Sterile neutrinos and structure formation

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Structure formation

- The first objects are a direct consequence of the growth of primordial density fluctuations.

$$\rho(t, \mathbf{r}) = \bar{\rho}(t)\left[1 + \delta(t, \mathbf{r})\right]$$

- primordial density fluctuations
- decoupling of the perturbation from the Hubble flow
- subsequent collapse
- formation of a virialized halo (cloud in the hydrostatic equilibrium)

Now we need some cooling mechanism

(cooling via H_2 and H collisional excitation and subsequent spontaneous de-excitation)

- the successive fragmentation, contraction processes and star formation
- re-ionization of the Universe

Radiation and H_2 molecule

In primordial gas clouds, H_2 molecules can form mainly through the coupled reactions

$$
\begin{aligned}
e^- + H &\rightarrow H^- + \gamma \\
H^- + H &\rightarrow H_2 + e^-
\end{aligned}
\qquad
\begin{aligned}
H^+ + H &\rightarrow H_2^+ + \gamma \\
H_2^+ + H &\rightarrow H_2 + H^+
\end{aligned}
$$

X-ray photons $\rightarrow$ ionization $\rightarrow$ enhancement of the H_2 fraction

Heating and ionization due to the X-rays

He and H ionization $\rightarrow$ secondary electrons $\rightarrow$ additional ionization

1/3 of the energy of the absorbed X-ray photon goes into ionization, 1/3 into excitation and 1/3 into gas heating.

There are several inconsistencies between the predictions of Lambda Cold Dark Matter (CDM) simulations and the observations

- an order of magnitude over-prediction of the observed small dwarf galaxies in our Local Group
- cold dark matter simulations predict that dark matter form cuspy density distributions, i.e. the density increases sharply to a high value at a central point, in opposition to the observation of the core profiles
- and many more...

Reduction of the initial power spectrum of density fluctuations on small scales, due to the warm dark matter (WDM), can alleviate all of these problems.

Warm dark matter problem

- Suppression of small scale fluctuations in most of the WDM models leads to the unacceptable delay in structure formation, which in turn, leads to inconsistency with the re-ionization redshift obtained by the three years measurements of the WMAP.

- One needs some mechanism which will be able to speed up the structure formation.

KeV sterile neutrino as a WDM candidate

Sterile neutrinos with the mass of several keV and small mixing angle with the ordinary neutrinos can radiatively decay, and since it is a two-body reaction, the photon energy is half the mass of the sterile neutrino, thus, it is in X-ray range. These photons can enhance H_2 production and speed up star formation. It makes keV sterile neutrinos very attractive candidate for the warm dark matter.

$\nu_s \rightarrow \nu_a + \gamma$

The inverse width of radiative sterile neutrino decay

$$\tau \equiv \Gamma^{-1}_{\nu_s \rightarrow \nu_a \gamma} = 1.3 \times 10^{26} \mathrm{s} \left(\frac{7 \ \mathrm{keV}}{\mathrm{m_s c^2}} \right)^5 \left(\frac{0.8 \times 10^{-9}}{\sin^2 \theta} \right)$$

Sterile neutrino hypothesis can be confirmed by detection of the X-ray line from their decays in the nearby galaxies.

Top-hat model - evolution of the overdensity

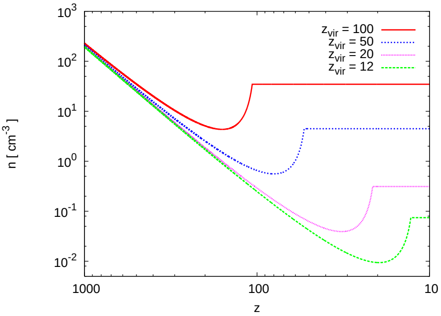
$$\delta(z,\mathbf{r}) = \begin{cases} \delta(z) & r < R \\ 0 & r > R \end{cases}$$

$$\delta(z) = \frac{9}{2}\frac{(\alpha - \sin\alpha)^2}{(1-\cos\alpha)^3} - 1$$

$$\frac{1+z_{vir}}{1+z} = \left(\frac{\alpha - \sin\alpha}{2\pi}\right)^{2/3}$$

After virialization

$$\rho_{vir} \simeq 18\pi^2 \rho_0 \Omega_0 (1+z_{vir})^3$$



Evolution of the gas temperature

Temperature of primordial cloud is evaluated according to the following equation

$$\frac{dT}{dz} = (\gamma - 1)\,\frac{T}{n_p}\frac{dn_p}{dz} + \gamma\frac{T}{\mu}\frac{d\mu}{dz} + \frac{T}{(\gamma-1)}\frac{d\gamma}{dz} + \frac{(\gamma-1)\Lambda}{n_p k H_0 (1+z)\sqrt{\Omega_\Lambda+\Omega_0(1+z)^3}}.$$

Soon before virialization we assume shocks and increase the gas temperature to its virial value

$$T_{vir} = 9.09\times 10^3\ \mathrm{K}\ \left(\frac{\mu_{vir}}{0.59}\right)\left(\frac{M}{10^9 h^{-1} M_\odot}\right)^{2/3}\left(\frac{\Delta_c(z_{vir})}{18\pi^2}\right)^{1/3}(1+z_{vir})$$

After virialization we switch to the first equation

Criterion for successful collapse

$$T\,(0.75 z_{vir}) < 0.75\,T\,(z_{vir})$$

The cooling/heating function

Heating

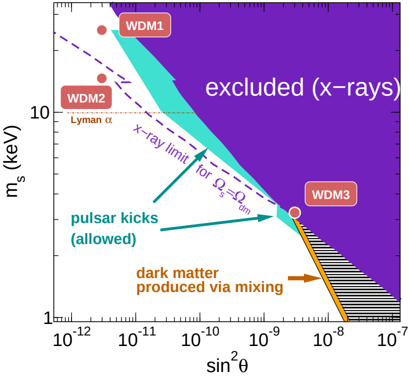
- Photo-dissociation of H_2 by the cosmic microwave background (CMB)
- Photo-ionization of H by the CMB radiation
- heating due to the sterile neutrino decays

Cooling

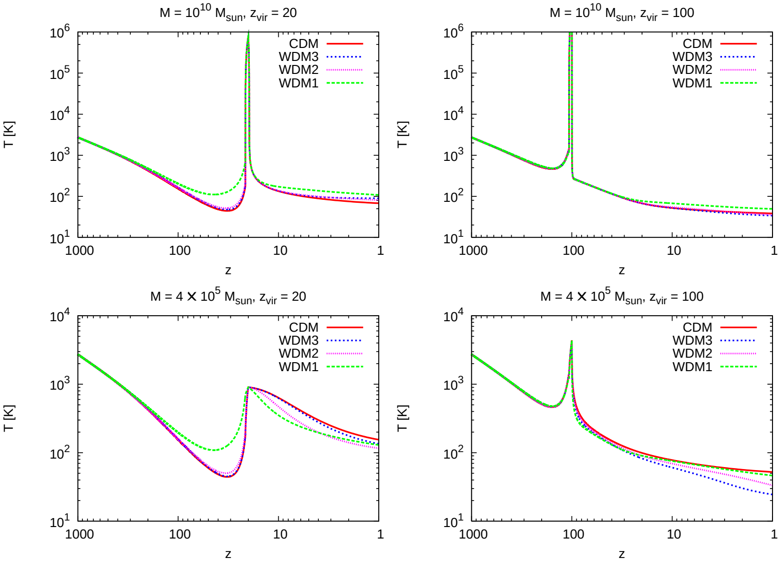
- collisional excitation of H and H_2
- collisional ionization of H and collisional dissociation of H_2
- H^- and H_2^+ formation
- recombination
- Bremsstrahlung
- Compton cooling
- H and He ionization due to the sterile neutrino decays

Simulation - models

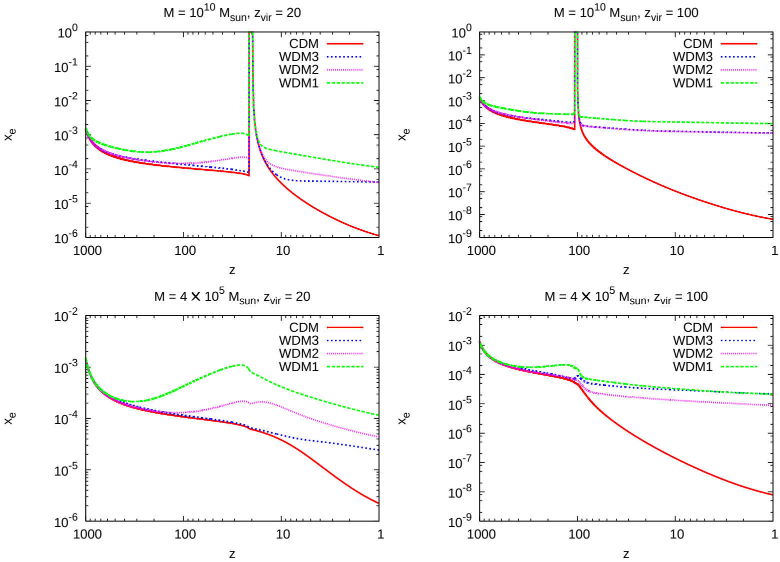
1. CDM
2. WDM1, $m_s = 25$ keV and mixing angle $\sin^2\theta = 3 \times 10^{-12}$
3. WDM2, $m_s = 15$ keV and $\sin^2\theta = 3 \times 10^{-12}$
4. WDM3, $m_s = 3.3$ keV and $\sin^2\theta = 3 \times 10^{-9}$



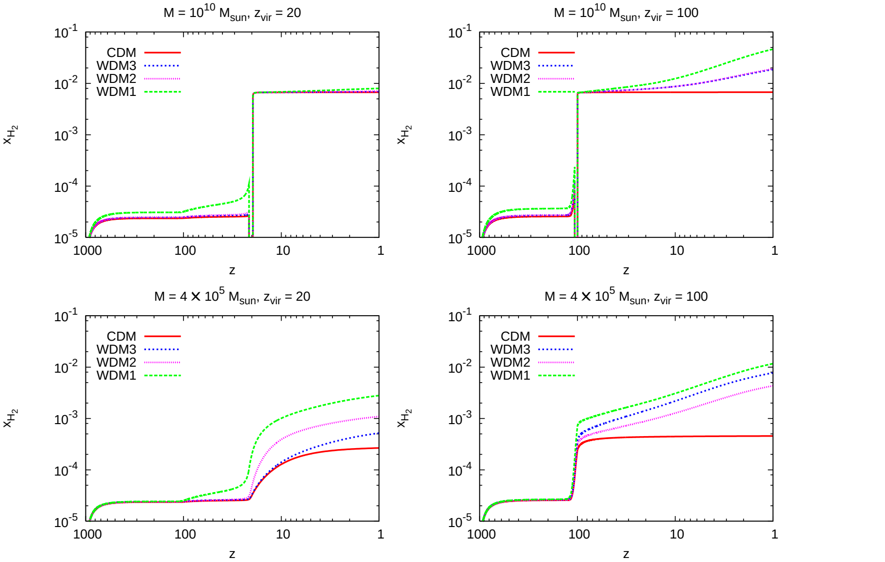
Evolution of the gas temperature



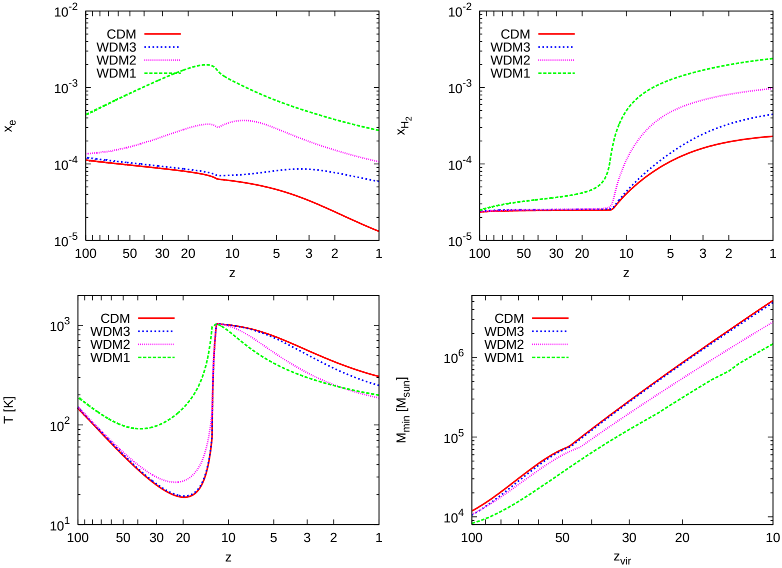
Evolution of the ionization fraction



Evolution of the H_2 fraction



Minimal mass able to collapse



Conclusions

- We have performed a detailed analysis of the cooling and collapse of primordial gas clouds in the model with warm dark matter, taking into account both the increase in the fraction of H2 and the heating due to the sterile neutrino decays.
- Our work shows importance of the radiation field in the collapse of primordial clouds and in the process of star formation.
- One can use the same technique to investigate the influence of another hypothetical particle decays.

Conclusions

- As expected, the effect of the sterile neutrino decays on the largest gas clouds is negligible, but the smaller clouds are, in fact, affected. For the largest clouds, the additional H_2 makes no difference and cooling via H is sufficient.
- The overall effect of sterile neutrino decays is to reduce the minimal mass able to collapse at all considered redshifts and to speed up structure formation.
- The sterile neutrino decays provide mechanism which could, in principle, move the re-ionization redshift in WDM model to the value consistent with the WMAP measurements ($z \approx 11$).
- The right handed (sterile) neutrino is an interesting hypothesis. Because of its properties, we may have to call them Weakly Interacting Neutrinos or just WINs.