THE QCD AXION AT FINITE DENSITY – PART II

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COST Workshop: Probing BSM physics at different scales

Technische Universität München

January, 2020

AXION–MATTER COUPLINGS AT FINITE DENSITY

Why do we care?

→ Astrophysical axion bounds: Star cooling, SN1987A,..

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c_N Is a linear combination of:

Hadronic matrix elements

$$s^\mu \Delta q = \langle p| \bar{q}\gamma^\mu\gamma_5 q |p\rangle$$

Ratio of quark masses

$$c_q^{\mathrm{IR}} = C_{qq'}(c_q^0 - (Q_a^*)_q)$$

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$\pi^0 N$ - interactions get quenched

$$\frac{(g_A)_n}{(g_A)_0} = \frac{(\Delta u - \Delta d)_n}{(\Delta u - \Delta d)_0} \simeq 1 + n \left(\frac{c_D}{4 (g_A)_0 f_\pi^2 \Lambda_\chi} - \frac{1}{3 f_\pi^2} \left(2c_4 - c_3 + \frac{1}{2M} \right) \right)$$

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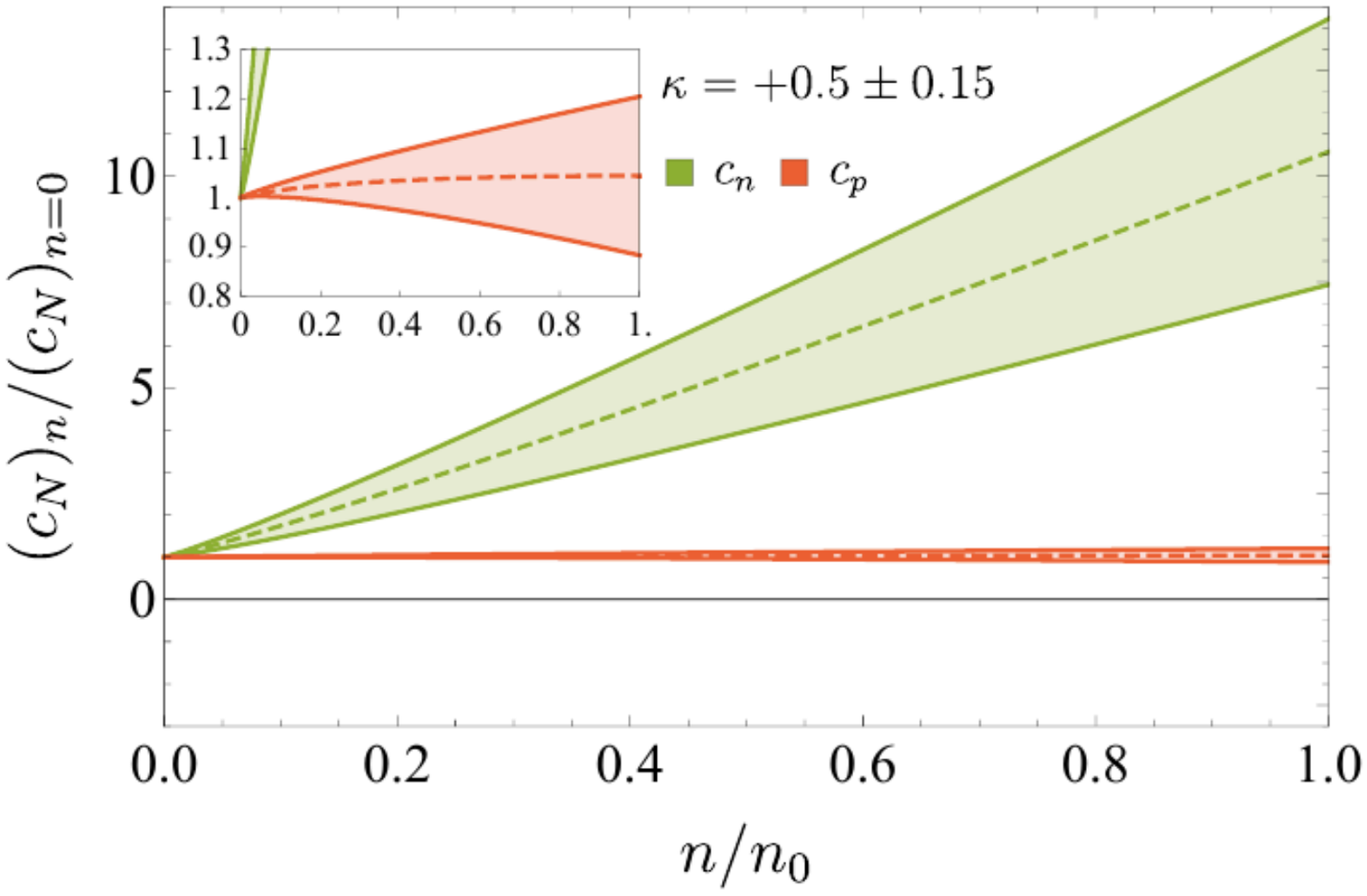
CHANGE AT FINITE DENSITY!

Naively, small correction:

$$\frac{m_u}{m_d} \to \frac{m_u}{m_d} \frac{\langle \bar{u} u \rangle_n}{\langle \bar{d} d \rangle_n} \qquad \frac{\langle \bar{u} u \rangle_{n_0}}{\langle \bar{d} d \rangle_{n_0}} - 1 = 0.07$$

Accidental cancellation: $c_n \simeq -0.02$ ⟶ $\mathcal{O}(1)$ correction

AXION–MATTER COUPLINGS AT FINITE DENSITY



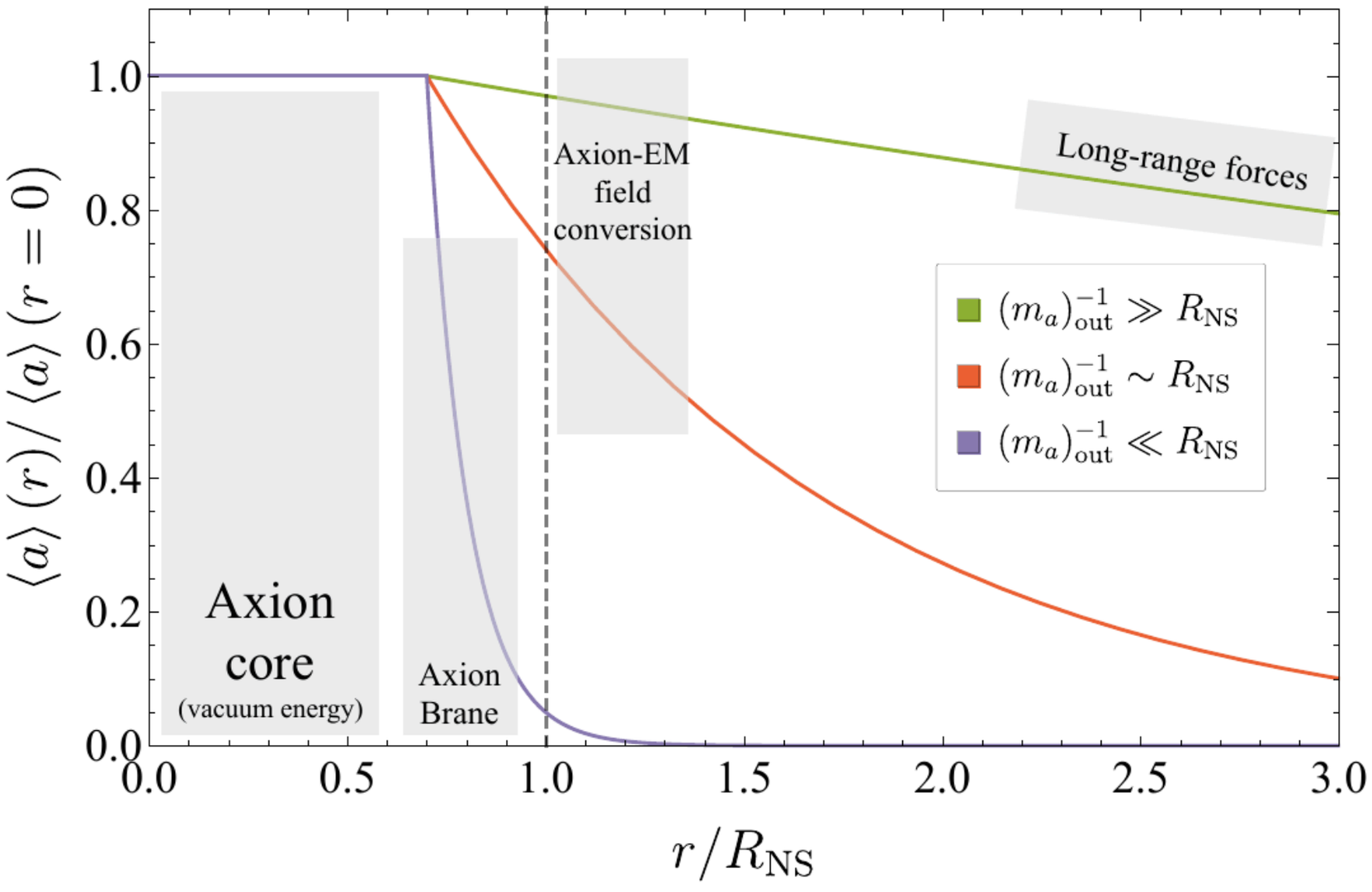
Emission rates for NS via axion bremmsstrahlung: $\Gamma_a \sim c_N^4$

⟶ Should change astrophysical axion bounds

SOURCING OBSERVABLES

Toy model: Axion gets sourced inside a neutron star for $r < r_c$

→ Numerically solve EOMs for Axion



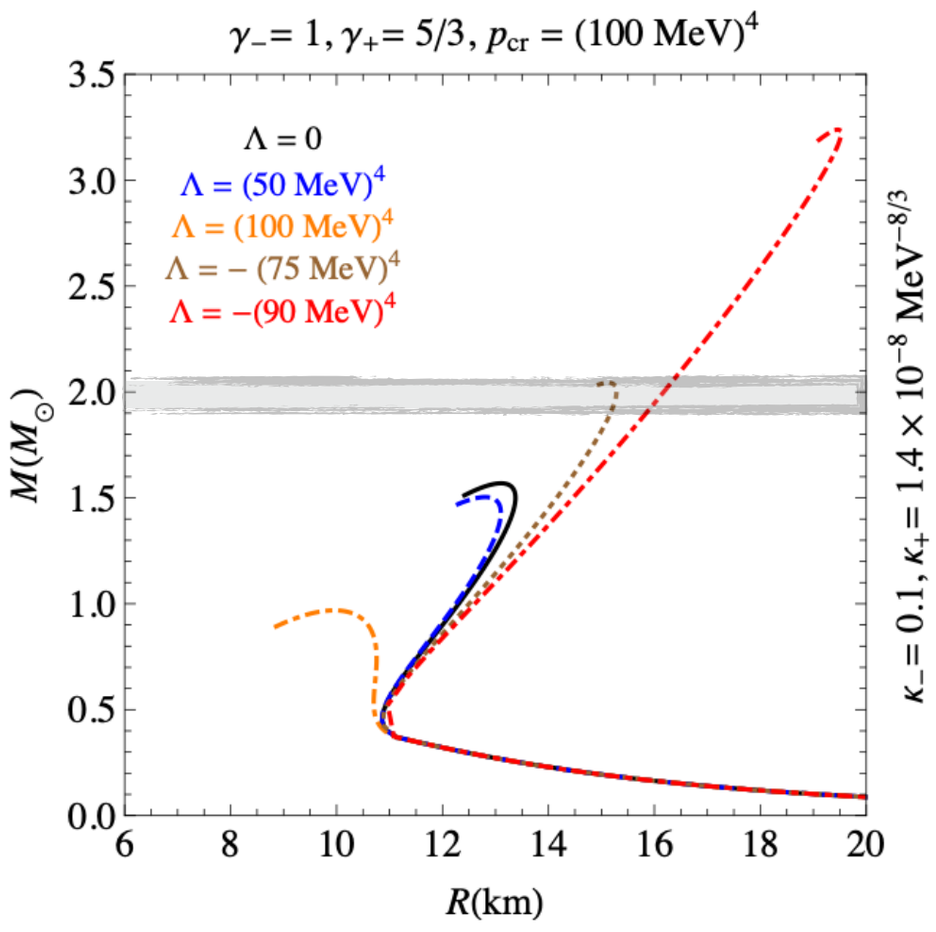
SOURCING OBSERVABLES

Vacuum energy:

- Potential energy shift: $\Delta V \sim -2 f_a^2 (m_a^2)_{\rm in}$
- Effects on neutron star EOS $p = p(\epsilon)$: $p_{\rm in}^{\rm total} = p_m - \Delta V$

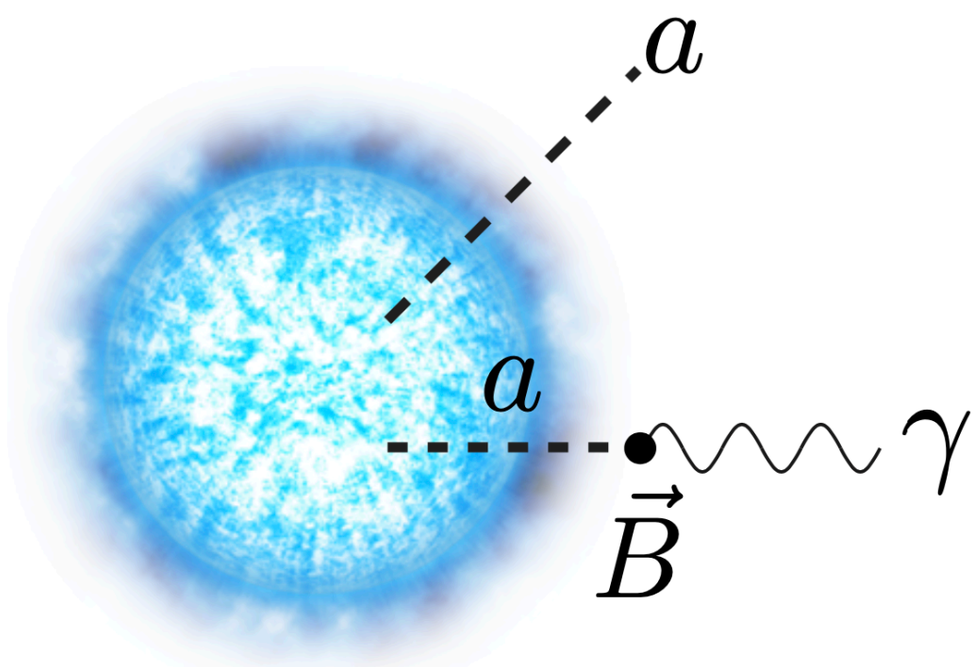
⟶ Adds pressure in the core: *stiffer* EOS

⟶ Tidal deformation in mergers



SOURCING OBSERVABLES

Axion/photon mixing: $(m_a^2)_{\rm in} \sim R_{\rm ns}$



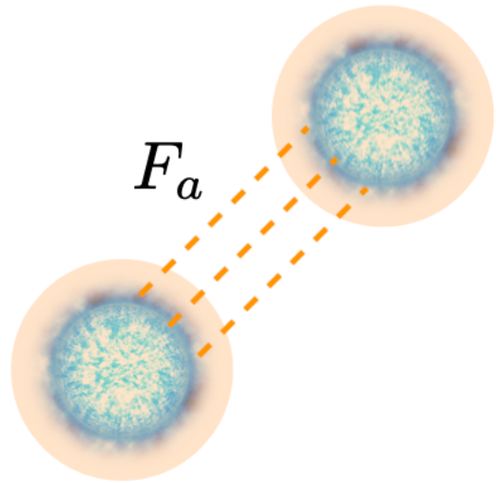
- Changes emissivity/ Energy depletion of the star

⟶ Axion sources $\mathcal{O}(1)$ effects in dipole radiation

$$\frac{P_a}{P_{\rm dipole}} \sim \left(\frac{2f_a}{10^{13}\,{\rm GeV}}\right)^2$$

SOURCING OBSERVABLES

Long range forces: $(m_a^2)_{\rm in} >> R_{\rm ns}$



5th force between NS: Merger events, LIGO

WHAT ABOUT THE RELAXION?

Back reaction ~ QCD non-perturbative potential

$$V_0 \supset -gM^3\phi + \langle \bar{q}q \rangle_0 \, y \, \langle h(\phi) \rangle \cos\left(\frac{\phi}{f}\right), \qquad \phi_0 \text{ Minimun}$$

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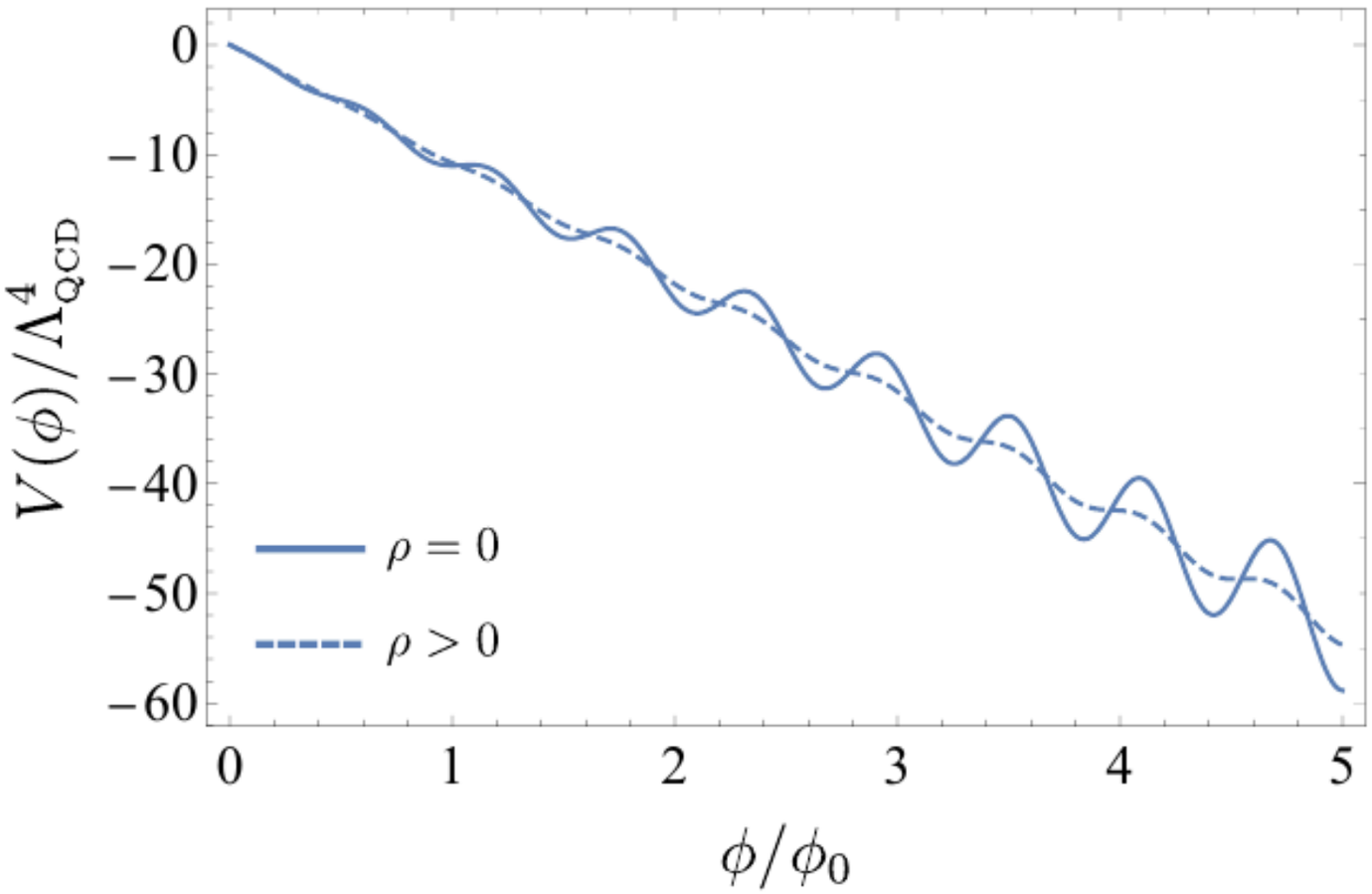
At finite density: first real minimum at $\phi_n = \phi_0 \left(\frac{\langle \bar{q}q \rangle_0}{\langle \bar{q}q \rangle_n} \right)^2$



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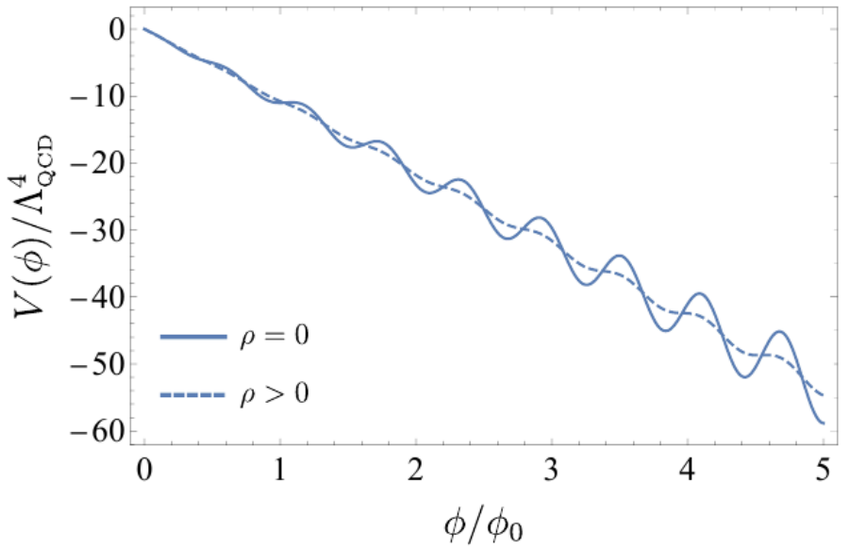

Dense objects as catalysts of bubble nucleation?

⟶ Non-local bubble $V_0(\phi_0) \not< V_0(\phi_n)$: would expand all over our universe.

⟶ After NS formation Higgs VEV must have changed $\mathcal{O}(1)$

AND must have come to a halt (particle production?)

Otherwise relaxion rolls into the abyss…

SUMMARY

- **Axion-Matter couplings:** depend on density, change astrophysical axion bounds
- If **Axion sourcing:** Plentitude of astrophysical observables
- Existence of neutron stars challenges simple relaxion models

OUTLOOK

- In even higher densities $n > 5n_0$: **Color Flavor Locked** phase
- **Axion brane in NS**: for $(m_a)^{-1} << R_{NS}$ Israel junction conditions

  lead to localised brane tension

  $\longrightarrow$ Discontinuous total pressure $p(r)$: NS stability?

BACK-UP

Relaxion model that solves strong CP problem:

Mechanism reduces slope of linear term after inflation ϵ:

$$V_n = -\Lambda_{\mathrm{QCD}}^4 \left(\epsilon \frac{\phi}{f} + \sqrt{\frac{\phi}{\phi_n}} \cos \frac{\phi}{f} \right)$$

For $\epsilon < 10^{-10}$ generated vacuum angle θ is within experimental bounds

1. $\epsilon \ll \frac{\langle \bar{q}q \rangle_n}{\langle \bar{q}q \rangle_0} < 1$ possibly a stable configuration is viable with

$$\theta_n = \left(\frac{\langle \bar{q}q \rangle_n}{\langle \bar{q}q \rangle_0} \right)^{-1} \theta_0$$

2. $\epsilon \sim \frac{\langle \bar{q}q \rangle_n}{\langle \bar{q}q \rangle_0} < 1$ back reaction too weak → Catastrophic instability

BACK-UP

With increasing density: quarks form diquark condensates

$$\langle q_L C q_L \rangle$$

⟶ Color superconductivity

CFL breaking pattern

$$SU(N_f)_L \times SU(N_f)_R \times SU(3)_c \times U(1)_A \times U(1)_B \to SU(N_f)_{L+R+c}$$

In some cases: Vacuum aligns such that the axion acquires a VEV

⟶ Could get a sourcing even for super high densities