

Limits on the axion-photon coupling from Chandrayaan-2 observations

Tanmoy Kumar^{1,*}, N. P. S. Mithun^{2,†}, Subhendra Mohanty^{3,4,‡}, Sourov Roy^{1,§},
B. S. Bharath Saiguhani^{2,||} and Santosh Vadawale^{2,¶}

¹*School of Physical Sciences, Indian Association for the Cultivation of Science,
2A & 2B Raja S.C. Mullick Road, Jadavpur, Kolkata 700032, India*

²*Physical Research Laboratory, Navrangpura, Ahmedabad 380009, India*

³*Department of Physics, Indian Institute of Technology Kanpur, Kanpur 208016, India*

⁴*Department of Physics, Indian Institute of Science Education and Research Bhopal, Bhopal 462066, India*



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Axions and axionlike particles have gained immense attention in searches for beyond Standard Model physics. Experiments searching for axions leverage their predicted couplings to Standard Model particles to look for observable signals. Though weak, these couplings allow axions to be produced abundantly in the interiors of stars such as the Sun. Once created, axions can escape the Sun and, while passing through the solar atmosphere, oscillate into photons in the magnetic field, producing x-rays. For the first time, to the best of our knowledge, we use data from the observation of soft x-rays from the quiet Sun during the 2019–2020 solar minimum by the Solar X-ray Monitor, on board India's Chandrayaan-2 lunar exploration mission, to constrain the coupling of axions to photons ($g_{a\gamma\gamma}$). Using the latest models of the solar atmosphere to calculate the magnetic field and plasma frequency, we constrain $g_{a\gamma\gamma} \lesssim (0.50 - 2.26) \times 10^{-10} \text{ GeV}^{-1}$ at 95% confidence level for axion masses $m_a \lesssim 5 \times 10^{-4} \text{ eV}$.

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Introduction. Axions and axionlike particles (ALPs) are well-motivated candidates for physics beyond the Standard Model (SM). They arise generically as pseudo-Nambu-Goldstone bosons (pNGBs) of spontaneously broken approximate global $U(1)$ symmetries in many extensions of the SM [1–3]. The best-known example is the QCD axion, originating from the Peccei-Quinn (PQ) solution to the strong CP problem [4–8]. Throughout this work, we use the term axions to denote generic pNGBs associated with nonlinearly realized approximate global symmetries.

Axions are predicted to have masses ranging from 10^{-22} eV to several GeV, interacting extremely weakly with SM particles. Consequently, light axions ($m_a \lesssim \text{few eV}$) are compelling cold dark matter (CDM) candidates [9–12]. Hence, most experimental searches for light axions target axion DM through its coupling to photons [13–23].

However, axions need not constitute the DM, motivating complementary search strategies.

Astrophysical objects such as stars provide powerful laboratories to search for axions. Owing to their high temperatures, densities, and volumes, they can efficiently produce axions [24–30], which can freely stream out of the stars for sufficiently small couplings. In particular, the Sun is a prime target: Axions produced in its core at $T \sim \text{few keV}$ and $\rho \sim 150 \text{ g cm}^{-3}$ escape with $\mathcal{O}(\text{keV})$ energies. The CERN Axion Solar Telescope (CAST) has searched for such solar axions and, in the absence of a signal, has placed stringent bounds on axion parameter space [31–33].

In this work, we explore a novel avenue for detecting solar axions by using the solar soft x-ray spectrum measured by the Solar X-ray Monitor (XSM) on board the Chandrayaan-2 lunar orbiter of the Indian Space Research Organization (ISRO), during the 2019–2020 solar minimum [34,35]. This soft x-ray spectrum consists of two components—the background quiet Sun emission and the emission from the flaring plasma. Additionally, solar axions will also contribute to the total solar soft x-ray emission due to their conversion into photons in the solar magnetic field. We conduct a search for this axion-induced x-ray emission from the Sun using the observed solar soft x-ray spectrum and put constraints on the axion-photon coupling. We find no evidence of an axion-induced signal over the background and consequently set an upper bound on the axion-photon coupling, which is comparable to the

*Contact author: kumartanmoy1998@gmail.com

†Contact author: mithun@prl.res.in

‡Contact author: subhendam@iiserb.ac.in

§Contact author: tpsr@iacs.res.in

||Contact author: bsg@prl.res.in

¶Contact author: santoshv@prl.res.in

present constraints from the CAST experiment and is limited only by the collecting area of the XSM.

A similar analysis using data from the NuSTAR observation of the Sun during the solar minimum has been presented in Ref. [36]. However, unlike NuSTAR, which was able to observe only a portion of the Sun because of its small field of view (FOV) ($12' \times 12'$), the XSM observes emission from the entire solar disk. Our work provides a compelling case for having a dedicated solar observatory operational during the next solar minimum which can significantly improve upon these bounds in an independent fashion.

Axion production inside the Sun. We start with the following Lagrangian for the axion field a :

$$\mathcal{L} \supset \frac{1}{2} \partial_\mu a \partial^\mu a - \frac{1}{2} m_a^2 a^2 + \frac{g_{aee}}{2m_e} \partial_\mu a \bar{\psi}_e \gamma^\mu \gamma_5 \psi_e - \frac{g_{a\gamma\gamma}}{4} a F^{\mu\nu} \tilde{F}_{\mu\nu}, \quad (1)$$

where $g_{a\gamma\gamma}$ is the axion-photon coupling, g_{aee} is the axion-electron coupling, m_a is the mass of the axion, ψ_e is the electron field, and $F^{\mu\nu}$ is the electromagnetic field strength tensor. For simplicity, we do not consider any particular axion model, and we treat $g_{a\gamma\gamma}$ as an independent parameter alongside m_a .

In the solar plasma where there exists huge quantities of free electrons and ions, due to the above couplings, axions can be produced abundantly via the following processes:

- (1) Primakoff process: $\gamma + (e^-, Ze) \rightarrow (e^-, Ze) + a$
- (2) Compton scattering: $\gamma + e \rightarrow e + a$
- (3) e-ion bremsstrahlung: $e + Ze \rightarrow e + Ze + a$
- (4) e-e bremsstrahlung: $e + e \rightarrow e + e + a$

where e stands for electron and Ze stands for charged ion. The amplitude of the Primakoff process is governed by $g_{a\gamma\gamma}$ while those of all the other processes are governed by g_{aee} .

Following Ref. [37], we calculate the axion emission rate per unit volume and integrate it over a standard solar model [38]; finally, dividing by the total surface area of the Sun, we obtain the flux of axions coming out of the Sun. For the light axions ($m_a \ll \text{eV}$) that we consider in this work, the spectral axion fluxes (in units of $\text{cm}^{-2} \text{s}^{-1} \text{keV}^{-1}$) produced by the Sun via the four processes are well approximated by the following fitting formulas [32]:

$$\begin{aligned} \left. \frac{d\phi_a}{dE_a} \right|_P &= 3.0 \times 10^{11} \left(\frac{g_{a\gamma\gamma}}{10^{-12} \text{ GeV}^{-1}} \right)^2 E_a^{2.450} e^{-0.829 E_a}, \\ \left. \frac{d\phi_a}{dE_a} \right|_B &= 1.25 \times 10^{14} \left(\frac{g_{aee}}{10^{-13}} \right)^2 \frac{E_a}{1 + 0.667 E_a^{1.278}} e^{-0.77 E_a}, \\ \left. \frac{d\phi_a}{dE_a} \right|_C &= 6.32 \times 10^{11} \left(\frac{g_{aee}}{10^{-13}} \right)^2 E_a^{2.987} e^{-0.776 E_a}, \end{aligned} \quad (2)$$

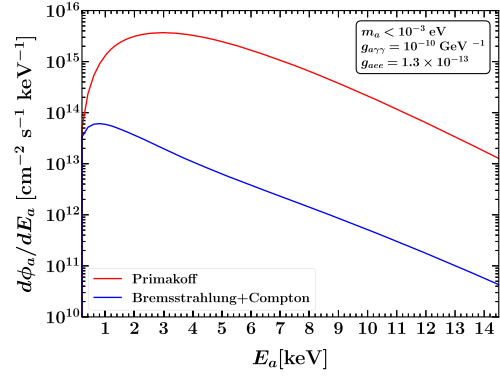


FIG. 1. Solar axion flux at the solar surface arising from the Primakoff process (red solid) and from the combined bremsstrahlung and Compton processes (blue solid). The couplings are set to $g_{a\gamma\gamma} = 10^{-10} \text{ GeV}^{-1}$ and $g_{aee} = 1.3 \times 10^{-13}$.

where E_a is the axion energy in keV and P , B , and C stand for Primakoff, bremsstrahlung, and Compton, respectively. In order to calculate the bremsstrahlung flux, both the electron-electron bremsstrahlung and electron-ion bremsstrahlung have been taken into account.

Figure 1 shows the fluxes of solar axions at the solar surface produced via the Primakoff process (solid red line) and through the combined bremsstrahlung and Compton processes (solid blue line), for $g_{a\gamma\gamma} = 10^{-10} \text{ GeV}^{-1}$ and $g_{aee} = 1.3 \times 10^{-13}$. The total solar axion flux is obtained as the sum of the individual contributions from the Primakoff, bremsstrahlung, and Compton processes; therefore, it depends on both $g_{a\gamma\gamma}$ and g_{aee} . Within the parameter space and energy range considered here, the Primakoff-induced flux is substantially larger than the combined bremsstrahlung and Compton components. Nevertheless, for completeness, all production channels are included in the subsequent analysis.

Axion-photon conversion outside the Sun. Relativistic axions produced in the solar core propagate along nearly radial trajectories and emerge from the solar surface. As they traverse the solar magnetic field, a fraction of them convert into photons, producing x-rays. The differential solar x-ray flux resulting from axion-photon conversion in the solar atmosphere is given by

$$\frac{d\phi_\gamma}{dE_\gamma} = \frac{d\phi_a}{dE_a} \times P_{a\gamma}, \quad (3)$$

where $d\phi_a/dE_a$ is the total axion flux at the solar surface, obtained as the sum of the Primakoff, bremsstrahlung, and Compton contributions in Eq. (2), and $P_{a\gamma}$ is the axion-photon conversion probability in the solar magnetic field.

To calculate the conversion probability, we start with the axion-photon mixing equation in an external magnetic field [39],

$$((E_a - i\partial_\ell)\mathbb{I} + M(\ell)) \begin{pmatrix} |A_\perp(\ell)\rangle \\ |A_\parallel(\ell)\rangle \\ |a(\ell)\rangle \end{pmatrix} = 0, \quad (4)$$

where $|A_{\parallel(\perp)}\rangle$ represents an electromagnetic wave polarized in the direction parallel (perpendicular) to $\vec{B}_T$, where $\vec{B}_T$ is the projection of the solar magnetic field $\vec{B}(\ell)$ on the plane perpendicular to the direction of propagation of the axions, and

$$M(\ell) = \begin{pmatrix} -\frac{\omega_p^2(\ell)}{2\omega} - i\frac{\Gamma(\ell)}{2} & 0 & 0 \\ 0 & -\frac{\omega_p^2(\ell)}{2\omega} - i\frac{\Gamma(\ell)}{2} & g_{a\gamma\gamma} \frac{B_T(\ell)}{2} \\ 0 & g_{a\gamma\gamma} \frac{B_T(\ell)}{2} & -\frac{m_a^2}{2\omega} \end{pmatrix}. \quad (5)$$

Here, $\omega_p(\ell) = \sqrt{4\pi\alpha n_e(\ell)/m_e}$ is the plasma frequency in the solar atmosphere, with α being the fine structure constant and $\Gamma(\ell)$ the absorption coefficient of x-rays in the solar atmosphere [40]. For this work, we neglect the Euler-Heisenberg term and Faraday rotation related to the longitudinal component of the external field. Since the axion field only couples to $A_\parallel$, axion-photon conversion can be described by the bottom 2×2 subblock of M , which we denote as $\hat{M}$. Starting from the point $\ell = 0$, the solution of Eq. (4) at some location $\ell = h$ is given by the path-ordered transfer matrix [39,41]

$$\begin{bmatrix} |A_\parallel(h)\rangle \\ |a(h)\rangle \end{bmatrix} = \mathcal{P}_\ell \left[\exp \left(-iE_a h \mathbb{I} - i \int_0^h \hat{M}(\ell) d\ell \right) \right] \begin{bmatrix} |A_\parallel(0)\rangle \\ |a(0)\rangle \end{bmatrix}, \quad (6)$$

where $|A_\parallel(0)\rangle$ and $|a(0)\rangle$ are the initial field values.

The above integral can be evaluated perturbatively in powers of $g_{a\gamma\gamma}$ [39]. Working up to first order in perturbation theory, one finds that the probability of conversion of axions into photons after traveling a distance h from the solar surface in the solar magnetic field is given by

$$P_{a\gamma}(h) = |\langle A_\parallel(h) | a(0) \rangle|^2 = \frac{1}{4} g_{a\gamma\gamma}^2 e^{-\int_0^h d\ell \Gamma(\ell)} \times \left| \int_0^h d\ell B_T(\ell) e^{i \int_0^\ell d\ell' q(\ell')} e^{\frac{1}{2} \int_0^\ell d\ell' \Gamma(\ell')} \right|^2, \quad (7)$$

where $q(\ell) = (\omega_p^2(\ell) - m_a^2)/2E_a$ is the momentum exchanged between the photon and the axion, both carrying energy E_a .

In this work, we compute the axion-photon conversion probability by numerically integrating Eq. (7) up to the required height h above the solar surface, using the magnetic-field and plasma-frequency profiles of the quiet Sun from Ref. [36]. The absorption coefficient is computed

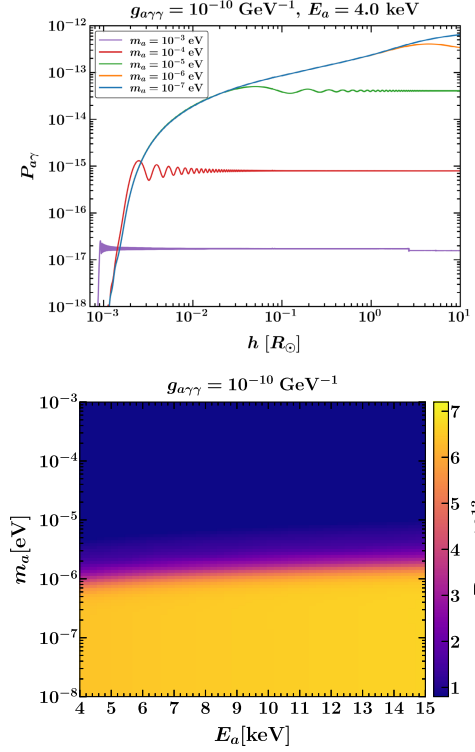


FIG. 2. Top panel: variation of the axion-to-photon conversion probability $P_{a\gamma}$ with distance from the solar surface h for fixed $g_{a\gamma\gamma}$ and E_a and for a range of m_a . Bottom panel: variation of $P_{a\gamma}$ with m_a and E_a for a fixed $g_{a\gamma\gamma}$.

as $\Gamma = \sum_{Z=1}^{30} n_Z \sigma_Z$, where n_Z is the number density of an element of atomic number Z and σ_Z is the total attenuation cross section of a photon passing through a gas of atomic number Z . To compute Γ , we consider all elements up to atomic number $Z = 30$. The individual elemental abundance in the solar atmosphere is obtained from the CHIANTI atomic database [42,43] by using the Python interface ChiantiPy [44]. For each element, we take the total photon attenuation cross section with coherent scattering from the XCOM database by NIST [45].

The top panel of Fig. 2 shows the axion-photon conversion probability $P_{a\gamma}$ as a function of height above the solar surface h for various axion masses. The probability saturates at large distances and increases for lighter axions, becoming mass independent for $m_a \lesssim 10^{-7} \text{ eV}$, where the curves converge.

The bottom panel of Fig. 2 shows $P_{a\gamma}$ far from the Sun as a function of m_a and E_a . The probability is almost independent of axion energy within the relevant range. Hence, from Eq. (3), the resulting x-ray spectrum from axion conversion mirrors the solar axion spectrum in Fig. 1, differing only by an overall normalization set by the conversion probability.

Chandrayaan-2 observation of the quiet Sun. The XSM on board Chandrayaan-2 measures the disk-integrated solar

x-ray spectrum in the 1–15 keV energy range [46,47]. Here, we use the XSM observations during its first two observing runs from September 2019 to May 2020, when the solar activity was at its minimum. Data taken during the same observing periods of the quiet Sun when no active regions or microflares are present, as reported in [34], are used for the analysis to obtain the total quiet Sun x-ray spectrum.

In addition to emission from the Sun, XSM also records background, which primarily consists of cosmic x-ray background (CXB), charged particle background, and emission from other bright astrophysical sources. This background component needs to be subtracted from the observations to obtain residual x-ray emission from the Sun. While the CXB component is steady, the measured CXB by XSM varies. Some part of the XSM FOV is usually obstructed by the Moon blocking the CXB emission, and the blocked fraction varies due to the variation in the orbital altitude of the spacecraft. The charged particle background has temporal variations due to passage through geotail regions, solar energetic particle (SEP) events, and coronal mass ejection (CME) events, which are also recorded by the upper level discriminator (ULD) counts of the XSM instrument [47]. As the spacecraft attitude varies, bright astrophysical sources, Sco X-1 being the brightest source in this energy range, enter within the XSM FOV for some periods and contribute to the background. For the purpose of the present analysis, such periods of varying background with high ULD counts and the presence of the Sco X-1 within the FOV are ignored while generating the quiet Sun x-ray spectrum to ensure that the background is as clean as possible. We use the modules of XSM Data Analysis Software [48] with custom good time intervals to generate the quiet Sun spectrum, resulting in the net effective exposure of 3.72×10^6 s.

Figure 3(a) shows the XSM quiet Sun spectrum in the 1–15 keV energy range, thus obtained along with a background spectrum when the Sun is out of FOV. The XSM spectrum of the quiet Sun is dominated by the quiescent coronal emission in the low energies up to around 3 keV [34]; thus, we use the spectrum above 3.4 keV to explore the x-ray emission produced by axion conversion. To obtain the most conservative residual x-ray emission from the Sun, the CXB component alone is subtracted from this observed XSM spectrum. The CXB model spectrum [49] taking into account the fraction of FOV obstructed by the Moon is subtracted from the observed XSM spectrum, and the resultant spectrum is shown in Fig. 3(b), top panel. We show the 1-sigma uncertainties that arise from Poisson errors on the observed counts. The slight excess near 7.5 keV is due to a known instrumental line and may be ignored [47]. As this spectrum includes the contribution from the charged particle background and other sources, a more realistic residual solar x-ray spectrum can be obtained by subtracting the background observed when the Sun is out of the FOV from the quiet Sun observations. However,

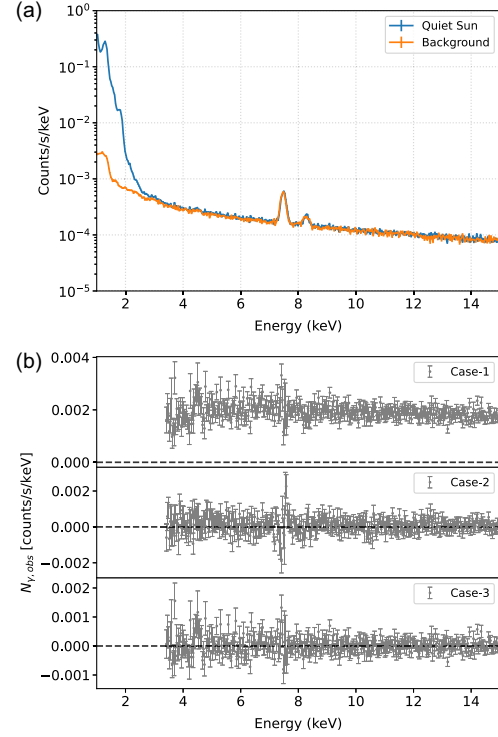


FIG. 3. (a) XSM observed solar x-ray spectrum and background spectrum when the Sun is not in FOV. (b) XSM observed solar x-ray spectrum after background subtraction with three different methods. Top panel (Case 1): only cosmic x-ray background subtraction, avoiding bright x-ray sources and energetic solar events (large SEP events). Center panel (Case 2): measured XSM background (when the Sun is out of FOV) subtraction, avoiding multiple bright x-ray sources and large SEP events. Bottom panel (Case 3): empirically modeled background subtraction.

this requires ignoring the periods when other bright sources contribute to the background. Sources that were bright enough to have a signal in XSM during the observing period were identified from the MAXI all-sky monitor data, and periods when 13 such sources were within the XSM FOV are ignored, resulting in an effective quiet Sun exposure of 2.15×10^6 s. The resulting spectrum after subtracting the background is shown in the middle panel of Fig. 3(b) (Case 2), where the errors incorporate uncertainties on the observed quiet Sun spectrum and the background spectrum. We also consider Case 3, where the entire observed spectrum in Case 1 is assumed to arise from the background, and in the case where the background is perfectly modeled, the resultant spectrum obtained is shown in the bottom panel of Fig. 3(b) by empirically modeling the observed spectrum and subtracting the best-fit model from the observed spectrum.

Data analysis. The expected number of photons per unit time per unit energy in a given energy bin i of the XSM solely due to axion-photon conversion in the solar atmosphere is

$$N_{\gamma, \text{exp}}^i = \frac{R_{\odot}^2}{(1 \text{ A.U.})^2} A_{\text{eff}}(E_i) \frac{d\phi_a}{dE_a}(E_i) P_{a\gamma}(E_i), \quad (8)$$

where E_i is the energy of the i th energy bin, $A_{\text{eff}}(E_i)$ is the effective collecting area of the XSM in the i th energy bin, and $R_{\odot}$ is the radius of the Sun. Given the observed number of counts per unit time per unit energy by the XSM, $N_{\gamma, \text{obs}}^i$, for a particular background subtraction scheme, we compute the likelihood assuming independent Gaussian statistics in each energy bin:

$$\mathcal{L}(g_{a\gamma\gamma}; m_a) \propto \prod_i \exp \left[-\frac{1}{2} \left(\frac{N_{\gamma, \text{exp}}^i - N_{\gamma, \text{obs}}^i}{\sigma^i} \right)^2 \right], \quad (9)$$

where σ^i denotes the uncertainty in the observed counts in the i th energy bin. To compute our limits, we consider all the energy bins between 3.4 keV and 15 keV.

To derive constraints in the m_a - $g_{a\gamma\gamma}$ plane, we fix the axion-electron coupling to $g_{aee} = 1.3 \times 10^{-13}$. For a given axion mass m_a , we adopt a uniform prior on the axion-photon coupling $g_{a\gamma\gamma} \in [10^{-14}, 10^{-8}] \text{ GeV}^{-1}$. The posterior probability density $\mathcal{P}(g_{a\gamma\gamma}|\text{data})$ is obtained within a Bayesian framework using the PyMultiNest implementation of the MultiNest algorithm [50]. The 95% credible upper limit on $g_{a\gamma\gamma}$ is defined as the value enclosing 95% of the posterior probability. Repeating this procedure for axion masses in the range $m_a \in [10^{-12}, 10^{-3}] \text{ eV}$ yields the corresponding mass-dependent upper limits on $g_{a\gamma\gamma}$.

In addition, we also derive constraints in the g_{aee} - $g_{a\gamma\gamma}$ plane by fixing the axion mass to $m_a = 10^{-6} \text{ eV}$. For $m_a \lesssim 10^{-4} \text{ eV}$, the expected signal is effectively independent of m_a , so this choice is representative of the entire low-mass regime. The analysis is repeated while scanning over g_{aee} , yielding the corresponding 95% credible upper limits on $g_{a\gamma\gamma}$ as a function of g_{aee} .

Results and discussion. With the analysis described above, the observation of soft solar x-rays from the quiet Sun by the XSM on board Chandrayaan-2 yields the following 95% credible upper limit on the axion-photon coupling:

$$g_{a\gamma\gamma} \lesssim (0.50 - 2.26) \times 10^{-10} \text{ GeV}^{-1}, \quad (10)$$

for axion masses $m_a \lesssim 5 \times 10^{-4} \text{ eV}$. Here, the numerical spread reflects the variation due to the three background subtraction schemes adopted in this analysis: Case 1 (green solid line) gives $g_{a\gamma\gamma} \lesssim 2.26 \times 10^{-10} \text{ GeV}^{-1}$ and is the most conservative limit, Case 2 (blue solid line) with realistic background subtraction gives $g_{a\gamma\gamma} \lesssim 1.29 \times 10^{-10} \text{ GeV}^{-1}$, and Case 3 (red solid line) yields the most stringent value $g_{a\gamma\gamma} \lesssim 5.0 \times 10^{-11} \text{ GeV}^{-1}$ and is the target or optimistic limit from our analysis. These limits are shown in the top panel of Fig. 4. The limits are effectively mass independent across this low-mass range; sensitivity degrades for larger

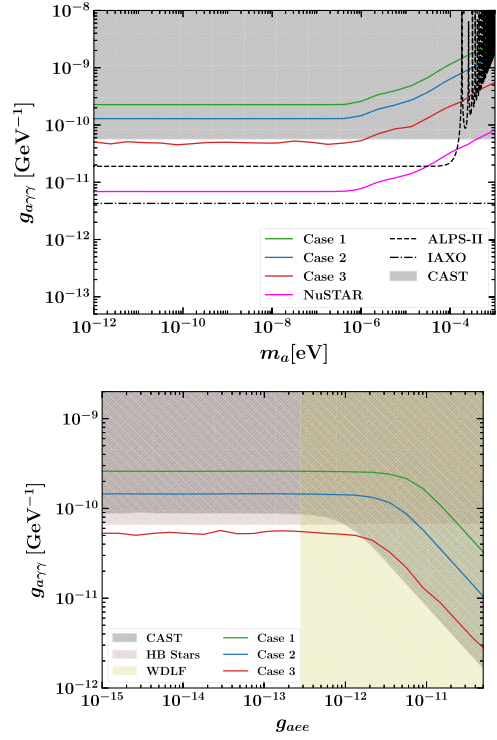


FIG. 4. The 95% confidence level upper limits on $g_{a\gamma\gamma}$ derived from the three background-subtracted solar x-ray spectra in Fig. 3. Top panel: constraints in the m_a - $g_{a\gamma\gamma}$ plane for a fixed $g_{aee} = 1.3 \times 10^{-13}$. Bottom panel: constraints in the g_{aee} - $g_{a\gamma\gamma}$ plane obtained for a fixed $m_a = 10^{-6} \text{ eV}$. Existing bounds and projected sensitivities are also shown for comparison.

m_a as coherence in the axion-photon conversion is lost when the axion mass exceeds the plasma frequency at the relevant solar-atmosphere heights.

To facilitate comparison with current and future laboratory searches, in Fig. 4 we overlay existing experimental limits from CAST [33] (gray shaded region) and projected limits for ALPS-II [51] (black dashed line) and IAXO [52,53] (black dot-dashed line). We also include the recent bound from NuSTAR [36] (magenta line), which is currently the most stringent astrophysical constraint. While the most optimistic XSM limit (Case 3) remains about an order of magnitude weaker than the NuSTAR bound of $7.3 \times 10^{-12} \text{ GeV}^{-1}$, the XSM constraints are competitive with CAST and complementary to NuSTAR: XSM observes the full solar disk simultaneously, unlike NuSTAR, thereby avoiding systematics associated with partial-disk observations.¹

Complementary to the mass-dependent limits above, the bottom panel of Fig. 4 shows constraints in the g_{aee} - $g_{a\gamma\gamma}$ plane, obtained by fixing $m_a = 10^{-6} \text{ eV}$, representative of the low-mass regime. The upper limits on $g_{a\gamma\gamma}$ strengthen

¹The smaller effective collecting area of XSM largely accounts for the difference relative to NuSTAR ($A_{\text{eff}} \simeq 800 \text{ cm}^2$).

monotonically with increasing g_{aee} , reflecting enhanced axion production in the solar interior. Existing bounds from horizontal-branch stars (brown shaded region), the white-dwarf luminosity function (olive shaded region), and CAST (gray shaded region) are shown for comparison [32,54], and within the allowed parameter space, the Chandrayaan-2 XSM results do not significantly improve existing constraints on g_{aee} .

We have presented all three background treatments for two reasons. First, showing all three cases makes explicit the degree to which the final sensitivity depends on background modeling; the spread quantifies the systematic uncertainty associated with background subtraction. Second, including Case 3 (the red or target curve) indicates the best sensitivity one may realistically expect from this dataset limited only by counting statistics, with an ideal background subtraction. The ideal background subtraction requires a comprehensive understanding of the various factors contributing to the detector background, including the CXB, the charged particle background of cosmic and solar origin, and secondary emission resulting from their interaction with the spacecraft structure. XSM, being a wide FOV instrument, is also affected by the variable bright astrophysical x-ray sources as well as the variable occultation of the CXB and particle background within the FOV by the Moon due to the altitude variation of the spacecraft. While Case 2 covers most of these aspects, some details, such as secondary emission from spacecraft structures and the time variability of all other x-ray sources within the FOV, which are very difficult to model, are not fully accounted for, and these will be necessary to reach the ideal Case 3. In practice, Case 2 should be regarded as our baseline (realistic) constraint, Case 1 as the conservative bound, and Case 3 as the target limit that motivates further work on accurate background modeling.

Theoretical uncertainties in the solar axion flux are at the few-percent level and do not dominate the error budget. The consistency of the limits across the three background

treatments—agreeing within an $\mathcal{O}(1)$ factor—shows that instrumental and modeling systematics are subdominant to statistical limitations, set primarily by the small XSM effective collecting area. The resulting constraint is consistent with astrophysical requirements from solar neutrino measurements and helioseismology, which require axion-induced energy loss to remain a small fraction of the solar luminosity.

This remains an ongoing experiment. The comparison of the three limits demonstrates current robustness and defines clear targets for future improvements: Increased exposure, improved background modeling, and coordinated solar monitoring can push sensitivity toward the Case 3 benchmark. Looking ahead, a next-generation solar x-ray observatory—especially near the solar minimum—with a substantially larger collecting area and improved spectral resolution could achieve order-of-magnitude gains, probing parameter space complementary to planned helioscopes. The Chandrayaan-2 XSM results thus motivate dedicated space-based solar observatories for searches for axions and other physics beyond the Standard Model.

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Data availability. The data that support the findings of this article are openly available [34,42,45].

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