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SOLITONIC DARK MATTER AND THE SOLAR NEUTRINO PROBLEM

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Weakly interacting massive particles (known as cosmions) have been proposed as a possible solution to the solar neutrino problem. However, in order to successfully reduce the neutrino flux, their scattering cross section on hydrogen must be two orders of magnitude larger than the typical weak cross section. We suggest that finite-size, bound configurations of weakly interacting particles, known as non-topological solitons, can naturally produce the necessary enhancement of the cross section. For a simple model exhibiting solitonic configurations formed in a primordial phase transition with a calculable mass spectrum, solitons with masses of a few GeV and higher are shown to solve the solar neutrino problem *and* to provide the energy density needed to close the universe.

There is a well-known discrepancy between the measured [1] and the predicted [2] flux of neutrinos from the Sun. For example, the more recent result from Kamiokande II finds that the ratio of the observed flux of ^{8}B neutrinos to the predicted flux is $0.46 \pm 0.13 \pm 0.08$, the first error being statistical and the second systematic [3]. Assuming that there is indeed a "solar neutriho problem", several solutions have been proposed in the literature over the past few years. They fall into one of two categories: either modify the properties of the neutrino or modify the Sun's interior conditions. Included in this latter category is the idea that the core temperature is slightly lower than expected in standard solar models (the ^{8}B decay neutrino flux is extremely temperature sensitive). As suggested by Spergel and Press [4], and calculated more accurately by Gilliland et al. [5], the presence in the Sun of a weakly interacting massive particle (hereafter cosmion) with just the right properties would indeed reduce the core temperature by the correct amount, as it enhances energy transport from the core to the exterior regions. The cosmion needs to have a scattering cross section on hydrogen of about $\sigma_s \sim 10^{-36}$ cm^2, a mass in the range 4–10 GeV, and to be present at the level of $N_{\rm cosmion}/N_{\rm baryon} \sim$

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10^{-12}–10^{-11}. Lower mass particles evaporate over the Sun's lifetime while those with a larger mass orbit too close to the center to alter the neutrino flux significantly. Press and Spergel [6] also demonstrated that if these particles are present in the galactic halo, they would be captured over the Sun's lifetime, achieving an abundance by number given by the expression

$$\frac{N_{\text{cosmion}}}{N_{\text{baryon}}} = 3 \times 10^{-9} \left(\frac{\rho_{\text{cosmion}}}{1 M_{\odot}\ \text{pc}^{-3}} \right) \left(\frac{v_{\text{esc}}}{v} \right) \left(\frac{\sigma_{\text{s}}}{\sigma_{\text{crit}}} \right) \left(\frac{m_{\text{p}}}{m_{\text{cosmion}}} \right). \tag{1}$$

Here ρ_{cosmion} is the density of the cosmions in the halo, $v_{\text{esc}} = 618$ km s^{-1} is the Sun's escape velocity, $v \sim 300$ km s^{-1} is the velocity dispersion of the cosmions in the halo, m_{p} is the proton mass, m_{cosmion} is the cosmion mass, $\sigma_{\text{crit}} \equiv 4.0 \times 10^{-36}$ cm^2, and σ_{s} is the cosmion's actual scattering cross section on hydrogen. For $\sigma_{\text{s}} > \sigma_{\text{crit}}$ the cross section ratio saturates at unity. The halo density is about $0.01 M_{\odot}$ pc^{-3}, and so we see that the Sun can capture cosmions with an abundance ratio in the range of 10^{-12}–10^{-11} for the cross section and mass range above, as is needed. Equation (1) ignores the possible annihilation of the cosmions once captured. We will discuss this below.

Various particle models have been given for the cosmion [7–11]. One of the main issues in the construction of these models is achieving the large required scattering cross section, which is about 100 times the typical weak cross section of $\sim 10^{-38}$ cm^2 [9, 10]. In this note we propose another model for the cosmion, namely one in which the cosmion is not an elementary particle but, instead, is a stable field configuration known as a non-topological soliton (hereafter NTS). In such a model, we shall argue that the large scattering cross section can easily be achieved. NTSs owe their stability to the conservation of a global charge, carried by either a spin-0 or spin-$\frac{1}{2}$ field. Within renormalizable theories, the simplest models exhibiting NTS solutions have the charge carrying field coupled to a real scalar field in such a way as to have different masses in the different vacua of the theory; in the NTS interior the charge carrying field is massless, while outside the field is massive. It is this mass gap that renders the soliton stable; the massless particles are trapped inside the soliton, giving rise to an effective kinetic pressure that balances the surface and/or volume pressures coming from the interaction potential of the real scalar field. If the trapped charge Q is larger than a certain value Q_{min}, stable equilibrium configurations are found to exist and to have smaller energy than the free massive particles would. In other words, the NTSs are the favored energy configuration. There is an extensive literature on NTSs, and we refer the reader to ref. [12] for details. Within realistic models of particle physics, the obvious candidate for the global charge is bayron number (or, if the particles are only weakly interacting, lepton number). Recently, there have been some efforts to construct NTS solutions in the standard model, with partial success; it has been found that NTS solutions are possible and are the ground state of matter for quite a narrow window of allowed Higgs masses around $m_H \sim 6.6$ GeV [13]. Extensions to the standard model, supersymmetric or not, offer a wider range of possibilities but remain largely unexplored. Here we will adopt the point of view that cosmion physics calls for physics beyond the standard model [7–11], and will assume that the requirements to find NTS solutions in particle physics models are general enough as to be met by most non-trivial extensions to the standard model.

The prime motivation for proposing the NTS as the cosmion comes from considering how such configurations would interact with a proton; a soliton of charge Q can be thought of as a coherent state of Q particles. Assuming that the constituent particles each interact with the proton with the typical weak cross section, the solitons and protons would scatter coherently with a cross section that scales as Q^2. Thus, a NTS with $Q = 10$ would "naturally" provide the desired enhancement of the weak cross section. Below we develop the properties of this NTS cosmion in the context of a simple model which accounts for its production in the early universe, proposed recently by Frieman, Gelmini, Gleiser and Kolb [14] (hereafter FGGK). We shall show, using this model, that it is possible for the solitons to *both* close the universe *and* to behave as cosmions. We assume throughout that $\Omega_{tot} \equiv \rho_{tot}/(3H_0^2/8\pi G) = 1$, as preferred by inflation, where ρ_{tot} is the total energy density of the universe, G is the gravitational constant and H_0 ($\equiv 100 h_0$ km s^{-1} Mpc^{-1}) is the present day Hubble parameter. For the calculations below, $h_0 = 0.5$.

The simplest generic theory with soliton solutions is given by the lagrangian

$$L = |\partial\phi|^2 + \tfrac{1}{2}(\partial\sigma)^2 - U, \tag{2}$$

where

$$U(|\phi|^2, \sigma) = \tfrac{1}{8}\lambda_1(\sigma^2 - \sigma_0^2)^2 + h|\phi|^2(\sigma - \sigma_0)^2 + \tfrac{1}{3}\lambda_2(\sigma - \sigma_0)^3\sigma_0 + g|\phi|^4 + \Lambda. \tag{3}$$

The soliton is a false vacuum configuration with $\sigma = \sigma_0$, and hence $m_\phi = 0$, as opposed to the true vacuum solution with $\sigma = \sigma_-$, the global minimum of $U(0, \sigma)$, and $m_\phi \neq 0$. We will follow FGGK and set the coupling g to zero. Being a repulsive self-interaction between the trapped particles, this coupling can change the properties of the solitons somewhat [15]. However, the approach used here can easily be extended to include this case, without change in the qualitative picture. Also, there is no fundamental reason for the charge carrying field to be a scalar. Solitons are as easily obtained by trapping fermions with false vacuum energy, in the same spirit as the bag models for hadrons. As at this point there is no compelling evidence in favor of either scalar or fermion solitons, we choose a model which has the virtue of simplicity without the burden of triviality. The vacuum scale Λ is defined such that $U(0, \sigma) = 0$ at the global minimum σ_-. The free parameters of the theory are thus taken to be λ_1, $a \equiv \lambda_2/\lambda_1$, h, σ_0 and η_ϕ, the cosmic asymmetry between ϕ and its antiparticle, which is assumed to exist in the FGGK model but can be relaxed in other models of solitogenesis [16]. Note, however, that if baryon number (lepton number) is the required global charge, an asymmetry comes about naturally. In what follows we present a model where the asymmetry is determined by the requirement that the NTSs close the universe.

The five parameters must be chosen to satisfy four constraints, thereby leaving one free parameter which we choose to be a. The four constraints are determined by the desire to both close the universe with the NTSs (fixing $\Omega^{\mathrm{T}}_{\mathrm{NTS}}$, the total contribution to the energy density from NTSs with *all* possible values of the charge Q) and to satisfy the cosmion conditions for the NTS with $Q = Q_{\min}$, the lightest stable NTS, which we call "minimal NTS" from now on; $M_{\mathrm{NTS}} = 4 - 10$ GeV, and $\sigma_{\mathrm{s}} \approx 100\sigma_{\mathrm{W}}$. We choose the minimal NTS as the cosmion since it is the most abundant, as we shall see. The free massive ϕ's outside are assumed to have decayed, giving negligible contribution to the energy density of the universe (see ref. [16]). The minimal solitons should be present at the level required for the Sun to capture enough over its lifetime to significantly alter the solar neutrino flux today. This implies that they should dominate the galactic halo density.However, the uncertainty in halo models and in expression (1) implies a factor of $\gtrsim 2$ uncertainty in the required halo density of cosmions. Since galactic halos amount to a cosmological abundance of ~ 0.1, we require the minimal NTS cosmic density to be $\Omega^{\min}_{\mathrm{NTS}} \geq 0.1$. For concreteness we will choose $\Omega^{\min}_{\mathrm{NTS}} = 0.1$. The NTSs with $Q > Q_{\min}$ then contribute $\Omega^{>}_{\mathrm{NTS}} = 0.8$, assuming the baryons have $\Omega_{\mathrm{b}} = 0.1$. With these definitions, the total contribution in NTSs is $\Omega^{\mathrm{T}}_{\mathrm{NTS}} = \Omega^{>}_{\mathrm{NTS}} + \Omega^{\min}_{\mathrm{NTS}} = 0.9$. (Of course, these specific values are just chosen for calculational purposes.) We also require that the minimal NTS satisfy the cosmion conditions on scattering cross section and mass, so that

$$\Omega^{>}_{\mathrm{NTS}} = 0.8, \qquad \Omega^{\min}_{\mathrm{NTS}} = 0.1, \qquad \Omega_{\mathrm{b}} = 0.1,$$
$$\sigma_{\mathrm{s}} \approx 10^{-36}\ \mathrm{cm}^2, \qquad M_{\mathrm{NTS}} \sim 4 - 10\ \mathrm{GeV}. \tag{4}$$

We must now apply these conditions to the FGGK model. First, let us recall how NTSs are formed in this model. The basic idea of the formation mechanism is to examine the evolution of the potential defined in eq. (3) in the early universe. As the temperature cools below the relevant mass scale in the model ($T \sim \sigma_0$), two vacua will appear in the effective potential, with the σ-field thermally fluctuating between them. Thus, both vacua will be populated with a rate given by the Boltzmann factor. (We assume thermal equilibrium is maintained, i.e. only weakly first order or second order.) As the temperature continues to go down, thermal fluctuations become progressively suppressed, until, at a temperature commonly called the Ginzburg temperature (T_{G}), they become dynamically forbidden; there is not enough thermal energy in the system to induce a "jump" over the potential barrier separating the two vacua. FGGK showed that the probability of having a fluctuation ending up in the false vacuum (the NTS) at freeze-out is very sensitive to the asymmetry between the two minima; the bigger the asymmetry the more difficult it is to be in the false vacuum. Thus, there are basically two possible outcomes for the freeze-out process, depending on the asymmetry of the potential.

Roughly, for $a < 0.13$ (recall that a, being the coefficient of the cubic coupling, induces the asymmetry in the potential at tree level) both vacua will percolate, and the universe will be permeated by an infinite domain wall, as is familiar from discrete symmetry breaking with degenerate potentials. Due to the asymmetry, the domain wall will move from the true to the false vacuum regions, pinching off domains of false vacuum in the process. If the charge trapped inside these pinched domains is larger than $Q_{\rm min}$, these domains will be stable NTSs. Domain walls in an asymmetric universe were studied in ref. [17]. If $a > 0.13$ only the true vacuum percolates, and the universe will be filled with isolated bubbles of false vacuum. Again, if the charge in these bubbles is bigger than $Q_{\rm min}$, NTSs are formed. FGGK showed that in this case it is possible to use results from percolation theory to estimate the population of NTSs in the universe. For this reason, we will consider only this latter case in our calculations, although other formation mechanisms are certainly possible. (The actual calculation of $T_{\rm G}$ involves comparing the expansion rate of the universe to the thermal fluctuation rate, obtained by exponentiation of the O(3)-symmetric euclidean action at finite temperatures [18]. The value of $T_{\rm G}$ is of extreme importance for the survival of NTSs, at least in the context of the present formation mechanism, as has been shown by Frieman et al. [16]. For temperatures $T \geqslant I_{\rm b} \sim m_\phi$ (where $I_{\rm b}$ is the NTSs binding energy per particle) the NTSs can evaporate into free ϕ's. Thus, the lower the value of $T_{\rm G}$ the better the chance the NTSs have for survival. For $T_{\rm G} \leqslant m_\phi/30$ or so, evaporation is substantially suppressed. It is not clear at present if such values of $T_{\rm G}$ are naturally attainable, although they are by no means prohibitive. We will assume our NTSs will not suffer substantial evaporation. Of course, if this assumption fails, the other formation mechanisms can be invoked, such as the pinching walls mechanism or the more recent random-charge fluctuations mechanism [16], although the estimates for the NTS population are not as clear in these mechanisms as in the FGGK mechanism.)

From FGGK the present density of NTSs with charge Q is given by

$$\Omega_{\rm NTS} h_0^2(Q) = 5 \times 10^9 \left(\frac{\eta_\phi}{\lambda_1} \right)^{3/2} Q^{-3/4} \left(\frac{\Lambda}{\rm TeV^4} \right)^{1/4} {\rm e}^{-Q\lambda_1^3/\eta_\phi}, \qquad (5)$$

where we have set their constants b and c to unity. Note that the contribution from NTSs with higher values of the charge Q is exponentially suppressed. This fact led the authors of refs. [14] and [16] to completely neglect the contribution to the energy density of the universe from all NTSs with $Q > Q_{\min}$. However, it can be seen that this approximation is incorrect in most cases; even though higher charges are exponentially suppressed, they still give a relevant (and in the present paper the dominant) contribution to Ω_{tot}. Indeed, the total contribution from NTSs can be written, from eq. (5), as

$$\Omega_{\text{NTS}}^{\text{T}} h_0^2 = \Omega_{\text{NTS}}^{>} h_0^2 + \Omega_{\text{NTS}}^{\min} h_0^2 = \sum_{Q \geq Q_{\min}} \Omega_{\text{NTS}}(Q) h_0^2 ,$$

or

$$\Omega_{\text{NTS}}^{\text{T}} h_0^2 = \Omega_{\text{NTS}}^{\min} h_0^2 \mathscr{S}, \qquad \mathscr{S} \equiv \sum_{j=0} \left(\frac{Q_{\min}}{Q_{\min} + j} \right)^{3/4} \exp\left(-j\lambda_1^3/\eta_\phi\right), \tag{6}$$

with $Q \equiv Q_{\min} + j$. Taking $\mathscr{S} = 1$ is, for most values of $Q_{\min}$, λ_1 and η_ϕ, incorrect, since the exponential is quite flat for values of Ω_{NTS} around unity. Figure 1 plots

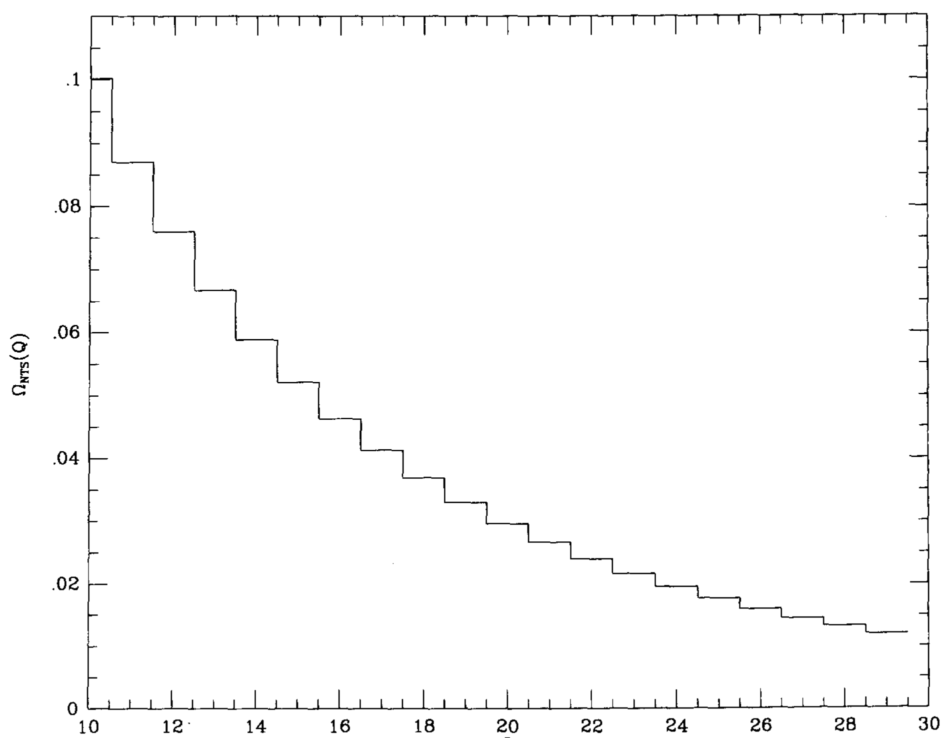

Fig. 1. The figure shows the abundance of solitons of charge Q, $\Omega_{\text{NTS}}(Q)$, as a function of Q. The parameters for which this plot was constructed are as given in the text [eq. (16)]: $a = 0.15$, $\eta_\phi = 1.0 \times 10^{-7}$, $\lambda_1 = 1.9 \times 10^{-3}$, $h = 5.9 \times 10^{-2}$, $\sigma_0 = 0.82$ GeV. The minimum stable charge in this case is $Q_{\min} = 10$. It is evident that solitons with charges greater than the minimum value contribute significantly to the total density of solitons today.

the abundance of solitons of a given charge Q as a function of Q for the parameters chosen below in eq. (16). It is easy to see that solitons with $Q > Q_{\min}$ contribute significantly to the sum in eq. (6). There is an upper value to the sum over Q coming from the maximum charge contained within the horizon at formation. For the present model, $Q_{\mathrm{HOR}} \sim \eta_{\phi}(M_{\mathrm{Pl}}/\sigma_0)^3$, where M_{Pl} is the Planck mass (see paper by Frieman et al. in ref. [16] for details). However, the sum converges much faster with Q, and such values of the charge give a negligible contribution to $\Omega^{\mathrm{T}}_{\mathrm{NTS}}$.

Following the above discussion we adopt a point of view different from previous work, one in which *all* NTSs contribute to Ω_{tot}, thus helping the minimal NTS to close the universe. So long as the free massive ϕ's outside the solitons are unstable and give a negligible contribution to Ω_{tot}, this seems to be the most adequate approach, if NTSs are to be taken as dark matter candidates. For stable ϕ's, a further partition of Ω_{tot} is required that would fix their primordial asymmetry.

We will require the following formulae, which can be derived from the results of FGGK (we neglect the contribution from the surface terms to the NTS's energy, a good approximation for the values of Q below)

$$Q_{\min} = 1231 \frac{C}{(A-1)^4} \frac{\lambda_1}{h^2}, \tag{7}$$

$$m_{\phi} = h^{1/2} |A-1| \sigma_0, \tag{8}$$

$$M_{\mathrm{NTS}}(Q) \approx m_{\phi} Q_{\min} \left(\frac{Q}{Q_{\min}} \right)^{3/4}, \tag{9}$$

where

$$A(a) \equiv \frac{\sigma_-}{\sigma_0} = -\tfrac{1}{2}\left\{(1+2a) + \left[(1+2a)^2 + 8a\right]^{1/2}\right\}, \tag{10}$$

and

$$C(a) \equiv \frac{\Lambda}{\lambda_1 \sigma_0^4} = -\tfrac{1}{8}(A^2-1)^2 - \tfrac{1}{3}a(A-1)^3. \tag{11}$$

Here $Q_{\min}$ is the minimum stable soliton charge, as can be seen from eq. (9).

If we assume that the ϕ's have the typical weak cross section of $\sim 10^{-38}\ \mathrm{cm}^2$ for scattering off hydrogen, then, as mentioned earlier, we need $Q = 10$ to reach the required cross section for cosmions. As the minimal NTS is the most abundant, the most natural candidate for the cosmion is the minimal NTS with $Q_{\min} = 10$. Due to their larger cross sections, NTSs with $Q > Q_{\min}$ need to be present in the Sun at a higher level than the minimal NTS. Hence we shall neglect their effect on the Sun and consider only the minimal NTS as the cosmion. To satisfy the cosmion mass range for the minimal NTS we are led to the restriction

$$0.4\ \mathrm{GeV} < m_\phi < 1.0\ \mathrm{GeV}. \tag{12}$$

By employing eq. (11) in eq. (7) and using this value of $Q_{\min}$, we find that

$$\Lambda = \frac{10}{1231}(A-1)^4 h^2 \sigma_0^4 .$$

Solving eq. (8) for $(A-1)$ and incorporating it into the above expression

$$\Lambda = 0.008 m_\phi^4 . \tag{13}$$

By using $\Omega_{\mathrm{NTS}}^{\mathrm{T}} = 0.9$ and $\Omega_{\mathrm{NTS}}^{\min} = 0.1$ (conditions (4)) in eq. (6), we see that $\mathscr{S} = 9$. This determines the ratio λ_1^3/η_ϕ. Using this and eq. (13) in eq. (5) for $Q = Q_{\min}$, we fix the value of both λ_1 and η_ϕ for a given value of m_ϕ. Furthermore, the parameters σ_0 and h may be expressed in terms of this value of λ_1 and a as follows. Using eq. (13) in eq. (11),

$$\sigma_0 = \left(\frac{0.008 m_\phi^4}{\lambda_1 C(a)} \right)^{1/4}, \tag{14}$$

where it is emphasized that C is a function of a only. Then eq. (8) may be solved for h

$$h = \left(\frac{m_\phi}{\sigma_0} \right)^2 \frac{1}{(A(a)-1)^2} = \left(\frac{\lambda_1}{0.008} \right)^{1/2} \frac{C(a)^{1/2}}{(A(a)-1)^2}, \tag{15}$$

where it is again emphasized that C and A are only functions of a.

The general scheme is to first choose values for m_ϕ and a, and then solve for the remaining parameters. (The freedom to choose m_ϕ is due to the *range* of values allowed by the mass constraint.) As discussed before, $a > 0.13$ in order to prevent both vacua from percolating. There is thus a range of parameter space in which solitons could both be cosmions and also provide the closure density. For example, let us take $m_\phi = 0.5$ GeV and $a = 0.15$. Then we find

$$\eta_\phi \approx 1.0 \times 10^{-7}, \qquad \lambda_1 \approx 1.9 \times 10^{-3}, \qquad h \approx 5.9 \times 10^{-2}, \qquad \sigma_0 \approx 0.82\ \mathrm{GeV}$$

and

$$M_{\mathrm{NTS}} \approx 5\ \mathrm{GeV}. \tag{16}$$

As with any cosmion candidate there are two additional concerns. First, the candidate must have an annihilation cross section $\sigma_a < \beta^{-1} 10^{-4} \sigma_s \sim 10^{-37}\ \mathrm{cm}^2$, with β being the NTS's thermal velocity, so that its population is not greatly reduced over that expected from continuous accretion over the Sun's lifetime [19]. For the models considered here we have built in an asymmetry for the ϕ's. One might think, therefore, that there would be no difficulty for the NTS cosmion. However, collisions among solitons in the Sun's interior should lead to a nonzero fusion rate. This process would reduce the number of NTSs with the desired cosmion properties (in favor of NTSs with larger masses and cross sections) thereby effectively acting as an annihilation of available cosmions. The fusion rate is at present unknown and in general difficult to calculate, as it involves a complicated skin–skin interaction among the underlying vacuum field σ. (Recall that at least in the present model the ϕ's do not self-interact.) Furthermore, it is possible that some of the binding energy released by the fusion of two solitons would appear in the form of detectable energetic neutrinos, making limits on the flux of such neutrinos applicable. Any details, though, must depend upon a more specific model of the ϕ's and their interactions. Even if fusion were to be energetically favored, the question remains as with what efficiency it would occur and, ultimately, how it would affect the NTS population in the Sun's interior. For comparison, the geometric cross section of the NTSs is $\sigma_g \sim R^2 \sim 10^{-28}$ cm^2, much greater than the limit on the annihilation cross section. Thus, although the effective cross section will probably be smaller than σ_g, one might expect the cosmions to interact effectively. These considerations should motivate the study of solitonic interactions, a topic of great importance if such configurations are to be taken seriously as a dark matter candidate.

The second concern is laboratory detection of the cosmion NTSs. (There is also a recent proposal for the detection of NTSs through gravitational radiation that would be emitted in their formation process [20].) Since they interact coherently with baryon number, we expect a cross section on a large nucleus of mass number A to be roughly $\sigma_N \sim 10^{-36} A^2$ cm^2. For the current limits imposed by the Germanium detector, we find $\sigma_N \sim 5 \times 10^{-33}$ cm^2 for the minimal soliton, well within the detectable range [21]. From this data the NTS is therefore limited to a mass $M \lesssim 10$ GeV. More stringent limits arise from recent results due to a silicon detector (described in ref. [22]). On such a target we expect that for the minimal soliton $\sigma_N \sim 10^{-33}$ cm^2. The data then restrict $\mathrm{M} \lesssim 5$ GeV [23]. However, new theoretical calculations by Gould [24] indicate that the evaporation mass of cosmions (which sets the lower mass limit in eq. (4)) may be as low as ~ 2 GeV. Thus, there remains a viable region of phase space between 2–5 GeV. Recall, however, that laboratory limits are obtained by assuming that the halo density is saturated by the cosmion. If the cosmion contributes only partially to the halo density, the limits should be modified.

In conclusion, we have suggested a new cosmion candidate, the non-topological soliton. The key idea behind this suggestion is the ability to reach the large scattering cross section of $100\sigma_W$ by placing weakly interacting particles into a soliton configuration. Coherent scattering of the soliton produces the required cross section for a NTS of charge about 10. Using the model of FGGK for their formation in a primordial phase transition, we were able to develop a scenario where the NTSs with the minimal charge required for their stability act as cosmions and, together with solitons of higher charge, provide the closure energy density for the universe.

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