Constraints on quark-hadron transition from lattice QCD and neutron-star observation

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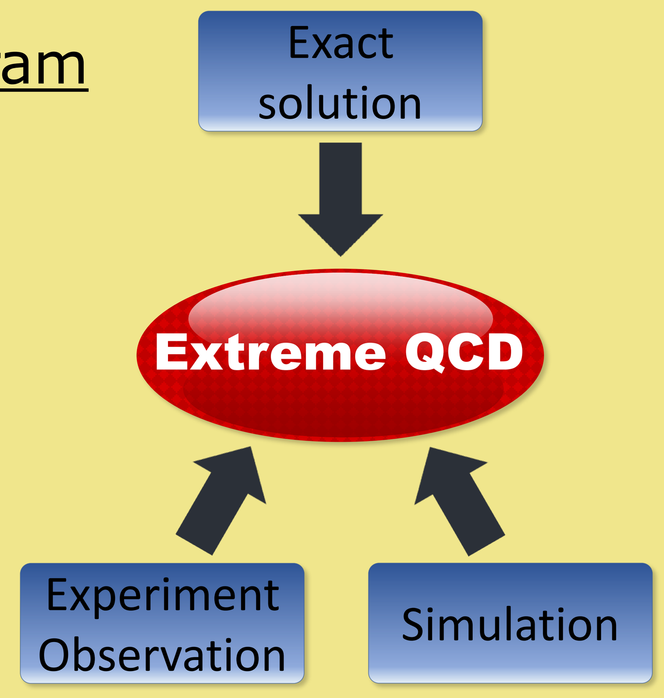
Introduction

Strategy for exploring QCD phase diagram

QCD phase diagram is a key issue of high energy physics, but it is still unknown particularly at middle and large μ_B/T. That is because the first-principle lattice QCD (LQCD) simulation has the severe sign problem there.

A steady way of approaching the middle and large μ_B/T regions is to gather solid results from different regions and extract a consistent picture from them.

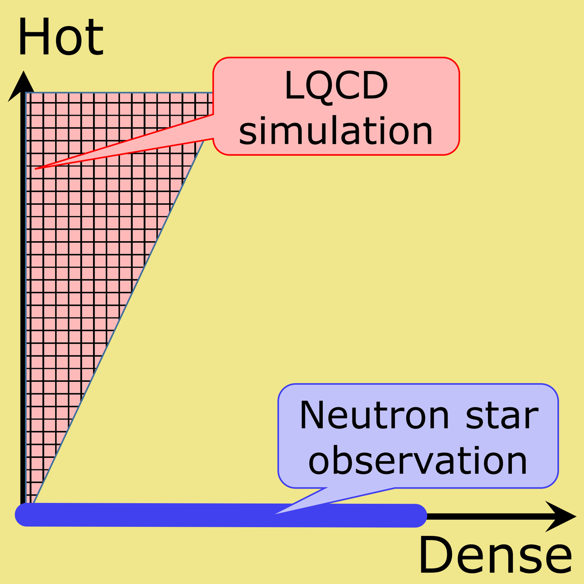


Solid results

There are several information for hot and dense QCD.

- Lattice QCD(LQCD) simulation at $\mu_B/T < 1$.
- Chiral perturbation theory
- Heavy ion collision experiment
- Neutron star (NS) observation

Particularly, a massive NS have been observed, and it strongly constraints equation of state (EoS) of dense matter.



We determine the QCD phase diagram from these solid results.

Two phase model

We consider a two-phase model to treat the quark-hadron phase transition for two-flavor QCD by assuming the first order transition.

Quark phase:
Polyakov-loop extended NJL model with entanglement vertex (EPNJL model) [1]
Hadron phase:
Hadron resonance gas model with the volume-exclusion effect for baryons

EPNJL model

$$\mathcal{L}_{\rm EPNJL} = \bar{q}(\gamma_\nu D_\nu + \hat{m}_0 - \gamma_4\hat{\mu})q - G(\Phi)[(\bar{q}q)^2 + (\bar{q}i\gamma_5\vec{\tau}q)^2] + G_{\rm V}(\bar{q}\gamma_\mu q)^2 + \mathcal{U}(\Phi[A],\Phi^*[A],T)$$

$$G(\Phi) = G_{\rm S}[1 - \alpha_1\Phi\Phi^* - \alpha_2(\Phi^3 + \Phi^{*3})]$$

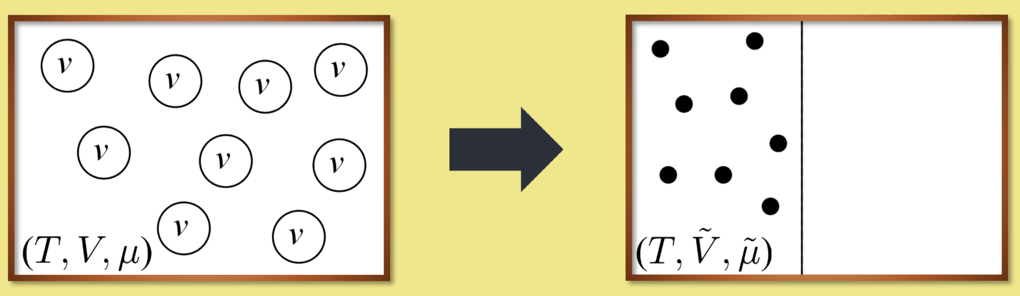
The effective potential $\mathcal{U}$ is determined to reproduce pure gauge LQCD results. In this work, G_V is treated as a free parameter and discussed later.

The EPNJL model is consistent with LQCD data for finite imaginary μ_B, finite real- and imaginary-isospin chemical potentials[1], small real μ_B[2], and strong magnetic field[3].

[1] Y. Sakai, T. Sasaki, H. Kouno, and M. Yahiro, Phys. Rev. D **82**, 096007 (2010).
[2] Y. Sakai, T. Sasaki, H. Kouno, and M. Yahiro, J. Phys. G: Nucl. Part. Phys. **39**, 035004 (2012).
[3] R. Gatto and M. Ruggieri, Phys. Rev. D **83**, 034016 (2011).

Volume exclusion effect

To reproduce the repulsive nature of baryons, we introduce the volume-exclusion effect[4]. In this scheme, we approximate the system of finite-volume particles by a mimic system of point particles.



$$\tilde{\mu} = \mu - vP$$
$$\tilde{V} = V - vN_{\rm B}$$

The volume parameter (v) is determined to reproduce the experimental data.

[4] H. Rischke, M.I. Gorenstein, H. Stöcker, and W. Greiner, Z Phys. C **51**, 485 (1991).

Nuclear matter EoS

Nuclear force is calculated by chiral effective field theory (Chi-EFT). The advantage is that 3 body force(3BF) is generated on the same footing with 2 body force(2BF). The parameters for N^3LO 2BF and N^2LO 3BF are determined in Ref. [5,6].

EoS is obtained by solving many body problem with 2 body forces. In this work, we reduce 3BF to effective 2BF and employ the lowest order Brueckner theory [7].

[5] E. Epelbaum,W. Göckle, and U.-G. Meißner, Nucl. Phys. A **747**, 362 (2005).
[6] K. Hebeler, S.K. Bogner, R.J. Furnstahl, A. Nogga, and A. Schwenk, Phys. Rev. C **83**, 031301(R) (2011).
[7] M. Kohno, Phys. Rev. C **86**, 061301(R) (2012).

Numerical results

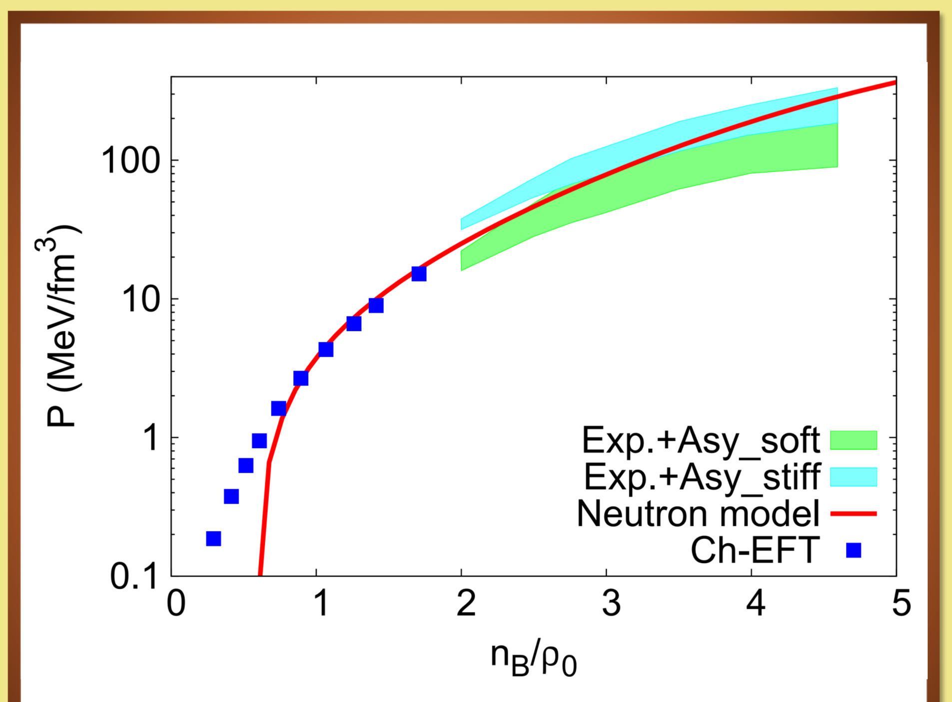
The Equation of state at T=0

This is the EoS of neuron matter. Model parameters are determined to reproduce

- Ch-EFT EoS,
- EoS from heavy ion collision[8],

and preserve causality. Then the present hadron model have good agreement at $n_B > \rho_0$.

[8] P. Danielewicz, R. Lacey, and W.G. Lynch, Science **298**, 1592 (2002).



ρ_0 : Normal nuclear density (0.17 fm^{-3})

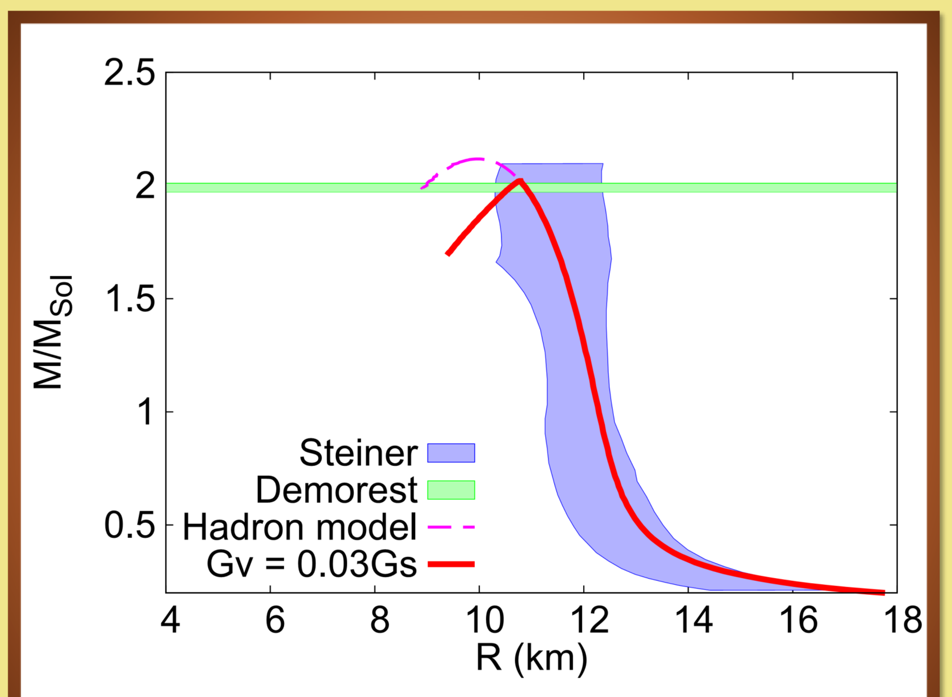
Mass-Radius relation

Mass and radius of NS is obtained by solving Tolman-Oppenheimer-Volkoff equation. The result is consistent with the NS observations[9,10].

Because quark matter softens the EoS, its appearance is strongly constrained. Then the vector coupling in the EPNJL model has lower bound,

$$G_V > 0.03\,G_S.$$

[9] A.W. Steiner, J.M. Lattimer, and E.F. Brown, Astrophys. J. **722**, 33 (2010).
[10] B. Demorest, T. Pennucci, S.M. Ransom, M.S.E. Roberts, and J.W.T. Hessels, Nature **467**, 1081 (2010).



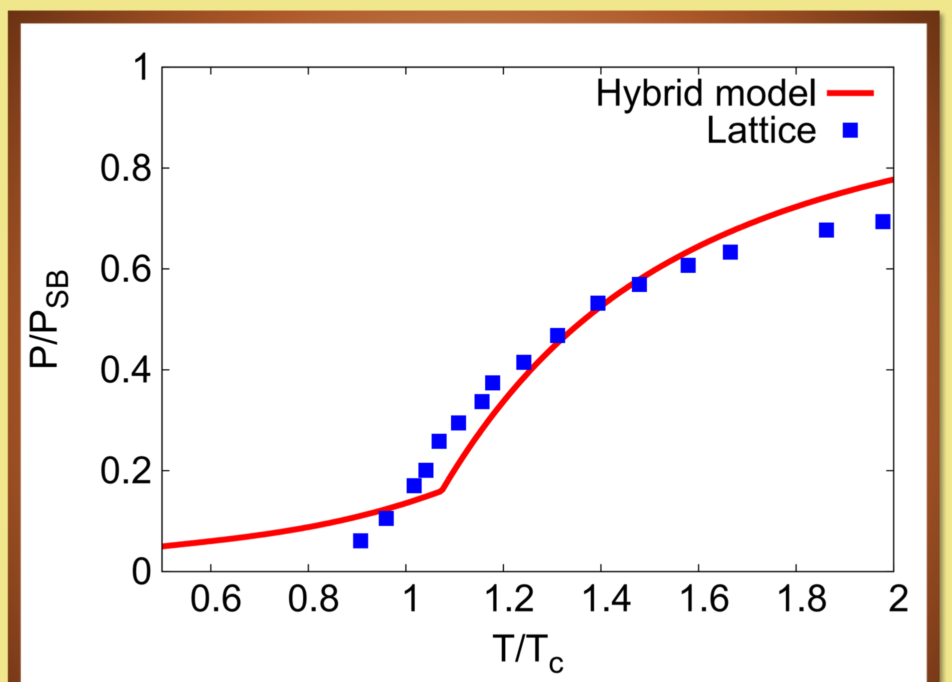
M_{Sol} : Solar mass (2.00 × 10^{30} kg)

The Equation of state at $\mu_B = 0$

This is T dependence of the pressure obtained by the hybrid model in comparison with LQCD results[11]. Here, T_c is deconfinement transition temperature and defined by the peak of susceptibility; T_c = 174 MeV for both the results.

The hybrid model almost reproduce the LQCD result. This means, the two-phase picture is applicable even at $\mu_B = 0$.

[11] A. Ali Khan *et al*, Phys. Rev. D **64**, 074510 (2001).

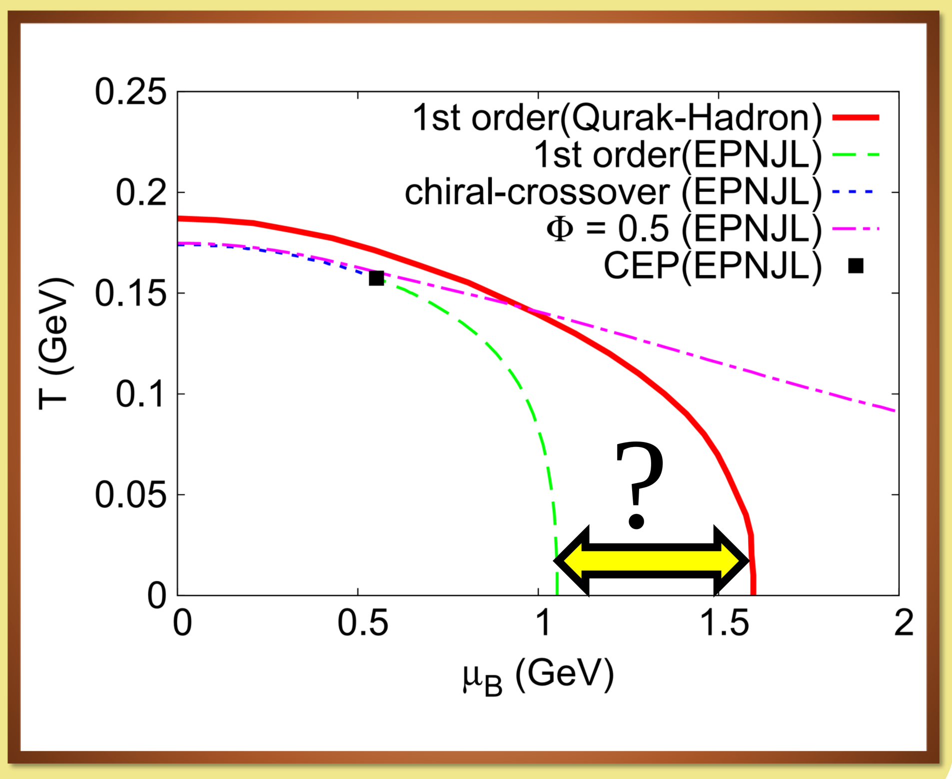


P_{SB} : Stefan-Boltzmann limit for QGP

QCD phase diagram

The red line is the quark-hadron transition line obtained by the hybrid model with $G_V = 0.03G_S$. The model gives a critical chemical potential at T = 0 as $\mu_B^{(c)}$ = 1.6 GeV. This is the lower bound to be consistent with the NS measurement.

EPNJL model gives $\mu_B^{(c)}$ = 1 GeV at T = 0, but the point belongs to the hadron phase in the hybrid model. This is an important problem to be solved in future.



Summary

We have studied the QCD phase diagram by constructing the quark-hadron hybrid model that is consistent with

- LQCD results,
- The neutron-matter EoS evaluated from the Ch-EFT 2NF and 3NF,
- The heavy-ion collision measurements,
- NS observations.

We have determined the lower bound of the quark-hadron transition point at T = 0:

$$\mu^{(c)}_B > 1.6 \text{ GeV}.$$

However, NJL model gives $\mu^{(c)}_B$= 1 GeV at T = 0, and the point is located in the hadron phase in the hybrid model. It is then highly required to introduce baryon degrees of freedom in the effective model.