Ghostly Galaxies as Solitons of Bose-Einstein Dark Matter

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The large dark cores of common dwarf galaxies are unexplained by the standard heavy particle interpretation of dark matter because gravity is scale free (1–3), so the particle density should continuously rise towards the center of galaxies. This puzzle is exacerbated by the discovery of a very large but barely
visible, dark matter dominated galaxy Antlia II orbiting the Milky Way, uncovered by tracking star motions with the Gaia satellite (4). Although Antlia II has a low mass, its visible radius is more than double any known dwarf galaxy, with an unprecedentedly low density core (4). We show that Antlia II favors dark matter as a Bose-Einstein condensate, for which the ground state is a stable soliton with a core radius given by the de Broglie wavelength (5, 6).

The lower the galaxy mass, the larger the de Broglie wavelength, so the least massive galaxies should have the widest soliton cores of lowest density. An ultra-light boson of $m_\psi \sim 0.8 - 1.2 \times 10^{-22}$ eV, accounts well for the large size and slowly moving stars within Antlia II, and agrees with boson mass estimates derived from the denser cores of more massive dwarf galaxies. For this very light boson, Antlia II is close to the lower limiting Jeans scale for galaxy formation permitted by the Uncertainty Principle, so other examples are expected but none significantly larger in size. This simple explanation for the puzzling dark cores of dwarf galaxies implies dark matter as an ultra-light boson, such as an axion generic in String Theory.

Dark matter (DM) is understood to be non-relativistic even in the early Universe, otherwise initial density perturbations destined to become galaxies would be smoothed away by free streaming of the dark matter. This cold dark matter (CDM) has long been synonymous with heavy particle interpretations beyond standard particle physics (7), but no such particles have been detected in stringent laboratory experiments (8, 9). Black holes also qualify as CDM, and although LIGO/Virgo has claimed an abundance of $30M_\odot$ black holes (10), their space density is limited to less than 5% of all dark matter by micro-lensing measurements through massive lensing clusters (11).

Enthusiasm for CDM has long been tempered by the shallow mass profiles of common
dwarf galaxies that appear to be cored rather than “cuspy” as predicted by N-body simulations (1), reflecting the fundamentally scale free nature of gravity. It has been hard to make sense of this apparent contradiction in the context of CDM without invoking hypothetical forces or implausibly transformational gas outflows (12). The very low density of stars in Antlia II and their low metallicities argues empirically against an explanation that repeated episodes of star formation somehow flatten a CDM cusp into a core (13), an idea that is no longer supported by accurate high resolution simulations (14, 15). This apparent contradiction with particle DM is all the more puzzling as dark matter is clearly demonstrated to be collisionless when galaxy clusters collide (16, 17), where gravity alone explains the observed dynamics without additional DM self-interaction.

The above contradictions do not arise for a very different non-relativistic form of dark matter, as a Bose-Einstein condensate. Pioneering simulations of this state show dark cores of very light bosons are required in the ground state (5) of this quantum, wave-like form of dark matter, termed $\psi$DM. These $\psi$DM simulations simply evolve a coupled Schrödinger-Poisson equation describing a non-relativistic self-gravitating condensate (18, 19) requiring only one free parameter, the boson mass, $m_\psi$, where the smaller $m_\psi$ the larger the de Broglie wavelength. Rich non-linear structure is revealed by the $\psi$DM simulations on the de Broglie scale, including a prominent, standing wave core at the center of every galaxy that is a stable soliton, representing the ground state, surrounded by a halo of turbulent, self interfering excited states (5, 6, 20) and confirmed by independent simulations (21, 22).

Here we compare Antlia II with the central prediction of $\psi$DM, that the least massive galaxies should have the widest soliton cores of lowest density. The de Broglie wavelength is of course larger at lower momentum, so the soliton radius depends inversely with soliton mass, $R_{\text{sol}} \propto M_{\text{sol}}^{-1}$. Also the $\psi$DM simulations have established $M_{\text{sol}}$ increases with the total galaxy mass, as $M_{\text{sol}} \propto M_{\text{gal}}^{1/3}$ (6, 22) so the central DM density of soliton cores scales with galaxy
mass as:

$$\bar{\rho}_{\text{sol}} = 1.9 \times 10^6 \left( \frac{M_{\text{gal}}}{10^9 M_\odot} \right)^{4/3} \left( \frac{m_\psi}{10^{-22} \text{eV}} \right)^2 M_\odot \text{kpc}^{-3}$$

(1)

Hence, at fixed $m_\psi$, the core density of a dwarf galaxy of $10^9 M_\odot$, should be much smaller, $10^{-4}$, than the central DM density of a massive galaxy of $10^{12} M_\odot$, like the Milky Way. This contrasts with a predicted increase in density of $\approx 30$ for standard CDM, from the “concentration-mass relation” of N-body simulations, where lower mass galaxies are predicted to have denser dark matter profiles.

Despite the general tendency to accommodate CDM, all well studied dwarf spheroidal (dSph) galaxies are consistently claimed to have large dark cores, traced by a diffuse distribution of old stars of low velocity dispersion. In particular, the best studied Fornax dSph is determined by several different methods to have a core radius of $\approx 1.0 \text{kpc}$ (23, 24) with a density profile that is accurately fitted by the soliton form (5) of $\psi_{\text{DM}}$, as shown in Figure 1, for which a Jeans analysis yields a boson mass of, $m_\psi = 0.8 \pm 0.2 \times 10^{-22} \text{eV}$ (5). Furthermore, Fornax provides another independent and compelling argument for $\psi_{\text{DM}}$ implied by the presence of ancient globular clusters on large orbits around Fornax. This is unexpected for discrete dark matter, such as CDM or black holes, that would be focused gravitationally by an orbiting globular cluster into a “wake”, so the globular clusters should have migrated long ago to the center of Fornax (25, 26). This “dynamical friction” is not significant for $\psi_{\text{DM}}$, which cannot be confined to less than the de Broglie scale because of the Uncertainty Principle (27, 28), leaving the Fornax globular cluster orbits little affected (27).

The newly discovered Antlia II galaxy has an exceptionally large core radius of $\approx 3 \text{kpc}$, which together with its small velocity dispersion $\approx 6 \text{km/s}$, corresponds to a mean DM density of only $\approx 10^5 M_\odot \text{kpc}^{-3}$, that is an order of magnitude lower than any known dwarf galaxy (4) and $\approx 30$ times lower than Fornax, as shown in Figure 1. Antlia II extends the trend of re-
cent discoveries towards larger, lower surface brightness galaxies of low velocity dispersion, including Crater II and other large dSph galaxies in orbit around Andromeda (29–31). At face value these ”ghostly” galaxies are encouraging for the $\psi$DM interpretation of DM, particularly Antlia II (4), and so here examine whether the well studied dwarf spheroidals follow the distinctive density-radius relation of eqn 1, that has the *opposite* sign to the behaviour expected for CDM. In Figure 1 we show a family of $\psi$DM profiles as a function of galaxy mass, following eqn 1, with the boson mass $m_\psi$ set to the canonical $10^{-22}$ eV, appropriate for $\psi$DM (5, 19, 32). These model profiles can be seen to match the reported mean densities of the well studied dwarf spheroidal, listed in Table 1 (supplement) showing that Antlia II has a soliton core that is 2.5 times larger than Fornax mass and hence 40% lower mass than the core mass of Fornax, of $5 \times 10^7 M_\odot$, and in good agreement with the mass estimated by Torrealba et al. (2018) based on the observed velocity dispersion of 6.5 km/s at the half light radius of 2.8 kpc.

We can also compare the measured radial velocity dispersion profile observed for Antlia II (4) with $\psi$DM predictions by solving the Jeans equation in projection (see supplement). We assume the commonly adopted Plummer profile (33) appropriate for the stellar distribution of dwarf spheroidal galaxies, normalized to the measured half light radius of 2.8 kpc (4). The predicted profiles shown in Figure 2 have a slow centrally declining velocity dispersion due to the declining interior mass, $M(<r)$ for constant density cores, with a somewhat steeper decline for low boson mass. Figure 2 shows that a boson mass is favoured $0.8 - 1.5 \times 10^{-22}$ eV, below which the observed mean dispersion of $\simeq 6.5$ km/s is under predicted and above which the soliton radius falls short of $2.5$ kpc radius of the outer bin, so the central velocity dispersion exceeds the measured value, shown in Figure 2. The opposite behavior is expected for CDM (Figure 2), where the continuously rising central density predicts a rising velocity dispersion that exceeds the data in Figure 2, for the best fitting NFW profile derived in the analysis of Torrealba et al. (2018) (4).
We now jointly constrain the boson mass and soliton core radius with galaxy mass in Figure 3. We compare Antlia II with Fornax and Sextans dSph’s because no tidal effects have been detected in deep imaging and careful dynamical work (34–36), so we need not be overly concerned that their masses are underestimated. In any case, these galaxies are established to have large orbits about the Milky Way extending to \( \geq 100 \) kpc, including Antila II which is presently at a radius of 130 kpc with a sizeable estimated pericenter of 50 kpc implying tidal effects are marginal (4, 37). In Figure 3 we define a contour corresponding to the measured mass of \( 5.4 \pm 2.1 \times 10^7 M_\odot \) interior to a limiting radius of \( \simeq 2.5 \) kpc within which the velocity dispersion profile of Antlia II is observed to be flat (4), as shown in Figure 2, so the soliton core extends to at least this radius. Importantly, Figure 3 shows that despite the considerable differences in mass and core radius between these three galaxies, a common boson mass is inferred of \( \simeq 0.8 \times 10^{-22} \) eV within the uncertainties.

The Uncertainty Principle not only sets the soliton scale above, but also provides another fundamental prediction of a sharp minimum halo mass by imposing a “quantum Jeans condition” (38, 39) because the DM cannot be confined within the de Broglie wavelength thereby preventing galaxy formation below a limiting Jeans mass:

\[
M_J = 1.7 \times 10^7 \left( \frac{\Omega_a h^2 (1 + z)}{0.12} \right)^{-3/4} \left( \frac{m_\psi}{10^{-22} \text{ eV}} \right)^{-3/2} M_\odot ,
\]

(2)

as shown in Figure 3, where \( \rho_a = \rho_c (1 + z)^3 \) is the cosmological dark matter density. This limit depends only weakly on formation redshift as the power spectrum cuts off below a Jeans-like wavelength, \( \lambda_J \propto (1 + z)^{1/4} \) (6, 39, 40), defining a relatively sharp lower limiting galaxy mass for \( \psi \)DM (6, 19, 41). Hence, low mass galaxies should be abundant towards this limit and firmly absent below it. Furthermore, the presence of this mass limit predicts a maximum soliton core radius of \( \simeq 3 \) kpc, as shown in Figure 3, because the lowest mass galaxies should have the widest solitons of lowest mass density, with Antlia II lying closest to this existential limit.
Another ghostly galaxy is the "feeble giant" Crater II, orbiting the Milky Way at 50 kpc, with a sizeable radius of 1.1 kpc and surprisingly low velocity dispersion of only \( \simeq 3 \) km/s (29). Most of the DM of Crater II has likely been stripped off tidally as indicated by surface brightness distortions and because of its small inferred pericenter of only 10 kpc (29) where stripping is generally expected to significantly reduce the velocity dispersion and truncate the stellar radius, depending on the phase of the orbit (34, 42, 43) and so previously Crater II may have resembled more Antlia II with a larger radius and higher velocity dispersion. Another large dwarf spheroidal galaxy, Cetus (44) at 800 kpc and is determined to be one of only a few "isolated" galaxies that has not suffered significant interaction with other local group galaxies (44). This galaxy extends to at least 3 kpc in deep imaging, with no detectable tidal truncation radius (44). The velocity dispersion of Cetus is close to 10 km/s and can traced beyond its its half light radius to \( \simeq 1.4 \) kpc (44). The extended stellar profile may indicate a soliton core similar to Fornax (in Figure 1) surrounded by a lower density DM halo as predicted for \( \psi \)DM in the absence of tidal truncation, extending to several kpc, as shown in Figure 1.

The above large core "classical" dSph galaxies may be contrasted with the newly discovered class of much smaller 20 – 50 pc "ultra faint dwarfs" uncovered in wide field surveys (45,46) on relatively small orbits, < 50 kpc, within the Milky Way. These relatively small objects are very DM dominated, given their typical velocity dispersion of \( \simeq 3 \) km/s and low luminosities, of typically only \( \simeq 1000 \) \( L_\odot \) and so together with their small orbits they are generally considered to be heavily stripped "remnants" (47–49) of originally large dSph galaxies. In the context of \( \psi \)DM, tidal stripping is estimated to be significantly more efficient than for CDM, as the soliton core expands in response to the loss of outer stripped halo mass pushing more DM beyond the tidal radius as the soliton expands in radius in response to the reduced mass, in a runaway process (50). This "remnant" origin for the UDF galaxies may be supported by the serendipitous discovery of central star clusters within several dSph galaxies, with sizes and luminosities
similar to the UDF galaxies (51–54) that may be clarified with deep velocity dispersion measurements. A wider $\psi_{\text{DM}}$ context may provide a natural origin for such dense central stars clusters, and in general for the puzzling presence of nuclear star clusters commonly found in all types of galaxy, where a minority contribution to the universal DM from a heavier boson of $\simeq 10^{-20}\text{eV}$ may sink within the wide solitons of the lighter, dominant DM (derived above of $10^{-22}\text{eV}$), resulting in a smaller dense DM structure that helps explain the puzzling origin and characteristic scale of nuclear star clusters (55). This ”multiple ultra-light” bosonic solution for the Universal dark matter has the attraction of being underpinned theoretically by String Theory, where a wide discrete spectrum of axion-like particles extending to very light masses is generically predicted (56–58) depending on the details of dimensional compactification.

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Figure 1: Here we show how the low mean density reported for Antlia II is readily reproduced by the wide solitonic core density profile of a low mass galaxy of $\sim 10^9 M_\odot$ in the context of $\psi$DM. For comparison we compare the reported core mass densities of other well studied dwarf spheroidal galaxies with the density profiles for $\psi$DM, for the same boson mass, $m_\psi = 10^{-22}$ eV, demonstrating the consistency with the family of predicted $\psi$DM profiles, where soliton radius and mass are inversely related.
Figure 2: The measured velocity dispersion (data points) (4), compared with the predictions of ψ/DM mass profiles for a range of light boson masses - see legend where \( m_{\psi,22} \equiv m_\psi / 10^{-22} \). The central decline in dispersion velocity for the lighter bosons matches well the data, and reflects the low central mass density. This contrasts with the relatively more concentrated best fitting NFW profile (dashed curve) where an enhancement is expected, unlike the data.
Figure 3: The plane of core radius versus $m_\psi$ as a function of galaxy mass (colour coded) predicted for $\psi$DM that are limited to the hatched regions derived from the observations of Antlia II. The Fornax, Sextans dwarf galaxies are included for comparison because their density profiles are understood not to have been modified significantly by tidal stripping. The limiting Jeans mass is also indicated as a dashed black curve that places an upper limit on the radius of Antlia II at fixed $m_\psi$. Despite the wide range of mass and radius these three galaxies which span well over an order of magnitude in density are compatible with the same boson mass, $m_\psi \sim 0.8 \times 10^{-22}$ eV.
Supplementary materials

Table 1: In columns 2 and 3, are listed the half-light radius and the corresponding mass from (4, 60, 61). In column 4 and 5, we report the boson mass and soliton radius analyzed in (5, 32). In the columns 6 and 7 are the predicted values of the masses within the soliton radius and the virial radius, \( M_{\text{sol}} \) and \( M_{200} \), assuming a boson mass \( 10^{-22} \text{ eV} \).

| Galaxy   | \( r_h \) (kpc) | \( M(<r_h) \) \((10^7 M_\odot)\) | \( m_\psi \) \((10^{-22}\text{eV})\) | \( r_c \) (kpc) | \( M_{\text{sol}} \) \((10^7 M_\odot)\) | \( M_{200} \) \((10^9 M_\odot)\) | Ref.          |
|----------|----------------|--------------------------------|-----------------|------------|----------------|----------------|--------------|
| Antlia II| 2.90 ± 0.31    | 5.4 ± 2.1                      | [0.6 – 1.4]     |            | 2.7            | 0.19           | This work & (4) |
| Fornax   | 0.67 ± 0.34    | 5.3 ± 0.9                      | 0.81±0.16       | 0.92±0.15  | 5.7            | 1.1            | (5, 60, 61)   |
| Sextans  | 0.68 ± 0.12    | 2.5 ± 0.9                      | -               | [1.5 – 3.0]| 4.6            | 0.63           | (60, 61)      |
| Sculptor | 0.26 ± 0.39    | 1.3 ± 0.4                      | 1.23±0.33       | 0.60±0.12  | 6.9            | 2.1            | (32, 60, 61)  |
| Draco    | 0.20 ± 0.12    | 0.94 ± 0.25                    | 1.12 ± 0.52     | 0.56 ± 0.13| 8.6            | 4.3            | (32, 60, 61)  |