QCD axion at finite temperature and density

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CONTENTS

Introduction

axion

- Proposed to solve the strong CP problem. Peccei and Quinn (PQ) in 1977
- Pseudo Goldstone boson with spontaneous breaking of global abelian symmetry
- Weak interaction and very light particles, the main candidates for cold dark matter
- It may form Bose Einstein condensation or Axion star

- The importance of QCD Axion as a solution to the strong CP problem and its potential in explaining the abundance of dark matter in the universe make it one of the most popular prospects outside the standard model of particle physics .

- Axions can be heated and form Bose Einstein condensates, which in turn indicates the relevance of the finite temperature extension of Axion properties.

- In a dense object such as a neutron star, the temperature is very low, but the baryon number density is very high. In this case, the influence of quark chemical potential on the properties of axions is of great significance in the study of axion physics.

- QCD has rich phase structures (hadronic phase, QGP, color superconductivity, meson condensation…). It is an important task to study the nature and role of QCD axion at finite temperature and density.

QCD axion at finite T and μ

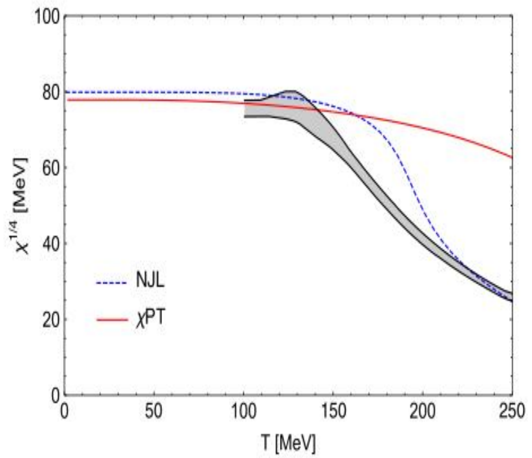
Methods:

- Lattice QCD: sign problem at finite μ
- Chiral perturbation theory: hadronic phase
- Nambu–Jona-Lasinio model (NJL): simple, relation to QCD?
- Polyakov-loop extended NJL
- Effective field theory for color superconductivity

- Thermal Axion Production at Low Temperatures: A Smooth Treatment of the QCD Phase Transition, F D'Eramo ect. PRL 2021.
- QCD axion and topological susceptibility in chiral effective Lagrangian models at finite temperature, S Bottaro, E Meggiolaro PRD 102, 014048 (2020)
- The QCD Axion at Finite Density, Reuven Balkin, Javi Serra, Konstantin Springmann, Andreas Weiler, JHEP 2020
- Abhishek A , Das A , Mohapatra R K , Mishra H.In medium properties of an axion within a 2 + 1 flavor Polyakov loop enhanced Nambu–Jona-Lasinio model American Physical Society, 2021(7).
- Aritra Bandyopadhyay,Ricardo L. S. Farias,Bruno S. Lopes,Rudnei O.Quantum chromodynamics axion in a hot and magnetized medium Ramos. Physical Review D,2019,100(7)
- Zhen-Yan Lu,Marco Ruggieri. Effect of the chiral phase transition on axion mass and self-coupling. Physical Review D,2019,100(1).

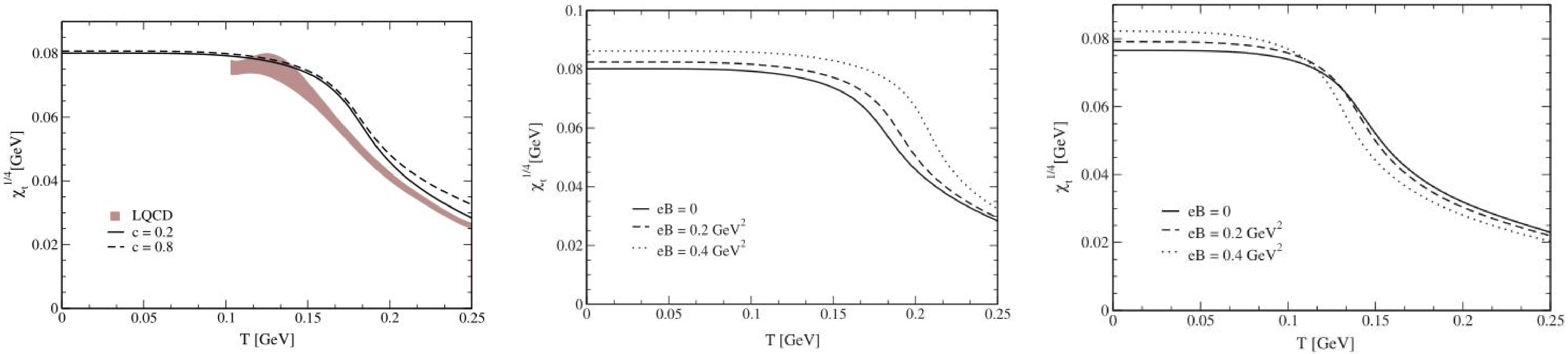
Topological susceptibility

The chiral perturbation theory is not applicable at high T and density.



From： Lu and Ruggieri, PRD,2019,100(1).

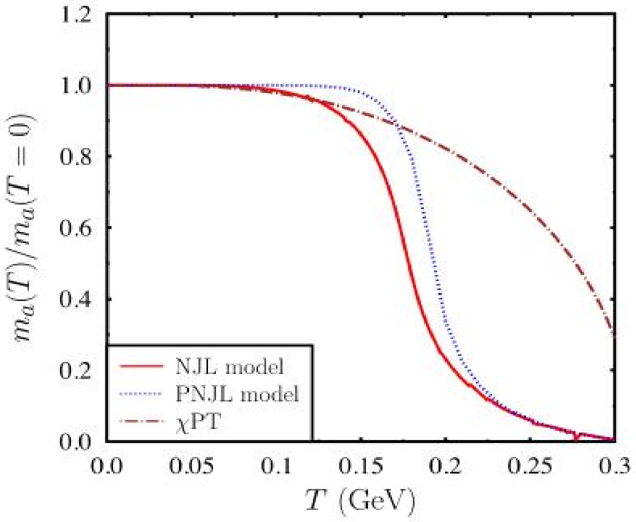
Adding magnetic field in NJL model



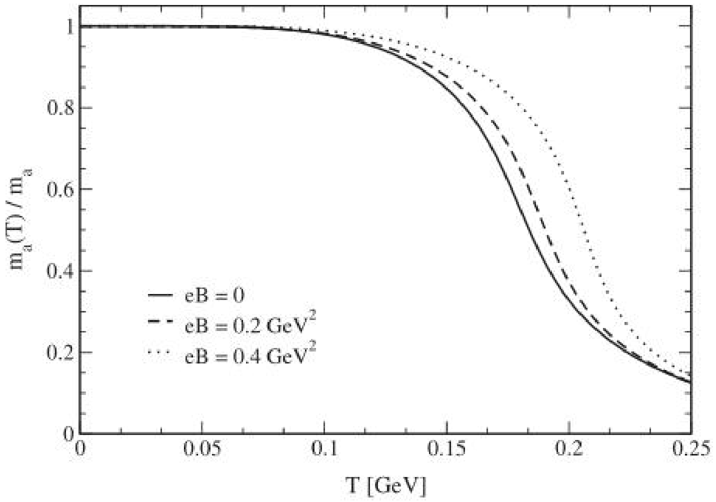
Aritra Bandyopadhyay,Ricardo L. S. Farias,Bruno S. Lopes,Rudnei O. Ramos. PRD,2019,100(7)

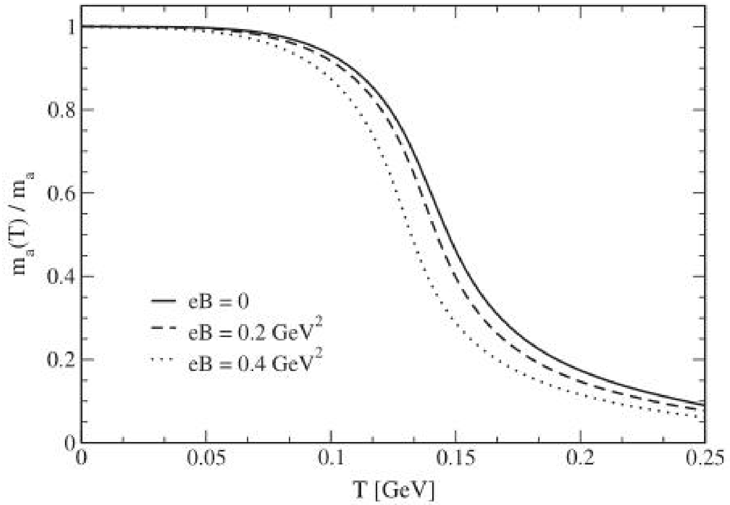
- The topological susceptibility decreases with the temperature.
- Signs of the magnetic catalysis and inverse magnetic catalysis for quark condensate can be read from the thermal behavior of the topological susceptibility in the improved NJL.

Axion mass



Abhishek A et al. PRD, 2021(7).





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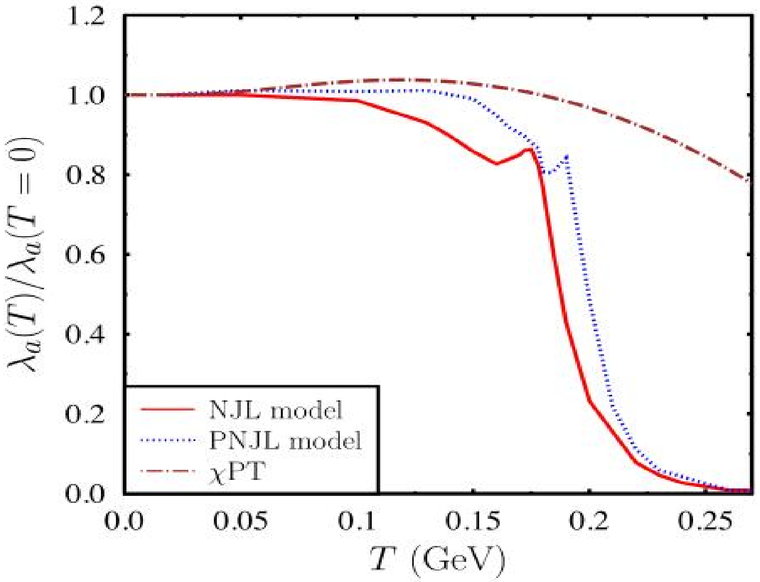
sign of magnetic catalysis.

sign of inverse magnetic catalysis

Axion self coupling



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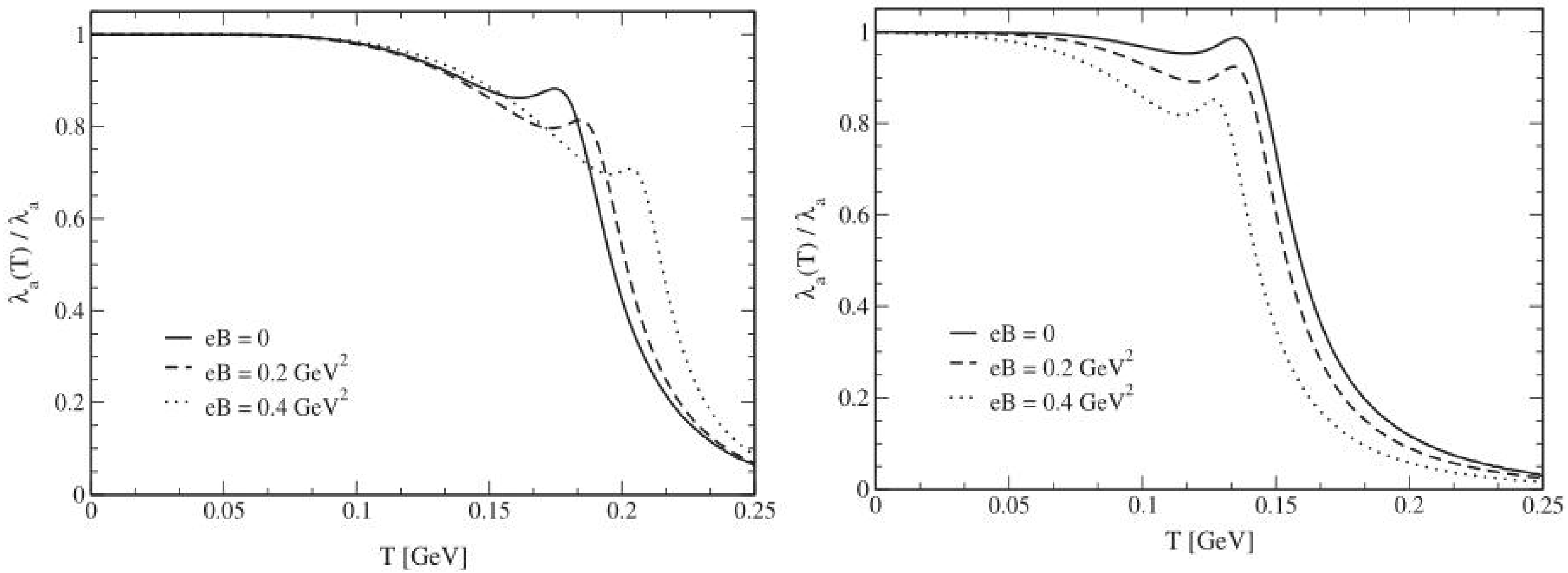


Aritra Bandyopadhyay,Ricardo L. S. Farias,Bruno S. Lopes,Rudnei O. Ramos. Physical Review D,2019,100(7)

- The pseudo critical temperature for chiral transition moves to a lower temperature with the increase of magnetic field.

Taking into account the electric charge neutrality

The baryon and electron chemical potentials are added to the NJL model by considering the charge neutrality:

Lagrangian of NJL model: $\mathcal{L} = \bar{q}\left(i\gamma^{\mu}\partial_{\mu} - m\right)q + \mathcal{L}_{\bar{q}q} + \mathcal{L}_{\det}$

$$\mathcal{L}_{\bar{q}q} = G_1\left[(\bar{q}\tau_a q)^2 + (\bar{q}\tau_a i\gamma_5 q)^2\right] \qquad \mathcal{L}_{\det} = 8G_2\left[e^{i\frac{a}{f_a}}\det(q_R q_L) + e^{-i\frac{a}{f_a}}\det(q_L q_R)\right]$$

$$\Omega(\alpha_0,\beta_0) = \Omega_q - G_2\left(\eta^2 - \sigma^2\right)\cos\frac{a}{f_a} + G_1\left(\eta^2 + \sigma^2\right) - 2G_2\sigma\eta\sin\frac{a}{f_a}$$

$$\Omega_q = -8N_c\int\frac{\mathrm{d}^3p}{(2\pi)^3}\left[\frac{E_p}{2} + T\log\left(1 + e^{-E_p/T}\right)\right]$$

$$\Omega(\mu_e,\sigma,\eta;\mu,T,a)$$
$$= \Omega_L - N_C\sum_{i=1}^{4}\int\frac{d^3p}{(2\pi)^3}\{E_i + 2T\ln(1 + e^{-E_i/T})\}$$
$$\Omega_L = -G_2\left(\eta^2 - \sigma^2\right)\cos\frac{a}{f_a} + G_1\left(\eta^2 + \sigma^2\right) - 2G_2\sigma\eta\sin\frac{a}{f_a}$$
$$\boxed{-\frac{1}{12\pi^2}(\mu_e^4 + 2\pi^2T^2\mu_e^2 + \frac{7\pi^4}{15}T^4)}$$

Contribution of free electron gas

NJL at mean field level

$$\Omega(\mu_e,\sigma,\eta;\mu,T,a)$$
$$=\Omega_L - N_C\sum_{i=1}^{4}\int\frac{d^3p}{(2\pi)^3}\{E_i+2T\ln(1+e^{-E_i/T})\}$$

$$E_i\begin{cases}E_1=E_p+\mu_u\\ E_2=E_p-\mu_u\\ E_3=E_p+\mu_d\\ E_4=E_p-\mu_d\end{cases}$$

$$\mu_u=\mu-\frac{2}{3}\mu_e$$
$$\mu_d=\mu+\frac{1}{3}\mu_d$$

$$\frac{\partial\Omega}{\partial\sigma}|_{\sigma=\bar\sigma}=0,\ \frac{\partial\Omega}{\partial\eta}|_{\eta=\bar\eta}=0$$

$$\frac{\partial\Omega}{\partial\sigma}|_{\sigma=\bar\sigma}=0,\ \frac{\partial\Omega}{\partial\eta}|_{\eta=\bar\eta}=0,\ \boxed{\frac{\partial\Omega}{\partial\mu_e}|_{\mu_e=\bar\mu_e}=0}$$

Electrical neutral condition

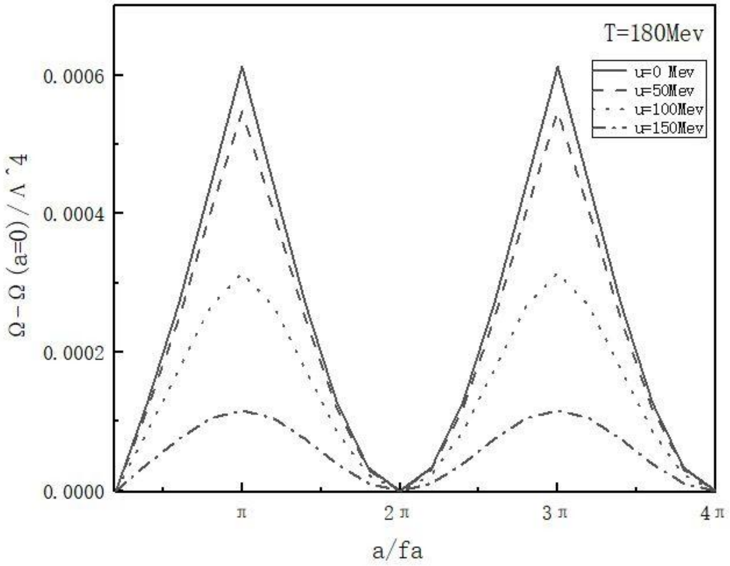
$$V(a)=\Omega(\sigma=\bar\sigma,\eta=\bar\eta,\mu_e=\bar\mu_e\,|\,a)$$

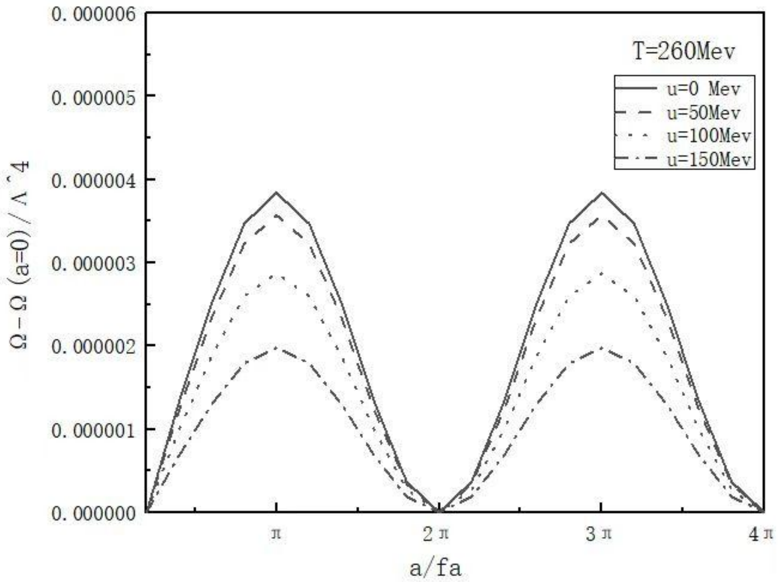
$$m_a^2=\frac{d^2V(a)}{da^2}|_{a=0}=\frac{\chi_t}{f_a^2}$$

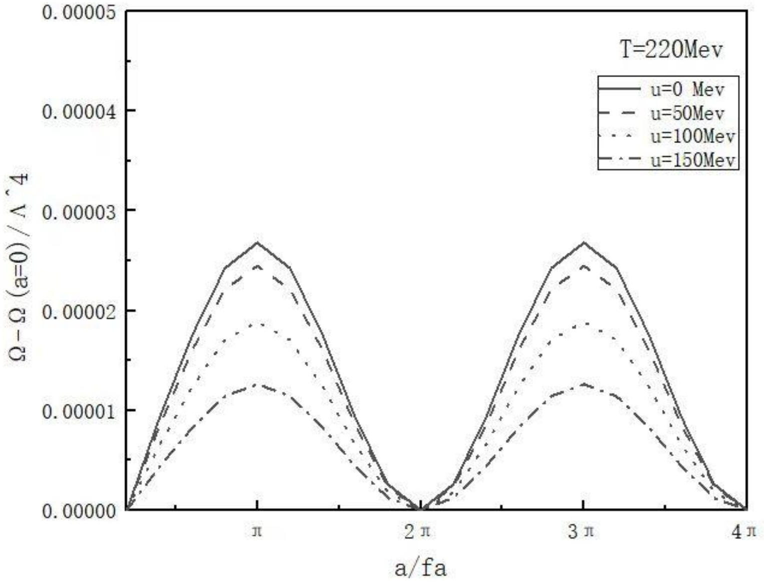
$$\lambda_a=\frac{d^4V(a)}{da^4}|_{a=0}$$

$$\frac{dV}{da}=\frac{\partial V}{\partial a}+\frac{\partial V}{\partial\sigma}\frac{\partial\sigma}{\partial a}+\frac{\partial V}{\partial\eta}\frac{\partial\eta}{\partial a}+\frac{\partial V}{\partial\mu_e}\frac{\partial\mu_e}{\partial a}$$

Thermal potential without the charge neutrality





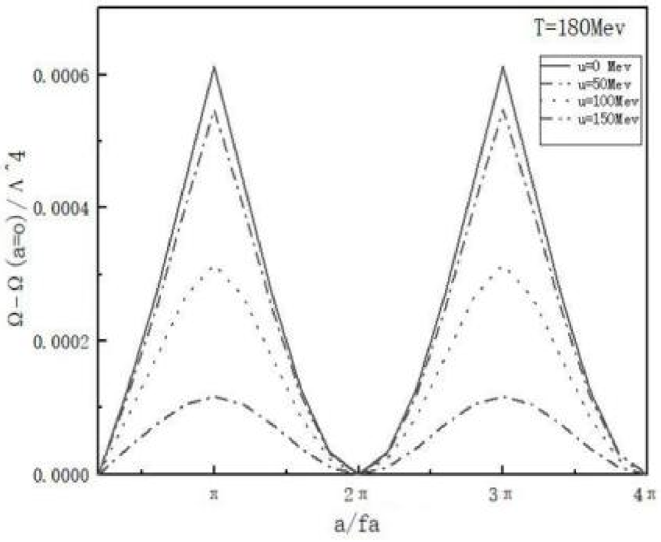


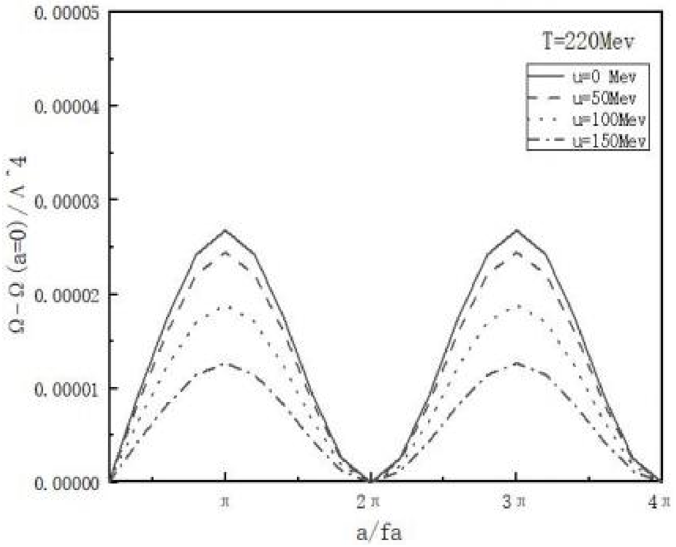
Electrical neutrality is not considered

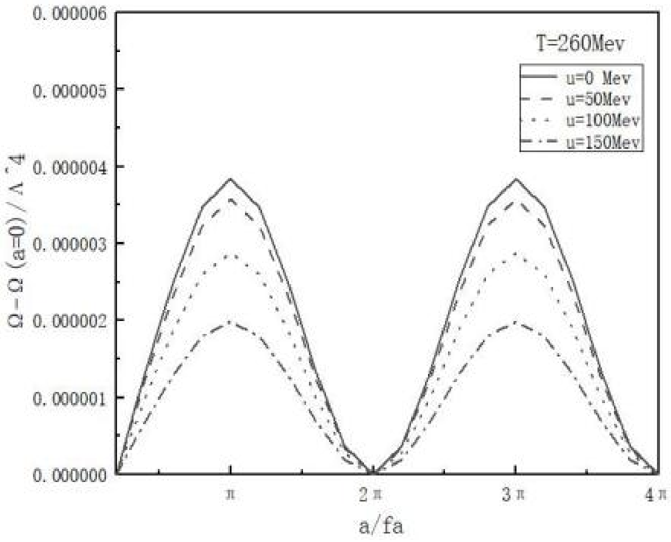
- The barrier height of the thermal potential is suppressed with the increase of temperature.

Thermodynamic potential

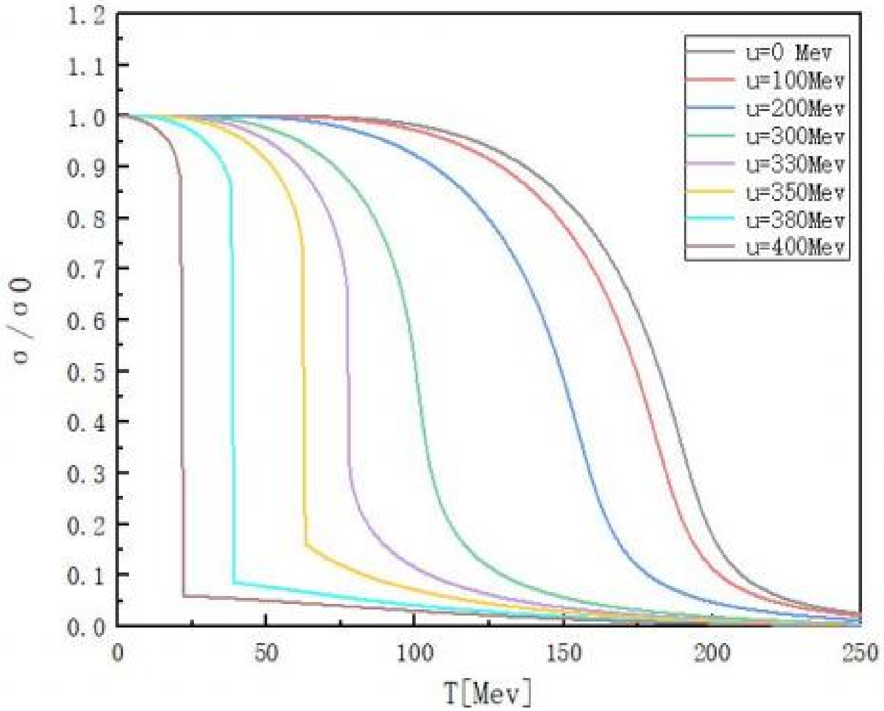
Considering electrical neutrality constraint



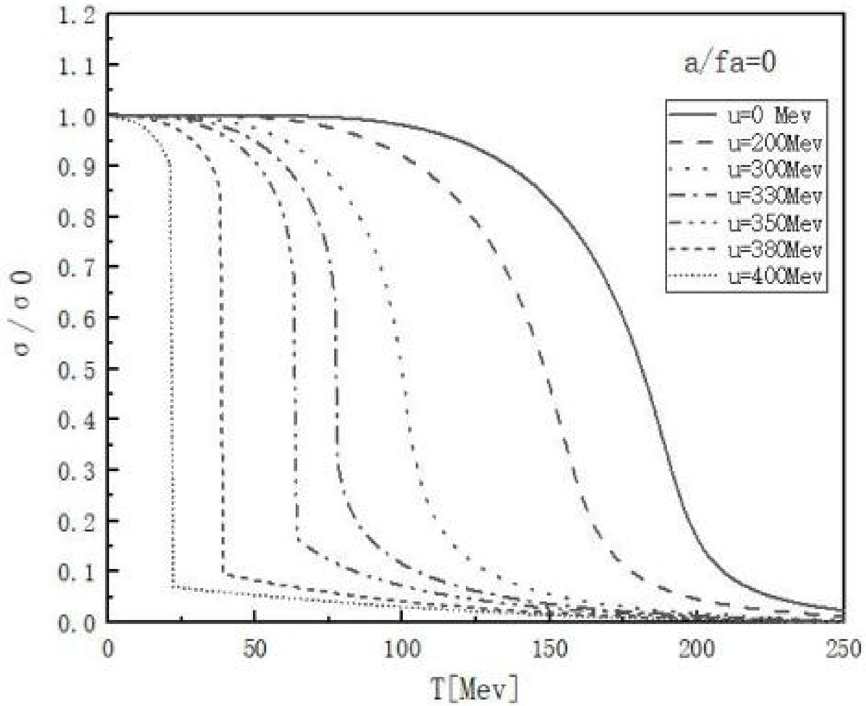




Quark condensate



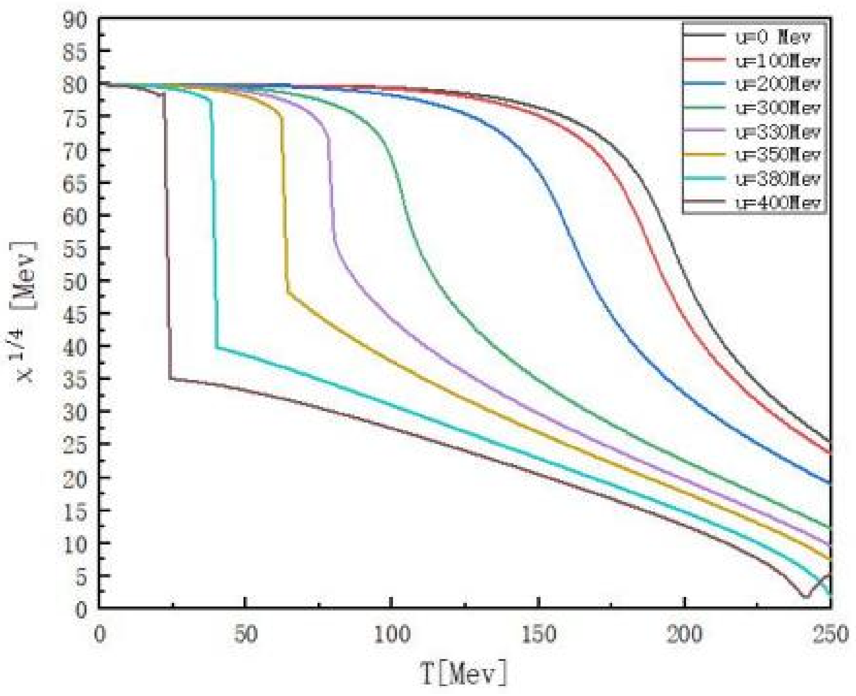
Electrical neutrality is not considered



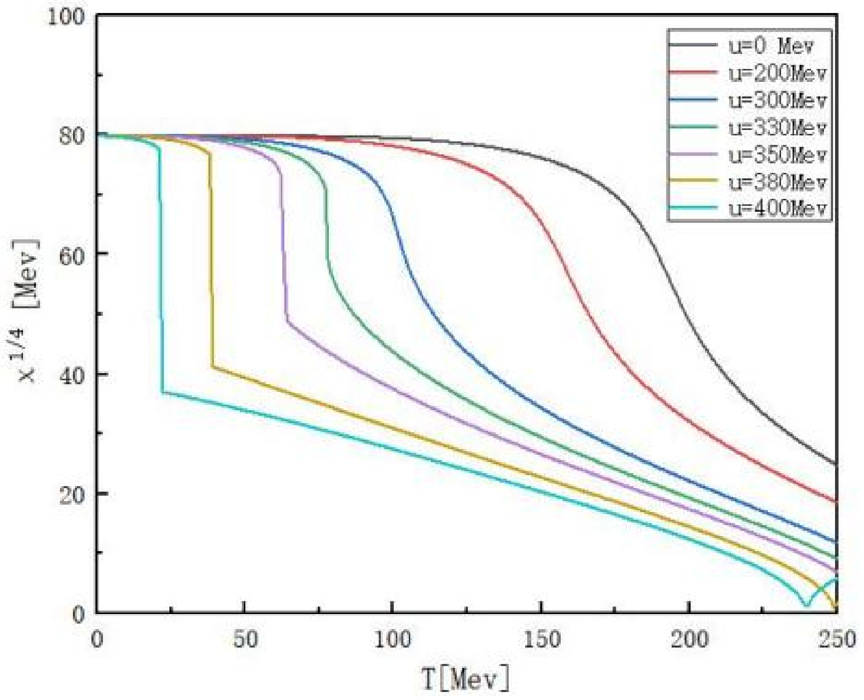
Consider electrical neutrality

- Electric charge neutrality has little effect on the quark condensate.

Topological susceptibility



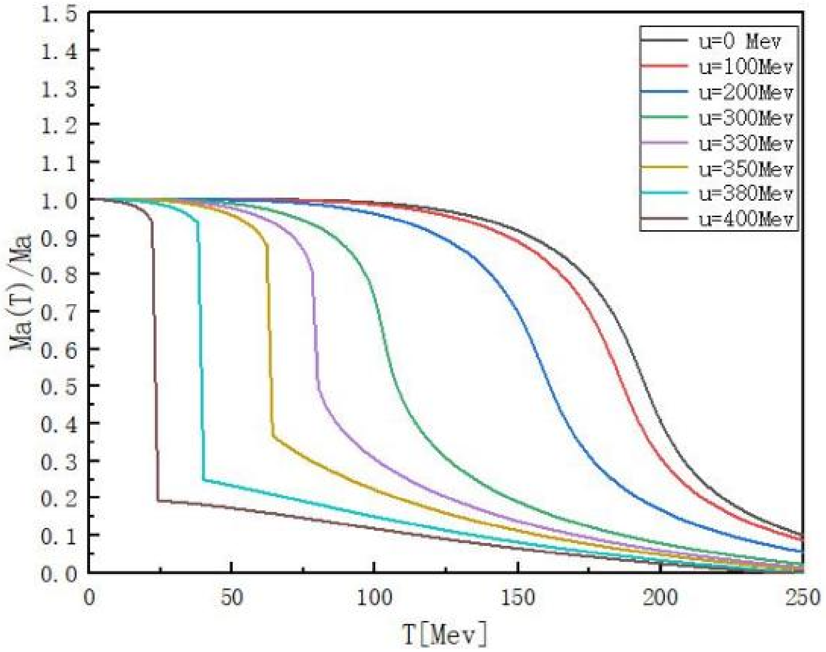
Electrical neutrality is not considered



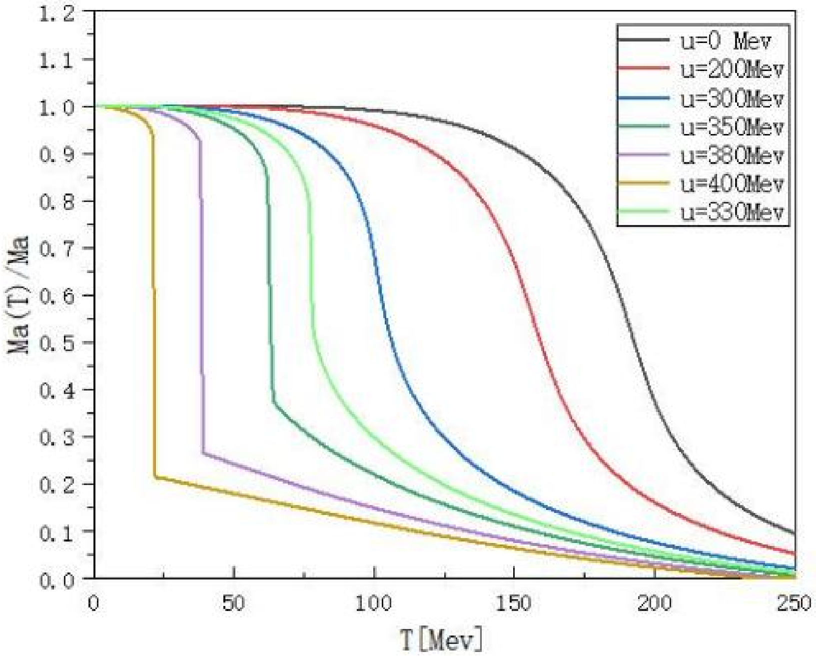
Consider electrical neutrality

- The temperature at which the mutation occurs is almost the same for the cases with and without charge neutrality.

Axion mass



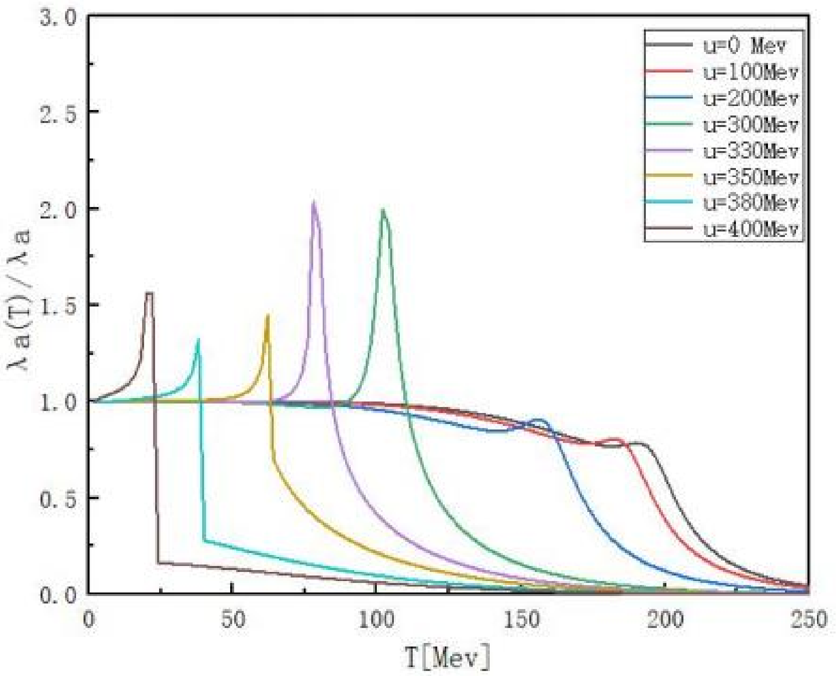
Without electrical neutrality constraint



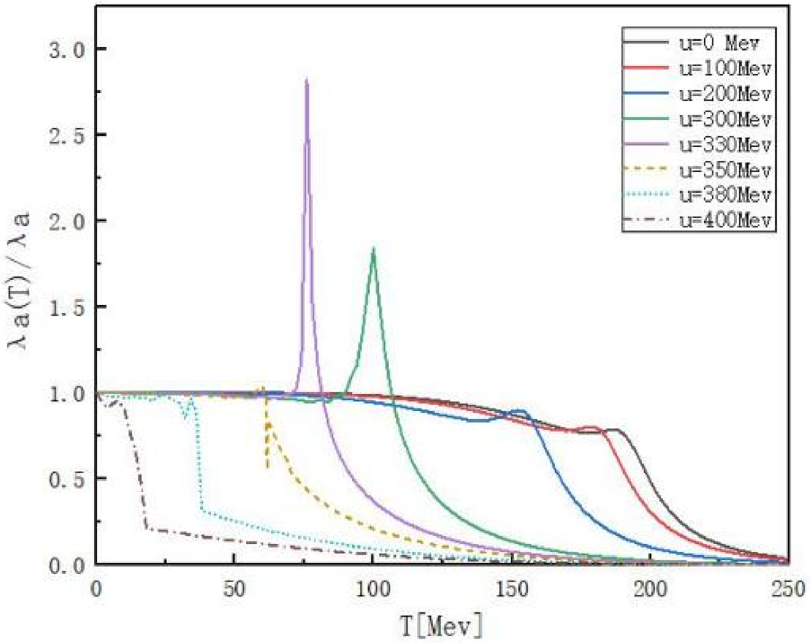
With electrical neutrality constraint

- The electric neutral condition has little effect on the axion mass.

Axion self coupling



Without electrical neutrality constraint



With electrical neutrality constraint

- The coupling has a sharp peak, which may be a limitation of the mean field approximation.

Summary and outlook

- The QCD axion at finite temperature and density is studied in the NJL model by considering the charge neutrality constraint. We find that the axion mass, self coupling and the topological susceptibility would suddenly drop at the first-order phase transition point.
- Compared with the case without the charge neutrality, it is found that the electric neutrality mainly affects the self coupling of axion at high chemical potential, but has no significant effect on the topological susceptibility, axion mass and quark condensation.
- The color-superconducting phase of QCD is not considered in this work and the related calculation is in progress.

Thank you for listening