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Joseph Bramante, Keita Fukushima, and Jason Kumar

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Constraints on Bosonic Dark Matter From Observations of Old Neutron Stars

Joseph Bramante[★,1], Keita Fukushima[★,2],and Jason Kumar[★,3]

[★] Department of Physics and Astronomy, University of Hawaii

ABSTRACT

Baryon interactions with bosonic dark matter are constrained by the potential for dark matter-rich neutron stars to collapse into black holes. We consider the effect of dark matter self-interactions and dark matter annihilation on these bounds, and treat the evolution of the black hole after formation. We show that, for non-annihilating dark matter, these bounds extend up to $m_X \sim 10^{5-7}$ GeV, depending on the strength of self-interactions. However, these bounds are completely unconstraining for annihilating bosonic dark matter with an annihilation cross-section of $\langle \sigma_a v \rangle \gtrsim 10^{-38}$ cm^3/s. Dark matter decay does not significantly affect these bounds. We thus show that bosonic dark matter accessible to near-future direct detection experiments must participate in an annihilation or self-interaction process to avoid black hole collapse constraints from very old neutron stars.

[1] bramante@hawaii.edu

[2] keitaf@hawaii.edu

[3] jkumar@hawaii.edu

1 Introduction

Dark matter (DM) has been detected only via gravitational interactions. While there is overwhelming cosmological and astronomical evidence for new matter which could have a weak coupling to standard model fermions, the mass and couplings of this dark matter are not yet established. Asymmetric dark matter (ADM) has been proposed as a compelling framework to explain both the dark matter abundance and the baryon asymmetry [1–33].

It has been pointed out that models of asymmetric dark matter can be tightly constrained by the existence of old neutron stars [34–41]. The basic point is that dark matter will be captured by neutron stars due to DM-neutron scattering; if dark matter does not annihilate or decay, then it will continue to accumulate until it collapses into a black hole. The observation of old neutron stars can thus bound the dark matter-neutron scattering cross section (σ_{nX}) for models with no dark matter annihilation or decay. It has also been demonstrated that bounds on non-annihilating dark matter shift with the introduction of self-interactions terms [42–46]. In this work, we will study a more general question. We will focus on the range of σ_{nX}, dark matter annihilation cross section ($\sigma_a v$), dark matter decay rate (Γ), and self-interaction strength which could be consistent with observations of old neutron stars.

As an initial point, we note that asymmetric dark matter is not necessarily non-annihilating. Asymmetric dark matter requires that the dark matter particle can be distinguished from the anti-particle, which implies the existence of a continuous unbroken symmetry under which the dark matter is charged. It is this symmetry which forbids the fermion Majorana mass term. However, asymmetric dark matter need not be the lightest particle charged under this continuous symmetry. For dark matter to be stable, it must be the lightest particle charged under some symmetry, but this may be a distinct Z_2 symmetry. In this case, self-annihilation of the asymmetric dark matter would not be forbidden.

Here we summarize the important features of the following analysis:

I. *Dark matter accumulation.* The rate at which a neutron star captures dark matter (C_X) depends on the local dark matter density (ρ_X), the dark matter-neutron scattering cross section (σ_{nX}), and the dark matter mass (m_X). The number of dark matter particles in a neutron star can be depleted by dark matter decay or annihilation.

II. *Black hole formation.* Bosonic dark matter collected in a neutron star will form a black hole if the total energy is minimized at a radius which is less than the Schwarzschild radius. This condition is usually fulfilled by requiring that the dark matter be self-gravitating and exceed the Chandrasekhar limit. The Chandrasekhar limit grows with the strength of repulsive self-interactions.

    a. If the dark matter cannot thermalize quickly enough, it will not form a black hole

within the lifetime of the neutron star (see Appendix B).

b. Thermalized dark matter will collect within a radius r_{th}, which determines the number of dark matter particles needed for the dark matter to self-gravitate. But if dark matter forms a Bose-Einstein condensate (BEC), then it will collect within a much smaller radius (r_c) and fewer particles will be needed before the dark matter becomes self-gravitating and gravitational collapse occurs.

III *Destruction of the neutron star.* The neutron star will be destroyed if the black hole grows large enough to consume the neutron star. The black hole will accrete baryonic and dark matter, but will emit Hawking radiation. To destroy the neutron star, the black hole must be large when it forms.

a. If dark matter forms a BEC, then dark matter captured by the neutron star after the formation of a black hole will be efficiently accreted by the black hole, potentially compensating for the effect of Hawking radiation.

b. If dark matter has a repulsive self-interaction, then the number of particles needed to form a black hole will increase. The resulting black hole, when formed, may then be large enough to continue growing.

In section 2, we describe the accumulation of dark matter in neutron stars, including effects from dark matter decay and annihilation. In section 3, we describe the formation of a black hole from dark matter in neutron stars, including the effects of self-interactions. In section 4, we describe evolution of a black hole which has formed in a neutron star, including the effects of baryonic and dark matter accretion and Hawking radiation. In section 5 we find the constraints on the parameter space of bosonic dark matter models from observations of old neutron stars. We conclude with a discussion of our results in section 6.

2 Dark Matter Accumulation in a Neutron Star

The dark matter capture rate (C_X) of neutron stars is given in [37,47]. For $m_X < \mathcal{O}(10^2)$ eV (assuming $T = 10^5$ K), dark matter within an old neutron star will be depleted by evaporation, and the rate of dark matter accumulation will also be suppressed. The probability for a dark matter particle to scatter while passing through a neutron star is given by [48]

$$P = 1 - \exp\left[-\int \eta_n \sigma_{nX} dl\right] \tag{1}$$

where η_n is the neutron number density and the integral is taken over the path of the dark matter particle through the neutron star. For small σ_{nX}, we have $P \sim \eta_n \Delta l \sigma_{nX}$. But $P \to 1$

for $\int \eta_n \sigma_{nX} dl \gg 1$. Taking a neutron star to have radius $R = 10.6$ km and baryonic density $\rho_b \sim 7.8 \times 10^{38}$ GeV/cm^3 [34,37,49], this saturation occurs for $\sigma_{nX} > \sigma_{sat} \sim 2.1 \times 10^{-45}$ cm^2.

For $m_X >$ GeV the capture rate is [37]

$$C_X \sim 2.3 \times 10^{45}\ \mathrm{Gyr}^{-1} \left(\frac{\mathrm{GeV}}{m_X}\right) \left(\frac{\rho_X}{10^3\ \mathrm{GeV/cm}^3}\right) f(\sigma_{nX}) \beta(m_X, m_N, v_{esc}, \bar{v}), \tag{2}$$

while for $m_X <$ GeV, due to the effects of Pauli blocking, the capture rate is [37],

$$C_X \sim 3.4 \times 10^{45}\ \mathrm{Gyr}^{-1} \left(\frac{\rho_X}{10^3\ \mathrm{GeV/cm}^3}\right) f(\sigma_{n_X}) \beta(m_X, m_N, v_{esc}, \bar{v}), \tag{3}$$

where ρ_X is the ambient density of dark matter. The factor $f(\sigma_{nX})$ is given by $f = \sigma_{nX}/\sigma_{sat}$ for $\sigma_{nX} \leq \sigma_{sat}$, and $f = 1$ for $\sigma_{nX} > \sigma_{sat}$. The factor

$$\beta(m_X, m_N, v_{esc}, \bar{v}) \ = \ 1 - \frac{1 - \exp\left[-6(v_{esc}^2/\bar{v}^2)(\mu/(\mu-1)^2)\right]}{6(v_{esc}^2/\bar{v}^2)(\mu/(\mu-1)^2)} \tag{4}$$

will take the value $\beta \sim 1$ for dark matter masses $m_X \lesssim 10^6$ GeV and for typical neutron star parameters, where $\mu \equiv m_X/m_N$, $v_{esc} \simeq 1.8 \times 10^5$ km/s is the escape velocity from the surface of the neutron star, and $\bar{v} \sim 220$ km/s is the ambient dark matter average velocity [34,37,50].

If t_{ns} is the lifetime of a neutron star, then the number of particles accumulated over that lifetime, $N_{acc}(t_{ns})$, is determined by the dark matter capture rate, decay rate, and the rate of dark matter annihilation. We will first consider the case where dark matter does not annihilate, but does decay at rate $\Gamma = \tau^{-1}$. In this case, the number of accumulated dark matter particles can be written as

$$N_{acc}^{(decay)} = C_X \tau \left(1 - e^{-t_{ns}/\tau}\right). \tag{5}$$

The tightest model-independent constraints on dark matter decay come from an analysis of the stability of dark matter halos. Measurements of halo mass-concentration and galaxy-cluster mass compared with simulations of dark matter halo mass distributions disturbed by dark matter decay constrain any dark matter lifetime to $\tau > 10$ Gyr for all velocities of the dark matter decay products [53]. Constraints on dark matter decay that heats the CMB are tighter for decay products with $v \gtrsim 0.6$c [54]. We see that for $\tau \sim 10$ Gyr and a neutron star lifetime of $t_{ns} \sim 10$ Gyr, the number of accumulated dark matter particles is only suppressed by an $\mathcal{O}(1)$ factor. Because the minimum allowed dark matter lifetime is on the order of the lifetime of a neutron star, dark matter decay does not significantly alter the amount of accumulated dark matter, and thus does not significantly alter constraints arising from observations of neutron stars.

Henceforth, we will assume that dark matter does not decay. The accumulated number of dark matter particles can then be approximated as [55, 56]

$$\begin{aligned} \frac{dN_{acc}}{dt} &\approx C_X - \frac{\langle \sigma_a v \rangle N_{acc}^2}{V_{th}} \\ \rightarrow N_{acc} &\approx \sqrt{\frac{C_X V_{th}}{\langle \sigma_a v \rangle}} \text{Tanh} \left[\sqrt{\frac{C_X \langle \sigma_a v \rangle}{V_{th}}} t_{ns} \right], \end{aligned} \tag{6}$$

where $V_{th} = (4/3)\pi r_{th}^3$ is the volume within which the dark matter is thermalized, here assumed to be of constant density, and $\langle \sigma_a v \rangle$ is the annihilation cross section. If the effect of self-interactions is small, the thermalization radius r_{th} can be written as [35, 37, 41],

$$r_{th} = 240 \text{ cm} \left(\frac{T}{10^5 \text{ K}} \cdot \frac{\text{GeV}}{m_X} \right)^{1/2}. \tag{7}$$

It is useful to determine the range of physical parameters for which the argument of the hyperbolic tangent in eq. 6 is greater than unity, indicating that the collection and annihilation of dark matter in the neutron star has reached an equilibrium. For a more complete treatment, see Appendix A.

3 Black Hole Formation

In order to form a black hole, the dark matter collected in a neutron star must become dense enough that the energy of the dark matter is minimized as the radius of the dark matter distribution approaches zero. If N_{DM} bosonic dark matter particles of mass m_X are confined to a sphere of radius r, then the energy of a boson is approximately given by

$$E \sim \frac{1}{r} - \frac{G m_X^2 N_{DM}}{r} - \frac{4\pi G \rho_b m_X r^2}{3}. \tag{8}$$

The first term is the relativistic kinetic energy, and the second and third terms are the gravitational potential energy due to DM-DM interactions and DM-baryon interactions, respectively. The requirement of "self-gravitation" ensures the second term of eq. (8) is larger than the third, so the second term will dominate as the dark matter collapses. The Chandrasekhar limit then corresponds to the requirement that the second term dominate the kinetic term.

However, this effective Chandrasekhar limit depends on the total local potential of the dark matter and is modified if dark matter has self-interactions. A $\lambda|\phi|^4$ term is generally not forbidden by any symmetry of the theory (in the absence of higher dimension terms,

stability of the potential would require this interaction to be repulsive, $\lambda \geq 0$). With this self-interaction [35], the number of self-gravitating particles required to form a black hole will be [51, 52]

$$N_{chand} = \frac{2m_{\rm Pl}^2}{\pi m_X^2}\left(1 + \frac{\lambda}{32\pi}\frac{m_{\rm Pl}^2}{m_X^2}\right)^{1/2}. \tag{9}$$

Of course this expression reduces to the simpler limit $N_{chand} \sim m_{\rm Pl}^2/m_X^2$ for non-interacting bosons when $\lambda = 0$. Note, however that if $\lambda/32\pi > m_X^2/m_{\rm Pl}^2$, then $N_{chand} \sim \lambda^{1/2} m_{\rm Pl}^3/m_X^3$. As the $\lambda|\phi|^4$ interaction is not forbidden by any symmetry, there is no reason to expect λ to be very small. Thus, unless m_X is quite large, one would expect the Chandrasekhar limit to be dominated by the interaction term. In this case, the Chandrasekhar limit on the number of particles is suppressed from the fermion case ($N_{chand}^{(ferm.)} \sim m_{\rm Pl}^3/m_X^3$) by a factor $\lambda^{1/2}$.

The dark matter particles will become self-gravitating when their density exceeds that of the baryons in the neutron star. If the dark matter is confined to a region of radius r, then the number of dark matter particles required to achieve self-gravitation is given by

$$N_{s-g}(r) \simeq \frac{4\pi r^3}{3m_X}\rho_b, \tag{10}$$

where $\rho_b \sim 7.8 \times 10^{38}$ GeV/cm^3 is taken as the baryon density in a neutron star.

If dark matter forms a Bose-Einstein condensate [35, 37], then a large fraction of the dark matter will be confined to a radius which is much smaller than the thermalization radius of the dark matter. Thermalized bosonic matter at the core of a neutron star will form a BEC if the number of thermalized particles exceeds

$$N_{BEC} = \zeta\left(\frac{3}{2}\right)\left(\frac{m_X T}{2\pi}\right)^{3/2}\left(\frac{4\pi r_{th}^3}{3}\right) \approx 10^{36}\left(\frac{T}{10^5\ {\rm K}}\right)^3. \tag{11}$$

The effect of self-interactions on the formation of a BEC is still not completely understood. In principle, self-interactions can affect the critical temperature and the size of the BEC state. A complete study of these effects is beyond the scope of this work. Instead, we will assume that the critical temperature and the size of the BEC state are unchanged by self-interactions of the magnitude which we will consider. If, due to self-interactions, dark matter does not form a BEC, then the analysis of Appendix C would be relevant.

If the number of dark matter particles in the BEC phase is small, and the gravitational potential energy is dominated by the baryonic contribution, then the size of the BEC, r_c, can be approximated by equating the magnitude of the non-relativistic kinetic energy and gravitational potential energy [35, 37], yielding:

$$r_c \;=\; \left(\frac{3}{8\pi G m_X^2 \rho_b}\right)^{1/4} = 1.5 \times 10^{-4}\ {\rm cm}\left(\frac{\rm GeV}{m_X}\right)^{1/2}. \tag{12}$$

We have assumed that the $\lambda\phi^4$ contribution is small. Considering the ground state to have size r_c, the contribution of the $\lambda\phi^4$ term to the energy of the BEC state scales approximately as $\propto \lambda N^2/r_c^3 m_X^2$. This contribution is negligible for $\lambda \ll 10^{-18}(m_X/\,\mathrm{GeV})^3$, implying that the value of the critical temperature and the size of the BEC state are essentially unchanged. From eq. (10) we find that the number of particles in the BEC phase required for self-gravitation is

$$N_{s-g}^{(BEC)} = 10^{28}\left(\frac{\mathrm{GeV}}{m_X}\right)^{5/2}. \tag{13}$$

Assuming $T = 10^5$ K, one finds $N_{chand} > N_{s-g}$ if $m_X > 4\times 10^{-21}$ GeV. For all m_X of interest BECs will become self-gravitating well before they reach the Chandrasekhar limit.

We may write the number of dark matter particles needed for black hole formation in the BEC phase as $N_{BHforms}^{(BEC)}$. We find

$$N_{BHforms}^{(BEC)}(m_X,\lambda,T) \;\; = \;\; N_{chand} + N_{BEC}. \tag{14}$$

Note that, if dark matter forms a BEC, the neutron star must collect N_{BEC} particles which lie within r_{th} and cause the formation of the BEC, as well as an additional N_{chand} particles which fall into a BEC of size r_c and which collapse to form a black hole. For sufficiently large m_X, one finds $N_{s-g}(r_{th}) > N_{BEC}$, in which case the dark matter collected within the thermalization radius will self-gravitate before enough dark matter is collected to form a BEC. This leads to the possibility that dark matter within the thermalized region will collapse without forming a BEC [46, 57]. However, as dark matter in the thermalized region collapses it will also lose energy, which can result a lower temperature and higher density. This may lead to subsequent the formation of a BEC [58].

4 Hawking Radiation and Neutron Star Destruction

The formation of a black hole within an old neutron star is not necessarily in conflict with observation – the black hole must also absorb the neutron star in a time much shorter than the lifetime of the neutron star, without first evaporating through Hawking radiation. We build on the analysis of [35, 37], but also consider the effect of dark matter accretion and repulsive self-interactions on the growth of the black hole.

The evolution of the black hole's mass is governed by the equation

$$\frac{dM_{bh}}{dt} = \frac{4\pi\rho_b (GM_{bh})^2}{v_s^3} + \left(\frac{dM_{bh}}{dt}\right)_{DM} - \frac{1}{15360\pi (GM_{bh})^2}, \tag{15}$$

where M_{bh} is the mass of the black hole and v_s is the sound speed of the neutron star (we take $v_s/c \sim 0.1$ [37]). The first term on the right hand side of eq. (15) is the Bondi accretion rate for baryonic matter, the second term is the rate at which the black hole accretes dark matter, and the last term is the Hawking radiation rate. $(dM_{bh}/dt)_{DM}$ will depend not only on how quickly the neutron star captures dark matter, but also on how quickly the black hole absorbs new dark matter captured by the neutron star. The initial black hole mass, M_{bhi} is given by $m_X N_{s-g}$ ($N_{s-g} > N_{chand}$) and $m_X N_{chand}$ ($N_{s-g} < N_{chand}$).

4.1 Rate of Black Hole Growth and Destruction

If a black hole within a neutron star begins to grow, then the baryonic accretion rate will increase as M_{bh}^2, while the Hawking radiation rate will decrease as M_{bh}^2. In this case, we can approximate the time it will take for the black hole to consume the neutron star by assuming that the baryonic accretion rate dominates, neglecting dark matter accretion and Hawking radiation. We then find

$$\begin{aligned} \frac{dt}{dM} &= \frac{v_s^3}{4\pi\rho_b (GM)^2} \\ &\rightarrow \quad t_{nscollapse} = \frac{v_s^3}{4\pi\rho_b G^2}\left(\frac{1}{M_{bhi}} - \frac{1}{M_{bhi}+M_{ns}}\right) \sim \frac{v_s^3}{4\pi\rho_b G^2 M_{bhi}}, \end{aligned} \tag{16}$$

where $M_{ns} \sim 3.3 \times 10^{57}$ GeV is the mass of a heavy neutron star [59]. We consider the rate of collapse for a black hole with initial mass given by

$$M_{bhi}^{(BEC)} = m_X N_{chand} = 9.5 \times 10^{37} \text{ GeV} \left(\frac{\text{GeV}}{m_X}\right)\left(1 + \frac{\lambda}{32\pi}\frac{m_{\rm Pl}^2}{m_X^2}\right)^{1/2}. \tag{17}$$

This initial mass yields a neutron star collapse time of

$$t_{nscollapse}^{(BEC)} = 2.6 \times 10^5 \text{ years} \left(\frac{m_X}{\text{GeV}}\right)\left(1 + \frac{\lambda}{32\pi}\frac{m_{\rm Pl}^2}{m_X^2}\right)^{-1/2}, \tag{18}$$

For all relevant regions of parameter space, this time of collapse will be small compared to the lifetime of an old neutron star.

Similarly, if a black hole begins to shrink, the baryonic accretion rate will quickly become small, while the Hawking radiation rate will grow rapidly. Considering only the Hawking radiation rate, we find

$$\begin{aligned} \frac{dt}{dM} &= -15360\pi (GM)^2, \\ t_{evap} &= 5120\pi G^2 M_{bhi}^3. \end{aligned} \tag{19}$$

We then find

$$t_{evap}^{(BEC)} = 5120\pi G^2 \left(9.2\times 10^{37}\frac{\mathrm{GeV}^2}{m_X}\right)^3 = 13\ \mathrm{Gyr}\left(\frac{\mathrm{GeV}}{m_X}\right)^3. \quad (20)$$

We thus see that the black hole will evaporate in a time much shorter than the lifetime of the neutron star if $m_X \gg 1$ GeV, for dark matter which forms a BEC.

4.2 Black Hole Accretion of Dark Matter in the BEC Phase

In order for dark matter to efficiently fall into a black hole after being captured by the neutron star, the impact parameter of the black hole must be small compared to the radius within which the dark matter settles [37]. In other words, additional dark matter will accumulate in the black hole at the rate it enters the neutron star if the size of the region where the dark matter particles settle is small compared to the black hole's impact parameter, $b_{infall} = 4GM_{bh}/v_\infty$. Here v_∞ is a dark matter particle velocity on approach to the black hole.

After a black hole is formed from a BEC, N_{BEC} dark matter particles will remain within radius r_{th}, and any further dark matter particles that collect in the star will fall into the BEC state. It can be shown that the radius of the BEC is smaller than the black hole's impact parameter [37], specifically $b_{infall} \sim 4r_c$, so in the case that all incoming dark matter settles into a BEC state, it will be efficiently captured by a black hole. Thus for dark matter which forms a BEC, the black hole dark matter accretion rate will equal the neutron star dark matter capture rate,

$$\left(\frac{dM_{bh}}{dt}\right)_{DM} \sim C_X m_X. \quad (21)$$

The black hole will continue to grow if

$$\begin{aligned} C_X m_X &> \frac{1}{15360\pi(Gm_X N_{chand})^2} - \frac{4\pi\rho_b(Gm_X N_{chand})^2}{v_s^3} \\ C_X &> \frac{1}{\mathrm{Gyr}}\left[2.4\times 10^{36}\left(\frac{m_X}{\mathrm{GeV}}\right)\left(1+\frac{\lambda}{32\pi}\frac{m_{\mathrm{Pl}}^2}{m_X^2}\right)^{-1}\right. \\ &\quad \left. -1.5\times 10^{42}\left(\frac{\mathrm{GeV}}{m_X}\right)^3\left(1+\frac{\lambda}{32\pi}\frac{m_{\mathrm{Pl}}^2}{m_X^2}\right)\right]. \end{aligned} \quad (22)$$

If the black hole begins to grow, it will quickly absorb the entire neutron star. On the other hand, for the range of masses in which it is possible for Hawking radiation to dominate, the black hole will evaporate quickly.

A possible exception to even this bound arises if one assumes that Hawking radiation preferentially heats bosonic dark matter via dark-sector radiation. We refer to a detailed discussion of this effect in [37]. However, we note that, since a growing black hole will in fact grow rapidly, the Hawking radiation rate will quickly become small, implying that there will be very little heating of the dark or baryonic matter due to Hawking radiation.

Bosonic dark matter with a large enough repulsive self-interaction cross section will have a larger mass at Chandrasekhar collapse and can avoid forming a small black hole that evaporates too quickly to destroy the neutron star. The result is an interesting phenomenon: very small repulsive self-interactions tighten neutron star collapse constraints on bosonic dark matter, but larger repulsive self-interactions loosen the same constraints.

5 Bosonic Dark Matter Bounds From Neutron Star Collapse

In this section we determine the constraints on σ_{nX} for bosonic dark matter arising from the existence of old neutron stars, including the effects of dark matter self-interactions, dark matter annihilation, and dark matter accretion onto black holes. The exclusion contour bounds the region

$$\begin{aligned} N_{acc}(\sigma_{nX}, m_X, \langle\sigma_a v\rangle, \rho_X, t_{ns}, T) &> N_{BHforms}(m_X, \lambda, T), \\ \left.\frac{dM_{BH}}{dt}\right|_{M_{BH}=M_{BHi}} &> 0. \end{aligned} \tag{23}$$

Figure 1 displays the exclusion contour in the (m_X, σ_{nX}) plane if the dark matter can form a BEC, assuming that old neutron stars have lifetime $t_{ns} = 10$ Gyr, core temperature $T = 10^5$ K, and ambient dark matter density $\rho_X = 10^3$ GeV/cm^3 (this is an estimate for the dark matter density at the center of globular clusters [38,39]). The various contours are for different choices of the self-interaction parameter λ and the annihilation cross section $\langle\sigma_a v\rangle$. We note that an order of magnitude increase in $\langle\sigma_a v\rangle$ corresponds to an order of magnitude relaxation of the bound, except in regions where the bound is significantly affected by dark matter accretion. Moreover, as the capture rate depends on ρ_X only through the factor $\rho_X \times \sigma_{nX}$, a scaling of the ambient dark matter density simply rescales the bound on σ_{nX}. For example, if the dark matter density at the center of globular clusters is as small as 0.3 GeV/cm^3, then the bound on σ_{nX} would be weakened by a factor of ~ 3000. Note that observations of old neutron stars can only provide constraints in the region $\sigma_{nX} \leq \sigma_{sat.}$. For the entire relevant range of masses, bounds from neutron stars become completely unconstraining if $\langle\sigma_a v\rangle \times f \gtrsim 10^{-38}$ cm^3/s,

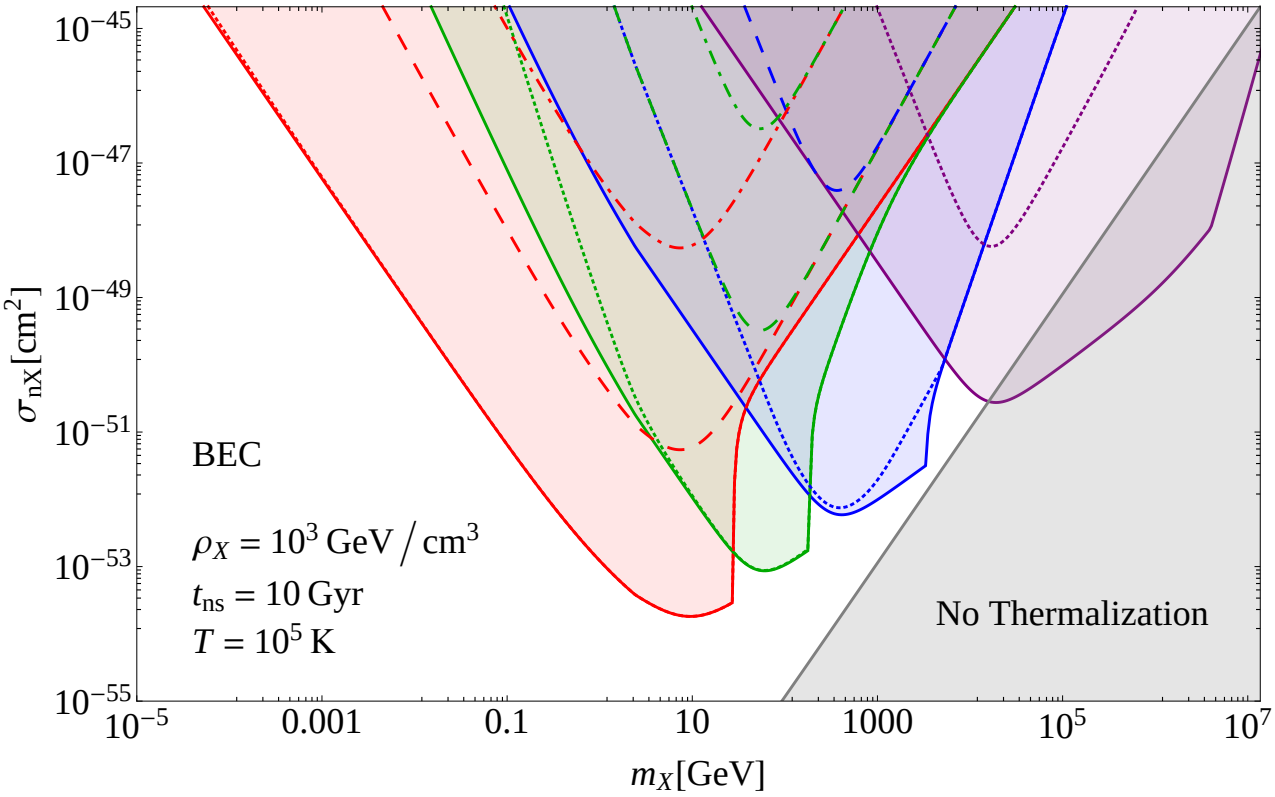

Figure 1: Neutron star collapse bounds for annihilating, self-interacting bosonic dark matter that forms a Bose-Einstein condensate at globular cluster density $\rho_X \sim 10^3$ GeV/cm^3. From left to right the red, green, blue, and purple contours denote regions for which the self interaction parameter $\lambda = \{0, 10^{-30}, 10^{-25}, 10^{-15}\}$, respectively. Solid, dotted, dashed, and dot-dashed contours denote annihilation cross sections $\langle \sigma_a v \rangle = \{0, 10^{-50}, 10^{-45}, 10^{-42}\}\mathrm{cm}^3/\mathrm{s}$, respectively.

because the neutron star can never capture enough dark matter for black hole collapse to occur.

As previously noted, if the self-interaction term is increased (contours farther right in Figure 1), the bound on high mass dark matter improves. As the Chandrasekhar bound increases with the self-interaction coupling, there is less Hawking radiation at the formation of higher mass black holes, and the black hole growth condition (eq. (23)) is met for higher masses and lower scattering cross sections.

Figure 1 also shows the excluded region (eq. (29)) within which dark matter captured by

a neutron star will not thermalize,

$$\sigma_{nX} < 1.1 \times 10^{-60}\ \mathrm{cm}^2 \left(\frac{m_X}{\mathrm{GeV}}\right)^2 \left(\frac{10^5 \mathrm{K}}{T}\right) \left(\frac{10\ \mathrm{Gyr}}{t_{th}}\right). \tag{24}$$

In the plot we assume a thermalization time scale of $t_{th} \sim$ Gyr. For $m_X < 28$ GeV, we reproduce the bounds of [37]. This analysis shows that old neutron stars in the center of globular clusters with a dark matter density $\rho_X = 10^3$ GeV/cm^3 [38, 39] provide a bound on non-annihilating bosonic dark matter competitive with planned terrestrial direct detection experiments for dark matter masses up to $m_X \sim 10^7$ GeV [60, 61]. We note that future detection of neutron stars in regions of dark matter density larger than 10^3 GeV/cm^3 will result in appropriately rescaled bounds.

6 Conclusions

We have studied the constraints that old neutron stars place on bosonic dark matter, allowing for self-interactions, decay, and self-annihilation of the bosonic dark matter. Observations of old neutron stars imply bosonic dark matter with a mass $\sim$ kev $- 10^6$ GeV detected at terrestrial experiments will have a minimum annihilation or self-interaction term. For example, we show that a neutron star of age $t_{ns} = 10$ Gyr found in a globular cluster with dark matter density $\rho_X = 10^3$ GeV/cm^3 will not constrain bosonic dark matter if the dark matter has an annihilation cross section $\langle \sigma_a v \rangle \gtrsim 10^{-38}$ cm^3/s. These bounds are thus most relevant if the unbroken symmetry which stabilizes an asymmetric dark matter candidate is continuous; if it is broken to a Z_2 symmetry (even weakly), then self-annihilation is permitted and these bounds can be weakened considerably. Conversely we demonstrate that permitted dark matter decay, which is constrained by the evolution of dark halos, will not significantly relax neutron star bounds on bosonic dark matter.

We also show that even small self-interaction terms can dramatically weaken bounds on asymmetric dark matter. These bounds are thus most constraining if there exists some (at least approximate) symmetry which can suppress a quartic self-interaction term. However, very small self-interactions can result in even more constraining bounds, by causing the formation of larger black holes which grow rapidly.

It is interesting to note that these bounds can extend up to large m_X. For such large masses, one cannot easily tie the dark matter asymmetry to the baryon asymmetry. Nevertheless, asymmetric dark matter with a small (or vanishing) annihilation cross section provides an interesting candidate for non-thermal dark matter, and observations of old neutron stars can provide significant constraints on these models.

Note added: while this paper was being completed, [58] appeared, which also discusses the effect of dark matter accretion on the evolution of a black hole. In [58], it is also argued that neutron star observations cannot bound dark matter particles with a large mass. Note that this argument refers to potential bounds on dark matter which self-gravitates in the thermalized region before forming a BEC. The bounds we have described for BEC dark matter at high mass are not affected by this argument. These bounds instead arise from a consideration of the effect of self-interactions, and the effect on the black hole's evolution of the accretion of dark matter in the BEC phase.

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A Dark Matter Capture and Annihilation Equilibrium

It is useful to determine the range of parameters for which the total dark matter in the neutron star will reach an equilibrium, at which point dark matter will annihilate at the same rate it collects in the neutron star. This happens when the argument of the hyperbolic tangent in eq. (6) is greater than unity – in this range the hyperbolic function will evaluate to unity and the formula for the number of accumulated dark matter particles simplifies considerably. For $m_X > \text{GeV}$,

$$\sqrt{\frac{C_X \langle \sigma_a v \rangle}{V_{th}}} t_{ns} \approx 3.5 \times 10^5 \left(\frac{m_X}{\text{GeV}}\right)^{1/4} \left(\frac{10^5 \text{ K}}{T}\right)^{3/4} \left(\frac{t_{ns}}{10 \text{ Gyr}}\right) \beta \times \left(\frac{\langle \sigma_a v \rangle}{10^{-45} \text{ cm}^3/\text{s}} \cdot \frac{\rho_X}{10^3 \text{ GeV/cm}^3} \cdot f(\sigma_{nX})\right)^{1/2}, \quad (25)$$

and for $m_X < \text{GeV}$,

$$\sqrt{\frac{C_X \langle \sigma_a v \rangle}{V_{th}}} t_{ns} \approx 5.1 \times 10^5 \left(\frac{m_X}{\text{GeV}}\right)^{3/4} \left(\frac{10^5 \text{ K}}{T}\right)^{3/4} \left(\frac{t_{ns}}{10 \text{ Gyr}}\right) \beta \times \left(\frac{\langle \sigma_a v \rangle}{10^{-45} \text{ cm}^3/\text{s}} \cdot \frac{\rho_X}{10^3 \text{ GeV/cm}^3} \cdot f(\sigma_{nX})\right)^{1/2}. \quad (26)$$

In figure 2, we plot the region in the $(m_X, \langle \sigma_a v \rangle \times f)$-plane such that the neutron star is in equilibrium, assuming $t_{ns} = 10$ Gyr, $T = 10^5$ K and $\rho_X = 10^3$ GeV/cm^3. Even for small

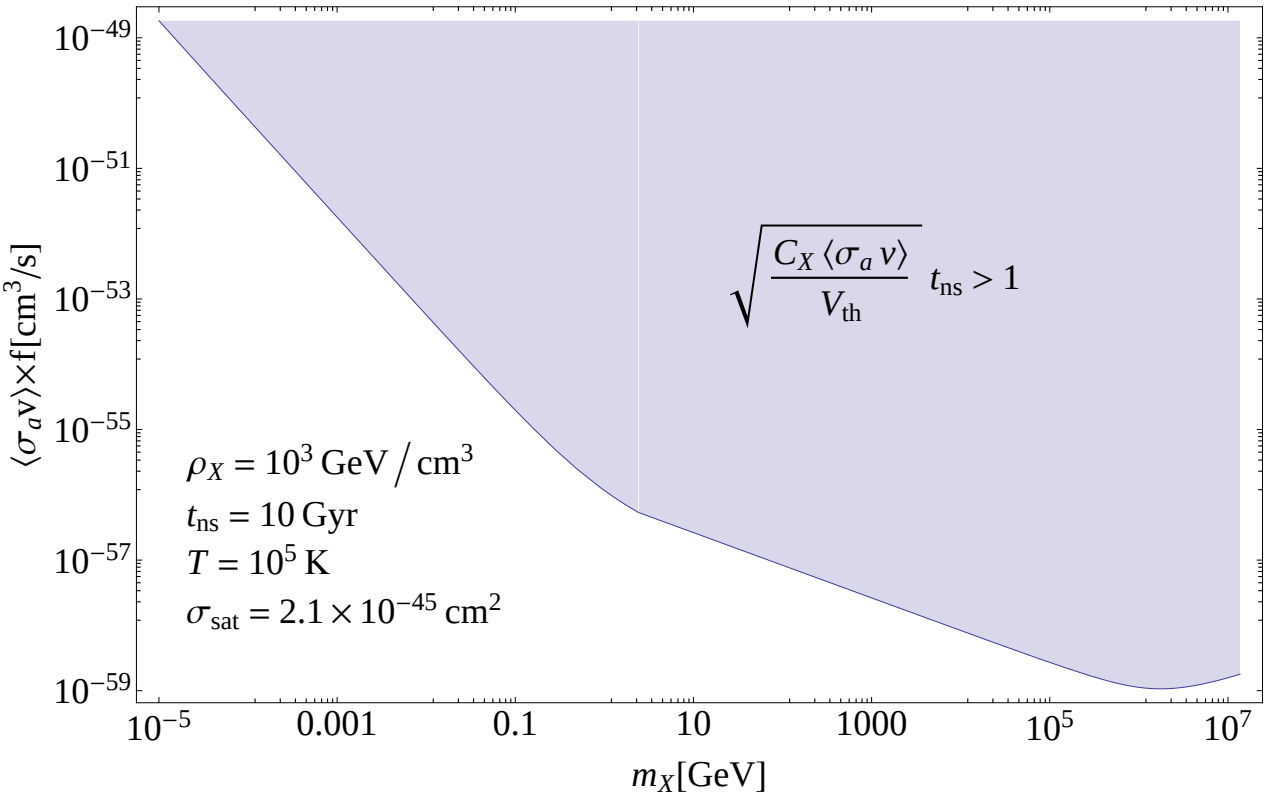

Figure 2: In the dark shaded region of the $(m_X, \langle\sigma_a v\rangle \times f)$-plane, the neutron star is in equilibrium, assuming $t_{ns} = 10$ Gyr, $T = 10^5$ K and $\rho_X = 10^3$ GeV/cm^3.

values of σ_{nX} and $\langle\sigma_a v\rangle$ (including any values which could be detected by current and planned observations), we may use the approximation

$$\begin{aligned} N_{acc} &\sim \sqrt{C_X V_{th}/\langle\sigma_a v\rangle} \\ &\sim \sqrt{\frac{4\pi C_X (240\ \mathrm{cm})^3}{3\langle\sigma_a v\rangle}} \left(\frac{T}{10^5 K}\frac{\mathrm{GeV}}{m_X}\right)^{3/4}. \end{aligned} \tag{27}$$

But if dark matter has not reached equilibrium, we instead find

$$N_{acc} \sim C_X t_{ns}. \tag{28}$$

B Thermalization Time

For the dark matter particles to achieve self-gravitation, the dark matter must thermalize with the neutron star on a time scale comparable to the neutron star lifetime. For $m_X \gtrsim$ GeV, the thermalization time is [37]

$$t_{th} = 5.4 \times 10^{-6} \text{years} \left(\frac{m_X}{\text{GeV}}\right)^2 \left(\frac{10^5 \text{ K}}{T}\right) f^{-1}, \tag{29}$$

where $f = \sigma_{nX}/\sigma_{sat.}$ if $\sigma_{nX} < \sigma_{sat.}$, and $f = 1$ otherwise. Here, σ_{nX} is the cross section for DM-neutron interactions, $\sigma_{sat.} \sim 2.1 \times 10^{-45} \text{cm}^2$ and T is the core temperature of the neutron star. Thus eq. (29) presents a firm exception to the application of the neutron star collapse bound (eq. (23)): if the dark matter does not thermalize over the lifetime of the star, it will not form a black hole.

It is important that the saturation of the likelihood of dark matter scattering implies a maximum dark matter mass for which neutron star bounds are applicable; beyond this mass the dark matter will not thermalize:

$$m_X^{(max)} = 1.4 \times 10^7 \text{GeV} \left(\frac{T}{10^5 \text{ K}}\right)^{1/2} \left(\frac{t_{ns}}{\text{Gyr}}\right)^{1/2}. \tag{30}$$

C Dark Matter Which Does Not Form a BEC

If dark matter does not form a BEC, then the analysis is slightly different. The number of dark matter particles in the thermalized region required to achieve self-gravitation is given by

$$N_{s-g}^{(th)} \simeq \frac{4\pi r_{th}^3}{3m_X}\rho_b \simeq 4.8 \times 10^{46} \left(\frac{T}{10^5 \text{ K}}\right)^{3/2} \left(\frac{\text{GeV}}{m_X}\right)^{5/2}. \tag{31}$$

For most regions of interest, dark matter which does not form a BEC will collapse when it becomes self-gravitating. But if λ is large enough, thermalized boson distributions will collapse only when they reach the Chandrasekhar limit. In figure 3, we plot the region where $N_{s-g}^{(th.)} > N_{chand}$ in the (m_X, λ)-plane for $T = 10^5$ K, in the case where a BEC does not form.

The number of particles required for a black hole to form in the case where a BEC does not form is then given by:

$$N_{BHforms}^{(th)}(m_X, \lambda, T) \;=\; \max[N_{chand}, N_{s-g}^{(th)}]. \tag{32}$$

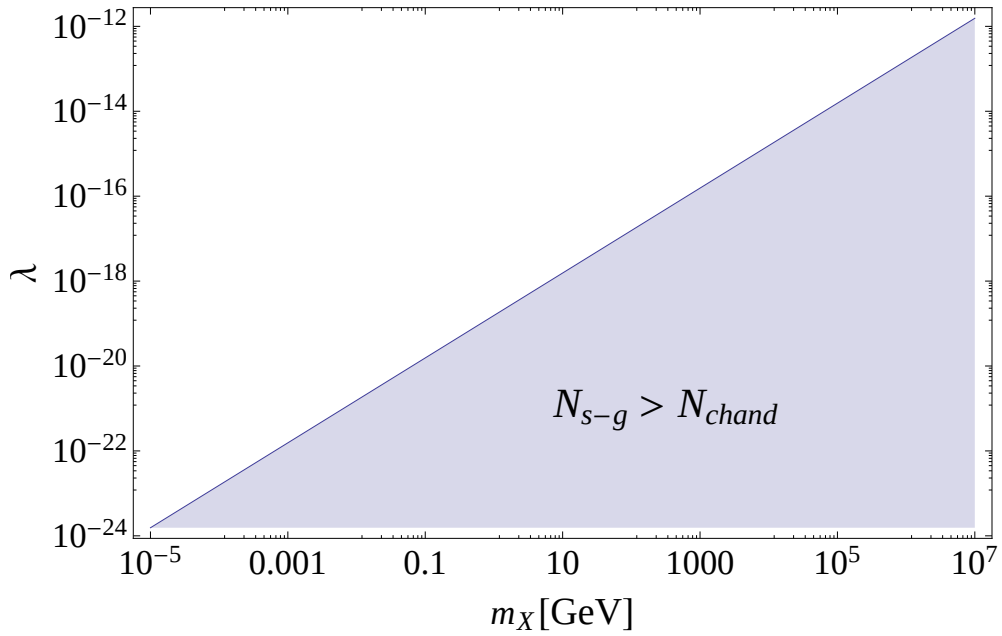

Figure 3: Parameter space in the (m_X, λ) plane where $N_{s-g}^{(th.)} > N_{chand}$, if a BEC does not form.

If $N_{chand} > N_{s-g}$, then the initial mass of the black hole is the same as the value given in eq. 17. But if $N_{s-g} > N_{chand}$, then the initial black hole mass is given by

$$M_{bhi}^{(therm)} = m_X N_{s-g}^{(therm)} = 4.8 \times 10^{46}\ \text{GeV} \left(\frac{T}{10^5\ \text{K}}\right)^{3/2} \left(\frac{\text{GeV}}{m_X}\right)^{3/2}. \tag{33}$$

In this case, if the black hole grows, the time required for the neutron star to be destroyed is

$$t_{nscollapse}^{(therm)} = 5.1 \times 10^{-4}\ \text{years} \left(\frac{m_X}{\text{GeV}}\right)^{3/2} \left(\frac{10^5\ \text{K}}{T}\right)^{3/2}, \tag{34}$$

and the black hole will quickly destroy the neutron star. If the black hole evaporates, the time required to complete the evaporation process is given by

$$\begin{aligned} t_{evap}^{(s-g)} &= 5120\pi G^2 \left(4.8 \times 10^{46} \left(\frac{\text{GeV}^{5/2}}{m_X^{3/2}}\right)\right)^3 \left(\frac{T}{10^5\ \text{K}}\right)^{\frac{9}{2}} \\ &= 1.6 \times 10^{27}\ \text{Gyr} \left(\frac{T}{10^5\ \text{K}} \frac{\text{GeV}}{m_X}\right)^{\frac{9}{2}}. \end{aligned} \tag{35}$$

If dark matter does not form a BEC, then the black hole will evaporation time will be short if $m_X \gg 10^4$ GeV.

The dark matter thermalization radius is much larger than the black hole impact parameter; thus dark matter will not be efficiently captured by a black hole for dark matter that does not form a BEC. Instead, the black hole will continue to capture dark matter through Bondi accretion. The dark matter accretion rate can then be written in terms of the coupled differential equations.

$$\begin{aligned} \left(\frac{dM_{bh}}{dt}\right)_{DM} &= \frac{3 m_X N_{DM} (G M_{bh})^2}{v_s^3 r_{th}^3} \\ \left(\frac{dN_{DM}}{dt}\right) &= C_X - \frac{1}{m_X}\left(\frac{dM_{bh}}{dt}\right)_{DM}. \end{aligned} \tag{36}$$

However in the case of non-BEC dark matter black holes, the Hawking radiation rate exceeds the baryonic Bondi accretion rate only for

$$m_X > 5.8 \times 10^6 \text{ GeV} \left(\frac{T}{10^5 \text{ K}}\right), \tag{37}$$

To accrete enough dark matter for the dark matter Bondi accretion rate to be of the same order of magnitude as the baryonic Bondi accretion rate would require about as much time as was required for the black hole to form in the first place. But as we have seen, for the range of masses where the Hawking radiation rate dominates when the black hole is formed, the black hole will evaporate relatively quickly, before the dark matter accretion rate becomes appreciable. We thus find that, for the case where dark matter does not form a BEC, we may essentially ignore the effect of dark matter accretion on the evolution of the black hole and the condition for a black hole to destroy the neutron star becomes,

$$\begin{aligned} 0 < \left.\frac{dM_{BH}}{dt}\right|_{M_{BH}=M_{BHi}} &\simeq \frac{4\pi \rho_b (G m_X \text{Max}[N_{chand}, N_{s-g}^{(th)}])^2}{v_s^3} \\ &\quad - \frac{1}{15360\pi (G m_X \text{Max}[N_{chand}, N_{s-g}^{(th)}])^2}. \end{aligned} \tag{38}$$

In Figure 4, we plot exclusion contours in the (m_X, σ_{nX}) plane if the dark matter cannot form a BEC, assuming that old neutron stars have lifetime $t_{ns} = 10$ Gyr and core temperature $T = 10^5$ K, and assuming an ambient dark matter density of $\rho_X = 10^3$ GeV/cm^3. As expected from Figure 3, the self-interaction coupling does not affect the bounds substantially until $\lambda \gtrsim 10^{-15}$ – at this value the number of particles required for self-gravitation is exceeded by the number of particles required by the Chandrasekhar bound.

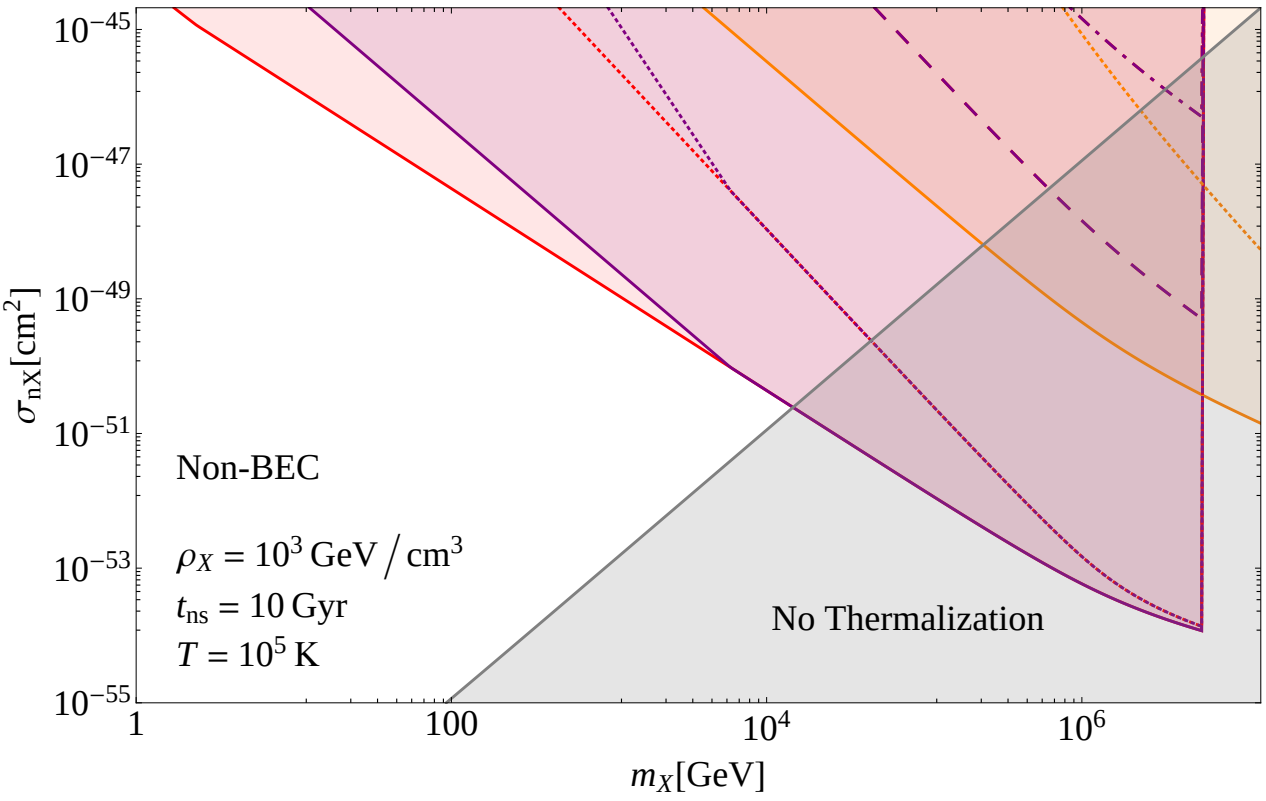

Figure 4: Neutron star collapse bounds for annihilating, self-interacting bosonic dark matter that does not form a Bose-Einstein condensate. From left to right the red, purple, and orange contours denote regions for which the self interaction parameter $\lambda = \{0, 10^{-15}, 10^{-5}\}$, respectively. Solid, dotted, dashed, and dot-dashed contours denote annihilation cross sections $\langle \sigma_a v \rangle = \{0, 10^{-50}, 10^{-45}, 10^{-42}\}\mathrm{cm}^3/\mathrm{s}$, respectively.

References

[1] S. Nussinov, "Technocosmology: Could A Technibaryon Excess Provide A 'natural' Missing Mass Candidate?," Phys. Lett. B **165**, 55 (1985).

[2] D. Hooper, J. March-Russell and S. M. West, "Asymmetric sneutrino dark matter and the Omega(b) / Omega(DM) puzzle," Phys. Lett. B **605**, 228 (2005) [hep-ph/0410114].

[3] S. B. Gudnason, C. Kouvaris and F. Sannino, "Towards working technicolor: Effective theories and dark matter," Phys. Rev. D **73**, 115003 (2006) [hep-ph/0603014].

[4] M. Y. .Khlopov and C. Kouvaris, "Strong Interactive Massive Particles from a Strong Coupled Theory," Phys. Rev. D **77**, 065002 (2008) [arXiv:0710.2189 [astro-ph]].

[5] R. Foadi, M. T. Frandsen and F. Sannino, "Technicolor Dark Matter," Phys. Rev. D **80**, 037702 (2009) [arXiv:0812.3406 [hep-ph]].

[6] D. E. Kaplan, M. A. Luty and K. M. Zurek, "Asymmetric Dark Matter," Phys. Rev. D **79**, 115016 (2009) [arXiv:0901.4117 [hep-ph]].

[7] T. Cohen, D. J. Phalen, A. Pierce and K. M. Zurek, "Asymmetric Dark Matter from a GeV Hidden Sector," Phys. Rev. D **82**, 056001 (2010) [arXiv:1005.1655 [hep-ph]].

[8] J. Shelton and K. M. Zurek, "Darkogenesis: A baryon asymmetry from the dark matter sector," Phys. Rev. D **82**, 123512 (2010) [arXiv:1008.1997 [hep-ph]].

[9] A. Falkowski, J. T. Ruderman and T. Volansky, "Asymmetric Dark Matter from Leptogenesis," JHEP **1105**, 106 (2011) [arXiv:1101.4936 [hep-ph]].

[10] M. R. Buckley and L. Randall, "Xogenesis," JHEP **1109**, 009 (2011) [arXiv:1009.0270 [hep-ph]].

[11] H. Davoudiasl, D. E. Morrissey, K. Sigurdson and S. Tulin, "Hylogenesis: A Unified Origin for Baryonic Visible Matter and Antibaryonic Dark Matter," Phys. Rev. Lett. **105**, 211304 (2010) [arXiv:1008.2399 [hep-ph]].

[12] M. Blennow, B. Dasgupta, E. Fernandez-Martinez and N. Rius, "Aidnogenesis via Leptogenesis and Dark Sphalerons," JHEP **1103**, 014 (2011) [arXiv:1009.3159 [hep-ph]].

[13] L. J. Hall, J. March-Russell and S. M. West, "A Unified Theory of Matter Genesis: Asymmetric Freeze-In," arXiv:1010.0245 [hep-ph].

[14] N. Haba and S. Matsumoto, "Baryogenesis from Dark Sector," Prog. Theor. Phys. **125**, 1311 (2011) [arXiv:1008.2487 [hep-ph]].

[15] M. T. Frandsen, S. Sarkar and K. Schmidt-Hoberg, "Light asymmetric dark matter from new strong dynamics," Phys. Rev. D **84**, 051703 (2011) [arXiv:1103.4350 [hep-ph]].

[16] M. L. Graesser, I. M. Shoemaker and L. Vecchi, "Asymmetric WIMP dark matter," JHEP **1110**, 110 (2011) [arXiv:1103.2771 [hep-ph]].

[17] C. Cheung and K. M. Zurek, "Affleck-Dine Cogenesis," Phys. Rev. D **84**, 035007 (2011) [arXiv:1105.4612 [hep-ph]].

[18] J. March-Russell and M. McCullough, "Asymmetric Dark Matter via Spontaneous Co-Genesis," JCAP **1203**, 019 (2012) [arXiv:1106.4319 [hep-ph]].

[19] B. Dutta and J. Kumar, "Asymmetric Dark Matter from Hidden Sector Baryogenesis," Phys. Lett. B **699**, 364 (2011) [arXiv:1012.1341 [hep-ph]].

[20] P. -H. Gu, M. Lindner, U. Sarkar and X. Zhang, "WIMP Dark Matter and Baryogenesis," Phys. Rev. D **83**, 055008 (2011) [arXiv:1009.2690 [hep-ph]].

[21] R. Allahverdi, B. Dutta and K. Sinha, "Cladogenesis: Baryon-Dark Matter Coincidence from Branchings in Moduli Decay," Phys. Rev. D **83**, 083502 (2011) [arXiv:1011.1286 [hep-ph]].

[22] E. Del Nobile, C. Kouvaris and F. Sannino, "Interfering Composite Asymmetric Dark Matter for DAMA and CoGeNT," Phys. Rev. D **84**, 027301 (2011) [arXiv:1105.5431 [hep-ph]].

[23] S. Tulin, H. -B. Yu and K. M. Zurek, "Oscillating Asymmetric Dark Matter," JCAP **1205**, 013 (2012) [arXiv:1202.0283 [hep-ph]].

[24] H. Iminniyaz, M. Drees and X. Chen, "Relic Abundance of Asymmetric Dark Matter," JCAP **1107**, 003 (2011) [arXiv:1104.5548 [hep-ph]].

[25] M. R. Buckley and S. Profumo, "Regenerating a Symmetry in Asymmetric Dark Matter," Phys. Rev. Lett. **108**, 011301 (2012) [arXiv:1109.2164 [hep-ph]].

[26] M. R. Buckley, "Asymmetric Dark Matter and Effective Operators," Phys. Rev. D **84**, 043510 (2011) [arXiv:1104.1429 [hep-ph]].

[27] Y. Cui, L. Randall and B. Shuve, "Emergent Dark Matter, Baryon, and Lepton Numbers," JHEP **1108**, 073 (2011) [arXiv:1106.4834 [hep-ph]].

[28] H. Davoudiasl, D. E. Morrissey, K. Sigurdson and S. Tulin, "Baryon Destruction by Asymmetric Dark Matter," Phys. Rev. D **84**, 096008 (2011) [arXiv:1106.4320 [hep-ph]].

[29] T. Lin, H. -B. Yu and K. M. Zurek, "On Symmetric and Asymmetric Light Dark Matter," Phys. Rev. D **85**, 063503 (2012) [arXiv:1111.0293 [hep-ph]].

[30] P. Kumar and E. Ponton, "Electroweak Baryogenesis and Dark Matter with an approximate R-symmetry," JHEP **1111**, 037 (2011) [arXiv:1107.1719 [hep-ph]].

[31] D. E. Kaplan, G. Z. Krnjaic, K. R. Rehermann and C. M. Wells, "Dark Atoms: Asymmetry and Direct Detection," JCAP **1110**, 011 (2011) [arXiv:1105.2073 [hep-ph]].

[32] M. Cirelli, P. Panci, G. Servant and G. Zaharijas, JCAP **1203** (2012) 015 [arXiv:1110.3809 [hep-ph]].

[33] J. March-Russell, J. Unwin and S. M. West, "Closing in on Asymmetric Dark Matter I: Model independent limits for interactions with quarks," JHEP **1208**, 029 (2012) [arXiv:1203.4854 [hep-ph]].

[34] A. de Lavallaz and M. Fairbairn, "Neutron Stars as Dark Matter Probes," Phys. Rev. D **81**, 123521 (2010) [arXiv:1004.0629 [astro-ph.GA]].

[35] C. Kouvaris and P. Tinyakov, "Excluding Light Asymmetric Bosonic Dark Matter," Phys. Rev. Lett. **107**, 091301 (2011) [arXiv:1104.0382 [astro-ph.CO]].

[36] C. Kouvaris and P. Tinyakov, "Constraining Asymmetric Dark Matter through observations of compact stars," Phys. Rev. D **83**, 083512 (2011) [arXiv:1012.2039 [astro-ph.HE]].

[37] S. D. McDermott, H. -B. Yu and K. M. Zurek, "Constraints on Scalar Asymmetric Dark Matter from Black Hole Formation in Neutron Stars," Phys. Rev. D **85**, 023519 (2012) [arXiv:1103.5472 [hep-ph]].

[38] G. Bertone and M. Fairbairn, "Compact Stars as Dark Matter Probes," Phys. Rev. D **77**, 043515 (2008) [arXiv:0709.1485 [astro-ph]].

[39] M. McCullough and M. Fairbairn, "Capture of Inelastic Dark Matter in White Dwarves," Phys. Rev. D **81**, 083520 (2010) [arXiv:1001.2737 [hep-ph]].

[40] W. H. Press and D. N. Spergel, "Capture by the sun of a galactic population of weakly interacting massive particles," Astrophys. J. **296**, 679 (1985);

[41] I. Goldman and S. Nussinov, "Weakly Interacting Massive Particles And Neutron Stars," Phys. Rev. D **40**, 3221 (1989).

[42] D. N. Spergel and P. J. Steinhardt, "Observational evidence for self-interacting cold dark matter," Phys. Rev. Lett. **84**, 3760 (2000) [astro-ph/9909386].

[43] S. W. Randall, M. Markevitch, D. Clowe, A. H. Gonzalez and M. Bradac, "Constraints on the Self-Interaction Cross-Section of Dark Matter from Numerical Simulations of the Merging Galaxy Cluster 1E 0657-56," Astrophys. J. **679**, 1173 (2008) [arXiv:0704.0261 [astro-ph]].

[44] Z. Slepian and J. Goodman, "Ruling Out Bosonic Repulsive Dark Matter in Thermal Equilibrium," arXiv:1109.3844 [astro-ph.CO].

[45] C. Kouvaris, "Limits on Self-Interacting Dark Matter," Phys. Rev. Lett. **108**, 191301 (2012) [arXiv:1111.4364 [astro-ph.CO]].

[46] T. Guver, A. E. Erkoca, M. H. Reno and I. Sarcevic, "On the capture of dark matter by neutron stars," arXiv:1201.2400 [hep-ph].

[47] A. Gould, "Resonant Enhancements in WIMP Capture by the Earth," Astrophys. J. **321**, 571 (1987).

[48] C. Kouvaris, "WIMP Annihilation and Cooling of Neutron Stars," Phys. Rev. D **77**, 023006 (2008) [arXiv:0708.2362 [astro-ph]].

[49] J. S. Clark, S. P. Goodwin, P. A. Crowther, L. Kaper, M. Fairbairn, N. Langer and C. Brocksopp, "Physical parameters of the high-mass X-ray binary 4U1700-37," Astron. Astrophys. **392**, 909 (2002) [astro-ph/0207334].

[50] A. Gould, "Wimp Distribution In And Evaporation From The Sun," Astrophys. J. **321**, 560 (1987).

[51] E. W. Mielke and F. E. Schunck, "Boson stars: Alternatives to primordial black holes?," Nucl. Phys. B **564**, 185 (2000) [gr-qc/0001061]. E. W. Mielke and F. E. Schunck, "Boson stars: Early history and recent prospects," gr-qc/9801063.

[52] P. Jetzer, "Boson stars," Phys. Rept. **220**, 163 (1992).

[53] A. H. G. Peter, C. E. Moody and M. Kamionkowski, "Dark-Matter Decays and Self-Gravitating Halos," Phys. Rev. D **81**, 103501 (2010) [arXiv:1003.0419 [astro-ph.CO]].

[54] S. Aoyama, K. Ichiki, D. Nitta and N. Sugiyama, "Formulation and constraints on decaying dark matter with finite mass daughter particles," JCAP **1109**, 025 (2011) [arXiv:1106.1984 [astro-ph.CO]].

[55] K. Griest and D. Seckel, "Cosmic Asymmetry, Neutrinos and the Sun," Nucl. Phys. B **283**, 681 (1987) [Erratum-ibid. B **296**, 1034 (1988)].

[56] G. Jungman, M. Kamionkowski, K. Griest, "Supersymmetric dark matter," Phys. Rept. **267**, 195-373 (1996). [hep-ph/9506380].

[57] Y. -z. Fan, R. -z. Yang and J. Chang, "Constraining Asymmetric Bosonic Non-interacting Dark Matter with Neutron Stars," arXiv:1204.2564 [astro-ph.HE].

[58] C. Kouvaris and P. Tinyakov, "On (Not)-Constraining Heavy Asymmetric Bosonic Dark Matter," arXiv:1212.4075 [astro-ph.HE].

[59] B. Kiziltan, A. Kottas and S. E. Thorsett, "The Neutron Star Mass Distribution," arXiv:1011.4291 [astro-ph.GA].

[60] A. Wright [DarkSide Collaboration], "The DarkSide Program at LNGS," arXiv:1109.2979 [physics.ins-det].

[61] E. Aprile [XENON1T Collaboration], "The XENON1T Dark Matter Search Experiment," arXiv:1206.6288 [astro-ph.IM].