Mass varying neutrinos coupled to the dark sector in the generalized Chaplygin gas scenario

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Abstract

We suggest a perturbative approach for generic choices for the universe equation of state and introduce a novel framework for studying mass varying neutrinos (MaVaN's) coupled to the dark sector. For concreteness, we examine the coupling between neutrinos and the underlying scalar field associated with the generalized Chaplygin gas (GCG), a unification model for dark energy and dark matter. After setting the GCG parameters in agreement with general cosmological constraints, we find that the squared speed of sound in the neutrino-scalar GCG fluid is naturally positive. In this scenario, the model stability depends on previously set up parameters associated with the equation of state of the universe. Our results suggest that the GCG is a particularly suitable candidate for constructing a stable MaVaN scenario.

The simplest realization of the MaVaN mechanism consists in writing down an effective potential which, in addition to a scalar field dependent term, contains a term related to the neutrino energy density. In this paper we consider the possibility of neutrino masses arising from an interaction with a real scalar field which describes the dynamics of the generalized Chaplygin gas [1, 2] that is characterized by an exotic equation of state [3, 4] given by,

$$p_\phi = -A_s \left(\frac{\rho_0}{\rho_\phi}\right)^\alpha, \qquad (1)$$

which can be obtained from a generalized Born-Infeld action [3].

The existence of a scalar field dark energy sector on its own constitutes a problem in what concerns order of magnitude equality with the energy densities of the other components of the universe. The theoretical assumptions suggest a stationary condition which allows circumventing the coincidence problem for cosmological neutrinos in a way that the dark energy is always diluted at the same rate as the neutrino fluid, that is,

$$\frac{dV_{(\phi)}}{d\phi} = -\frac{dm_\nu}{d\phi}\frac{\partial\rho_\nu}{\partial m_\nu}. \qquad (2)$$

This introduces a constraint over the neutrino mass since it promotes it into a dynamical quantity. The main feature of this scenario [5] is that it is equivalent as adopting cosmological constant like dark sector, with an energy density that varies as a function of the neutrino mass. As already mentioned, the effectiveness of this coupling is restricted to values of the scale factor larger than a_{NR}, where a_{NR} parameterizes the transition between the relativistic and NR regimes. The assumption of a universe with the dark energy sector governed by the equation of state $p_\phi = -\rho_\phi$ implies, through Eq. (2), that $\rho_\Lambda = V$, and allows to recover the stationary condition, exactly as obtained in Ref. [5]. It is clear that the relevance and the considerations about the constraints on the equation of state are actually dominated by the competition among scalar field potentials and its adequacy for neutrino mass generation. In fact, once one assumes that $p_\phi = -\rho_\phi$, the neutrino mass evolution and the form of the potential become automatically entangled by the stationary condition.

At our approach[8, 9], we start from an unperturbed equation, and establish the conditions for treating the neutrino coupling in a perturbative way. We can obtain the value of the coefficient of this perturbation in terms of the physical input parameters,

$$\epsilon \simeq \frac{-\frac{dm_\nu}{d\phi}\frac{\partial\rho_\nu}{\partial m_\nu}}{\left[\phi^2\frac{d}{d\phi}\left(\frac{1}{\phi}\frac{dV_{(\phi)}}{d\phi}\right)\right]}, \qquad (3)$$

which for consistency is required to satisfy the condition $|\epsilon| << 1$.

Current cosmological data constrain the number of active neutrino flavours as well as the sum of their masses to $\sum_{i=1}^{3} m_{\nu i} < 0.75\,eV$ at 95 % c.l.. Actually, improvement on experimental data are expected to be sensitive to the effects of a finite sum of neutrino masses as small as $0.06\,eV$ [6, 7], the lower limit arising by neutrino oscillation experiments that set $\Delta m^2 \sim 7.5$ - $8.7 \times 10^{-5}\,eV^2$ (2σ) for solar neutrinos, and $\Delta m^2 \sim 1.7$ - $2.9 \times 10^{-3}\,eV^2$ (2σ) for atmospheric neutrinos. Thus, in order to test our scenario, we shall consider present neutrino masses varying from $0.05\,eV$ to $5\,eV$. With these values we can illustrate the behaviour of the neutrino mass in terms of the GCG parameters as a function the scale factor (FIGS. 01-02).

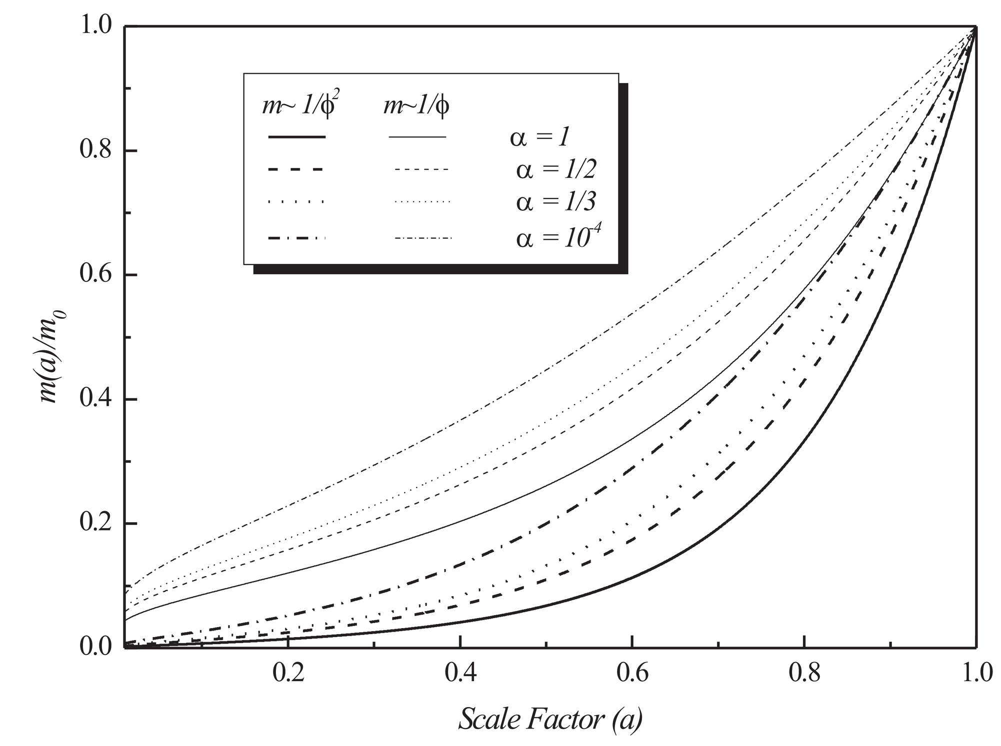

FIG.01: The neutrino mass $(m_{\nu(a)}/m_0)$ dependence on the scale factor a.

One sees that for $m_\nu \sim 1/\phi$ neutrinos become NR earlier than the $m_\nu \sim 1/\phi^2$ case. Since there are strong phenomenological constraints on the choice of m_0, it is important to pay attention to the present-day value of neutrino mass interval, from $0.05\,eV$ to $5\,eV$, where a clear dependence on the model for mass generation is observed.

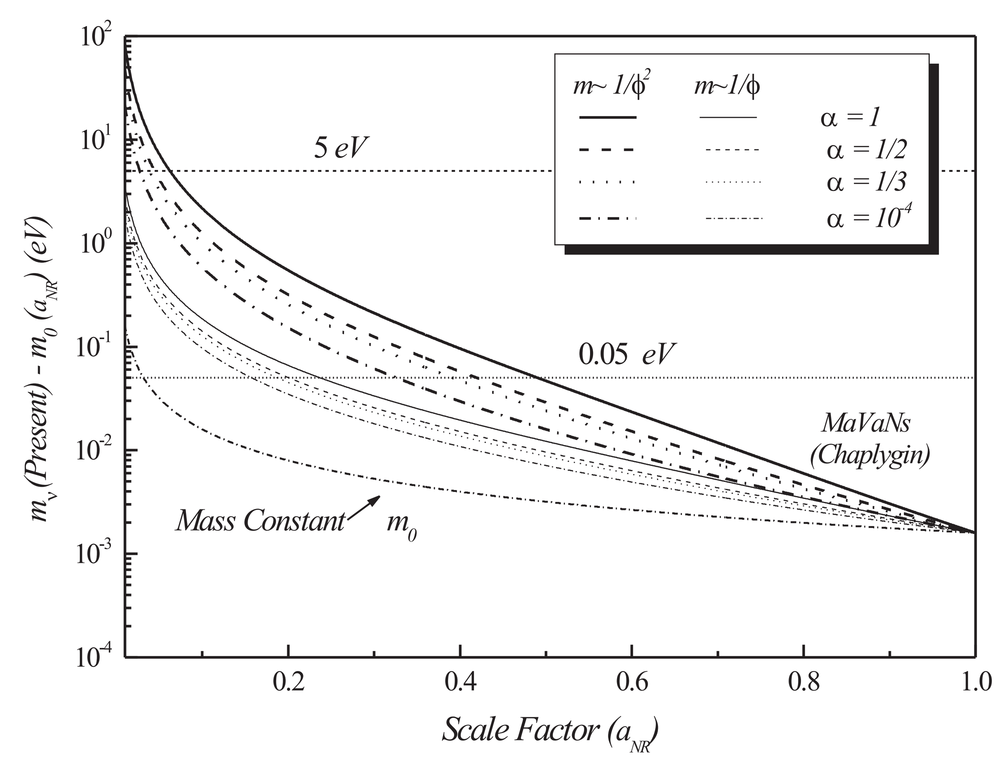

FIG.02: Present-day values of the neutrino mass m_0 and the corresponding values of a_{NR} for which the transition between the NR and UR regimes takes place.

By observing the model dependent conditions discussed above, namely the value of $a = a_{NR}$, and the present-day neutrino mass corresponding to the maximal value of the linear perturbation coefficient ϵ_{Max}, we can, for instance, set the phenomenologically acceptable values of $m_0 = 1\,eV$ and $m_0 = 0.1\,eV$, in order to perturbatively quantify the modifications to the energy density components of the coupled fluid.

Interestingly, for $m_0 = 1\,eV$, a fairly typical value, we can see in FIG.03 that stable MaVaN perturbations correspond, for the GCG case, to a well defined effective squared speed of sound speed

$$c_s^2 \simeq \frac{dp_\phi}{d(\rho_\phi + \rho_\nu)} > 0. \qquad (4)$$

The larger are the m_0 values, the larger are the corrections to the squared speed of sound, up to the limit where the perturbative approach cannot be applied.

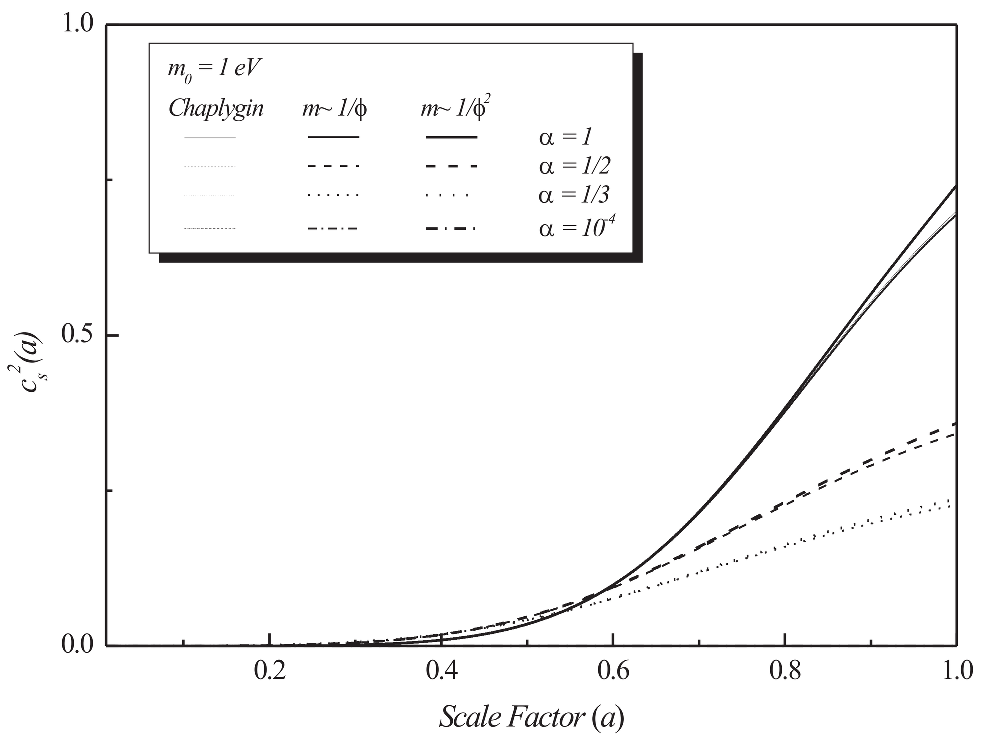

FIG.03: Perturbative modification on the square of the speed of sound $c^2_{s(a)}$.

Therefore, as far as the perturbative approach is valid, our model does not run into stability problems in the NR neutrino regime. In opposition, in the usual treatment where neutrinos are just coupled to dark energy, cosmic expansion together with the gravitational drag due to cold dark matter have a major impact on the stability of MaVaN models. Usually, for a general fluid for which we know the equation of state, the dominant effect on c_s^2 arises from the dark sector component and not by the neutrino component. For the models where the stationary condition (cf. Eq. (2)) implies a cosmological constant type equation of state, $p_\phi = -\rho_\phi$, one obtains $c_s^2 = -1$ from the very start of the analysis. For sure the situation cannot be fixed by the perturbative contribution of neutrinos. Our GCG-neutrino model is free from this inconsistency. **Acknowledgments** A. E. B. would like to thank the financial support from the CAPES (Brazilian Agency) grant 0174-08-4.

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