Probing QCD axions with Neutron Stars: Cooling and Oscillations

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Constraints on the QCD axion

Light QCD axion model

NS structure

NS cooling

More scenarios

Constraints on the QCD axion

Astrophysics can constrain QCD axion properties.
("Astrophysical Axion Bounds": Raffelt 2008; Caputo and Raffelt 2024).

- Neutron Star (NS) and Proto Neutron Star (PNS) cooling provide some of the strongest bounds. (Raffelt and Seckel 1988; Buschmann et al. 2022; Carenza et al. 2019).
- Most constraints are derived from the energy-loss argument.

Light QCD axion models can be constrained by NS cooling (and many more).

- Gómez-Bañón, A., Bartnick, K., Springmann, K., & Pons, J. A. (2024). PRL, 133(25), 251002.
- M. Kumamoto, J. Huang, C. Drischler, M. Baryakhtar, and S. Reddy (2025). PRD, 112, 043008.

Constraints on the QCD axion

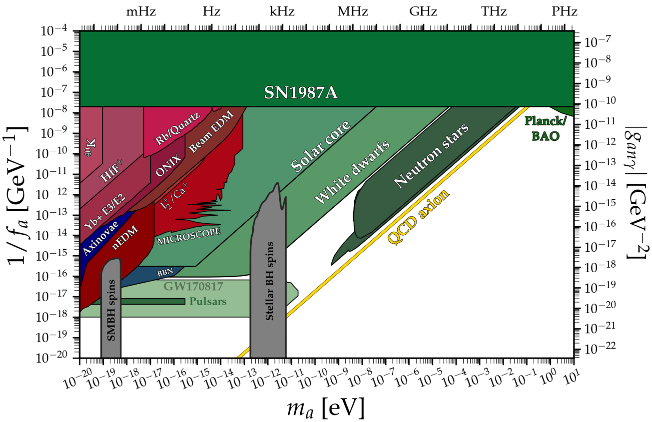

Figure 1: From O'Hare 2020. Regions excluded by astrophysical bounds are shown in green.

Light QCD axion model

- Light QCD axion: axion mass is suppressed by $\epsilon \leq 1$ (Hook and Huang 2018).

$$
a\, G\tilde{G} \quad \longrightarrow \quad \begin{cases} V_{\rm QCD} = -\epsilon\, m_\pi^2 f_\pi^2 \left(\sqrt{1 - \beta \sin^2\left(\frac{a}{2f_a}\right)} - 1 \right), \\ \mathcal{L}_{\rm int} = -\sigma_N\, \bar{N}N \left(\sqrt{1 - \beta \sin^2\left(\frac{a}{2f_a}\right)} - 1 \right). \end{cases}
$$

- $\mathcal{L}_{\rm int}$ sources the axion field and reduces m_N^*:

$$
\langle \bar{N}N \rangle \equiv n_s > n_s^c \equiv \epsilon \frac{m_\pi^2 f_\pi^2}{\sigma_N} \sim \epsilon \left(0.4\ {\rm fm}^{-3}\right) \sim 3\epsilon n_{\rm sat},
$$

$$
m_N^*(a = \pi f_a) \sim m_N - (32\ {\rm MeV}).
$$

- A New Ground State (NGS) of nuclear matter with $a = \pi f_a$ is possible for $\epsilon \lesssim 0.1$ in 'realistic' NS EOS (BSk26).

Light QCD axion model

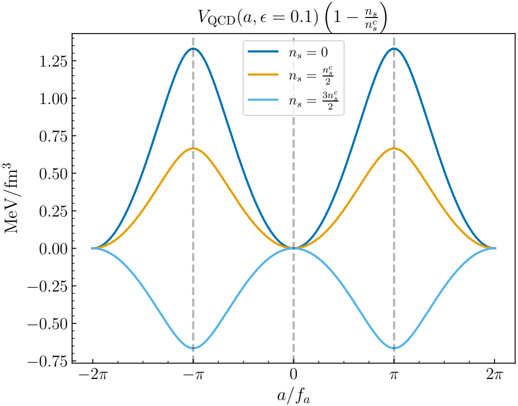

Figure 2: Effective QCD axion potential when $\langle \bar{N} N \rangle \equiv n_s \neq 0$.

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- Hydrostatic equilibrium:

$$p' = -(\varepsilon + p)\,\Phi' - n_s \frac{\partial m_N^*}{\partial a} a',$$

$$p' = -(\varepsilon + p)\,(g + g_a)\,.$$

- The axion gradient term can be interpreted as an additional source of gravity:

$$g_a \equiv \frac{n_s}{\varepsilon + p} \frac{\partial m_N^*}{\partial a} a' \propto \frac{1}{f_a} \propto m_a.$$

- In the NGS phase ($\epsilon \lesssim 0.1$), the axion gradient defines the **NS surface** as $f_a \to 0$.

NS structure

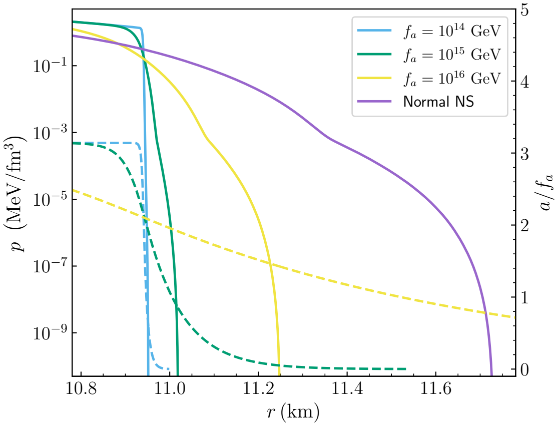

Figure 3: Axion gradient is localized at the edge of the NS as $f_a \to 0$ for $\epsilon \lesssim 0.1$.

Why is the surface of the NS important?

- Envelope (or *ocean*) region acts as a heat blanket. Important for cooling. $\rho_{\rm env} \sim 10^8 - 10^{11}\ {\rm g/cm^3}$.

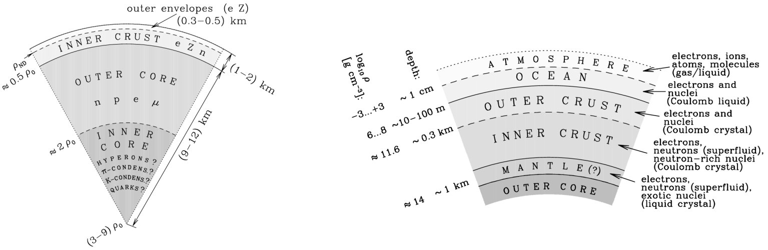

Figure 4: Left: Bulk structure of a NS, illustrating its inner layers. Right: A detailed view of the outermost kilometer. From Haensel, Potekhin, and Yakovlev 2007.

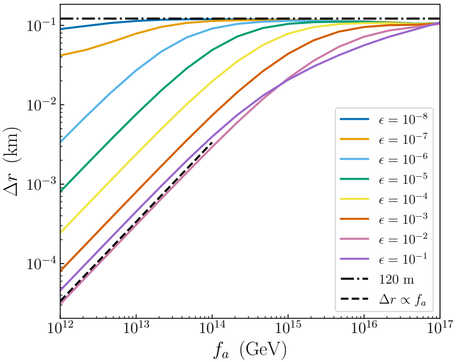

Figure 5: Size of the envelope as a function of f_a.

Standard NS cooling

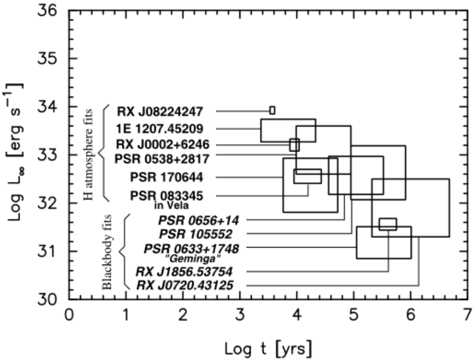

Figure 6: NS thermal luminosity vs age data (Page et al. 2004).

Standard NS Cooling

The cooling history of a typical isolated NS has three main stages:

- **Thermal relaxation stage** ($t \lesssim 10 - 100 \ \mathrm{yrs}$)
  - The crust cools and couples to the core.
  - The redshifted temperature $T(t) \equiv T_i(r,t)e^{\Phi(r)}$ becomes uniform.
- **Neutrino cooling stage** ($100 \ \mathrm{yrs} \lesssim t \lesssim 10^5 \ \mathrm{yrs}$)
  - The dominant cooling process is neutrino emission from the core.
- **Photon cooling stage** ($t \gtrsim 10^5 \ \mathrm{yrs}$)
  - The surface photon emission becomes the dominant cooling process.

For the later stages ($t \gtrsim 100 \ \mathrm{yrs}$), the cooling is governed by:

$$C_v(T)\frac{dT}{dt} = -L_\nu(T) - L_\gamma(T_s)$$

Standard NS cooling

Two main energy sinks:

- ν emission from the core

$$L_\nu(T) \propto T^8 \text{ (mURCA)},$$

- γ thermal emission from the surface

$$L_\gamma(T_s) = 4\pi R^2 \sigma_{SB} T_s^4(T).$$

The strength of the thermal emission is highly sensitive to the $T_s(T)$ relation. Envelope model.

Standard NS cooling

- A fit for $T_s(T_b)$ is found under generic NS conditions (Gudmundsson, Pethick, and Epstein 1983):

$$\left(\frac{T_s}{10^6\ \mathrm{K}}\right)^4 = \left(\frac{g_s}{10^{14}\ \mathrm{cm/s^2}}\right)\left[0.78\left(\frac{T_b}{10^8\ \mathrm{K}}\right)\right]^{2.2},$$

The relation depends almost uniquely on the parameter $\left(\frac{T_s^4}{g_s}\right)$.

Standard NS cooling

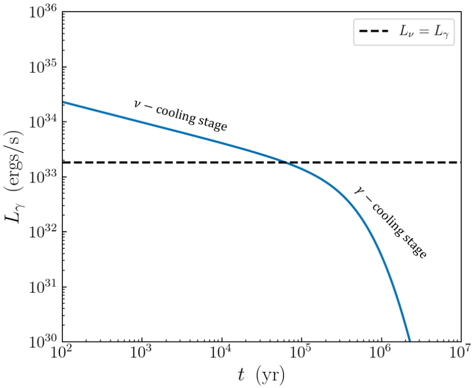

Figure 7: Cooling is dominated by ν emission from the core until $L_\nu \sim L_\gamma$ at around 10^5 yrs.

Modified envelope

$$T_{s6}{}^4 = (g_s)_{14}(0.78\ \ T_{b8})^{2.2}$$

- The axion gradient contributes to g_s, increasing surface gravity across the envelope:

$$g_s = g + g_a,$$

$$g_a = \frac{n_s}{\varepsilon + p}\frac{\partial m_N^*}{\partial a}a' \propto \frac{1}{f_a} \propto m_a.$$

- For sufficiently low f_a, g_a dominates, reducing the envelope size and causing T_s to approach T_b.

Cooling curves

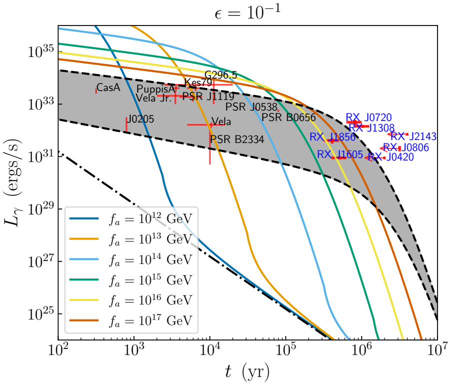

Figure 8: NS cooling curves with the axion-modified envelope (solid lines) vs. standard models. M7 are shown in blue.

Exclusion criterion?

- We establish an exclusion criterion based on the Magnificient Seven (M7) data.
- These are the nearest known thermally emitting NSs.

We consider ruled out any cooling curve with $L_\gamma(10^5 \text{ yrs}) \lesssim 5 \times 10^{30} \text{ ergs/s}$**.**

Exclusion plot

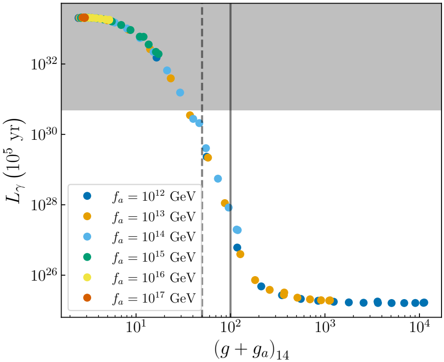

Figure 9: L_γ at $t \sim 10^5$ yr.

Exclusion plot

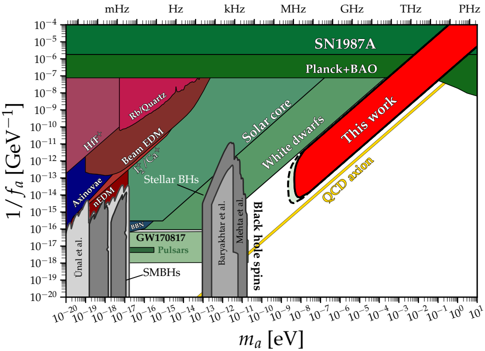

Figure 10: The $(g + g_a)_{14} > 50$ condition (dashed region) can be translated into a region in the (f_a, m_a) parameter space. Solid region corresponds to $(g + g_a)_{14} > 100$

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Other consequences?

- The QCD axion couples with the NS nucleon density.
- The QCD axion is a scalar field: axion radiation can be emitted even from purely radial pulsations.
- If the QCD axion is sourced in NSs, radial pulsations should be damped by axion emission.

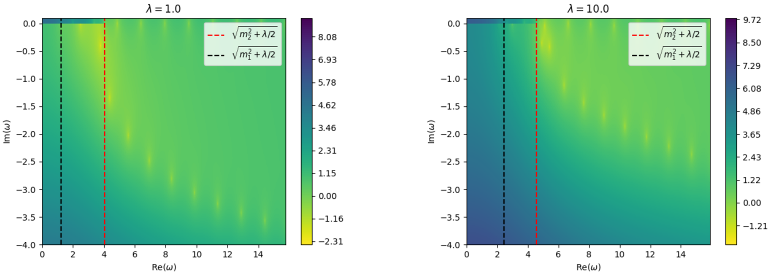
Toy model

- Two coupled oscillating systems
- One system is finite and has a discrete spectrum of modes (NS, ϕ_1)
- The finite system is coupled to a second one that extends to infinity (QCD axion, ϕ_2).

$$\mathcal{L}_{\rm toy} = \underbrace{\frac{1}{2}\partial_\mu\phi_1\partial^\mu\phi_1 - \frac{1}{2}m_1^2\phi_1^2}_{\text{Field 1 dynamics}} + \underbrace{\frac{1}{2}\partial_\mu\phi_2\partial^\mu\phi_2 - \frac{1}{2}m_2^2\phi_2^2}_{\text{Field 2 dynamics}} - \underbrace{\frac{\lambda}{4}\left(\phi_2 - \phi_1\right)^2}_{\text{Coupling term}}.$$

(K. D. Kokkotas and B. F. Schutz, Normal modes of a model radiating system, Gen. Relativ. Gravitation 18, 913 (1986))

Toy model



$\lambda = 1.0$
$\lambda = 10.0$
$\sqrt{m_2^2 + \lambda/2}$
$\sqrt{m_1^2 + \lambda/2}$
Im(ω)
Re(ω)

No more toys

$$
\begin{aligned}
&e^{-2\lambda}\delta a'' + e^{-2\lambda}\delta a'\left(\Phi' - \lambda' + \frac{2}{r}\right)\\
&- 2\delta\lambda\left(\frac{\partial V}{\partial a} + n_s\frac{\partial m^*}{\partial a}\right) + e^{-2\lambda}a'\left(\delta\Phi' - \delta\lambda'\right)\\
&- \left(\frac{\partial^2 V}{\partial a^2} + n_s\frac{\partial^2 m^*}{\partial a^2} - \omega^2 e^{-2\Phi}\right)\delta a = \delta n_s\frac{\partial m^*}{\partial a},
\end{aligned}
$$

$$
\delta\Phi' - \delta\lambda\left(\frac{1}{r} + 2\Phi'\right) = 4\pi G r e^{2\lambda}\left[\delta p - \frac{\partial V}{\partial a}\delta a - \delta\lambda e^{-2\lambda}(a')^2 + e^{-2\lambda}a'(\delta a)'\right],
$$

$$
\delta\lambda = -4\pi G r e^{2\lambda}\left[(\varepsilon + p)\xi^r - e^{-2\lambda}a'\delta a\right],
$$

$$
\begin{aligned}
&(\delta p)' + (\delta\varepsilon + \delta p)\,\Phi' + (\varepsilon + p)\,\delta\Phi' - \omega^2\,(\varepsilon + p)\,e^{2(\lambda-\Phi)}\xi^r =\\
&= -\frac{\partial m^*}{\partial a}\left(\delta n_s a' + n_s(\delta a)'\right) - n_s\frac{\partial^2 m^*}{\partial a^2}a'\delta a,
\end{aligned}
$$

$$
\left[(\varepsilon + p)\,\xi^r\right]' + (\varepsilon + p)\,\xi^r\left(\frac{2}{r} + \lambda' + \Phi'\right) = -\left(\frac{\delta p}{c_s^2} + (\varepsilon + p)\,\delta\lambda\right).
$$

No more toys

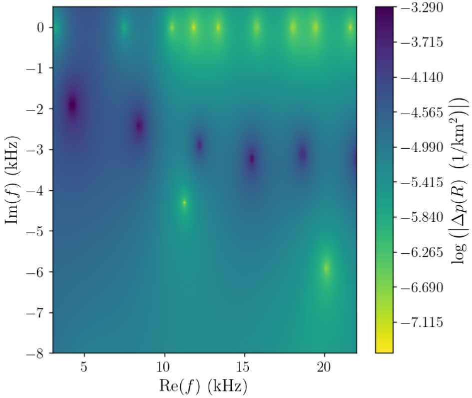


Figure 11: $m_a = 3$ kHz, $\epsilon = 0.1$.

No more toys

Table 1: Radial mode frequencies for an axion condensed NS with a central pressure of $p_0 = 100\ \mathrm{MeV/fm^3}$ and $\epsilon = 0.1$. The number of nodes in the radial displacement profile, $\xi(r)$, is indicated in the first column.

No axion	3.0 kHz		4.0 kHz		12.0 kHz	
f(kHz)	Re(f)	-Im(f)	Re(f)	-Im(f)	Re(f)	-Im(f)
3.10	3.26	0.04	3.49	0	3.35	0
7.27	7.49	6×10^{-3}	7.96	0.038	8.08	0
10.22	10.46	2×10^{-3}	11.21	4.6×10^{-3}	11.98	0
11.63	11.84	8.5×10^{-4}			15.08	0.012

And I wonder

Our long-term goal is to compute non-radial oscillations. In the meantime, we can speculate:

- If NS radial oscillations are ever observed, they could be used to put a lower bound on the QCD axion mass (?)
- If the QCD axion is ever detected, could be used to measure NS radial oscillations (??)
- Qualitative features hold for non-radial oscillations, probing axion physics through GW observations (???)
- QCD axion asteroseismology (??)

Thanks for your attention!

NS structure

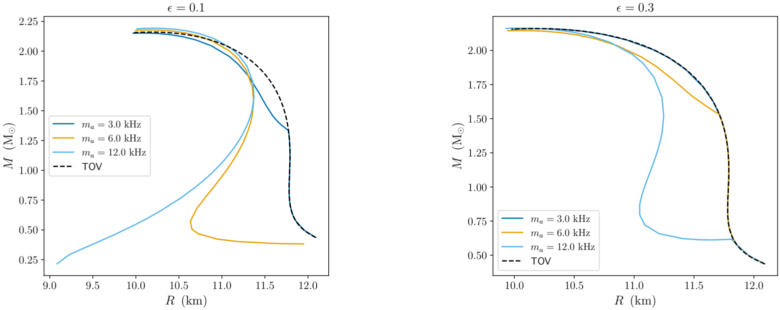


Figure 12: Mass radius relations for different m_a values.

Modified Envelope

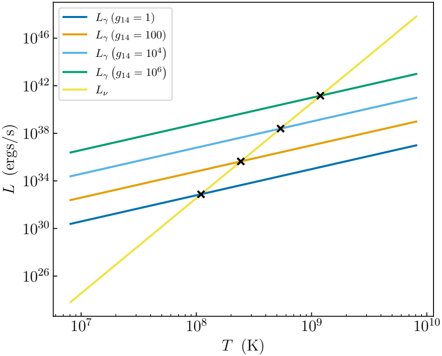


Figure 13: Dependence of L_γ with g_{14}.

NGS energy

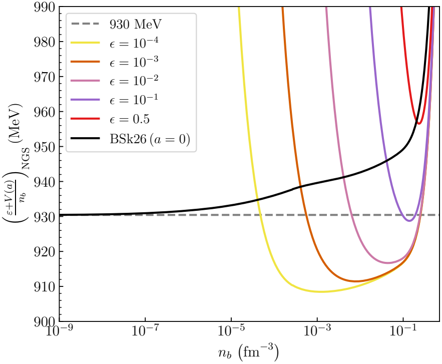


Figure 14: energy per particle in the two phases $a = 0$ (black) and $a = \pi f_a$ (colored) for the BSk26 EOS.

NGS energy

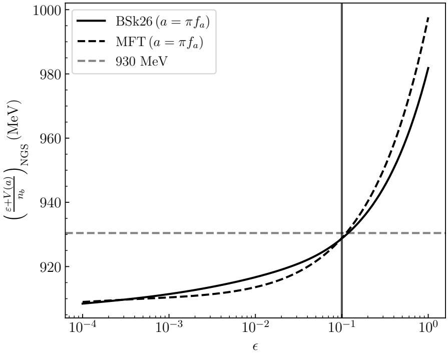


Figure 15: minimum value of the energy per particle in the $a = \pi f_a$ phase as a function of ϵ

Modified envelope

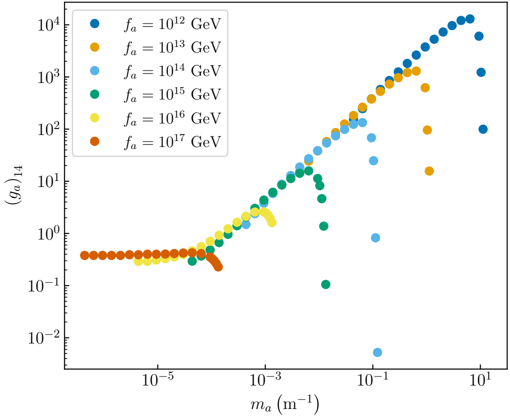


Figure 16: Axion surface gravity for different f_a.

NGS energy

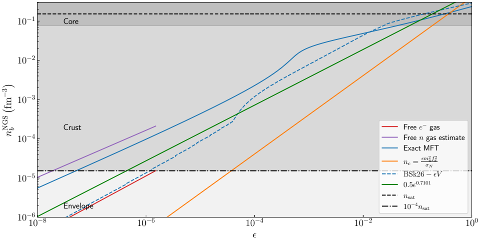


Figure 17: NGS baryon density as a function of ϵ for the β-equilibrated MFT model and the BSk26 EoS.

Modified Envelope

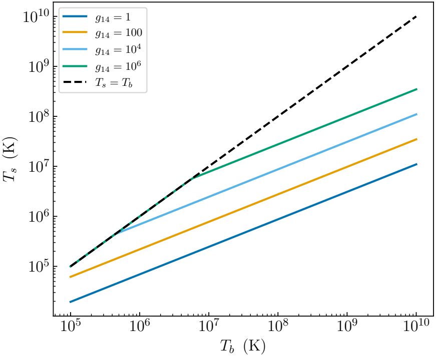
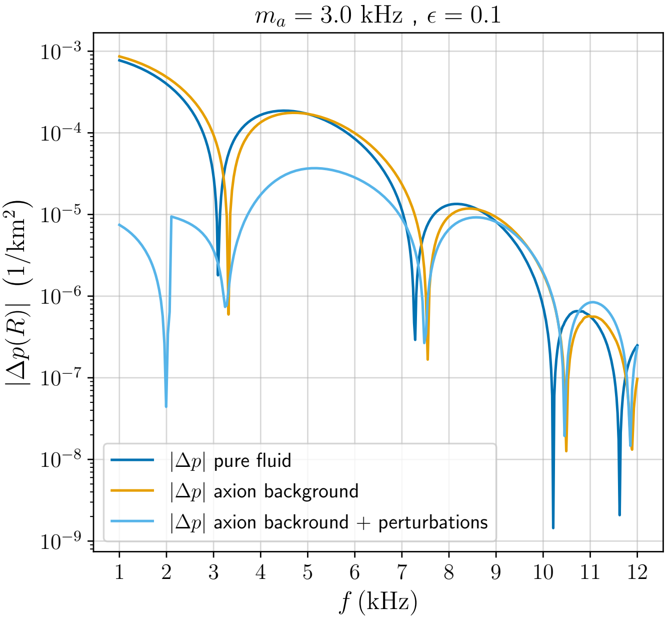
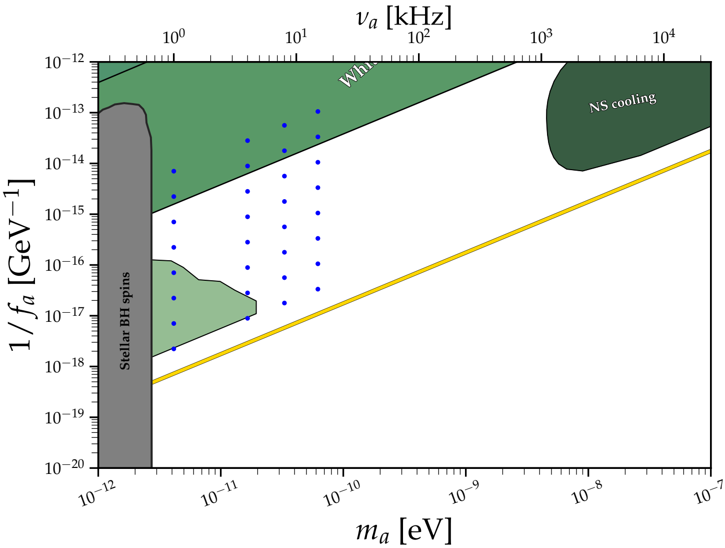


Figure 18: Dependence of $T_s(T_b)$ with $g_{14} \equiv \frac{g_s}{10^{14}\ \mathrm{cm/s^2}}$.



$m_a = 3.0$ kHz , $\epsilon = 0.1$
$|\Delta p(R)|$ (1/km^2)
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
1 2 3 4 5 6 7 8 9 10 11 12
f (kHz)
$|\Delta p|$ pure fluid
$|\Delta p|$ axion background
$|\Delta p|$ axion backround + perturbations



ν_a [kHz]
10^0
10^1
10^2
10^3
10^4
$1/f_a$ [GeV^{-1}]
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
Whit
NS cooling
Stellar BH spins
10^{-12}
10^{-11}
10^{-10}
10^{-9}
10^{-8}
10^{-7}
m_a [eV]

$$\varepsilon\left(n, m^*(a)\right) \sim \varepsilon\left(n, m^*(0)\right) - n\Delta m(a),$$

where $\Delta m(a)$ represents the effective mass reduction due to the axion field, given by

$$\Delta m(a) = \sigma_N \left(1 - \sqrt{1 - \beta \sin^2\left(\frac{a}{2f_a}\right)}\right).$$

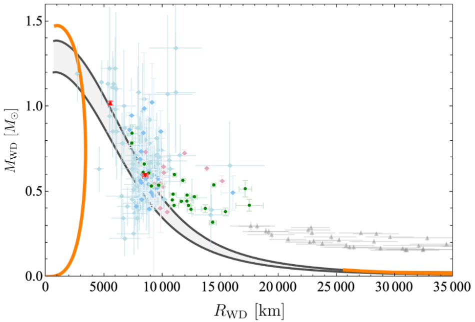


Figure 19: WD M-R relation in light QCD axion models, from Balkin et al. 2024a. A new phase of matter with $a = \pi f_a$ is possible for $\epsilon \lesssim 10^{-7}$, leading to a gap in the M-R relation inconsistent with observational data.