Pi in the Sky: Axion Condensation in Neutron Stars

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Pronouns: she/her

Based on arXiv:2410.21590 (MK, Huang, Drischler, Baryakhtar, Reddy 2024)

INSTITUTE for NUCLEAR THEORY

Using neutron stars to test BSM theories

- Typical mass 1.4 $M_\odot$, typical radius 12 km.
- Central density 5-10x nuclear density but temperatures below an MeV after initial cooling.
- 10^{57} baryons and $E_F \sim 10 - 100$MeV make good detectors for rare events above laboratory energies.
- Although there are many things we do not know about neutron stars, we are poised for many discoveries in the next few decades!

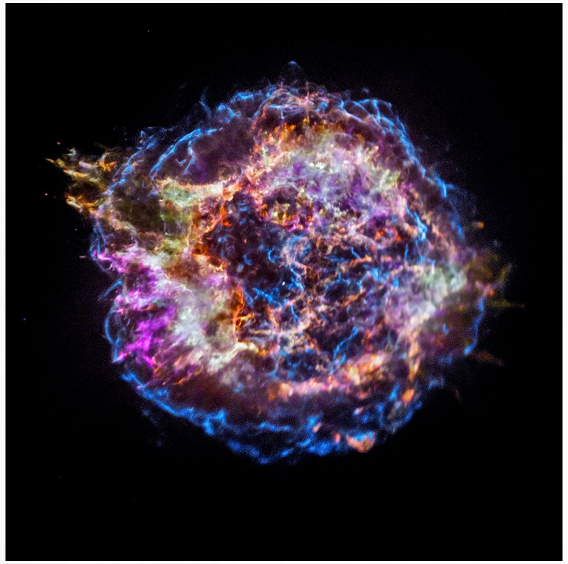
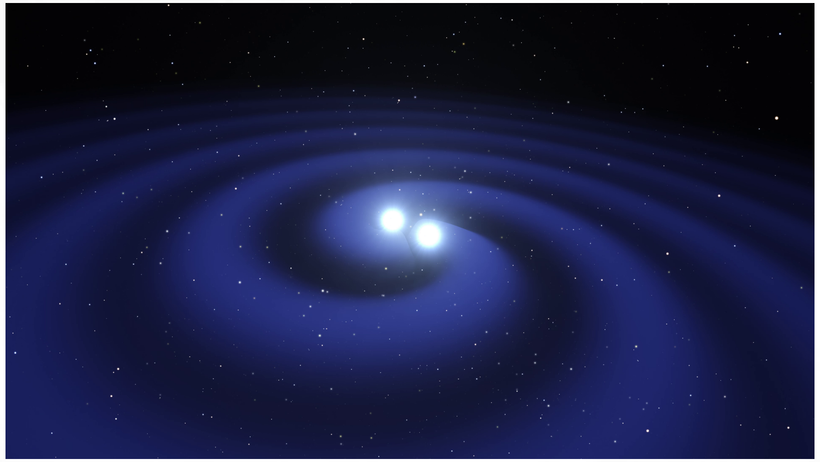


Image: NASA/CXC/SAO

Image: ESA



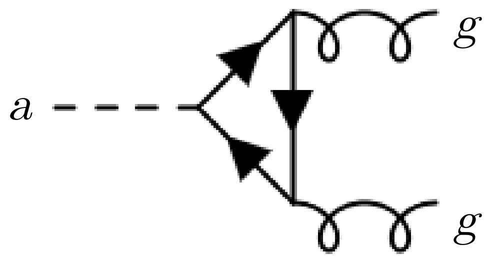
The Strong CP Problem

- If the quark mass matrix is real, CP violation in QCD is encoded in the θ angle.

$$\mathcal{L} = \bar{q} i \not{D} q - \bar{q} \mathcal{M}_q q - \frac{1}{4} G_{\mu\nu} G^{\mu\nu} + \theta \frac{\alpha_s}{8\pi} G_{\mu\nu} \tilde{G}^{\mu\nu}$$

- Neutron EDM measurements constrain $|\theta| < 10^{-10}$ (Abel et al 2020)
- But why? CP violation in the weak sector is O(1) in line with expectations.
- One solution: The QCD axion (Peccei + Quinn 1977, Weinberg 1978, Wilczek 1978)

$$\left(\frac{a}{f_a} - \theta_{\mathrm{QCD}} \right) \frac{\alpha_s}{8\pi} G_{\mu\nu} \tilde{G}^{\mu\nu} \equiv \theta \frac{\alpha_s}{8\pi} G_{\mu\nu} \tilde{G}^{\mu\nu}$$

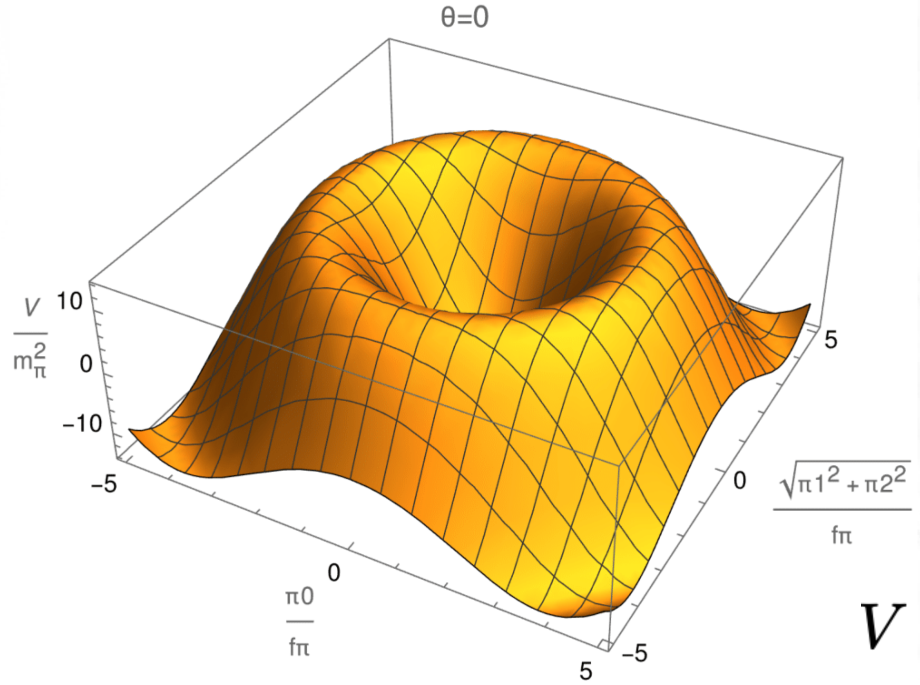


Going from θ to low energy nuclear physics

- To get a description in terms of hadrons, absorb θ into the quark mass matrix.

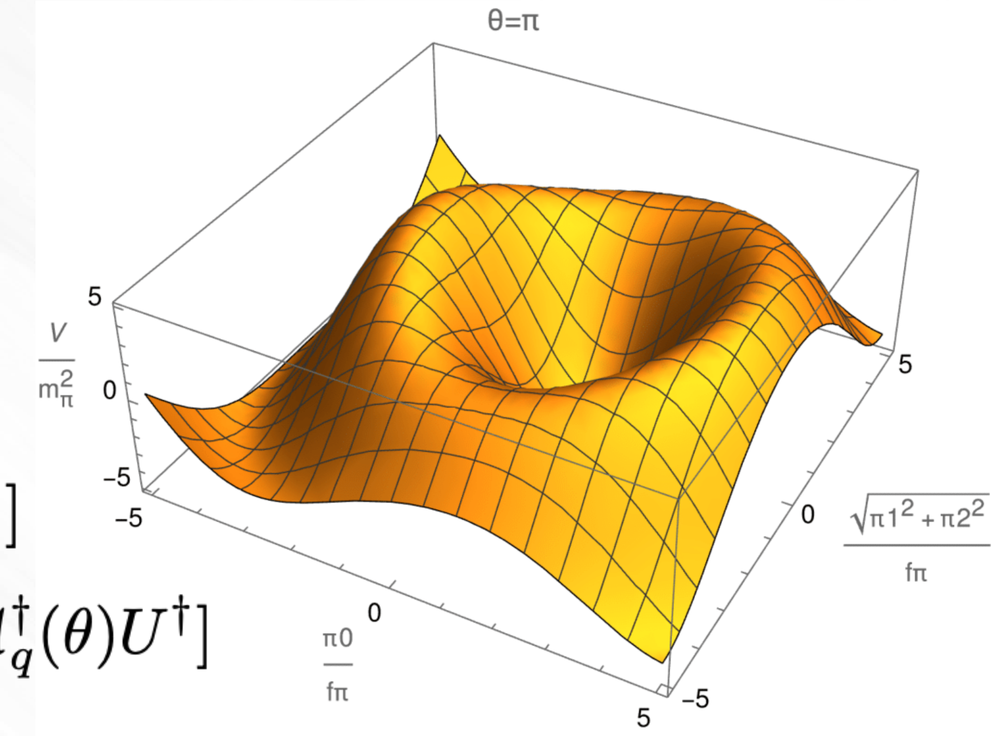
$$q \to e^{i\theta\gamma_5 Q_a/2} q \qquad \begin{bmatrix} m_u & 0 \\ 0 & m_d \end{bmatrix} = \mathcal{M}_q \to e^{i\theta Q_a/2} \mathcal{M}_q e^{i\theta Q_a/2}$$

- In Chiral Perturbation Theory, this couples θ to the potential for pions.



$$U = \exp[i\vec{\pi}\cdot\vec{\tau}/f_\pi]$$

$$V \propto \mathrm{Tr}[U\mathcal{M}_q(\theta) + \mathcal{M}_q^\dagger(\theta)U^\dagger]$$



QCD Axion vs. "Exceptionally light" QCD Axions

- Potential for axions in vacuum:

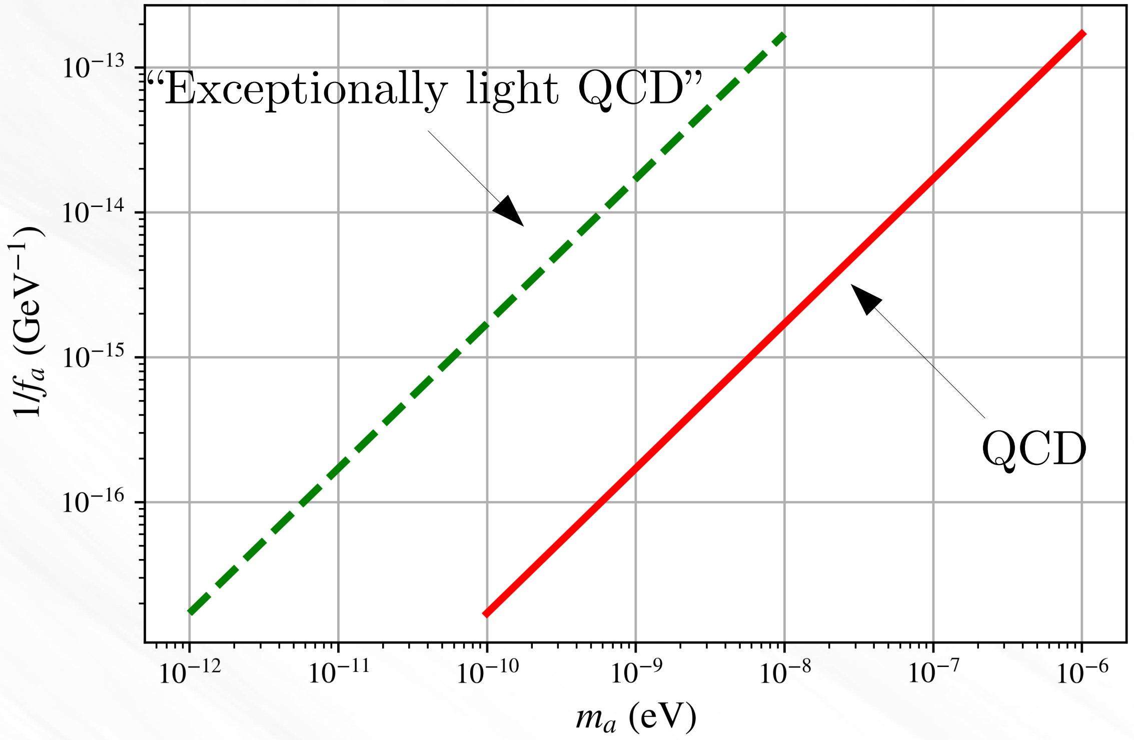
$$V_{\rm QCD}(\theta) = m_\pi^2 f_\pi^2 \left(1 - \sqrt{1 - \frac{4 m_u m_d}{(m_u + m_d)^2} \sin^2 \frac{\theta}{2}}\right) \qquad m_{a,\rm QCD}^2 = \frac{m_\pi^2 f_\pi^2}{f_a^2} \frac{m_u m_d}{(m_u + m_d)^2}$$

- "Exceptionally light QCD axions" have the normal coupling to gluons but a lighter mass.

$$m_a^2 = \varepsilon m_{a,\rm QCD}^2 \qquad V(\theta) = \varepsilon V_{\rm QCD}(\theta)$$

- We will focus on $5 \times 10^{-7} < \varepsilon < 1$

- More complicated theories motivate these lighter axions, but we will use the simple model. (Hook 2018, Di Luzio et al 2021)

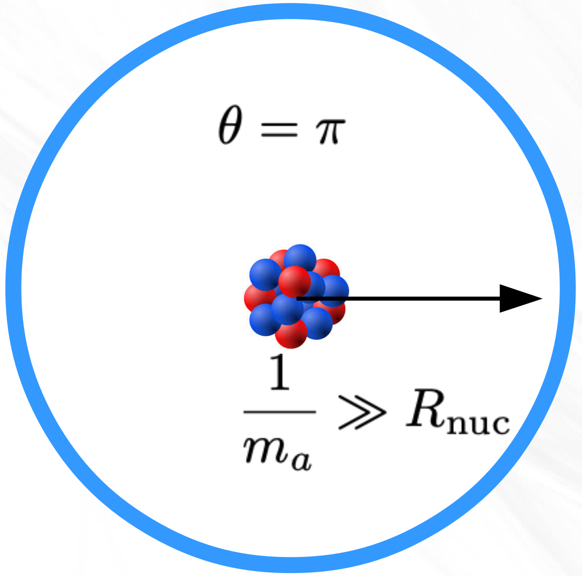


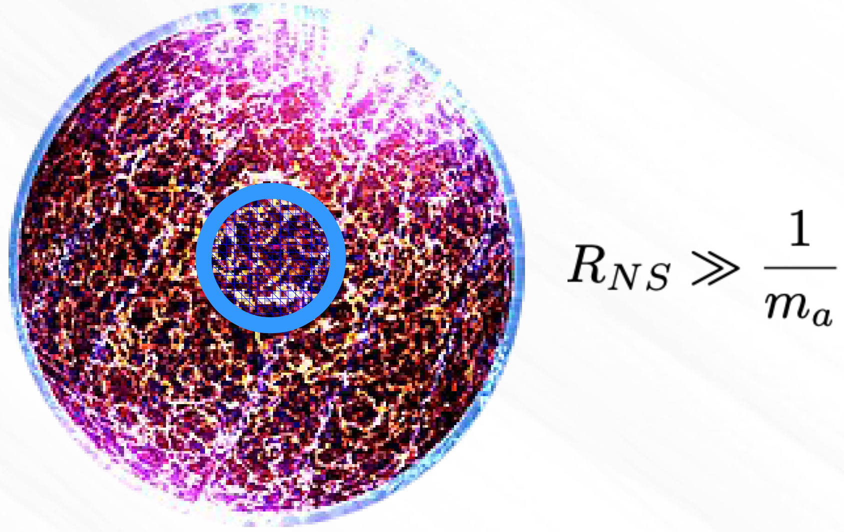
Why neutron stars?

- Axion condensation occurs when the modifications to QCD cause the energy of a local distribution of matter to be decreased more than the axion vacuum energy.

$$V(\theta) = \varepsilon m_\pi^2 f_\pi^2 \left(1 - \sqrt{1 - \frac{4 m_u m_d}{(m_u + m_d)^2} \sin^2 \frac{\theta}{2}}\right)$$

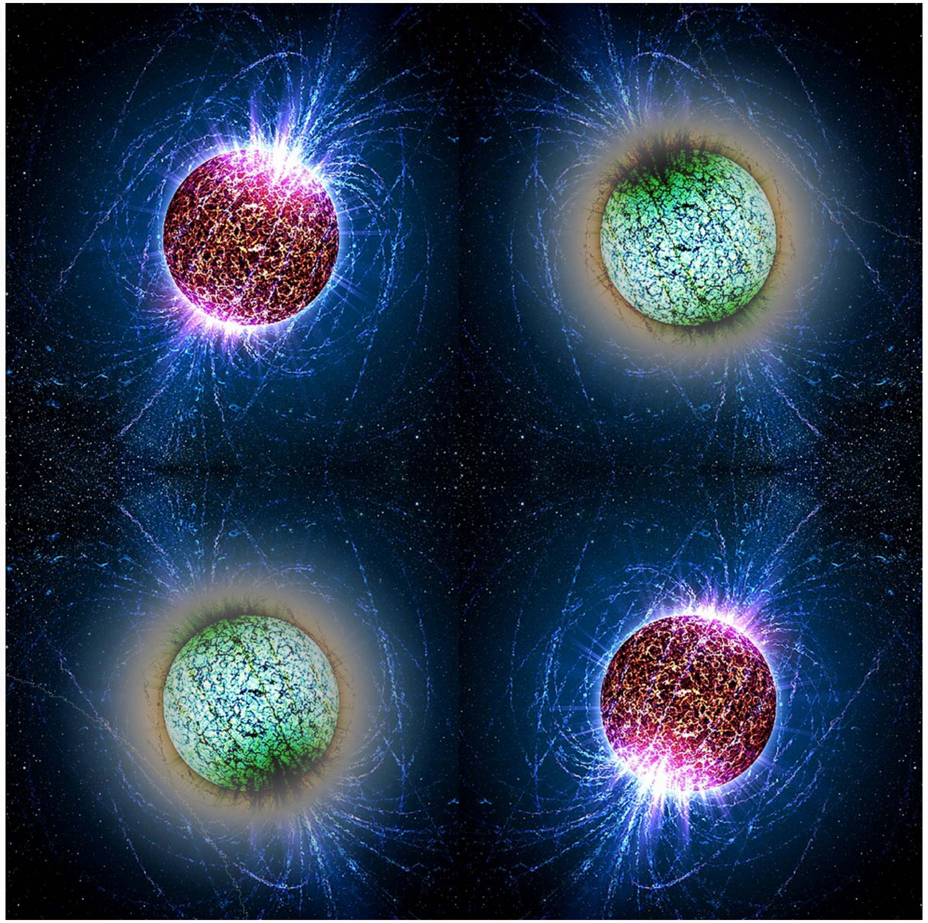
- Our probe needs to work on energy scales of order Λ_{QCD}, but we need an object that is larger than the Compton wavelength of the axion (>μm), hence neutron stars!





Outline

- Modifications to QCD from axion condensation
- Phases of axion condensed matter in neutron stars
- Observational consequences for neutron stars
- Summary and outlook



Base image: Casey Reed via wikipedia

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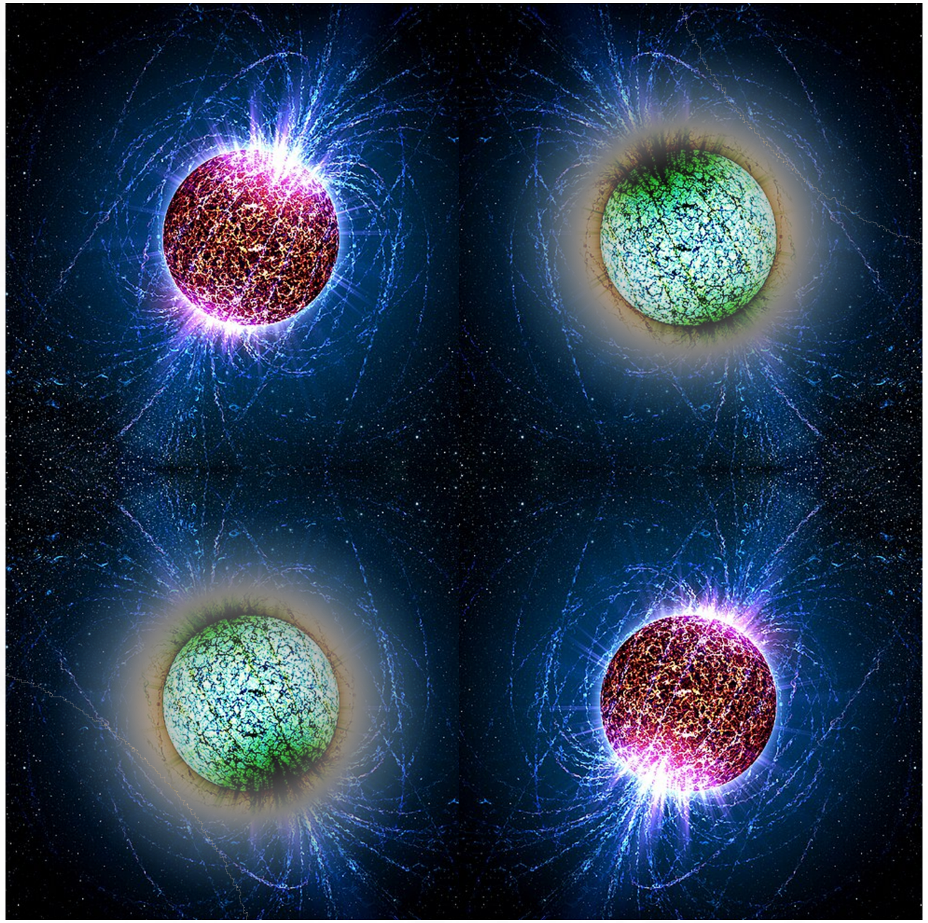

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Effects of finite θ on QCD

- New minimum of the potential at finite θ has lighter pions.

$$m_\pi^2(\theta) = m_\pi^2(\theta=0)\sqrt{1-\frac{4m_u m_d}{(m_u+m_d)^2}\sin^2\frac{\theta}{2}}$$

← Reduced to 82 MeV in axion condensed phase

- Nucleon masses (additional terms in Chiral PT suppressed as m_q/m_N):

$$m_N(\theta) = m_0 + \sigma_{\pi N}\frac{m_\pi^2(\theta)}{m_\pi^2(\theta=0)} - \tau_3\Delta\sigma\frac{m_\pi^2(\theta=0)}{m_\pi^2(\theta)}$$

← Reduced by about 30 MeV in axion condensed phase

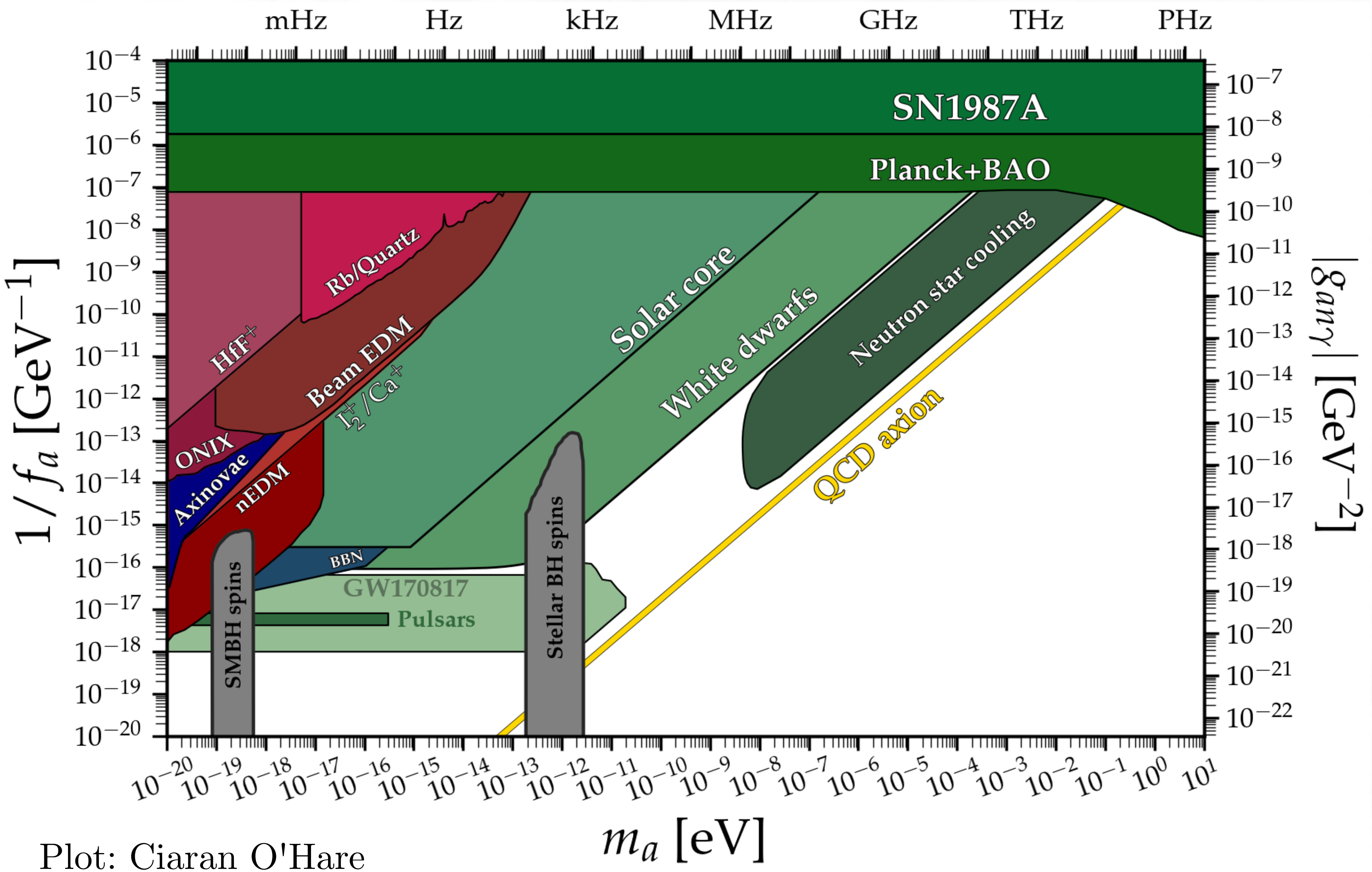
$\sigma_{\pi N}$: $45-60\,\mathrm{MeV}$; $\Delta\sigma$: $1-2\,\mathrm{MeV}$

- For sufficiently large baryon density, the leading term predicts axion condensation!

$$\Delta\Omega = (\varepsilon m_\pi^2(0) f_\pi^2 - \sigma_{\pi N} n_B)\left(1-\frac{m_\pi^2(\theta)}{m_\pi^2(0)}\right)$$

$$n_B^{\mathrm{crit}} = \frac{\varepsilon m_\pi^2 f_\pi^2}{\sigma_N} \simeq 2.65\varepsilon n_{\mathrm{sat}}$$

The landscape of exceptionally light QCD axions ca. August 2024



Plot: Ciaran O'Hare

What about nuclear interactions?

χEFT… not the answer you would hope for

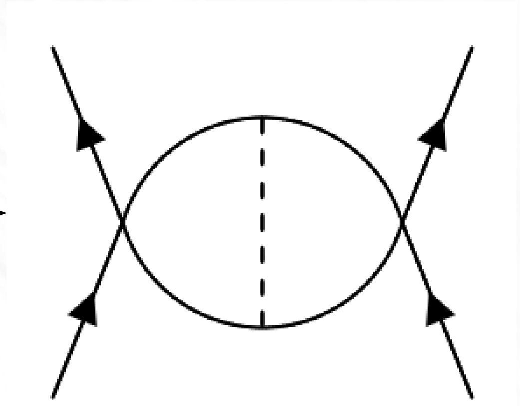
- Good news: We know the pion mass dependence of all terms involved in pion exchanges.

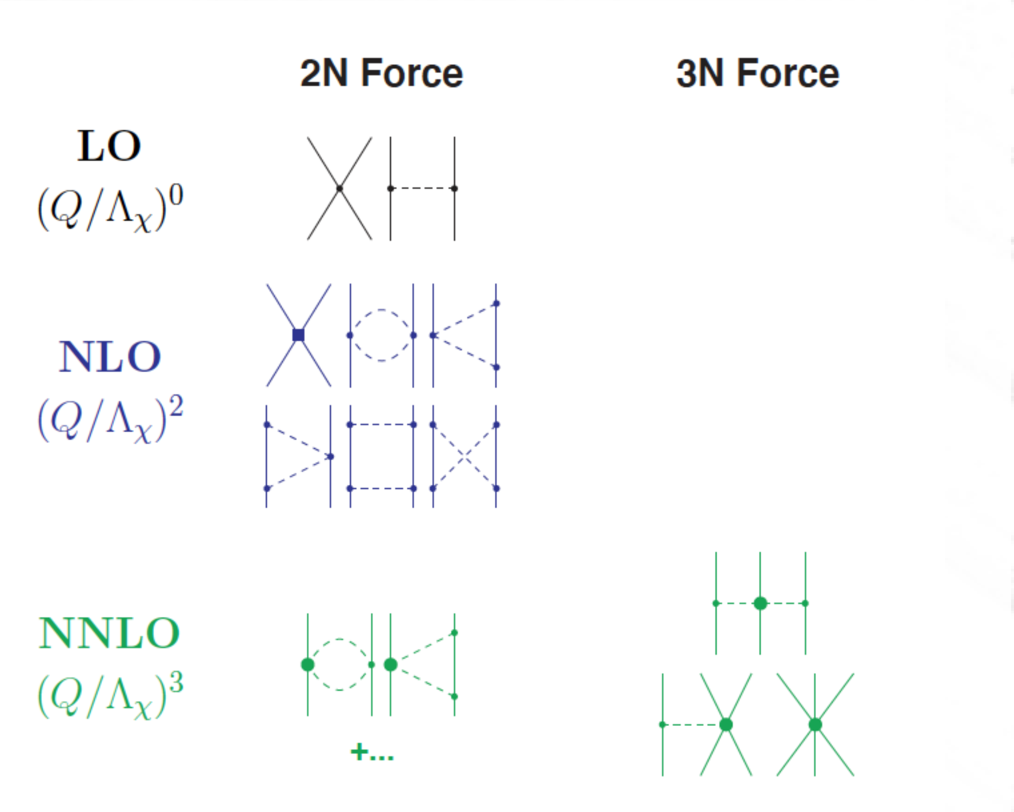
  (f_π, g_A, m_π, …)

- Bad news: We don't even know the sign of the pion mass dependence of the short range forces, but it can't be zero. (Kaplan, Savage, Wise 1996)

$$\mathcal{L} \supset C(\bar{\psi}\Gamma\psi)^2 \qquad\qquad C = C_0 + D_2 m_\pi^2$$

Need D_2 to regulate this diagram. →





Machleidt and Entem (2011) [arXiv:1105.2919]

How to get a handle on the size of D_2

- A renormalization group calculation gives an approximate scale for these operators.

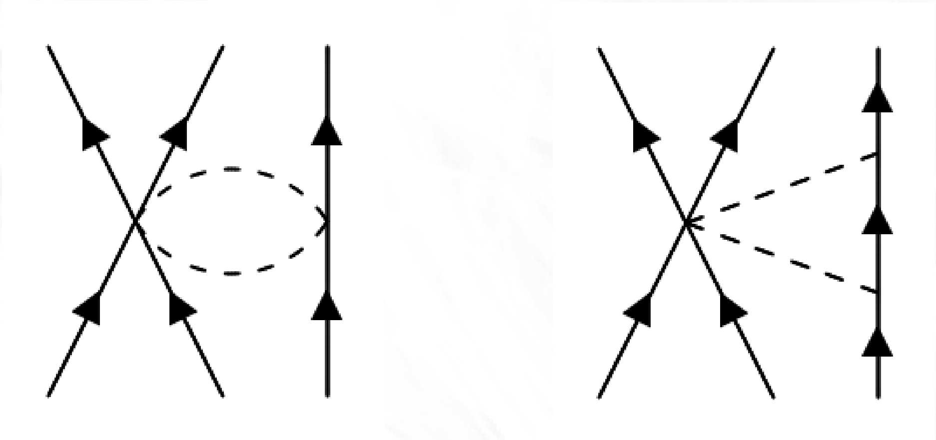
$$|D_2(\mu)| \simeq \frac{g_A^2 m_N^2}{64\pi^2 f_\pi^2} C_0^2(\mu) \simeq \frac{1}{5 f_\pi^4}$$

- A more precise value from first principles would likely require Lattice QCD.

- Other approaches:
  - Use the equation of state?
  - Use the regulator dependence of the nuclear force?

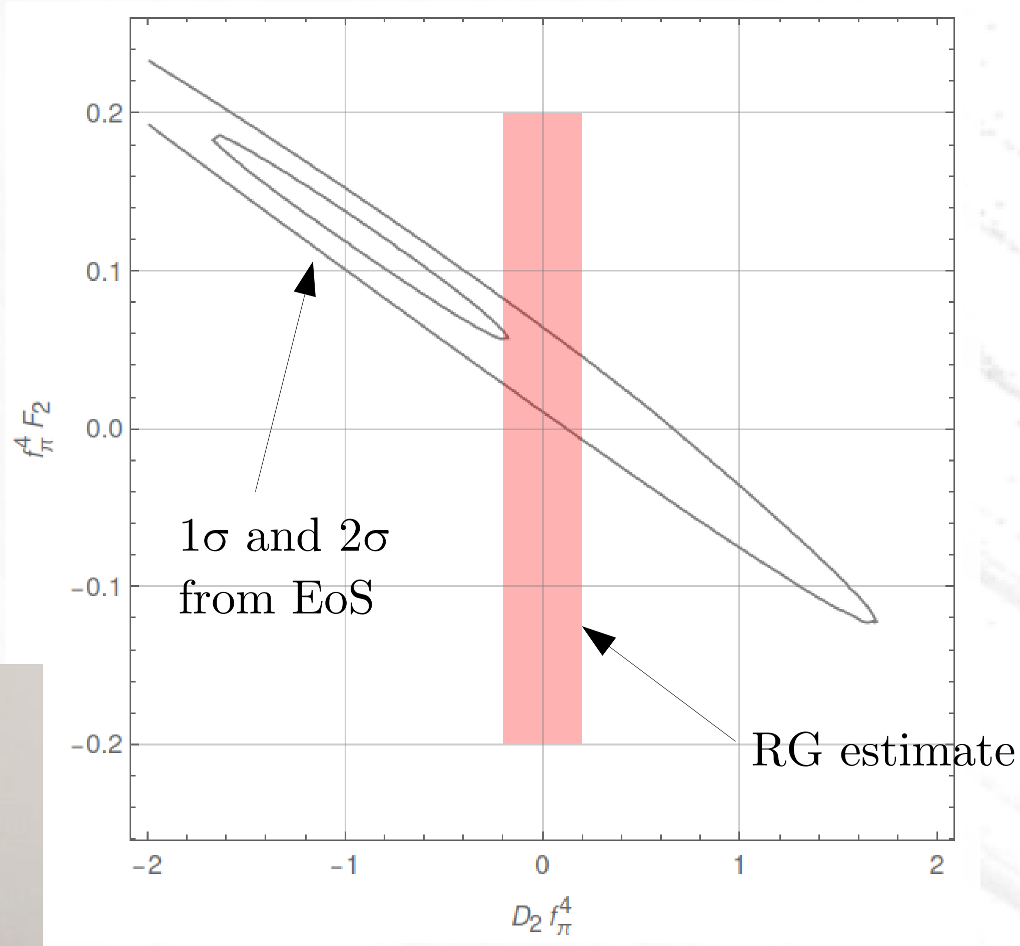
Using the EoS to constrain D_2 (and F_2)

- Chiral symmetry dictates that pion mass dependence also requires pion couplings.



- These 3NF enter at an order that has relevance for the equation of state.
(Cirigliano et al 2024)

Also one of those authors!

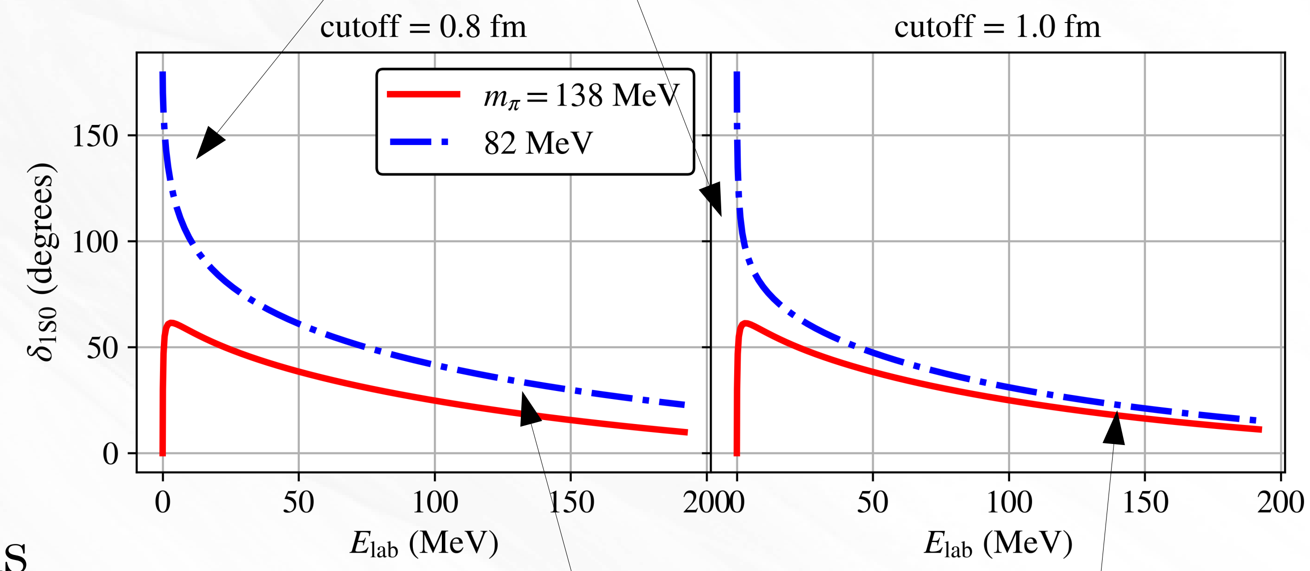


Maria Dawid did the hard work on this plot

Cutoff dependence of the nuclear force

- The short range forces in Chiral EFT are part of the regulation of the theory.
- Correct D_2 (and higher orders?) should yield cutoff independent forces.
- Phase shift analysis may allow an order-by-order estimate of necessary corrections in each channel.

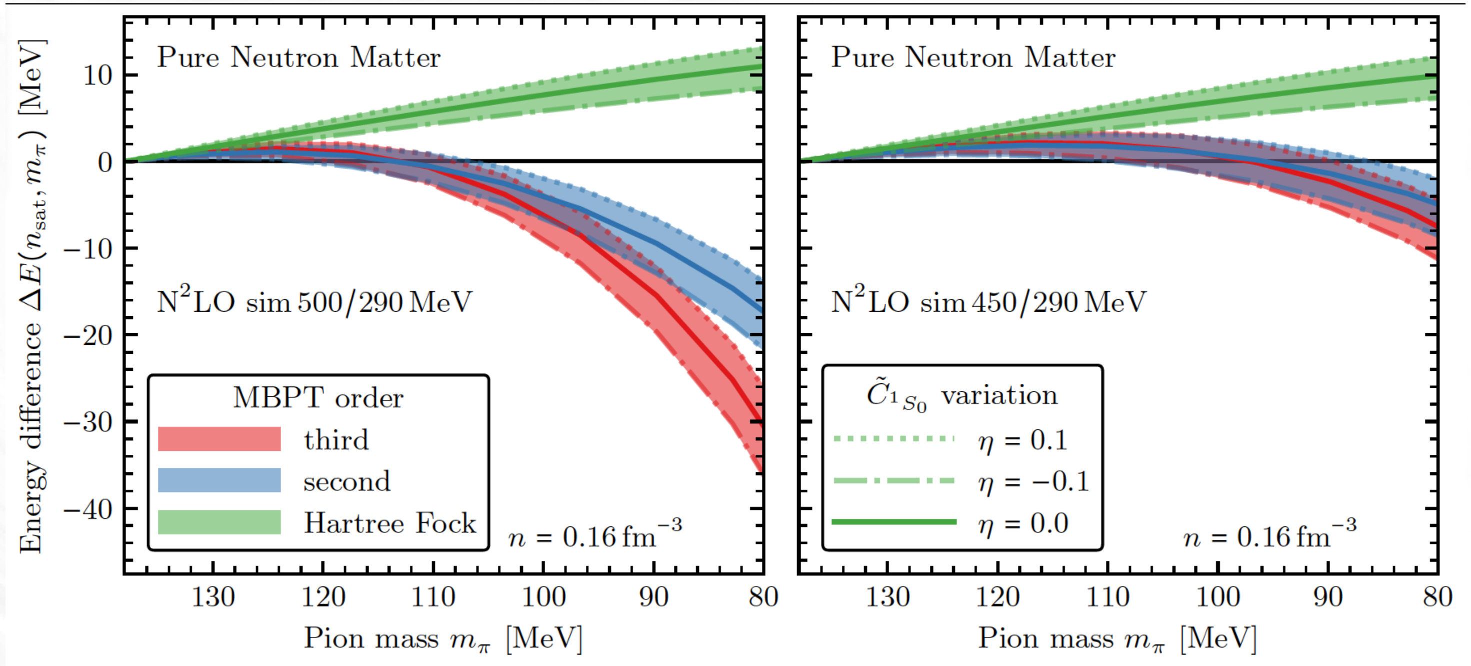
Correct D_2 should get matching scattering lengths



Higher order corrections should get matching large momentum behavior

MBPT is giving large cutoff dependence

- Cutoff dependence? Poor convergence? (We are currently working on verifying the convergence of this series.)
- Qualitative agreement with calculations of chiral condensate at various pion masses (Kaiser, de Homont, Wise 2007, Kruger et al 2013)
- Lacking a full treatment in Chiral EFT, for now we use Chiral EFT as a guide for tuning a phenomenological model.

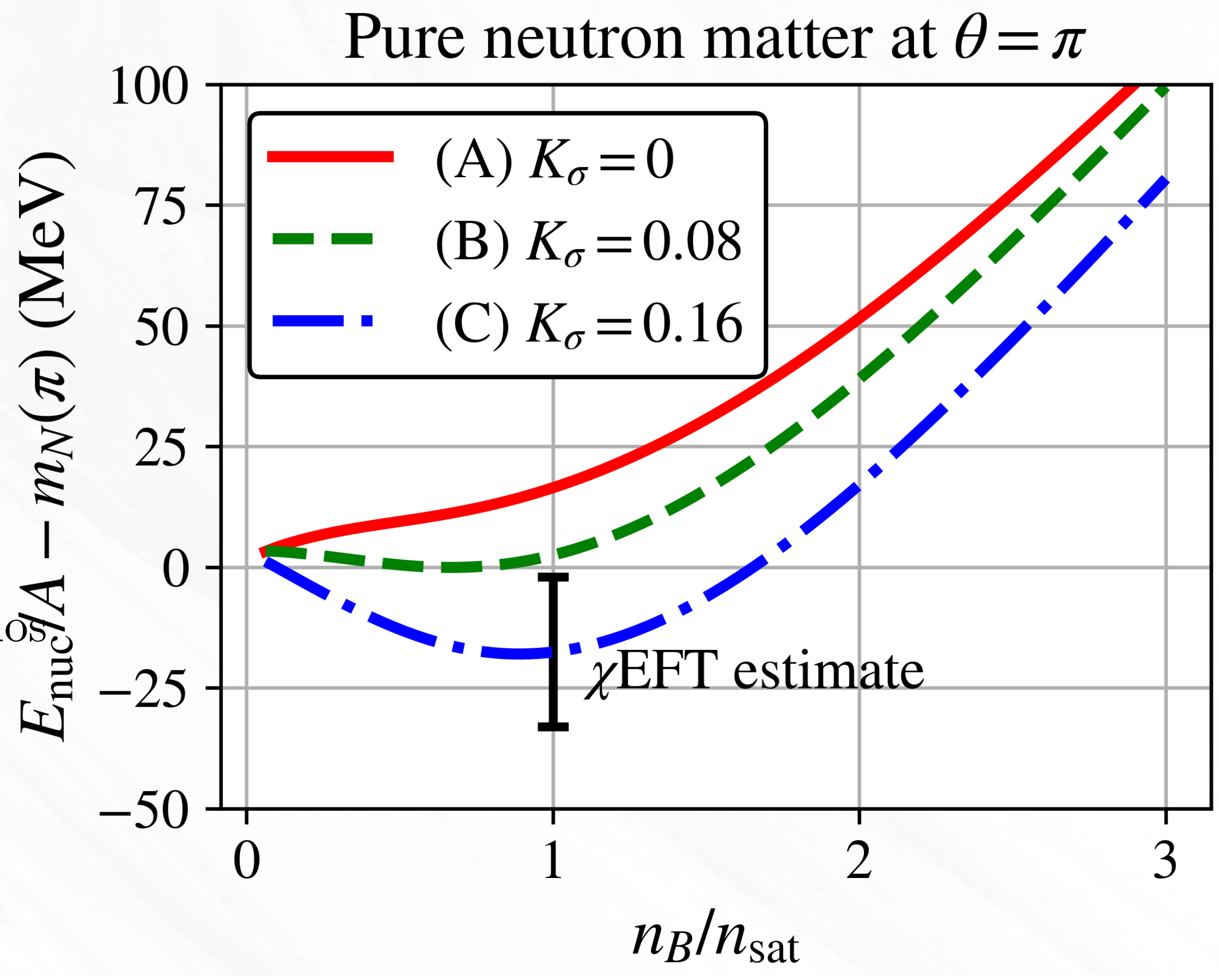


Finite θ in a meson exchange model

- Ansatz: decrease the σ mass with decreased pion mass.

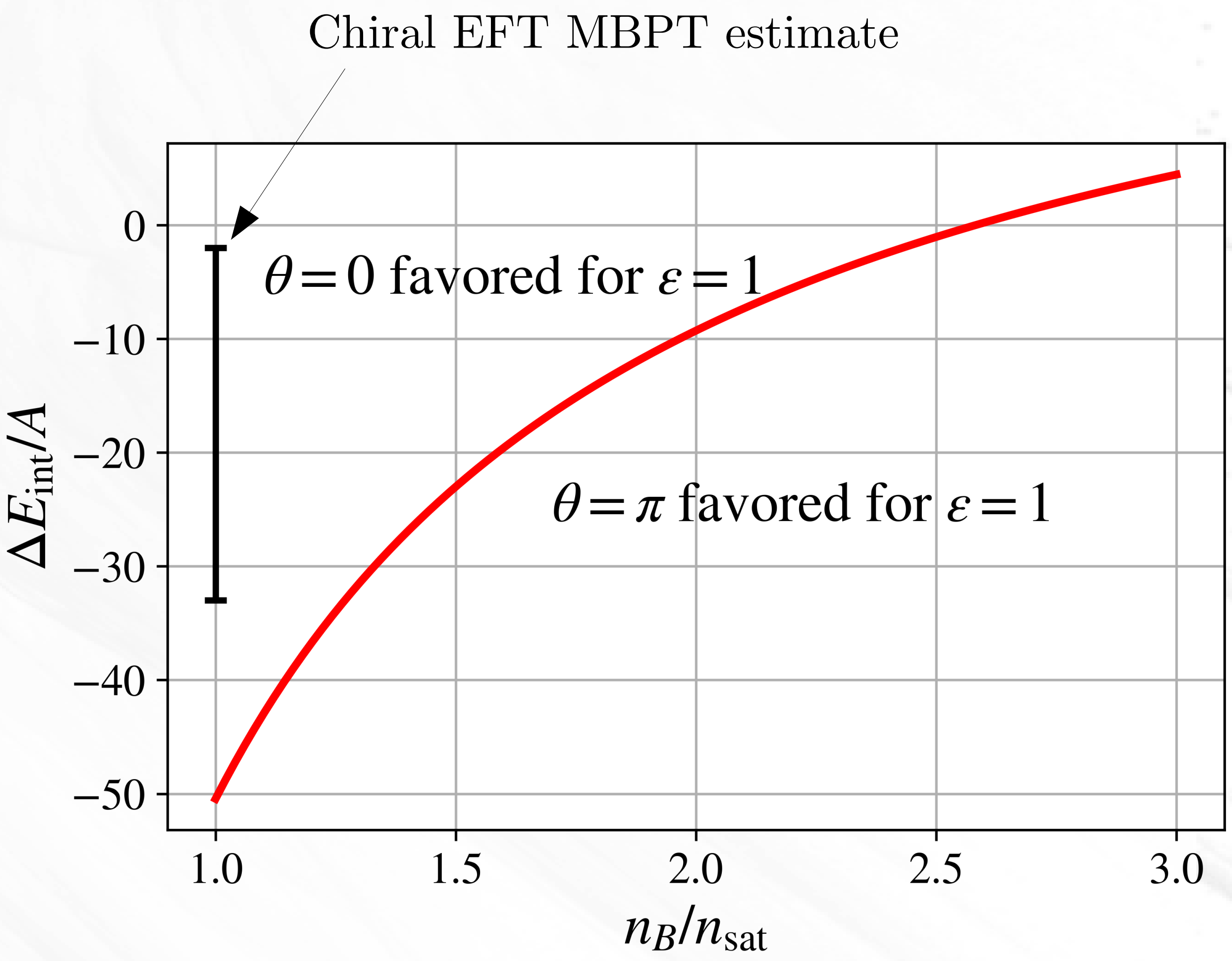
$$K_\sigma = \frac{m_\pi^2}{m_\sigma}\frac{dm_\sigma}{dm_\pi^2}$$

- Scenario A: Nuclear force unmodified
- Scenario B: σ mass modified to match meson mass calculations (Hanhart, Pelaez, Rios 2008, Pelaez and Rios 2010)
- Scenario C: Neutron matter binding matches central value of estimate from MBPT calculation.



What could this approach be missing?

- The error bars are big and we have tuned RMFT to land in the middle, maybe the truth is closer to the edges.
- We only have results from Chiral EFT at saturation density, maybe there is complicated density dependence.
- We are only including an isoscalar modification to the nuclear force while the symmetry energy is likely to also be affected.



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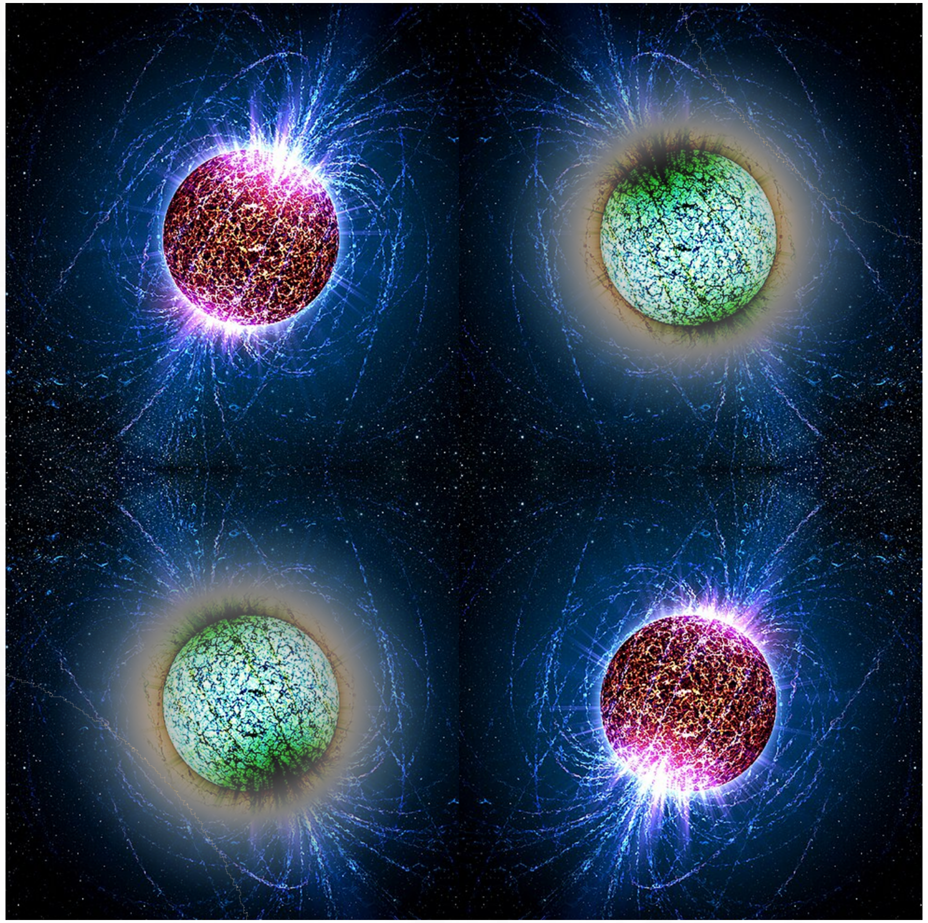


Base image: Casey Reed via wikipedia

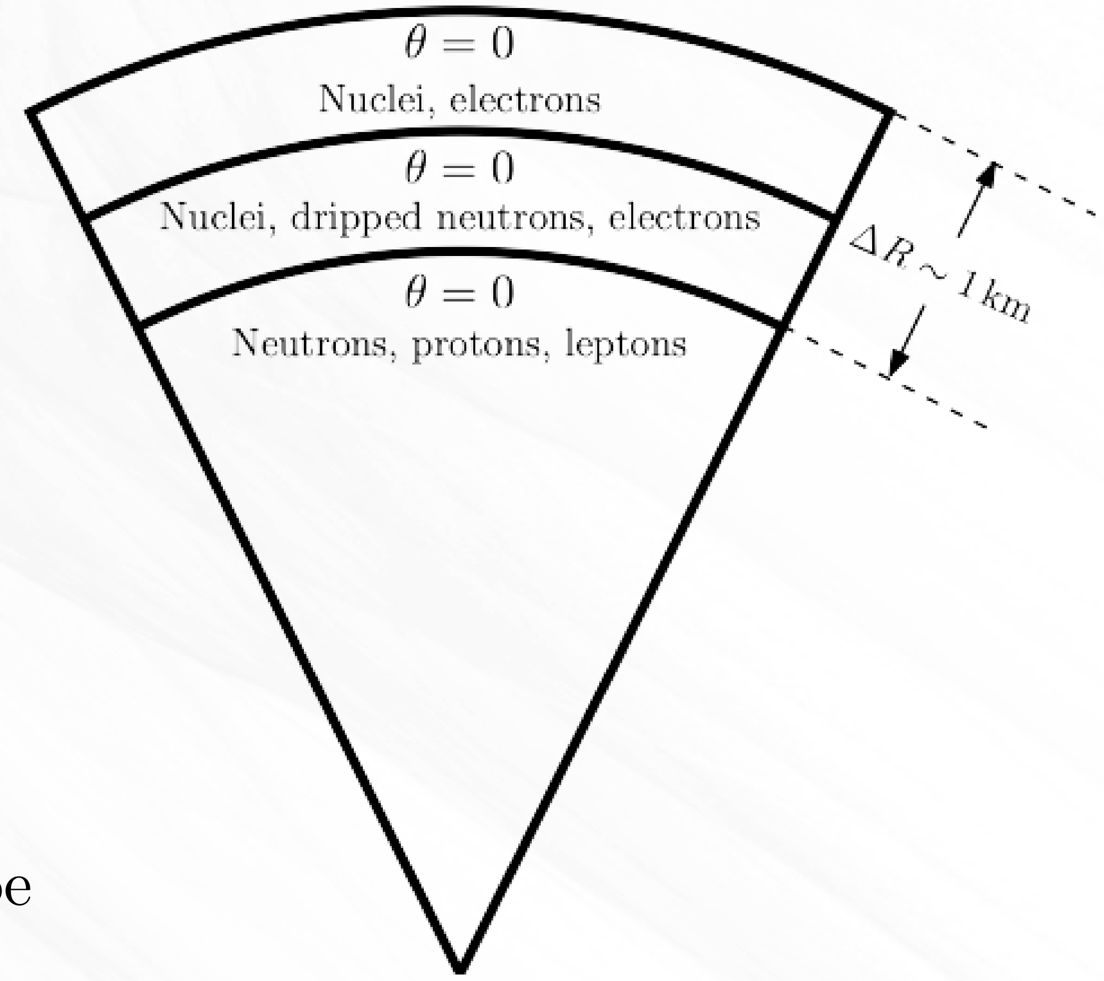
Neutron star crust without axions

- Crust has many useful observables, focus there!

- Normal neutron stars have a crust approximately 1 km thick.

- The outer crust has nuclei and electrons and the inner crust has nuclei, electrons, and free neutrons.

- The outermost edge of the star has an envelope with poor heat conductivity that is about 100 m thick.



How is the crust changed by axions?

- An axion domain wall with thickness of the Compton wavelength of the axion separates axion condensed and normal regions at a critical chemical potential.

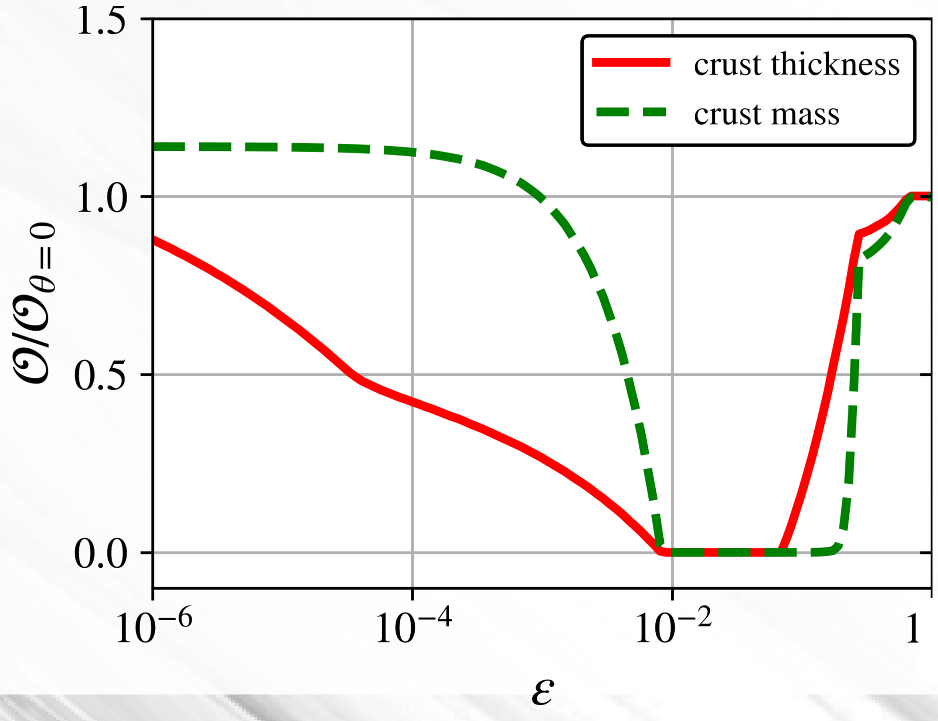
$$p_{\rm nuc}(\mu_B^c, \theta = \pi) - V(\theta) = p_{\rm nuc}(\mu_B^c, \theta = 0)$$

- If the critical chemical potential is less than the binding of normal nuclei in the outer crust, the entire star will be axion condensed.

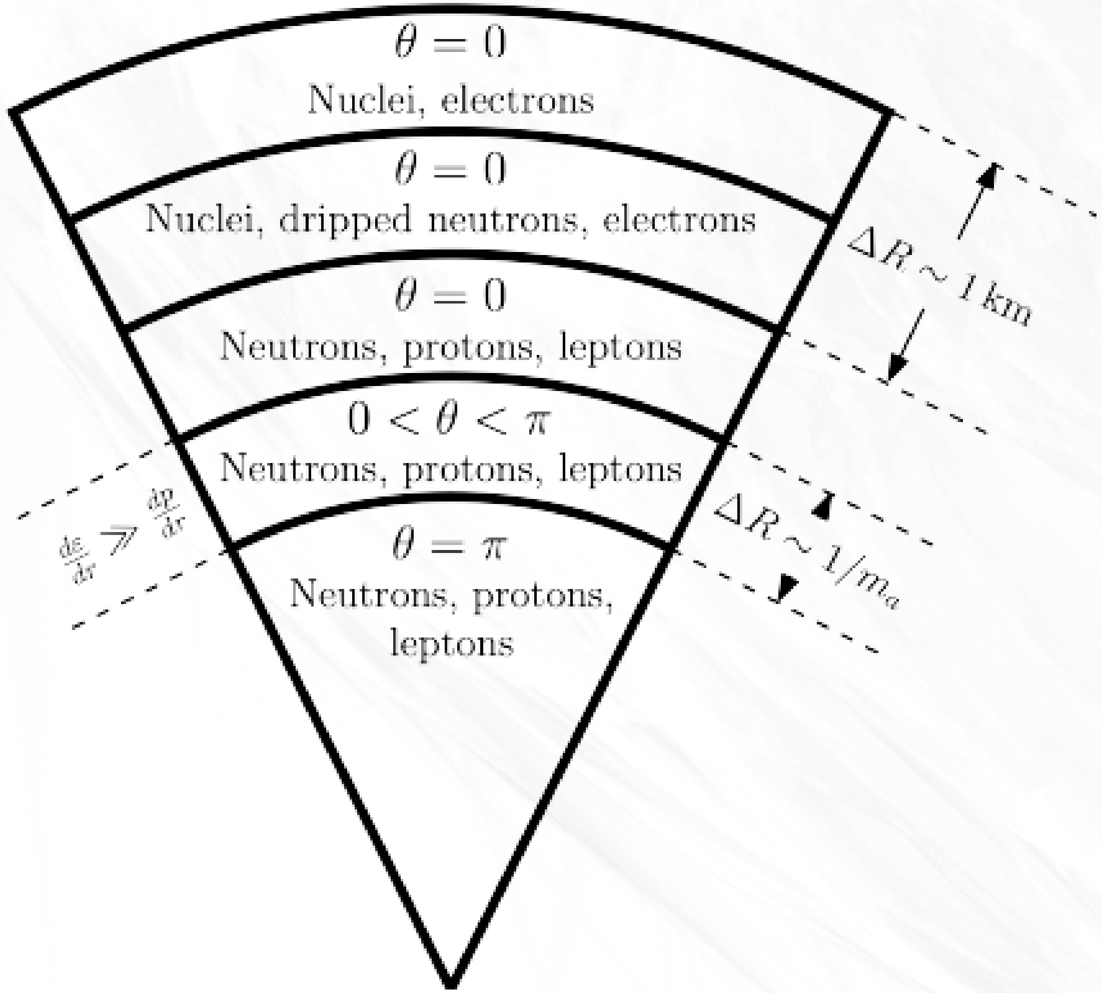
- If the entire star is axion condensed, phases where $p_{\rm nuc}(\theta = \pi) < V(\theta)$ will be missing.

- A more attractive nuclear force disfavors the dripped neutron phase.

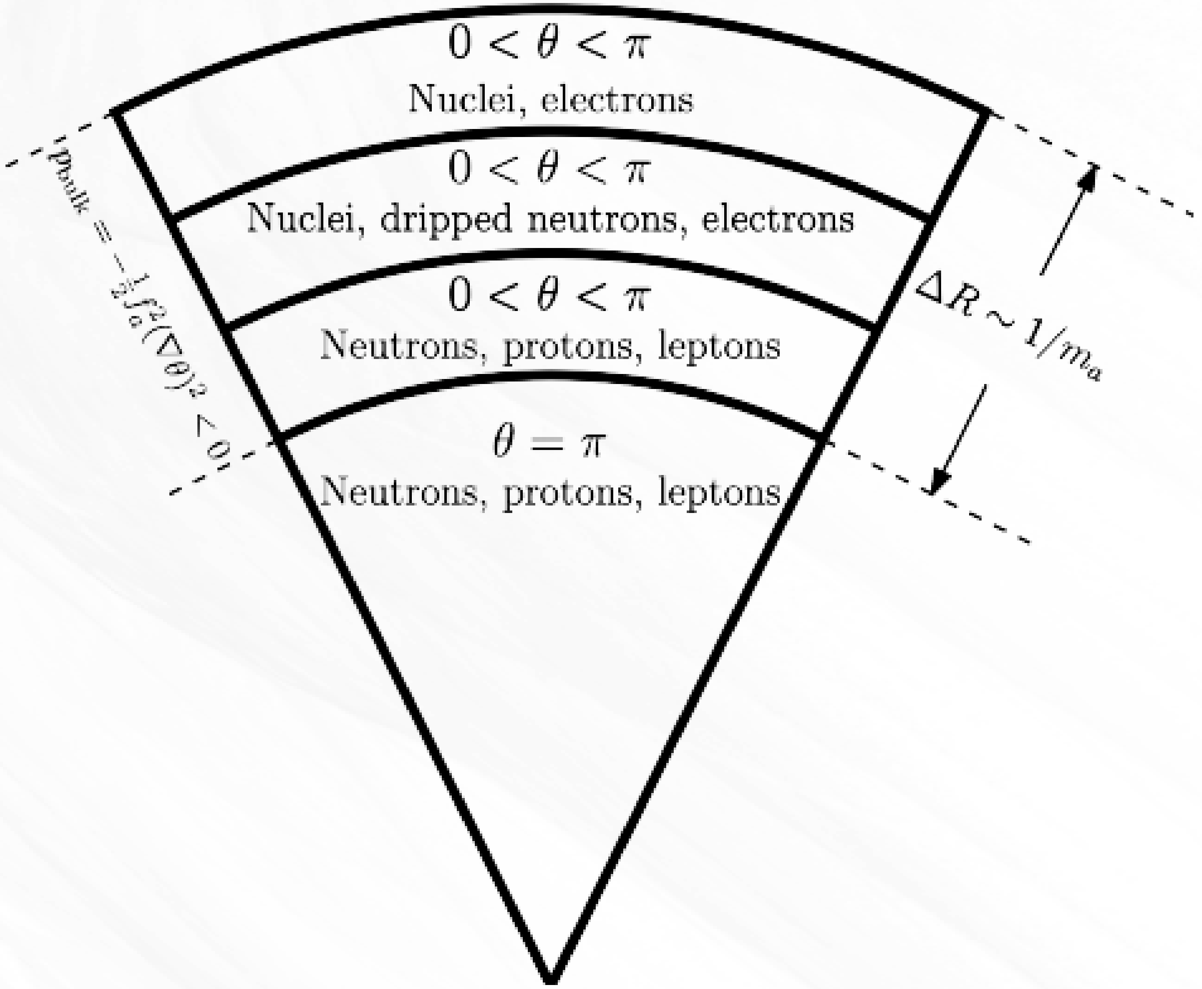
$$p_{\rm drip}(\theta = \pi) > p_{\rm crust-core}(\theta = \pi)$$



Neutron star structure with axions



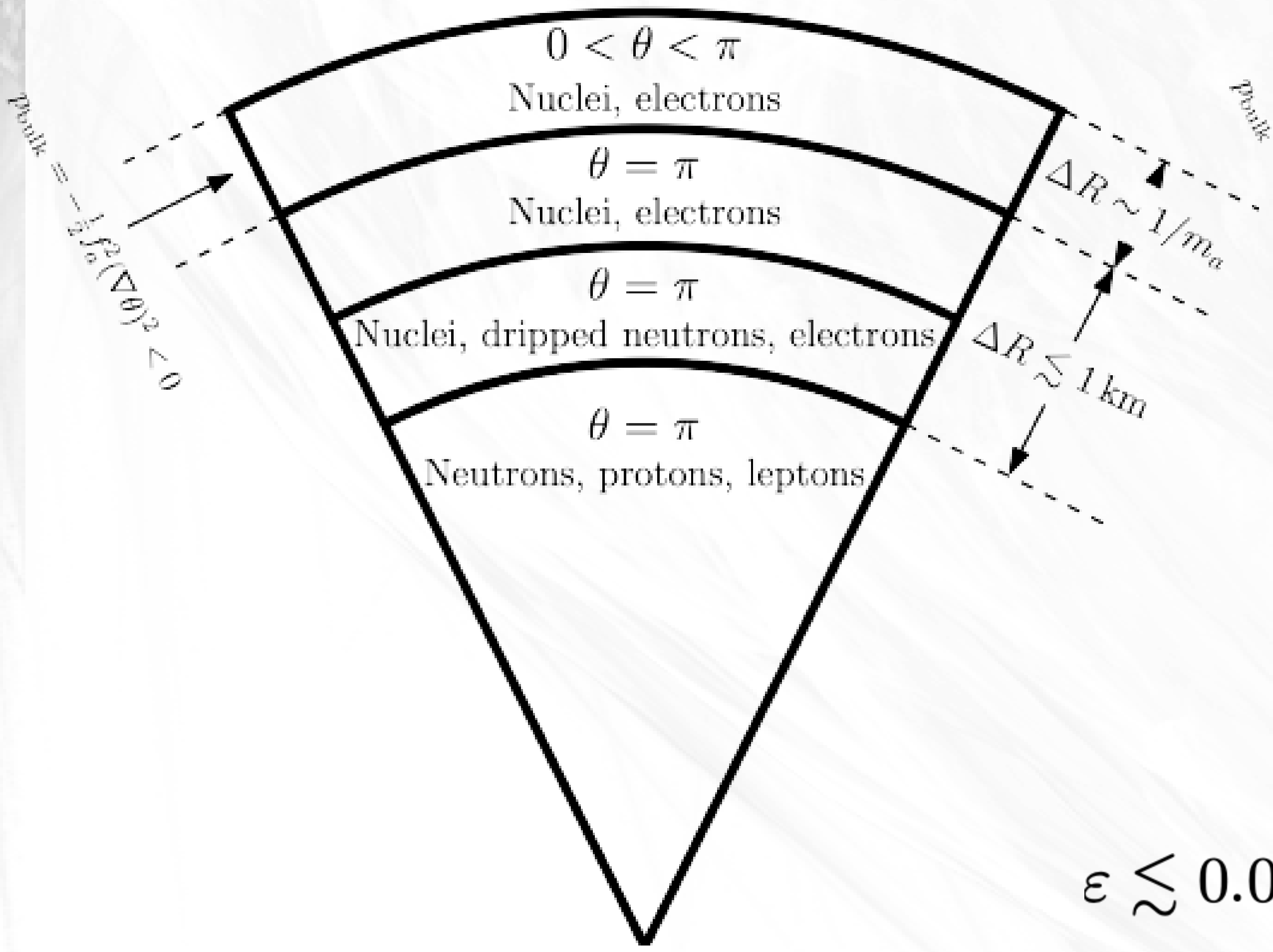
$0.1 \lesssim \varepsilon \lesssim ?$



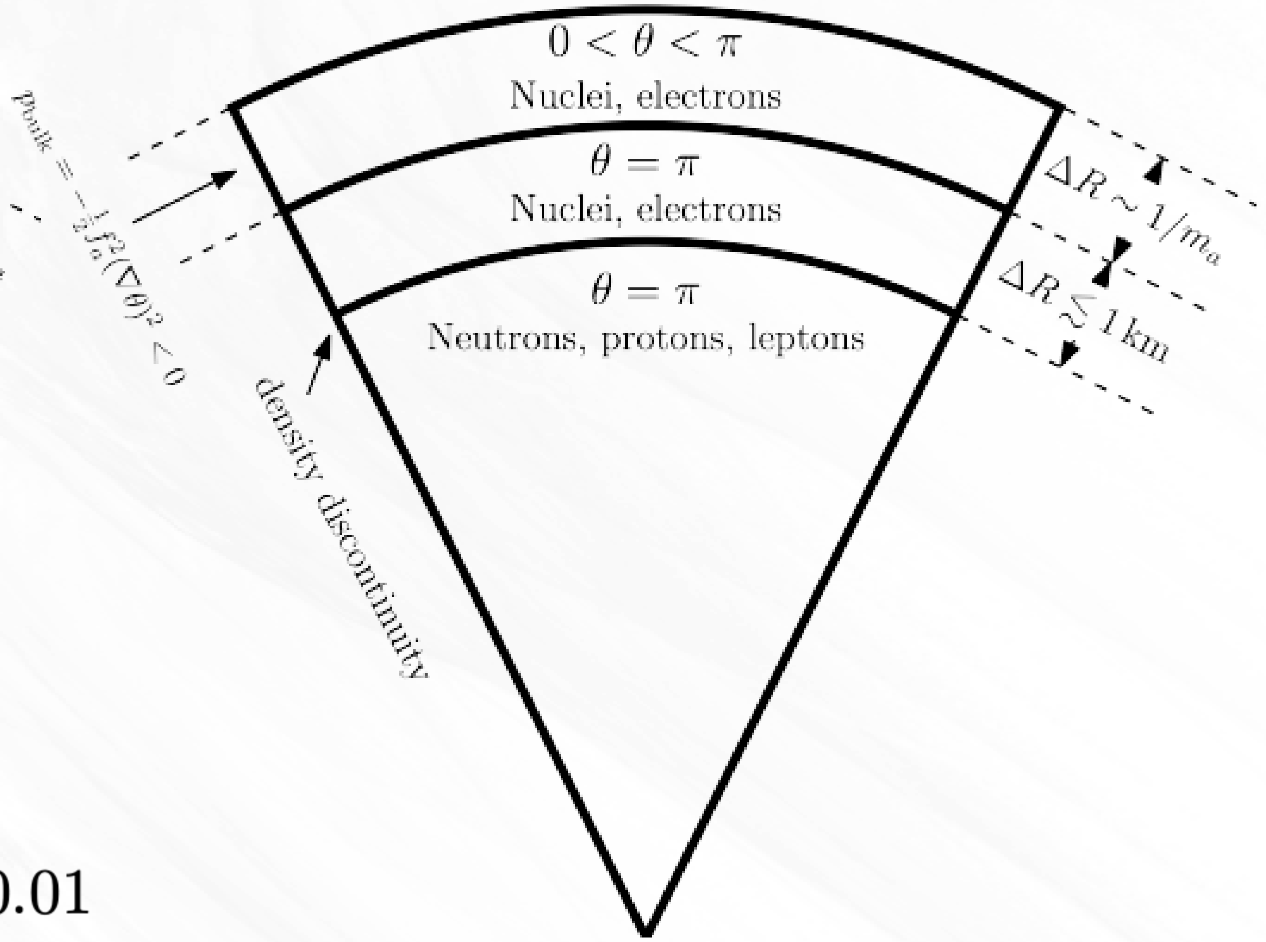
$0.01 \lesssim \varepsilon \lesssim 0.1$

Neutron star structure with axions

Nuclear force unmodified



Nuclear force more attractive



$\varepsilon \lesssim 0.01$

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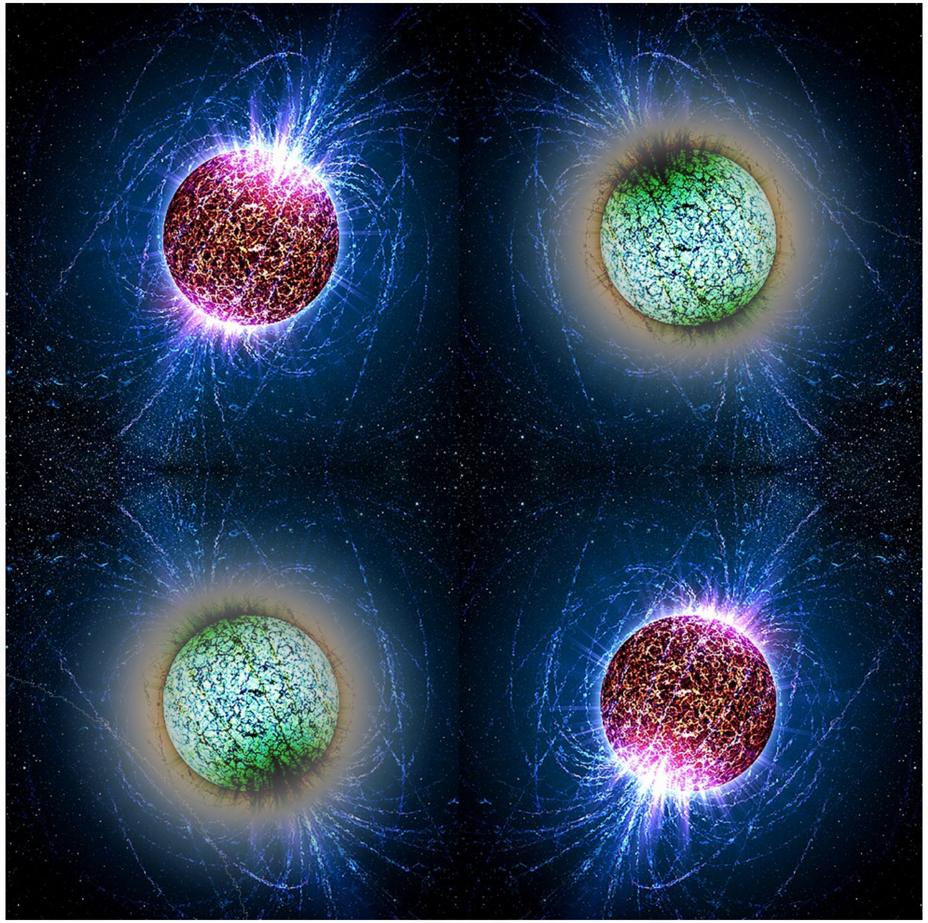


Base image: Casey Reed via wikipedia

Crust thermal relaxation

- Some neutron stars in x-ray binaries transiently accrete material from their companion.

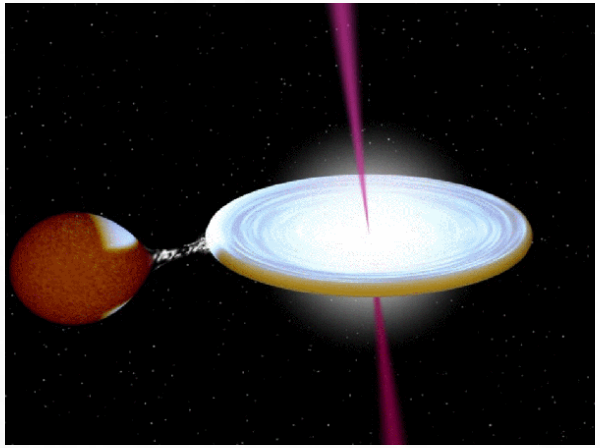
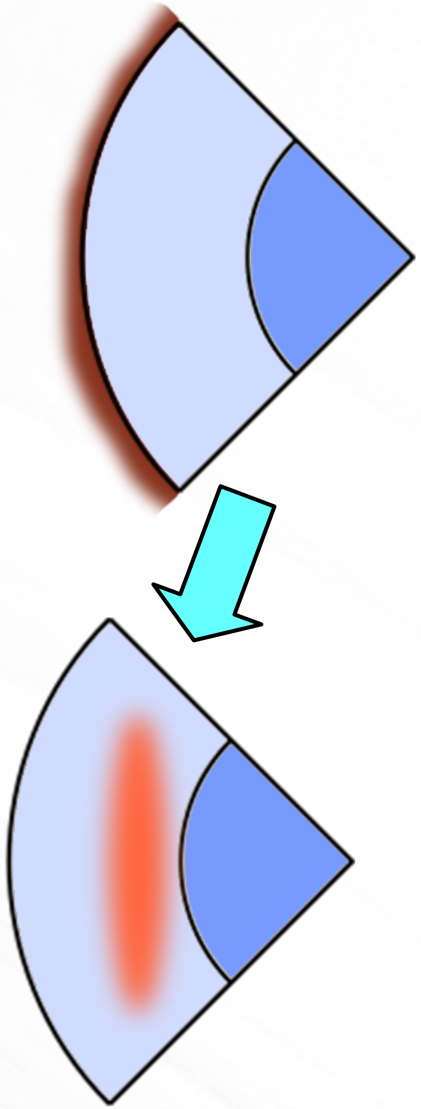
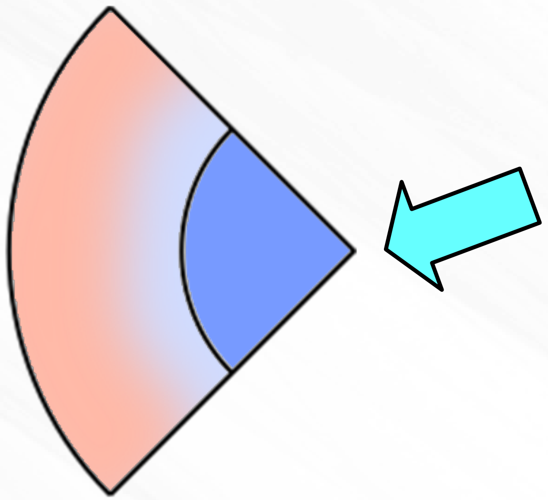


Image: Rob Hynes

- Pycnonuclear reactions deep in the crust heat the neutron star.

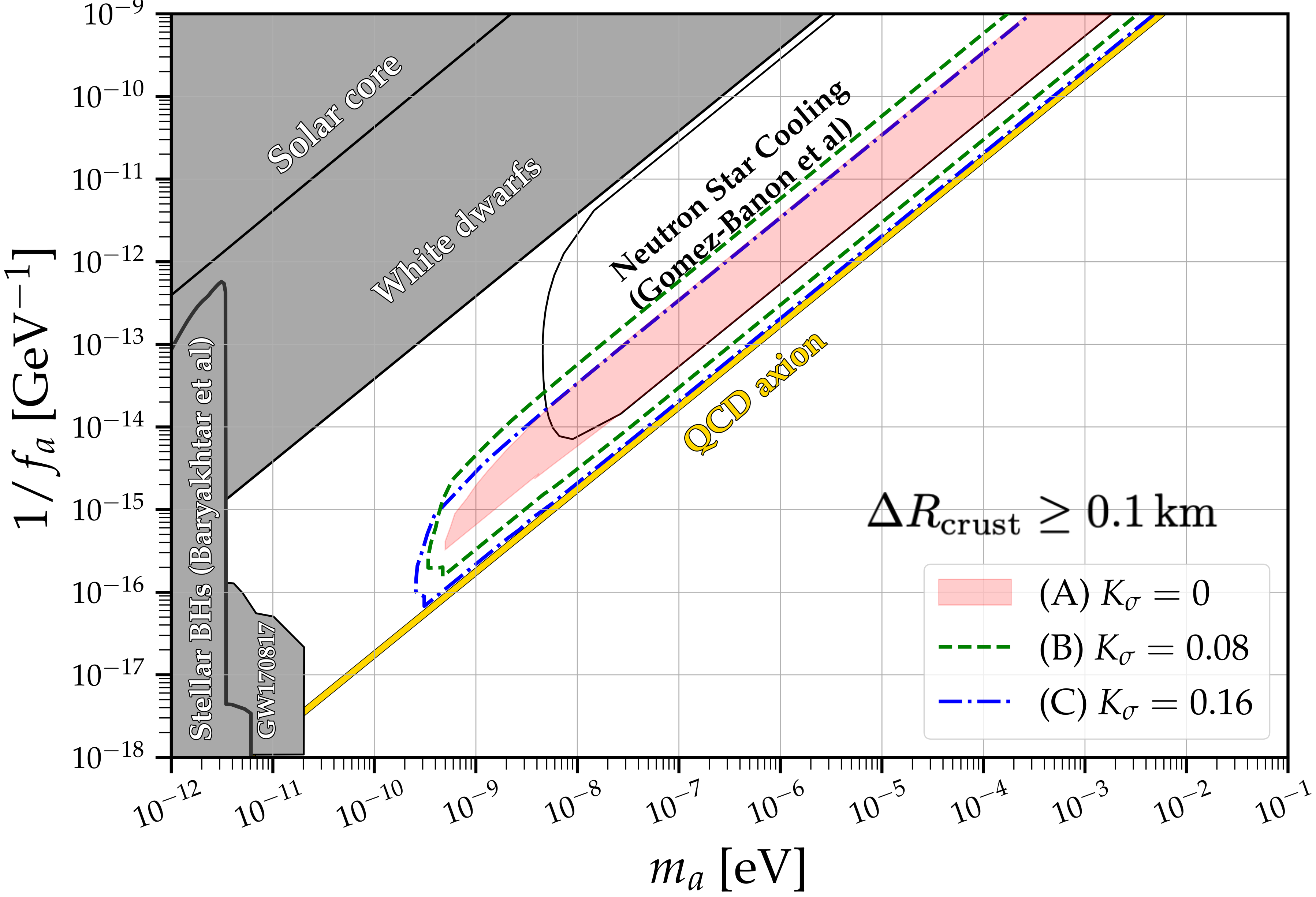




- Timescale for the crust to thermally relax following outburst can be observed and is roughly given by

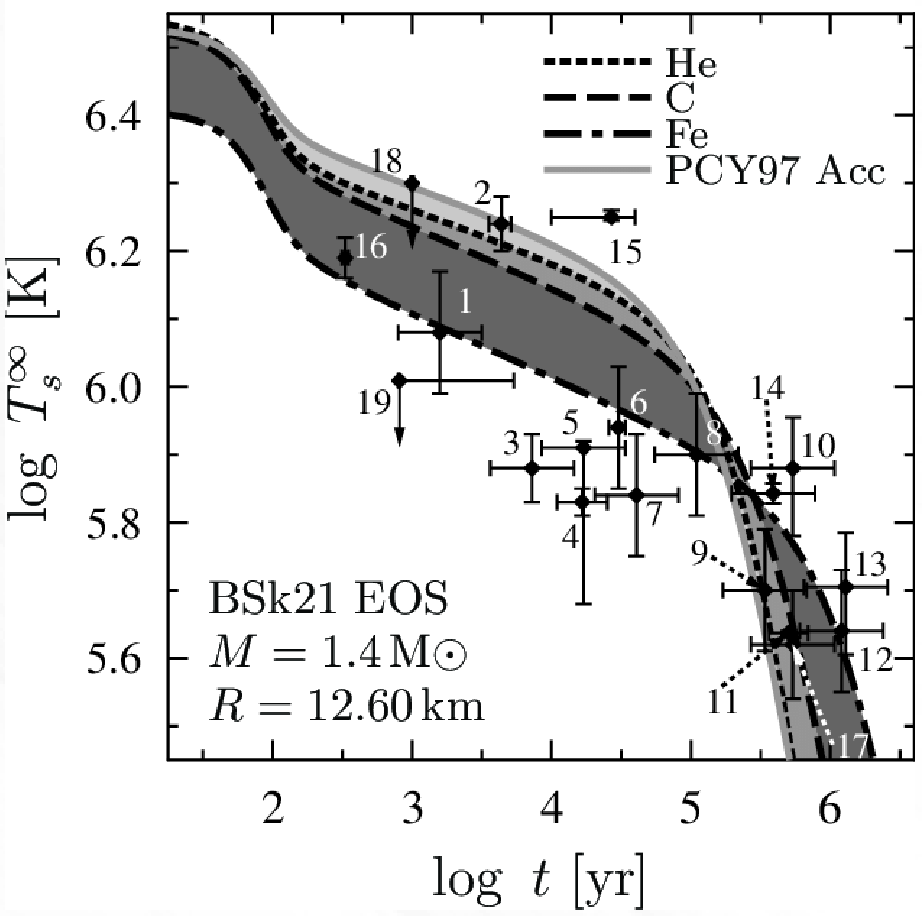
$$\tau_{\mathrm{th}} \simeq \frac{C_V(\Delta r)^2}{\kappa}$$

Constraint from crust thermal relaxation



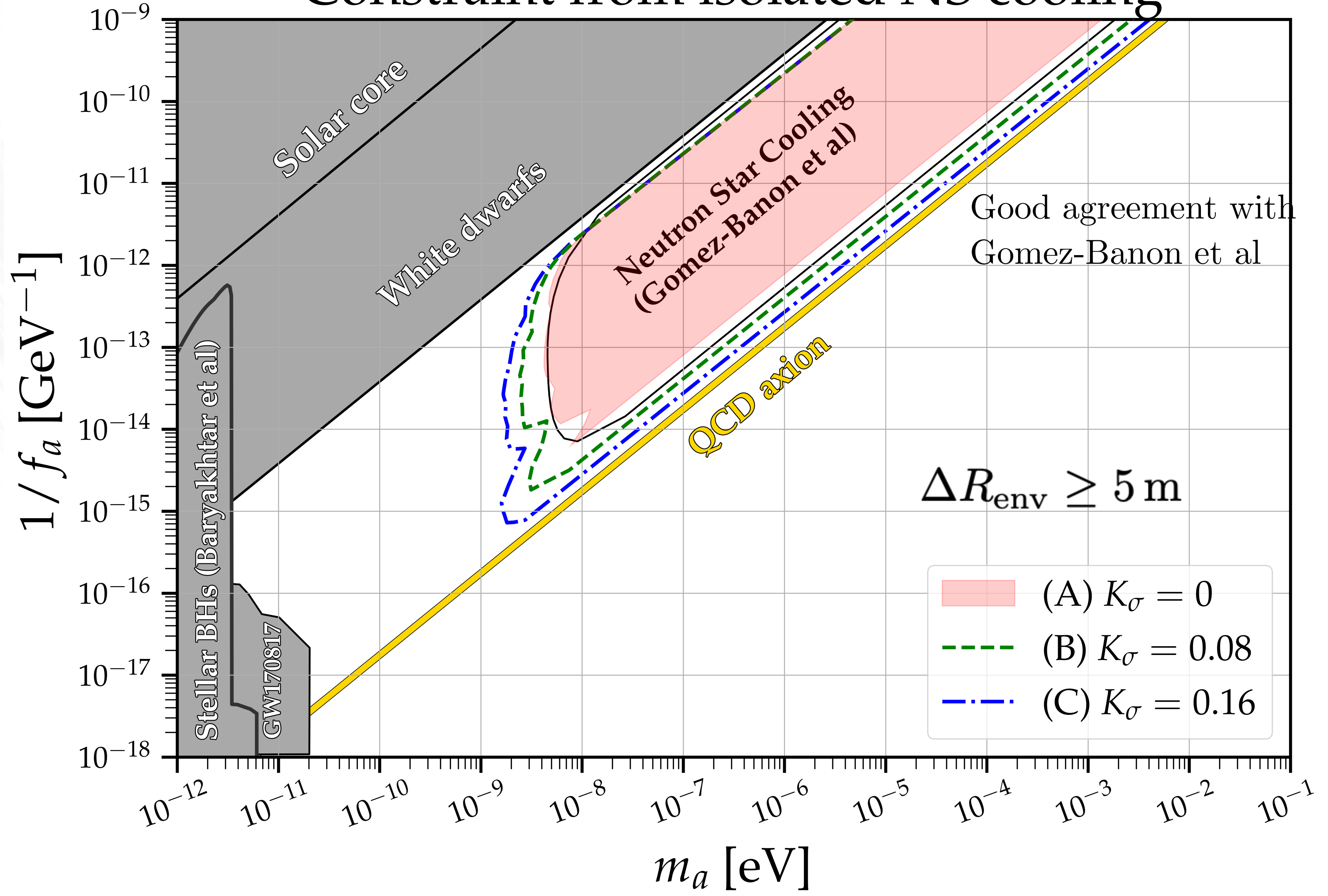
Isolated neutron star cooling

- Normal neutron stars have a heat blanketing envelope with poor heat conductivity that slows cooling from the surface.
- If this layer is too thin, the star cools too quickly. (Gomez-Banon et al 2024)
- Axion condensation also likely decreases the Direct Urca threshold (requiring $Y_p > 1/9$) above which neutron stars cool very rapidly (not yet included).



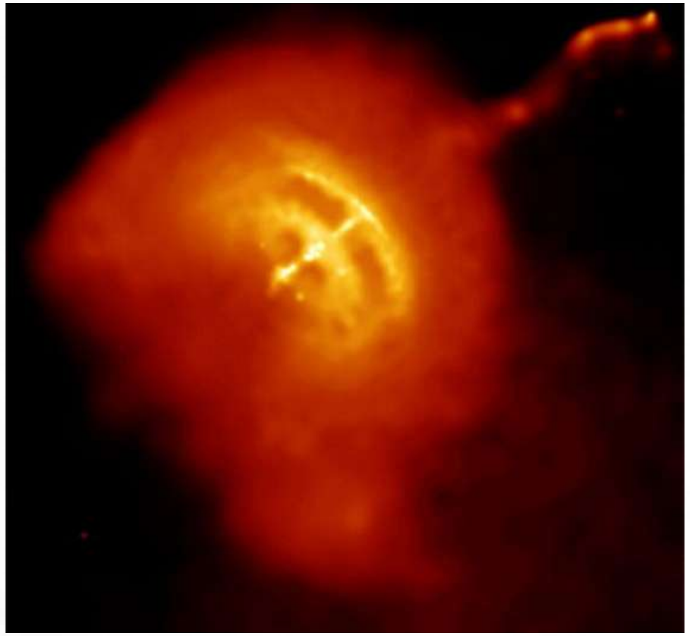
Beznogov et al (2017)

Constraint from isolated NS cooling



Pulsar glitches

- Some pulsars have been observed to glitch, a sudden decrease in pulse period on timescales of a day.
- Typically this is explained as a transfer of angular momentum from the core to superfluid neutrons in the crust. (Lots of details, see Andersson et al 2012 vs. Piekarewicz et al 2014)
- Glitches of the Vela pulsar suggest $I_{\mathrm{crust}}/I \geq 7\,\%$



NASA/CXC/PSU/Pavlov et al

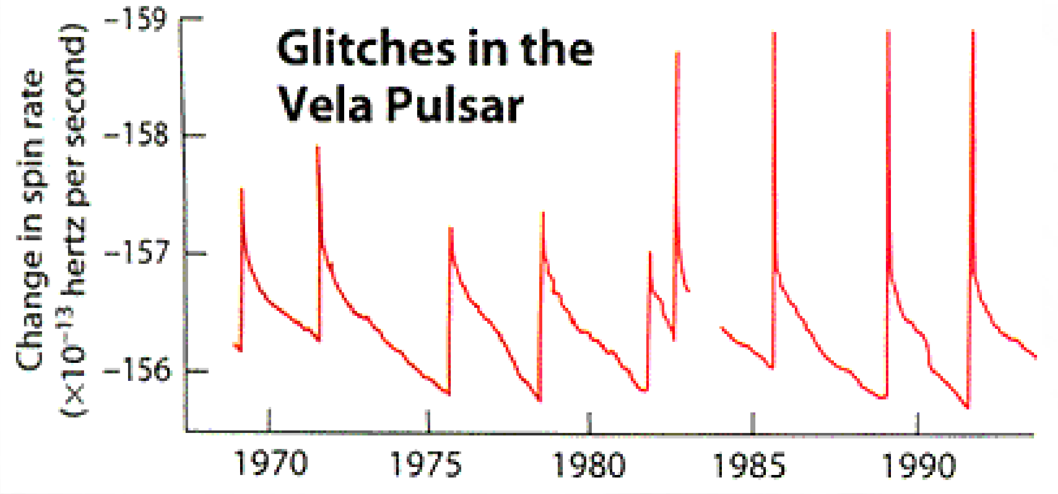
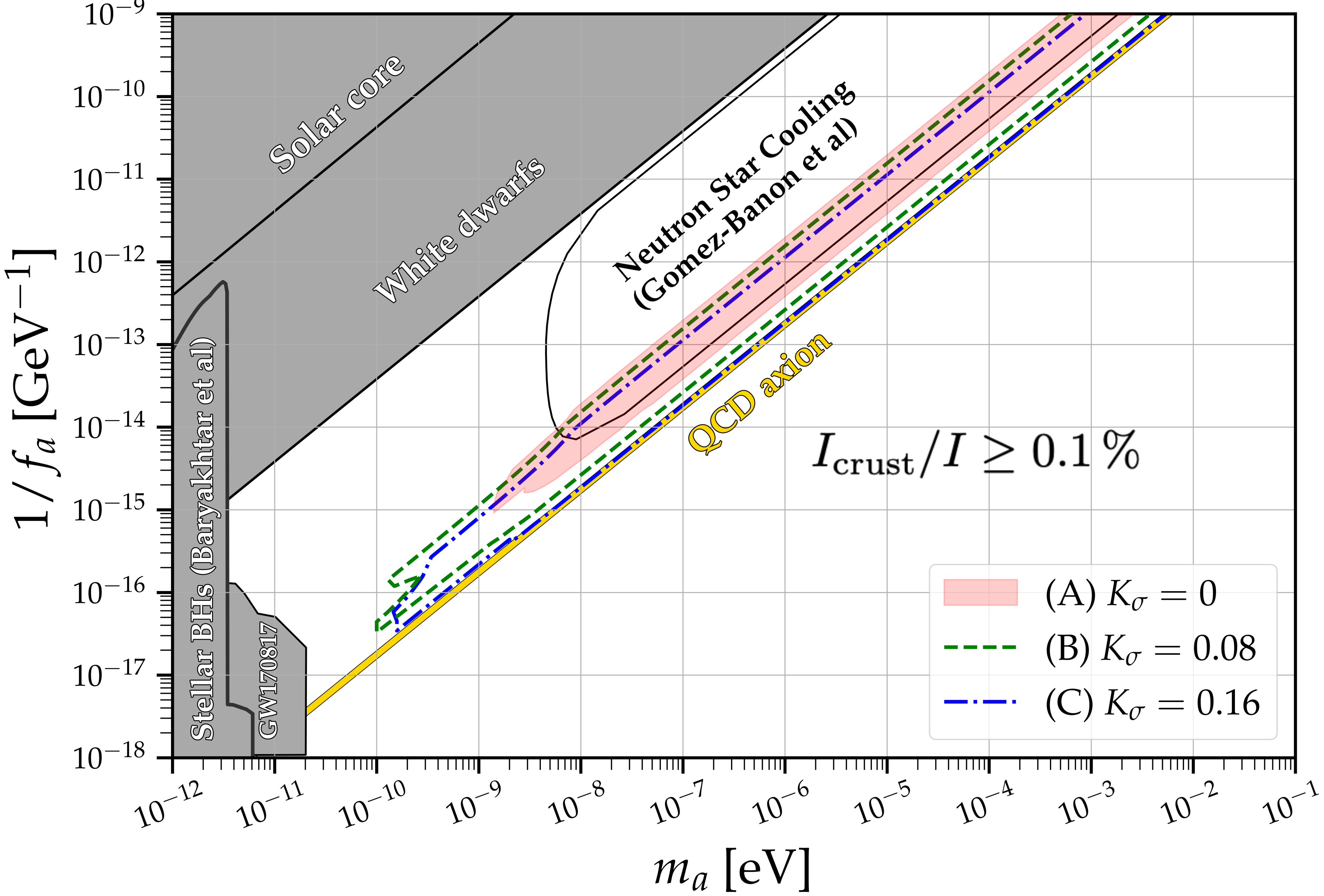
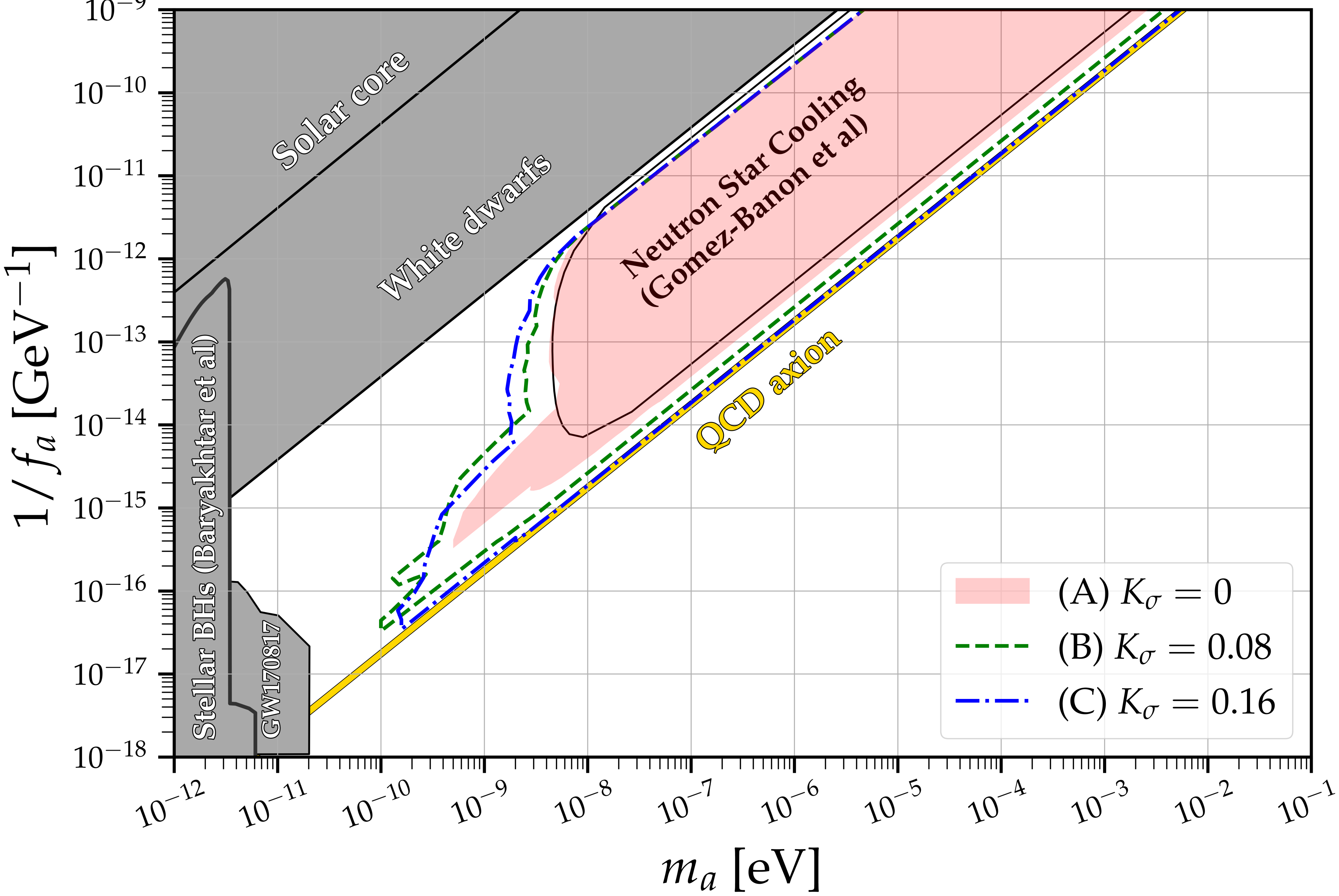


Image: *Pulsar Astronomy* by Lyne and Graham-Smith

Constraint from crust moment of inertia



Combined constraint



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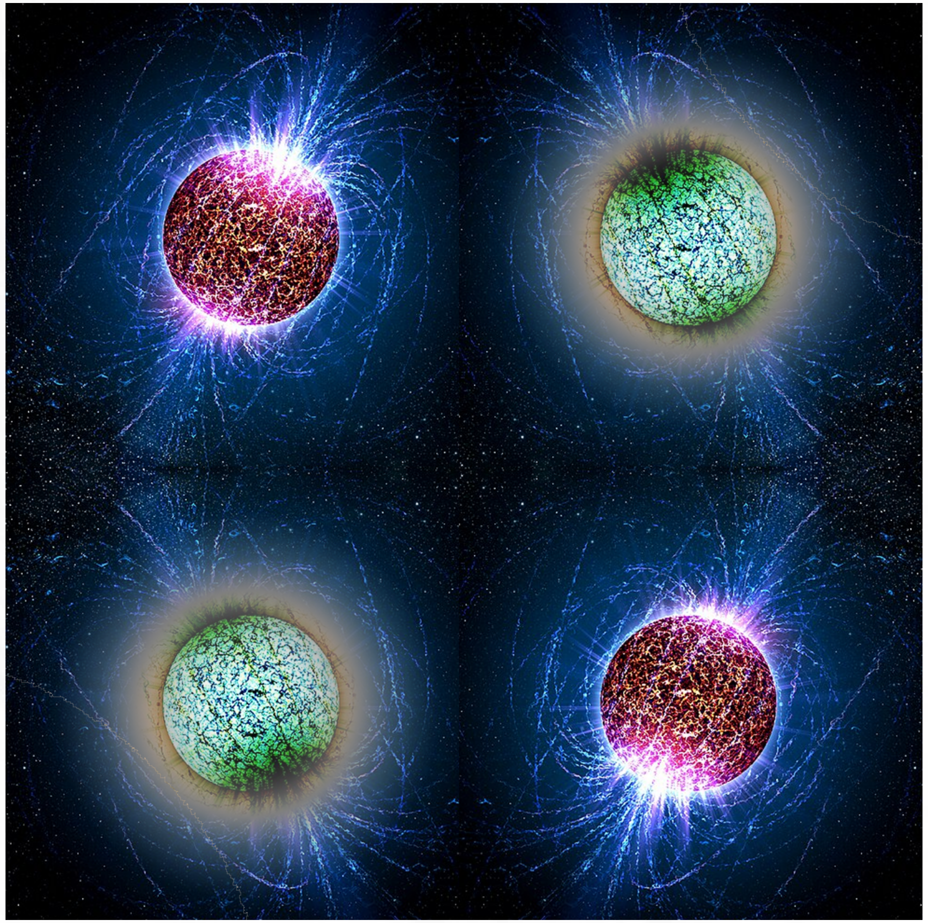

Base image: Casey Reed via wikipedia

What are we doing next?

- Exceptionally light QCD axions seems fairly constrained, what about the QCD axion?
- We need to understand the nuclear force at reduced pion mass better. The convergence of MBPT at reduced pion mass needs to be verified and the pion mass dependence of the contact operators in Chiral EFT needs to be better constrained.
- What observables are relevant for the core that the QCD axion might affect?
  - Mass and radius are probably too uncertain to provide a useful constraint.
  - Oscillation modes of the neutron star may be strongly affected by the presence of a domain wall.
  - If the symmetry energy is strongly affected by axion condensation, the proton fraction may be large enough that neutron stars cool too quickly via neutrinos.

Summary

- In the presence of a large density of baryons, a light QCD axion will condense.

- Neutron stars can probe such an axion and when the axion is very light, axion condensed matter may be favored all the way to the surface of the star.

- Neutron star observations strongly constrain exceptionally light QCD axions with mass greater than $10^{-8}\,\mathrm{eV}$ and $5 \times 10^{-7} < \varepsilon < 0.2$

- Chiral EFT indicates that the nuclear force may become significantly more attractive in the axion condensed phase. There is more work to be done to get the details right. Whether the QCD axion will condense needs to be further investigated.

Thank you for your attention!

Cass A (JWST NIRCam)

Cass (cat)