Wave Dark Matter and Ultra Diffuse Galaxies.

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ABSTRACT

Dark matter as a Bose-Einstein condensate, such as the axionic scalar field particles of String Theory, can explain the coldness of dark matter on large scales. Pioneering simulations in this context predict a rich wave-like structure, with a ground state soliton core in every galaxy surrounded by a halo of excited states that interfere on the de Broglie scale. This de Broglie scale is largest for low mass galaxies as momentum is lower, providing a simple explanation for the wide cores of dwarf spheroidal galaxies. Here we extend these “wave dark matter” (ψDM) predictions to the newly discovered class of “Ultra Diffuse Galaxies” (UDG) that resemble dwarf spheroidal galaxies but with more extended stellar profiles. Currently the best studied example, DF44, has a uniform velocity dispersion of ≃ 33 km/s, extending to a least 3 kpc, that we show is reproduced by our ψDM simulations with a soliton radius of ≃ 0.5 kpc. In the ψDM context, we show the relatively flat dispersion profile of DF44 lies between massive galaxies with compact dense solitons, as may be present in the Milky Way on a scale of 100 pc and lower mass galaxies where the velocity dispersion declines centrally within a wide, low density soliton, like Antlia II, of radius 3 kpc. In contrast, standard CDM requires excessive tangential stellar motions to counter the inherent central cusp which would otherwise enhance the central velocity dispersion.

1 INTRODUCTION

The origin of the cosmological Dark Matter (DM) is understood to lie “beyond” the standard model of particle physics, which describes only 17% of the total cosmological energy density (Cyburt et al. 2016; Planck Collaboration 2016). It is also clear that DM is non-relativistic, to the earliest limits of observation given the Cosmic Microwave Background and galaxy power spectrum. Furthermore, DM behaves collisionlessly for pairs of clusters undergoing a collision, implying there is no detectable significant self interaction other than gravity, in particular the iconic Bullet cluster (Markevitch et al. 2004; Clowe et al. 2006) and other massive examples (Molnar & Broadhurst 2018).

This collisionless “Cold Dark Matter” (CDM) has long been synonymous with heavy particles of some new form, that must be unusually stable and interact with light only via gravity, and principally motivated by a super-symmetric extension of the Standard Model (Ellis 1984). However, enthusiasm for WIMP-based CDM is now fading with the continued absence of any such particles and also because the mass spectrum of galaxies does not conform to the generic gravitationally scale-free CDM expectation because dwarf galaxies are relatively rare and contain large DM cores (Broadhurst et al. 2019).

The dwarf galaxy tension applies to the primordial black hole interpretation of DM, and has been revived by the puzzlingly strong LIGO events (Bird et al. 2016), as black holes effectively act as CDM “particles” (except when coalescing). However, the LIGO inferred black hole mass (BBH) scale of 30 M⊙ is not present in Galactic microlensing searches, nor in the light curves of individual lensed stars recently discovered through high columns of cluster DM, limiting such a contribution to a small fraction of the DM (Diego et al. 2018; Kelly et al. 2018; Oguri et al. 2018).

Instead, a light boson solution for the universal DM is gaining credence on the strength of the first simulations to evolve the coupled Schrödinger-Poisson equations, dubbed ψDM, (Schive et al. 2014a) that reveal distinctive, testable predictions for the non-linear structure of this wave-like form of DM. The Uncertainty principle means bosons cannot be confined to a scale smaller than the de Broglie one, so this “pressure” naturally suppresses dwarf galaxy formation and generates rich structure on the de Broglie scale, as revealed by the first simulations (Schive et al. 2014a,b; Mocz et al. 2020).
2. **Dynamical Model of Ultra-Diffuse Galaxies with a Wave Dark Matter Halo**

The light bosons paradigm was firstly introduced by Widrow & Kaiser (1993), and Hu et al. (2000), and subsequently reconsidered by Marsh & Silk (2014); Schive et al. (2014a); Bozek et al. (2015) in relation to the puzzling properties of dwarf spheroidal galaxies. In the simplest version, without self- interaction, the boson mass is the only free parameter, with a fiducial value of $10^{-22}$ eV.

The first simulations in this context have revealed a surprisingly rich wave-like structure with a solitonic standing wave core, surrounded by a halo of interference that is fully modulated on the de Broglie scale (Schive et al. 2014a). The solitonic core corresponds to the ground-state solution of the coupled Schrödinger-Poisson equations, with a soliton density profile well-approximated by Schive et al. (2014a, b)

\[
\rho_{\psi}(r) \sim \frac{1.9 \times 10^{-22}}{[1 + 9.1 \times 10^{-20} (r/r_{sol})^2]^2} \quad M_{\odot} \text{pc}^{-3}. \tag{1}
\]

Here $m_{\psi}$ is the boson mass, and $r_{sol}$ is the solitonic core radius, which simulations show scales as halo mass ($Schive et al. 2014b$) in the following way:

\[
r_{sol} \propto M_{\odot}^{-1/3}. \tag{2}
\]

The simulations also show the soliton core is surrounded by an extended halo of density fluctuations on the de Broglie scale that arise by self-interference of the wave function (Schive et al. 2014a) and is "hydrogenic" in form (Hui et al. 2017; Vicens et al. 2018). These cellular fluctuations are large, with full density modulation on the de Broglie scale (Schive et al. 2014a) that modulate the amplitude of the Compton frequency oscillation of the coherent bosonic field, allowing a direct detection via pulsar timing (De Martino et al. 2017, 2018).

This extended halo region, when azimuthally averaged, is found to follow the Navarro-Frank-White (NFW) density profile (Navarro et al. 2000; Woo & Chiu 2009; Schive et al. 2014a, b) so that the full radial profile may be approximated as:

\[
\rho_{DM}(r) = \begin{cases} 
\rho_{0} \left( \frac{r}{r_{s}} \right)^{2} & \text{if } r < 2r_{sol}, \\
\rho_{0} \left( \frac{r}{r_{s}} \right)^{2} & \text{otherwise},
\end{cases} \tag{3}
\]

where $\rho_{0}$ is chosen such that the inner solitonic profile matches the outer NFW-like profile at approximately $2r_{sol}$, and $r_{s}$ is the scale radius.

In this context, we can now predict the corresponding velocity dispersion profile by solving the spherically symmetric Jeans equation:

\[
\frac{d(\rho_{v}(r)\sigma_{v}^2(r))}{dr} = -\rho_{v}(r)\frac{d\Phi_{DM}(r)}{dr} - 2\beta \rho_{v}(r)\sigma_{v}^2(r). \tag{4}
\]

where $\rho_{v}(r)$ is the stellar density distribution defined by the standard Plummer profile for the stellar population:

\[
\rho_{v}(r) = \frac{3M_{s}}{4\pi r_{half}^3} \left( 1 + \frac{r^2}{r_{half}^2} \right)^{-2}. \tag{5}
\]

Here, $r_{half}$ is the half-light radius, and $M_{s}$ is the stellar mass. $\beta$ is the anisotropy parameter, defined as (see Binney & Tremaine 2008, Equation 4.61))

\[
\beta = 1 - \frac{\sigma_{v}^2}{\sigma_{r}^2}. \tag{6}
\]
Thus, the gravitational potential is given by:

$$d\Phi_{DM}(r) = \frac{GM_{DM}(r)}{r^2} dr,$$

(7)

with a boundary condition $\Phi_{DM}(\infty) = 0$, and the mass enclosed in a sphere of radius $r$ is computed as follows

$$M_{DM}(r) = 4\pi \int_0^r \rho_{DM}(x) dx .$$

(8)

Finally, to directly compare our predicted dispersion velocity profile with the observations, we have to project the solution of the Jeans equation along the line of sight as follows:

$$\sigma^2_{los}(R) = \frac{2}{\Sigma(R)} \int_R^\infty \left(1 - \frac{\beta}{\sqrt{2}} \frac{R^2}{r^2}\right) \sigma^2_{los}(r) \rho_s(r) (r^2 - R^2)^{-1/2} dr ,$$

(9)

where

$$\Sigma(R) = 2 \int_R^\infty \rho_s(r) (r^2 - R^2)^{-1/2} dr .$$

(10)

We now apply the above to the newly measured dispersion profile of the recently discovered galaxy “Dragon Fly 44” (DF44). This unusual galaxy was recently discovered in a Coma cluster survey using the unique multi-beam optical Dragon Fly imager, designed to search for extended low-surface-brightness emissions (van Dokkum et al. 2016). This unique telescope has successfully surveyed sizeable areas to unprecedentedly low levels of surface brightness from the ground (Abraham & van Dokkum 2014), uncovering a surprising, unknown extreme class of “Ultra Diffuse Galaxies”, that are smooth, diffuse clouds of stars found mainly in massive galaxy clusters, that contrast with the centrally sharp and bright elliptical galaxy members (van Dokkum et al. 2016). The galaxy DF44 is one of the largest example of this UDG class, with a half-light radius $\sim 4.6$ kpc, and a stellar mass of $\sim 3 \times 10^{10} M_\odot$. Its stellar velocity dispersion profile has recently been measured with deep spectroscopy (van Dokkum et al. 2016, 2019).

3 MINIMAL WAVE-DARK-MATTER RADIAL PROFILE COMPARISON

Here we first compare the measured velocity dispersion and light profile of DF44 with Wave-DM with the minimum number of parameters that are consistent with the findings from our simulations and then subsequently we allow a wider range of soliton and halo mass to allow comparison with previous work for more general conclusions.

For our minimal model profiles we solve the spherically symmetric Jeans equation, described above, Eq. (4), subject to a total mass of $4 \times 10^{10} M_\odot$, which is the dynamical mass estimated by van Dokkum et al. (2019) for this galaxy adopting the virial estimate commonly used for dwarf spheroidal galaxies (Walker 2009). We also adopt the commonly used Plummer profile for the stellar profile and match it the measured half-light projected radius of 4.6 kpc measured for DF44 (van Dokkum et al. 2019).

For our minimal model adopt the soliton–halo mass scaling relation of Eq. (2) discovered in the $\phi$DM simulations (Schive et al. 2014b). This provides the scale of the soliton for a fixed total halo mass. The $\phi$DM simulations have also shown that the NFW form provides a good azimuthal description of the granular $\phi$DM halos outside the soliton core. Hence we may fix the scale length of the NFW profile, $r_s$, to provide the total mass computed with our model for a given choice of concentration we set $r_s = 8$ kpc. All values are summarized in Table 2.

![Figure 1](image_url)

Figure 1. The figure shows the acceptable range of predicted velocity dispersion profiles comparison with DF44 for our minimal model, where the soliton scale is determined by the halo mass and the boson mass. We vary boson mass in the upper panel, setting $\beta = -0.8$ and in the lower panel we set the boson mass to $m_\phi = 10^{-22} \text{eV}$ and vary $\beta$ according to the legend. This show that a light boson mass in the above range, with modestly negative $\beta$, produces acceptable reduced $\chi^2$.

This comparison shows simply that the general level of velocity dispersion measured for DF44 of $\sim 30 \text{ km/s}$ is consistent with the widely favoured boson mass from similar analyses of dwarf spheroidal galaxies $\sim 10^{-22} \text{eV}$, for which the observed absence of any central rise in the velocity dispersion favours a predominance of tangential over radial dispersion. We can also see that for a larger choice of boson mass of $1.2 \times 10^{-22} \text{eV}$, a larger value of $\beta$ can be tolerated. This contrasts with the significantly larger mean boson mass of $\sim 3 \times 10^{-22} \text{eV}$, highlighted by Wasserman (2019) in a recent analysis of DF44, but is consistent with the lower end of their 95% range of $1.2 \times 10^{-22} \text{eV}$.

Acceptable minimal model profiles for DF44 are shown in Figure 1 for several illustrative values for the minimal set of parameters listed in Table 2, varying the boson mass and the velocity anisotropy parameter. These profiles have reduced $\chi^2$ values near unity, consistent with the measured dispersion profile of DF44 for its observed large half light radius and virial mass estimate. In the upper panel of Figure 1 we vary the boson mass in the range $[0.6, 1.2] \times 10^{-22} \text{eV}$, setting $\beta = -0.8$ on the basis of the analysis in van Dokkum et al. (2019). In the bottom panel, we do the opposite by setting $m_\phi = 10^{-22} \text{eV}$ and varying the anisotropy parameter in the range $[-0.75, -1.5]$. In both cases, the wave-like DM is able acceptably reproduce to the dispersion velocity profile out to $r \sim 3$ kpc and even outsider for lower panel profiles.

3.1 Comparison of the velocity profile of DF44 with other low and intermediate mass Galaxies

Here we place the velocity profile of DF44 in the wider context of dwarf galaxy profiles for the $\phi$DM framework, spanning the full range of lower masses appropriate for dwarf galaxies. We compare...
our minimal model with the velocity dispersion profile of representative well studied low mass galaxies whose halo mass and half-light radius span the ranges from $\sim 10^9 M_\odot$ to $\sim 5 \times 10^{10} M_\odot$ and from $\sim 0.8$ kpc to $\sim 5$ kpc, respectively. Since our minimal model must assume a halo mass to compute the corresponding solitonic profile, Eq. (2), we take care to check that the predicted total mass from our model is compatible within the errors with the total mass estimates from observations.

In Figure 2 shows illustrative velocity dispersion profiles for a range of DM mass profiles highlighting the transition from the soliton core to the outer NFW-like outer profile (Schive et al. 2014a,b; Vicens et al. 2018). The velocity dispersion profile are listed in Table 1, and cover one order of magnitude in the total mass starting from $10^9 M_\odot$ and for different choices for the extent of the stellar profile, and for each model profile compare two representative values of $\beta = [0.0, -0.5]$ to show the effect of the transition in a family of physical systems representing dwarf galaxies. Solid and dashed lines depict in Fig. 2 for each system, our predicted dispersion profile for $\beta$ set to $0.0$, and $-0.5$, respectively.

Finally, in Figure 3, we apply our model to the dwarf galaxies listed in Table 2, together with the reduced chi-square. Our results show that the minimal model is able to provide a good fit of the data. We always vary to whole set of parameters, namely $(M_{\text{halo}}, r_s, \beta)$. For all galaxies, we also compute the total mass within the half-light radius to ensure that it matches the observed one. All results are listed in Table 2.

### 3.2 Pure NFW profile.

Here we consider a pure NFW profile for a range of relatively high concentration parameter, $c$, appropriate for relatively low mass galaxies like DF44, ranging over $20 < c < 40$, guided by the mass-concentration relation and its inherent dispersion derived from CDM simulations.

Generically of course a centrally rising dispersion profile is predicted for NFW profiles, shown in Figure 4 (and Table 3 labeled as NFW1 and NFW2) as expected given the inherently cuspy density profile of CDM, but is quite unlike the flat profile observed for DF44.

### Table 1. Values of the parameters used to construct the velocity dispersion profile of a set of simulated dwarf galaxies [G1,G2,G3,G4] for two values of the anisotropy parameter. We also vary here the Plummer scale radius for the stars, which allows for a range in "depth" that the stars may occupy in 3D, as listed in Table 1, given by the half light radius.

\[
\begin{array}{cccccc}
\text{Model} & M_{\text{halo}} & r_{\text{sol}} & r_{\text{halo}} & M_{\text{s}} & r_s & \beta \\
\hline
G_1^0 & 0.1 & 1.6 & 0.6 & 0.3 & 8.5 & 0.0 \\
G_1^- & & & & & & -0.5 \\
G_2^0 & 0.5 & 0.94 & 0.6 & 0.3 & 10.5 & 0.0 \\
G_2^- & & & & & & -0.5 \\
G_3^0 & 1.0 & 0.74 & 2.5 & 3.0 & 9.0 & 0.0 \\
G_3^- & & & & & & -0.5 \\
G_4^0 & 5.0 & 0.43 & 2.5 & 3.0 & 7.5 & 0.0 \\
G_4^- & & & & & & -0.5 \\
\end{array}
\]

A better match DF44 requires a negative anisotropy parameter, with $\beta < -1$ as shown in Figure 4 (and Table 3 labeled as NFW3, NFW4 and NFW5) in order to more than counter the CDM cusp. The NFW5 model has a concentration parameter has been set to the best NFW fit obtained by Torrealba (2019), while $\beta$ is the same as explored by van Dokkum et al. (2019) and this is marginally acceptable with $\beta = -1.25$, in terms of the velocity dispersion profile. However, the scale length predicted for this model $r_s = 3.6kpc$ is smaller than the measured half light radius of DF44, therefore appearing to be unreasonable, and this is generally the case for the other solutions we have explored here and listed in Table 3, as generically the cooling of gas required to form stars is not expected to produce a stellar distribution is expected to be more concentrated that a dominant...
Table 2. Observed and estimated magnitudes of the dwarfs galaxies.

| Galaxies | $m_b$ ($10^{-22}$ eV) | $M_{\text{halo},\text{obs}}$ ($10^9M_\odot$) | $r_{\text{sol}}$ (kpc) | $r_s$ (kpc) | $r_{\text{halo}}$ (kpc) | $M(r<r_{\text{halo}})_{\text{obs}}$ ($10^9M_\odot$) | $M(r<r_{\text{halo}})_{\text{th}}$ ($10^9M_\odot$) | $\beta$ | $\chi^2_{\text{red}}$ | Refs. |
|----------|----------------------|---------------------------------------------|-----------------------|---------|-------------------|---------------------------------------------|---------------------------------------------|-------|---------------|------|
| DF44     | 1                    | 40                                          | 0.47                  | 8       | 4.6 ± 0.2         | 390 ± 50                                    | 300                           | -1.25 | 0.87          | van Dokkum et al. (2019) |
| WLM      | 1                    | 10                                          | 0.74                  | 7       | 1.66 ± 0.49       | 43 ± 3                                      | 25                            | -0.75 | 0.82          | Leaman et al. (2012)     |
| Fornax   | 1                    | 7                                           | 0.84                  | 4       | 0.85              | 6.1-8                                       | 6.57                          | 0.0    | 1.21          | Mashchenko (2015)        |
| Antlia II | 1                    | 7                                           | 1.6                   | 7       | 2.9 ± 0.3         | 5.5 ± 2.2                                   | 9.75                          | -0.75 | 1.34          | Torrealba (2019)         |

Table 3. DragonFly 44 NFW predicted profiles

| Profiles | $M_{\text{halo}}$ ($10^9M_\odot$) | $r_s$ (kpc) | $c$ | $\beta$ |
|----------|-----------------------------------|---------|-----|------|
| NFW1     | 10                                | 2.89    | 15  | 0    |
| NFW2     | 8                                 | 2.01    | 20  | 0    |
| NFW3     | 40                                | 4.59    | 15  | -2   |
| NFW4     | 40                                | 3.44    | 20  | -3   |
| NFW5     | 20                                | 3.64    | 15  | -1.25|

Figure 4. Result of the best pure NFW fits for DF44 listed in table 3. The black vertical line is the limit of the calculated soliton for the wave DM profile.

3.3 Generalised Wave-Dark-Matter profile fitting

Here we explore a fuller range of parameters that does not rely on the “standard” dynamical mass advocated by Walker (2009) for simple stellar systems, since this may not be fully appropriate for the Wave-DM model that we examine here, but has been calibrated in the context of CDM simulations.

For this purpose we have constructed an MCMC multi-parameter scheme that we compare with the dynamical data and observed scale length for DF-44, which we link through the Jeans analysis outlined earlier. In addition to the parameters of the minimal model above, we allow the halo mass to be free and some freedom in "transition radius” between the central soliton and outer NFW halo components given by $\epsilon$ below that is consistent with the spread found in the first simulations (Schive et al. 2014a).

Wide priors are adopted for the above model:

- $-0.5 < \log_{10}(m_{22}) < 2.5$; (11)
- $1 < \log_{10}(r_c) < 4$; (12)
- $-1 < -\log_{10}(1 - \beta) < 1$; (13)
- $2 < \epsilon < 3.5$. (14)

Note, here we have let the matching radius between the soliton and the NFW halo vary over a range of scale, where $r_{\text{trans}} = \epsilon r_c$, implied by the inherent spread found in the simulations.

The best fit velocity dispersion curve of the above model is shown in Figure 5, together with the 1-$\sigma$ uncertainty. The preferred value is of the core radius of this model is $\approx 100$ pc, which is quite small compared to the size of DF44 ($\sim 4.7$ kpc). The preferred halo mass, $1.5^{+3.5}_{-0.7} \times 10^{11}M_\odot$, is several times larger than the dynamical mass adopted earlier of $4 \times 10^{10}M_\odot$ for our minimal model and the best fitting soliton mass is lower in relation to the halo mass, only 2% of the halo mass and hence this model is essentially a pure NFW profile with a relatively large tangential anisotropy $\beta = -2$ that counters the inherent NFW cusp, lowering the central velocity dispersion as shown in Figure 5. This halo dominated solution is very similar in terms of halo mass and velocity anisotropy to our best fitting pure NFW profile, NFW4 described in section §3.2.

This halo dominated $\phi$DM solution has a somewhat higher favoured boson mass than we derived in section §3.1 for our minimal model, but with a sizeable uncertainty: $M_b = 2.1^{+4.9}_{-1.3} \times 10^{-22}eV$. This value of the boson mass is compatible with that obtained by Wassereman (2019) for their independent MCMC analysis of DF44 and also agrees with the lower limit of $\beta$. Hence, this higher mass soliton for both the boson mass and the halo mass may be less physically compelling than the minimal model solution we found earlier, for which the reduced $\chi^2$ is certainly acceptable, and for which the soliton is wider so that a relatively less extreme value of $\beta$ is required.

4 DISCUSSION AND CONCLUSIONS

Here we have focused on the large low surface brightness galaxy DF44, currently the only example of the newly defined “ultra diffuse” galaxy class with a measured velocity dispersion profile. A relatively large number of globular clusters appears to be associated with DF44 and initially taken to imply a relatively high mass.
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Figure 5. The best fit soliton + NFW model and its one-sigma deviation is calculated by randomly sampling from the distributions of velocity dispersion at each radius.

Figure 6. Correlated distributions of inferred parameters: core mass, half-light mass and halo mass from MCMC simulation.

Figure 7. Correlated distributions of free parameters: boson mass, core radius and anisotropy from MCMC simulation. Transition factor distribution is not shown here due to its uniformity.

Here we have been particularly interested in whether this class of galaxy may have implications for the newly appreciated “Wave-DM” interpretation of DM, because of the distinctive density profiles found in the first cosmological simulations in this context that predict a rich wave-like structure in the non-linear regime with collapsed halos that should contain solitonic standing wave core of dark bosonic matter at the center surrounded by a wide halo of excited states that are fully modulated in density on the de Broglie scale (Schive et al. 2014a,b, 2016). This characteristic wavelike behaviour has subsequently been verified by other groups independently (Veltmaat et al. 2018; Mocz et al. 2017) providing a clear distinguishing prediction of rich wavelike structure, unanticipated in the definition of “Fuzzy Dark Matter” (Hu et al. 2000) which we can now see is somewhat of a misnomer, implying an incoherent density profile with a smooth core, quite unlike the rich coherent wavelike structure uncovered in the simulations that is pervasive due to interfere on the de Broglie scale with a prominent standing wave core at the center (Schive et al. 2014a,b). The de Broglie scale sets the scale of soliton radius which is larger for less massive galaxies of lower momentum, as the de Broglie scale is simply set by $\lambda_{dB} = h/(m_p v)$, the momentum, given by the level of internal velocity dispersion, and the boson mass, $m_p$.

We have shown that this distinctive wave-DM profile can account for the puzzling combination of the large radius of DF44 and its shallow, low velocity dispersion profile predicted for intermediate mass halos, of approximately $\approx 4 \times 10^{10} M_\odot$ with a soliton radius of $\approx 400$ pc, this is several times more massive than typical dwarf spheroidal galaxies in the local group neighbourhood for which Wave-DM profiles fitted typically have masses of a few $\times 10^9 M_\odot$ with a soliton radius of $\approx 700$ pc (Schive et al. 2014a; Chen et al. 2017). In this intermediate mass range the dispersion profile is relatively flat for DF44, unlike more massive galaxies of high
internal soliton momentum, that are predicted to have a narrower, denser central soliton core of approximately 100pc in radius with a correspondingly enhanced central velocity dispersion. This is supported by the rising central velocity dispersion recently measured in the Milky Way (De Martino et al. 2018). For lower mass galaxies than DF44, wider solitons are predicted, reaching 3 kpc in scale close to the lower limiting “Jeans mass”, below which galaxies do not form in Wave-DM as the dark matter cannot be confined below the de Broglie scale. This limiting soliton size appears to be matched by the newly discovered Antlia II galaxy which is extremely “ghostly” despite its large size and proximity orbiting the Milky Way and identified by star proper motions with Gaia (Torrealba 2019). For the newly discovered Antlia II galaxy which is extremely “ghostly” in Wave-DM as the dark matter cannot be confined below the de DF44,widersolitonsarepredicted,reaching3kpcinscaleclosetoDF44,that is consistent with our analysis here for DF44 and other well studied dSph galaxies, (Broadhurst et al. 2019).

For DF44 we have found here that its extended light profile and flat velocity dispersion profile can be reproduced by a Wave-DM profile for a halo of intermediate mass $\approx 10^{11} M_\odot$, consistent with conclusion of Wasserman (2019).

It is now becoming clear that UDG galaxies like DF44 are surprisingly common in clusters and are also present in the field (Martinez-Delgado et al. 2016; RomÅ¡n et al. 2017) that as a class appear to challenge conventional expectations regarding galaxy formation with their large sizes and low surface brightnesses. It is also understood that UDG galaxies are more numerous in more massive galaxy clusters (van der Burg et al. 2016) like Coma where they were first recognised by van Dokkum et al. (2016) and within the exceptionally massive cluster A2744 where the highest number of UDG galaxies has been detected (Kendall et al. 2019). A interesting connection with HI rich “HUDS” optically diffuse galaxies has been found by Leisman et al. (2017), who have identified in the HI selected Alfalfa survey that have stellar profiles resembling UDG galaxies. Isolated red UDG have also been discovered “DGSTAR” (Martinez-Delgado et al. 2016) and “S82-DG-1” (RomÅ¡n et al. 2017) but with limited dynamical and distance information. There also apparently related star forming examples of UDGs (Prole et al. 2019) which resemble the class of local “transition” dwarf galaxies with stellar velocity dispersion profiles like the dSph’s with the additional presence of some rotating HI. Collectively this has been taken to imply that UDGs found in clusters may in general be born in low density environments and either used up their gas over time and subsequently ram pressure stripped of their gas by the hot intra-cluster gas (Liao et al. 2019).

There is still a dearth of dynamical measurements for UDG galaxies, with DF44 currently the only example reported with a resolved stellar dispersion profile. Improving uncertain distance estimates are also crucial for establishing reliable M/L and radius estimates. The clarity this will bring will then allow the origins of UDG’s to clariﬁed in relation to less extreme “normal” galaxies. A unifying picture may be emerging regarding the role of environment, at least for UDGs-like galaxies detected in the HI selected ALFALFA survey, where no preference is found for clusters or underdense regions relative to the general galaxy population (Janowiecki et al. 2019) so the surprising properties of UDG galaxies may be intrinsic rather than primarily driven by interaction (Janowiecki et al. 2019).

In conclusion, we have argued that CDM does not easily account for the unusual properties of DF44, as the rising central mass density inherent to the NFW proﬁle means low mass halos are preferred together with a large negative velocity dispersion anisotropy, so that the central dispersion is not exceeded for DF44 but then the observed stellar scale length of DF44 exceeds the predicted scale length of the DM expected for concentrations of $\approx 15 - 20$ predicted by LCDM simulations. This apparent size scale contradiction is not present for $\psi_{DM}$ where the central dispersion is readily reduced by the presence of a soliton core, without the need for excessive tangential velocity anisotropy.

This consistency we find for DF44 with $\psi_{DM}$ is important as it extends the viability of this form of wave-like DM beyond the dSph class for which clear agreement has been claimed with the wide solitonic cores predicted for this lower mass class of galaxy. The Milky Way provides more evidence of this possibility, as a dense, dark central mass of $10^9 M_\odot$ has been uncovered (Portail et al. 2017) from the centrally rising dispersion profile of bulge stars that appears in excellent agreement with the expectation of $\psi_{DM}$ for a boson mass of $\approx 10^{-22} eV$ (De Martino 2020).

Further dynamical data and extension to higher mass galaxies should now be explored with high resolution spectroscopy to clarify further where the relatively compact and massive solitons predicted at high mass are supported by the data to establish the basic viability of the coheret light boson hypothesis for the Universal dark matter.

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