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# Mass Varying Neutrinos: a model-independent approach

Massimiliano Lattanzi [a] [b]

[a]Oxford Astrophysics, Denys Wilkinson Building, Keble Road, OX1 3RH, Oxford, UK

[b]Istituto Nazionale di Fisica Nucleare, Via Enrico Fermi, 40 - 00044 Frascati, Rome, Italy

In Mass Varying Neutrinos (MaVaNs) models, the neutrinos are coupled with the quintessence field supposed to be responsible for the acceleration of the Universe. Here we propose a new parameterization for the neutrino mass variation that is independent on the details of the scalar field potential and still captures the essential of most MaVaNs models. We also find an upper limit on the mass variation in the case of decreasing mass models, independent of the particular parameterization.

## 1. Introduction

Observations of the Cosmic Microwave Background (CMB) anisotropy [1–4], combined with measurements of the expansion rate of the Universe using type Ia supernovae [5,6], show that roughly 70% of the density of the Universe is in the form of a cosmological constant-like fluid dubbed Dark Energy (DE). The remaining 30% is in turn composed by an equally mysterious Dark Matter (DM) component (25% of the total) and by baryons (5% of the total).

Several models have been proposed trying to account for the existence of DE; among those, the so-called "quintessence" models [7] identify DE with a scalar field $\phi$. In these models the dark energy equation of state becomes a dynamical quantity and can then be different from the cosmological constant value $w = -1$, although many models can mimic this behaviour at late times. Usually, the scalar field is assumed to have only gravitational interaction with other particle species; however the idea of coupled dark energy has been considered, in particular with respect to its interaction with dark matter. Another possibility is that instead the dark energy couples to neutrinos, in the so-called Mass-Varying Neutrinos (MaVaNs) scenarios [8–11]. Neutrinos, being almost massless particles and interacting only weakly, could have cosmologically relevant couplings with quintessence. Moreover, although nowadays their contribution to the energy density of the universe is sub- dominant their number density is extremely high and they were very important in the early universe. In this sense, a possible coupling between them and the quintessence field could, at least in principle, strongly affect the cosmological model. Comparison between the prediction of the MaVaNs scenario and the cosmological observation have been made in the past, but they have assumed particular models for the interactions between the neutrinos and the dark sector [12–14].

Here we will instead discuss a model-independent approach to the MaVaNs scenario. The results of a more detailed analysis, including constraints resulting from cosmological observations, will be the subject of a forthcoming paper [15].

## 2. Model Independent Approach

In MaVaNs models, the energy densities $\rho_\nu$, $\rho_\phi$ of neutrinos and DE are coupled together. This has two important consequences: $\rho_\phi$ depends on the neutrino mass, and this in turn is no longer a fixed quantity but instead it depends on the neutrino number density $n_\nu$.

In the usual approach one gives a potential $V(\phi)$ for the scalar field and a mass-dependent neutrino mass term $m_\nu(\phi)$, and then is able to write down the coupled Klein-Gordon equation for the scalar field and fluid equation for the neutrinos, and work out their evolution. In this way

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one is focusing on one particular functional form of the potential and of the mass variation, thus assuming a particular model for the interaction between neutrinos and DE. Here we use a different approach, namely we choose to parameterize directly the $\nu$ mass variation. The goal is to study the cosmological consequences of MaVaNs scenarios in a more general way [15].

The fluid equations for neutrinos and DE read:

$$\dot{\rho}_\nu + 3\mathcal{H}\rho_\nu\left(1+w_\nu\right) = \frac{d\ln m_\nu}{du}\mathcal{H}\left(\rho_\nu - 3p_\nu\right), \quad (1)$$

$$\dot{\rho}_\phi + 3\mathcal{H}\rho_\phi\left(1+w_\phi\right) = -\frac{d\ln m_\nu}{du}\mathcal{H}\left(\rho_\nu - 3p_\nu\right), \quad (2)$$

where dots denote derivatives with respect to conformal time, $\mathcal{H} \equiv \dot{a}/a$, and $u \equiv \ln a$, $a$ being the cosmological scale factor. For the neutrino mass, we choose a parameterization of the form:

$$m_\nu = m_0 + (m_1 - m_0) \times \Gamma(u, u_{\rm NR}, \Delta)\ , \quad (3)$$

where $m_0$ and $m_1$ are the present and early value of the neutrino mass, respectively, and

$$\Gamma(u, u_{\rm NR}, \Delta) = \left[1 - \frac{1+e^{u_{\rm NR}/\Delta}}{1+e^{-[u\ (1+\Delta)-u_{\rm NR}]/\Delta}}\right]. \quad (4)$$

The quantity $\Delta$ is a parameter related to the number of e-folds that it takes to complete the transition from $m_1$ to $m_0$. The quantity $u_{\rm NR} = -\ln(1+z_{\rm NR})$ is related to the time where the transition starts; in all models, this happens when neutrinos become non-relativistic (hence the subscript NR), which corresponds approximately to $z_{\rm NR} \simeq 2\times 10^3 m_1/\mathrm{eV}$. Since $z_{\rm NR}$ is fixed by $m_1$, the number of independent parameters is actually three: $m_1$, $m_0$, $\Delta$. This parameterization captures the main features of MaVaNs scenarios, and allows to consider at the same time models in which the neutrino mass is either increasing ($m_1 < m_0$) or decreasing ($m_1 > m_0$) with time.

The latter class of models poses however a potential problem, especially in the case of fast ($\Delta \ll 1$) transition. This can be understood as follows. Starting from the present time, and going backwards, one arrives at the moment of the transition; taking this to be instantaneous, the neutrino density at this time will increase (going backwards) by an amount $\delta\rho_\nu \simeq (m_1 - m_0)n_\nu$. The DE density will decrease of the same amount, i.e. $\delta\rho_\phi = -\delta\rho_\nu$. The point here is that, if the transition happens early enough, $\rho_\nu \gg \rho_\phi$, and a small fractional change in the neutrino density could become a large fractional change in the DE change. In particular one could end up with $\delta\rho_\phi > \rho_\phi$, i.e., with a negative DE energy density. In other words, one finds that the energy transfer from neutrinos to DE is so large (from the DE "point of view") that the DE density should start from a negative value at early times in order not to overshoot its present value. Requiring this not to happen, gives the following condition for decreasing mass models:

$$\frac{m_1 - m_0}{m_0} \lesssim \frac{\Omega_\Lambda}{\Omega_\nu}\left[5\times 10^{-4}\left(\frac{m_1}{\mathrm{eV}}\right)^{-1}\right]^{-3w_\phi}, \quad (5)$$

where the dependence from $m_1$ inside the square brackets comes from the redshift of the transition $z_{\rm NR}$. It is worth noting that this result does not depend on the particular parameterization, as long as the transition is fast enough to be considered instantaneous.

Taking $m_1 \sim 1\,\mathrm{eV}$, and putting in the appropriate numbers for $\Omega_\Lambda$ and $\Omega_\nu$, one finds that $(m_1 - m_0)/m_0 \lesssim 10^{-3}$ for $w_\phi = -0.5$. However the dependence on $w_\phi$ is quite strong, since it appears as an exponent, then we get $(m_1 - m_0)/m_0 \lesssim 10^{-8}$ for a cosmological constant-like DE ($w_\phi = -1$). This limits are of course relaxed in the case of non-instantaneous transitions.

In order to quantify this more precisely, we have run Markov Chain Monte Carlo (MCMC) simulations of (mass decreasing) MaVaNs models. We have assigned zero likelihood to all models that have negative DE density at early times, and given a constant (=1) likelihood to all the others. The results are shown in Fig. 1. The results are as expected, i.e., larger values of $w$ allow for larger mass differences. Also larger values of $\Delta$ allow larger mass difference, although in this case the enlargement of the available parameter space is less dramatic than expected. We find that, in any case, the quantity $\mu \equiv (m_1 - m_0)/m_0$ is constrained to be $\ll 1$.

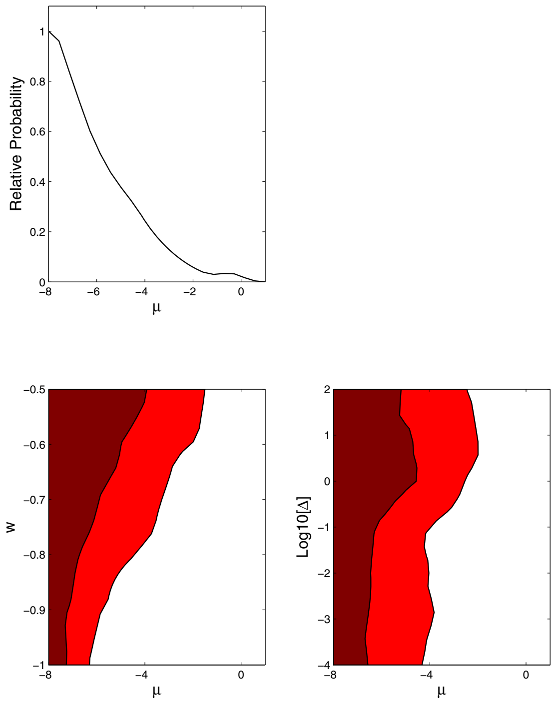


Figure 1. Probability distribution for the quantity $\mu \equiv (m_1 - m_0)/m_0$. The upper panel shows the 1D probability distribution. The lower panels show the 2D probability distribution in the $(\mu, w)$ (left) and $(\mu, \log_{10}\Delta)$ (right) planes. The dark (light) shaded regions is where 68% (95%) of the models is contained.

## 3. Future perspectives

We plan to compare the predictions of the MaVaNs scenario to the cosmological data, using the model-independent approach described above. This will allow to deal with a wider class of models instead of focusing on a particular model for the coupling between the neutrinos and the dark sector, and to obtain constraints directly on the mass variation instead than on the parameters of the underlying particle physics model.

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