Massive neutrinos and dark energy

Paolo Serra,\textsuperscript{a} Rachel Bean\textsuperscript{b}, Axel De La Macorra\textsuperscript{c}, Alessandro Melchiorri\textsuperscript{a}

\textsuperscript{a}Physics Department, University of Rome “La Sapienza” and INFN - Sezione di Roma
\textsuperscript{b}Dept. of Astronomy, Cornell University, Ithaca, NY 14853
\textsuperscript{c}Instituto de Física, UNAM, Apdo. Postal 20-364, 01000 México D.F., México

We consider the impact of the Heidelberg-Moscow claim for a detection of neutrino mass 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., 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.

1. Introduction

As very well known in the literature massive neutrinos can be extremely relevant for cosmology and leave key signatures in several cosmological data sets. 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.\cite{1} and are in tension with the Heidelberg-Moscow claim (HM hereafter). In fact, double beta decay searches from the HM experiment have reported a signal for a neutrino mass at $> 4\sigma$ level\cite{2}, recently promoted to $> 6\sigma$ level by a pulse-shape analysis\cite{3}. 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.\cite{4}), 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.

However, as first noticed by\cite{5}, 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\%.

2. Method

The method we adopt is based on the publicly available Markov Chain Monte Carlo package \texttt{cosmomc} \cite{8} 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, $\theta_s$, 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 impose flatness.

We include the three-year WMAP data\cite{11} (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\cite{10}, VSA\cite{11}, ACBAR\cite{12} and BOOMERANG-2k2\cite{13}. 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)\cite{14} and 2dF\cite{15}, and the Supernovae Legacy Survey data from
Finally, we include the Heidelberg-Moscow as in the recent analysis of [17]. Fore a more detailed description of the analysis see [18].

Using the theoretical input for $C_{mm}(^{76}\text{Ge})$ from Ref. [19], the $0\nu2\beta$ claim of [2] 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 [17]) and under the assumption of a 3 flavor neutrino mixing the above constraint yields:

$$0.0137 < \Omega_\nu h^2 < 0.026$$

at 95% c.l. where we used the well known relation: $\Omega_\nu h^2 = \Sigma m_\nu/93.2 \text{eV}$.

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 HM prior we are able to reproduce the results already presented in the literature (see e.g. [4]), namely current cosmological data constrain neutrino masses to be $\Sigma m_\nu < 0.75 \text{eV}$. 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 ($\Sigma m_\nu \sim 1.8 \pm 0.6 \text{eV}$ 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 $2\sigma$ with $\Sigma m_\nu = 0.85 \text{eV}$, $w = -1.31$ and $\Omega_m = 0.35$ as best fit values. Without the HM prior the data gives $-1.28 < w < -0.92$ and $\Sigma m_\nu < 0.73 \text{eV}$ again at 95% c.l. with $w = -1.02$, $\Sigma m_\nu = 0.05 \text{eV}$ 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 < $n_s < 0.989$ without 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. From a theoretical point of view, there are several possibilities for an equation of state of dark energy less than $-1$. Scalar fields with positive kinetic energy have $w > -1$ while phantom fields [9] can have $w < -1$ but they have a negative kinetic energy and many fundamental theoretical problems. Another possibility is to follow the approach of interacting DE [7]-[18]. Interacting DE are models where the dark energy interacts with other particles, as for example dark matter or neutrinos. In fact, the energy scale of DE ($\mathcal{O}(10^{-3}) \text{eV}$) is of the order of the neutrino mass scale and this may suggest for a link between neutrino physics and DE that must certainly be further investigated. In particular, the net effect of this interaction is to change the apparent equation of state of DE[7].

3. Conclusions

We have considered the cosmological implications of the controversial HMresult. 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 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.

Systematics can be present in the HM data and a more conservative treatment (see [2]) 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 ([6,17]) imply tight constraints on neutrino masses \(\Sigma m_{\nu} < 0.2\) 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.

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.

**ACKNOWLEDGMENTS**

It is a pleasure to thank the organizers of the NOW 2006 conference for a beautiful and stimulating workshop.

**REFERENCES**

1. D. N. Spergel et al., Arxiv: astro-ph/0603449 (2006).
2. H. V. Klapdor-Kleingrothaus et al. Phys. Lett. B 586 (2004) 198.
3. H. V. Klapdor-Kleingrothaus, talk at SNOW 2006, 2nd Scandinavian Neutrino Workshop (Stockholm, Sweden, (2006)).
4. S.R. Elliott and J. Engel, J. Phys. G 30 (2004) R183.
5. S. Hannestad, Phys. Rev. Lett. 95 (2005) 221301.
6. U. Seljak, A. Slosar and P. McDonald, Arxiv: astro-ph/0603335 (2006).
7. W. Zimdahl and D. Pavon, Phys. Lett. B 521 (2001), 133; D. B. Kaplan et al. Phys. Rev. Lett. 93 (2004) 091801; R. D. Peccei, Phys. Rev. D 71 (2005) 023527; S. Das, P. S. Corasaniti and J. Khoury, Phys. Rev. D 73 (2006) 083509; A. W. Brookfield et al. Phys.Rev.D 73 (2006) 083515; M. Kaplinghat and A. Rajaraman, [arXiv:astro-ph/0601517](http://arxiv.org/abs/astro-ph/0601517) (2006).
8. A. Lewis and S. Bridle, Phys. Rev. D 66 (2002) 103511.
9. S. M. Carroll, M. Hoffman and M. Trodden, Phys. Rev. D 68 (2003) 023509.
10. A. C. S. Readhead et al., ApJ 609 (2004) 498.
11. C. Dickinson et al., MNRAS 353 (2004) 732.
12. C. L. Kuo et al., American Astronomical Society Meeting, Vol. (2002) 201.
13. C. J. MacTavish et al., [arXiv:astro-ph/0507503](http://arxiv.org/abs/astro-ph/0507503) (2005).
14. M. Tegmark et al., ApJ 606 (2004) 702.
15. S. Cole et al., MNRAS 362 (2005) 505.
16. P. Astier et al., A&A 447 (2006) 31.
17. G. L. Fogli et al., [arXiv:hep-ph/0608060](http://arxiv.org/abs/hep-ph/0608060) (2006).
18. A. De La Macorra et al. - Arxiv preprint astro-ph/0608351 (2006), in press.
19. V. A. Rodin et al., Nucl. Phys. A 766 (2006) 107.