The impact of neutrino masses on the determination of dark energy properties

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Recently, the Heidelberg-Moscow double beta decay experiment has claimed a detection for a neutrino mass with high significance. Here we consider the impact of this measurement on the determination of the dark energy equation of state. By combining the Heidelberg-Moscow result with the WMAP 3-years data and other cosmological datasets we constrain 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..

Interestingly enough, coupled neutrino-dark energy models may be consistent with such equation of state. While future data are certainly needed for a confirmation of the controversial Heidelberg-Moscow claim, our result shows that future laboratory searches for neutrino masses may play a crucial role in the determination of the dark energy properties.

The recent results of precision cosmology and the measurements of Cosmic Microwave Background (CMB) anisotropies are in excellent agreement with the standard model of structure formation (see e.g. \cite{1}). The price-tag of this success story is a very puzzling consequence: the evolution of the universe is dominated by a mysterious form of energy, coined dark energy "DE" (an unclustered negative pressure component of the mass-energy density) with a present-day energy density fraction $\Omega_{DE} \approx 2/3$ and equation of state $w \sim -1$. \cite{1}, \cite{2}. This discovery may turn out to be one of the most important contribution to physics in our generation.

Up to now, most data analysis have found a dark energy scenario consistent with a true cosmological constant $\Lambda$, with $w = -1$. However, the nature of dark matter and dark energy remains an enigma, and we are entering an era when their origins might be better understood not only through precision indirect (observational) evidence from cosmological measurements but also, crucially, through direct ground based measurements of particles within and beyond the Standard model. In this letter we discuss such a combination of data looking at what can be learned about the possible interactions between neutrinos and dark energy from combining cosmological observations with the neutrino mass measurements from the Heidelberg-Moscow experiment (\cite{3}, \cite{4}, \cite{5} hereafter).

Let us recall that in the past years mass differences between neutrino mass eigenstates ($m_1,m_2,m_3$) have been measured in oscillation experiments \cite{6}. Observations of atmospheric neutrinos suggest a squared mass difference of $\Delta m^2 \sim 3 \times 10^{-3}\text{eV}^2$ and solar neutrino observations, together with results from the KamLAND reactor neutrino experiment, point towards $\Delta m^2 \sim 5 \times 10^{-5}\text{eV}^2$. While only weak constraints on the absolute mass scale ($\Sigma m_\nu = m_1 + m_2 + m_3$) have been obtained from single $\beta$-decay experiments, double beta decay searches from the HM experiment have reported a signal for a neutrino mass at $> 4\sigma$ level \cite{3}, recently promoted to $> 6\sigma$ level by a pulse-shape analysis \cite{4}. As we will see in the next section, this claim translates in a total neutrino mass of $\Sigma m_\nu > 1.2\text{eV}$ at 95% c.l.. While this claim is still considered as controversial (see e.g. \cite{6}), it should be noted that it comes from the most sensitive ($^{76}\text{Ge}$) detector to date and no independent experiment can, at the moment, falsify it.

As very well known in the literature (see e.g. \cite{6}) massive neutrinos can be extremely relevant for cosmology 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 $\Sigma m_\nu < 0.75 \text{eV}$ at 95% c.l. \cite{1} and are in tension with the HM claim. However, as first noticed by \cite{3}, there is some form of anticorrelation between the equation of state parameter $w$ and $\Sigma m_\nu$. 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%.

While the HM claim must certainly verified by future experiments there are several theoretical motivations that one should consider before discarding the result as simply due to unaccounted systematics. In the past years, indeed, the interesting idea of a possible link between neutrinos and DE has been proposed \cite{7}. The main motivation for this connection relies on the fact that the energy scale of DE ($O(10^{-3}) \text{eV}$) is of the order of the neutrino mass scale. Interestingly enough, coupled neutrino-DE models \cite{7} predict...
in general an effective equation of state (averaged over
redshift) \( w_{eff} < -1 \). Our result may therefore be the
consequence of a deeper connection between DE and
neutrino physics.

The method we adopt is based on the publicly
available Markov Chain Monte Carlo package cosmomc
\[3\] with a convergence diagnostics done through
the Gelman and Rubin statistic. We sample the follow-
ing 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 \( \Omega_v h^2 \), the ratio of the
sound horizon to the angular diameter distance at
decoupling, \( \theta_s \), the scalar spectral index \( n_s \), the overall
normalization of the spectrum \( A \) at \( k = 0.05 \) Mpc\(^{-1}\),
the optical depth to reionization, \( \tau \), and, finally, the
DE equation of state parameter \( w \). Furthermore, we
consider purely adiabatic initial conditions and we im-
pose flatness.

We include the three-year WMAP data \[1\] (tem-
perature and polarization) with the routine for com-
puting the likelihood supplied by the WMAP team.
Together with the WMAP data we also consider the
small-scale CMB measurements of CBI \[11\], VSA \[12\],
ACBAR \[13\] and BOOMERANG-2k2 \[14\]. 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) \[15\] and 2dF
\[16\], and the Supernovae Legacy Survey data from
\[17\]. Finally, we include the Heidelberg-Moscow as in
the recent analysis of \[18\].

Let us just remind that the 0\( \nu \)\( \beta \) decay half-life \( T^{\nu\beta}_{1/2} \) is
linked to the effective Majorana mass \( m_{\beta\beta} \) by the
relation \( m_{\beta\beta}^2 = m_c^2/C_{mm} T^{\nu\beta}_{1/2} \), in the assumption that
the 0\( \nu \)\( \beta \) process proceeds only through light Majo-
rana neutrinos and where the nuclear matrix element
\( C_{mm} \) needs to be theoretically evaluated. Using the
theoretical input for \( C_{mm} (76 \text{GeV}) \) from Ref. \[19\], the
0\( \nu \)\( \beta \) claim of \[18\] is transformed in the 2\( \sigma \) range
\[
\log_{10}(m_{\beta\beta}/\text{eV}) = -0.23 \pm 0.14 ,
\]
i.e., \( 0.43 < m_{\beta\beta} < 0.81 \) (at 2\( \sigma \), in eV).

Considering all current oscillation data (see \[18\])
and under the assumption of a 3 flavor neutrino mix-
ing the above constraint yields:

\[
0.0137 < \Omega_\nu h^2 < 0.26
\]
at 95\% c.l. where we used the well known relation:
\( \Omega_\nu h^2 = \Sigma_\nu /93.2 eV \).

Our main results are plotted in Fig.1 where we show
the constraints on the \( w - \Sigma_\nu \) plane in two cases,
with and without the HM prior on neutrino masses.
As we can see, without the HM prior we are able to re-
produce the results already presented in the literature
(see e.g. \[1\]), namely current cosmological data con-
strain neutrino masses to be \( \Sigma_\nu < 0.75 \) eV. However
an interesting anti-correlation is present between the
DE parameter \( w \) and the neutrino masses and larger

![Figure 1](image_url)

**FIG. 1:** Constraints on the \( w - \Sigma \) plane in two cases
with and without the Heidelberg-Moscow prior on neu-
trino masses.
evolution of DE as an observer that takes into account for the interaction of DE. This effect allows to have an apparent equation of state \( w < -1 \) for the “non-interaction” DE observer even though the true equation of state of the DE is larger than -1.

To see this more clearly let us define the energy density and pressure of the scalar field as \( \rho_\phi = \frac{1}{2} \dot{\phi}^2 + V(\phi) \) and the equation of state parameter \( w_\phi = \rho_\phi / \rho_\phi \), where the potential \( V(\phi) \) does not include the interaction with dark matter. If there is no interaction between DE and dark matter, \( w_\phi \) gives the complete evolution of DE and \( w > -1 \). We now include an interaction term between dark matter (or neutrinos) with \( \phi \) via the function \( f(\phi) \) which gives an interacting dark matter energy density \([20] \)

\[
\rho_{1M} = \rho_{1Mo} f(\phi) \frac{1}{f_o} \end{matrix} \tag{3}
\]

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 \( \rho_{1M} \) and \( \phi \) are given by

\[
\dot{\rho}_{1M} + 3H(\rho_{1M} + p_{DM}) = \frac{\rho_{1Mo} f'}{f_o} \dot{\phi} \end{matrix} \tag{4}
\]

\[
\ddot{\phi} + 3H \dot{\phi} + V' = -\frac{\rho_{1Mo} f'}{f_o} \end{matrix} \tag{5}
\]

where the prime denotes derivative w.r.t. \( \phi \), i.e. \( V' \equiv dV/d\phi \), \( f' \equiv df/d\phi \). The total dark matter does not need to coincide with \( \rho_{1M} \). This would be the case if we want to interpret \( \rho_{1M} \) 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.

It was pointed out in [2] that the apparent equation of state, i.e. the equation of state of DE if we had assumed that there was no interaction, is

\[
w_{ap} = \frac{w_\phi}{1-x}, \quad x = -\frac{\rho_{1Mo}}{\rho_\phi a_o^3} \left( \frac{f(\phi)}{f_o} - 1 \right). \tag{6}
\]

In this case the noninteracting DE and dark matter observer sees a standard evolution, \( \rho_m = -3H \rho_m \) and \( \dot{\rho}_{DE} = -3H \rho_{DE}(1 + w_{ap}) \). We see from eq. (6) that for \( f < f_o \) 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 as 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 \( a_o = 1 \),

\[
f(\phi) = f_o + \left( \frac{df}{d\phi} \right) \frac{d\phi}{da} \big|_{a_o} (a - 1) + \ldots \tag{7}
\]

For generality and presentation purposes we assume that the scalar field is already tracking, i.e. we take \( w_\phi \) constant, and then the energy density is given by

\[
\rho_\phi = \rho_{\phi o} a^{-3(1+w_\phi)} = \frac{2}{(1-w_\phi)} V(\phi), \quad \text{where we have used that the kinetic energy can be expressed as}
\]

\[
E_k = (1+w_\phi)/(1-w_\phi) V. \quad \text{Taking the derivative of} \rho_\phi \text{w.r.t.} \ a \text{we can relate} \ d\phi/da \text{to the potential} V, \ d\phi/da = -3(1+w_\phi)V/(aV'). \text{Using this expression of} \ d\phi/da, \rho_\phi \text{as a function of} a \text{and eq. (7), we can write} \ x \text{in eq. (6), in terms of redshift} z = 1/a - 1, \text{as}
\]

\[
x = 3 A \left( \frac{1 + w_\phi}{\Omega_{\phi o}} \right) \frac{z}{(1+z)^{3w_\phi}} \tag{8}
\]

where we have defined \( A \equiv -\Omega_{M o} \lambda_{M o} / \lambda_\phi \) with \( \lambda_{M o} \equiv f_o'/f_o, \lambda_\phi \equiv V_o'/V_o \). A positive \( x \) requires \( A > 0 \). Notice that the evolution of \( w_{ap} \) and \( x \) depends on \( z \) only via the term \( z/(1+z)^{3w_\phi} \) in eq. (8) and once \( w_\phi \) and \( \Omega_{\phi o} \) are fixed the value of \( w_{ap} \) is determined by the present day values of \( \Omega_{M o}, f_o, V_o, f_o', V_o' \) only through \( A \).

Since \( w_{ap} \) is a function of \( z \) it is better to use the weighted average equation of state to compare the models with the observational data. The average equation of state is defined by

\[
w_{eff} = \frac{\int w_{ap} \Omega_{DE} \ dz}{\int \Omega_{DE} \ dz} \tag{9}
\]

where the integral runs from \( z = 0 \) to \( z = 1.2 \). The effective \( w_{eff} \) is then a function of \( \Omega_{\phi o}, w_\phi \) and \( A \).

We show in Fig. 1 the evolution of \( w_{ap} \) as a function of \( z \) (dashed line) for \( \Omega_{\phi o} = 0.65, A = 0.35 \) (i.e. \( \Omega_{M o} = 0.35 \) if \( \lambda_{M o} / \lambda_\phi = -1 \), \( w_\phi = -0.98 \). 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. 1 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 \( \Omega_{M o} h^2 = \Omega_{\nu} h^2 = 0.009 \) and \( \lambda_{M o} / \lambda_\phi = -40 \) 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 surveys, in tandem with high-z supernova surveys should provide a powerful mechanism to look for such deviations from \( w = -1 \).

To summarize and conclude, we have considered in this letter the cosmological implications of 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
FIG. 2: We show $w_{\nu}$ as a function of $z$ (dashed line) and $w_{\nu,\text{eff}}$ as a function of $A \equiv -\Omega_{\Lambda}\lambda_{\text{IM}}/\lambda_{0}$ (solid line) with integration limits $0 \leq z \leq 1.2$ for $\Omega_{\phi} = 0.65$, $w_{\phi} = -0.98$.

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 dataset 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 ($\mathcal{O}(10^{-3})$ 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. Systematics can be present in the HM data and a more conservative treatment (see [3]) would lead to a better agreement with a cosmological constant. However, phantom models with $w < -1$ would still provide a better fit to the data.

On the other hand, using a more conservative approach towards cosmology, by, for example, combining HM only with the CMB dataset, would provide even larger values of $\Sigma m_{\nu}$ and more negative values for $w$. Recent combined analysis with Lyman-$\alpha$ forest data ([2,15]) imply tight constraints on neutrino masses ($\Sigma m_{\nu} < 0.2\text{eV}$), seemingly at discord with the HM result, and also in some tension with CMB data alone. Future larger scale Lyman-$\alpha$ surveys and refinements in the analysis, addressing systematic uncertainties and sensitivity to modeling assumptions, will allow a better assessment of how these tensions will be resolved.

If the HM result is correct, a signal in the range $m_{\nu} \sim \text{few} \times 10^{-1}$ eV is clearly expected, and could be found in the next-generation Karksruhe Tritium Neutrino Experiment (KATRIN) [21], which should take data in the next decade, with an estimated sensitivity down to $\sim 0.2$ eV. Cosmological data will also reach a 2$\sigma$ accuracy of about $\sim 0.1$ eV on $\Sigma m_{\nu}$ in the future [4] mostly thanks to Planck satellite CMB experiment expected to launch in 2008, and future precision high-$z$ supernovae and baryon satellite CMB surveys.

A 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. Future direct particle detection and indirect astronomical experiments will scrutinize this interesting hypothesis.

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