# Constraints on the basic parameters of dark matter using the Planck data

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# Constraints on the basic parameters of dark matter using the Planck data

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Dark Matter annihilation or decay can affect the anisotropy of the cosmic microwave background (CMB). Therefore the CMB data can be used to constrain the properties of dark matter particle. In this work, we use the new CMB data obtained by the Planck satellite to investigate the limits on the basic parameters of dark matter particle. The parameters are the dark matter mass ($m_\chi$) and the thermally averaged cross section ($\langle\sigma v\rangle$) for dark matter annihilation and the decay rate ($\Gamma$) (or life time $\tau = 1/\Gamma$) for dark matter decay. For dark matter annihilation we also consider the impact of the structure formation process which is neglected by the recent work. We found that for DM annihilation the constraints on the parameters are $f_{ann} = \langle\sigma v\rangle/m_\chi < 0.16 \times 10^{-26}\mathrm{cm^3 s^{-1} GeV^{-1}}$(or $f_{ann} < 0.89 \times 10^{-6}\mathrm{m^3 s^{-1} kg^{-1}}$, 95% CL). For DM decay the constraints on the decay rate are $\Gamma < 0.28 \times 10^{-25}\mathrm{s^{-1}}$(95% CL).

## I. INTRODUCTION

Dark matter (DM), the main components of the Universe, confirmed by many observations still keeps its nature mysterious [1–3]. Its most widely accepted model, the Weakly Interacting Massive Particles (WIMPs) model, claims DM particles can self-annihilate into standard model particles, such as photons, electrons, positrons [1], which might be observed by various experiments, such as PAMALA [4] and AMS-2 [5]. During the evolution of the Universe these particles produced by DM annihilation interact with the medium of the Universe [6–8]. For example, the photons produced through DM annihilation can ionize the hydrogens formed in the epoch of recombination before appearance of the first stars. The changes of the ionization will be reflected in the anisotropy of the cosmic microwave background (CMB) [7–11]. Therefore the observation data of CMB can be used to investigate the nature of DM particles. Recently, the authors of [11] used the Planck data to investigate the limits on the DM parameters, the mass $m_\chi$ and the thermally averaged cross section $\langle\sigma v\rangle$. In that paper, they considered the uniform distribution of DM while neglecting the structure formation process of the Universe which claimed the DM halos were formed in the redshift $z \sim 100$. Moreover, the sub-halos or sub-sub-halos are also formed in DM halos [12]. The DM annihilation rate can be enhanced in all these DM halos. In this work, we consider these effects. In addition to annihilation DM particles are not stable in some models and they can decay into the standard model particles [13, 14]. In this paper, we also use the Planck data to get the constraints on the decay rate (or life time) of DM. Not setting any specific DM model, the results of this work can be applied widely to those DM particles can annihilate or decay.

This paper is organized as follows: In Sec. II, we briefly show that how the DM particles annihilation and decay affect the evolution of Universe and we give the constraints on the basic parameters of DM by the use of the Planck data. We conclude in Sec. III.

## II. THE IMPACT OF DM ON THE EVOLUTION OF THE UNIVERSE AND CONSTRAINTS ON THE BASIC PARAMETERS

DM particles can affect the Universe through the interaction between the medium of the Universe and the productions of DM annihilation or decay. Two of main effects are to ionize the hydrogens and heat the medium [6]. The changes of ionization with the redshift are governed by the equation [6, 7]

$$(1+z)\frac{dx_e}{dz} = [R_s(z) - I_s(z) - I_\chi(z)] \tag{1}$$

where $I_\chi(z)$ is the ionization rate due to the DM, $R_s(z)$ and $I_s(z)$ are the standard recombination rate and ionization rate by the standard sources respectively. The ionization rate by the DM can be be written as

$$I_\chi(z) = \chi_i f(z) \Gamma_{ann} \frac{m_\chi}{n_b E_b} \tag{2}$$

for the DM annihilation and

$$I_\chi(z) = \chi_i f(z) \Gamma_{dec} \frac{\Omega_\chi}{\Omega_b} \frac{m_b}{n_b E_b} \tag{3}$$

for the DM decay. $\Gamma_{ann}$ and $\Gamma_{dec}$ (or $\Gamma_{dec} = 1/\tau_{dec}$, $\tau_{dec}$ is life time ) are the DM annihilation and decay rate, $n_b$ is the number density of baryon, $E_b = 13.6\mathrm{eV}$ is the ionization energy.

If the structure formation effect is included, the DM annihilation rate can be written as

$$\begin{aligned}\Gamma_{ann} =& \frac{\langle\sigma v\rangle}{m_\chi} \rho_{cri}^2 \Omega_c^2 (1+z)^6 B(z) \\ =& f_{ann} \rho_{cri}^2 \Omega_c^2 (1+z)^6 B(z)\end{aligned} \tag{4}$$

where $B(z)$ is the 'boost factor' (or 'clumping factor') due to the structure formation effect, for more detailed

discussions one can see the Ref. [15]. $\rho_{cri}$ is the critical density of the Universe. $f_{ann}$ is a new parameter which is the combination of the basic parameters of DM, $f_{ann} = \langle\sigma v\rangle/m_\chi$.

For the boost factor $B(z)$ we followed the Ref.[15] and used the form as

$$B(z) = 1 + \frac{(1+z)^3}{\bar{\rho}^2_{DM}(z)} \int dM \frac{dn}{dM}(M,z) \int \rho^2(r) dV \quad (5)$$

where $dn/dM$ is the mass function of DM halos and we use the Press-Schechters formalism for our calculations [16]. For the DM halos, we use the NFW (Navarro-Frenk-White) density profile. It is also found that the there are many sub- and sub-sub-structures in DM halos [12]. The DM annihilation rate can be enhanced in these subhalos. In this paper, we include these subhalos while neglecting the contributions from the sub-sub-halos. We set the smallest mass of DM halo as $\sim 10^{-6} M_\odot$ [17]. We adopt that $\sim 10\%$ mass of DM halos is in the form of subhalos. We use the power law form of the mass function $\sim M^{1.95}$ for the subhalos [12]. The total boost factor of DM halos including the subhalos is [15]

$$B_{total} = 1 + (B_{halos} - 1) + (B_{subhalos} - 1) \quad (6)$$

In the equations 2 and 3, $\chi_i$ stands for the fraction of the energy which contributes to the ionization and is discussed firstly in the Ref. [18]. Here we adopt the form given by the Ref. [6], $\chi_i = (1 - x_e)/3$. **It should be noticed that although this form has been used frequently in previous works [6–8, 10], it is not accurate. In the Ref. [19], the difference of the constraints on DM parameters occured both in the approximate and the accurate have been investigated and only slightly differences of the upper limits for the present null detection of DM found. The similar discussions are also present in the Ref. [20].** $f(z)$ is the fraction of the energy which deposits to the medium of the Universe. It is different for different annihilation or decay channels and is a function of the redshift. Here we treat it as a free parameter. For more detail discussions one can see the Refs. [11]. In addition to the ionization another important effect of DM to the evolution of the Universe is to heat the medium, e.g. the baryonic gas. The evolution the gas temperature can be written as

$$(1+z)\frac{dT_b}{dz} = \frac{8\sigma_T a_R T^4_{cmb}}{3 m_e c H(z)} \frac{x_e}{1 + f_{He} + x_e}(T_b - T_{cmb}) - \frac{2}{3 k_B H(z)} \frac{K_\chi}{1 + f_{He} + x_e} + 2T_b \quad (7)$$

where $K_\chi$ is similar with $I_\chi$ and stands for the heating rate to the medium by the DM. Following the Refs. [6], we use the form as $K_\chi = (1 + 2x_e)/3$.

Recently, the authors of [11] used the Planck data to get the constraints on the DM parameters for the annihilation case, but they did not consider the effect of the structure formation. In this work, we include this effect and we also get the constraints on the decay rate (or life time) for the DM decay. Because the limits are independent on any specific DM models, the results can be used widely for many DM annihilation or decay models.

We modified the public code RECFAST [1]to include the DM effect, used the public code CosmoMC [2] to get the constraints on the parameters. We consider 6 cosmological parameters and a new parameter

$$\{\Omega_b h^2, \Omega_c h^2, \theta, \tau, n_s, A_s, F_{ann}\}, \quad (8)$$

for the DM annihilation and

$$\{\Omega_b h^2, \Omega_c h^2, \theta, \tau, n_s, A_s, F_{dec}\}, \quad (9)$$

for the DM decay. Here are the new parameters $F_{ann} = f(z) f_{ann} = f(z)\langle\sigma v\rangle/m_\chi$ and $F_{dec} = \Gamma_{dec} f(z)$.

The final constraints on the parameters are given in the Tab. I for the DM annihilation and Tab. II for the DM decay. **For making comparisons, the results for the case of smooth DM distribution are given too. In this case, the 'boost factor' is $B(z) = 1$.** From these results it can be seen that for the $f(z) = 1$ the 95% upper limits are

$$\frac{\langle\sigma v\rangle}{m_\chi} < 0.16(0.24) \times 10^{-26} \mathrm{cm^3 s^{-1} GeV^{-1}} \quad (10)$$

for the DM annihilation case (0.24 is the case of smooth distribution) and

$$\Gamma < 0.28 \times 10^{-25} \mathrm{s^{-1}} \quad (11)$$

for the DM decay case.

For the DM annihilation case, our results are consistent with the Ref. [11](e.g Tab II). For this point, we can convert our results as

$$\frac{\langle\sigma v\rangle}{m_\chi} < 0.16(0.24) \times 10^{-26} \mathrm{cm^3 s^{-1} GeV^{-1}} = 0.89(1.34) \times 10^{-6} \mathrm{m^3 s^{-1} kg^{-1}} \quad (12)$$

We also plot the 1D and 2D probability distributions in Figs. 1 and 2 for the DM annihilation (including the smooth distribution case, dotted lines) and Figs. 3 and 4 for the DM decay respectively. From these plots one can find that the correlation between the $F_{ann}$ parameter

[1] http://camb.info
[2] http://cosmologist.info/cosmomc/

and the cosmological parameters is stronger for the DM annihilation than that the $F_{dec}$ for the DM decay. The main reason is that the DM annihilation rate is proportional to the number density square, so the effects due to the annihilation are very strong during the recombination. For the DM annihilation, the differences between the clumpy and smooth DM distribution cases are not so huge. These results indicate once again that the limits on the DM parameters are mainly from the epoch of the recombination.

## III. SUMMARY AND DISCUSSIONS

In this work, we used the new data from the Planck satellite to investigate the limits on the DM basic parameters for the annihilation and decay. By considering the structure formation effect for the DM annihilation case, we can find that the constraints on the $f_{ann}$ parameter are $f_{ann} < 0.16(0.24) \times 10^{-26}\mathrm{cm}^3\mathrm{s}^{-1}\mathrm{GeV}^{-1}$ or $f_{ann} < 0.89(1.34) \times 10^{-6}\mathrm{m}^3\mathrm{s}^{-1}\mathrm{kg}^{-1}$(95% CL). For the DM decay the constraints on the decay rate are $\Gamma < 0.28 \times 10^{-25}s^{-1}$(95% CL).

**As mentioned in the Sec.II, for the clumpy DM distribution, the smallest mass of DM halo is set as $\sim 10^{-6}M_{\odot}$, which is different for different DM models. In theory for WIMPs DM, this value ranges from $10^{-12}M_{\odot}$ to $10^{-4}M_{\odot}$ for typical kinetic decoupling temperatures. From the results of current numerical simulations, the typical smallest mass of DM halos is $\sim 10^{6}M_{\odot}$. In the Ref. [15], the authors discussed the effects on the 'boost factor' for the different values of the smallest DM halos. They found that there are differences of $\sim 2$ orders of magnitude of the 'boost factor' for DM halo mass $10^{-12}M_{\odot}$ and $10^{-4}M_{\odot}$ at $z \sim 50$ (upper panel of Fig. 1 in Ref. [15]). For DM halo mass $10^{6}M_{\odot}$, the differences of $\sim 5$ orders of magnitude differences are present at $z \sim 20$ compared with the DM smooth distribution. Therefore, the largest differences usually appear in nearby universe, and it is believed that the changes of limits on the DM parameters are slight if one change the values of the smallest mass of DM halos.**

**Another factor which can affect the limits on the DM is the density profile of DM halos. In this work, we have used the NFW profile, which is well in fitting many observations data. In addition there are still many other observations or N-body simulations which are favored by the other profiles, such as Einasto profile [21–24], which are slightly different from that of NFW profile for the final constrains.**

One point in this work should be noticed that we have set $f(z)$ as a free parameter and for the final constraints we have set $f(z) = 1$ which means that all the energy produced by the DM annihilation or decay have deposited into the medium of the Universe. In the Ref. [11], the dependence of $f(z)$ on the redshift and different annihilation channels were discussed by the authors. It can be seen that the final constraints are slight different (Tab. II of Ref. [11]).

TABLE I. Posterior constraints on the parameters for the DM annihilation. The first and second lines of every items correspond to the clumpy and smooth DM distribution respectively.

| Parameter | $\Omega_b h^2$ | $\Omega_c h^2$ | $100\theta$ | $\tau$ | $n_s$ | $ln(10^{10}A_s)$ | $F_{ann}(10^{-26}\mathrm{cm}^3\mathrm{s}^{-1}\mathrm{GeV}^{-1})$ |
|---|---|---|---|---|---|---|---|
| mean | 0.02207 | 0.1196 | 1.0412 | 0.088 | 0.962 | 3.09 | 0.053 |
| | 0.02209 | 0.1195 | 1.0413 | 0.089 | 0.963 | 3.10 | 0.070 |
| $2\sigma$ low | 0.02155 | 0.1147 | 1.0401 | 0.061 | 0.948 | 3.05 | 0 |
| | 0.02152 | 0.1140 | 1.0401 | 0.062 | 0.949 | 3.05 | 0 |
| $2\sigma$ up | 0.02260 | 0.1251 | 1.0425 | 0.1149 | 0.977 | 3.15 | 0.16 |
| | 0.02265 | 0.1244 | 1.0425 | 0.1154 | 0.978 | 3.15 | 0.24 |

TABLE II. Posterior constraints on the parameters for the DM decay.

| Parameter | $\Omega_b h^2$ | $\Omega_c h^2$ | $100\theta$ | $\tau$ | $n_s$ | $ln(10^{10}A_s)$ | $F_{dec}(10^{-25}s^{-1})$ |
|---|---|---|---|---|---|---|---|
| mean | 0.02205 | 0.1199 | 1.0413 | 0.088 | 0.960 | 3.09 | 0.077 |
| $2\sigma$ low | 0.02152 | 0.1147 | 1.0401 | 0.064 | 0.94 | 3.04 | 0 |
| $2\sigma$ up | 0.02262 | 0.1251 | 1.0425 | 0.115 | 0.97 | 3.14 | 0.28 |

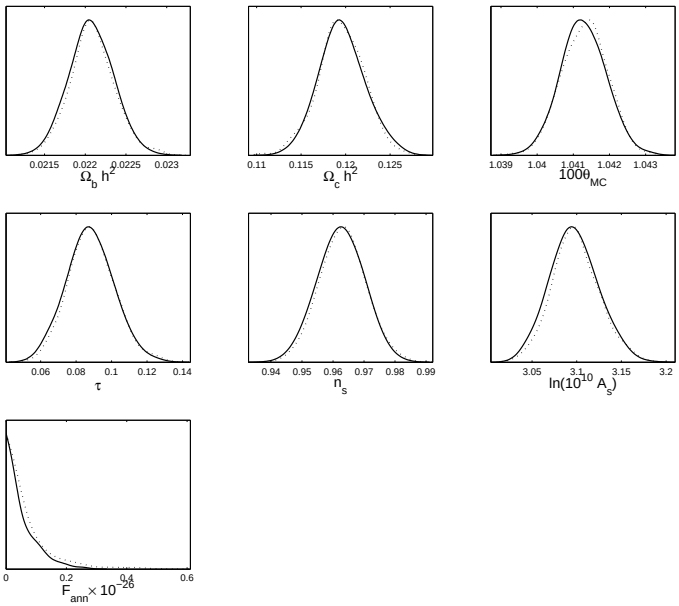


FIG. 1. The marginalized probability distribution function of parameters for the DM annihilation case. The solid and dotted lines correspond to the clumpy and smooth DM distribution respectively.

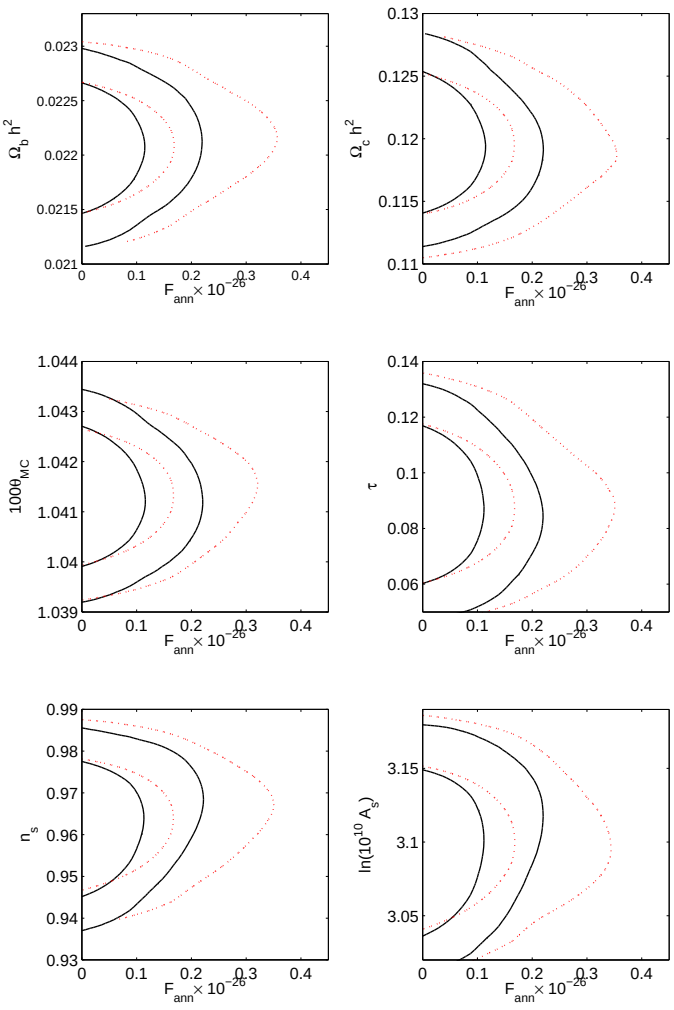


FIG. 2. The 2D contours distribution function of parameters for the DM annihilation case(68% and 95% confidence level). The solid (black) and dotted (red) lines correspond to the clumpy and smooth DM distribution respectively.

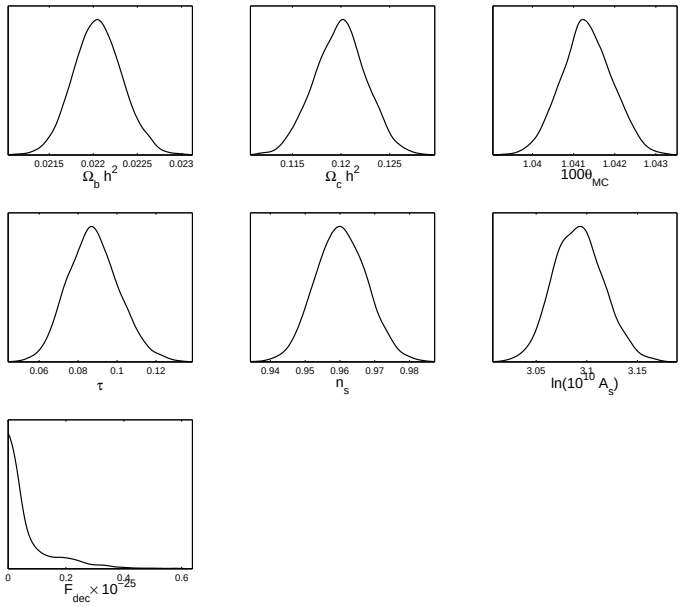


FIG. 3. The marginalized probability distribution function of parameters for the DM decay case.

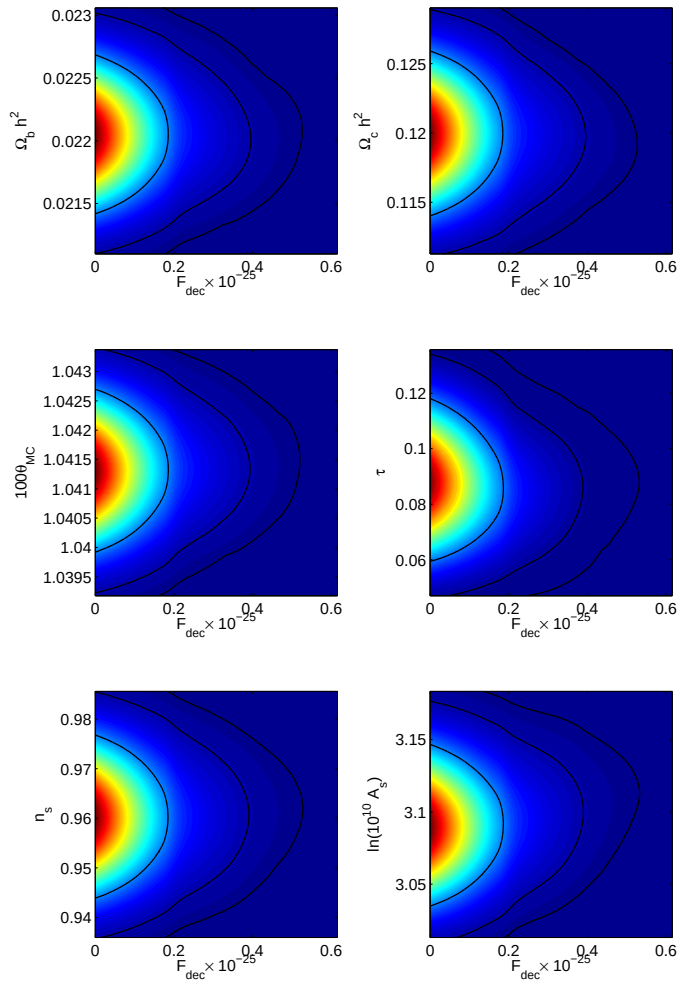


FIG. 4. The 2D contours distribution function of parameters for the DM annihilation case(68%, 95% and 99% confidence level).

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[1] G. Jungman, M. Kamionkowski, and K. Griest, Phys.Rept. **267**, 195 (1996).
[2] G. Bertone, D. Hooper, and J. Silk, Phys.Rept **405**, 279 (2005).
[3] L. Bergstrm, New Journal of Physics **11**, 105006 (2009).
[4] O. Adriani *et al.*, Nature **458**, 607 (2009).
[5] M. Aguilar *et al.*, Phys. Rev. Lett. **110**, 141102 (2013).
[6] X.-L. Chen and M. Kamionkowski, Phys.Rev. **D70**, 043502 (2004).
[7] L. Zhang, X.-L. Chen, Y.-A. Lei, and Z.-G. Si, Phys.Rev. **D74**, 103519 (2006).
[8] L. Zhang *et al.*, Phys.Rev. **D76**, 061301 (2007).
[9] T. R. Slatyer, N. Padmanabhan, and D. P. Finkbeiner, Phys. Rev. D **80**, 043526 (2009).
[10] Y. Yang, X. Huang, X. Chen, and H. Zong, Phys. Rev. D **84**, 043506 (2011).
[11] M. S. Madhavacheril, N. Sehgal, and T. R. Slatyer, Phys.Rev. **D89**, 103508 (2014).
[12] J. Diemand, B. Moore, and J. Stadel, Nature **433**, 389 (2005).
[13] F. Takayama and M. Yamaguchi, Phys.Lett. **B485**, 388 (2000).
[14] A. Arvanitaki *et al.*, Phys.Rev. **D79**, 105022 (2009).
[15] D. T. Cumberbatch, M. Lattanzi, and J. Silk, Phys. Rev. D **82**, 103508 (2010).
[16] W. H. Press and P. Schechter, Astrophys. J.**187**, 425 (1974).
[17] A. M. Green, S. Hofmann, and D. J. Schwarz, Journal of Cosmology and Astroparticle Physics **2005**, 003 (2005).
[18] J. M. Shull and M. E. van Steenberg, Astrophys. J.**298**, 268 (1985).
[19] S. Galli, T. R. Slatyer, M. Valdes, and F. Iocco, Phys.Rev. **D88**, 063502 (2013).
[20] J. Chluba, Monthly Notices of the Royal Astronomical Society **402**, 1195 (2010).
[21] E. J., Trudy Astrofizicheskogo Instituta AlmaAta **5**, 87 (1965).
[22] L. Chemin, W. J. G. de Blok, and G. A. Mamon, The Astronomical Journal **142**, 109 (2011).
[23] J. F. Navarro *et al.*, Mon.Not.Roy.Astron.Soc. **349**, 1039 (2004).
[24] M. Breddels and A. Helmi, Astron.Astrophys. **558**, A35 (2013).