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QUANTUM TUNNELING OF FUZZY DARK MATTER OUT OF SATELLITE GALAXIES

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ABSTRACT

I show that the tidal gravitational potential of the Milky-Way galaxy removes fuzzy dark matter from its satellite dwarf galaxies through quantum-mechanical tunneling. The existence of dark matter in satellites rules-out ultra-light axions (ULAs) as dark matter with a particle mass, $m_a < 2 \times 10^{-21}$ eV. This limit exceeds the canonical mass range proposed as a solution to the small-scale challenges of the cold-dark-matter paradigm.

1. INTRODUCTION

The axion explains the lack of observed CP violation in quantum chromodynamics and is also an attractive dark matter candidate (Peccei & Quinn 1977; Weinberg 1978; Wilczek 1978). Ultra-light axions (ULAs) with masses $\sim 10^{-22}$ eV, also known as fuzzy dark matter (Hu et al. 2000; Hui et al. 2017; Visinelli & Vagnozzi 2019; Rogers & Peiris 2021), are of particular interest in relieving small-scale challenges to the cold dark matter paradigm, stemming from discrepancies between observations and simulations of galaxies (Bullock & Boylan-Kolchin 2017).

2. METHOD

Dwarf galaxies (DG) in the halo of the Milky-Way galaxy are subject to stripping by the gravitational tidal force (Fattahi et al. 2018; Gajda & Łokas 2016; Łokas 2020; Genina et al. 2022; Errani et al. 2022). To leading order, the tidal force scales in proportion to the distance from the DG center, r, implying a tidal potential that scales as r^2. This modifies the binding gravitational potential of an isolated DG, $\phi(r)$. Along the axis connecting the two galaxies, it yields a net potential,

$$V(r) = m_a \left[\phi(r) - \sigma^2 \left(\frac{r}{r_t}\right)^2\right], \tag{1}$$

where σ is the characteristic 3D velocity dispersion of the DG and r_t is the tidal radius. Classically, dark matter particles at $r > r_t$ are stripped from the DG. But quantum-mechnical tunneling allows particles which are classically-bound to leak through the gravitational potential barrier and escape from $r < r_t$ as a result of the extended tail of their wavefunction. This constitutes a new source for evaporation of dark matter particles with a small mass, such as ULAs.

The characteristic escape timescale of ULAs from $V(r)$ due to quantum-mechanical tunneling is,

$$T_{\rm esc} \sim \left(\frac{r_t}{\sigma}\right) \exp\left\{-\frac{r_t}{\lambda_a}\right\}, \tag{2}$$

and

$$\lambda_a = \frac{\hbar}{2\sqrt{m_a|\langle\phi\rangle|}}, \tag{3}$$

with the virial theorem implying that the average kinetic energy of the bound particles is roughly half of their average gravitational binding energy, namely $\langle\phi\rangle \sim -\sigma^2$, and so

$$\lambda_a = \left[\frac{1\ \text{kpc}}{(m_a/10^{-22}\ \text{eV})(\sigma/10\ \text{km s}^{-1})}\right]. \tag{4}$$

3. RESULTS

Given that some dark-matter-rich DGs in the Milky-Way halo have $r_t \lesssim 0.5$ kpc, $\sigma \lesssim 5$ km s^{-1} (Łokas et al. 2011; Gajda & Łokas 2016; Łokas 2020; Genina et al. 2022; Errani et al. 2022), and $(r_t/\sigma) \lesssim 10^8$ yr, their possession of dark matter over a Hubble time implies $T_{\rm esc} \gtrsim 10^{10}$ yr and therefore $m_a \gtrsim 2 \times 10^{-21}$ eV, based on equations (1-4).

This new constraint based on inevitable escape resulting from quantum-mechanical tunneling, rules out the preferred mass range for ULAs as dark matter.

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