

Constraints on neutrino-dark matter interactions from cosmic microwave background and large scale structure data

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(Received 1 December 2009; published 2 February 2010)

We update a previous investigation of cosmological effects of a nonstandard interaction between neutrinos and dark matter. Parametrizing the elastic-scattering cross section between the two species as a function of the temperature of the Universe, the resulting neutrino-dark matter fluid has a nonzero pressure, which determines diffusion-damped oscillations in the matter power spectrum similar to the acoustic oscillations generated by the photon-baryon fluid. Using cosmic microwave background data in combination with large scale structure experiment results, we then put constraints on the fraction of the interacting dark matter component as well as on the corresponding opacity.

DOI: 10.1103/PhysRevD.81.043507

PACS numbers: 95.35.+d

I. INTRODUCTION

Both the existence and the energy content of dark matter (dm) in the Universe have been firmly established by several observations (see [1] for a review), yet, after decades of research its nature is still unknown. The favored candidate for dark matter has three main features, namely, it seems to be a long-lived, cold, and collisionless species. However, it is possible to relax some of these assumptions and in fact, several different dark matter candidates have been proposed through the years ([2,3]) and it is not even clear if only one species is responsible for the whole dark matter in the Universe. An interacting component has been proposed by many authors; couplings with a light scalar or pseudoscalar boson, as in the Majoron model has been investigated in [4–7] and interaction with neutrinos and more generally with the electromagnetic plasma have been considered, for example, in [8–12]. In this paper we study the scenario where at least a fraction of dark matter is coupled to neutrinos. We parametrize the neutrino-dark matter interaction in terms of the opacity $P \equiv \langle \sigma_{\text{dm}-\nu} |v| \rangle / m_{\text{dm}}$, the ratio of the thermal averaged dark matter-neutrino scattering cross section to the mass of the dark matter particle, where $P = Qa^{-2}$ with Q a constant and a the scale factor. We will briefly review the underlying theoretical basis of this choice in the next section. The main observable consequence of such a coupling is a pattern of oscillations in the matter power spectrum, which can in principle mimic the baryon acoustic oscillations observed in the large scale clustering of galaxies [13,14]. The cosmic microwave background (CMB) radiation is also affected by this interaction. Indeed, for sufficiently small scales, the temporal growth of a dark matter perturbation is lowered because of the coupling with neutrinos, and this determines a small enhancement of the small scale peaks at a level which depends on both the strength of the

interaction and the percentage of interacting dark matter. This effect can be also described in terms of a lowering of the neutrino “viscosity parameter” c_{vis}^2 [15] from its standard value $c_{\text{vis}}^2 = 1/3$. This paper updates and improves the results of a previous work [16]. In fact, we present the results of a likelihood analysis based on a Monte Carlo Markov chain sampling of the full cosmological parameter space, which allows us to take into account for possible degeneracies with the new parameters introduced in the analysis. To this aim, we use the latest CMB datasets available from the WMAP experiment [17] in combination with large scale structure data from SDSS.

The paper is organized as follows. In Sec. II we briefly discuss possible theoretical models for the dark matter-neutrino interaction and corresponding opacity due to scatterings. We refer to [16] for a more detailed discussion of these topics. In Sec. III we explain the method considered in the analysis and the data used to constrain both the strength of the interaction and the fraction of interacting dark matter. Finally, we give our results and conclusions.

II. NEUTRINO-DARK MATTER SCATTERINGS

Neutrino-dark matter interactions can be modeled in several ways, depending on the spin of the dark matter candidates as well the specific coupling Lagrangian. This issue is covered in detail in [9,16] to which we refer for more details, while we summarize in this section the main general features of such interactions and report the thermal averaged cross section times velocity as function of the scale factor. The latter, denoted by a is normalized to unity today, and scales as the inverse neutrino temperature.

As was shown in [16], if scatterings are supposed to affect the structure formation on large scales, it is unlikely that the relic abundance of these nonstandard dark matter candidates formed via the well-known freezing phenome-

non, as the pair annihilations would be quite efficient until recent times in depleting their number density, unless they represent a too light species. On the other hand, a different scenario has been also considered in the literature, where dark matter relic density today is the remnant of an initial particle-antiparticle asymmetry produced in the early universe, thus similar to the mechanism of baryogenesis which leads to a baryon density today much larger than what is expected by freezing of strong interactions alone [18,19]. This possibility may also account for the intriguing similarity between the values of Ω_b and Ω_{dm} we observe today, which differ by a factor of 5 only, a feature which may call for a common mechanism for their formation. In the following we therefore, consider the case of a non self-conjugated fermion or scalar particle ψ with a conserved global $U(1)$ charge, at least in the low energy scale regime, say below their mass scale, which also corresponds to the relevant stages for structure formation we are interested in.

In case of a spin zero species, the interaction Lagrangian can be chosen as a Yukawa term

$$\mathcal{L}_{\text{int}} = h\bar{F}_R\nu_L\psi + \text{H.c.}, \quad (1)$$

with F a spinor field, or via coupling with an intermediate vector-boson field U_μ ,

$$\begin{aligned} \mathcal{L}_{\text{int}} = & ig(\psi^*\partial^\mu\psi - \psi\partial^\mu\psi^*)U_\mu + g^2\psi^*\psi U_\mu U^\mu \\ & + g_\nu\bar{\nu}_L\gamma^\mu\nu_L U_\mu. \end{aligned} \quad (2)$$

In both cases F and U fields will be assumed to have mass larger than ψ , to prevent fast ψ decay at tree level, see [16].

In case of spin 1/2 dark matter, one has

$$\mathcal{L}_{\text{int}} = h\bar{\psi}_R\nu_L F + \text{H.c.}, \quad (3)$$

with F a scalar field or finally,

$$\begin{aligned} \mathcal{L}_{\text{int}} = & g(c_L\bar{\psi}_L\gamma^\mu\psi_L + c_R\bar{\psi}_R\gamma^\mu\psi_R)U_\mu \\ & + g_\nu\bar{\nu}_L\gamma^\mu\nu_L U_\mu. \end{aligned} \quad (4)$$

We notice that, as we will see in the next section, bounds on the dark matter-neutrino scattering cross section from CMB and large scale data correspond to a mass scale for ψ as well as the other field involved in the interaction Lagrangian (F or U) larger than MeV. Thus, we will assume this lower bound in the following: $m_{\text{dm}} \geq \text{MeV}$, $m_{F,U} \geq \text{MeV}$.

It is quite easy to compute the thermal averaged scattering cross section corresponding to these interaction terms in the nonrelativistic limit for the dark matter particle ψ and F or U . For example in the case of Eq. (1) or (3) and (2) one gets, respectively,

$$\langle\sigma_{\text{dm}-\nu}|v\rangle \sim |h|^4 \frac{T_\nu^2}{(m_F^2 - m_{\text{dm}}^2)^2}, \quad (5)$$

TABLE I. Mean values and marginalized confidence levels for the cosmological parameters of interest for WMAP + SDSS. When not otherwise stated, all constraints are at 68% C.L.

Parameter	WMAP + SDSS
$\Omega_b h^2$	0.02271 ± 0.00062
$\Omega_c h^2$	$0.059^{+0.020}_{-0.019}$
$\Omega_s h^2$	$< 0.093(2\sigma)$
Ω_Λ	0.754 ± 0.018
n_s	0.964 ± 0.014
τ	0.089 ± 0.017
Δ_R^2	$(2.38 \pm 0.10) \times 10^{-9}$
H_0	72.7 ± 1.8
z_{reion}	10.4 ± 1.3
t_0	13.69 ± 0.13
A_{SZ}	$1.08^{+0.92}_{-0.51}$

$$\langle\sigma_{\text{dm}-\nu}|v\rangle \sim g^2 g_\nu^2 \frac{T_\nu^2}{m_U^4}. \quad (6)$$

The first result holds for $m_F \neq m_{\text{dm}}$, otherwise the cross section takes a constant value, as for the well-known Thomson cross section. This special case has been considered in detail in [16], and will not be worked out here, as it is quite fine-tuned. Similar results hold for a spinorial dark matter interacting via an intermediate gauge boson U ,

$$\langle\sigma_{\text{dm}-\nu}|v\rangle \sim g^2 g_\nu^2 (c_L^2 + c_R^2 - c_L c_R) \frac{T_\nu^2}{m_U^4}. \quad (7)$$

We see that for both Yukawa-type or intermediate gauge boson interaction, the opacity assumes a simple expression, of the form

$$P \sim \frac{1}{M^4 m_{\text{dm}}} T_\nu^2 = \frac{T_\nu^{(0)2}}{M^4 m_{\text{dm}}} a^{-2} \equiv Q a^{-2}, \quad (8)$$

with M a mass scale and Q a constant parametrizing the strength of interaction

$$Q = \frac{1}{(M/\text{MeV})^4} \frac{1}{m_{\text{dm}}/\text{MeV}} \times 10^{-41} \text{ cm}^2 \text{ MeV}^{-1}, \quad (9)$$

where we have used the value of neutrino temperature today $T_\nu^{(0)}$.

III. ANALYSIS

In the early universe, the opacity P is strong enough to determine acoustic oscillations in the coupled neutrino-dark matter fluid, just like the usual electromagnetic force does with the photon-baryon fluid before recombination. In order to include a neutrino-dark matter interaction, we modify the standard Euler equation for dark matter, resulting in an analogue of that for baryon matter

$$\dot{\theta}_{\text{dm}} = -\frac{\dot{a}}{a}\theta_{\text{dm}} + \frac{4\rho_\nu}{3\rho_{\text{dm}}} a n_{\text{dm}} \sigma_{\text{dm}-\nu} (\theta_\nu - \theta_{\text{dm}}), \quad (10)$$

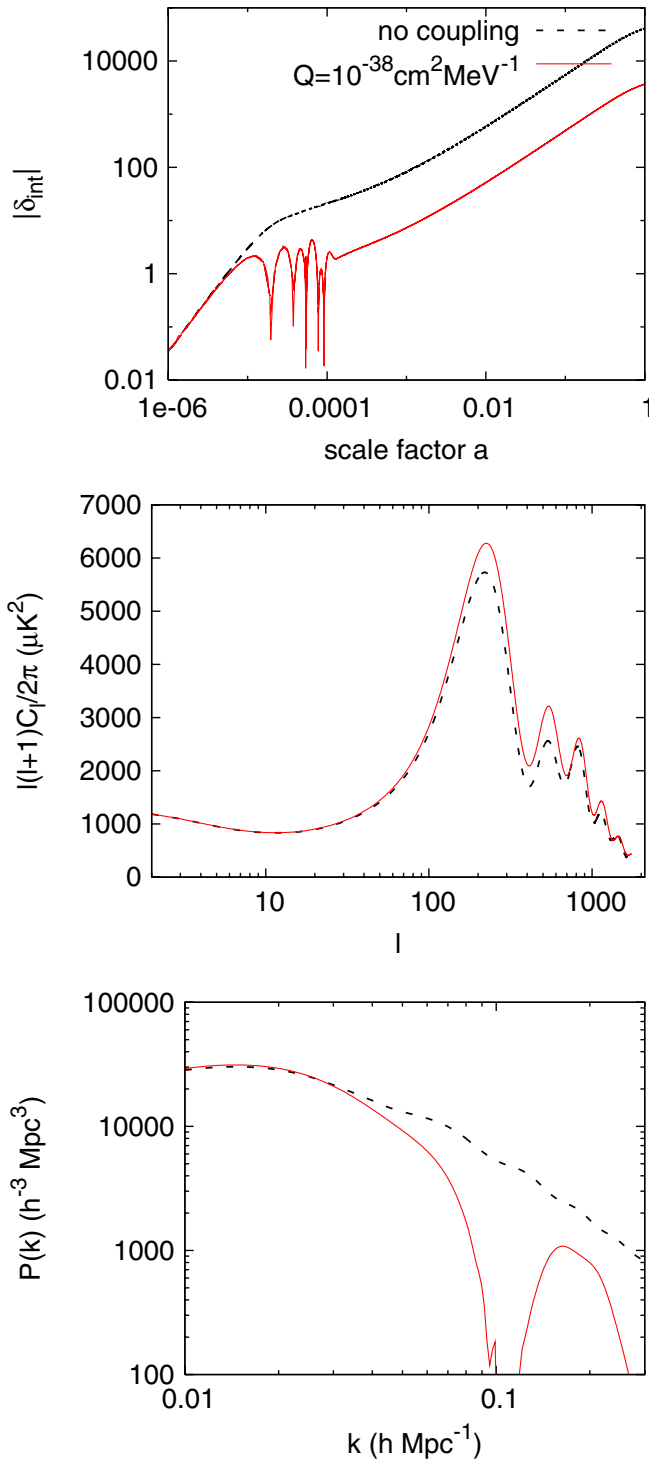


FIG. 1 (color online). A perturbation of interacting dark matter (red line) of wave number $k = 0.81h \text{ Mpc}^{-1}$ is plotted against a perturbation of noninteracting dark matter (black dotted line) in the upper panel. The effects of this interaction are clearly seen in the angular power spectrum of the CMB (middle panel) and on the matter power spectrum (lower panel). We have chosen a very large value of Q to magnify the effect on the main cosmological observables.

where momentum conservation in scattering processes has been accounted for. With θ we denote the velocity perturbations and the product $an_{\text{dm}}\sigma_{\text{dm}-\nu}$ quantifies the scattering rate of neutrinos by dark matter. As in the case of the baryon-photon interaction, we can neglect both the shear contribution $k^2\sigma$ and the term $c_{\text{dm}}^2 k^2\delta$, where c_{dm} is the sound speed of the dark matter fluid. The hierarchy of equations for neutrinos has been modified accordingly. As we can see from the upper panel of Fig. 1, any interacting dark matter perturbation of sufficiently small scale will be affected by the coupling with neutrinos. When it enters the horizon, the mode will experience a series of acoustic oscillations while coupled with neutrinos, rather than growing slightly in the radiation dominated epoch and then more rapidly in the matter dominated epoch. This determines a pattern of oscillations in the matter power spectrum (lower panel) as well as an enhancement of the peaks in the angular power spectrum (middle panel). We make use of the publicly available Markov chain Monte Carlo package COSMOMC [20] with a convergence diagnostic based on the Gelman and Rubin statistic [21] to put constraints on the cosmological parameters. We consider a flat Λ CDM model described by the following set of nine cosmological parameters:

$$\{\omega_b, \omega_c, \omega_x, \Theta_s, \tau, n_s, \log[10^{10}A_s], Q, A_{\text{SZ}}\}, \quad (11)$$

where $\omega_b (\equiv \Omega_b h^2)$, $\omega_c (\equiv \Omega_c h^2)$, $\omega_x (\equiv \Omega_x h^2)$ are the baryon, standard collisionless cold dark matter, and interacting cold dark matter densities relative to the critical density, respectively; Θ_s is the ratio of the sound horizon to the angular diameter distance at decoupling, τ the optical depth to reionization, and A_s and n_s are the ampli-

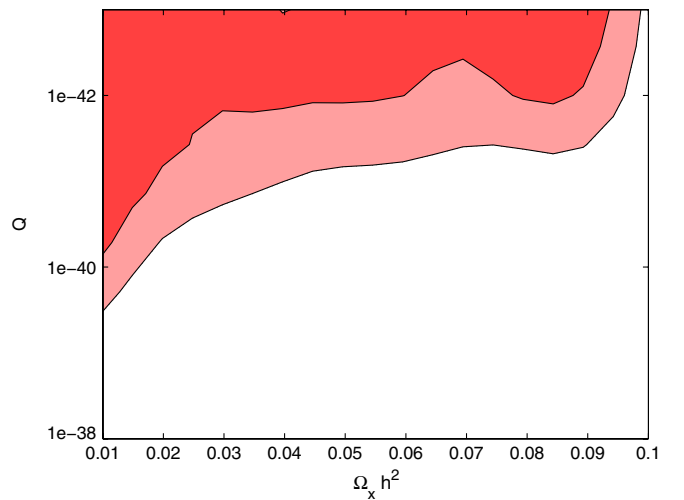


FIG. 2 (color online). Constraints in the cross section parameter Q versus the $\Omega_x h^2$ plane from the combination of WMAP and SDSS data. Large values for the neutrino-dark matter interaction are always compatible with the standard picture, provided that the energy content of the interacting dark matter is small enough.

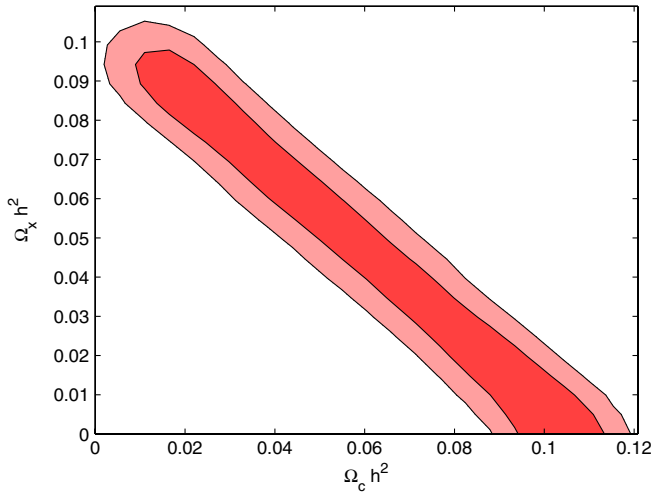


FIG. 3 (color online). Two dimensional constraints on $\Omega_\chi h^2$ versus $\Omega_c h^2$; as we can see, values of $\Omega_c h^2 = 0$ are not compatible with the data at more than 95% C.L.

tude of the primordial spectrum and the spectral index. They are both evaluated at $k = 0.002 \text{ Mpc}^{-1}$. The parameter Q (measured in units of $\text{cm}^2 \text{ MeV}^{-1}$) quantifies the strength of the neutrino-dark matter interaction, as discussed in the previous section. Finally, we take into account for the contribution to the power spectrum by Sunyaev-Zel'dovich (SZ) fluctuations [22] by adding the predicted template spectrum from [23], multiplied by the constant amplitude A_{SZ} . We use data and the likelihood code from the WMAP team's 5 yr release [17,24] (both temperature and polarization) in combination with the SDSS LRG data release [25]. In Fig. 2 we plot the combined constraints on both the parameter Q and the energy content in interacting dark matter. As expected, there is a clear correlation between these two parameters as the lower the energy content in interacting dark matter the weaker the constraint on the strength of the interaction. It has been shown in [16] that the baryon acoustic oscillations due to the coupled photon-baryon plasma and seen in the large scale clustering of matter [13,14] can mimic the coupled neutrino-dark matter fluid in a universe with a lower energy content in baryon, seriously affecting constraints on $\Omega_b h^2$ derived by large scale structures data only. We find here that when a full parameter space analysis is performed using additional data from the CMB, we always

recover the standard constraints for the baryon density, as shown in Table I. Of course the energy content in standard dark matter is smaller than the usual amount simply because we are splitting all the dark matter in an interacting and a noninteracting component. All the other values for the cosmological parameters are compatible with the standard values at 1σ and the reduced χ^2 , defined as $\chi^2_{\text{red}} = \chi^2/\nu$, where ν denotes the number of degrees of freedom, does not significantly improve for the model with interacting dark matter. We also note that, as shown in Fig. 3, a model in which all of the dark matter is interacting with neutrinos is ruled out at more than 2σ .

IV. CONCLUSIONS

In this paper we have investigated the effects of a non-standard interaction between neutrinos and dark matter using the to date available data from WMAP and SDSS Collaborations on cosmic microwave background and large scale structures. These effects are the presence of diffusion—damped oscillations in the matter power spectrum and a small enhancement of the peaks in the cosmic microwave background angular power spectrum. Parametrizing the opacity parameter as Qa^{-2} with Q a constant, which holds in a large class of models for neutrino-dark matter interactions, we found that the bound on Q becomes stronger as the percentage $\Omega_\chi h^2$ of interacting dark matter component grows. Typical upper bound on Q is of the order of $10^{-42} \div 10^{-40} \text{ cm}^2 \text{ MeV}^{-1}$, while the bound becomes weaker for very low values of Ω_χ . Finally, we note that cosmological constraints on neutrino masses can be affected because of possible degeneracies. In fact, both massive neutrinos and an interacting dark matter component determine a lowering of the matter power spectrum at sufficiently small scales; we do not expect to have an exact degeneracy (for example an interacting dark matter component also determines oscillations in the matter power spectrum) but we naively expect that the constraints on both the neutrino mass and the parameters Q and $\Omega_\chi h^2$ would be stronger when $m_\nu > 0$.

ACKNOWLEDGMENTS

This research was funded by NSF CAREER AST-0605427 and by LANL IGPP-08-505.

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