QCD phase diagram at finite baryon and isospin chemical potentials in PQM model with vector interaction

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HU, T.Z.Nakano, A.Ohnishi, M.Ruggieri and K.Sumiyoshi, PRD 88,074006(2013)
A.Ohnishi, HU, T.Z.Nakano, M.Ruggieri and K.Sumiyoshi, PLB 704, 284(2011)

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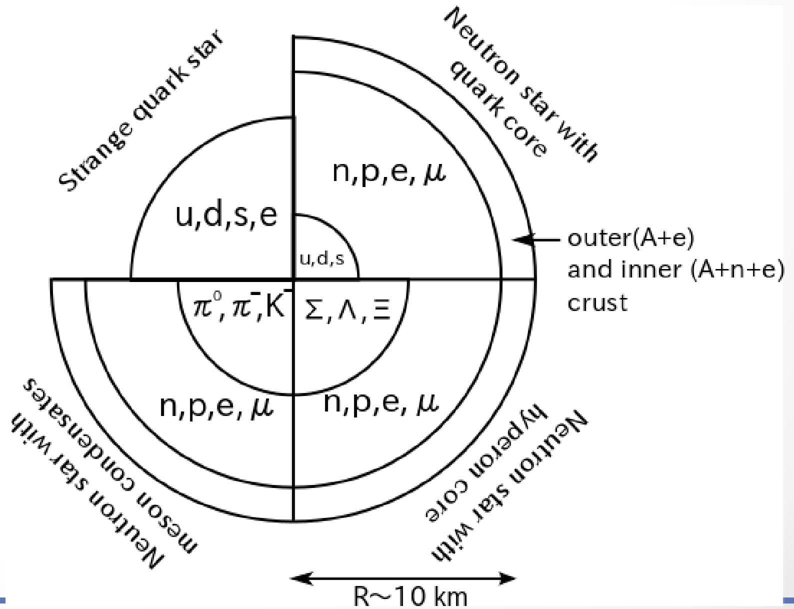
Quark matter in compact astrophysical phenomena

Neutron star core → low T and high ϱ
(∼10^{-4} MeV, a few times of ϱ_0)

Core comosition
- Hybrid Stars,
  Strange Quark Stars
  Bodmer('71), Witten('84)

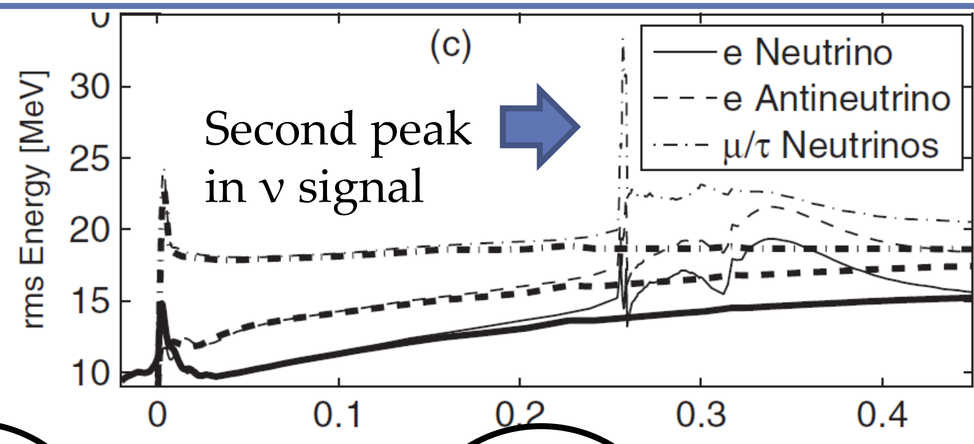
→M-R relation…



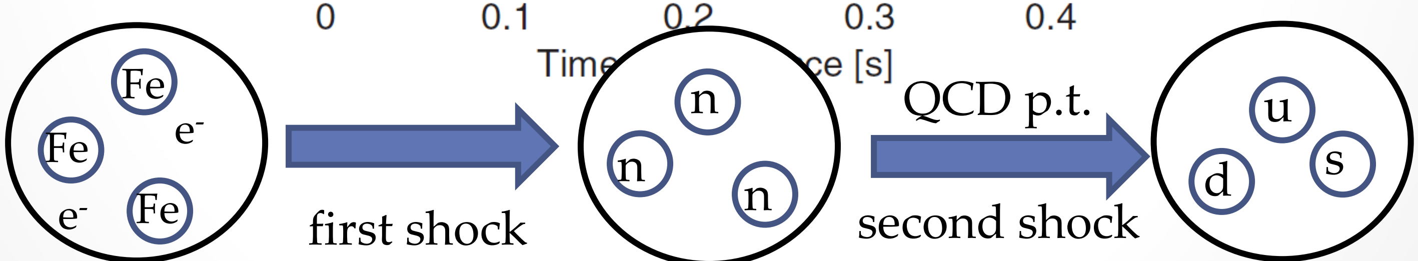
Quark matter in compact astrophysical phenomena

- From the core-collapse explosion, we may get information on the QCD phase transition.

Supernovae



Hatsuda('87), Sagert et. al.,('09)



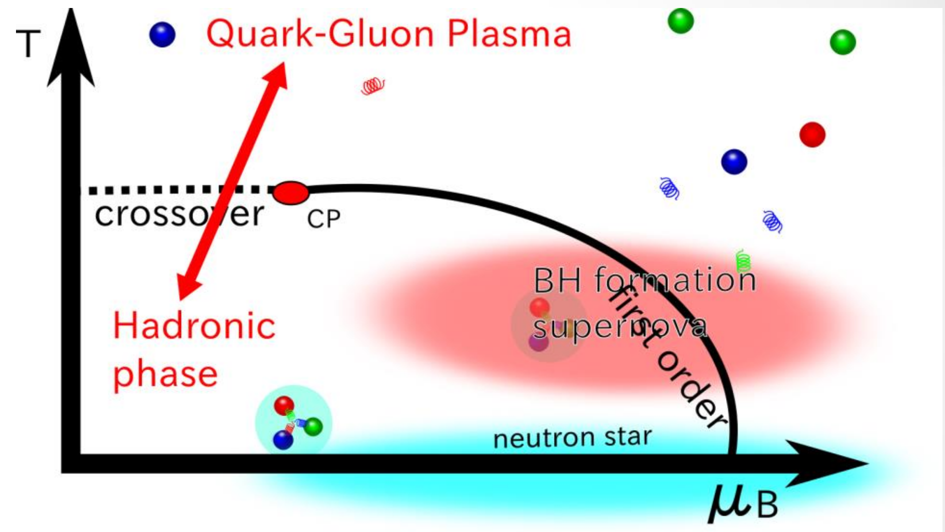
Black Hole formation

→neutrino duration time is shorten

Nakazato et. al.,('10),

QCD phase diagram

- Compact star phen. would involve QCD p.t. at high T and/or ρ. →QCD phase diagram
- QCD critical point connects crossover and first-order phase boundaries.



- QCD phase transition in compact star matter is closely related to recent nuclear physics experiments
  - Symmetry energy studies in FRIB → Isospin asymmetric (N>Z) matter in Compact Star phenomena
  - Critical point search at RHIC → Order of the phase transition affects the EoS and dynamics

QCD phase transition in compact astrophysical phenomena

We need 3D phase diagram (T, μ, δμ) in compact stars !

- In astrophysical phenomena,

Charge neutrality → $\delta\mu \equiv (\mu_n - \mu_p)/2 = (\mu_d - \mu_u)/2 \neq 0$

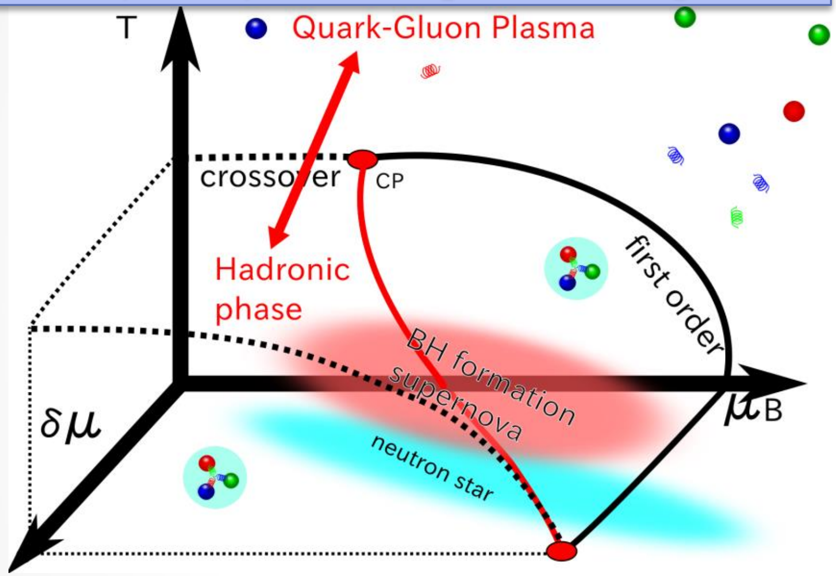
- In particular, for supernovae and BH formations,

Out of beta equilibrium
$\delta\mu \neq \mu_e/2$
→ $\delta\mu$ appear as another independent variable

→ It is necessary to consider $\delta\mu$ dependence of the QCD phase diagram in order to discuss the QCD phase transition in compact stars.

QCD phase diagram in Asym. Matter

3D(T, μB, δμ) QCD phase diagram



Previous works to study δμ dependence of the QCD phase diagram

Kogut et. al ('04) [Lattice QCD], Abuki et. al., ('05)[NJL] ('08)[PNJL], Sasaki et. al.,('10)[PNJL], Kamikado et.al, ('12)[quark meson model + FRG]

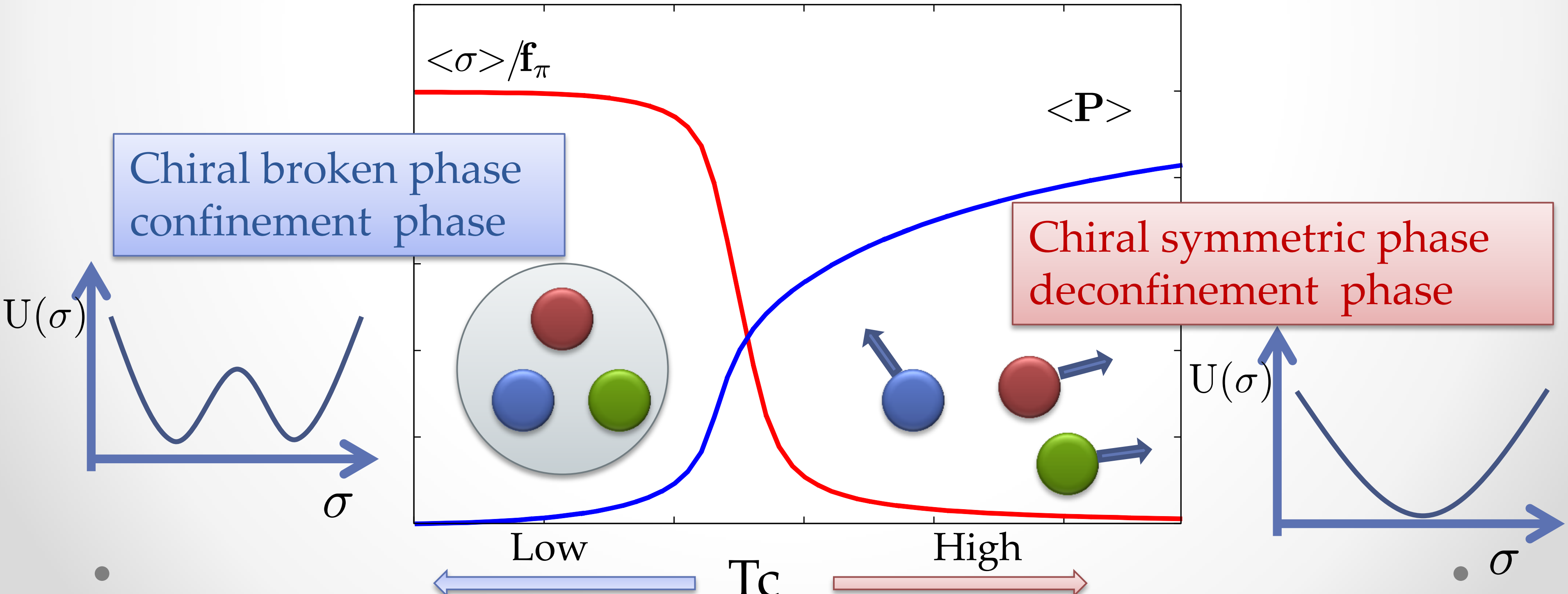
- In this work
  - We investigate the isospin chemical potential dependence of the QCD phase diagram by using PQM model,
  - and discuss the order of the chiral phase transition in the neutron star core

Methods and Results

Polyakov loop extended Quark Meson model

Schaefer et.al., ('07), Skokov et.al.,('10)

PQM is a Nambu-Jona-Lasinio like QCD effective model which has the chiral symmetry and confinement property.



Polyakov loop extended Quark Meson model

Schaefer et.al., ('07), Skokov et.al.,('10)

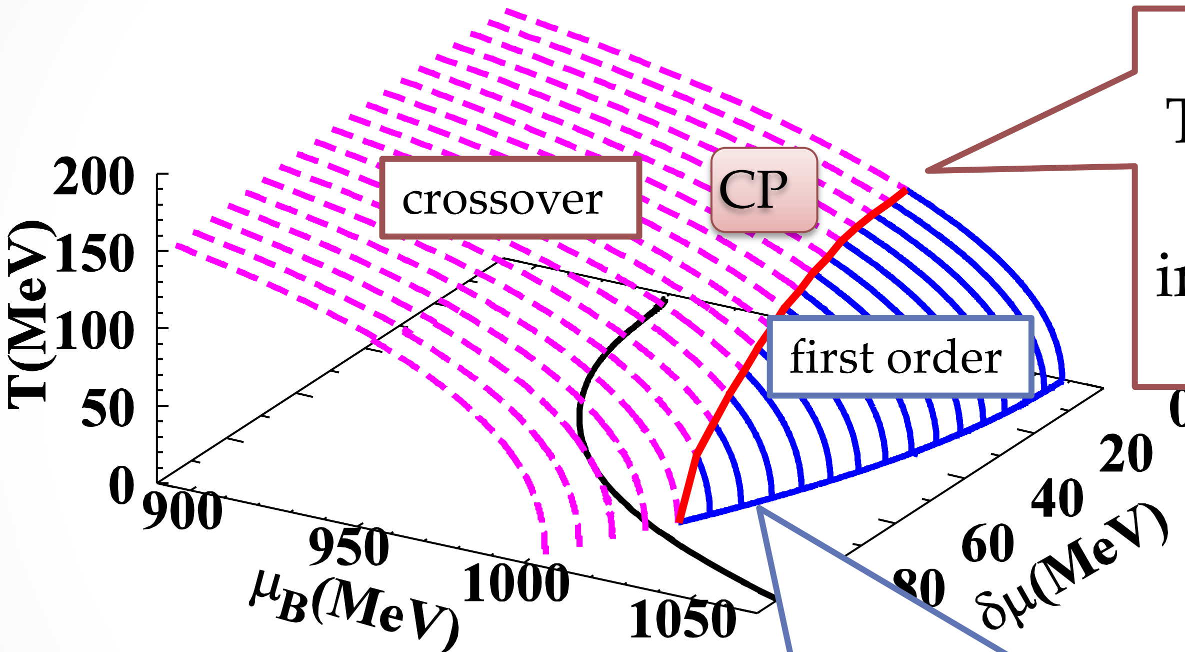
- PQM Lagrangian

$$\mathcal{L} = \bar{q}\left[i\gamma^\mu D_\mu - g(\sigma + i\gamma_5 \boldsymbol{\tau}\cdot\boldsymbol{\pi}) - g_\omega \gamma^\mu \omega_\mu - g_\rho \gamma^\mu \boldsymbol{\tau}\cdot\boldsymbol{R}_\mu\right] q$$
$$+ \frac{1}{2}(\partial_\mu \sigma)^2 + \frac{1}{2}(\partial_\mu \boldsymbol{\pi})^2 - U(\sigma, \boldsymbol{\pi})$$
$$- \frac{1}{4}\omega_{\mu\nu}\omega^{\mu\nu} - \frac{1}{4}\boldsymbol{R}_{\mu\nu}\cdot\boldsymbol{R}^{\mu\nu} + \frac{1}{2}m_v^2(\omega_\mu\omega^\mu + \boldsymbol{R}_\mu\cdot\boldsymbol{R}^\mu)$$
$$- \mathcal{U}(P, \bar{P}, T)$$

PQM property.

- DOF = quarks, order parameters(σ, P), vector fields(ω, ρ)
- Inputs = Vacuum hadron masses and condensate, lattice data of the Polyakov loop.
- Free parameters = vector meson coupling with quarks
- Mean field approximation
- No nucleon DOF are included

3D(T, μB, δμ) QCD phase diagram

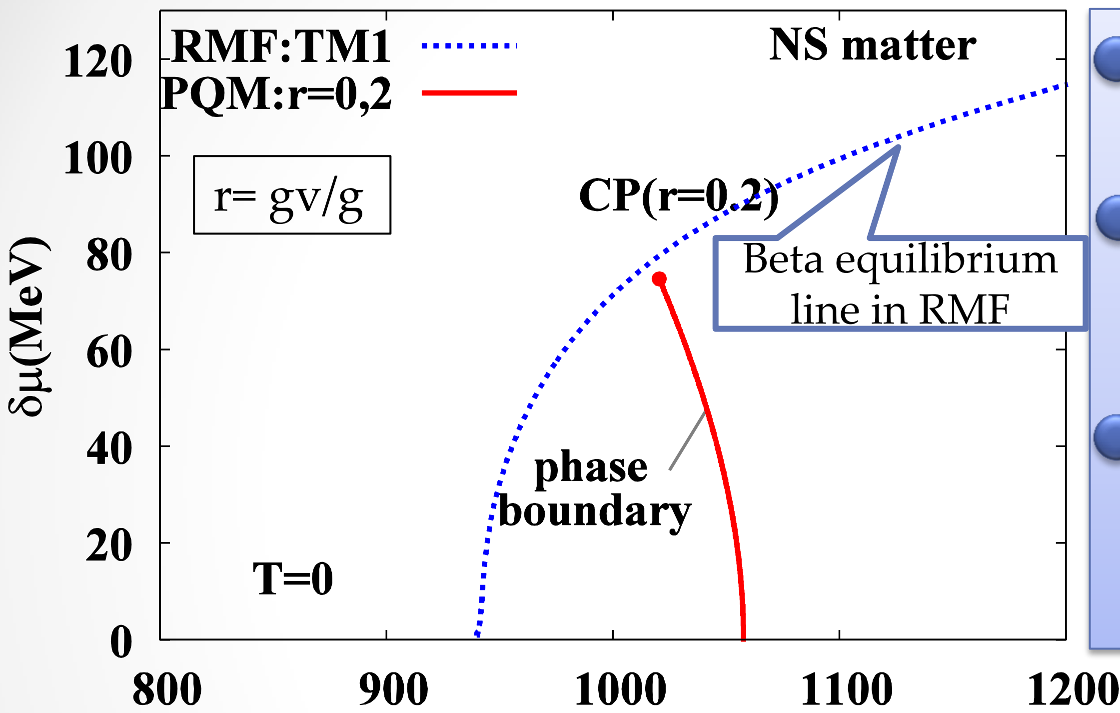


Tcp decrease with increasing δμ

The hadron phase shrink a little

At a certain value of δμ, the CP disappears.

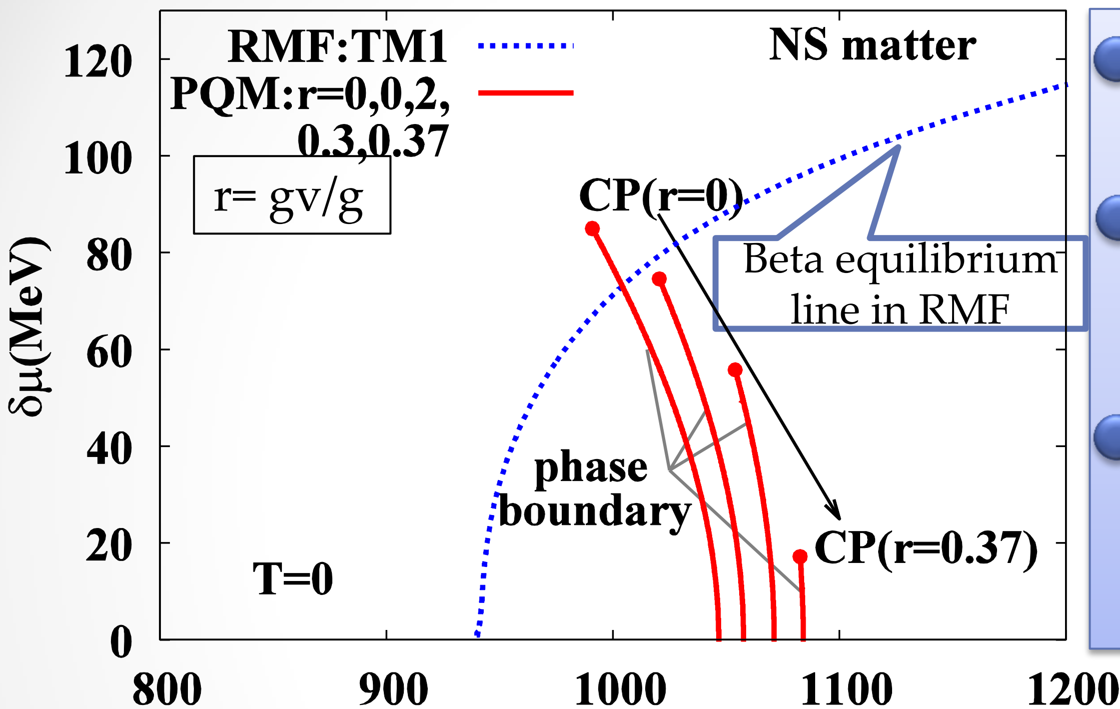
QCD phase transition in NS core



- beta eq. line > CP crossover in NS
-
-

hadronic EoS parameter sets of TM1, used in Shen EoS, [Sugahara et.al.,('94)]
- bulk properties of normal and neutron rich nuclei- nuclear matter saturation properties.

QCD phase transition in NS core



- beta eq. line > CP
  crossover in NS
- parameter dep.
  vector coupling
  1 st order @r< 0.15
-

hadronic EoS parameter sets of TM1, used in Shen EoS, [Sugahara et.al.,('94)]
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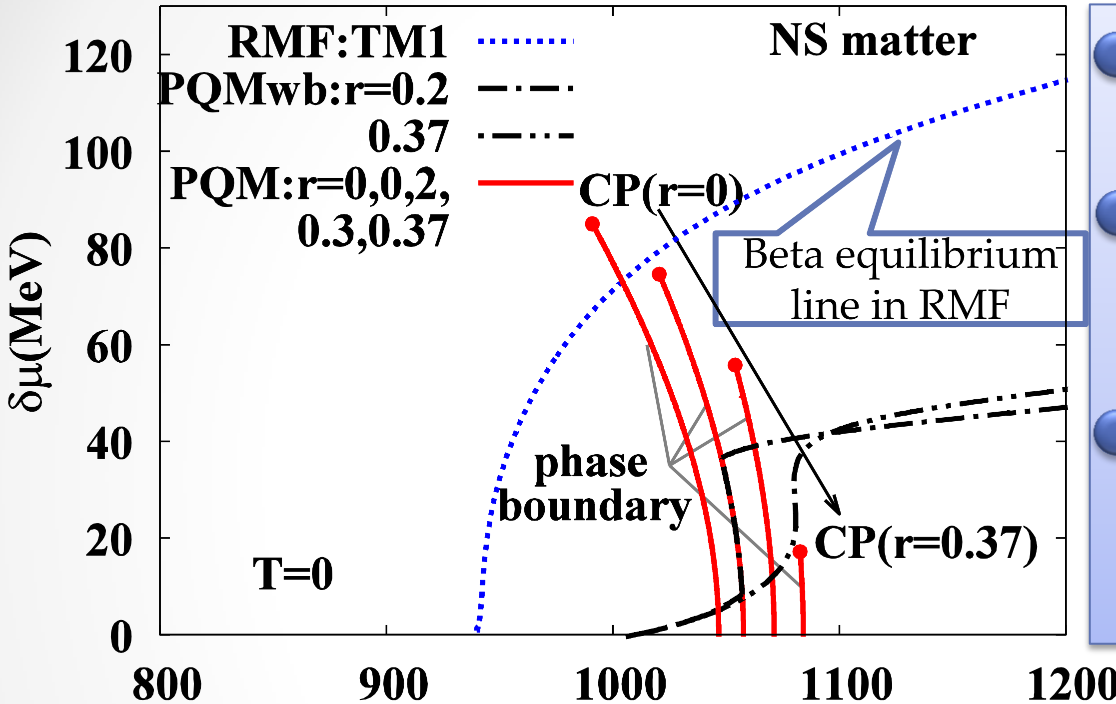
QCD phase transition in NS core



- beta eq. line > CP
  crossover in NS
- parameter dep.
  vector coupling
  1 st order @r< 0.15
- Model dep.
  PQM beta-eq.
  1st order @ r<0.37

hadronic EoS parameter sets of TM1, used in Shen EoS, [Sugahara et.al.,('94)]
- bulk properties of normal and neutron rich nuclei- nuclear matter saturation properties.

δμ effects may make the QCD p.t. crossover in NS core, even if the transition in sym. matter is the first order.

Summary

We show the possibility that the QCD phase transition in compact astrophysical phenomena may become crossover because of $\delta\mu$ effects on the QCD phase transition.

- We have investigated the QCD phase transition in isospin asymmetric matter using PQM. Specifically, we have discussed isospin chemical potential dependence of the QCD phase boundaries.

  $\Rightarrow$ we show reduces the temperature of the QCD critical point, and for large $\delta\mu$, the critical point is found to disappear.

- We have also discussed the order of the chiral phase transition in NS from the comparison of the QCD phase diagram in PQM and the beta equilibrium line in RMF.

  $\Rightarrow$In NS, $\delta\mu$ is large, then the temperature of the CP becomes lower. Therefore the chiral phase transition may be crossover, even if the transition in symmetric matter ($\delta\mu = 0$) is the first order.

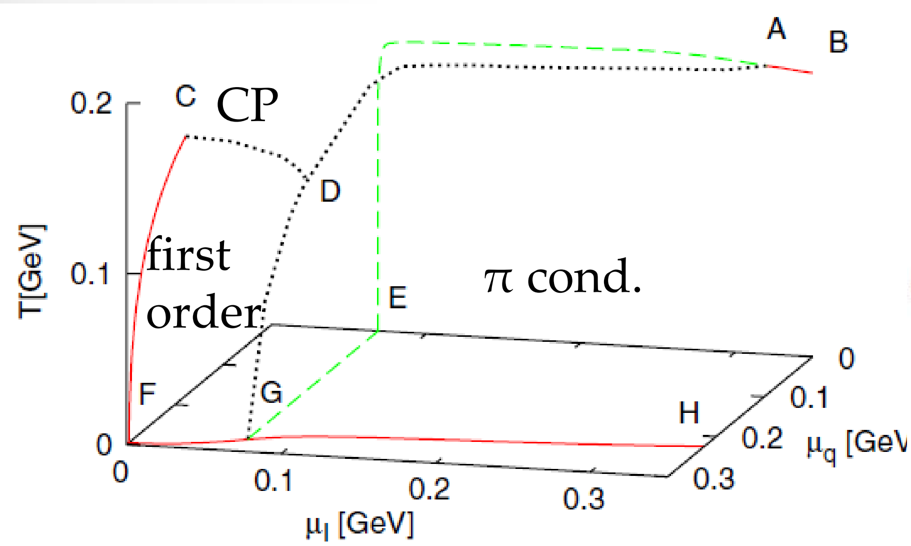
- In order to discuss the QCD phase transition in compact astrophysical phenomena more precisely, we need the EOS which includes both baryonic and quark degrees of freedom.

Thank you for your attention!

Back up

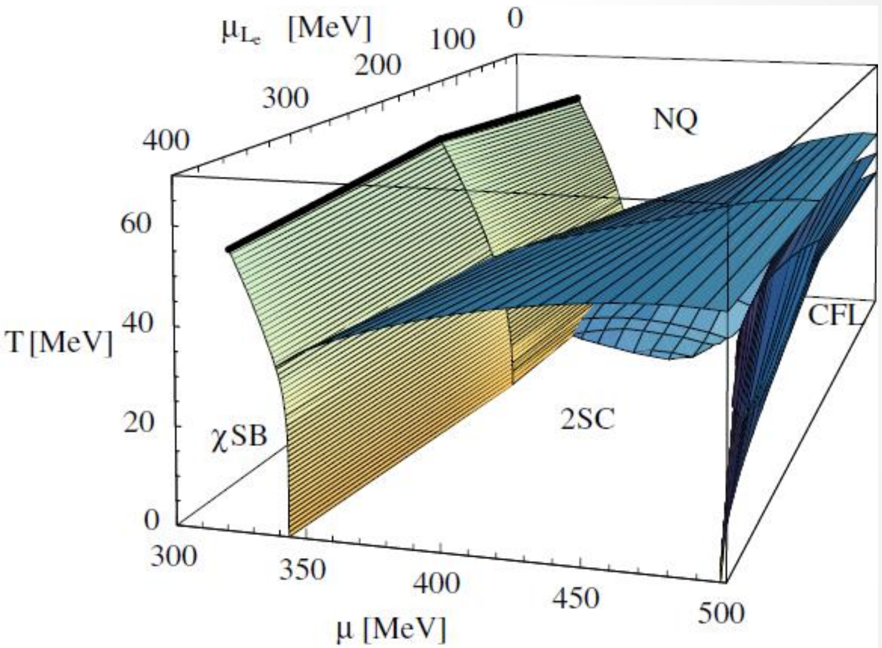
Previous Works

- *T.Sasaki et.al., PRD 82, 116004 (2010)*



3D(T, μ, δμ) QCD phase diagram
-PNJL(NF=2) with pion condensation

- *S.B.Ruster et.al., PRD 73, 034025 (2006)*



3D(T, μ, μL) QCD phase diagram

-PNJL (NF=3)
with neutrino trapping effect
and color superconductivity

Order Parameter

- Chiral condensate

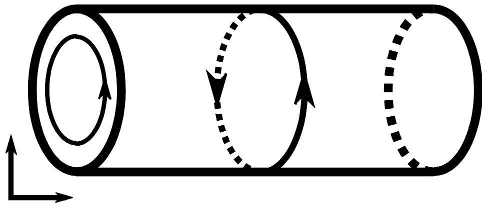
SSB of chiral symmetry ・・・ $SU(N_f)_L \times SU(N_f)_R \Rightarrow SU(N_f)_V$

Chiral condensate ・・・ $\langle \bar{q}q \rangle = \langle \bar{q}_L q_R + \bar{q}_R q_L \rangle$

$$\langle \bar{q}q \rangle \begin{cases} = 0 & \text{(chirally symmetric phase)} \\ \neq 0 & \text{(chirally broken phase)} \end{cases}$$

- Polyakov loop

$$P = \frac{1}{N_c} \left\langle \mathrm{Tr}_c \mathcal{P} \exp\left(i \int_0^\beta d\tau A_4 \right) \right\rangle_\beta$$



Without dynamical quark,

$$P = \exp(-\beta f_q) \to \Phi \begin{cases} \neq 0 & \text{(deconfinement phase)} \\ = 0 & \text{(confinement phase)} \end{cases}$$

Potential

- Mesonic Potential

$$U(\sigma, \boldsymbol{\pi}) = \lambda(\sigma^2 + \boldsymbol{\pi}^2 - v^2)^2/4 - h\sigma$$

$SU(N_f)_L \times SU(N_f)_R$

Explicitly symmetry braking term

- Polyakov loop potential Roessner et.al., ('07), Fukushima et.al.,('04)

$$\mathcal{U}[P, \bar{P}, T] = T^4 \left\{ -\frac{a(T)}{2} \bar{P}P + b(T) \ln H(P, \bar{P}) \right\} ,$$

$$H(P, \bar{P}) = 1 - 6\bar{P}P + 4(\bar{P}^3 + P^3) - 3(\bar{P}P)^2$$

comes from the Haar measure of the group integral

$$a(T) = a_0 + a_1(T_0/T) + a_2(T_0/T)^2, \quad b(T) = b_3(T_0/T)^3$$

⇒ The parameter are fitted to the pure gauge lattice data

Effective potential

- Integrating over the quark fields results in

$$\Omega_{PQM} = \mathcal{U}(P,\bar{P},T) + U(\sigma,\boldsymbol{\pi}=0) + \Omega_0 + \Omega_T,$$

$$\Omega_0 = -2N_f N_c \int \frac{d\boldsymbol{p}}{(2\pi)^3} E_p \theta\left(\Lambda^2 - \boldsymbol{p}^2\right),$$

necessary to reproduce the second-order chiral phase transition at μB = 0 MeV in the chiral limit. [Skokov et,al.,('10)]

$$\Omega_T = -\frac{1}{2}\left(m_\omega^2 \omega^2 + m_\rho^2 R^2\right) - 2T \sum_f \int \frac{d\boldsymbol{p}}{(2\pi)^3} \log\left(F_-^f F_+^f\right),$$

$$F_-^f = 1 + 3Pe^{-\beta\mathcal{E}_-^f} + 3\bar{P}e^{-2\beta\mathcal{E}_-^f} + e^{-3\beta\mathcal{E}_-^f}, \quad F_+^f = 1 + 3\bar{P}e^{-\beta\mathcal{E}_+^f} + 3Pe^{-2\beta\mathcal{E}_+^f} + e^{-3\beta\mathcal{E}_+^f},$$

$$\mathcal{E}_\pm^f = E_p \pm \tilde{\mu}_f \; E_p = \sqrt{\boldsymbol{p}^2 + M^2}, \quad M = g\sigma .$$

- The EoMs are obtained from the stationary condistions,

$$\frac{\partial\Omega}{\partial\sigma} = \frac{\partial\Omega}{\partial P} = \frac{\partial\Omega}{\partial\bar{P}} = \frac{\partial\Omega}{\partial\omega} = \frac{\partial\Omega}{\partial R} = 0$$

By solving these equations, we obtain (T, μB,δμ) dependence of the mean fields

Model parametrization

- Scalar-pseudoscalar part (g, λ, ν, h)
  fixed to reproduce in vacuum for Λ = 600 MeV

$$m_q = g\sigma = 335\text{MeV},\ \sigma = f_\pi,\ m_\sigma = \partial^2\Omega/\partial\sigma^2 = 700\text{MeV},\ m_\pi^2 = h/f_\pi(139\text{MeV})^2$$

- Vector part
  for simplisity ⇒ $g_\omega = g_\rho = g_v,\quad m_\omega = m_\rho = m_v = 770$ MeV
  we regard $r = g_v/g$ as free parameter.

- Polyakov loop part [Roesner et.al.,('07)]
  fitted to the pure gauge lattice data.

$$a_0 = 3.51, a_1 = -2.47, a_2 = 15.2, b_3 = -1.75, T_0 = 270\text{MeV}$$

- Here, Nf and μB dependence is not considered.

δμ dependence of QCD phase diagram

- The reduction of the μ_{BC} may be understood as the density effects.
  For a simple estimate…
  - low T , chiral limit, without vector interaction

$$\rho_q \propto (\mu + \delta\mu)^3 + (\mu - \delta\mu)^3 = 2\mu^3(1 + 3\delta\mu^2/\mu^2)$$

⇓ If QCD phase transition at finite δμ occurs same density as that for δμ=0

$$\mu \simeq \mu_c - \delta\mu^2/\mu_c$$

• • • for $\delta\mu = 50\text{MeV} \Rightarrow \mu_c - \mu = 7.2\text{MeV}$ (7.0MeV)

• • • for $\delta\mu = 70\text{MeV} \Rightarrow \mu_c - \mu = 14\text{MeV}$ (13MeV)

r dependence of the QCD phase diagram