Comment on "Is Dark Matter with Long-Range Interactions a Solution to All Small-Scale Problems of ΛCDM Cosmology?"

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In a recent Letter [1], van den Aarssen *et al.* suggested a general scenario for dark matter, where both the dark-matter particle χ and ordinary neutrinos ν interact with an MeV-mass vector boson V via $\mathcal{L} \supset g_\chi \overline{\chi}\gamma^\mu \chi V_\mu + g_\nu \overline{\nu}\gamma^\mu \nu V_\mu$ with g_χ and g_ν being the corresponding coupling constants. Given a vector-boson mass $0.05~\text{MeV} \lesssim m_V \lesssim 1~\text{MeV}$, one needs $10^{-5} \lesssim g_\nu \lesssim 0.1$ to solve all the small-scale structure problems in the scenario of cold dark matter [1].

Recently, Laha *et al.* [2] found that the ν-V interaction might lead to too large decay rates of $K^- \to \mu^- + \overline{\nu}_\mu + V$ and $W^- \to l^- + \overline{\nu}_l + V$, indicating that the scenario proposed in Ref. [1] is severely constrained. However, such experimental bounds can be evaded if the longitudinal polarization state of V is sterile or if V is coupled to sterile neutrinos rather than ordinary ones [1, 2].

Now, we show that the constraints on g_ν and m_V from Big Bang Nucleosynthesis (BBN) are very restrictive. In the early Universe, V can be thermalized via the inverse decay $\nu + \overline{\nu} \to V$ and pair annihilation $\nu + \overline{\nu} \to V + V$ and contribute to the energy density. If the inverse-decay rate exceeds the expansion rate H around the temperature $T = 1$ MeV, we obtain $g_\nu > 1.5 \times 10^{-10}~\text{MeV}/m_V$ for $m_V \lesssim 1$ MeV. For $m_V \ll 1$ MeV, pair annihilation is more efficient than inverse decay to thermalize V. Requiring the annihilation rate $\Gamma_{\rm pair} \propto g_\nu^4 T > H$, one obtains $g_\nu > 3.4 \times 10^{-5}$. For $m_V > 1$ MeV, however, even if V is in thermal equilibrium, its number density will be suppressed by a Boltzmann factor. To derive the BBN bound, we first solve the non-integrated Boltzmann equation for the distribution function of V for given g_ν and m_V, where only the decay and inverse-decay processes are included in the computations [3–7]. Then, we calculate its energy density, and require the extra number of neutrino species $\Delta N_\nu < 1$ at $T = 1$ MeV [8]. Thus, we can exclude a large region of the parameter space, as shown in Fig. 1. The contribution from V in thermal equilibrium reaches its maximum $\Delta N_\nu \approx 1.71$ in the relativistic limit.

Note that we have assumed ΔN_ν to be constant, but for $m_V > 1$ MeV it actually decreases during the BBN era, so our constraint should be somehow relaxed in the large-mass region. Since only the transverse polarizations of V are involved in inverse decay in the limit of zero neutrino masses, the BBN constraint does not depend on whether the longitudinal polarization is thermalized or not. If neutrinos are Dirac particles, the right-handed neutrinos $\nu_{\rm R}$ can be in thermal equilibrium as well. Both V and $\nu_{\rm R}$ contribute to the energy density, so one or more species of $\nu_{\rm R}$ is obviously ruled out. In addition, if V is coupled to sterile neutrinos, which are supposed to be thermalized, the BBN bound on g_ν and m_V becomes more stringent.

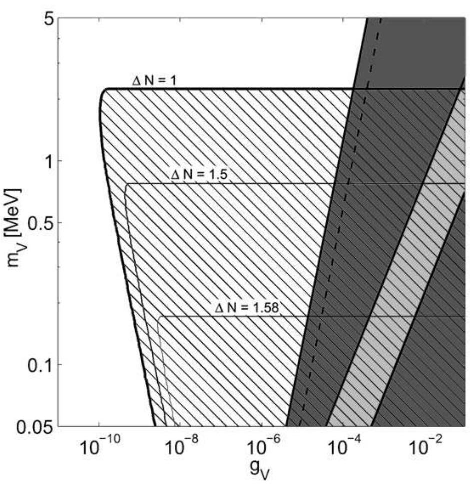

FIG. 1: Constraints on g_ν and m_V from K decays (gray, solid line), W decays (gray, dashed line), and BBN. The two former are reproduced from Ref. [2], and the sample region in Fig. 3 of Ref. [1] is also presented (light gray). The hashed region bounded by the thick solid curve is excluded by $\Delta N_\nu < 1$ at 95% C.L. [8]. The excluded region will shrink for $\Delta N_\nu < 1.5$ (see, e.g., Ref. [9]), and even further for the "maximally conservative" limit $\Delta N_\nu \lesssim 1.58$ for $m_V > 0.05$ MeV.

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[1] L.G. van den Aarssen, T. Bringmann and C. Pfrommer, Phys. Rev. Lett. **109**, 231301 (2012).
[2] R. Laha, B. Dasgupta and J.F. Beacom, arXiv:1304.3460.
[3] E.W. Kolb and M.S. Turner, *The Early Universe*, Front. Phys. **69**, 1 (1990).
[4] M. Kawasaki, G. Steigman and H.-S. Kang, Nucl. Phys. B **403**, 671 (1993).
[5] A. Basbøll and S. Hannestad, JCAP **0701**, 003 (2007).

[6] J. Garayoa, S. Pastor, T. Pinto, N. Rius and O. Vives, JCAP **0909**, 035 (2009).
[7] F. Hahn-Woernle, M. Plümacher and Y.Y.Y. Wong, JCAP **0908**, 028 (2009).
[8] G. Mangano and P.D. Serpico, Phys. Lett. B **701**, 296 (2011).
[9] J. Hamann, S. Hannestad, G.G. Raffelt and Y.Y.Y. Wong, JCAP **1109**, 034 (2011).