Solar luminosity bounds on mirror matter

Erez Michaely¹*, Itzhak Goldman²⁻³, and Shmuel Nussinov²

1 Astronomy Department, University of Maryland, College Park, MD
2 School of Physics and Astronomy, Tel-Aviv University, Tel-Aviv, Israel
3 Department of Physics, Afeka Tel-Aviv Engineering College, Tel-Aviv, Israel

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ABSTRACT
We present bounds on mirror dark matter scenario derived by using the effect of mirror matter on the luminosity of the Sun. In the perturbative regime where the mirror matter concentration is small relative to the ordinary matter we estimate the heat transfer from ordinary matter to the mirror sector by simple analytic consideration. That amount of heat transfer is radiated via mirror photons and increases the required energy production in order to maintain the observed luminosity. We then present more detailed numerical calculations of the total amount of this energy transfer.

Key words: dark matter – Sun: general

1 INTRODUCTION
Finding the nature of Dark Matter (DM) which most likely contributes ~ 25% of the energy density of the universe is an outstanding challenge (Feng 2010). Some types of DM which arise beyond the standard model (BSM) of particle physics are being experimentally searched and or are constrained by astrophysics. In particular DM particles such as axions, dark photons and new types of neutrinos can be emitted from and lead to excessive cooling of neutron stars, white dwarfs red giants etc. (Raffelt 1996).

The apparent inconsistency of the observed solar neutrino fluxes with the predicted values was the first indication (Bahcall (1989); Bahcall et al. (2004, 2006) for the only piece of BSM physics (apart from DM!) known today, namely that of neutrino masses and mixings (Tanabashi et al. (2018)). Early on it motivated an alternative suggestion that small accumulation in the sun of weakly interacting DM particles (WIMPs) could cool the solar core and evade the "small neutrino problem" (Spergel & Press (1985); Press & Spergel (1985); Faulkner & Gilliland (1985); Gilliland et al. (1986)). Indeed at that time the main difficulty was the paucity of the energetic \( ^8B \) neutrinos whose rate scales as \( T^3 \) with \( T_e \) the central temperature.

In this note we again use the Sun to limit DM arising in mirror models in which a hidden sector exists where every particle or parameter in the standart model - \( x \) is mirrored by an identical particle/ parameter \( x' \) (Lee & Yang (1956); Foot (2014); Kobzarev & Okun' (1968); for review see Foot (2014) and references within. In much of the work these models the symmetry between the mirror and ordinary sector is broken allowing different masses of particles and their mirrors which helped address many astrophysical and cosmological issues (Berezhiani et al. (1996)). Still almost exact mirror models with minor changes made to allow \( \Omega (B') = 5 \Omega (B) \sim \Omega (DM) \) and a lower CMB temperature in the mirror sector (which is required to avoid conflict with BBN- Big Bang Nucleosynthesis) have been discussed at length (Berezhiani et al. (2001); Foot (2014)). It was suggested that this most restrictive framework with appropriate minimal weak mirror-ordinary matter interaction, can evade the bullet cluster bound and the infall of DM into parallel galactic disks expected for the strongly mutually interacting and dissipative DM made up of mirror atoms. Here we will focus on the possible effect of the accumulation of mirror DM particles arising in the framework of "almost exact" mirror symmetry in the Sun at a relative concentration

\[
\eta = \frac{M'}{M\odot}
\]

where \( M' \) is the overall mass of the mirror particles in the Sun. We find that the resulting changes of the solar luminosity exclude \( \eta \) and mirror-ordinary matter cross-sections \( \sigma_{xx'} \) values in a region allowed by all other constraints and which was strongly favoured by mirror DM models. This exclude most exact mirror DM variants.

2 THE EFFECT OF MIRROR MATTER ACCUMULATION IN THE SUN
We start by describing the differences between earlier attempts to constrain massive DM particles by considering the consequences of their accumulation in the Sun and our present discussion of almost exact mirror model particles.

In the earliest works mentioned above (Press & Spergel (1985))...
Spergel & Press (1985), only the mutual DM-nuclear cross-section $\sigma_{\text{ xx'}}$ are used to trap in the Sun DM particles of masses in the $5-10\text{GeV}$ range. In this case $\sigma_{\text{ xx'}} \gtrsim 10^{-36}\text{cm}^2$ was required in order to accumulate the minimal $\eta \sim 10^{-11}$ which allows sufficient heat transport from the solar core so as to significantly reduce the $^8B$ neutrino flux. Extensive direct searches for DM in large cryogenic, underground detectors restrict by now Tanabashi et al. (2018) the He (the dominant mirror dark matter component in mirror models) nucleon cross-section, to be less than $10^{-30}\text{cm}^2$ Foot (2014).

The next class of DM particles considered in this context was that of asymmetric, strongly self interacting DM Frandsen & Sarkar (2010); Cumberbatch et al. (2010); Taoso et al. (2010). In this case newly falling DM particles can be captured by scattering on DM particles which were captured earlier in the Sun. This increases the capture rate until it reaches the "Unitarity bound" when essentially every DM particle hitting the Sun is captured. The integrated accumulation over the solar lifetime can then lead to the concentration of $\eta \sim 10^{-11}$, the value mentioned above. With the present understanding of neutrino mixing, extra heat convection from the very central region is no longer required to explain the solar neutrino "Problem". The resulting cooling of the core still has other more subtle yet observable effects on the standard solar model as discussed in Frandsen & Sarkar (2010); Cumberbatch et al. (2010); Taoso et al. (2010).

The strong mutual x'-x' scattering helps retain the captured DM inside the Sun. Indeed in the absence of such strong scattering some x's with energy of $E \sim$ few $kT_0 \sim$ few KeV and a velocity $v = (2E/m_x)^{1/2}$ exceeding the escape velocity from the solar core of $\sim 1000\text{Km}/\text{Sec}$ will be kicked from the solar core, if the DM particles are lighter than $\sim 5\text{GeV}$. This limit does not apply for strongly self interacting DM: the kicked x' suffers many collisions with the ambient x's quickly sharing its energy and no escape of DM particles is expected even if $m_x = m_H \approx \text{GeV}$. The Mirror dark matter considered here differs from that in the above two cases. Thanks to the exchange of the mass-less mirror photon it is strongly interacting via Ruthdeford scattering

$$\sigma_{\text{ xx'}} \sim \alpha^2/E^2 = \sigma_{\text{ xx}} \quad (2)$$

which is $\sim 10^{-18}\text{cm}^2$ for the relevant KeV energies. \(^1\)

The other most important feature is that mirror nuclei/electrons can emit the massless mirror photons and therefore constitute dissipative DM.

To make our argument as model independent as possible we use the concentration of the mirror particles in the Sun $\eta$ and the ordinary- mirror scattering cross-section $\sigma_{\text{ xx'}}$ as the two independent parameters of the particle physics model to be constrained by the astrophysical considerations. In generic almost exact mirror models not only the cross-sections for mirror- mirror interactions are fixed by the above Ruthdeford scattering but also the coupling of mirror charged particles with the ordinary sector is via the "Photon Portal" - namely the kinetic mixing: $\epsilon F_{\mu\nu} F'_{\mu\nu}$ of the mirror photon field strength tensor $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$ and the field strength tensor of the ordinary photon. Since both our photon $\gamma$ and the mirror photon $\gamma'$ are massless we should identify our physical photon $\tilde{\gamma}$ with the superposition of original fields: $A_\mu = A_\mu + \epsilon A'\mu$. Indeed the two fields $\tilde{\gamma}$ and $\tilde{\gamma'}$ in this particular superposition are coherently emitted, propagated and absorbed by SM charges. This redefinition then subsumes all the ordinary matter mirror photon interaction and therefore ordinary particles no longer couple to the mirror photon. Yet each mirror particle x' with a mirror electric charge of $e'(x') = e(x) \equiv e$ couples to the ordinary photon with a milli-charge of $ee$. The cross-section for mirror- ordinary matter x'-x scattering generated by ordinary photon exchange is then the standard Ruthdeford scattering above reduced by $\epsilon^2$

$$\sigma_{\text{ xx'}} = \epsilon^2 \sigma_{\text{ xx}} \approx \epsilon^2 \frac{\alpha^2}{E^2}. \quad (3)$$

To address the apparent departure from exact mirror symmetry we note that the above definition is appropriate in regions of space which are dominated by ordinary matter. The opposite scheme where the redefined physical mirror photon does not couple to ordinary matter and ordinary charged particles are milli-charged with respect to $\tilde{\gamma'}$ is appropriate in regions dominated by mirror matter such as the interior of mirror stars discussed later.

The effect of capturing mirror particles differs from that in the previous case due to the fact that the mirror particles radiate dark (mirror) photons. This provides yet another channel for radiating the energy generated by nuclear reactions in the solar core- a channel which operates in parallel with the usual ordinary photon radiation. Thus the mirror matter not only transports heat, but just like the emission of axions or massive dark photons that directly couple to the solar nuclei/ electrons , it also changes the overall solar energetics. This will allow us to derive limits on the mirror concentration $\eta$ and the mirror ordinary sector particle scattering cross-section $\sigma_{\text{ xx'}}$ which are more robust and less model dependent than earlier limits.

A second important difference between the almost exact mirror matter discussed here and the previous merely strongly interacting DM, is that it’s concentration in the Sun is no longer restricted by the maximal capture rate during the lifetime of the Sun to be: $\eta \sim 10^{-11}$.

Both ordinary and mirror matter are dissipative and mutually attract gravitationally. We therefore expect ordinary matter to cluster in the gravitational wells of mini haloes generated in the mirror matter. Conversely, mirror matter should cluster in the gravitational wells due to ordinary matter galactic disks. This co-clustering or even co-collapses tends to mix the two types of matter. In particular it could lead to an initial mirror matter concentration in the Sun which much exceeds the above limiting $\eta \sim 10^{-11}$. Indeed it has been estimated Foot (2014) that the original pre-solar

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\(^1\) In the solar core the plasma (Debye) screening correction to the above cross-section amounts to replacing the momentum transfer squared $k^2$ in the photon momentum space propagator by $k^2 \to k^2 + k_s^2$ where $k_s^2 =$ $k_B^2$ = $4\pi\alpha_0(e)/T$ $\sim$ $40\text{KeV}^2$. Using the temperature and electron density appropriate to the solar core we find $k_s^2 \approx 40\text{KeV}^2$. This screening cuts-off the very forward, low momentum transfer scattering but only mildly affects the relevant transport cross-section as the average $k_T^2$ $\sim 2m\Delta E$ $\sim$ $2m\Delta T$ $\sim 40\text{KeV}^2$ even for the case of e-e or e'-e' scattering with $m \approx 1/2\text{MeV}$. The net effect of replacing $1/k^2$ by $1/(k^2 + k_s^2)$ is to reduce the cross-sections by just a factor of two Raffelt (1996).
cloud can efficiently accumulate mirror particles leading to \( \eta \sim 10^{-5} \).

It is important to note that mirror matter is still a rather subdominant component of the Sun. This justifies treating the effect of this admixture perturbatively using the known solar profiles of ordinary density, \( \rho(r) \), and temperature, \( T(r) \).

For solar/stellar cooling by weakly interacting particles emitted by nucleons and/or electrons it suffices to compute the volume emission of these particles which freely stream out. This is not the case here. First the mirror photons are not emitted directly from the electron/protons in the Sun but only by the mirror particles after kinetic/heat energy is transferred to them via collisions with ordinary core particles at a total rate which we denote by \( \frac{dQ}{dt} \). Thanks to their very strong mutual interactions the mirror particles will then equilibrate and generate at each radius a local temperature profile \( T'(r) \). In general this \( T'(r) \) is different from \( T(r) \), the temperature profile of ordinary protons/electrons. These mirror particles will then emit their energy via mirror photons generated by bremsstrahlung in \( e'e' \) or \( e'e'' \) collisions. Also unlike for the simple volume emission case mentioned above, the mirror photons will often scatter on their way out on the ambient mirror particles and will be trapped for some time \( \tau' \). Both \( \frac{dQ}{dt} \) and \( \tau' \) depend on the, as yet unknown, profiles of the density \( \rho'(r) \sim n'(r) \) and of the temperature \( T'(r) \) of the mirror matter. Before embarking on the calculation of these profiles and the resulting \( \frac{dQ}{dt} \) we will first make some estimates using a simpler approach.

### 2.1 Estimate of the energy transferred and radiated by the mirror photons

While we find that \( \frac{dQ}{dt} \) is comparable with the observed ordinary solar luminosity \( L_{\odot} \) for a range of allowed DM parameters \( \sigma_{ee'} \) and \( \eta \), the reverse heat flow to the ordinary matter reservoir \( \frac{dQ}{dt} \) is negligible. The reason for this are the large self scattering of mirror matter \( \sigma_{ee''} \) which exceeds by \( e^{-2} > 10^{28} \) the mirror-ordinary particle collision cross-section \( \sigma_{ee'} \) and the large bremsstrahlung cross-section leading to \( \gamma' \) emission: \( \sigma_{ee' \rightarrow ee'' \rightarrow e' \gamma'} \sim \alpha \times \sigma_{ee' \rightarrow ee''} \sim 10^{-20} \text{cm}^2 \). Thus a mirror particle which has gained energy by a collision with an ordinary particle in the solar core will collide and share its energy with other ambient mirror particles rather than collide again with an ordinary ion or electron. In turn bremsstrahlung quickly transfer this energy to mirror photons. Since these mirror photons do not scatter at all from protons or electrons but only from mirror particles the energy transferred to the mirror sector, be it the matter or radiation part, stays in that sector and eventually is emitted as mirror photons. Thus to find the extra luminosity emitted via mirror photons we need only to find \( \frac{dQ}{dt} \).

We will mainly focus on the inner core, \( R \approx 0.2R_{\odot} = 1.4 \times 10^{10} \text{cm} \) which includes a total mass \( M(R) \approx 0.35M_{\odot} \) and generates \( \approx 90\% \) of the solar luminosity Paxton et al. (2011). The mainly ordinary matter densities therein of \( \sim 165 \text{gr/cm}^3 \) corresponds to electron number density of \( n_e \approx 4.8 \cdot 10^{29} \text{cm}^{-3} \). The almost constant temperature is on average \( T \sim 1.3 \text{KeV} \) or \( 2 \cdot 10^{-18} \text{ergs/particle} \). Since the Ruthefodr scattering depends only on the energy and not the mass of the colliding particles and in thermal equilibrium electrons have the same energy of \( 3/2kT \) as protons or He ions, the scattering of the faster moving \( e \) and \( e' \) will dominate the heat transfer process. Such scattering of two equal mass particles tends to equalise their energy and on average an energy

\[
\Delta E = \frac{3}{4} \left(kT(r) - kT'(r)\right) \approx \frac{2}{4} kT(r) = 1.5 \times 10^{-9} \text{erg} \tag{4}
\]

will be transferred to the mirror sector in each collision. The density profile of mirror particles is given by the Boltzmann distribution \( \exp(-V(r)/kT') \). \( V(r) \approx 4\pi/3G\rho m_{H,e} r^2 \) is the gravitational potential due to the ordinary roughly constant density \( \rho_0 = 165 \text{gr/cm}^3 \) of ordinary matter. The mass \( m_{H,e} \) rather than \( m_e \) was used as mirror helium is the dominant component in the mirror sector, namely

\[
X' = \frac{\rho_H}{\rho'} = 0.2 \quad \text{and} \quad Y' = \frac{\rho_H}{\rho} = 0.8. \tag{5}
\]

Foot (2014). \( \rho'(r) \) then is a Gaussian, \( \exp(-r/r_0)^2 \) with \( r_0 = \left(\frac{4\pi}{3G\rho m_{H,e}}\right)^{1/2} \approx 10^{10} \text{cm} \). (6)

Since this is less than \( R \approx 0.2R_{\odot} \) most mirror particles are inside the above core. Each mirror electron experiences

\[
\Gamma_{xx'} = n_e n_{e'} \sigma_{ee'} \approx 1.2 \times 10^{35} \sigma_{ee'} \text{sec}^{-1} \tag{7}
\]

collisions per second, where \( v_e = (3kT/m_e)^{1/2} \) is the electron velocity and \( n_e \approx 4.8 \cdot 10^{25} \text{cm}^{-3} \) is the electron number density.

The total energy transferred to the mirror particles per second then is:

\[
\frac{dQ}{dt} = N_{tot, e'} \Gamma_{xx'} \Delta E \tag{8}
\]

where

\[
N_{tot, e'} = N_{He'}/2N_{He} = \frac{\eta M_{He}}{m_{He}} \left(X' + \frac{1}{2} Y'\right) = 0.6 \frac{\eta M_{He}}{m_{He}} \approx 7.2 \times 10^{56}. \tag{9}
\]

Hence the total energy transfer per second is

\[
\frac{dQ}{dt} = \eta \sigma_{ee'} 1.3 \times 10^{33} \text{erg sec}^{-1} = \eta \sigma_{ee'} 3.4 \times 10^{40} L_{\odot}. \tag{10}
\]

Rewriting the previous equation in terms of \( \sigma_{ee'} \approx \sigma_{ee'}/10^{-38} \) and \( \eta \ll 1/\eta \) we find

\[
\frac{dQ}{dt} = \eta \sigma_{ee'} 3.4 L_{\odot}. \tag{11}
\]

The rather modest requirement that \( \frac{dQ}{dt} < 0.04 L_{\odot} \) then limits the region of allowed parameters by:

\[
\eta \sigma_{ee'} < 1.1 \times 10^{-2}. \tag{12}
\]

The rational for requiring \( \frac{dQ}{dt} < 0.04 L_{\odot} \) is that the flux of pp solar neutrinos which directly reflects the nuclear energy output is measured and understood at \( \sim 4\% \) level Bergström et al. (2016). Originally considerations of energy loss were used e.g. by Raffelt (1996) in a conservative way, requiring only that the new extra luminosity will not exceed the ordinary luminosity. During the past decades measurements of all types (pp, Berilium, Boron , etc) of solar neutrinos and the understanding of their apparent deficit via neutrino mixing, the parameters of which was independently measured in terrestrial experiments, have greatly improved Vissani (2017).
3 NUMERICAL CALCULATION OF THE MIRROR LUMINOSITY IN THE SUN

In this section we describe the numerical results and calculation of $dQ/dt$, the rate of the total heat transferred from the ordinary matter to the mirror matter. The amount of heat transferred to the mirror particles depends on their density profile (number density), $\rho'(r)$ ($n'(r)$) and temperature profile, $T'(r)$. For a given $\eta$ and $\sigma_{\text{ww}}$ these functions are unknown apriori, however they must satisfy the four well known stellar structure equations:

$$
\frac{dP'(r)}{dr} = -\frac{GM(r)\rho'(r)}{r^2} \tag{13}
$$

$$
\frac{dM'(r)}{dr} = 4\pi r^2 \rho'(r) \tag{14}
$$

$$
\frac{dT'(r)}{dr} = -\frac{3L'(r)\kappa'(r)\rho'(r)}{4\pi r^2 a c T'(r)^3} \tag{15}
$$

$$
\frac{dL'(r)}{dr} = 4\pi r^2 \rho'(r) \epsilon'(r) \tag{16}
$$

where $\kappa'$ is the opacity for Thomson scattering, $a$ is the radiation constant and $\epsilon'$ is the energy source per unit mirror mass of the mirror particles. We identify the product $\rho'(r)\epsilon'(r)$ to be the transfers heat per unit mirror mass.

For a specific pair of $\eta$ and $\sigma_{\text{ww}}$ we postulate an ansatz for $\rho'(r) = \eta\rho(r)$ and $T'(r) = 0.9T(r)$, where $\rho(r)$ and $T(r)$ are the density and temperature profiles of the Sun taken from MESA, stellar evolution code Paxton et al. (2011). Using this ansatz one can calculate the left hand side (lhs) and right hand side (rhs) of equations (13-16). The ratios of the lhs and the rhs, $q_i$, where $i$ runs over the above four stellar structure equations, is a measure of the quality of the initial guess. We repeatedly altered the functions $\rho'(r)$ and $T'(r)$ in order to minimize $|q_i - 1|$. We are able to find the profiles that satisfy the stellar structure equations within the tiny errors so that the computed integrated luminosity satisfies

$$
\frac{\int L'_{n+1}dr - \int L'_{n}dr}{\int L'_{n}dr} < 5 \times 10^{-9} \tag{17}
$$

where $n$ indicated that $n$-th iteration. In figure 2 we present a representative example, the black solid line is the Sun temperature profile, $T(r)$, while the red dashed line is the ansatz, $T'(r) = 0.9T(r)$. After many iterations that minimize $q_i$, the calculated profile satisfied eq. (17), we found the blue dotted line. The same mechanism is done for the density profile, $\rho'(r)$.

Once we find the mirror density, $\rho'(r)$ and temperature profile, $T'(r)$ for a pair of $\eta$ and $\sigma_{\text{ww}}$ we calculate the total energy transferred and hence emitted by mirror photon and record it. We calculated $dQ/dt \equiv L_{\text{tot}} = \int L' dr$ for the following parameters: 15 values equally spaced in log of the mirror matter- ordinary mirror cross-section $\sigma_{\text{ww}} = \{10^{-45} - 10^{-38}\}$ and 15 values equally spaced in log of $\eta = \{10^{-12} - 10^{-7}\}$. Figure 1 present the results of our calculation on the above 15X15 grid. The results are presented in terms of log($L_{\text{tot}}/L_{\odot}$). Our results agree well with our estimate from subsection 2.1 for $1L_{\odot}$ (black solid line) and $0.04L_{\odot}$ (black dot-dashed line). Any pair of values $(\eta, \sigma_{\text{ww}})$ which is above the $0.04L_{\odot}$ is therefore excluded.
4 DISCUSSION AND SUMMARY

We start by pointing that:

- Since our analysis above was essentially perturbative in nature it cannot directly apply to the cases where the computed mirror photon luminosity considerably exceeds the 4% of the solar luminosity, as the ordinary solar parameters would need then to be modified as well. Still it is quite safe to assume that the very large mirror luminosity arising when $\eta\sigma_{\text{ex}} > 10^{-46}$ will be indicative of some fatal difficulties with the observed Sun.

- In order to evade the Bullet cluster upper bound on the dark dark (here mirror-mirror scattering cross-section) we need that only some fraction, say 15%, of the mirror matter in the haloes will stay unclustered and that majority form collisionless stars. The argument for $\eta \sim 10^{-5}$ can then be "mirrored " to suggest a similar admixture of ordinary matter within the mirror stars. If the latter are still active then even a small fraction of their nuclear energy production channeled into ordinary radiation, analogous to that found above, will make these stars visible and no allow them to be DM in the first place.

To summarize we note that the most relevant difference between our and previous limits stemming from DM captured in the Sun is the fact that we use the solar luminosity rather than more subtle aspects like Helio-seismography. This in turn limits the product of $\eta$ the solar concentration of DM and $\sigma_{\text{ex}}$ the dark-ordinary matter cross-sections, rather than each of these separately. This is particularly relevant for the case of (almost) symmetric mirror models which provided the framework of the present analysis. The point is that in these models both $\sigma_{\text{ex}}$ and $\eta$ are fixed by the same single dimensionless kinetic mixing parameter $\epsilon$ of the photon and mirror photon. Specifically $\epsilon^2$ appears in the mirror-ordinary matter Rudhefore like scattering (3) above. In order to evade the apparent difficulties associated with mirror matter forming a disc overlapign the ordinary Milky Way disc one needs a minimal $\sigma_{\text{ex}}$ corresponding to a high epsilon value of $\sim 10^{-9}$. The parameter $\epsilon$ also controls the expected fraction of mirror matter $\eta \sim \epsilon^2$ which is mixed into the presolar cloud. This preferred optimal value yields the $\eta \sim 10^{-5}$ and $\sigma_{\text{ex}} \sim 10^{-36}$. The product $\eta\sigma_{\text{ex}} \sim 10^{-41}$ will then exceed the maximum value we found from the 4% limit of the solar luminosity emitted via mirror photons to be $\eta\sigma_{\text{ex}} \sim 10^{-51}$, by a factor of $10^{10}$! Thus our new limits tend to most strongly exclude the above optimal $\epsilon$ value and the large class of almost exactly symmetric mirror models which depend on it.

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