π in the Sky: Neutron Stars with Exceptionally Light QCD Axions

Masha Baryakhtar

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Nuclear Physics in Mergers:
Going Beyond the Equation of State

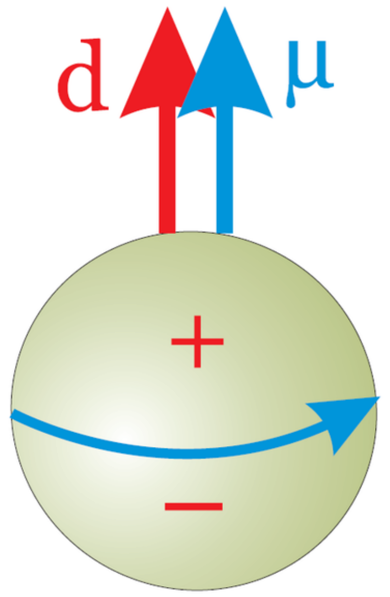
INSTITUTE for NUCLEAR THEORY

UNIVERSITY · OF · WASHINGTON · LVX · SIT · 1861

The Strong-CP problem

- Theoretically expect significant Charge+Parity violation in potential of strong interactions

- This would give the neutron an electric dipole moment



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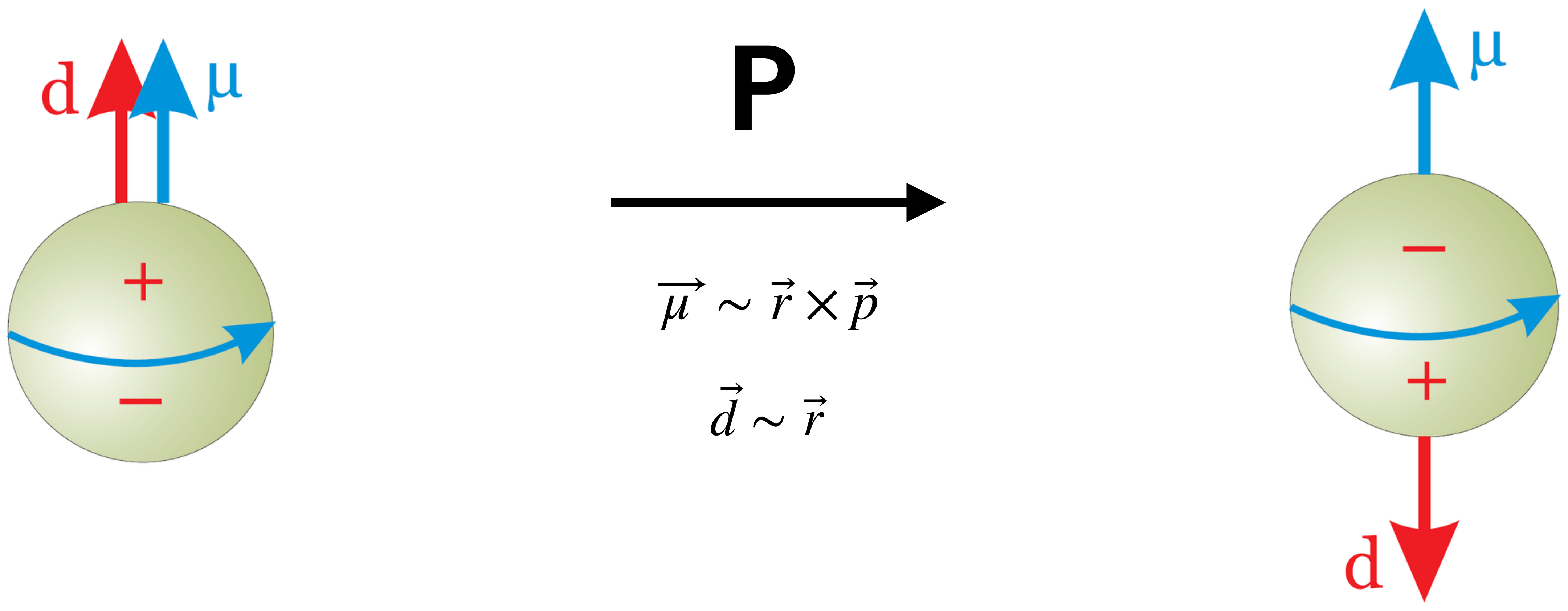


$$\vec{\mu} \cdot \vec{d} \rightarrow -\vec{\mu} \cdot \vec{d}$$

The Strong-CP problem

- Characterized by CP violating parameter of gluon field strength θ and the quark mass matrix phase

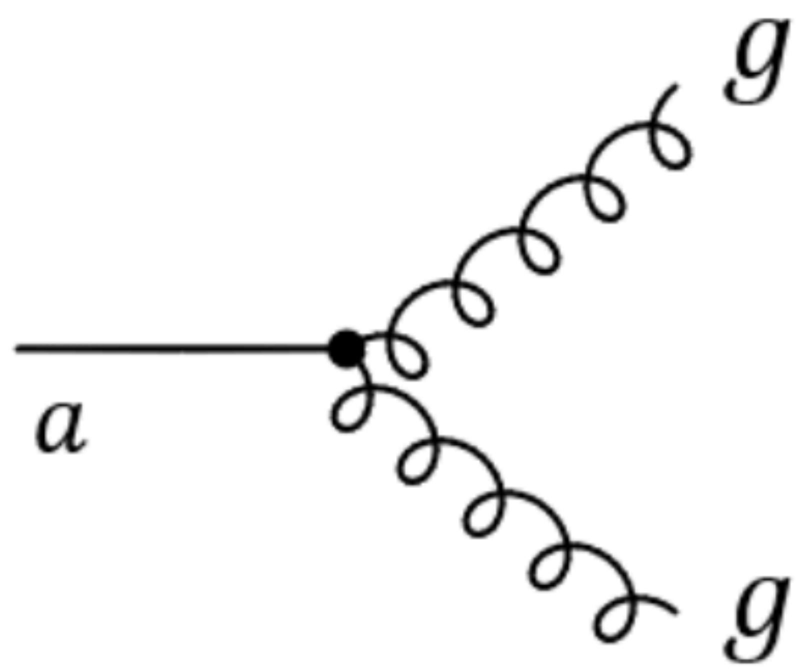
  - Expected value: $|d_n| \sim 2 \times 10^{-16} \theta \cdot e \cdot \mathrm{cm}$

  - Experimental upper bound: $|d_n| < 10^{-26} \cdot e \cdot \mathrm{cm}$

$$\longrightarrow \theta < 10^{-10}$$

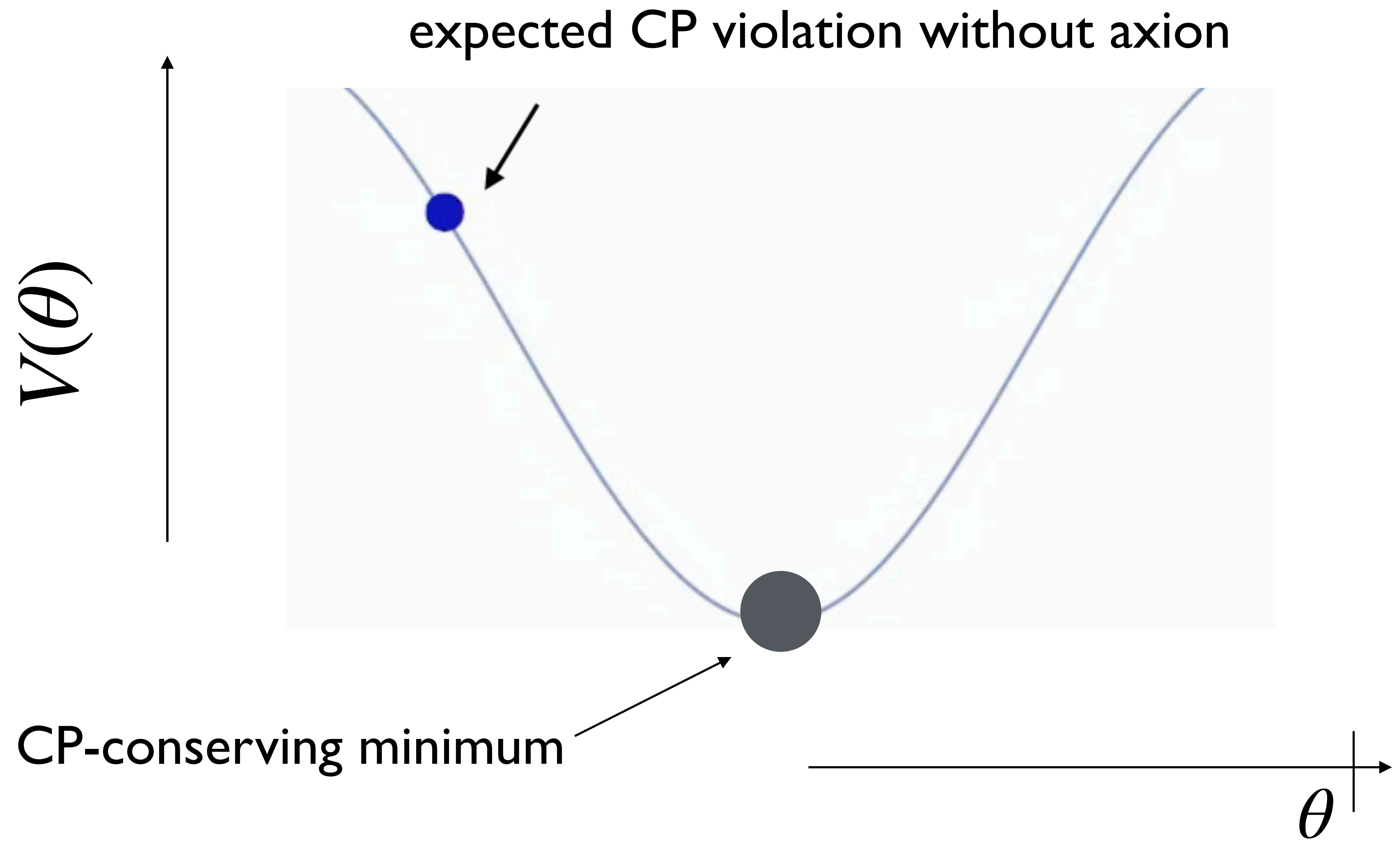
- If θ is a fixed parameter of the theory, this is a huge unexplained tuning

The Strong-CP Solution?



- Solve the problem by promoting $\theta \rightarrow a/f_a$ to a dynamical field, the axion

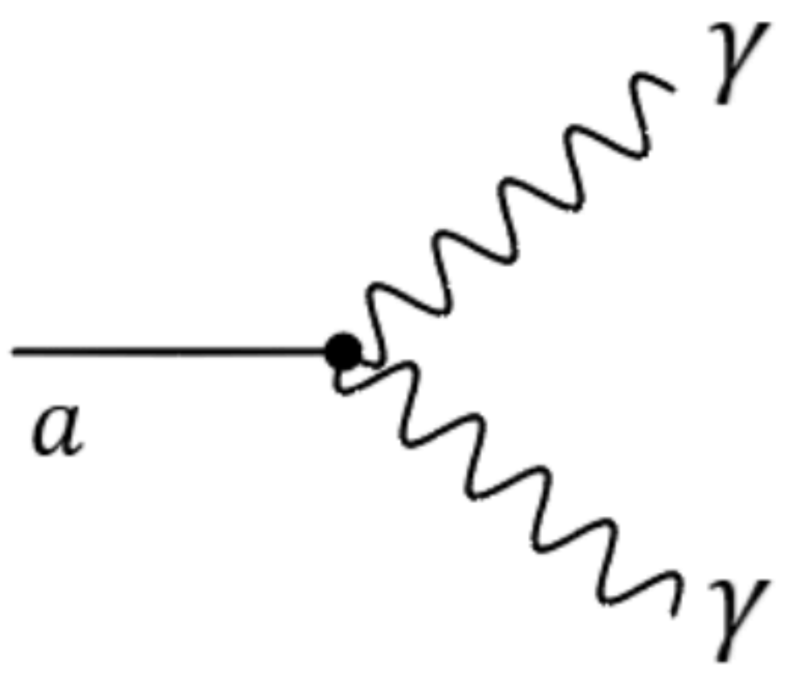
- Strong interaction effects give axion a potential and it relaxes the CP angle to zero, solving the strong-CP problem

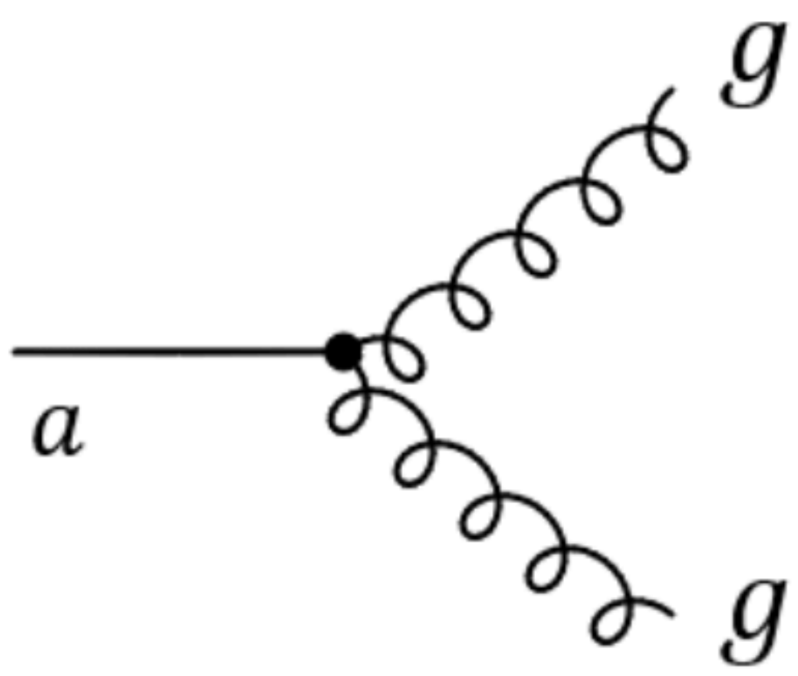


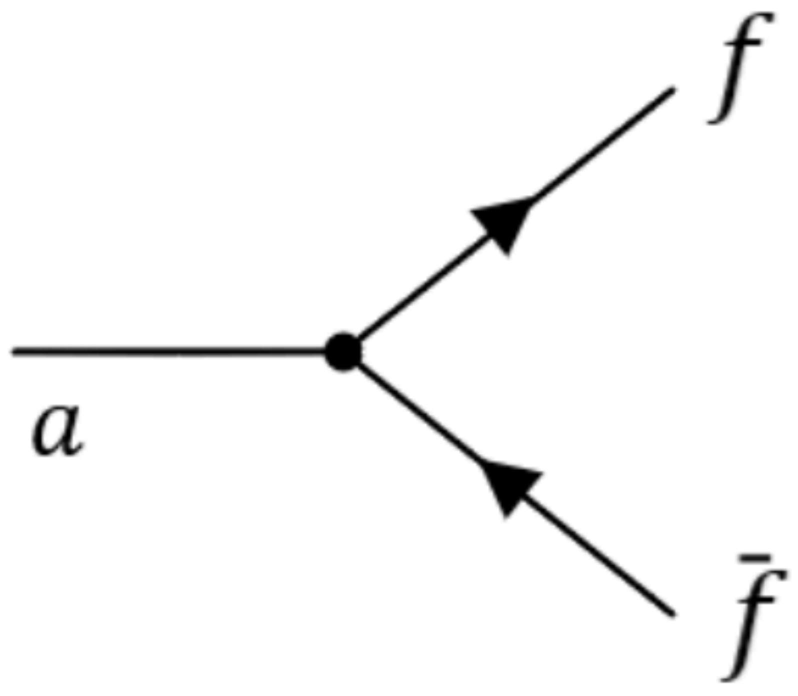
Peccei and Quinn, PRL 38, 1440, 1977
Weinberg, PRL 40, 223, 1978
Wilczek, PRL 40, 279, 1978

How to observe an axion

- Axions are ultralight and weakly coupled: `harmless' or `invisible'
- Generically have couplings to photons, standard model fermions







$$g_{a\gamma\gamma} \sim \frac{\alpha_{\mathrm{EM}}}{\pi f_a} \qquad \frac{1}{f_a}$$

J. E. Kim Phys. Rev. Lett. 43 (1979) 103.
M. A. Shifman, A. I. Vainshtein and V. I. Zakharov Nucl. Phys. B 166 (1980) 493.
M. Dine, W. Fischler and M. Srednicki Phys. Lett. B 104 (1981) 199.
A. R. Zhitnitsky Sov. J. Nucl. Phys. 31 (1980) 260.

How to observe an axion

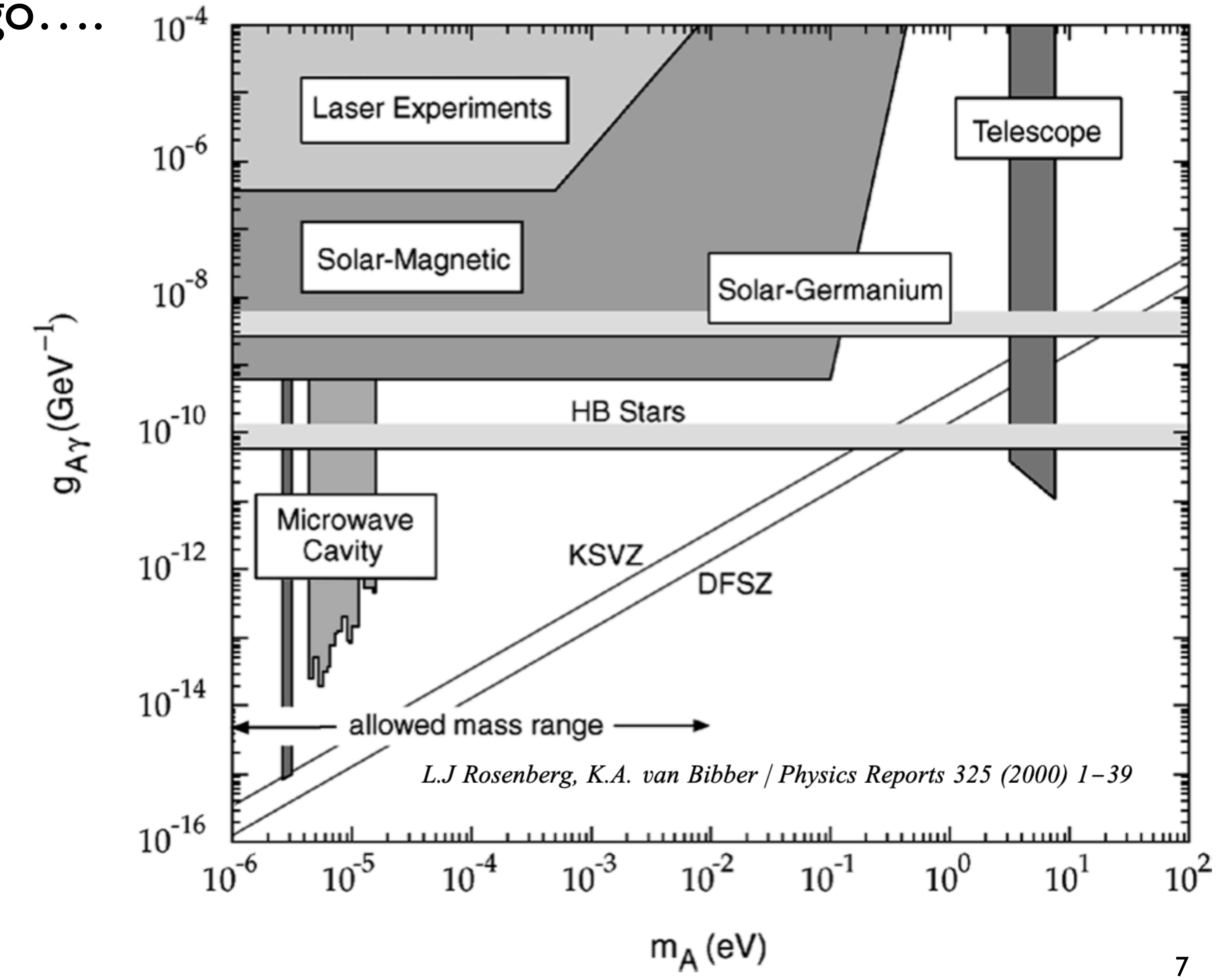
- Axions most elegant solution to the Strong-CP problem
- Consistent (`inevitable') production as dark matter candidate in much of parameter space

- a window into the **highest scales. 25 years ago….**

To reach QCD axion line:

-DM production plus lab detection

- production in and modification of astrophysical objects



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How to observe an axion

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- a window into the **highest scales**
- **Today…**

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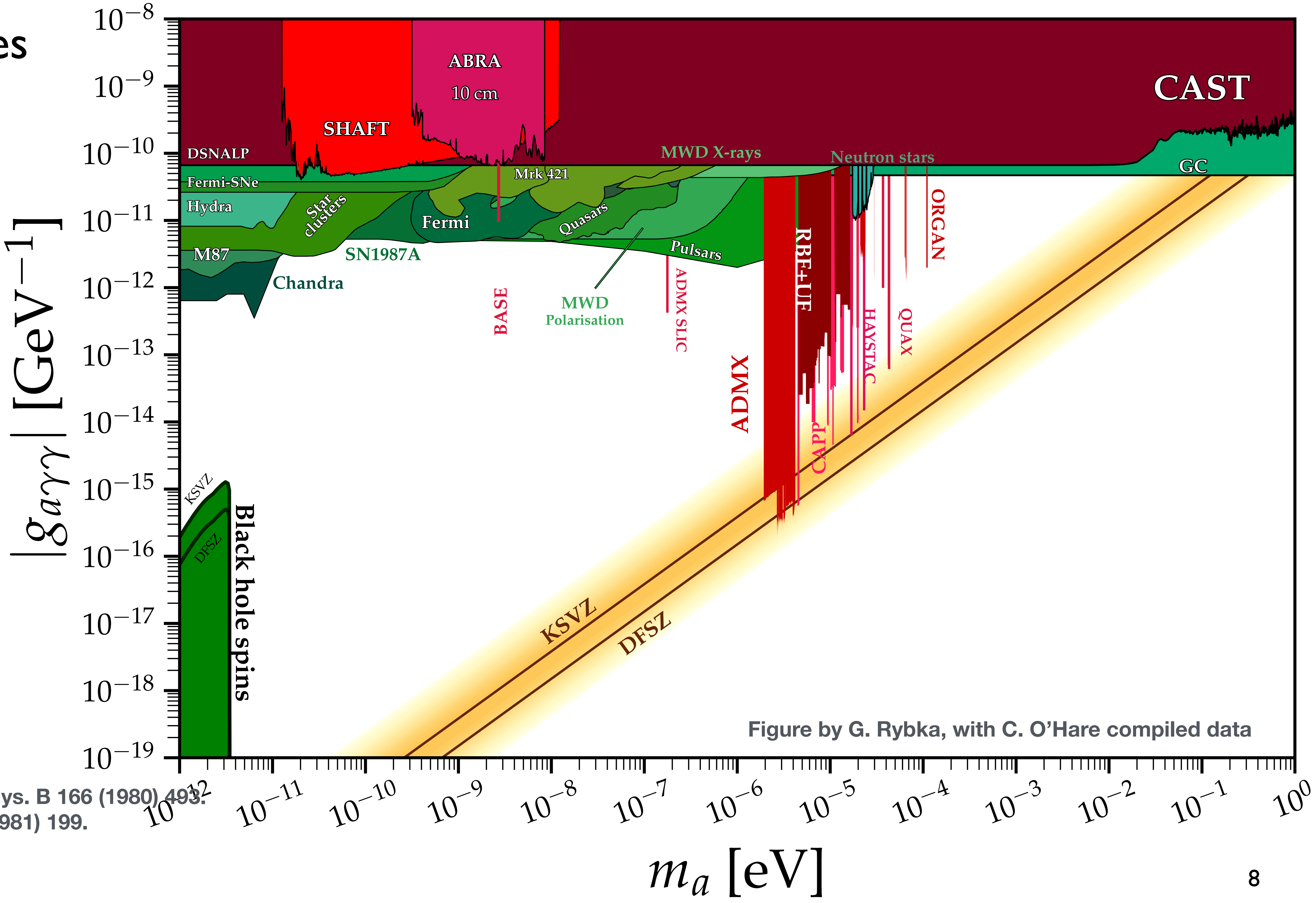
- production in and modification of astrophysical objects



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- θ and QCD

- QCD at $\theta=\pi$

- Toward QCD axions in neutron stars

arXiv:1708.08464 Hook & Huang
arXiv:2410.21590 Kumamoto, Huang, Drischler, MB, Reddy + work in progress

θ and QCD

At low temperature and density, degrees of freedom are goldstones of chiral symmetry breaking, the three pions

Pion potential proportional to chiral condensate and light quark mass (spurion of explicit breaking)

Chiral rotation of quarks moves θ from gluons to quarks; can absorb dependence in quark mass matrix

$$u \to \exp\{(i\gamma_5\phi_u)\}u \qquad d \to \exp\{(i\gamma_5\phi_d)\}d \qquad \phi_u + \phi_d = \theta$$

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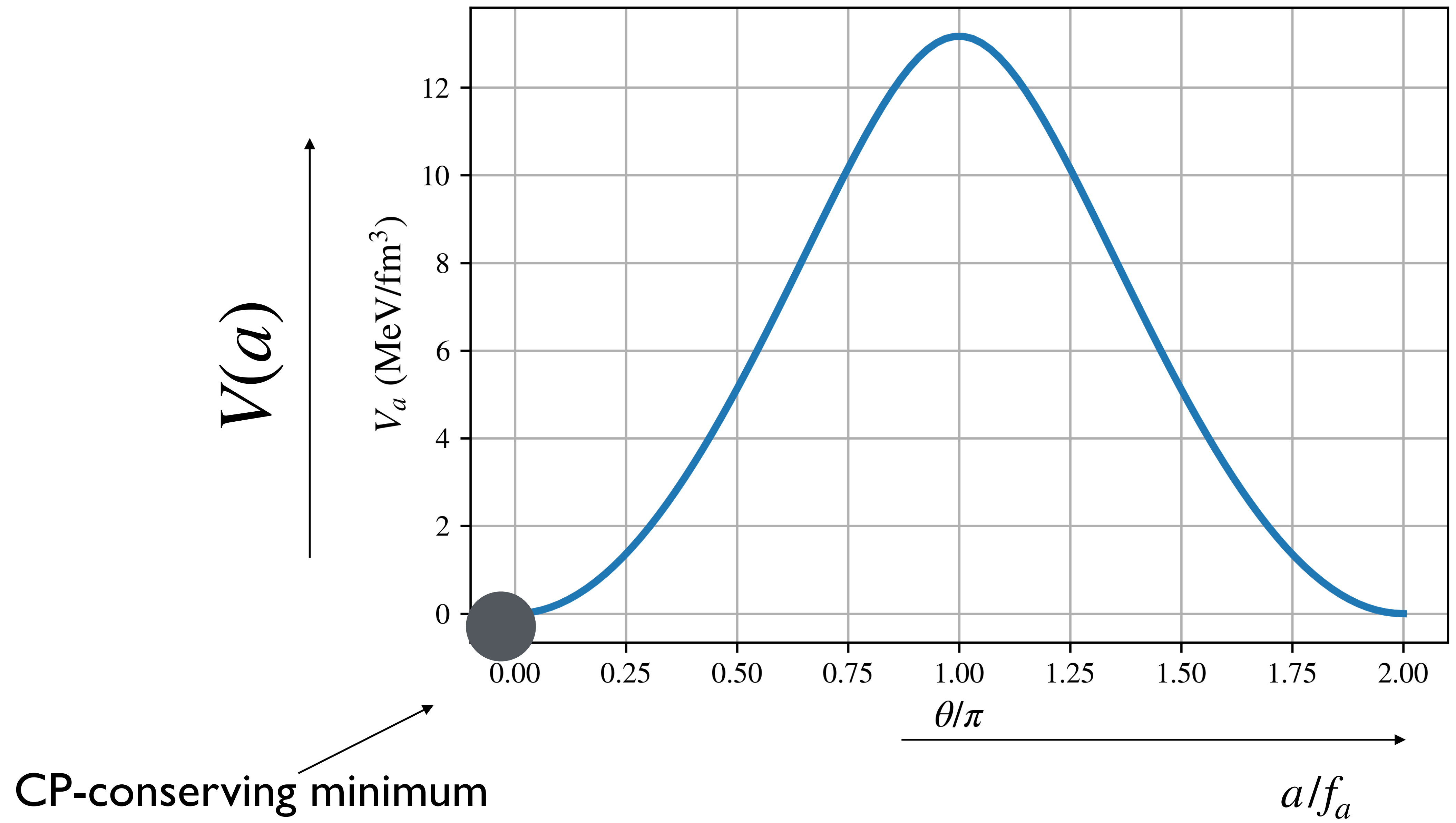
Finite θ shifts the QCD vacuum with an energy cost, generating a potential for the axion



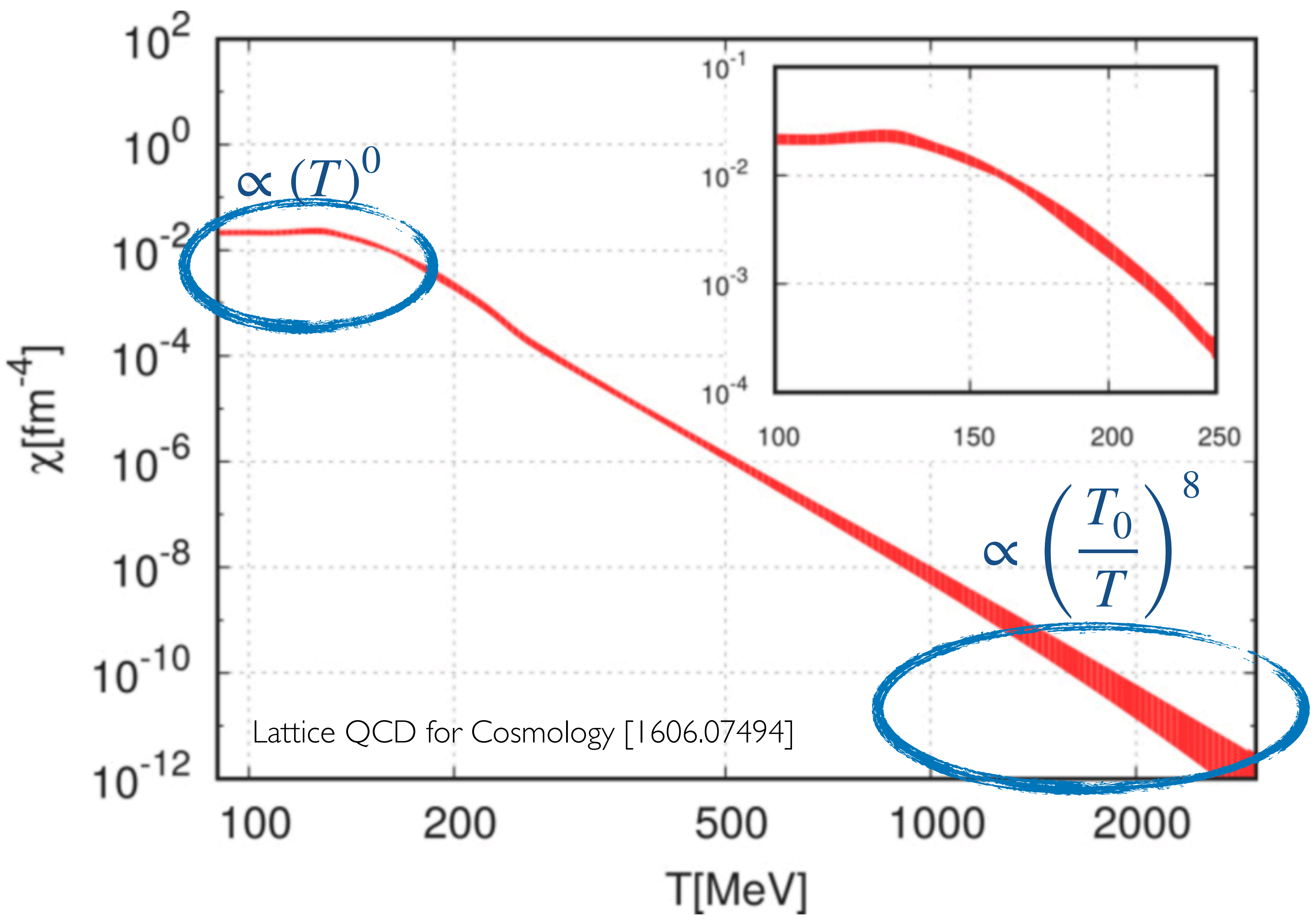
$$V_a(\theta) = (f(\theta) - 1) \times 2m_q\langle\bar{q}q\rangle$$

$$\langle\bar{q}q\rangle \to -f_\pi^2 m_\pi^2$$

$$f(\theta) = \sqrt{1 - \frac{4m_u m_d}{(m_u+m_d)^2}\sin^2\frac{\theta}{2}}$$

Ranges from 1 to ~0.36

θ and strong interactions at finite temperature



$$m_a^2(T) f_a^2 = \left.\frac{\partial^2 F(\theta, T)}{\partial \theta^2}\right|_{\theta=0} \equiv \chi(T)$$

- Finite θ shifts the QCD vacuum creating an energy cost which reduces at high temperatures
- Consistent expansions at low and high temperatures
- Possible to use lattice techniques to interpolate at intermediate densities
- Important for understanding axion dark matter evolution in our universe's history

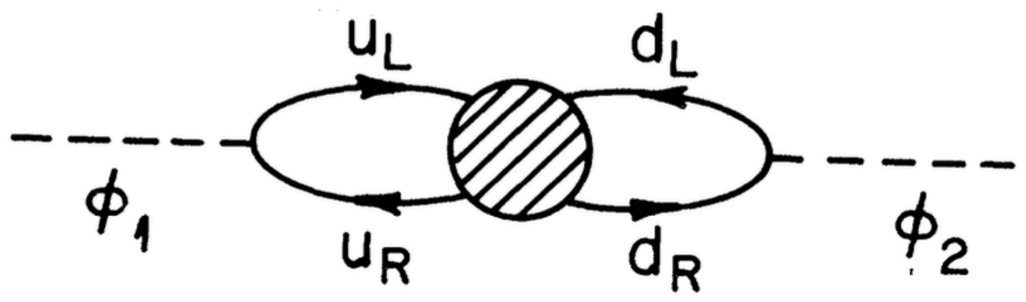


FIG. 1. Instanton interaction generating the axion mass.

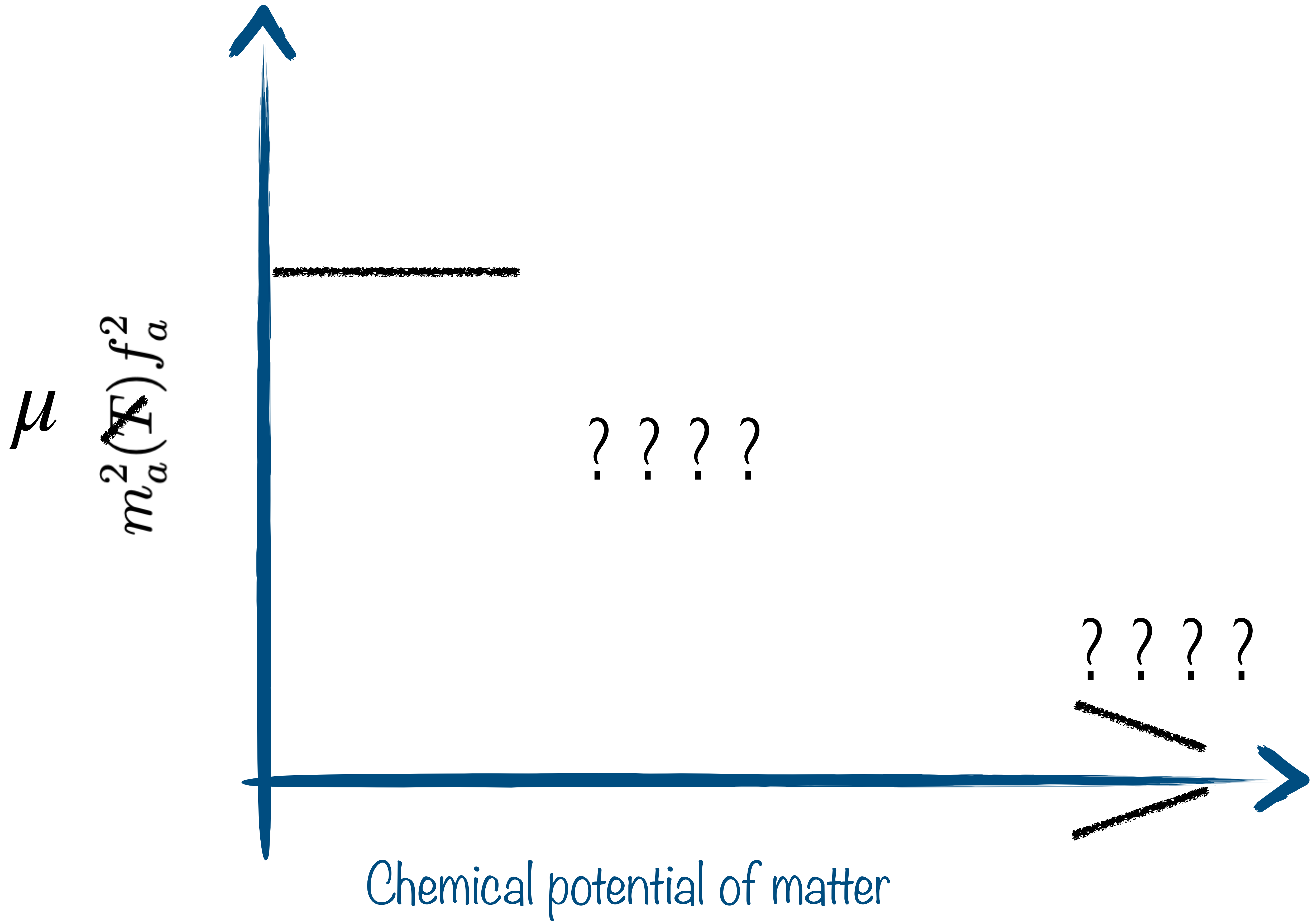
Wilczek, PRL 40, 279, 1978

θ and QCD at finite density

- Unlike finite temperature, little understanding at intermediate densities and even limited at high density

- Not currently possible to use lattice techniques to address the question

- Determines nature of dense matter in the presence of axions



θ and QCD at finite density

- Can get some insight at low density: quark condensates are modified in nuclear matter

$$2m_q\left(\langle\bar{q}q\rangle_{n_B} - \langle\bar{q}q\rangle_{vac}\right) = m_q\frac{d\mathcal{E}}{dm_q}$$

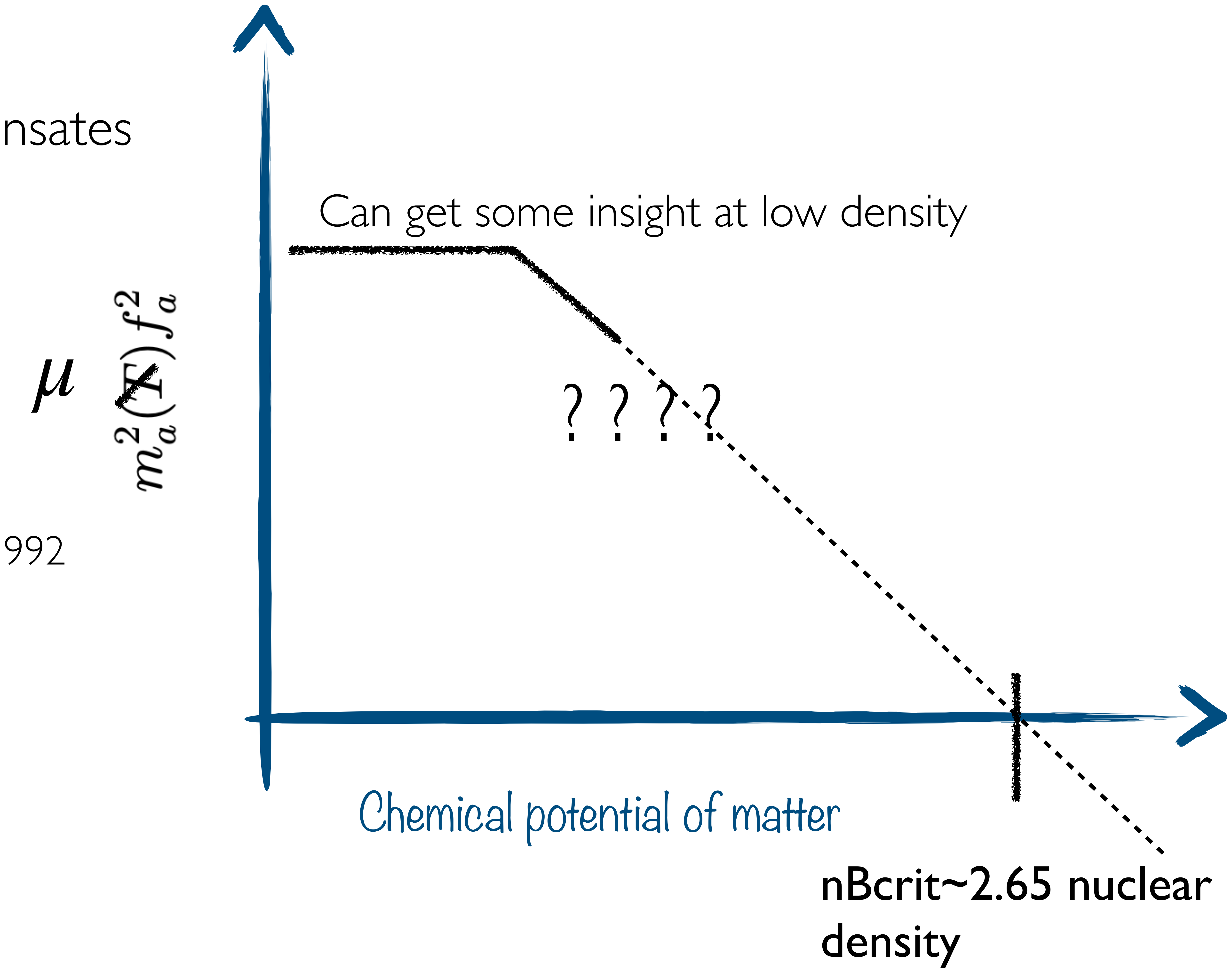
$$\mathcal{E} \simeq M_N n_B + d\mathcal{E}$$

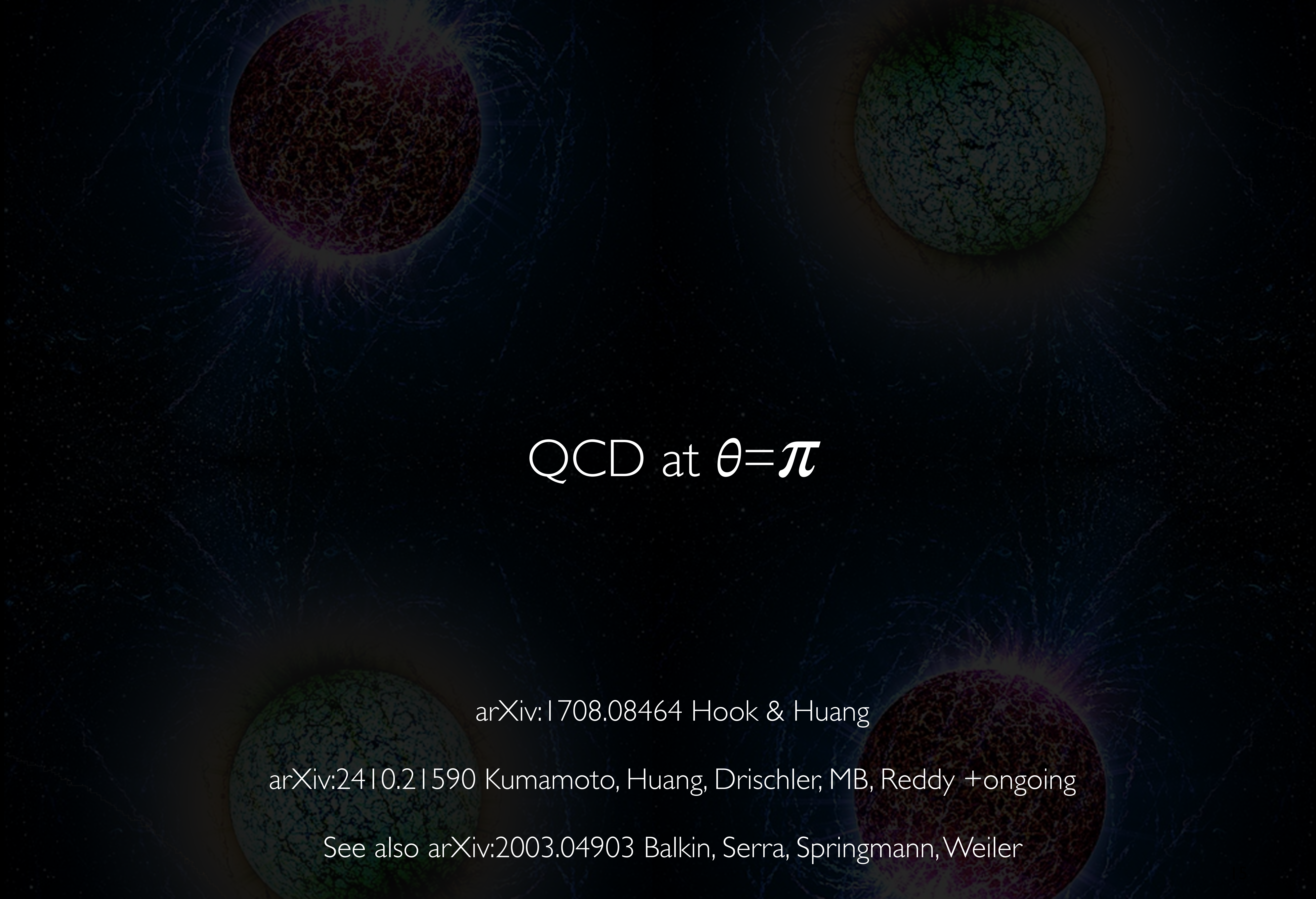
Cohen, Furnstahl, Griegl Phys Rev C 1992

$$m^2_{a,\text{eff}}(n_B, n_I) = m_a^2\left[1 - \frac{\sigma_N n_B}{f_\pi^2 m_\pi^2} + \ldots\right]$$

$$\sigma_N = m_q\frac{dM_N}{dm_q}$$ ~50 MeV

Anson Hook & Junwu Huang **1708.08464**





QCD at $\theta = \pi$

arXiv:1708.08464 Hook & Huang

arXiv:2410.21590 Kumamoto, Huang, Drischler, MB, Reddy +ongoing

See also arXiv:2003.04903 Balkin, Serra, Springmann, Weiler

QCD at $\theta = \pi$

- The up quark mass effectively switches sign, making the pions significantly lighter

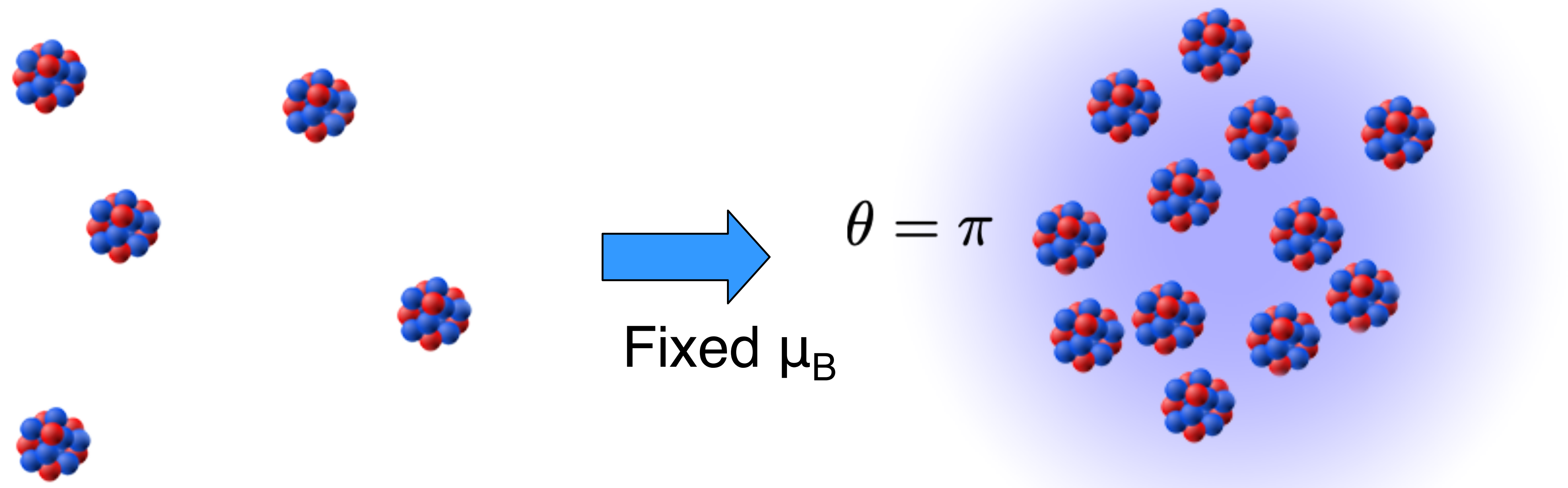
$$m_\pi^2 \propto (m_u e^{i\pi} + m_d) = (-m_u + m_d) \sim 80\,\mathrm{MeV}$$

- Nucleon masses are reduced, by a relatively smaller amount (~30 MeV)

$$m_N(\theta) = m_N(0) + \underbrace{\sigma_N(f(\theta)-1)}_{45-60\,\mathrm{MeV}} - \tau_3 \Delta\sigma \underbrace{\left(\frac{1}{f(\theta)} - 1\right)}_{1-2\,\mathrm{MeV}} + \mathcal{O}(m_\pi^3)$$

reduced mass **isospin breaking** higher-order effects

- Modifications to QCD could *in principle* cause a local distribution of matter to **gain more energy** in the presence of an axion **than it loses** to the axion vacuum potential!

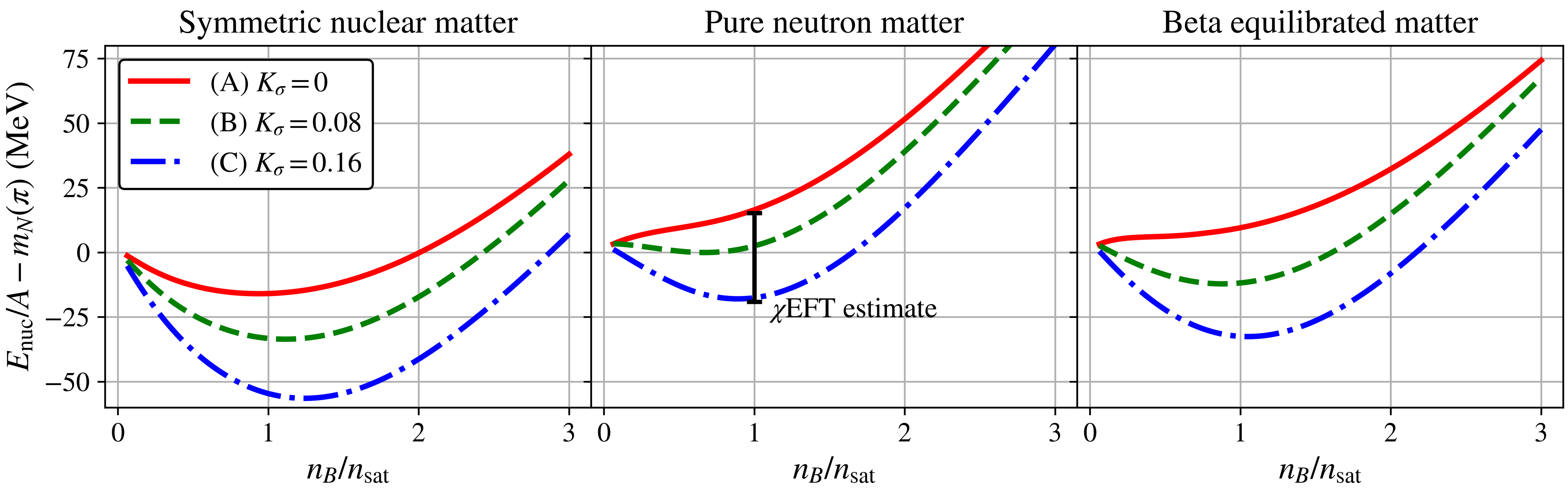


$$\Delta\Omega \simeq (m_\pi^2 f_\pi^2 - \sigma_N n_B)(1 - f(\theta))$$

$$n_B^{\mathrm{crit}} = \frac{f_\pi^2 m_\pi^2}{\sigma_N}$$

Slide from Mia Kumamoto

Taking into account nuclear interactions



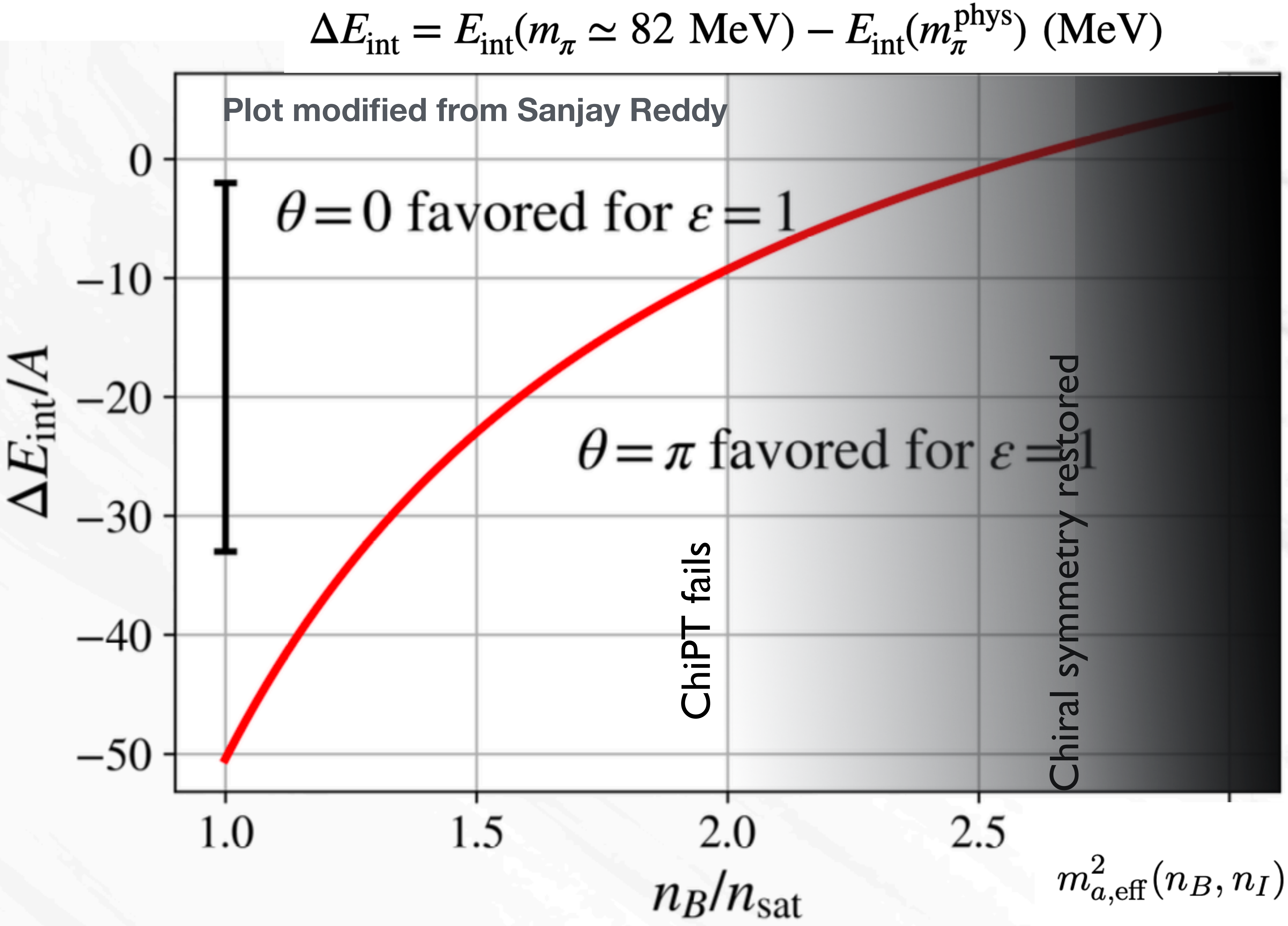
- Scenario B : σ mass modified to match meson mass calculations
- Scenario C : Neutron matter binding matches estimate from MBPT calculation

$$K_\sigma = \frac{m_\pi^2}{m_\sigma}\frac{\partial m_\sigma}{\partial m_\pi^2}$$

$$m_{a,\rm eff}^2(n_B, n_I) = m_a^2\left[1 - \frac{1}{\varepsilon}\frac{\sigma_N n_B}{f_\pi^2 m_\pi^2}\left(1 + \frac{K_\sigma g_\sigma^2 n_B}{\sigma_N \chi m_\sigma^2} - \frac{n_I}{n_B}\frac{\Delta\sigma}{\sigma_N}\right)\right]$$

What happens at higher density where interactions are important?

Does the QCD axion condense?



Higher density: more nuclei get lighter per unit volume, can overcome axion potential barrier ~13MeV / fm^3

Nuclei get about 30 MeV/nucleus of mass energy at theta=pi

Can we also gain interaction energy? Pions are lighter so nuclear forces may get stronger/more attractive

$$m_{a,\rm eff}^2(n_B, n_I) = m_a^2 \left[1 - \frac{\sigma_N n_B}{f_\pi^2 m_\pi^2}\left(1 + \frac{K_\sigma g_\sigma^2 n_B}{\sigma_N \chi m_\sigma^2} - \frac{n_I}{n_B}\frac{\Delta\sigma}{\sigma_N}\right)\right]$$

In the meantime…

π in the sky

Neutron Stars with Exceptionally Light QCD Axions

arXiv:1708.08464 Hook & Huang
arXiv:2410.21590 Kumamoto, Huang, Drischler, MB, Reddy
… ongoing work

See also Reuven Balkin, Javi Serra, Konstantin Springmann, Stefan Stelzl, Andreas Weiler

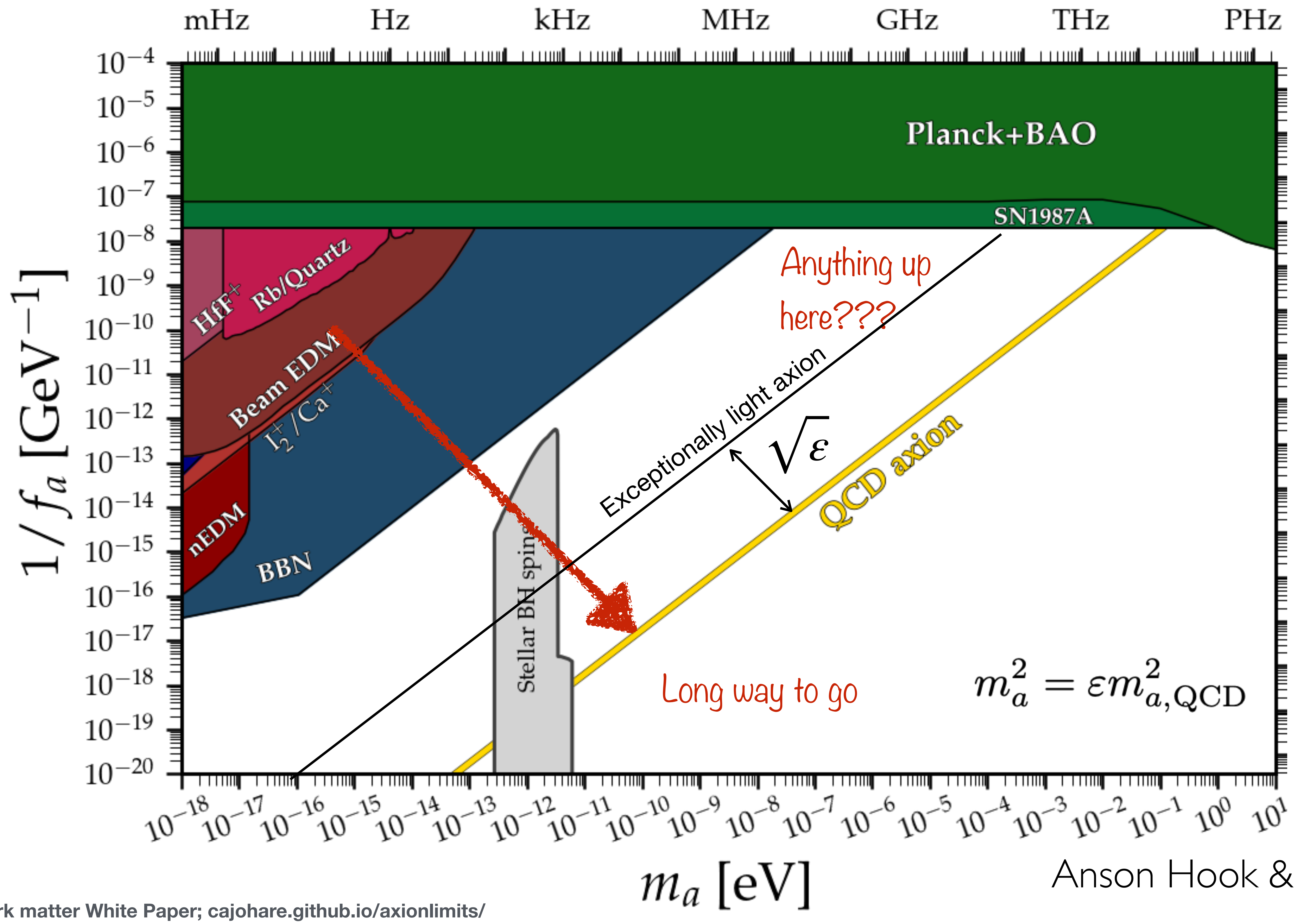
[arXiv:2307.14418] and [arXiv:2211.02661] —heavy neutron stars and modified white dwarfs

2110.07012 Gao and Stebbins - compact stars and scalars

Gomez-Banon et al 2024 —modifications to neutron star cooling

Why "Exceptionally light" QCD Axions?

- Make progress on interesting dynamics at densities where we still have perturbative control
- Have to go through this parameter space on the way to the QCD axion



Anson Hook & Junwu Huang **1708.08464**

CF2 axion dark matter White Paper; cajohare.github.io/axionlimits/

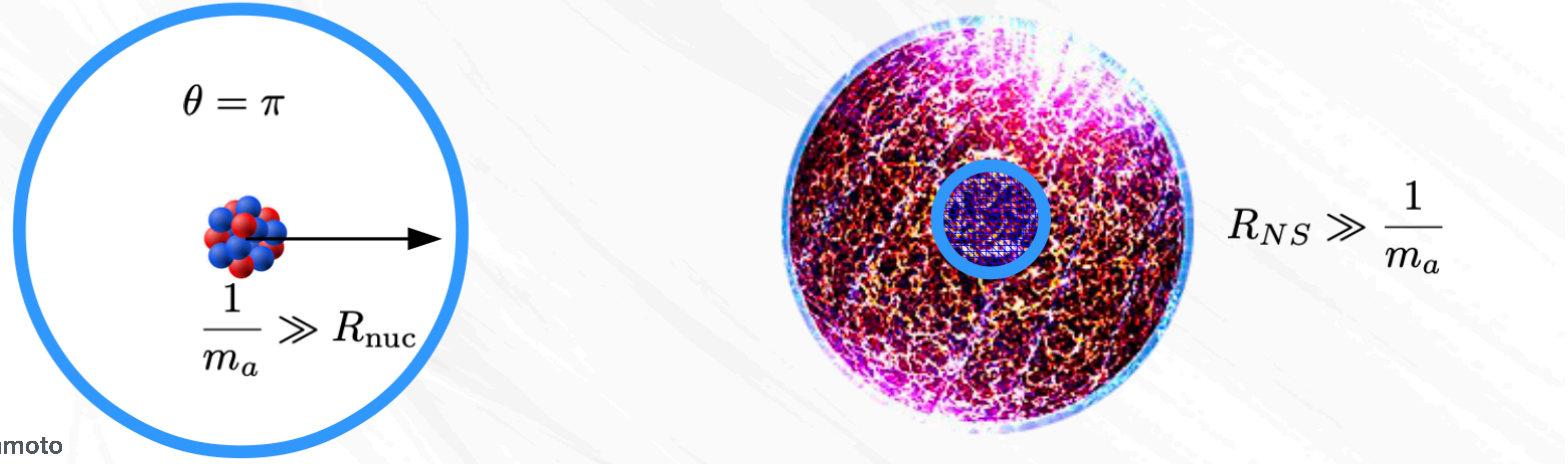
Neutron Stars and Exceptional Axions

$$\Delta\Omega \simeq (\varepsilon m_\pi^2 f_\pi^2 - \sigma_N n_B)(1 - f(\theta)) \qquad n_B^{\rm crit} = \frac{\varepsilon f_\pi^2 m_\pi^2}{\sigma_N}$$

Potential energy $m_\pi^2 f_\pi^2(\epsilon - \frac{\sigma_N n_N}{m_\pi^2 f_\pi^2})$ minimized if axion value is of order π inside matter

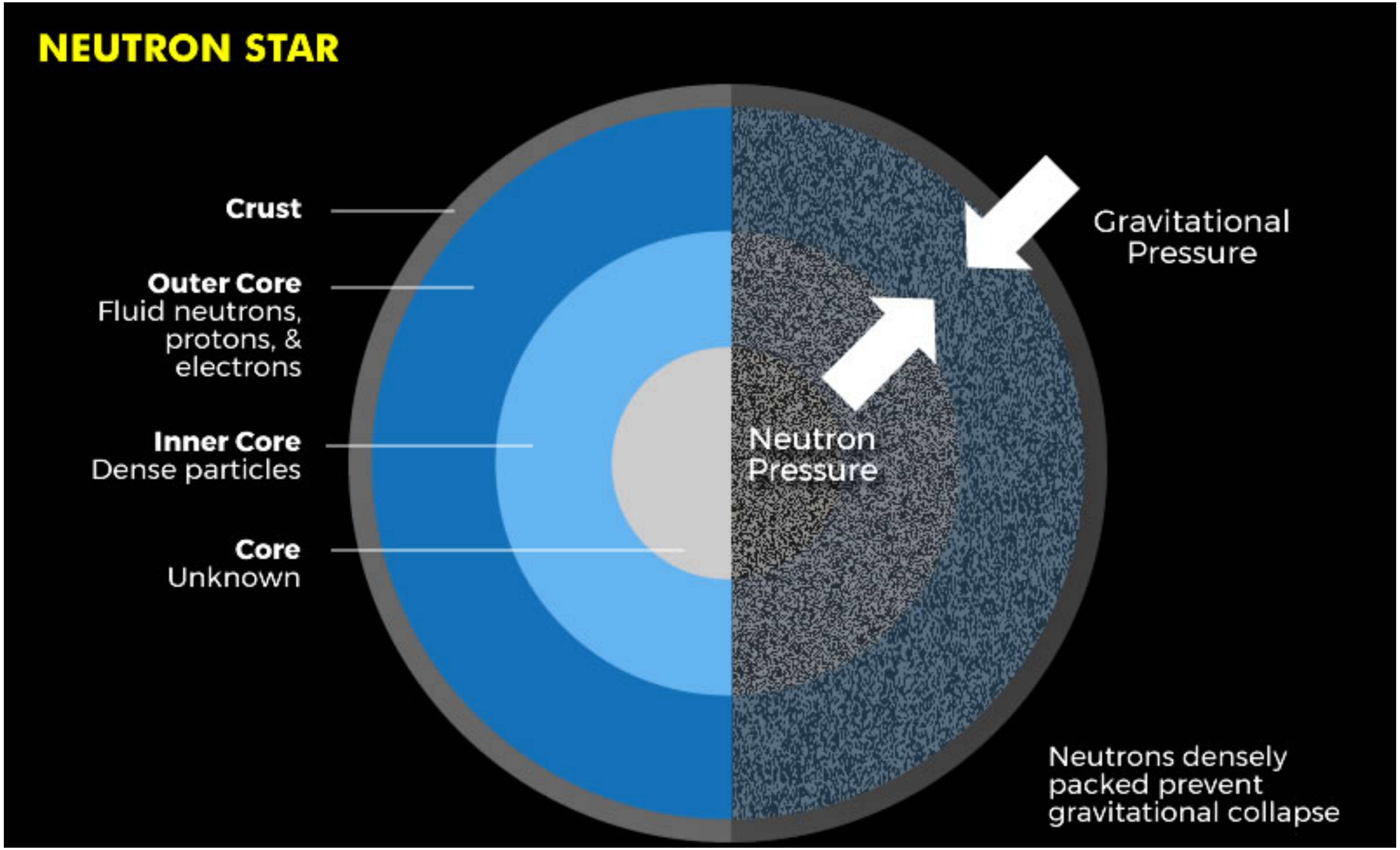
Gradient energy f_a^2/r^2 minimized if axion value remains zero throughout

For large, dense objects like neutron stars the potential energy wins and the axion has a profile sourced by the neutron star



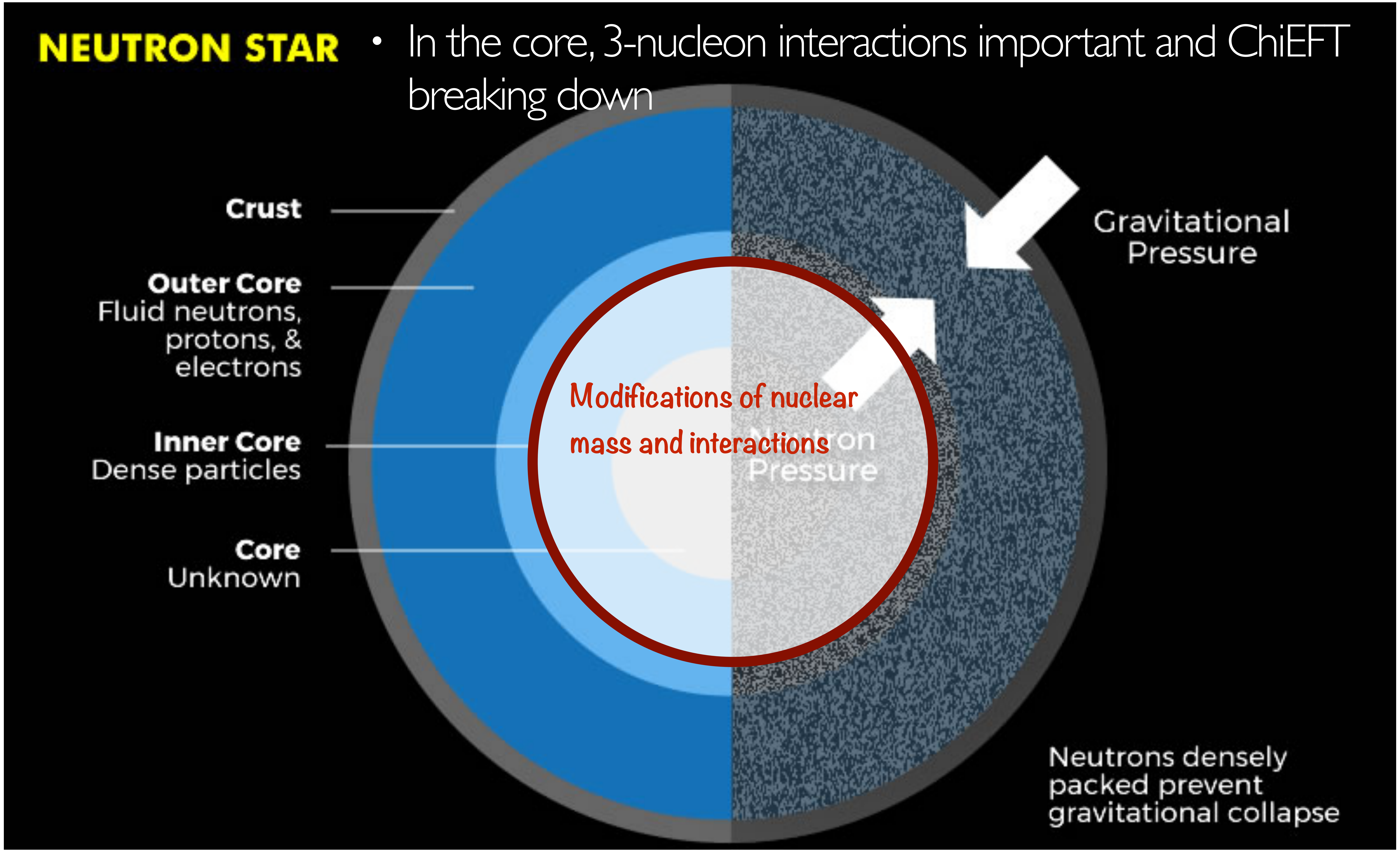
Slide from Mia Kumamoto

Neutron stars without axions



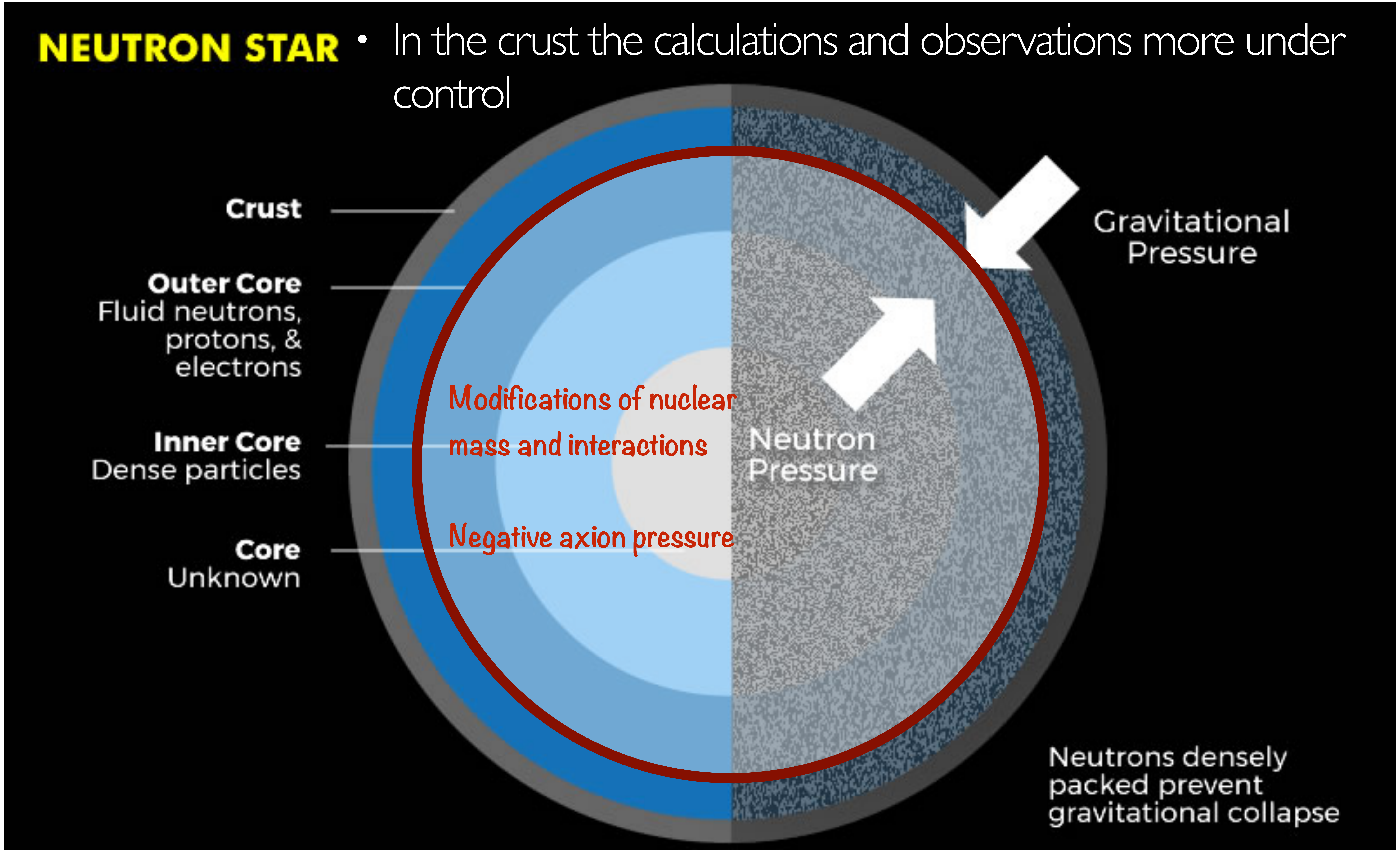
Neutron stars with axions: large epsilon

- In the core, 3-nucleon interactions important and ChiEFT breaking down



Neutron stars with axions: intermediate epsilon

- In the crust the calculations and observations more under control



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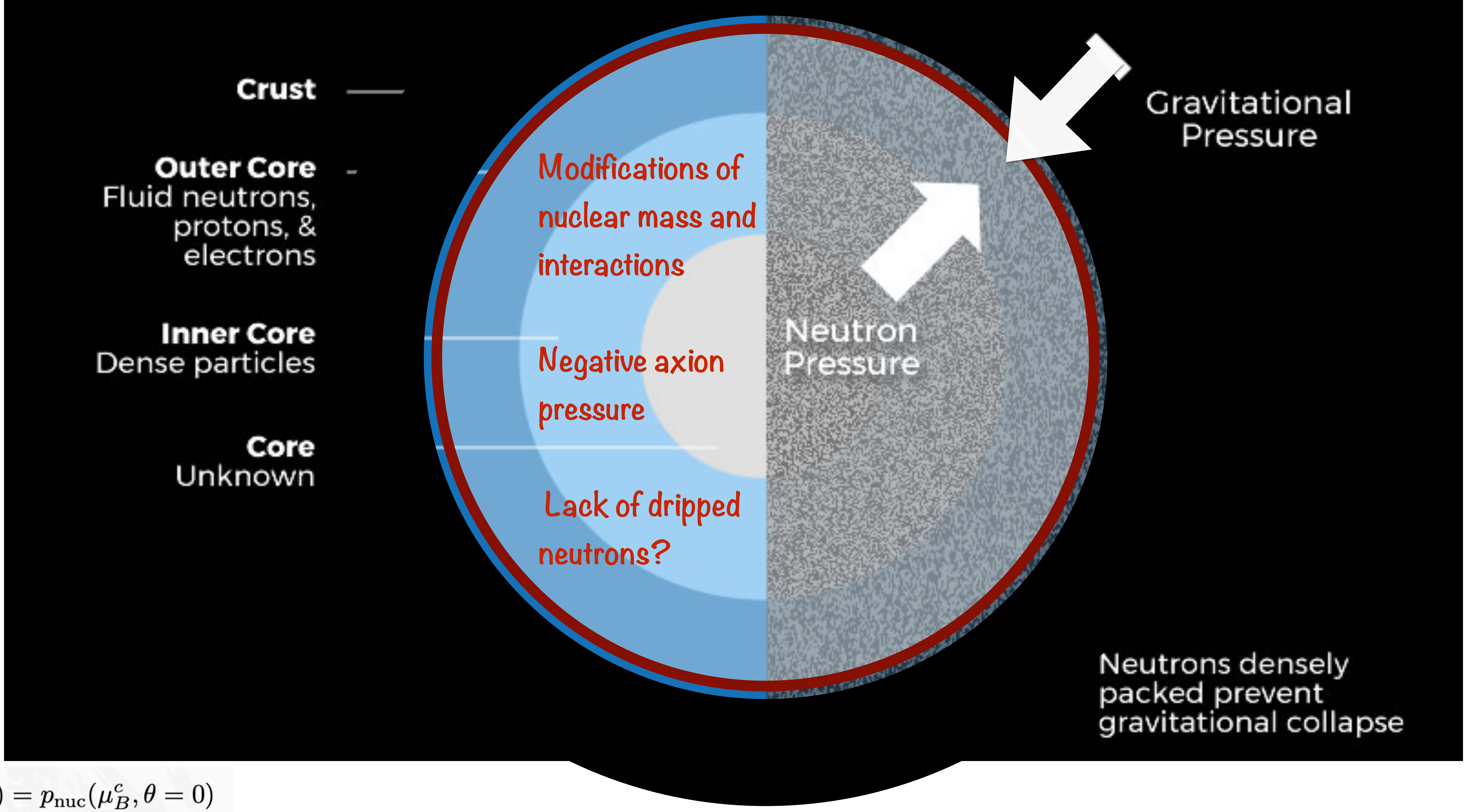
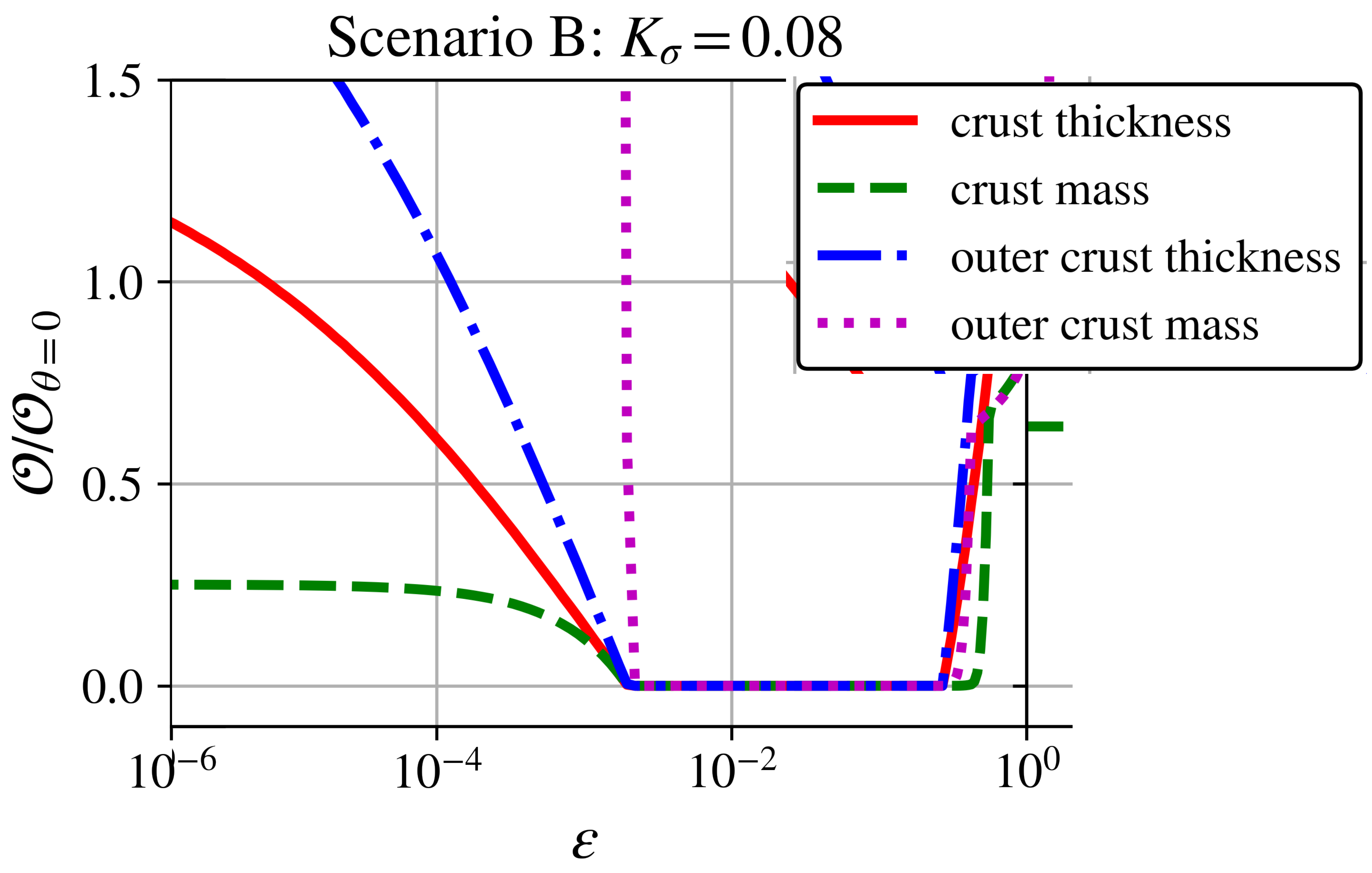


$$p_{\rm nuc}(\mu_B^c, \theta = \pi) - V(\theta) = p_{\rm nuc}(\mu_B^c, \theta = 0)$$

Crustless neutron stars with axions



$$p_{\rm nuc}(\mu_B^c, \theta = \pi) - V(\theta) = p_{\rm nuc}(\mu_B^c, \theta = 0)$$

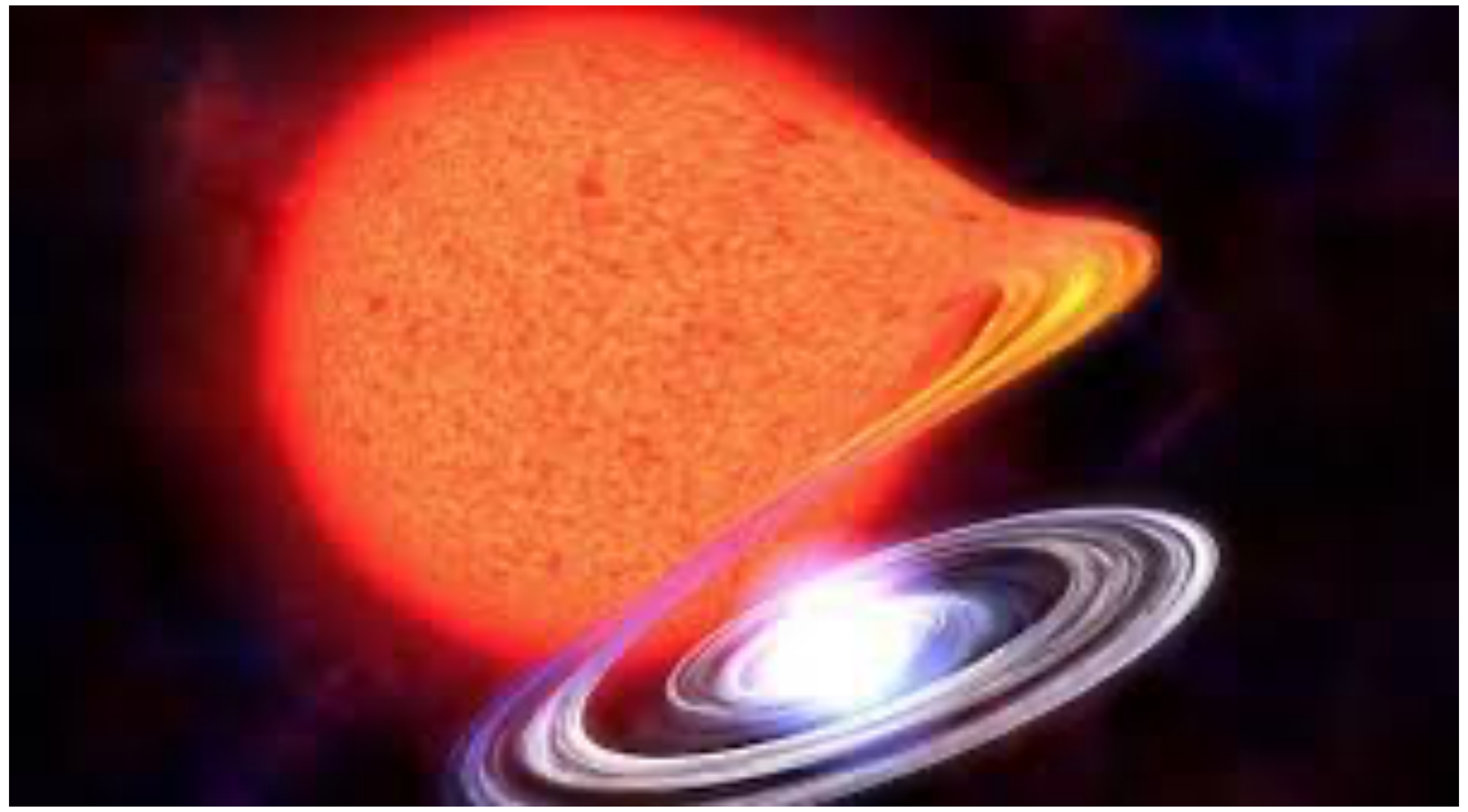
- An axion domain wall order the Compton wavelength of the axion sits at a position where where the resulting pressures of axion and normal regions are equal
- Axion potential provides negative contribution to the pressure, causing the star to `end' at finite density
- If interactions are more attractive, there are no dripped neutrons

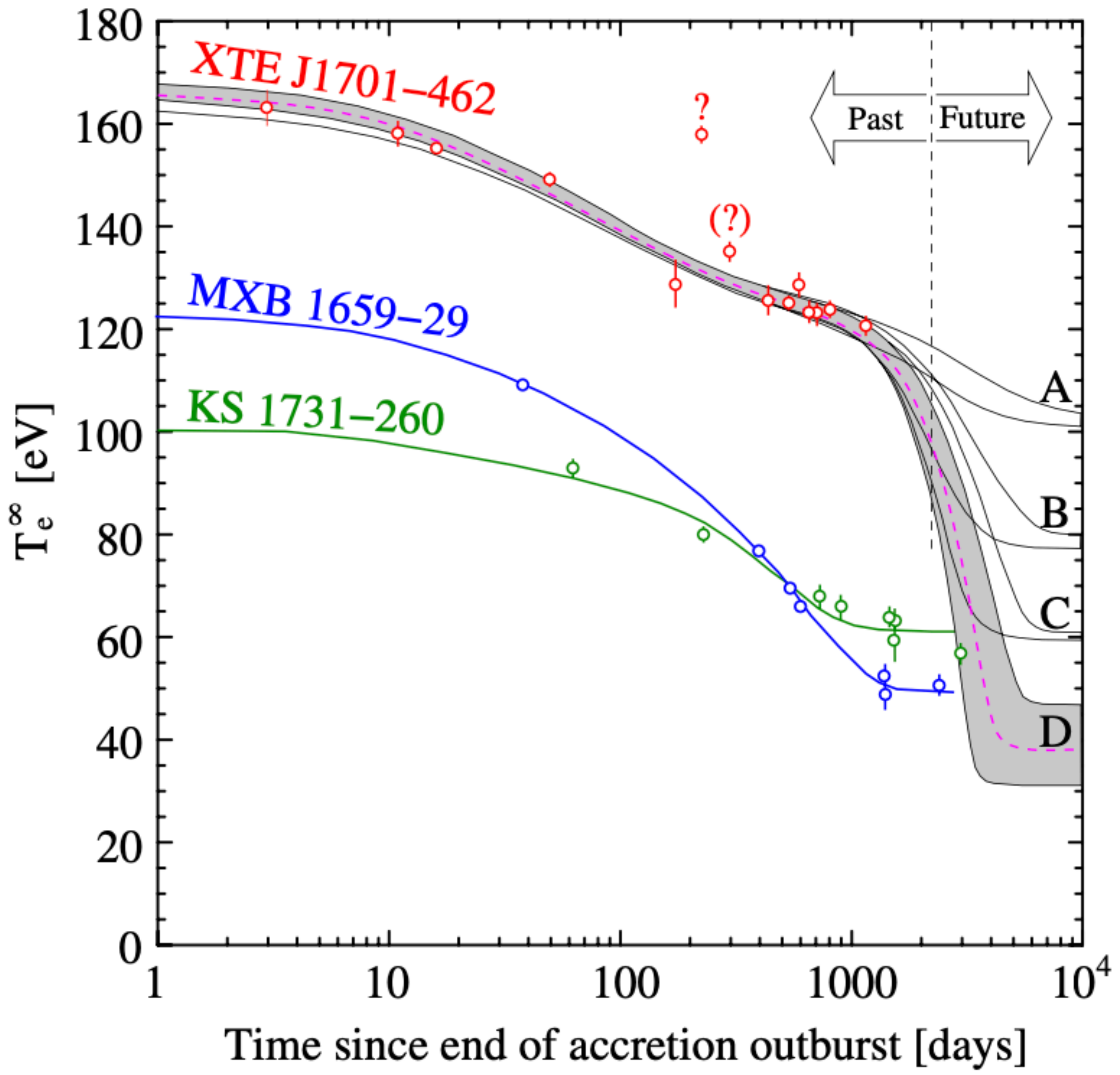
Crust thermal relaxation

- Some neutron stars in x-ray binaries transiently accrete material from their companion, heating the neutron star during accretion outbursts.
- Timescale for the crust to thermally relax following outburst can be observed, given by heat capacity, conductivity and the thickness of the crust squared:

$$\tau_{\rm th} \simeq \frac{C_V (\Delta r)^2}{\kappa}$$

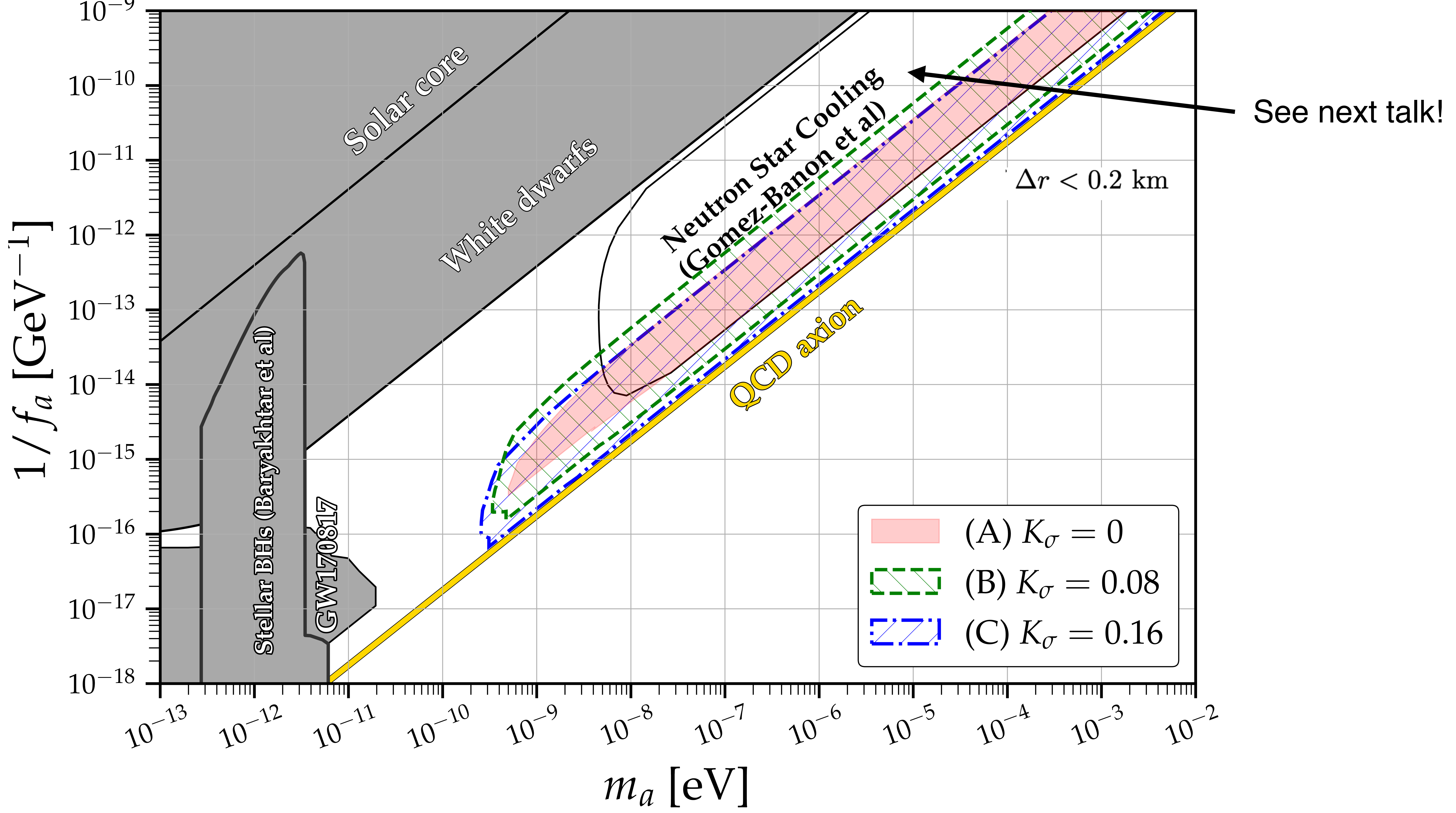
- Conservatively estimate that a crust thickness decrease by a factor of 5 is excluded by observations





Page and Reddy (2013)

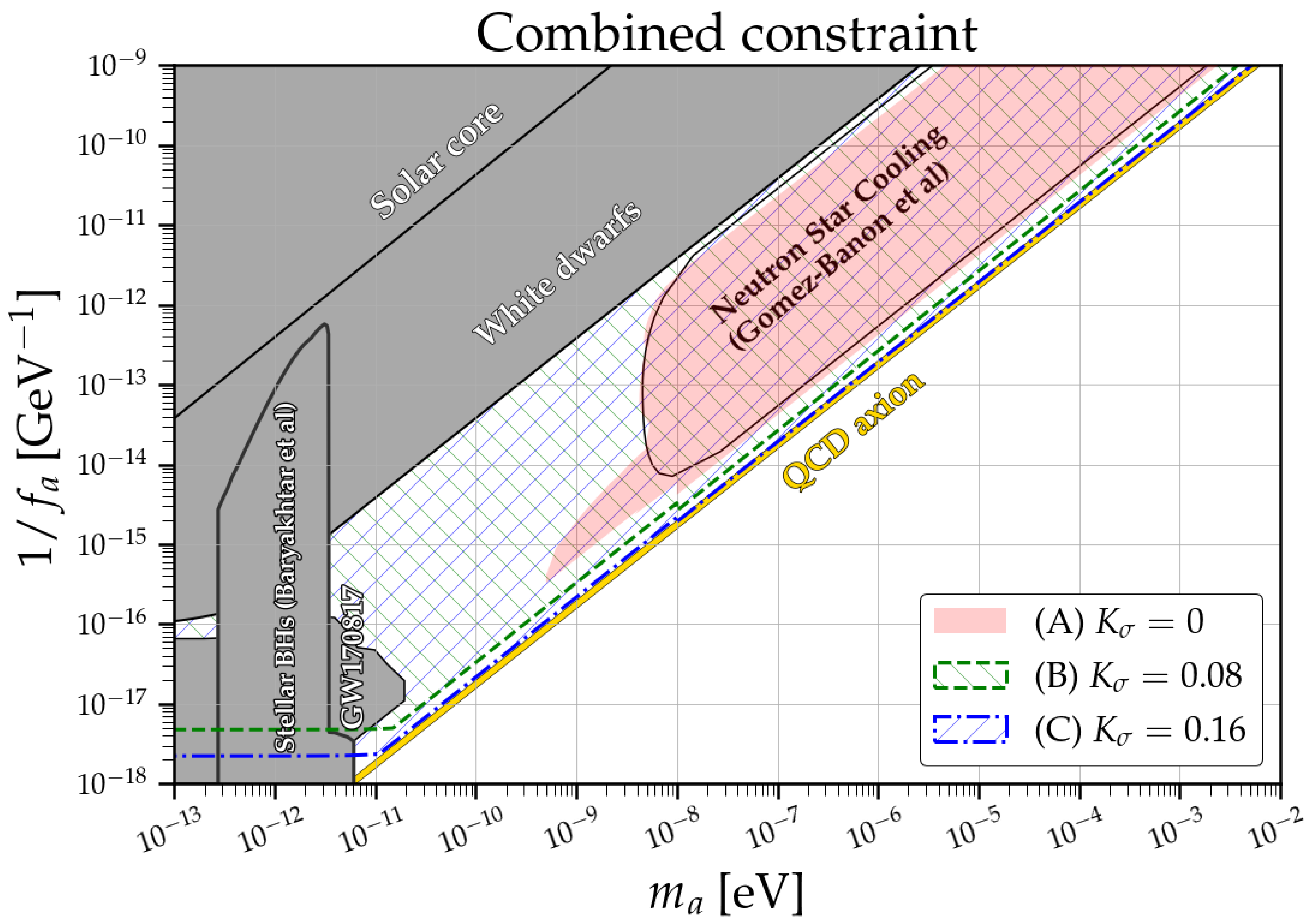
Constraint from crust thermal relaxation



	(A) $K_\sigma = 0$	(B) $K_\sigma = 0.08$	(C) $K_\sigma = 0.16$
Min. excluded ε	2.2×10^{-3}	8.7×10^{-4}	2.5×10^{-3}
Max. excluded ε	0.10	0.32	0.69

Summary

- The axion potential is controlled by QCD and is suppressed with increasing nuclear density
- With increasing θ, nucleons and pions become lighter and dense matter is significantly affected
- Up to nuclear densities, the QCD axion does not condense but outer regions of neutron stars can explore exceptionally light axion parameter space;
- Observables include neutron star cooling, crust thermal relaxation, and pulsar glitches
- More attractive interactions can make condensation more likely; is there *any* density at which $\theta = \pi$ is preferred?



π in the Sky:

Interplay between axions and dense matter creates new ways to create and test axions in our universe

Better understanding of high density QCD is increasingly crucial for progress!