, i.e. the redshift when the Universe was changing from a deceleration to an acceleration phase, which is given by

$$z_T = \left(\frac{3(2-m)(1-\Omega_{m0})}{3\Omega_{m0}-m}\right)^{\frac{1}{3-m}} - 1 \qquad (14)$$

From this result we have that the larger m is, the earlier the Universe changes from deceleration to acceleration.

Multi-redshift measurements of T_{CMB}

a) Quasar spectral features

c) SZ effect

a) CMB temperature at high redshift from the analysis of quasar absorption line spectra which give atomic or ionic fine structure levels excited by the photo-absorption of the cosmic microwave background radiation. For instance in QSO 0013-004 the CMB temperature is

$$T_{\mathrm{CMB}} = 7.9 \pm 1.0 \text{ K at } z = 1.9731. \qquad (15)$$

The cosmic microwave background can also excite levels of molecular species, as observed in the galaxy which acts as lens for the quasar PKS 1830-211 (S. Muller et al. arXiv 1212.5456)

$$T_{\mathrm{CMB}} = 5.08 \pm 0.10 \text{ K at } z = 0.89. \qquad (16)$$

b) During passage through a cluster of galaxies some of the photons of the cosmic microwave background radiation are scattered by electrons in the hot intracluster medium (Sunyaev-Zel'dovich effect)

Thus, spectral measurements of galaxy clusters at different frequency bands yield independent intensity ratios for each cluster. The combinations of these measured ratios permit to extract the cosmic microwave background radiation temperature.

Luzzi et al. have analyzed the results of multi-frequency Sunyaev-Zel'dovich measurements toward several clusters.

RESULTS

We have tested our model by comparing the CMB temperature predicted with the collection of multi-redshift measurements of T_{CMB}.

We set $T_0 = 2.725$ K, and the matter density $\Omega_{\mathrm{m}0} = 0.273$.

If we take $\gamma = 4/3$, then we find $m = 0.03 \pm 0.09$ and $z_T = 0.78 \pm 0.08$.

If we leave both γ and m free to vary $m = 0.25^{+0.23}_{-0.17}$ and $\gamma = 1.35^{+0.03}_{-0.03}$ and $z_T = 1.1 \pm 0.6$.

In both the cases, the best fitted m values are positive, but consistent with 0 within 1σ uncertainty, while in the latter case the estimated value for γ of 1.35 is consistent within the errors with the canonical value for radiation. Within the uncertainties, the derived z_T are consistent with the typical values in literature, although, on average, higher.

Assuming a constant value for the ratio

$\psi_\gamma / 3 n_\gamma H = \beta$

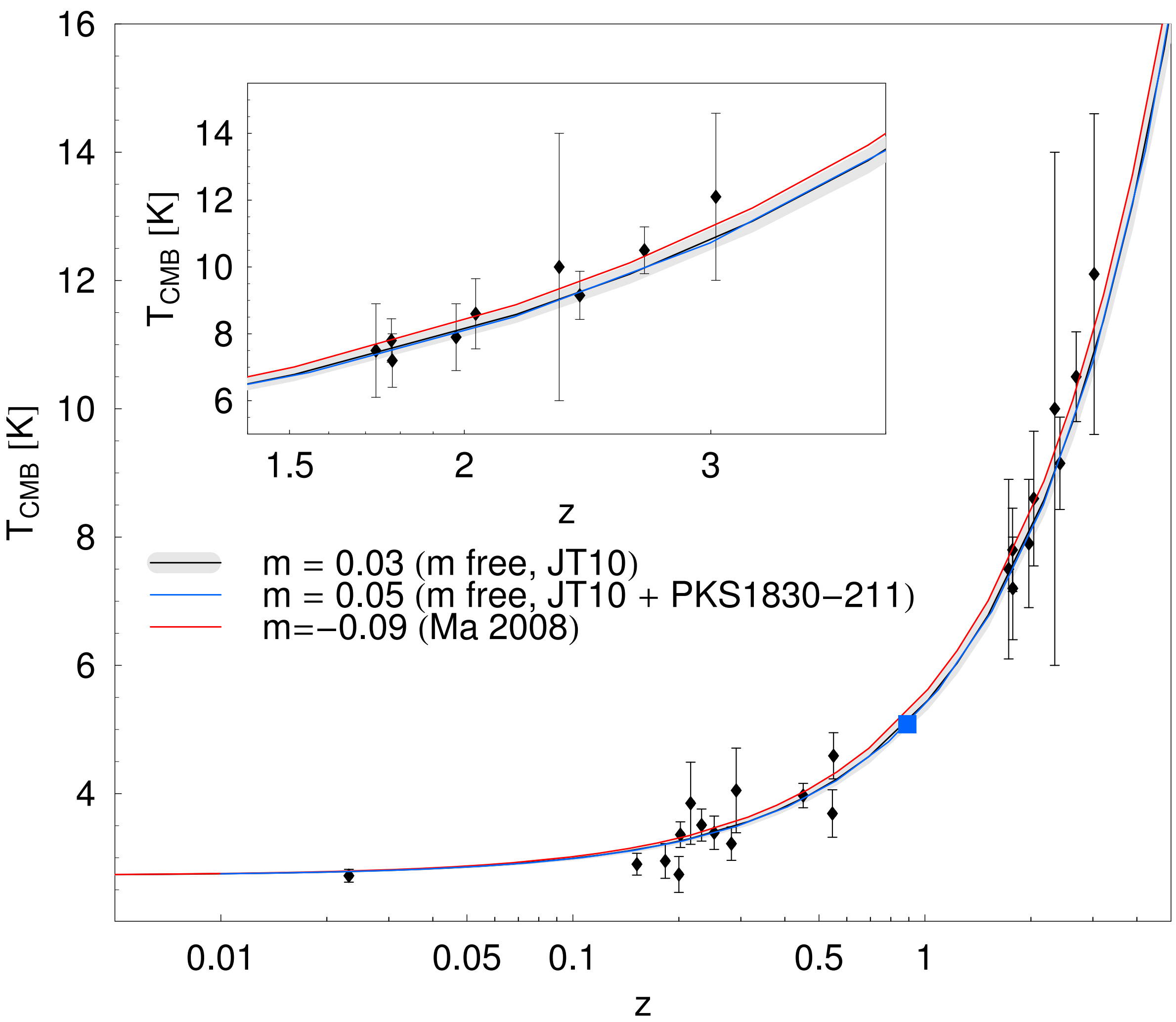
with the constraint $0 \leq \beta \leq 1$, Lima et al. found as a result instead the relation

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

For a value of β different from zero the temperature of the expanding universe at high values of z is slightly lower than in the standard photon-conserved scenario.

Luzzi et al. found using their data as best fit the value

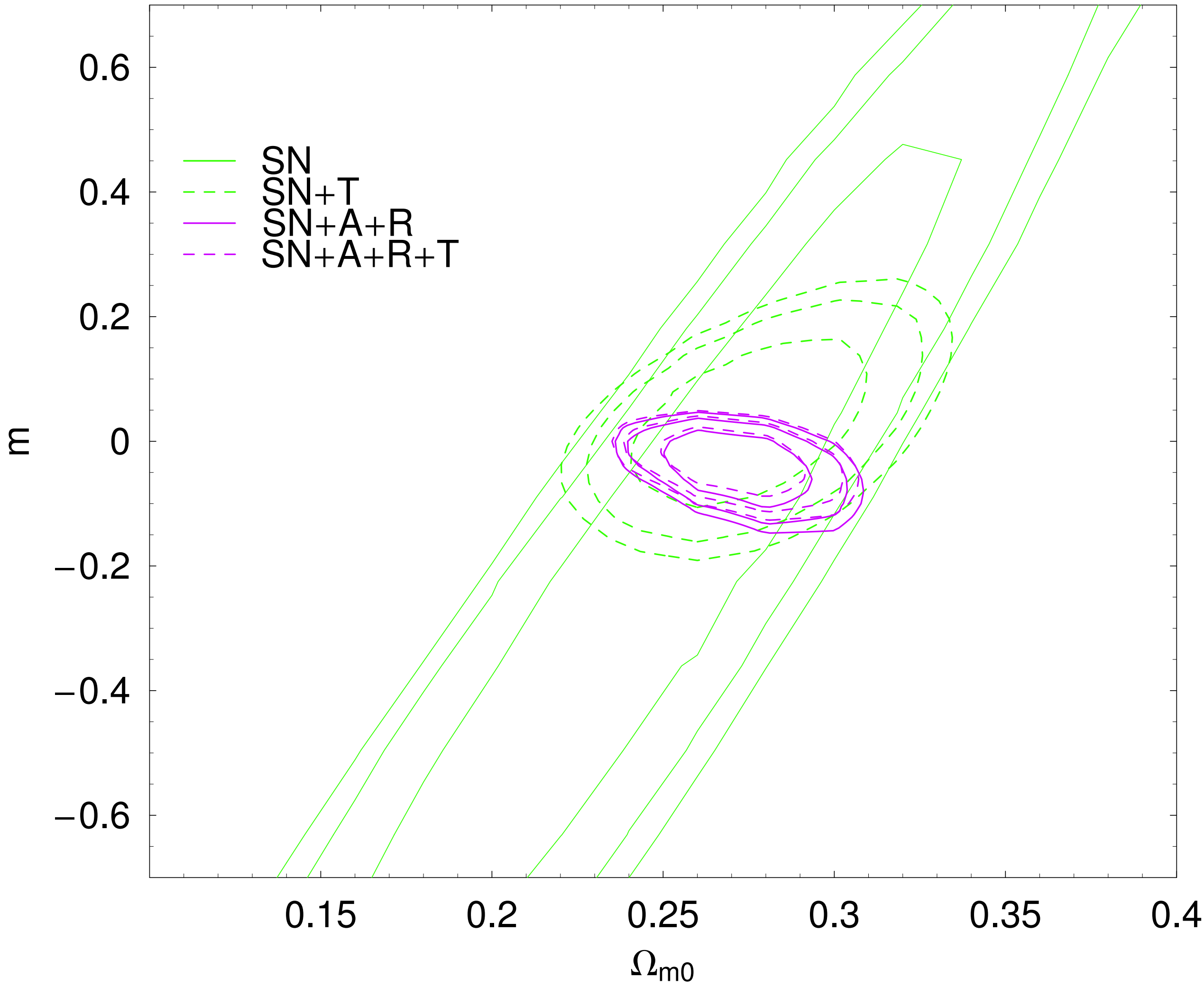
$\beta = 0.024^{+0.068}_{-0.024}$.



CMB temperature for different m-models (with $\gamma = 4/3$): data are plotted as black symbols (blue one for PKS 1830-211).

(Inset, difference between the data points and each best fitted curve as a function of redshift)

Combination of all data



68%, 90% and 95% confidence limit contours in the $\Omega_{m0} - m$ plane. (SN: Supernovae type Ia, A: Baryon Acoustic Oscillations, R: CMB anisotropies, T: temperature measurements)

CONCLUSIONS

Assuming the canonical 4/3 value for γ we found

$m = 0.03 \pm 0.09$ corresponding to $w_{eff} = -0.99 \pm 0.03$,

whereas leaving γ open we got

$m = 0.25 \pm 0.23$ or $w_{eff} = -0.92 \pm 0.07$.

Both results are within 1σ consistent with the canonical value of -1 for the cosmological constant. Using SNe Ia data combined with CMB and Baryon Acoustic Oscillations, and assuming a flat universe, Kowalski et al. found

$w_{eff} = -0.97 \pm 0.06 \pm 0.06$ (stat,sys)

and similarly Kessler et al. estimated

$w_{eff} = -0.96 \pm 0.06 \pm 0.12$.

Our best fit value for w_{eff} compares quite well with these values.