湖南科技大學
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致密物质中的 QCD 轴子与畴壁性质

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Outline

- ☼ Theta vacuum, strong CP problem and axions
- ☼ Axion properties and domain walls
- ☼ Summary

Why study QCD in compact stars?

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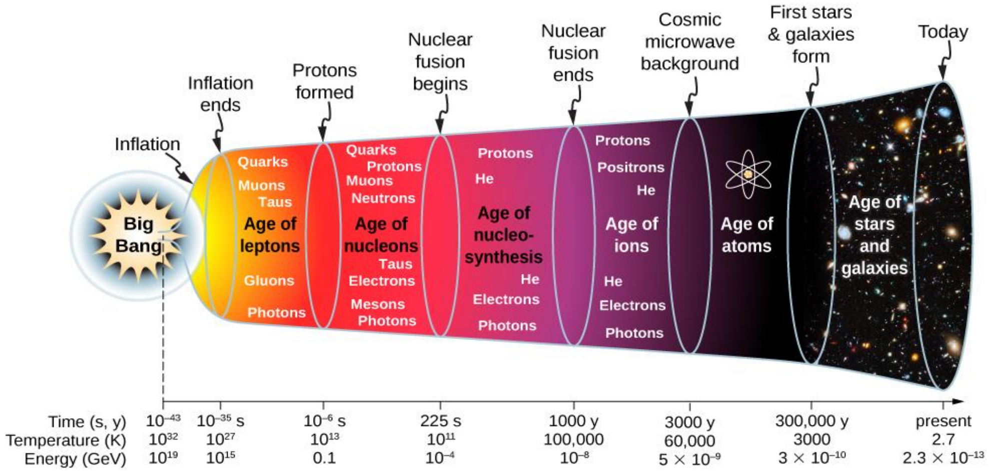
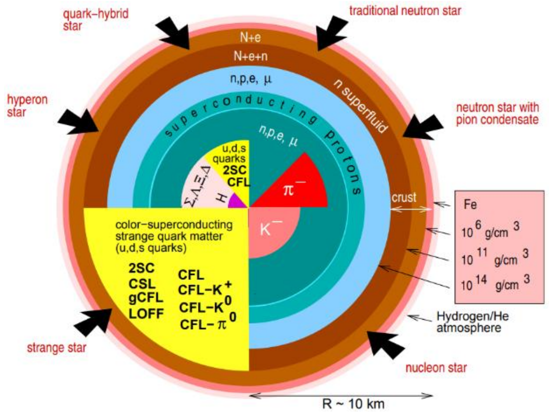
- Neutron stars provide **extreme QCD environments**
    - High baryon density
    - Moderate temperature
- Nonperturbative QCD dominates
    - Chiral symmetry breaking
    - Topological structures

Compact stars are natural laboratories for nonperturbative QCD

- Early universe
- Heavy ion collision experiments
- Compact stars (e.g. neutron stars, quark stars)





Topology in QCD

Due to the existence of instantons, $G_{\mu\nu} = \pm\, \tilde{G}_{\mu\nu}$, their contribution to the action:

$$\frac{1}{4}\int d^4x G^c_{\mu\nu}\tilde{G}^{c,\mu\nu} = \pm\, 8\pi^2 n$$

with n is the winding number.

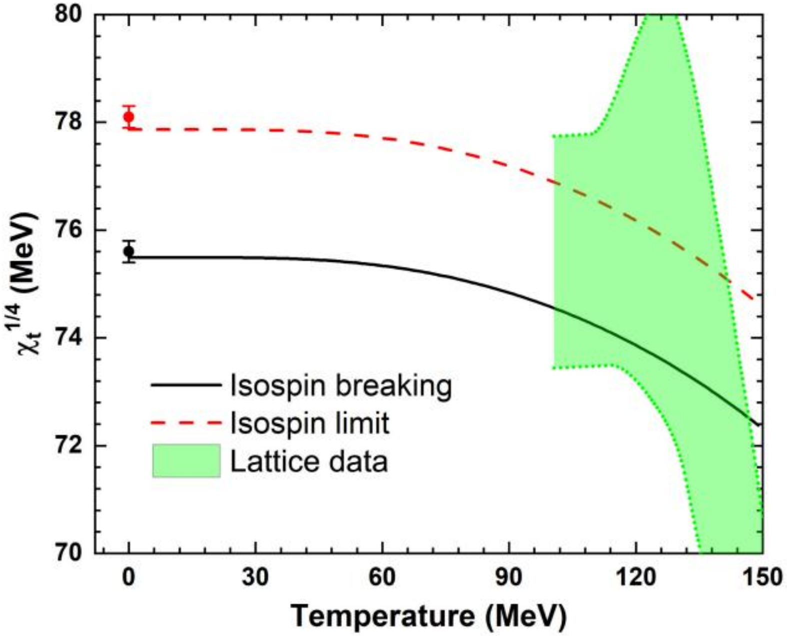
- True vacuum i,e, theta vacuum is linear superpositions of infinitely $|n>$ vacua:

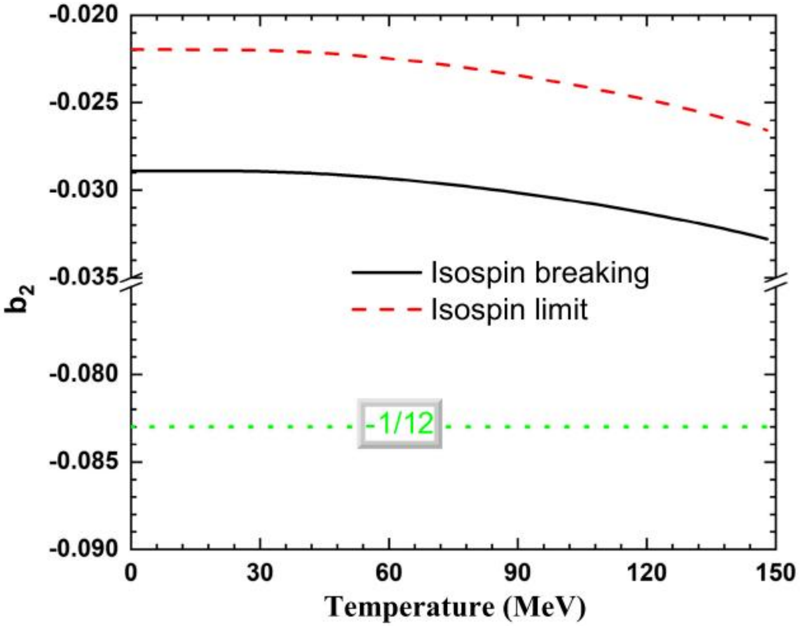
$$|\theta\rangle = \sum_n e^{-in\theta}|n\rangle$$

The complete massless QCD Lagrangian

$$\mathcal{L}_{QCD} = \mathcal{L}^0_{QCD} - \theta\frac{g^2}{32\pi^2}G^c_{\mu\nu}\tilde{G}^{c,\mu\nu}$$

Cumulants of the QCD topological charge distribution





$$F(\theta) - F(0) = \frac{1}{2}\chi\,\theta^2\left(1 + b_2\theta^2 + b_4\theta^4 + \cdots\right)$$

ZYL, Q. Tang, S.-P. Wang, Y. Huang, Z. Zhang, B. Zhang, Phys. Rev. D 113, 014013 (2026)

T = 0

$$\chi^{1/4} = \begin{cases} 75.5(5)\ \text{MeV}, & \text{SU(2)CHPT} \\ 75.6(6)\ \text{MeV}, & \text{SU(3)CHPT} \\ 75.6(2)\ \text{MeV}, & \text{Lattice data} \end{cases}$$

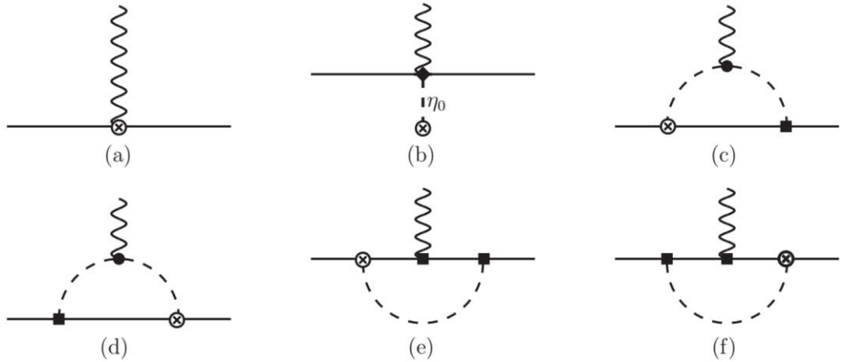
ZYL, M.-L. Du, F.-K. Guo, U.-G. Meißner, T. Vonk, JHEP 05, 001 (2020)

Axion: solution to the Strong CP problem

The topological theta term

$$\mathcal{L}_\theta = -\theta \frac{g^2}{32\pi^2} G^c_{\mu\nu}\tilde{G}^{c,\mu\nu} \qquad (\tilde{G}^c_{\mu\nu} = \frac{1}{2}\epsilon_{\mu\nu\rho\sigma}G^{c,\rho\sigma})$$

$\theta = \theta_0 + \arg \det M$ (when the quarks are massive)



F. K. Guo, U. G. Meißner,
J. High Energy Phys. 12, 97 (2012)

Feynman diagrams contributing to the baryon electric dipole form factor up to next-to-leading order

$$d_n = d_n(\theta)$$

Experiment + Lattice

$|d_n| < 2.9 \times 10^{-26}\mathrm{e} \cdot \mathrm{cm}(90\%\ \mathrm{C.L.}) \Rightarrow \theta \lesssim 10^{-10}$

Why θ is so small? (Strong CP problem) ⇒ PQ mechanism ⇒ $\langle \theta + a/f_a \rangle = 0$

New pseudo Nambu-Goldstone boson: ***Axion***

R. D. Peccei, H. R. Quinn, Phys. Rev. Lett. 38, 1440 (1977); Phys. Rev. D 16, 1791 (1977)

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NJL model at finite baryon chemical potential

The Lagrangian density of the two-flavor NJL model is given by

$$\mathcal{L} = \bar{q}\left(i\gamma^{\mu}\partial_{\mu} + \mu\gamma_0 - m_0\right)q + \mathcal{L}_{\text{int}}$$

with

$$\begin{aligned}\mathcal{L}_{\text{int}} = &G_1\left[(\bar{q}\tau_a q)(\bar{q}\tau_a q) + (\bar{q}i\tau_a\gamma_5 q)(\bar{q}i\tau_a\gamma_5 q)\right] \\ &+ 8G_2\left[e^{i\theta}\det\left(\bar{q}_R q_L\right) + e^{-i\theta}\det\left(\bar{q}_L q_R\right)\right]\end{aligned}$$

Mean field approximation

$$\begin{aligned}(\bar{q}q)^2 &\approx 2(\bar{q}q)\langle\bar{q}q\rangle - \langle\bar{q}q\rangle^2, \\ (\bar{q}i\tau_a\gamma_5 q)^2 &\approx 2(\bar{q}i\tau_a\gamma_5 q)\langle\bar{q}i\tau_a\gamma_5 q\rangle - \langle\bar{q}i\tau_a\gamma_5 q\rangle^2,\end{aligned}$$

The thermodynamic potential of the system $\Omega = \Omega_{\text{mf}} + \Omega_q$

with

$$\begin{aligned}\Omega_{\text{mf}} = &-G_2\left(\eta^2 - \sigma^2\right)\cos\theta + G_1\left(\eta^2 + \sigma^2\right) \\ &- 2G_2\sigma\eta\sin\theta,\end{aligned}$$

and

$$\begin{aligned}\Omega_q = &-2N_c T\sum_{f=u,d}\int\frac{d^3p}{(2\pi)^3}\left\{\frac{E_p}{T}\right. \\ &\left.+\ln\left[1+e^{-(E_p-\mu_f)/T}\right] + \ln\left[1+e^{-(E_p+\mu_f)/T}\right]\right\}\end{aligned}$$

ZYL, M. Ruggieri,
Phys. Rev. D 100, 014013 (2019)

Topological susceptibility

The topological susceptibility from chiral perturbation theory up to next-to-leading order with non-degenerate quark masses

$$\chi_{\rm top}^{1/4} = \sqrt{m_a f_a} = 75.5(5)\,{\rm MeV}$$

The topological susceptibility in the isospin symmetric case

NJL model $$\chi_t^{1/4} = 79.87\ {\rm MeV}$$

ZYL, M. Ruggieri, Phys. Rev. D 100, 014013 (2019)

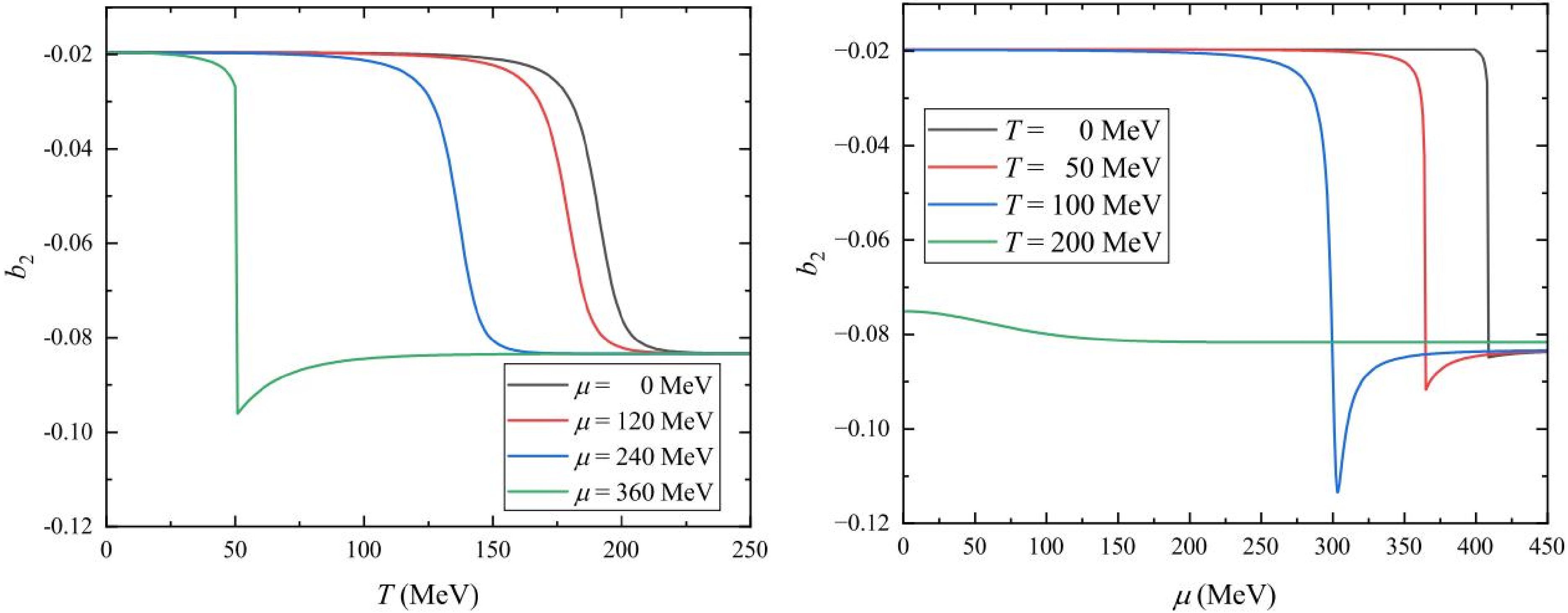
Chiral perturbation theory $$\chi_t^{1/4} = 77.8(4)\ {\rm MeV}$$

G. G. di Cortona, E. Hardy, J. P. Vega, G. Villadoro, J. High Energy Phys. 2016, 34 (2016)

Lattice simulation $$\chi_t^{1/4} = 78.1(2)\ {\rm MeV}$$

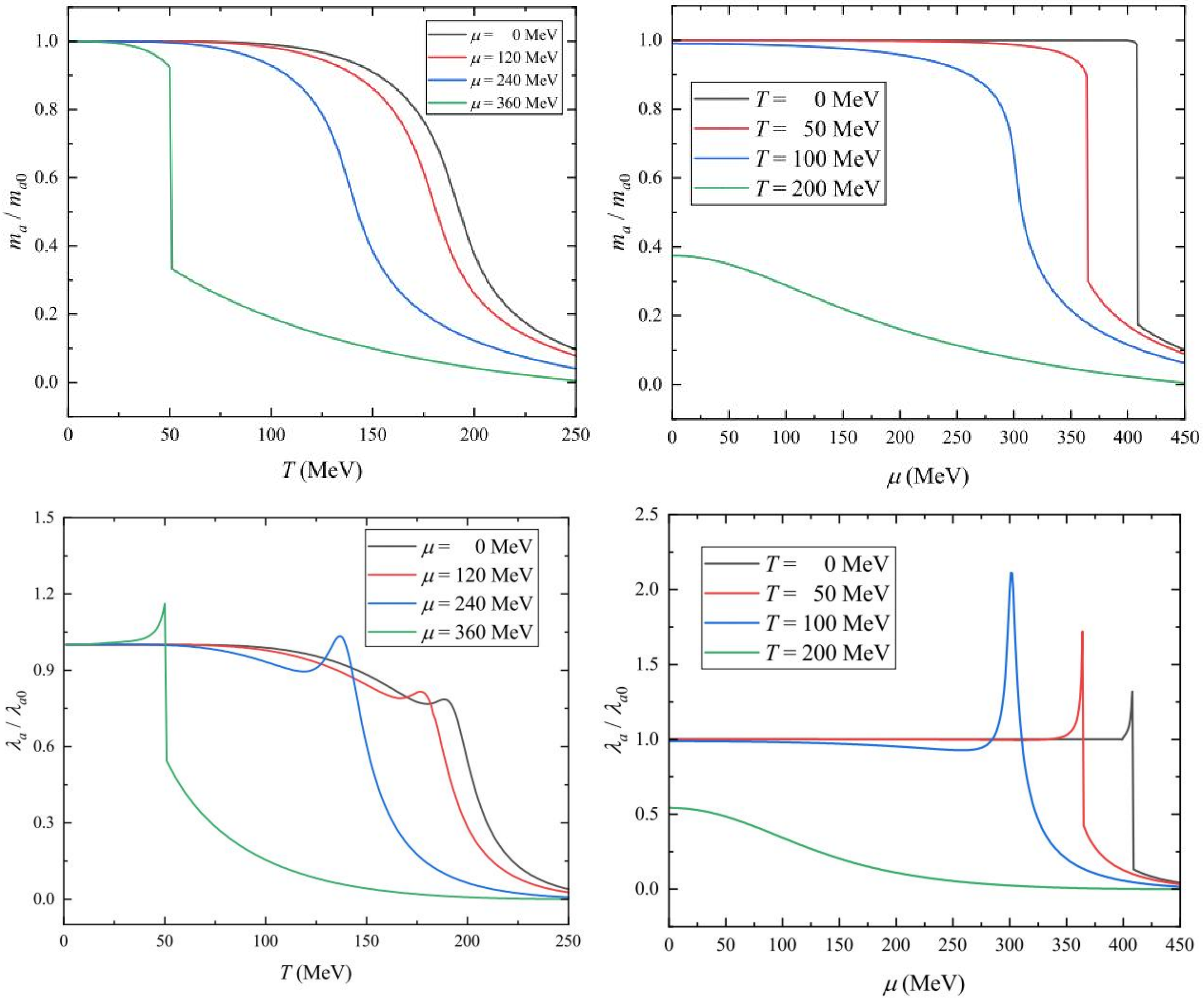
S. Borsanyi, Z. Fodor, J. Guenther, K.-H. Kampert, S. D. Katz, and et al., Nature 539, 69 (2016)

Normalized fourth cumulant



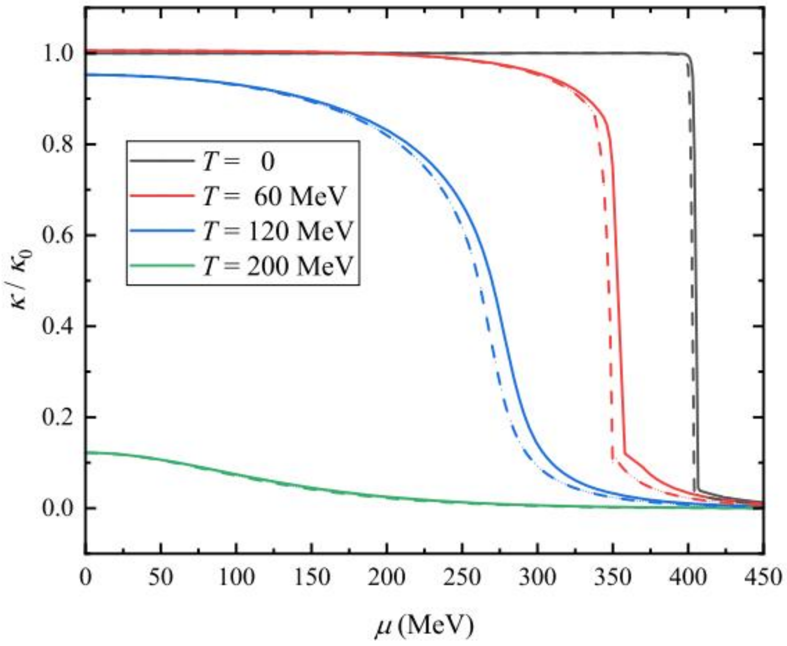
- Variation of the normalized fourth cumulant, scaled by its value in the vacuum, with respect to the temperature at different chemical potentials (left panel) and to the chemical potential at different temperatures (right panel), respectively.

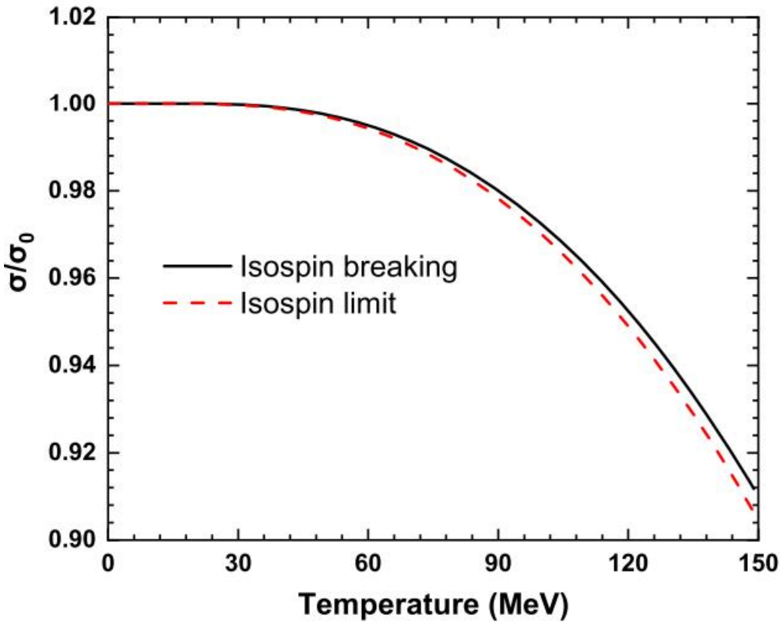
Axion mass and self-coupling constant



Domain wall tension

Domain wall tension $$\kappa = 2 f_a \int_0^\pi d\theta \sqrt{2\left[V(\theta) - V(0)\right]}$$





ZYL, S.-P. Wang, Q. Lu, B.-N. Zhang, M. Ruggieri, Eur. Phys. J. C 85, 1371 (2025)

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Summary

- The **topological susceptibility and the axion mass** follow the response of the chiral condensate to temperature and chemical potential, showing that both quantities **decrease monotonically with the increment of temperature and/or chemical potential.**

- The **axion self-coupling constant exhibits a sharp peak around the critical point**, which can be several times its vacuum value.

- The **chiral phase transition** significantly **reduces the axion mass** while considerably **enhancing the self-coupling constant**.

- The **stability** of axion domain walls is significantly reduced in hot and dense matter, with important implications for their dynamics in compact stellar environments.

Thank you!