Limit on the axion decay constant from the cooling neutron star in Cassiopeia A

Koichi Hamaguchi,[1,2,*] Natsumi Nagata,[1,†] Keisuke Yanagi,[1,‡] and Jiaming Zheng[1,§]

[1]*Department of Physics, University of Tokyo, Tokyo 113–0033, Japan*
[2]*Kavli Institute for the Physics and Mathematics of the Universe (Kavli IPMU), University of Tokyo, Kashiwa 277–8583, Japan*

(Received 22 June 2018; published 16 November 2018)

The observed rapid cooling of the neutron star (NS) located at the center of the supernova remnant Cassiopeia A (Cas A) can be explained in the minimal NS cooling scenario. This consequence may be changed if there exists an extra cooling source, such as axion emission. In this work, we study the Cas A NS cooling in the presence of axion emission, taking account of the temperature evolution in the whole life of the Cas A NS. We obtain a lower limit on the axion decay constant, $f_a \gtrsim (5-7) \times 10^8$ GeV, if the star has an envelope with a thin carbon layer. This is as strong as existing limits imposed by other astrophysical observations such as SN1987A.

DOI: 10.1103/PhysRevD.98.103015

I. INTRODUCTION

The Cassiopeia A (Cas A) is a supernova remnant in the Cassiopeia constellation. This supernova may be identical to the *3 Cassiopeiae* recorded by John Flamsteed on August 16, 1680 [1], which is consistent with the supernova explosion date estimated from the remnant expansion: 1681 ± 19 [2]. In 1999, the *Chandra* x-ray observatory discovered a hot pointlike source in the center of the supernova remnant [3], which is now identified as a neutron star (NS).

Given the distance to Cas A, $d = 3.4^{+0.3}_{-0.1}$ kpc [4], the NS radius can be determined by measuring the x-ray spectrum thermally emitted from the NS. With the black-body and hydrogen atmosphere models, a rather small radius of the x-ray emission area was obtained—about 0.5 and 2 km, respectively [5]. This implied a hot spot on the NS surface. On the other hand, a lack of the observation of pulsations in the x-ray flux [6] indicates that the x-ray emission comes from the whole surface, which is incompatible with the above observation. This contradiction was resolved by Heinke and Ho, who found that a carbon atmosphere model with low magnetic field gave a good fit to the x-ray spectrum with a typical size of the NS radius ($\gtrsim$10 km) [7]. Moreover, they observed that the surface temperature of the NS evaluated with the carbon atmosphere model was decreasing over the years, which provided the first direct observation of NS cooling [8].

In the standard NS cooling scenario (see, e.g., Refs. [9]), a young NS like the Cas A NS cools down mainly through neutrino emission. Soon after the work by Heinke and Ho [8], the authors in Refs. [10,11] tried to fit the observed data with the standard NS cooling model.[1] They argued that the cooling rate of the Cas A NS was so rapid that the "slow" neutrino processes could not fit the cooling curve, while the "fast" neutrino processes predicted a temperature smaller than the observed one around the time $t \simeq 320$ years. It was then concluded that the neutron triplet superfluid transition should occur around this time so that neutrino emission was accelerated through the breaking of neutron Cooper pairs and their subsequent reformation, dubbed as the "pair-breaking and formation (PBF)" process [13]. In addition, proton superconductivity should operate well before $t \simeq 320$ years in order to suppress neutrino emission in the early times, which results in a steep decrease in temperature right after the onset of the PBF process. The observed cooling curve of the Cas A NS was found to be fitted quite well under these conditions.

This conclusion may be altered if there is an additional source of NS cooling. One of the most well-motivated candidates for such a cooling source is the emission of axions [14], the Nambu-Goldstone bosons associated with the Peccei-Quinn symmetry [15]. The axions are emitted

*hama@hep-th.phys.s.u-tokyo.ac.jp
†natsumi@hep-th.phys.s.u-tokyo.ac.jp
‡yanagi@hep-th.phys.s.u-tokyo.ac.jp
§zhengjm3@hep-th.phys.s.u-tokyo.ac.jp

[1]See Refs. [12] for other possible mechanisms.

through the axion PBF and bremsstrahlung processes caused by the couplings to nucleons. Indeed, there are several studies that discuss their effects on the Cas A NS cooling. A detailed study on the axion emission processes and their consequences on NS cooling was performed in Ref. [16], where predicted cooling curves were compared with the temperature data of young NSs including the Cas A NS. However, only the average temperature of the Cas A NS was concerned and no attempt was made to fit the slope of its cooling curve. In Ref. [17], the axion-neutron PBF process was utilized to enhance the cooling rate so that the slope of the Cas A NS cooling curve was reproduced. This analysis focused on the time around which the neutron superfluid transition was supposed to occur, with the axion-proton PBF and axion bremsstrahlung processes neglected; especially, there was no discussion on the temperature evolution at $t \lesssim 300$ years.

In this work, we study the Cas A NS cooling in the presence of axion emission, taking account of the temperature evolution in the whole lifetime of the Cas A NS. It is found that for a sufficiently small axion-nucleon coupling, the observed cooling curve can still be fitted if we take a moderate gap for neutron triplet pairing and a large gap for proton singlet pairing. This success is, however, spoiled once the axion coupling exceeds a certain value, and therefore imposes a lower limit on the axion decay constant. This new limit turns out to be as strong as the existing limits given by other astrophysical observations such as SN1987A.

II. STANDARD NS COOLING AND CAS A NS

The Cas A NS cooling data collected so far [18] clearly shows that the temperature is decreasing at a constant rate. The measured x-ray spectrum is fitted with an atmosphere model, and the radius R and mass M of the Cas A NS are inferred through their effects on the brightness and gravitational redshift. In Ref. [18], the authors performed such a fit using a nonmagnetic carbon atmosphere model [7] and obtained $M \simeq (1.4 \pm 0.3) M_\odot$.

In the standard NS cooling scenario [9], the NS cooling proceeds via the emission of neutrinos and photons. The former dominates over the latter in the earlier epoch ($t \lesssim 10^5$ years). Various processes participate in neutrino emission, such as the direct Urca process, the modified Urca process, bremsstrahlung, and the PBF process. The direct Urca process, comprised of the β-decay and inverse decay processes, is called the "fast" process. If this occurs, a NS cools quite rapidly. However, this process can occur only at very high density regions [19], which can be achieved only for a heavy NS. For instance, the Akmal-Pandharipande-Ravenhall (APR) equation of state [20] allows the direct Urca process only for $M \gtrsim 1.97\ M_\odot$, which is well above the Cas A NS mass estimated in Ref. [18]. Thus, we can safely assume that the fast process never occurs in the Cas A NS, as in the minimal cooling paradigm [21,22]. In this case, the neutrino emission proceeds through the "slow" processes such as the modified Urca and bremsstrahlung processes. In the absence of nucleon pairings, the neutrino luminosity L_ν caused by these processes is expressed as $L_\nu \simeq L_9 T_9^8$ with the internal temperature $T_9 \equiv T/(10^9\ \mathrm{K})$ and the coefficient $L_9 \sim 10^{40}\ \mathrm{erg \cdot s^{-1}}$ [9].

In general, a NS is brought into an isothermal state with relaxation time ~10–100 years [23], and in fact the Cas A NS is very likely to be thermally relaxed [24]. For an isothermal NS, the evolution of the internal temperature T is determined by the thermal balance equation

$$C \frac{dT}{dt} = -L_\nu - L_{\mathrm{cool}}, \tag{1}$$

where C is the total stellar heat capacity and L_{cool} denotes the luminosity caused by potential extra cooling sources. We have dropped the photon luminosity since this is much smaller than L_ν for a young NS like the Cas A NS. The heat capacity C has temperature dependence of the form $C = C_9 T_9$ with $C_9 \sim 10^{39}\ \mathrm{erg \cdot K^{-1}}$ [9]. If $L_{\mathrm{cool}} = 0$, Eq. (1) leads to

$$T_9 = \left(\frac{C_9 \cdot 10^9\ \mathrm{K}}{6 L_9 t}\right)^{\frac{1}{6}} \sim \left(\frac{1\ \mathrm{year}}{t}\right)^{\frac{1}{6}}, \tag{2}$$

where we have assumed that the initial temperature is much larger than that at the time of interest.

The NS surface is insulated from the hot interior by its envelope. For a nonmagnetic iron envelope at temperatures as high as the Cas A NS temperature, the relation between the surface temperature T_s and the internal temperature T is approximated by [25]

$$T_9 \simeq 0.1288 \times \left(\frac{T_{s6}^4}{g_{14}}\right)^{0.455}, \tag{3}$$

with g_{14} the surface gravity in units of $10^{14}\ \mathrm{cm \cdot s^{-2}}$ and $T_{s6} \equiv T_s/(10^6\ \mathrm{K})$. A more accurate relation, which is also applicable to the case where a sizable amount of light elements exist in the envelope (characterized by the parameter $\eta \equiv g_{14}^2 \Delta M/M$ with ΔM the mass of the light elements), can also be found in the literature [26].

The cooling rate of the Cas A NS observed in Ref. [8,18] was about 3%–4% in ten years around $t \simeq 320$ years.[2] On the other hand, from Eq. (2) and Eq. (3), we find that the surface temperature goes as $T_s \propto t^{0.09}$, which results in only 0.3% decrease in temperature in ten years. Hence, the slow neutrino emission cannot explain the observed rapid cooling of the Cas A NS.

This difficulty can be resolved with the help of superfluidity in the NS (for a review, see Ref. [28]). It is known that the onset of Cooper pairing of nucleons triggers the

[2]See also [27] for possible uncertainties.

rapid PBF emission of neutrino while suppresses other emission processes which these nucleons participate in [13]. The PBF lasts only for a short time—to explain the rapid cooling of the Cas A NS by this PBF process, therefore, the phase transition of the neutron triplet pairing should occur just before $t \simeq 320$ years. This condition implies that the critical temperature of this phase transition, $T_c^{(n)}$, should agree to the internal temperature around this time; thus, $T_c^{(n)}$ is fixed via Eq. (2). One also finds that the resultant cooling rate increases as $T_c^{(n)}$ gets larger, which is achieved with a smaller L_9 according to Eq. (2). The reduction in L_ν can be realized again with the aid of Cooper pairing—with proton pairings formed, the neutrino emission processes which contain protons are suppressed by the proton gap, which then results in a small L_9. A small L_9 also ensures that the NS was not overcooled by the time of observation.

Indeed, the authors in Refs. [10,11] found that the rapid cooling of the Cas A NS can be explained in the minimal cooling scenario with an appropriate choice of $T_c^{(n)}$ and a sufficiently large proton pairing gap. For instance, it is shown in Ref. [10] that the observed data points are fitted quite well for $T_c^{(n)} \simeq 5.5 \times 10^8$ K and $\Delta M = 5 \times 10^{-13}\ M_\odot$, where the CCDK model for proton gap [29] and the APR equation of state [20] are adopted. In Refs. [11,30], it was shown that the temperature observations of other NSs can also be fitted by cooling curves with pairing models required by the rapid cooling of the Cas A NS. Because of its simplicity, the minimal cooling scenario is a very promising candidate of the correct NS cooling model. In the rest of this paper, we will consider the compatibility between the minimal NS cooling model and axion models by looking for the highest axion decay constant f_a with which the rapid Cas A NS cooling cannot be fitted by any pairing model. This serves as a lower bound of f_a under the assumption that the minimal NS cooling model describes the cooling of NS correctly.

III. AXION EMISSION FROM NEUTRON STARS

The discussion in the last section would be changed if there is an additional cooling source, i.e., if $L_{\rm cool} \neq 0$ in Eq. (1). In this case, the temperature at $t \simeq 320$ years is predicted to be lower than that in the minimal cooling scenario. However, the observed surface temperature of the Cas A NS, $T_s \simeq 2 \times 10^6$ K, implies $T \simeq 4 \times 10^8$ K (see Eq. (3), and $T_c^{(n)}$ needs to be larger than this value in order for the PBF process to operate at $t \simeq 320$ years. In other words, if we fix $T_c^{(n)} \simeq 5.5 \times 10^8$ K in the case of $L_{\rm cool} \neq 0$, the rapid cooling due to the PBF process has occurred much before $t \simeq 320$ years—then, the rapid cooling would have already ceased and/or the present surface temperature would be much lower than the observed value. Accordingly, we may obtain a constraint on extra cooling sources from the Cas A NS cooling data.

To discuss this possibility, in this work, we take axion [14] as a concrete example for a cooling source. Axions are emitted out of NSs through their couplings to nucleons. The axion-nucleon couplings have the form

$$\mathcal{L}_{\rm int} = \sum_{N=p,n} \frac{C_N}{2f_a} \bar{N}\gamma^\mu\gamma_5 N \partial_\mu a, \tag{4}$$

where f_a is the axion decay constant. The coefficients C_N are expressed in terms of the axion-quark couplings C_q [having the same form as in Eq. (4)], the quark masses m_q, and the spin fractions $\Delta q^{(N)}$ defined by $2s_\mu^{(N)}\Delta q^{(N)} \equiv \langle N|\bar{q}\gamma_\mu\gamma_5 q|N\rangle$ with $s_\mu^{(N)}$ the spin of the nucleon N. At the leading order in the strong coupling constant α_s, we have $C_N = \sum_q (C_q - m_*/m_q)\Delta q^{(N)}$ with $m_* \equiv m_u m_d m_s/(m_u m_d + m_d m_s + m_u m_s)$. QCD corrections to this formula are discussed in Ref. [31]; for instance, in the case of the Kim-Shifman-Vainshtein-Zakharov (KSVZ) axion ($C_q = 0$) [32], we have $C_p = -0.47(3)$ and $C_n = -0.02(3)$, while for the Dine-Fischler-Srednicki-Zhitnitsky (DFSZ) axion [33] ($C_{u,c,t} = \cos^2\beta/3$ and $C_{d,s,b} = \sin^2\beta/3$ with $\tan\beta$ the ratio of the vacuum expectation values of the two doublet Higgs fields, $\tan\beta \equiv \langle H_u\rangle/\langle H_d\rangle$), $C_p = -0.182(25) - 0.435\sin^2\beta$ and $C_n = -0.160(25) + 0.414\sin^2\beta$ [34], where $\Delta u^{(p)} = \Delta d^{(n)} = 0.897(27)$, $\Delta d^{(p)} = \Delta u^{(n)} = -0.376(27)$, and $\Delta s^{(p)} = \Delta s^{(n)} = -0.026(4)$ are used.

The axion-nucleon couplings induce axion emission via the PBF and bremsstrahlung processes, which have been studied so far in the literature [16,17,35,36]. We have modified the public code NSCool [37] to implement these processes and use it to compute the luminosity of axion and its effect on the NS cooling curves. We adopt the APR equation of state [20] and fix the NS mass to be $M = 1.4\ M_\odot$ in this work.

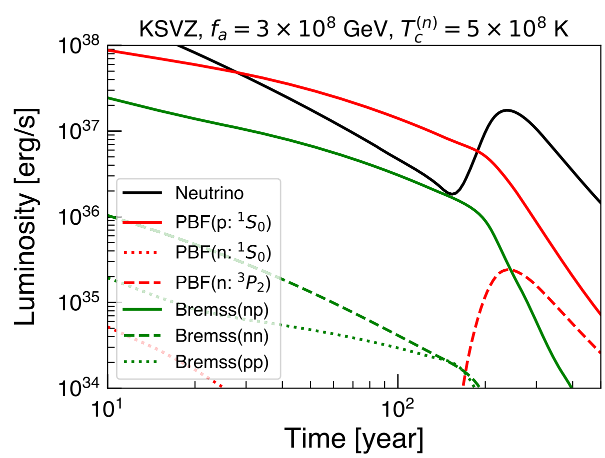

FIG. 1. Luminosity of each axion emission (red and green) and the total neutrino emission (black) processes as a function of time.

In Fig. 1, we show luminosities of various axion emission processes in the KSVZ model with $f_a = 3 \times 10^8$ GeV as functions of time (red and green). For comparison, we also show the total luminosity of neutrino emission (black). We use the SFB model [38] for the gap of singlet neutron pairings. Our analysis is insensitive to this choice. For the proton singlet pairings, the CCDK model [29] is chosen because it has the largest gap in the NS core among those presented in Ref. [21]—this results in a strong suppression of neutrino emission before the onset of the neutron triplet Cooper pairing and thus improves the fit onto the observed Cas A NS data [10] as we discussed above. Note that a large gap for the proton singlet pairing also suppresses the axion emission, and therefore the CCDK model gives a conservative bound. On the contrary, there are large uncertainties in choosing a model of neutron triplet pairings. We thus model this gap with a Gaussian shape with respect to the neutron Fermi momentum and regard its height, width, and central position as free parameters. In Fig. 1, we take $T_c^{(n)} = 5 \times 10^8$ K. The instantaneous increase in luminosity at $t \simeq 300$ years for the neutrino emission, as well as the axion emission in the PBF process, is due to the formation of neutron triplet pairings. As we see from this plot, the axion emission via the proton PBF and proton-neutron bremsstrahlung processes is as strong as the neutrino emission before the formation of neutron triplet parings. In particular, the emission via the proton PBF dominates over other axion emission processes in this case because it is suppressed by less powers of $T_{\rm core}$ resulting from a smaller number of states involved in the process. This allows us to set stringent bounds even on the KSVZ model where $|C_n|$ is vanishingly small. If $|C_n|$ is sizable as in the DFSZ model, the neutron bremsstrahlung process is also significant.

IV. LIMIT ON AXION DECAY CONSTANT

Now let us study the effect of the axion emission processes on the NS temperature evolution. In Fig. 2, we show the core temperature $T_{\rm core}$ at the time of the Cas A NS age on January 30, 2000 ($t = 300$–338 years) as functions of f_a for the KSVZ and DFSZ ($\tan\beta = 10$) models in the red and green bands, respectively, with the bands reflecting the uncertainty in the NS age. Since we are interested in the drop in the temperature before the onset of neutron triplet pairings, we have switched off the neutron triplet superfluidity in this plot. The Cas A NS core temperature $T_{\rm core,A}$ inferred from the observation for the envelope model Ref. [26] with $\eta = 5 \times 10^{-13}$ is shown in the gray line, while its uncertainty is estimated by varying $\eta = 10^{-(8-18)}$ (gray band) [18]. We find that the predicted core temperature falls below $T_{\rm core,A} \simeq 5 \times 10^8$ K for $f_a = (\text{a few}) \times 10^8$ GeV, and thus f_a smaller than this value is disfavored. We also note that the bound derived in this manner has a large uncertainty due to the ignorance of the envelope parameter η.

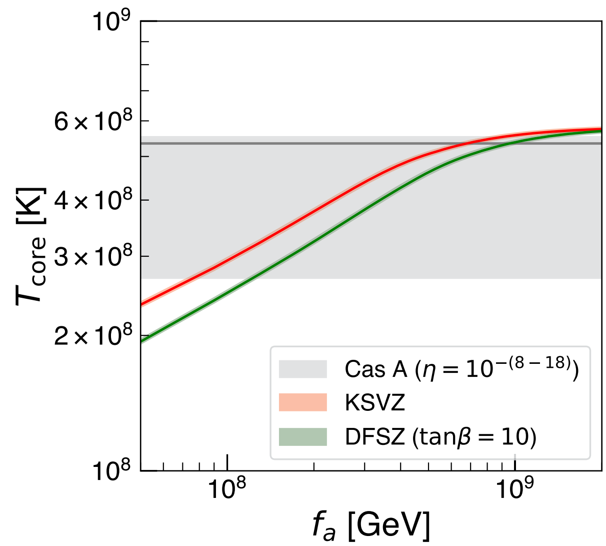

FIG. 2. The core temperature $T_{\rm core}$ at $t = 300$–338 years against f_a, without neutron triplet superfluidity. The gray shaded region reflects the uncertainty of $T_{\rm core}$ due to η and the grey solid line corresponds to $\eta = 5 \times 10^{-13}$.

Figure 3 shows the best-fit curves of the redshifted surface temperature T_s^∞ for several values of f_a in the KSVZ model (blue lines), as well as that obtained in the minimal cooling scenario (black line). For each curve, we vary the neutron triplet gap parameters and the Cas A NS age to fit the observed data shown in the green points [18], where the envelope parameter is fixed to be $\eta = 5 \times 10^{-13}$ as in [10]. We find that as f_a gets smaller, the NS temperature at $t \simeq 320$ years gets lower, which then requires a smaller value of $T_c^{(n)}$ and results in a shallower slope. As a result, the fit gets considerably worse for a smaller f_a.

Finally, we show the lower bound on f_a obtained from our attempt to fit the observed data. If the Cas A NS has an

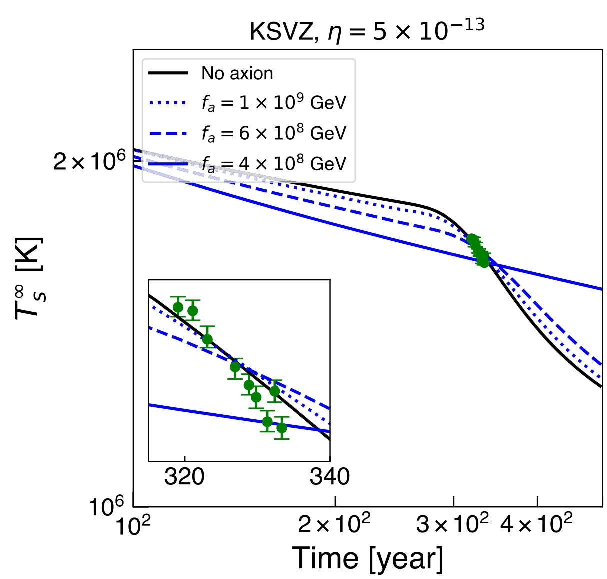

FIG. 3. Cooling curves compared to observed data.

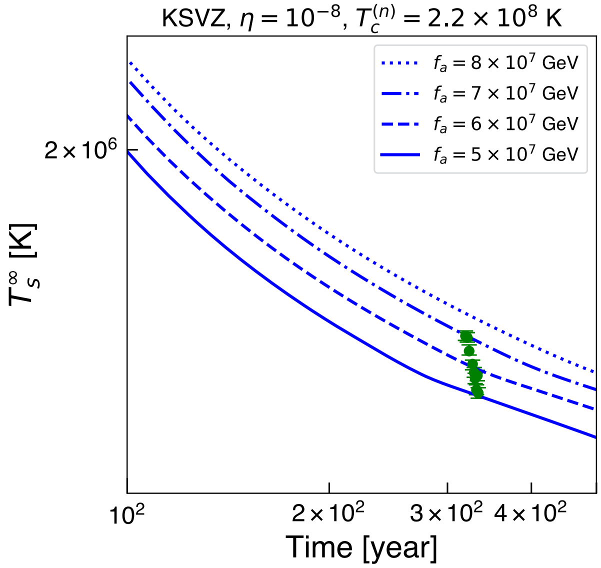

FIG. 4. Cooling curves of the KSVZ model for $\eta = 10^{-8}$.

iron envelope with a thin carbon layer ($\eta = 5 \times 10^{-13}$ as in [10]),

$$f_a \gtrsim 5(7) \times 10^8\ \text{GeV} \qquad \text{KSVZ (DFSZ)}, \tag{5}$$

where we take $\tan\beta = 10$ for the DFSZ model. The bound on the DFSZ model is comparable to the one on the KSVZ model with $C_n \simeq 0$ because of the large luminosity from proton PBF and the proton-neutron bremsstrahlung as shown in Fig. 1. For general couplings, the limit can be roughly estimated by

$$f_a \gtrsim \sqrt{0.9C_p^2 + 1.4C_n^2} \times 10^9\ \text{GeV}. \tag{6}$$

As a comparison, the bound derived from SN1987A is $f_a \gtrsim 4 \times 10^8$ GeV [39] for the KSVZ model, comparable to the bounds from the Cas A NS obtained above. If the envelope is maximally carbon-rich ($\eta = 10^{-8}$) instead, naively, the bound will be weakened by an $\mathcal{O}(1)$ factor as shown in Fig. 2. However, as we increase η and hence the thermal conductivity of the envelope, the same observed effective temperature corresponds to a lower core temperature in the NS. This reduces drastically the neutrino luminosity from the neutron PBF that scales as $T_{\rm core}^7$ for $T_{\rm core} \simeq T_c^{(n)}$, making it harder to fit the rapid cooling slope alone. An axion emission may help to cool the NS, but in the KSVZ model the neutrino emission dominates over axion in the neutron PBF process and hence it can be incompatible with the observed rapid cooling. In Fig. 4, we plot the cooling curves of the KSVZ model for a NS with $\eta = 10^{-8}$. Due to the large η, neutrino emission cannot cool the NS to its observed temperature and a sizable axion emission from proton with $f_a \lesssim 8 \times 10^7$ GeV is needed. The neutron triplet pairing temperature is set to $T_c^{(n)} = 2.2 \times 10^8$ K so that the phase transition occurs shortly before the observation. However, we cannot see any rapid cooling drop in the curves because the neutrino PBF luminosity is suppressed as described above. For a moderate η ($\sim 10^{-10}$), on the other hand, we find that the slope of the cooling data constrains $f_a \gtrsim 5 \times 10^8$ GeV, which is similar to that for $\eta = 5 \times 10^{-13}$ given in Eq. (5). Thus the limit on the KSVZ model is rather stringent even if we allow η to vary. For the DFSZ model, $|C_n|$ is non-vanishing in general so the axion emission during the neutron triplet-pairing phase transition can rapidly cool the Cas A NS via the PBF process even when $\eta = 10^{-8}$. According to Fig. 2, $f_a \sim 10^8$ GeV is needed to reproduce the observed rapid cooling in this case. We note in passing that such a stellar cooling source may be favored by several astrophysical observations [40], for which our new limits (or a favored value of f_a in the case of the DFSZ model for a large η) may have important implications.

To conclude this section, we point out that if f_a is too small the axion may have a short mean free path in the NS and thus avoid all the limits set above. For the purpose of qualitative estimation, we only consider the partial axion decay rate by the inverse proton PBF $a \to \tilde{p}^+ + \tilde{p}^-$ that is important to both the KSVZ and DFSZ models. Here, $\tilde{p}^\pm$ is the quasiparticle excitation inside a medium of proton Cooper pairs. A more careful evaluation is beyond the scope of this paper. The matrix element of the related process is given in [41], which leads to

$$\Gamma_{a\to\tilde{p}^+\tilde{p}^-} \sim \frac{m_p^* p_F v_F^2 T}{3\pi f_a^2}\left(\frac{C_p}{2}\right)^2, \tag{7}$$

where m_p^*, p_F, v_F are the effective mass, the Fermi momentum, and the Fermi velocity of proton in the NS, respectively. For $p_F \sim 100$ MeV, $m_p^* \sim 1$ GeV, $T \sim \Delta_p \sim 1$ MeV, we need

$$f_a \gtrsim \left(\frac{C_p}{2}\right) \times 10^6\ \text{GeV}, \tag{8}$$

for the mean free path of axion $l_a = 1/\Gamma_{a\to\tilde{p}^+\tilde{p}^-}$ to be larger than $\sim$10 km, the radius of the Cas A NS.

V. CONCLUSION AND DISCUSSION

We have discussed the implications of the Cas A NS rapid cooling for axion models. It is found that the requirement of fitting the slope of the Cas A NS cooling curve in accordance with the temperature evolution from its birth results in a limit of $f_a \gtrsim 5 \times 10^8$ GeV if the envelope only has a thin layer of carbon.

This limit is stronger than those obtained in the previous studies. For instance, Ref. [16] sets $f_a \gtrsim (5-10) \times 10^7$ for the KSVZ model without taking the cooling rate of the

Cas A NS into account. In Ref. [17], it is argued that the rapid cooling of the Cas A NS can be explained with $|C_n|/f_a \simeq \sqrt{0.16}/(10^9 \text{ GeV})$ in the KSVZ model—this corresponds to $f_a \simeq 5 \times 10^7$ GeV for $C_n = -0.02$, which is actually in tension with the observation as shown in Fig. 2.

Finally, some remarks on the uncertainties of our analysis are in order. First of all, lower cooling rates of the Cas A NS have been reported and the actual cooling rate is still in dispute [27]. In the worst case scenario where the NS is found to cool slowly by future observations, our strong limit on the KSVZ model will no longer hold. However, the conservative limits obtained directly from Fig. 2 by assuming maximal η are hardly affected since they do not rely on the cooling rate and depend dominantly on the emission from proton. Other mechanisms [12] such as an extended thermal relaxation time have also been proposed to explain the rapid cooling rate and more study on neutron star physics is needed to test them against the minimal cooling scenario that we base our work on.

Apart from the observation and theoretical uncertainties stated above, the limit on f_a obtained in this work also suffers from the ignorance of the envelope parameter η. While a maximal η parameter is inconsistent with the KSVZ axion model, it is compatible with the DFSZ model with $f_a \sim 10^8$ GeV. Further cooling data of the Cas A NS, as well as additional observations of direct cooling curves of other NSs, are of great importance to verify the rapid cooling of the Cas A NS and to test the present scenario against potential alternative explanations of the rapid cooling of the Cas A NS, and may allow us to obtain a more robust limit on the axion. The analysis performed in this paper can also be applied to other cooling sources, e.g., heavier axionlike particles and dark photons. Such an analysis will be given in a future work [42].

ACKNOWLEDGMENTS

This work was supported in part by the Grant-in-Aid for Scientific Research A (No. 16H02189 [K. H.]), Young Scientists B (No. 17K14270 [N. N.]), and Innovative Areas (No. 26104001 [K. H.], 26104009 [K. H., J. Z.]). The work of K. Y. was supported by JSPS KAKENHI Grant No. JP18J10202.

[1] W. B. Ashworth, Jr., Journal for the history of astronomy **11**, 1 (1980); K. W. Kamper, The Observatory **100**, 3 (1980); D. W. Hughes, Nature (London) **285**, 132 (1980).

[2] R. A. Fesen, M. C. Hammell, J. Morse, R. A. Chevalier, K. J. Borkowski, M. A. Dopita, C. L. Gerardy, S. S. Lawrence, J. C. Raymond, and S. van den Bergh, Astrophys. J. **645**, 283 (2006).

[3] H. Tananbaum, IAU Circ. **7246** (1999).

[4] J. E. Reed, J. J. Hester, A. C. Fabian, and P. F. Winkler, Astrophys. J. **440**, 706 (1995).

[5] G. G. Pavlov, V. E. Zavlin, B. Aschenbach, J. Truemper, and D. Sanwal, Astrophys. J. **531**, L53 (2000); D. Chakrabarty, M. J. Pivovaroff, L. E. Hernquist, J. S. Heyl, and R. Narayan, Astrophys. J. **548**, 800 (2001); G. G. Pavlov, D. Sanwal, and M. A. Teter, IAU Symp. **218**, 239 (2004).

[6] S. S. Murray, S. M. Ransom, M. Juda, U. Hwang, and S. S. Holt, Astrophys. J. **566**, 1039 (2002); S. Mereghetti, A. Tiengo, and G. L. Israel, Astrophys. J. **569**, 275 (2002).

[7] W. C. G. Ho and C. O. Heinke, Nature (London) **462**, 71 (2009).

[8] C. O. Heinke and W. C. G. Ho, Astrophys. J. **719**, L167 (2010).

[9] D. G. Yakovlev and C. J. Pethick, Annu. Rev. Astron. Astrophys. **42**, 169 (2004); D. Page, U. Geppert, and F. Weber, Nucl. Phys. **A777**, 497 (2006).

[10] D. Page, M. Prakash, J. M. Lattimer, and A. W. Steiner, Phys. Rev. Lett. **106**, 081101 (2011).

[11] P. S. Shternin, D. G. Yakovlev, C. O. Heinke, W. C. G. Ho, and D. J. Patnaude, Mon. Not. R. Astron. Soc. **412**, L108 (2011).

[12] S.-H. Yang, C.-M. Pi, and X.-P. Zheng, Astrophys. J. **735**, L29 (2011); R. Negreiros, S. Schramm, and F. Weber, Phys. Lett. B **718**, 1176 (2013); D. Blaschke, H. Grigorian, D. N. Voskresensky, and F. Weber, Phys. Rev. C **85**, 022802 (2012); T. Noda, M.-A. Hashimoto, N. Yasutake, T. Maruyama, T. Tatsumi, and M. Fujimoto, Astrophys. J. **765**, 1 (2013); A. Sedrakian, Astron. Astrophys. **555**, L10 (2013); D. Blaschke, H. Grigorian, and D. N. Voskresensky, Phys. Rev. C **88**, 065805 (2013); A. Bonanno, M. Baldo, G. F. Burgio, and V. Urpin, Astron. Astrophys. **561**, L5 (2014); L. B. Leinson, Phys. Lett. B **741**, 87 (2015); G. Taranto, G. F. Burgio, and H. J. Schulze, Mon. Not. R. Astron. Soc. **456**, 1451 (2016); T. Noda, N. Yasutake, M.-A. Hashimoto, T. Maruyama, T. Tatsumi, and M. Y. Fujimoto, Acta Astronomica Sinica **56**, 52 (2015); H. Grigorian, D. N. Voskresensky, and D. Blaschke, Eur. Phys. J. A **52**, 67 (2016).

[13] E. Flowers, M. Ruderman, and P. Sutherland, Astrophys. J. **205**, 541 (1976); D. N. Voskresensky and A. V. Senatorov, Yad. Fiz. **45**, 657 (1987) [Sov. J. Nucl. Phys. **45**, 411 (1987)].

[14] S. Weinberg, Phys. Rev. Lett. **40**, 223 (1978); F. Wilczek, Phys. Rev. Lett. **40**, 279 (1978).

[15] R. D. Peccei and H. R. Quinn, Phys. Rev. Lett. **38**, 1440 (1977); **38**, 32 (1977); Phys. Rev. D **16**, 1791 (1977).

[16] A. Sedrakian, Phys. Rev. D **93**, 065044 (2016).

[17] L. B. Leinson, J. Cosmol. Astropart. Phys. 08 (2014) 031.

[18] W. C. G. Ho, K. G. Elshamouty, C. O. Heinke, and A. Y. Potekhin, Phys. Rev. C **91**, 015806 (2015).

[19] J. M. Lattimer, M. Prakash, C. J. Pethick, and P. Haensel, Phys. Rev. Lett. **66**, 2701 (1991);

[20] A. Akmal, V. R. Pandharipande, and D. G. Ravenhall, Phys. Rev. C **58**, 1804 (1998).

[21] D. Page, J. M. Lattimer, M. Prakash, and A. W. Steiner, Astrophys. J. Suppl. Ser. **155**, 623 (2004).

[22] D. Page, J. M. Lattimer, M. Prakash, and A. W. Steiner, Astrophys. J. **707**, 1131 (2009).

[23] J. M. Lattimer, K. A. van Riper, M. Prakash, and M. Prakash, Astrophys. J. **425**, 802 (1994); O. Y. Gnedin, D. G. Yakovlev, and A. Y. Potekhin, Mon. Not. R. Astron. Soc. **324**, 725 (2001).

[24] D. G. Yakovlev, W. C. G. Ho, P. S. Shternin, C. O. Heinke, and A. Y. Potekhin, Mon. Not. R. Astron. Soc. **411**, 1977 (2011).

[25] E. H. Gudmundsson, C. J. Pethick, and R. I. Epstein, Astrophys. J. **272**, 286 (1983).

[26] A. Y. Potekhin, G. Chabrier, and D. G. Yakovlev, Astron. Astrophys. **323**, 415 (1997).

[27] K. G. Elshamouty, C. O. Heinke, G. R. Sivakoff, W. C. G. Ho, P. S. Shternin, D. G. Yakovlev, D. J. Patnaude, and L. David, Astrophys. J. **777**, 22 (2013); B. Posselt, G. G. Pavlov, V. Suleimanov, and O. Kargaltsev, Astrophys. J. **779**, 186 (2013).

[28] D. Page, J. M. Lattimer, M. Prakash, and A. W. Steiner, arXiv:1302.6626.

[29] J. M. C. Chen, J. W. Clark, R. D. Davé, and V. V. Khodel, Nucl. Phys. **A555**, 59 (1993).

[30] D. Page, arXiv:1206.5011.

[31] G. G. di Cortona, E. Hardy, J. Pardo Vega, and G. Villadoro, J. High Energy Phys. 01 (2016) 034.

[32] J. E. Kim, Phys. Rev. Lett. **43**, 103 (1979); M. A. Shifman, A. I. Vainshtein, and V. I. Zakharov, Nucl. Phys. **B166**, 493 (1980).

[33] A. R. Zhitnitsky, Yad. Fiz. **31**, 497 (1980) [Sov. J. Nucl. Phys. **31**, 260 (1980)]; M. Dine, W. Fischler, and M. Srednicki, Phys. Lett. **104B**, 199 (1981).

[34] C. Patrignani *et al.* (Particle Data Group), Chin. Phys. C **40**, 100001 (2016).

[35] N. Iwamoto, Phys. Rev. Lett. **53**, 1198 (1984); M. Nakagawa, Y. Kohyama, and N. Itoh, Astrophys. J. **322**, 291 (1987);
M. Nakagawa, T. Adachi, Y. Kohyama, and N. Itoh, Astrophys. J. **326**, 241 (1988); N. Iwamoto, Phys. Rev. D **64**, 043002 (2001); H. Umeda, N. Iwamoto, S. Tsuruta, L. Qin, and K. Nomoto, arXiv:astro-ph/9806337.

[36] A. Paul, D. Majumdar, and K. P. Modak, arXiv:1801.07928.

[37] http://www.astroscu.unam.mx/neutrones/NSCool/.

[38] A. Schwenk, B. Friman, and G. E. Brown, Nucl. Phys. **A713**, 191 (2003).

[39] G. G. Raffelt, Lect. Notes Phys. **741**, 51 (2008); **741**, 51 (2006).

[40] M. Giannotti, I. Irastorza, J. Redondo, and A. Ringwald, J. Cosmol. Astropart. Phys. 05 (2016) 057; M. Giannotti, I. G. Irastorza, J. Redondo, A. Ringwald, and K. Saikawa, J. Cosmol. Astropart. Phys. 10 (2017) 010.

[41] J. Keller and A. Sedrakian, Nucl. Phys. **A897**, 62 (2013).

[42] K. Hamaguchi, N. Nagata, K. Yanagi, and J. Zheng (to be published).