Main Sequence Stars with Asymmetric Dark Matter

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We study the effects of feebly or nonannihilating weakly interacting dark matter (DM) particles on stars that live in DM environments denser than that of our Sun. We find that the energy transport mechanism induced by DM particles can produce unusual conditions in the cores of main sequence stars, with effects which can potentially be used to probe DM properties. We find that solar mass stars placed in DM densities of $\rho_\chi \geq 10^2\ \mathrm{GeV/cm^3}$ are sensitive to spin-dependent scattering cross section $\sigma_{\mathrm{SD}} \geq 10^{-37}\ \mathrm{cm}^2$ and a DM particle mass as low as $m_\chi = 5$ GeV, accessing a parameter range weakly constrained by current direct detection experiments.

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Introduction.—Identifying the dark matter (DM) is one of the most enthralling problems of modern cosmology and particle physics. Weakly interacting massive particles (WIMPs) are among the most popular candidates and are currently searched for with different strategies; see, e.g., Ref. [1] for reviews. The effects of WIMPs on stars have been recently investigated as possible additional probes for DM searches: in the presence of self-annihilations, WIMPs captured inside a star can provide an exotic source of energy. Whereas the effects on the Sun are negligible because of the small DM density in the solar neighborhood, they may be remarkable on stars living in dense DM environments such as the Galactic center or the first halos to harbor star formation at high redshift [2–5]. In general, indirect searches of DM would fail for very feebly annihilating DM candidates. This is the case, for instance, of many asymmetric DM (ADM) models (see, e.g., [6]), where DM annihilations may not occur in the presence of an asymmetry between DM particles and antiparticles. Still, these particles accumulated in a star can scatter off nuclei and transport energy within its bosom. This effect results in a modification of the density and temperature profiles which can lead to detectable changes of the solar neutrino fluxes and gravity modes [7–10]. Stellar physics can thus provide a strategy to indirectly test this class of models. Interestingly, the evolution of the main sequence (MS), solar mass stars placed in environments with higher ADM densities, has not been studied yet (while this Letter was being refereed, a recent study addressing very low-mass stars in ADM has been published [11]). Here, we address this topic, showing that the energy transport induced by ADM cumulating inside such stars can provoke dramatic effects on the stellar structure.

Whether DM particles are actually intrinsically "asymmetric" or if their self-annihilation rate in a stellar environment is low enough ($\langle \sigma v \rangle \lesssim 10^{-33}\ \mathrm{cm^3/s}$ for the Sun) is indistinguishable for its effects in stellar evolution [9]; hereafter, our definition of asymmetric embraces the previous condition.

ADM in stars.—Here, we adopt the same formalism as in [9], to which we address the reader for details. A thorough description of the underlying theory can be found also in [2] and references therein. DM particles can be captured by a star via scattering off nuclei, the evolution of the total number of DM particles N_χ inside the star reading

$$\dot{N}_\chi = C - 2AN_\chi^2 - EN_\chi, \tag{1}$$

where C is the particle capture rate over the star, A is the annihilation rate, and E the evaporation rate. For the asymmetric DM candidates we are considering, the annihilation rate is null and evaporation is negligible for the physical conditions on which we focus; Eq. (1) therefore becomes trivial for ADM. Here, we recall the linear dependence of the capture rate on the spin-dependent scattering cross section σ_{SD} and the environmental DM density ρ_χ. Captured particles keep on scattering, with the stellar gas reaching a thermally relaxed distribution inside the star, $n_\chi(r) = n_{\chi,0} e^{-r^2/r_\chi^2}$. For the DM masses and cross sections we are going to consider, in a Sun-like star, the thermal DM radius r_χ is of the order of $r_\chi \lesssim 10^9$ cm ($\sim 0.03 R_\odot$), thus making DM particles confined within the nuclear energy generation region. DM particles weakly interacting with the baryons provide an additional energy transport mechanism to the standard ones. In their orbits, DM particles scatter in the innermost regions (called the "inversion core" hereafter), absorbing the heat and releasing it in the immediate surroundings, within the nuclear energy production region.

Stars in high ADM densities.—The effects of the DM energy transport are enhanced for increasing DM densities, since the number of particles cumulated inside the star grows linearly with ρ_χ. Hence, we have studied the evolution of a solar-type star ($1M_\odot$, $X = 0.72$, $Y = 0.266$, and $Z = 0.014$) for increasing DM densities. In this section, we fix the DM-proton spin-dependent cross section $\sigma_{\rm SD} = 10^{-37}$ cm^2 and DM particle mass $m_\chi = 10$ GeV. We will discuss the effect of varying these parameters in the following sections, whereas we keep the stellar velocity through the DM halo $\bar{v} = 220$ km/s.

We have modified the publicly available DARKSTARS code [12], in order to use the Spergel and Press formalism (Eq. 4.9 in [13]) rather than the Gould and Raffelt one in [14]. Whereas the latter has been proved to correct the overestimate—of order unity—present in the previous formalism, we have noticed that, in critical conditions such as the ones we meet in our study, the implementation of this formalism may easily induce an unphysical behavior of the solution obtained by numerical codes. We have found this numerical artifact to show up both with the original DARKSTARS code and the GENEVA stellar evolution code [15], modified for the inclusion of DM effects, as we have described in [9]. The effects we describe in the following could therefore be overestimated of a factor unity; namely, they could show up for DM densities ρ_χ, a factor unity bigger than the actually quoted ones.

We evolve the star from the zero age main sequence, by adopting an environmental $\rho_\chi = 10^3$ GeV/cm^3, which for a Navarro-Frenk-White (NFW) DM density profile corresponds to $R_{\rm gal} \sim 10$ pc from the Galactic center. As long as the absolute value of the DM transport energy term $\epsilon_{\rm trans}$ is much smaller than the nuclear energy generation term $\epsilon_{\rm nuc}$, the global properties of the star are not modified. We have verified that the central temperature and density profile *are* altered with respect to the same star evolved without DM, according to what we have seen in [9]: neutrino fluxes and seismic g modes of the star *get* modified with respect to the standard case, and we defer a systematic analysis of this to later studies.

Here, we focus on a much more dramatic effect, taking place when $\epsilon_{\rm trans}$ becomes comparable with $\epsilon_{\rm nuc}$. For our choice of DM parameters m_χ and $\sigma_{\rm SD}$, this takes place when the total population of DM particles in the star $n_{\rm tot} \sim 5 \times 10^{47}$ (for this particular choice of parameters and stellar mass, this takes place approximately 5 Gyr after the zero age main sequence). In these conditions, DM is able to transport out of a very central region the entire energy generated by nuclear reactions, thus resulting in an efficient sink of energy for the stellar region within the inversion radius $r_i \sim 0.04R_\odot$, namely, the region where the isothermal WIMP temperature is lower than the local baryonic temperature, $T_\chi < T_b$. Outside of r_i, yet within the nuclear energy generation region $r_{\rm nuc} \sim 0.1R_\odot$, DM particles deposit the energy absorbed from the innermost, hotter baryons into the local medium, colder than T_χ. This energy deposit is not crucial; what matters most is the effective diminished efficiency of the nuclear energy source at the center. The star is forced to compensate for this decrease by increasing the nuclear energy production outside the inversion core.

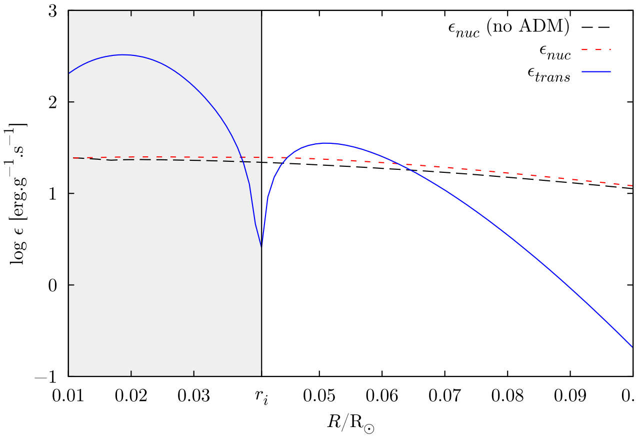

FIG. 1 (color online). The structure of $\epsilon_{\rm trans}$ and $\epsilon_{\rm nuc}$ for a $1M_\odot$ star evolved with the ADM parameters $\rho_\chi = 10^3$ GeV/cm^3, $\sigma_{\rm SD} = 10^{-37}$ cm^2, and $m_\chi = 10$ GeV. The profile is taken when the central hydrogen fraction $X_c = 0.2$. Also shown for comparison is the $\epsilon_{\rm nuc}$ of a star evolved without ADM, at the same age. The shaded area—the innermost of r_i—shows where $\epsilon_{\rm trans}$ has a negative sign, thus absorbing energy from the stellar gas.

In Fig. 1, we show the radial structure of $\epsilon_{\rm trans}$ compared to $\epsilon_{\rm nuc}$: it is clearly visible how the DM energy transport is the mechanism dictating the energetics of the region within the inversion radius r_i, and the energy sink caused by DM in this region induces a temperature drop. An example of the resulting temperature profile is shown in Fig. 2, where both the central drop within r_i caused by the ADM energy absorption and a raise in the shell between r_i and $r_{\rm nuc}$ are

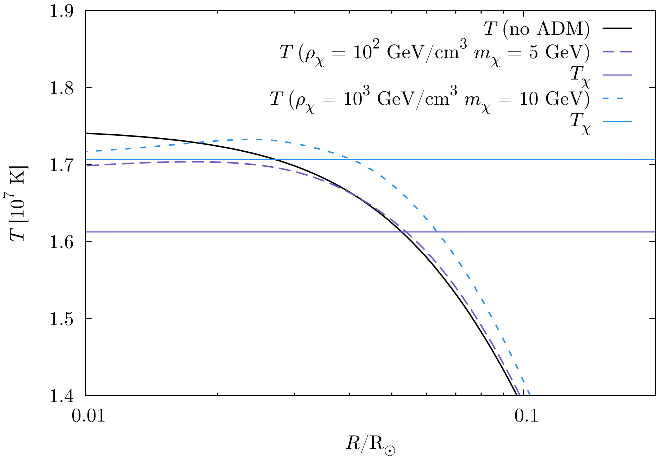

FIG. 2 (color online). Stellar (baryonic) temperature profile for a two-ADM parameter set, as from the plot; the solid black line is a model evolved without DM. The profile is taken when the central hydrogen fraction $X_c = 0.2$. This corresponds at an age of approximately 5.3, 5.4, and 5.6 Gyr for the case with no ADM and increasing ADM density ρ_χ, respectively.

clearly visible. Such a new temperature profile is the result of the new equilibrium reached by the star, which readjusts its structure in order to provide the correct energetics; the new nuclear reaction rate $\epsilon_{\rm nuc}$ is visible in Fig. 1. These modifications are quite remarkable, modifying the chemical evolution of the star as well as its external appearance; see more in the next section.

The behavior we have described is reached when DM particles are enough that $\epsilon_{\rm trans} > \epsilon_{\rm nuc}$ in the central region of the star, within r_i. For the value of *environmental* DM density $\rho_\chi = 10^3$ GeV/cm^3 and $\bar{v} = 220$ km/s adopted in this run, this happens quite early during the evolution of the star, whereas, for DM densities smaller than $\rho_\chi = 10^3$ GeV/cm^3 (with $m_\chi = 10$ GeV), the time needed for the star to capture enough particles is longer than the MS itself, so the mechanism we have described cannot take place. Conversely, for increasing DM densities ρ_χ (and therefore the capture rate C), this arrives at shorter times during the main sequence.

We have evolved several stellar models for different values of the environmental DM density (keeping constant $\sigma_{\rm SD}$ and m_χ), finding that remarkable effects on the stellar structure are present for different DM densities ρ_χ. It is worthwhile to remark that, for increasing ρ_χ, DM particles start being an effective sink of energy at decreasing times. The cumulation of more particles during the MS boosts the $\epsilon_{\rm trans}$ increasingly, with even more remarkable effects: in Fig. 3, we show the impact of increasing ADM densities on the star's evolution. Whereas, for $\rho_\chi \lesssim 10^4$ GeV/cm^3, $|\epsilon_{\rm trans}| > \epsilon_{\rm nuc}$ for $R \lesssim r_{\rm nuc}$, its integral over the whole star is smaller than the total nuclear luminosity of the star, $L_{\rm trans} \equiv \int |\epsilon_{\rm trans}| dV < L_{\rm nuc}$: the structure reacts to it by finding a new stable configuration at increased luminosities, by readjusting the nuclear reaction rate between r_i and $r_{\rm nuc}$. On the other hand, at very high ADM density ($\rho_\chi \gtrsim 10^5$ GeV/cm^3), the temperature is mitigated in the whole nuclear energy generation region, rather than only in the inversion core. This is because the energy reinjected by the WIMPs at $R > r_i$ is now sufficient to inflate that region, thus cooling it and reducing the efficiency of $\epsilon_{\rm nuc}$. The envelope then contracts to extract energy from the gravitational potential well.

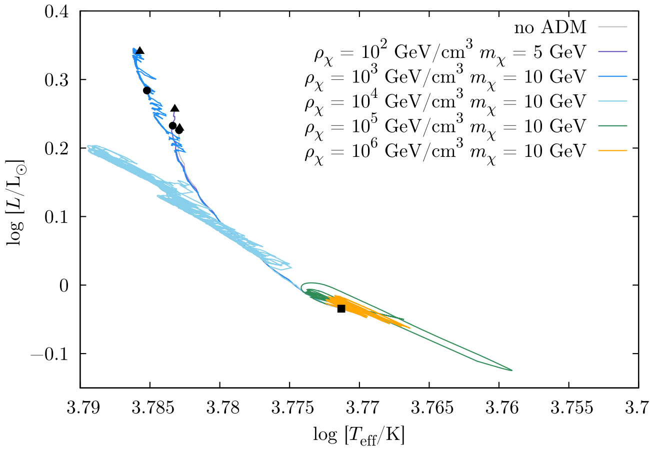

FIG. 3 (color online). The Hertzsprung-Russel diagram for $1M_\odot$, for varying DM parameters as marked in the plot, with $\sigma_{\rm SD} = 10^{-37}$ cm^2. The solid black square is the starting point of our simulation; the solid black circles mark an age of 6 Gyr, not achieved for runs with $\rho_\chi > 10^3$ GeV/cm^3. Solid black triangles mark the fall of the central hydrogen fraction X_c below 0.1. This takes place at an age of 6.05, 6.36, and 6.39 Gyr for the no ADM case, $\rho_\chi = 10^2, 10^3$ GeV/cm^3, respectively. Notice that the fluctuations may be numerical artifacts.

Summarizing, when $L_{\rm trans} < L_{\rm nuc}$, the star compensates for the deficit of nuclear energy generation in the center by increasing the nuclear energy generation outside the inversion core. At $L_{\rm trans} > L_{\rm nuc}$, the redistribution of the energy by the WIMPs is such that $\epsilon_{\rm nuc}$ is reduced in the whole nuclear core and the star must compensate this deficit by the contraction of its envelope.

Diagnostic power.—Is it possible to use such a mechanism as a possible probe for ADM parameter space, namely, are stellar observables affected from this mechanism at a testable level? Deviations from the standard path in the Hertzsprung-Russel (HR) diagram are the ideal observable.

The modifications of the stellar structure described in the previous section, induced by ADM, are clearly visible in the HR diagram. In our Fig. 3, it is possible to see how the model described above detaches from a normal path in the temperature-luminosity plane once captured DM particles have achieved the right number $n_{\rm tot}$. The new distribution of temperature makes the star more luminous and bigger, thus moving left and upward in the plane for low ADM densities. The resulting position of the star in the HR diagram is therefore unusual, and more so as the star ages and gets toward the end of the MS. In Fig. 3, it can be appreciated how, by increasing ρ_χ, the actual position of the star in the HR changes, finally reverting it to lower luminosities as a consequence of the dramatic drop in temperature, as explained in the previous section; still, these stars are kept away from the usual track. This could indeed be used to identify a peculiar generation of stars and to probe ADM parameters or the distribution of ADM in our Galaxy. However, we caution that these observational tests are challenged by the difficulty of observing stars close to the Galactic center (or in the very center of dwarf galaxies, where DM environmental conditions could be similar), which makes current uncertainties on the position of these stars in the HR diagram quite large.

However, it is worth it to remark that, unlike the case of annihilating DM, the effects of ADM may be made "portable" by the star throughout its journey in space. In the case of DM annihilating and providing an additional energy source to the star, the effects are tightly related to the environmental DM density the star is experiencing within the short equilibrium time $-O(10^6$ yr). Self-annihilation depletes the DM cumulated inside the star, and a continuous provision is required to keep the effects going [2]. ADM does not escape from the star: in principle, stars may capture ADM in a dense environment and migrate somewhere else in the Galaxy and the effects would still be visible.

The effect of varying DM parameters.—For the values of $\sigma_{\rm SD}$ we are considering, the DM energy transport is nonlocal, i.e., the DM free path is larger than r_χ and DM particles can efficiently transport energy between distant regions in the stellar core. In this case, $\epsilon_{\rm trans}$ is enhanced for larger $\sigma_{\rm SD}$, until the DM energy transport becomes local, and so $\epsilon_{\rm trans}$ is decreased, this happening for $\sigma_{\rm SD} \gtrsim 10^{-34}$ cm^2. The capture of DM particles is easier for lighter ones, and heavier DM particles tend to be confined in smaller regions inside the core, both effects making the DM transport inside stars more sensitive to small values of m_χ.

For $m_\chi = 10$ GeV and $\sigma_{\rm SD} = 10^{-38}$ cm^2, the dramatic effects on the stellar structure which we have previously discussed start to appear for $\rho_\chi \geq 10^5$ GeV/cm^3. This actually demonstrates that smaller SD cross sections can be explored, although the price to pay is to shrink the region of the Galaxy potentially probing this mechanism. On the other hand, for $\sigma_{\rm SD} = 10^{-36}$ cm^2, the same situation is reached at lower DM densities, $\rho_\chi = 10^2$ GeV/cm^3. For smaller DM masses (but still above the evaporation mass ~5 GeV), it is possible to probe smaller $\sigma_{\rm SD}$, for the same value of DM density.

Effects on massive stars.—In principle, the accumulation of ADM particles inside massive stars should have the same effects as in low-mass ones, the transport effects of DM not depending (explicitly) on the burning mechanism (hydrogen via *p*-*p* or CNO). However, one crucial fact is to be stressed: transport effects start modifying dramatically the structure of a star when $\epsilon_{\rm trans}$ is of the same order as $\epsilon_{\rm nuc}$ within r_i. Two important things are to be noticed: (i) the stellar luminosity scales nonlinearly with the stellar mass, $L_* \propto M_*^{3.5}$, and (ii) the lifetime becomes shorter as the stellar mass increases. The latter, combined with the fact that the capture rate does *not* scale strongly with the stellar mass (roughly $C \propto M_*$), leads to the conclusion that higher-mass stars are less sensitive than low-mass ones to the same DM parameters. We have evolved models of increasing stellar mass between 1 and $10M_\odot$ for the same ADM parameters, in which we take $\sigma_{\rm SD} = 10^{-37}$ cm^2, $\rho_\chi = 10^7$ GeV/cm^3, and $m_\chi = 5$ GeV. The $5M_\odot$ model gets out of the typical path on the HR at an age of approximately 90 Myr ($X_c \sim 0.2$). Stars with masses larger than $6M_\odot$ evolve normally; i.e., the impact of such ADM densities on their evolution is negligible.

This shows that stars with masses around the solar value—or even smaller, as in [11]—are better ADM probes than bigger ones, and yet this is good news, as approximately 60% of the stellar mass in our Galaxy is expected to be present in the $0.1M_\odot \leq M_* \leq 1M_\odot$ range. In the very same environment, low-mass stars may be affected by the dramatic ADM effects, whereas more massive ones are insensitive to it.

Conclusions.—In this Letter, we have shown that feebly or nonannihilating DM, carrying weak interactions with the baryons, can have dramatic effects on solar mass and main sequence stars placed in DM environments denser than that of our Sun. This is due to the enhancement of DM-driven transport effects that evacuate the nuclear energy produced in the center of the core of the star. We have shown that, once this happens, this may provoke dramatic changes in the structure and external appearance of the star. We have shown that such dramatic effects take place in solar mass stars in environments with DM densities $\rho_\chi \gtrsim 10^2$ GeV/cm^3 (for $\bar{v} = 220$ km/s—i.e., for capture rates enhanced by a factor of ~250 with respect to the solar neighborhood), and that they can in principle be used as a probe for DM particle masses as low as $m_\chi = 5$ GeV and spin-dependent cross sections $\sigma_{\rm SD} \gtrsim 10^{-37}$ cm^2.

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