Snowmass2021 - Letter of Interest

Bose-Einstein Condensates made of Multiple Interacting Scalars

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Thematic Areas: (check all that apply □/■)
■ (TF09) Astro-particle physics & cosmology
■ (CF2) Dark Matter: Wavelike
■ (CF3) Dark Matter: Cosmic Probes
■ (CF7) Cosmic Probes of Fundamental Physics

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Abstract:

The last a few years has seen a rising interest in ultra-light bosonic fields as dark matter candidates. The collective behavior of Bose-Einstein Condensate (BEC) leads to emergent phenomena that are not obvious at the Lagrangian level. Due to numerical challenges, past studies have mostly focused on single scalar BEC systems, multiple scalar BEC systems with negligible non-gravitational interactions, or analytically for multi-scalar BEC systems with self-interactions. We propose a systematic study of the properties of BECs made of multiple interacting scalars, including both non-gravitational self-interactions and interactions between the scalars. To verify the analytical ansatz used in previous studies, independent numerical analysis is needed. To investigate whether such objects are gravitationally stable, radial perturbations and numerical temporal evolution need to be performed. To facilitate future analysis, we propose to draw a clean mapping between the BEC properties and properties at the Lagrangian level. Upon building up this knowledge, we can study the probes of such BEC objects. *At stellar scales*, gravitational wave and electromagnetic signals from such objects can be powerful probes for detection. Their unique mass profile distinguishes such systems from ordinary compact objects and also compact objects formed of a single scalar field. *At galactic scales*, BEC from multi-scalar systems can be constrained with rotation curves. Their difference from single scalar BEC may have important implications for the core-cusp problem.

Motivation:

There is compelling evidence for the existence of dark matter (DM) [1, 2]. With direct detection and collider searches putting stronger constraints in the mass range above GeV [3–8], and sub-GeV range [4, 9], there emerges an increasing urgency in understanding realistic models of non-thermally produced light dark matter and their possible signals.

On the other hand, while the QCD axion was originally motivated by the strong CP problem [10, 11], string theory predicts a vast landscape of axion-like particles (ALPs) [12–15] with mass across multiple orders of magnitude and rich phenomenology. Studies of sub-eV (pseudo-)scalars as DM candidates have yielded interesting signals and novel proposals for direct detection experiments [16–20].

In particular, due to its bosonic nature, ultra-light bosonic dark matter can exhibit collective behaviors at the macroscopic level that are not obvious at the Lagrangian level. It has been observed and well understood in condensed matter physics that for bosons there exists a unique phase, the Bose-Einstein Condensate (BEC) phase, once the ensemble is cooled down below the critical temperature. Given the abundance of the DM population, this translates the requirement of the occupancy number $n > (mv)^3$ to an upper bound of the scalar mass, $m <$ eV [21]. The maximal mass of the BEC object can be crudely estimated as [22] $M \lesssim M_{Pl}^2/m$ when the self-interaction is negligible. This singles out two scales of particular interest to us, stellar scale BEC from $m \sim 10^{-10}$ eV, and galactic scale BEC from $m \sim 10^{-22}$ eV.

While some studies were dedicated to understand the mapping between properties at the Lagrangian level and the behavior of the BEC system such as the mass and density profile [21, 23–35], the effect of extra scalars in a self-gravitating system due to both gravitational and non-gravitational interactions remains largely under-explored [36, 37]. Given that feeble repulsive self-interactions can lead to drastic change of the mass profile on the macroscopic level [22, 29], it is highly likely that interactions between different scalars will have an important impact and perhaps unique imprint in the BEC system.

Implication at Stellar Scale: At the stellar scale, a light scalar of mass $m \sim 10^{-10}$ eV allows the formation of solar mass exotic compact objects (ECO's, alternatively referred to as boson stars or dark stars.) The formation can be enhanced due to the presence of a repulsive self-interaction in the scalar potential, or compromised by an attractive self-interaction [23, 29, 38]. In the case of a binary merger made of ECO's, this can in turn affect both the GW luminosity and the frequency evolution during the inspiral phase of the merger. While the chirp mass shows up in the leading order of the GW signal, $M_c = (M_1 M_2)^{3/5}/(M_1 + M_2)^{1/5} \sim M$, with M_1, M_2 the mass of the two mergers, the GW frequency at the innermost stable circular orbit (ISCO) is determined by both the mass and compactness, $f_{ISCO} \propto (M_1 + M_2)^{1/2}/R^{3/2} \sim C^{3/2}/M$, where we assume $M_1 \approx M_2 \approx M$, R is the radius of each object, and $C = G_N M/R$ the compactness of each object. The strength of the non-gravitational interactions and more importantly the specific form of the interaction leaves imprints as a change in the GW signal as shown in [29]. With the presence of extra scalars and interactions between multiple scalars, the features in GW is expected to be richer.

Alternative to the ECO mergers setup, if such ECO's are captured by ordinary objects such as super-massive black holes at the galactic center, they form an extreme-mass-ratio-inspiral (EMRI) system. Due to great homogeneity of the gravitational field at the surface of a super-massive black hole compared to stellar scale compact objects, the captured ECO can inspiral for a long time before gets disrupted by the tidal force as shown in [39]. As a result, EMRI setup allows less dense objects, such as ECO's formed out of $-\phi^4$ potentials, to be detectible. This extends both probable types and parameter range of ALPs through the formation of BEC. With the mass profile being affected due to the non-gravitational interactions and multiple scalars [37], we expect this can leave distinguishable signals at GW detectors.

Implication at Galactic Scale: For a fixed compactness, the BEC object scales inversely proportional to the component particle. For a scalar of mass $m \sim 10^{-22}$ eV, if the velocity is taken to be the virial velocity corresponding to the BEC core, this gives a de Broglie wavelength $\lambda = 1/mv \sim \mathcal{O}(1) - \mathcal{O}(10)$ kpc. The BEC mass corresponding to it is of order $M \sim 10^9$ $\mathrm{M}_\odot$. This was originally motivated in [40, 41] to relieve the core-cusp problem [42] although the problem can also be addressed by other processes such as baryonic processes [43–45], self-interacting dark matter (SIDM) [46, 47].

At the galactic scale, the main constraints of ultra-light dark matter comes from suppression of matter power spectrum. This can be probed by Lyamn-α [48–51], stellar streams [52,53], and gravitationally lensed quasars [53,54]. On the other hand, it is known that non-gravitational self-interaction can affect the growth of density contrast [21,55]. Therefore, a thorough study of the cosmic perturbation with the presence of self-interaction is called for.

Another main constraint on ultra-light dark matter roots from the fact that the BEC system has a very unique density profile. When fitted against galaxies at different scales, it lacks degrees of freedom to reproduce the scaling behavior in the data [24,56–58]. With single scalar BEC system, the density and the radius of the BEC object scales as $R \sim 1/\rho^{1/4}$ for non-interacting scalars [33,34], and $R \sim const.$ with repulsive ϕ^4 interactions [24,29]. There have been recent attempts to address this problem using multiple scalars [36] where there is no self-interaction, and [37] where the authors apply the variational methods as an approximation and observe interesting results. We propose a systematic study employing rigorous numerical methods be performed to pinpoint the needed degree of freedom to address the proper scaling behavior as shown in [24] in the context of multiple scalars.

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