

Pulse and Polarization Structures in Axion-Converted X-Rays from Pulsars

JiJi Fan,^{1,*} Lingfeng Li^{2,†} and Chen Sun^{3,‡}

¹*Department of Physics and Brown Theoretical Physics Center, Brown University, Providence, Rhode Island 02912, USA*

²*Department of Physics, Brown University, Providence, Rhode Island 02912, USA*

³*Abdus Salam International Centre for Theoretical Physics, Strada Costiera 11, 34151 Trieste, Italy*



(Received 6 February 2025; accepted 12 November 2025; published 2 December 2025)

Neutron stars (NSs) with their strong magnetic fields and hot dense cores could be powerful probes of axions, a classic benchmark of feebly coupled new particles, through abundant production of axions with the axion-nucleon coupling and subsequent conversion into x-rays due to the axion-photon coupling. In this Letter, we point out that the pulsation structures in both the intensity and polarization of x-rays from NSs could provide us additional information about axions and their couplings. We develop new analytical formalisms of pulsation-polarization structure applicable to a wide range of NSs in the axion scenario and argue that they hold in complicated astrophysical environments. As a case study, we apply our formalism to a representative X-ray Dim Isolated Neutron Star, RX J1856.6-3754, with an unexpected hard x-ray excess which might be axion induced. We show with an updated fit that the axion explanation is compatible with both the intensity and pulsation data available, and combining the pulsation data does not shift the posterior by more than 1σ . Yet, the preferred parameter space is close to being excluded by other astrophysical constraints. With a 75% reduction of the uncertainties in the pulsation data, we could potentially draw a definite conclusion on the axion-induced x-rays at more than 3σ level.

DOI: [10.1103/66m2-6w2p](https://doi.org/10.1103/66m2-6w2p)

Introduction—An axion, a pseudoscalar field with a discrete shift symmetry, could have a wide range of phenomenological and cosmological applications. Its most notable applications include solving the strong CP problem [1–4], as well as serving as a classic cold dark matter candidate [5–7]. Though the axion scenario was proposed more than 40 years ago, it continues to serve as one of the most motivated hypothetical feebly coupled particles beyond the standard model of particle physics, with heightening interests in all kinds of search strategies. Among the astrophysical probes, neutron stars (NSs) with high nucleon densities could be powerful factories for axions, in the presence of axion couplings to nucleons [8–12]. The axions produced could subsequently convert into hard x-rays in the strong magnetic fields around the NSs, if axions also couple to photons. Such a combined process has been studied intensively in the literature, for different types of NSs [13–16], and already gives us highly nontrivial constraints and even potential hints of axions.

In this Letter, we study new observables beyond the overall x-ray flux from rotating NSs, the pulsars, which could potentially provide further valuable information about axions and their couplings [17]. Since the NS magnetic field configuration is not axisymmetric around its spin axis generically, the axion conversion rate depends on the phase of rotation, giving rise to interesting pulse structures in the converted x-ray intensity. In addition, the x-ray photons converted from the axion are nearly 100% linearly polarized with the associated electric field aligned along the local NS magnetic field. As a result, the polarization signal is also phase dependent as the magnetic field configuration changes with the pulsar rotation.

For an isolated NS without a strong accretion process, the axion-to-photon conversion happens dominantly in regions far from the NS surface. Thus, unlike the astrophysical sources of x-rays, which are usually located close to the surfaces of NSs (e.g., local hot spots [18,19]), the predictions of the polarization and pulsation signals in the axion scenario are not susceptible to complications in modeling the NS surface and atmosphere. In addition, the higher moments of the magnetic field beyond the dipole one fade away much faster in the effective axion-photon conversion region, and have much less impact on the axion-induced signals than on astrophysically originated x-rays. Consequently, the results obtained in this Letter are applicable to a wide range of NSs, including X-ray Dim Isolated Neutron Stars (XDINS) and magnetars. The joint pulse-polarization structure from axion-induced x-ray flux

*Contact author: jjj_fan@brown.edu

†Contact author: l.f.li165@gmail.com

‡Contact author: csun@ictp.it

Published by the American Physical Society under the terms of the [Creative Commons Attribution 4.0 International](https://creativecommons.org/licenses/by/4.0/) license. Further distribution of this work must maintain attribution to the author(s) and the published article's title, journal citation, and DOI. Funded by SCOAP³.

can help discern potential axion signals from astrophysical backgrounds. We note in passing that the opposite photon-to-axion conversion can potentially induce interesting polarization signals (see, e.g., Refs. [20,21] and references therein), although such studies focus on the surface photon spectrum and require careful modeling of the astrophysical environment and standard model contribution to the polarization aside from the axion-induced one.

Taking into account the pulse structure, we revisit the axion explanation for the keV x-ray excess of XDINS [16], taking RX J1856.6-3754 (J1856) as an example. We show that the pulse structure from the axion explanation of the x-ray excess is compatible with the current spectrum and pulsation data. However, the preferred parameter space is on the verge of being excluded by other astrophysical bounds. We will also demonstrate how a solid conclusion on the axion explanation could be achieved with reduced uncertainties in the pulsation data, which are feasible in the near-future observations.

Axion production and conversion in the keV-band—The hot dense core of a NS mainly consists of nucleons and becomes a significant source of axions with energy in the keV band in the presence of an axion-nucleon coupling. Here we follow the conventional way of parametrizing coupling of an axion, a , to a fermion f with mass m_f , as $\mathcal{L} \supset g_{af} \partial^\mu a \bar{f} \gamma_\mu \gamma^5 f / (2m_f)$, where the coefficient g_{af} is dimensionless. We set the axion coupling to a nucleon (denoted by a subscript N), either a proton (p) or a neutron (n) to be the same $g_{aN} = g_{ap} = g_{an}$. The axion production mechanism in the NS core is dominated by nucleon bremsstrahlung, while the Cooper-pair breaking may become important for certain temperature ranges [22]. Both mechanisms are subject to large systematic uncertainties from high-density nuclear physics and NS interior conditions. As a leading approximation, the axion emission from the NS core is spherically symmetric. For further discussions, see Ref. [24].

The produced axion could also couple to the electromagnetic field through the operator $-(g_{a\gamma}/4)aF_{\mu\nu}\tilde{F}^{\mu\nu}$, where $g_{a\gamma}$ is the dimensionful coupling with energy dimension -1 and $F(\tilde{F})$ the (dual) electromagnetic field strength. This operator leads to $a\mathbf{E} \cdot \mathbf{B}$ with $\mathbf{E}(\mathbf{B})$ being the electric (magnetic) field. It determines that the photons converted from axions are always polarized in the direction of the local background magnetic field. In other words, x-rays from the conversion are always in the so-called ordinary mode (O mode) parallel to the $\mathbf{k} - \mathbf{B}$ plane with $\mathbf{k}$ the photon wave vector.

The axion-photon conversion probability could be computed from the leading-order solution to the time-dependent perturbation theory in quantum mechanics [14]. A benchmark conversion probability as a function of radial distance r in the unit of r_0 , the NS radius is shown in Fig. 1. We define the axion-photon conversion radius, r_{con} , to be the scale at which the conversion probability is half of the

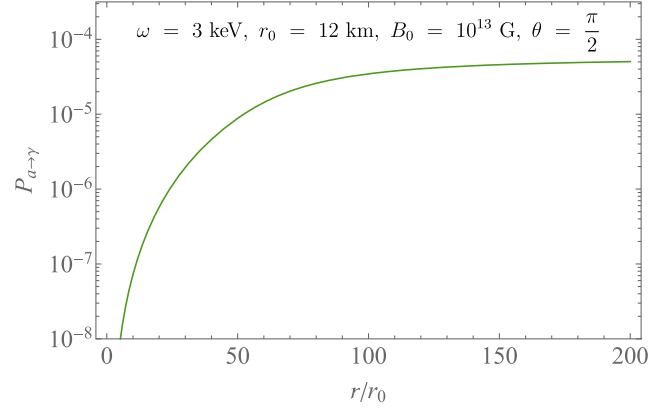


FIG. 1. Probability of axions converting to photons ($P_{a \rightarrow \gamma}$) as a function of r/r_0 . It approaches half of its asymptotic value at $\sim 85r_0$, distant from the surface, for the benchmark shown.

asymptotic value, which is given by

$$\frac{r_{\text{con}}}{r_0} = 85 \left(\frac{\omega}{3 \text{ keV}} \right)^{\frac{1}{3}} \left(\frac{B_0}{10^{13} \text{ G}} \right)^{\frac{2}{3}} \left(\frac{r_0}{12 \text{ km}} \right)^{\frac{1}{3}} (\sin \theta)^{\frac{2}{3}}, \quad (1)$$

where ω is the photon energy, $r_0 \approx 12 \text{ km}$ the typical NS radius [25], and θ the angle between the direction of axion (photon) propagation and the local magnetic field. In the above equation, we only consider the dipole component of the magnetic field which scales as $B_0(r/r_0)^{-3}$ with B_0 the magnitude of the dipole field at the surface. From Fig. 1, one could see that for axions propagating in the NS magnetosphere, the conversion probability is negligible at small radii as the large effective photon mass induced by vacuum polarization suppresses the mixing. The conversion happens dominantly at larger radii. Thus, higher-order moments of the magnetic field, which vanish faster with the radius, have negligible effects on the conversion rate.

Note that r_{con} is independent of the axion mass m_a as long as $m_a \lesssim (\omega^2 m_e^2 / (\alpha r_0^3 B_0 \sin \theta))^{\frac{1}{3}}$ [24], with m_e the electron mass and α the fine-structure constant. This remains true for most NSs except when $\sin \theta \ll 1$ near the magnetic poles. Yet the axion-photon conversion around the pole is suppressed $\propto |\sin \theta|^{2/5}$. Moreover, since the conversion dominantly happens far away from the NS, predicted properties of converted x-rays are robust against astrophysical factors effective close to the NS. These include vacuum resonance in the thin atmosphere, which is only about $\mathcal{O}(\text{cm})$ thick [26], and photon bending due to general relativity. On the other hand, astrophysical sources of hard x-rays such as local hot spots [18,19] are subject to all these effects. As shown in the NS literature (summarized in [27]), these complications have competing effects on the polarization and usually predict a mixture of the O mode and X mode (orthogonal to the $\mathbf{k} - \mathbf{B}$ plane) with an energy-dependent polarization fraction, in contrast to the clean polarization signal in the axion scenario: a

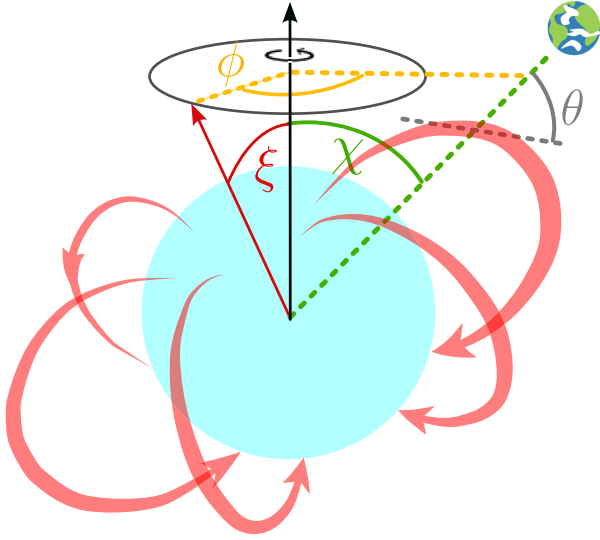


FIG. 2. Schematic of pulsar field configuration and definition of the χ , ξ , and ϕ angles.

dominant O mode with a polarization fraction ~ 1 at a given phase.

Pulses in intensity and polarization—The axion-converted x-ray photons have specific pulse structures in both the intensity and polarization, which are underexplored.

Pulsation: The time evolution of the flux, or equivalently, the pulse structure, could provide us important information about axion conversion. The nontrivial pulse structure of the converted photons from axions arises from the misalignment of the pulsar spin axis with the line of sight (LOS) and the magnetic field's dipole moment. Conventionally, the angle between the pulsar spin axis and the LOS (magnetic dipole moment) is labeled as χ (ξ), as shown in Fig. 2. We also show ϕ , the pulsar rotation angle. In the maximal conversion case, the LOS passes through the pulsar's magnetic equator and $\theta = \pi/2$. Generically, θ deviates from $\pi/2$, decreasing the converted photon flux. During pulsar's rotation, the direction and intensity of the B field along the LOS is phase dependent. The converted photon intensity I along the LOS follows

$$I = I_{\max} \times \left(1 - \cos^2 \chi \cos^2 \xi - \sin^2 \chi \sin^2 \xi \cos^2 \phi + \frac{1}{2} \sin 2\chi \sin 2\xi \cos \phi \right)^{\frac{1}{2}}, \quad (2)$$

where $I_{\max}$ is the maximum intensity. The pulse fraction (PF), defined as the ratio of the difference between the maximum and minimum fluxes and the sum of the two, is given by

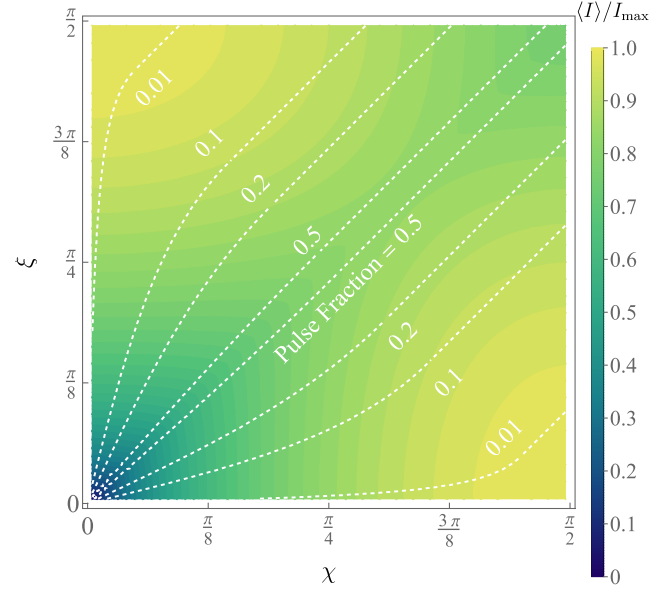


FIG. 3. The phase-averaged attenuation factor of the photon flux from axion conversions compared to $I_{\max}$, color-coded. Both the magnetic dipole approximation and the central LOS approximations are adopted. The white contours show the pulse fraction.

$$\text{PF} = \begin{cases} \frac{\sin^{2/5}(\xi+\chi) - \sin^{2/5}(|\xi-\chi|)}{\sin^{2/5}(\xi+\chi) + \sin^{2/5}(|\xi-\chi|)}, & \chi + \xi \leq \pi/2, \\ \frac{1 - \sin^{2/5}(\xi-\chi)}{1 + \sin^{2/5}(\xi-\chi)}, & \chi + \xi > \pi/2. \end{cases} \quad (3)$$

Here PF is independent of axion energy as it arises from magnetic field geometry, which we plot as a function of χ and ξ in Fig. 3. Interestingly, when $\chi + \xi < \pi/2$, there is only one minimum in Eq. (2) when ϕ goes from 0 to 2π , corresponding to the single pulse scenario. There are two minima when $\chi + \xi > \pi/2$ since both magnetic poles will approach LOS once per pulsar spin. This will lead to a double pulse structure, which is observed for many pulsars, e.g., [28–30].

For phase-averaged intensity measurements, the average of photon intensity $\langle I \rangle \equiv (1/2\pi) \int_0^{2\pi} I d\phi$ introduces an attenuation factor when compared with $I_{\max}$, $\langle I \rangle / I_{\max} < 1$. Numerically, we find the attenuation is mild for most of the parameter space, except where both χ and ξ are close to zero, as presented in Fig. 3, in which case the conversion is suppressed since $\theta \rightarrow 0$. Note that the pulse structure is symmetric under the exchange $\chi \leftrightarrow \xi$. Therefore, there is a degeneracy between the two angles even with very precise pulse measurements. However, the degeneracy will be broken after considering the x-ray polarization discussed below.

Polarization: As discussed earlier, the photon converted from axions will be $\sim 100\%$ polarized following the dipole direction. An instantaneous polarization ~ 1 in high energy bins could be a strong indicator of the axion origin. However, the magnetic field configuration becomes phase-dependent as long as $\xi \neq 0$. The angle Θ between the

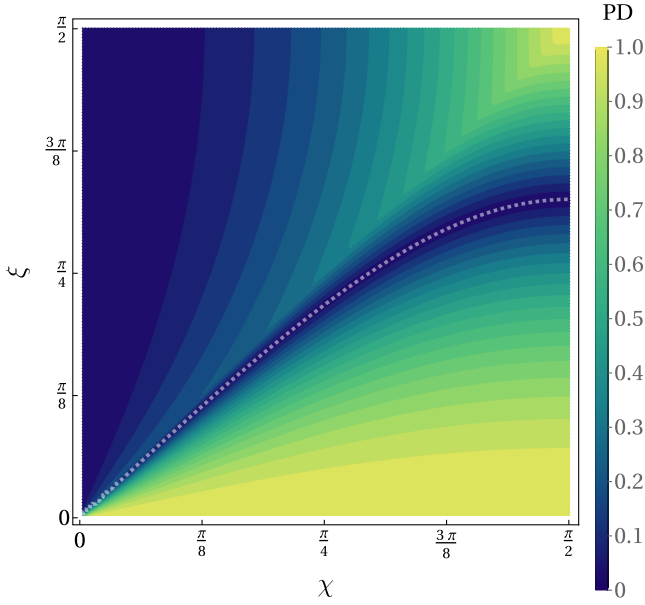


FIG. 4. Polarization degree for phase-averaged measurements. The white-dashed curve corresponds to the Stokes parameter $Q = 0$, above (below) which we have $Q < 0$ ($Q > 0$), corresponding to the phase-averaged photons being orthogonal (parallel) to the spin axis, respectively. The color code corresponds to contours of constant polarization degree.

polarization vector and the pulsar spin axis, projected onto the plane of the sky is given as

$$\tan \Theta = \frac{\sin \phi \sin \xi}{\cos \chi \sin \xi \cos \phi - \sin \chi \cos \xi}, \quad (4)$$

which lifts the degeneracy between χ and ξ .

When the measurements have limited time resolution and cannot fully resolve the phase-dependent polarization, the polarization of different phases may cancel each other and attenuate the averaged polarization, similar to the flux. Detailed calculations of the phase-averaged polarization angle (PA) and polarization degree (PD) are given in Supplemental Material [31]. Due to the system's symmetry, the averaged polarization angle will either align with the rotational axis' projection along the LOS or be orthogonal to it, as shown in Fig. 4.

RX J1856.5-3754: A case study—The discussions above apply to a wide range of observed NSs. In this section, we will focus on XDINS, a special class of NS, which offers a unique search opportunity for axions in the hard x-ray band. XDINS feature soft thermal x-ray emissions, well characterized by a simple blackbody (BB) spectrum with a temperature between 50 and 100 eV [50–53]. There are seven of them [54–60], nicknamed the “Magnificent Seven.” More recently, several works reported unexpected hard x-ray excesses around and above a keV from XDINS, with enhanced fluxes several orders of magnitude above the BB spectra, based on data from Suzaku, XMM-Newton,

and Chandra X-ray telescopes [18,19,61,62]. As with all anomalies in the sky, these excesses may be due to pure astrophysical effects such as a nonthermal rotation-powered emission. Yet, it is unclear that an astrophysical explanation could be consistent with all the features of the excesses and other properties of XDINS.

Among the seven of them, RX J1856.6-3754 (J1856 for short later) is the brightest and closest to us, serving as a frequently observed target for the calibration of the x-ray telescope. Its soft x-ray spectrum is described to a high accuracy by a soft blackbody (SBB) emission with a temperature at infinity $T_{\text{SBB}}^{\infty} \approx 62$ eV [63–65]. Observations also point to nontrivial pulse profiles of its hard x-ray emission using Neutron Star Interior Composition Explorer (NICER) and XMM-Newton data. In particular, in the (1.2–2) keV bin, the PF is 0.29 ± 0.11 while in the (2–7.5) keV bin, the PF is ~ 0.5 but with an even larger error bar due to the systematic error mainly induced by background subtraction and also the lower count rates [19]. In contrast, in the energy bins below 1 keV, the PF is of $\mathcal{O}(0.01)$ [19].

It is suggested in [16] that the excess might be accounted by the axion conversion scenario with a light axion and a range of $g_{a\gamma}g_{aN}$ in some tension with existing limits from CAST [66] and SN 1987A [67,68]. Here we implement a new fit to a larger dataset of J1856 from [19], including both the flux data above 1.05 keV and the pulsation data in the two high-energy regions (1.2–2.0 and 2.0–7.5 keV), compared to the previous fit with only flux data above 2 keV. The x-ray emission has three major contributors [19]: an SBB dominantly determined by the soft spectrum below keV as mentioned above, a hard blackbody (HBB) mostly relevant for the intermediate energy between 1 and 2 keV, and the hard excess $\gtrsim 2$ keV, which we assume to be axion-induced below. Below we simply fix the SBB spectrum following [19]. This choice renders seven free parameters to be fit: χ , ξ , rotation phase at a reference time ϕ_0 , the temperature and intensity of the HBB, NS core temperature at infinity T_c^{∞} , and the axion coupling product $g_{a\gamma}g_{aN}$. Details of the fits are listed in Supplemental Material [31]. Posteriors of three key parameters are shown in Fig. 5.

From Fig. 5, we see that the preferred core temperatures from spectrum-only or the combined fits are both around 1.2 keV with large variations. Since the total axion emission rate increases when T_c^{∞} increases, there is an anticorrelation between T_c^{∞} and $g_{a\gamma}g_{aN}$. The posterior coupling product is only compatible with the current axion bounds when $T_c^{\infty} \gtrsim 2$ keV. Even higher T_c^{∞} leads to a stronger tension in the spectrum shape measured. The impact of including current pulse data is not obvious due to its large systematic uncertainties. To better examine the usefulness of the pulse data, we conduct a parallel fit assuming a reduction of the systematic uncertainty to 25% of the current size. We take a benchmark for the central

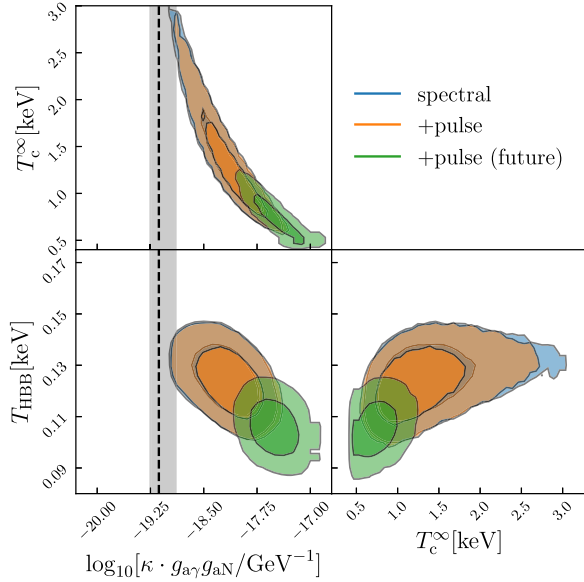


FIG. 5. Posterior distributions of HBB temperature T_{HBB}^{∞} , T_c^{∞} , and $g_{\gamma\gamma}g_{aN}$. We absorb the uncertainty due to J1856's mass profile into a dimensionless parameter κ and present its impact as a vertical gray band of existing bounds on $\kappa g_{\gamma\gamma}g_{aN}$. More details could be found in the last section of Supplemental Material [31]. Different contours correspond to the fit with spectrum data only (blue), combined spectrum and pulse data (orange), and combined data with reduced systematic uncertainties in the pulse data (green). The constraint on $g_{\gamma\gamma}g_{aN}$ (vertical dashed) is from the CAST [66] and SN 1987A [67] with $\kappa = 1$. For $m_a \gtrsim 10^{-5}$ eV, the stronger polar cap constraints [70,71] do not directly apply. Gaussian smoothing was applied to the contours with 0.5 σ kernel size.

values to be the current ones. The result is shown as the green contours in Fig. 5 [72]. Indeed, this improved pulse precision could potentially exclude the axion explanation of the hard x-ray excess, as it prefers much larger axion couplings. The power of spectral-pulsation analysis lies in PF's energy dependence. In the large core temperature small coupling limit, the PF across different high energy bins is expected to become similar in the axion scenario as discussed in the previous section, contradicting what the pulsation data prefers. The tension between the axion coupling constraints and the J1856 data will be greater than 3 σ in this scenario.

Conclusions and outlook—In this Letter, we aim to expand current astrophysical probes of axions with pulsation and polarization measurements on x-rays from pulsars. We focus on the synergy between the three probes of intensity, pulsation, and polarization in disentangling potential axion signals from astrophysical backgrounds. The work is timely given the intriguing hard x-ray excess observed from the XDINS. In particular, we take a critical examination of what information about axions can be extracted from pulsation and polarization measurements. We show that, when fitted against a model of axions

coupling to photons and nucleons, the current timing data from XMM-Newton is compatible with the theory points preferred by the hard x-ray excess, albeit in some tension with other astrophysical bounds. We demonstrate that a reduction of systematic errors by a factor of 4 in the timing data will reach the precision level needed to rule out the axion explanation of the hard x-ray excess.

Currently, Imaging X-ray Polarimetry Explorer (IXPE) is in the middle of its 5-yr mission to measure the polarization of cosmic x-rays [73]. So far IXPE has discovered polarized x-rays from magnetars with significantly larger x-ray fluxes [74,75], and the data has been used to constrain the axion scenario [76]. However, it has not provided any information about XDINS. It would be highly interesting if IXPE and future x-ray polarimeters such as eXTP [77], CATCH [78], and GOSoX [79] could collect data from XDINS (i.e., time-dependent polarization data), which could shed light on the origin of their mysterious hard x-ray excesses and probe axion physics simultaneously.

Again, we stress that the axion-induced x-ray pulse structures presented are generic for a wide group of sufficiently isolated pulsars. For much brighter sources such as magnetars with both flux and polarization data available, it would be interesting to apply our framework to extract information about axion models from the timing data, which has not been implemented so far and could help resolve astrophysical backgrounds. Alternatively, if an axion is discovered with parameters that can induce observable x-ray signals, this Letter may serve as a way to probe NS properties [31].

Acknowledgments—We thank Kfir Blum, Joshua Foster, Fazlollah Hajkarim, Steven Harris, Anirudh Prabhu, Kuver Sinha, Shuxu Yi, and Zhen Zhang for useful communication and discussions. We thank Matt Reece for reading the manuscript and providing useful feedback. J.F. and L.L. are supported by NASA Grant No. 80NSSC22K081 and DOE Grant No. DE-SC-0010010. C.S. acknowledges receipt of the grant from the Abdus Salam International Center for Theoretical Physics (ICTP), Trieste, Italy. C.S. also thanks the hospitality and support of Institute for Basic Science—Center for Theoretical Physics of the Universe (IBS-CTPU) and support of CKC for the CTPU-CKC Joint Focus Program: Let there be light (particles) Workshop, where part of this work was performed. This work was performed in part at Aspen Center for Physics, which is supported by National Science Foundation Grant No. PHY-2210452.

Data availability—The data that support the findings of this article are openly available [19].

[1] R. D. Peccei and H. R. Quinn, *CP conservation in the presence of instantons*, *Phys. Rev. Lett.* **38**, 1440 (1977).

- [2] R. D. Peccei and H. R. Quinn, Constraints imposed by CP conservation in the presence of instantons, *Phys. Rev. D* **16**, 1791 (1977).
- [3] S. Weinberg, A new light boson?, *Phys. Rev. Lett.* **40**, 223 (1978).
- [4] F. Wilczek, Problem of strong P and T invariance in the presence of instantons, *Phys. Rev. Lett.* **40**, 279 (1978).
- [5] J. Preskill, M. B. Wise, and F. Wilczek, Cosmology of the invisible axion, *Phys. Lett.* **120B**, 127 (1983).
- [6] M. Dine and W. Fischler, The not-so-harmless axion, *Phys. Lett.* **120B**, 137 (1983).
- [7] L. F. Abbott and P. Sikivie, A cosmological bound on the invisible axion, *Phys. Lett.* **120B**, 133 (1983).
- [8] R. P. Brinkmann and M. S. Turner, Numerical rates for nucleon-nucleon axion bremsstrahlung, *Phys. Rev. D* **38**, 2338 (1988).
- [9] F. Weber, Pulsars as astrophysical laboratories for nuclear and particle physics, 1st ed. (Routledge, New York, 1999), 10.1201/9780203741719.
- [10] A. Sedrakian, The physics of dense hadronic matter and compact stars, *Prog. Part. Nucl. Phys.* **58**, 168 (2007).
- [11] D. Page, J. M. Lattimer, M. Prakash, and A. W. Steiner, Stellar superfluids, [arXiv:1302.6626](https://arxiv.org/abs/1302.6626).
- [12] A. Sedrakian, Axion cooling of neutron stars, *Phys. Rev. D* **93**, 065044 (2016).
- [13] D. E. Morris, Axion mass limits from pulsar x-rays, *Phys. Rev. D* **34**, 843 (1986).
- [14] G. Raffelt and L. Stodolsky, Mixing of the photon with low-mass particles, *Phys. Rev. D* **37**, 1237 (1988).
- [15] J.-F. Fortin and K. Sinha, Constraining axion-like-particles with hard x-ray emission from magnetars, *J. High Energy Phys.* **06** (2018) 048.
- [16] M. Buschmann, R. T. Co, C. Dessert, and B. R. Safdi, Axion emission can explain a new hard x-ray excess from nearby isolated neutron stars, *Phys. Rev. Lett.* **126**, 021102 (2021).
- [17] Below we will use NS's and pulsars interchangeably.
- [18] T. Yoneyama, K. Hayashida, H. Nakajima, and H. Matsumoto, Universal detection of high-temperature emission in X-ray Isolated Neutron Stars, *Publ. Astron. Soc. Jpn.* **71**, 1 (2019).
- [19] D. De Grandis, M. Rigoselli, S. Mereghetti, G. Younes, P. Pizzochero, R. Taverna, A. Tiengo, R. Turolla, and S. Zane, Two decades of x-ray observations of the isolated neutron star RX J1856.5-3754: Detection of thermal and non-thermal hard x-rays and refined spin-down measurement, *Mon. Not. R. Astron. Soc.* **516**, 4932 (2022).
- [20] R. Perna, W. C. G. Ho, L. Verde, M. van Adelsberg, and R. Jimenez, Signatures of photon-axion conversion in the thermal spectra and polarization of neutron stars, *Astrophys. J.* **748**, 116 (2012).
- [21] N. Song, L. Su, and L. Wu, Polarization signals from axion-photon resonant conversion in a neutron star magnetosphere, *Phys. Rev. D* **111**, 043025 (2025).
- [22] Electromagnetic fields surrounding pulsars may also source axions when axions are very light with masses below 10^{-13} eV [23]. Here we consider heavier axions with masses $\sim 10^{-5}$ eV.
- [23] M. Khelashvili, M. Lisanti, A. Prabhu, and B. R. Safdi, An axion pulsarscope, *Phys. Rev. D* **111**, 083027 (2025).
- [24] J.-F. Fortin, H.-K. Guo, S. P. Harris, E. Sheridan, and K. Sinha, Magnetars and axion-like particles: Probes with the hard x-ray spectrum, *J. Cosmol. Astropart. Phys.* **06** (2021) 036.
- [25] G. F. Burgio, H. J. Schulze, I. Vidana, and J. B. Wei, Neutron stars and the nuclear equation of state, *Prog. Part. Nucl. Phys.* **120**, 103879 (2021).
- [26] D. Lai and W. C. G. Ho, Polarized x-ray emission from magnetized neutron stars: Signature of strong-field vacuum polarization, *Phys. Rev. Lett.* **91**, 071101 (2003).
- [27] I. Caiazzo, QED and x-ray polarization from neutron stars and black holes, Ph.D. thesis, University of British Columbia, 2019.
- [28] J. Kurpas, A. D. Schwöpe, A. M. Pires, and F. Haberl, Detection of pulsed x-ray emission from the isolated neutron star candidate eRASSU J131716.9-402647, *Astron. Astrophys.* **683**, A164 (2024).
- [29] M. Rigoselli, S. Mereghetti, V. Suleimanov, A. Y. Potekhin, R. Turolla, R. Taverna, and F. Pintore, XMM-Newton observations of PSR J0726-2612, a radio-loud XDINS, *Astron. Astrophys.* **627**, A69 (2019).
- [30] T. E. Riley *et al.*, A *NICER* view of PSR J0030 + 0451: Millisecond pulsar parameter estimation, *Astrophys. J. Lett.* **887**, L21 (2019).
- [31] See Supplemental Material at <http://link.aps.org/supplemental/10.1103/66m2-6w2p> for more details of the computation, which includes Refs. [23,32–49].
- [32] A. Caputo and G. Raffelt, Astrophysical axion bounds: The 2024 edition, *Proc. Sci. COSMICWISPer* (2024) 041 [[arXiv:2401.13728](https://arxiv.org/abs/2401.13728)].
- [33] A. Y. Potekhin, D. Lai, G. Chabrier, and W. C. G. Ho, Electromagnetic polarization in partially ionized plasmas with strong magnetic fields and neutron star atmosphere models, *Astrophys. J.* **612**, 1034 (2004).
- [34] D. Lai and J. Heyl, Probing axions with radiation from magnetic stars, *Phys. Rev. D* **74**, 123003 (2006).
- [35] J.-F. Fortin and K. Sinha, X-ray polarization signals from magnetars with axion-like-particles, *J. High Energy Phys.* **01** (2019) 163.
- [36] V. Radhakrishnan and D. J. Cooke, Magnetic poles and the polarization structure of pulsar radiation, *Astrophys. Lett.* **3**, 225 (1969), http://dspace.rri.res.in/bitstream/2289/4270/1/1969_Astrophysical%20Letters,%20Vol.%203,%20p.225.pdf.
- [37] J. Poutanen, Relativistic rotating vector model for x-ray millisecond pulsars, *Astron. Astrophys.* **641**, A166 (2020).
- [38] R. Taverna *et al.*, Polarized x-rays from a magnetar, 10.1126/science.add0080 (2022).
- [39] W. C. G. Ho, D. L. Kaplan, P. Chang, M. van Adelsberg, and A. Y. Potekhin, Magnetic hydrogen atmosphere models and the neutron star RX J1856.5-3754, *Mon. Not. R. Astron. Soc.* **375**, 821 (2007).
- [40] F. M. Walter, T. Eisenbeiss, J. M. Lattimer, B. Kim, V. Hambaryan, and R. Neuhaeuser, Revisiting the parallax of the isolated neutron star RX J185635-3754 using HST/ACS imaging, *Astrophys. J.* **724**, 669 (2010).
- [41] M. H. van Kerkwijk and D. L. Kaplan, Timing the nearby isolated neutron star RX J1856.5-3754, *Astrophys. J. Lett.* **673**, L163 (2008).

- [42] C. Huang *et al.*, CompactObject: An open-source Python package for full-scope neutron star equation of state inference, [arXiv:2411.14615](https://arxiv.org/abs/2411.14615).
- [43] N. Iwamoto, Nucleon-nucleon bremsstrahlung of axions and pseudoscalar particles from neutron-star matter, *Phys. Rev. D* **64**, 043002 (2001).
- [44] D. Foreman-Mackey, D.W. Hogg, D. Lang, and J. Goodman, EMCEE: The MCMC Hammer, *Publ. Astron. Soc. Pac.* **125**, 306 (2013).
- [45] G. Ashton *et al.*, Nested sampling for physical scientists, *Nature (London)* **2**, 39 (2022).
- [46] A. W. Steiner, J. M. Lattimer, and E. F. Brown, The neutron star mass-radius relation and the equation of state of dense matter, *Astrophys. J. Lett.* **765**, L5 (2013).
- [47] F. J. Fattoyev, C. J. Horowitz, J. Piekarewicz, and G. Shen, Relativistic effective interaction for nuclei, giant resonances, and neutron stars, *Phys. Rev. C* **82**, 055803 (2010).
- [48] T. Malik, M. Ferreira, B. K. Agrawal, and C. Providência, Relativistic description of dense matter equation of state and compatibility with neutron star observables: A Bayesian approach, *Astrophys. J.* **930**, 17 (2022).
- [49] P. Char, C. Mondal, F. Gulminelli, and M. Oertel, Generalized description of neutron star matter with a nucleonic relativistic density functional, *Phys. Rev. D* **108**, 103045 (2023).
- [50] F. Haberl, A. D. Schwope, V. Hambaryan, G. Hasinger, and C. Motch, A broad absorption feature in the x-ray spectrum of the isolated neutron star RBS1223 (1RXS J130848.6 + 212708), *Astron. Astrophys.* **403**, L19 (2003).
- [51] M. H. van Kerkwijk, D. L. Kaplan, M. Durant, S. R. Kulkarni, and F. Paerels, A Strong, broad absorption feature in the x-ray spectrum of the nearby neutron star RX J1605.3 + 3249, *Astrophys. J.* **608**, 432 (2004).
- [52] F. Haberl, C. Motch, V. E. Zavlin, K. Reinsch, B. T. Gaensicke, M. Cropper, A. D. Schwope, R. Turolla, and S. Zane, The Isolated neutron star x-ray pulsars RX J0420.0 – 5022 and RX J0806.4 – 4123: New x-ray and optical observations, *Astron. Astrophys.* **424**, 635 (2004).
- [53] S. Zane, M. Cropper, R. Turolla, L. Zampieri, M. Chierigato, J. J. Drake, and A. Treves, Detection of pulsations and a spectral feature in the x-ray emission of the isolated neutron star 1RXS J214303.7 + 065419/RBS 1774, *Astrophys. J.* **627**, 397 (2005).
- [54] F. M. Walter, S. J. Wolk, and R. Neuhäuser, Discovery of a nearby isolated neutron star, *Nature (London)* **379**, 233 (1996).
- [55] F. Haberl, C. Motch, D. Buckley, F.-J. Zickgraf, and W. Pietsch, RX J0720.4-3125: Strong evidence for an isolated pulsating neutron star, *Astron. Astrophys.* **326**, 662 (1997), <https://ui.adsabs.harvard.edu/abs/1997A%26A...326..662H/abstract>.
- [56] F. Haberl, C. Motch, and W. Pietsch, Isolated neutron stars in the ROSAT survey, *Astron. Nachr.* **319**, 97 (1998).
- [57] A. D. Schwope, G. Hasinger, R. Schwarz, F. Haberl, and M. Schmidt, The isolated neutron star candidate RBS1223 (1RXS J130848.6 + 212708), *Astron. Astrophys.* **341**, L51 (1999), <https://inspirehep.net/arxiv/astro-ph/9811326>.
- [58] C. Motch, F. Haberl, F. J. Zickgraf, G. Hasinger, and A. D. Schwope, The isolated neutron star candidate RX J1605.3 + 3249, *Astron. Astrophys.* **351**, 177 (1999), <https://inspirehep.net/arxiv/astro-ph/9907306>.
- [59] F. Haberl, W. Pietsch, and C. Motch, RX J0420.0-5022: An isolated neutron star candidate with evidence for 22.7 s x-ray pulsations, *Astron. Astrophys.* **351**, L53 (1999), <https://inspirehep.net/arxiv/astro-ph/9911159>.
- [60] L. Zampieri, S. Campana, R. Turolla, M. Chierigato, R. Falomo, D. Fugazza, A. Moretti, and A. Treves, 1RXS J214303.7 + 065419/RBS 1774: A new isolated neutron star candidate, *Astron. Astrophys.* **378**, L5 (2001).
- [61] T. Yoneyama, K. Hayashida, H. Nakajima, S. Inoue, and H. Tsunemi, Discovery of a keV-x-ray excess in RX J1856.5-3754, *Publ. Astron. Soc. Jpn.* **69**, 50 (2017).
- [62] C. Dessert, J. W. Foster, and B. R. Safdi, Hard x-ray excess from the magnificent seven neutron stars, *Astrophys. J.* **904**, 42 (2020).
- [63] V. Burwitz, V. E. Zavlin, R. Neuhäuser, P. Predehl, J. Trümper, and A. C. Brinkman, The chandra lets high resolution x-ray spectrum of the isolated neutron star RX J1856.5-3754, *Astron. Astrophys.* **379**, L35 (2001).
- [64] V. Burwitz, F. Haberl, R. Neuhäuser, P. Predehl, J. Trümper, and V. E. Zavlin, The thermal radiation of the isolated neutron star RX J1856.5-3754 observed with Chandra and XMM-Newton, *Astron. Astrophys.* **399**, 1109 (2003).
- [65] N. Sartore, A. Tiengo, S. Mereghetti, A. De Luca, R. Turolla, and F. Haberl, Spectral monitoring of RX J1856.5-3754 with XMM-Newton: Analysis of EPIC-pn data, *Astron. Astrophys.* **541**, A66 (2012).
- [66] K. Altenmüller *et al.* (CAST Collaboration), New upper limit on the axion-photon coupling with an extended CAST run with a Xe-based micromegas detector, *Phys. Rev. Lett.* **133**, 221005 (2024).
- [67] Partial Data Group, Review of particle physics, *Prog. Theor. Exp. Phys.* **2020**, 083C01 (2020).
- [68] See Ref. [69] for a study on an alternative scenario in producing the SN 1987A neutrino signal to avoid its bound on axions. See also Sec. 8.6 in [32] for arguments against this scenario.
- [69] N. Bar, K. Blum, and G. D'Amico, Is there a supernova bound on axions?, *Phys. Rev. D* **101**, 123025 (2020).
- [70] D. Noordhuis, A. Prabhu, S. J. Witte, A. Y. Chen, F. Cruz, and C. Weniger, Novel constraints on axions produced in pulsar polar-cap cascades, *Phys. Rev. Lett.* **131**, 111004 (2023).
- [71] A. Caputo, S. J. Witte, A. A. Philippov, and T. Jacobson, Pulsar nulling and vacuum radio emission from axion clouds, *Phys. Rev. Lett.* **133**, 161001 (2024).
- [72] Assuming that the dominant systematic uncertainty comes from the subtraction of diffusion backgrounds, this reduction is equivalent to improving the angular resolution by a factor of 2 while keeping the observation time to be the same.
- [73] M. C. Weisskopf, B. Ramsey, S. O'Dell, A. Tennant, R. Elsner, P. Soffitta, R. Bellazzini, E. Costa, J. Kolodziejczak, V. Kaspi, F. Muleri, H. Marshall, G. Matt, and R. Romani, The imaging x-ray polarimetry explorer (IXPE), *Results Phys.* **378**, 1179 (2016).
- [74] R. Taverna *et al.*, Polarized x-rays from a magnetar, *Science* **378**, 646 (2022).

-
- [75] S. Zane *et al.*, A strong x-ray polarization signal from the magnetar 1RXS J170849.0-400910, *Astrophys. J. Lett.* **944**, L27 (2023).
- [76] E. Gau, F. Hajkarim, S. P. Harris, P. S. B. Dev, J.-F. Fortin, H. Krawczynski, and K. Sinha, New constraints on axion-like particles from IXPE polarization data for magnetars, *Phys. Dark Universe* **46**, 101709 (2024).
- [77] S.-N. Zhang *et al.* (eXTP Collaboration), The enhanced x-ray timing and polarimetry mission—eXTP, *Sci. China Phys. Mech. Astron.* **62**, 29502 (2019).
- [78] P. Li *et al.*, CATCH: Chasing all transients constellation hunters space mission, *Exp. Astron.* **55**, 447 (2023).
- [79] H. L. Marshall, S. N. T. Heine, R. Davidson, A. Garner, E. M. Gullikson, H. M. Günther, C. Leitz, R. Masterson, E. D. Miller, J. S. Stenzel, W. W. Zhang, R. Boissay-Malaquin, I. Caiazzo, D. Chakrabarty, L. G. Gallo, R. K. Heilmann, J. Heyl, E. Kara, and N. S. Schulz, The globe orbiting soft x-ray (GOSoX) polarimeter concept study, in *Optics for EUV, X-Ray, and Gamma-Ray Astronomy X*, Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series Vol. 11822, edited by S. L. O'Dell, J. A. Gaskin, and G. Pareschi (SPIE Optical Engineering + Applications, San Diego, California, USA, 2021), p. 118220O.