

Hard X-rays from Axion to Photon Converted Flux Employing Density Dependent Critical Temperature

Charul Rathod, **Madhukar Mishra** and P. K. Das

Department of Physics
Birla Institute of Technology and Science - Pilani, Pilani, Rajasthan, India,

The UNSW, Sydney, Australia

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- Motivation
- Introduction
- Formulation
- Results
- Conclusions

- Various observations such as; Galaxy rotation curve, Galaxy cluster formation, gravitational lensing etc. cannot be explained by using the normal visible form of what is called baryonic matter (BM).
- Two approaches: Modified gravity theories & existence of the DM are used to explain the above mentioned unexplained observations. [We here concentrate on Axionic DM.](#)
- So far axion like particles (ALPs) are used to explain hard X-ray emission from few of the M7 NSs.
- It gives freedom to choose ALPs mass; m_a and Peccei–Quinn scale f_a unlike QCD axion.

- ALPs and QCD axions are considered as potential DM candidates. However, ALPs cannot solve strong-CP problem.
- RX J1856.5–3754 NS and a few more show a hard X-ray excess above its dominant thermal emission.
- Thermally produced axions can escape the neutron-star core and convert into photons in the magnetosphere.
- The study tests whether a QCD-axion framework can reproduce the observed 2 – 8 keV signal using axion emission via N-N bremsstrahlung and PBF process.
- Two benchmarks are compared: canonical KSVZ and selectively enhanced Model B.

- NS cools down due to neutrino, photon emission along with QCD axions (Maybe a DM candidate too !!)
- QCD axion: mass and interactions remain correlated through the Peccei–Quinn scale f_a .
- KSVZ fixes the low-energy coupling coefficients at a given f_a .
- Enhanced Model B preserves the QCD, $f_a - m_a$ relation while selectively enhancing photon and nucleon couplings.
- The enhancement in couplings is motivated by a clockwork-inspired multi-Higgs construction.

- QCD axions:

$$m_a \simeq 5.7 \mu\text{eV} \left(\frac{10^{12} \text{ GeV}}{f_a} \right),$$

- $$f_a \simeq \frac{5.7 \times 10^6}{m_a(\text{eV})} \text{ GeV},$$

- $$g_{a\gamma} = C_\gamma \frac{\alpha}{2\pi f_a},$$

$$g_{an} = C_n \frac{m_n}{f_a}; \quad g_{ap} = C_p \frac{m_p}{f_a}.$$

KSVZ & Enhanced Model B

- **KSVZ:** In the canonical KSVZ scenario, the PQ symmetry is introduced with a new heavy quark doublet.
- The coupling coefficients are $C_p^{\text{KSVZ}} = -0.47$, $C_n^{\text{KSVZ}} = -0.02$, and $C_\gamma^{\text{KSVZ}} = -1.92$.
- The axion production and conversion factors are therefore fixed by the same scale f_a , in contrast to a general ALPs model.
- **Enhanced Model B:** Under the low energy approximation, the coupling coefficients are expressed as:

$$C_\gamma^{\text{B}} = 2^\lambda + \frac{8}{3} - 1.92,$$

$$C_p^{\text{B}} = -0.4735 + 2^{\lambda-1} (0.026 - 1.3015 \kappa),$$

$$C_n^{\text{B}} = -0.0235 + 2^{\lambda-1} (0.026 + 1.2385 \kappa).$$

Neutron-Star Model and Thermal Evolution

- Canonical non-rotating spherically symmetric neutron star: $M = 1.40 M_{\odot}$.
- Core EOS: APR A18+ δv +UIX*; stellar production/profile from TOV equations.
- NSCool evolves the internal/surface temperature and axion luminosity.
- Pairing in core: proton 1S_0 ; neutron 3P_2 and density dependent T_c .
- RX J1856 age: $(4.2 \pm 0.8) \times 10^5$ yr; $k_B T_{\text{eff}}^{\infty} = 50 \pm 14$ eV.

Axion Production Channels

- Nucleon–nucleon bremsstrahlung described by:

$$N + N \rightarrow N + N + a.$$

- Corresponding emissivity:

$$\epsilon_{a,N}^{\text{brem}} = \frac{\alpha_{aN} n_B \Gamma_{\sigma,N} T^3}{4\pi m_N^2} I_a^{\text{brem}}, \quad N \in \{n, p\}, \quad (1)$$

where

$$\alpha_{aN} = \frac{g_{aN}^2}{4\pi}, \quad g_{aN} = C_N \frac{m_N}{f_a}.$$

Here, $\Gamma_{\sigma,N}$ is the nucleon spin-fluctuation rate.

- In the degenerate one-pion-exchange approximation:

$$\Gamma_{\sigma,N} = \frac{4\alpha_\pi^2 p_{F,N} T^3}{3\pi n_B}, \quad \alpha_\pi = 17. \quad (2)$$

- The dimensionless response integral is expressed as:

$$I_a^{\text{brem}} = \int_0^\infty s(x) x^2 e^{-x} dx, \quad s(x) = \frac{(x^2 + 4\pi^2)x}{4\pi^2(1 - e^{-x})}, \quad x = \frac{\omega_a}{T}. \quad (3)$$

The quantities T and ω_a denote the temperature and axion energy.

- The above is with and without pair-breaking and formation (PBF) process [affects via a suppression factor in neutrino production channel].
- PBF below/or around density-dependent critical temperatures.
- Pairing modifies heat capacity, neutrino emission, axion emissivity and the preceding thermal history.

- Emissivity of axions in PBF process: For proton 1S_0 and neutron 3P_2 pairing, the axion emissivities are:

$$\begin{aligned}\epsilon_a^{p^1S_0} &= \frac{8C_p^2}{3\pi f_a^2} \nu_p(0) v_{F,p}^2 T^5 I_a^s, \\ \epsilon_a^{n^3P_2} &= \frac{2C_n^2}{3\pi f_a^2} \nu_n(0) T^5 I_a^p,\end{aligned}\tag{4}$$

- Here,

$$\nu_N(0) = \frac{m_N^* p_{F,N}}{\pi^2}, \quad N \in \{n, p\}.\tag{5}$$

and m_N^* , $p_{F,N}$, and $v_{F,p}$ denote the effective mass, Fermi momentum, and proton Fermi velocity, respectively.

Magnetospheric Axion–Photon Conversion

- Axions produced from the NSs propagate through the strong magnetic field of the magnetosphere:

- $$\mathcal{L}_{a\gamma} = -\frac{g_{a\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu}.$$

- $$\frac{dF_\gamma}{dE_\infty} = \frac{P_{a\rightarrow\gamma}(E)}{4\pi d^2} \frac{dL_a^\infty}{dE_\infty}.$$

- The adopted conversion prescription is the light-axion, non-resonant approximation.

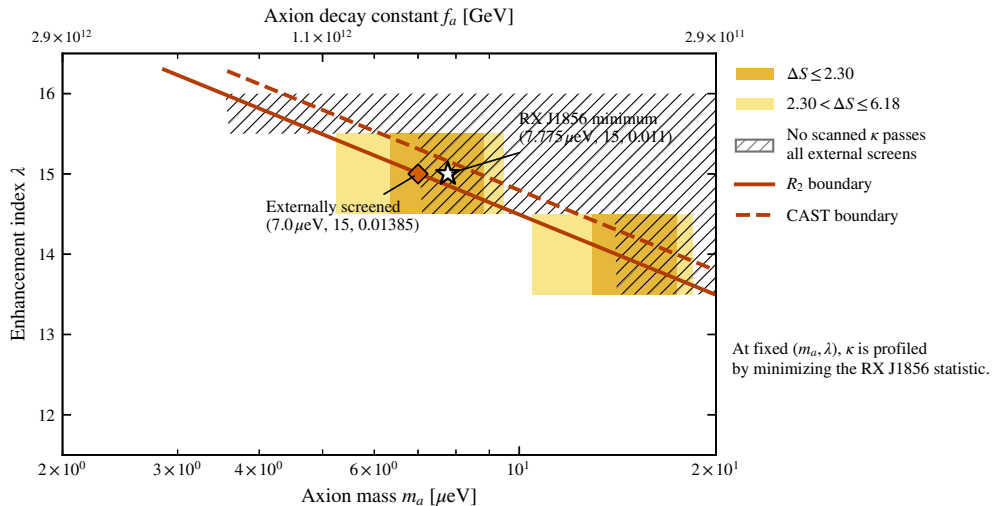
Preferred Model-B Benchmark

RX J1856-preferred point

$$(m_a, \lambda, \kappa) = (7.775 \mu\text{eV}, 15, 0.011).$$

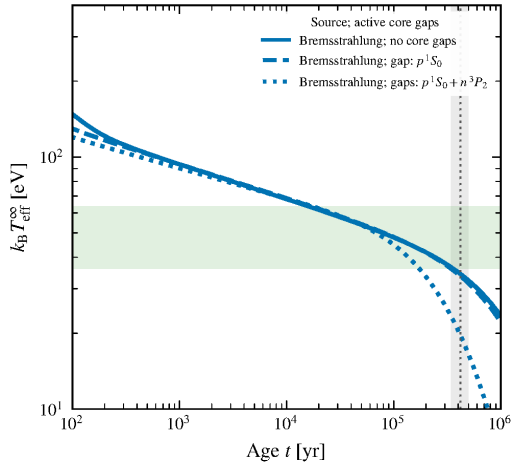
- $C_n = 649.168$, $C_p = 190.949$, $C_\gamma = 32768.747$, $C_e = 184.852$.
- $g_{an} = 8.32 \times 10^{-10}$, $g_{ap} = 2.44 \times 10^{-10}$.
- $g_{a\gamma} = 5.19 \times 10^{-11} \text{ GeV}^{-1}$.
- $S_{\min} = 2.095$.

Model-B Parameter Scan

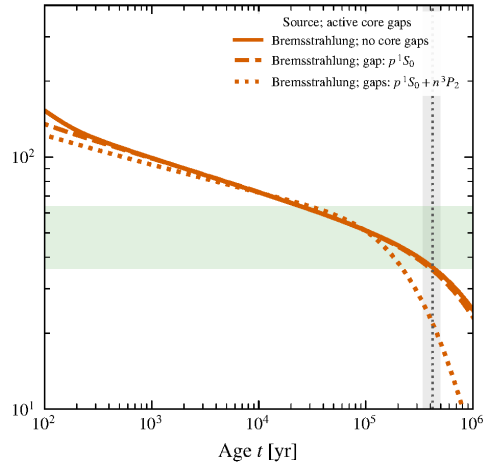


Thermal Evolution: Bremsstrahlung

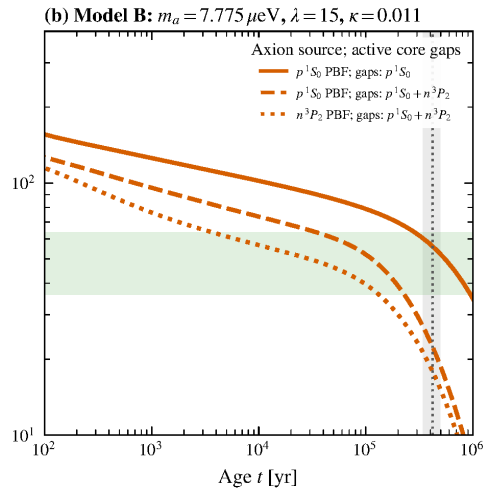
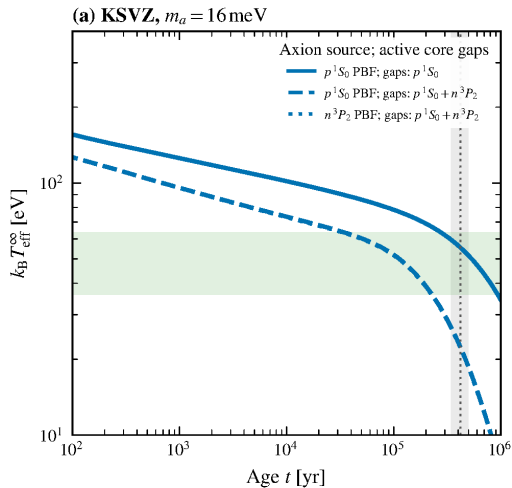
(a) KSVZ, $m_a = 16 \text{ meV}$



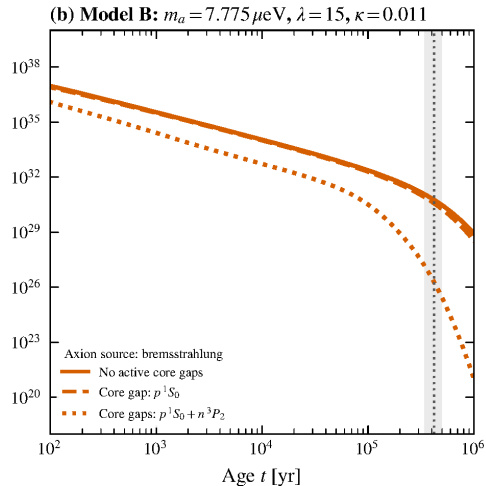
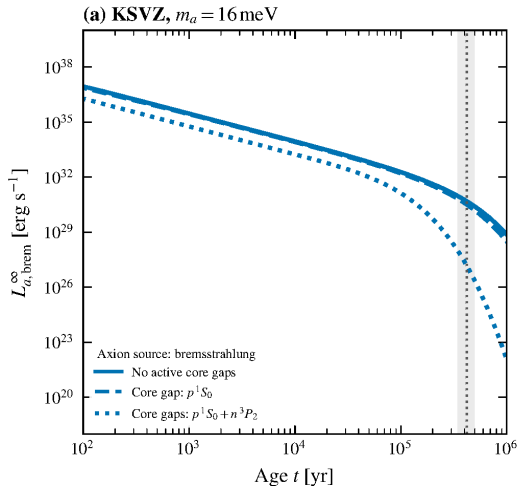
(b) Model B: $m_a = 7.775 \mu\text{eV}$, $\lambda = 15$, $\kappa = 0.011$



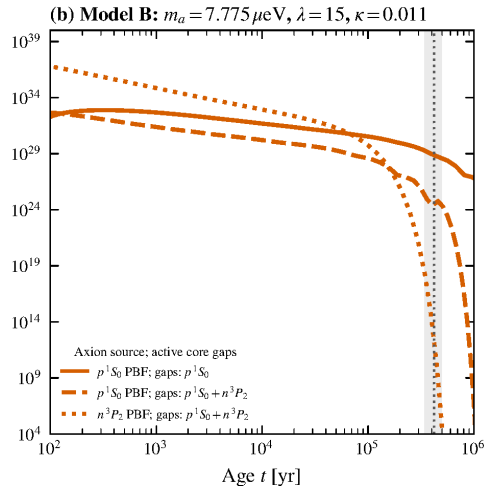
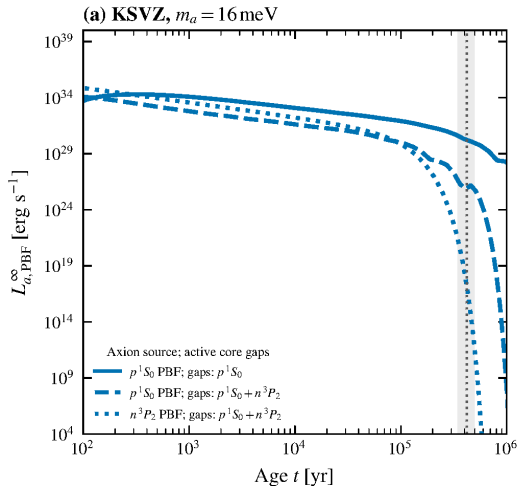
Thermal Evolution: PBF



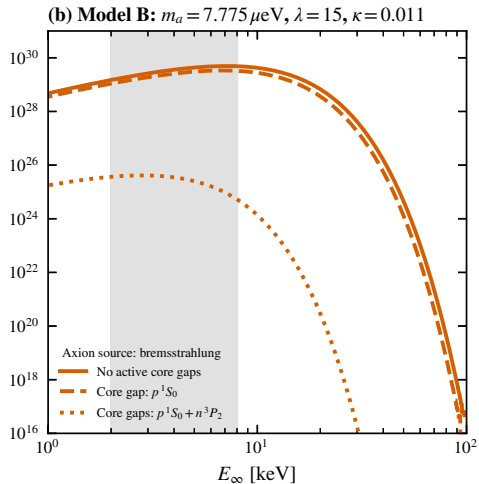
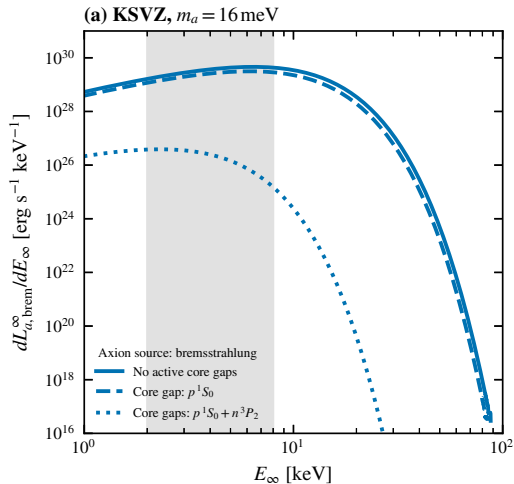
Axion Luminosity: Bremsstrahlung



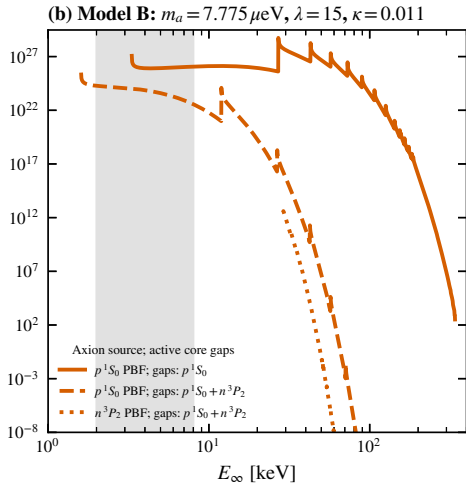
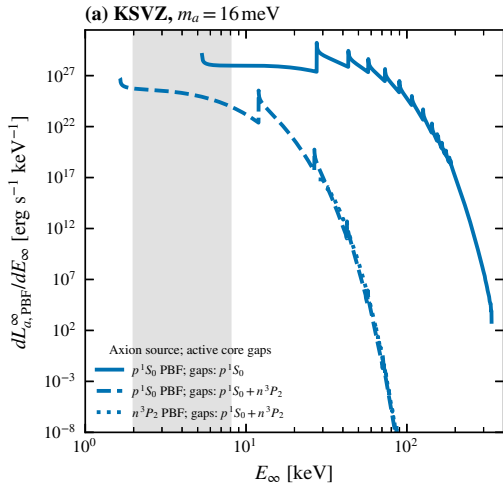
Axion Luminosity: PBF Photon



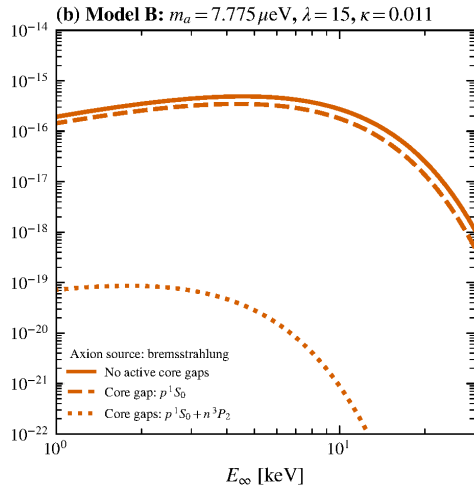
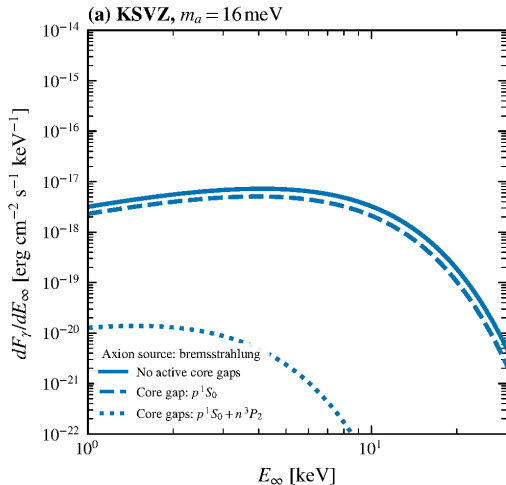
Axion Spectra: Bremsstrahlung



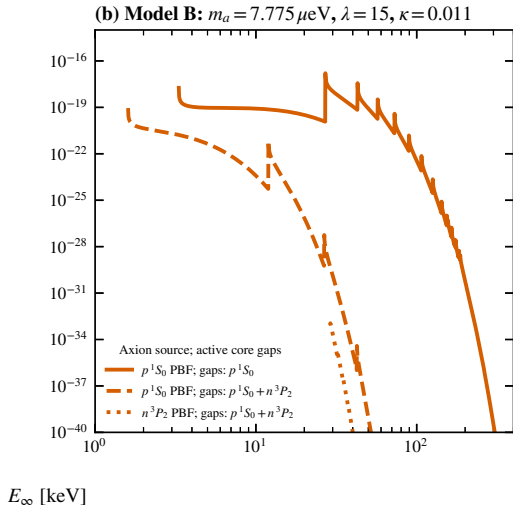
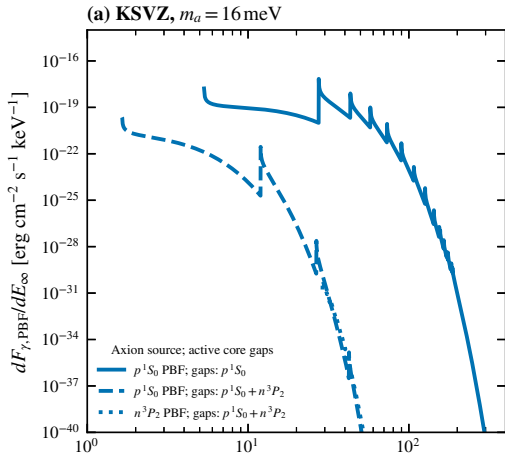
Axion Spectra: PBF Photon



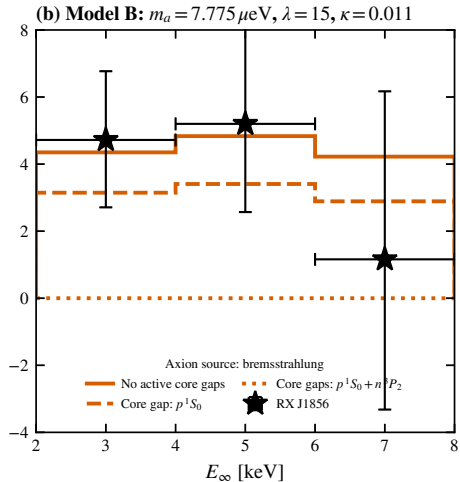
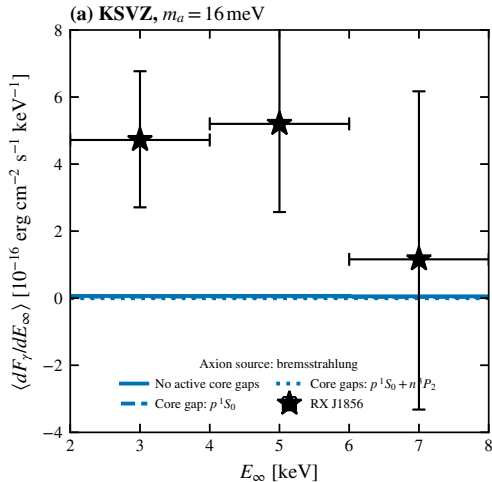
Converted Hard X-ray Signal: Bremsstrahlung



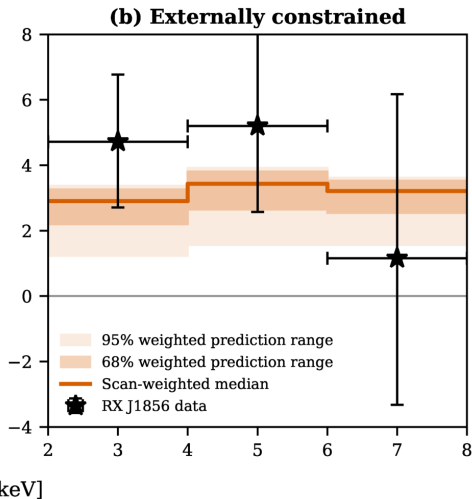
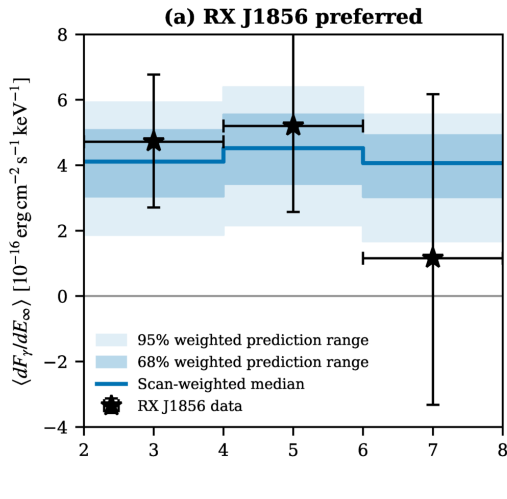
Converted Hard X-ray Signal: PBF



Converted Hard X-ray Signal; Bremsstrahlung with observed data



Converted Hard X-ray Signal; Bremsstrahlung with observed data



Key Numerical Results

- Unpaired Model B: $k_B T_{\text{eff}}^{\infty} = 36.48 \text{ eV}$.
- Predicted 2–8 keV bin fluxes:

$$(4.35, 4.83, 4.22) \times 10^{-16} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ keV}^{-1}.$$

- Observed central values:

$$(4.72, 5.20, 1.16) \times 10^{-16}.$$

- All three unpaired Model-B predictions lie within the published 68% intervals.
- Full pairing suppresses the present-day bremsstrahlung signal by several orders of magnitude.

Conclusions

- Selectively enhanced Model B can reproduce the observed RX J1856 hard-X-ray flux scale under the assumptions used.
- Preferred benchmark: $(7.775 \mu\text{eV}, 15, 0.011)$.
- Nucleon pairing is crucial: proton 1S_0 moderately suppresses the signal, while proton + neutron pairing strongly suppresses it.
- Axions due to PBF channels are negligible in the observed 2 – 8 keV band for the adopted present-day pairing gaps.
- The future may change the situation due to the possibility of new pairing prescriptions/formations and consequent $T_c - \rho$ relation.
- Further assessment requires more robust finite-mass magnetospheric propagation, systematic pairing & envelope variations, and response-folded X-ray analysis to reach any firm conclusions.

References

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-  A. Akmal, V. R. Pandharipande and D. G. Ravenhall, Phys. Rev. C 58, 1804 (1998).
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Thank you