Constraints on Light Dark Matter from Core-Collapse Supernovae

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(Received 22 February 2006; published 1 June 2006)

We show that light ($\simeq$ 1–30 MeV) dark matter particles can play a significant role in core-collapse supernovae, if they have relatively large annihilation and scattering cross sections, as compared to neutrinos. We find that if such particles are lighter than $\simeq$ 10 MeV and reproduce the observed dark matter relic density, supernovae would cool on a much longer time scale and would emit neutrinos with significantly smaller energies than in the standard scenario, in disagreement with observations. This constraint may be avoided, however, in certain situations for which the neutrino-dark-matter scattering cross sections remain comparatively small.

DOI: 10.1103/PhysRevLett.96.211302 PACS numbers: 95.35.+d, 97.60.Bw

The identity of our Universe's dark matter is one of the most interesting questions in modern cosmology. Although a wide range of viable particle candidates have been proposed, none has been confirmed experimentally. The dark matter candidates most often studied are weakly interacting particles with masses in the $\sim$100 GeV to TeV scale.

Such dark matter particles should not be too light, otherwise they could not annihilate sufficiently. Still it is possible to consider light dark matter (LDM) particles, with the right relic abundance to constitute the nonbaryonic dark matter of the Universe, provided one also introduces new efficient mechanisms responsible for their annihilations. Such annihilations into, most notably, e^+e^-, could correspond to the exchanges of new heavy (e.g., mirror) fermions (in the case of light spin-0 dark matter particles), or of a new neutral gauge boson U [1], light but very weakly coupled [2], and still leading to relatively "large" annihilation cross sections.

The subsequent observation by the INTEGRAL/SPI experiment of a bright 511 keV γ-ray line from the galactic bulge [3] could then be viewed as a sign of the annihilations of positrons originating from such light dark matter particle annihilations [4,5]. These particles, explaining both the *nonbaryonic dark matter* of the Universe and *the 511 keV line*, may have spin-$\frac{1}{2}$ as well as spin-0 [6]. They could even potentially improve the agreement between the predicted and observed abundances of primordial ^{2}H and ^{4}He, as long as LDM particles are not too strongly coupled to neutrinos [7].

It may well be that the required positrons [8] come from one or another kind of stellar explosions [9], but it is worth considering alternatives, given our present state of understanding. We shall therefore focus on the light dark matter interpretation of the 511 keV line. [Other exotic particle physics scenarios which could generate this emission have been proposed in [10].]

Given the large rate of positrons produced, smaller dark matter masses tend to be preferred, to avoid an excessive production of unobserved γ rays [6]. More specifically, if such particles are heavier than 20–30 MeV, internal bremsstrahlung (and bremsstrahlung) photons are likely to exceed the observed number of γ rays from the galactic bulge [11]. And, if they were heavier than even 3 MeV, the γ rays generated through the resulting e^+e^- annihilations might also be inconsistent with observations [12].

If MeV-scale dark matter particles do exist, they will be thermally generated in the core of collapsing stars. They can affect thermal freeze-out of weakly interacting neutrinos, depending on their mass, and annihilation and elastic scattering cross sections.

Ordinary neutrinos stay in thermal equilibrium down to temperatures $\simeq$2 or 3 MeV during the expansion of the Universe, and down to $\simeq$8 MeV or so, in supernovae explosions. Light dark matter particles of mass m_X annihilate into ordinary ones, staying in equilibrium until they decouple. This occurs, during the expansion of the Universe, at $T_F = m_X/x_F$, with $x_F \simeq 17$. In a supernova explosion LDM particles will remain in chemical equilibrium with other particles, until the temperature drops down to some value $T_{\rm DMS}$, to be determined later (cf. Fig. 1).

As long as their abundance remains sufficient, these light dark matter particles can also influence the behavior of neutrinos in a supernova by having relatively "large" interactions with them, e.g., through U exchanges [1,13]. Neutrinos may then be kept longer in thermal equilibrium as a result of stronger-than-weak interactions with LDM particles, so that their decoupling temperature, in supernovae explosions, would be significantly lower than in the standard model, if dark matter particles are sufficiently light. A crucial ingredient will then be the magnitude of the neutrino-LDM elastic scattering cross section.

We now consider quantitatively these effects through a simple model based on the diffusion approximation [15]. We begin with the transport equation:

$$\dot{n} + \vec{\nabla} \cdot \vec{\phi} = -\sigma_{\rm ann} v_{\rm r} (n^2 - n_{\rm eq}^2), \tag{1}$$

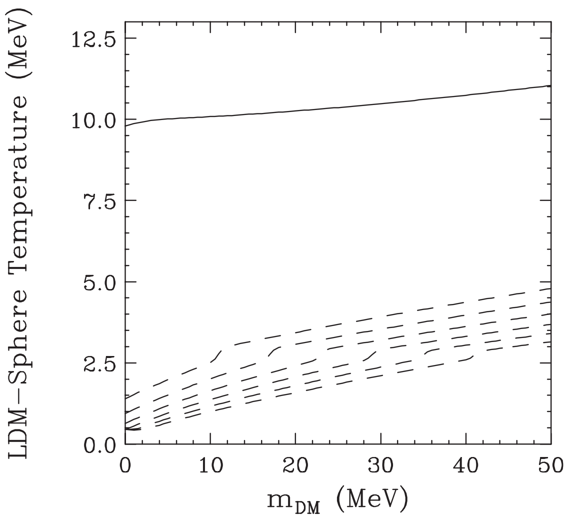

FIG. 1. Temperature of the LDM sphere $T_{\rm DMS}$ for $\sigma_{\rm ann} v_{\rm r} \propto v^2$ (P wave), normalized so as to lead to the observed relic density. The dashed lines correspond to LDM-nucleon elastic scattering cross section $\propto T^2$ and (from top to bottom) 1, 10, 10^2, 10^3, 10^4, and 10^5 times larger than the corresponding neutrino-nucleon cross section. The solid line shows the case of a massive ν_τ, for comparison.

where $\vec{\phi}$ is the LDM flux, n the number density of LDM particles, and $n_{\rm eq}$ its equilibrium value for a LDM mass m_X at temperature T with vanishing chemical potential. $\sigma_{\rm ann}$ is the LDM, anti-LDM annihilation cross section [or self-annihilation if the LDM is its own antiparticle [16]], and $v_{\rm r}$ the relative velocity of the two annihilating particles.

In the following, cross sections will be taken at typical thermal energies. We now adopt the diffusion approximation, $\vec{\phi} = -D\vec{\nabla} n$, where $D = \lambda v/3$ is the diffusion coefficient and $\lambda = (\sum_i n_i \sigma_{Xi})^{-1}$ the LDM mean free path, which depends on the densities n_i of all the particle species with which the LDM interacts with cross sections σ_{Xi}. Assuming spherical symmetry and stationarity, we can write Eq. (1) as

$$Dn'' + \left(D' + \frac{2D}{r}\right)n' = \sigma_{\rm ann} v_{\rm r}(n^2 - n_{\rm eq}^2), \qquad (2)$$

where the primes denote derivatives with respect to radius r.

We define the "LDM sphere" as the surface beyond which LDM annihilations (into e^+e^-, $\nu\bar{\nu}$, ...) "freeze out". The number density of LDM particles inside of this LDM sphere should approach its equilibrium value $n_{\rm eq}$. The radius of this sphere, $R_{\rm DMS}$, can be estimated by solving

$$\left| Dn_{\rm eq}'' + \left(D' + \frac{2D}{r}\right)n_{\rm eq}' \right|_{R_{\rm DMS}} = [\sigma_{\rm ann} v_{\rm r} n_{\rm eq}^2]_{R_{\rm DMS}}. \qquad (3)$$

The radius of the surface of last scattering of LDM particles is found by solving $\int_{R_{\rm LS}}^{\infty} dr \sum_i n_i(r)\sigma_{Xi} \simeq 1$. We shall concentrate here on LDM scatterings on nucleons (in practice mostly neutrons) with density $n_N(r)$, and elastic cross section σ_{XN}, the actual $R_{\rm LS}$ radius being at least as large as the one we shall estimate by disregarding the other species. This is sufficient to demonstrate that LDMs (and therefore eventually neutrinos, with which these LDM particles are normally coupled) decouple at lower densities and temperatures than in the standard model [17].

For the situations of interest, the LDM sphere lies within the last scattering sphere, so that the diffusion approximation is justified. Indeed, annihilation cross sections of LDM particles are normally comparable to LDM scattering cross sections with ordinary particles [18], so that if LDMs can still annihilate they can still also scatter.

To determine the LDM sphere and surface of last scattering, we must adopt a LDM mass and a set of (annihilation and scattering) cross sections, as well as a distribution of nucleons $n_N(r)$ and their temperature $T(r)$ in the proto-neutron star. We will use the following parametrizations, which should be reasonable within the range ~15–100 km we are concerned with [19]:

$$n_N(r) \simeq \begin{cases} 6\times10^{35}\ \text{cm}^{-3}(\frac{23\ \text{km}}{r})^{7.8}, & r < 23\ \text{km}, \\ 6\times10^{35}\ \text{cm}^{-3}(\frac{23\ \text{km}}{r})^{12.8}, & 23\ \text{km} < r < 44\ \text{km}, \\ 1.2\times10^{33}\ \text{cm}^{-3}(\frac{44\text{km}}{r})^{3.0}, & r > 44\ \text{km}, \end{cases} \qquad T(r) = \begin{cases} 5.2\ \text{MeV}(\frac{25\ \text{km}}{r})^{2.6}, & r < 25\ \text{km}, \\ 5.2\ \text{MeV}(\frac{25\ \text{km}}{r})^{1.2}, & r > 25\ \text{km}. \end{cases} \qquad (4)$$

These are characteristic for the first few seconds over which most of the cooling takes place, in the standard scenario.

We note that the presence of LDM could considerably modify profiles compared to the standard scenario. However, we will find (Fig. 1) that LDM reproducing the relic density and having $\sigma_{XN} \sim \sigma_{\rm ann}$ are so strongly coupled that they essentially stay in equilibrium as long as they are not Boltzmann suppressed, so that they freeze out at temperatures $T_{\rm DMS} \lesssim m_X/3$ for LDM masses of interest here.

Annihilation cross sections.—The magnitude of the annihilation cross section of LDM particles, at cosmological freeze-out time, is fixed by the relic density requirement [1,6]. This leads to $(\sigma_{\rm ann} v_{\rm r}/c)_{\rm F} \simeq$ a few pb.

In the preferred case of a P-wave annihilation cross section (or at least P-wave dominated at freeze-out), $\sigma_{\rm ann} v_{\rm r}$ is roughly proportional to v^2, so that $(\sigma_{\rm ann} v_{\rm r}/c)_{P\text{-wave}} \simeq (3\times10^{-35}\ \text{cm}^2)v^2/c^2$. This also turns out to be the right order of magnitude for a correct injection rate of positrons in the galactic bulge. More precise statements about the respective roles of P-wave and S-wave contributions to LDM annihilations in the galactic bulge depend on assumptions for the profile of the dark matter mass and velocity distribution within the bulge [20].

We shall often have in mind a simple situation in which a scalar or fermionic dark matter particle annihilates (or interacts) through the virtual production (or exchange) [1,6] of a new light gauge boson, U [2]. This leads naturally to a P-wave annihilation cross section, both in the spin-0 case, and in the spin-$\frac{1}{2}$ case as well if the U boson has vectorial (or mostly vectorial) couplings to leptons and quarks.

The couplings of the light U to standard model particles should of course be relatively small. They are restricted, especially for the axial couplings, by searches for axionlike particles, low-$|q^2|$ neutrino scattering experiments, parity-violation atomic-physics experiments, anomalous magnetic moments of charged leptons, etc. [1,2,6,21,22]. The U is then generally expected to be more strongly coupled to dark matter than to standard model particles. For spin-0 LDMs there may also be S-wave contributions to the annihilation amplitudes, from the exchanges of new heavy (e.g., mirror) fermions.

Results on the temperature of the LDM sphere.—In Fig. 1, we plot the temperature of this sphere for a P-wave dominated annihilation cross section ($\propto v^2$), normalized to generate the measured relic density. The results for a S-wave dominated one are found to be very similar, since it has the same value as a P-wave dominated one (up to a factor $\simeq 2$) for a dark matter velocity equal to its freeze-out value, $v_{\rm F} \simeq 0.4c$. The dashed lines in Fig. 1 correspond to various elastic scattering cross sections. The solid line shows, for comparison, the case of a weakly interacting ν_τ with a MeV-scale mass. While the temperature $T \simeq 10$ MeV resulting for massless neutrinos in Fig. 1 comes out a bit higher than the value $\simeq 8$ MeV from more detailed treatments [23], what is most important is the relative value of the LDM and neutrino temperatures.

This shows that MeV-scale LDMs will remain in equilibrium throughout the proto-neutron star at least down to relatively low temperatures $T \simeq 3$ MeV, *as an effect of the large values of the annihilation cross sections of LDM particles*. This occurs even if we do not assume rather high values of the scattering cross sections of LDM particles with ordinary ones. Large scattering cross sections then contribute to further reinforce the effect by increasing the LDM diffusion time allowing to keep LDM particles at chemical equilibrium down to even lower values of the temperature, possibly down to $T_{\rm DMS} \simeq 1$ MeV, as illustrated by the lower dashed curves of Fig. 1.

Consequences for the neutrino temperature.—Thus light dark matter particles with relatively large annihilation cross sections (as required from relic abundance) remain in equilibrium down to lower temperatures, $T \lesssim 3$ MeV. This feature may be transmitted to neutrinos that will stay longer in thermal equilibrium as a result of their interactions with LDM particles, *provided neutrino-LDM cross sections are also enhanced as compared to ordinary neutrino cross sections*.

The kinetic Eqs. (2) and (3), and the one fixing $R_{\rm LS}$ are formally the same for neutrinos, substituting the relevant cross sections and equilibrium density for the neutrino flavor considered. Inside the LDM sphere the relevant quantities may be approximated as

$$D_\nu \simeq \frac{v}{3(n_N \sigma_{\nu N} + n_{\rm eq,X}\sigma_{\nu X})},\qquad \sigma_{\rm ann\nu} \simeq \sigma_{\nu\bar{\nu}\to X\bar{X}({\rm or}XX)} + \sigma_{\rm SM}, \tag{5}$$

where $\sigma_{\rm SM}$ indicates the standard model contribution. The LDMs are kinematically accessible by neutrinos for temperatures not much lower than $m_X/3$. If indeed the cross sections for neutrino-LDM scattering and neutrino annihilations into LDMs are comparable to the ones for LDM-nucleon scattering and LDM annihilations into leptons (supposed to be large), respectively, the quantities in Eq. (5) will be dominated by the nonstandard contributions. This is because LDM cross sections are normally $\simeq$ a few pb (at freeze-out velocity), more than $\simeq 10^4$ larger than weak-interaction cross sections ($\simeq G_F^2 T^2$), at the relevant energies.

Neutrinos should then stay in chemical equilibrium *at least as long as the LDMs do and $T \gtrsim m_X/3$*. We then conclude that $m_X \lesssim 10$ MeV would give rise to neutrino decoupling temperatures $\lesssim 3.3$ MeV for *all* flavors, as compared to $\simeq 8$ MeV for ν_μ and ν_τ in the standard scenario.

This would make it quite unlikely to observe neutrinos with energy of order 30–40 MeV, as have been observed from SN1987A [24], especially for emission spectra that are suppressed at the highest energies compared to thermal distributions because the cross sections increase with energy [23], in which case we can conclude that *lighter LDM masses $\lesssim 10$ MeV are practically excluded*.

All this relies, of course, on the potentially "large" size of the neutrino-LDM scattering and $\nu\bar{\nu} \to$ LDM's annihilation cross sections, normally expected to be comparable to the large LDM's $\to e^+e^-$ annihilation cross section.

There are special situations, however, for which the U boson would have no coupling at all (or suppressed couplings) to neutrinos [25]. Also, for a spin-0 LDM particle interacting through the exchanges of heavy (e.g., mirror) fermions, the ν-LDM interactions gets severely suppressed (as compared to electron or nucleon-LDM interactions), due to the chiral character of the neutrino field [1,6]. In both cases we end up with *no significant enhancement* of neutrino-LDM interactions, so that the presence of the LDM particles has no direct significant effect on the behavior of neutrinos, then still expected to decouple at $\simeq$ 8 MeV (for ν_μ and ν_τ), as usual. In such a case, *no new constraint is obtained on the mass m_X of LDM particles*.

The above results may also be obtained, or understood, as follows. Let us return to LDM particles rather "strongly" coupled to neutrinos (and nucleons), both types of particles decoupling at $T \lesssim 3.3$ MeV. As LDMs can then contribute, at most, as much to the cooling flux as the neutrinos (due to fewer degrees of freedom), the cooling time scale would be larger than in the standard scenario by a factor $\gtrsim (8/3.3)^4/2 \simeq 20$ because the thermal flux is also $\propto T^4$. As SN1987A observations were consistent with the standard cooling time scale of 10–20 s, such nonstandard scenarios are then very strongly disfavored, to say the least.

The cooling time scale can also be estimated by the diffusion time $\tau_{\mathrm{diff}} \sim R_{\mathrm{NS}}^2/\lambda$. This is dominated by the innermost regions of the hot neutron star of size $R_{\mathrm{NS}} \simeq 10$ km, whose density is not significantly modified by the presence of LDM. At a typical temperature $T \simeq 30$ MeV, $\sigma_{\nu N} \simeq 11 G_{\mathrm{F}}^2 T^2/\pi \simeq 1.7 \times 10^{-40}$ cm^2, and at nuclear densities $n_{\mathrm{eq}} \sim n_N/100$. Thus, for neutrino-LDM cross sections comparable to electron-LDM ones (i.e., typically $\gtrsim 4 \times 10^{-36}$ cm^2, so that $\sigma_{\nu X} \gtrsim 10^4 \sigma_{\nu N}$), the neutrino mean free path is dominated by interactions with the thermal population of LDMs, so that $\lambda_\nu \sim (n_{\mathrm{eq}}\sigma_{\nu X})^{-1} \lesssim 0.3$ cm, as compared to $\lambda_\nu \sim (n_N \sigma_{\nu N})^{-1} \sim 35$ cm in the standard scenario. The LDM mean free path is even shorter, $\lambda_{\mathrm{LDM}} \sim (n_N \sigma_{XN})^{-1} \lesssim 1.5 \times 10^{-3}$ cm, assuming $\sigma_{XN} \sim \sigma_{\nu X} \sim \sigma_{eX}$ (or even less if LDM self-interactions were to contribute significantly). In the interior of the proto-neutron star the energy flux is thus dominated by neutrinos. The cooling time scale is a factor $\gtrsim 100$ larger than in the standard scenario, consistent with the previous argument. This cooling time argument may be extended up to higher LDM masses $\simeq 20$ or even 30 MeV, i.e., as long as LDMs are significantly present at $T \simeq 30$ MeV, and rather strongly coupled to neutrinos.

Given that about 3×10^{53} erg of binding energy has to be liberated during τ_{diff}, in the relativistic regime the freeze-out temperature will scale as $T_\nu \propto \tau_{\mathrm{diff}}^{-1/4}$. For $\sigma_{XN} \gtrsim 10^4 \sigma_{\nu N}(T \sim 30\ \mathrm{MeV})$, this argument suggests T_ν will be a factor $\gtrsim 3$ times smaller than usual, as found previously.

In conclusion, we have demonstrated that light dark matter models with generically "large" cross sections fixed to reproduce the relic dark matter density are considerably disfavored by the resulting modification of core-collapse supernova cooling dynamics if the dark matter mass is $\lesssim 10$ MeV, at least.

Depending on how strict γ-ray constraints from the galactic bulge are, the new supernovae constraint presented here could strongly disfavor the possibility that annihilating dark matter particles be the source of the 511 keV emission from the galactic bulge.

Or, conversely, these new results could indicate that neutrino-LDM interactions should *not* be enhanced, favoring a U boson with no (or small) couplings to neutrinos and/or a spin-0 dark matter particle interacting through heavy fermion exchanges.

We would like to thank G. Bertone, T. Janka, and G. Raffelt for helpful discussions. D. H. is supported by the US DOE and by NASA Grant No. NAG5-10842.

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