Influence of three-body recombination on formation of dark atoms

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Summary

Self-interacting Dark Matter (SIDM)

Self-interacting DM is DM particles with some kind of dark interaction: Couloumb-like, Yukawa, elastic scattering, etc.

This new kind of DM can be described with the help of parameter $\frac{\sigma}{m_{\mathrm{X}}}$ (additionaly to Ω_{DM} and $T_{\text{freeze-out}}$ of CDM).

Problems

Small-scale issues of ΛCDM:

- Cuspy halo problem (Core-cusp)
- Dwarf galaxy problem
- Too-big-to-fail problem

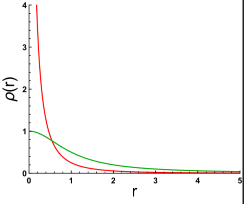


Figure 1: Core-cusp [de Blok 2010]

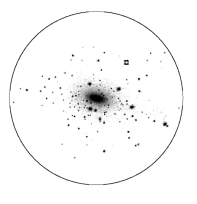


Figure 2: Missing satelite [Klypin 1999]

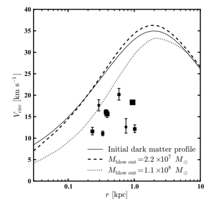


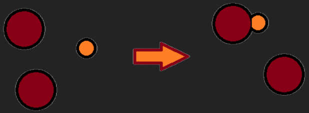
Figure 3: Too-big-to-fail [Boylan-Kolchin 2012]

Advanteges of SIDM models

1. solving small-scale issues of ΛCDM
2. similarity with particles of SM
3. possible solution of other astrophysical problems (cosmic rays anomalies, formation of supermassive black holes)

Recombination of SIDM

In that work we consider SIDM model with dark Coulunb-like interaction between particles a and b. Particles have lower mass and can form a bound state with b.



Dynamical properties of SIDM are crutualy dependent on amount of recombined particles.

Kramer's and classical approach

There are different mechanism of radiative recombination. Kramer's and classical approach for this problem have been studied in work [Belotsky 2016].

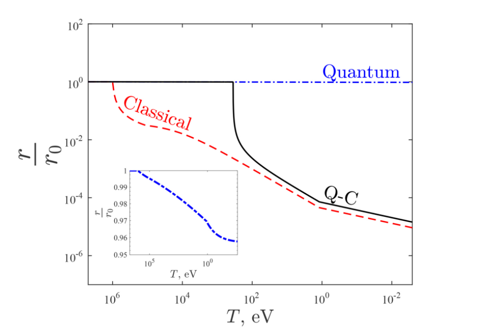


Figure 4: Relative density of unbound y-charged DM particles as function of T

Three-body recombination

In plasma there are different recombination processes. In this work we review three-body recombination.
Three-body recombination is the process in which three free atoms collide, producing a molecule.

$$a + b + b \rightarrow ab + b + y. \tag{1}$$

Three-body recombination rate [Knyazev 2003] can be calculated from the formula :

$$\beta(T) = \frac{2\sqrt{m_a}(4\pi\alpha_y)^5}{m_b T^{9/2}}, \tag{2}$$

where T – temperature of plasma, α_y – dark fine structure constant.

Goals

In present work we want to estimate density of unbound DM particles as function of time in case of three-body recombination.

Density evolution

$$-\frac{\mathrm{d}n_a}{\mathrm{d}t} = \langle \sigma v \rangle \, n_a n_b + 3HT, \tag{3}$$

where $n_a, \; n_b$ – densities of particle a and b, $\langle \sigma v \rangle$ – recombination frequency, H – Hubble constant and T – temperature of photons.
n can be connected with number density parameter r and entropy density s: $n = rs$. Cosmological time can be connected with T: $-\mathrm{d}t = H \frac{\mathrm{d}T}{T}$. So we can consider equation for r(T):

$$\frac{\mathrm{d}r_a}{\mathrm{d}T} = \frac{r_a r_b s}{HT} \langle \sigma v \rangle \, . \tag{4}$$

Switching to other variables

Let us consider, that $n_a = n_b$ for electroneutrality of dark plasma. Then for three-body recombination:

$$\frac{\mathrm{d}r}{\mathrm{d}T} = \frac{r^3 s^2}{HT} \cdot \frac{2\sqrt{m_a}(4\pi\alpha)^5}{m_b T_a^{9/2}}. \qquad (5)$$

T_a is non-relativistic matter particle, so we can assume that:
$T_a \approx \frac{T^2 \kappa^{1/3}}{T_{ay}} = \frac{T^2}{T_o}$, where T_{ay} – temperature of a-y decoupling.
$s = 2\pi^2 g T^3/45$. Then,

$$\frac{\mathrm{d}r}{\mathrm{d}T} = \left(\frac{2\pi g}{45}\right)^2 \frac{2\sqrt{m_a}(4\pi\alpha)^5 T_0^{9/2}}{m_b} \cdot \frac{r^3}{HT^4} = \frac{r^3}{HT^4}\mathrm{D_s}. \qquad (6)$$

Solution

Let us assume initial condition as $r(T_{rec}) = r_{rec}$. Then we solve this equation for radiation dominated (RD) era:

$$r_{\text{RD}}(T) = r_{rec}\sqrt{\frac{1}{1+\frac{4}{9}\mathrm{r}_{\mathrm{rec}}^2\mathrm{D}_{\text{RD}}\left(\frac{1}{T^{9/2}}-\frac{1}{T_{rec}^{9/2}}\right)}}. \tag{7}$$

Parameter D depends on y-interaction, masses of dark particles, stage of universe.

Solution

For matter dominated (MD) era:

$$r_{\mathsf{MD}}(T) = r_{rec}\sqrt{\frac{1}{1+\frac{2}{5}\mathrm{r}_{\mathrm{rec}}^{2}\mathrm{D}_{\mathsf{MD}}\left(\frac{1}{T^5}-\frac{1}{T_{rec}^5}\right)}}. \tag{8}$$

Testing model

We use this data for the study of the function:

m_a	100 GeV
m_b	1 TeV
α_y	1/100
r_{rec}	$4.6 \cdot 10^{-13}$
T_{rec}	0.1 MeV

$$\frac{r_{3body}}{r_{\text{kramers}}}(T \approx 1\text{eV}) = 10^{-4}. \tag{9}$$

Conclussion

1. Recombination in cold plasma is complicated process. In first oder it can be approximate as Kramers recombination. **But sometimes**, we need to consider effects like three-body recombination.
2. In the early universe, a large number of uncharged dark atoms could accumulate due to three-body recombination.

References

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3. De Blok, W. J. G. The Core-Cusp Problem. *Advances in Astronomy* **2010,** 1–14. `https://doi.org/10.1155%2F2010%2F789293` (2010).
4. Klypin, A., Kravtsov, A. V., Valenzuela, O. & Prada, F. Where Are the Missing Galactic Satellites? *The Astrophysical Journal* **522,** 82–92. `https://doi.org/10.1086%2F307643` (Sept. 1999).

Thank you for attention

Kramer's recombination

$$\sigma_K = \frac{32\pi}{3\sqrt{3}} \frac{\alpha_y^3}{\mu^2} \frac{\ln\left(v^{-1}\right)}{v^2}, \qquad \frac{r}{r_0} < 5\% \tag{10}$$

Applicabillity

1. Equation on rate: $< \sigma_3 v > \ll < \sigma_K v >$
2. Condition on concentration: if plasma has low density – particels have low probability of three-body interation.

Schedule without limitation of applicability

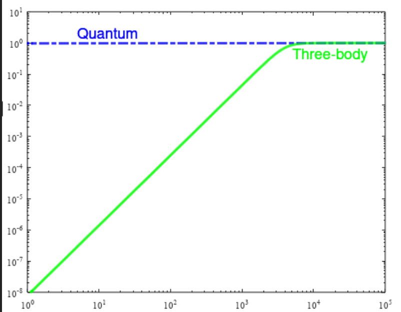

Figure 5: r/r_0 parameter from tempreture of photons.

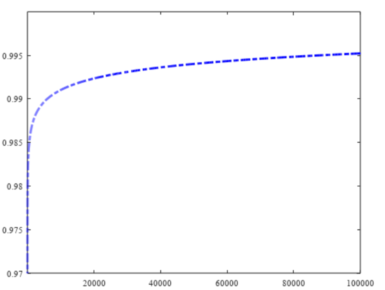

Figure 6: r/r_0 parameter from tempreture of photons for Kramers cross-section.