Galaxy Formation with BECDM - II. Cosmic Filaments and First Galaxies

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ABSTRACT
Bose-Einstein Condensate Dark Matter (BECDM; also known as Fuzzy Dark Matter) is motivated by fundamental physics and has recently received significant attention as a serious alternative to the established Cold Dark Matter (CDM) model. We perform cosmological simulations of BECDM gravitationally coupled to baryons and investigate structure formation at high redshifts ($z > \sim 5$) for a boson mass $m = 2.5 \cdot 10^{-22} \text{eV}$, exploring the dynamical effects of its wavelike nature on the cosmic web and the formation of first galaxies. Our BECDM simulations are directly compared to CDM as well as to simulations where the dynamical quantum potential is ignored and only the initial suppression of the power spectrum is considered – a Warm Dark Matter-like (“WDM”) model often used as a proxy for BECDM. Our simulations confirm that “WDM” is a good approximation to BECDM on large cosmological scales even in the presence of the baryonic feedback. Similarities also exist on small scales, with primordial star formation happening both in isolated haloes and continuously along cosmic filaments; the latter effect is not present in CDM. Global star formation and metal enrichment in these first galaxies are delayed in BECDM/“WDM” compared to the CDM case: in BECDM/“WDM” first stars form at $z \sim 13/13.5$ while in CDM star formation starts at $z \sim 35$. The signature of BECDM interference, not present in “WDM”, is seen in the evolved dark matter power spectrum: although the small scale structure is initially suppressed, power on kpc scales is added at lower redshifts. Our simulations lay the groundwork for realistic simulations of galaxy formation in BECDM.

Key words: galaxies: formation – galaxies: high redshift – cosmology: theory – dark matter

1 INTRODUCTION

The Lambda Cold Dark Matter (ΛCDM) theory has proven to be quite successful in describing the observable Universe: it explains both the homogeneity of the Universe on the
largest cosmological scales and the structure of the cosmic web (Planck Collaboration et al. 2016). Numerical simulations based on ΛCDM are able to correctly predict statistical properties of the observed different populations of galaxies, including Milky Way-like disk galaxies (e.g., Vogelsberger et al. 2014a,b; Pillepich et al. 2017; Hopkins et al. 2018; Grand et al. 2017; Springel et al. 2018; Vogelsberger et al. 2019a). However, on small-scales, certain challenges have been claimed to afflict the CDM model (Weinberg et al. 2015; Bullock & Boylan-Kolchin 2017) such as the “cusp-core problem” (ACDM predicts cuspy haloes instead of the observed cored haloes; Moore 1994; Flores & Primack 1994; Gentile et al. 2004; Donato et al. 2009; de Blok 2010); the “missing satellites problem” (Klypin et al. 1999; Moore et al. 1999) and the related problem with the abundance of isolated dwarfs (Zavala et al. 2009; Papastergis et al. 2011; Klypin et al. 2015); and the “too-big-to-fail problem” (in ACDM large dark matter subhaloes are too dense towards their centers when compared to the brightest observed dwarf satellite galaxies Boylan-Kolchin, Bullock & Kaplinghat 2011, 2012). Many of these do, however, rely on comparison of observational data with collisionless simulations. Indeed, the inclusion of baryon physics has been demonstrated to reduce or reconcile many of these issues (e.g., Kim, Peter & Hargis 2018; Ostriker et al. 2019; Dutton et al. 2019). Still, ACDM theory is not universally accepted partially because of the nature of its Cold Dark Matter (CDM) component remains a mystery. Multiple ground-based searches for a Weakly Interactive Massive Particle (WIMP) of mass \( 10^{-33} < m < 10^{-10} \) eV and the subsequent deficit of dwarf galaxies. BECDM can be tested with current and upcoming observations. At present, the majority of observational constraints place the boson mass at \( m > 10^{-22} \) eV (Hołzæk, Marsh & Grin 2018; Amorisco & Loeb 2018; Church, Mocz & Ostriker 2019; Lancaster et al. 2019), with Lyman-alpha constraints being potentially the most strict \( m > 10^{-21} \) eV (Iršič et al. 2017a; Nori et al. 2019). For a summary of various recent astrophysical constraints on the BECDM particle, see Yarnell Davies & Mocz (2019). However, the majority of these constraints in the literature are derived using approximate modeling of BECDM. Until recently, the study of structure formation in BECDM has been done using analytic methods as well as BECDM-only simulations (although see Hirano, Sullivan & Bromm 2017, for the first approximate hydrodynamical treatment of BECDM minus wave effects). Using analytic tools, Hu, Barkana & Gruzinov (2000) showed that perturbations grow linearly on scales much larger than the Jeans scale at equality, \( k_{eq} = 9 (m/10^{-22} \text{eV})^{1/2} \text{Mpc}^{-1} \), but oscillate on smaller scales leading to a suppression of clustering power and the subsequent deficit of dwarf galaxies. BECDM-only numerical simulations confirmed this picture: modest-resolution simulations verified the suppression of low-mass haloes (Woo & Chiu 2009), while higher resolution simulations characterized the formation of solitonic cores (e.g., Schive, Chiu & Broadhurst 2014; Schwabe, Niemeyer & Engels 2016a; Mocz et al. 2017), although, we remark that these simulations did not use self-consistent initial conditions predicted by the BECDM model (Hołzæk et al. 2015), but artificial ones instead to highlight/exaggerate growth of structure. Simulations with WDM, although ignoring the quantum effects of BECDM, also serve as a guideline for understanding structure formation in BECDM. For instance, the fact that first star forming objects in WDM are filamentary (Yoshida et al. 2003b; Gao & Theuns 2007) suggests that also in BECDM first stars will form in dense filaments rather than spherical haloes (Hirano, Sullivan & Bromm 2017). In this paper we explore structure and galaxy formation in BECDM using the first fully self-consistent simulations of BECDM coupled to baryonic physics, which were recently presented by Mocz et al. (2019). Such simulations are indispensable for future validation or rejection of BECDM.
In order to explore the observable effects of BECDM, we have developed a spectral BECDM solver and used it to investigate properties of idealized, virialized BECDM haloes (Mocz et al. 2017, Paper I). We have also integrated the solver into the hydrodynamics code Arepo\(^1\) (Springel 2010; Pakmor et al. 2016), and performed first-of-their-kind hydrodynamical simulations with BECDM and explored star-forming filamentary structures at \(z \sim 5.5\) (Mocz et al. 2019). In this work we look deeper into the simulated universe and explore structure and galaxy formation across cosmic time. For reference, we also compare our BECDM simulations to ΛCDM and WDM-like (“WDM”) simulations with the same initial seed for the perturbations.

This paper is organized as follows. In Section 2 we set the stage describing the mathematical formalism behind BECDM and summarize the numerical method that we employ. In Section 3 we discuss the setup of our cosmological simulations, and present large-scale results in Section 4. In Sections 5, 6, and 7 we explore the formation of dark matter structure, evolution of structure in gas and formation of first star-forming objects, respectively. Observational prospects with telescopes such as the James Webb Space Telescope are discussed in Section 8. Main differences between BECDM and CDM, as well as between BECDM and “WDM”, are summarized in Section 9. We offer our concluding remarks in Section 10.

## 2 NUMERICAL METHODOLOGY

In this section we outline the mathematical framework that governs BECDM, the numerical methods, and the physics included in our cosmological simulations. We also offer comments on the computational challenges in simulating BECDM compared to CDM.

### 2.1 BECDM cosmology

BECDM is governed by the Schrödinger-Poisson (SP) equations. In an expanding universe, these are:

\[
\frac{i\hbar}{\partial t} \left( \frac{\partial \psi}{\partial t} + \frac{3}{2} \mathcal{H} \right) = -\frac{\hbar^2}{2m} \nabla^2 \psi + mV\psi
\]

and

\[
\nabla^2 V = 4\pi G (\rho - \rho_c)
\]

where \(\psi\) is the wave function describing the scalar-field boson in the non-relativistic limit, \(\rho \equiv |\psi|^2\) is the dark matter density field, \(\rho_c\) is the volume-average density, \(m\) is the boson (axion) mass, and \(\mathcal{H} \equiv \dot{a}/a\) is the rate of Hubble expansion where at redshift \(z\) the scale factor is \(a \equiv 1/(1 + z)\).

In terms of comoving coordinate \(x\) (with the physical distance \(r \equiv ax\)) the SP equations become:

\[
\frac{i\hbar}{\partial t} \psi = -\frac{\hbar^2}{2m} \nabla^2 \psi + a^{-1} mV \psi
\]

where \(V = \sum_i m_i V_i\) is the total gravitational potential.

The SP equations, which describe a self-gravitating superfluid, can be recast into a fluid formulation per the Madelung (1927) transformation, which can aid with physical intuition. Decomposing the wavefunction as by its amplitude \(\psi\) and phase \(S\):

\[
\psi = R e^{i S / \hbar}
\]

and defining a velocity \((v_M; \text{Madelung velocity}) as the gradient of the phase:

\[
v_M \equiv \nabla S / m
\]

the Schrödinger equation can then be written as:

\[
\frac{\partial \rho_c}{\partial t} + \nabla \cdot (\rho_c v_M) = 0,
\]

\[
\frac{\partial v_M}{\partial t} + a^{-2} v_M \cdot \nabla v_M = -a^{-1} \nabla V_c + a^{-2} \frac{\hbar^2}{2m^2} \nabla \left( \frac{\nabla^2 R}{R} \right).
\]

Aside from the quantum potential term on the r.h.s. (defined as \(V_Q \equiv -\frac{\hbar^2}{2m} \nabla^2 R / R\)), the evolution equations look like those of classical evolution of individual particles under self-gravity, in the spirit of a Bohmian interpretation of quantum mechanics. The quantum potential is responsible for quantum wave effects, including dispersion and interference. The potential can also provide support against localized collapse due to self-gravity.

In contrast, CDM, a collisionless fluid as opposed to a superfluid, is governed by the Vlasov-Poisson (VP) equations. In terms of canonical coordinates these are:

\[
\frac{\partial f}{\partial t} + a^{-2} \mathbf{p} \cdot \nabla f - a^{-1} \nabla V \cdot \frac{\partial f}{\partial \mathbf{p}} = 0,
\]

\[
\nabla^2 V_c = 4\pi G (\rho - \rho_c)
\]

where \(f = f(x, p, t)\) is the distribution function, \(\rho_c = \int f d^3p\) is the canonical momentum coordinate (c.f. peculiar velocity is given by \(v = a\dot{x}\)) and the density is given by \(\rho_c = \int f d^3p\).

On scales much larger than the local de-Broglie wavelength:

\[
\lambda_{DB} = \frac{\hbar}{mv_M}
\]

\(\nu\text{MHz}\) is the on order of a kpc for the axion masses and typical velocities inside low mass haloes that we consider here) the SP and the VP equations approximate each other, even in the case of multi-stream flows (Kopp & Kaiser 1993; Kopp, Vattis & Skordis 2017; Mocz et al. 2018). Thus on the largest spatial scales, one expects BECDM to behave just like CDM. In the SP equations, the parameter \(\hbar/m\) controls the level of macroscopic quantum-ness (“fuzziness”) in the equations. In the limit \(\hbar/m \to 0\) (i.e., heavy particles), the SP equations may be expected to recover the classical VP limit (Kopp, Vattis & Skordis 2017; Mocz et al. 2018). In particular Mocz et al. (2018) have shown that the gravitational force-field converges to the classical collisionless limit as \(O(m^{-1})\) despite the density field not converging due to

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1. Arepo has been used to carry out state-of-the-art large-scale cosmological simulations, including the Illustris-TNG project (Pillepich et al. 2017; Springel et al. 2018).
2. Our WDM-like particles are collisionless (like CDM) but feature a truncated initial power spectrum of BECDM.
order unity fluctuations. Hence baryonic physics coupled to
the dark matter converges to classical CDM behavior as well
in the limit $\hbar/m \to 0$.

On smaller scales, the SP system is expected to show
quantum wave phenomena, such as soliton cores (stable,
ground-state eigenmodes where the uncertainty prin-
cipal/quantum potential opposes the gravitational collapse;
Schive, Chiuhe & Broadhurst 2014), vortex lines and recon-
nection (Mocz et al. 2017), interference patterns, quantum
tunneling, and non-classical phenomena if there exist jumps
in the wavefunction phase (e.g., colliding cores can bounce
off each other; Schwabe, Niemeyer & Engels 2016a).

Finally, we point out the scaling symmetry of the SP
and VP equations:
\[
\{x, t, \rho, m\} \rightarrow \{\alpha x, \beta t, \beta^{-2} \rho, \alpha \beta^{-2} m\},
\]
where $\alpha$ and $\beta$ are arbitrary scaling parameters. The VP
equations are scale-free, whereas the SP equations have a
single-scale (the de Broglie wavelength) set by the value of
\(\hbar/m\).

We note the SP equations for BECDM are obtained by
taking the non-relativistic limit of a Universe with a scalar
field. Higher order corrections may include an attractive self-
potential which is of interest for future work because it has
been recently shown that even a weak coupling strength can
cause an instability in structure formation (Desjacques, Ke-
hagias & Riotto 2018).

2.1.1 Spectral Method

The SP equations in comoving form (Eqns 3 and 4) are
evolved numerically using the spectral method we have de-
veloped and used in Mocz et al. (2017) – see reference for
details. The method uses a 2nd-order time-stepping method
and gives exponential convergence in space. The time-steps
are decomposed into a kick-drift-kick leapfrog-like scheme,
where each ‘kick’ and ‘drift’ are unitary operators acting on
the wavefunction. This makes it natural to automatically
couple the method to particle-based N-body techniques that
evolve gas and star particles in the simulation on the same
sub-timestep spacings. In our simulations, the BECDM is
fully coupled to baryons by including the baryonic contri-
bution to the potential in the Poisson equation (Eqn 4) and
using the full gravitational potential in Eqn 3.

The spectral method proves to be useful at capturing
interference patterns and vortex lines, which turn out to
be an integral feature of filamentary and halos in these cos-
ological simulations (Mocz et al. 2017). Vortex lines are
locations where the density $\rho = 0$, but are sites of quantized
vorticity in the fluid (the rest of the fluid is vortex free, as
$\nabla \times v_{\text{vm}} = 0$ since the velocity is the gradient of a scalar –
the phase). An alternative approach would be to work in the
fluid (Madelung) formulation, and use fluid solver methods
such as the smooth-particle-hydrodynamics approach devel-
oped by Mocz & Succi (2015), but the fluid formulation may
prove difficult to capture vortex lines accurately, as the den-
sity vanishes and the velocity is formally infinite here. The
spectral method is able to capture vortex lines without dif-
ficulty, owing to its exponential spatial convergence and the
fact that the calculations are done in terms of the phase
rather than its gradient (i.e., the velocity).

The spectral method is limited to uniform grids. The
resolution requirements are strict to be able to resolve soli-
ton cores expected to be in the centers of haloes (Schive,
Chiuhe & Broadhurst 2014). The soliton comoving radius
scales approximately as (Schive et al. 2014):
\[
x_c \sim 2 \left( \frac{m}{2.5 \cdot 10^{-22} \text{ eV}} \right)^{-1} \left( \frac{1 + z}{7} \right)^{1/2} \left( \frac{M_{\text{halo}}}{10^9 \; M_{\odot}} \right)^{-1/3} \text{ kpc}
\]
and is on order of few kpc for the selected axion mass. Fur-
thermore, because the velocity is defined as the gradient of
the phase, the spatial resolution defines a maximum velocity
that can be numerically represented as:
\[
v_{\text{M, max}} = \frac{\hbar}{m} \frac{\pi}{\Delta x}.
\]
One needs to resolve the velocity dispersion of the highest
mass halo expected to be formed in the cosmological box of
a given volume. These limitations mean that with present
computational supercomputing resources, one is limited to
simulated box sizes of a few $h^{-1}$ Mpc and is confined to
the high-redshift regime for axion masses of interest around
$10^{-22}$–$10^{-21}$ eV.

2.1.2 Discussion of various numerical approaches for
BECDM and their advantages and limitations

BECDM is more computationally challenging than CDM,
due to the need to resolve kpc-scale interference patterns
and large velocities (present throughout the halo) and soli-
ton cores. Here we outline the advantages and disadvantages
of different methods (spectral, adaptive grid finite differ-
ence, and SPH and mesh-free finite-volume methods for the
Madelung formulation).

Spectral methods are an ideal choice for the
Schrödinger-Poisson equations, owing to the smoothness
of the wavefunction, and the unitary nature of the dis-
cretization (Mocz et al. 2017). Spectral accuracy allows for
machine-precision control of spatial truncation errors.
The only limitation of the method is that the largest
wave-number in the solution (corresponding to the smallest
scale of $2\pi/k_{\text{max}}$) needs to be resolved. To robustly model
BECDM, one needs to resolve the de Broglie wavelength,
which is of order a kpc for our choice of the boson mass.
Thus, the box size for a cosmological simulation is limited to
a few comoving Mpc for a resolution of $10^{24}$
. This limits
applications of spectral methods to systems with low val-
ues of maximal velocities, such as low-mass first galaxies (in
haloes of mass $< 10^{11} \; M_{\odot}$), such as the work presented by
Mocz et al. (2019) and the one here. Due to the resolution
requirements we stop our simulations at $z = 5.5$. It is not
possible at the current resolution for us to evolve the so-
lution further to lower redshifts. This is because the halo
masses would increase, as well as their velocity dispersion,
which would not be resolved and the spectral method would
break. Moreover, the physical soliton size becomes smaller
in these cases; more massive haloes have more compact soli-
ton cores, and soliton size on the fixed comoving grid shrinks as
the inverse of the scale factor $1/a$.

To achieve a slightly larger cosmological box, one may
use an adaptive refined mesh as done by Schive, Chiuhe &
Broadhurst (2014). The wave function can be evolved with
a finite difference technique in this case (taking special care
that truncation errors of the complex field do not exponentially blow up the solution). This approach makes it possible to capture the evolution of BECDM in larger volumes utilizing the fact that haloes and filaments show interference patterns which need to be resolved, but voids, which have only a single velocity, are feature-free (and make up the majority of the volume). Still, such simulations are limited to box sizes $<10$ Mpc, whereas CDM simulations can be much larger ($>100$ Mpc – Gpc, Springel et al. 2005; Villaescusa-Navarro et al. 2019).

The SP equation can also be rewritten in fluid (Madelung) form, and solved with an SPH discretization, a concept shown in Mocz & Succi (2015). The method has a theoretical limitation, which is that velocities can formally diverge where the density is vanishing, and it remains to be shown that such regions (such as vortex lines in 3D) can be accurately resolved. Second, at least $O(10)$ particles are needed per interference wave-crest in order to resolve it (i.e., the SPH smoothing length needs to be smaller than the local interference scale). An SPH approach has been developed by Nori & Baldi (2018) for the study of large-scale cosmic structure. However, their simulations do not have enough resolution to resolve interference crests or the soliton core at the halo centers, which we are interested in. The SPH numerical method is able to capture the Mpc-scale effects of the quantum potential (e.g. suppressed power spectrum) while missing small-scale features. The fluid formulation has also been discretized recently for the mesh-free finite-volume method (Hopkins 2019). However, it remains to be shown that these Madelung methods can accurately capture coherent interference patterns in the simulations.

A review of some of the numerical methods for BECDM is also given by Zhang, Liu & Chu (2018). An open-source pseudo-spectral solver (PyULTRALIGHT) exists for Python as well (Edwards et al. 2018).

2.2 Baryons

Dark matter is coupled to baryons (gas, stars) in the universe through gravity. The baryons themselves experience complex physical processes, which in our simulations are covered by Arepo and include sub-grid models for primordial and metal-line cooling, chemical enrichment, stochastic star formation with a density threshold of 0.13 $\text{cm}^{-3}$, supernova feedback via kinetic winds, and instantaneous uniform reionization at $z \sim 6$ (Vogelsberger et al. 2013; Torrey et al. 2014; Pillepich et al. 2017; Springel et al. 2018). Such models have been used in the Illustris and Illustris-TNG projects which aimed at reproducing the observed properties of galaxies in a $\Lambda$CDM Universe. We refer the reader to the papers cited in this paragraph for the full details of the baryonic physics implementation. For the purposes of this work, we used the fiducial framework of Vogelsberger et al. (2013). Feedback from supermassive black holes was not included as it would not be relevant for the low mass first haloes studied here.

The stellar feedback models have been tuned previously to CDM simulations, with free parameters constrained based on the overall star formation efficiency using smaller scale simulations (Vogelsberger et al. 2013). We use the same model for our BECDM simulations here. Whether the tuned feedback parameters in smaller CDM simulations apply to BECDM simulations requires further study.

Stellar feedback affects low mass galaxies most. Our subgrid model for feedback is meant to describe the effects of Type II supernovae (SNII), and uses the local star formation rate to set the mass loading of stellar winds driven by the energy available through SNII (Vogelsberger et al. 2013; Pillepich et al. 2018). Reduced star formation in BECDM compared to CDM will also lessen the impact of such feedback, unless the mass loading factor is re-tuned.

3 SIMULATIONS

The spectral BECDM solver has been implemented in the Arepo code (Springel 2010), a high-performance parallel code for solving gravity and (magneto)hydrodynamics which incorporates star formation via sub-grid prescription. Here we describe our simulation setups and output.

We carry out three types of cosmological simulations with a full physical treatment of the baryons:

(i) CDM: the dark matter component is CDM, with proper CDM initial conditions (Gaussian random field conditions evolved to $z = 127$ via second-order Lagrangian perturbation theory).

(ii) BECDM: all dark matter is in the form of BECDM. We model both the initial suppression in the power spectrum (using axionCAMB, Hlozek et al. 2015) and posterior evolution which accounts for the quantum potential;

(iii) “WDM”: an intermediate approach where we simulate the dark matter as collisionless (like CDM) but with BECDM initial conditions. In this type of simulation, we explore just the effect of the suppression in the power spectrum on the subsequent structure formation and evolution, and ignore the dynamical effects of the quantum potential. We refer to this simulation as a “WDM” simulation, in quotes, because full-physics WDM should include the contribution of thermal velocities which we ignore here. Such an analogy between BECDM and WDM has been made in the past (Hui et al. 2017; Hirano, Sullivan & Bromm 2017): our boson particle mass of $m = 2.5 \cdot 10^{-22}$ eV corresponds roughly to a WDM particle mass of 1.4 keV.

Finally, to isolate the effect of baryonic feedback, we run three corresponding dark matter-only simulations.

3.1 Generating initial conditions for BECDM

Initial power spectra for the BECDM cosmology are generated at $z = 127$ using axionCAMB and assuming that all dark matter is in the form of axions. The code adds a relativistic axion fluid (with boson mass $m$) component to the universe, and calculates its early evolution using the first order perturbed Klein-Gordon equations. At late times, the treatment uses a WKB approximation that matches the axion fluid to an effective fluid with equation of state zero and a scale-dependent sound-speed.

The initial power spectra match that of CDM on large scales ($>1$ Mpc), and the main effect of BECDM is to introduce a cutoff on small scales due to the length-scale introduced by the de Broglie wavelength of the axion. For an axion mass of $m = 2.5 \cdot 10^{-22}$, the cutoff is approximately...
We select an “interesting” initial seed for structure formation out of 20 randomly generated initial conditions to contain a nearly-spherical halo and a well-defined filament. This was done with an aim to explore the variety of structures that could form in a BECDM universe. The drawback of our selection process is that the simulated volume is not representative.

We have carried out our simulations on the Stampede 2 supercomputing cluster, part of the Texas Advanced Computing Center (TACC) at the University of Texas, and the Odyssey cluster supported by the FAS Division of Science, Research Computing Group at Harvard University. The computational cost for the BECDM simulation is ~ 3 million CPU core hours. The other simulations are cheap (by more than a factor of 20) because they use 8 times fewer particles and have a less stringent timestep criterion (Mocz et al. 2017).

4 LARGE SCALE STRUCTURE

We compare 3 small-box cosmological simulations (CDM, “WDM”, BECDM), which have led to the formation of ~ 10^7–10^10 M⊙ haloes by z ~ 6. In Fig. 1 we show the projected densities of the dark matter and baryonic gas at z = 63, 31, 15, 7, 5.5, that is, at the scale factor increasing by a factor of 2 at each step. The BECDM and “WDM” projected densities resemble each other closely on the scales of the box, indicating that on large scales the primary effect of the quantum potential is the initial suppression of the power spectrum, while dispersion and interference have not up-scattered significantly to affect large scale modes. The truncated initial power spectrum leads to the formation of filaments as well as haloes. The CDM simulations show the
same large-scale structures as well, but the filaments are now comprised of numerous subhaloes owing to the lack of a length scale in CDM (the fragmentation into subhaloes is a function of the mass resolution of the dark matter).

The baryonic gas initially traces the dark matter density very closely. The gas follows the gravitational potential on large scales, and shocks and cooling are unimportant for the dynamics. But the gas has a sound-speed/pressure, so the cosmic Jeans criterion prevents collapse of gas in the smallest substructures (the Jeans mass is about $10^5 M_\odot$ at $z = 100$ and $2 \times 10^4 M_\odot$ at $z = 20$). Additionally, star formation triggers reionization which, in these simulations, is driven by a uniform ionizing background that is turned on by hand at $z \sim 6$; the ionization erases small scale features. Furthermore, after stars form the gas distribution is also modified by feedback – stellar winds from supernovae blow hot, low-density 100 kpc scale bubbles.

Even though on large scales three simulations resemble each other, on small scales all these scenarios yield very different structures highlighted by (Mocz et al. 2019) and investigated in more details in the following Sections (Sections 5, 6, and 7).

5 DARK MATTER STRUCTURES

5.1 The dark matter power spectra

The evolved dark matter power spectrum is shown in Fig. 2. At wavenumbers smaller than the initial suppression scale $k_{1/2}$ (shown by vertical dashed line in the figure), BECDM and “WDM” continue to follow CDM closely down to the end of our simulation at $z = 5.5$, which means that there is no inverse-cascade of power to scales $\gtrsim 1$ Mpc due to, for example, the quantum potential. BECDM and “WDM” follow each other closely between the initial redshift and $z \sim 15$, indicating that the dynamically active quantum potential has not modified structure significantly. In both cases of BECDM and “WDM”, the power spectra show a lack of power at large $k$ compared to CDM due to the initial cutoff. But by redshift $z = 7$ BECDM exhibits excess power on small scales (few kpc) compared to both CDM and “WDM” due to interference patterns in the simulations that have formed as a result of shell-crossing and virialization inside haloes (more on this in our Section 5.3 on dark matter filaments). This highlights the need to solve BECDM self-consistently, with the inclusion of the quantum potential.

5.2 First dark matter objects

In all of the considered cosmologies, structure formation is hierarchical with smallest objects forming first. In CDM, the minimum mass is defined by the resolution of our simulation; while in BECDM/“WDM” the truncated initial power spectrum sets the minimum mass of a halo that is allowed to form (Hui et al. 2017)

$$M_{\text{min}} \approx 4 \times 10^6 M_\odot \left( \frac{2.5 \times 10^{-22} \text{ eV}}{m} \right)^{3/2}. \tag{17}$$

Our limited cosmological volume forms 3 haloes of mass $M_{200} \sim 10^{10} M_\odot$ by redshift $z \sim 6$. Some of the main properties of the haloes (masses, sizes, fraction of mass in gas and stars, triaxiality parameters, and when stars first form), discussed here and in the subsequent sections, are summarized in Table 1. We also show zoom-in projections of the haloes (dark matter, gas, and stars) in Fig. 3. Here we discuss the leftmost panels of Fig. 3, which show the halo dark matter distributions. The structures that form are quite interesting. In BECDM/“WDM”, filaments are able to form early. They are unstable and eventually fragment to form a core / halo. In CDM (a scale-free theory) haloes form much earlier, as they are seeded by smaller-scale perturbations, and filaments themselves have substructure down to the mass resolution scale.

Table 1 also lists when each of the $z \sim 6$ haloes formed under the three different cosmologies. In BECDM/“WDM” we quote when the initial filamentary structure fragments to form a spherically-collapsed object, which occurs well after stars form in the (cylindrical) filament that hosts haloes 2 and 3; stars form in the filaments around $z \sim 12$ but the fragmentation into haloes only occurs at $z \sim 7$, around which time central solitons start becoming visible too. Halo 1 forms out of more spherical conditions at $z \sim 13$ and also starts forming stars at that time. In CDM the halo is a result of many smaller mergers, so we quote the redshift of the last major merger prior to $z = 6$. Stars begin to form in subhaloes quite early $z > 30$ that then merge to form the $z = 6$ halo. Last major mergers for these CDM haloes occurs at $z \sim 10$.

5.2.1 Triaxiality

There is a stark contrast in the triaxiality of first haloes in CDM vs BECDM/“WDM”. Triaxiality is an important measure for dark matter haloes, because non-sphericity affects weak and strong lens statistics, the nonlinear clustering of dark matter, and the orbital evolution of satellites galaxies (Jing & Suto 2002), as well as the orbits of stars in the stellar halo of our own Milky-Way (Iorio et al. 2018). Our results indicate that triaxiality could be used as a probe of dark matter nature, and, therefore, it is important to quantify systematic differences in triaxialities for different dark matter models. We estimate the triaxiality of the haloes at $z = 6$ and list $q$ and $s$ triaxiality measures in Table 1. The triaxiality parameters of the halo are computed at the radius $R_{200}$ following the procedure in Chua et al. (2019), haloes are characterized by $0 < q \leq 1$, the intermediate-to-major axis ratio, and $0 < s \leq q$, the minor-to-major axis ratio. In CDM, haloes may have typical intermediate-to-major axis ratios of $q \sim 0.7$ (Chua et al. 2019) which is what we observe in our CDM simulation as well (our haloes have $q = 0.55 - 0.85$ at $z \sim 6$). For comparison, BECDM/“WDM” haloes are significantly more triaxial than in CDM with $q = 0.3 - 0.4$. Furthermore, BECDM/“WDM” low-mass haloes are much more elongated than those of CDM with $s = 0.2 - 0.3$, while for CDM this parameter measures $s = 0.4 - 0.5$.

5.2.2 Halo radial profiles

The shape of the dark matter gravitational potential wells determines the distribution and motion of the observed luminous objects. The structure of virialized DM haloes in the case of BECDM is predicted to be very different from the
Figure 1. Structure formation of dark matter (orange/purple) and gas (green/blue) in our simulations under the 3 cosmologies studied. We plot projected (comoving) densities along the line of sight (see colorbars at the bottom of the figures for the values of the projected density field). The snapshots are shown at intervals of the scale factor increasing by a factor of 2, as well as the final snapshot of the simulation. The box size is $1.7 h^{-1}$ Mpc. In these large-scale projections, gas follows the dark matter potential wells, and BECDM and “WDM” appear similarly filamentary, while CDM has filaments fragmented into subhaloes.
Table 1. Summary of halo properties at $z \approx 6$ under different cosmologies. $M_{200} \ [M_\odot]$ is the total mass of each halo at mean density over the critical density of $\Delta_c = 200$; $R_{200}$ [kpc] is the virial radius; $f_{\text{gas},200}$ is the fraction of matter in gas; $f_{*,200}$ is the fraction of matter in stars; $q$ is the first triaxiality parameter defined as the intermediate-to-major axis ratio; $s$ is the second triaxiality parameter defined as the minor-to-major axis ratio; $z_{\text{stars form}}$ is the formation redshift of the first stars ($> 100 \ M_\odot$); $z_{\text{halo forms}}$ is the formation redshift of the halo, defined as the time of the last major merger for CDM; and as the first instant at which one can identify a central halo. We plot radial density profiles for dark matter, gas, and stars of our three haloes in Fig. 4. Halo centres are identified by gravitational potential minima. We also compare the dark matter profiles to corresponding dark matter haloes from the CDM simulations themselves are not fully NFW-like.

|         | $M_{200} \ [M_\odot]$ | $R_{200}$ [kpc] | $f_{\text{gas},200}$ | $f_{*,200}$ | $q$ | $s$ | $z_{\text{stars form}}$ | $z_{\text{halo forms}}$ |
|---------|-----------------------|-----------------|---------------------|-------------|-----|-----|----------------------|----------------------|
| halo 1  | CDM                   | 1.4 \times 10^{10} | 61                  | 0.095       | 0.0058 | 0.7 | 0.5              | 35                   | 10                   |
|         | “WDM”                 | 1.1 \times 10^{10} | 51                  | 0.077       | 0.0049 | 0.4 | 0.3              | 13.5                 | 13.5                 |
|         | BECDM                 | 8.2 \times 10^{9}  | 42                  | 0.11        | 0.0057 | 0.4 | 0.3              | 13                   | 13                   |
| halo 2  | CDM                   | 4.5 \times 10^{9}  | 42                  | 0.082       | 0.0033 | 0.6 | 0.4              | 35                   | 13                   |
|         | “WDM”                 | 4.4 \times 10^{9}  | 42                  | 0.11        | 0.0033 | 0.3 | 0.2              | 11.5                 | 7.5                   |
|         | BECDM                 | 3.9 \times 10^{9}  | 40                  | 0.13        | 0.0032 | 0.3 | 0.2              | 11.0                 | 7                    |
| halo 3  | CDM                   | 4.6 \times 10^{9}  | 42                  | 0.095       | 0.0027 | 0.8 | 0.5              | 35                   | 13                   |
|         | “WDM”                 | 5.1 \times 10^{9}  | 44                  | 0.084       | 0.0025 | 0.4 | 0.3              | 12.5                 | 7.5                   |
|         | BECDM                 | 4.6 \times 10^{9}  | 42                  | 0.10        | 0.0023 | 0.4 | 0.3              | 12.0                 | 7                    |

Even though there is less spherical symmetry observed in BECDM/”WDM” cosmologies at high redshifts, as we go lower in redshift, large, more-spherically symmetric cores are formed embedded in filaments. In contrast, in CDM filaments fragment into subhaloes which can merge into the central halo. We plot radial density profiles for dark matter, gas, and stars of our three haloes in Fig. 4. Halo centres are identified by gravitational potential minima. We also compare the dark matter profiles to corresponding dark matter haloes from the CDM simulations themselves are not fully NFW-like.

5.3 Dark matter filaments

Even though large scale structure above $\sim 1$ comoving Mpc is the same under the different cosmologies, the small scale structure is strikingly varied. To illustrate this, we consider a density slice through a cosmic filament, shown in Fig. 5. In CDM the filament is comprised of low mass subhaloes. In the “WDM” simulation the same filament is formed, but there are no small scale initial perturbations and, hence, no fragmentation. Instead, dark matter is distributed continuously along the “WDM” filament. Caustic structures are seen as material converges towards the filament. The filament formed with BECDM is distinct in that it displays interference patterns due to the relative velocity of the matter converging onto the filament. The interference in the filaments stays regular/coherent over time as there are just...
a small number of phase-sheets overlapping (see the lowest panels of the figure which exemplifies the temporal evolution of the interference profile). Inside the virial radius of the halo, the density structure appears much more ‘turbulent’ (Mocz et al. 2017) as it is the superposition of a large number of plane waves that encode the velocity dispersion in the halo. These features are linear in the sense that they are not held together by self-gravity but arise simply from the superposition of modes, as in the linear Schrödinger equations.

We point out that the scale of the interference patterns in the BECDM simulations can be estimated (to within a factor of 2) as a function of location from “WDM” simulations by taking the de Broglie wavelength of the measured velocity dispersion of the dark matter particles that sample the 6D distribution function (see Fig. 5). This is expected by the Vlasov/Schrödinger-Poisson correspondence (Mocz et al. 2018), as the interference features are just linear features (i.e., self-gravity is unimportant) and the BECDM equations approximate collisionless dynamics. Thus, it may be possible to conduct “WDM” simulations where quantum effects are post-processed, as a way to simulate larger box sizes. This method would not be exact, however, because it ignores areas in the superfluid where the quantum pressure support is important (e.g. support in soliton cores and the spines of filaments), which can feed back to reshaping larger scales of the internal structure of the haloes.

Even though discreteness noise is well-known to sometimes artificially collapse structure in such WDM filaments (Wang & White 2007), it only marginally affects our simulation and is not apparent in Fig. 5. This is due to the high particle resolution used (the cores formed in “WDM” are physical and not due to numerical effects because the same cores form in BECDM, which is unaffected by discreteness noise).

Mocz et al. (2019) showed that unstable cylindrical soliton-like core can be found in the center of dark matter filaments. This cylindrical structure is unstable and can fragment and form spherical solitons. The solitonic structures are unique to BECDM, and detecting them would be a smoking gun of such cosmologies. Therefore, of interest is the core/filament mass per unit length relation along the cylinder, and whether the normalization is similar to the relation found for spherical solitons embedded in haloes (e.g. Schive, Chimeh & Broadhurst 2014). Desjacques, Kehagias & Riotto (2018) have carried out an analytic calculation of the structure and stability of such cylindrical cores, including the presence of an axion self-interacting force, and check whether such structures would be visible in the Lyman-α forest power spectrum. They find that there would be a detectable impact on the distribution of Lyman-α lines if the core/filament mass per unit length relation is different from the relation of haloes by a factor of $A_c \gtrsim 100$. However, for our object we find $A_c \approx 0.3 \sim 1$, in agreement with the spherical relation.

6 GAS

In this section we discuss the distribution of gas in the simulated cosmological volume. The middle panels of Fig. 3 show projected densities of the gas, zoomed in on our 3 haloes.

6.1 Density distribution and power spectra

The distribution of baryonic gas in the intergalactic medium is quite similar in BECDM and “WDM”, as can be seen readily in the projected densities (Fig. 3), despite the small-scale disparities in the dark matter density field (there is order unity differences due to quantum interference patterns). However, baryons are only coupled to dark matter via the long-range gravitational force, and, thus, in the dark matter force field, the small scale structures (e.g. interference patterns) are suppressed by a factor of $k$, the wave number, relative to the density field, and the coupled baryonic motions.
in BECDM is expected to approximate that of “WDM”, converging as $O(m^{-1})$ (Mocz et al. 2018).

Fig. 6 shows the probability density distribution (PDF) of the baryon gas density in the cosmic volume. We see that the distribution of gas in BECDM/“WDM” is significantly narrower in these cosmologies than in CDM. This is because in “WDM”/BECDM cosmologies, structure is smoothed and there is a dearth of both over- and under-dense regions compared to CDM. At lower redshifts “WDM”/BECDM catch up with CDM in terms of the abundance of overdense regions; however, CDM voids are still much emptier than those in “WDM”/BECDM. Exploring the contrast of matter density in voids might be an interesting route to constrain “WDM”/BECDM cosmologies.

The baryonic power spectrum is shown in Fig. 7. The baryons initially follow the dark matter quite closely from $z = 12$ to $z \sim 10$. Following the dark matter, baryons evolved under BECDM/“WDM” show the same lack of...
Figure 4. Radially averaged (comoving) density profiles for the dark matter, gas, and stars for 3 haloes in our simulations under different cosmologies are shown at $z = 6$. The thick solid lines are dark matter density in the baryon full-physics run, and we also show corresponding thin lines in the dark matter only runs, which are similar and show that the baryons have not strongly modified the dark matter potential wells for these low mass haloes in the early universe. Thick grey lines show where soliton profiles of various mass/size lie, which are just marginally resolved by our simulations. The smallest, densest, most massive soliton profile approximately matches the simulations.

Figure 5. Anatomy of a cosmic web dark matter filament. Three upper panels show a density slice through a filament at $z = 7$. CDM has subhaloes on all scales. “WDM” shows caustic structures. And BECDM has large-scale coherent interference patterns due to converging flow towards the filament, and a coarse-graining of caustics on the local de Broglie length scale. The forth subpanel shows the estimated sizes of BECDM interference patterns (at $z = 7$) by taking $\lambda_{dB}$ of the velocity dispersion of “WDM”, which are in good agreement with the actual BECDM simulation. Bottom panel shows redshift evolution of the interference pattern in the BECDM filament (middle snapshot is the same as BECDM case in panel above, just rotated).
power at large $k$ compared to CDM as is seen in dark matter due to the initial exponential cutoff. However, after about a free-fall time, by $z \sim 7$, the baryons start feeling their own pressure as well, and their distribution can become different from the dark matter in this non-linear regime. We highlight this fact by showing the relative power between gas and dark matter in Fig. 8 at $z = 7$. The ratio between gas and dark matter power spectra in “WDM” is closer to unity at small scales (large wavenumbers) than in CDM reflecting the fact that the dark matter distribution is smoother. Similarly, in BECDM, the ratio is close to unity at small values of $k$; however, it drops to very low values at large wavenumbers owing to the small scale dark matter structures (interference profile) which are not imprinted in the gas spectrum. Even though in CDM the baryons have less small-scale power than the underlying dark matter (we discuss the reasons for this – baryons feel gas pressure and are no longer as tightly coupled to dark matter below filtering scale – in the next Section 6.2), the gas distribution in BECDM/“WDM” is smoother compared to CDM even after reionization and feedback have affected it. This is because for our choice of the axion mass, the minimum dark matter halo mass is slightly above the filtering scale in BECDM/“WDM” (small scale structures were never formed). But, importantly, the baryonic power spectra between the different cosmologies agree to a much better extent than the dark matter ones by $z \sim 7$. We will investigate the implications of this agreement for the Lyman-$\alpha$ forest, which depends on the full phase distribution of the gas (density, temperature, ionization), in future work.

6.2 Accretion of Gas onto Collapsed Objects

Here we discuss the formation of baryonic objects in our simulations – the accretion of gas onto collapsed DM structures (haloes, filaments and sheets) – under the different cosmologies. In CDM, despite dark matter structure forming at all scales, baryons do not cluster below the filtering scale (Gnedin & Hui 1998). This scale relates to the amount of gas available for cooling and star formation inside collapsed objects. At low redshifts, where large haloes dominate, there may be no large difference in the accretion process in BECDM/“WDM” compared to CDM. However, in the high-redshift domain there is an important difference: in the case of CDM, baryonic objects form on all scales above the filtering scale; however, in BECDM/“WDM” the suppression in
the initial power spectrum of BECDM/“WDM” defines the minimum dark matter halo mass that can form, which in our case is above the filter scale. Therefore, BECDM/“WDM” baryonic objects look “fuzzier”/more smoothed than those in CDM. To give a quantitative comparison, we list fraction of mass in stars and gas inside $R_{200}$ at $z \sim 6$ in Table 1 (and shown in Fig. 3). Despite different values of the total stellar masses in haloes (total mass of gas and stars in CDM haloes is larger than in “WDM”, which is larger than in BECDM), the fractions of gas and stars are comparable across cosmologies $f_{\text{gas,200}} \sim 0.1$, $f_{\star,200} \sim \text{few} \times 0.001$, despite differences in halo shapes, although some systematic differences are observed: at $z = 6$ BECDM/“WDM” may have slightly larger gas fractions and smaller stellar fraction than CDM.

6.3 Baryon feedback

We point out that stellar winds / supernovae feedback is active in our simulations. By $z \sim 7$ this leads to $\sim 100$ kpc scale winds, which adds to small-scale power in the baryon distribution, and may help resolve some of the observational tension with constraints on the axion particle mass from the Lyman-$\alpha$ forest. The differences in the gas distribution across our three cosmological models is also less significant compared to the underlying dark matter distribution, in part due to how feedback reshapes power on small-scales.

7 FIRST STAR FORMATION

Chemically pristine gas heats as it falls into dark matter potential wells, cools radiatively due to the formation of molecular hydrogen, and becomes self-gravitating collapsing to form first stars. The Rees-Ostriker-Silk (Rees & Ostriker 1977) cooling criterion sets the minimum dark matter halo mass which is able to host star formation. In the CDM cosmology, first sites of star formation are in mini-haloes ($M_{\text{halo}} \sim 10^5$–$10^6 M_\odot$) at $z \sim 50$–60 (Bromm 2013a,b; Naoz, Noter & Barkana 2006); while a more significant amount of stars can be built up by $z \sim 20$–30. Formation of first stars and black holes provides a sensitive probe of the small-scale nature of dark matter (Gao & Theuns 2007; Yoshida et al. 2003a), and changing the properties of dark matter might have a strong effect on the formation of first objects. For instance, Hirano et al. (2015) assumed initial matter power spectrum with a blue tilt and found that in this case stars form early ($z \sim 100$) and are very massive. The case of BECDM is expected to be similar to the WDM scenario in which star formation starts in filaments (Gao & Theuns 2007; Hirano, Sullivan & Bromm 2017). In the WDM scenario the way filaments fragment affects the initial spatial distribution and amount of first stars, and, as a result, the rate of supernovae explosions and early metal enrichment. The likely very different initial mass function of stars and the rapid formation of massive black holes in a WDM scenario, as opposed to CDM, implies very different reionization, thermal and metal enrichment histories, greatly affecting galaxy formation and predictions for the James Webb Space Telescope (JWST) and Square Kilometre Array (SKA). Some of these effects of the change in abundance of low-mass haloes have been explored in the context of the ETHOS model with a cutoff in the power spectrum similar to WDM (Lovell et al. 2018; Lovell, Zavala & Vogelsberger 2019).

In our simulations, under BECDM/“WDM”, the lack of small scale power elevates the minimum mass of star forming haloes leading to a delay in star formation. On average in our simulated volume we find star formation is delayed due to the suppression in the initial power spectrum in BECDM/“WDM” relative to CDM (see Fig. 9). Additionally, the quantum effects further delay star formation in BECDM, compared to the “WDM” case. For instance, in the most massive halo (#1), first stars are formed at $z \sim 35, 13.5$ and 13 in CDM, “WDM” and BECDM respectively (see details in Table 1). The simulations reach a stellar density per cosmic volume of $10^6 M_\odot$ Mpc$^{-3}$ at $z \sim 20$ in CDM, $z \sim 11$ in “WDM”, and $z \sim 10.5$ in BECDM. Contrary to “WDM” where the distribution of gas and stars in the galactic centers are cuspy, in BECDM first galaxies can develop a solitonic core, as was discussed in detail by Mocz et al. (2019). Furthermore, we point out here that only half as many stars as in CDM form per unit volume in BECDM/“WDM” by $z \sim 6$ in the low mass haloes probed by our simulations. The suppressed star formation would have an important impact on delaying reionization. In this paper we had included, by hand, a particular UVB background model that completed reionization by redshift $z \sim 6$ inferred from CDM simulations. However, for self-consistency, it should be modified by taking into account the differences in cosmic star formation history.

We briefly explore the metallicity distribution under the three different cosmologies. Fig. 9 shows that the time evolution of the global mass in metals follows that of stars. Mass-averaged line-of-sight metallicities in the cosmic volume at $z = 6$ is shown in Fig. 10. We see that BECDM/“WDM” leaves much of the cosmic volume pristine at this redshift, compared to CDM. This can be attributed to the absence of subhaloes below a critical mass and the delayed star formation and consequently reduced wind feedback.

We point out again that the baryonic modules have been tuned using CDM simulations. It is possible that is the efficacy of, e.g., the feedback or indeed the star formation law was modified so as to promote an earlier onset of star formation, some of the differences between BECDM and CDM may be reduced. This is left for future work. It will also be
of interest to consider whether first stars that form in filaments under BECDM/“WDM” could fragment and become globular clusters formed outside of galaxies.

7.1 Cosmic Diversity

In our simulations with dark matter fully coupled to the baryonic physics we observe filamentary star formation in BECDM and “WDM” cosmologies (in agreement with Gao & Theuns 2007; Hirano, Sullivan & Bromm 2017). In filaments, we find, stars start forming much earlier than virialized haloes can be identified (Table 1). For instance, at the same location, where halo #2 appears at $z = 7.5/7$ in “WDM”/BECDM, star formation along the 2-D potential well starts $\sim 0.31$ Gyrs earlier, e.g., at at $z = 11.5/11$. This filamentary mode of star formation is clearly seen in Fig. 3 (right column), where we show the projected stellar density of the three haloes at $z = 10.9, 7.8, 5.5$ under the three different cosmologies.

However, the filamentary mode is reserved for small-mass objects (haloes # 2 & 3 in our simulated box, Fig. 3), while in more massive haloes (such as halo # 1, Fig. 3) stars are distributed in a similar way to the CDM case – in an isolated halo – even at high redshifts. In halo # 1 the redshifts of star formation and halo formation are the same (13.5 in “WDM” and 13 in BECDM).

This dependence of the shape of the first galaxies on the initial conditions and the environment suggests that there is larger diversity of first star forming objects in BECDM/“WDM” cosmologies compared to CDM. We note again that our simulations are not statistically representative, and the relative abundance of the extended filamentary galaxies compared to the isolated CDM-like galaxies cannot be inferred from our simulations. Our finding may have implications for the ‘diversity problem’ of observed dwarf galaxies if the formation history of these dwarfs affects their late-time structure as well (Oman et al. 2015; Read et al. 2016).

Finally, we also find that in “WDM”/BECDM cosmology the morphology of the first small galaxies can be very different from low-redshift massive and evolved structures. To illustrate this aspect, we show the evolution of the stellar content of a filament in “WDM” down to $z = 2.3$ in Fig. 11 (unfortunately our full BECDM simulation lacks the resolution to go to such low redshifts, but the evolution is expected to be qualitatively similar). The ultimate fate of the filamentary first galaxies is that stars do end up being accreted into the few haloes that have formed along the filament, thus shaping more familiar-looking galaxies at low redshifts.

8 JWST MOCK IMAGES

If the filamentary first galaxies (and not the spherical CDM galaxies) are realized in nature, next-generation telescopes such as JWST could see bright a filamentary cosmic web illuminated by the first stars.

To demonstrate what telescopes such as JWST would actually see, we generate mock JWST images at $z = 5.5$ for the filamentary structure (stretching between haloes 2 and 3). To this end we adopt the Monte Carlo radiative transfer code SKIRT (Baes et al. 2011; Camps, Baes & Saftly 2013; Camps & Baes 2015; Saftly, Baes & Camps 2014). Details of the parameter setup for SKIRT were introduced by Vogelsberger et al. (2019b). The images are synthesized based on the apparent surface brightness in F277W, F356W and F444W bands. We note that we do not include dust attenuation in generating these images. A radiative transfer calculation including dust attenuation performed on the biggest galaxy of this cluster has shown that dust attenuation has very limited influence on the broadband photometry of the galaxy. The raw images without any surface brightness limit are shown in the first row of Fig. 12. The camera is set in the positive-z direction of the simulation coordinates and the field-of-view is roughly 180 × 180 physical kpc (pkpc). On the image we see that, as expected, at $z = 5.5$ stars are distributed along the entire filament in both BECDM and WDM, while they are grouped into distinct galaxies in CDM.

The detection limit in surface brightness of the JWST NIRCam is calculated with the JWST Exposure Time Cal-
Figure 11. Ultimate fate of filamentary first “galaxies”. We show the projected stellar densities in CDM (top row) “WDM” (bottom row). Stars that in “WDM” form along cosmic web filaments before $z \sim 6$ accrete into more familiar-looking galaxies by lower redshifts.

Figure 12. JWST NIRCam mock images of the first filamentary galaxy in the simulations at $z \sim 5.5$. The images are synthesized based on the apparent surface brightness in F277W, F356W and F444W bands. The first row shows images without any surface brightness limit. The second row shows images with a surface brightness limit that is 50 times deeper than the detection limit of JWST.
culator $^3$ (ETC; Pontoppidan et al. 2016) with the following configuration details. Mock source is treated as extended with a flat surface brightness profile with a radius of 0.25''.

The aperture radius is set to 0.5''. The target signal-to-noise ratio (SNR) is set to 5 and the exposure time is set to $10^5$ s. The readout pattern is set to DEEP8, which yields a high SNR and can efficiently reach a maximum survey depth. We employ 20 groups per integration, 1 integration per exposure and 24 exposures per specification.

For the background configuration, we choose the fiducial background at RA = 17:26:44, Dec = -73:19:56 on June 19, 2019 $^4$. The surface brightness limit we derive for the F277W band is $\sim 0.0013$ MJy/sr which is equivalent to 27.69 ABmag/arcsec$^2$. Unfortunately, we find that these particular galaxies and the filamentary structure shown in the raw images cannot be detected under this detection limit. Therefore, in the second row of Fig. 12, we show the images with a surface brightness limit that is 50 times deeper than the detection limit of the actual JWST. We also point out that limited box statistics may mean there could be more visible cosmic filaments as well, than the one simulated. Under this super-JWST detection limit, the filamentary structure can be revealed and the differences between three simulations are striking. Interestingly, some amount of clumping of the star particles is observed in “WDM” and to a lesser extent in BECDM. Even though the clumping in “WDM” is a known numerical issue of “WDM” simulations (due to dark matter clumping) and is purely artificial, this is not the case in BECDM which is immune to the “WDM” numerical issues in the dark matter. Instead, minor clumping in BECDM might be a result of self gravity of stellar particles distributed along a smooth potential well, which is not accurately resolved due to the addition of a particle smoothing length. We will investigate this issue further in future work.

9 SUMMARY OF DIFFERENCES
Comparing BECDM to the same-seed cosmological simulation of CDM and “WDM”, we summarize the several qualitative differences between these cosmologies:

9.1 Between BECDM and CDM

- BECDM appears filamentary while CDM has filaments fragmented into spherical subhalos.
- BECDM filaments appear striated due to quantum interferences on the boson de Broglie scale while CDM has subhalos on all astrophysical scales.
- BECDM forms smoother structures than CDM on kpc scale due to quantum pressure.
- BECDM shows soliton cores while CDM shows much denser cusps.
- In the BECDM scenario stars form along dense filaments (before they fragment) while in the CDM scenario they form in nearly spherical halos (after the filaments have fragmented). In the BECDM scenario stars are distributed along the entire filaments while they are grouped into distinct galaxies in the CDM scenario.
  - The dark matter filaments develop cylindrical soliton-like cores that are unstable under gravity and collapse into kpc scale spherical solitons. There is no lower scale of collapse in CDM.
  - The distribution of gas and stars, which do form along the entire filament, exhibit central cores imprinted by dark matter. There is no equivalent in CDM.
  - BECDM halos are more triaxial than CDM halos.
  - BECDM halos shows granules (incoherent interference patterns) contrary to CDM halos.
  - Stars form later in BECDM than in CDM, and star formation is reduced in BECDM as compared to CDM. These two points should have significant consequences on the reionization history and signatures of the Universe.
  - BECDM galaxies are dimmer than in CDM model.
  - The splashback radius of halos is more distinct in BECDM than in CDM.

9.2 Between BECDM and “WDM”

BECDM and “WDM” show similarities on large scale (e.g., both cosmologies feature dense star forming filaments), but the small scale structure is very different.

- BECDM filaments show quantum interferences on the boson de Broglie scale while distribution in “WDM” is smooth, except for sharp caustics.
- The dark matter density field in BECDM features cylindrical (in filaments) and spherical (inside halos) solitonic cores, while “WDM” profiles are cuspy.
- The dark matter cores are imprinted in the distribution of gas and stars in BECDM (in both filaments and halos), while the profiles of gas and stars are cuspy in “WDM”.
- Due to the effect of the quantum potential, star formation and metal enrichment are slightly delayed (by $\Delta z \sim 0.5$) in BECDM compared to “WDM”, and star formation is slightly systematically reduced in BECDM as compared to “WDM”.

10 CONCLUSIONS

In this work we have explored high-redshift galaxy formation in BECDM using first-of-the-kind cosmological simulations with BECDM fully coupled to baryons. We used the Arepo code, a state-of-the-art high-performance parallel code for solving gravity and (magneto)hydrodynamics (Springel 2010), in tandem with a newly developed but well tested module that solves the Schrödinger-Poisson (SP) equations for BECDM (Mocz et al. 2017). In addition, we ran simulations with CDM and “WDM” (WDM-like) cosmologies for comparison. “WDM” simulations are often used as a proxy for BECDM on large cosmological scales and ignore the effect of the quantum potential on the evolution of the BECDM by only implementing the initial cutoff in the power spectrum. “WDM” simulations are much more economical compared to BECDM. One of the goals of this paper was to test whether or not “WDM” is a good approximation to BECDM when full baryonic physics is taken into account.

$^3$ https://jwst.etc.stsci.edu/
$^4$ https://jwst-docs.stsci.edu/display/JTI/NIRCam+ Imaging+Sensitivity
We compared BECDM to the same-seed cosmological simulation of “WDM”. We find that, even with the baryonic feedback included, on large scales and at high redshifts \((z > 5.5)\) BECDM is well approximated by “WDM” on scales of above a few 100 kpc. The evolved baryonic power spectrum agrees well with that of “WDM” on all scales and at all redshifts that we have explored. We also find that in “WDM” and BECDM (compared to CDM) haloes are much more triaxial (e.g., \(q \sim 0.3 - 0.4\) instead of \(0.6 - 0.8\) as is expected in CDM); star formation and metal enrichment are delayed from \(z = 35\) to \(z \sim 13\); the fraction of gas and stars inside virialized haloes is similar to that of CDM; depending on the initial conditions, stars can form both in isolated massive three-dimensional regions (haloes) and in more extended deep two-dimensional potential wells (along the cosmic web filaments). However, there is a systematic delay in star formation in BECDM compared to the “WDM” case (\(\Delta z \sim 0.5\)) also resulted in slower metal enrichment.

Important differences between “WDM” and BECDM due to the effect of the quantum potential are manifested on small scales. Smoking gun signatures of BECDM include: striated interference patterns seen in the cosmic web which result in enhanced small-scale power of dark matter fluctuations at low redshifts, formation of cylindrical and spherical solitonic cores inside haloes and filaments which are imprinted in the distribution of gas and stars (see Mocz et al. 2019).

Our numerical method allows one to perform cosmological hydrodynamical simulations of BECDM with the same rigor as is done for CDM (although we are limited in cosmological box size due to the resolution requirements). The results of our simulations suggest new observational ways to test BECDM indicating that the key is in its small scale structure. Triaxiality of dark matter halos, rate of tidal disruption events, gravitational lensing, splash-back radius, abundance of supermassive and intermediate black holes might point out the nature of dark matter. We leave more quantitative study to future work. Our simulations are a firm step towards making robust constraints of this dark matter theory.

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