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WIMP Dark Matter and the First Stars: a critical overview

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If Dark Matter (DM) is composed by Weakly Interacting Massive Particles, its annihilation in the halos harboring the earliest star formation episode may strongly influence the first generation of stars (Population III). Whereas DM annihilation at early stages of gas collapse does not dramatically affect the properties of the cloud, the formation of a hydrostatic object (protostar) and its evolution toward the main sequence may be delayed. This process involves DM concentrated in the center of the halo by gravitational drag, and no consensus is yet reached over whether this can push the initial mass of Population III to higher masses. DM can also be captured through scattering over the baryons in a dense object, onto or very close to the Main Sequence. This mechanism can affect formed stars and in principle prolonge their lifetimes. The strength of both mechanisms depends upon several environmental conditions and on DM parameters; such spread in the parameter space leads to very different scenarios for the observables in the Population. Here I summarize the state of the art in modelling and observational expectations, eventually highlighting the most critical assumptions and reasons of uncertainty.

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In Lambda cold dark matter (ΛCDM) cosmology, most of the matter in the Universe is in the form of one or more electromagnetically undetected species of particles whose only known influence is gravitational. If dark matter is composed of WIMPs that self-annihilate, such annihilations occur in the particularly high central densities of collapsing primordial gas clouds, and the energy released may affect the first stars (Population III) by two different mechanisms.

1. Gravitational accretion of DM

DM self-annihilates and injects energy everywhere inside a primordial star-forming halo at a rate that depends on the local DM density and the opacity of the gas to the high-energy primaries produced in the annihilation [1, 2]. The deposited energy per unit volume, per unit time can be written as:

$$\frac{dL}{dV}(r) = n^2_{DM}(r)\langle\sigma v\rangle m_{DM} \times \kappa(r) \tag{1.1}$$

with $n_{DM}(r)$ being the DM number density at a given radius, $\kappa(r)$ the opacity of the gas to the high energy primary shower induced by DM annihilation, $\langle\sigma v\rangle$ is the velocity averaged self-annihilation rate of DM; the formula clearly suggests that the bigger effects are going to manifest at the center of the halo, where gas (and DM) densities are typically highest.

The effects of this process are more dramatic in high-z minihalos than in the local Universe; this is due to the peculiarities of PopIII star formation, which is believed to take place in the very center of the DM halo, following a very smooth collapse of the gas, consequence of the absence of strong coolants, see e.g. [3]. This favors the build-up of a central, massive gaseous object, which can gravitationally drag the collisionless matter, permitting the formation of very high densities of DM, [4]. In the latter, using a semianalytical model without feedback on primordial gas chemistry, the authors found that for a wide range of DM parameters the gas cloud always enters a stage in which energy injection due to DM annihilation equals the feeble H_2 cooling in the innermost region of the cloud. This occurs before a hydrostatic object forms there, when central densities reach $n_c \sim 10^{12}$ cm^3 (the actual value depending on DM mass, $\langle\sigma v\rangle$, and primary annihilation channels). They speculated that the gas cloud could actually halt its collapse and form an object powered by DM annihilation, which they refer to as a "*dark star*".

Most recently, full 1-D hydrodynamical simulations have been performed which properly model gas chemistry, the coupling of DM annihilations to chemistry, and the response of DM to the variation of gravitational potential induced by baryonic collapse (which is modeled through the so-called "adiabatic" contraction approximation).

By taking into account the feedback of DM annihilations on gas chemistry, we have shown [5] that although they *do* modify the temperature and ionization state of the cloud, these effects are however vastly mitigated by their feedback. The high energy shower is injected at the center of the cloud by annihilating DM (where annihilation rates are greatest and couple most efficiently to the gas) and it *does* heat the halo core and its surrounding regions. However, we find that the large ionized fractions induced by the annihilations impact the chemistry, which in turn regulates the temperature, eventually without dramatic effects on the stability of the cloud or its Jeans mass.

Following the collapse of the cloud beyond the time when DM annihilation heating equals chemical cooling (for a variety of astrophysical and DM parameters) we find that the collapse

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does **not** halt, and a "dark star" does **not** form, at least at this stage. Simulations capable of following the formation of a hydrostatic core and DM annihilations therein (even better, doing so in 3D) are needed to determine the nature of the resulting proto-star. We have anyways assumed that eventually a hydrostatic object powered by annihilation of the local (object-embedded) DM environment can form, and we have wondered which may be its properties. We have modeled a hydrostatic object, powered by energy from the annihilations of DM embedded in the cloud, the "local bath". The latter is assumed to be following the gravitational contraction of the gas using the so-called adiabatic contraction approximation [6]. We find that the equilibrium of such objects is unstable, and that DM annihilation can only delay collapse for times that are short compared to contraction timescales -O(10^4-10^5yr)-, which again suggests that the annihilation of gravitationally contracting DM cannot give rise to any stable or long-lived phase. This is in contrast with results achieved by [7], that observe equilibrium between DM gravitational accretion and annihilation, and gravitational collapse of gas, over times of O(10^6yr); by including gas accretion on the hydrostatic, stable object, they observe the formation of extremely massive objects, up to $10^5 M_\odot$, before they reach the nuclear burning and collapse to Black Holes.

It is worth stressing that the process described so far can take place only once during the life of a celestial object: it is intrinsically related to the contraction phase of a *pre* and then *proto* stellar object, and its contraction toward the hydrostatic equilibrium and then the Main Sequence. Such process is characteristic of a metal-free, smooth collapse without of fragmentation in early stages. This process is usually (and almost univocally) associated with Population III stars, and alien to galactic star formation.

2. Scattering accretion of DM

At a given point, a "DM-affected proto-PopIII" moves out of the Hayashi track. At this point the object -either with a humongous mass built-up under the effect of DM sustaining or with a "traditional" PopIII mass- ignites nuclear reactions as a consequence of structure contraction and heating. However, at this point the star is still embedded in a very high DM bath, *external* to the star itself. No earlier than this point in proto-stellar evolution, and if the cross-section between baryons and WIMPs is high enough, capture of DM in the star via a *scattering* process becomes efficient. That is, DM captured onto the star by scattering will thermalize and "sink" in an equilibrium configuration in a small region of the stellar core itself within short timescales. The annihilation of such concentrated distribution can indeed power the star entirely (depending on parameters), as found in [8]. The most dramatic effect of such "DM burning" is that the star either halts its contraction before hydrogen burning or later causes *H* to burn at a reduced rate because DM energy release supports the star against further collapse [6, 9]. This implies that the duration of the main sequence is prolonged until most of the hydrogen in the core is converted into helium at such slowed rate, and that the subsequent chemical evolution (and thus aging) of the star are delayed. A DM-burning star's evolution is frozen as long as DM capture can proceed at the rate necessary to power entirely the stellar luminosity. The formal details of scattering and gravitational accretion are described in the original literature [6, 9], and summarized in previous proceedings [10] and in [12]. It is worth stressing that while gravitational accretion depends only on the self-annihilation of the DM density field in the core of the cloud, scattering accretion involves DM particles originally

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outside of it, and relies on the existence of a sizeable scattering cross section between baryons and WIMPs to enable DM capture within the star. On the other hand, the scattering-driven annihilation process is not as intrinsically unstable as the gravitational-accretion process, and can apply to galactic stars, provided that the environment DM density is high enough. This is possibly the case of regions around the central Black Hole, see [11].

3. Detection prospects

The delay of nuclear ignition in a hydrostatic protostar by the DM scattering process can be visualized as an interrupted track toward the ZAMS in the HR diagram. The position of Pop III stars of different masses (and with different DM parameters) is shown in Fig 1: DM-burning stars in the grey region are entirely supported by scattering-accreted DM annihilations as long as WIMPs can be replenished. DM-burning Pop III stars (those that are *entirely* supported by energy from DM annihilation, sometimes referred to as *dark stars*) are colder and larger than normal Pop III stars. The nature of dark stars is critical to determine their observational signatures. In principle, the life-prolonging effect spread over an entire population, coul decouple the pair-instability supernova (PISN) rates from star formation rate (Iocco (2009) in [10]), especially at high redshifts. Other authors have studied whether a dark star could be directly observed by JWST; as a matter of fact the possibility to detect dark stars with current instruments (i.e. HST) has already been ruled out for reasonable models [12]. We concluded that even JWST will be unable to observe directly any of these objects unless they are lensed by massive intervening structures along the line of sight; even then, detection would be difficult.

However, the life-prolonging effect of DM burning on stars may allow several of these objects to be conveyed up in the first galaxies, following the halo merger history. This would imprint a peculiar color-color signature on protogalaxies, which would be recognizable in the JWST fields. However, the number and characteristics of affected and detectable galaxies varies strongly with the parameters assumed for the nature of DM particles (like the elastic scattering cross section between baryons and WIMPs), the size of the central cusp of the DM halo, the likelihood of star formation within it, and the number of Pop III stars that form in the halo. Such sensitivity could constitute a diagnostic tool for discriminating between formation scenarios; however, for now, detectability of these objects lies beyond our reach.

4. Which *Population* effects?

Wondering if Population III stars affected by Dark Matter are observable, is equivalent to ask whether these effects are really so dramatic at all. The possibility to observe an indirect signature of “DM burning”, would implicitly mean that the gap between the standard and the exotic scenario is significant, and that the whole Population III is strongly affected by this mechanism.

On one hand our discriminant power is plagued by the fact that we have no observational evidence for the standard Population III, that is to say we know very little, and our expectations strongly vary with the parameters of the "standard" PopIII model. On the other, it seems that

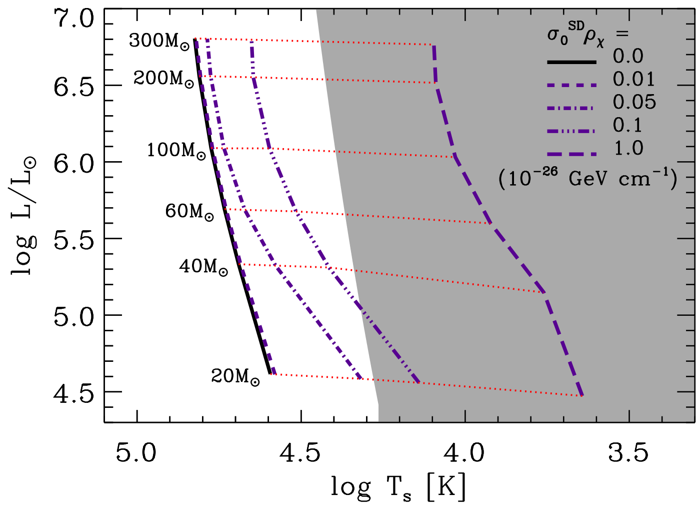

Figure 1: The HR diagram of massive, metal free stars of several masses that are influenced by scatter-captured DM burning, for different values of the product of the spin-dependent elastic scattering cross section σ_0 and the DM density ρ_χ in which the star is embedded. From Yoon, Iocco, and Akiyama '08 in [9].

DM burning will little affect the final properties of the Population, thus creating little hope for observations, at least now.

Nonetheless, it is still extremely interesting to wonder whether Dark Matter has affected, beyond the pure gravitational or "inert" effects, a whole population of stars. Whereas the motivations leading us to believe it plausible are strong (as summarized so far) yet they rely on untested, although extremely reasonable, assumptions. Here is a list of what skepticists should definitely consider as the most ucertain ingredients of the models.

4.1 Open issues

i): The formation of DM dense profile (hereafter called "cusp", whereas it could also be a cored, this definition referring to a density enhanced with respect to the original profile) is a condition for both the *gravitation* and *scattering* phases. Beside being predicted by seminanalitic models adopting different flavors of the "adiabatic contraction" approximation [4, 6], the enhancement of the DM profile due to gravitational drag of the baryons has been observed in simulations down to the resolved scale ($n_{gas} \lesssim 10^{12}$#/cm^3, $r \lesssim 10^{-1}$pc), by [13]. Whereas a still higher density is to be expected in the unresolved center, even a plateau at the level of the one found in the innermost resolved region would be enough for the first stages of gravitational contraction. Which raises the issue *ii)*: the alignment between object and the DM cusp. In PopIII formation the definition of the halo "centering" is well posed: the gravitational potential being given by the collapse of only one (baryonic) object, the DM will in first approximation overlap with the source of such radial profile. This approximation holds until very fine tuning is needed: for the *gravitational* phase the hydrostatic object of size of O(1AU) must lie within a DM cusp with radius of O(100AU); in the *scattering* phase the size of the region with the right DM density is of O(10AU), whereas the size of the hydrostatic object varies between one and tenth of solar radii O(0.01-0.1AU). With respect to this, it worth noticing that *iii)*: 3-dimensional effects have not yet been included when following the gravitational effects: these might have consequences on both the aligment and the following issue: that *iv)*: adiabatic contraction approximation is used in order to compute the DM build-up during the *gravitational* phase of the hydrostatic object. This might overestimate to some extent the DM response to baryons, see discussion in Ripamonti et al. [2010].

This list of the critical issues of the "Dark Stars" scenario shows that, whereas there are very sound reasons to argue about the possible relevance WIMP DM effects onto the Population III, our predictive power is very low, as little do we know about these critical issues and can only make predictions within reasonable range of parameters. Second, it is reasonable to expect that the global effects on the whole Population will be limited, as extremely favorable conditions for "Dark Stars" existence would be the outcome of superposition of several coincidences.

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