# THE QCD AXION AT FINITE DENSITY – PART II

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COST Workshop: Probing BSM physics at different scales

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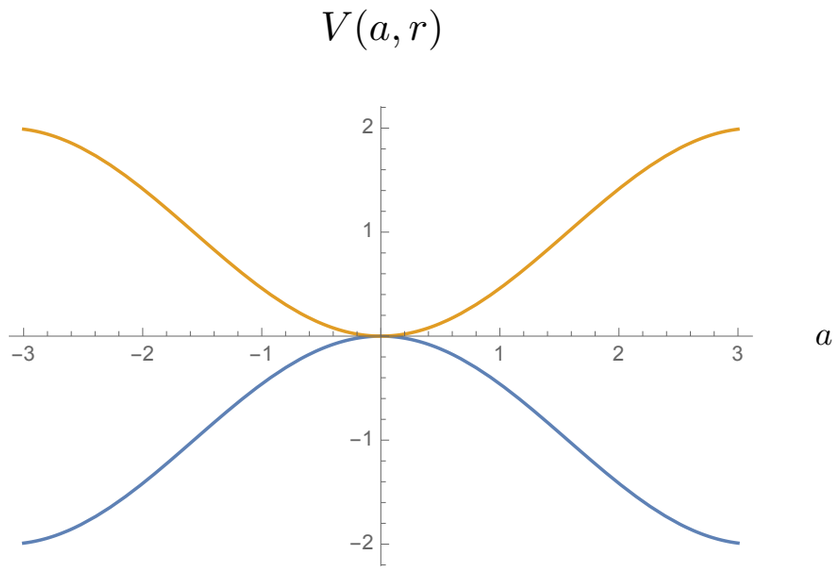
# SOURCING OBSERVABLES

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

$$V(a,r) = \begin{cases} f_a^2(m_a^2)_{\text{in}} \left[\cos\left(\frac{a}{f_a}\right) - 1\right] & r < r_c \\ -f_a^2(m_a^2)_{\text{out}} \left[\cos\left(\frac{a}{f_a}\right) - 1\right] & r > r_c \end{cases} ,$$

$$\text{with} \quad f_a^2(m_a^2)_{\text{out}} \sim \Lambda_{\text{QCD}}^4 \, .$$




⟶ Numerically solve static axion EOMs

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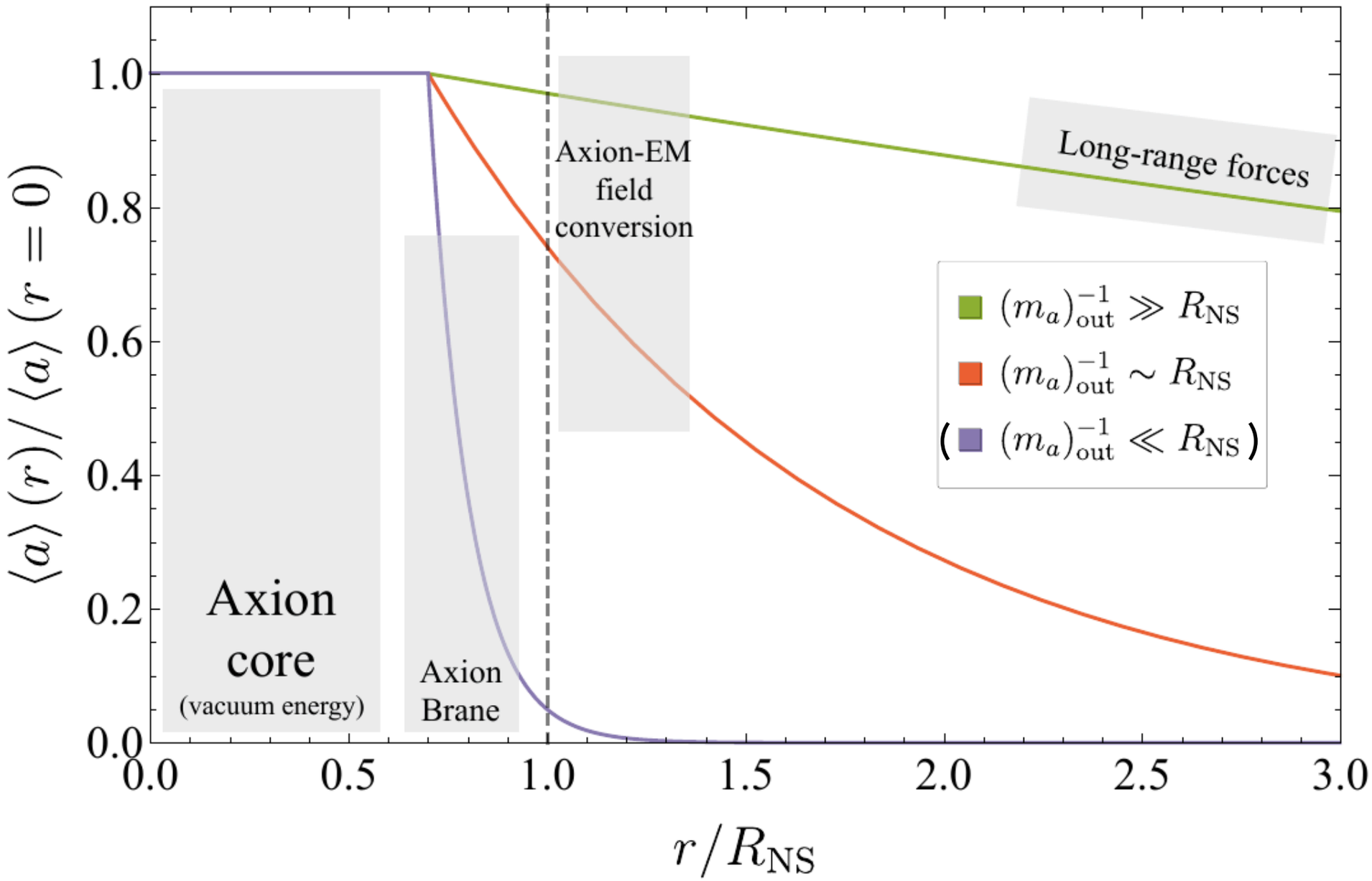


# SOURCING OBSERVABLES

## Vacuum energy:

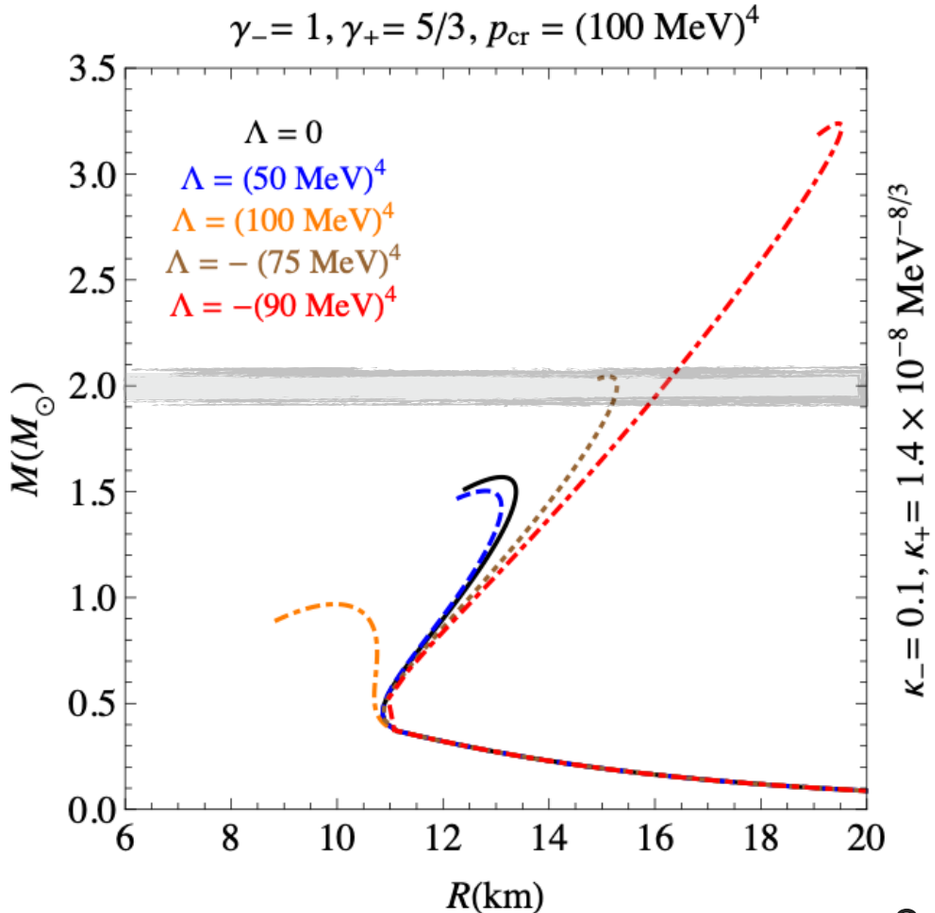
- Potential energy shift: $\Delta V \sim -2 f_a^2 (m_a^2)_{\rm in}$ (Csaki, Serra, et. al. '15)

⟶ Effects on neutron star EOS $p = p(\epsilon)$: $p_{\rm in}^{\rm total} = p_m - \Delta V$

⟶ Adds pressure in the core: *stiffer* EOS

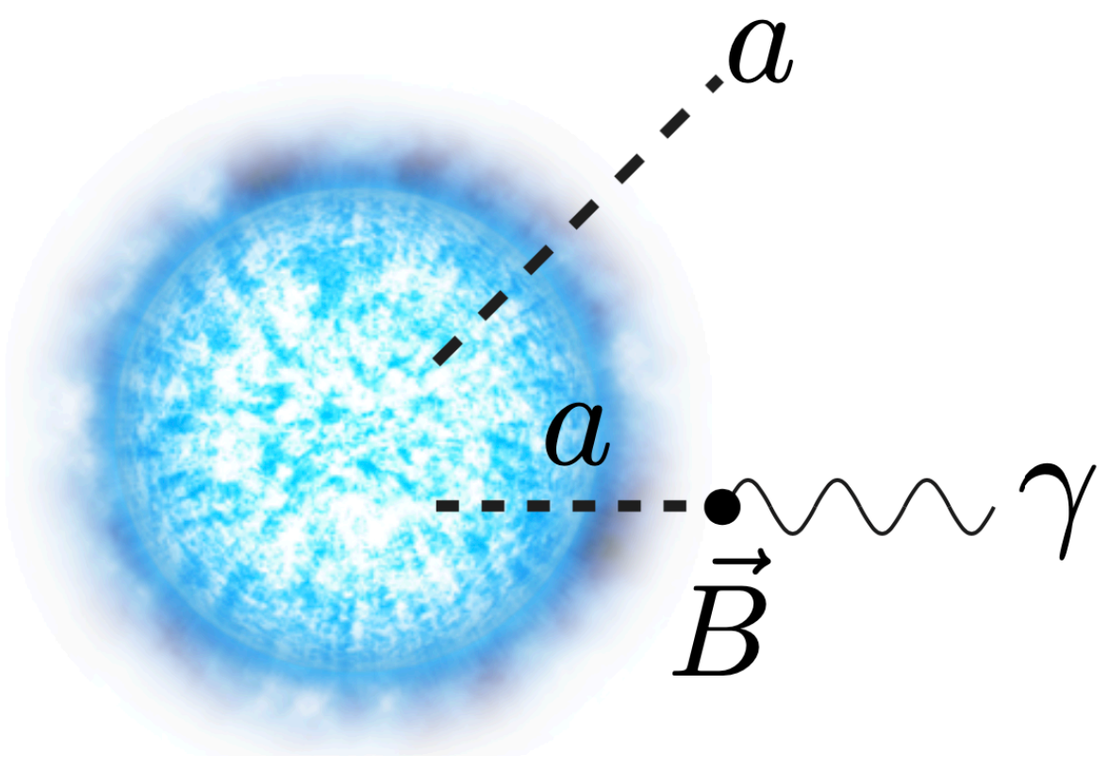
⟶ Tidal deformation in mergers

(Csaki, Terning, et. al. '18)



# SOURCING OBSERVABLES

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




- Changes emissivity/ Energy depletion of the star

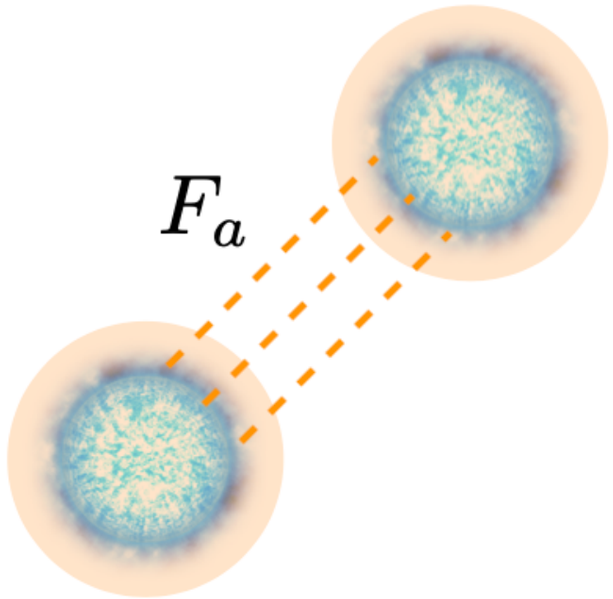
$$\frac{P_a}{P_{\rm dipole}} \sim \left(\frac{2 f_a}{10^{13}\,{\rm GeV}}\right)^2$$

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

# SOURCING OBSERVABLES

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

$$V = -\frac{q_1 q_2}{4\pi D}$$



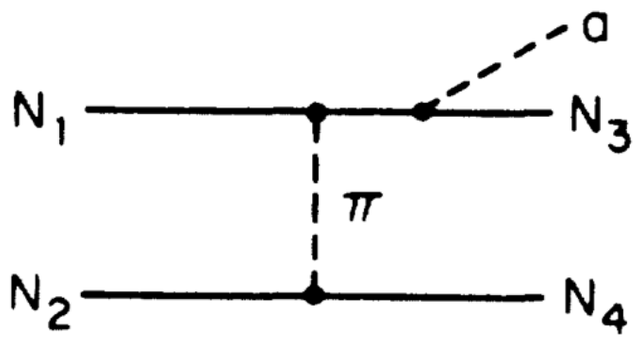

(Hook, Huang '17)

5th force between NS: Merger events, LIGO

# AXION–MATTER COUPLINGS AT FINITE DENSITY

Why do we care? (Raffelt '06 hep-ph/0611350)

E.g. cooling rates for Neutron Stars via axion bremmsstrahlung:




$$\Gamma_a \sim c_N^4$$

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

# AXION–MATTER COUPLINGS AT FINITE DENSITY

Axion-Nucleon coupling

$$c_N \frac{\partial_\mu a}{2f_a} \bar{N} \gamma^\mu \gamma_5 N, \quad N = p, n$$

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$c_N$ linear combination of:

$$c_p = +g_A c_-^{\rm IR} + g_0^{ud} c_+^{\rm IR} + c_s^{\rm IR} \Delta s$$
$$c_n = -g_A c_-^{\rm IR} + g_0^{ud} c_+^{\rm IR} + c_s^{\rm IR} \Delta s \,.$$

Hadronic matrix elements

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

Ratio of quark masses

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

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RG mixing

Model dependent

Axial rotation in UV

(Villadoro ’15)

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$\pi^0 N$ - interactions quench linear combinations of $\Delta q$

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

(Schwenk et. al. 1103.3622)

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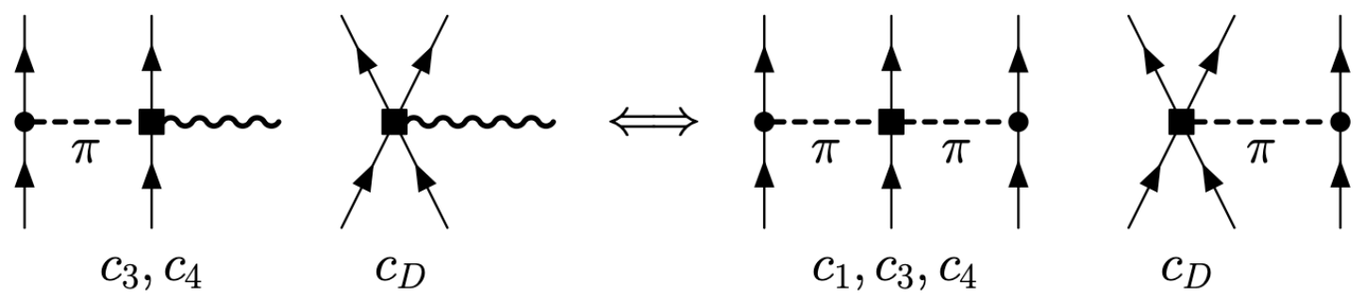

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Naively, small correction:

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

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

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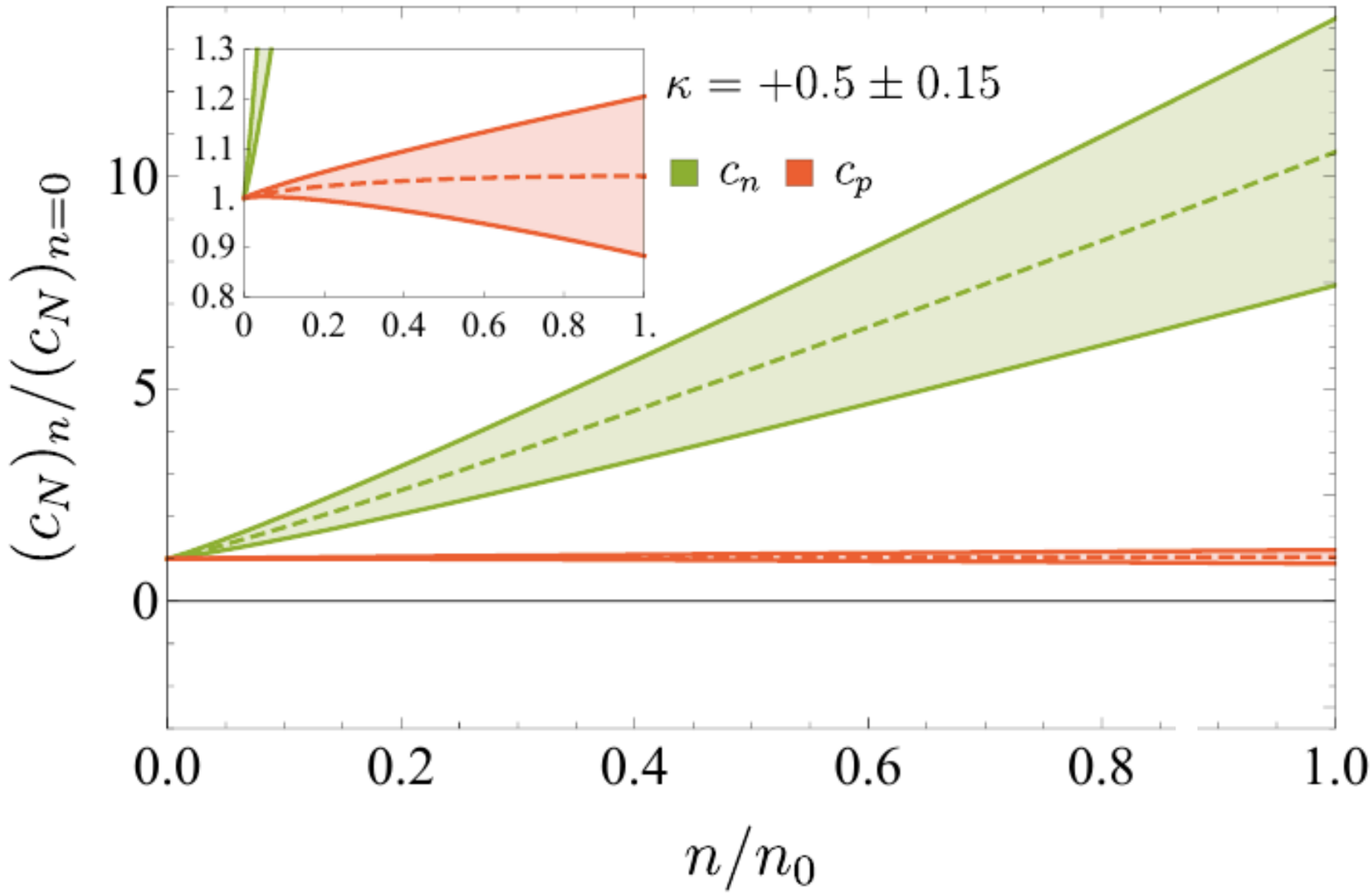


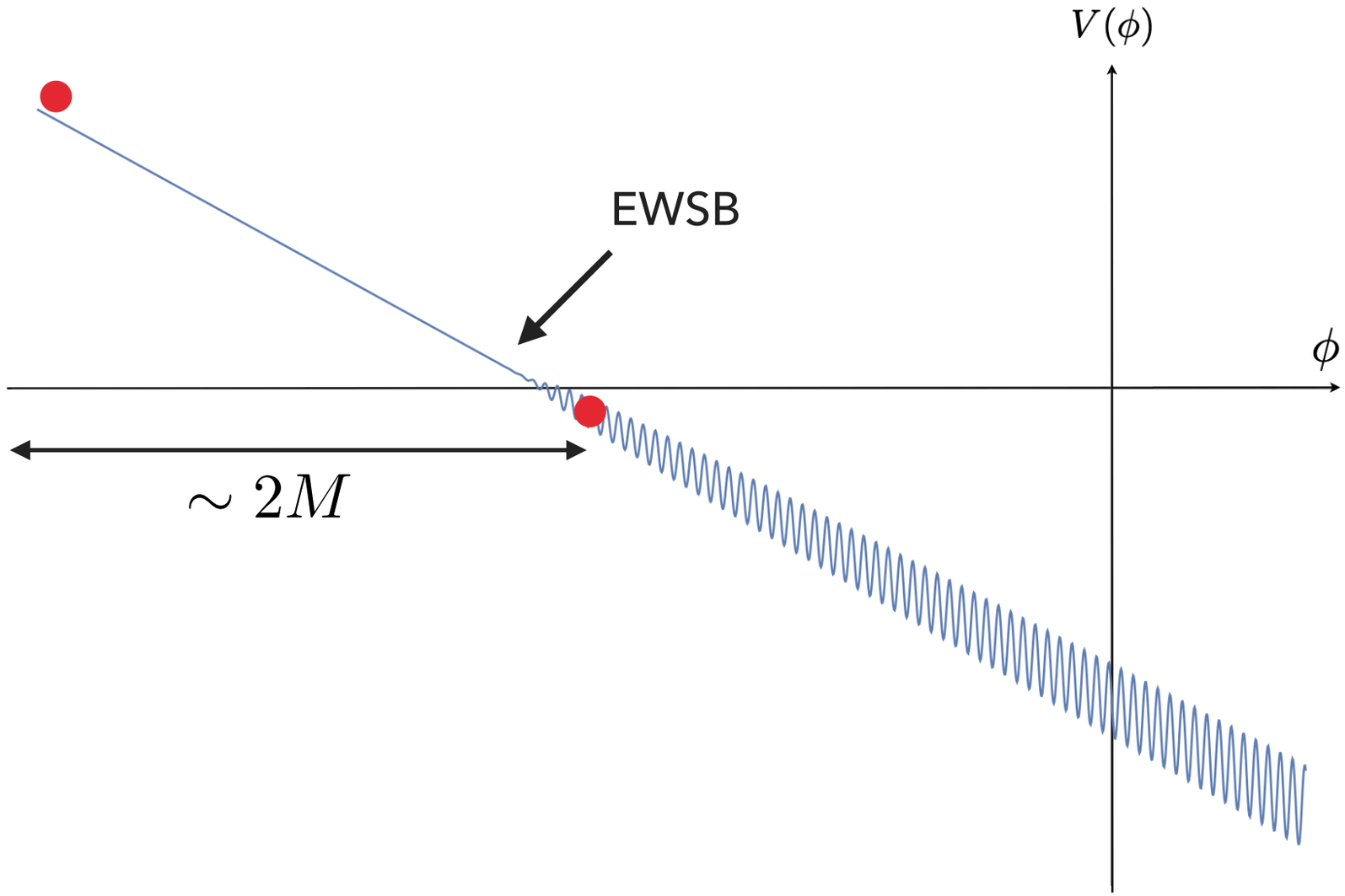

⟶ Astrophysical bounds should take this into account!

# WHAT ABOUT THE RELAXION?

Solving the hierarchy problem dynamically:

$$V \supset (-M + g\phi)\,|h|^2 + \Lambda(\phi)^4 \cos\left(\frac{\phi}{f}\right)$$

(Graham, Kaplan, Rajendran '15)



# WHAT ABOUT THE RELAXION?

Back reaction ~ QCD non-perturbative potential

$$V_0 \supset -gM^3\phi + \langle \bar{q}q \rangle_0 \, y \, \langle h(\phi) \rangle \cos\left(\frac{\phi}{f}\right), \quad \phi_0 \sim \frac{f v_0^2 M^2}{\Lambda_{\rm QCD}^4}$$ Minimun

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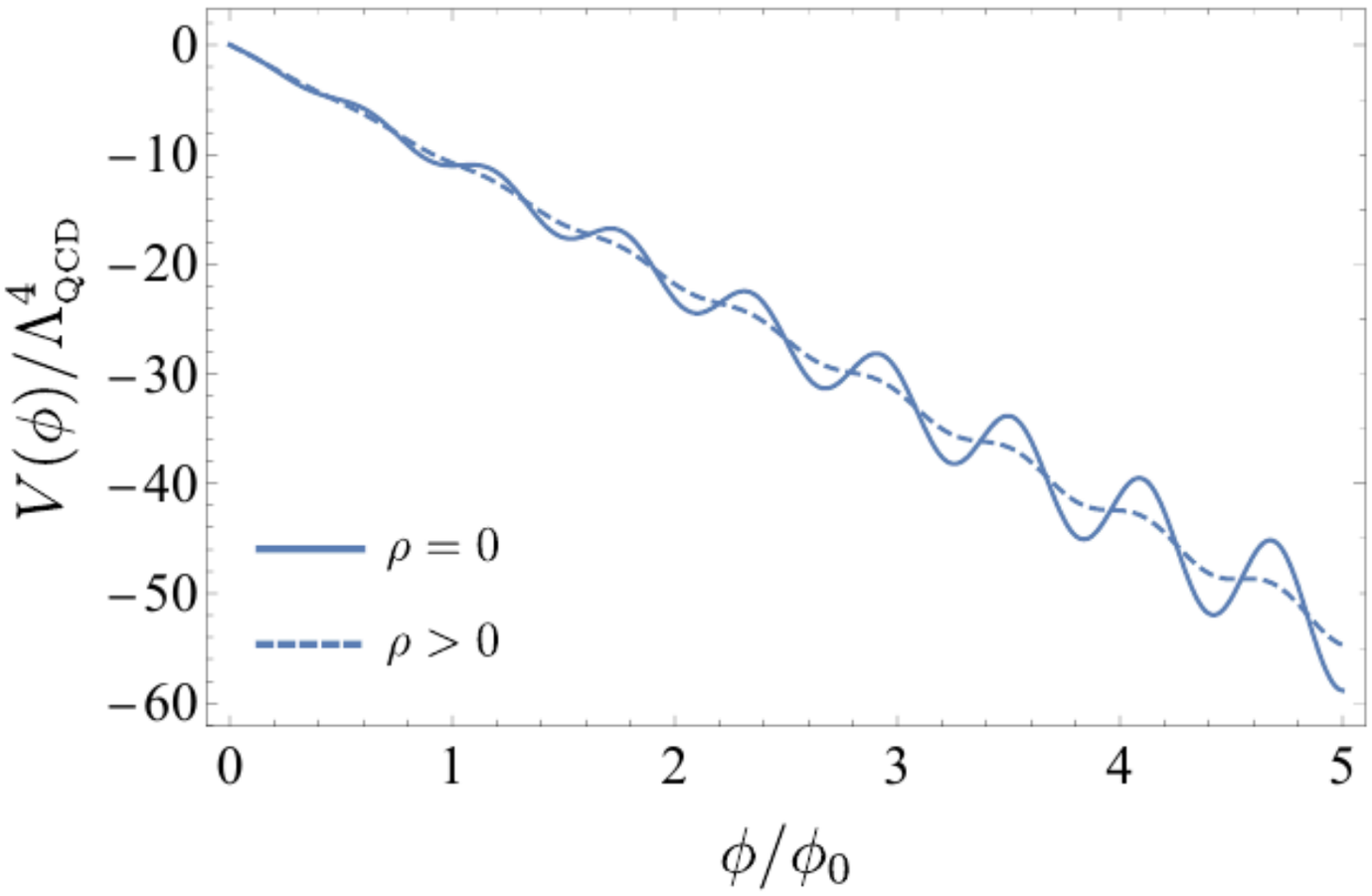
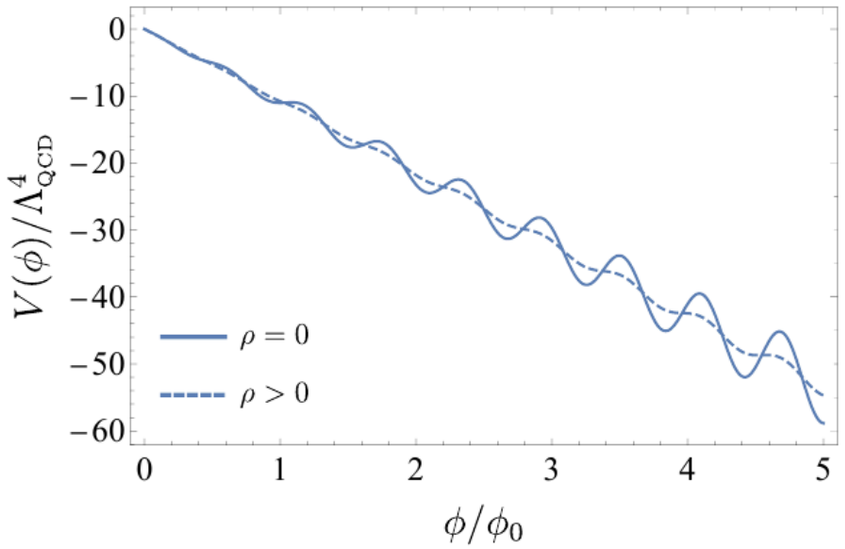
**At finite density**: first real minimum at $\phi_n = \phi_0 \left(\frac{\langle\bar{q}q\rangle_0}{\langle\bar{q}q\rangle_n}\right)^2$



# WHAT ABOUT THE RELAXION?

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. (Hook et. al. '18)

⟶ 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**

# SUMMARY

- **Axion-Matter couplings:** depend on density, change astrophysical axion bounds
- **Axion sourcing:** Should look for astrophysical signatures
- Super dense objects constrain **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

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

# Thanks!

# BACK-UP

**Accidental cancelation structure of the neutron coupling:**

$$\frac{c_n}{c_p} \simeq \frac{g_0^{ud} - g_A \frac{1-z}{1+z}}{g_0^{ud} + g_A \frac{1-z}{1+z}} \sim 10^{-2}$$

The linear combination $g_0^{ud} = \Delta u + \Delta d$ has not been calculated in medium ⟶ Assume dependence as

$$(g_0^{ud})_n = g_0^{ud}(1 + \kappa u), \quad \kappa = \pm(0.5 \pm 0.15)$$

# BACK-UP

## Explicit form of the Axion-Nucleon couplings

$$c_p = +g_A c_-^{\rm IR} + g_0^{ud} c_+^{\rm IR} + c_s^{\rm IR} \Delta s$$
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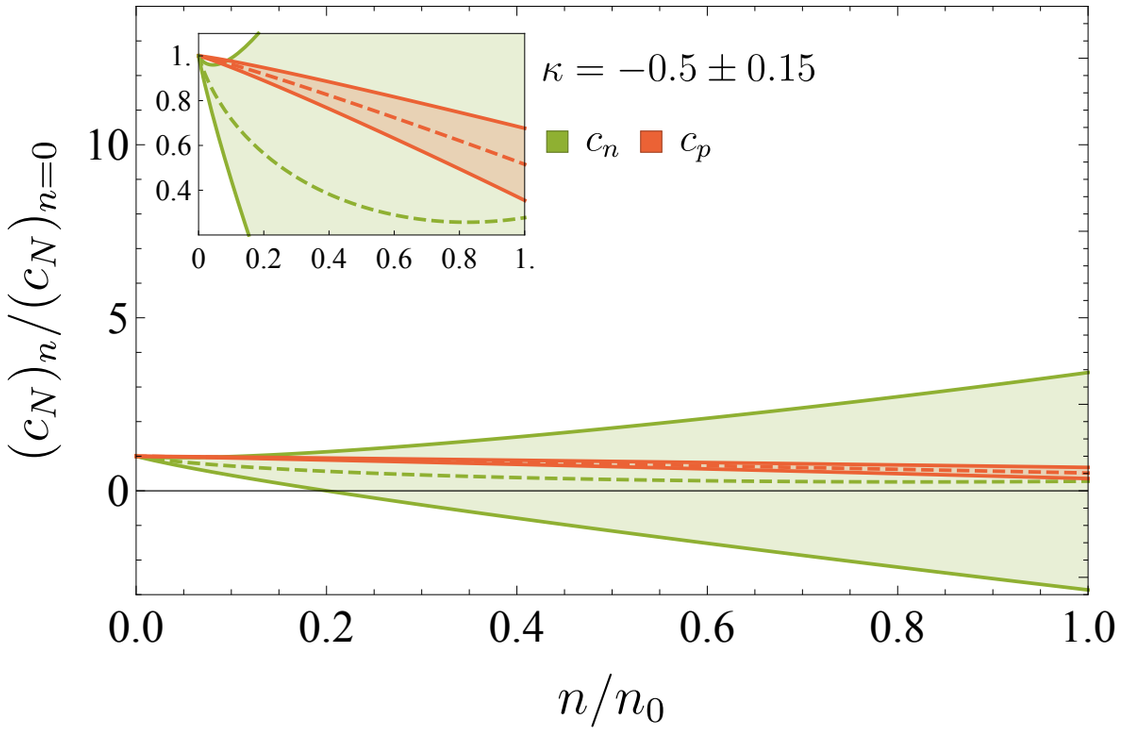


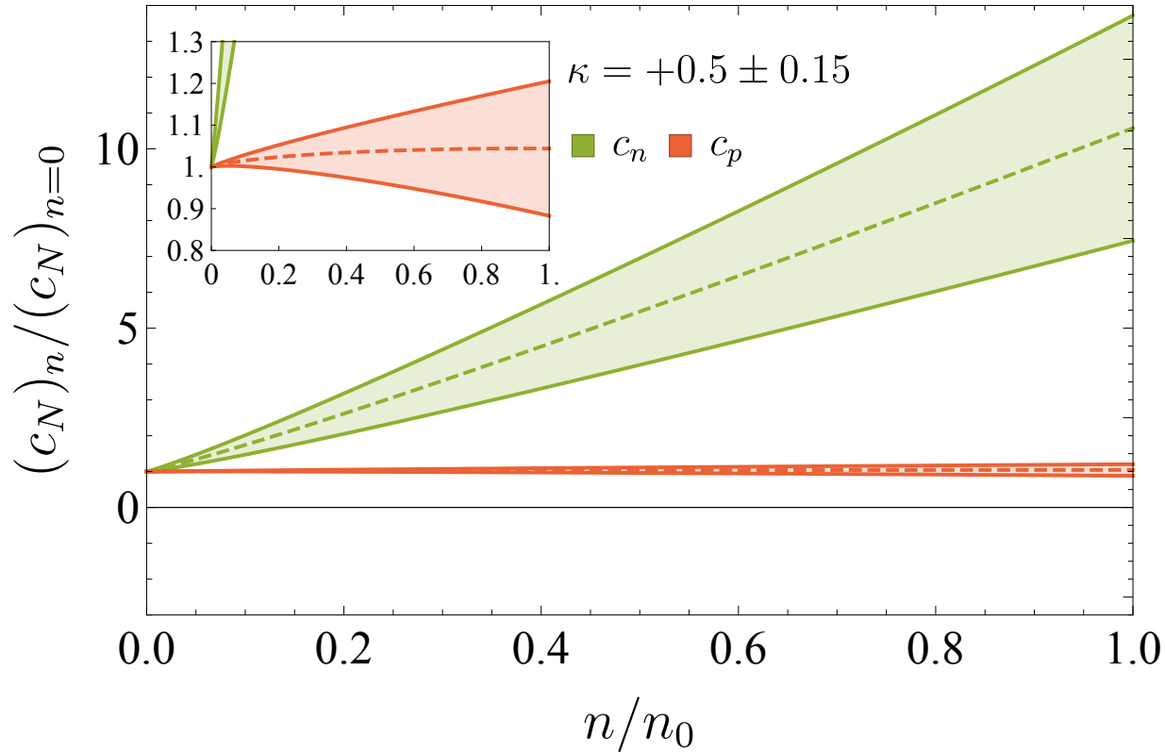

# BACK-UP

## Relaxion model that solves strong CP problem:

Mechanism reduces slope of linear term after inflation $\epsilon$:

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

For $\epsilon < 10^{-10}$ generated vacuum angle $\theta$ 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

## Color-Flavor-Locked phase

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