

Solar neutrinos constraints on light asymmetric dark matter.

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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. We find that 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. Finally, we revisit the recent claim that DM models with large self-interacting cross sections can lead to a modification of the position of the convective zone, alleviating or solving the solar composition problem. We show that when the ‘geometric’ upper limit on the capture rate is correctly taken into account, the effects of DM are reduced by orders of magnitude, and the position of the convective zone remains unchanged.

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1. Introduction

Dark Matter particles captured inside a star can affect the structure of the celestial body in two ways: they can scatter with the nuclei and transfer energy inside the object and if they are self-annihilating particles they can provide 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, first stars and compact objects (see e.g. [2, 3] and references therein). However, 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 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 e.g. [4]). 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 [5, 6]. 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 [7] CoGent [8] and CDMSII [9] 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_χ , is limited by annihilations and after a transient τ_χ , 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 $N_\chi = Ct_\odot$, 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 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 kind of scenario is realized in the so-called asymmetric DM models (see e.g.[10, 11] for more details).

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 [5, 6], 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.

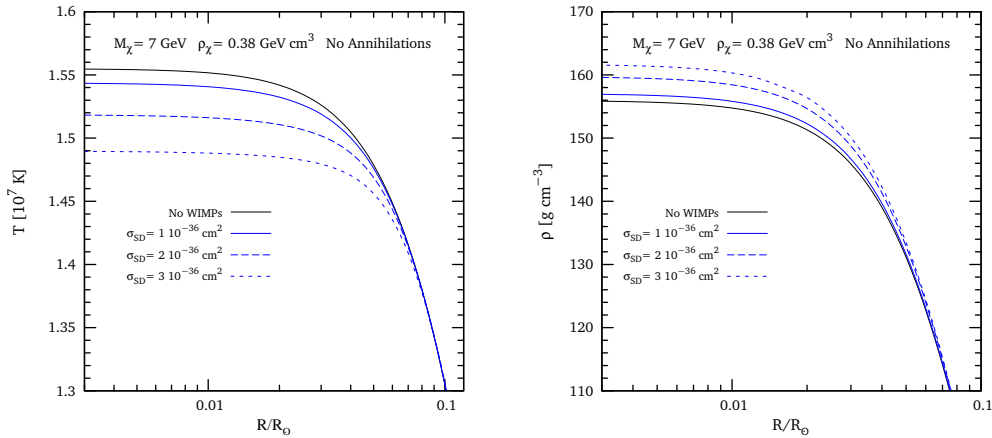


Figure 1: Impact of asymmetric DM on the Sun. *Left Panel:* Temperature profile of the Sun for different SD scattering cross-sections at $t_{\odot} = 4.57$ Gyrs. *Right Panel:* Density profile (baryons only) inside the Sun.

The 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_{χ} , of the order of 10^9 cm $\sim 0.01 R_{\odot}$, for a DM mass of 100 GeV (r_{χ} scales as $m_{\chi}^{-1/2}$). The DM energy transport will be therefore more efficient in the innermost regions of the Sun core. This means that neutrinos produced in the innermost regions are the most affected by the presence of DM, as it can be appreciated in the left panel of Fig. 2. For this reason and considering the experimental uncertainties in the determination of 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.

The ${}^8\text{B}$ flux has been determined with good accuracy by SNO [13]:

$$\phi_B^{\nu} = 5.046_{-0.152}^{+0.159}(\text{stat})_{-0.123}^{+0.107}(\text{syst}) 10^6 \text{ cm}^{-2}\text{s}^{-1}.$$

The solar model we use, as described in [17], predicts at the solar age t_{\odot} : $\phi_B^{\nu} = 4.56 \times 10^6 \text{ cm}^{-2}\text{s}^{-1}$ value that is well in agreement with the experimental results to within the theoretical uncertainties of solar model calculations [14, 15].

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 [16] for recent results) and solar models incorporating these revised metallicities conflict dramatically with helioseismological measurements, in particular right below the solar convective envelope. With the solar abundances of [16], the radius of the convective zone, R_{CZ} , is more than 10σ higher than the measured value: $R_{CZ} = 0.713 \pm 0.001 R_{\odot}$ (see Ref.[14] for an analysis of comparison of different solar models with helioseismology measurements.) High and low heavy elements models also produce differences on ϕ_B^{ν} of $\sim 20\%$. However, the theoretical uncertainties obtained within a particular solar model (with high or low metallicity estimations) are significantly smaller, $\sim 10\%$ [15]. Considering the theoretical and experimental uncertainties on ϕ_B^{ν} , we study the region of the DM parameter space where significant deviations on ϕ_B^{ν} are found (the maximum allowed deviation of the ${}^8\text{B}$ 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.

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_χ inside the Sun is thus obtained solving

$$\dot{N}_\chi = C - EN_\chi, \quad (3.1)$$

where C is the particle capture rate over the Sun and E the evaporation one. 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 [17].

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 readjustment of the entire stellar structure.

The increase of density is due to the contraction of the Sun, as a reaction of the loss of the core cooling

Left panel of Figure 2 shows the differential ^8B and ^7Be 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 ^8B neutrino flux, ϕ_B^V , 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 ^7Be neutrino flux, ϕ_{Be}^V .

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 fluxes only for very large values of the scattering cross section σ_{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 ϕ_B^V 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.

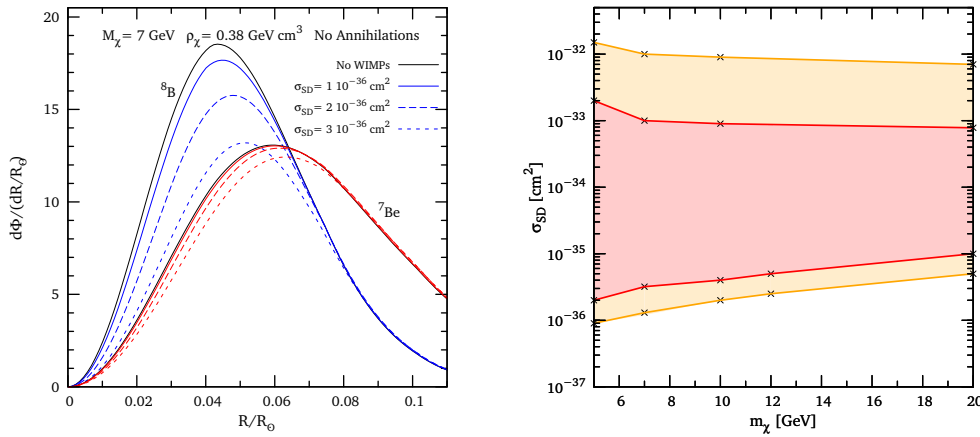


Figure 2: Solar neutrino fluxes in presence of asymmetric DM in the Sun. Left Panel: Differential ^8B and ^7Be neutrino fluxes as a function of radius. The curves referring to our solar model are normalized to unity. Right panel: isocontours of 25% (red) and 5% (yellow) ϕ_B^V deviations with respect our solar model prediction in the m_χ - σ_{SD} plane. The red area show the region of the parameter space with ϕ_B^V modifications larger than 25% and therefore in tension with present ϕ_B^V 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.

Above $m_\chi = 20 \text{ GeV}$ 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 ϕ_B^V 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. $\geq 10^{-33} \text{ cm}^2$), DM particles remain progressively “trapped” in the interior of the star. This implies that the heat transport from DM particles becomes local and the the modifications of ϕ_B^V 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 ϕ_B^V above $\sim 30\%$ are excluded at 95% CL. The maximum modifications that we obtained in our computations are slightly below this level: further increasing σ_{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 ϕ_B^V of the order of 20%, further small changes of σ_{SD} induce rapid modifications of ϕ_B^V . Because of that, the isocontours corresponding to 30% ϕ_B^V variations should be closed to the ones corresponding to $\delta\phi_B^V = 25\%$ shown in Fig. 2.

Considering a more optimistic value for the theoretical uncertainties on the ϕ_B^V 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 ϕ_B^V in the next years may in principle improve the sensitivities on σ_{SD} . We show however in Fig.2 that considering a 5 % modification of ϕ_B^V the region of the $m_\chi - \sigma_{SD}$ parameter space which can be probed enlarges very little.

3.1 Dark Matter and the solar composition problem

As noted above, since DM annihilations limit the number of trapped WIMPs in the Sun, asymmetric DM models are promising scenarios to look for modifications of the Sun properties. This is particularly true if DM is also strongly self interacting, as for Self Interacting DM models (SIDM). Indeed, in this case, the number of DM particle inside the Sun is exponentially enhanced by the additional capture induced by DM particles already trapped in the Sun.

In Ref.[18], adopting a polytropic model for the Sun structure and the linearized solar model of Ref. [19], the authors concluded that for suitable values of SIDM parameters the boundary of the solar convective zone R_{CZ} is decreased. They claimed that these modifications are such that the solar composition problem mentioned above can be solved, i.e. the position of the convective zone and helioseismology data can be reproduced. Our analysis does not confirm their conclusions.

We have studied the effect of a population of SIDM models in the Sun. In order to maximize the number of SIDM in the Sun we have considered the maximum value of DM self-interaction cross-section compatible with present astrophysical bounds. We have found a dramatical reduction of the core temperature, which produces a significant decrease of ϕ_B^V , in agreement with what is obtained in Sec. 3. At the center of the star, the luminosity is reduced, due to the evacuation of energy produced by the WIMPs, and the radiative opacity is increased, as a result of the decrease of the temperature and the increase of the density. However, the external zones are not significantly affected by the WIMPs so we do not see any significant change in the position of the convective zone. We conclude that a population of WIMPs, being strongly localized at the center of the Sun, can not affect its external shells without at the same time completely change the internal structure of the star. On the other hand, strong modifications of the central solar structure traduce in dramatic changes on the solar neutrino fluxes and helioseismology g-modes, as also demonstrated in Ref. [20], and in general of any observable sensitive to the physical conditions in that inner regions. The results of Ref. [20] appear in good agreement with our own and confirm that the presence of WIMPs inside the Sun can not modify the solar sound speed profile in such a way to restore the agreement with helioseismological data.

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 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 solar neutrino fluxes. Considering the present theoretical and experimental uncertainties on ϕ_B^V , 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 ϕ_B^Y , the region of the parameter space which can be probed remains approximately the same, therefore future experimental advances will not significantly change the situation. We have then revisited the recent claim that DM can solve the solar composition problem. We have found that the effects induced by DM matter is relevant only in the inner regions of the Sun. We can therefore exclude that the transport of energy produced by a population of WIMPs can solve or even alleviate the solar composition problem.

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