Can the dark matter halo be a collisionless ensemble of axion stars?

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If dark matter is mainly composed of axions, the density distribution can be nonuniformly distributed, being clumpy instead. By solving the Einstein-Klein-Gordon system of a scalar field with the potential energy density of an axionlike particle, we obtain the maximum mass of the self-gravitating system made of axions, called axion stars. The collision of axion stars with neutron stars may release the energy of axions due to the conversion of axions into photons in the presence of the neutron star's magnetic field. We estimate the energy release and show that it should be much less than previous estimates [A. Iwazaki, Phys. Lett. B **486**, 147 (2000); Phys. Rev. D **60**, 025001 (1999)]. Future data from femtolensing should strongly constrain this scenario.

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I. INTRODUCTION

Nowadays one of the most interesting problems in physics is to reveal the nature of dark matter (DM). The existence of DM is supported by a large amount of astrophysical observations, on both galactic and cosmological scales [1,2]. Since those effects are purely gravitational, the standard candidate is a massive particle with null or very weak interaction with the rest of the particles of the standard model of particles. Two of the leading candidates for dark matter are axions and weakly-interacting massive particles such as neutralinos [3].

The axion is the pseudo-Nambu-Goldstone boson generated in the spontaneous breaking of the $U(1)$ Peccei-Quinn (PQ) global symmetry [4–6]. PQ symmetry was introduced to explain the smallness of the strong *CP* violation in QCD. Initially, this new field was assumed to be "invisible" as very weakly interacting, but in 1983, it was shown that the axion couples to two photons through Primakoff effects [7] and could be detected through its conversion into a photon in the presence of a strong magnetic field [8].

Most of the direct detection methods for the axion are based on the conversion of axions into photons [9–11]. But it is also possible to constrain the axion mass and coupling through astrophysical observation. As stars usually have strong magnetic fields, the Sun or any other astrophysical object such as a dwarf star, supernova, etc., could produce axions in its core during cooling processes and transform them into photons through Primakoff effects. The search for photons produced in stars through axion conversion can be used to put an upper limit on axion mass m_a and coupling f_a, where f_a defines the scale of $U(1)_{\rm PQ}$ symmetry breaking: $m_a \leq 10^{-3}$ eV and $f_a \geq 10^9$ GeV [12–21]. Cosmological observations impose constraints on m_a to be bigger than 10^{-6} eV, and $f_a \leq 10^{12}$ GeV [22–25]. Therefore, cosmological and astrophysical observations constrain the range of m_a to be

$$10^{-6}\ \text{eV} < m_a < 10^{-3}\ \text{eV}. \tag{1}$$

So, an axion mass within this range could be a nice candidate for cold dark matter [26,27], as it could form Bose-Einstein condensate [28].

The rate of detection needs a prescription on the dark matter distribution in the Galactic halo, and in particular, the local dark matter density. There are arguments in favor of a nonuniform distribution of dark matter in the Galaxy [29–34]. For instance, early fluctuations in the dark matter may go nonlinear long before photon decoupling, producing density-enhanced dark matter clumps. The evolution of the axion field at the QCD transition epoch may produce gravitationally bound miniclusters of axions [35,36]. Such miniclusters, due to collisional $2a \to 2a$ processes, may relax to a self-gravitating system [37–39]. These self-gravitating systems made of axions are simply called axion stars (AS). Previously, some authors explored the possibility that such axion stars may have some observable consequences. For instance, the collisions between axion stars and neutron stars may induce gamma-ray bursts [40], ultra-high-energy cosmic rays [41], or emission of x rays by neutron stars [42]. All of these observables have in common the possibility that the axion may oscillate into a photon.

In this paper, we study the self-gravitating system made of axions with a realistic potential for the scalar field as in Ref. [43], contrary to Refs. [40–42]. In Sec. II, we obtain the typical mass-density curve by varying the central density. This curve exhibits a maximum mass which depends on the value of the axion mass and the central density. Section III is dedicated to update signatures of the axion stars in the Galactic halo due to AS collisions with neutron stars (NSs). The huge magnetic field in NSs, $B \sim 10^8$ Gauss, may convert to photons all axions involved in the collisions. In this section, an estimate of the total radiated

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energy is computed. Finally, we present our results and compare them to previous estimates in Sec. IV.

II. AXION STARS

A. On the formation of axion stars

The formation of axion miniclusters was studied in Refs. [35,37,38]. They did a numerical study of the evolution of a spherically symmetric axion fluctuation in an expanding Universe at the QCD epoch, where the mass of the axion effectively switches on. The axion potential considered was

$$V(\phi) = m_a^2 f_a^2\left[1 - \cos\left(\frac{\phi}{f_a}\right)\right], \tag{2}$$

where ϕ is the axion field, f_a the energy scale of decoupling, and m_a the axion mass. The study was done for a wide range of initial conditions, and a common feature of the final density distribution is that it developed a sharp peak in the center—i.e., due to the attractive self-interaction, some nonlinear effects induce axion perturbations that lead to very dense axion miniclusters. If such density peaks are high enough, gravitational collapse and subsequent virialization can occur. This relaxation is due to $2a \to 2a$ scattering, and the associated relaxation time is smaller than the age of the Universe if the energy density of the minicluster is $\rho > 10^{10}$ eV^4 [37]. As we will see later, the axion star fulfills the conditions needed, such as relaxation, and annihilation processes prevent a gravothermal catastrophe for the axion minicluster [39].

An improved numerical resolution of the axion miniclusters revealed that $\sim$10% of the axion density will be in miniclusters with densities that can virialize to coherent axion fields on a self-gravitational well, i.e., axion stars [44].

Other mechanisms that may lead the formation of axion miniclusters and dark matter miniclusters were proposed in Ref. [36]. There, at the time when the phase transition from a quark-gluon plasma to a hadron gas takes place, the spectrum of density perturbations develops peaks and dips produced by the growth of hadronic bubbles. Afterwards, kinematically decoupled cold dark matter falls into the gravitational potential wells provided from those peaks, leading to the formation of dark matter clumps with masses $< 10^{-10} M_\odot$.

B. Properties of the axion stars

The previous picture of the formation of axion stars did not study the final self-gravitating system made of coherent axion fields. In order to do so, we have solved the Einstein-Klein-Gordon (EKG) equation in the semiclassical limit:

$$G_{\mu\nu} = 8\pi G\langle \hat{T}_{\mu\nu}\rangle, \tag{3}$$

$$\left(\Box - \frac{dV(\Phi)}{d\Phi^2}\right)\Phi = 0, \tag{4}$$

where the source of Einstein equations, the energy-momentum tensor $\langle \hat{T}_{\mu\nu}\rangle$, is the average over the ground state of a real, quantized scalar field $\Phi(r,t)$ with potential given by the energy potential in Eq. (2). We work in a spherically symmetric metric, $ds^2 = B(r)dt^2 - A(r)dr^2 - r^2(\sin^2\theta d\phi^2 + d\theta)$, and to assume a harmonic dependence of the field, $\Phi(r,t) = e^{i\omega t}\phi(r)$. The EKG system reduces to the following system of equations:

$$\begin{aligned} a' + \frac{(1-a)a}{x} + (1-a)^2 x\left[\left(\frac{1}{\tilde{B}} + 1\right)m_a^2\sigma^2 - \frac{m_a\sigma^4}{12} + \frac{\alpha\sigma'^2}{1-a} + \frac{\sigma^6}{360}\right] &= 0,\\ \tilde{B} + \frac{a\tilde{B}}{x} - (1-a)\tilde{B}x\left[\left(\frac{1}{\tilde{B}} - 1\right)m_a^2\sigma^2 + \frac{m_a\sigma^4}{12} + \frac{\alpha\sigma'^2}{1-a} - \frac{\sigma^6}{360}\right] &= 0,\\ \sigma'' + \left(\frac{2}{x} + \frac{\tilde{B}'}{2\tilde{B}} - \frac{a'}{2(1-a)}\right)\sigma' + + \frac{1-a}{\alpha}\left[\left(\frac{1}{\tilde{B}} - 1\right)m_a^2\sigma^2 + \frac{m_a\sigma^3}{6} - \frac{\sigma^5}{120}\right] &= 0, \end{aligned} \tag{5}$$

where we have defined $\phi = \frac{f_a}{\sqrt{m_a}}\sigma$, $\tilde{B} = \frac{m_a^2 B}{\omega^2}$, $r = \frac{m_p}{f_a}\sqrt{\frac{m_a}{4\pi}}x$, $a = 1 - A$ and $\alpha = \frac{4\pi}{m_a}\frac{f_a^2}{m_p^2}$, as was done in Ref. [43]. In the present work, we extend the results of Ref. [43] by solving the same system but for a wider range of masses of the axion field and many initial values of the axion field at the center $\sigma(x=0)$. Since the axion mass is restricted to be 10^{-6} eV $< m_a < 10^{-3}$ eV, we show in Fig. 1 the resulting mass of the AS as a function of the value of the central density $\rho(0) = m_a^2\sigma(0)^2/2$. The mass-density plot shows that there exists a maximum mass for a particular value of the central density. The density profiles of those maximum mass configurations are shown in Fig. 2, and the numerical values are reported in Table I. Those configurations are our benchmark in order to study possible astrophysical signatures. Once we have computed the maximum masses of axion stars for different choices of m_a, we can come back to the question of their plausibility. In Ref. [39] it was found that AS formation is possible if the mass in the core region M, the escape velocity v_e and the axion self-coupling f_a satisfy the relation $M < 10^8 v_e^{5/2}(f_a/10^{10}\text{ GeV})^{-1/4}$. By using the lower value of $f_a = 10^9$ GeV [12–21], and the maximum mass we have

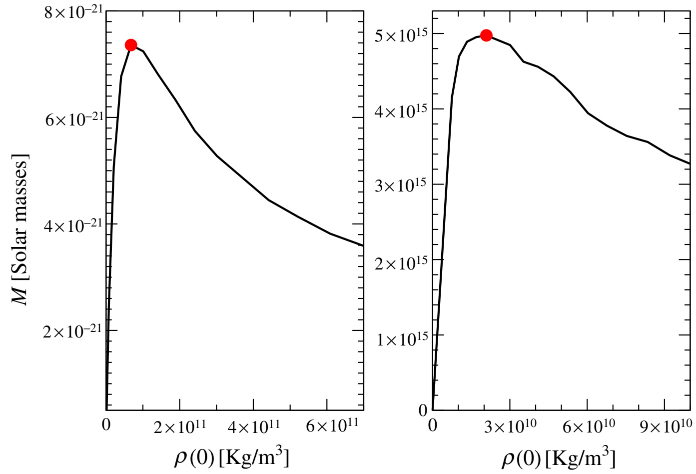

FIG. 1 (color online). Mass of axion star. Left panel: $m_a = 10^{-3}$ eV. Right panel: $m_a = 10^{-5}$ eV.

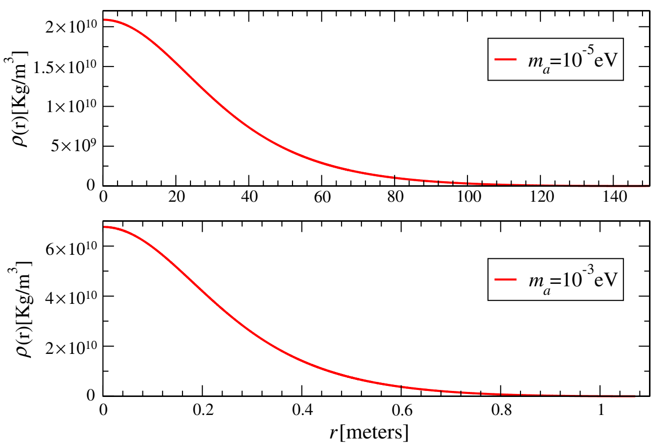

FIG. 2 (color online). Density profile. Top panel: $m_a = 10^{-5}$ eV. Bottom panel: $m_a = 10^{-5}$ eV.

obtained for an AS for $m_a = 10^{-5}$ eV, and $v_e = \sqrt{2GM/r}$, we can check that such a condition is fulfilled, and then, that the relaxation time is lower than the age of the Universe. For the annihilation processes, one may be worried about the stimulated decay into photons. It occurs when the condition $\Gamma_\pi m_p^2 v_e f_\pi/(R m_\pi^4 f_a) > 1$ is fulfilled [45,46], but such a condition implies densities $\rho > 10^{15}$ kg/m^3 for $m_a = 10^{-5}$ eV. As we can see from Fig. 2, the AS's density is always below $\rho(0) < 2.1 \times 10^{10}$ kg/m^3. Hence, no stimulated decay of axions is produced.

TABLE I. Masses and typical radii R_{99} for the maximum mass configurations shown in Fig. 1, where R_{99} is the radius of the AS where 99% of the mass is contained.

Axion mass (eV)	$\rho(0)$(Kg/m^3)	Mass ($M_\odot$)	R_{99} (meters)
$m_a = 10^{-5}$	2.1×10^{10}	5.0×10^{-15}	119.40
$m_a = 10^{-3}$	6.8×10^{10}	7.4×10^{-21}	0.89

III. POSSIBLE AXION STAR SIGNATURES IN THE GALACTIC HALO

The dark matter halos of galaxies can be considered a collisionless ensemble of mini-MACHOs, as far as this hypothesis is not in contradiction with the limits imposed by microlensing or gravothermal instability. In particular, scalar-field mini-MACHOs have been considered as a possible realization if their masses are below $10^{-7} M_\odot$ [47] to evade the microlensing limits. Recently, it was shown that mini-MACHOs with masses below $10^{-10} M_\odot$ have no measurable dynamical consequences in internal Solar System dynamics (planets, Earth-Moon) [48]. It turns out from our analysis on the maximum mass for an axion star, for $m_a = 10^{-5}$ eV, axion stars may play the role of such mini-MACHOs. In addition to microlensing, femtolensing could be a useful tool in order to look for axion stars [44]. Recently, new limits from femtolensing of gamma-ray bursts provide new evidence that primordial black holes in the mass range 10^{-16}–$10^{-13} M_\odot$ do not constitute a major fraction of the dark matter [49], and once again, the maximum mass of the axion star is consistent with those limits. In the case of an axion mass of $m_a = 10^{-3}$ eV, the maximum AS mass is far from being excluded from these current limits from the femtolensing of GRBs, since $M_{\max} \sim 10^{-21} M_\odot$, but it is encouraging that in the future, femtolensing measurement may confirm or deny the possibility that the dark matter halo may be made of an ensemble of axion stars. In addition to axion stars, other types of dark matter clumps may play the role of mini-MACHOs. In particular, if dark matter is a non-self-annihilating fermion, for some values of its mass it may fulfill the requirements to be a mini-MACHO [50]. For a self-annihilating fermion such as the neutralino, neutralino stars [51–53] have been proposed. Actually, the maximum mass for a neutralino star is $\sim 10^{-7} M_\odot$, making them suitable dark matter mini-MACHO candidates, although their stability is questionable [54].

The clumping of dark matter may change the expected number of events for direct dark matter searches, since the local density may be largely affected in the vicinity of the Earth. Nevertheless, the clumpy dark matter may offer new ways for indirect detection. In the case of the axion, early studies of luminous axion clusters were done in the 1980s [55]. In this work, we reconsider the proposal of Iwazaki [40] that axion stars interact with the strong magnetic field of a neutron star producing photons—now we consider the mass and radius of the AS obtained as general relativity indicates by solving Eq. (5). First, we shall estimate the number of axion stars in a Galactic halo using dark matter density profiles. The AS number density is modified by the tidal destruction of axion miniclusters which occurs within a hierarchical model of clump structure. The tidal destruction arises by the gravitational interaction of two clumps passing near each other or when the minicluster falls into the gravitational field of the host. The clump survival probability, as a function of the mass and radius of the clump, for non-dissipative DM particles, was computed in Refs. [33,34]. It was found that only 0.1%–0.5% of the small clumps survive the stage of tidal destruction. In Fig. 3, the left y axis (right y axis) shows the number of axion stars with a mass of $10^{-15}M_\odot$ ($10^{-21}M_\odot$) for five different DM density profiles: the Navarro-Frenk-White profile [56], the Moore profile [57], the Kravtsov profile [58], the modified isothermal profile [59] and the Salucci *et al.* profile [60,61]. The values reported in Fig. 3 include a factor 10^{-3} to account for the tidal destruction of clumps and a factor 10^{-1} due to the fact that ~10% of the axion density will be in miniclusters with densities that can virialize to coherent axion fields [44]. Notice the high number of axion stars at the center of the Galaxy. Furthermore, it is expected that ~.1% of a galaxy's total stars will finish their lives as neutron stars. The Milky Way, for instance, could have $\sim 10^9$ neutron stars.

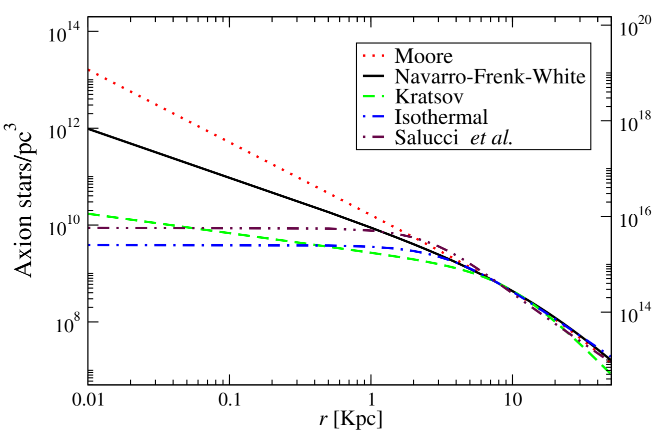

FIG. 3 (color online). Number of axion stars. The left y axis corresponds to the case for a mass of $10^{-15}M_\odot$, while the right y axis corresponds to an AS mass of $10^{-21}M_\odot$.

The high number of axion stars (see Fig. 3) and the expected number of neutron stars implies a nonzero probability that axion stars collide with neutron stars and dissipate their energy under the effect of the neutron stars' magnetic fields. In order to estimate the amount of energy radiated by this process, we closely follow Ref. [40]. Starting with the Lagrangian

$$\mathcal{L} = \frac{1}{2}(\partial^\mu a \partial_\mu a - m^2 a^2) - \frac{1}{4}\frac{ca}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu} - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}, \tag{6}$$

here c is a coupling constant of order unity, a is the axion field, $F^{\mu\nu}$ is the electromagnetic stress tensor and $\tilde{F}^{\mu\nu}$ its dual [8,62]. And by expressing this Lagrangian of Eq. (6) in terms of the electric and magnetic fields $\vec{E}$, $\vec{B}$,

$$\mathcal{L}_{a\gamma\gamma} = \frac{c\alpha}{f_a} a \vec{E}\cdot\vec{B}, \tag{7}$$

we can now derive a "modified" Gauss law, namely

$$\partial \vec{E} = \frac{-c\alpha}{f_a}\vec{\partial}\cdot(a\vec{B}). \tag{8}$$

Thus, the axion field a may induce an electric field $\vec{E}_a = -c\alpha a\vec{B}/f_a$. If the neutron star has an electric conductivity σ, an electric current $J_m = \sigma E_a$ is produced. The dissipation in the magnetized conducting media, with average σ electric conductivity, is evaluated using Ohm's law $W = \int_{AS}\sigma E_a^2 d^3x$, which, with the help of the modified Gauss law, can be directly related with the axion field and the neutron star magnetic field:

$$W = 4\pi \frac{c^2\alpha^2 B^2 \sigma}{f_a^2}\int_0^R a(r)^2 r^2 dr. \tag{9}$$

Taking the two profiles for the axion field shown in Fig. 2, we perform the integration of Eq. (9) numerically. The radiated energy is shown in Table II. Finally, we estimate the rate of collisions, such as we estimate the luminosity radiated every second. The number of collisions per pc^3 per second will be

TABLE II. Energy radiated for an AS with the maximum mass configurations shown in Fig. 2 for a NS magnetic field $B = 10^8$ G and an electric conductivity $\sigma = 10^{26}$ s^{-1} [63].

Axion mass (eV)	f_a (GeV)	Mass ($M_\odot$)	W (erg/s)
$m_a = 10^{-5}$	6×10^{9}	5.0×10^{-15}	5.3×10^{43}
$m_a = 10^{-3}$	6×10^{11}	7.4×10^{-21}	7.9×10^{37}

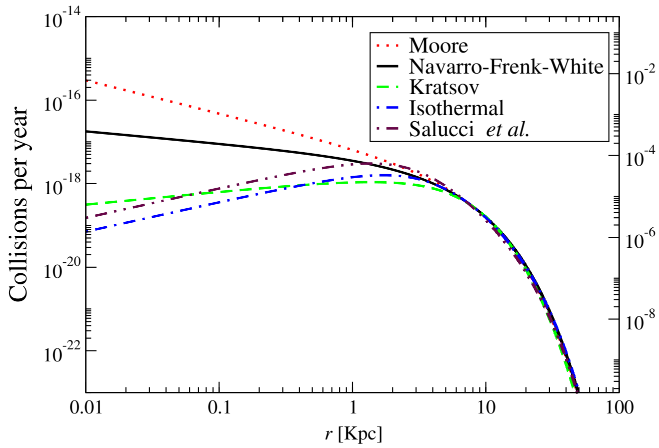

FIG. 4 (color online). Number of collisions of axion stars with neutron stars per year as a function of radial distance to the center. The left y axis corresponds to an axion star mass $5 \times 10^{-15} M_\odot$ and an effective cross section $S = \pi R_{99}^2$. The right y axis corresponds to an axion star mass $7.4 \times 10^{-21} M_\odot$ and $S = \pi L_c^2$, with L_c defined as in the text.

$$R_c = n_{\rm AS}(r) \times \rho_{\rm NS}(r) \times S \times v, \tag{10}$$

where $n_{\rm AS}$ is the number of AS per pc^3 as a function of the distance to the Galactic center (Fig. 1) and $\rho_{\rm NS}$ is the probability of finding a neutron star at that point, and we will assume this distribution to be [64]

$$\rho_{\rm NS}(r) = A r^{\alpha-1}/\lambda^\alpha e^{-r/\lambda}, \tag{11}$$

where $\alpha \simeq 1.7$ and $\lambda(\text{kpc}) = 5.21$, as given in Ref. [64]. For simplicity, the z dependence is neglected. This assumption implies that NS distribution is assumed to be spherically symmetric. A is the normalization constant defined such that

$$10^9 \text{NS} = \int A \rho_{\rm NS}(r) r^2 \sin^2\theta dr d\theta d\phi. \tag{12}$$

The velocity v of AS is assumed to be around $v = 2 \times 10^7$ cm/s. Finally, S is the cross section which can be computed as the effective area of the AS, i.e., $S_{99} = \pi R_{99}^2$, or we can define a distance L_c such that the kinetic energy of the axion star is equal to the potential energy between the AS and the neutron star, $GM_{\rm AS}M_{\rm NS}/L_c$. When such a condition happens, we can say the collision occurs. Thus, $S_{L_c} = \pi L_c^2$. The number of collisions per year R_c is shown in Fig. 4 for two cases: The left y axis illustrates the case for the maximum mass of the axion star $M_{\rm AS} = 10^{-15} M_\odot$ and $S = S_{99}$, while the right y axis shows the case where $M_{\rm AS} = 7.4 \times 10^{-21} M_\odot$ and the effective cross section $S = S_{L_c}$. R_c is very small in the first case, while the second case is more optimistic, $\sim$ one per century per galaxy. Nevertheless, even in this ideal case, the effects will be hard to detect. The release of energy due to the collision is shown for both maximum cases in Table II. We can estimate the change in temperature if all energy is transferred to the NS. Assuming that the thermal energy in the NS is $U = 6 \times 10^{47}$ erg$(M_{\rm NS}/M) \times (\rho/\rho_n)^{-2/3}(T/10^9\ \text{K})^2$ [42], with $\rho_n = 2.8 \times 10^{14}$ cm^{-3} g the nucleon density and ρ the average density of the NS, for $W = U = 7.9 \times 10^{37}$ erg/s implies a change in the NS's temperature of $\Delta T \sim 10^3$ K, hence it is very hard to detect such changes of temperature in NS cooling observations. For the maximum AS mass $M_{\rm AS} = 10^{-15} M_\odot$, the change in temperature will be $\Delta T \sim 10^9$ K, but the rate of collisions per year is very small.

It may happen that the energy is not completely absorbed by the NS, but instead the axion-photon conversion occurs out on the NS's crust, perhaps on the NS's magnetosphere. If this scenario happens, some photons may escape, liberating the whole energy. But in this case, a particle physics treatment for the oscillation may be required to compute the photon spectrum.

IV. CONCLUSIONS

As we can see from Table II, the energy dissipated by one collision of an AS with a NS is many orders of magnitude bigger than the solar luminosity. But our results for the total dissipated energy per second in NS-AS collisions are around 10 orders of magnitude less than previous estimates [42,65]. As it can be seen from Fig. 1, this difference comes from our computation of the maximal AS mass obtained through resolution of EKG equations. The obtained maximal AS mass is much smaller than the corresponding parameter used in Refs. [42,65]. It is important to notice that the maximal AS masses used in these references are now excluded by the last observational results from femtolensing of gamma-ray bursts [49].

Furthermore, improvement in femtolensing will help us to constrain the axion mass by constraining the maximum mass of axion stars. Observation of a sudden release of energy in neutron stars may indicate the interaction of an AS with its strong magnetic field. If some of those signatures are observed, they can be considered as indications that the dark matter halo is made of an ensemble of axion stars. In our estimations, we have considered the largest mass of the AS and a hypothetical electric conductivity σ [63]; nevertheless, we hope our results will encourage further studies in the possibility of detecting the axion by its possible clustering.

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