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Dark Matter annihilations effects on the first protostars

E. Ripamonti[*][†]
Università di Milano-Bicocca
E-mail: `ripamonti.e@gmail.com`

We look at the hypothesis that dark matter (DM) particles self-annihilate, and examine the effects of DM annihilations on the formation of the first stars in the Universe. We find two main results. First, the DM chemical feedback does alter the properties of the gas during the collapse, but the typical Jeans mass within the halo is not strongly affected: then, DM annihilations are unlikely to modify the Initial Mass Function of primordial stars. Second, we reached the regime where the energy injection from DM annihilations exceeds the cooling from molecular hydrogen, and found that the protostar keeps collapsing, thanks to the contribution of previously neglected mechanisms.

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[*] Speaker.

[†] Dipartimento di Fisica “G. Occhialini”; Piazza della Scienza, 3; I-20126 Milano, Italy

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1. Introduction

In the currently favoured ΛCDM cosmological model, dark matter (DM) represents the bulk of the matter component. Some well-motivated theoretical models (see e.g. [2]) carry the properties of being weakly coupled to ordinary matter and being self-annihilating. Here we will focus on such models, assuming that all the DM is made of self-annihilating WIMPs.

In the local Universe, the energy released by DM annihilations (DMAs) is only a tiny fraction of that released by baryonic processes (except, perhaps, for peculiar locations such as the central parsec of the Milky Way; see e.g. [19], [4]). At high redshift DMAs have only small effects on the properties of the intergalactic medium (e.g. [13]; [9]; [24]; [20]), unless the clumping factor is very high (e.g. [10]). DMAs affect primordial star-formation in a more significant way: [16] showed that they do not change the properties of the first star-forming halos; but, as both the DMA rate and the absorbed fraction increase, DMAs gain in importance as the collapse proceeds ([1]). During the protostellar collapse of the first stars, DMAs reach a “critical point” where their energy injection compensates the gas radiative cooling ([21]), potentially altering the evolutionary path of the protostar and of the resulting star (e.g. [8], [5], [22]).

Even if the results in [21] clearly indicated that DMAs start to be important ad densities much lower than those of typical protostellar cores, so far the early phases of the collapse received less attention then the more advanced ones (e.g. after core formation). Here we summarize our attempt at filling this gap (more information is given in [18]).

2. Method

Our investigation is based on the 1-D spherically symmetric code described by [14], as extended in [15], [16], [17], and [18]. Such code includes the treatment of gravitation, hydrodynamics, chemistry and gas heating/cooling processes. The energy input from DMAs was added to the code, assuming that (i) the DM density profile can be estimated from the adiabatic contraction ([3]; [7]) of a NFW profile ([11]); (ii) the luminosity (per unit volume) due to DMAs is $l_{\rm DM} = c^2\langle\sigma v\rangle\rho_{\rm DM}^2/m_{\rm DM}$ ($\langle\sigma v\rangle$ is the thermally averaged annihilation cross section; $m_{\rm DM}$ is the WIMP mass); (iii) $\sim$2/3 of the DM-originated energy (the fraction not going into neutrinos) can be absorbed by baryons, the exact amount being estimated via a radiative transfer calculation for gray continuum, assuming a constant gas opacity κ; (iv) the absorbed energy goes into ionization/dissociation, excitation and heating of atoms and molecules according to the results of [23].

We ran a set of simulations of the collapse of a $10^6\,{\rm M}_\odot$ halo virializing at $z = 20$, assuming that (absent adiabatic contraction) the DM profile would settle into a NFW profile with $R_{200} = R_{\rm vir} \simeq 5\times10^{20}$ cm and concentration 10. We kept $\langle\sigma v\rangle$ fixes at $3\times10^{-26}\,{\rm cm}^3\,{\rm s}^{-1}$, while varying (i) the WIMP mass (1 GeV $\le m_{\rm DM}c^2 \le$ 1 TeV), (ii) the opacity κ ($0.001\,{\rm cm}^2\,{\rm g}^{-1} \le \kappa \le 0.1\,{\rm cm}^2\,{\rm g}^{-1}$), and (iii) the details of DMAs feedback upon H_2 formation and disruption.

3. Results

3.1 The indirect feedback phase

Fig. 1 compares the evolution of the central density ($n_{\rm c} \equiv \rho_{\rm c}/m_p$) and temperature ($T_{\rm c}$) in 4

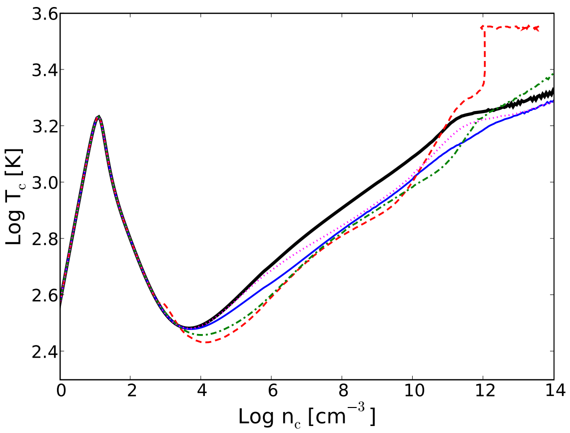

Figure 1: Temperature evolution in the central shell ($m_{\rm shell} \simeq 2 \times 10^{-4}\,{\rm M}_\odot$) as a function of baryon density, starting before virialization. Lines refer to the NODM case (thick solid, black), and to cases with $m_{\rm DM}c^2$=1 (dashed, red), 10 (dot-dashed, green), 100 (thin solid, blue), and 1000 (dotted, magenta) GeV.

models including DMAs to the one of a model without DMAs (NODM case). As expected, models with lower values of $m_{\rm DM}$ (e.g. the dashed line) deviate more strongly from the NODM case: this is because DMA energy production is $\propto \langle\sigma v\rangle/m_{\rm DM}$, and $\langle\sigma v\rangle$ is fixed. However, it is quite remarkable that, for $n_{\rm c} \lesssim 10^{10}\,{\rm cm}^{-3}$, the injection of energy by DMAs results in a temperature *decrease*. The reason is that in the low-density regime *indirect* effects of DMAs are often more important than direct ones. In this case, the ionizations induced by the DMAs keep the free electron fraction at a relatively high level (10^{-5}–10^{-6}, rather than $\lesssim 10^{-9}$). Since free electrons act as catalyzers for H_2 production, the gas molecular fraction grows much faster when DMAs are present. In turn, H_2 is the main coolant in the protostellar core: then, DMAs strongly enhance the cooling properties of the core, easily reversing the heating increase due to DMA direct effects, and causing a decrease in $T_{\rm c}$. However, it must be noted that (due to the strong dependence of the H_2 cooling function on temperature), despite an increase in H_2 fraction that can exceed a factor of 100, $T_{\rm c}$ decreases only by a factor of $\lesssim 1.3$, so that the Jeans mass scale ($\propto T^{3/2}$) is reduced only by a factor of $\lesssim 2$. Then, DMAs might somewhat favour the fragmentation of primordial gas, but are unlikely to have dramatic effects upon the primordial initial mass function.

3.2 The direct feedback phase

In all the models we calculated, heating from DMAs is able to overcome the H_2 cooling, reaching the “critical point”. This happens at densities which depend on the model details (especially $m_{\rm DM}$), but which are generally in good agreement with the simple predictions by [21] for the formation of a “dark star”. As a result, $T_{\rm c}$ generally reaches and overcomes the value calculated in the NODM case, at least at high densities.

Reaching the critical point marks the beginning of a phase where the *direct* effects of DMAs dominate over the indirect ones. In such phase, DMAs are often (though not always) the most important source of heating, and their presence affects the evolution of the protostar. However, reaching the critical point does not appear to have the dramatic consequences suggested by [21]. In particular, the collapse *does not stop* because of several mechanisms that are able to dispose of

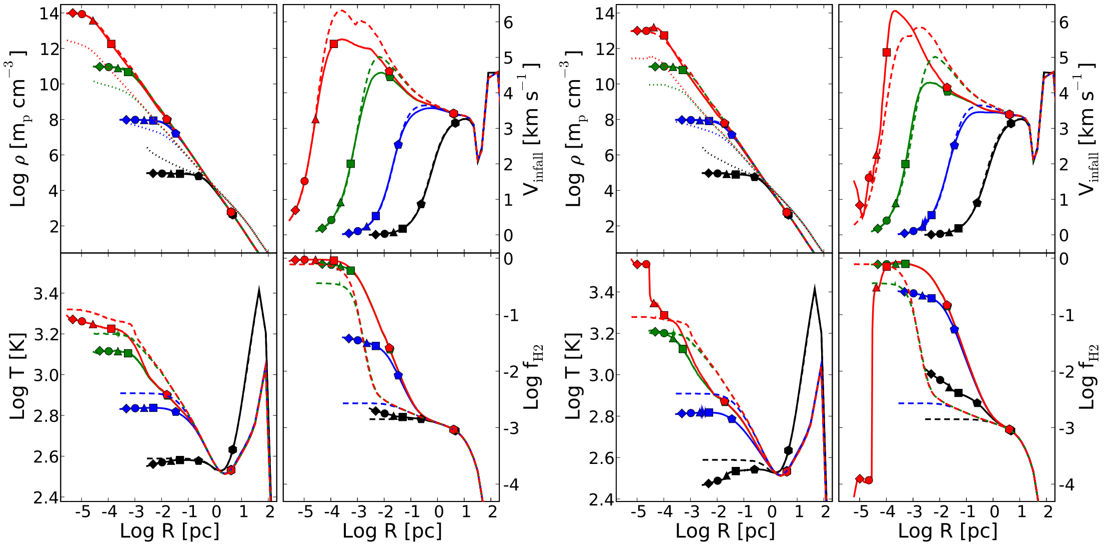

Figure 2: Evolution of radial profiles of DM and gas densities, infall velocity, temperature, and H_2 fraction. Both sets of panels compare a run with DMAs to the NODM case. The DMA models use $m_{DM}c^2$=100 GeV (left) or $m_{DM}c^2$=1 GeV (right). Solid and dashed lines refer to gas quantities in the DMA case, and in the NODM case, respectively. Different sets refer to central gas densities $n_c = 10^5$, 10^8, 10^{11}, $10^{13}\,\mathrm{cm}^{-3}$. Dotted lines refer to DM densities in the DMA model. Markers indicate the radii enclosing baryonic masses of 10^4 (hexagons), 100 (pentagons), 1 (squares), 0.1 (triangles), 0.01 (circles), and 10^{-3} $M_\odot$ (diamonds).

the excess heating from DMAs. First, a large amount of energy from DMAs ends up into chemical energy, as H_2 is slowly dissociated: even in the model where DMA effects are strongest (dashed line, corresponding to $m_{DM}c^2$=1 GeV) this enables the collapse to proceed by 3 more order of magnitudes in n_c; after H_2 is exhausted, the temperature might undergo a sudden increase (see Fig. 1), but other cooling mechanisms (such as continuum cooling by H^- and atomic H) rapidly gain importance, capping the increase in T_c, and enabling the collapse to proceed further.

3.3 Opacity and feedback dependence

As already mentioned, the importance of DMAs effects strongly depends upon m_{DM}, because the energy generated by DMAs is $\propto \langle\sigma v\rangle/m_{DM}$, and $\langle\sigma v\rangle$ is kept fixed. However, we explored also the effects of our assumptions on the opacity κ for the absorption of the DMA-originated energy by the baryons, and on the feedback effects of DMAs upon H_2 formation and disruption.

In the case of κ, we found that, at low n_c, models are roughly degenerate in $\langle\sigma v\rangle\kappa/m_{DM}$, whereas at high n_c the effects of differences in κ tend to vanish.

In the case of the H_2 feedback, the situation is slightly more complicated: if the H_2 feedback is removed (i.e. if we assume that the energy from DMAs does not dissociate any H_2), there are little changes in the indirect feedback phase, whereas in the direct feedback phase there is a substantial delay in the temperature growth (in this phase, “switching off” the H_2 feedback is roughly equivalent to halving the heating from DMAs). Instead, an enhanced H_2 feedback produces significant differences during the indirect feedback phase (especially at the start), but has no influence on the protostellar evolution when the direct feedback phase is reached.

3.4 Hints of core formation

In Fig. 2 we show the evolution of the spatial profiles for the NODM case and for two models including the effects of DMAs. The model where DMAs are less important (leftmost set of panels) is clearly different from the NODM case (e.g., the extent of the molecular core is much larger), but the general dynamical properties are quite similar: in particular, the self-similar density profile is preserved even at the highest densities.

In the model with the strongest DMA effects (rightmost set of panels) the most evolved density profile is starting to differ from the self-similar one (the maximum density is not at the centre, and there is a large temperature change at $R \simeq 2 \times 10^{-5}\,\mathrm{pc}$). Unfortunately, our code is unable to reach higher densities, mainly because of the increased computational cost; but in runs without DMAs such behaviour usually indicates that an hydrostatic core is starting to form, though it would take a further increase of 1–3 orders of magnitude in n_c before having a "proper" core. If so, the core would form with n_c in the 10^{14}–$10^{16}\,\mathrm{cm}^{-3}$ range, a density much lower than the typical value ($10^{19}\,\mathrm{cm}^{-3}$) for the NODM case (e.g. [12]; [14]).

However, it should be noted that the DMA parameters corresponding to the rightmost panels of Fig. 2 are likely too extreme, as they are currently disfavoured by multimessenger constraints on DM (e.g. [6]); with less extreme parameters (such as those used for the leftmost set of panels) core formation would likely occur earlier than without DMAs, but only by a minor or moderate amount.

4. Summary and conclusions

We followed the collapse of gas and DM within a typical population III halo from $z = 1000$ down to slightly before the formation of a hydrostatic core, including many processes induced by DMAs, and exploring the dependence of the results on different parameters.

Independent of such parameters, when the central baryon density is lower than that of the "critical point" ($n_\mathrm{c} \lesssim 10^9$–$10^{13}\,\mathrm{cm}^{-3}$), the indirect feedback effects of DMAs catalyze an increase in the H_2 abundance. Then, the cooling rate goes up, decreasing the temperature by $\sim$30 per cent, with a weak reduction of the fragmentation mass scale. For densities above n_crit the direct feedback of DMAs becomes important; their main effect is to induce an early transition to the continuum-dominated cooling regime; such transition is usually smooth, even if there might be some relatively abrupt transition (by a factor of $\lesssim 2$ in the cases where the DMA energy injection is highest).

In conclusion, only small differences are found with respect to the case without DMAs; in particular, the collapse does not stall and the cloud keeps contracting even when $n_\mathrm{c} \gg n_\mathrm{crit}$. This is particularly significant since some implicit assumptions of our model (e.g. the fact that the DM cusp and the protostellar core are perfectly coincident) might induce an overestimation of the effects of DMAs. However, our simulations stop at $n_\mathrm{c} = 10^{13}$–$10^{14}\,\mathrm{cm}^{-3}$, and it is possible that some difference might arise at higher densities, before the density where a hydrostatic core is expected to form in the case with no DMAs ($\sim 10^{19}\,\mathrm{cm}^{-3}$). In particular, the case with the strongest feedback effects suggests that hydrostatic core formation might occur earlier if DMAs are present.

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