

COSMOLOGY, GRAVITATION, ASTROPARTICLE PHYSICS, HIGH ENERGY PHYSICS

DOI:<http://dx.doi.org/10.18524/1810-4215.2020.33.216299>THE HOT DARK MATTER MODEL:
FURTHER INVESTIGATION

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ABSTRACT. In a recent paper, the model of the galaxy with hot dark matter was considered. The galaxy is divided into the inner region with the dominant baryonic matter (the elliptic orbit of the test particle) and the outer region with the dominant hot dark matter (the parabolic orbit of the test particle). It was assumed that the hot dark matter consists of hypothetical Planck neutrinos arising in the decay of the protons at the Planck scale. Galaxies formed from the baryonic matter, and the hot dark matter appears in the galaxies later. The rotation curves of the galaxies were studied in the model, including Milky Way, M33, NGC 2366 and IC 2574. In the present paper, the hot dark matter model is further investigated, with the application to M31, the system of M31 and the Milky Way, the globular clusters NGC 2419 and MGC1, the dwarf spheroidal galaxy Sculptor, ultra-massive quiescent galaxies from the COSMOS and UDS fields. The baryonic matter mass of M31 was estimated from the rotation curves, with the average value $1.6 \times 10^{11} m_{\odot}$. The gravitational interaction of the Milky Way and M31 is considered. In the hot dark matter model, the dynamical masses of the Milky Way and M31 are twice their baryonic matter masses that gives the radial velocity of M31 toward the Milky Way, 106 km s^{-1} . The hot dark matter mass in the globular clusters NGC 2419 and MGC1 is estimated. The value is small compared to the stellar mass in both the clusters. The hot dark matter mass within the half-light radius of the dwarf spheroidal galaxy Sculptor is estimated, $0.5 \times 10^6 m_{\odot}$. The sum of the stellar and hot dark matter mass within the half-light radius is consistent with the dynamical mass within the half-light radius of the Sculptor derived from the kinematics of the metal rich stars. The instability of the baryonic matter due to the influence of the hot dark matter and some perturbations flattens the velocity profile of the metal poor stars which is unsuitable to derive the dynamical mass. The evolution of ultra-massive quiescent galaxies from the COSMOS and UDS fields is considered. The dynamical to stellar mass relation is doubling during the evolution from $z = 2$ to 0 that

can be explained by the absence of dark matter at $z = 2$ and the presence of the hot dark matter at $z = 0$.

Keywords: dark matter; galaxies: kinematics and dynamics; galaxies: dwarf; globular clusters: general.

АНОТАЦІЯ. В недавній статті нами розглядалася модель галактики з гарячою темною матерією. Галактика розділена на внутрішню область з переважно баріонної матерії (еліптична орбіта пробної частинки) і зовнішню область з переважно гарячою темною матерією (параболічна орбіта пробної частинки). Припускається, що гаряча темна матерія складається з гіпотетичних Планківських нейтрино, що виникають у розпаді протонів на Планковській шкалі. Галактики формуються з баріонної матерії, а гаряча темна матерія з'являється в галактиках пізніше. Криві обертання галактик вивчалися в рамках моделі, в тому числі Чумацький Шлях, M33, NGC 2366 і IC 2574. У даній статті продовжено вивчення моделі з гарячою темною матерією стосовно M31, системи M31 і Чумацького Шляху, кулястих скупчень NGC 2419 та MGC1, карликової сфероїдальної галактиці Скульптор, ультрамасивних пасивних галактик з полів COSMOS та UDS. Маса баріонної матерії у M31 була оцінена з кривих обертання, середня величина $1.6 \times 10^{11} m_{\odot}$. Розглядалася гравітаційна взаємодія Чумацького Шляху та M31. У моделі з гарячою темною матерією динамічні маси Чумацького Шляху і M31 у два рази більше маси баріонної матерії, що дає радіальну швидкість M31 у напрямку Чумацького Шляху, 106 км с^{-1} . Була оцінена маса гарячої темної матерії в кулястих скупченнях NGC 2419 та MGC1. Її величина невелика у порівнянні із зоряною масою в обох скупченнях. Маса гарячої темної матерії всередині ефективного радіуса карликової сфероїдальної галактики Скульптор була оцінена як $0.5 \times 10^6 m_{\odot}$. Сума зоряної маси і маси гарячої темної матерії всередині ефективного радіуса узгоджується з динамічною масою всередині ефективного радіуса галактики

Скульптор, отриманої з кінематики зірок з високим вмістом металів. Нестабільність баріонної матерії, яка викликана гарячої темною матерією і деякими збуреннями, призводить до плоского профілю швидкостей зірок з низьким вмістом металів, який не підходить для отримання динамічної маси. Розглядалася еволюція ультрамасивних пасивних галактик з полів COSMOS та UDS. Відношення динамічної і зоряної мас подвоюється протягом еволюції від $z = 2$ до 0, що можна пояснити відсутністю темної матерії при $z = 2$ і наявністю гарячої темної матерії при $z = 0$.

Ключові слова: темна матерія; галактики: кінематика і динаміка; галактики: карликові; кулясті скупчення: загальне.

Introduction

The flat rotation curves of spiral galaxies can be explained by the presence of dark matter (DM), e.g. (Battaner & Florido, 2000) and references therein. The modified Newtonian gravity (MOND) (Famaey & McGuagh, 2012) gives another explanation. DM is a main component ($\sim 85\%$) in the universe (Ade et al., 2016). The nature of DM is thought to be non-baryonic (Trimble, 1987). There is a belief that DM was present in the early universe and took part in the structure formation (Trimble, 1987). Observational constraints on the structure formation give support to the models with cold dark matter (CDM) and disfavour those with hot dark matter (HDM). All the known particle species are not suitable for the CDM candidates. Among the proposed CDM candidates, the most popular are weakly interacting massive particles (WIMPs) (Bertone & Tait, 2018). Attempts to detect WIMPs in several experiments have failed (Marrodán Undagoitia & Rauch, 2016; Liu et al., 2017).

The rotation curves of massive star-forming galaxies at $0.6 \leq z \leq 2.6$ from the KMOS^{3D} and SINS/zC-SINF surveys show a fall-off beyond the turnover (Lang et al., 2017). The discs of these galaxies are strongly baryon dominated (Genzel et al., 2017). This is in contrast to the flat rotation curves of local spiral galaxies of similar masses. Several studies of observed high redshift galaxies (Tanaka et al., 2019; Casey et al., 2019; Stockmann et al., 2020) found the dynamical to stellar mass relation, $m_{dyn}/m_* \sim 1$. The EDGES collaboration reported the detection of 21 cm absorption at $z \approx 17$ (Bowman et al., 2018). The observed signal is about twice the value predicted in the Λ CDM model. The EDGES result can be explained in a universe devoid of DM, with the baryon fraction 100% (McGaugh, 2018).

The foregoing data imply the absence of DM in the universe at high redshifts above $z \sim 2$. In this case, the galaxies formed from the baryonic matter (BM),

and the DM come there later. As such, there is no restrictions on the models with HDM from the structure formation.

DM may emerge in the decay of the protons (Khokhlov, 2015). The mode of the decay of proton at the Planck scale into positron and hypothetical Planck neutrinos, $p \rightarrow e^+ 4\nu_{Pl}$, was suggested in Khokhlov (2011c). The process was studied for the protons falling onto the gravastar, by giving an example of Sgr A* while interpreting Sgr A* as a gravastar (Khokhlov, 2014, 2017). Planck neutrino can be classified as a HDM candidate.

The standard cosmology is considered within the framework of the Λ CDM model (Ostriker & Steinhardt, 1995). It complies with the observations on large scales (Reyes et al., 2010), see however (López-Corredoira, 2017) and references therein. Also, observational constraints from the density perturbations in the range $10^6 - 10^{15} m_\odot$ give the preference to the model with the dominant HDM fraction rather than the Λ CDM model (Demiański & Doroshkevich, 2017). The standard cosmology is in contrast to the electrodynamics in the laboratory frame (Khokhlov, 2013). An alternative model of the universe was developed in Khokhlov (2011a,b). Testing the Λ CDM model on galaxy scales reveals several problems, e.g. (Weinberg et al., 2015; Kroupa, 2012, 2015) and references therein.

In a recent paper (Khokhlov, 2018), the model of the galaxy with HDM was considered. The HDM was treated as a gas of hypothetical Planck neutrinos, arising from the decaying BM. It was assumed that only BM took part in the galaxy formation, and the HDM appears in the galaxies later. The proposed model was successfully tested on the galaxies: Milky Way, M33, NGC 2366 and IC 2574. In the present paper, we shall further investigate the HDM model, with the application to M31 (Andromeda galaxy), the system of M31 and the Milky Way, the globular clusters NGC 2419 and MGC1, the dwarf spheroidal galaxy Sculptor. Also, we shall consider the evolution of ultra-massive quiescent galaxies from $z = 2$ to 0.

1. The HDM model of the galaxy

We shall review the HDM model of the galaxy presented in Khokhlov (2018). Assume that the HDM consists of hypothetical Planck neutrinos arising in the decay of the protons at the Planck scale, $p \rightarrow e^+ 4\nu_{Pl}$ (Khokhlov, 2011c). Planck neutrino is specified as a massless particle propagating with the speed of light (Khokhlov, 2011c). Therefore, Planck neutrinos do not form a condensed structure. Assume that the galaxy is formed from the BM, and the HDM comes there later.

Consider the BM of the galaxy embedded into the HDM. The circular velocity of the test particle at the

radius r is defined by the BM mass and the HDM mass (energy) within the radius r as

$$v_c^2 = \frac{G(m_b(< r) + m_{hdm}(< r))}{r} \quad (1)$$

where G is the Newton constant, $m_b(< r)$ is the BM mass within the radius r , $m_{hdm}(< r)$ is the HDM mass within the radius r . The radial velocity of the test particle at the radius r is defined by the HDM pressure

$$v_r^2 = \frac{2Gm_{hdm}(< r)}{r}. \quad (2)$$

The energy of the test particle of the unity mass is given by

$$E = \frac{1}{2}v_r^2 + \frac{1}{2}v_c^2 - \frac{G(m_b(< r) + m_{hdm}(< r))}{r}. \quad (3)$$

The energy eq. (3) defines the motion of the test particle in the galaxy with HDM.

The distribution of the HDM is supposed to be homogeneous, with the HDM $\rho_{hdm} = const$ and the HDM mass $m_{hdm}(< r) \propto r^3$. The galaxy is divided into the inner region with the dominant BM and the outer region with the dominant HDM. The border between the regions at some radius r_0 is defined by the equality of the HDM and BM mass, $m_{hdm}(< r_0) = m_b(< r_0)$. In the inner region $r < r_0$, the energy of the test particle is negative, $E < 0$, that defines the elliptic orbit of the test particle (Landau & Lifshitz, 1960). In the outer region $r \geq r_0$, the energy of the test particle is equal zero, $E = 0$, that defines the parabolic orbit of the test particle (Landau & Lifshitz, 1960). The stability of the structure of the galaxy implies that the HDM perturbation does not exceed the BM gravitational potential. Hence, the enclosed dynamical mass is limited by the double baryonic mass enclosed. In the outer region $r \geq r_0$, the enclosed dynamical mass is the double baryonic mass enclosed, $m_{dyn}(< r) = 2m_b(< r)$.

2. Observational constraints on the model of M31

The rotation curve of M31 was under study in several works (Geehan et al., 2006; Seigar et al., 2008; Chemin et al., 2009; Corbelli et al., 2010; Tamm et al., 2012). From ~ 10 kpc to ~ 30 kpc, it is approximately flat, decreasing from ~ 250 km s $^{-1}$ to ~ 220 km s $^{-1}$. Above ~ 30 kpc, the rotation curve is decreasing (Tamm et al., 2012). The models of the rotation curve include the mass components: the bulge, the stellar disc and the DM halo. Besides, the mass of the gas is added in Chemin et al. (2009); Corbelli et al. (2010).

Consider the HDM model of M31. We need to define the radius r_0 of the border between the inner and outer

regions in M31. In Khokhlov (2018) the radius r_0 was determined through the features in the anisotropy profile in the Milky Way, in the curve of the position angle in M33, NGC 2366, in the curve of the inclination in IC 2574. Two warps of the disc in M31 can be seen from the curves of inclination and position angle (Chemin et al., 2009). The location of the second warp have been reported by several authors, using the HI data: $r > 18$ kpc (Henderson, 1979; Brinks & Burton, 1984), $r > 25$ kpc (Corbelli et al., 2010), $r > 27$ kpc (Chemin et al., 2009), $r > 28.5$ kpc (Newton & Emerson, 1977), and the optical data: $r > 20.5$ kpc (Walterbos & Kennicutt, 1988), the values are rescaled to the distance to M31, 785 kpc (McConnachie et al., 2005). Assume that the second warp of the disc in M31 exhibits the transition to the outer region. Adopt the radius of the border between the inner and outer regions in M31, $r_0 = 19$ kpc. The BM and HDM masses are equal at $r_0 = 19$ kpc.

Estimate the BM mass of M31 from the circular velocity at $r_0 = 19$ kpc. The rotation curve in Corbelli et al. (2010) gives the circular velocity, $v(r_0) = 238$ km s $^{-1}$. From this, the BM circular velocity is estimated to be $v_{bm}(r_0) = v(r_0)/\sqrt{2} = 168$ km s $^{-1}$, and the BM mass, $m_b(< r_0) = 1.25 \times 10^{11} m_\odot$. Beyond ~ 20 kpc, the fraction of the luminous mass in M31 is estimated to be $\sim 10\%$ (Ibata et al., 2005). Then, the total BM mass of M31 can be estimated as $m_b = 1.4 \times 10^{11} m_\odot$. The rotation curve in Chemin et al. (2009) gives the circular velocity, $v(r_0) = 252$ km s $^{-1}$. From this, the BM circular velocity is estimated to be $v_{bm}(r_0) = v(r_0)/\sqrt{2} = 178$ km s $^{-1}$, and the BM mass, $m_b(< r_0) = 1.4 \times 10^{11} m_\odot$. By adding $\sim 10\%$, the total BM mass of M31 is $m_b = 1.5 \times 10^{11} m_\odot$.

At $r_0 = 19$ kpc, the radial velocity is equal to the circular velocity. The radial velocity can be calculated through the radial velocity dispersion as $v_r = 2\sigma_r$. Chapman et al. (2006) reported the radial velocities of the red giant branch stars in M31 in the range 10 – 70 kpc. The radial velocity dispersion at 19 kpc is $\sigma_r = 135$ km s $^{-1}$ (Chapman et al., 2006) that gives the radial velocity, $v_r = 270$ km s $^{-1}$. Adopt the same circular velocity, $v_c = 270$ km s $^{-1}$. The BM circular velocity is estimated to be $v_{bm}(r_0) = 191$ km s $^{-1}$. This gives the BM mass, $m_b(< r_0) = 1.6 \times 10^{11} m_\odot$. By adding $\sim 10\%$, the total BM mass of M31 is $m_b = 1.8 \times 10^{11} m_\odot$. Taking the average, the BM mass within the radius $r_0 = 19$ kpc is $m_b(< 19 \text{ kpc}) = 1.45 \times 10^{11} m_\odot$, and the total BM mass of M31 is $m_b = 1.6 \times 10^{11} m_\odot$.

The observational circular velocities in the outer region of M31, $r \geq 19$ kpc, correspond to the elliptic orbit of the test particle. Hence, they are not suitable to test the HDM model wherein the test particle moves along the parabolic orbit in the outer region. The enclosed dynamical mass in the far outer region, $r \gg r_0$, can be calculated through the radial velocity. Veljanoski et al. (2014) reported the

radial velocities of the globular clusters in M31 in the range 30 – 140 kpc. The radial velocity dispersion at 80 kpc is $\sigma_r = 83 \text{ km s}^{-1}$ (Veljanoski et al., 2014) that gives the radial velocity, $v_r = 166 \text{ km s}^{-1}$. The enclosed dynamical mass can be estimated as $m_{dyn}(< 80 \text{ kpc}) \approx v_r^2 r / 2G = 2.6 \times 10^{11} m_\odot$, and the enclosed BM mass, $m_b(< 80 \text{ kpc}) \approx 1.3 \times 10^{11} m_\odot$. The radial velocity dispersion at 100 kpc is $\sigma_r = 75 \text{ km s}^{-1}$ (Veljanoski et al., 2014) that gives the radial velocity, $v_r = 150 \text{ km s}^{-1}$. The enclosed dynamical mass can be estimated as $m_{dyn}(< 100 \text{ kpc}) \approx v_r^2 r / 2G = 2.6 \times 10^{11} m_\odot$, and the enclosed BM mass, $m_b(< 100 \text{ kpc}) \approx 1.3 \times 10^{11} m_\odot$. The radial velocity dispersion at 120 kpc is $\sigma_r = 69 \text{ km s}^{-1}$ (Veljanoski et al., 2014) that gives the radial velocity, $v_r = 138 \text{ km s}^{-1}$. The enclosed dynamical mass can be estimated as $m_{dyn}(< 120 \text{ kpc}) \approx v_r^2 r / 2G = 2.65 \times 10^{11} m_\odot$, and the enclosed BM mass, $m_b(< 120 \text{ kpc}) \approx 1.3 \times 10^{11} m_\odot$.

The mass models estimate the BM mass of M31 to be $m_b = 1.04 \times 10^{11} m_\odot$ (Geehan et al., 2006), $m_b = 0.93 \times 10^{11} m_\odot$ (Seigar et al., 2008), $m_b = 0.99 \times 10^{11} m_\odot$ (Chemin et al., 2009), $m_b = 1.4 \times 10^{11} m_\odot$ (Corbelli et al., 2010), $m_b = 1.01 \times 10^{11} m_\odot$ (Tamm et al., 2012). The BM mass consists of the bulge+disc+gas mass in Chemin et al. (2009); Corbelli et al. (2010), and of the bulge+disc mass in the other works. Tamm et al. (2012) note the uncertainties in the bulge mass, $(4.4 - 6.6) \times 10^{10} m_\odot$, and in the disc mass, $(5.7 - 8.6) \times 10^{10} m_\odot$. Thus, the BM mass of M31 estimated in the HDM model is consistent with the literature data.

Estimate the HDM density from the HDM mass at $r_0 = 19 \text{ kpc}$. The HDM mass is equal to the BM mass at $r_0 = 19 \text{ kpc}$. Hence, $m_{hdm}(< 19 \text{ kpc}) = 1.45 \times 10^{11} m_\odot$ that gives the HDM density $\rho_{hdm} = 3.4 \times 10^{-25} \text{ g cm}^{-3} = 5.05 \times 10^{-3} m_\odot \text{ pc}^{-3}$. This is consistent with the value in the Milky Way, $\rho_{hdm} = 3.1 \times 10^{-25} \text{ g cm}^{-3} = 4.6 \times 10^{-3} m_\odot \text{ pc}^{-3}$ (Khokhlov, 2018) and with the local DM density at the solar position, $\rho_{dm}(R_\odot) = 0.005 - 0.01 m_\odot \text{ pc}^{-3}$ (Weber & de Boer, 2010), $\rho_{dm}(R_\odot) = 0.005 - 0.015 m_\odot \text{ pc}^{-3}$ (Read, 2014). The similar values were obtained for M33, NGC 2366, IC 2574 (Khokhlov, 2018).

3. Radial velocity of M31 toward the Milky Way

Consider the system of the Milky Way and M31 in the HDM model. We shall treat the Milky Way and M31 as points of the BM mass, $m_{b,MW} = 1.0 \times 10^{11} m_\odot$ (Khokhlov, 2018) and $m_{b,M31} = 1.6 \times 10^{11} m_\odot$, respectively. The gravitational interaction of the Milky Way and M31 is defined by the dynamical masses of the Milky Way and M31 which are twice the BM masses of the Milky Way and M31. The radial velocity of M31

toward the Milky Way is given by

$$v = \left(\frac{4Gm_{b,MW}}{R} \right)^{1/2} + \left(\frac{4Gm_{b,M31}}{R} \right)^{1/2} \quad (4)$$

where R is the distance between the Milky Way and M31. For $R = 785 \text{ kpc}$ (McConnachie et al., 2005), the radial velocity of M31 toward the Milky Way is 106 km s^{-1} . The observational value is $109.3 \pm 4.4 \text{ km s}^{-1}$ (van der Marel et al., 2012), they adopt the distance between the Milky Way and M31, $R = 770 \text{ kpc}$. Thus, the radial velocity of M31 toward the Milky Way estimated in the HDM model is consistent with the observational value.

4. Dark matter in the globular clusters

Globular clusters (GCs) pose a problem for the Λ CDM model. According to the hierarchical structure formation, the GCs form within their own DM halos (Peebles, 1984). Observations show no evidence for DM halos of GCs, e.g. (Mashchenko & Sills, 2005a). It is reasonable to think that the DM halos of GCs were stripped by the tidal field of the host galaxy, e.g. (Mashchenko & Sills, 2005b). However, there exist GCs at large distances from the centre of the host galaxy where the effect of the tidal field is negligible. NGC 2419 in our Galaxy ($\sim 90 \text{ kpc}$ from the galactic center) and MGC1 in M31 ($\sim 200 \text{ kpc}$ from the galactic center) are distant GCs with negligible tidal effects. Observations show that the DM mass in these clusters is limited by the stellar mass as $m_{DM}/m_* < 1$ (Conroy et al., 2011; Ibata et al., 2013). Although the DM is admitted in the clusters, it is not needed to explain the data.

Consider NGC 2419 and MGC1 in the HDM model. Observations show the stellar mass $m_* \sim 10^6 m_\odot$ within the radius $r \sim 250 \text{ pc}$ in both the clusters. For the HDM density $\rho_{hdm} = 5 \times 10^{-3} m_\odot \text{ pc}^{-3}$, the HDM mass within the radius $\sim 250 \text{ pc}$ is $m_{hdm}(< 250 \text{ pc}) = 3 \times 10^5 m_\odot$. Thus, the HDM content within the radius $\sim 250 \text{ pc}$ is small compared to the stellar matter. This is consistent with the observational data.

5. Dark matter in the dwarf spheroidal galaxies

Dwarf spheroidal galaxies (dSphs) exhibit the flat velocity dispersion curves which cannot be explained by the baryonic mass alone, e.g. (Walker, 2013). The velocity dispersion gives the dynamical masses which substantially exceed the stellar masses within the half-light radii, and the dynamical mass-to-light ratios are increasing toward the outskirts of the galaxies. For the Local Group dSphs, the dynamical mass-to-light

ratios within the half-light radii can be found in Collins et al. (2014), with $[M/L]_{half}$ from $\sim 10 m_{\odot}/L_{\odot}$ to $\sim 1000 m_{\odot}/L_{\odot}$, except for several outliers. Typically, the discrepancy between the dynamical and stellar masses is ascribed to the DM.

Sculptor is a typical dSph at a distance of 86 kpc from the centre of our Galaxy (McConnachie, 2012). Battaglia et al. (2008) studied the kinematics in the Sculptor for two components of RGB stars, metal rich $[Fe/H] > -1.5$ and metal poor $[Fe/H] < -1.7$. The profile of the metal rich stars in the l.o.s. velocity dispersion shows a fall off from $\sigma \sim 9 \text{ km s}^{-1}$ in the centre to $\sigma \sim 2 \text{ km s}^{-1}$ at 0.7 kpc. The profile of the metal poor stars in the l.o.s. velocity dispersion is approximately flat, $\sigma \sim 11 \text{ km s}^{-1}$, from the centre to 0.5 kpc, and then is slightly declining to 1.8 kpc.

The difference of the profiles of the metal rich and metal poor stars can be interpreted as follows. Suppose that the metal rich stars are young, and the metal poor stars are old. Assume that the declining profile of the metal rich (young) stars traces the real gravitational potential of the galaxy while the flat profile of the metal poor (old) stars is a result of evolution not related to the gravity of the galaxy. When neglecting the HDM, the gravity of the BM is balanced by the acceleration due to the velocity dispersion thus holding the stable galaxy structure. Addition of the HDM leads to the instability of the BM. Under the influence of some perturbations, the unstable BM is spreading out that results in growing of the size of the dwarf galaxy with time. The velocity dispersion is defined by the value of perturbations and cannot be used to derive the dynamical mass of the galaxy. Perturbations may be caused by the tidal forces of the host galaxy. Hammer et al. (2018) showed for a bulk of dwarf galaxies in the Milky Way that the velocity dispersions of the dwarf galaxies can be explained by the tidal forces exerted by the Milky Way.

Estimate the dynamical mass within the half-light radius of the Sculptor from the velocity dispersion of the metal rich stars. The half-light radius of the Sculptor is $r_{half} = 283 \text{ pc}$ (McConnachie, 2012). The l.o.s. velocity dispersion of the metal rich stars at 283 pc is $\sigma \sim 5 \text{ km s}^{-1}$ (Battaglia et al., 2008). The calculation gives $[m_{dyn}]_{half} = \sigma^2 r_{half} / G = 1.6 \times 10^6 m_{\odot}$.

The observed stellar mass of the Sculptor is $m_* = 2.3 \times 10^6 m_{\odot}$ (McConnachie, 2012). The stellar mass within the half-light radius is $[m_*]_{half} = 1.15 \times 10^6 m_{\odot}$. For the HDM density $\rho_{hdm} = 5 \times 10^{-3} m_{\odot} \text{ pc}^{-3}$, the HDM mass within the half-light radius is $[m_{hdm}]_{half} = 0.5 \times 10^6 m_{\odot}$. The sum of the stellar and HDM mass within the half-light radius is $[m_* + m_{hdm}]_{half} = 1.65 \times 10^6 m_{\odot}$. Thus, the dynamical mass within the half-light radius of the Sculptor derived from the kinematics of the metal rich stars is consistent with the sum of the stellar and HDM mass within the half-light radius.

6. Evolution of ultra-massive quiescent galaxies

Stockmann et al. (2020) presented an analysis of 15 ultra-massive quiescent galaxies from the COSMOS and UDS fields ($\log(m_*/m_{\odot}) \sim 11.5$) at $z \gtrsim 2$. They obtained the ratio of dynamical to stellar mass of order unity, $m_{dyn}/m_* \sim 1$. This implies the absence of DM in the galaxies at $z = 2$. A sample of early-type galaxies from the MASSIVE Survey was taken as the local reference sample.

Comparison of the galaxies from the two samples allows to study the evolution of ultra-massive quiescent galaxies from $z = 2$ to 0. The analysis of the data shows that the local galaxies have grown by a factor of 2 in stellar mass, 4 in size, with no evolution in velocity dispersion. As a result, the dynamical to stellar mass relation is doubling during the evolution from $z = 2$ to 0. When assuming the absence of DM at $z = 2$, the two times increase in the dynamical mass can be ascribed to the HDM in the local galaxies ($z = 0$). This is consistent with the HDM model which predicts the dynamical mass of the local galaxy as twice its stellar mass.

Conclusion

In a recent paper (Khokhlov, 2018), the model of the galaxy with HDM had been considered. The model was successfully tested on the galaxies: Milky Way, M33, NGC 2366 and IC 2574. In the present paper, we have continued investigation of the HDM model, addressing M31, the radial velocity of M31 toward the Milky Way, the globular clusters NGC 2419 and MGC1, the dwarf spheroidal galaxy Sculptor. Also, we have considered the evolution of ultra-massive quiescent galaxies from $z = 2$ to 0.

The galaxy structure in the HDM model is divided into the inner and outer regions at some radius where the BM mass is equal to the HDM mass (energy). The radius of the border between the regions in M31 is taken $r_0 = 19 \text{ kpc}$, corresponding to the second warp of the disc in M31.

The BM mass of M31 within $r_0 = 19 \text{ kpc}$ has been estimated from the circular velocity at $r_0 = 19 \text{ kpc}$, and the value is $m_b(< r_0) = (1.25 - 1.4) \times 10^{11} m_{\odot}$. By adding $\sim 10\%$, the total BM mass of M31 is estimated to be $m_b = (1.4 - 1.5) \times 10^{11} m_{\odot}$. Also, the BM mass of M31 within $r_0 = 19 \text{ kpc}$ has been estimated from the radial velocity dispersion of the red giant branch stars at $r_0 = 19 \text{ kpc}$, and the value is $m_b(< r_0) = 1.6 \times 10^{11} m_{\odot}$. By adding $\sim 10\%$, the total BM mass of M31 is estimated to be $m_b = 1.8 \times 10^{11} m_{\odot}$.

The BM mass of M31 has been estimated from the radial velocities of the globular clusters in the range 80 – 120 kpc. The BM mass of M31 is estimated to be

$m_b = 1.3 \times 10^{11} m_\odot$. The BM mass of M31 estimated at $r_0 = 19$ kpc and at 80 – 120 kpc is consistent with the literature data for the bulge mass, $(4.4 - 6.6) \times 10^{10} m_\odot$, and the disc mass, $(5.7 - 8.6) \times 10^{10} m_\odot$ (Tamm et al., 2012).

The HDM density in M31 has been estimated. The value obtained is $\rho_{hdm} = 3.4 \times 10^{-25} \text{ g cm}^{-3} = 5.05 \times 10^{-3} m_\odot \text{ pc}^{-3}$. This is consistent with the values in the Milky Way, M33, NGC 2366, IC 2574 (Khokhlov, 2018) and with the local DM density at the solar position (Weber & de Boer, 2010; Read, 2014).

The gravitational interaction of the Milky Way and M31 has been considered in the HDM model. The radial velocity of M31 toward the Milky Way is estimated to be 106 km s^{-1} which is consistent with the observational value, $109.3 \pm 4.4 \text{ km s}^{-1}$ (van der Marel et al., 2012).

We have considered distant GCs NGC 2419 in our Galaxy and MGC1 in M31. The HDM mass within the radius ~ 250 pc is estimated to be $m_{hdm}(< 250 \text{ pc}) = 3 \times 10^5 m_\odot$ compared to the stellar mass $m_* \sim 10^6 m_\odot$ in both the clusters. The small DM content in these clusters is consistent with the observational data.

We have considered the problem of dark matter in the dwarf spheroidal galaxies in the HDM model, based on the kinematics of RGB stars in the Sculptor presented in Battaglia et al. (2008). We have assumed that the declining profile of the metal rich (young) RGB stars traces the real gravitational potential of the galaxy while the flat profile of the metal poor (old) RGB stars does not. It is a result of evolution caused by the instability of the BM due to the presence of the HDM and the influence of some perturbations. The dynamical mass within the half-light radius of the Sculptor derived from the kinematics of the metal rich RGB stars, $[m_{dyn}]_{half} = 1.6 \times 10^6 m_\odot$, is consistent with the sum of the stellar and HDM mass within the half-light radius, $[m_* + m_{hdm}]_{half} = 1.65 \times 10^6 m_\odot$.

We have considered the evolution of ultra-massive quiescent galaxies from $z = 2$ to 0, based on the analysis of the sample of 15 galaxies from the COSMOS and UDS fields presented in Stockmann et al. (2020). The dynamical to stellar mass relation evolves from $m_{dyn}/m_* \sim 1$ at $z = 2$ to $m_{dyn}/m_* \sim 2$ at $z = 0$ that is consistent with the HDM model.

References

- Ade P.A.R., Aghanim N., Arnaud M. et al.: 2016, *A&A*, **594**, A13
- Battaglia G., Helmi A., Tolstoy E., Irwin M., Hill V., Jablonka P.: 2008, *ApJ*, **681**, L13
- Battaner E., Florido E.: 2000, *Fund. Cosmic Phys.*, **21**, 1
- Bertone G., Tait T.M.P.: 2018, *Nature*, **562**, 51
- Brinks E., Burton W.B.: 1984, *A&A*, **141**, 195
- Bowman J.D., Rogers A.E.E., Monsalve R.A., Mozdzen T.J., Mahesh N.: 2018, *Nature*, **555**, 67
- Casey C.M., Zavala J.A., Araven M. et al.: 2019, *ApJ*, **887**, 55
- Chapman S.C., Ibata R., Lewis G.F. et al.: 2006, *ApJ*, **653**, 255
- Chemin L., Carignan C., Foster T.: 2009, *ApJ*, **705**, 1395
- Collins M.L.M., Chapman S.C., Rich R.M. et al.: 2014, *ApJ*, **783**, 7
- Conroy C., Loeb A., Spergel D.N.: 2011, *ApJ*, **741**, 72
- Corbelli E., Lorenzoni S., Walterbos R., Braun R., Thilker D.: 2010, *A&A*, **511**, A89
- Demiański M., Doroshkevich A.: 2017, preprint (arXiv:1701.03474)
- Famaey B., McGuagh S.: 2012, *Living Reviews in Relativity*, **15**, 10
- Geehan J.J., Fardal M.A., Babul A., Guhathakurta P.: 2006, *MNRAS*, **366**, 996
- Genzel R., Förster Schreiber N.M., Übler H. et al.: 2017, *Nature*, **543**, 397
- Hammer F., Yang Y., Arenou F. et al.: 2018, *ApJ*, **860**, 76
- Henderson A.P.: 1979, *A&A*, **75**, 311
- Ibata R., Chapman S., Ferguson A.M.N., Lewis G., Irwin M., Tanvir N.: 2005, *ApJ*, **634**, 287
- Ibata R., Nipoti C., Sollima A., Bellazzini M., Chapman S.C., Dalessandro E.: 2013, *MNRAS*, **428**, 3648
- Khokhlov D.L.: 2011a, *Ap&SS*, **333**, 209
- Khokhlov D.L.: 2011b, *Ap&SS*, **335**, 577
- Khokhlov D.L.: 2011c, *Open Astron. J.*, **4 SI 1**, 151
- Khokhlov D.L.: 2013, *Ap&SS*, **343**, 787
- Khokhlov D.L.: 2014, *Phys. Lett. B*, **729**, 1
- Khokhlov D.L.: 2015, *Ap&SS*, **360**, 27
- Khokhlov D.L.: 2017, *Int. J. Mod. Phys. Appl.*, **4**, 8
- Khokhlov D.L.: 2018, *Open Astronomy*, **27**, 294
- Kroupa P.: 2012, *PASA*, **29**, 395
- Kroupa P.: 2015, *Can. J. Phys.*, **93**, 169
- Landau L., Lifshitz Ye.: 1960, *Mechanics*, Pergamon Press, Oxford
- Lang P., Förster Schreiber N.M., Genzel R. et al.: 2017, *ApJ*, **840**, 92
- Liu J., Chen X., Ji X.: 2017, *Nat. Phys.*, **13**, 212
- López-Corredoira M.: 2017, *Found. Phys.*, **47**, 711
- McConnachie A.W., Irwin M.J., Ferguson R.A., Ibata R.A., Lewis G.F., Tanvir N.: 2005, *MNRAS*, **356**, 979
- McConnachie A.W.: 2012, *AJ*, **144**, 4
- McGaugh S.S.: 2018, *Phys. Rev. Lett.*, **121**, 081305
- Marrodán Undagoitia T., Rauch L.: 2016, *J. Phys. G: Nucl. Part. Phys.*, **43**, 013001
- Mashchenko S., Sills A.: 2005a, *ApJ*, **619**, 243
- Mashchenko S., Sills A.: 2005b, *ApJ*, **619**, 258
- Newton K., Emerson D.T.: 1977, *MNRAS*, **181**, 573
- Ostriker J.P., Steinhardt P.J.: 1995, *Nature*, **377**, 600
- Peebles P.J.E.: 1984, *ApJ*, **277**, 470
- Read J.I.: 2014, *J. Phys. G: Nucl. Part. Phys.*, **41**, 063101
- Reyes R., Mandelbaum R., Seljak U. et al.: 2010, *Nature*, **464**, 256

- Seigar M.S., Barth A.J., Bullock J.S.: 2008, *MNRAS*, **389**, 1911
- Stockmann M., Toft S., Gallazzi A. et al.: 2020, *ApJ*, **888**, 4
- Tamm A., Tempel E., Tenjes P., Tihhonova O., Tuvikene T.: 2012, *A&A*, **546**, A4
- Tanaka M., Valentino F., Toft S. et al.: 2019, *ApJL*, **885**, L34
- Trimble V.: 1987, *ARA&A*, **25**, 425
- van der Marel R.P., Fardal M., Besla G. et al.: 2012, *ApJ*, **753**, 8
- Veljanoski J., Mackey A.D., Ferguson A.M.N. et al.: 2014, *MNRAS*, **442**, 2929
- Walker M.: 2013, In: Oswalt T.D., Gilmore G. (eds) *Planets, Stars and Stellar Systems*, Springer, Dordrecht
- Walterbos R., Kennicutt R.: 1988, *A&A*, **198**, 61
- Weber M., de Boer W.: 2010, *A&A*, **509**, 25
- Weinberg D.H., Bullock J.S., Governato F., de Naray R.K., Peter A.H.G.: 2015, *Proc. Nat. Acad. Sci.*, **112**, 12249