Cosmological constraints on Neutrino - Dark Matter interactions

G. Mangano

aINFN, Sezione di Napoli, Dipartimento di Scienze Fisiche, Università di Napoli Federico II

I summarize the results of a recent analysis where the cosmological effects of interactions of neutrinos with cold Dark Matter (DM) is investigated. This interaction produces diffusion-damped oscillations in the matter power spectrum, analogous to the acoustic oscillations in the baryon-photon fluid. I discuss the bounds from the Sloan Digital Sky Survey on the corresponding opacity defined as the ratio of neutrino-DM scattering cross section over DM mass, and compare with the constraint from observation of neutrinos from supernova 1987A.

1. INTRODUCTION

The most favored candidates for dark matter (DM) are cold, collisionless massive particles, which are non-relativistic for most of the history of the Universe and so can cluster gravitationally during matter domination. Candidates for these dark matter particles can be found in supersymmetric extensions of the standard electroweak model. However, observations on galactic and sub-galactic scales may conflict with the predictions from numerical simulations and analytic calculations. Indeed, cold and collisionless dark matter models seem to predict an excess of small-scale structures [1], and numerical simulations predict far more satellite galaxies in the Milky Way halo than are observed.

Several solutions have been proposed to explain these discrepancies. In this paper, I summarize some results for scenarios where light (MeV) dark matter interacts with standard species such as leptons [2]. In particular, if DM and neutrinos interact, so that there was an epoch in the very early universe during which they were strongly coupled we expect to see some effect on the Large Scale Structure (LSS) power spectrum [3]. In fact, DM perturbations that entered the horizon during this period would then be erased because of diffusion damping, and the suppression scale will depend on the dark matter–neutrino interaction. Even if only a fraction of the dark matter interacts with neutrinos, a pattern of oscillations in the matter power spectrum arises, much like the oscillations in the baryon-photon fluid.

2. BOUNDS ON NEUTRINO DARK MATTER INTERACTION

We consider here the case of a non-self-conjugated scalar particle $\psi$ with mass $m_{DM}$ in the MeV range as a candidate for DM [2] and an interaction term dictated by the following lagrangian density

$$ L_{\text{int}} = g \overline{F} R \nu_L \psi + h.c. $$

where $F$ is a spinor field. Other possible couplings, for example via the exchange of an intermediate vector-boson field $U_\mu$, are extensively discussed in [3].

In the range of neutrino temperature $T \lesssim MeV$ we are interested in (earlier evolution affects in fact, the power spectrum at very small scales with wavenumber larger than $10^5$ h Mpc$^{-1}$) the opacity, i.e. the thermally averaged $\psi$-neutrino scattering cross section is

$$ \left\langle \frac{\sigma_{DM-\nu} |v|}{m_{DM}} \right\rangle \sim \frac{|g|^4}{m_{DM}} \frac{T^2}{(m_F^2 - m_{DM}^2)^2} \equiv Q_2 \frac{1}{a^2} $$

with $a$ the scale factor normalized to unity at the present time. If the $\psi$ and $F$ fields are degenerate in mass the low-energy transfer scattering cross section has instead a Thomson behavior,

$$ \left\langle \frac{\sigma_{DM-\nu} |v|}{m_{DM}} \right\rangle \sim \frac{|g|^4}{m_{DM}^2} \equiv Q_0 $$

The effect of neutrino-DM scattering processes is to modify the standard Euler equations for the
velocity perturbations, which now keep an additional term proportional to the opacity.

Consider for example the case \( \langle \sigma_{DM-\nu}|v| \rangle \propto a^{-2} \) (similar considerations can be made for the constant cross section of Eq. (3)). In Fig. 1 I show what happens when a perturbation of wavenumber \( k = 1.04 \, h \, \text{Mpc}^{-1} \) enters the horizon for different values of \( Q_2 \). If the coupling is zero the mode enters the horizon in the radiation-dominated era, and it starts to grow first logarithmically and then linearly with the expansion factor (during matter domination). When the same mode enters the horizon with \( Q_2 = 5 \times 10^{-44} \, \text{cm}^2 \, \text{MeV}^{-1} \), the growth is nearly zero during the radiation epoch, while the mode starts growing linearly with the scale factor during matter domination, since the coupling with neutrinos becomes negligible at this stage for this value of \( Q_2 \). For a larger \( Q_2 = 10^{-39} \, \text{cm}^2 \, \text{MeV}^{-1} \), when the perturbation enters the horizon, dark matter is coupled with neutrinos and this results in a series of oscillations until decoupling is reached. Notice that the amplitude of oscillations decreases near decoupling due to diffusion damping for the dark matter–neutrino fluid. In Fig. 2 I show several matter power spectra for different values of the DM-neutrino interaction for both the case considered. The effect can be seen on small scales. Larger couplings will correspond to later epochs of neutrino-DM decoupling and to a damped oscillating regime on larger scales. On the other hand, even considering values of \( Q_2 \) or \( Q_0 \) which are already at odds with current clustering data, there is only a small enhancement in the small-scale CMB anisotropies which are therefore, very weakly affected by the neutrino-DM interactions.

In order to bound the strength of DM coupling to neutrinos, one can use the real-space power spectrum of galaxies in the Sloan Digital Sky Survey (SDSS) using the data and window functions of the analysis of Ref. [4]. To compute the likelihood function for the SDSS, the analysis has been

Figure 1. Dark matter perturbations of \( k = 1.04 \, h \, \text{Mpc}^{-1} \). The opacity \( Q_2 \) is in unit of \( \text{cm}^2 \, \text{MeV}^{-1} \) [3].

Figure 2. Matter power spectra for different opacities \( Q_0 \) (top panel) and \( Q_2 \) (bottom panel) [3].
conservatively restricted in [3] to a range of scales over which the fluctuations are assumed to be in the linear regime \((k < 0.2 h^{-1} \text{Mpc})\) marginalizing over a bias \(b\) considered to be an additional free input. Assuming a cosmological concordance model with \(\Omega_\Lambda = 0.70\) and \(\Omega_{DM} = 0.25\) which produces a good fit to current CMB data, one obtains

\[
\begin{align*}
Q_2 & \leq 10^{-42} \text{cm}^2 \text{MeV}^{-1} \\
Q_0 & \leq 10^{-34} \text{cm}^2 \text{MeV}^{-1}
\end{align*}
\]

at the 2\(\sigma\) confidence level. Comparing these results with Eq. \((2)\), we see that for couplings \(g\) of order one the bound is saturated if both \(m_{DM}\) and \(m_F\) are of the order of MeV. Smaller values of \(g\) imply lighter masses for the DM and the intermediate exchanged particle in the scattering process. In view of the bound on neutrino coupled dark matter from Big Bang Nucleosynthesis found in \([3]\), \(m_{DM} \geq 1\) MeV, these values are already disfavored, so the LSS constraint above is not further constraining the model. More stringent bounds might be obtained by studying the LSS power spectrum at larger wavenumbers, \(k \geq 0.2 h\) Mpc\(^{-1}\), taking into account the nonlinear behavior of perturbations for very small scales. On the other hand, the result for \(Q_0\) which we recall corresponds to an intermediate particle and DM mass degeneracy, is more severely constraining \(m_{DM}\). We get in this case \(m_{DM} \geq 10^{5/3}\) GeV.

Notice that if one assumes that DM couples to neutrinos strongly enough to produce observable effects that can be constrained by CMB and LSS observations, one has to abandon the idea that relic DM density formed via the usual mechanism based on freezing of DM annihilation processes at temperatures \(T \sim m_{DM}\), for annihilation into neutrino-antineutrino pairs would reduce the DM energy density to a very tiny value today. An interesting alternative possibility is that the relic DM abundance is the outcome of a particle-antiparticle asymmetry produced at higher temperatures in the DM sector, very much akin to the mechanism by which the baryon number is produced in the early Universe. Indeed, in this case one might also account for the fact that intriguingly the two energy density parameters for baryons and DM, \(\Omega_b\) and \(\Omega_{DM}\) only differ by a factor five today, yet their production mechanism is usually considered to be quite distinct.

To conclude, it is interesting to compare the bounds on \(Q_2\) and \(Q_0\) with those which can be obtained from the propagation of astrophysical neutrinos. The most important constraint is provided by observation of neutrinos from SN1987A. These neutrinos have energies of order 10 MeV.

The thickness of the dark matter layer that they propagate through is approximately \(\int \rho(l) dl\), the integral of the DM density along the line of sight \(l\) to the LMC. Approximating the DM density \(\rho(l) \sim \rho_0 (l/l_0)^{-2}\), where \(\rho_0 \approx 0.4\) GeV cm\(^{-3}\) is the local density and \(l_0 \approx 8\) kpc our distance from the Galactic center, we find a dark matter thickness \(\sim 10^{25}\) MeV cm\(^{-2}\). Given the agreement between the predicted and observed neutrino flux and energy spectrum, one infers that neutrinos from SN1987A were not significantly absorbed by dark matter along the line of sight from which one gets \(Q_2 \leq 10^{-45}\) cm\(^2\) MeV\(^{-1}\) for both \(m_{DM}\) and \(m_F\) in the MeV range, and \(Q_0 \leq 10^{-25}\) cm\(^2\) MeV\(^{-1}\). Note that the bound on \(Q_2\) is stronger than what is obtained using LSS data, while for \(Q_0\) the stronger bound is still provided by LSS.

ACKNOWLEDGMENTS

I am pleased to thank the Organizers and Conveners of the NOW 2006 Workshop for their successful efforts in creating a fruitful and relaxed atmosphere during the Conference. I also thank my collaborators who enjoyed with me the study of this subject discussed in more details in \([3]\).

REFERENCES

1. R. Schaeffer and J. Silk, ApJ 292, (1985) 319.
2. C. Boehm and P. Fayet, Nucl. Phys. B 683, (2004) 219.
3. G. Mangano, A. Melchiorri, P. Serra, A. Cooray and M. Kamionkowski, Phys. Rev. D 74, (2006) 043517.
4. M. Tegmark et al., ApJ 606, (2004) 702.
5. P. D. Serpico and G. G. Raffelt, Phys. Rev. D 70, (2004) 043526.