Part II Astrophysics Essay 2021

Observational constraints on Fuzzy Dark Matter

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The dark matter problem has been around for almost 100 years: we do not know the nature of 84 percent of matter in the Universe, yet it is thought to govern cosmic structure and hold galaxies and clusters together. Observations on scales larger than a few megaparsecs (Mpc) show the behaviour of dark matter is collision-less. However, on small scales at and below the size of dwarf galaxies (a few kiloparsecs, kpc) dark matter is not well constrained (Gilman et al., 2019), allowing for many plausible theories with exotic small-scale physics and particle masses spanning over 30 orders of magnitude (e.g., Hu, Barkana & Gruzinov, 2000; Viel et al., 2013; Ferreira, 2020).

Ultra-light scalar field dark matter (also known as FDM) is a recent, physically-motivated dark matter model (e.g., such scalar fields are naturally present in the framework of string theory, Arvanitaki et al., 2010) that also addresses the standard cold dark matter (CDM) paradigm's small-scale challenges (Bullock & Boylan-Kolchin, 2017; Hui et al., 2017).

Due to the small mass of FDM particles their de-Broglie (mass-dependent) scale is of order of few kpc, meaning that the particles do not cluster on smaller scales. As a result, formation of small cosmological structures is affected: the matter density field is smoothed, quantum interference patterns are seen in filaments, there is a lack of small dark matter halos (in which first stars and galaxies would form in CDM), profiles of larger dark matter halos are diffused in the centres which form solitonic cores, a feature that is inherited by the distributions of gas and stars (Mocz et al., 2019, Mocz et al. 2020). An additional appeal of FDM is that it aims to solve low-redshift small-scale controversies present in the CDM including `cusp-core', `too-big-to-fail', and other dwarf statistics problems (Bullock & Boylan-Kolchin, 2017), although most of these issues may be resolved by baryonic feedback (Lazar et al., 2020).

The goal of this project is to review observational signature and constraints of FDM. For example, a FDM particle mass of $m = 10^{-22}$ eV does an excellent job at describing the structure of dwarf spheroidals such as Sculptor and Fornax
(Marsh & Pop, 2015). Stellar motions infer large, low-density cored dark matter halos, which are difficult to form in CDM but easy in FDM. However, FDM with such a particle mass does face moderate tension with the Lyman-alpha forest: a $m = 10^{-22}$ eV particle mass predicts too little structure at $z = 5$ on Mpc scales compared to observations (Irsic et al., 2017; Nori et al., 2019).

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