Is Sextans dwarf galaxy in a scalar field dark matter halo?

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Abstract. The Bose-Einstein condensate/scalar field dark matter model, considers that the dark matter is composed by spinless-ultra-light particles which can be described by a scalar field. This model is an alternative model to the Λ-cold dark matter paradigm, and therefore should be studied at galactic and cosmological scales. Dwarf spheroidal galaxies have been very useful when studying any dark matter theory, because the dark matter dominates their dynamics. In this paper we study the Sextans dwarf spheroidal galaxy, embedded in a scalar field dark matter halo. We explore how the dissolution time-scale of the stellar substructures in Sextans, constrain the mass, and the self-interacting parameter of the scalar field dark matter boson. We find that for masses in the range \((0.12 < m_\phi < 8) \times 10^{-22} \text{eV}\), scalar field dark halos without self-interaction would have cores large enough to explain the longevity of the stellar substructures in Sextans, and small enough mass to be compatible with dynamical limits. If the self-interacting parameter is distinct to zero, then the mass of the boson could be as high as \(m_\phi \approx 2 \times 10^{-21} \text{eV}\), but it would correspond to an unrealistic low mass for the Sextans dark matter halo. Therefore, the Sextans dwarf galaxy could be embedded in a scalar field/BEC dark matter halo with a preferred self-interacting parameter equal to zero.

Keywords: dark matter theory, dark matter simulations, dwarfs galaxies

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1 Introduction

The nature of dark matter (DM) is a puzzle in modern Cosmology. The standard interpretation supposes that DM is made up of weakly interacting massive particles which are non-relativistic at the epoch of decoupling (i.e., cold DM; hereafter CDM).

Despite the predictions of the CDM are in agreement with several cosmological observations, it has fundamental inconsistencies which remain to be solved. A popular example is the well-known overpopulation of dark substructure [1]. Nevertheless, there are many other less-known questions that the CDM model cannot explain. The expected number of galaxies in the local void [2], is one example. The observational data at galactic scales seem to disagree with CDM predictions, when comparing the density profiles of dark halos predicted in simulations with those derived from observations of dwarf spheroidal (dSph) galaxies and Low Surface Brightness galaxies (LSB’s). N-body simulations predict a universal cuspy density profile, while observations indicate that a cored halo is preferred in an important fraction of low-mass galaxies [3–5]. This discrepancy is known as the cusp/core problem.

The failures of the CDM model have motivated the study of several DM alternatives. Lately, a hypothesis that has gained interest is to consider that DM is made up bosons described by a real (or complex) scalar field \( \Phi \). Such paradigm is called the scalar field DM (SFDM) model [6–13] (also known as Fuzzy DM [14] or recently as Wave DM [15]).

In the SFDM model, the scalar field \( \Phi \) is minimally coupled to gravity and interacts only gravitationally with the baryonic matter. In the early Universe, the scalar field is in a thermal bath of temperature \( T \). When a critical temperature \( T_c \) is reached, the scalar field has a symmetry breaking and possibly a phase transition. This phase transition can be interpreted as the condensation of the scalar field \( \Phi \) (BEC/SFDM model). After this stage, the scalar field is driven towards a minimum of the potential. Once the scalar field reaches the minimum \( (T \ll T_c) \), and if the mass of the boson associated to the scalar field \( \Phi \) is greater than the expansion rate of the Universe \( (m_\phi \gg H) \), then the scalar field has a fast oscillation phase [20]. At this regime, if the boson mass is in the range \( m_\phi \sim 10^{-23} - 10^{-21} \) eV,
the SFDM behaves as CDM and their linear perturbations evolve as those in the standard CDM model [21–24]. Moreover, due to the fact that the effective Jeans length for a scalar field depends on the boson mass as $\lambda_J \sim m_\phi^{-1}$, the mass power spectrum has a natural cut-off and the overpopulation of substructures is avoided in a natural way.

The dynamics of the BEC/SFDM model at cosmological and galactic scales, have been studied both, theoretically and numerically [25–31] to put constraints on the free parameters of the model: mainly the SFDM boson mass. For example, [32] found that the SFDM model is consistent with the anisotropies of the cosmic microwave background radiation (CMB), if the mass of the boson is $m_\phi \sim 10^{-22}$ eV. [33], study the vortex formation in BEC/SFDM halos, including the angular momentum, obtaining a window for the mass of the boson of $10^{-21} - 10^{-23}$ eV, for dwarf-galaxy-sized halos.

Recently, Li et al. [34] put constraints on a complex SFDM model, using the effective number of neutrino species during the Big Bang nucleosynthesis, obtaining $m_\phi \geq 2.4 \times 10^{-21} \text{eV}/c^2$ and $9.5 \times 10^{-19} \text{eV}^{-1} \text{cm}^3 \leq \lambda/(m_\phi c^2)^2 \leq 4 \times 10^{-17} \text{eV}^{-1} \text{cm}^3$.

[35] use the internal stellar structures of dwarf spheroidal (dSph) galaxies to establish a preferred range for the mass $m_\phi$ of the bosonic particle. They performed N-body simulations of the Ursa Minor (UMi) dSph and explored how the dissolution time-scale of the cold stellar clump in UMi depends on $m_\phi$. They found that for a mass in the range of $(0.3 < m_\phi < 1) \times 10^{-22}$ eV, the BEC/SFDM model would have large enough cores to explain the longevity of the cold stellar clump in UMi, and the wide distribution of globular clusters in the Fornax dSph. It has to be noted, that dark matter halos with a NFW density profiles predict the dissolution of the UMi stellar substructure in a very short time (during the first $\sim 2$ Gyr [36]).

On the other hand, [37] fit the high-resolution rotation curves of a sample of 13 low-surface-brightness galaxies, obtaining a better fit with the SFDM/BEC model over the NFW [38] profile.

The BEC/SFDM has proved to be a promising DM alternative because it mimics the standard model at cosmological scales. In addition, it has the ability to suppress the substructure in a natural way and hence the overpopulation of dark matter substructure problem of CDM paradigm can be alleviated. Moreover, it can also explain the cusp/core problem at the center of dSph and LSB galaxies where the standard model fails. Nevertheless, further tests are needed in galactic systems dominated by DM, such as the dSph galaxies of the Local Group (LG).

There has been recent evidence of stellar substructure in other dSph galaxy: Sextans. [39] reported the existence of a dissolving cluster at the centre of Sextans. Later on, [40] detected a region near Sextans core radius that appeared kinematically colder than the overall stellar population of Sextans. Recently, [41] reported a nine-star group of very metal-poor stars which they suggest could be in fact the same substructure previously found by [39]. Lora et al. (2013) studied both stellar substructures in Sextans dwarf, with a NFW mass density profile. They found that, Sextans’ two substructures, get destroyed within $\sim 4$ Gyr, even if the substructures are very compact.

In this work we will perform N-body simulations of the Sextans dSph galaxy, embedded in a rigid SFDM halo. The survival of the stellar clump in Sextans will give us dynamic constraints on the mass $m_\phi$ and on the self-interacting parameter $\lambda$.

The article is organised as follows. In section 1.1 we describe the SFDM model and briefly review the Schrödinger-Poisson system. We present the characteristics of Sextans and its stellar clump in section 2. In section 3, we discuss the DM for Sextans, the set-up for the N-body models, and describe the code used. In section 4, we describe our results. Finally, in section 5 we discuss the results and give our conclusions.
1.1 The BEC/SFDM halos

The BEC/SFDM forms relativistic and Newtonian configurations in equilibrium, which can be interpreted as DM halos. In the relativistic regime, these gravitational structures, described by the Einstein-Klein-Gordon (EKG) equations, are known as boson stars (for complex scalar fields) and oscillatons (for real scalar fields). Several numerical studies \cite{43,44} have shown that both structures have a critical mass $M_{\text{crit}} \sim 0.6 \left(\frac{m_P}{m_\phi}\right) \sim 10^{12} \text{M}_\odot$, a typical-galaxy size, for an ultra-light boson with mass $m_\phi$, and $m_P = \sqrt{\hbar c/G}$ the Planck mass.

In this work, we study the dynamics of the Sextans dSph, which is well described by a Newtonian gravitational configuration. We model the BEC/SFDM halos, by performing the weak field and low velocity limit of the EKG equations, for a complex scalar field $\Phi$, endowed with a self-interacting potential $V(\Phi) = \frac{m^2}{2} \Phi^2 + \frac{\lambda}{4} \Phi^4$. This leads to the Schrödinger-Poisson system:

\begin{align}
    i \hbar \frac{\partial \psi}{\partial t} & = -\frac{\hbar^2}{2m_\phi} \nabla^2 \psi + U m_\phi \psi + \frac{\lambda}{2m_\phi} |\psi|^2 \psi, \quad (1.1) \\
    \nabla^2 U & = 4\pi G m_\phi^2 |\psi|^2. \quad (1.2)
\end{align}

In the latter equations, $m_\phi$ is the mass of the boson associated to $\Phi$. $U$ is the gravitational potential produced by the DM density source ($\rho = m_\phi^2 |\psi|^2$), $\lambda$ is the self-interacting coupling constant, and the field $\psi$ is related to the relativistic field $\Phi$ through $\Phi = e^{-im_\phi c^2 t/\hbar} \psi$ [45–47].

To construct spherical BEC/SFDM halos in equilibrium, we assume $\psi(r, t) = e^{-i\gamma t/\hbar} \phi(r)$, reducing the Schrödinger-Poisson system to an eigenvalue problem for $\phi(r)$.

Using the dimensionless variables

\begin{align}
    \hat{\phi} & = \frac{\sqrt{4\pi G} \hbar \phi}{c^2} \\
    \hat{r} & = \frac{m_\phi c r}{\hbar} \\
    \hat{t} & = \frac{m_\phi c^2 t}{\hbar} \\
    \hat{U} & = \frac{U}{c^2} \\
    \Lambda & = \frac{m_P^2 c^4 \lambda}{8\pi m_\phi^2 \hbar^3} \\
    \hat{\gamma} & = m_\phi c^2 \hat{\gamma},
\end{align}

then, the Schrödinger-Poisson system now reads as,

\begin{align}
    \frac{d^2}{d\hat{r}^2} (\hat{\phi}) & = 2\hat{r} \left(\hat{U} - \hat{\gamma}\right) + 2\hat{r} \Lambda \hat{\phi}^3, \quad (1.4) \\
    \frac{d^2}{d\hat{r}^2} (\hat{U}) & = \hat{r} \hat{\phi}^2. \quad (1.5)
\end{align}

Following \cite{48} we construct SFDM halos by obtaining ground state solutions of the system (1.4)--(1.5). The mass of this BEC/SFDM halo can be estimated as

\begin{align}
    M = \int_0^{\infty} \hat{\phi}^2 \hat{r}^2 d\hat{r}. \quad (1.6)
\end{align}
Figure 1. Potential and force associated to the SFDM, for ground states, for the values of the self interacting parameter $\Lambda = 0, 1$ and 2 in dimensionless units.

In addition, we define the radius of this configuration as $r_{95}$, the radius containing 95% of the mass. Note that both properties, the mass and the radius, of the scalar halo depend on the boson mass, and the self-interacting term. Thus, to model the Sextans halo with several $m_\phi$ and $\Lambda$ values, we use the invariance of the Schrödinger-Poisson system under the following scaling

$$
\hat{\phi} \to \epsilon^2 \hat{\phi} \\
\hat{U} \to \epsilon^2 \hat{U} \\
\hat{\gamma} \to \epsilon^2 \hat{\gamma} \\
\Lambda \to \epsilon^2 \Lambda \\
\hat{r} \to \epsilon^{-1} \hat{r} \\
\hat{M} \to \epsilon \hat{M}.
$$

(1.7)

It is worth mentioning that the excited state solutions of the Schrödinger-Poisson system are unstable. Thus, we only model the Sextans halo with ground state scalar configurations. In figure 1, we show the potential and the force (in dimensionless units) associated to the SFDM, for ground states for three different values of the self interacting parameter $\Lambda$.

If we consider the self-interacting term $\Lambda$ to be zero in the system of equations (1.1)–(1.2), the fuzzy dark matter model studied by [14], is recovered. In addition, the Schrödinger-Poisson equations could be interpreted as the mean-field approximation at zero temperature of the Gross-Pitaevskii-Poisson (GPP) system, governing the dynamics of a Newtonian BEC. In the BEC interpretation, $U$ is the trapping potential of the BEC, and the coupling constant $\lambda$, is related to s-wave scattering length $a$ of the bosons. The regime where the self-interacting term strongly dominates the GP equation, is called the Thomas-Fermi limit (TFL). For a static BEC in the TFL, the GP reduces to a Lane-Emden (LE) equation, which has an analytical solution, when the BEC has a polytropic equation of state (EoS) with index $n = 1$. In this case, the BEC density profile is $\rho_{\text{BEC}}(r) \propto \frac{\sin(r/r_{\text{max}})}{r/r_{\text{max}}}$, where $r_{\text{max}}$, the maximum size of the gravitational structures, depend on $m$ and $\lambda$. Although these configurations are widely used, Guzmán et al. [49] claim that they are unstable and dissipate in a short time (see also
the discussion by [50]). Nevertheless, [51] found that the stability of BEC halos in the TFL depend on the mass and the scattering length of the particle. In this work we do not consider the TFL solutions.

2 Sextans and its stellar substructures

The Sextans dSph galaxy satellite of the Milky Way is located at a Galactocentric distance of $R_{GC} = 86$ kpc [52] and it has a luminosity of $L_V = (4.37 \pm 1.69) \times 10^5$ $L_\odot$ [53]. It has a core radius of $R_{core} \approx 0.4$ kpc and a tidal radius of $R_{tidal} \approx 4$ kpc [54]. It has a stellar mass of $\sim 8.9 \pm 4.1 \times 10^5$ $M_\odot$ [55]. The values of the mass and luminosity of Sextans give a typical stellar mass-to-light ratio of $\Upsilon_* \approx 2$.

Based on the velocity dispersion profile, [56] obtain a $M/L \sim 130$ (M/L)$_\odot$. On the other hand, [57] estimate a $M/L \sim 260$ (M/L)$_\odot$, and [53] obtain a $M/L$ value of $\sim 96$ (M/L)$_\odot$. The latter studies based on Sextans’ internal dynamics, suggest that the Sextans dwarf is a highly DM dominated dSph.

Sextans is also very interesting because it contains (at least) two stellar substructures. [39] found that the velocity dispersion at the centre of Sextans was close to zero, and that such a low value of the dispersion was in agreement with significant radial gradients in the stellar populations (change in the ratio of red horizontal branch stars to blue horizontal branch stars). They suggested that this is caused by the sinking and gradual dissolution of a star cluster at the centre of Sextans.

On the other hand, [40] presented radial velocities of 294 possible Sextans members. Their data did not confirm [39]’s report of a kinematically distinct stellar population at the centre of Sextans with their more complete sample. Instead, they detect a region near Sextans core radius ($\sim 0.4$ kpc) kinematically colder than the overall Sextans sample with 95% confidence.

Lately, [41] reported nine old stars that share very similar spatial location, kinematics, and metallicities, being the substructure’s average metallicity $[Fe/H] = -2.6$ dex. This stellar substructure is consistent with being a remnant of an old stellar cluster, with a luminosity of $2.2 \times 10^4$ $L_\odot$.

The present spatial extent of the substructures is very uncertain. The contours of statistical significance for regions of cold kinematics [40] show that their stellar substructure is centred on a location 15 arcmin north of the Sextans centre and has a radial size of 4 arcmin ($\sim 100$ pc). On the other hand, the nine innermost metal-poor stars that constitute [41] substructure, are found at $R < 0.22$, i.e., at $\approx 330$ pc.

Since we do not know the orbital parameters of the substructures, we explored different orbits for the clumps around the Sextans centre. We only know lower limits for the semi-major axes of the substructures ($\sim 400$ pc for [40] substructure, and $\sim 200$ pc for [41] substructure). Since the substructures are not necessarily on circular orbits, we also consider the case of eccentric orbits.

3 The modelling of Sextans

3.1 Sextans’ dark matter component

[41] computed the DM mass models for Sextans, based on their best-fitting of their observed line-of-sight velocity dispersion profile. They found that for a NFW [38] DM model, the best fitting model corresponds to a concentration $c = 10$ and a virial mass $M_V = 2.6 \times 10^9$ $M_\odot$. 

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We show the density profile of the SFDM halo for Sextans dwarf galaxy, for different values of the mass of the boson $m_\phi$, and for the self-interacting parameters $\Lambda = 0, 0.5, 1$ and 2.

They also fit their data to a cored DM profile. For the best fitting, they obtained a cored radius $r_c = 3$ kpc, and a mass within the last measured point ($\sim 2.3$ kpc assuming a distance to Sextans of 86 kpc; Mateo 1998) of $M(<R_{\text{last}}) = 4 \times 10^8 M_\odot$.

[57, 58] compute the Sextans’ DM mass within 0.6 kpc, $M(<0.6) = 0.9 \pm 0.4 \times 10^7 M_\odot$, for a CDM model. [41] obtained a mass $M(<0.6) = 2 \pm 0.6 \times 10^7 M_\odot$, for their best-fitting NFW model. They also find an enclosed mass of $M(<0.6) = 0.9 \pm 0.2 \times 10^7 M_\odot$ for their best-fitting cored DM profile, very similar to [57]’s mass estimate. Therefore, to construct the Sextans’ SFDM halo, we impose that the halo mass within 0.6 is $M(<0.6) = 9 \times 10^6 M_\odot$.

In figure 2, we show the Sextans’ SFDM density profile (for $\Lambda = 0, 0.5, 1$ and 2) for different mass of the boson $m_\phi$. From this figure, we can see that for a self interacting parameter $\Lambda = 0$, the central density is $\rho_0 \approx 0.07 M_\odot \text{pc}^{-3}$, for $m_\phi = 10^{-21}$ eV. For larger values of the self interacting parameter, for example $\Lambda = 2$, the central density for the same mass of the boson $m_\phi = 10^{-21}$ eV, is $\rho_0 \approx 0.01 M_\odot \text{pc}^{-3}$. The value of the central density drops when $\Lambda$ increases. We define the SFDM core radius, as the radius at which the central density has dropped a factor 2 (see table 1). We can see from figure 2, that for a fixed mass of the boson $m_\phi$ (say $10^{-21}$ eV), the core radius for $\Lambda = 0$ is $r_{\text{core}} = 0.34$ kpc. Whereas, for the same $m_\phi$ and $\Lambda = 2$, the core radius is $r_{\text{core}} = 0.71$. The value of the core radius increases when $\Lambda$ increases, for a fixed value of $m_\phi$.

Recently, [59] analysed the Aquarius simulations to characterize the shape of the DM halos with maximum circular velocities between 8 and 200 km/s. They found that DM subhalos, comparable to those hosting classical dSph galaxies in the LG, are mildly triaxial with $(b/a) \sim 0.75$ and $(c/a) \sim 0.6$ at $r \sim 1$ kpc. Therefore, as a first approximation, it is a reasonable assumption to adopt an spherical BEC/SFDM DM halo for the Sextans dSph.

### 3.2 Sextans’ stellar substructures

For the initial mass density profile of the stellar clump, we used a Plummer [60] mass density profile given by the following equation:

$$
\rho_{c}(r) = \rho_0 \left(1 + \frac{r}{r_p}\right)^{-5/2}.
$$

The present spatial extent of the substructures is very uncertain. The contours of statistical significance for regions of cold kinematics in [40] show, that their substructure is located at $\sim 375$ arcmin north of the Sextans centre, and has a radial size of $\sim 100$ pc.
| $\Lambda$ | $m_{\phi}$ | $\epsilon$ | $M$ | $r_{95}$ | $r_{\text{core}}$ | $H_5$ | $H_{65}$ | $H_{80}$ | Orbit type |
|----------|-------------|-----------|-----|---------|-----------------|-------|-------|-------|-------------|
| 0        | 0.1         | 22.7996  | 62.8| 10.6555 | 5.4345          | >10   | >10   | >10   | circular, $x=200$ pc |
| 0        | 0.1         | 22.7996  | 62.8| 10.6555 | 5.4345          | >10   | >10   | >10   | circular, $x=400$ pc |
| 0.5      | 1.0         | 7.3881   | 2.035| 3.2882  | 1.6770          | >10   | >10   | >10   | circular, $x=200$ pc |
| 0.5      | 1.0         | 7.3881   | 2.035| 3.2882  | 1.6770          | >10   | >10   | >10   | circular, $x=400$ pc |
| 0.5      | 5.0         | 3.8120   | 0.21 | 1.2746  | 0.6501          | >10   | >10   | >10   | circular, $x=200$ pc |
| 0.5      | 5.0         | 3.8120   | 0.21 | 1.2746  | 0.6501          | >10   | >10   | >10   | circular, $x=200$ pc |
| 0.5      | 7.0         | 3.5477   | 0.139| 0.9782  | 0.4989          | >10   | >10   | >10   | circular, $x=200$ pc |
| 0.5      | 7.0         | 3.5477   | 0.139| 0.9782  | 0.4989          | >10   | >10   | >10   | circular, $x=400$ pc |
| 0.5      | 8.0         | 3.5152   | 0.121| 0.8638  | 0.4046          | >10   | >10   | >10   | circular, $x=200$ pc |
| 0.5      | 8.0         | 3.5152   | 0.121| 0.8638  | 0.4046          | >10   | >10   | >10   | circular, $x=400$ pc |
| 0.5      | 9.0         | 3.5452   | 0.108| 0.7614  | 0.3883          | >10   | >10   | >10   | circular, $x=200$ pc |
| 0.5      | 9.0         | 3.5452   | 0.108| 0.7614  | 0.3883          | >10   | >10   | >10   | circular, $x=400$ pc |
| 0.5      | 10.0        | 3.6305   | 0.1  | 0.6691  | 0.3412          | >10   | >10   | >10   | circular, $x=400$ pc |
| 0.5      | 10.0        | 3.6305   | 0.1  | 0.6691  | 0.3412          | >10   | >10   | >10   | circular, $x=400$ pc |
| 0.5      | 10.0        | 3.6305   | 0.1  | 0.6691  | 0.3412          | >10   | >10   | >10   | circular, $x=400$ pc |

| $\Lambda$ | $m_{\phi}$ | $\epsilon$ | $M$ | $r_{95}$ | $r_{\text{core}}$ | $H_5$ | $H_{65}$ | $H_{80}$ | Orbit type |
|----------|-------------|-----------|-----|---------|-----------------|-------|-------|-------|-------------|
| 0.5      | 0.1         | 22.7423  | 95.79| 11.2252 | 4.5685          | >10   | >10   | >10   | circular, $x=200$ pc |
| 0.5      | 0.1         | 22.7423  | 95.79| 11.2252 | 4.5685          | >10   | >10   | >10   | circular, $x=400$ pc |
| 0.5      | 1.0         | 7.3124   | 3.08 | 3.4911  | 1.4208          | >10   | >10   | >10   | circular, $x=200$ pc |
| 0.5      | 1.0         | 7.3124   | 3.08 | 3.4911  | 1.4208          | >10   | >10   | >10   | circular, $x=400$ pc |
| 0.5      | 5.0         | 3.5684   | 0.3006| 1.4308  | 0.5823          | >10   | >10   | >10   | circular, $x=200$ pc |
| 0.5      | 5.0         | 3.5684   | 0.3006| 1.4308  | 0.5823          | >10   | >10   | >10   | circular, $x=400$ pc |
| 0.5      | 7.0         | 3.1875   | 0.1918| 1.1441  | 0.4656          | >10   | >10   | >10   | circular, $x=200$ pc |
| 0.5      | 7.0         | 3.1875   | 0.1918| 1.1441  | 0.4656          | >10   | >10   | >10   | circular, $x=400$ pc |
| 0.5      | 8.0         | 3.0788   | 0.1621| 1.0364  | 0.4218          | >10   | >10   | >10   | circular, $x=200$ pc |
| 0.5      | 8.0         | 3.0788   | 0.1621| 1.0364  | 0.4218          | >10   | >10   | >10   | circular, $x=400$ pc |
| 0.5      | 8.0         | 3.0788   | 0.1621| 1.0364  | 0.4218          | >10   | >10   | >10   | circular, $x=400$ pc |
| 0.5      | 8.0         | 3.0788   | 0.1621| 1.0364  | 0.4218          | >10   | >10   | >10   | circular, $x=400$ pc |
| 0.5      | 10.0        | 2.9701   | 0.1251| 0.8595  | 0.3498          | >10   | >10   | >10   | circular, $x=200$ pc |
| 0.5      | 10.0        | 2.9701   | 0.1251| 0.8595  | 0.3498          | >10   | >10   | >10   | circular, $x=400$ pc |
| 0.5      | 10.0        | 2.9701   | 0.1251| 0.8595  | 0.3498          | >10   | >10   | >10   | circular, $x=400$ pc |
| 0.5      | 12.0        | 4.2782   | 0.0901| 0.2983  | 0.1214          | >10   | >10   | >10   | circular, $x=200$ pc |
| 0.5      | 12.0        | 4.2782   | 0.0901| 0.2983  | 0.1214          | >10   | >10   | >10   | circular, $x=400$ pc |
| 0.5      | 12.0        | 4.2782   | 0.0901| 0.2983  | 0.1214          | >10   | >10   | >10   | circular, $x=400$ pc |

Table 1. Destruction times (II) of the stellar clump in Sextans for the $\Lambda = 0$, 0.5, 1 and 2 case, for different values of $m_{\phi}$. The sub-index in II corresponds to the Plummer radius of the clump (5, 35 and 80 pc). The SF boson mass, $\epsilon$, the total mass $M$; the radius at which 95% of the total mass is contained, $r_{95}$; and the core radius, $r_{\text{core}}$; are also given for each of the models.
On the other hand, the nine innermost metal-poor stars that conform the stellar clump \cite{Mateo1998}, are found at $R < 0^\circ.22 \ (\sim 330 \text{pc})$, if we assume a distance to Sextans of 86 kpc; \cite{Battaglia2011}. In Battaglia et al.’s (2011) data, there are no metal-poor stars within $R < 0^\circ.1$, which suggests that the stellar substructure extends in projected galactocentric radius from $0^\circ.1$ to $0^\circ.22$ (equivalent to 150–330 pc). Indicating that, in projection, its centre is at $\sim 240 \text{pc}$ from the centre of Sextans, with a radius (at most) of $\sim 90 \text{pc}$.

We assume that the $V$-band mass-to-light ratio $M/L_V$ of the clump is the same as it is for the underlying stellar component ($\Upsilon_\star = 2$). A crude estimate of the stellar substructures’ total luminosity is $L_c = 2.2 \times 10^4 \text{ L}_\odot$ \cite{Mateo1998}, then, a mass of the clump $M_c \simeq 4.4 \times 10^4 \text{ M}_\odot$ is obtained.

We run sets of simulations varying the plummer radius of the clump (5, 35 and 80 pc). We drop the stellar clumps in a circular orbit with a galactocentric distance of 0.4 kpc, mimicking the stellar substructure found by \cite{Battaglia2011}. Then, we drop the stellar clumps at a galactocentric distance of 0.2 kpc in a circular orbit, representing the stellar substructure found by \cite{Mateo1998}. Finally, we explore the possibility that a stellar substructure could be in an eccentric orbit with an apocenter distance from the centre of Sextans of 0.4 kpc, and a pericenter distance of 0.1 kpc (which corresponds to an eccentricity of $e = 0.6$).

3.3 The N-body code

The crossing time is defined as

$$t_{\text{cross}} = \frac{2\pi R_c^{3/2}}{\sqrt{G M_c}},$$

then the relaxation time can be defined as a function of the crossing time,

$$t_{\text{relax}} \simeq \frac{0.1 N}{\ln N} \times t_{\text{cross}}.$$  (3.3)

The relaxation times for both clumps radii are $\gtrsim t_H$ therefore the two-body relaxation processes can be neglected and the system can be represented as collisionless \cite{Hansen2014}. We simulated the evolution of the Sextans’ stellar clump embedded in a rigid SFDM halo potential, using the N-body code SUPERBOX \cite{Okamoto2009, Okamoto2011}. SUPERBOX is a highly efficient particle-mesh, collisionless-dynamics code with high resolution sub-grids. In our case, SUPERBOX uses three nested grids centred in the centre of density of the Sextans’ stellar clump. We used $128^3$ cubic cells for each of the grids. The inner grid is meant to resolve the inner region of Sextans’ clump, and the outer grid (with radii of 10 kpc) resolves the stars that are stripped away from Sextans’ clump. The spatial resolution is determined by the number of grid cells per dimension ($N_c$) and the grid radius ($r_{\text{grid}}$). Then the side length of one grid cell is defined as $l = \frac{2r_{\text{grid}}}{N_c - 1}$. For $N_c = 128$, the resolution is 0.5 pc. SUPERBOX integrates the equations of motion with a leap-frog algorithm, and a constant time step $dt$. We selected a time step of $dt = 0.1 \text{ Myr}$ in our simulations in order to guarantee that the energy is conserved better than 1%.

4 Results

4.1 The $\Lambda = 0$ case

We ran N-body simulations from $t = 0$ to $t = 10 \text{ Gyr}$, of the stellar clump in the Sextans dwarf (for three different plummer radius; 5, 35 and 80) embedded in a SFDM halo, with a self-interacting parameter $\Lambda = 0$, varying the mass of the boson $m_\phi$. As we mentioned
Figure 3. Time evolution ($t = 0, 3, 6$ and $10$ Gyr) of the stellar clump’s surface mass density in the Sextans dSph. In the top panels we show the evolution of the clump with $r_c = 35$ pc, and in the bottom panels we show the time evolution of model with $r_c = 80$ pc. The white circle shows the initial orbit with $0.4$ kpc radius. The white cross marks the centre of Sextans. We set the clump on a circular orbit in the $(x,y)$-plane at a distance of $r = 0.4$ kpc from Sextans’ centre. The mass of the boson is $m_\phi = 10^{-23}$ eV and the self interacting parameter is $\Lambda = 0$, which corresponds to a total mass of the galaxy $M = 6.28 \times 10^9 M_\odot$ (see table 1).

before, we selected three different types of orbits; a circular orbit at a galactocentric distance of $0.4$ kpc, a circular orbit with a galactocentric distance of $0.2$ kpc, and an eccentric orbit with $e = 0.6$. All the stellar-clump-models, orbit in the $(x,y)$-plane. In order to quantify the destruction time $\Pi$ of the stellar clump in Sextans, we build a map of the surface mass density (in units of $M_\odot$ pc$^{-2}$) of the stellar clump in the $(x,y)$-plane, for every time $t$ in the simulation. When the surface mass density falls below the value $\sim 1.5$ $M_\odot$ pc$^{-2}$, which is the typical surface mass density of the underlying stellar component in Sextans, we define that the stellar clump is destroyed (i.e., at this value, the particles in the clump would not be recognizable form the particles of the main stellar component in Sextans).

In the top panels of figure 3, we show the time evolution of the surface mass density of the clump at $t = 0, 3, 6$ and $10$ Gyr, for the model with $m_\phi = 10^{-23}$ eV in a circular orbit at a galactocentric distance of $0.4$ kpc. The stellar clump has an initial plummer radius, $r_p = 35$ pc. Such a location of the clump, resembles the stellar substructure found by [40]. The white line shows the initial orbit of the stellar clump, and the white cross shows the centre of Sextans.

We see that the clump remains intact for $\sim 10$ Gyr. In the lower panels of figure 3, we show the time evolution of the stellar clump with a radius $r_p = 80$ pc. Also in this extended-radius case, the clump remains unchanged for $\sim 10$ Gyr. The survival of both stellar clumps is a consequence that the SFDM halo has a very large core ($\sim 5.4$ kpc; see table 1), that guarantees the survival of the clump [4, 35]. In contrast, with a NFW mass density profile, both stellar clumps in Sextans dwarf galaxy get destroyed within $\sim 4$ Gyr, even if the stellar clumps are very compact ($r_p = 5$ pc) [36].
In table 1, we give the mass of the SF boson, the properties of the SFDM halos, the destruction time (II) for each clump radius case, and the orbit of the stellar clump.

There is a positive correlation between the size of the SFDM core radius \( r_{\text{core}} \), and the maximum of the circular velocity \( V_{\text{max}} \). Large values of the core are favoured to explain the persistence of the stellar clump, but they require very large values of \( V_{\text{max}} \) and thus, the total DM halo mass. For example, for a SF boson mass of \( m_{\phi} = 10^{-23} \) eV the total dynamical mass is \( M \approx 6.3 \times 10^9 \, M_\odot \), and therefore, \( V_{\text{max}} \approx 52 \, \text{km s}^{-1} \). But a value of \( V_{\text{max}} \approx 8 - 12 \, \text{km s}^{-1} \) is computed for Sextans dwarf [64–66], which indicates that the latter DM halo is too massive.

Moreover, [41] suggest that Sextans’ DM halo virial mass, derived from the assumption of a NFW model, is \( \sim 2.6 \times 10^9 M_\odot \). This is a factor \( \sim 2 \) smaller, than the mass of the halo that we find for a \( m_{\phi} = 10^{-23} \) eV. [64] point out, that only 5\% of the sub-halos in a Milky Way-sized halo have a total mass \( M > 5 \times 10^9 M_\odot \). Therefore, \( 5 \times 10^9 M_\odot \) is a natural first upper limit to the mass of Sextans DM halo [35]. Adopting the latter maximum value for the mass, we obtain a lower limit to the mass of the boson of \( m_{\phi} \gtrsim 1.2 \times 10^{-23} \) eV.

Both, the shape of the underlying gravitational potential, and the longevity of the clump, depend on the mass of the SF boson \( m_{\phi} \). Since both, the size of the DM core, and the total mass increase when \( m_{\phi} \) decreases, the next step is to consider the evolution of the clump in models with larger values of \( m_{\phi} \).

We increase the mass of the boson one order of magnitude to \( m_{\phi} = 10^{-22} \) eV. The stellar clump (for the three different radius; 5, 35 and 80 pc) also remains undisturbed for \( \sim 10 \) Gyr. The corresponding core radius and mass are, \( 1.7 \text{kpc} \) and \( \sim 2 \times 10^8 \, M_\odot \), respectively (see table 1). With the latter data, we compute a \( V_{\text{max}} \approx 17 \, \text{km s}^{-1} \), still large for Sextans, but close enough to set a better lower limit to the mass of the SF boson.

Next, we raise the value of the mass of the SF boson to \( m_{\phi} = 5 \times 10^{-22} \) eV. We observe that the clump with \( r_p = 35 \) pc looses some particles but remains without much damage for a Hubble time. On the other hand, for the extended \( r_p = 80 \) case, the clump suffers a drastic damage, and appears almost destroyed by \( \sim 10 \) Gyr. Then, we raise the value of \( m_{\phi} \) to \( 8 \times 10^{-22} \) eV, the clump (for radius \( r_p = 35 \) and 80 pc) is destroyed within 2 Gyr, due to strong tidal effects (see figure 4). But a compact stellar clump with \( r_p = 5 \) pc survives for 10 Gyr. The \( m_{\phi} = 8 \times 10^{-22} \) eV case has a value for the core radius of \( \sim 0.5 \text{kpc} \) and \( V_{\text{max}} \approx 8 \, \text{km s}^{-1} \), which is in agreement with the value given by [64].

It has to be noted that the stellar clump with \( r_p = 5 \) and 35 pc remains without being destroyed for the adopted mass range \( m_{\phi} = 10^{-23} - 10^{-21} \) eV, when the clump is orbiting at a galactocentric distance of 0.2 kpc (similar to Battaglia et al.’s 2011 substructure case). The fact that the clump is located well inside the SFDM core radius, guarantees its longevity. Even the extended \( r_p = 80 \) pc case survives for 3 Gyr, when orbiting so close to the centre of the SFDM potential of Sextans.

For the eccentric orbit case, the clumps with \( r_p = 35 \) and 80 pc get destroyed when \( m_{\phi} = 8 \times 10^{-22} - 10^{-21} \) eV. The \( r_p = 5 \) pc clump gets destroyed when we raise the mass of the boson to \( m_{\phi} = 9 \times 10^{-22} - 10^{-21} \) eV (see table 1).

The survival of the stellar substructures in Sextans set an upper limit to the mass of the boson of \( m_{\phi} < 8 - 9 \times 10^{-22} \) eV. The destruction times, for each of \( m_{\phi} \) cases are given in table 1. We conclude that the mass of the boson in the \( \Lambda = 0 \) case lays in the range \( 10^{-21} < m_{\phi} < 8 \times 10^{-22} \) eV.
Figure 4. Time evolution ($t = 0, 0.5, 1$ and $1.5$ Gyr) of the stellar clump’s surface mass density in the Sextans dSph. In the top panels (a-d) we show the evolution of the compact $r_c = 5$ pc clump. In the middle panels (e-h) we show the time evolution of model with $r_c = 35$ pc. In the bottom panels (i-l) we show the time evolution for the extended model with a radius $r_c = 80$ pc. The white circle shows the clump orbit, and the white cross marks the centre of Sextans. We set the clump in a circular orbit, in the $(x, y)$-plane, at a galctocentric distance of 0.4 kpc. In this case, the mass of the boson is $m_\phi = 8 \times 10^{-22}$ eV and the self interacting parameter is $\Lambda = 0$, which corresponds to a total mass of the galaxy $M \sim 1.2 \times 10^7 M_\odot$ (see table 1).

4.2 The small $\Lambda \neq 0$ case

In the subsection 4.1, we assumed that the boson self-interaction is negligible ($\Lambda = 0$). In order to see how $m_\phi$ depends on self-interaction, we explore models with the third term of equation 1.1 being distinct from zero ($\Lambda \neq 0$). We consider only small values of $\Lambda$ (in dimensionless units 0.5, 1 and 2). The parameters of the models are summarized in table 1.

For a $\Lambda = 0.5$ value, the clump with radius 5 and 35 pc remains without being destroyed even when $m_\phi = 10^{-21}$ eV, for all three different orbital cases: circular orbit with a galactocentric distance of 0.2 and 0.4 kpc, and eccentric orbit with $e = 0.6$. Only the extended $r_p = 80$ pc case gets destroyed ($\Pi_80 \approx 1.4$ and 0.5 Gyr) when the stellar clump orbits at a galactocentric distance of 0.4 kpc for $m_\phi = 8 \times 10^{-22}$ eV and $m_\phi = 10^{-21}$ eV, respectively. For the other cases (circular orbit at a galactocentric distance of 0.2 kpc and eccentric orbit), even if the stellar clump is so extended, it remains without being destroyed for 10 Gyr. Only when we increase the mass of the boson to $m_\phi = 2 \times 10^{-21}$ eV, the stellar clump gets destroyed for all $r_p$, and all orbital cases. This happens because the SFDM core radius is too small to guarantee its survival ($\sim 0.1$ kpc).

When $\Lambda = 1$, the stellar clump only gets destroyed when the mass of the boson has reached the high value of $m_\phi = 2 \times 10^{-21}$ eV, which corresponds to a DM core radius of
Figure 5. Time evolution ($t = 0, 3, 6$ and $10$ Gyr) of the stellar clump’s surface mass density in the Sextans dSph for a $m_φ = 10^{-21}$ eV, and with a self interacting parameter of $Λ = 2$. In the top panels (a-d) we show the evolution of the compact $r_c = 5$ pc clump. In the middle panels (e-h) we show the time evolution of model with $r_c = 35$ pc. In the bottom panels (i-l) we show the time evolution for the extended model with a radius $r_c = 80$ pc. The white line shows the clump orbit in the ($x, y$)-plane (with apocenter at $0.4$ kpc and pericenter at $0.1$ kpc), and the white cross marks the centre of Sextans.

The clumps are destroyed earlier, when orbiting at a galactocentric distance of $0.4$ kpc. For the orbit with a galactocentric distance of $0.2$ kpc, the stellar clump only gets destroyed for the extended stellar clump with $r_p = 80$ pc. Lastly, when the clump is orbiting the eccentric orbit, the $r_p = 35$ and $80$ pc clumps get destroyed within the first Gyr ($0.61$ and $0.46$ Gyr respectively, see table 1). Because the $r_p = 5$ pc clump is very compact, it overcomes the tidal effect of the SFDM halo, and gets destroyed later at ~ $3.77$ Gyr.

When $Λ = 2$, we observe that the clump never gets destroyed, for any radius $r_p$ case, or any orbital case. In figure 5, we show the case of the stellar clump embedded in a SFDM halo with $m_φ = 10^{-21}$ eV. For such a mass of the boson, and self-interacting parameter, the SFDM core radius is $0.7$ kpc, guaranteeing the survival of the clump. But it has to be noted, that in order to have a total mass of the DM halo $\geq 10^8 M_\odot$, as suggested by [57], a $m_φ \approx 10^{-22}$ eV is needed for a self interacting parameter $Λ = 2$.

For the same value of $m_φ$, the masses and core radii of the DM halos increase when $Λ$ increases (see table 1). For example, for a boson mass of $10^{-21}$ eV, the SFDM core radius is $0.35$, $0.47$ and $0.71$ for $Λ = 0.5$, 1 and 2, respectively. Then, the permitted window for the mass $m_φ$ of the bosonic particles is shifted to larger values ($m_φ \approx 10^{-21}$ eV). We observe from our results, that the clump must be embedded in a SFDM halo with a mass $M \approx 10^7 M_\odot$, a “size” of the DM halo of $r_{95} \approx 0.8$ kpc, and a core radius of $\approx 0.4$ kpc, in order to guarantee the survival of the stellar substructures.
5 Conclusions

In this work we consider an alternative to the CDM model, where ultra-light bosons are the main components of the DM halos. We constrain the mass of the ultra-light bosons (the SFDM particle) using as a tool the stellar substructures found in the Sextans dwarf galaxy. Using $N$-body simulations, we found that the survival of the stellar substructures is only possible if $m_\phi < 8 \times 10^{-22}$ eV for a self-interacting parameter $\Lambda = 0$. By imposing a realistic upper limit on the dynamical mass of Sextans, we place a lower limit of $1.2 \times 10^{-23}$ eV. Therefore, we have a possible mass window for the SF boson of $1.2 \times 10^{-23} \text{eV} < m_\phi < 8 \times 10^{-22} \text{eV}$. These constraints imply SFDM halos with masses between $10^7 - 10^9 \text{M}_\odot$, maximum circular velocities between $48 - 8 \text{ km s}^{-1}$, and sizes between $\sim 1 - 10 \text{kpc}$.

For the SFDM halos, where we include the self-interacting parameter, the upper limit grows with $\Lambda$. For example, for $\Lambda = 2$, the halos made up by bosons with a mass as high as $m_\phi = 2 \times 10^{-21}$ eV, accounts for the observed internal Sextans dynamics ($v_c \approx 8 \text{ km s}^{-1}$), but the corresponding DM halo mass ($1.3 \times 10^7 \text{M}_\odot$) would be too low for Sextans dwarf.

The preferred range for the mass of the boson, found in this work, derived from the dynamics of Sextans, is compatible with those given by other authors to ameliorate the problem of over-abundance of dark substructures [14, 21]. It is also in agreement with the mass range for the boson mass based on the dynamics of the UMi and the Fornax dSph galaxies [35].

In a recent work, [67] used the velocity dispersion profiles from eight dSph satellites of the Milky Way to put constraints on the free parameters of a BEC DM model in the TFL approximation. They obtain a maximum radius for the DM halos (which they claim could be interpreted as the halo core radius) of $\sim 1 \text{kpc}$. Although [67] estimated the latter radius using the TFL configuration ($\lambda \gg 1$), it is consistent with our estimations.

Recently, [15] performed a high resolution cosmological simulation for a BEC/SFDM model without self-interaction evolving a modified Schrödinger-Poisson system in an expanding Universe. They obtain that the large-scale structure formed by this model is indistinguishable of the standard ΛCDM, but it has the advantage of suppressing the small scale structures. Moreover, this BEC/SFDM model predicts coherent standing waves of dark matter in the centre of the virialized dark matter halos, forming flat cores. Because of this feature, the SFDM model is also called wave-like dark matter (this behaviour is similar to those found for oscillations [44]). By comparing the core radius of a simulated dark matter halo with the dynamics of the Fornax dSph galaxy, [15] estimated a mass of the SFDM boson $m_\phi = (8.1^{+1.6}_{-1.7}) \times 10^{-23} \text{eV}$. Such a range in mass of the SFDM boson, is in a very good agreement with the estimated mass of the boson that we found in order to alleviate the Fornax globular clusters timing problem ($m_\phi \sim 10 \times 10^{-23} \text{eV}$) [35].

The BEC/SFDM model has several challenges to overcome mainly at galactic scales and related to the baryonic dynamics. For example, [68] found discrepancies of one order of magnitude in the size of TFL BEC/SFDM halos estimated from dwarf galaxy dynamics and those derived from other galactic systems (strong lensing, rotation curves). Nevertheless, Robles & Matos [69] can reconcile the discrepancy when the finite temperature corrections in BEC/SFDM halos are considered [70]. The BEC/SFDM configurations in the TFL for ultra-light bosons are numerically unstable. However, the problem could be solved if the BEC/SFDM halos have angular momentum [71] or if the boson mass and the scattering length have an appropriate value [51]. The BEC/SFDM is a viable model to explain the nature of the DM, at cosmological and galactic scales, and therefore should be further tested in more astrophysical systems.
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