Dark matter refers to mass that cannot be observed via electromagnetic radiation. It was first discovered in the 1930s when scientists noticed flat galactic rotation curves, in which the orbital velocities of galactic bodies far from the center of the galaxy do not decrease as Newtonian gravity predicts. Further observations of rotation curves, along with evidence collected through techniques such as gravitational lensing, have suggested dark matter must be over five times as abundant as luminous matter. Despite our universe's wealth of dark matter, we know little about its nature. Dark matter is observed to interact gravitationally, but very weakly otherwise. Specifically, dark matter has neither been observed to emit photons, nor interact electromagnetically or through nuclear forces.

Axions were proposed in the 1970s to solve the strong CP problem, a disparity between observed and expected symmetries, in quantum chromodynamics (QCD), a subsection of particle physics concerning the strong force [1]. Axions are electrically neutral elementary particles with zero spin and, if they exist, primarily interact gravitationally but very weakly otherwise. Axion theory allows for various classes of axions with differing mass ranges. Individual axions are long-living, and at low temperatures will condense in the same energy state and clump together, forming a Bose-Einstein Condensate (BEC). These characteristics make axions excellent dark matter candidates. On a cosmological scale, axion condensates could be gravitationally bound. When comprised of QCD axions these gravitationally bound BECs are called "axion stars". However, different classes of ultra-light axions (ULAs), prompted by theories beyond the standard model, could form similar structures the size of observed ultra-compact dwarf galaxies (UCDs). ULAs are a type of fuzzy dark matter (FDM) [2].

Axion BECs can be described using semi-classical dynamics, by finding expressions for kinetic and self-gravitational energy, as well as energy contributions from particles' self-interactions. In my past work [3,4], I analyzed the stability of axion stars, which form metastable configurations approximately the size (~200 km) and mass ($\sim 10^{19}$ kg) of an asteroid. It was proposed that axion stars with mass larger than this collapse to black holes. But by improving the typical approximations applied to self-interaction terms, I discovered that collapsing axion stars become stable again at a radius of about 7 m, and thus do not form black holes. In a dilute state, the self-interaction forces are dominantly attractive, and in previous studies the repulsive forces were neglected. However, at radii smaller than ~25 m, the repulsive self-interactions are more significant than the attractive, and are no longer negligible.

My analysis of an axion star's sensitivity to changes in self- or external gravitational forces revealed a dense state with distinct self-interaction behaviors. Just as there exists a critical mass for QCD axion stars, above which the axion star is no longer stable, upper bounds on mass also exist for FDM condensates. Following the formalism outlined in [3], I found the FDM condensate has a metastable configuration with mass $\sim 10^{9}\ M_{\odot}$ and radius ~100 lightyears. If the metastable state is sufficiently perturbed, the condensate becomes unstable and will collapse to a dense state with radius ~1 lightyear within 10,000 years (note this radius is 100 times larger than the Schwarzschild radius for this mass, indicating collapse to a black hole is extremely rare). In the dense states, condensates are subject to decay processes which result in the emission of relativistic free particles.

In [5] I altered an axion star's energy expression to incorporate an external gravitational force. This was meant to simulate collision between axion stars and other astrophysical sources. I found that a collision with a sufficiently dense external object (such as a sun-like star) could destabilize an otherwise stable axion star, causing it to collapse to a configuration with a much smaller radius. Likewise, the energy of a FDM condensate changes when it encounters the central bulge of a galaxy. In [6] we find the gravity of the bulge's baryonic matter does not perturb the structure enough to catalyze collapse, but a galaxy's central black hole has an appreciable gravitational effect. I determined that metastable FDM condensates which meet black holes of mass ~10^7-10^9 $M_\odot$ could collapse to the dense state described above. This connection to observable phenomena (dark matter dense dwarf galaxies with central black holes) will test the viability of ULAs as dark matter candidates, and constrain the percentage of UCD mass which could be in FDM.

Since galaxies rotate, it is natural to assume their dark matter does, as well. Much like an excited electron orbital, particles with non-zero angular momenta could condense into a BEC whose wavefunction has angular dependence. Therefore, I am analyzing the stability of a non-spherical dark matter condensate. Rotating BECs have also been shown to induce vortices, which further influence the structure's energy and stability. Using the framework constructed in my past projects, I will address the stable configurations and collapse of rotating dark matter BECs comprised of various dark matter candidates, with induced vortices, and in the presence of external gravitational sources. Similarly, I am exploring the possibility of a fragmented BEC in which a fraction of the particles resides in a ground state and the remainder exists in an excited state. With this unique configuration comes the potential of transition between the two states, and an exchange particle to facilitate the interaction.

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