Growth of black holes and dark matter accretion

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Abstract. We investigate the distribution of fermion dark matter in the Milky Way galaxy and find that dark matter could gravitationally condensate in a degenerate core of mass of $3 \times 10^6 M_\odot$ embedded in a dark matter halo of $3 \times 10^{12} M_\odot$ with a size of about 200 kpc. We then show that the galactic black hole of mass of about $3 \times 10^6 M_\odot$ might have grown from a stellar seed black hole by mainly accreting dark matter from the compact degenerate fermion core. This leads to a lower limit on the mass of the fermion dark matter of about $(6-10)$ keV. It is then argued that the constrained dark matter could be a sterile neutrino.

1. Introduction

There is mounting evidence that most galaxies harbor supermassive black holes (BHs) of masses from $10^{6.5}$ to $10^{10} M_\odot$. The typical case is of the Galactic black hole of mass $(3.1 \pm 0.9) \times 10^6 M_\odot$ [1, 2], which is associated with the radio source Sagittarius A*. It has also been established that the mass of the central black hole is tightly correlated with the velocity dispersion $\sigma$ of its host bulge, where it is found that $M_{BH} \sim \sigma^{4-5}$ [3]. In spite of the vast and tantalizing work on black hole physics, their genesis and evolution are not well understood. Moreover, the particle nature of dark matter (DM) remains a mystery. Two scenarios have been discussed in modeling the growth of BHs. One is that BHs grow out of a low mass ‘seed’ BH through accretion of dark matter and baryonic matter [4], and another one is that BHs grow by merging [5]. In this work, we explore the first scenario and consider a seed BH in the mass range from 5 to 10 $M_\odot$ which might have evolved in BH binaries [6]. We will then constrain the mass of the dark matter particle by establishing the relationship between the growth of the black hole in galactic centers and the dark matter accretion.

2. Main equations

We will assume that the dark matter particles are fermions that are described by the Fermi-Dirac distribution

$$f(E) = \begin{cases} \frac{g_f}{8\pi^3 k^3} \exp \left( \frac{E-\mu}{kT} \right) + 1 & , \quad E < E_c \\ 0 & , \quad E > E_c \end{cases} \tag{1}$$

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Figure 1. The mass density $\rho$ and the mass enclosed $M_F$ are plotted as a function of the radius $r$ in the upper and lower panels, respectively. The velocity dispersion $\sigma$ is varied as shown on the plot. In the outer edge of the DM halo, the density $\rho$ scales as $1/r^2$. The mass of fermions used in this plot is $m_f c^2 \approx 12\text{keV}$ and the size of the fermion ball is about $10^{-2}\text{pc}$. The data points for the mass within 50 kpc and 200 kpc are taken from [8].

where $E$ is the DM particle total energy, $\mu$ is the chemical potential and $T$ is the temperature. The constant $C$ is chosen so that the distribution function vanishes at the cutoff energy $E = E_c[7]$. The mass density $\rho(r)$ and the gravitational potential $\Phi(r)$ are given by

$$\rho(r) = m_f \int_0^{E_c} 4\pi f(p)p^2 dp(E), \quad \Delta\Phi(r) = 4\pi G\rho(r).$$

(2)

We then integrate equation (2) to get the density and the total mass of DM [7] as shown in Fig. 1, for solutions with a $3 \times 10^{12} M_\odot$ mass and a radius of 200 kpc. The assumption of a degenerate fermion ball of $3 \times 10^6 M_\odot$ at the center of a DM halo of $3 \times 10^{12} M_\odot$ with a density scaling as $1/r^2$ in the outer edge of the halo constrains the fermion mass to

$$m_f c^2 \gtrsim 12\text{keV}. \quad (3)$$

Near the center of the DM halo, fermions become degenerate and can form gravitationally stable objects called fermion balls. The physics of fermion balls has been studied in a series of papers [7, 9, 10, 11, 12, 13, 14]. The mass and radius of non relativistic degenerate fermi balls scale as

$$M_F R_F^3 = 27.836 M_\odot \left( \frac{15\text{keV}}{m_f c^2} \right)^8 \left( \frac{2}{g_f} \right)^2 \text{pc}^3. \quad (4)$$
Figure 2. The mass - radius relation for degenerate fermion balls. The total mass scales as $M_F \sim R_F^{-3} m_f^{-8}$. In the same plot, we have shown the BH line and two horizontal lines for the lower and upper limits for the total mass of the degenerate Fermi balls.

The relativistic fermi ball can have a maximum mass, also called the Oppenheimer-Volkoff limit $M_{OV} \sim m_{pl}^3 m_f^{-2}$, where $m_{pl} = (\hbar c/G)^{1/2}$ is the Planck’s mass. One could use the virial theorem to express the rotational velocity $v_{rot}^2 = \alpha GM_F/R_F$, where $\alpha$ is chosen so that for $M_F = 3 \times 10^6 M_\odot$, $v_{rot} = 220$ km/s, we get $m_f = 12$ keV/c^2 and this leads to the following relation

$$m_f \approx 12\text{keV}/c^2 \left( \frac{v_{rot}}{220\text{km/s}} \right)^{3/4} \left( \frac{M_{bh}}{3 \times 10^6 M_\odot} \right)^{-1/2} \left( \frac{2}{g_f} \right)^{1/4},$$

where $M_F$ has been replaced by the BH mass $M_{bh}$ as it assumed here that the black hole will eat the whole fermion ball. Using the relation between the velocity dispersion and the rotational velocity for an isothermal sphere, i.e. $v_{rot} = \sqrt{2\sigma}$ and using $\sigma = 100 \pm 20$ km/s [3] and the mass of the black hole of $M_{BH} \sim (2.2 - 4) \times 10^6 M_\odot$ [1], then we obtain the lower limit on the mass of the DM particle

$$m_f \gtrsim (6 - 10) \text{keV}/c^2.$$  

The above limits lie within the range obtained by Kusenko [15]from the study of the origin of the high velocities up to 1000 km/s of pulsars. Moreover, similar limits were also obtained from X-ray background studies [16]. Recently, Biermann & Kusenko [17] showed that the decay of such a sterile neutrino could help initiate star formation in the early Universe.

In Fig. 2 we plot the mass - radius relation for fermion balls for different values of the fermion mass $m_f$.

3. Black hole growth

The black hole growth law for Eddington baryonic matter accretion is given by

$$M_{BH}(t) = M_{BH}^i \exp \left( \frac{t - t^i}{\tau_{EDD}} \right),$$

where $\tau_{EDD} = 10^{7.69}$ years $\times \left( \frac{M}{10^4 M_\odot} \right)$ is the relevant timescale and $\epsilon$ being the efficiency.

In Fig. 3 we illustrate the growth of a seed black hole from Eddington baryonic matter accretion. The mass of the seed black hole is varied from 5 to $10^4 M_\odot$ and the seed formation
Figure 3. The growth of the black hole mass from Eddington baryonic matter accretion. The curves 1 to 3 have different seed BHs masses of $5 \times 10^3$ and $10^4 M_\odot$. The accretion starting time $t_i$ is also varied.

time is changed from $t = 0$ to $t = 2 \times 10^8$ years. From this plot, we learn that in order to fit the data point of mass $M \sim 3 \times 10^9 M_\odot$, the mass of seed black hole should be greater than $10^3 M_\odot$ and the accretion onto the black hole cannot start later than $z \sim 17$. In order to grow a stellar seed black hole to $10^{3-4} M_\odot$, we use DM accretion to boost its initial growth. In order to study the accretion of DM onto the BH\[7\], we will assume that dark matter is degenerate near the center of the DM halo and we will then assume a spherical accretion onto the BH. Under the above assumptions, the density of dark matter near the BH scales as

$$n = \frac{g_f}{6\pi^2} \frac{m_f^3}{h^2} \left( \frac{2GM_{\text{BH}}}{r} \right)^{3/2}. \tag{8}$$

The BH accretion rate is given by

$$\dot{M}_{\text{BH}} = 1.03 \times 10^{-7} g_f \left( \frac{m_f c^2}{15 \text{ keV}} \right)^4 \left( \frac{M_{\text{BH}}}{M_\odot} \right)^2 M_\odot \text{yr}^{-1}, \tag{9}$$

which is integrated to yield the following growth law

$$M_{\text{BH}} = M_\odot \left[ \frac{M_\odot}{M_{\text{BH}}^i} - \frac{1}{t_0} (t - t^i) \right]^{-1}, \tag{10}$$

where $M_{\text{BH}}^i$ is the mass of the seed BH at the starting time $t^i$ of accretion, and $t_0 = 9.7 \times 10^6 \text{yr} \left( \frac{15 \text{keV}}{m_f c^2} \right)^4 g_f^{-1}$ is the corresponding timescale. In order to fit the Galactic center black hole of $M \sim 3 \times 10^6 M_\odot$ from only DM accretion, the mass of the fermions should be $m_f \approx 1.4 \text{ keV}/c^2$. Thus, the degeneracy pressure of fermions near the black hole allows to capture a huge amount of DM in a short time. In Fig. 4, we plot the growth of a seed black hole that fully consumes the whole fermion ball of mass of $M \sim 3 \times 10^6 M_\odot$ and then grows by Eddington limited baryonic accretion to a supermassive black hole of $M \sim 3 \times 10^9 M_\odot$ at redshift $z \sim 6.41$. We find that DM accretion could be started at $z \sim 10$ which corresponds to the reionisation time from most recent WMAP observations. A fermion mass of $m_f \approx 10 \text{keV}/c^2$ is used in this plot.
Figure 4. The growth of a seed black mass from DM and Eddington limited baryonic matter accretion.

4. Conclusion
We find that in order to grow the Galactic center black hole of $3 \times 10^6 M_\odot$ and the supermassive black hole in SDSS quasars of $3 \times 10^9 M_\odot$, the DM mass is constrained to a lower limit of about $(6-10)$ keV. DM accretion boosts the growth of stellar seed black holes to $10^{3-4} M_\odot$ and a further growth to $10^{6.5-9.5} M_\odot$ is achieved through Eddington baryonic matter accretion. Such DM could be interpreted as a sterile neutrino [15, 16, 17] and it has been shown that its decay could speed up the cooling of the gas and the early star formation [18], which, in turn lead to an early reionisation. A key prediction of this sterile neutrino mass will be the detection of an X-ray line at half the sterile neutrino by XMM-Newton and CHANDRA satellites.

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