Scalar field dark matter as an alternative explanation for the polar orbits of satellite galaxies

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In recent years the Scalar Field Dark Matter (SFDM), also called ultralight bosonic dark matter, has received considerable attention due to the number of problems it might help to solve. Among these we find the cusp-core problem and the abundance of small structures of the standard Cold Dark Matter (CDM) model. In this letter we show that mixed state solutions of the low energy and weak gravitational field limit of field equations, interpreted as galactic halo density profiles, could explain the anisotropic concentration of satellite galaxies observed in the Milky Way, M31 and Centaurus A, where satellites seem to concentrate more towards the poles of the galaxies instead of following randomly distributed trajectories. For this we assume a mixed state configuration containing the monopolar and the first dipolar contributions.

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The standard model of cosmology ΛCDM assumes dark matter is made of particles that interact only gravitationally. The advances on the knowledge of structure formation at large scales, the distribution of dark matter and its comparison with the observed distribution of structures are in great degree due to CDM simulations [1–3]. These simulations reveal that a bottom-up hierarchical structure formation model holds and that galactic and cluster structures clump to end with a self-similar shape [1, 4].

However, there are observations that are still puzzling to understand in the CDM model [5]. These include the well-known cusp-core problem [6] and the excess of substructure abundance [7–8]. More recently, it has been suggested that satellite galaxies around the Milky Way (MW) accumulate near the galactic poles in the Vast Polar Structure (VPOS) [9] (see also Fig. 6 in [10]). The motion of satellite galaxies around M31 also seems to be far from isotropic [11, 12]. In contrast, CDM simulations predict that satellite hosted by the Milky Way rarely display the observed coherence of satellite positions and orbits [13].

Among the 50 satellites in the Local Group, 43 are contained in four different planes [10, 14], which is inconsistent with the isotropy predicted by simulations based on CDM. Some possible explanations within the CDM frame are still plausible. For instance, that there are more satellites outside of the VPOS that are still too faint to be detected. Other possibilities to explain the plane of satellites is that interactions between gas and radiation might affect the isotropy of the final distribution of satellites; or that the Milky Way and M31 are atypical galaxies in which this unexpected coherent distribution of dwarfs happens. According to [15], if the orbits of satellite galaxies in the VPOS are integrated backwards in time they should disperse away, which would suggest that the VOPS is unstable and the anisotropic satellite distribution is temporary. Nevertheless, recently it has been reported that a set of 31 satellites in the constellation of Centaurus interacts gravitationally with the elliptic galaxy Centaurus A and displays a similar anisotropic alignment [16]. The probability of finding such anisotropic satellite distribution in CDM simulations is less than 0.5% [16]. Moreover, considering the fact that there are now three galaxies (Cen A, Milky Way and M31) of at least two different types, all displaying this anisotropy, suggests perhaps the need of a different origin to the anisotropic satellite distributions.

One possible mechanism to drive break the isotropy of satellites could come from the scalar field dark matter (SFDM) model. This alternative model to CDM started at the end of the last century (see for example [17–18]). The first systematic study of this model began in [19], since then, this same model has appeared under various names, like Fuzzy Dark Matter [20], Quintessential Dark Matter [21], Wave Dark Matter [22] and more recently as ultra-light Dark Matter [23]. The main idea of the model assumes the dark matter is an ultralight spin-0
boson such that its associated de Broglie wavelength will be of galactic scales, leading to quantum-like phenomena at the scale of galaxies and larger. The first time the cosmology of this model was analysed was in [24], here the ultralight mass of the boson in the SFDM model was established to be of order \( \mu \sim 10^{-22} \text{eV}/c^2 \). With this mass, the model mimics the behavior of ΛCDM model at cosmological scales, having the same mass power spectrum and the CMB spectrum as in ΛCDM [24, 25].

The first essential difference with ΛCDM was that the SFDM model has a natural cut-off of the mass power spectrum at small scales, which would be more consistent with the estimated amount of satellites unlike ΛCDM which predicts a higher power at those scales [24]. The SFDM model could also provide an alternative explanation to the formation of super massive black holes at high redshift [26]. Another main difference is the central density distribution in SFDM halos. As shown in previous works [27-30], SFDM halos have inner flat density profiles (cores) instead of cuspy density profiles as in ΛCDM. Later on, in [31] numerical simulations with gas containing a SFDM halo show appropriate rotation curves for LSB galaxies, in [32] the spiral arms were generated resembling real galaxies and [33] show that dwarf spheroidal galaxies are also well modelled. Recent cosmological simulations of the first galaxies in SFDM [34-36] reveal early-forming cores in the dark matter, gas and stellar components.

In the present letter, we explore the possibility of higher energy configurations of the scalar field mixed with the ground state. As the universe expands, the SFDM cools down homogeneously, i.e., the bosons forming the SFDM go to the ground state. Nevertheless, primordial fluctuations provoke that the SFDM collides until the condensation appears, forming Bose-Einstein condensates in gravitational equilibrium which would form halos of galaxies. This collapse naturally causes a decrease of the local volume containing the SFDM, thus the temperature of the bosons forming the SFDM halos increases. This implies that some of the bosons go to the excited states and others remain in the ground state, this leads to the possibility of halos in mixed energy configurations which we will consider in this work.

If a halo is described by a mixed configuration of scalar field states, there could be a preferential direction where the mass concentration is higher, which could influence trajectories of structures within the halo and produce an anisotropic distribution of mass, which could eventually explain the coherent motion of satellite galaxies in the MW, Andromeda and Centaurus A. It has been argued that the probability that the CDM paradigm explains the satellites behaviour in simulations is less than 0.5% [9], but now we know at least three galaxies (the first three we observe, in fact) with this behaviour. In the present work, we study the trajectories of test particles orbiting an axially symmetric SFDM configuration, which are found to be long-living, revealing that the anisotropy in the orbits emerges as discussed above, without fine tuning or exotic explanations, the anisotropy being completely a natural consequence of the mass distribution of the configuration.

The bosonic nature of this candidate allows the Bose-Einstein condensation with a critical temperature of order \( T_c \sim 1/\mu^{5/3} \sim \text{TeV} \) for the typical ultralight value of \( \mu \sim 10^{-22} \text{eV}/c^2 \). Structure formation simulations under this paradigm confirm that at large scales the behavior is equivalent to that of CDM while small scale structures are suppressed, as shown theoretically based on cosmological perturbation theory [24]. Surviving structures show the expected central density cores [30, 38] resulting from the Heisenberg uncertainty principle preventing cusps at galactic scales.

We show that the quantum-like properties of the scalar field model could offer a novel explanation to the anisotropic distribution of satellites in a halo which could source the observed satellite planes in the MW, M31 and Cen A.

**The model.** In order to explain the anisotropic distribution of satellites we first assume the gravitational potential of the host-galaxy halo is dominated by dark matter, whereas satellites are assumed to behave as test particles orbiting around the halo. Second, we assume the low energy and weak field regimes to hold, which is valid in the galactic scale regime. Third, under these conditions the resulting scalar field is the order parameter of the Gross-Pitaevskii-Poisson system that rules the dynamics of a condensate of bosons in coherent states \( \Psi_{nlm} \).

\[
i\dot{\Psi}_{nlm} = -\frac{\hbar^2}{2\mu} \nabla^2 \Psi_{nlm} + V \Psi_{nlm}, \quad \nabla^2 V = \sum_{nlm} |\Psi_{nlm}|^2
\]

where \( \mu \) is the boson mass. We search for stationary solutions of mixed state wave functions of this system of equations. For this we assume the wave function has the following shape in spherical coordinates

\[
\Psi_{nlm}(r, \theta, \varphi) = \sqrt{\frac{4\pi}{\rho\lambda}} e^{-i\gamma_{nlm}t} \psi_{nlm}(r) Y_{lm} (\theta, \varphi)
\]

where \( \gamma_{nlm} \) is an eigen-frequency obtained from a well posed eigenvalue problem as described in [39], where \( m = 1, 2, ..., l = 1, 2, ..., n - 1 \) and \( m = -l + 1, ..., -1, l \). We find stationary solutions with the spherical and first dipolar contributions that resemble the atom like structure first envisioned in [40]. That is, we solve for the combination of states \( \Psi_{100} \) together with \( \Psi_{210} \). In Fig. 1 we show the projected density profile of this axially symmetric mixed state, the simulated configuration has a mass ratio between states \( M_{100}/M_{210} = 0.78 \).

**Trajectories of test particles.** The motion of dwarf galaxies is assumed to follow trajectories of test particles within the gravitational potential \( V \) that is solution of Eq. (1) for the mixed-state host halo. The trajectory equations are

\[
\ddot{r} = \frac{r^2}{\rho^3} - \frac{\partial V}{\partial \rho}; \quad \ddot{z} = -\frac{\partial V}{\partial z}
\]
FIG. 1. Projection of the total SFDM halo density mixed state configuration $|\Psi_{100}|^2 + |\Psi_{210}|^2$ on the $x-z$ plane. While the ground state is spherically symmetric and is confined at the center of the halo, the observed dipole shape comes from the angular dependence of the excited state $\Psi_{210}$. The eigen frequencies for the ground state and the excited state resulting from the solution of the eigenvalue problem are $\gamma_{100} = 1.8$ and $\gamma_{210} = 1.4$, respectively.

with $l = \rho^2 \dot{\phi}$ the angular momentum per unit mass, which is a constant of motion.

We then integrate numerically in time equations (3) assuming $\rho = \rho(t)$ and $z = z(t)$, with the parameter of the orbit $l\mu/c = 10^{-1}$. In order to show that the mixed state configuration makes the satellites distribution inhomogeneous and anisotropic we place an initial distribution of 50 test particles with random positions inside a sphere of dimensionless radius $R = 2$ with the initial conditions $\dot{\rho}(0) = \dot{z}(0) = 0$. They start to orbit around the atom-like halo in a large variety of non-closed and not necessarily elliptical-like orbits. After several orbital periods the test particle distribution stops being isotropically distributed and particles cluster along the polar axis as shown in Fig. 2. Notably, this behavior is observed independently of the projected plane, the initial trajectories are modified by the background SFDM halo potential to end preferentially within the peanut-shaped halo region.

The resulting test particle distribution is in contrast with the case of CDM simulations where the particles off the galaxy plane stay randomly distributed in the halo, in our atom-like halo, most of the particles redistribute in the zone close to $\theta = \pi/6$ and $\theta = 5\pi/6$. This is due to the angular dependence of the dipolar contribution to the mixed state solution, giving the projected peanut-like shape in Fig. 2.

We have shown that trajectories of test particles prefer planes out of the equatorial plane, we have checked that this happens for a number of initial conditions for the test particles. We now show this multistate configuration is long-living. For this we solve the fully time-dependent equations (4) with initial condition corresponding to the stationary solution found by solving the eigenvalue problem for (2) using a multistate generalization of the full 3-D code that solves the Gross-Pitaevskii-Poisson system [41]. It is found that this configuration oscillates around a virialized state and is long-lived. In Fig. 3 we show the Fourier Transform of the maximum of the individual wave functions $\Psi_{100}$ and $\Psi_{210}$ that define our halo. The peak frequencies indicate the evolution is consistent with the frequencies found by solving the stationary configuration. We also show the density of the two states oscillate without being destroyed.

Our results show that the quantum character of the SFDM model allows the construction of halo configurations that resemble an atom-like structure. In this configuration particles close enough to the center are influenced by the spherical component, whereas particles far from the center are influenced by the dipolar distribution that determine the redistribution of test particle trajectories, deviating from the initial isotropic distribution.

Since these configurations naturally break the isotropy of the orbiting satellites, it could provide an explanation of the accumulation of trajectories on particular planes in systems like our Milky Way. The explanation of this distribution has been a great challenge for other dark mat-
FIG. 3. Top: Fourier transform of the maximum of the real part of the ground state $\Psi_{100}$ and excited state $\Psi_{210}$. The peaks appear near the eigen-frequencies $\gamma_{100} = 1.8$ and $\gamma_{210} = 1.42$, which confirms the wave functions oscillate with the eigenfrequency throughout the evolution. Bottom: Time evolution of the individual densities of each state $|\Psi_{100}|^2$ and $|\Psi_{210}|^2$, which are due to the truncation error intrinsic to the construction of axis-symmetric equilibrium configurations. The time window for the Fourier Transform and the various snapshots contains more than 200 cycles of the wave function. The facts that $\Psi_{100}$ and $\Psi_{210}$ oscillate with the appropriate frequency and that the density does not show a runaway behavior together, are a good indication of stability of this type of configuration.

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J.F. Navarro, C. S. Frenk, and S. D. M. White, Astrophys. J. 490, 493 (1997) [arXiv:astro-ph/9611107 [astro-ph]].

B. Moore, S. Ghigna, F. Governato, G. Lake, T. Quinn, J. Stadel, and P. Tozzi, The Astrophysical Journal 524, L19 (1999).

R. A. Ibata, G. F. Lewis, A. R. Conn, M. J. Irwin, A. W. McConnachie, N. G. Ibata, et al., Nature 493, 62 (2013).

[1] J. F. Navarro, C. S. Frenk, and S. D. M. White, Astrophys. J. 490, 493 (1997) [arXiv:astro-ph/9611107 [astro-ph]].
[2] V. Springel et al., Nature 435, 629 (2005) [arXiv:astro-ph/0504097 [astro-ph]].
[3] T. Sawala et al., Mon. Not. Roy. Astron. Soc. 457, 1931 (2016) [arXiv:1511.01098 [astro-ph.GA]].
[4] J. Wang, S. Bose, C. S. Frenk, L. Gao, A. Jenkins, V. Springel, and S. D. M. White, “Universality in the structure of dark matter haloes over twenty orders of magnitude in halo mass,” (2019) arXiv:1911.09720 [astro-ph.CO].
[5] J. S. Bullock and M. Boylan-Kolchin, Annual Review of Astronomy and Astrophysics 55, 343387 (2017).
[6] I. M. E. Santos-Santos, J. F. Navarro, A. Robertson, A. Bentez-Llambay, K. A. Oman, M. R. Lovell, C. S. Frenk, A. D. Ludlow, A. Fattnahi, and A. Ritz, “Baryonic clues to the puzzling diversity of dwarf galaxy rotation curves,” (2019) arXiv:1911.09116 [astro-ph.GA].
[7] A. Klypin, A. V. Kravtsov, O. Valenzuela, and F. Prada, The Astrophysical Journal 522, 82 (1999).
[8] B. Moore, S. Ghigna, F. Governato, G. Lake, T. Quinn, J. Stadel, and P. Tozzi, The Astrophysical Journal 524, L19 (1999).
[9] M. S. Pawlowski and P. Kroupa, (2019), arXiv:1911.05081 [astro-ph.GA].
[10] M. S. Pawlowski, P. Kroupa, and H. Jerjen, Mon. Not. Roy. Astron. Soc. 435, 1928 (2013) http://oup.prod.sis.lan/mnras/article-pdf/435/3/1928/3350570/stt1384.pdf.
[11] A. R. Conn, G. F. Lewis, R. A. Ibata, Q. A. Parker, D. B. Zucker, A. W. McConnachie, N. F. Martin, D. Valls-Gabaud, N. Tanvir, M. J. Irwin, A. M. N. Ferguson, and S. C. Chapman, The Astrophysical Journal 766, 120 (2013).
[12] R. A. Ibata, G. F. Lewis, A. R. Conn, M. J. Irwin, A. W. McConnachie, S. C. Chapman, M. L. Collins, M. Fardal, A. M. Ferguson, N. G. Ibata, et al., Nature 493, 62 (2013).
[13] M. S. Pawlowski, Modern Physics Letters A 33 No. 6, 1830004 (2018).
[14] E. J. Shaya and R. B. Tully, Monthly Notices of the Royal Astronomical Society 436, 2096 (2013) [arXiv:1802.00081 [astro-ph.GA]]
[15] A. Lipnicky and S. Chakrabarti, Mon. Not. Roy. Astron. Soc. 468, 1671 (2017) [arXiv:1612.07325 [astro-ph.GA]]
[16] O. Muller, M. S. Pawlowski, H. Jerjen, and F. Lelli, Science 359, 534 (2018) [arXiv:1802.00081 [astro-ph.GA]]
[17] S.-J. Sin, Phys. Rev. D 50, 3656 (1994) [arXiv:hep-ph/9205208 [hep-ph]]
[18] T. Matos and L. A. Urena-Lopez, Phys. Rev. D 63, 063506 (2001) [arXiv:astro-ph/0006024 [astro-ph]]
[19] A. Arbey, J. Lesgourges, and P. Salati, Phys. Rev. D 85, 1158 (2000) [arXiv:astro-ph/0003365 [astro-ph]]
[20] W. Hu, R. Barkana, and A. Gruzinov, Phys. Rev. Lett. 85, 1158 (2000) [arXiv:astro-ph/0003365 [astro-ph]]
[21] L. Hui, J. P. Ostriker, S. Tremaine, and E. Witten, Phys. Rev. D 95, 043541 (2017) [arXiv:1610.08297 [astro-ph.CO]]
[22] T. Matos and L. A. Urena-Lopez, Phys. Rev. D 63, 063506 (2001) [arXiv:astro-ph/0006024 [astro-ph]]
[23] R. Hlozek, D. Grin, D. J. E. Marsh, and P. G. Ferreira, Phys. Rev. D 91, 103512 (2015) [arXiv:1410.2897 [astro-ph.CO]]
[24] V. H. Robles and T. Matos, The Astrophysical Journal 763, 19 (2012)
[28] V. H. Robles and T. Matos, Monthly Notices of the Royal Astronomical Society 422, 282289 (2012)
[29] A. Bernal and T. Matos, 2nd Mexican Meeting on Mathematical and Experimental Physics Mexico City, Mexico, September 6-10, 2004, AIP Conf. Proc. 758, 161 (2005) [arXiv:1610.08297 [astro-ph.CO]]
[30] V. H. Robles, J. S. Bullock, and M. Boylan-Kolchin, Monthly Notices of the Royal Astronomical Society 483, 289298 (2018)
[31] L. A. Martinez-Medina and T. Matos, Mon. Not. Roy. Astron. Soc. 444, 185 (2014) [arXiv:1407.7056 [astro-ph.GA]]
[32] L. A. Martinez-Medina, H. L. Bray, and T. Matos, JCAP 1512, 025 (2015) [arXiv:1505.07154 [astro-ph.GA]]
[33] L. Martinez-Medina, V. Robles, and T. Matos, Physical Review D 91 (2015), 10.1103/physrevd.91.023519
[34] P. Mocz, A. Fialkov, M. Vogelsberger, F. Becerra, M. A. Amin, S. Bose, M. Boylan-Kolchin, P.-H. Chavanis, L. Hernquist, L. Lancaster, and et al., Physical Review Letters 123 (2019), 10.1103/physrevlett.123.141301
[35] P. Mocz, A. Fialkov, M. Vogelsberger, F. Becerra, X. Shen, V. H. Robles, M. A. Amin, J. Zavala, M. Boylan-Kolchin, S. Bose, F. Marinacci, P.-H. Chavanis, L. Lancaster, and L. Hernquist, (2019), arXiv:1911.05746 [astro-ph.CO]
[36] H.-Y. Schive, T. Chiueh, and T. Broadhurst, Nature Phys. 10, 496 (2014) [arXiv:1406.6586 [astro-ph.GA]]
[37] P. Mocz, M. Vogelsberger, V. H. Robles, J. Zavala, M. Boylan-Kolchin, A. Fialkov, and L. Hernquist, Mon. Not. Roy. Astron. Soc. 471, 4559 (2017) [arXiv:1705.05845 [astro-ph.CO]]
[38] P. F. Hopkins, Monthly Notices of the Royal Astronomical Society 489, 23623767 (2019)
[39] U.-L. A. Guzman, F. S. and T. Matos, in preparation.
[40] R. Ferrell and M. Gleiser, Phys. Rev. D 40, 2524 (1989)
[41] F. S. Guzmán, F. D. Lora-Clavijo, J. J. González-Avilés, and F. J. Rivera-Paleo, Phys. Rev. D 89, 063507 (2014)