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Evolution of Low-Mass Stars Within Dense Dark Matter Halos

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Abstract: The evolution of low-mass stars within dense dark matter halos can be an useful tool to test and constrain the properties of DM candidates. The presence of DM particles on stars deflect the standard evolution of stars on the main-sequence. In this work, we describe these new scenarios that depend on the density of the dark matter halos, based on the work of Jordi Cassanelas & Ilídio Lopes [1] [2].

Keywords: dark matter; stars: evolution; Hertzsprung-Russel diagram; stars: formation

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1. Introduction

In the Universe, only 5% of the matter is regular visible matter, this means that 95% of the Universe is composed by invisible matter and energy [1]. This major percentage is still very mysterious and speculative and have been an object of interest and study by Astrophysics, Cosmology and Particle Physics.

From those 95%, 23% is non-baryonic matter - dark matter (DM) - and it was found in several observations that it is responsible for the existence of external gravitational field sources in different locations of the Universe [3]. This affirmation is the result of many observational evidences obtained throughout the years, that suggest that DM has, in some way, contributed for the formation and the structure of the Universe.

Some evidences of the existence of DM are the accelerated expansion of the Universe obtained by using type Ia Supernovae as standard candles, the rotation curves of galaxies that are not consistent with the Keplerian motion, the cosmic microwave background anisotropies, and others. With these astrophysical and cosmological observations the best DM particle candidates are known as *Weakly Interacting Massive Particles* (WIMPs). As the name suggests these type of particles must be massive, electrically neutral and non-relativistic. WIMPs interact through gravity and possibly through the weak nuclear force [1] with baryons. Something that is well-established regarding DM particles is that they were produced in the primitive universe, such as baryons, in a similar process to Baryogenesis [3]. This means that at the moment, a substantial amount of residual dark matter exists as a result of an unbalance between DM particles and antiparticles (asymmetry).

To better understand the properties of WIMPs, one objective is, therefore, the experimental search of these DM particles. There are two methods to detect them:

- Direct Detection: infers the properties of DM particles by the type of interaction that they have with a target-baryon [3].
- Indirect Detection: infers the properties of DM particles by detecting an astronomical decay or annihilation signal [7], which means detecting one of the products resulting from one of the previous processes.

There are already some hints of DM detection and it is thought that the maximum type of interaction between a DM particle and a baryon is of the order of the weak interaction.

One method that have been explored by many authors, in order to unveil some characteristics of the nature of the fundamental particles that DM is made of, is offered by astrophysical objects, such as the Sun, white dwarfs, neutron stars and low-mass stars. If a star is embedded in a dark matter halo, it can capture WIMPs during its formation and evolution and thus suffer some alterations in its classical evolutionary path.

The astrophysical objects of interest in this work are low-mass stars. When these capture and accumulate WIMPs in their core, two things can happen: WIMPs can annihilate among themselves, providing a new source of energy for the star or, they can provide an additional mechanism of heat transport inside the star [1]. So how this will affect the behaviour of low-mass stars? Will their internal structure remain the same? Where could these type of stars evolve? These are all questions that we will explore.

This work is organized as follows: in section 2 we make a brief revision on the evolution of low-mass stars through the main-sequence, not considering dark matter; what happens when dark matter particles remain trapped in the stellar cores is explained in section 3; then we have some results of Jordi Casanellas & Ilídio Lopes (2009) regarding the different scenarios of stellar evolution in low and high density dark matter halos in section 4.

2. Summary of the Classical Evolution of Low-Mass Stars through the Main-Sequence

Cold and dark molecular clouds constituted by dust and gas, in the form of molecular hydrogen, are usually called the "stellar nurseries". In these, clumps form, i.e, higher density regions, that due, or not, to external perturbations, such as shock waves of the explosion of a supernova or a collision between molecular clouds, undergo gravitational collapse if the cloud surpasses the Jean's mass. This means that within these type of clouds several proto-stars will be formed, with different masses and thus different evolutionary paths.

As it reaches its final mass, the star becomes a pre-main sequence star. One can say that a star reaches the main-sequence phase once the gravitational collapse is balanced out by the pressure exerted by thermonuclear reactions that start in the stellar core due to the high temperature and pressure. At this stage, the hydrogen fusion begins, the net result of this process is the conversion of four ^{1}H atoms to one ^{4}He atom [8]. Depending on the star's mass this conversion can be done by two different processes that lead to the same result: the *pp* chain (proton-proton) and the CNO cycle (Carbon-Nitrogen-Oxygen). For stars with $1M_\odot$ or smaller, the *pp* chain is the dominant source of energy, for stars with masses slightly above the solar mass, the CNO cycle start to contribute largely to the energy generation rate. The mass of the stars dictate the evolutionary path that they will take.

As mentioned previously, in this work our focus is on low-mass stars, $0.4M_\odot < M < 4M_\odot$ [4]. In the main-sequence this type of stars develop a radiative core and a convective envelope in the external layers, as represented on figure 1.

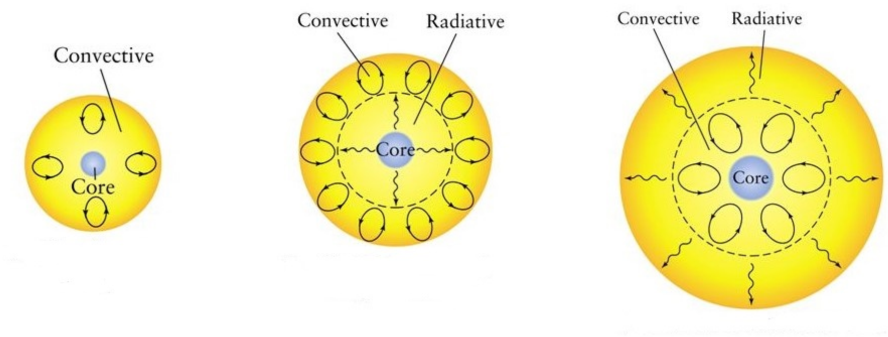

Figure 1. Internal structures of main-sequence stars. On the left; a star with $M < 0.4M_\odot$ is convective in all of its interior; on the center, a star with $0.4M_\odot < M < 4M_\odot$ has a radiative core involved by a convective envelope; and on the right, a star with $M > 4M_\odot$ has a convective core involved by a radiative envelope. Credits: Bertha McBride.

Low-mass stars are thus fueled, on the main-sequence, by both of the processes mentioned above, the *pp* chain and the CNO cycle.

Low-mass stars do not need as much temperature and pressure in order to support themselves against gravitational collapse as massive stars. This makes them spend more time in the main-sequence as they will need more time to spend the totality of the hydrogen fuel present in their core.

3. Dark Matter Particles Inside Stars

When WIMPs travel through stars two scenarios can happen: they can pass right through the star without suffering any interaction, which is what happens to most of them, while a small portion of them experience scattering off the nuclei they encounter in the core of the star, such as hydrogen, helium, carbon or oxygen. The interactions may or may not depend on the spin content of the nucleus in question. The scattering interaction of a DM particle with hydrogen is spin-dependent, while with the other elements is spin-independent.

In the case that the DM particle loses enough energy it will not be able to escape the gravitational field of the star, remaining trapped in the stellar core. The capture rate, C_χ, gives us the total number of WIMPs accumulated inside the star [5]:

$$C_\chi = \sum_i \left(\frac{8}{3\pi}\right)^{1/2} \sigma_\chi \frac{\rho_\chi}{m_\chi} \overline{v}_\chi \frac{x_i M_\star}{A_i m_p} \frac{3v_{esc}^2}{2\overline{v}_\chi^2} \zeta \tag{1}$$

The capture rate is thus proportional to the WIMP scattering cross section off nuclei σ_χ, to the dark matter density of the halo ρ_χ, the mass fraction of element i x_i, the star's mass $M_\star$ and to the escape velocity given as $v_{esc} = \sqrt{2GM_\star/R_\star}$, where $R_\star$ is the radius of the star. It is inversely proportional to the WIMP mass m_χ, the number of nucleons of element i A_i, the proton's mass m_p and to the WIMP dispersion velocity $\overline{v}_\chi$. The last term of the expression, ζ, can be approximated to the order of the unity as it will not have significant effects on the study of DM particles in stars, and it reduces immensely the time of computation.

If we have WIMPs captured in the stellar core, the evolution of the star will not be the same as the one expected in the classical scenario of the star's evolution. Instead, the DM particles can change it through two different mechanisms that can work simultaneously:

- The annihilation of the DM particle and antiparticle pairs act like a new source of energy that balance the self-gravitational contraction of the star [3]. This new source of energy complements the *pp* chain and the CNO cycle.
- DM particles can provide a new mechanism of energy transport by scattering off nuclei inside the star [1]. This complements the radiative and convective transports.

However, when it comes to stellar evolution within a dense dark matter halo, in most cases, the presence of a DM energy source is much more significant than the DM energy transport. Thus the latter can be neglected.

Thereby, one can say that the total number of WIMPs, N_χ, inside the star is determined by the balance between the capture rate and the annihilation rate, Γ_χ. The evolution over time of N_χ is then given by the following expression [1]:

$$\frac{dN_\chi}{dt} = C_\chi - 2\Gamma_\chi \tag{2}$$

It is considered the term $2\Gamma_\chi$ because each annihilation requires two WIMPs, with the assumption that the DM particle is its own antiparticle. Likewise, the equilibrium is reached when $\frac{dN_\chi}{dt} = 0$ or $C_\chi = 2\Gamma_\chi$.

With the additional DM energy source, every annihilation contributes to the total luminosity of the star. This happens according to the following expression:

$$L_\chi = f_\chi C_\chi m_\chi \tag{3}$$

where $f_\chi = \frac{2}{3}$ is a factor to take into account that $\frac{1}{3}$ of the DM annihilation's products will escape out of the star in the form of neutrinos [2].

4. Stellar Evolution Scenarios within DM Halos

Considering the presence of the new energy source due to the DM annihilation, the more accretion of WIMPs in the stellar core, the more energy is produced by WIMP pair annihilation and thus the more different will be the evolutionary path of the star regarding the classical path.

With this in mind, it is possible to define two cases beside the classical scenario: the weak scenario where the star evolves in a halo with "low" DM density ($\rho_\chi = 0.3 \times 10^8$ GeV cm^{-3}) and the strong scenario where the star evolves in a halo with high DM density ($\rho_\chi = 3 \times 10^{11}$ GeV cm^{-3}) [1].

Figure 2 translates the different energy sources, during the evolution of a sun-like star:

- The gravitational energy rate, ϵ_{grav}, due to the gravitational contraction of the star;
- The thermonuclear energy rate, ϵ_{pp}, produced by the *pp* chain;
- The thermonuclear energy rate, ϵ_{CNO}, produced by the CNO cycle;
- The WIMP pair annihilation energy rate, ϵ_χ.

All of these contribute to the total energy generation rate of a star, ϵ_T.

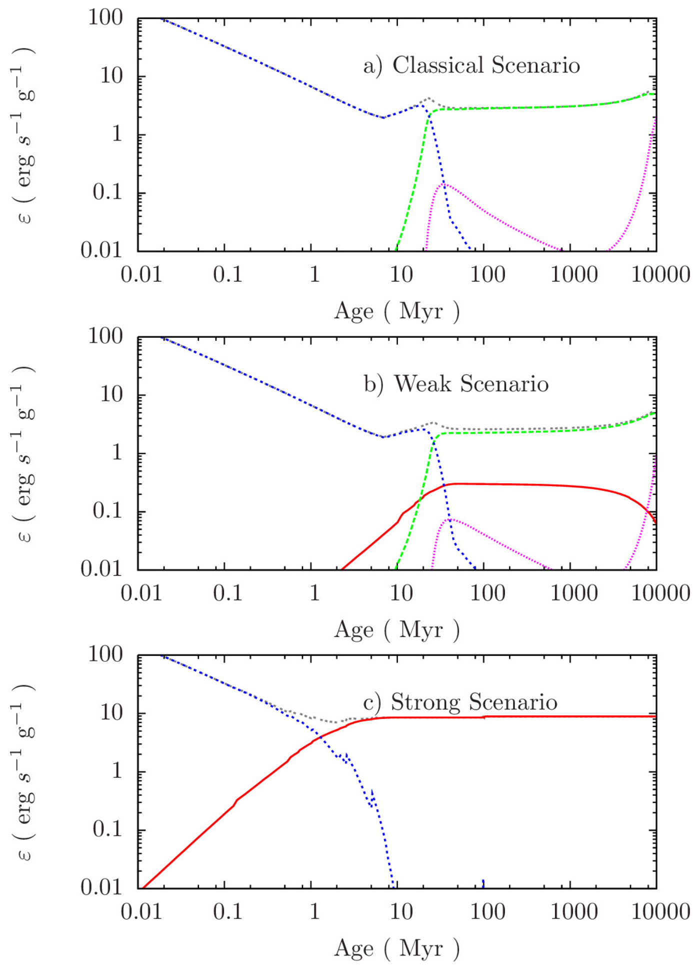

Figure 2. Energy rates during the evolution of a 1 $M_\odot$ star on the a) Classical, b) Weak ($\rho_\chi = 0.3 \times 10^8$ GeV cm^{-3}) and c) Strong scenarios ($\rho_\chi = 3 \times 10^{11}$ GeV cm^{-3}). The light grey dashed line represents ϵ_T; the blue dashed line is ϵ_{grav}; the green dashed line represents ϵ_{pp}; the pink dotted line, ϵ_{CNO}; and the red continous line is ϵ_χ. Credits: [1]

The plots present in this work were obtained by Cassanelas, J. & Lopes, I. (2009) assuming a WIMP mass of m_χ =100 Gev, the maximal value of the spin-dependent WIMP-nucleon scattering cross-section currently allowed by direct and indirect detections given as $\sigma_{\chi,SD} = 10^{-38}$ cm^2 and the annihilation cross-section $< \sigma_a v >= 3 \times 10^{-26}$ cm^3 s^{-1}.

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1 Notice that these values are considered halos with low and high dark matter densities for a star of mass 1M$_\odot$. The definition of low and high densities for DM halos will be different according to the mass of the star in question.

4.1. Weak Case Scenario

As we have seen on section 2, the gravitational contraction experienced by the star increases the core's temperature, originating an additional source of energy - thermonuclear reactions - that counteracts the collapse. In a low DM density halo, WIMPs are captured in the stellar core and annihilate each other, acting like a complementary source of energy to the *pp* chain and CNO cycle.

With this new source of energy, the gravitational collapse is very slightly delayed (see figure 2a) and b)) and thus the star takes longer to reach the hydrogen burning phase, i.e, the main-sequence phase. The equilibrium state is reached at a lower temperature of the core and therefore the energy generated by the thermonuclear reactions is smaller than the classical scenario, as we can also see on figure 2.

As it is not necessary so much hydrogen fusion to obtain the equilibrium state, the star will save fuel and hence live a longer period of time on the main-sequence, compared to the classical scenario. In order to have the same effect on different stars, the more massive the star, the higher the DM density, as seen in figure 3. For example, a dark matter halo of $\rho_\chi = 10^9$ GeV cm^{-3} affects the time in the main-sequence of a star of mass 1M$\odot$ but it do not affect those with higher masses.

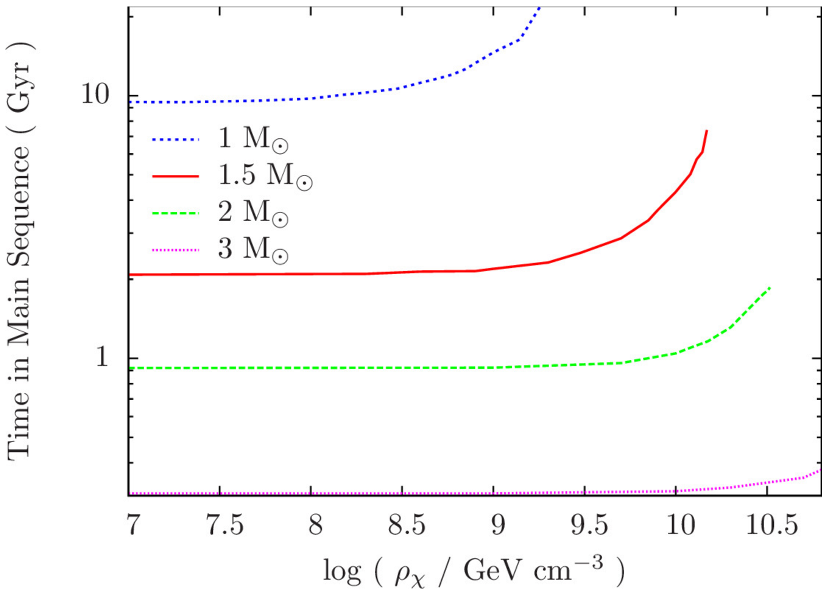

Figure 3. Time that stars of masses $1M_\odot$, $1.5M_\odot$, $2M_\odot$ and $3M_\odot$ spend in the main-sequence when embedded in dark matter halos of densities between 10^7 GeV cm^{-3} and 10^{11} GeV cm^{-3}. Credits: [1]

If there is a new source of energy that counteracts the gravitational collapse, it follows that the equilibrium state is reached more rapidly (reason why this state is reached in a lower central temperature, as mentioned above), therefore at a larger radius than that of the classical scenario. This must change the path expected for low-mass stars on the Hertzsprung-Russell (HR) diagram, and, in fact, as we can see on figure 4, the main-sequence phase will start at a lower effective temperature. This is visible through the different positions that the ZAMS[2] (Zero Age Main Sequence) take on the diagram, when is considered an halo with and without dark matter. In order for the stars to evolve in a weak scenario, their thermonuclear energy needs to account for more than 10% of the total energy in the ZAMS [1]. Otherwise, it is considered the strong case scenario that we will discuss further on.

On the classical scenario, in the pre-main sequence evolution of a star of 1M$_\odot$ beginning on the Hayashi track[3], the star has a small convective core within the radiative interior, which will disappear when the star reaches the main sequence [1] to give place to a radiative core involved in a convective envelope (as seen on section 2). The internal structure of the star under the influence of DM will have some modifications. As there is an excess of luminosity

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[2] Time when a star starts the nuclear reactions and therefore joins the main sequence on the Hertzsprung-Russell diagram.
[3] The nearly vertical line on the HR diagram that contracting proto-stars initially descend before reaching the main-sequence phase.

produced by the WIMPs annihilation at a very congregated region in the stellar center, the star will need a transport mechanism more efficient to evacuate the extra energy present on the stellar core. Thus it will conserve its convective core for a longer period of its evolution. This means that on the main sequence, the structure of these stars will be, during a certain time interval, the small convective core, involved with a radiative envelope and an external convective layer at the surface.

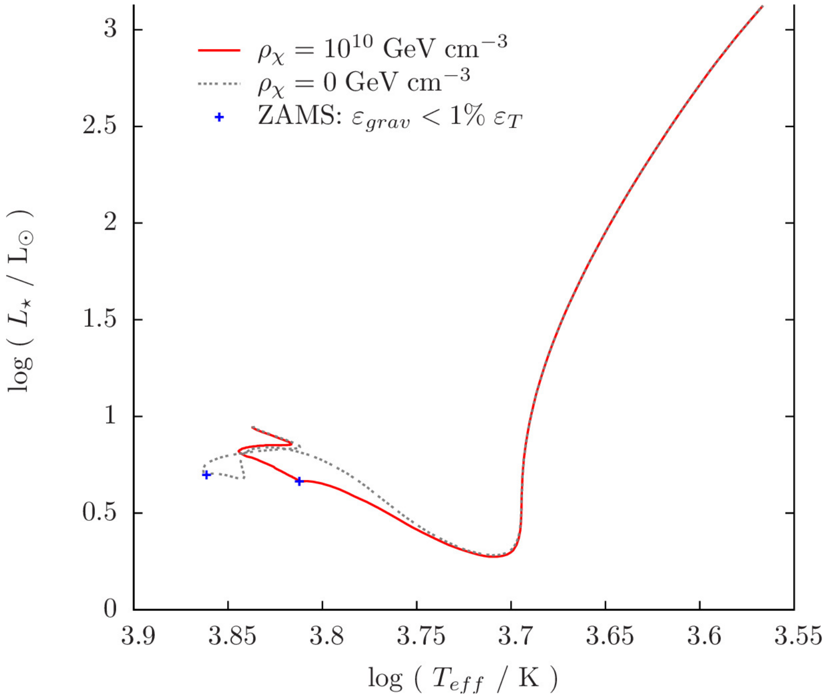


Figure 4. Hertzsprung-Russell diagram of the formation and evolution through the main-sequence of a star of 1.5M$_\odot$. The red line represents the path taken by the star when it is embedded in a DM halo of $\rho_\chi = 10^{10}$ GeV cm^{-3}, the gray dashed line is the classical evolution, i.e, without the presence of dark matter particles and the blue symbols "+" represent the ZAMS position on each case. Credits: [1]

4.2. Strong Case Scenario

Increasing the density of the DM halo, ρ_χ, the capture rate of WIMPs inside the star, C_χ, also increases. The energy source from the DM annihilation start to exert the pressure necessary to compensate the gravitational energy source. With this, the stellar core never reaches the critical temperature for the thermonuclear reactions to start, making the DM burning the only source of energy that fuel the star (see figure 2c)). ϵ_χ is high enough in order to stop ϵ_{grav}, and the star "freezes" in an indefinite state of equilibrium. These stars are typically called *Dark Stars*.

How is this "freeze" affected by the stars' mass? Figure 5 answers this question. We can see that, as expected, for more massive stars we need higher DM densities in order to completely stop the collapse. A star of mass 1.5M$_\odot$ evolving in a DM halo with $\rho_\chi = 10^{11}$ GeV cm^{-3} completely stops its collapse at an effective temperature of approximately $T_{eff} \approx 5011$ K and a luminosity of $L_\star \approx 1.8$ L$_\odot$. However, this plot was obtained using equation 1 to calculate the capture rate, being it a simpler expression of this parameter.

The original expressions of Gould (1987) [5] for the calculation of the capture rate of DM particles in the interior of stars, are given as follow:

$$C_\chi(t) = \int_0^{R_\star} 4\pi r^2 \int_0^\infty \frac{f_{v_\star}(u)}{u} w\Omega_v^-(w)\,\mathrm{d}u\,\mathrm{d}r \tag{4}$$

where $f_{v_\star}(u)$ is the distribution of the velocities of the DM particles seen by the star, considering different velocities of the star $v_\star$:

$$f_{v_\star}(u) = f_0(u)\exp\Big(-\frac{3v_\star^2}{2\bar{v_\chi}^2}\Big)\frac{\sinh(3uv_\star/\bar{v_\chi}^2)}{3uv_\star/\bar{v_\chi}^2} \tag{5}$$

$f_0(u)$ is the velocity distribution of the DM particles, which is assumed to be a Maxwell-Boltzmann distribution with a dispersion velocity $\bar{v_\chi}$:

$$f_0(u) = \frac{\rho_\chi}{m_\chi}\frac{4}{\sqrt{\pi}}\Big(\frac{3}{2}\Big)^{3/2}\frac{u^2}{\bar{v_\chi}^3}\exp\Big(-\frac{3u^2}{2\bar{v_\chi}^2}\Big). \tag{6}$$

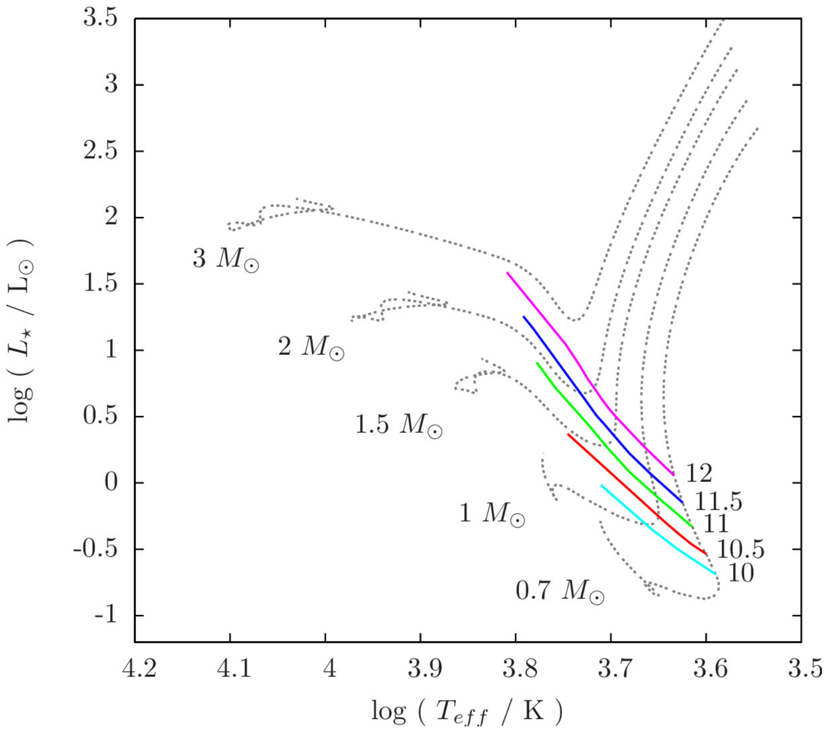


Figure 5. Stationary states reached by stars with masses between 0.7M$_\odot$ and 3M$_\odot$ in the strong case scenario. Different DM halo densities are plotted from 10^{10} GeV cm^{-3} to 10^{12} GeV cm^{-3}, indicated at the side of each coloured line, in units of log(ρ_χ/GeV cm^{-3}). The grey dashed lines represent the classical evolutionary path that the stars follow before stopping. Result obtained if equation 1 is considered in the computation. Credits: [1]

On equation 4, $\Omega_v^-(w)$ is the probability of a DM particle with a velocity w to have, after the collision with the nucleus of an element i, a velocity v lower than the escape velocity of the star $v_{esc,r}$ at the radius of the collision, [2]

$$\Omega_v^-(w) = \sum_i \frac{\sigma_i n_i(r,t)}{w}\Big(v_{esc,r}^2 - \frac{\mu_{-,i}^2}{\mu_i}u^2\Big)\theta\Big(v_{esc,r}^2 - \frac{\mu_{-,i}^2}{\mu_i}u^2\Big), \tag{7}$$

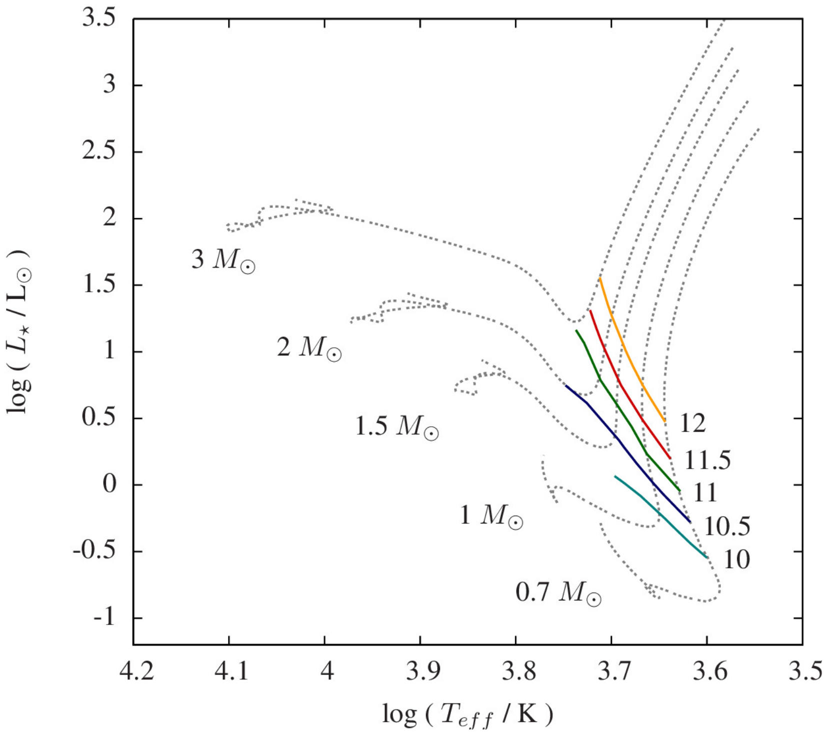
$$\mu \equiv \frac{m_\chi}{m_\mathrm{n}}, \quad \mu_\pm \equiv \frac{\mu \pm 1}{2}\ . \tag{8}$$

Having into account these expressions on the computation of the new stationary states reached by stars when the DM annihilation compensate the gravitational collapse, the result is figure 6.

This result shows that the "freeze out" point happens in the pre-main-sequence phase at an earlier stage of the stars evolution, than that represented on figure 5. The same star with a mass of 1.5M$_\odot$, as discussed previously, evolving in a DM halo with $\rho_\chi = 10^{11}$ GeV cm^{-3} completely stops its collapse at an effective temperature of approximately $T_{eff} \approx 4786$ K and a luminosity of $L_\star \approx 3.9$ L$_\odot$. Consequently, stars of mass 3M$_\odot$ will already "freeze" when embedded in a DM halo of density $\rho_\chi > 10^{11.5}$ GeV cm^{-3}. It is not necessary a denser DM halo, as suggested previously on figure 5, in order to see such behaviour.

In this scenario, where WIMP pair annihilation produce a constant energy source, stars can in principle remain forever with the same radius, effective temperature and luminosity in these stationary states.

Being the stellar core more packed with WIMP particles, the central luminosity is higher. This excess of energy needs to be transported to the star's outer layers through an efficient mechanism of transportation. On that account, the star becomes fully convective, as convection is the only mechanism capable of transporting the huge amount of energy through the whole star if it evolves in halos with very high DM densities [2].



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There are two possible approaches regarding the evolution of low-mass starts within dark matter halos:

1. Considering that, since the collapse of the star, there is influence of dark matter, i.e, WIMPs are captured;
2. Considering stars that are formed without the influence of dark matter and evolving them from the ZAMS position under the influence of WIMPs.

All the plots presented previously were obtained under the consideration of approach 1. What if approach 2 was considered? To see, in particular, if the equilibrium state in this scenario would be different, we can analyze figure 7. The red line represents approach 1 and the green dashed line approach 2, we can see that both of them lead to approximately equivalent final equilibrium states. This is quite interesting as the paths taken by each case is completely different, but somehow it leads, basically, to the same result. When evolved from the ZAMS, stars go back through the pre-main sequence phase, where they reach the same equilibrium states than those obtained when the collapse is "frozen" [1]. In these new stationary states, the star is therefore fueled only by the energy generated by the WIMPs pair annihilation process.

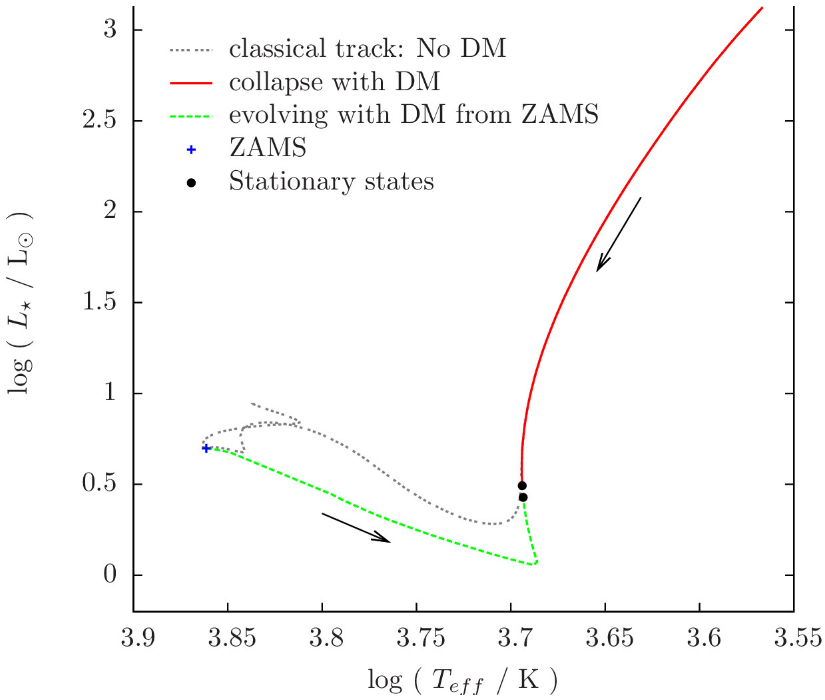

Figure 7. HR diagram of a star of $1.5M_\odot$ evolving in a halo of DM with $\rho_\chi = 10^{12}$ GeV cm^{-3}.The red line represents the collapse of the protostar considering DM; the green dashed line represents the evolution of the star in a halo of DM from the ZAMS (blue plus sign); and the black dots are the new equilibrium states considering the strong case scenario where the star is powered only by the DM annihilation; The grey dashed line represents the classical evolutionary path that the star follow without considering DM. Credits: [1]

Finally, figure 8 allow us to see how the different properties of stars with $1M_\odot$ change within dark matter halos of different densities, acting like a graphical resume of the two different scenarios and the intermediate between them.

For $\rho_\chi < 3 \times 10^9$ GeV cm^{-3} the energy from the DM annihilation acts like a complementary source of energy of the star that adds up to the *pp* chain and CNO cycle (see figure 8a)). This will lead to an equilibrium state reached at a lower central temperature (bigger radius) than in the classical scenario, which translates to a lower rate of hydrogen fusion and, consequently, to a longer period of time in the main sequence phase. This can be seen on figure 8b) along with the endurance of the convective core for a longer time than in the classical scenario, in order to evacuate the additional energy to the surface layers more efficiently.

For $\rho_\chi > 3 \times 10^{10}$ GeV cm^{-3} the energy from the DM annihilation start to be high enough to compensate the gravitational energy source due to the protostar's collapse. This will "freeze" the stars at an equilibrium state reached at an earlier stage of their evolution. These stars will never reach the central temperature necessary to start hydrogen burning, remaining for an arbitrarily long time (being the energy rate in the core by WIMP pair annihilation constant) in the same position on the HR diagram. The denser the DM halo, the sooner the star "freeze" its position on the HR diagram at a lower effective temperature and an higher luminosity. In halos with very high DM densities, convection is the only transportation mechanism that is efficient enough to evacuate the huge amount of energy through the whole star. Therefore, the sun-like stars become fully convective being their effective temperature lower (see figure 8c) and d)).

For densities between 10^9 GeV cm^{-3} and 10^{10} GeV cm^{-3} we have sort of an intermediate scenario where the star will remain with a convective core for the rest of its life (see figure 8b) and c)) [2]. This happens because the WIMP annihilation is also the only fuel of these type of stars (like in the strong scenario) and the process happens in a more centralized region than the nuclear one would. This makes the temperature gradient in the stellar core to be steeper, allowing the development of a convective core that adds up to the typical structure of a star of $1M_\odot$ in the main sequence that is composed by a radiative core and convective outer layers. Increasing the WIMP density, i.e, moving on to the strong case, the luminosity will increase drastically forcing the convective core to grow and merge with the convective outer envelope, dropping the effective temperature for 10^3K for a Sun-like star.

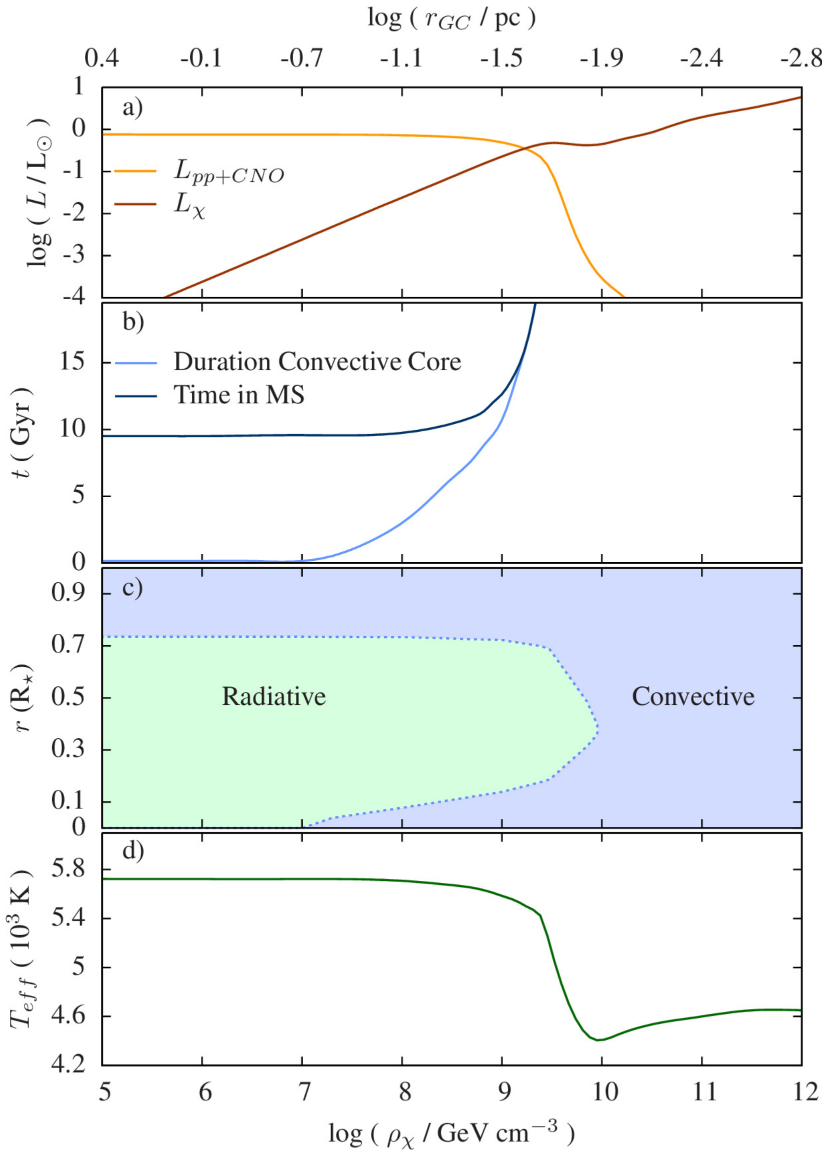

Figure 8. Resume of the alterations in the properties of stars with 1M$_\odot$ that evolve in halos with DM densities from 10^5 GeV cm^{-3} to 10^{12} GeV cm^{-3}: a) luminosity of the thermonuclear reactions and from DM annihilation; b) duration of the Main Sequence phase and time until the convective core disappears; c) location of the convective and radiative zones inside the star; d) effective temperature of the star. These characteristics were plotted considering that the stars are already in the equilibrium state, which means, in the beginning of the main-sequence for $\rho_\chi < 3 \times 10^9$ GeV cm^{-3} and in the stationary states powered only by the energy of DM annihilation for $\rho_\chi \geq 3 \times 10^9$ GeV cm^{-3}. The higher horizontal axe show the expected distances toward the center of our galaxy where stars with such properties may be found. Credits: [2]

5. Conclusions

As we have seen, stars that evolve in regions with high concentrations of DM will have their evolutionary path altered compared to that on the classical scenario.

This work explores simulations of the different paths taken by low-mass stars in DM halos with different densities. It is safe to say that the search for stars with these unusual properties is of huge interest as they can potentially contribute to the testing and constraining of the properties of DM candidates. Figure 8 has as its higher axis the expected distances toward the center of our galaxy where these type of stars may be found (in the inner parsec of the Milky Way). If found, such stars would be probes of DM particles near super-massive black holes and their excess of luminosity, due to WIMPs' burning, could be used to derive the WIMPs' matter density at their location

[1]. The absence of such stars would also be curious as it could provide constraints on WIMP-nuclei scattering, pair annihilation cross-section and WIMPs' density.

There are still many parameters regarding WIMPs and the orbit followed by these stars that add an high level of uncertainty that influence the predictions explored on this work. However, it is expected that coming observations of the galactic center will be made with the sensitivity necessary to detect such stars and therefore provide a different access to the nature of dark matter particles.

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