# Supermassive Black Holes from Bose-Einstein Condensate Dark Matter

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We study the origin of the supermassive black holes (SMBH) harbored in most of the galactic centers. The standard analysis of the ordinary accretion process of baryon gas cannot explain the mature SMBH which have already existed at the redshift$6-7$. Therefore, we propose the possibility that the quantum condensed coherent dark matter collapses into SMBH at redshift $10-20$. We use the Gross-Pitaevskii equation for the macroscopic wave function with the Gaussian approximation at the stage of the tidal torque acquisition. The mass ratio of the SMBH and the dark halo $M_{SMBH}/M_{halo}$ turns out to be about $10^{-4}$. In the case of axion dark matter that has weak attractive force, many smaller black holes of mass range $10^{2-5}M_{\odot}$ are formed as well as the central SMBH. The mass function of them is also discussed.

## 1. Introduction

Most of the galaxies harbor supermassive black holes (SMBH) in their center. We study the origin of such black holes. The standard analysis of the ordinary accretion process of baryon particles cannot explain many SMBH which have already existed at the redshift 6-7[1]. Therefore, we would like to propose a different scenario for the SMBH formation which is deeply related to the dark matter (DM) as quantum condensate (Bose-Einstein Condensation, BEC)[2]. We explore the possibility that such coherent condensation collapses into SMBH at redshift $10-20$. We assume light boson DM such as Axions since they can easily form BEC and they collapse to form black holes.

We use the Gross-Pitaevskii equation for the macroscopic wave function with the Gaussian approximation in the general anisotropic collapse. We proceed, for the moment, with this semi-analytic method, though the numerical general relativity would be needed for the detailed process of the black hole formation.

The BEC collapse naturally takes place if we neglect the angular momentum and most of the body collapses into a black hole. On the other hand, if we consider the full effect of the angular momentum, no black hole would be formed. Both of these are quite different from the observations. A SMBH should form surrounded by the huge amount of dark halo. In order to get this separation into SMBH and the dark halo, we have to go back to the much earlier stage when the galaxy is acquiring their angular momentum through the tidal torque mechanism. We thus consider the time-dependent DM density as well as angular momentum. We need to get the mass ratio of the SMBH and the dark halo $M_{SMBH}/M_{darkhalo}$.

If we further specify the condensed DM is the Axion, which has very weak attractive force, the effective potential would be very different from the non-interacting DM condensate. Furthermore, in this Axion case, many smaller black holes would also be formed on the outskirts of the galaxy. The mass function of them is needed.

We are ready to proceed to the calculations in the following sections.

## 2. SMBH formation from Bose-Einstein Condensation

We use the Gross-Pitaevskii equation

$$i\hbar \frac{\partial \psi(t,x)}{\partial t} = \left(-\frac{\hbar^2}{2m}\Delta + m\phi + g|\psi|^2\right)\psi \tag{1}$$

for the macroscopic wave function $\psi(t,x)$ and the Poisson equation $\Delta\phi = 4\pi G m |\psi|^2$. In order to make the semi-analytic calculations possible, we use the Gaussian approximation [3],

$$\psi(t,x) = N e^{-r^2/(2\sigma(t))^2 + ir^2\alpha(t)},\ \phi(t,x) = N e^{-r^2/(2\tau(t))^2} \tag{2}$$

where $N$ is the number density of the boson particles. We roughly estimate the black hole formation when the portion of the DM enters inside the Schwarzschild radius.

### 2.1. *isotropic collapse*

The Lagrangian that yields the GP equation is

$$\begin{aligned} L = (\mathrm{i}\hbar/2)\left(\psi^\dagger\dot{\psi} - \dot{\psi}^\dagger\psi\right) - \left(\hbar^2/2m\right)\nabla\psi^\dagger\nabla\psi - (g/2)\left(\psi^\dagger\psi\right)^2 \\ - (1/8\pi G)\nabla\phi\nabla\phi - m\phi\psi^\dagger\psi. \end{aligned} \tag{3}$$

Integrating this over the entire space, we have the effective Lagrangian for the relevant variables,

$$\begin{aligned} L = {} & 1/16(-(2\sqrt{2}gN^2)/(\pi^{3/2}\sigma(t)^3) - (12nn\hbar^2)/(m\sigma(t)^2) - (48nn\hbar^2\alpha(t)^2\sigma(t)^2)/m \\ & + (32\sqrt{2}nn\mu(t))/(\sigma(t)^2(2/\sigma(t)^2 + 1/\tau(t)^2)^{3/2})) \\ & - (3\sqrt{\pi}\mu(t)^2\tau(t))/G - 24N\hbar\,\sigma(t)^2\dot{\alpha}(t)). \end{aligned} \tag{4}$$

The derived set of ordinary differential equations can be easily analyzed. It turns out, for the free case $g = 0$, that the effective potential has a minimum that yields the black hole formation condition: $M_r > M_{kaup}$, where $M_r$ is the total mass inside the radius $r$ and $M_{kaup} = 0.633\hbar c/(Gm)$. Most of the mass turns into a black hole.

### 2.2. *anisotropic collapse*

It is easy to extend the above method to the anisotropic BEC collapse, simply introducing the independent dispersions for each spatial directions $\sigma_i(t)$, $i = 1, 2, 3$. Further, it would be interesting to introduce a dissipative collapse. Usually, the BEC decay into the normal gas is expressed by an extra term $i\gamma\psi(t,x)$ on the left-hand side of Eq.(1). However, this term yields a constant trivial normalization term in the Lagrangian, as expected. Therefore we first trick this term as if the time derivative exists and then, after integration, remove it at the level of equation of motion. We thus found the shrinking bounce solution in general (Fig.1). This may leave some trace, such as the random concentric shell structure, in the later evolution of the galaxy.

Unfortunately, at the first collapse, most of the DM turns into SMBH and almost no dark halo is left if we neglect the angular momentum. This is apparently not allowed by observations.

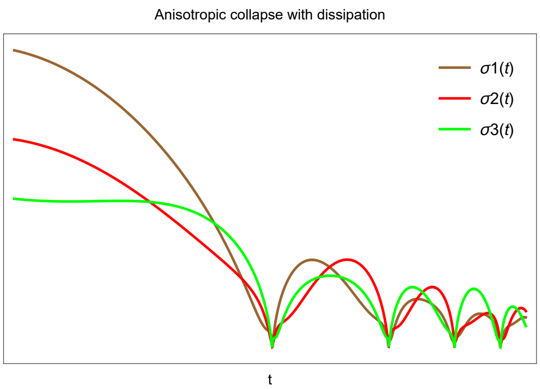


Fig. 1. Time evolution of a general bouncing solution of the anisotropic BEC collapse. A typical solution of the set of equations derived from the effective Lagrangian Eq.(4) with dissipation.

### 2.3. *angular momentum*

The angular momentum would be important to get the coexistence of SMBH and the surrounding dark halo. The total angular momentum of the cosmological objects (Fig.2) are given by $J = \kappa \frac{G}{c} M^2, \quad \kappa \approx 10^4$. We assume the original DM density profile as $\rho = \rho_0 / \left(1 + (r/r_0)^2\right)$, and calculate which portion of it can turn into a black hole. Due to the strong angular momentum, no black hole is formed at all and only the dark halo remains in this case.

Therefore we have to go back to the much earlier stage when the galaxy is acquiring their angular momentum through the tidal torque mechanism[4]. This mechanism suggests a linear time evolution of the angular momentum: $\Omega(t) = \alpha t$. The black hole formation condition becomes

$$\mu \leq 1, \ \mu(t, r) \equiv \frac{cJ}{GM^2} = \frac{cr\Omega(t)}{12\pi\beta(t)G\rho_0 r_0^2}, \tag{5}$$

where $\beta \propto t^{2/3}$ is the density evolution factor.

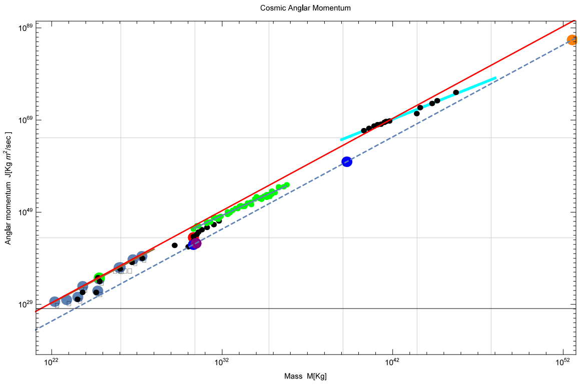


Fig. 2. The angular momentum of the various cosmic objects. They roughly scale as $J = \kappa \frac{G}{c} M^2, \quad \kappa \approx 10^4$.

### 2.4. *before the full acquisition of the angular momentum*

Using the results of the numerical results[4], we set our time dependence of the angular momentum and the DM density by the time scale 3 giga-year.

Setting the black hole formation condition as $t_{ff} = t$, $\mu(t, r) = 1$, we find the BH formation time and the mass. If we use typical values $M_{tot} = 10^{11} M_{\odot}$, $R_{tot} = 10^3 pc$, and $\alpha = (2 \times 10^5 m/sec)/R_{tot}/3 \times 10^9 year$, we obtain $r = 146pc$, $t = 9.6 \times 10^6 year$, $M_{tot} = 3.2 \times 10^7 M_{\odot}$. The mass ratio of the SMBH and the dark halo becomes $M_{SMBH}/M_{halo} \approx 3 \times 10^{-4}$. More generally, this ratio is a mildly increasing function of the total mass $M_{SMBH}/M_{halo} = 2 \times 10^{-6} (M/M_{\odot})^{1/5}$ .

## 3. Axion case

We further consider the axion DM[5]. We found that Axion attractive force, despite being very weak, just cancels the effective potential barrier formed by the angular momentum at the scale $r_{hb} \approx \sqrt{a_s/Gm^3}\hbar$, where $m$ is the boson mass, $a_s$ is the scattering length (Fig.3). This scale is several parsecs and the time scale for the SMBH formation turns out to be about $10^8$ years, well within the observational constraints. Furthermore, in this axion case, many smaller black holes, of mass range $10^{2-5} M_{\odot}$, are formed as well on the outskirts of the galaxy. The mass function of them has a power law distribution and one dominant contribution from SMBH (Fig.4). A galaxy turns out to be filled with plenty of black holes of various masses in this case.

## 4. Conclusions

We have proposed the possibility that the BEC DM forms SMBH in the galactic center. The angular momentum turns out to control the whole dynamics of the SMBH formation. The appropriate SMBH formation, as well as dark halo, is pos-

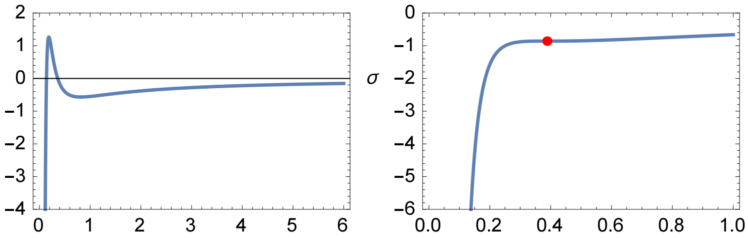


Fig. 3. The effective potential for the Axion DM. (left)A bottom and a hill appear in general. (right)They merge at a special scale and generates SMBH.

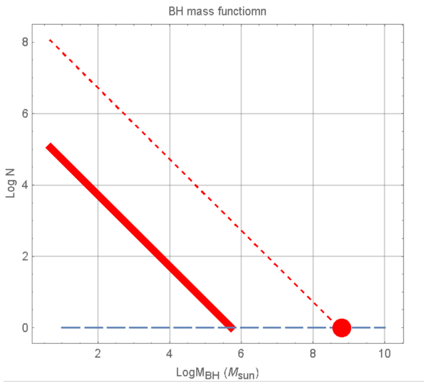


Fig. 4. The mass functions of SMBH. (broken line) shows a case for $a_S = 10^{-29}$meter, while (solid line) shows for $a_S = 10^{-29}$meter. This case represents more realistic estimate considering the dynamical merging of the central black holes within the time scale $t_d = 6.8 \times 10^7 year$.

sible in the tension between the time developing density and angular momentum in the early Universe.

## References


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