Upper Limit on the QCD Axion Mass from Isolated Neutron Star Cooling

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The quantum chromodynamics (QCD) axion may modify the cooling rates of neutron stars (NSs). The axions are produced within the NS cores from nucleon bremsstrahlung and, when the nucleons are in superfluid states, Cooper pair breaking and formation processes. We show that four of the nearby isolated magnificent seven NSs along with PSR J0659 are prime candidates for axion cooling studies because they are coeval, with ages of a few hundred thousand years known from kinematic considerations, and they have well-measured surface luminosities. We compare these data to dedicated NS cooling simulations incorporating axions, profiling over uncertainties related to the equation of state, NS masses, surface compositions, and superfluidity. Our calculations of the axion and neutrino emissivities include high-density suppression factors that also affect SN 1987A and previous NS cooling limits on axions. We find no evidence for axions in the isolated NS data, and within the context of the Kim-Shifman-Vainshtein-Zakharov QCD axion model, we constrain $m_a \lesssim 16$ meV at 95% confidence level. An improved understanding of NS cooling and nucleon superfluidity could further improve these limits or lead to the discovery of the axion at weaker couplings.

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The quantum chromodynamics (QCD) axion is a well-motivated beyond-the-standard-model particle candidate that may explain the absence of the neutron electric dipole moment [1–4] and the dark matter (DM) in our Universe [5–7]. However, the axion remains remarkably unconstrained experimentally and observationally, despite nearly 45 years of effort dedicated to axion searches (see Ref. [8] for a review). The QCD axion is primarily characterized by its decay constant f_a, which sets both its mass [9] $m_a \approx 5.7\ \mu\text{eV}\ (10^{12}\ \text{GeV}/f_a)$and its interaction strengths with matter. Requiring f_a below the Planck scale implies $m_a \gtrsim 10^{-12}$ eV. The axion mass is currently bounded from above by supernova (SN) and stellar cooling constraints at the level of tens of meV, subject to model dependence and astrophysical uncertainties that are discussed further below.

The neutron star (NS) axion constraints presented in this Letter are part of a broader effort to probe the QCD axion over its full possible mass range. Black hole superradiance disfavors QCD axion masses $m_a < 2 \times 10^{-11}$ eV [10–12], while the ADMX experiment has reached sensitivity to Dine-Fischler-Srednicki-Zhitnitsky (DFSZ) [13,14] QCD axion DM over the narrow mass range $m_a \sim 2.7$–$4.2\ \mu$eV by using the axion-photon coupling [15–17]. Apart from these constraints, and additional narrow-band constraints from the ADMX [18] and HAYSTAC [19] experiments at the level of the more strongly coupled Kim-Shifman-Vainshtein-Zakharov (KSVZ) [20,21] axion, there is nearly a decade of orders of magnitude of parameter space open for the axion mass that is unprobed at present. On the other hand, near-term plans exist to experimentally cover most of the remaining parameter space for QCD axion DM, including ABRACADABRA [22–24], DM-Radio [25], and CASPEr [26–28] at axion masses $m_a \ll \mu$eV, ADMX and HAYSTAC at axion masses $m_a \sim 1$–$100\ \mu$eV, and MADMAX and plasma haloscopes at masses ~40–400 μeV [29,30]. However, astrophysical searches such as that presented in this Letter play an important role in constraining higher axion masses near and above the meV scale. Axions with $m_a \gtrsim$ meV are difficult to probe in the laboratory, even under the nontrivial assumption that the axion is DM (but see Ref. [31–36] for proposals). While it was previously thought that the QCD axion cannot explain the entirety of DM at masses at and above ~meV masses, this assumption has been challenged, recently (see, e.g., Ref. [37,38]), further motivating the search for meV-scale axions.

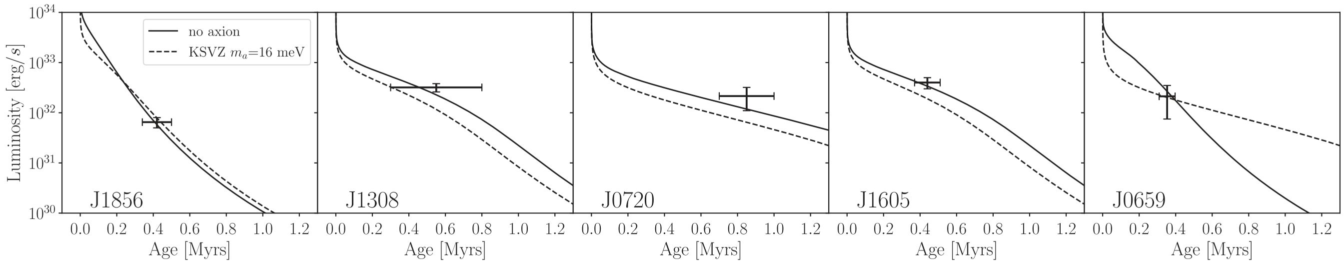

FIG. 1. The luminosity and age data for each of the NSs considered in this Letter (see Table I). We show the best-fit cooling curves computed in this Letter for each of these NSs under the null hypothesis and with the axion mass fixed to $m_a = 16$ meV, which is our 95% upper limit on the QCD axion mass in the context of the KSVZ model.

The fundamental idea behind how axions may modify NS cooling is that these particles, just like neutrinos [39], may be produced in thermal scattering processes within the NS cores and escape the stars due to their weak interactions [40,41]. Most previous studies of axion-induced NS cooling have focused on either proto-NSs, like that from SN 1987A [42–46], that are seconds old or young NSs like Cas A [47–52], which has an age ~300 years. In this Letter, we show that robust and competitive constraints on m_a may be found from analyses of older NS cooling, focusing on NSs with ages $\sim 10^5 - 10^6$ years (see Ref. [53,54] for related studies of older NSs). This is important when considering the possible issues that affect the SN 1987A and Cas A constraints, such as the lack of fully self-consistent 3D simulations [43] for SN 1987A and uncertainties related to the formation of the proto-NS [55] (but see Ref. [56]). Axion constraints from Cas A arise by using the observed temperature drop of the young NS over the past ~two decades by the Chandra telescope, but it was realized, recently, that this drop may be due to a systematic evolution of the energy calibration of the detector over time [57]. Moreover, the Cas A constraints are typically derived under the assumptions of specific superfluidity and equation of state (EOS) models, which are themselves uncertain. It is clear that additional, independent probes are needed to robustly disfavor or detect the QCD axion at masses above a few meV.

Isolated NS data and modeling.—In this Letter, we use luminosity and kinematic age data from four of the seven magnificent seven (M7) NSs, which are those where kinematic age data is available (see Table I and Fig. 1 for their relevant data). We add to this list PSR J0659, identified with the Monogem ring, as it also has an age above 10^5 years known from kinematic considerations [58,59] and a thermal luminosity measurement. The NSs with ages $\sim 10^5$ years live at a unique era, as illustrated in Fig. 2, where cooling from axion bremsstrahlung emission is maximally important; at lower ages neutrino emission plays a more important role since the neutrino (axion) emissivity scales as $\propto T^8$ (T^6) with temperature T, while at older ages the thermal surface emission dominates the energy loss. We discuss NSs with ages less than 10^5 years, including Cas A, in the Supplemental Material (SM) [60]. The age data have been determined by tracing the NSs back to their birthplaces. A measured NS orbit is run backwards in the Galactic potential and a parent stellar cluster is identified in each case. J1856 and J1308 are found to originate in the Upper Scorpius OB association [102,103]. J0720 was likely born in the Trumpler association [104]. J1605 can be associated with a runaway former binary companion, which was disrupted in a supernova [105].

The thermal luminosity data for these NSs are measured from spectral fitting of NS surface models to the x-ray spectra. The strong magnetic fields create localized temperature inhomogeneities on the surfaces, so the total thermal luminosity is a more robust observable for our purposes, since it is less affected by the temperature inhomogeneities than direct temperature measurements. For this reason, we use the luminosity data in this Letter rather than surface temperature measurements [106]. Typically, a NS atmosphere model or a double-blackbody model is fit to the x-ray spectral data. For J1856, a thin partially ionized hydrogen atmosphere model suggests our lower luminosity bound $\sim 5 \times 10^{31}$ erg/s [107] while a double blackbody model suggests the upper bound $\sim 8 \times 10^{31}$ erg/s [108]. For J1308, the same models suggest $(3.3 \pm 0.5) \times 10^{32}$ erg/s and 2.6×10^{32} erg/s, respectively [109]. For J0720, both types of models give similar luminosities $\sim 2 \times 10^{32}$ erg/s [104]. A double blackbody fit yields the luminosity $(4 \pm 1) \times 10^{32}$ erg/s for J1605, which we adopt in our analysis [110]. The J0659 luminosity was determined with a double blackbody model including a power law, since it emits nonthermally in hard x rays as it is a pulsar [111]. We assume Gaussian priors on the NS luminosities and ages that include all measurements at 1σ. Note that the M7 have previously been the subject of searches for axion-induced hard x-ray emission [112,113].

In this Letter, we build off of the one-dimensional NS cooling code NSCOOL [114] to simulate NS cooling curves with axion energy losses. NSCOOL solves the energy balance and transport equations in full general relativity in the core and crust of the NS. An envelope model $T_s(T_b)$ that relates the interior and surface temperatures, T_b and T_s, respectively, is glued to the exterior of the crust. After

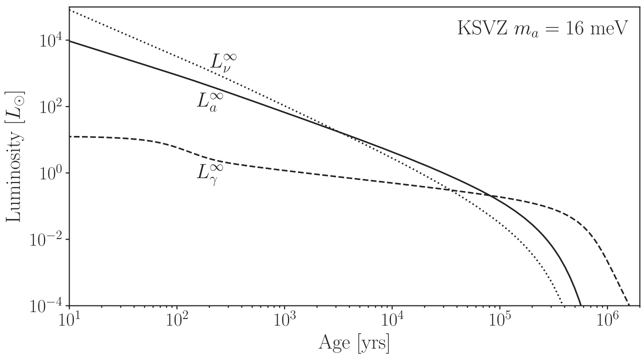

FIG. 2. The luminosity production from neutrinos, axions, and surface radiation for an example NS with the KSVZ axion at $m_a = 16$ meV. The NS parameters have been chosen to be those found in the profile likelihood procedure for J1605 with this axion mass: the BSk22 EOS, SBF-0-0 superfluidity model, $M_{\rm NS} = 1.0\ M_\odot$, and $\Delta M/M_\odot = 10^{-12}$.

thermal relaxation, so that the NS has a uniform core temperature, integrating the energy balance equation over the interior of the NS leads to the cooling equation

$$L_\gamma^\infty = -C\frac{dT_b^\infty}{dt} - L_\nu^\infty - L_a^\infty + H, \tag{1}$$

where $L_\gamma^\infty = 4\pi R_{*,\infty}^2 (T_s^\infty)^4$ is the photon luminosity, and t is time. (Throughout this Letter, the infinity superscript will indicate that the value is taken to be that as measured by a distant observer.) The heat capacity of the NS is C, L_ν^∞ is the neutrino luminosity, L_a^∞ is the axion luminosity, and H accounts for possible heating sources, such as from magnetic field decay (see Fig. 2 for an illustration). Note that we include important corrections to the neutrino emissivities relative to those in NSCOOL [114], which we discuss shortly, and we also assume that $H = 0$, since magnetic field induced heating likely plays a subdominant role in constraining L_a^∞ (see the SM [60]). The solution of this equation yields the NS cooling curve $L_\gamma^\infty(t, \boldsymbol{\theta})$, where $\boldsymbol{\theta}$ parametrizes the particular choices of axion and NS properties. The axion is parametrized by its mass m_a and coupling constants to nucleons, while for the NS, we need to know (i) the NS mass $M_{\rm NS}$, (ii) the EOS, (iii) the superfluidity model $\Delta(T_b)$, and (iv) the envelope model parametrized by the mass of light elements ΔM.

The axion energy losses from nucleon scattering processes are determined by the axion-neutron and axion-proton dimensionless coupling constants C_p and C_n, respectively, in addition to f_a; the axion-nucleon interactions are of the form $\mathcal{L} \supset (C_N/2f_a)\bar{\psi}_N\gamma^\mu\gamma_5\psi_N\partial_\mu a$ with $N = p, n$, ψ_N the nucleon fields, and a the axion field. In the KSVZ axion model, $C_p = -0.47 \pm 0.03$ and $C_n = -0.02 \pm 0.03$ [9], while in the DFSZ model C_p and C_n are functions of $\tan\beta$, which is the ratio of the vacuum expectation values of the up- to down-type Higgs doublets in that theory: $C_n = (-0.160 \pm 0.025) + 0.414\sin^2\beta$, $C_p = (-0.182 \pm 0.025) - 0.435\sin^2\beta$ [9]. Additional axion models are also possible [115], for which it is useful to define the dimensionless coupling constants $g_{aNN} = C_N m_N/f_a$, with m_N the nucleon mass. Note that the uncertainties on the KSVZ and DFSZ axion couplings arise from lattice QCD [9]; to make contact with previous literature, we assume the central values.

When computing the axion luminosities, we account for axion bremsstrahlung [40,41] from nucleons and axion production from Cooper pair breaking and formation (PBF). If the NS core temperature is below the superfluid critical temperature, nucleons form Cooper pairs and condense into a superfluid phase. These Cooper pairs can liberate energy in the form of neutrinos [116,117] or axions [53,118] when breaking and forming. The PBF processes may dominate the axion luminosity at temperatures near the superfluid transition temperature, while the bremsstrahlung processes are exponentially suppressed at lower temperatures. To evaluate the axion and neutrino emission rates, for both PBF and bremsstrahlung production, we account for the medium-dependent axion-nucleon and pion-nucleon couplings [119,120], which have not been included in earlier work on axion emission from compact stars or supernovae. See the SM [60] for details.

We make one additional modification to NSCOOL to help quantify the effects of astrophysical uncertainties. The addition of light elements (hydrogen, helium, and carbon) in the NS envelope changes the expected relation between the surface and core temperatures, which, in turn, affects the observed surface luminosity even for the same internal state. We incorporate the analytic formulae in Ref. [121] into NSCOOL in order to cool a NS with a mass ΔM of light elements layered on top of the default iron surface. Values for ΔM can span from 0 $M_\odot$, such that the NS has a pure iron surface, to $\sim 10^{-7}\ M_\odot$, which is the mass of the entire envelope. In practice, we modify the equation $T_s(T_b)$ to account for the addition of light elements, which can change the photon luminosity of the NS by up to a factor ~ 5 before the photon cooling stage and $\gtrsim 100$ after. Since each ΔM value requires a dedicated NSCOOL simulation, we use a discrete number eight of equally log-spaced values for $\Delta M/M_\odot$ ranging from $10^{-20}\ M_\odot$ to $10^{-6}\ M_\odot$. Similarly, we discretize the NS mass range with six equally spaced masses between 1 $M_\odot$ and 2 $M_\odot$.

We simulate NSs for five distinct EOSs: APR [122], BSk22, BSk24, BSk25, and BSk26 [123]. The APR EOS is constructed using variational methods to model the two-nucleon interaction incorporating the effects of many-body interactions and with the input of nucleon-nucleon scattering data. The BSk family of EOSs are generated by fitting the Skyrme effective interaction to atomic mass data. The distinct BSk EOSs are constructed with different assumed values of the Skyrme symmetry energy. These EOSs phenomenologically characterize the range of possible stiffnesses of the EOSs. Recently, data from the NICER telescope has allowed for the simultaneous measurements of the mass and radius of two NSs, PSR J0030 [124] and PSR J0740 [125], which can be used in conjunction with gravitational wave observations of NS mergers to constrain the EOS [125]. As we show in SM [60] Fig. S3, only the BSk22, BSk24, and BSk25 EOSs are consistent with the mass-radius data to within $1-2\sigma$ significance. Thus, we restrict ourselves to this set of EOSs in the main Letter.

We consider three distinct superfluidity models, denoted in NSCOOL and here as 0-0-0, SFB-0-0, and SFB-0-T73. The first model assumes no superfluidity by setting the gaps to zero. The second model turns on the $^1S_0$ neutron pairing gap from [126], and the third model additionally turns on the $^1S_0$ proton pairing gap from [127]. Neutron $^3P_2$-$^3F_2$ pairing may also be possible (we will refer to this as $^3P_2$ for brevity), but the estimate of this gap is more complicated, in part, because it appears at higher density where many-body interactions are more important (see, e.g., Ref. [128]).

Data analysis and results.—Given the set of cooling curves, we can compare them to the observed data in Table I. For a given QCD axion model, under the assumption of a particular NS EOS and superfluidity model $\Delta(T_b)$, let us label the present-day luminosity of a NS by $L(m_a, \boldsymbol{\theta})$. The luminosity of NS i is, then, jointly determined by the axion mass m_a and the nuisance parameters $\boldsymbol{\theta^i} = \{M^i_{\rm NS}, \Delta M^i, t^i\}$ that characterize the NS. Now, we can write the likelihood for a single NS i as

$$\mathcal{L}_i(\boldsymbol{d}_i|m_a, \boldsymbol{\theta^i}) = \mathcal{N}(L(m_a, \boldsymbol{\theta}^i) - L^i_0, \sigma^i_L) \times \mathcal{N}(t^i - t^i_0, \sigma^i_t), \quad (2)$$

where we have introduced the NS data set $\boldsymbol{d}_i = \{L^i_0, \sigma^i_L, t^i_0, \sigma^i_t\}$, where L^i_0 is the measured luminosity of the NS with uncertainty σ^i_L. Similarly, t^i_0 is the measured age of the NS with uncertainty σ^i_t. The probability of observing a value x under the zero-mean Gaussian distribution with standard deviation σ is denoted by $\mathcal{N}(x, \sigma)$. The joint likelihood $\mathcal{L}(\boldsymbol{d}|m_a, \boldsymbol{\theta})$ over all five NSs is constructed by taking the product of (2) over the NSs. Note that the total list of model parameters is denoted by $\boldsymbol{\theta} = \{\boldsymbol{\theta^i}\}^5_{i=1}$. The best-fit axion mass $\hat{m}_a$ and nuisance parameters $\hat{\boldsymbol{\theta}}$ can be determined for a given choice of EOS and superfluidity model by maximizing the joint likelihood. To test for systematic mismodeling, we allow $m_a < 0$, with the axion luminosity multiplied by $\text{sign}(m_a)$.

Additionally, given the large number of nuisance parameters, many of which have nontrivial degeneracy with the signal parameter m_a, we determine the 95% upper limit on m_a, defined by m^{95}_a, by the Neyman construction of the 95% confidence interval for m_a through a Monte Carlo (MC) procedure rather than by invoking Wilks' theorem.

TABLE I. The properties of the NSs considered in this Letter—RX J1856.6 − 3754, RX J1308.6 + 2127, RX J0720.4 − 3125, RX J1605.3 + 3249, PSR J0659 + 1414—which we abbreviate throughout this Letter. We include all known NSs with ages above 10^5 years and robust age and luminosity measurements (see, e.g., Ref. [58]). Younger NSs are discussed in the SM [60].

Name	L^∞_γ (10^{33} erg/s)	Age (Myr)	References
J1856	0.065 ± 0.015	0.42 ± 0.08	[102,107,108]
J1308	0.32 ± 0.06	0.55 ± 0.25	[103,109]
J0720	0.22 ± 0.11	0.85 ± 0.15	[104,129]
J1605	0.4 ± 0.1	0.44 ± 0.07	[105,110]
J0659	0.28 ± 0.14	0.35 ± 0.044	[59,111]

Similarly, we determine the significance of the axion model over the null hypothesis through MC simulations of the null hypothesis, instead of relying on Wilks' theorem. (See the SM [60] for details.)

We choose the 95% upper limit over the ensemble of nine EOS and superfluidity combinations that gives the most conservative limit. For the KSVZ axion model, we find that $m^{95}_a \approx 16$ meV with the BSk22 EOS model and the SFB-0-0 superfluidity model; the strongest constraint over all combinations is $m^{95}_a \approx 6$ meV with the BSk25 EOS and the SFB-0-T73 model. With that said, the SFB-0-T73 model is the worst fit to the data, with the best-fit axion mass being negative at $\sim 1.6\sigma$ significance. The best-fitting model is that with the BSk22 EOS and no superfluidity, for which the limit is $m^{95}_a \approx 14$ meV and the best-fit axion mass being negative at $\sim 0.36\sigma$. From these results, we conclude that the NS cooling data show no evidence for the KSVZ axion.

For the DFSZ axion, the results depend on the value of $\tan\beta$. In Fig. 3, we show m^{95}_a as a function of $\tan\beta$, with the shaded band showing the range of limits found over all EOS and superfluidity combinations. The weakest limit (bold) is achieved for all $\tan\beta$ for the no superfluidity model with the BSk22 EOS. We compare these upper limits to those from horizontal branch (HB) [130,131], red giant branch (RGB) [132,133], and SN 1987A [45] cooling. Note, however, that the SN 1987A limit is approximate, since, e.g., it arises from the rough requirement $L^\infty_a < L^\infty_\nu$ for the proto-NS, and also, it does not account for the density-dependent couplings for axions and neutrinos, which we estimate should weaken the SN 1987A limit by a factor ∼1.3–1.6, depending on the EOS. We also show the projected discovery reach for the future IAXO experiment [33]; our results leave open a narrow mass range ∼10 meV where IAXO may discover the QCD axion. In the axion model with only an axion-neutron (axion-proton) coupling, we constrain $|g_{\rm ann}| < 1.3 \times 10^{-9}$ ($|g_{\rm app}| < 1.5 \times 10^{-9}$) at 95% confidence.

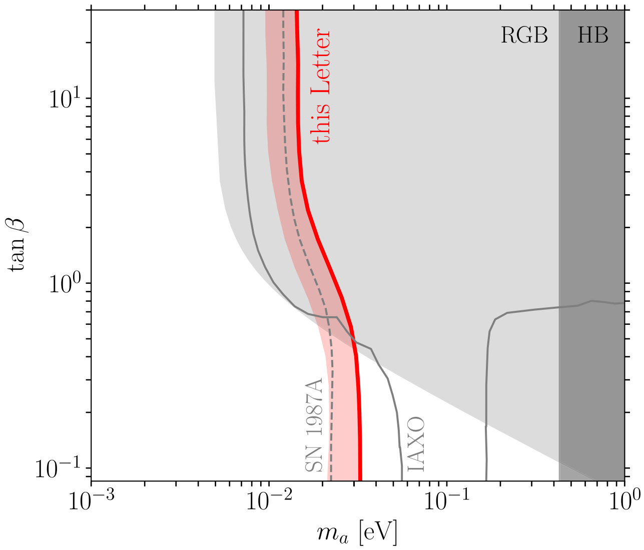

FIG. 3. Upper limit from this Letter on the DFSZ axion mass m_a as a function of $\tan\beta$, which controls the relative coupling of the axion to neutrons and protons. The width of the shaded red band reflects the uncertainty on the upper limit by varying over superfluidity and EOS models. We compare our upper limits to existing constraints and the projected IAXO discovery sensitivity.

Discussion.—In this Letter, we present a search for the QCD axion from NS cooling, comparing NS cooling simulations with axions to luminosity and kinematically determined age data from five NSs. The NSs that are most important for our analysis are J0720, J1605, and J1308, as further highlighted in the SM [60].

Our upper limits disfavor at 95% QCD axions with masses $m_a \gtrsim 10$–30 meV, depending on the axion model, which constrains the axion interpretation of the previously observed stellar cooling anomalies [134,135]. The limits may be stronger if $^3P_2$ superfluidity is active in the NS cores, as we discuss in the SM [60], though large $^3P_2$ gaps appear disfavored by the isolated NS data. Many-body nuclear techniques should provide improved estimates of the energy gaps of the $^1S_0$ (neutron), $^1S_0$ (proton), and $^3P_2$ (neutron) pairings in the future [128]. On the other hand, more work should be done to rigorously assess the possible impact of heating mechanisms such as magnetic field decay on the axion limits, for example, using fully self-consistent simulations along the lines of those in Ref. [136,137]. Axions may also be produced from more exotic forms of matter, such as hyperon superfluids and pionic and kaonic Bose Einstein condensates, and these channels should be investigated as the NS EOS and composition becomes better understood.

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