Neutron star cooling simulations set new constraints on light QCD axions

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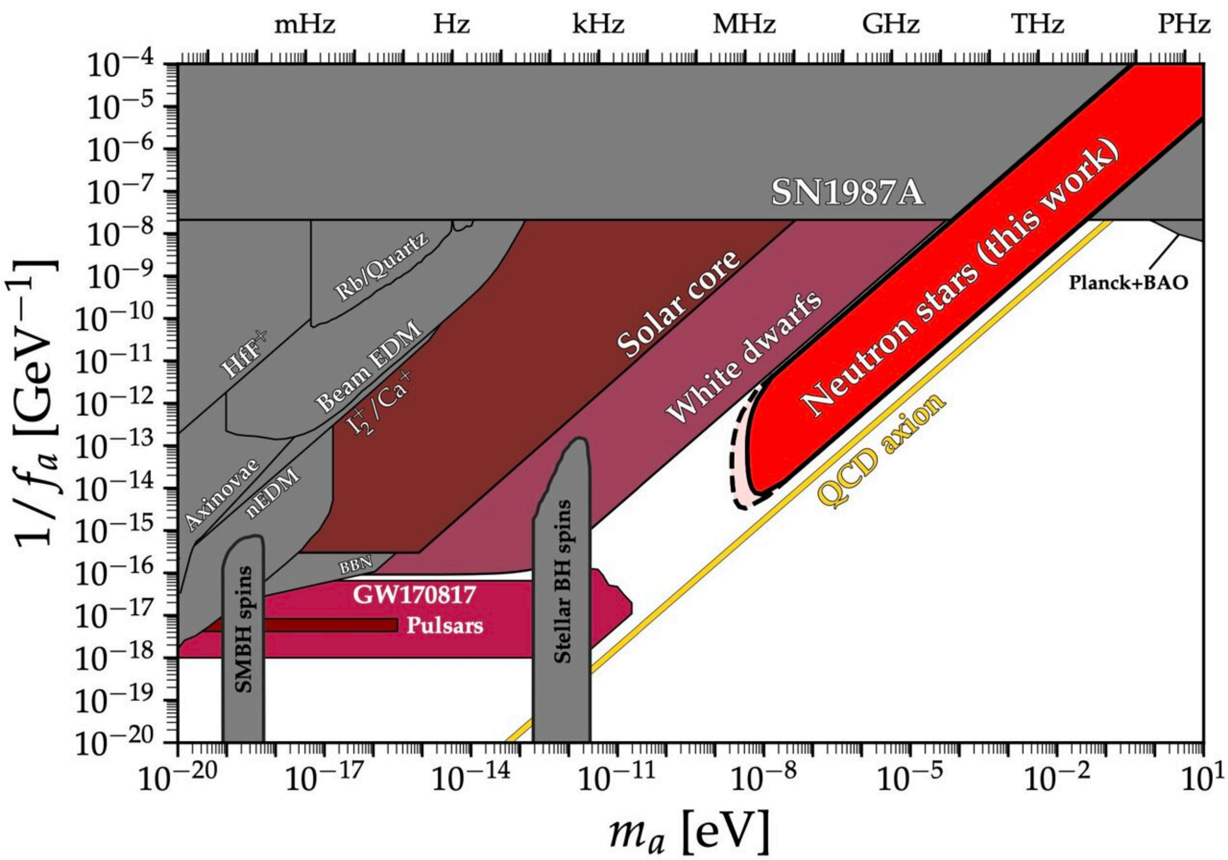


Astrophysical and experimental constraints on the axion parameter space. The region labeled "Neutron stars," shown in red, represents the parameter space ruled out by our study. The yellow line labeled "QCD Axion" indicates the most natural and theoretically motivated QCD axion models. This plot is a modified version of the one available at https://cajohare.github.io/AxionLimits/. Credit: Gómez-Bañón et al.

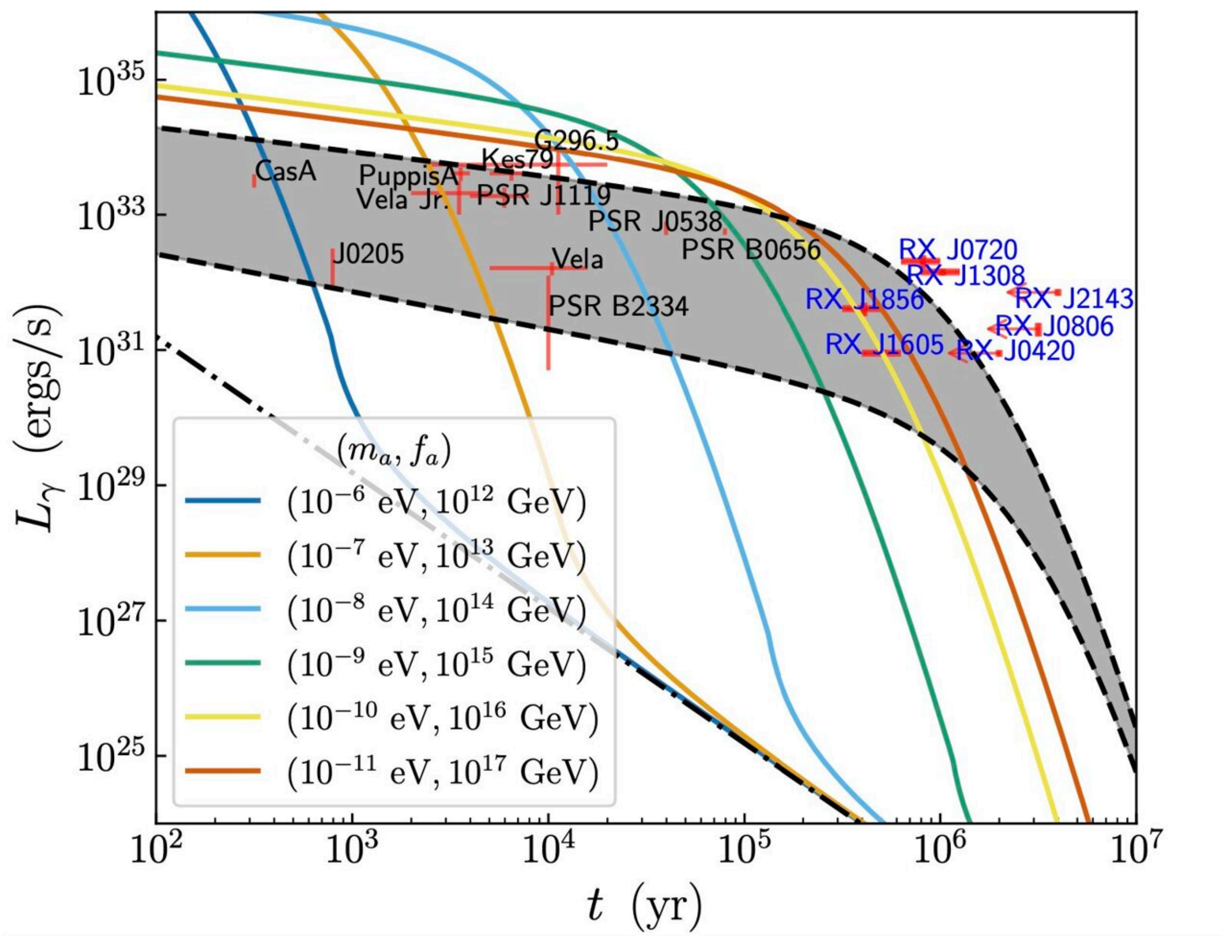
Neutron stars, the remnants of massive stars after a supernova explosion, have often been the focus of studies aimed at testing and unveiling exotic physics. This is because these stars are among the densest objects in the universe, so they host extremely high temperatures and pressures.

Recent theoretical studies have explored the possibility that quantum chromodynamics (QCD) axions, elementary particles hypothesized to emerge from the so-called Peccei-Quinn mechanism, influence the properties of neutron stars. By interacting with nucleons, these particles could alter the structure of neutron stars, which could in turn impact their cooling.

Building on this idea, researchers at the University of Alicante and the Technical University of Munich recently simulated neutron star cooling processes and compared them with theoretical predictions to probe previously unexplored regions of the axion parameter space. Their paper, published in *Physical Review Letters*, set new constraints on light QCD axions, which could inform future searches for these exotic particles.

"This study originated from discussions about how a hypothetical particle like the QCD axion might influence the properties of nuclear matter," Antonio Gómez-Bañón, first author of the paper, told Phys.org. "We realized that, if light enough, the QCD axion could alter the size of a neutron star's envelope, an outer layer that regulates its cooling."

The primary objective of the recent work by Gómez-Bañón and his colleagues was to determine whether the influence of a QCD axion on the envelope of a neutron star could significantly accelerate the star's cooling, which would conflict with previous observations. To do this, they first looked at how a QCD axion could affect the energy and pressure of the nuclear matter within neutron stars.



Cooling curves for neutron stars affected by the presence of the QCD axion field are shown in color. The gray region illustrates the typical range of variability in the cooling curves of ordinary neutron stars, consistent with observations. After 0.1 million years, three of the colored curves have luminosities that fall orders of magnitude below observations. Credit: Gómez-Bañón et al.

"Leveraging this understanding, we then solved the differential equations describing the balance of forces between the QCD axion field, nuclear matter, and gravity within a neutron star," explained Gómez-Bañón. "Our solutions showed that the neutron star's envelope becomes considerably thinner for certain axion parameter choices."

The simulations and analyses carried out by Gómez-Bañón and his colleagues suggest that when a neutron star's envelope becomes thinner, the star becomes less insulated, which causes it to cool faster. To further validate this prediction, they incorporated their equilibrium equations into their neutron star cooling simulation and looked at how the neutron star's temperature changed over time.

"As expected, the cooling curves obtained from the simulation predicted neutron stars that were cooler than observations at a given age," said Gómez-Bañón. "This discrepancy allows us to place new constraints on the QCD axion parameters."

The simulations and analyses performed by this team of researchers excluded a new region within the QCD axion parameter space. In addition, their work introduces an alternative approach to set constraints on these hypothetical particles, which relies on the observations of neutron stars.

"Unlike previous bounds based on axion emission and energy loss, our approach is based on how the QCD axion field alters the neutron star's structure, compressing its envelope and accelerating cooling," added Gómez-Bañón.

"In our next studies, we plan to focus on finding astrophysical scenarios that could constrain 'the QCD Axion Line,' a region of axion masses where many theoretically motivated models reside but which is challenging to probe. Ruling out parts of this region would represent a significant advancement."

More information: Antonio Gómez-Bañón et al, Constraining Light QCD Axions with Isolated Neutron Star Cooling, *Physical Review Letters* (2024). DOI: 10.1103/PhysRevLett.133.251002.