Constraining Dark Energy with Neutrino Physics

A. de la Macorra

Instituto de Física, Universidad Nacional Aufonoma de México
Apdo. Postal 20-364, 01000 México D.F., México

Abstract.
We show that the particle properties of the Standard Model fields can determine the nature of Dark Energy. In particular, the mass of the neutrinos plays an important role in the determination of the equation of state w of Dark Energy. Using the Heidelberg-Moscow double beta decay experiment, which detects a large neutrino mass, we show that the impact of this measurement with the other cosmological data sets constrains the equation of state to $-1.67 < w < -1.05$ at 95% c.l., ruling out a cosmological constant at more than 95% c.l.. A $w < -1$ can be naturally obtained by coupling dark energy models with other particles such as neutrinos.

INTRODUCTION

Particle properties of the Standard Model fields can be relevant in determining the nature of Dark Energy "DE". In particular, it is not clear with present date set whether DE is a non dynamical cosmological constant or it is due to the dynamics of a particle. A cosmological constant, by definition, has $w \equiv -1$ and it does not interact with any particles, so any deviation from $w = -1$ or any DE interaction would ruled a cosmological constant out.

Here we use a combination of cosmological data sets [1] with the neutrino mass measurements from the Heidelberg-Moscow experiment ([2],[3], HM hereafter) to study the nature of dark energy. In particular a large mass for neutrinos, as suggested by the HM experiment constrains the equation of state to $-1.67 < w < -1.05$ at 95% c.l., ruling out a cosmological constant at more than 95% c.l.. Mass differences between neutrino mass eigenstates (m_1,m_2,m_3) have been measured in oscillation experiments [4]. Observations of atmospheric neutrinos suggest a squared mass difference of $\Delta m^2 \sim 3 \times 10^{-3} eV^2$ and solar neutrino observations, together with results from the KamLAND reactor neutrino experiment, point towards $\Delta m^2 \sim 5 \times 10^{-5} eV^2$. While only weak constraints on the absolute mass scale ($\Sigma m_\nu = m_1 + m_2 + m_3$) have been obtained from single β-decay experiments, double beta decay searches from the HM experiment have reported a signal for a neutrino mass at $> 4\sigma$ level [2], recently promoted to $> 6\sigma$ level by a pulse-shape analysis [3]. As we will see in the next section, this claim translates in a total neutrino mass of $\Sigma m_\nu > 1.2 eV$ at 95% c.l.. While this claim is still considered as controversial (see e.g. [5]), it should be noted that it comes from the most sensitive (^{76}Ge) detector to date and no independent experiment can, at the moment, falsify it.

Massive neutrinos can be extremely relevant for cosmology (see e.g. [4]) and leave key signatures in several cosmological data sets. More specifically, massive neutrinos suppress the growth of fluctuations on scales below the horizon when they become non relativistic. Current cosmological data, in the framework of a cosmological constant, are able to indirectly constrain the absolute neutrino mass to $\Sigma m_\nu < 0.75$ eV at 95% c.l. [1] and are in tension with the HM claim. However, as first noticed by [12], there is some form of anticorrelation between the equation of state parameter w and Σm_ν. The cosmological bound on neutrino masses can therefore be relaxed by using a DE component with a more negative value of w than a cosmological constant. As we show here, the HM claim is compatible with the cosmological data only if the equation of state (parameterized as constant) is $w < -1$ at 95%, ruling out a cosmological constant. A $w < -1$ can be naturally obtained by coupling dark energy models with other particles such as neutrinos.

ANALYSIS

The method we adopt is based on the publicly available Markov Chain Monte Carlo package `cosmomc` [10] with a convergence diagnostics done through the Gelman and Rubin statistic. We sample the following eight-dimensional set of cosmological parameters, adopting flat priors on them: the physical baryon, Cold Dark Matter and massive neutrinos densities, $\omega_b = \Omega_b h^2$, $\omega_c = \Omega_c h^2$ and $\Omega_\nu h^2$, the ratio of the sound horizon to the angular diameter distance at decoupling, θ_s, the scalar spectral index n_s, the overall normalization of the spectrum A at $k = 0.05$ Mpc^{-1}, the optical depth to reionization, τ, and, finally, the DE equation of state parameter w. Furthermore, we consider purely adiabatic initial conditions and we impose flatness.

We include the three-year WMAP data [1] (temperature and polarization) with the routine for computing the likelihood supplied by the WMAP team. Together with the WMAP data we also consider the small-scale CMB measurements of CBI [13], VSA [14], ACBAR [15] and BOOMERANG-2k2 [16]. In addition to the CMB data, we include the constraints on the real-space power spectrum of galaxies from the SLOAN galaxy redshift survey (SDSS) [17] and 2dF [18], and the Supernovae Legacy Survey data from [19] and the Heidelberg-Moscow as in the recent analysis of [20].

Let us just remind that the $0\nu2\beta$ decay half-life $T^{0\nu}_{1/2}$ is linked to the effective Majorana mass $m_{\beta\beta}$ by the relation $m^2_{\beta\beta} = m^2_e / C_{mm} T^{0\nu}_{1/2}$, in the assumption that the $0\nu2\beta$ process proceeds *only* through light Majorana neutrinos and where the nuclear matrix element C_{mm} needs to be theoretically evaluated. Using the theoretical input for $C_{mm}(^{76}\mathrm{Ge})$ from Ref. [21], the $0\nu2\beta$ claim of [2] is transformed in the 2σ range

$$\log_{10}(m_{\beta\beta}/\mathrm{eV}) = -0.23 \pm 0.14\ , \tag{1}$$

i.e., $0.43 < m_{\beta\beta} < 0.81$ (at 2σ, in eV). Considering all current oscillation data (see [20]) and under the assumption of a 3 flavor neutrino mixing the above constraint yields:

$$0.0137 < \Omega_\nu h^2 < 0.026 \tag{2}$$

at 95% c.l. where we used the well known relation: $\Omega_\nu h^2 = \Sigma m_\nu / 93.2eV$. Our main results are plotted in Fig.1 where we show the constraints on the $w - \Sigma m_\nu$ plane in two cases, with and without the HM prior on neutrino masses. As we can see, without the

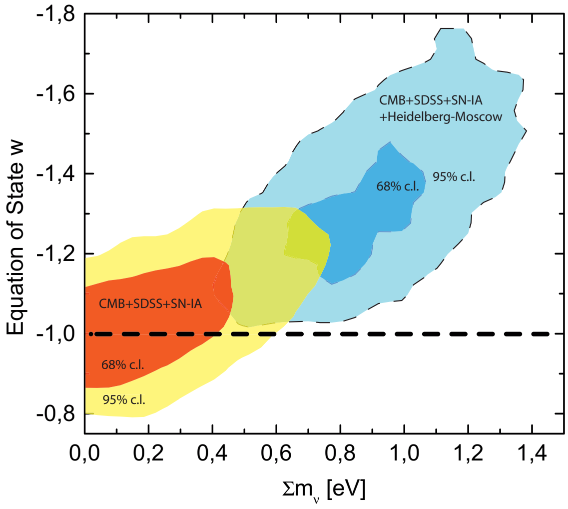

FIGURE 1. Constraints on the $w-\Sigma$ plane in two cases with and without the Heidelberg-Moscow prior on neutrino masses.

HM prior we are able to reproduce the results already presented in the literature (see e.g. [1]), namely current cosmological data constrain neutrino masses to be $\Sigma m_\nu < 0.75\, eV$. However an interesting anti-correlation is present between the DE parameter w and the neutrino masses and larger neutrino masses are in better agreement with the data for more negative values of w. It is therefore clear that when we add the HM prior ($\Sigma m_\nu \sim 1.8 \pm 0.6\, eV$ at 95% c.l., again see Fig.1) the contours are shifted towards higher values of neutrino masses and towards lower values of w. A combined analysis of cosmological data with the HM priors gives $-1.67 < w < -1.05$ and $0.66 < \Sigma m_\nu < 1.11$ (in eV) at 95% c.l. excluding the case of the cosmological constant at more than 2σ with $\Sigma m_\nu = 0.85\, eV$, $w = -1.31$ and $\Omega_m = 0.35$ as best fit values. Without the HM prior the data gives $-0.92 < w < -1.28$ and $\Sigma m_\nu < 0.73\, eV$ again at 95% c.l. with $w = -1.02$, $\Sigma m_\nu = 0.05\, eV$ and $\Omega_m = 0.29$ as best fit values.

The inclusion of the HM prior affects also other parameters. We found, at 95% c.l.: $0.916 < n_s < 0.979$ ($0.926 < n_s < 0.989$ withouth HM), $0.0209 < \Omega_b h^2 < 0.0235$ ($0.0211 < \Omega_b h^2 < 0.0238$ without HM), $0.302 < \Omega_m < 0.444$ ($0.262 < \Omega_m < 0.360$ without HM). It is interesting to notice that the inclusion of massive neutrinos seems to further rule out the scale-invariant $n_s = 1$ model.

INTERACTING DARK ENERGY

An interesting result of the interaction between dark energy with other particles is to change the apparent equation of state of dark energy [6],[7],[8]. An observer that supposes that DE has no interaction sees a different evolution of DE as an observer that takes into account for the interaction between DE and another fluid. This effect allows to have an apparent equation of state $w < -1$ for the “non-interaction" DE [7] even though the true equation of state of DE is larger than -1. As we have seen, the combination of a neutrino mass $\Sigma m_\nu \simeq 0.85\,eV$ and the cosmological observations indicate that the equation of state of DE w is less than -1, excluding a cosmological constant. Scalar fields with positive kinetic energy have $w > -1$ while phantom fields [11] can have $w < -1$ but they have a negative kinetic energy and many fundamental theoretical problems.

Let us define the energy density and pressure of the scalar field as $\rho_\phi = \frac{1}{2}\dot{\phi}^2 + V(\phi)$, $p_\phi = \frac{1}{2}\dot{\phi}^2 - V(\phi)$ and the equation of state parameter $w_\phi = p_\phi/\rho_\phi$, where the potential $V(\phi)$ does not include the interaction with dark matter. If there is no interaction between DE and dark matter, w_ϕ gives the complete evolution of DE and $w > -1$. We now include an interaction term between dark matter (or neutrinos) with ϕ via the function $f(\phi)$ which gives an interacting dark matter energy density [22]

$$\rho_{IM} = \rho_{IMo}\frac{f(\phi)}{f_o}\frac{1}{a^3} \tag{3}$$

where $f_o \equiv f(\phi_o)$ and $a_o = 1$ at present time. In this case dark matter no longer redshifts as a^{-3} since the evolution of $f(\phi)$ will also contribute to the redshift. The evolution of ρ_{IM} and ϕ are given by

$$\begin{aligned} \dot{\rho}_{IM} + 3H(\rho_{IM} + p_{DM}) &= \frac{\rho_{IMo}}{a^3}\frac{f'}{f_o}\,\dot{\phi} \qquad (4)\\ \ddot{\phi} + 3H\dot{\phi} + V' &= -\frac{\rho_{IMo}}{a^3}\frac{f'}{f_o} \qquad (5) \end{aligned}$$

where the prime denotes derivative w.r.t. ϕ, i.e. $V' \equiv dV/d\phi$, $f' \equiv df/d\phi$. The total dark matter does not need to coincide with ρ_{IM}. This would be the case if we want to interpret ρ_{IM} as the energy density of neutrinos since we know that they cannot give the total amount of dark matter. However, since neutrinos are massive they certainly contribute to dark matter. The apparent equation of state, i.e. the equation of state of DE if we had assume that there was no interaction, is [6]

$$w_{ap} = \frac{w_\phi}{1-x}, \qquad x = -\frac{\rho_{IMo}}{\rho_\phi\, a^3}\left(\frac{f(\phi)}{f_o} - 1\right). \tag{6}$$

In this case the noninteracting DE and dark matter observer sees a standard evolution, $\dot{\rho}_m = -3H\rho_m$ and $\dot{\rho}_{DE} = -3H\rho_{DE}(1+w_{ap})$. We see from eq.(6) that for $f < fo$ we have $x > 0$ and $w_{ap} < w_\phi$, which allows to have a w_{ap} less than -1. The effect of an apparent w_{ap} less than -1 has a stronger effect on small redshifts when the DE dominates. This effect is measured by the SNIa and the actual values for the redshifts of these supernovae are mostly in the range $0 < z < 1.2$. So, let us expand the function $f(\phi(a))$ as a function of the scale factor around $a_o = 1$, $f(\phi) = f_o + \left(\frac{df}{d\phi}\frac{d\phi}{da}\right)|_{a_o}(a-1) + \ldots$. For generality and presentation purposes we assume that the scalar field is already tracking, i.e. we take w_ϕ constant, and then the energy density is given by $\rho_\phi = \rho_{\phi o}a^{-3(1+w_\phi)} = (2/(1-w_\phi))V(\phi)$, where we have used that the kinetic energy can be expressed as

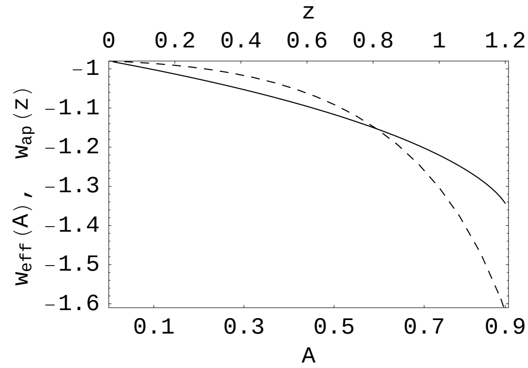

FIGURE 2. We show w_{ap} as a function of z (dashed line) and w_{eff} as a function of $A \equiv -\Omega_{IMo}\lambda_{IM}/\lambda_\phi$ (solid line) with integration limits $0 \leq z \leq 1.2$ for $\Omega_{\phi o} = 0.65$, $w_\phi = -0.98$.

$E_k = (1+w_\phi)/(1-w_\phi)V$ and x in eq.(6) can be expressed as [9]

$$x = 3A \left(\frac{1+w_\phi}{\Omega_{\phi o}}\right) \frac{z}{(1+z)^{3w_\phi}} \tag{7}$$

with z=1/a-1, $A \equiv -\Omega_{IMo}\lambda_{IM}/\lambda_\phi$ and $\lambda_{IM} \equiv f_o'/f_o$, $\lambda_\phi \equiv V_o'/V_o$. A positive x requires $A > 0$. The evolution of w_{ap} and x depends on z only via the term $z/(1+z)^{3w_\phi}$ in eq.(7) and once w_ϕ and $\Omega_{\phi o}$ are fixed the value of w_{ap} is determined by the present day values of $\Omega_{IMo}, f_o, V_o, f_0', V_o'$ only through A. We use a weighted average equation of state to compare the models with the observational data, since w_{ap} is a function of z, defined by

$$w_{eff} = \frac{\int w_{ap}\Omega_{DE}\, dz}{\int \Omega_{DE}\, dz} \tag{8}$$

where the integral runs from $z = 0$ to $z = 1.2$. The effective w_{eff} is then a function of $\Omega_{\phi o}$, w_ϕ and A. We show in Fig.(2) the evolution of w_{ap} as a function of z (dashed line) for $\Omega_{\phi o} = 0.65, A = 0.35$ (i.e. $\Omega_{IMo} = 0.35$ if $\lambda_{IM}/\lambda_\phi = -1$), $w_\phi = -0.98$. We see that w_{ap} decreases with increasing z and becomes less than -1 at $z = 0.3$ and it is $w_{ap} = -1.6$ at $z = 1.2$. We also show in Fig.(2) the behavior of w_{eff} as a function of A (solid line) with the same parameters $\Omega_{\phi o} = 0.65$, $w_\phi = -0.98$. With increasing values of A, w_{eff} becomes more negative and for $A = 0.1$ we find $w_{eff} = -1$ and at $A = 0.84$ we have $w_{eff} = -1.3$ as required by the cosmological plus HM data. Finally, if we assume that the interacting matter is only due to neutrinos with the total amount of neutrinos today given by the central values of the CMB plus HM analysis $\Sigma m_\nu = 0.85\, eV$ then $\Omega_{IMo}h^2 = \Omega_\nu h^2 = 0.009$ and $\lambda_{IM}/\lambda_\phi = -40$ for $w_{eff} = -1.3$.

We have seen in a model independent study that using interacting DE it is possible to obtain w_{eff} less than -1, consistent with the values given by the cosmological data plus HM. Future high-z baryon acoustic oscillation and high-z supernovae surveys should provide a powerful mechanism to look for such deviations from $w \equiv -1$.

CONCLUSIONS

We have studied in this *letter* the cosmological implications of a large neutrino mass, as suggested by the controversial Heidelberg-Moscow result. We have found that a scenario based on a cosmological constant is unable to provide a good fit to current data when a massive neutrino component as large as suggested by HM is included in the analysis. A better fit to the data is obtained when the DE component is described with an equation of state $w \sim -1.3$, with $w < -1$ at more than 95% c.l.. As far as we know, this is the only data set able to exclude a cosmological constant at such high significance.

There exists, therefore, a significant tension between the indirect, observational measurements leading to the LCDM scenario and the direct HM observations. Rather than implying one should rule out evidence from the direct measurements purely on the basis of disparity with the indirect observations, this tension suggests we should keep our minds open to alternative dark energy scenarios beyond a cosmological constant. This, together with the fact that the energy scale of DE ($\mathscr{O}(10^{-3})$ eV) is of the order of the neutrino mass scale, may suggest for a link between neutrino physics and DE that must certainly be further investigated. We show that interacting Dark Energy can account naturally for an apparent equation of state $w < -1$.

Future determination of the absolute neutrino mass scale will therefore not only bring relevant information for neutrino physics but may be extremely important in the determination of the dark energy properties and in shedding light on a possible neutrino-dark energy connection.

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REFERENCES

1. D. N. Spergel *et al.*, astro-ph/0603449.
2. H.V. Klapdor-Kleingrothaus, I.V. Krivosheina, A. Dietz, and O. Chkvorets, Phys. Lett. B **586**, 198 (2004).
3. H.V. Klapdor-Kleingrothaus, talk at *SNOW 2006*, 2nd Scandinavian Neutrino Workshop (Stockholm, Sweden, 2006).
4. J. Lesgourgues and S. Pastor, Phys. Rept. **429**, 307 (2006)
5. S.R. Elliott and J. Engel, J. Phys. G **30**, R183 (2004).
6. D. B. Kaplan, A. E. Nelson and N. Weiner, Phys. Rev. Lett. **93**, 091801 (2004) [arXiv:hep-ph/0401099]; R. D. Peccei, Phys. Rev. D **71**, 023527 (2005) [arXiv:hep-ph/0411137]; A. W. Brookfield, C. van de Bruck, D. F. Mota and D. Tocchini-Valentini, Phys.Rev.D **73** (2006) 083515.
7. S. Das, P. S. Corasaniti and J. Khoury,Phys. Rev. D 73, 083509 (2006)
8. A. de la Macorra, Astropart. Phys. **28**, 196 (2007) [arXiv:astro-ph/0702239]; A. de la Macorra, Phys. Rev. D **76**, 027301 (2007) [arXiv:astro-ph/0701635]
9. A. De La Macorra, A. Melchiorri, P. Serra and R. Bean, Astropart. Phys. **27**, 406 (2007) [arXiv:astro-ph/0608351]
10. A.Lewis and S.Bridle, Phys.Rev.D **66**, 103511 (2002)
11. S. M. Carroll, M. Hoffman and M. Trodden, Phys. Rev. D **68**, 023509 (2003).
12. S. Hannestad, Phys. Rev. Lett. **95** (2005) 221301.

13. A. C. S. Readhead *et al.*, ApJ **609**, 498 (2004).
14. C. Dickinson *et al.*, MNRAS **353**, 732 (2004).
15. C. L. Kuo *et al.*, American Astronomical Society Meeting, Vol. **201** (2002).
16. C. J. MacTavish *et al.*, astro-ph/0507503.
17. M. Tegmark *et al.*, ApJ **606**, 702 (2004).
18. S. Cole *et al.*, MNRAS **362**, 505 (2005).
19. P. Astier *et al.*, A&A **447**, 31 (2006).
20. G. L. Fogli *et al.*, hep-ph/0608060.
21. V. A. Rodin, A. Faessler, F. Simkovic and P. Vogel, Nucl. Phys. A **766**, 107 (2006).
22. L. Amendola, Phys. Rev. D **62**, 043511 (2000) [arXiv:astro-ph/9908023].
23. See talks by P. Doe and F. Glück at *Neutrino 2006*.