Mem. S.A.It. Vol. 78, 800

Memorie della

Primordial gas heating by dark matter and structure formation

M. Mapelli[1] and E. Ripamonti[2]

[1] Institute for Theoretical Physics – University of Zurich, Winterthurerstrasse 190, CH-8057 Zurich, Switzerland; e-mail: mapelli@physik.unizh.ch
[2] Kapteyn Astronomical Institute, University of Groningen, Postbus 800, 9700 AV, Groningen, The Netherlands

Abstract. Dark matter (DM) decays and annihilations might heat and partially reionize the Universe at high redshift. Although this effect is not important for the cosmic reionization, the gas heating due to DM particles might affect the structure formation. In particular, the critical halo mass for collapse is increased up to a factor of ~ 2. Also the fraction of gas which collapses inside the smallest halos is substantially reduced with respect to the cosmological value. These effects imply that DM decays and annihilations might delay the formation of the first structures and reduce the total star mass in the smallest halos.

Key words. galaxies: formation – cosmology: theory – dark matter – neutrinos

1. Introduction

Dark matter (DM) particles can either decay or annihilate, producing photons, neutrinos, electron-positron pairs, and/or more massive particles, depending on the mass of the progenitor. In this way, DM particles indirectly interact with the intergalactic medium (IGM), transferring to it a part of their mass-energy. Then, DM decays and annihilations can influence the thermal and ionization history of the Universe.

The fraction of energy produced by decays/annihilations which is effectively absorbed by the IGM ($f_{abs}(z)$) is a crucial ingredient in this scenario, and depends on the mass of the progenitor and on the nature of the product particles. If the product particles are quite massive ($\gtrsim$ 135 MeV), they can generate a cascade, so that predicting the behaviour of $f_{abs}(z)$ is difficult. However, Mapelli et al. (2006) proved that ordinary cold DM (i.e. particles with mass greater than a few GeV) has negligible effects on the history of reionization and heating even assuming $f_{abs}(z) = 1$.

Instead, in the case of lighter DM particles (such as sterile neutrinos and light dark matter) the effects on reionization might be important, if we assume $f_{abs}(z) = 1$ (Mapelli et al. 2006). Then, for lighter DM particles it is crucial to correctly estimate the behaviour of $f_{abs}(z)$.

Luckily, $f_{abs}(z)$ can be calculated (Ripamonti et al. 2007a; Mapelli & Ripamonti 2007) if the product particles are photons, electron-positron pairs or neutrinos (which have negligible interactions). In fact, photons interact with the IGM via Compton scattering and photo-ionization; while pairs are involved in inverse Compton scattering, collisional

Send offprint requests to: M. Mapelli

ionizations and positron annihilations. The resulting $f_{abs}(z)$, both in case of photons and pairs, is close to 1 at high redshift ($z >> 100$), whereas it drops to values $\lesssim 0.1$ at low redshift. This result implies that DM is not an efficient source of cosmic reionization at redshift $\lesssim 20$. However, DM decays and annihilations can heat and partially reionize the Universe already at very high redshift ($z \approx 50 - 100$), when the first stars and structures have not appeared yet. In this proceeding, we will show that the heating and partial ionization produced at high redshift by DM decays and annihilations have an impact on the process of structure formation itself.

2. Heating and molecular abundance enhancement

In the following, we will consider three different scenarios: decays of sterile neutrinos with mass 4 – 25 keV (top panel) into photons and active neutrinos, decays of light DM (LDM) particles with mass 3 – 10 MeV (central) and annihilations of LDM with mass 1 – 10 MeV (bottom) into pairs. Further details on these DM models can be found in Ripamonti et al. (2007a).

DM decays and annihilations increase both the temperature of the IGM and the fraction of free electrons (Fig. 1). Free electrons are also catalysts for the formation of molecular hydrogen (H_2) and HD molecules, whose fractional abundance is thus enhanced (Fig. 1).

H_2 and HD play a fundamental role in the primordial Universe, as they are the most efficient coolants in absence of metals. Then, if their abundance is increased, structure formation is favoured. On the other hand, the temperature increase due to DM decays/annihilations tends to delay structure formation.

To understand which of these two effects dominates, we cannot limit our analysis to the IGM, where the density is uniform, but we have to study the chemical and dynamical evolution inside the first halos. To this purpose, we used a one-dimensional Lagrangian code (Ripamonti 2007), which simulates the gravitational and hydro-dynamical evolution of the gas, accounting for the behaviour of 12 chemical species, for the cooling/heating effects and for the gravitational influence of DM halo. Fig. 2 shows the evolution of gas density, temperature, ionization fraction and H_2 fractional abundances within a simulated halo of $6 \times 10^5\, M_\odot$ virializing at $z = 12$. Black solid line is the case without DM decays/annihilations, while the colour lines account for DM decays/annihilations. From the density plot it is evident that DM decays/annihilations delay the collapse, especially in the case of LDM annihilations (red dotted line). Thus, the temperature increase dominates over the coolant enhancement.

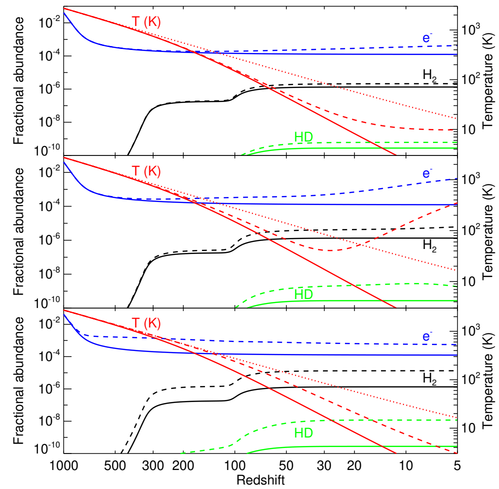

Fig. 1. Effects of decaying/annihilating DM on the IGM evolution. Left axis: fractional abundances of free electrons (e^-), H_2 and HD as a function of redshift. Right axis: matter temperature as a function of redshift. Top panel: Effect of decaying sterile neutrinos of mass 25 keV (dashed line). Central panel: decaying LDM of mass 10 MeV (dashed line). Bottom panel: annihilating LDM of mass 1 MeV (dashed line). In all the panels the dotted line is the cosmic microwave background (CMB) temperature and the solid line represents the thermal and chemical evolution without DM decays/annihilations.

3. The critical mass

To quantify the importance of DM decays and annihilations in delaying the collapse we calculated the critical mass (m_{crit}), i.e. the min-

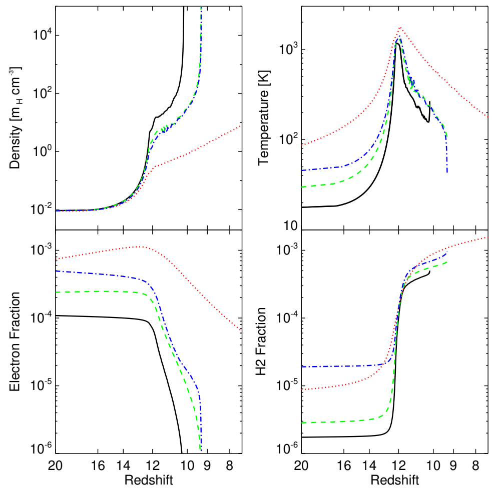

Fig. 2. Evolution of the central region of a $6 \times 10^5\ M_{\odot}$ isothermal halo virializing at $z_{vir} = 12$. From left to right and from top to bottom: density, temperature, electron abundance and H_2 abundance as function of redshift. The solid line represents the unperturbed case (i.e. without DM decays and annihilations). The dashed, dot-dashed and dotted lines account for the contribution of 25-keV sterile neutrino decays, 1-MeV LDM annihilations and 10-MeV LDM decays, respectively.

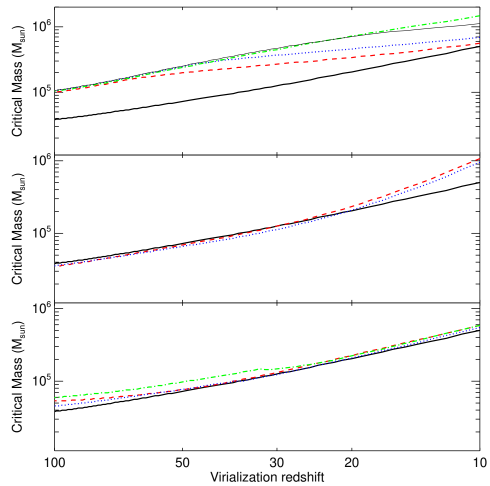

Fig. 3. The critical mass as a function of the virialization redshift z_{vir} for isothermal DM halos. Top panel: Effect of decaying sterile neutrinos of mass 25 (dashed line), 15 (dotted) and 4 keV (dot-dashed). Central panel: Decaying LDM of mass 10 (dashed line) and 3 MeV (dotted). Bottom panel: Annihilating LDM of mass 10 (dashed line), 3 (dotted) and 1 MeV (dot-dashed). In all the panels the solid line represents the thermal and chemical evolution without DM decays/annihilations. The thin solid line used in the top panel represents the case of non-decaying warm DM (with mass 4 keV).

imum halo mass for collapse at a given redshift (Tegmark et al. 1997). Fig. 3 shows the behaviour of m_{crit} in the case we assume an isothermal DM halo. The results do not change significantly for a Navarro, Frenk & White (1996) profile. In presence of DM decays and annihilations m_{crit} is always increased (Ripamonti et al. 2007b; Ripamonti & Mapelli 2007). However, the increase of m_{crit} in the case of sterile neutrinos is due not only to decays, but mainly to the fact that these particles are warm DM. In fact, given their large dispersion velocity, they prevent the formation of small and highly concentrated halos.

In the case of LDM decays and annihilations the increase of m_{crit} is always less than a factor of ~ 2. In the case of LDM decays the effect is maximum at relatively low redshifts ($z \lesssim 20$, whereas in the case of LDM annihilations it is stronger at high redshift ($z > 30$). This difference arises from the fact that the decay and the annihilation rate are proportional to the DM density and to the square of the DM density, respectively.

4. The dearth of baryons in primordial halos

In conclusion, DM decays and annihilations tend to increase m_{crit}; but this is a tiny effect, probably impossible to observe. However, DM decays and annihilations can have also an other effect on structure formation, possibly more important.

The temperature increase due to DM decays and annihilations leads also to an increase of the gas pressure, which counterbalances the gravitational potential of DM. Then, it is more difficult for the gas to sink at the center of the DM halo.

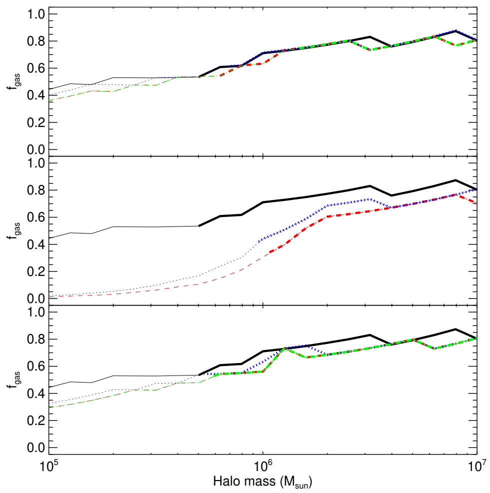

Fig. 4. Halo baryonic mass fraction (see definition in equation 1) as a function of the halo mass for a fixed virialization redshift (z_{vir} = 10) and for an isothermal DM profile. Top panel: Effect of decaying sterile neutrinos. Central: Decaying LDM. Bottom: Annihilating LDM. The lines used in the three panels are the same as in Fig. 3. Thick (thin) lines indicate that the halo mass is larger (smaller) than m_{crit}.

To quantify this effect, in Fig. 4 we show the quantity f_{gas}, defined as

$$f_{gas} = \frac{M_{gas}(R_{vir})}{M_{\rm halo}} \frac{\Omega_M}{\Omega_b}, \quad (1)$$

where $M_{gas}(R_{vir})$ is the mass of gas within the virialization radius (R_{vir}) of a halo of total mass $M_{\rm halo}$ and Ω_b/Ω_M is the cosmological ratio of baryonic versus total matter in the Universe (Ω_b = 0.042, Ω_M = 0.24, Spergel et al. 2007). Then, f_{gas} measures what is the real ratio (from our simulations) between baryonic and total mass in the halo, normalized to the cosmological value.

The more interesting case in Fig. 4 are LDM decays, where f_{gas} for halos with $M_{\rm halo} \sim m_{crit}$ is of the order of 0.3-0.4. This means that, in presence of DM decays, the real fraction of gas mass inside the virialized halo is much lower than the cosmological value.

Then, even if halos are still allowed to collapse, the quantity of gas at their center is a factor of $\sim$ 2 smaller than it is expected from cosmology. As the reservoir of gas is smaller, also the total mass of stars which form within these low mass halos might be less than expected. Further investigations might clarify whether this effect is significant for the formation of first stars.

Acknowledgements. MM is grateful to the Società Astronomica Italiana (SAIt) for awarding her the Tacchini Prize 2007. MM also thanks the DAVID group for the useful and pleasant collaboration.

References

Mapelli, M., Ferrara A. & Pierpaoli E., 2006, MNRAS, 369, 1719

Mapelli, M. & Ripamonti, E. 2007, to appear in the proceedings of the 11th Marcel Grossmann Meeting held in Berlin, Germany, July 23-29 2006, (arXiv:astro-ph/0701672v1)

Navarro J. F., Frenk C. S., White S. D. M., 1996, ApJ, 462, 563

Ripamonti, E., 2007, MNRAS, 376, 709

Ripamonti, E. & Mapelli, M. 2007, to appear in the proceedings of the 11th Marcel Grossmann Meeting held in Berlin, Germany, July 23-29 2006, (arXiv:astro-ph/0701673v1)

Ripamonti, E., Mapelli, M. & Ferrara, A. 2007a, MNRAS, 374, 1067

Ripamonti, E., Mapelli, M. & Ferrara, A. 2007b, MNRAS, 375, 1399

Spergel, D. N. et al. 2007, ApJ, accepted, (arXiv:astro-ph/0603449v2)

Tegmark M., Silk J., Rees M. J., Blanchard A., Abel T., Palla F. 1997, ApJ, 474, 1