Do WMAP data favor neutrino mass and a coupling between Cold Dark Matter and Dark Energy?

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We allow simultaneously for a CDM–DE coupling and non–zero neutrino masses and find that significant coupling and neutrino mass are (slightly) statistically favoured in respect to a cosmology with no coupling and negligible neutrino mass (our best fits are: $C \sim 1/2m_p$, $m_\nu \sim 0.12$ eV each flavor). We assume DE to be a self–interacting scalar field and use a standard Monte Carlo Markov Chain approach.

One of the main puzzles of cosmology is why a model as ΛCDM, implying so many conceptual problems, apparently fits all linear data [1,2,3] in such unrivalled fashion.

The fine tuning paradox of ΛCDM is actually eased in dynamical DE (dDE) cosmologies, where DE is a self–interacting scalar field, facing no likelihood downgrade [4]. The coincidence paradox is also eased if an energy flow from CDM to dDE occurs (cDE cosmologies [5]). CDM–DE coupling, however, cuts the model likelihood, as soon as an intensity suitable to attenuate coincidence is approached.

The right physical cosmology could however include a further ingredient, able to compensate coupling distortions. Here we shall show a possible option of this kind: when we assume CDM–DE coupling or a significant $\nu$ mass, we cause opposite spectral shifts [6]. If we try to compensate them, the residual tiny distortions (slightly) favor coupling and $\nu$ mass, in respect to dDE or ΛCDM.

In this paper we consider the self–interaction potentials, admitting tracker solutions,

$$V(\phi) = \Lambda^{\alpha+4}/\phi^\alpha$$  \hspace{1cm} (1)

or

$$V(\phi) = (\Lambda^{\alpha+4}/\phi^\alpha) \exp(4\pi \phi^2/m_p^2),$$  \hspace{1cm} (2)

(RP [7] and SUGRA [8], respectively). Uncoupled RP (SUGRA) yields a slowly (fastly) varying $w(a)$ state parameter. Coupling is however an essential feature and modifies these behaviors, mostly lowering $w(a)$ at low $z$, and boosting it up to +1, for $z \sim 10$.

For any choice of $\Lambda$ and $\alpha$ these cosmologies have a precise DE density parameter $\Omega_{de}$. Here we take $\Lambda$ and $\Omega_{de}$ as free parameters in flat cosmologies; the related $\alpha$ value then follows.

In these scenarios, DE energy density and pressure read

$$\rho = \rho_k + V(\phi), \quad p = \rho_k - V(\phi),$$  \hspace{1cm} (3)

with

$$\rho_k = \dot{\phi}^2/2a^2;$$  \hspace{1cm} (4)

dots indicating differentiation in respect to $\tau$, the background metrics being

$$ds^2 = a^2(\tau) [d\tau^2 - d\lambda^2],$$  \hspace{1cm} (5)

with

$$d\lambda^2 = dr^2 + r^2(d\theta^2 + \cos^2\theta d\phi^2).$$  \hspace{1cm} (6)
Until \( \rho_k \gg V \), therefore, \( w(a) = p/\rho \) approaches +1 and DE density would rapidly dilute (\( \rho \propto a^{-6} \)), unless a feeding from CDM occurs. When the \( V \gg \rho_k \) regime is attained, then, the state parameter approaches -1 and DE can account for cosmic acceleration.

DE cannot couple to baryons, because of the equivalence principle (see, e.g. \cite{9}). Constraints to CDM–DE interactions, however, can only derive from cosmological data.

The simplest coupling is a linear one, formally Brans–Dicke theory (see, e.g., \cite{10}). The energy transfer from CDM to DE keeps then the latter at a non–negligible density level even when \( w(a) \sim +1 \). CDM density then declines slightly more rapidly than \( a^{-3} \). When \( \phi \) approaches \( m_p \) and \( V(\phi) \) exceeds \( \rho_k \), DE dilution stops and DE eventually exceeds CDM density.

All tenable cosmological models comprise a 2–component dark sector non interacting with baryons or radiation, so that \( T^{(c)}_{\mu \nu} + T^{(de)}_{\mu \nu} = 0 \) \( (T^{(c,de)}_{\mu \nu}) \) stress–energy tensors for CDM and DE, let their traces read \( T^{(c,de)} \). The assumption that CDM and DE are separate leads to take \( C \equiv 0 \) in the relations

\[
T^{(de)}_{\mu \nu} = + C T^{(c)}_{\phi \nu}, \quad T^{(c)}_{\mu \nu} = - C T^{(c)}_{\phi \nu}. \tag{7}
\]

describing the most general form of linear coupling (incidentally, this shows why DE cannot couple to any component with vanishing stress–energy tensor trace). Besides of \( C \), we shall also use the dimensionless coupling parameter \( \beta = (3/16\pi)^{1/2} m_p C \).

The results shown in this paper are based on our generalization of the public program CAMB \cite{11}, enabling it to study cDE models. Likelihood distributions are then worked out by using CosmoMC \cite{12}.

In Figure 1 we then illustrate the compensating effects between coupling and \( \nu \) mass. Details are provided in the caption.

When the fitting procedure is performed, we find most parameter values in the same range as in dDE or ΛCDM cosmologies. The significant parameters in our approach are however the energy scale A, the coupling intensity \( \beta \) and the sum of \( \nu \) masses \( M_\nu \). In Figures 2 and 3 we provide one–dimensional likelihood distributions on these parameters for SUGRA and RP cosmologies.

A basic information is however the correlation between likelihood distributions. These are shown in Figures 4 and 5 again for SUGRA and RP cosmologies, respectively.

These Figures, as well as one–dimensional plots, clearly exhibit maxima, both for average and marginalized likelihood, for significantly non–zero coupling and \( \nu \)–masses. Although their statistical significance is not enough to indicate any “detection” level, the indication is impressive. Furthermore, a stronger signal, with the present observational sensitivity, would be impossible.

Let us however outline that this work aimed at finding how far one could go from ΛCDM, adding non–zero coupling and \( \nu \)–mass, without facing a likelihood degrade. It came then as an unexpected bonus that likelihood does not peak on the 0–0 option.

The allowed \( \beta \) values open the possibility of a critically modified DE behavior. Figure 6 shows the scale dependence of the cosmic components for various \( \beta – M_\nu \) pairs.

Let us then outline that the \( M_\nu \) values allowed here approach the \( \nu \)–mass detection area in the forthcoming tritium decay experiment KATRIN \cite{13}. Should particle data lead to an external prior on \( M_\nu \), the strong degeneracy between the coupling parameter \( \beta \) and the neutrino mass \( M_\nu \) is broken, and new insight into the DE nature is gained \cite{14}. In Figure 7 we show how a neutrino mass determination simultaneously implies an almost model independent CDM–DE coupling detection. This would be a revival of mixed DM models \cite{15}, in the form of Mildly Mixed Coupled (MMC) cosmologies.

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Figure 1. **Top panel:** Transfer functions (multiplied by $k^{1.5}$, for graphic aims) in example cosmologies with/without coupling and with/without 2 massive $\nu$’s (00/CM models).

**Bottom panel:** Binned anisotropy spectral data, normalized to the best–fit $\Lambda$CDM model (upper frame) or to the best fit SUGRA cDE model including $\nu$–masses (lower frame). The distortions arising when coupling or $\nu$–mass are separately considered are also shown.

Figure 2. Marginalized (solid line) and average (dotted line) likelihood of cosmological parameters in SUGRA models. Notice that the $\beta$ signal appears when high– and low–$z$ data are put together, and is strengthened by SNIa data. As a matter of fact, coupling allows to lower the “tension” between $\Omega_c$ and fluctuation amplitude detected from CMB and deep sample data. For $M_\nu$ we also show the corresponding likelihood distributions obtained in the case of a standard $\Lambda$CDM+$M_\nu$ model (gray lines).
Figure 3. As previous Figure, in RP models.

Figure 4. Two parameter contours for the SUGRA model. Solid lines are 1- and 2-σ limits for marginalized likelihood. Colors refer to average likelihood, and the 50% likelihood contour from the average likelihood is indicated by the dotted line.
Figure 5. As previous Figure, for a RP potential.

Figure 6. Evolution of density parameters in a SUGRA model with coupling and $\nu$ mass. Colors refer to different components, as specified in the frame; lines to the different models: $M_\nu = 0, \beta = 0$ (continuous line); $M_\nu = 0.5$ eV, $\beta = 0.085$ (dotted); $M_\nu = 1.1$ eV, $\beta = 0.17$ (short dashed); $M_\nu = 1.2$ eV, $\beta = 0.22$ (long dashed).

Figure 7. Detection of CDM–DE coupling, following an hypothetical determination of an electron neutrino mass $m_\nu \approx 0.3$ eV, by the experiment KATRIN, yielding $M_\nu \approx 0.9$ eV. Here we show the likelihood distribution, with such a prior on $M_\nu$. Colors and lines convey the same indications as in Figures 4 and 5.