Constraints on Light Dark Matter From Core-Collapse Supernovae

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(Dated: February 18, 2006)

We show that light (\(1 \sim 30\) 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 \(\sim 10\) 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.

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 100 GeV to TeV scale; neutralinos in supersymmetric theories being one prominent example.

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 non-baryonic 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 \(U\) \cite{1}, light but very weakly coupled \cite{2}, and still leading to relatively “large” annihilation cross sections.

The subsequent observation by the INTEGRAL/SPI experiment of a bright 511 keV gamma-ray line from the galactic bulge \cite{3} could then be viewed as a sign of the annihilations of positrons originating from such light dark matter particle annihilations \cite{4,5}. These LDM particles, explaining both the non-baryonic dark matter of the Universe and the 511 keV line, may have spin \(\frac{1}{2}\) as well as spin-0 \cite{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 \cite{7}.

Although astrophysical sources such as hypernovae have also been proposed as the source of the required positrons \cite{8}, such an origin seems in contradiction with the large extent of the 511 keV emission zone \cite{9} (even if the uncertainties on the low-energy positron propagation and hypernova rate in the bulge are such that it is premature to conclude \cite{10}). 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 \cite{11}).

Given the large rate of positrons produced, smaller dark matter masses tend to be preferred, to avoid an excessive production of unobserved gamma rays \cite{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 gamma rays from the galactic bulge \cite{12}. And, if they were heavier than even 3 MeV, the gamma rays generated through the resulting \(e^+e^-\) annihilations might also be inconsistent with observations \cite{13}.

If MeV-scale dark matter particles do exist, they will be thermally generated in the core of collapsing stars. The presence of these particles 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 through weak interactions down to temperatures \(\sim 2\) or 3 MeV during the expansion of the Universe, and down to \(\sim 8\) 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 \(T_F = m_X = m_p\) with \(m_p\) \(\sim 17\). In a supernova explosion LDM particles will remain in chemical equilibrium with other particles, until the temperature drops down to some value \(T_{D\text{M5}}\) to be determined later (cf. Fig. \textbf{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 \cite{11,22}. 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 for this discussion 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, largely following Ref. \cite{15}. We begin with the transport equation:

\[
\bar{n} + 5^{\gamma} = \frac{\bar{n}_v f}{n^2 \bar{n}_{eq}} \bar{\nu}_L
\]

where \(\bar{n}\) is the LDM flux, \(n\) the number density of LDM par-
particles and \( n_{eq} \) its equilibrium value for a LDM mass \( m_X \) at temperature \( T \) with vanishing chemical potential. \( \sigma_{ann} \) is the LDM, anti-LDM annihilation cross section (or self-annihilation cross section if the LDM is its own antiparticle), and \( v_F \) is representative of 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, 

\[ n = \frac{D}{r} \frac{\partial n}{\partial r} + \frac{D}{r} \frac{\partial^2 n}{\partial r^2} \]

(2)

where the primes denote derivatives with respect to radius \( r \).

We define the “LDM-sphere” as the surface beyond which LDM annihilations (into \( e^+e^- \)) \( \rightarrow \) “freeze out” such that the LDM number is effectively conserved further out. The number density of LDM particles inside of this LDM-sphere should approach its equilibrium value \( n_{eq} \). The radius of the LDM-sphere, \( R_{DS} \), can be estimated by solving

\[ D \frac{n_{eq}}{r} + \frac{D}{r} \frac{\partial n_{eq}}{\partial r} = \sigma_{ann} v_F n_{eq}^2 \]

(3)

The radius of the surface of last scattering of LDM particles is found by solving \( R_{DS} \) \( \rightarrow \) 1: We shall concentrate here on LDM scatterings on nucleons (in practice mostly neutrons) with density \( n_n \) (\( r \)), and elastic cross section \( \sigma_n \) the actual \( R_{DS} \) being at least as large as the one we shall estimate by disregarding the other species. This conservative assumption 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.

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

To determine the LDM-sphere and surface of last scattering for a light dark matter particle, 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. For the latter, we will use the following parameterizations, which should be reasonable within the range 15–100 km we are concerned with.

For LDM masses of interest here.

Results on the temperature of the LDM sphere. In Fig. 1 we plot the temperature of the LDM-sphere in the case of a \( P^- \) wave annihilated dominated annihilation cross section \( \sigma_{ann} \) (\( /r^2 \)), normalized to generate the measured dark matter relic density. The results for a \( S^- \) wave dominated cross section are found to be very similar, since it has the same value as a \( P^- \) wave.

\( R_{DS} \) of a new light gauge boson, \( U \), although the present analysis is more general. This leads naturally to a \( P^- \) wave annihilation cross section, both in the spin-0 case, and in the spin-1 \( S^- \) case as well if the \( U \) boson has vectorial (or mostly vectorial) couplings to leptons and quarks. Axial couplings are already strongly constrained from the non-observation of axiallike particles, and parity-violation effects in atomic physics. For spin-0 particles there may also be \( S^- \) wave contributions to the annihilation amplitudes, from the exchanges of new heavy (e.g. mirror) fermions.
dominated one (up to a factor $\frac{1}{2}$) for a dark matter velocity equal to its freeze-out value, $v_{\text{f.o.}} \approx 0.1 \, c$. The dashed lines in Fig. 1 correspond to various elastic scattering cross sections (see caption). The solid line shows, for comparison, the case of a weakly-interacting dark matter particles with a MeV-scale mass. While the temperature $T \approx 10$ MeV resulting for massless neutrinos in Fig. 1 comes out a bit higher than the value $\approx 8$ MeV from more detailed treatments \cite{19}, 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 $T \approx 3$ MeV, as an effect of the large values of the annihilation cross sections of LDM particles (into ordinary ones). 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 $T_{\text{D M}} \approx 1$ 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, $T < 3$ MeV. This feature may be transmitted to neutrinos, that will themselves 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 equations \cite{18} and the one fixing $R_{L,S}$ are formally the same for neutrinos, substituting the relevant cross sections for scattering and annihilation of neutrinos and the equilibrium density of the relevant neutrino flavor. Inside the LDM sphere the relevant quantities for neutrinos may be approximated as

$$\frac{D}{D t} \left( \frac{\rho_{\nu}}{\rho_{\text{eq}}^{\nu}} \right) = \frac{\lambda_{\text{ann}}}{v^{2}} \left( \frac{n_{\nu}}{n_{\text{eq}}^{\nu}} \right) ;$$

$$\frac{\lambda_{\text{ann}}}{v^{2}} = \frac{1}{x} \left( \frac{\rho_{\nu}}{\rho_{\text{eq}}^{\nu}} \right) ;$$

where cross sections are for the processes indicated as subscript (taking also into account the anti-LDM contribution if LDM particles are not self-conjugate), and $\text{SM}$ indicates the Standard Model contribution. Note that the LDMs are kinetically accessible by neutrinos for temperatures not much lower than $m_{X} = 3$. If indeed the cross sections for neutrino-LDM scattering and neutrino annihilation 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. (6) will be dominated by the non-standard contributions. This is because LDM cross sections are normally a few pb (at freeze-out velocity, to give the appropriate relic abundance), more than $10^{3}$ larger than weak-interaction cross sections ($\frac{\lambda_{\text{ann}}}{v^{2}} \approx 10^{-4}$), at the relevant energies.

This implies that neutrinos (if indeed they have relatively “large” interactions with LDM particles) should stay in chemical equilibrium at least as long as the LDMs do and $T > m_{X} = 3$. We then conclude that $m_{X} < 10$ MeV would give rise to neutrino decoupling temperatures $< 3 \pm 3$ MeV for all flavors, as compared to $8$ MeV for and in the standard scenario.

This would make it quite unlikely to observe neutrinos with energy of order $30 \sim 40$ MeV, as have been observed from SN1987A \cite{20}, especially for emission spectra that are suppressed at the highest energies compared to thermal distributions because the cross sections increase with energy \cite{19}, in which case we can conclude that lighter LDM masses $< 10$ MeV are practically excluded.

All this relies, of course, on the potentially “large” size of the neutrino-LDM scattering and LDM’s annihilation cross sections, normally expected to be comparable to the “large” LDM’s $e^{+} e^{−}$ annihilation cross section. It is worth noting, however, that there are special situations for which the $U$ boson would have no coupling at all (or suppressed couplings) to neutrinos \cite{21}. And that for a spin-0 LDM particle interacting with ordinary ones through the exchanges of heavy (e.g. mirror) fermions, the –LDM interactions would be severely suppressed (as compared to electron or nucleon-LDM interactions), as a result of the chiral character of the neutrino field \cite{18,17}. 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 $\approx 8$ MeV (for and ), as usual. In such a case, no new constraint is obtained on the mass $m_{X}$ of LDM particles.
Furthermore, 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 < 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 \( > \frac{1}{(0.3)^2} \approx 2 \) 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 non-standard scenarios are then very strongly disfavored, to say the least.

The cooling time scale can also be estimated by the diffusion time \( \tau_d \) of \( R_{NS}^2 \). This is dominated by the innermost regions of the hot neutron star of size \( R_{NS} \approx 10 \) km, whose density is not significantly modified by the presence of LDM. At a typical temperature \( T \approx 30 \) MeV, \( n_{\text{eq}} \approx 10^{-2} \) cm\(^{-3}\), and at nuclear densities \( n_{\text{eq}} \rightarrow 100 \). Thus, for neutrino-LDM cross sections comparable to electron-LDM ones (i.e. typically \( > 4 \times 10^{-36} \) cm\(^2\), so that \( X > 10^4 \)), the neutrino mean free path is dominated by interactions with the thermal population of LDMs, so that \( \psi_{\text{eq}} (X) > 0.5 \) cm, as compared to \( \psi_{\text{eq}} (X) \approx 0.5 \) cm in the standard scenario. The LDM mean free path is even shorter, \( \psi_{\text{eq}} (X) < 1 \) cm (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 \( > 100 \) larger than in the standard scenario, consistent with the previous argument. This cooling time argument may be extended up to higher LDM masses \( > 20 \) or even 30 MeV, i.e. as long as LDMs are significantly present at \( T > 30 \) MeV, and rather "strongly" coupled to neutrinos.

Given that about \( 3 \times 10^{53} \) erg of binding energy has to be liberated during \( \tau_d \), in the relativistic regime the freeze out temperature will scale as \( T \sim \tau_d^{1/4} \). For \( X > 10^4 \) (\( T > 30 \) MeV eV), this argument suggests \( T \) will be a factor \( > 3 \) times smaller than usual, as found previously.

In conclusion, we have demonstrated that light dark matter models with generically "large" cross sections fixed by requiring them 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 \( < 10 \) MeV, at least.

Depending on how strict 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 Gianfranco Bertone, Thomas Janka and Georg Raffelt for helpful discussions. DH is supported by the US Dep. of Energy and by NASA grant NAG5-10842.

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[22] This appears as the counterpart of situations in which the propagation of neutrinos could affect the dark matter properties [14].
[23] The factor \( \frac{\tau_d}{\tau_c} \) that ought to be present in the r.h.s. of Eq. 10 then disappears since two self-conjugate LDM particles are removed in each annihilation.
[24] The scatterings of dark matter particles with each other and with themselves may also be important, in which case \( R_{LS} \) would be larger than considered here (solely from nucleons). The same may occur for the scatterings of LDM particles with themselves, as in many situations they are expected to interact more strongly with themselves than with other (Standard Model) particles [12].
[25] Except of course in specific situations for which \( \langle a_n \rangle \) gets reinforced as the exchanged particle (e.g. a U boson) can be nearly on-shell. \( \langle a_n \rangle V_\nu \) could then be large while scattering cross sec-
tions would be significantly smaller.