Constraints on light asymmetric dark matter from solar neutrinos

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Abstract. We study the effect of dark matter (DM) particles in the Sun, focusing in particular on the possible reduction of the solar neutrinos flux due to the energy carried away by DM particles from the innermost regions of the Sun, and to the consequent reduction of the temperature of the solar core. In the very low-mass range between 4 and 10 GeV, recently advocated to explain the findings of the DAMA and CoGent experiments, the effects on neutrino fluxes are detectable only for DM models with very small, or vanishing, self-annihilation cross section, such as the so-called asymmetric DM models, and we study the combination of DM masses and Spin Dependent cross sections which can be excluded with current solar neutrino data.

1. Introduction
Dark Matter (DM) particles crossing a star can be scattered to velocities lower than the star escape velocity and be therefore gravitationally trapped by the celestial body, the efficiency of the process depending on the DM scattering cross section and DM ambient density. Once captured, DM particles can still scatter with the star nuclei transferring energy inside the object and eventually annihilate, providing therefore an exotic source of energy. These effects have been shown to significantly change the evolution and the properties of stars placed in environments with high DM density like main sequence stars at the Galactic center [1, 2], first stars [3, 4, 5] and compact objects [6, 7]. In these scenarios it is however impossible to set robust constraints on the DM cross sections and mass because of the large uncertainties on the DM densities and/or the lack of precise enough observations of the star targets.

Here instead we focus on the Sun, which properties have been measured with good precision. In addition to that, recent studies [8, 9, 10] have shown that current observations constrain the DM density in the solar system within a factor two, assuming spherical DM profiles (significant deviations may occur for other DM distributions, see [11] and references therein). For these reasons, the Sun can be used as a diagnostic tool to test small modifications of its structure induced by DM. The most recent works in this direction have focused on modifications of the solar neutrino fluxes and helioseismology data [12, 13]. Here we perform a complete and self-consistent calculation of the Sun evolution inside the galactic DM halo. In particular we extend previous works considering light DM candidates, with masses in the range suggested by DAMA [14] CoGent [15] and CDMS II [16] experiments.

In this paper, we focus on scenarios with negligible annihilations which are the most promising in order to detect the small modifications of the Sun structure induced by DM particles. In fact,
for Standard Weakly Interacting Massive Particles (WIMPs) models the number of WIMPs inside the Sun, $N_\chi$, is limited by annihilations and after a transient $\tau_\chi$, typically much shorter than the age of the Sun, an equilibrium between capture and annihilation is reached. The number of WIMPs in the Sun stays then constant $N_\chi = C \tau_\chi$, where $C$ is the capture rate. Instead, for annihilation cross section much smaller than those found in WIMPs model, i.e. for $\sigma v \leq 10^{-33} \text{cm}^3\text{s}^{-1}$, the equilibrium between capture and annihilations is not yet reach in the Sun and the number of trapped DM particles is simply $N_\chi = C t_\odot$, with $t_\odot$ the age of the Sun. The number of DM particles inside the Sun is therefore greatly enhanced with respect to the that obtained in WIMPs models and detectable modifications on the Sun properties can be obtained.

For the rest of the paper we neglect any DM annihilation. This possibility can be realized for instance in the so-called asymmetric DM models. In these scenarios, despite the DM candidates can in principle have weak-scale interactions and therefore sizable scattering cross sections off baryons, annihilations do not occur because of the presence of an asymmetry in the DM sector between particles and anti-particles. Concrete realizations of this idea are for example models where the dark sector contains a conserved $U(1)_X$ symmetry, analogue of the baryon number, responsible for the stability of the lightest particle in the DM sector. If this quantum charge is shared between baryons and DM it can link the asymmetries in the two sectors and this may naturally explain why the baryons and DM abundances are of the same order of magnitude (see e.g.[17, 18, 19]).

The results here presented are based on [27], where also other dark matter models have been considered.

The paper is organised as follows: in Sec 2 we discuss how the solar neutrino fluxes can be used to constrain the DM parameter space. In Sec. 3 we briefly describe the methodology used and we present our results.

2. Diagnostic tools
The modification of the stellar structure produced by DM induces changes in the frequencies of stellar oscillations modes and in the neutrino fluxes. The first signature can in principle be observed with helioseismic measurements [12, 13], however, the neutrino flux is much more sensitive to the variation of temperature and density profile of the innermost regions of the Sun, and hence it is a much more powerful diagnostic tool.

For the standard solar model, Ref. [20] indicates that the $^8\text{B}$ neutrino flux varies as $T^{25}$, therefore a 1% temperature change will produce a 25% change in the $^8\text{B}$ neutrino flux. However, as it has been in shown in Ref. [13] , this simple scaling law is not valid to describe the peculiar modifications of the temperature profile induced by the DM particles. Therefore, the use of a stellar code is mandatory to study the effects on DM on the solar neutrino fluxes.

The distribution of DM inside the Sun is crucial to determine the modifications of the neutrino fluxes. Once captured, the DM particles get redistributed inside a small spatial scale, $r_\chi$, of the order of $10^6 \text{cm} \sim 0.01 R_\odot$, for a DM mass of 100 GeV ($r_\chi$ scales as $m_\chi^{-1/2}$). The DM energy transport will be therefore more efficient in the innermost regions of the Sun core, as can be appreciated in the left panel of Fig. 2. The $^8\text{B}$ and $^7\text{Be}$ neutrinos, which are mostly produced at $\sim 0.04 R_\odot$ and $\sim 0.06 R_\odot$, will be more affected by the presence of DM than the $pp$ neutrinos. In fact, although the $pp$ neutrinos are the most abundant solar neutrinos, they are mainly produced at $\sim 0.1 R_\odot$, thus is a region well outside the one affected by the DM energy transfer. For the same reason and considering the experimental uncertainties in the determination of $^8\text{B}$ and $^7\text{Be}$ neutrino fluxes, we conclude that the $^8\text{B}$ neutrino flux is the best diagnostic tool in order to test the effects of DM on the Sun.
Figure 1. Impact of asymmetric DM on the Sun. Left Panel: Temperature profile of the Sun for different SD scattering cross-sections at $t_\odot = 4.57$ Gyrs. Right Panel: Density profile (baryons only) inside the Sun.

The $^8$B flux has been determined with good accuracy by SNO [21]:

$$\phi_B^\nu = 5.046^{+0.150}_{-0.152} \text{(stat)}^{+0.107}_{-0.123} \text{(syst)} \times 10^6 \text{ cm}^{-2} \text{s}^{-1}.$$ 

For completeness, we report also the $^7$Be neutrino flux inferred by Borexino[22]:

$$\phi_{Be}^\nu = (5.18 \pm 0.51) \times 10^9 \text{ cm}^{-2} \text{s}^{-1}.$$ 

The solar model we use, as described in [27], predicts at the solar age $t_\odot$:

$$\phi_B^\nu = 4.56 \times 10^6 \text{ cm}^{-2} \text{s}^{-1} \phi_{Be}^\nu 7 = 4.47 \times 10^9 \text{ cm}^{-2} \text{s}^{-1},$$

values that are well in agreement with the experimental results to within the theoretical uncertainties of solar model calculations [23, 24].

Despite its great success in explaining a large variety of observations, the standard solar model suffers nowadays from the so-called solar composition problems. Recent analysis points to a lower surface heavy element content than previously thought (see [25] for recent results) and solar models incorporating these revised metallicities conflict dramatically with helioseimological measurements, in particular right below the solar convective envelope. With the solar abundances of [25], the radius of the convective zone, $R_{CZ}$, is more than $10 \sigma$ higher than the measured value: $R_{CZ} = 0.713 \pm 0.001 R_\odot$ (see Ref.[23] for an analysis of comparison of different solar models with helioseismology measurements.) High and low heavy elements models also produce differences on $\phi_B^\nu$ and $\phi_{Be}^\nu$ respectively of $\sim 20\%$ and $10\%$. However, the theoretical uncertainties obtained within a particular solar model (with high or low metallicity estimations) are significantly smaller, $\sim 10\%$ and $6\%$ for $\phi_B^\nu$ and $\phi_{Be}^\nu$ [24]. Considering the theoretical and experimental uncertainties on $\phi_B^\nu$, we study the region of the DM parameter space where significant deviations on $\phi_B^\nu$ are found (the maximum allowed deviation of the $^8$B flux depends on the value of the theoretical uncertainties considered. We define this threshold in Sec.3). As reference value, we consider the neutrino flux obtained from our solar model without DM particles and in the Sec. 3 we define the maximum deviations compatible with present data.
Figure 2. Solar neutrino fluxes in presence of asymmetric DM in the Sun. Left Panel: Differential $^8$B and $^7$Be neutrino fluxes as a function of radius. The curves referring to our solar model are normalized to unity. Right panel: isocontours of 25% (red) and 5% (yellow) $\phi_B^\nu$ deviations with respect our solar model prediction in the $m_\chi$-$\sigma_{SD}$ plane. The red area show the region of the parameter space with $\phi_B^\nu$ modifications larger than 25% and therefore in tension with present $\phi_B^\nu$ data. The weakening of the DM transport effects at high cross sections is due to the transition to local transport regime. See text for details.

3. Results

In order to model the presence of DM in the Sun we have implemented the DM capture and evaporation in the GENEVA code. The total number of DM particles $N_\chi$ inside the Sun is thus obtained solving

$$\dot{N}_\chi = C - EN_\chi,$$

where $C$ is the particle capture rate over the Sun and $E$ the evaporation one. The energy transported by DM particles inside the Sun is then computed following ref.[26]. We have evolved the Sun from the ZAMS up to its current age $t_\odot = 4.57 \times 10^9$ years with the GENEVA stellar code. More details on the equations and the code used can be found in [27].

The first two panels of Figure 1 shows the temperature and density profiles of the Sun in presence of asymmetric DM. Note the change in temperature with increasing SD scattering cross section: the temperature decreases at the center and (although this is difficult to appreciate in the plot) slightly increases close to the external edge of the stellar core. The reason of the decrease in temperature can be understood in terms of energy transported away by DM from the solar core. For these values of scattering cross sections, the DM mean free path is much higher than the typical radius of the DM cloud, this indicating that DM transport effects are non local. In this regime, the DM particles scatters can efficiently transport the heat from the inside of the stellar out to colder regions, thus operating toward a flattening of the temperature profile, and a consequent readjustement of the entire stellar structure.

In general, any amount of energy removed from the core leads to its contraction. Naively, one would expect a warming of the internal regions of the Sun since part of the energy extracted from the gravitational energy reservoir goes into internal energy. However, the energy carried away by the DM particles is well above the energy released by the core contraction, resulting therefore in a cooling of the central regions.

Left panel of Figure 2 shows the differential $^8$B and $^7$Be neutrino fluxes as a function of the stellar radius, in presence of different DM models. As expected, the reduction of the neutrino
production, due to the cooling of the baryons inside the Sun, is more efficient at small radii, where the DM particles are concentrated. As noticed in Sec. 2, this leads to a larger modification on the total $^8$B neutrino flux, $\phi_B$, which is the integral over the whole Sun of the corresponding differential quantity plotted in the left panel of Figure 2, than those on the $^7$Be neutrino flux, $\phi_{Be}$.

To study the impact of these structural variations on the solar neutrino flux, we have performed a systematic study of the DM parameter space, varying the DM scattering cross section and mass. For Spin Independent interactions we find sensible variations of the neutrino flux only for very large values of the scattering cross section $\sigma_{SI}$, already severely excluded by direct detection experiments, therefore we focus for the rest of the section on Spin Dependent interactions.

In the right panel of Fig. 2, we show in the $m_\chi - \sigma_{SD}$ plane the isocontours corresponding to $\phi_B$ variations of 25% and 5% with respect to our solar model without DM particles.

The DM mass plays a relevant role in determining the effects on DM in stars since lowering the DM mass goes in the direction of maximizing the transport effects, but also the evaporation rate. For masses below 5 GeV the evaporation becomes relevant and the number of DM particles inside the star is strongly suppressed so that the changes induced on the solar neutrinos fluxes are negligible. On the contrary, above this mass threshold evaporation can be safely neglected. Above $m_\chi = 20$ GeV the DM transport starts to become inefficient and even for high scattering cross section the DM energy transport is relevant only at the very center of the star, providing a local dip of energy. However, for increasing DM masses the existing constraints from direct detection experiments become more severe, and the region of the parameter space able to produce sizeable modifications of $\phi_B$ is already excluded. Because of that, we do not explore that region any further.

Increasing the DM scattering cross section the DM mean free path reduced and at large annihilation cross section (i.e. $\gtrsim 10^{-33}$ cm$^2$), DM particles remain progressively “trapped” in the interior of the star. This implies that the heat transport from DM particles becomes local and the modifications of $\phi_B$ tend to decrease. This is also the reason of the non specularity of the exclusion curves in Figure 3: the low and high cross-section regions are characterized by different physics (non-local vs local transport effects, respectively).

Combining experimental and conservative (20%) theoretical uncertainties we derive that modifications of the $\phi_B$ above $\sim 30\%$ are excluded at 95% CL. The maximum modifications that we obtained in our computations are slightly below this level: further increasing $\sigma_{SD}$, problems are encountered in solving the stellar structure at ages well below the solar one. We have not further investigated if these difficulties are merely a numerical artifact or are instead related to the non existence of a solution of the stellar structure. However, we notice that once we obtain variations of $\phi_B$ of the order of 20%, further small changes of $\sigma_{SD}$ induce rapid modifications of $\phi_B$. Because of that, the isocontours corresponding to 30% $\phi_B$ variations should be closed to the ones corresponding to $\delta\phi_B = 25\%$ shown in Fig. 2.

Considering a more optimistic value for the theoretical uncertainties on the $\phi_B$ predictions, i.e. 10%, the threshold for exclusion at 95% CL is lowered to 18% variations from our solar model prediction. Most of the SD cross-sections inside the 25% region in Fig.2 are excluded by the direct detection experiments constraints, apart from a small region at low masses which is somewhat in tension with those bounds. A reduction of the theoretical and experimental uncertainties on $\phi_B$ in the next years may in principle improve the sensitivities on $\sigma_{SD}$. We show however in Fig.2 that considering a 5% modification of $\phi_B$ the region of the $m_\chi - \sigma_{SD}$ parameter space which can be probed enlarges very little.
4. Conclusions

By the use of a stellar evolution code, we have studied the modifications on the Sun structure induced by the DM particles captured by the Sun. We have focused on scenarios with null or very small annihilation cross sections, like asymmetric dark matter models, for which the number of DM particles trapped in the Sun can be sufficiently high to induce detectable modifications of the Sun observables. In fact, in presence of sizeable DM scattering cross sections off nuclei, the transport of energy by the DM from the interior of the Sun to the outer shells can dramatically reduce the core temperature, the most important consequence being a reduction of the $^8B$ neutrino flux. Considering the present theoretical and experimental uncertainties on $\phi_B^\nu$, we have studied the combination of DM masses and SD scattering cross sections which can be ruled out with this argument, finding only a small region of the parameter space which is not already excluded by direct detection bounds. Even with a significant decrease of the uncertainties on $\phi_B^\nu$, the region of the parameter space which can be probed remains approximately the same, therefore future experimental advances will not significantly change the situation.

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