Effective gravitational interactions of dark matter axions†

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Recent developments of observational studies have constrained the properties of dark matter significantly, yet its origin is unknown. The axion is one of leading candidates of dark matter, which emerges out of the solution to the strong CP problem in QCD. One important property of dark matter axions is that it is produced non-thermally in the early universe and described as a coherently oscillating scalar field. Since this coherent oscillation is interpreted as highly condensed Bose gas, dark matter axions may form Bose-Einstein condensate (BEC) in the universe.

The formation of axion BEC dark matter, if it occurred, leads to some interesting phenomenological implications. It was argued that the angular momentum distribution of infalling dark matter particles affects the structure of inner caustics (the over dense region produced by the fall of dark matter surrounding the galaxy).[1] If the particles have a net overall rotation, which is predicted by axion BEC dark matter,[2] the inner caustics become ring-like structure. Since such a structure is not predicted in another leading candidates such as the weakly interacting massive particle (WIMP) dark matter scenario, there is a possibility to distinguish dark matter candidates observationally.

The crucial point for the above scenario is that the thermalization occurs due to gravitational interactions. Gravitational thermalization of dark matter axions was first discussed in detail in[3]. They claimed that the formation of axion BEC occurs in the condensed regime, where the interaction rate is large compared to the typical energy exchanged in the interaction. The thermalization process in the condensed regime was further studied by two of the present authors.[4] By representing coherently oscillating axions as coherent states, they evaluated the gravitational self interaction rate Γ of axions within the flat space Newtonian approximation. They showed that the interaction rate Γ exceeds the expansion rate H of the universe when the temperature of the universe is $T \simeq$ keV. This result might imply that the gravitational self interactions affect the evolution of dark matter axions and their occupation number changes rapidly at that time.

In the BEC formation process, however, low energy modes, i.e. superhorizon modes, will play an central role and such a subhorizon mode is sensitive to the cosmic expansion. Therefore, it is not clear whether we can apply the previous result[3,4] based on the flat space Newtonian approximation. In this report, to clarify this issue, we reanalyze the interaction rate Γ of the axion gravitational self interactions taking into account effects of the cosmic expansion based on general relativity. In the general relativistic framework, the gravitational interaction is mediated by metric perturbations $\delta g_{\mu\nu}$. The kinetic and mass terms of the axion ϕ generically contain cubic interactions schematically in the form $\delta g_{\mu\nu}\phi^2$ and these cubic interactions induce the following effective quartic interactions (Fig. 1):

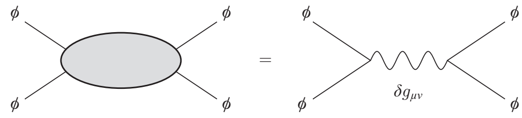

Fig. 1. Effective gravitational interaction of axions.

$$H_{\rm eff} \simeq -\sum_{\mathbf{k}_i,\,\sum \mathbf{k}_i=0} \frac{2\pi G m^2}{a^3}\frac{f(x)}{(\delta p)^2} a^\dagger_{\mathbf{k}_1} a^\dagger_{\mathbf{k}_2} a_{\mathbf{k}_3} a_{\mathbf{k}_4}\,, \quad (1)$$

with the function $f(x)$ being

$$f(x) = 1 - \cos x - x\sin x \simeq \begin{cases} 1 & (x \gg 1)\,, \\ -\frac{1}{2}x^2 & (x \ll 1)\,. \end{cases} \quad (2)$$

Here $\delta p = |\mathbf{k}_1 - \mathbf{k}_3|/a$ is the physical exchange momentum and $x = c_s \delta p/H$ represents how it is inside the (sound) horizon. We can see that the gravitational interaction is well approximated by Newton gravity when the exchange momentum is inside the horizon $x \gtrsim 1$, while it is suppressed for $x \lesssim 1$. An important point is that even if some of external momenta are superhorizon, the interaction is not suppressed unless the exchange momentum is superhorizon.

Applying the obtained effective gravitational interaction, we showed that the interaction rate Γ exceeds the expansion rate H of the universe when the temperature of the universe is $T \simeq$ keV, as in the previous studies[3,4]. However, it should be noted that the thermalization process of axion BEC has been not fully understood yet in the previous studies[3,4] and it is still nontrivial whether the thermalization occurs at that time (see e.g.[5] for recent arguments). Further studies in this direction will be required.

† Condensed from the article in arXiv:1310.0167

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