Hints on halo evolution in SFDM models with galaxy observations

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A massive, self-interacting scalar field has been considered as a possible candidate for the dark matter in the universe. We present an observational constraint to the model arising from strong lensing observations in galaxies. The result points to a discrepancy in the properties of scalar field dark matter halos for dwarf and lens galaxies, mainly because halo parameters are directly related to physical quantities in the model. This is an important indication that it becomes necessary to have a better understanding of halo evolution in scalar field dark matter models, where the presence of baryons can play an important role.

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I INTRODUCTION

The nature of dark matter (DM) remains elusive today,even though a generic cold particle weakly coupled to the standard model seems to be the most promising candidate [1]. Treating DM as a bunch of classical particles isan appropriate effective description for many physical sit-uations. However, if DM is composed of bosons, the zero mode can develop a non-vanishing expectation value; this effect is usually known as Bose-Einstein condensation. A condensed phase does not admit a description in terms of classical particles, and the concept of a coherent excitation (i.e. a classical field) is more appropriate for practical purposes [5]. A specific realization of this scenario can be provided by the axion [3], see also [4].

In this paper we shall explore the lensing properties of a generic model of DM particles in a condensate, and compare the conditions necessary to produce strong lensing with those required to explain the dynamics of dwarf galaxies. As a result we will get some insight into halo evolution arising from this type of models.

In particular, we will consider the case of a complex, massive, self-interacting scalar field ϕ satisfying the Klein-Gordon (KG) equation, $\phi - (mc/\hbar)^2\phi - \lambda|\phi|^2\phi = 0$,with the box denoting the d'Alembertian operator in four dimensions. For those natural situations in which the scalar field massmis much smaller than the Planck scale, $m_{Plank} = (\hbar/c)^{1/2}$, such that $\Lambda \equiv \lambda m_{Plank}^2/4\pi m^2 \gg 1$, the coherent (self-gravitating,spherically symmetric) solutions to the KG equation admit a very simple expression for the mass density [5, 6],

$$\rho(r) = \begin{cases} \rho c \frac{\sin(\pi r/r_{max})}{(\pi r/r_{max})} & for \quad r < r_{max} \\ 0 & for \quad r \geq r_{max} \end{cases} \quad (1)$$

As usual we will refer to this model as scalar field dark matter (SFDM). Here $r_{max} \equiv \sqrt{\pi^2\Lambda/2}(\hbar/mc)$ is a constant with dimensions of length (notice that r_{max} is just the Compton wavelength of the scalar particle, /mc,scaled by a factor of order $A^{1/2}$), and ρc he density at the center of the configuration. The mass density profilein Eq. (1) leads to compact objects of size r_{max} and typical masses, $4\rho r_{max}^3/\pi$ hat vary from configuration to configuration according to the value of the central den-sity.

Eq. (1) was obtained without taking into account thegravitational influence of any other matter sources, andassuming that all the scalar particles are in the conden-sate. It has been used as a first order approximation todescribe the distribution of matter in dwarf shperoidals,which are expected to be DM dominated [6–8]. The massdistribution would be smooth close to the center of thesegalaxies, alleviating the cusp/core problem motivated bythe discrepancies between the observed high resolutionrotation curves and the profiles suggested by N-body sim-ulations [9]; see however [10].

The dynamics of dwarf galaxies suggests a self-interacting scalar with $m^4/\lambda \sim 50 - 75(eV)^4$ (i.e. $r_{max} \sim 5.5 - 7Kco$) , and typical central densities of theorder of $\rho c \sim 10^{-3} M_{\odot}/pc^3$see Ref. [6]. We are awarethat Milky Way size galaxies are, at least, an order ofmagnitude larger than this value of $r_{max}$and then theydo not fit in this model as it stands. Nonetheless, ifnot all the DM particles are in the condensate, there isa possibility to have gravitational configurations wherethe inner regions are still described by the mass densityprofile in Eq. (1), wrapped in a cloud of non-condensedparticles [11]. For the purpose of this paper we do notneed to specify the complete halo model. This is becausestrong lensing is not very sensitive to the mass distribu-tion outside the Einstein radius, at most of the order ofa few Kpc, just bellow the expected value of r_{max}Wecould not neglect the exterior profile of the halo if we wereinterested, for instance, in weak lensing observations.

II LENSING PROPERTIES OF SFDM HALOS

In the weak field limit the gravitational lensing produced by a mass distribution can be read directly fromthe density profile. As usual we assume spherical symme-try, and use the thin lens approximation, that is, the sizeof the object is negligible when compared to the otherlength scales in the configuration, i.e. the (angular) dis-tances between the observer and the lens,,DOL, the lensand the source,DLS, and from the observer to the source,DOS.
Under these assumptions the lens equation takes theform

$$\beta = \theta - \frac{M(\theta)}{\pi D^2 OL\theta \sum cr}, \tag{2}$$

whit β and θ enoting the actual (unobservable) angularposition of the source, and the apparent (observable) an-gular position of the image, respectively, both measuredwith respect to the line-of-sight [12]. The (projected)mass enclosed in a circle of radius ξ,$M(\xi)$, s definedfrom the (projected) surface mass density, $\sum(\xi)$ through,

$$\sum(\xi) \equiv \int_{-\infty}^{\infty} dz\rho(z,\xi), M(\xi) \equiv 2\pi \int_0^{\xi} d\xi\prime\xi\prime \sum(\xi\prime) \tag{3}$$

Here $\xi = D_{OL}\theta$ In general, Eq. (2) will be non-linear in θ, and it couldbe possible that for a given position of the source,β, therewould be multiple solutions (i.e. multiple images) forthe angle θ. This is what happens in the strong lensingregime to be discussed below. One particular case is thatwith a perfect alignment between the source and the lens,that actually defines the Einstein ring, with an angularradius of $\theta E \equiv \theta(\beta = 0)$.
For a SFDM halo, and in terms of the normalized lengths $\xi \equiv \xi/r_{max}$ and $z \equiv z/r_{max}$ he surface massdensity takes the form.

$$\sum SFDM(\xi) = \frac{2\rho_c r_{max}}{\pi} \int_0^{z_{max}} \frac{\sin(\pi\sqrt{\xi^2+z^2})}{\sqrt{\xi^2+z_*^2}} \tag{4}$$

wirh $0 \leq \xi \leq 1$ and $z_{max} = \sqrt{1-\xi^2}$. A similar-expression can be obtained for the mass enclosed in acircle or radius ξ see Eq. (3) above. Here we are notconsidering the effect of a scalar cloud surrounding thecondensate. For $r \leq r_{max}$ his will appear as a projectioneffect, which is usually considered to be small [3]. In-deed, we have corroborated that the inclusion of an outerisothermal sphere does not affect the conclusions of thispaper.With the use of the expression for the projected mass,$M_{SFDM}(\xi_*)$ he lens equation simplifies to

$$\beta(\theta) = \theta - \bar{\lambda}\frac{m(\theta)}{\theta_*} \tag{5}$$

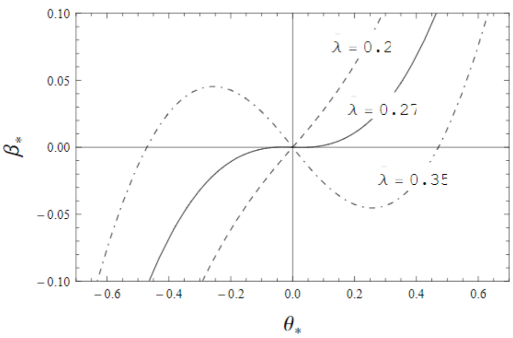

FIG. 1. The lens equation of a SFDM halo model, Eq. (5), as a function of $\bar{\lambda}$ The roots define the Einstein radius, θ_{*E}E, andits local maximum (minimum) the critical impact parameter, β_{*cr} Both quantities are well defined only for values of $\bar{\lambda} > \bar{\lambda}_{cr} \simeq 0.27$, which is the threshold value for strong lensing.

where $m(\xi) \equiv M_{SFDM}(\xi)/\rho_c r_{max}^3$ is a normalized massfunction, evaluated numerically. Here $\beta = D_{OL}\beta/r_{max}$ and $\theta = D_{OL}\theta/r_{max}$ are the normalized angular posi-tions of the source and images, respectively, and the parameter $\bar{\lambda}$

$$\bar{\lambda} \equiv \frac{\rho_c r_{max}}{\pi \sum_{cr}} = 0.57\hbar^{-1}(\frac{\rho_c}{M_{\odot}pc^{-3}})(\frac{r_{max}}{kcp})\frac{d_{OL}d_{LS}}{d_{OS}} \tag{5b}$$

In order to avoid confusion with the self-interaction term, λ, we have introduced a bar in the new parameter $\bar{\lambda}$. Wehave also defined the reduced angular distances $d_a \equiv D_A H_0/c$, and considered $H_0 \equiv 100\hbar(km/s)/Mpe$ as the Hubble constant today, with $h = 0.710 \pm 0.025$ [14].In Fig. II we show the behavior of the lens equation (5) as the $\bar{\lambda}$ parameter varies (i.e. for different values of the combination $\rho_c r_{max}$). Some notes are in turn:i) Stronglensing can be produced only for configurations with $\bar{\lambda} > \bar{\lambda}cr \simeq 0.27$, andii) For these configurations, only thosewith an impact parameter $|\beta*| < \beta_{*cr}$ can produce threeimages (note that the actual value of β_{*cr} depends on theparameter $\bar{\lambda}$, $\beta_{*cr}(\bar{\lambda})$).

These conditions on the SFDM profile are very similarto those obtained for the Burkert model in [4]; this is notsurprising because both of them have a core in radius. Inthat sense SFDM halos are analogous to those proposedby Burkert [2], but with the advantage that their prop-erties are clearly connected to physical parameters in themodel.

In Fig. II we show the magnitude of the Einstein radius, θ_{*E}, as a function of the paramete $\bar{\lambda}$, where forcomparison we have also plotted the same quantity forthe NFW [17] and Burkert [15] profiles. The minimumvalue of $\bar{\lambda}$ needed to produce multiple images is higher fora SFDM halo $\bar{\lambda}cr^{NFW} = 0 < \bar{\lambda}er^{Burkert} = 2/\pi^2 < \bar{\lambda}_{cr}^{SFDM} \simeq 0.27$. (Notice that there is an extra factor of $1/4\pi$ inour definition of $\bar{\lambda}$ when compared to that reported inRef. [15].) SFDM halos seem to require larger values of

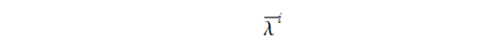

FIG. 2 The Einstein radius, θ_{*E} as function of $\bar{\lambda}^i$ forSFDM (solid line), NFW (dashed line), and Burkert (dottedline) halo models. Einstein rings of similar magnitude require $\bar{\lambda}^{NFW} < \bar{\lambda}^{Burkert} < \bar{\lambda}^{SFDM}$.

$\bar{\lambda}$ in order to produce Einstein rings of similar magnitudeto those obtained for the other profiles, but this is in partdue to projection effects that have not been consideredin this paper [13, 18].

III LENSING VS DYNAMICS

Taking into account that in SFDM models there is acritical value for the parameter $\bar{\lambda}, \bar{\lambda}_{cr} \simeq .027$, and con-sidering the definition in Eq. (5), we can write the con-dition to produce strong lensing in the form

$$\rho_c r_{max}[M_\odot pc^{-2}] < 473.68\hbar f_{dist} \tag{6}$$

with $f_{dist} \equiv d_{OS}/d_{OL}d_{LS}$ a distance factor.In order to evaluate the right-hand-side (r.h.s.) of Eq. (6), we consider two surveys of multiply-imaged sys-tems, the CASTLES [19] and the SLACS [20]. Fromthem we select only those elements for which the red-shifts of the source and the lens have been determined(which amounts to approximately 60 el-ements in eachsurvey), and calculate the corre-sponding distance fac-torfdistfor every element in the reduced sample. InCASTLES (SLACS) the distance factors are in the interval $4 < f_{dist} < 27, (6 < f_{dist}) < 25$, with a mean value of $f_{dist} \simeq 7, (f_{dist} \simeq 11)$, and then the r.h.s. of Eq. (6)takes on values in the range $1400-9000, (2000-8500)$.Some representative elements from SLACS are shown inTable I (galaxy lensing). In terms of the mean values,the inequality in Eq. (6) translates into

$$\rho_c r_{max}[M_\odot pc^{-2}] > 2000, (CASTLES) \tag{7}$$

$$\rho_c r_{max}[M_\odot pc^{-2}] > 4000, (SLACS) \tag{8}$$

These numbers are an order of magnitude greaterthan those obtained from dwarf galaxies dynamics, $\rho_C r_{max}[M_\odot] \simeq 100$, , when interpreted us-ing the samedensity profile [7]; see again Table I. This is the main re-sult of the paper. Remember that the value of r_{max} is re-lated to the fundamental parameters of the model, which are the mass of the scalar particle and the self-interactionterm, and it remains constant throughout the formationof cosmic structure.We must recall that inequalities in Eq. (7) do not takeinto account the presence of baryons in galaxies. Gravitydoes not distinguish between luminous and dark matter;then the contribution of the former to the lens could besignificant in some cases. For instance, for those systemsin SLACS the stellar mass fraction within the Einsteinradius is 0.4, on average, with a scatter of 0.1 [21].We have corroborated that our estimates in Eq. (7) arenot sensitive to the inclusion of a baryonic component.To see that we add the contribution of a de Vacoulersurface brightness profile [22] to the lens equation,

$$\beta(\theta) = \theta - \bar{\lambda}\frac{m(\theta)}{\theta} - \bar{\lambda}lum\frac{f(\theta/r_{e*})}{\theta_*} \tag{9}$$

Here $\bar{\lambda}$ is a parameter analogous to that given inEq (5b),

$$\bar{\lambda}lum \equiv \frac{(M/L)M}{2\pi \sum cr}, \tag{8b}$$

and f(x) a dimensionless projected stellar mass,

$$f(x) = \frac{1}{2520}[e^q(q^7 - 7q^6 + 42q^5 - 210q^4 + 840q^3 - 2520q^2 + 5040q - 5040) + 5040], \tag{8c}$$

with $q \equiv -7.76x^{-1/4}$. he mass-to-light ratio, M/L(from a Chabrier initial mass function), and the effec-tive radius, r_e,for each system in SLACS are reportedin Ref. [21]. With the use of Eq. (**??**) strong lensing is al-ways possible. Consequently, we must impose a differentcondition to constrain the product, $\rho_c r_{max}$ in each galaxy,such as demand the formation of Einstein rings of certainradius.

o proceed we use a small subsample of SLACS that in-cludes configurations with the minimum, maximum, andmean Einstein radius, and stellar surface mass density,respectively. This is because the new lens equation is afunction of the ratio $r_{e*} = r_e/r_{max}$; then, to compute themagnitudes of the Einstein radii, we shall fix the value of r_{max} a priori.

Using the new lens equation we find the value of $\bar{\lambda}$ thatproduces the appropriate Einstein radius for each of theelements in the subsample. This is done using two differ-ent values of r_{max}:5 and 10 Kpc. The resultant products $\rho_c r_{max}$ are compati-ble (in order of magnitude) with theinequalities ob-tained from Eq. (6). Only for those sys-tems in the subsample with a high stellar surface massdensity the value of $\rho_c r_{max}$ can decrease substantially,but it is important to have in mind that all the pos-sibleuncertainties associated to the distribution of the lumi-nous matter, like the choice of the stellar initial massfunction, will be more relevant in such cases. In gen-eral, these estimations are sensitive to the details of theparticular configuration, and a more exhaustive analy-sis, considering the complete sample, will be presented elsewhere.

DINAMICS OF GALAXIES		**GALAXY LENSING**		
Galaxy	$\rho_C r_{max}[M_\odot pc^{-2}]$	Galaxy	fdist	$\rho_C r_{max}[M_\odot pc^{-2}]$
Ho II	36.19	J0008-0004	6.16	2029.68
DDO 154	66.46	J1250+0523	8.46	28320.41
DDO 53	67.53	J2341+0000	9.12	3053.38
IC2574	81.89	J1538+5817	11.74	3930.44
NGC2366	85.45	J0216-0813	13.03	4362.44
Ursa Minor	104.72	J1106+5228	15.74	5269.75
Ho I	120.23	J2321-0939	16.23	54433.8
DDO 39	145.94	J1420+6019	19.72	6602.26
M81 dwB	265.87	J0044+0113	25.26	8457.05

TABLE I. Estimates of the productcrmaxfor different galaxies.Left.As reported in Refs. [7], using galactic dynamics.Right.Derived from equation (6) in this paper; recall that these values represent a lower limit (here we show only a representativesubsample of the SLACS survey). Note the difference of an order of magnitude between the values ofcrmaxfor dwarf galaxiesin the local universe, and the lower limit of this same quantity for galaxies producing strong lensing atz0.5.

IV DISCUSSION AND FINAL REMARKS

We have shown that a discrepancy between lensing anddynamical studies appears if we consider that the SFDMmass density profile in Eq. (1) describes the inner regionsof galactic halos at different red-shifts, up to radii of order510 Kpc. More specif-ically, we have found that lensgalaxies atz0.5, if correctly described by a SFDM haloprofile, should be denser than dwarf spheroidals in thelocal uni-verse, in order to satisfy the conditions neces-saryto produce strong lensing.In principle nothing guarantees that halos of differ-ent kind of galax-ies share the same physical properties.Our studies took into account galaxies that are intrin-sically different in terms of their total mass and baryon-concentration. While dwarf galaxies show low stel-lar sur-face brightness, stellar component in mas-sive, early typegalaxies is typically compact and dense.In the standard cosmological model the evo-lution ofDM halos may trigger differences in con-centrations forhalos with different masses due to differences in the as-sembling epoch; smaller halos collapsed in an earlier anddenser universe, there-fore they are expected to be moreconcentrated. However, it is also well known that thepresence of baryons during the assembly of galaxies canalter the density profile of the host halos and modifythis tendency, making them shallower (supernova feed-back [23]), or even cuspier (adiabatic contraction [24]).Therefore, the stellar distribution may reveal differentdynamical evolution for low and high mass halos trig-gered by galaxy formation.For SFDM, the dynamical interaction between baryonsand the scalar field may also modify the internal halostruc-ture predicted by the model, Eq. (1), clarifying thediscrepancy. For instance, if the concentration of stel-lar distribution were correlated with that of the halo,like in the adiabatic contraction model when applied tostandard DM halos, this may ex-plain our findings. Butat this time it is unknown how compressible SFDM ha-los are, and if such effect will be enough to explain ourresults, because there are no predictions on its magni-tude. If the modification triggered by baryons were insufficient, then it might be suggesting an intrinsic evolutionof SFDM halos across cosmic time. For example, if biggalaxies emerge as the result of the collision of smallerones, then the central densities of the resultant galaxieswould be naturally higher; after all,rmaxis a constantin the model, and one would expect that total mass ispreserved in galaxy-galaxy mergers. At this point we donot know which of these two mechanisms, the intrinsic tothe model, or that due to the evolution of SFDM halosin the presence of baryons, is the dominant one. In thatsense, a theoretical description of these processes may bevery useful and welcome.A full picture requires a distribution of values for thecentral density generated from the evolution of the spec-trum of primordial density perturbations after inflation.Such a result is not available now, but it is possible tostart tracing this distribution with galaxy observations.We present, for the first time, observational constraintson the dynamical evolution of SFDM halos in the pres-ence of baryons, that must be considered for future semi-analytical/numerical studies of galaxy formation.

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