New Physics in Neutron Stars

TNPI2019 — Conference on Theoretical Nuclear Physics in Italy

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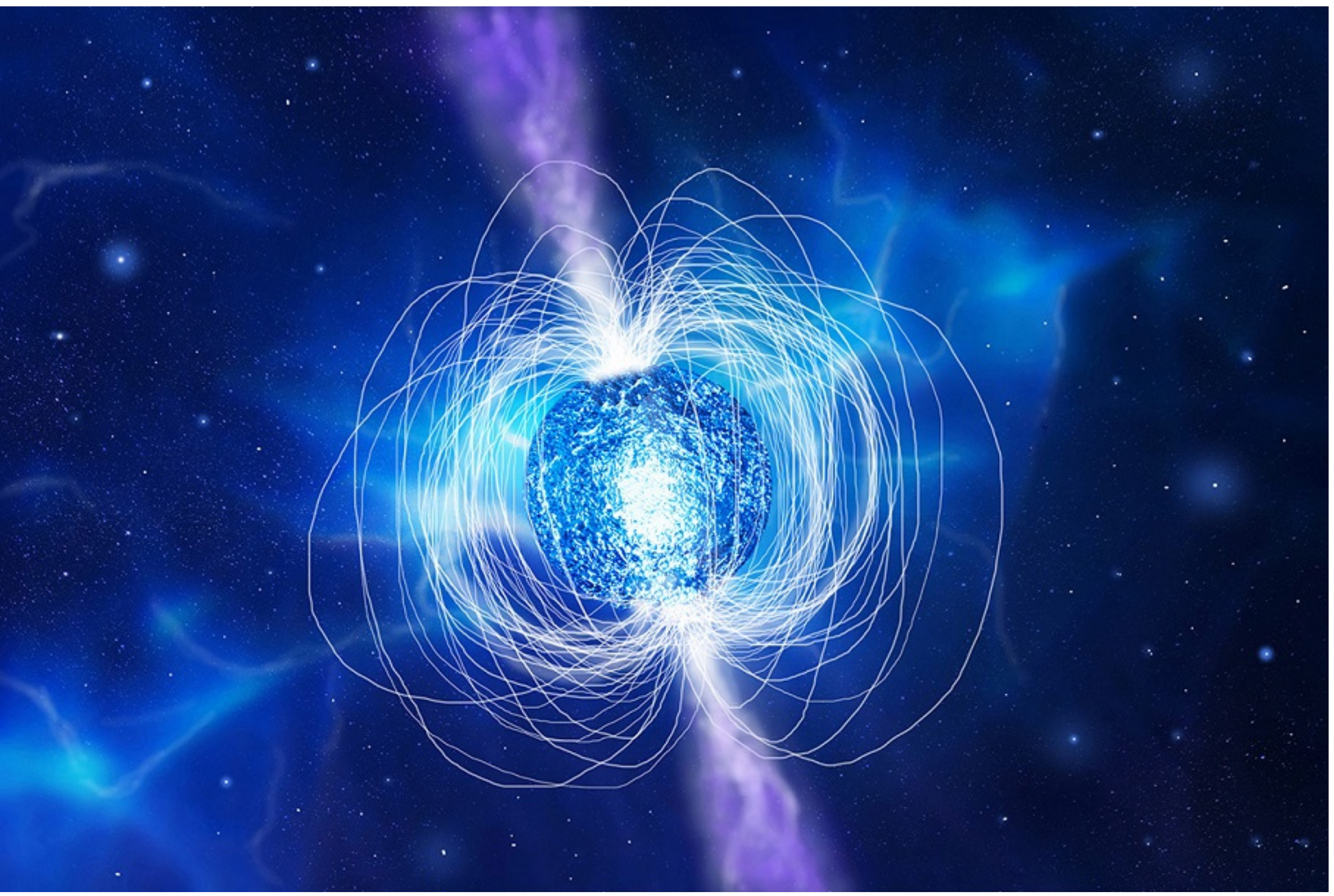
Neutron Stars

An exceptional laboratory for fundamental physics.



The densest stars in the universe,

$$\rho \sim \frac{M_\odot}{\frac{4\pi}{3}(10\,\mathrm{km})^3} \sim 10^{14}\,\mathrm{g/cm}^3 \sim (200\,\mathrm{MeV})^4$$

The strongest magnetic fields in the universe.

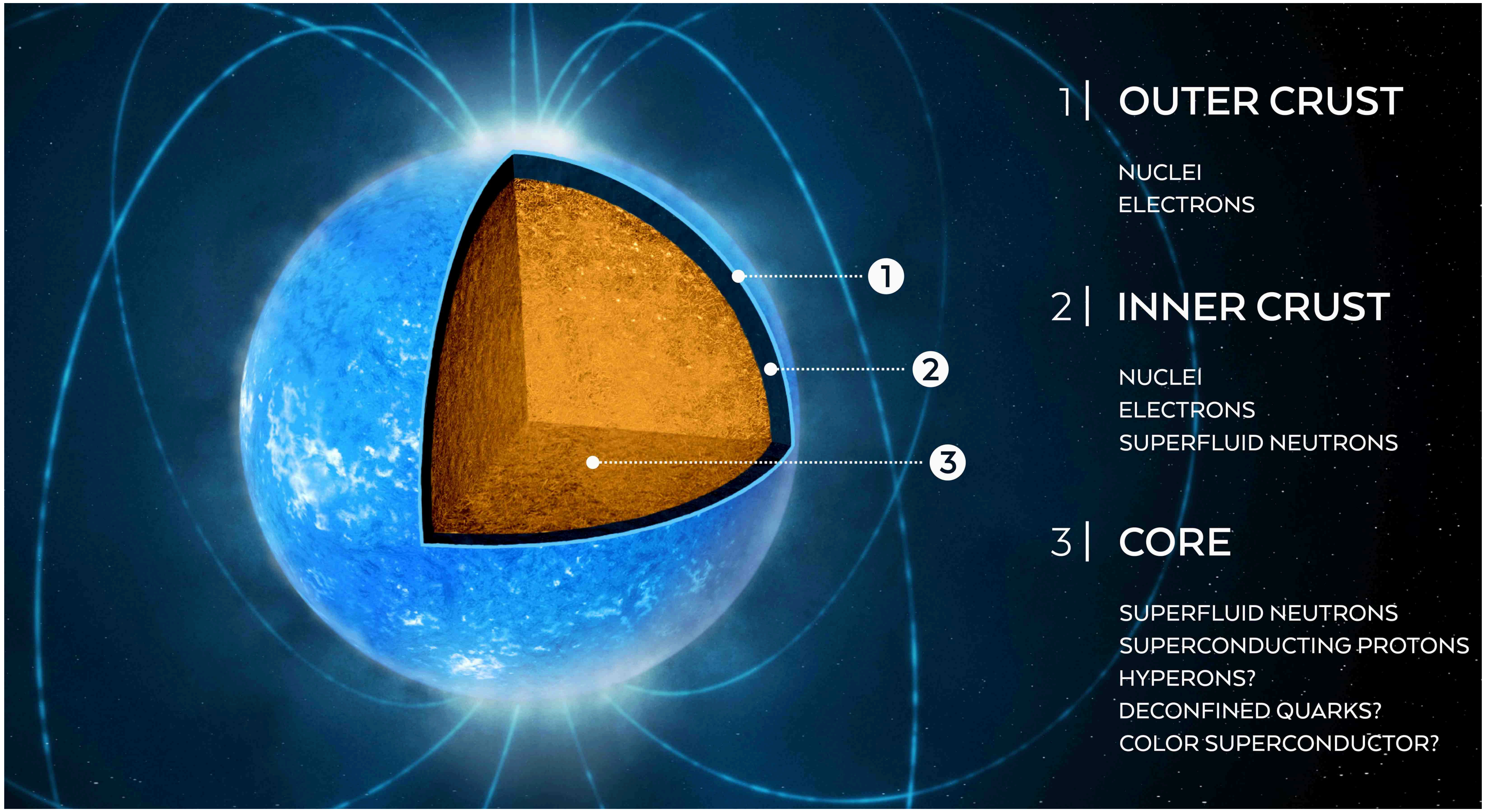
Very precise measurements of their spin (pulsars).

Observed in merger events via gravitational waves.

Excellent experimental prospects in the next decade.

Neutron Stars

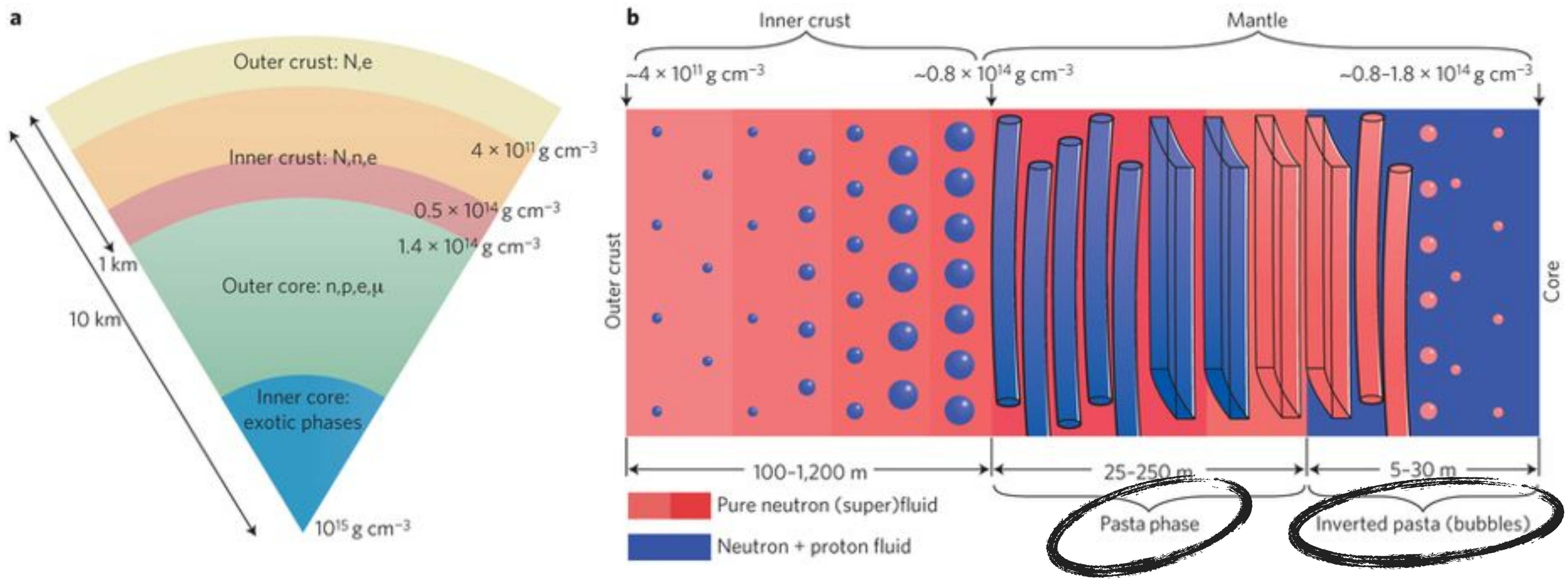
We can learn about how matter behaves at such extreme densities.



(Watts et al. '16)

Neutron Stars

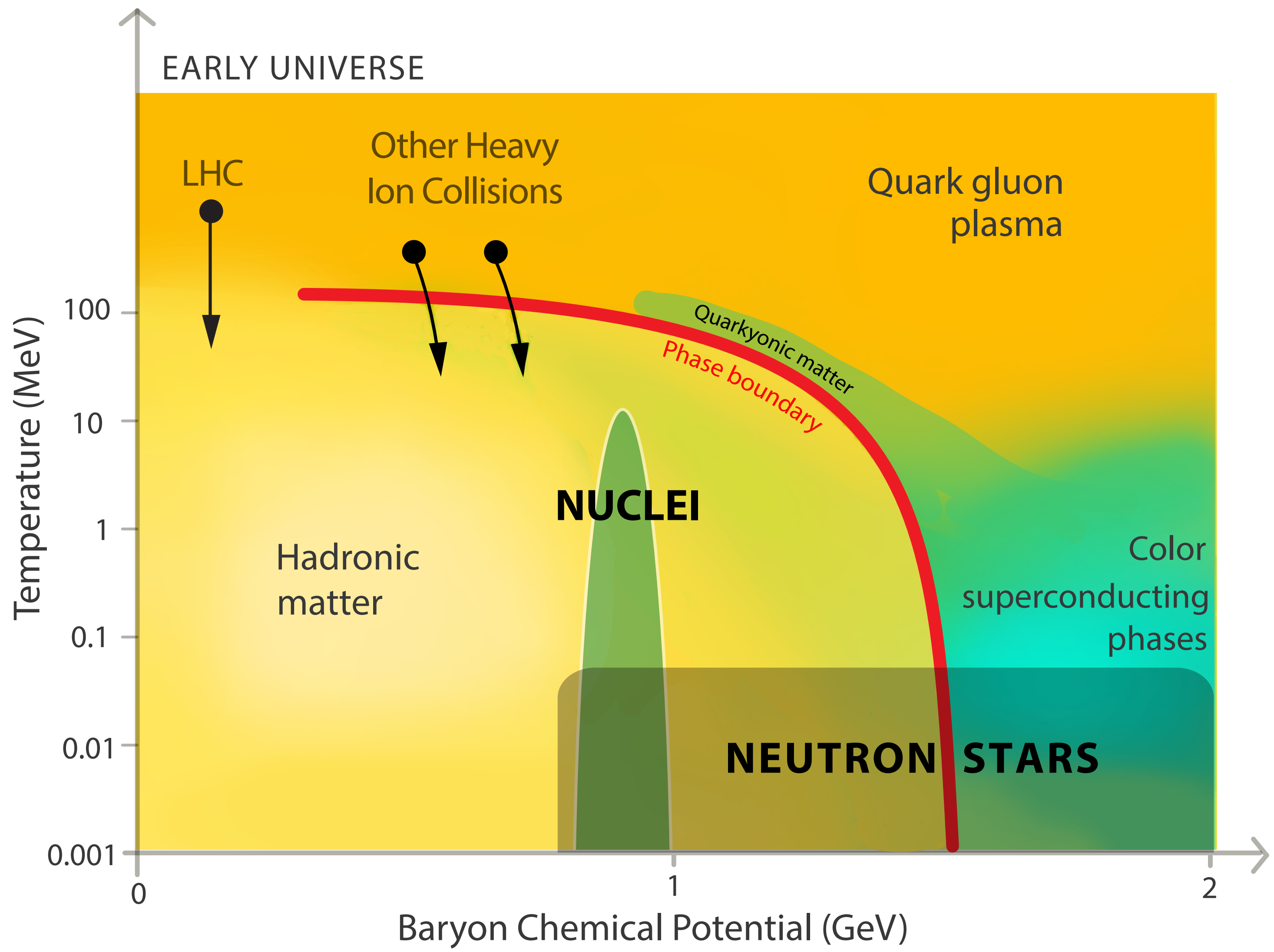
We can learn about how matter behaves at such extreme densities.



(Newton '13, Nature Phys. 9 396)

Neutron Stars

Probe of QCD at high densities (low temperatures) — extremely important to understand.

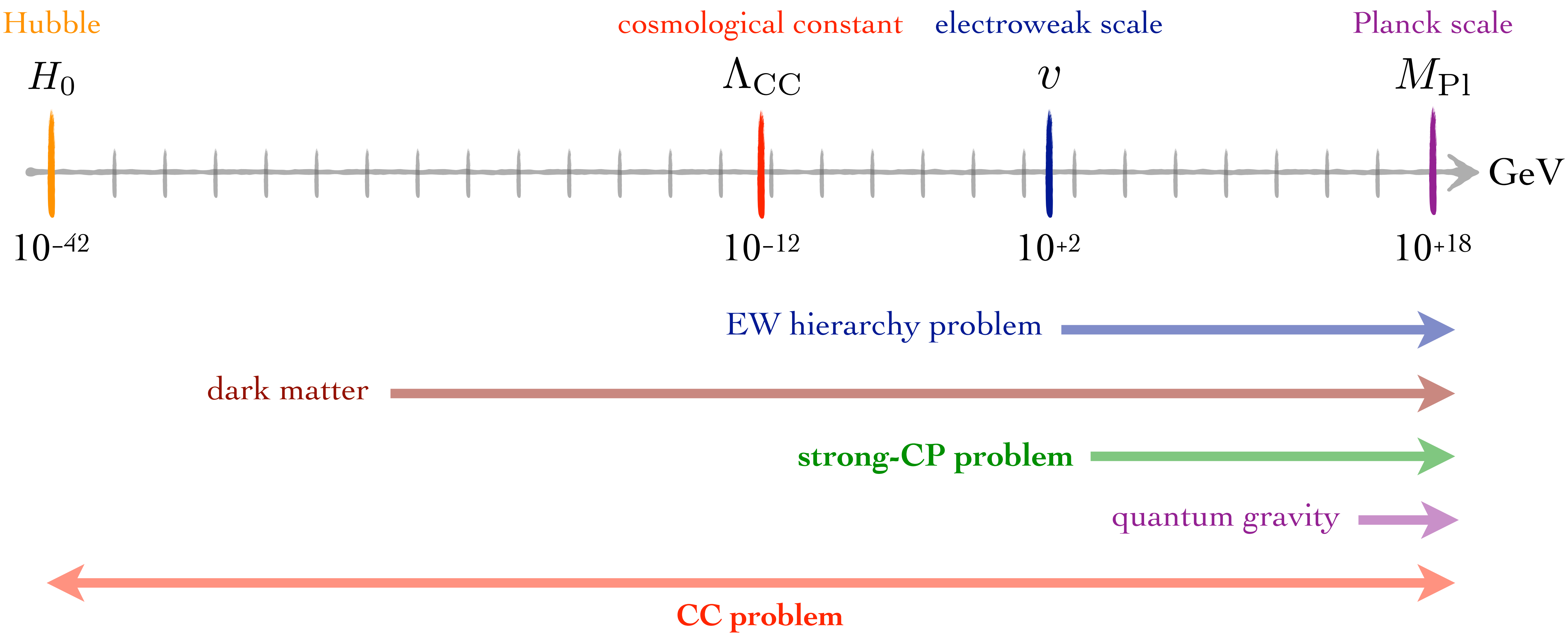


(Watts et al. '16)

Such an environment serves also as probe of physics beyond the Standard Model.

New Physics in Neutron Stars

There are many good reasons to expect physics beyond the SM.



Neutron stars can offer valuable clues on many of these problems.

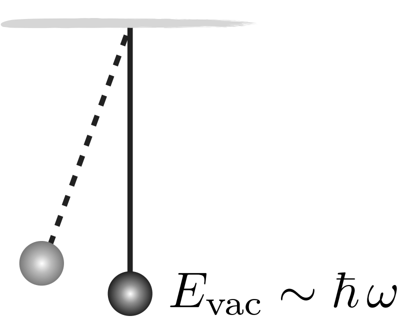
Cosmological Constant

$$\mathcal{S} = \int d^4x \sqrt{-g} \left\{ \frac{M_{\rm Pl}^2}{2} R + \Lambda_{\rm CC} \right\}$$

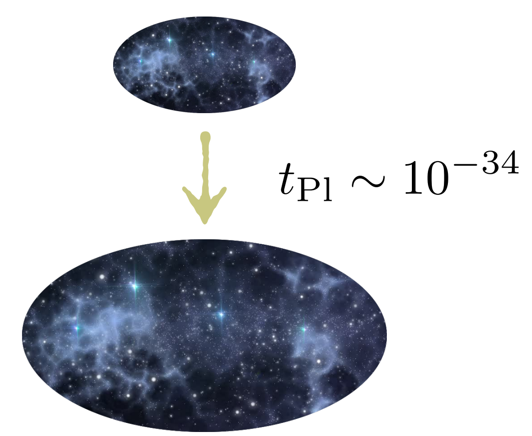
Infamous constant term in Einstein's equations,

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R + \frac{1}{M_{\rm Pl}^2} g_{\mu\nu} \Lambda_{\rm CC} = 0$$

quantum fields = oscillators



$$\longrightarrow \quad \frac{\Lambda_{\rm CC}}{M_{\rm Pl}^4} \sim 1$$



Vacuum energy shows largest disagreement between natural expectation and experiment.

$$\frac{\Lambda_{\rm CC}}{M_{\rm Pl}^4} \sim 10^{-120}$$

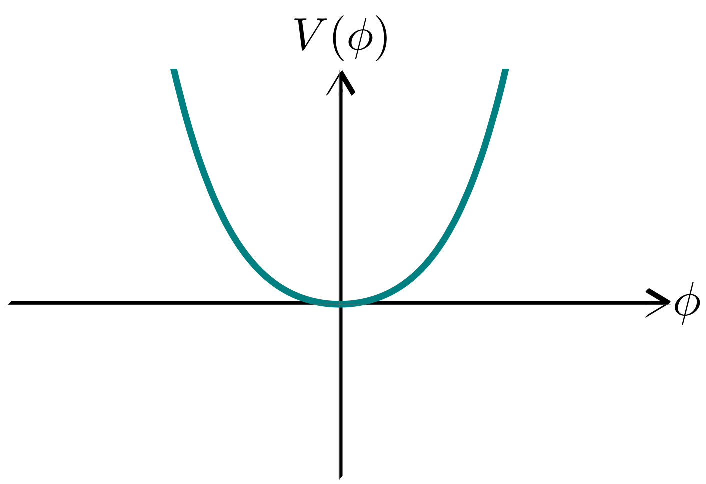
- environmental selection (anthropics)
- relaxation mechanism
- UV-IR connection (swampland)
- modified/composite gravity
- acausal dynamics

Varying Vacuum Energy

One should try to test the problem experimentally.

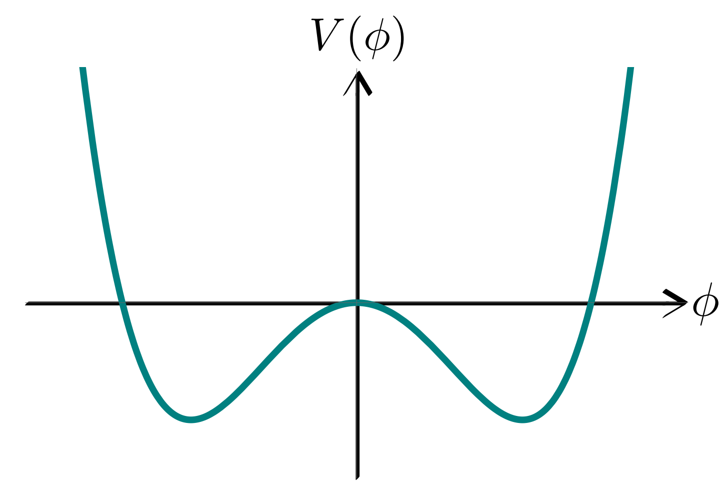
$$V(\phi) = m^2\phi^2 + \lambda\phi^4$$

$m^2 > 0$



$V(\langle\phi\rangle) = 0$

$$m = m(T, \mu, \dots)$$



$m^2 > 0$

$V(\langle\phi\rangle) \neq 0$

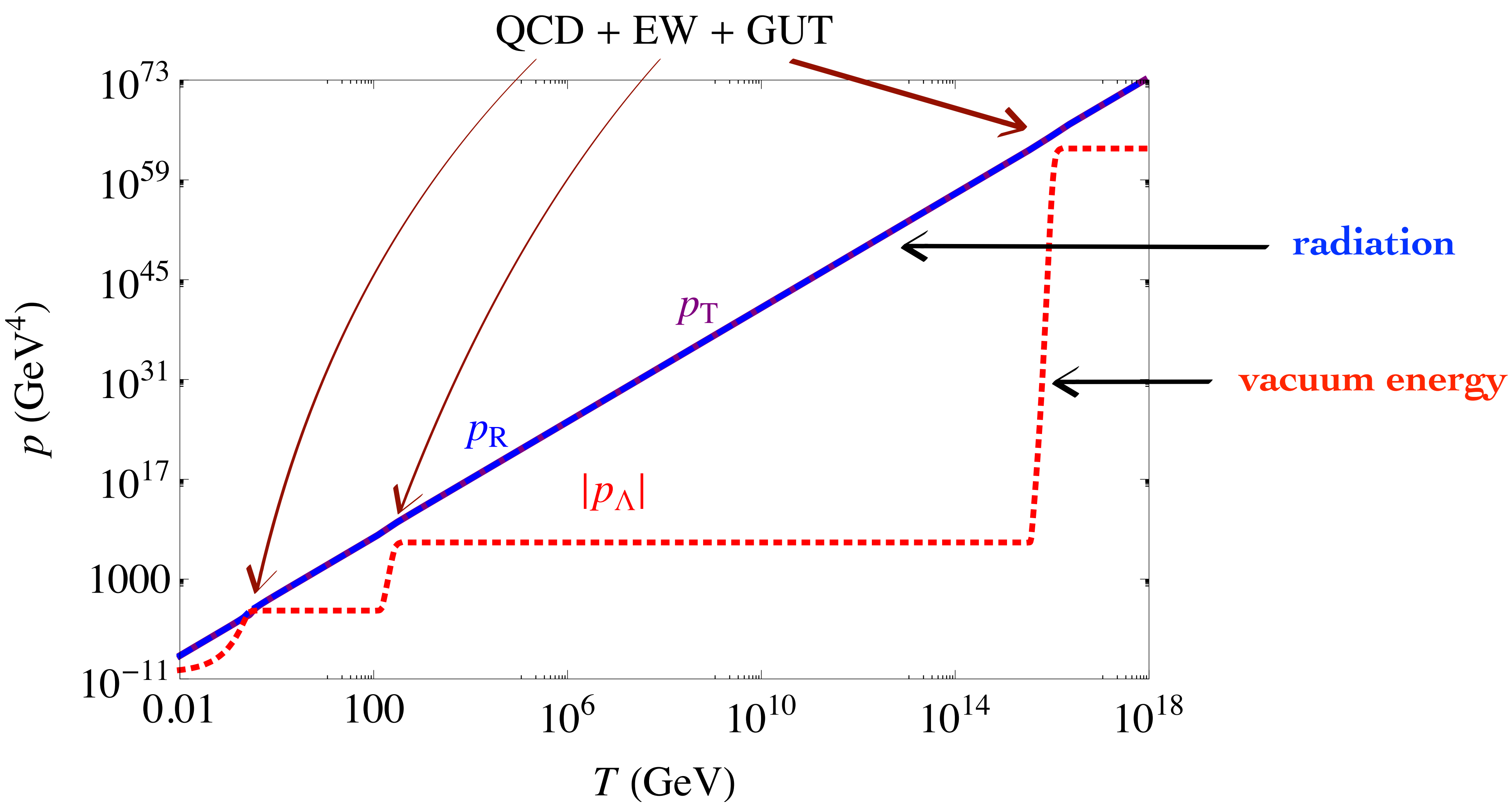
Vacuum energy changes at phase transitions.

- QCD: $\langle\phi\rangle = \langle\bar{q}q\rangle,\ \langle qq\rangle,\ \dots$
- EW: $\langle\phi\rangle = v$

(Bellazzini, Csaki, Hubisz, JS, Terning '15)

Varying Vacuum Energy

Evolution during expansion/cooling of the universe.

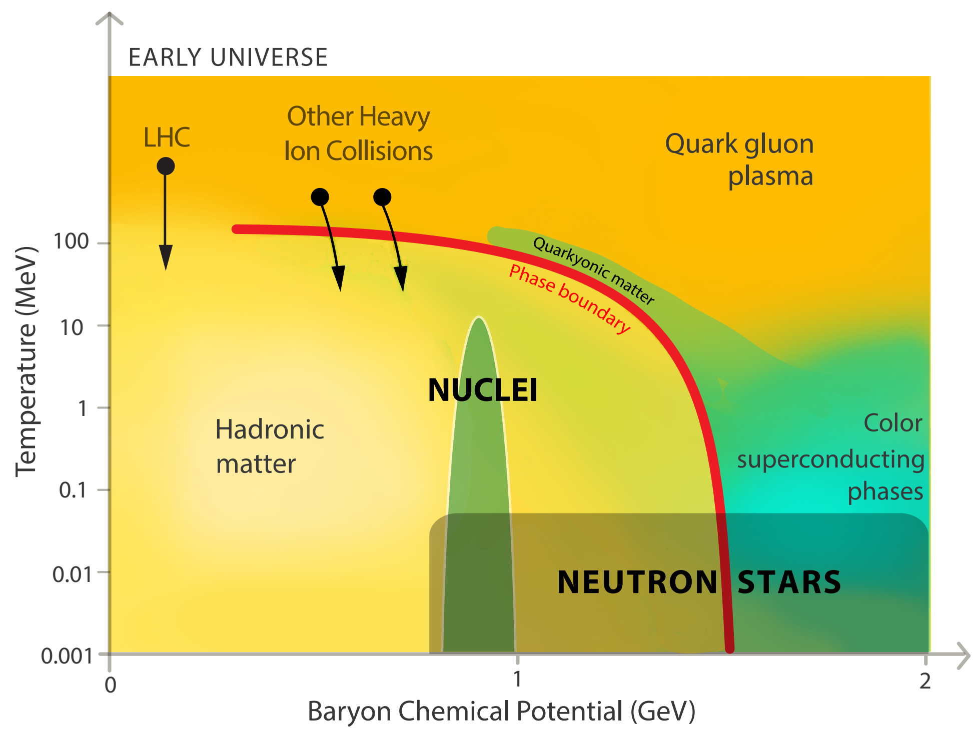


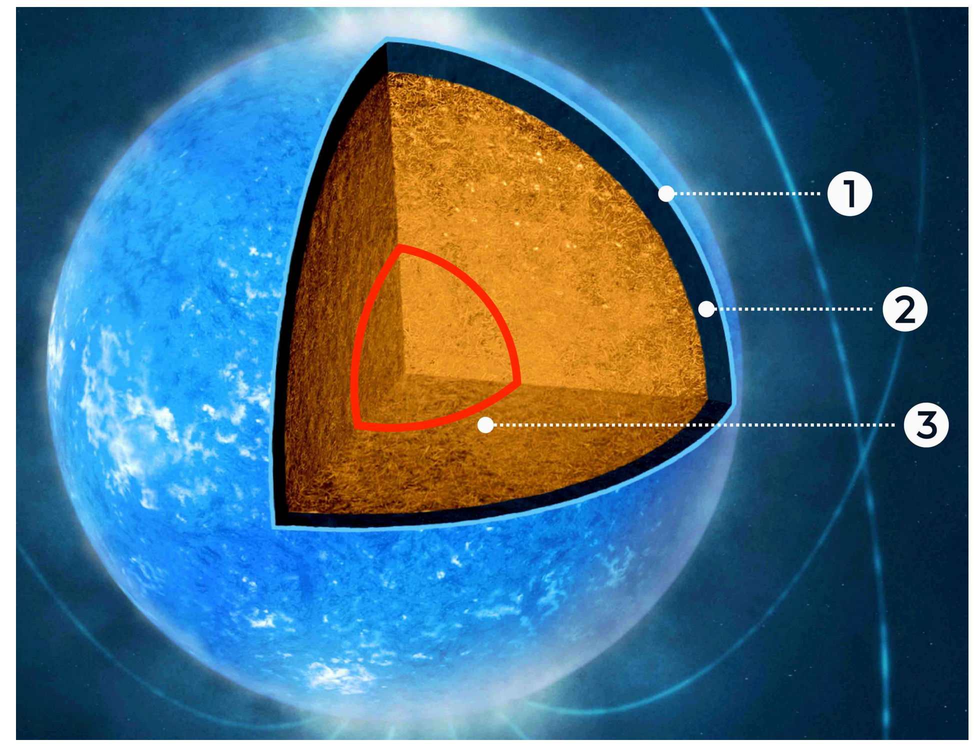
O(1) contribution to pressure/energy close to phase transitions.

(Bellazzini, Csaki, Hubisz, JS, Terning '15)

Vacuum Energy in Neutron Stars

Vacuum energy can be O(1) fraction of total energy.





Study how vacuum energy changes the properties of the neutron star, e.g. mass-radius relation.

Possibly test cosmological constant relaxation mechanism vs anthropics.

spherically symmetric metric

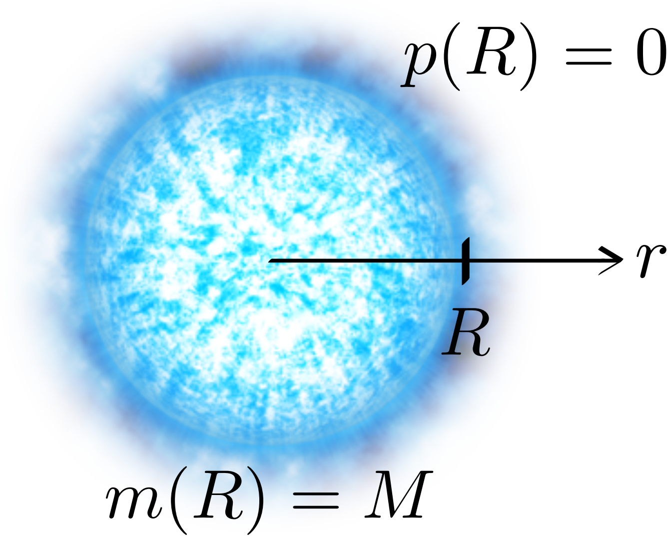
$$ds^2 = e^{\nu(r)} dt^2 - \left(1 - \frac{2Gm(r)}{r}\right)^{-1} dr^2 - r^2 d\Omega^2$$

Tolman-Oppenheimer-Volkoff equations

$$m'(r) = 4\pi r^2 \epsilon(r)$$

$$p'(r) = -\frac{p(r) + \epsilon(r)}{r\left(r - 2Gm(r)\right)} \left[Gm(r) + 4\pi r^3 p(r)\right]$$

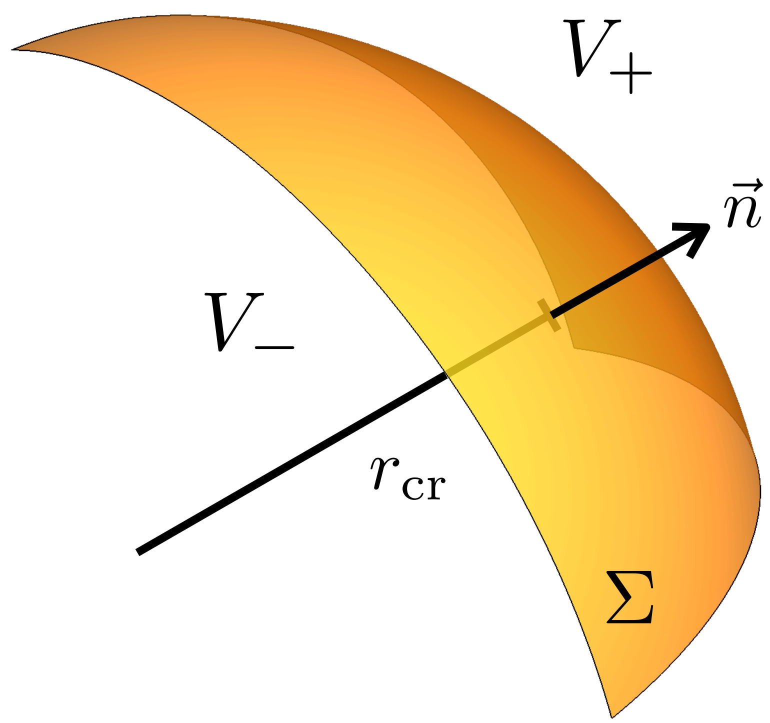
$$\nu'(r) = -\frac{2p'(r)}{p(r) + \epsilon(r)}$$



model dependent equation of state

$$p = p(\epsilon)$$

Israel junction conditions



$$[h_{ij}]^+_- = 0$$

$$[K_{ij}]^+_- - h_{ij}[K]^+_- = 8\pi G\, S_{ij}$$

$$[\nu]^+_- = 0$$

$$[m]^+_-,\ [\nu']^+_-,\ [p]^+_- = 0 \quad \text{if} \quad S_{ij} = 0$$

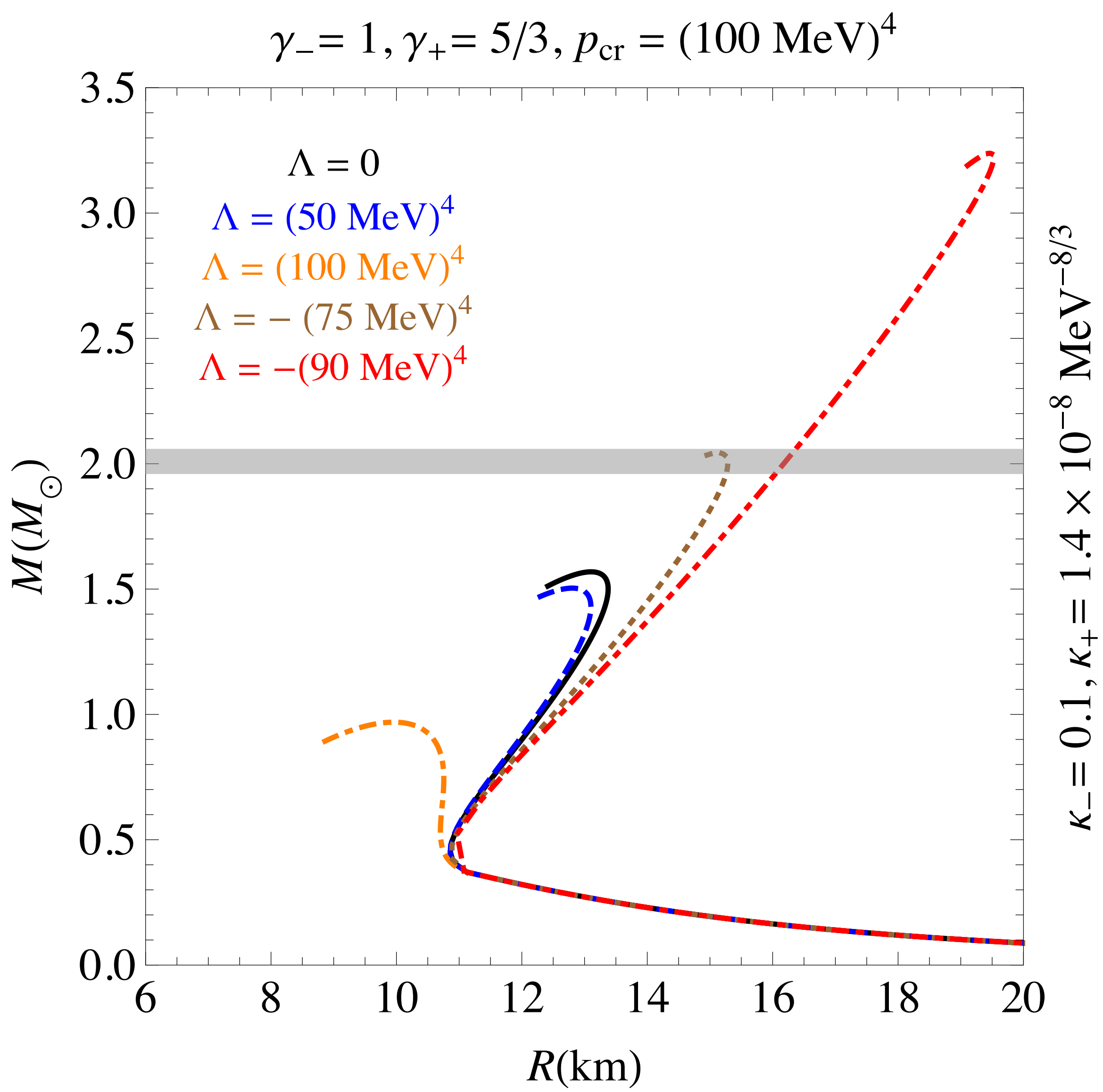
$$[\epsilon]^+_- \neq 0$$

(unexplored) additional model dependence — customarily, continuous pressure and energy

Toy Model I (+6 months)

1 layer, polytropic outside, polytropic + adjustable vacuum energy inside, discontinuous ϵ.

$$p_+ = \kappa_+ \epsilon_m^{\gamma_+}\,, \qquad \epsilon_+ = \epsilon_m$$
$$p_- = \kappa_- \epsilon_m^{\gamma_-} - \Lambda\,, \quad \epsilon_- = \epsilon_m + \Lambda$$



(Bellazzini, Csaki, Hubisz, JS, Terning '15)

O(1) change of the mass-radius relation.

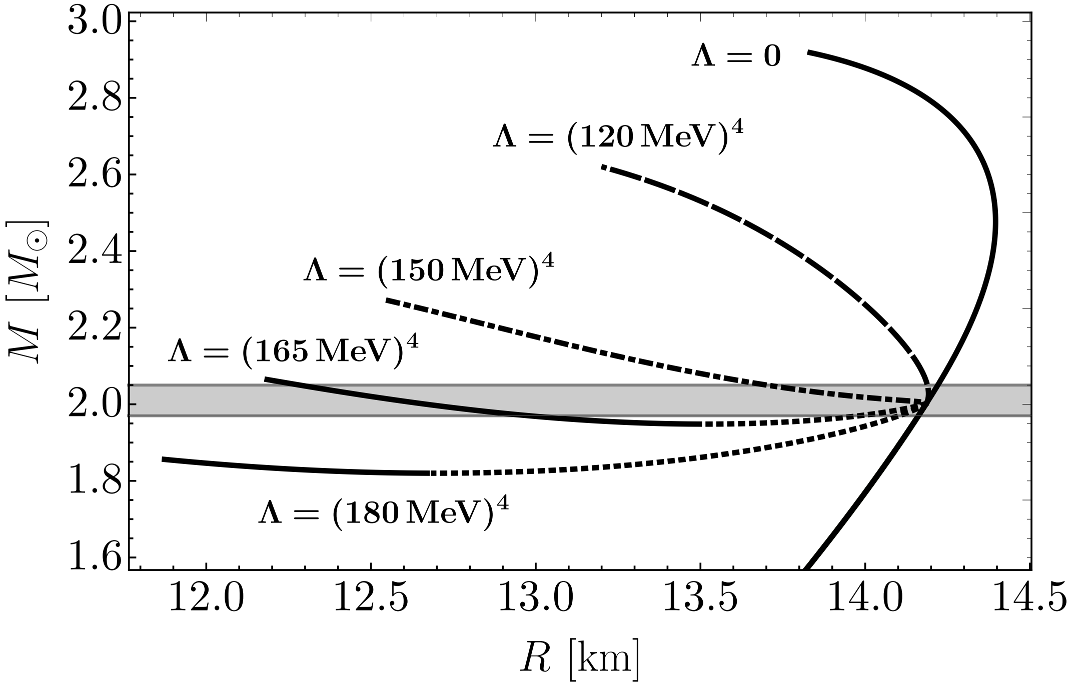
Maximal mass particularly sensitive.
(sensitive as well as to other EOS parameters)

Need more experiment and theory input.

Toy Model II (+3 years)

7 layers, polytropics, polytropic + vacuum energy in core, continuous μB, discontinuous ϵ in core.

(Csaki, Eroncel, Hubisz, Rigo, Terning '18)

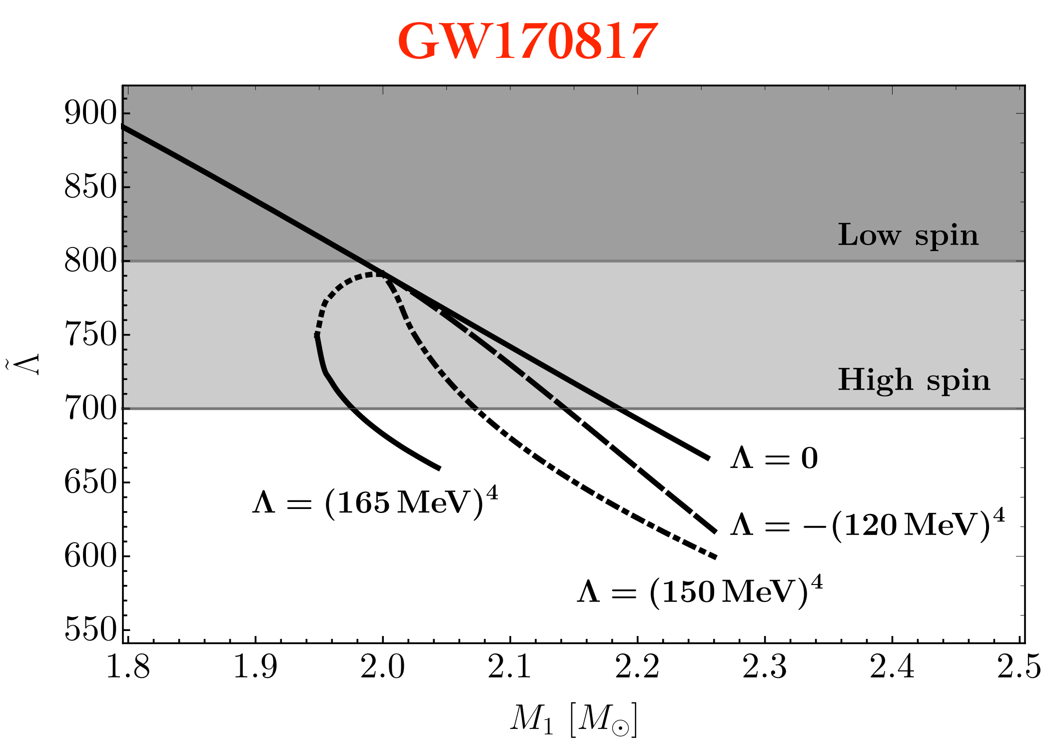


Modelling clearly important.

Main message remains: vacuum energy important.

Vacuum energy relevant also for tidal deformability.

$$\tilde{\Lambda} = \frac{16}{13}\frac{(M_1 + 12M_2)M_1^4\bar{\lambda}_1 + (M_2 + 12M_1)M_2^4\bar{\lambda}_2}{(M_1+M_2)^5}$$



Strong CP-problem and Axion Solution

The puzzling absence of CP violation in the interactions of hadrons.

$$\mathcal{L}_\theta = \theta \frac{g_s^2}{32\pi^2} G_{\mu\nu}\widetilde{G}^{\mu\nu}$$

theory	*experiment*
$\theta = \theta_0 + \arg\det M_q$	$\theta < O(10^{-10})$

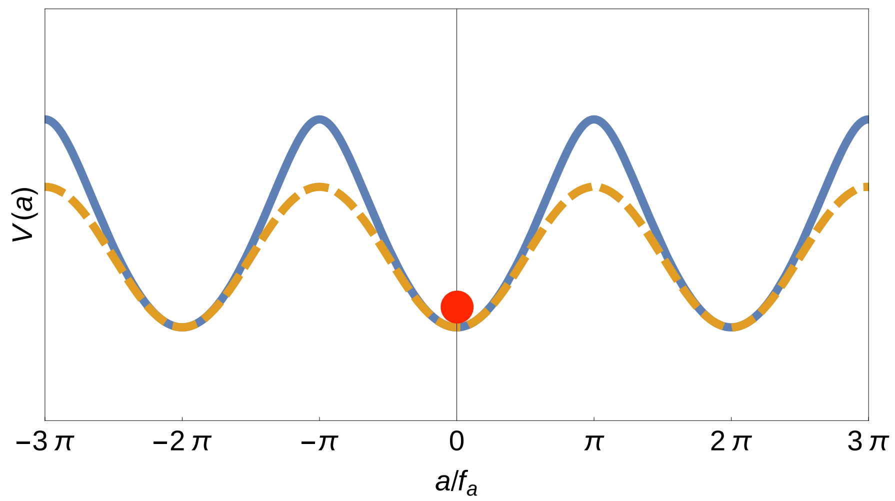
$\delta_{\mathrm{CKM}} = O(1)$

$$\Downarrow$$

Nambu-Goldstone boson of QCD-anomalous $\mathrm{U}(1)_{\mathrm{PQ}}$ symmetry

$$\mathcal{L}_{\theta+a} = \frac{1}{2}(\partial_\mu a)^2 + \underbrace{\left(\theta + \frac{a}{f_a}\right)}_{\to\, a/f_a} \frac{g_s^2}{32\pi^2} G_{\mu\nu}\widetilde{G}^{\mu\nu}$$

(Grilli et al '16)



$$m_a \simeq \frac{m_\pi f_\pi}{f_a}$$

$$10^8 \lesssim f_a/\mathrm{GeV} \lesssim 10^{17}$$
$$10^{-10} \lesssim m_a/\mathrm{eV} \lesssim 10^{-1}$$

Vacuum Axion Potential

Low-energy chiral Lagrangian plus axion.

$$\frac{SU(3)_L \times SU(3)_R \times U(1)_B \times U(1)_A}{SU(3)_{L+R} \times U(1)_B} \longrightarrow \Phi = \exp\left[\frac{i\pi^a \lambda^a}{f_\pi}\right] \exp\left[\frac{i\eta'}{3f_{\eta'}}\right] \Sigma_0$$

$$V_0 = b\,\mathrm{tr}[\Phi^\dagger M_q] - c\, e^{-\frac{ia}{f_a}} \det[\Phi^\dagger] + \mathrm{h.c.}$$

$$b = \frac{\langle \bar{u}u\rangle_0}{2} = -\frac{m_\pi^2 f_\pi^2}{2(m_u + m_d)}$$

$$c = \frac{m_{\eta'}^2 f_\pi^2}{12}$$

$$\Big\downarrow \quad q \to e^{\frac{ia}{2f_a}\gamma_5 Q_a} q$$

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

Axion potential is of QCD size.

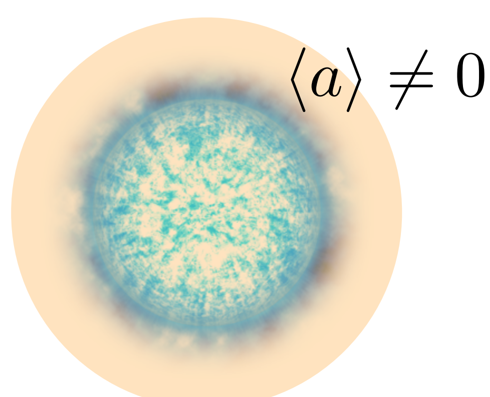
Axion in Neutron Stars

Properties of the axion change at finite baryon chemical potential.

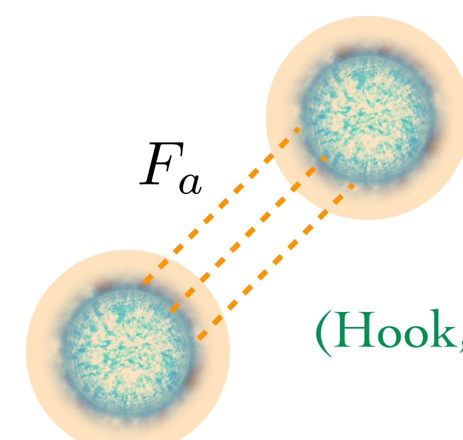
$$\partial_0 \to \partial_0 + i\mu T$$

(expectation value, mass, self-coupling, couplings to matter)

- Axion background and neutron star EOS:

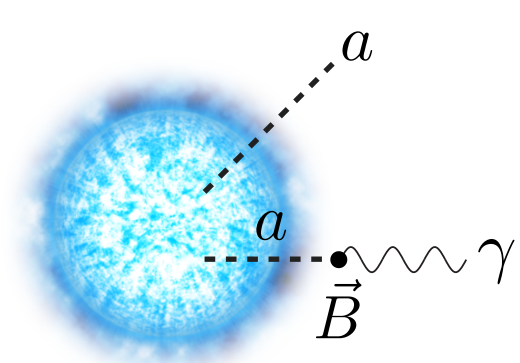


- Axion force in merger events:



(Hook, Huang '17)

- Axion/photon emissivity:



Small Density Axion Potential

$$\mu/\Lambda_{\rm QCD} \ll 1$$

- Decreasing chiral condensate:

$$(m_a^2)_{n_b} = (m_a^2)_0 \frac{\langle \bar{q}q \rangle_{n_b}}{\langle \bar{q}q \rangle_0} = (m_a^2)_0 \left(1 - \frac{\sigma_{\pi N} n_b}{m_\pi^2 f_\pi^2}\right)_{n_b \sim \mu^3}$$

$$\sigma_{\pi N} \equiv \bar{m} \frac{\partial m_p}{\partial \bar{m}} = 45 \pm 15 \text{MeV}$$

Predictivity is lost at relatively low nuclear densities.

$$n_b \lesssim 2 n_0 \approx (140\,\text{MeV})^3$$

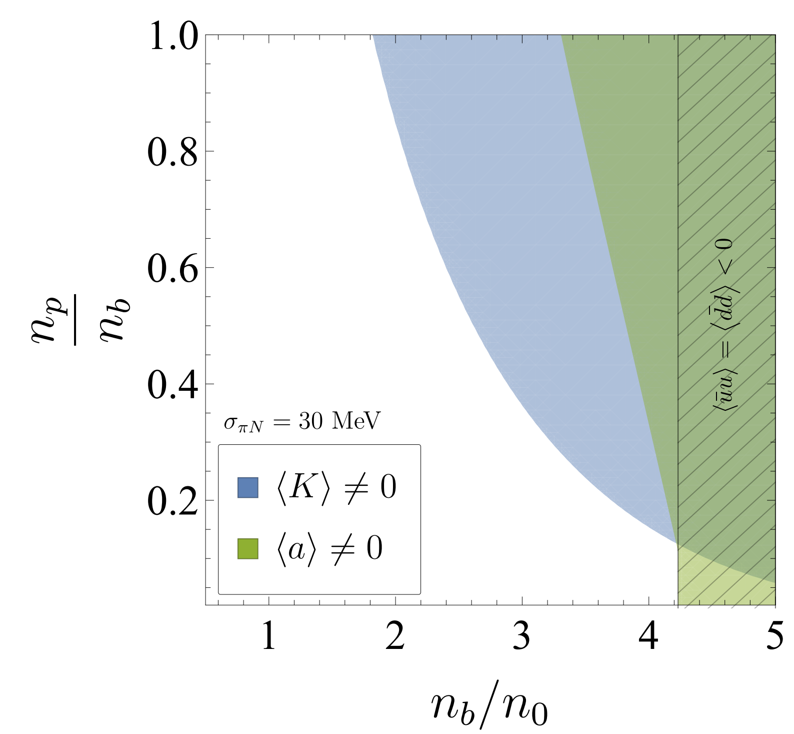
- Meson (kaon) condensation:

$$n \to p^+ + K^-$$

possibly favoured over

$$n \to p^+ + e^-$$

$$\Sigma_K = \begin{pmatrix} \cos\theta & 0 & i\sin\theta \\ 0 & 1 & 0 \\ i\sin\theta & 0 & \cos\theta \end{pmatrix} \longrightarrow$$



Large Density Axion Potential

$$\mu/\Lambda_{\rm QCD} \gg 1$$

New vacuum of QCD: Color-Flavor-Locked (CFL) phase.

$$\langle qq\rangle \gg \langle \bar{q}q\rangle$$

$$\frac{SU(3)_L \times SU(3)_R \times SU(3)_C \times U(1)_B \times U(1)_A}{SU(3)_{L+R+C}} \longrightarrow \begin{array}{c} \Phi = \exp\left[\dfrac{i\pi^a\lambda^a}{f_\pi}\right] \\ \exp\left[\dfrac{i\eta'}{f_{\eta'}}\right] \quad \exp\left[\dfrac{iH}{f_H}\right] \end{array}$$

and massive gluons

$$m_g = g\mu$$

Instantons are suppressed and calculable at such high densities.

$$V_M^{(3,6)} = \mp A_{1,2}\Delta_{3,6}^2 e^{\frac{i4\eta'}{f_{\eta'}}}\left(\mathrm{tr}[\Phi^\dagger M]\mathrm{tr}[\Phi^\dagger M] \mp \mathrm{tr}[\Phi^\dagger M \Phi^\dagger M]\right) + \mathrm{h.c.}$$

$$A_1 = 2A_2 = \frac{3}{4\pi^2}$$

$$V_{1-\mathrm{inst.}} = -A_3\Delta_3^2 e^{\frac{i4\eta'}{f_{\eta'}}+\frac{ia}{f_a}}\mathrm{tr}[\Phi M^\dagger] + \mathrm{h.c.}$$

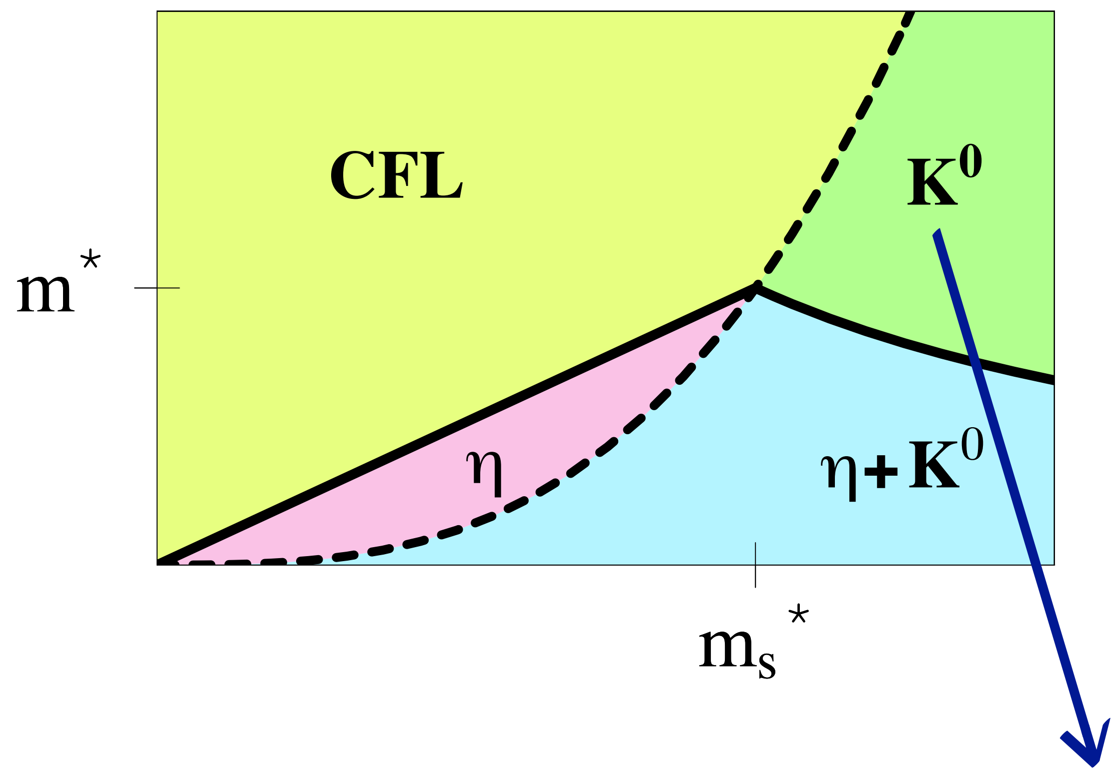
$$A_3 \sim \frac{(4\pi)^3}{\alpha_s^7}\frac{\Lambda_{\rm QCD}^9}{\mu^8}$$

$$\Delta_{3,6} \sim \mu \exp\left(-\frac{3\pi^2}{\sqrt{2}g_s}\right)$$

Large Density Axion Potential

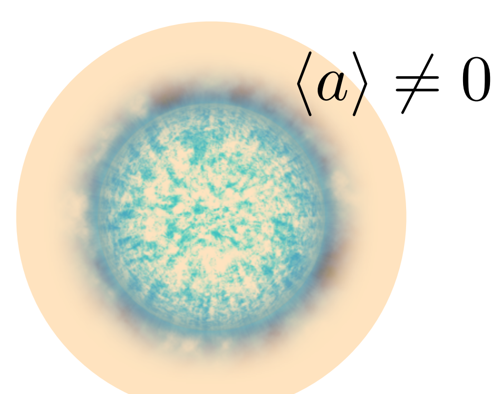
$$\mu/\Lambda_{\rm QCD} \gg 1$$

(e.g. Kaplan '05)



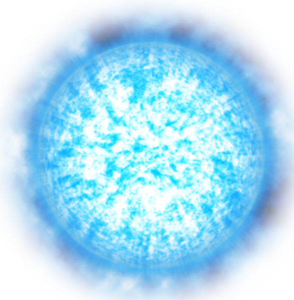
$$\langle a/f_a \rangle = \pi \,, \quad A_1 \Delta_3^2 m^2 < A_2 \Delta_6^2 m_s^2 \cos\theta$$

It is plausible that the QCD-axion is sourced inside neutron stars.



Summary

Neutron stars offer an unexplored playground to look for physics beyond the SM.



To test the validity of the current cosmological constant paradigm.

To gain clues on axion solution to the strong CP-problem.

Needless to say, theoretical input on the nuclear/QCD phase diagram is crucial.

Thank you.