# SOLAR NEUTRINO SEARCHES AND COLD DARK MATTER

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We consider new data on high energy neutrinos ($E_\nu > 2$ GeV) obtained from the Frejus and Kamioka detectors as well as previous data from the IMB detector and compare the experimental limits on neutrinos from the sun to our expectations based on a cold dark matter hypothesis. We also extend previous work to include a wide variety of cold dark matter candidates.

Postulating the existence of dark matter in the Universe solves a host of astrophysical and cosmological problems. (For a review, see ref. [1].) However, until an experimental determination of the existence and identity of a dark matter candidate, dark matter scenarios remain hypothetical. One approach to searching for dark matter is to look for indirect signatures of its presence. A promising idea is to look for an enhanced high energy neutrino flux from the sun due to annihilations within of dark matter particles [2]. In this letter, we utilize new data from underground "proton decay" detectors to place constraints on properties of dark matter candidates. We also extend previous work to include a wider variety of candidates.

Many scenarios for solving dark matter problems involve a cold dark matter particle X which is massive, $m_X \gtrsim 1$ GeV. If present in the galactic halo, these particles will become trapped [3–5] in the sun due to their elastic scatterings with protons and other nuclei. Inside the sun, they would annihilate and produce a flux of high energy neutrinos [2,6–12]. If the neutrino flux is sufficiently large compared with the atmospheric background flux, a signal could be detected in present underground experiments. Indeed, several experimental groups are searching for such a signal [13–15]. To date, there is no evidence for an enhanced flux in the direction of the sun. The best we can do is place limits on the neutrino flux and hence on the properties of X.

There are many possibilities for dark matter particles: photinos [16,17], higgsinos [17], Majorana neutrinos [18,19], Dirac neutrinos [20,19], and sneutrinos [21]. The capture rate [4,5] of X's in the sun and the flux [6–8] of neutrinos resulting from the annihilations of X's have been calculated. The integrated flux of solar neutrinos, $\bar{S}$, is given by

$$\bar{S} = \tau n_N \int dE\, V_F(E) \times\left(\sigma_\nu(E)\frac{d\Phi_{S,\nu}}{dE} + \sigma_{\bar\nu}(E)\frac{d\Phi_{S,\bar\nu}}{dE}\right), \tag{1}$$

where $\tau$ is the observation time, $n_N$ is the number density of nucleons in the detector, $V_F(E)$ is the fiducial volume of the detector, $\sigma_{\nu(\bar\nu)}(E)$ is the interaction cross section per nucleon for a neutrino (antineutrino) and $d\Phi_{S,\nu(\bar\nu)}/dE$ is the predicted differential flux of solar neutrinos (antineutrinos) integrated over solid angle. A similar formula gives $\bar{A}$, the integrated flux of atmospheric neutrinos; one simply replaces $d\Phi_S/dE$ with $d\Phi_A/dE$. We would like to compare the solar flux to the atmospheric flux. Towards this end we define the ratio

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$$r \equiv \bar{S}/\bar{A}. \tag{2}$$

There are at least two advantages to setting limits on $r$ rather than the number of solar neutrino events per kiloton-year. First, any systematic errors in the overall normalization of the experimental rates will cancel when computing $r$. Second, the experimental limit on $r$ may be computed just by knowing the numbers of events of a given type; it is not necessary to know the observation time, fiducial volume, etc. It is, however, necessary to have a theoretical determination of the atmospheric flux in order to predict $r$ for a given dark matter candidate. We use the calculation of Volkova [22]; Volkova's results are in agreement with the data to date. (For a review, see ref. [23].)

The calculation of $\bar{S}$ and $\bar{A}$, as given by eq. (1), depends on the type of neutrino event we wish to consider: contained events, or through-going muons produced in the surrounding rock. Previously [10], we calculated limits on $r$ based on the IMB data [13] for contained events with $1\ \mathrm{GeV} < E_\nu < 2\ \mathrm{GeV}$ and through-going muon events with $E_{\nu_\mu} > 2\ \mathrm{GeV}$. We compared these limits to the predictions resulting from photinos, higgsinos, and sneutrinos as dark matter. Here we will use data from Kamioka [14] and Frejus [15] as well as IMB to derive a limit on $r$ for contained events with $E_\nu > 2\ \mathrm{GeV}$. We will also compute the expected value of $r$ for this case for a large variety of dark matter candidates.

Because the data we are using involves relatively few events, any limit we quote only makes sense up to some confidence level which depends on our statistical analysis. We use an analysis suggested by Protheroe [24] which is based on bayesian statistics [25]. Let $T$ be the total number of events of a specified type (i.e., contained, neutrino energy within a certain range, etc.). Let $C$ be the number of events of this type due to neutrinos coming from within a cone of solid angle $4\pi p$ centered on the sun. Given the values of $\bar{A}$ and $\bar{S}$, the probability of observing $C$ events in the solar cone with a total of $T$ events is the product of two Poisson distributions, one for events inside the cone, and one for events outside:

$$P(C, T; \bar{A}, \bar{S}) = \left( \frac{(\bar{S}+p\bar{A})^C \exp[-(\bar{S}+p\bar{A})]}{C!} \right) \times \left( \frac{[(1-p)\bar{A}]^{T-C} \exp[-(1-p)\bar{A}]}{(T-C)!} \right). \tag{3}$$

Of course, what we really want to do is use the observed values of $C$ and $T$ to get information on $\bar{A}$ and $\bar{S}$. All we know about $\bar{A}$ and $\bar{S}$, a priori, is that neither can be negative. We therefore assume that, a priori, $\bar{A}$ and $\bar{S}$ are equally likely to have any non-negative values. Then, according to Bayes' theorem [25], after doing the experiment (and finding $C$ events in the solar cone with a total of $T$ events) we can interpret $P(C, T; \bar{A}, \bar{S})$ as an unnormalized joint probability distribution for $\bar{A} \geqslant 0$ and $\bar{S} \geqslant 0$. The 90% confidence level (CL) upper limit on $r$, $r_{90}$, is then found by demanding that the probability that $\bar{S}$ is less than $r_{90}\bar{A}$ be exactly 0.9:

$$\frac{\int_0^\infty \mathrm{d}\bar{A} \int_0^{r_{90}\bar{A}} \mathrm{d}\bar{S}\, P(C, T; \bar{A}, \bar{S})}{\int_0^\infty \mathrm{d}\bar{A} \int_0^\infty \mathrm{d}\bar{S}\, P(C, T; \bar{A}, \bar{S})} = 0.9. \tag{4}$$

By changing the integration variables from $\bar{A}$ and $\bar{S}$ to $\bar{A}+\bar{S}$ and $r$, we can do the integral over $\bar{A}+\bar{S}$ and rewrite eq. (4) as

$$\frac{\int_0^{r_{90}} \mathrm{d}r\, (1+r)^{-2} (r+p)^C (1+r)^{-T}}{\int_0^\infty \mathrm{d}r\, (1+r)^{-2} (r+p)^C (1+r)^{-T}} = 0.9. \tag{5}$$

The integrals in eq. (5) can be done in closed form; a convenient statement of the result is

$$F(\lambda_{90}) = (0.1)\, F(p), \tag{6}$$

where

$$F(x) \equiv (1-x)^{T-C+1} \sum_{S=0}^{C} \frac{(T-C+S)!}{(T-C)!\,S!} x^S, \tag{7}$$

and

$$r_{90} = \frac{\lambda_{90} - p}{1 - \lambda_{90}}. \tag{8}$$

Here $\lambda = (\bar{S}+p\bar{A})/(\bar{S}+\bar{A})$ is the probability that any one event is in the solar cone. Eq. (5) has a particularly simple solution when there are no events in the solar cone ($C=0$):

$$r_{90} = 10^{1/(T+1)} - 1. \tag{9}$$

Note that in this case, $r_{90}$ is independent of $p$. This may seem counterintuitive. The point is that if $\bar{S}=0$, the expected value of $C$ is $pT$. So we only expect to find $C=0$ if $pT \lesssim 1$. Further reducing $p$, so that $pT \ll 1$, does not give us any more information; in fact, one could argue that it gives us *less*, since $C=0$ is now even closer to the expectation value $pT$. (A conventional [26], as opposed to bayesian, statistical analysis reflects this: it yields a value of $\lambda_{90}$ which is always independent of $p$, and so $r_{90}$ [see eq. (8)] *increases* as $p$ decreases for fixed $C$ and $T$.)

Previously, we had analyzed the IMB data for the following types of events:

(1) Contained events with 1 GeV $< E_\nu <$ 2 GeV, of which there were 11 events within 30° of the sun ($p=0.067$) out of a total of 89 events, yielding [10] $R \equiv r/p < 2.1$ at the 90% CL or

$$r < 0.14$$

$$\text{(IMB, contained, } 1\text{ GeV} < E_\nu < 2\text{ GeV}). \qquad (10)$$

(2) Through-going muon events with $E_\nu < 2$ GeV, of which there were two events within 8° of the sun ($p=0.005$) out of a total of 187 events, yielding [10] $R < 4.8$ at the 90% CL or

$$r < 0.024$$

$$\text{(IMB, through-going muons, } E_\nu > 2\text{ GeV}). \qquad (11)$$

(3) Contained events with $E_\nu > 2$ GeV, of which there were none within 30° of the sun out of a total of 10 events, yielding a 90% CL limit of

$$r < 0.23$$

$$\text{(IMB, contained, } E_\nu > 2\text{ GeV}). \qquad (12)$$

(This number was not given in ref. [10]; we include it here for completeness.)

Recently, both the Kamioka and Frejus Collaborations reported data in searches for a high energy solar neutrino excess. For contained events with $E_\nu > 2$ GeV, Kamioka reports a total of 23 events, none in the solar direction, giving a 90% CL limit of

$$r < 0.10$$

$$\text{(Kamioka, contained, } E_\nu > 2\text{ GeV}). \qquad (13)$$

Frejus reports a total of 31 events, again with none in the solar direction, giving a 90% CL limit of

$$r < 0.075$$

$$\text{(Frejus, contained, } E_\nu > 2\text{ GeV}). \qquad (14)$$

Note that we do not need to know the angular resolutions of the detectors, since $r_{90}$ is independent of $p$ when $C=0$.

To combine data for contained events with $E_\nu > 2$ GeV from the three experiments, we need to modify eq. (3). The right-hand side is replaced by a multiple product of Poisson distributions (two for each experiment). Since each experiment will have a different observing time and fiducial volume, the values of $\bar{A}$ and $\bar{S}$ will differ among the experiments; however, the ratio $r=\bar{S}/\bar{A}$ will be universal (provided we are considering events of the same type). If $p_i$, $C_i$, and $T_i$ are the corresponding quantities for each experiment, then the integrand in eq. (5), in both the numerator and denominator, is replaced by

$$(1+r)^{-2} \prod_i (r+p_i)^{C_i} (1+r)^{-T_i}. \qquad (15)$$

The product is over the different experiments. If $C_i=0$ for all experiments, as it does for the data in the three experiments for contained events with $E_\nu > 2$ GeV, one can simply use eq. (9) with $T=\sum_i T_i$. In this case, there are a total of 64 events, yielding the 90% CL limit

$$r < 0.036$$

$$\text{(combined, contained, } E_\nu > 2\text{ GeV}). \qquad (16)$$

We note that these limits on $r$ can be converted to limits on solar events per kiloton-year (for a given detector) by multiplying by the predicted number of atmospheric events per kiloton-year (for that detector).

Let us now compare these limits with our expectations for the various dark matter candidates. In tables 1–6, we show our predictions for $r$ for the three event types we have discussed: (1) contained events

Table 1
Photinos.

| $m_{\tilde\gamma}$ (GeV) | $r$ | | |
|---|---|---|---|
| | case 1 | case 2 | case 3 |
| 4 | 0.11 | 0.014 | 0.097 |
| 6 | 0.032 | 0.015 | 0.077 |
| 10 | 0.0067 | 0.016 | 0.054 |
| 20 | – | 0.0066 | 0.013 |
| 40 | – | 0.0023 | 0.0023 |
| limit | 0.14 | 0.024 | 0.036 |

Table 2
Higgsinos.

| $m_{\tilde{H}}$ (GeV) | $r$ | | |
|---|---|---|---|
| | case 1 | case 2 | case 3 |
| 6 | 0.045 | 0.0091 | 0.052 |
| 10 | 0.0084 | 0.010 | 0.040 |
| 20 | – | 0.0057 | 0.012 |
| 40 | – | 0.0023 | 0.0025 |
| limit | 0.14 | 0.024 | 0.036 |

Table 3
Majorana neutrinos.

| $m_{\nu_M}$ (GeV) | $r$ | | |
|---|---|---|---|
| | case 1 | case 2 | case 3 |
| 6 | 0.055 | 0.011 | 0.064 |
| 10 | 0.023 | 0.028 | 0.11 |
| 20 | 0.0058 | 0.051 | 0.11 |
| 40 | – | 0.078 | 0.082 |
| limit | 0.14 | 0.024 | 0.036 |

Table 4
Dirac neutrinos.

| $m_{\nu_D}$ (GeV) | $r$ | | |
|---|---|---|---|
| | case 1 | case 2 | case 3 |
| 4 | – | 0.022 | 0.087 |
| 6 | – | 0.044 | 0.12 |
| 10 | – | 0.10 | 0.17 |
| 20 | – | 0.30 | 0.24 |
| 40 | – | 0.70 | 0.28 |
| limit | 0.14 | 0.024 | 0.036 |

Table 5
Scalar electron neutrinos.

| $m_{\tilde{\nu}_e}$ (GeV) | $r$ | | |
|---|---|---|---|
| | case 1 | case 2 | case 3 |
| 4 | – | – | 3.7 |
| 6 | – | – | 6.3 |
| 10 | – | – | 11 |
| 20 | – | – | 20 |
| 40 | – | – | 26 |
| limit | 0.14 | 0.024 | 0.036 |

Table 6
Scalar muon neutrinos.

| $m_{\tilde{\nu}_\mu}$ (GeV) | $r$ | | |
|---|---|---|---|
| | case 1 | case 2 | case 3 |
| 4 | – | 0.50 | 1.4 |
| 6 | – | 1.3 | 2.3 |
| 10 | – | 3.8 | 4.1 |
| 20 | – | 13 | 9.5 |
| 40 | – | 35 | 18 |
| limit | 0.14 | 0.024 | 0.036 |

with 1 GeV $<E_\nu<2$ GeV; (2) through-going muon events with $E_{\nu_\mu}>2$ GeV; and (3) contained events with $E_\nu>2$ GeV. To calculate $\bar{A}$, we use the differential atmospheric fluxes derived by Volkova [22]. To calculate $\bar{S}$ for photinos, higgsinos, and Majorana neutrinos, we take the differential fluxes $\mathrm{d}\Phi_S/\mathrm{d}E$ from ref. [8]. For solar neutrinos, $\mathrm{d}\Phi_{S,\nu_e}/\mathrm{d}E=\mathrm{d}\Phi_{S,\bar{\nu}_e}/\mathrm{d}E=\mathrm{d}\Phi_{S,\nu_\mu}/\mathrm{d}E=\mathrm{d}\Phi_{S,\bar{\nu}_\mu}/\mathrm{d}E$. These fluxes are integrated over the appropriate energy range. For Dirac neutrinos and sneutrinos, we consider only the monochromatic flux of neutrinos resulting from annihilation into a single $\nu\bar{\nu}$ pair, and use the total flux calculated in ref. [6]. The differential flux in these cases is just $\mathrm{d}\Phi_S/\mathrm{d}E=\Phi_S\delta(E-m_X)$. For photinos, we assume that all scalar quark and lepton masses are equal, and adjust the value of this common mass so that $\Omega=1$ with $h=0.5$ [#1]. For higgsinos, we adjust the ratio of Higgs field expectation values $V_1/V_2$ so that $\Omega=1$ with $h=0.5$. These adjustments, in turn, affect the scattering cross sections which are used to compute the rate at which the sun traps dark matter particles. For heavy neutrinos (Majorana or Dirac) and sneutrinos, we do not adjust any parameters other than the mass. In the case of heavy neutrinos, this means that $\Omega$ will vary with the mass; it will equal one for $m_{\nu_M}\simeq 6$ GeV in the Majorana case and for $m_{\nu_D}\simeq 4.5$ GeV in the Dirac case [19,27], but drop as these masses increase. We also note that a higgsino with $V_1/V_2$ equal to zero or infinity (called "generic" in ref. [8]) is equivalent to a Majorana neutrino. For sneutrinos with $m_{\tilde{\nu}}\lesssim 7$ GeV, the scattering cross sec-

[#1] $\Omega$ is the mass density of relic particles in units of the critical density $\rho_c=1.054\times10^{-5}$ GeV cm$^{-3}$, and $h$ is the Hubble parameter in units of 100 km s$^{-1}$ Mpc$^{-1}$.

tion is independent of the annihilation cross section, and we can have $\Omega=1$; for larger values of $m_{\tilde{\nu}}$, the annihilation cross section rises due to $Z^0$ exchange, and $\Omega$ decreases [6]. We make use of the detailed results of a forthcoming numerical study of the rate equation governing relic stable particle densities [27]. In some cases these results differ substantially from the approximate formulas we used previously. The greatest uncertainty in the results comes from our lack of knowledge about the quark/hadron phase transition, and is most significant for particles with masses of 5 GeV to 10 GeV. To be conservative, we have assumed a transition temperature near 100 MeV, which minimizes the expected solar fluxes relative to those we would find using a larger transition temperature. We have also employed Gould's corrections [5] to the Press–Spergel [4] trapping rate; in addition to an overall correction factor of 1.5, we used the solid line in Gould's fig. 3 for photinos, higgsinos, and Majorana neutrinos, and the dashed line for Dirac neutrinos and sneutrinos.

Comparing the values in the tables, we see that the expected value of $r$ exceeds the experimental 90% CL upper limit in case 2 or case 3 for a variety of dark matter candidates: photinos with 4 GeV $\lesssim m_{\tilde{\gamma}} \lesssim 10$ GeV; higgsinos with 6 GeV $\lesssim m_{\tilde{H}} \lesssim 10$ GeV; Majorana neutrinos with $m_{\nu_M} \gtrsim 6$ GeV; Dirac neutrinos with $m_{\nu_D} \gtrsim 4$ GeV; and sneutrinos (either electron type or muon type) with $m_{\tilde{\nu}} \gtrsim 4$ GeV. However, the uncertainties involved make it difficult to make a strong case against any of the candidates except sneutrinos. An example of the type of uncertainty involved is the local density of dark matter. The trapping rate – and hence the annihilation rate and the neutrino flux – depend on the combination of $n_X/\bar{v}$, where $n_X$ is the local number density for X's and $\bar{v}$ is their RMS velocity. We have taken $n_X = (0.3\ \mathrm{GeV}/m_X)\ \mathrm{cm}^{-3}$ and $\bar{v}=300$ km/s. Previously [10] we noted that uncertainties in both $n_X$ and $\bar{v}$ would allow the ratio to vary from 0.14 to 2.3 times our nominal value. Recently, the question of local density has been reexamined [28] and it was suggested that perhaps the uncertainty range is much smaller: 0.7–1.4 times our nominal value. Other studies [29] involving a flattened halo allow for larger densities of up to a factor of three times our nominal value. Another uncertainty [12] is the effect of fragmentation on the annihilation products. Such an effect might lower the neutrino fluxes by a factor of two. We think the overall uncertainty is at least a factor of four.

Looking back at the tables, we see that for photinos and higgsinos, the predicted values of $r$ never exceed the experimental limits by a factor of four or more. For heavy neutrinos and sneutrinos, we still exceed the limits by a factor of four for larger values of the mass. However, it is worth mentioning again that these cases are somewhat artificial in that we do not expect $\Omega=1$ for these candidates except for specific values of the mass. At those values, we have the excess factor of four that we would like only for sneutrinos (both electron and muon type). Furthermore, if $\Omega$ drops below about 0.05, there would not be enough dark matter to form galactic halos; this occurs for Majorana neutrinos if $m_{\nu_M} \gtrsim 35$ GeV and for Dirac neutrinos if $m_{\nu_D} \gtrsim 16$ GeV [27].

It is also important to note that we are using a 90% confidence level. If we consider the 95% CL instead, the limit on $r$ in case 3, eq. (16), becomes $r<0.047$; at the 99% CL, the limit becomes $r<0.073$.

In conclusion, the non-observation of a high energy solar neutrino flux appears to rule out scalar muon neutrinos and scalar electron neutrinos as dark matter. The other dark matter candidates are not presently ruled out when one takes into account the various uncertainties in the input parameters (such as $n_X$), but certain ranges of this parameter space can be excluded. The viability of photinos and higgsinos as dark matter will be further challenged by future data.

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## References

[1] D.N. Schramm, Nucl. Phys. B 252 (1985) 53.
[2] J. Silk, K.A. Olive and M. Srednicki, Phys. Rev. Lett. 55 (1985) 257.
[3] G. Steigman, C. Sarazin, H. Quintana and J. Faulkner, Astron. J. 83 (1978) 1050.
[4] W.H. Press and D.N. Spergel, Astrophys. J. 296 (1985) 67.
[5] A. Gould, Astrophys. J. 231 (1987) 571.

[6] M. Srednicki, K.A. Olive and J. Silk, Nucl. Phys. B 279 (1987) 804.
[7] T.K. Gaisser, G. Steigman and S. Tilav, Phys. Rev. D 34 (1986) 2206.
[8] J.S. Hagelin, K.-W. Ng and K.A. Olive, Phys. Lett. B 180 (1986) 375.
[9] K. Greist and D. Seckel, Nucl. Phys. B 283 (1987) 681.
[10] K.-W. Ng, K.A. Olive and M. Srednicki, Phys. Lett. B 188 (1987) 138.
[11] S. Ritz and D. Seckel, CERN preprint TH-4627 (1987).
[12] J. Ellis, R.A. Flores and S. Ritz, Phys. Lett. B 198 (1987) 393.
[13] IBM Collab., J. LoSecco et al., Phys. Lett. B 188 (1987) 388.
[14] Kamioka Collab., Y. Totsuka, University of Tokyo preprint UT-ICEPP-87-02 (1987).
[15] Frejus Collab., B. Kuznik, Orsay preprint LAL 87-21 (1987).
[16] H. Goldberg, Phys. Rev. Lett. 50 (1983) 1419;
L.M. Krauss, Nucl. Phys. B 227 (1983) 556.
[17] J. Ellis, J. Hagelin, D.V. Nanopoulos, K.A. Olive and M. Srednicki, Nucl. Phys. B 238 (1984) 453.
[18] L.M. Krauss, Phys. Lett. B 128 (1983) 37.
[19] E.W. Kolb and K.A. Olive, Phys. Rev. D 33 (1986) 1202; D 34 (1986) 2531 (E).
[20] P. Hut, Phys. Lett. B 69 (1977) 85;
B. Lee and S. Weinberg, Phys. Rev. Lett. 39 (1977) 165.
[21] L.E. Ibáñez, Phys. Lett. B 137 (1984) 160;
J. Hagelin, G.L. Kane and S. Raby, Nucl. Phys. B 241 (1984) 638.
[22] L.V. Volkova, Sov. J. Nucl. Phys. 31 (1980) 784.
[23] D.H. Perkins, Annu. Rev. Nucl. Part. Sci. 34 (1984) 1.
[24] R.J. Protheroe, Astron. Express 1 (1984) 33.
[25] S.A. Schmitt, Measuring uncertainty: an elementary introduction to bayesian statistics (Addison-Wesley, Reading, 1969).
[26] Particle Data Group, M. Aguilar-Benitez et al., Review of particle properties, Phys. Lett. B 170 (1986) 52.
[27] M. Srednicki, R. Watkins and K.A. Olive, in preparation.
[28] R. Flores, CERN preprint TH-4736/87 (1987).
[29] J. Binney, A. May and J. Ostriker, Mon. Not. R. Astron. Soc. 226 (1987) 149.