Axion production in magnetars

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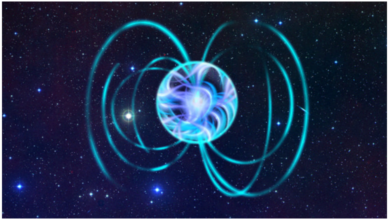


Fortin, Guo, SPH, Sheridan, Sinha arXiv:2101.05302

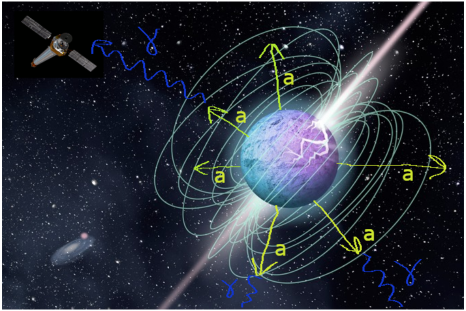
Fortin, Guo, SPH, Kim, Sinha, Sun arXiv:2102.12503 (IJMPD review)

Fortin & Sinha, arXiv:1804.01992

N3AS Seminar, April 27, 2021

Image credit: ESA - Christophe Carreau.

Outline



1. Nuclear interactions produce axions inside magnetar
2. Axion escape magnetar, some convert to photons in magnetosphere
3. Hard X-ray photons observed by X-ray telescopes
4. Demand axion-induced photons < observed photons (spectral analysis)
   - Constrains product of axion coupling to nucleons and photons

Image adapted from McGill University Graphic Design Team

Axions and their interactions

- Axions are pseudoscalar bosons introduced to explain CP symmetry in QCD
- Axion-like particles (ALPs) are defined through their interactions with standard model particles.
  - Coupling strengths are unknown, but constrained.

$$\mathcal{L} \supset \frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu} + i g_{aee} a \bar{e} \gamma_5 e + G_{an} \partial_\mu a \bar{N} \gamma^\mu \gamma_5 N.$$

Axions can be created by:

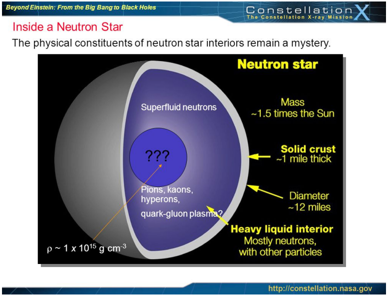
$$N + N' \to N + N' + a$$
$$e^- + (N, Z) \to e^- + (N, Z) + a$$
$$\pi^- + p \to n + a$$

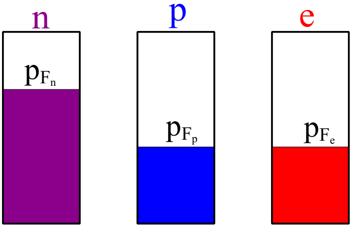
$$a \leftrightarrow \gamma (\text{Primakoff})$$
$$e^+ + e^- \to \gamma + a$$

Neutron star structure

Particle content of neutron star:

- Crust: lattice of nuclei, sea of electrons.
- "Core": uniform fluid of neutrons, protons, electrons.

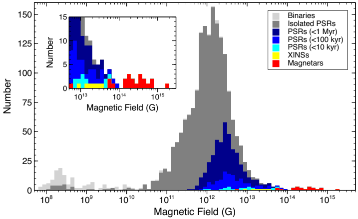


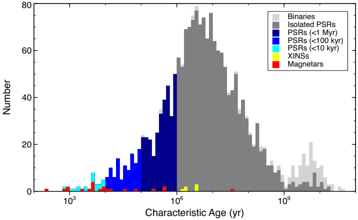


We assume neutron star does not contain exotic phases of matter.
$1.4M_\odot$, IUF EoS, superfluid (discussed later).

Magnetars

McGill magnetar catalog: Olausen & Kaspi arXiv:1309.4167

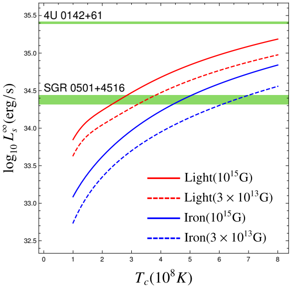




Conventional neutron stars:

$T_{\text{surface}} \rightarrow T_{\text{core}}$

Magnetars have anomalously high surface temperatures. What is magnetar T_{core}?



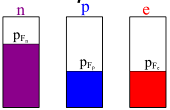
Adapted from Beloborodov & Li arXiv:1605.09077

We do our calculations for a range of core temperatures, $T_{\text{core}} = 10^8 - 10^9$ K.

It's possible that the core temperature of some magnetars is smaller than this.

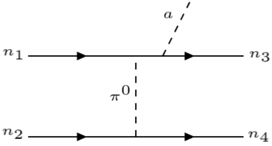
Axion production in uniform, ungapped nuclear matter

Degenerate npe^- matter



Particles at the Fermi surface dominate scattering

Only consider axion emission from core. Produced by 3 neutron bremsstrahlung processes $N + N' \to N + N' + a$



How much energy is emitted in axions per volume per time?

$$Q^0_{nn} = \frac{31}{2835\pi} C_\pi (m_n/m_\pi)^4 f^4 G^2_{an} p_{Fn} F(n_B) T^6$$

$$Q \sim \underbrace{T^4}_{\text{4 deg. fermions}} \times \underbrace{T^3/T}_{d^3\omega\ /(2\omega)} \times \underbrace{T^{-1}}_{\text{E-cons.}} \times \underbrace{T}_{\omega\sim T} \sim T^6$$

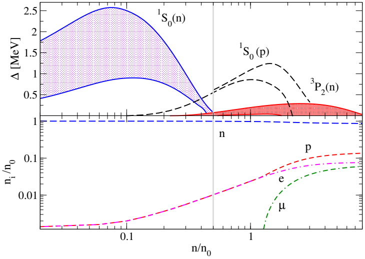
Also, first analytic calculation of Q for $n + p \to n + p + a$ in the degenerate limit (see arXiv:2101.05302.)

Superfluid nuclear matter

Cooper theorem - Degenerate fermions (near the FS) can form Cooper pairs if there is an attractive interaction between them

- What is the nuclear force?
- For what energy scales and which angular momentum channels is it attractive?

$T = 0$ gaps throughout neutron star

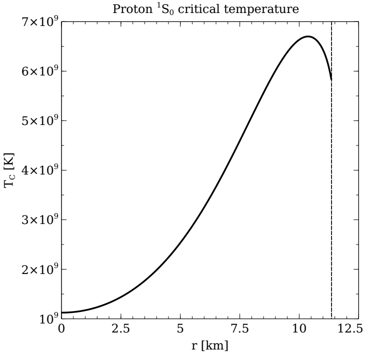


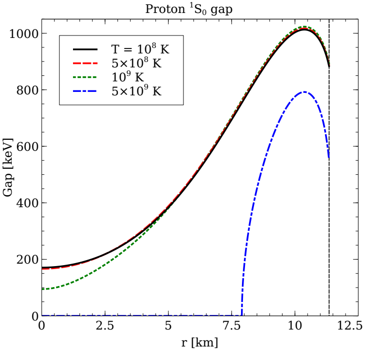
Sedrakian & Clark arXiv:1802.00017

- Superfluid phase for $T < T_c$.
- Neutron star cooling requires (for a star with $T_{\text{core}} \sim 10^8 - 10^9$ K):
  - $^1S_0$ proton pairing in most of the core
  - No $^3P_2$ neutron pairing in core

Superfluid profiles

We treat McGill magnetars as $1.4 M_{\odot}$ neutron stars with ${}^{1}S_{0}$ proton pairing (CCDK model) when $T < T_{C}(n_{B})$.

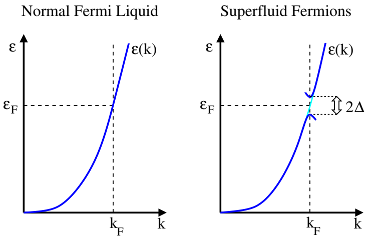




Assume magnetar core has uniform temperature, due to high thermal conductivity.

Axion production in superfluid nuclear matter

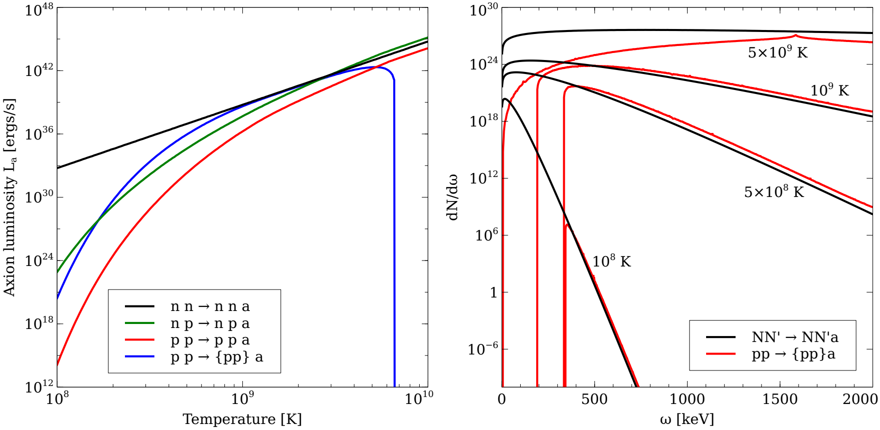
When protons are in the superconducting phase, their energy spectrum develops a gap $2\Delta(n_B, T)$ at the Fermi surface.



Page, Lattimer, Prakash, Steiner
arXiv:1302.6626

- Bulk properties not impacted
- "Transport" processes (specific heat, rates) suppressed by $e^{-\Delta/T}$.
- Axion production rates involving protons $Q \to Q \times R(n_B, T)$ where $R \sim e^{-\Delta/T}$.
- Axions can be produced by forming Cooper pairs $p + p \to \{pp\} + a$. Rate enhanced as $T \to T_c$ from below. Produces axions with $\omega > 2\Delta$.

Emissivity of axions profiles



We only care about axions produced with energies $20\text{ keV} < \omega < 150\text{ keV}$ (since $\omega = E_\gamma$), so we ignore Cooper-pair formation as an axion production mechanism.

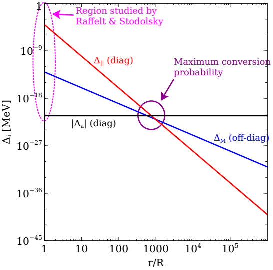
Axion-photon conversion

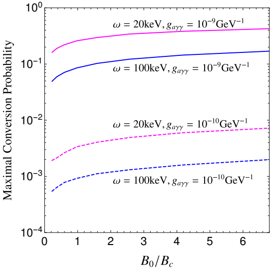
- $\frac{1}{4}g_{a\gamma\gamma}aF_{\mu\nu}\tilde{F}^{\mu\nu}$ vertex allows photon to convert into an axion in an external magnetic field.
- "Mixing" between photons and axions occurs, similar to ν oscillations.
- Include Euler-Heisenberg strong-B-field effects in $\mathcal{L}$
- Assume B-field outside magnetar is dipolar (Is this still true!? - see NICER results)
- Energy conserved in $a \leftrightarrow \gamma$ conversion process

$$i\frac{d}{dx}\begin{pmatrix} a \\ E_{\parallel} \\ E_{\perp} \end{pmatrix} = \begin{pmatrix} (\omega+\Delta_a)R & \Delta_M R & 0 \\ \Delta_M R & (\omega+\Delta_{\parallel})R & 0 \\ 0 & 0 & (\omega+\Delta_{\perp})R \end{pmatrix}\begin{pmatrix} a \\ E_{\parallel} \\ E_{\perp} \end{pmatrix},$$

where

$$\Delta_a = -\frac{m_a^2}{2\omega}, \qquad \Delta_{\parallel} = (n_{\parallel}-1)\omega, \qquad \Delta_{\perp} = (n_{\perp}-1)\omega, \qquad \Delta_M = \frac{1}{2}g_{a\gamma\gamma}B\sin\theta.$$



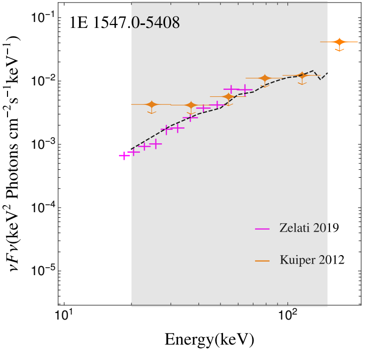


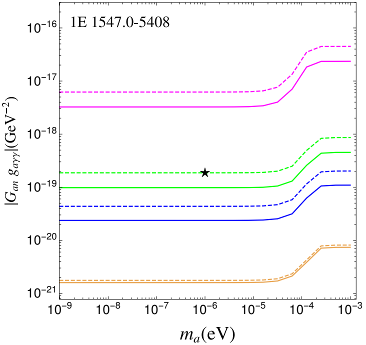
Predicted photon spectrum

Luminosity of photons which originate from axions

$$\frac{dL_{a\to\gamma}}{d\omega} = \frac{1}{2\pi}\int_0^{2\pi} d\theta \left[\omega \frac{dN}{d\omega} P_{a\to\gamma}(\omega,\theta)\right] \sim (G_{an} g_{a\gamma\gamma})^2.$$

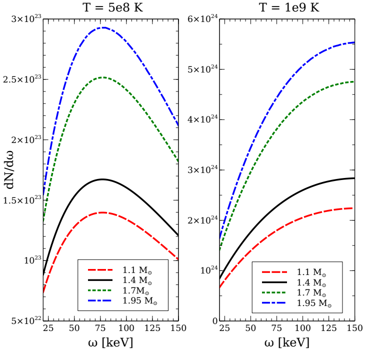
Spectral analysis, demanding $L_{a\to\gamma} < L_{\text{observed}}$ in each energy bin in the hard X-ray range. This sets upper bound on $G_{an} g_{a\gamma\gamma}$.



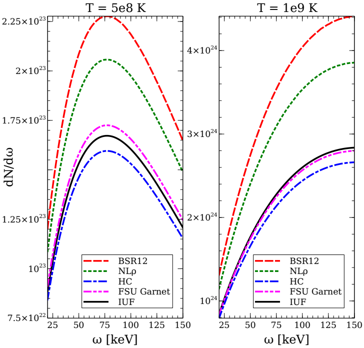


Uncertainties in mass and EoS

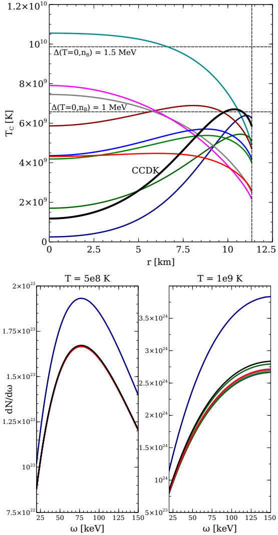
Vary magnetar mass



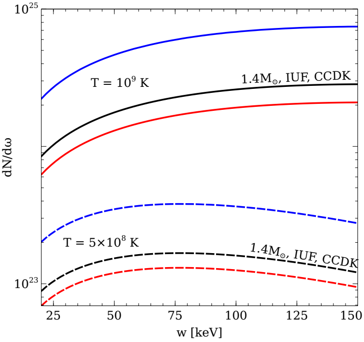
Vary nuclear matter equation of state



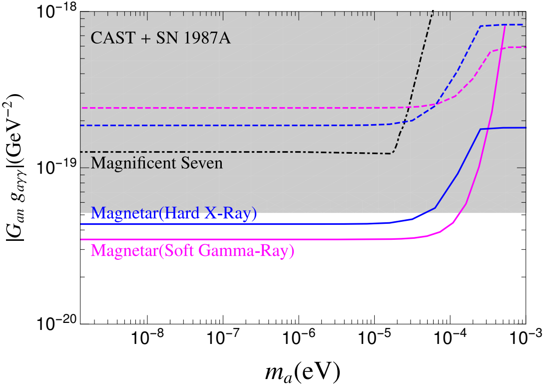
Uncertainties in proton superfluid gap



Combined uncertanties (M, EoS, superfluidity)



Magnetar hard X-ray constraints in context



- Magnetars can yield constraints on axion couplings competitive with (or perhaps better than!) other methods.
- Magnetar core temperature is the biggest source of uncertainty

Conclusions

- Magnetar emits axions ($\sim G_{an}^2$), axions convert to photons in magnetosphere ($\sim g_{a\gamma\gamma}^2$). Detectors measure hard X-ray photons.
- Constrain $G_{an}g_{a\gamma\gamma}$ (for an assumed magnetar core temperature) by enforcing $L_{a\to\gamma} < L_{\text{observed}}$ for each photon energy bin.
- An analysis of the axion-induced photon spectrum (hard X-ray and soft gamma ray) from magnetars constrains axion couplings, with results competitive (or better than) other methods.
  - Why? Because magnetars have high temperature and high magnetic field.

Future prospects

- Better understand core-crust temperature relationship in magnetars
- Incorporate sophisticated modeling of magnetar magnetosphere (Baring *et al.* arXiv:2012.10815)
- Study effects of nondipolar magnetic field of neutron star on axion-photon conversion in the magnetosphere (Bilous *et al.* arXiv:1912.05704)
- Magnetic-field driven axion production processes (Maruyama *et al.* arXiv:1707.00384)
- Firmer calculation of neutron (triplet) pairing critical temperature
- Presence of exotic phases in neutron star core?
- Density-dependence of axion-nucleon coupling? (Balkin *et al.* arXiv:2003.04903)

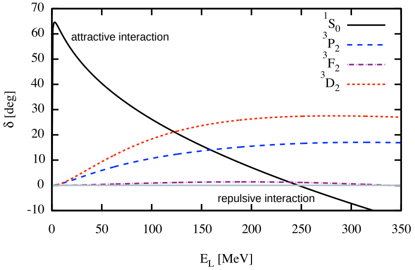
Backup slides

Cooper pairing in nuclear matter

Cooper theorem - Degenerate fermions (near the FS) can form Cooper pairs if there is an attractive interaction between them

- What is the nuclear force?
- For what energy scales and which angular momentum channels is it attractive?

In Vacuum:



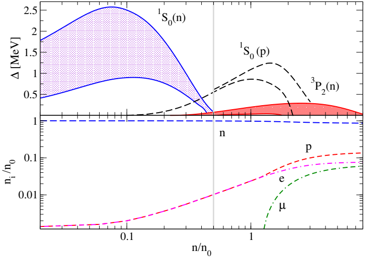
Haskell & Sedrakian arXiv:1709.10340

In medium: n-p pairing is unlikely.

- Choose a model of the nuclear force (uncertain!)
- In a particular angular momentum channel, calculate $\Delta(T = 0, n_B)$.
- The BCS gap equation gives $\Delta(T, n_B)$.
- Pairing vanishes for $T > T_C$. Superfluidity is a "low-temperature" phenomenon.

Constraints on superfluidity in nuclear matter

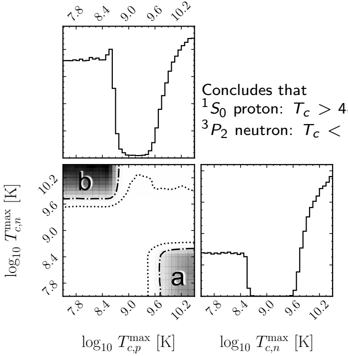
$T = 0$ gaps throughout neutron star



Sedrakian & Clark arXiv:1802.00017

Constraints on gaps from neutron star cooling

Beznogov, Rrapaj, Page, Reddy arXiv:1806.07991



Concludes that
$^1S_0$ proton: $T_c > 4e9$ K.
$^3P_2$ neutron: $T_c < 3e8$ K.

Emissivity of axions profiles