BEC dark matter can explain collisions of galaxy clusters

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(Dated: May 27, 2008)

We suggest that the dark matter model based on Bose Einstein condensate or scalar field can resolve the apparently contradictory behaviors of dark matter in the Abell 520 and the Bullet cluster. During a collision of two galaxies in the cluster, if initial kinetic energy of the galaxies is large enough, two dark matter halos pass each other in a soliton-like way as observed in the Bullet cluster. If not, the halos merge due to the tiny repulsive interaction among dark matter particles as observed in the Abell 520. This idea can also explain the origin of the dark galaxy and the galaxy without dark matter.

PACS numbers: 98.62.Gq, 95.35.+d, 98.80.Cq

Dark matter (DM) constituting about 24 percent of the mass of the universe is one of the big puzzles in modern physics and cosmology [1, 2]. According to numerical simulations, while the cold dark matter (CDM) with the cosmological constant model (i.e., ΛCDM) is remarkably successful in explaining the formation of the structure larger than galaxies, it seems to encounter problems on the scale of galaxy or sub-galactic structure. ΛCDM model usually predict the cusped central density and too many sub-halos, and too small angular momentum of the galaxies, which are, arguably, in contradiction with observations [3, 4, 5]. On the other hand the models based on Bose Einstein condensate (BEC) DM or scalar field dark matter (SFDM) of ultra-light scalar particles well explain the observed rotation curves of galaxies [6, 7] and solve the above problems of CDM models [8, 9, 10, 11, 12].

The mystery deepened further after recent observations of massive intergalactic collisions in two clusters of galaxy; the bullet cluster (1E0657-56) [13] and the Abell 520 [14]. Galaxy clusters are composed of three main components behaving differently during collision; galaxies composed of stars, hot gas between the galaxies, and DM [15]. According to the prevailing theories, DM composed of very weakly interacting particles moves only under the influence of gravity and is presumed to be collisionless. Since the stars are sparse, they can be also treated as effectively collisionless particles. Thus, when two clusters of galaxy collide, we expect stars and dark matter to move together even during a violent collision, while intergalactic gases self-interact electromagnetically and lag behind the other matters at the collision center. The distribution of DM can be inferred by optical telescopes using the gravitational lensing effect, while that of the hot gases by X-ray telescopes like Chandra. The observation of the Bullet cluster [13] using these telescopes seems to be consistent with this expectation, and to support the collisionless CDM theory. On the contrary, in the Abell 520, galaxies (stars) were stripped away from the central dense core of the cluster, where gases and DM are left. This indicates DM as well as gases is collisional, which is puzzling. The collision separating DM from visible matter is also recently observed [16] in the ring-like structure in the galaxy cluster Cl 0024+17 [17]. It is very hard to explain the contradictory behaviors of DM in these clusters in the context of the standard CDM model or even with the modified gravity theories.

In this paper, we suggest that this contradiction can be also readily resolved in BEC/SFDM model. Furthermore, our theory can explain the origin of the dark galaxy and the galaxy without dark matter.

First, let us briefly review BEC/SFDM model. In 1992, to explain the observed galactic rotation curves, Sin [18, 19] suggested that galactic halos are astronomical objects in BEC of ultra light DM particles such as pseudo Nambu-Goldstone boson (PNGB) which have Compton wavelength \( \lambda_{\text{comp}} = h/mc \sim 10 \text{ pc} \), i.e. \( m \sim 10^{-24} \text{eV} \). In this model the halos are like gigantic atoms where cold boson DM particles are condensed in a single macroscopic wave function and the quantum mechanical uncertainty principle provides a force against self-gravitational collapse. In the same year one of the author (Lee) and Koh [20, 21] generalized Sin’s BEC model by considering a repulsive self-interaction among DM particles, in the context of field theory and the general relativity. (See [22] for a review.) In this model a BEC DM halo is a gi-
ant boson star (boson halo) surrounding a visible matter of galaxy and is described by a coherent complex scalar field $\phi$ having a typical action

$$S = \int \sqrt{-g} d^4 x \left[ -\frac{R}{16\pi G} - \frac{g^{\mu\nu}}{2} \phi^*_{,\mu} \phi_{,\nu} - U(\phi) \right]$$

(1)

with a repulsive potential $U(\phi) = m^2 |\phi|^2 + \frac{\lambda}{4} |\phi|^4$. It was found that \cite{21} there are constraints $\lambda \left( \frac{M_p}{m} \right)^2 \lesssim 10^{50}$, and $10^{-24} eV \lesssim m \lesssim 10^3 eV$, where $M_p$ is the Planck mass. We will call two models as BEC/SFDM model \cite{22}.

In this model, for $\lambda = 0$, the formation of DM structures smaller than the Compton wavelength is suppressed by the uncertainty principle and this property could alleviate the aforementioned problems of the $\Lambda$CDM model. For $\lambda \neq 0$ the minimum scale becomes $\Lambda^{1/2}/m$, where a dimensionless coupling term $\Lambda = \lambda M_p^2/4\pi m^2$ is very large even for very small $\lambda$ due to the smallness of $m$ relative to $M_p$. Thus, the self-interaction effect is non-negligible, if $\lambda \neq 0$. Despite of their tiny mass, BEC DM particles act as CDM particles \cite{26} for the cosmological structure formation, because their velocity dispersion is very small. Thus, BEC/SFDM is an ideal alternative to the standard CDM playing a role of CDM at the scale larger than a galaxy, and at the same time suppressing sub-galactic structures. Later similar ideas were rediscovered by many authors \cite{8, 11, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40}. (See \cite{41} for a review.)

Now, we investigate in detail the idea that the repulsive self-interaction between BEC DM particles separate stars from DM during the collision between galaxies or cluster of galaxies. To do this we need equations describing the motion of DM halos.

With a spherical symmetric metric $ds^2 = -B(r)dt^2 + A(r)dr^2 + r^2d\Omega^2$, the equation of motion for the scalar field becomes \cite{12}

$$\sigma'' + \left[ \frac{2}{x} + \frac{B'}{2B} - \frac{A'}{2A} \right] \sigma' + A[(\frac{\Omega^2}{B} - 1)\sigma - \Lambda \sigma^3] = 0,$$

(2)

where $x = mr, \Omega = x m$ and $\phi(x, t) = (4\pi G)^{-\frac{1}{4}} e^{-i\omega t}$. Since the collision velocity is non-relativistic ($v \sim 10^{-3}c$) we can use a Newtonian approximation, in which Einstein equation for this system reduces to

$$\nabla^2 V = 4\pi G T_{00},$$

(3)

where the energy momentum tensor is

$$T_{\mu\nu} = \frac{1}{2} \left( \partial_{\mu} \phi^* \partial_{\nu} \phi + \partial_{\nu} \phi \partial_{\mu} \phi^* \right) - g_{\mu\nu} \left( \frac{1}{2} \partial^\mu \phi^* \partial^\nu \phi + U(\phi) \right)$$

(4)

and $V$ is the Newtonian gravitational potential. The Newtonian limit of Eq. (2) and the dimensionless form of Eq. (3) can be simply written as

$$\begin{cases} \nabla^2 V = \sigma'' + \frac{\Lambda \sigma^3}{4} \\ \nabla^2 \sigma = 2V \sigma \end{cases},$$

(5)

For $\Lambda = 0$ these equations are equivalent to the non-linear Schrödinger equation of Sin’s model \cite{43}.

Since galaxy clusters are composed of about 50 ~ 1000 individual galaxies each surrounded by galactic DM halos, we can treat the collision of galaxy clusters as massive collisions of individual galaxies and expect our analysis below on the collision of two galaxies can be applied to the collision of clusters too. Since DM is the major component of a galaxy, one can assume that the collision dynamics of two galaxies is mainly governed by that of DM, and baryonic matter (stars and gases) plays a passive role during the collision.

Choi and others \cite{44, 45, 46, 47} numerically studied the head-on collision of the boson stars described by Eq. (6). It was shown that there are two regimes with very different dynamical properties: solitonic and merging regimes. If two colliding boson stars (galactic DM halos in our theory) have large enough kinetic energy, then the halos pass each other like solitons during the collision. We argue that this is just what happened to galactic DM halos in the Bullet cluster. In this case the total energy $E$ which is composed of kinetic energy $K$, the gravitational potential energy $W$ and the repulsion energy $I$ between DM particles (determined by the term $\lambda |\phi|^4$) should be positive, i.e., $E = K + W + I > 0$. In other
FIG. 2: (Color online) The same diagram in Fig. 1 with smaller initial kinetic energy. In this case the repulsion between DM particles plays a significant role. Two DM halos merge to form a larger DM halo, which can be identified as a dark galaxy, while stars keep going outward and could form galaxies without DM later. This could be what happened to galaxies in the Abell 520.

words, initial relative velocity of colliding galaxies should be large enough to overcome the self-gravitational attraction and repulsion force between DM particles. Fig. 1. shows the schematic diagram representing collision of two galaxies. (We ignored the hot intergalactic gases which mainly exist between the galaxies. This does not change our conclusion significantly.) If the initial kinetic energy is large enough, DM and the stars in each galaxy move together even after the collision like solitons. This could be what happened to galaxies in the Abell 520.

On the contrary, if the kinetic energy is small so that $E = K + W + I < 0$, they merge to form a single large DM halos as shown in Fig. 2. This could be what happened to DM halos in the Abell 520. Since our model treat galactic DM halos as boson stars, two different regimes of the boson star collision explain the observed contradictory behaviors of DM in two clusters. The DM halos in the Abell 520 did not have an enough velocity and was even slowed by the repulsion, while the stars, having the same initial velocity, managed to escape the potential well because they are collisionless. This situation can happen only when the collision velocity is within an appropriate range. We expect usually the collision velocity of other colliding clusters or galaxies is too slow or fast to separate efficiently stars from DM halos. This explain why stars usually trace DM. The large DM halo left at the center can be identified as a dark galaxy like VIRGOHI21, while two star groups going outward could form two independent galaxies without DM later, argu-ably, like M94 (NGC 4736). The origin of these galaxies was a mystery so far. Thus, our theory explain not only the mystery of galaxy clusters but also the origin of the dark galaxy and the galaxy without DM. This scenario also implies that there are many dark galaxies at the center of the Abell 520 and galaxies without or very small DM at outermost region of the cluster.

For the scenario to be plausible the initial collision velocity of galaxies in the Bullet cluster should be much larger than that of the Abell 520. Interestingly, according to the observations, the Abell 520 actually had much small collision velocity than the Bullet cluster. The estimated collision velocity of the clusters inferred from the X-ray temperature of the gases are about 4700 km/s and 1000 km/s for the Bullet cluster and the Abell 520, respectively. This observational data support our theory.

Our theory provides a possibility of determining the mass $m$ and self-coupling $\lambda$ of DM particles using the data from the collision of galaxy clusters. Recently, it is also suggested that the observed size evolution of very massive galaxies and the early compact galaxies can be also well explained in BEC/SFDM model. In conclusion, since BEC/SFDM model have passed many tests and explain many mysteries of galaxies and galaxy clusters which seems to be hardly possible in other DM theories, this model can be a promising alternative to the usual CDM model.

ACKNOWLEDGMENTS

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