Ultra-Light Dark Matter in Ultra-Faint Dwarf Galaxies

Erminia Calabrese\textsuperscript{1,2} and David N. Spergel\textsuperscript{1}†
\textsuperscript{1} Department of Astrophysical Sciences, Peyton Hall, Princeton University, 4 Ivy Lane, Princeton, NJ USA 08544
\textsuperscript{2} Sub-department of Astrophysics, University of Oxford, Denys Wilkinson Building, Oxford, OX1 3RH, UK

23 May 2016

ABSTRACT
Cold Dark Matter (CDM) models struggle to match the observations at galactic scales. The tension can be reduced either by dramatic baryonic feedback effects or by modifying the particle physics of CDM. Here, we consider an ultra-light scalar field DM particle manifesting a wave nature below a DM particle mass-dependent Jeans scale. For DM mass \( m \sim 10^{-22}\) eV, this scenario delays galaxy formation and avoids cusps in the center of the dark matter haloes. We use new measurements of half-light mass in ultra-faint dwarf galaxies Draco II and Triangulum II to estimate the mass of the DM particle in this model. We find that if the stellar populations are within the core of the density profile then the data are in agreement with a wave dark matter model having a DM particle with \( m \sim 3.7 - 5.6 \times 10^{-22}\) eV. The presence of this extremely light particle will contribute to the formation of a central solitonic core replacing the cusp of a Navarro-Frenk-White profile and bringing predictions closer to observations of cored central density in dwarf galaxies.

Key words: Cosmology: theory, dark matter – galaxies: dwarf, haloes.

1 INTRODUCTION
The ΛCDM model emerged in the last two decades as the simplest model that consistently accounts for most astrophysical and cosmological observations (Spergel et al. 2003, Planck Collaboration et al. 2015). In this scenario most of the matter content of the Universe is in the form of a non-interacting and non-relativistic matter component, Cold Dark Matter (CDM), and at present its nature is unknown.

CDM models successfully reproduce the evolution of a smooth early Universe into the cosmic structures observed today on a wide range of redshifts and scales. However, the agreement between models and observations degrades rapidly when zooming into the innermost galactic regions.

In the standard model of galaxy formation, galaxies are seeded by dark matter haloes (White & Rees 1978; Blumenthal et al. 1984; White & Frenk 1991), whose structure is a very powerful probe to distinguish between different theoretical models. DM haloes have been extensively studied with N-body simulations (see e.g., Kuhlen et al. 2012 for a review) and the similarities between different CDM-only simulated haloes have justified the definition of a universal dark matter halo profile, the Navarro-Frenk-White (hereafter NFW, (Navarro et al. 1996)) profile. However, improved resolution in N-body simulations has revealed that at small scales the CDM paradigm presents three major problems (see Weinberg et al. 2013 and references therein): (i) the cusp-core problem - NFW density profiles arising from CDM-only simulations predict a steeper density (cusp) towards the center of the DM halo compared to disc and dwarf spheroidal galaxies observations of a flatter central density (core); (ii) the missing satellites problem - CDM models predict more-than-observed Milky Way satellite galaxies living in DM sub-haloes; (iii) the too-big-too-fail problem - CDM models predict more-than-observed massive DM sub-haloes.

These problems can be solved at the theory level with two possible approaches: including baryonic feedback or other astrophysical effects into the simulations (see e.g., Governato et al. 2012; Di Cintio et al. 2014; Pontzen & Governato 2014; Pawlowski et al. 2015; Oñorbe et al. 2015; Papastergis & Shankar 2015 for recent discussions), or modifying the CDM component.

Here, we take the latter approach and consider a
modification of the particle physics of DM, allowing for
the presence of a light bosonic, axion-like, dark mat-
ter particle. If the DM particle is ultra-light, with mass
$\sim 10^{-22}\text{eV}$, than its wave nature can manifest on astro-
physical scales and bring theoretical predictions closer
to the observations (Goodman 2000; Hu et al. 2000;
Schive et al. 2014a,b; Marsh & Silk 2014).

Ultra-light axion-like particles are one of the most
compelling candidates for CDM and have been ex-
plored with different observables covering many cos-
mic epochs (from Cosmic Microwave Background data
(Hlozek et al. 2015), Lyman-$\alpha$ systems (Amendola &
Barbieri 2006), reionization history (Bozek et al. 2015;
Schive et al. 2016; Sarkar et al. 2015), galaxy formation
and dwarf galaxy dynamics (Schive et al. 2014a; Lora
& Magaña 2014; Lora 2015; Marsh & Pop 2015)). Ax-
ions will behave like matter in the present Universe as
long as their mass is $> 10^{-13}\text{eV}$ and consistency with
the CMB demands that the dominant DM component
has $m > 10^{-24}\text{eV}$ (Hlozek et al. 2015). On the other
end, axions can feasibly be distinguished from CDM
as long as $m < 10^{-18}\text{eV}$ (Marsh 2015b); heavier ax-
ions are allowed as DM, but are indistinguishable form
CDM in their effects on structure formation. Collect-
ing all cosmological and astrophysical information we then
currently know that $10^{-24} < m < 10^{-18}\text{eV}$. See Marsh
2015a for a comprehensive review.

To add to these DM mass constraints here we con-
sider two recently discovered ultra-faint dwarf galaxies
in the Milky Way, Draco II and Triangulum II (Laevens
et al. 2015a,b). Both objects seem to be very peculiar.
The analysis of Martin et al. 2016a classifies Draco II as
the smallest dwarf galaxy ever confirmed. Triangulum
II is bigger than Draco II but fainter. Its nature is still
controversial (see discussion in Kirby et al. 2015 and
Martin et al. 2016b) but preliminary data reductions
suggest it is likely to be a dwarf galaxy. In particular, it
seems to be the dwarf with the largest mass-to-light ra-
tio and so the most DM dominated object ever observed.
These two galaxies will complement existing constraints
on DM.

The paper is organized as follows. We describe the
wave dark matter model in Section 2 and the data in
Section 3. In Section 4 we estimate the DM particle
mass and compare the predictions with a ΛCDM NFW
model. We discuss our results and conclude in Section 5.

2 WAVE DARK MATTER HALOES

An alternative to CDM that has recently gained much
attention is the Bose-Einstein Condensate Scalar Field
Dark Matter model (BEC/SFDM) (see e.g., Turner
1983; Ji & Sin 1994; Lee & Koh 1996; Guzmán et al.
1999; Goodman 2000; Matos et al. 2000; Böhmer &
Harko 2007; Sikivie & Yang 2009; Woo & Chiueh 2009;
Lundgren et al. 2010; Harko 2011a,b; Chavanis 2011;
Chavanis & Dellini 2011; Chavanis 2012; Magaña &
Matos 2012; Harko & Mocanu 2012; Harko & Madarassy
2012; Lora et al. 2012; Suárez et al. 2014; Lora &
Magaña 2014; Li et al. 2014; Harko 2014; Lora 2015;
Marsh & Pop 2015; Guzmán & Lora-Clavijo 2015;
Harko et al. 2015; Harko & Lobo 2015; Davidson 2015;
Guth et al. 2015 and references therein), also known
as Fuzzy Dark Matter (Hu et al. 2000) or Wave Dark
Matter (Schive et al. 2014a). In this scenario DM is
made of extremely light bosons, such as axion-like parti-
cles, non-thermally generated and described by a scalar
field $\psi$. If the field’s bosons are ultra-light, with a mass
$\sim 10^{-22}\text{eV}$, quantum pressure from the bosons occu-
pying the same ground state counters gravity and in the
early Universe they condensate in a single coherent
macroscopic wave (a self-gravitating Bose-Einstein con-
densate). The field is minimally coupled to gravity and
interacts only gravitationally with the baryonic matter.
In the Newtonian approximation and in the case of neg-
ligible self-interaction between bosons (as in the case
presented in Hu et al. 2000; Schive et al. 2014a that we
will follow here), the scalar field is then well described
by the coupled Schrödinger and Poisson equations (see
e.g., Widrow & Kaiser 1993) and DM haloes are the
ground-state solution – the gravitational configuration
in equilibrium – of the system.

A very interesting feature of this model is an ef-
fective Jeans scale depending on the DM particle mass
below which the uncertainty principle counters gravity.
Galactic haloes form typically by the usual gravitational sta-
stility but with perturbations suppressed below a scale
that is set by the particle mass. As a result, interestingly
for galaxy formation, for $m \sim 10^{-22}\text{eV}$ flat (cored) den-
sity profiles are produced within $\sim 0.1 – 1\text{ kpc}$, galaxy
formation is delayed and the halo mass function shows
suppression of haloes smaller than $\sim 10^{10}\text{M}_\odot$, helping
with both the cusp-core and missing satellites problems
(Goodman 2000; Hu et al. 2000; Schive et al. 2014a,
2016; Marsh & Silk 2014).

In this work we consider the wave dark matter model,
$\psi$DM, presented in Schive et al. 2014a,b. Schive et al.
2014a performed the first high-resolution cosmolo-
gical simulations for wave dark matter and showed
that the central density profiles of all collapsed ob-
jects are well described by the stable soliton solution
of the Schrödinger-Poisson equation. A gravitationally
self-bound soliton core is found in every halo superposed
on a NFW profile. The NFW behaviour is recovered at
larger radii and the $\psi$DM cosmology is indistinguishable
from CDM on large scales.

Fitting cosmological simulations Schive et al. 2014a
shows that the density profile of the innermost central
region at redshift $0$ is well approximated by:

$$\rho_s(r) = \frac{1.9(10m_{22})^{-2}r^{-4}}{[1 + 9.1 \times 10^{-2}(r/r_c)^2]^{3/2}} 10^2\text{M}_\odot\text{kpc}^{-3}, \quad (1)$$

where $m_{22} \equiv m/10^{22}\text{eV}$ is the DM particle mass and
$r_c$ is the core radius of the halo. The soliton extends up
to $\sim 3r_c$ (Schive et al. 2014a,b).

From the density profile we can estimate the en-
closed mass at a given radius $r$:

$$M(< r) = \int_{0}^{r} 4\pi \rho_s(r’)r'^2 dr’. \quad (2)$$

$$M_c \equiv M(< r_c) \text{ gives the central core mass and the total mass of the halo, } M_h, \text{ hosting the galaxy. At the present time these relations are:}$$

$$M_c \sim \frac{1}{4} M_h^{1/3} (4.4 \times 10^{7} m_{22}^{-3/2})^{2/3}, \quad (3)$$

$$r_c \sim 1.6 m_{22}^{-1} \left( \frac{M_h}{10^{9} M_{\odot}} \right)^{-1/3} \text{ kpc,} \quad (4)$$

so that, for a given $m_{22}$, the largest cores are embedded on the smallest haloes.

For our purposes the soliton is the only component of the density profile that compares to the data. We assume that the stellar populations are within the core and we do not need any extrapolation to NFW at larger scales.\(^2\)

### 3 ULTRA-FAINT DWARF GALAXIES

Dwarf galaxies are believed to be the most common type of galaxies in the Universe. In a hierarchical formation scenario these objects are the building blocks of more massive galaxies and are believed to have been even more numerous at earlier times.\(^1\) The large mass-to-light ratios of dwarf galaxies, and in particular of ultra-faint dwarfs (half-light radius $<50$ pc), suggest that they are the most DM dominated objects and therefore a great laboratory to test DM models.

The richest source of information are nearby dwarfs, e.g., the Milky Way dwarf satellites, where individual stars can be resolved and stellar dynamics can track the density profile and the gravitational field. A candidate object identified in a survey can be considered a dwarf galaxy, and distinguished from stellar clusters, if it shows a velocity dispersion in excess of what would be expected from stellar mass alone ($\sim 0.3 \text{ km s}^{-1}$) or a dispersion in stellar metallicity ($\geq 0.1 \text{ dex in iron}$) indicating chemical self-enrichment (Willman & Strader 2012). These two properties make the candidate a dwarf galaxy dominated by dark matter.

\(^1\) We note that for this density profile the enclosed mass integral cannot be solved analytically and we will perform numerical estimates.

\(^2\) This approach follows the analysis of Schive et al. 2014a,b that found the soliton to be a good approximation of the full density profile. Marsh & Pop 2015 included the NFW component and found that it was unconstrained, and the data could be fit using only the soliton.

\(^3\) This is not necessarily the case in the ψDM model where structure formation is not strictly hierarchical because of the mass function cut-off.

In the last two decades many faint dwarf galaxies have been discovered with photometric surveys (SDSS (Belokurov et al. 2007), DES (Bechtol et al. 2015; Drlica-Wagner et al. 2015; Koposov et al. 2015)). Here we consider newly discovered ultra-faint dwarf galaxies, Draco II and Triangulum II, with the Pan-STARRS1 3\(\pi\) survey (Laevens et al. 2015a,b).

- **Draco II**
  - Draco II discovery (Laevens et al. 2015b) reported a close (distance from the Sun 20 ± 3 kpc), extremely compact (half-light radius $r_h = 19^{+6}_{-5}$ pc) and faint ($L_s = 10^{4.1-0.3}$) object whose nature was uncertain. The addition of spectroscopic observations led Martin et al. 2016a to find a small, yet marginally detected, velocity dispersion, $\sigma_v = 2.9 \pm 2.1 \text{ km s}^{-1}$, and a highly sub-solar metallicity, [Fe/H] $< -2.1$. Draco II stellar dynamics constrain the half-light mass to $\log_{10}(M_{1/2}) = 5.5^{+0.4}_{-0.6}$ and a mass-to-light ratio $\log_{10}(M/L)_{1/2} = 2.7^{+0.8}_{-0.6}$ (Martin et al. 2016a, using the definition of $M_{1/2}$ presented in Wolf et al. 2010). These estimates hint to a strongly dark matter dominated system and in particular to the smallest compact dwarf galaxy ever confirmed.

- **Triangulum II**
  - Similarly to Draco II, Triangulum II photometric properties were first reported in Laevens et al. 2015a and then followed-up with a spectroscopic analysis in Kirby et al. 2015 and Martin et al. 2016b. Triangulum II is a larger ($r_h = 34^{+8}_{-6}$ pc) but fainter ($L_s = 10^{2.5-0.2}$) system located at 30 ± 2 kpc. The velocity dispersion of the member stars was found to be $\sigma_v = 5.1^{+1.4}_{-1.1} \text{ km s}^{-1}$ with a corresponding $\log_{10}(M_{1/2}) = 5.9^{+0.4}_{-0.2}$ and $\log_{10}(M/L)_{1/2} = 3.00^{+0.09}_{-0.08}$ in solar units (Kirby et al. 2015). As for Draco II, these estimates (together with very low metallicity, [Fe/H] $\sim -2.5 \pm 0.8$) suggest that Triangulum II is a dwarf galaxy. A later analysis by Martin et al. 2016b reported somehow different results ($\sigma_v = 9.9^{+3.2}_{-2.2} \text{ km s}^{-1}$, $M_{1/2} \sim 3 \times 10^{5} M_{\odot}$, $(M/L)_{1/2} \sim 15000$) with inner and outer stars’ velocities in slight disagreement and with the nature of Triangulum II more uncertain. With current data, the uncertainty on these numbers is too big to have statistical significance and therefore we choose to continue our analysis assuming Triangulum II is a faint dwarf galaxy and using the estimates in Kirby et al. 2015. Both analyses, however, highlight that Triangulum II has a very large mass-to-light ratio, classifying it as the most DM dominated dwarf galaxy ever observed.

### 4 M22 ESTIMATE

To estimate the DM particle mass we match enclosed mass predictions with the observed half-light masses; fitting theoretical halos to half-light measurements of satellite galaxies has been widely done in the literature to investigate different density profiles (see e.g., Collins et al. 2014; Brook & Di Cintio 2015).
Schive et al. 2014a and Marsh & Pop 2015 constrained the DM particle mass performing a simplified Jeans analysis on the resolved stellar populations of Fornax and analyzing the mass profile slopes of Fornax and Sculptor dwarfs, respectively. A full Jeans analysis using the standard 8 Milky Way dwarf satellite galaxies to estimate $m_{22}$ (which is indeed a universal parameter) will soon appear in Gonzalez-Morales et al. 2016. The galaxies we consider here are very faint and observations do not have the needed resolution to better resolve the stellar dynamics (e.g., no information on velocity anisotropy). Our calculations are then preliminary estimates of the DM component and we defer a more extensive analysis to future data.

We use two observational limits:

- The half-light mass, $M_{1/2}$
  We assume that the stellar populations observed in Draco II and Triangulum II are within the respective core radius and we use the $M_{1/2}$ measurements to anchor the enclosed mass profile:

$$M_{1/2} = \int_{r_{1/2}}^{r_0} 4\pi r'^2 (\frac{M_{\text{halo}}}{10^9 M_\odot})^{-2} \frac{1}{1 + \frac{r'}{r_0}} \frac{dr'}{r'}$$

where $r_{1/2} = 4/3 r_0$ is the 3D deprojected half-light radius (Wolf et al. 2010).

This assumption is a good approximation with the current resolution, in both cases only very few stars are resolved (9 in Draco II and 6 in Triangulum II) and they seem to be in a single stellar system.

- The maximum halo mass, $M_{\text{max}}$
  We impose a maximum halo mass based on the mass function of the Milky Way dwarf satellite galaxies (Gio-coli et al. 2008). We choose $M_{\text{max}}$ to be $10^{-2} M_{\text{MW}} \sim 2 \times 10^{10} M_\odot$. Such a maximum halo mass for satellites is in agreement with recent Local Group abundance matching results (Brook et al. 2014). Moreover, $M_{\text{max}} \sim \text{ few } 10^{10} M_\odot$ are forbidden by dynamical friction time scales limits (Gerhard & Spergel 1992).

We fold this into Eq. 4 and get:

$$m_{22} = \frac{1.6}{r_c} \left( \frac{M_{\text{max}}}{10^9 M_\odot} \right)^{-1/3}.$$  

We will discuss later how the results change had we chosen a different $M_{\text{max}}$.

### 4.1 Numerical results

We can now combine Eq. 5 and Eq. 6 and numerically estimate the two parameters of the model ($r_c - m_{22}$) for the two galaxies. We find:

$$r_c \sim 105 \text{ pc}; m_{22} \sim 5.6$$

for Draco II and

$$r_c \sim 160 \text{ pc}; m_{22} \sim 3.8$$

for Triangulum II.

The corresponding core masses, using Eq. 3, are $M_{\text{DracII}} \sim 1.5 \times 10^5 M_\odot$ and $M_{\text{TriII}} \sim 2.3 \times 10^5 M_\odot$.

We show the $\psi$DM model predictions using these estimates and the half-light mass data in Fig. 1. The plot also shows NFW predictions for different values of the halo mass. In a NFW model these ultra-faint dwarfs lies systematically high compared to what we would expect, $M_h \approx 10^8 - 10^{10} M_\odot$ (see also Fig. 6 in Martin et al. 2016b).

However, given the uncertainty on these measurements, the data points seem to agree with a wide range of values for the halo mass; all models with $M_h \approx 10^9 - 10^{10} M_\odot$ are within the $1-\sigma$ errorbar and no definitive conclusion can be drawn. This plot is in fact highlighting an intrinsic limitation of constraining mass profiles with the innermost regions of galaxies. As shown in Ferrero et al. 2012, different theoretical predictions lie very close to each other at very small radii ($r < 1\text{kpc}$).
and a wide range of models agree with the data. To break the models degeneracy, observations of stars outside the core, constraining the velocity dispersion – or equivalently the mass – at larger radii are needed. Nevertheless, the higher NFW curves conflict with physical constraints, \( M_h \) can’t reach the same mass of the host galaxy (the Milky Way in this case) and can’t be bigger than the limits imposed by dynamical friction. In the case of \( \psi \)DM, we avoid this by imposing in the parameters model extraction the \( M_h^{\text{max}} \) quantity and finding a lower bound on \( m_{22} \) corresponding to the maximum mass we allow for the halo. If we choose a lower value for \( M_h^{\text{max}} \), e.g., \( \sim 5 \times 10^5 M_\odot \), the estimates become \( r_c \sim 66 \text{pc} - m_{22} \sim 14 - M_e \sim 3.8 \times 10^8 M_\odot \) for Draco II and \( r_c \sim 99 \text{pc} - m_{22} \sim 9.5 - M_e \sim 5.7 \times 10^8 M_\odot \) for Triangulum II. This means that our estimates for \( m_{22} \) in the case \( M_h^{\text{max}} = 2 \times 10^{10} M_\odot \) are lower limits for the DM particle mass. In the \( \psi \)DM model we can easily reconcile the data with smaller haloes at the expenses of a more massive DM particle.

We want to stress that in these results we are strongly dominated by the anti-correlation between \( r_c \) and \( m_{22} \) (see Fig. S4 in Schive et al. 2014a), deeper observations, resolving multiple stellar systems positioned at different radii in the enclosed mass predictions, will be fundamental to get more robust estimates.

We report in Fig. 2 the predicted circular velocities, \( v(r) = \sqrt{GM(<r)/r} \), out to 3-times the core radius – where the soliton density is a good approximation of the total halo density – for the \( \psi \)DM estimates derived above and for a NFW profile with the same \( M_h^{\text{max}} \). As previously anticipated, the plot highlights that measurements of the stellar velocities at larger distances from the center will help distinguish between different curves and impose strong constraints on the density profiles. We note that this plot does not extend to the constant velocity regime generated by the additional NFW-like density profile term overtaking the soliton profile at large scales.

5 DISCUSSION

In this paper we have estimated the dark matter particle mass from newly discovered ultra-faint dwarf galaxies in a scenario where dark matter is made of ultra-light bosons, axion-like particles, condensate in a coherent wave.

Wave Dark Matter (\( \psi \)DM) has recently been a very valuable alternative to Cold Dark Matter (CDM) to solve the small-scale crisis of CDM in galaxy formation (Schive et al. 2014a,b, 2016; Marsh & Pop 2015). The \( \psi \)DM model in fact superpose a soliton core depending on the DM particle mass \( m \) on a Navarro-Frenk-White (NFW) density profile, smoothing the unwanted cusp in the center of the density profile and suppressing formation of haloes smaller than \( 10^{10} M_\odot \). At large scales \( \psi \)DM clustering is statistically indistinguishable from CDM.

![Figure 2. Circular velocity distribution predicted using the \( \psi \)DM model estimates for Draco II (blue line) and Triangulum II (magenta line) and using a NFW density profile with a \( 2 \times 10^{10} M_\odot \) halo mass.](image)

We have considered in this work data from recently discovered Draco II and Triangulum II Milky Way dwarf satellites. The measurements of the luminosity of these objects suggest that they are systems with a mass-to-light ratio of \( \sim 10^7 \) in the outer regions and therefore completely DM dominated. With such extreme DM environments, these dwarfs provide a great laboratory to study dark matter physics despite the contribution of baryonic feedback.

We anchor the soliton density profile of the \( \psi \)DM model using Draco II and Triangulum II half-light mass measurements and limits from the halo mass function of Milky Way satellite galaxies, and estimate at the same time the core radius \( r_c \) and the DM particle mass \( m \). We find that the \( \psi \)DM model requires \( r_c \sim 105 \text{pc} - m \sim 5.6 \times 10^{-22} \text{eV} \) for Draco II and \( r_c \sim 160 \text{pc} - m \sim 3.8 \times 10^{-22} \text{eV} \) for Triangulum II. With these values of the parameters, the haloes hosting the galaxies have a total mass of \( 2 \times 10^{10} M_\odot \). If we impose a smaller halo mass, we can readjust the estimates of \( r_c \) and \( m \) and embed these dwarfs in less massive haloes with a smaller core radius and a more massive DM particle.

Ultra-light axion-like particles have been recently tested with many cosmological probes as an alternative to CDM and the interesting scenario of many data supporting \( 10^{-21} \text{eV} \lesssim m \lesssim 10^{-21} \text{eV} \) is lately emerging: Lyman-\( \alpha \) systems constraints are presented in Amendola & Barbieri 2006, galaxy formation, galaxy dynamics and UV luminosity function tests in Lora & Mañaña 2014; Lora 2015; Schive et al. 2014a, 2016; Marsh & Pop 2015; Marsh & Silk 2014, reionization constraints in Bozek et al. 2015; Sarkar et al. 2015 and Cosmic Microwave Background limits in Hlozek et al. 2015. Our
estimates fit very nicely into these bounds and highlight how promising ultra-faint dwarf galaxies are in testing DM models.

Deeper observations from future experiments like JWST (Gardner et al. 2006), WFIRST (Spergel et al. 2013), LSST (LSST Science Collaboration et al. 2009), and Euclid (Laureijs et al. 2011) will enable further discoveries of Milky Way satellites and will characterize the stellar systems within these dwarfs with the resolution needed for more detailed analysis. They will, for example, enable some potential tests for the ψDM model:

- **minimum halo mass** – Following Schive et al. 2014a,b we can estimate the minimum halo mass possible in this scenario, \( M_{h_{\text{min}}} \sim 4.4 \times 10^7 m_{\odot}^{3/2} \sim 5 \times 10^6 M_\odot \). These objects will be the target of sub-halo detection via milli-lensing (Dalal & Kochanek 2002) and strong-lensing (Hezaveh et al. 2014).

- **late galaxy formation** – Lyman-\( \alpha \) emission, galaxy luminosity function (from JWST) and reionization (from CMB (Calabrese et al. 2014) or 21cm (Kadota et al. 2014)) will test the suppression of galaxy formation at high redshift predicted by this model (Marsh & Silk 2014; Schive et al. 2016).

- **sub-halo masses** – The halo mass function will manifest a truncation at low masses in the case of ψDM (Marsh & Silk 2014; Schive et al. 2016), with a suppression of objects below the Jeans scale set by the DM particle mass. Moreover, considering that our knowledge of the Galactic plane will soon dramatically improve with Gaia (Perryman et al. 2001), we can test this natural cut-off of the model by observing the predicted suppression of tidal streams.

**ACKNOWLEDGMENTS**

We are grateful to D.J.E. Marsh and H.Y. Schive for useful discussions. We especially thank D.J.E. Marsh, J.P. Ostriker, A. Di Cintio and R. Hlozek for reading the manuscript and providing useful feedback. EC is supported by Lyman Spitzer Jr. and STFC Rutherford Fellowships.

**REFERENCES**

Amendola L., Barbieri R., 2006, Physics Letters B, 642, 192
Bechtol K., et al., 2015, ApJ, 807, 50
Belokurov V., et al., 2007, ApJ, 654, 897
Blumenthal G. R., Faber S. M., Primack J. R., Rees M. J., 1984, Nature, 311, 517
Böhmer C. G., Harko T., 2007, J. Cosmology Astropart. Phys., 6, 25
Bozek B., Marshall J. D. E., Silk J., Wyse R. F. G., 2015, MNRAS, 450, 209
Brook C. B., Di Cintio A., 2015, MNRAS, 450, 3920
Brook C. B., Di Cintio A., Knebe A., Gottlöber S., Hoffman Y.,Yepes G., Garrison-Kimmel S., 2014, ApJ, 784, L14
Calabrese E., et al., 2014, J. Cosmology Astropart. Phys., 8, 040
Chavanis P.-H., 2011, Phys. Rev. D, 84, 043531
Chavanis P. H., 2012, A&A, 537, A127
Chavanis P.-H., Delphin L., 2011, Phys. Rev. D, 84, 043532
Collins M. L. M., et al., 2014, ApJ, 783, 7
Dalal N., Kochanek C. S., 2002, ApJ, 572, 25
Davidson S., 2015, Astroparticle Physics, 65, 101
Di Cintio A., Brook C. B., Macciò A. V., Stinson G. S., Knebe A., Dutton A. A., Wadsley J., 2014, MNRAS, 437, 415
Dolci-Wagner A., et al., 2015, ApJ, 813, 109
Dutton A. A., Macciò A. V., 2014, MNRAS, 441, 3359
Ferrero I., Abadi M. G., Navarro J. F., Sales L. V., Gurovich S., 2012, MNRAS, 425, 2817
Gardner J. P., et al., 2006, Space Sci. Rev., 123, 485
Gerhard O. E., Spergel D. N., 1992, ApJ, 398, L9
Giocoli C., Tormen G., van den Bosch F. C., 2008, MNRAS, 386, 2135
Guzmán-Morales A. X., Marsh D. J. E., Penarrubia J., Urena-Lopez L., 2016, In prep.
Goodman J., 2000, New Astron., 5, 103
Governato F., et al., 2012, MNRAS, 422, 1231
Guth A. H., Hertzberg M. P., Prescod-Weinstein C., 2015, Phys. Rev. D, 92, 103513
Guzmán F. S., Matos-Téllez H. B., 1999, Astronomische Nachrichten, 320, 97
Harko, T., 2011a, J. Cosmology Astropart. Phys., 5, 22
Harko, T., 2011b, Phys. Rev. D, 83, 123515
Harko, T., 2014, Phys. Rev. D, 89, 084040
Harko, T., Lobo F. S. N., 2015, Phys. Rev. D, 92, 043011
Harko, T., Madarassy E. J. M., 2012, J. Cosmology Astropart. Phys., 1, 20
Harko, T., Mocanu G., 2012, Phys. Rev. D, 85, 084012
Harko, T., Liang P., Liang S.-D., Mocanu G., 2015, J. Cosmology Astropart. Phys., 11, 27
Hezaveh Y., Dalal N., Holder G., Kisner T., Kuhlen M., Perreault Levasseur L., 2014, preprint, (arXiv:1403.2720)
Hlozek R., Girin D., Marsh D. J. E., Ferreira P. G., 2015, Phys. Rev. D, 91, 103512
Hu W., Barkana R., Gruzinov A., 2000, Physical Review Letters, 85, 1158
Ji S. U., Sin S. J., 1994, Phys. Rev. D, 50, 3655
Kadota K., Mao Y., Ichiki K., Silk J., 2014, J. Cosmology Astropart. Phys., 6, 011
Kirby E. N., Cohen J. G., Simon J. D., Guhathakurta P., 2014, ApJ, 784, L8
Koposov S. E., Belokurov V., Torrealba G., Evans N. W., 2015, ApJ, 805, 130
Kuhlen M., Vogelberger M., Angulo R., 2012, Physics of the Dark Universe, 1, 50
Laevens B. P. M., et al., 2015a, ApJ, 813, 44
Laureijs R., et al., 2011, preprint, (arXiv:1110.3193)
Lee J.-W., Koh I.-G., 1996, Phys. Rev. D, 53, 2236
Li B., Rindler-Daller T., Shapiro P. R., 2014, Phys. Rev. D, 89, 083536
Lora V., Magaña J., Bernal A., Sánchez-Salcedo F. J., Grebel E. K., 2012, J. Cosmology Astropart. Phys., 2, 11
Lundgren A. P., Bondarescu M., Bondarescu R., Balakrishna J., 2010, ApJ, 715, L35
MNRAS 000, 000–000 (0000)
Macciò A. V., Dutton A. A., van den Bosch F. C., 2008, MNRAS, 391, 1940
Magaña J., Matos T., 2012, Journal of Physics Conference Series, 378, 012012
Marsh D. J. E., 2015a, preprint, (arXiv:1510.07633)
Marsh D. J. E., 2015b, Phys. Rev. D, 91, 123520
Marsh D. J. E., Pop A.-R., 2015, MNRAS, 451, 2479
Marsh D. J. E., Silk J., 2014, MNRAS, 437, 2652
Martin N. F., et al., 2016a, MNRAS, 458, L59
Martin N. F., et al., 2016b, ApJ, 818, 40
Matos T., Guzmán F. S., Ureña-López L. A., 2000, Classical and Quantum Gravity, 17, 1707
Navarro J. F., Frenk C. S., White S. D. M., 1996, ApJ, 462, 563
Oserbe J., Boylan-Kolchin M., Bullock J. S., Hopkins P. F., Kereš D., Faucher-Giguère C.-A., Quataert E., Murray N., 2015, MNRAS, 454, 2092
Papastergis E., Shankar F., 2015, preprint, (arXiv:1511.08741)
Pawlowski M. S., Famaey B., Merritt D., Kroupa P., 2015, ApJ, 815, 19
Perryman M. A. C., et al., 2001, A&A, 369, 339
Planck Collaboration et al., 2014, A&A, 571, A16
Planck Collaboration et al., 2015, preprint, (arXiv:1502.01589)
Pontzen A., Governato F., 2014, Nature, 506, 171
Sarkar A., Mondal R., Das S., Sethi S. K., Bharadwaj S., Marsh D. J. E., 2015, preprint, (arXiv:1512.03325)
Schive H.-Y., Chiueh T., Broadhurst T., 2014a, Nature Physics, 10, 496
Schive H.-Y., Liao M.-H., Woo T.-P., Wong S.-K., Chiueh T., Broadhurst T., Hwang W.-Y. P., 2014b, Physical Review Letters, 113, 261302
Schive H.-Y., Chiueh T., Broadhurst T., Huang K.-W., 2016, ApJ, 818, 89
Sikivie P., Yang Q., 2009, Physical Review Letters, 103, 111301
Spergel D. N., et al., 2003, ApJS, 148, 175
Spergel D., et al., 2013, preprint, (arXiv:1305.5422)
Sudre A., Robles V. H., Matos T., 2014, Astrophysics and Space Science Proceedings, 38, 107
Turner M. S., 1983, Phys. Rev. D, 28, 1243
Weinberg D. H., Bullock J. S., Governato F., Kuzio de Naray R., Peter A. H. G., 2013, preprint, (arXiv:1306.0913)
White S. D. M., Frenk C. S., 1991, ApJ, 379, 52
White S. D. M., Rees M. J., 1978, MNRAS, 183, 341
Widrow L. M., Kaiser N., 1993, ApJ, 416, L71
Willman B., Strader J., 2012, AJ, 144, 76
Wolf J., Martinez G. D., Bullock J. S., Kaplinghat M., Geha M., Muñoz R. R., Simon J. D., Avedo F. F., 2010, MNRAS, 406, 1220
Woo T.-P., Chiueh T., 2009, ApJ, 697, 850