QCD phase diagram V.S. Holographic QCD

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w/. Rong-Gen Cai, Li Li, Yuan-Xu Wang, 2201.02004,

Outline

I. Motivations & hQCD

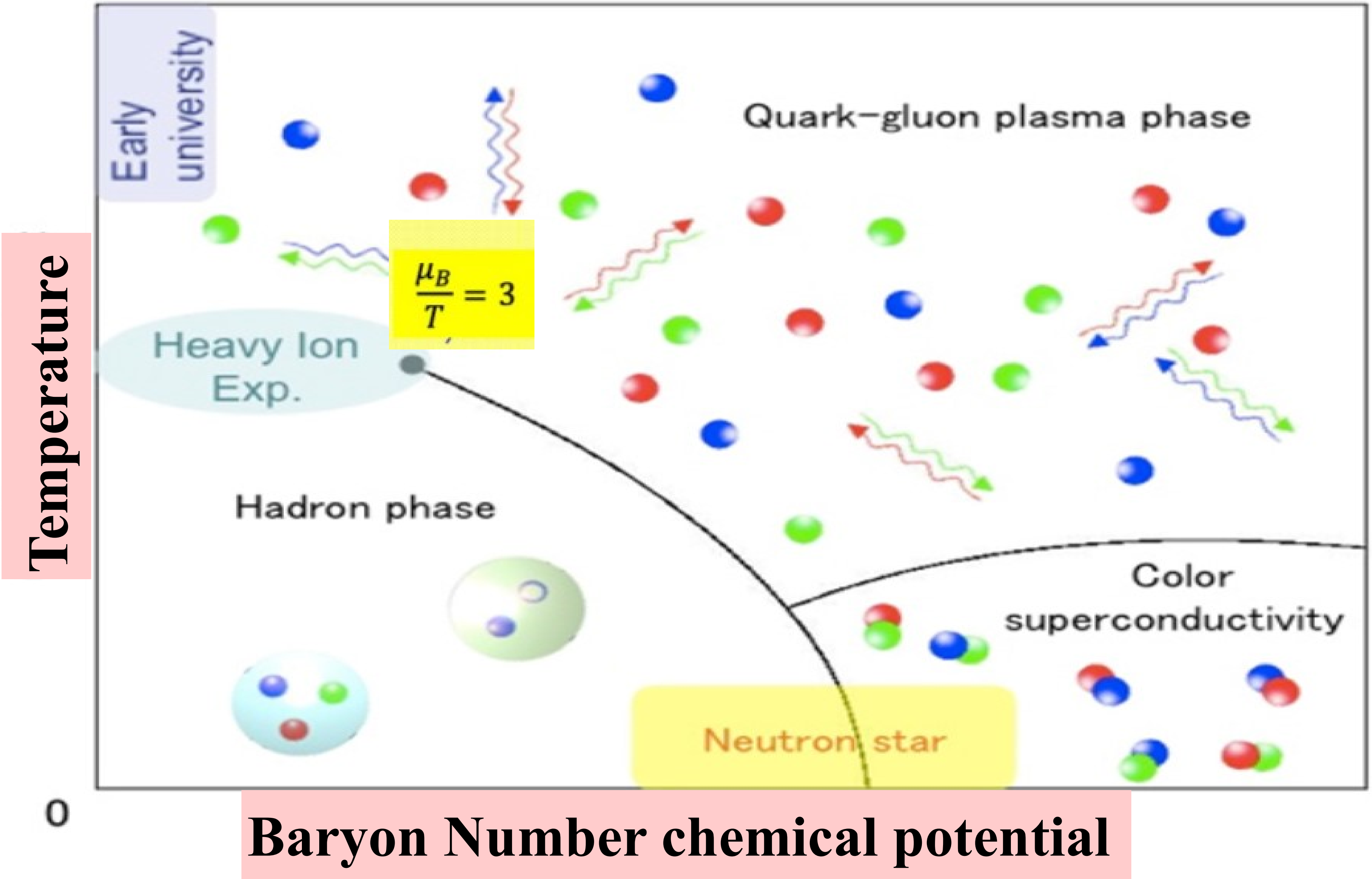
II. Holographic QCD model (hQCD)

III. Confront with QCD Phase diagram

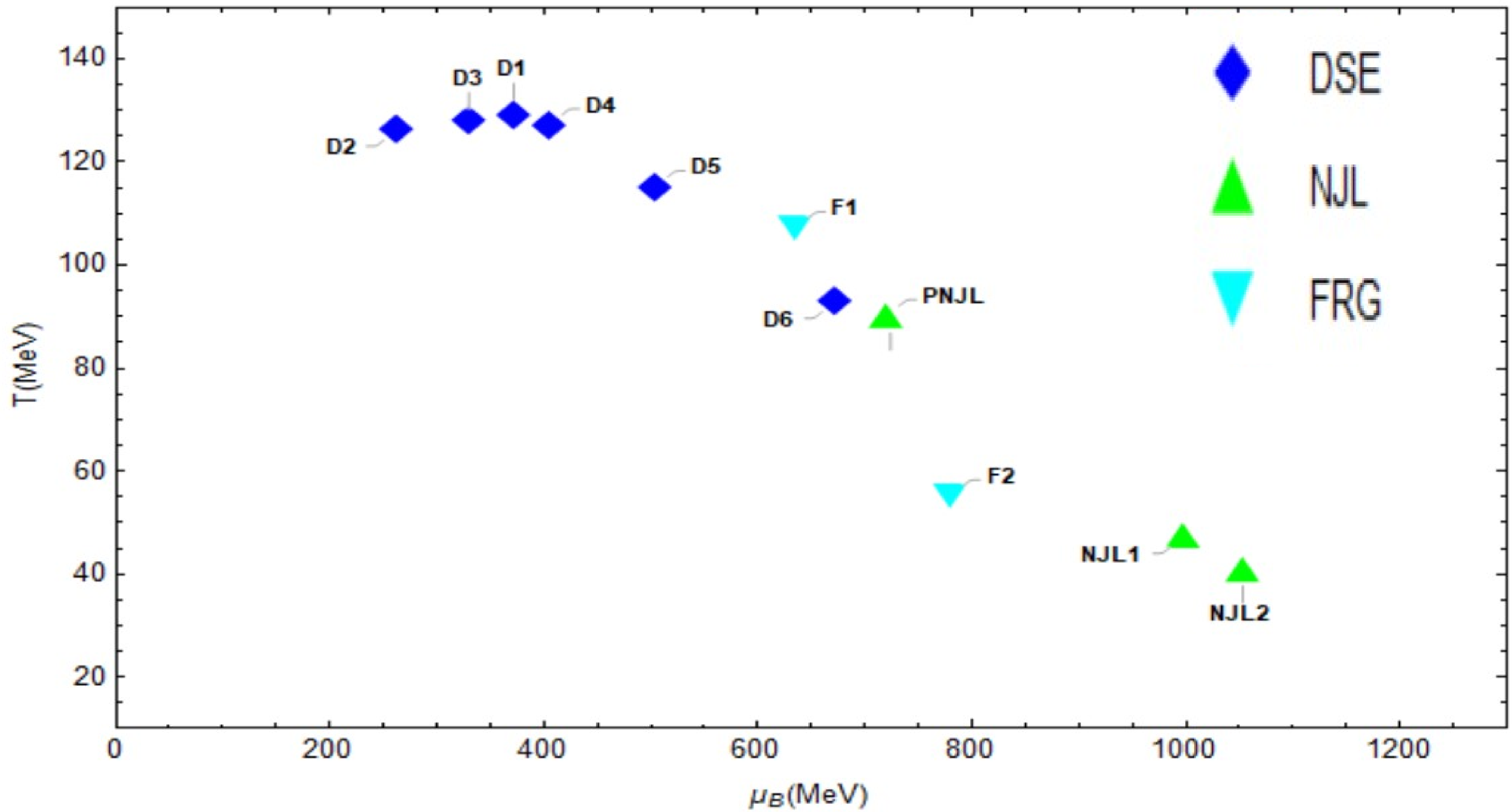
IV. Summary

Motivations

A schematic view of QCD Phase diagram



Status of searching CEP



Schwinger–Dyson equation (DSE), 2109.09935 [hep-ph], 1607.01675 [hep-ph], 1011.2876 [nucl-th], 1403.3797 [hep-ph], 1405.4762 [hep-ph]], 2002.07500 [hep-ph]].
Nambu–Jona-Lasinio models (NJL, PNJL), arXiv:1801.09215 [hep-ph]], Nucl. Phys. A 504 (1989), 668-684
Functional renormalization group (FRG). 1909.02991 [hep-ph]], 1709.05654 [hep-ph]].

Motivations

I. Low energy QCD is strong coupled system

P. Braun-Munzinger and J. Wambach, Rev. Mod. Phys. 81 (2009), 1031-1050 [arXiv:0801.4256 [hep-ph]].

S. Gupta, X. Luo, B. Mohanty, H. G. Ritter and N. Xu, Science 332 (2011), 1525-1528 [arXiv:1105.3934[hep-ph]].

II. Finite density QCD v.s. sign Problem

O. Philipsen, Prog. Part. Nucl. Phys. 70 (2013), 55-107 [arXiv:1207.5999 [hep-lat]].

III. AdS/QCD offers a practical approach

O. DeWolfe, S. S. Gubser and C. Rosen, Phys. Rev. D 84 (2011), 126014 [arXiv:1108.2029 [hep-th]].

R. G. Cai, S. He and D. Li, JHEP 03 (2012), 033 [arXiv:1201.0820 [hep-th]].

U. Gursoy, M. Jarvinen and G. Nijs, Phys. Rev. Lett. 120 (2018) no.24,242002 [arXiv:1707.00872 [hep-th]].

J. Grefa, J. Noronha, J. Noronha-Hostler, I. Portillo,C. Ratti and R. Rougemont,Phys. Rev. D 104 (2021) no.3, 034002 [arXiv:2102.12042[nucl-th]]. ….

Intro AdS/QCD

AdS/QCD

AdS/CFT conjecture

$$AdS_5 \times S^5 \quad \Longleftrightarrow \quad N = 4 \text{ SYM theory}$$

If it is true for any gauge theory
(???)

String theory, quantum gravity	⟺	**Non-Abelian gauge theory**

Then what is the dual string theory of QCD?
(It is nature to ask the question here)

? ⟺ **QCD**

Question: Is it possible to find a string theory dual to QCD?

Top-Down models: D3-D7, D4-D8D8bar …

hQCD model

HQCD model for 2+1 flavor system

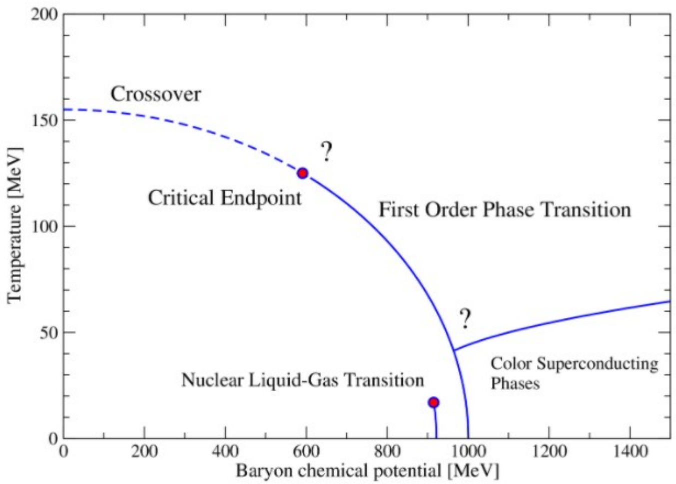
Einstein-Maxwell-Dilaton system

Motivation

To cover the degree of freedom in QCD phase Diagram.
Quarks (chemical potential) & gluons(dilaton potential)

Gravity Action

$$S = \frac{1}{2\kappa_N^2}\int d^5x\sqrt{-g}\Big[\mathcal{R} - \frac{1}{2}\nabla_\mu\phi\nabla^\mu\phi - \frac{Z(\phi)}{4}F_{\mu\nu}F^{\mu\nu} - V(\phi)\Big],$$



ϕ Break conformal symmetry

$F^{\mu\nu}$ Introduce baryon chemical potential

HQCD model

Rong-Gen Cai, Song He, Li Li, Yuan-Xu Wang, 2201.02004

Ansatz

$$ds^2 = -f(r)e^{-\eta(r)}dt^2 + \frac{dr^2}{f(r)} + r^2 d\boldsymbol{x}_3^2$$

$$\phi = \phi(r), \quad A_t = A_t(r)$$

EOM

$$\nabla_\mu \nabla^\mu \phi - \frac{\partial_\phi Z}{4} F_{\mu\nu} F^{\mu\nu} - \partial_\phi V = 0$$

$$\nabla^\nu (Z F_{\nu\mu}) = 0$$

$$\mathcal{R}_{\mu\nu} - \frac{1}{2}\mathcal{R} g_{\mu\nu} = \frac{1}{2}\partial_\mu \phi \partial_\nu \phi + \frac{Z}{2} F_{\mu\rho} F_\nu{}^\rho + \frac{1}{2}\left(-\frac{1}{2}\nabla_\mu \phi \nabla^\mu \phi - \frac{Z}{4} F_{\mu\nu} F^{\mu\nu} - V\right) g_{\mu\nu}$$

Model Parameters

$$V(\phi) = -12\cosh[c_1\phi] + (6c_1^2 - \frac{3}{2})\phi^2 + c_2\phi^6 \,,$$

$$Z(\phi) = \frac{1}{1+c_3}\operatorname{sech}[c_4\phi^3] + \frac{c_3}{1+c_3} e^{-c_5\phi} \,,$$

c_1, c_2, c_3, c_4, c_5 | Effective Newton constant κ_N^2 | Scalar source ϕ_s +Renormalization **b**

Boundary Stress Tensor

Rong-Gen Cai, Song He, Li Li, Yuan-Xu Wang, 2201.02004

On-Shell Action

$$-\Omega V = T(S + S_{\partial})_{on-shell} ,$$

$$S_{\partial} = \frac{1}{2\kappa_N^2} \int_{r\to\infty} dx^4 \sqrt{-h} \Big[2K - 6 - \frac{1}{2}\phi^2 - \frac{6c_1^4 - 1}{12}\phi^4 \ln[r] - b\,\phi^4 + \frac{1}{4}F_{\rho\lambda}F^{\rho\lambda}\ln[r]\Big]$$

c_1, c_2, c_3, c_4, c_5 Effective Newton constant κ_N^2 Scalar source ϕ_s+Renormalization **b**

Boundary stress tensor

$$T_{\mu\nu} = \lim_{r\to\infty} \frac{2}{\sqrt{-\det g}} \frac{\delta(S + S_{\partial})_{on-shell}}{\delta g^{\mu\nu}},$$

$$= \frac{1}{2\kappa_N^2} \lim_{r\to\infty} r^2 \Big[2(K h_{\mu\nu} - K_{\mu\nu} - 3h_{\mu\nu}) - (\frac{1}{2}\phi^2 + \frac{6c_1^4 - 1}{12}\phi^4 \ln[r] + b\,\phi^4) h_{\mu\nu}$$

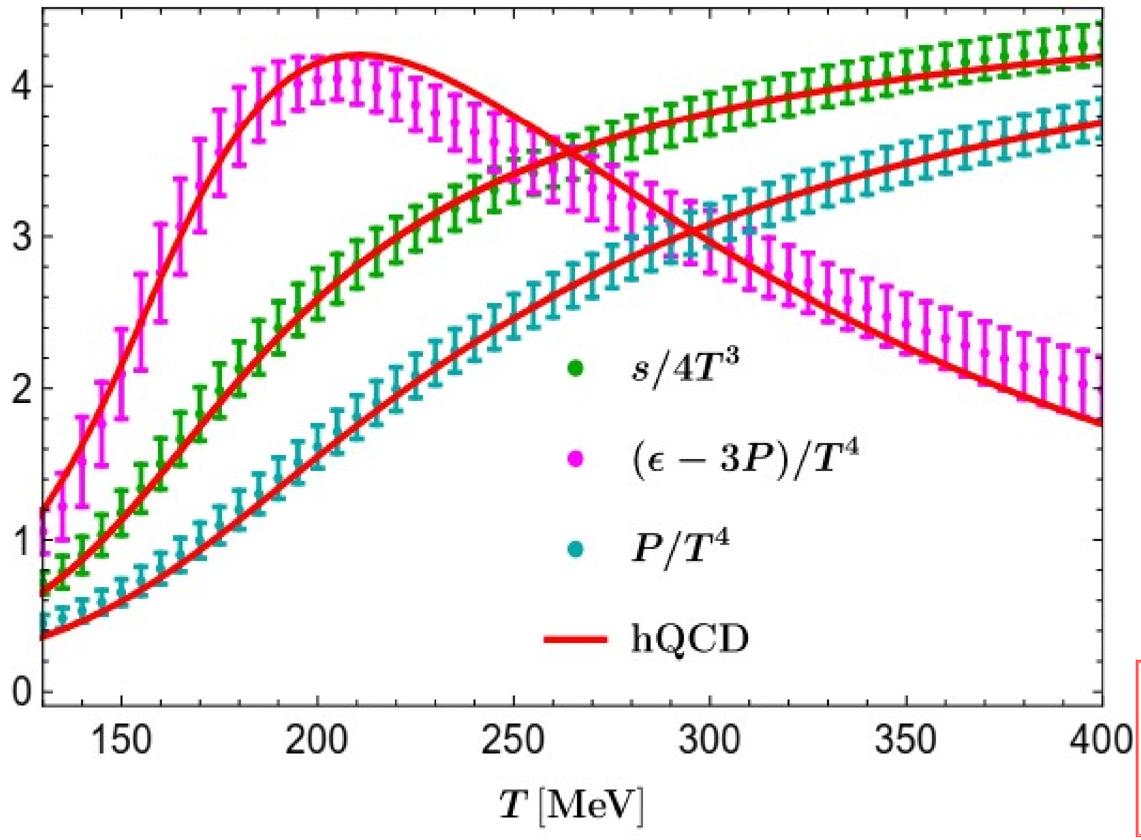
$$- (F_{\mu\rho}F_{\nu}{}^{\rho} - \frac{1}{4}h_{\mu\nu}F_{\rho\lambda}F^{\rho\lambda}) \ln[r]\Big] ,$$

To fix model parameters by thermal dynamics

Rong-Gen Cai, Song He, Li Li, Yuan-Xu Wang, 2201.02004

c_1, c_2, c_3, c_4, c_5 Effective Newton constant κ_N^2 Scalar source ϕ_s+**Renormalization b**

Equations of state at vanishing chemical potential, s, trace anomaly, pressure



$$T = \frac{1}{4\pi} f'(r_h) e^{-\eta(r_h)/2},$$

$$s = \frac{2\pi}{\kappa_N^2} r_h^3$$

$$\epsilon := T_{tt}$$

$$P := T_{xx}$$

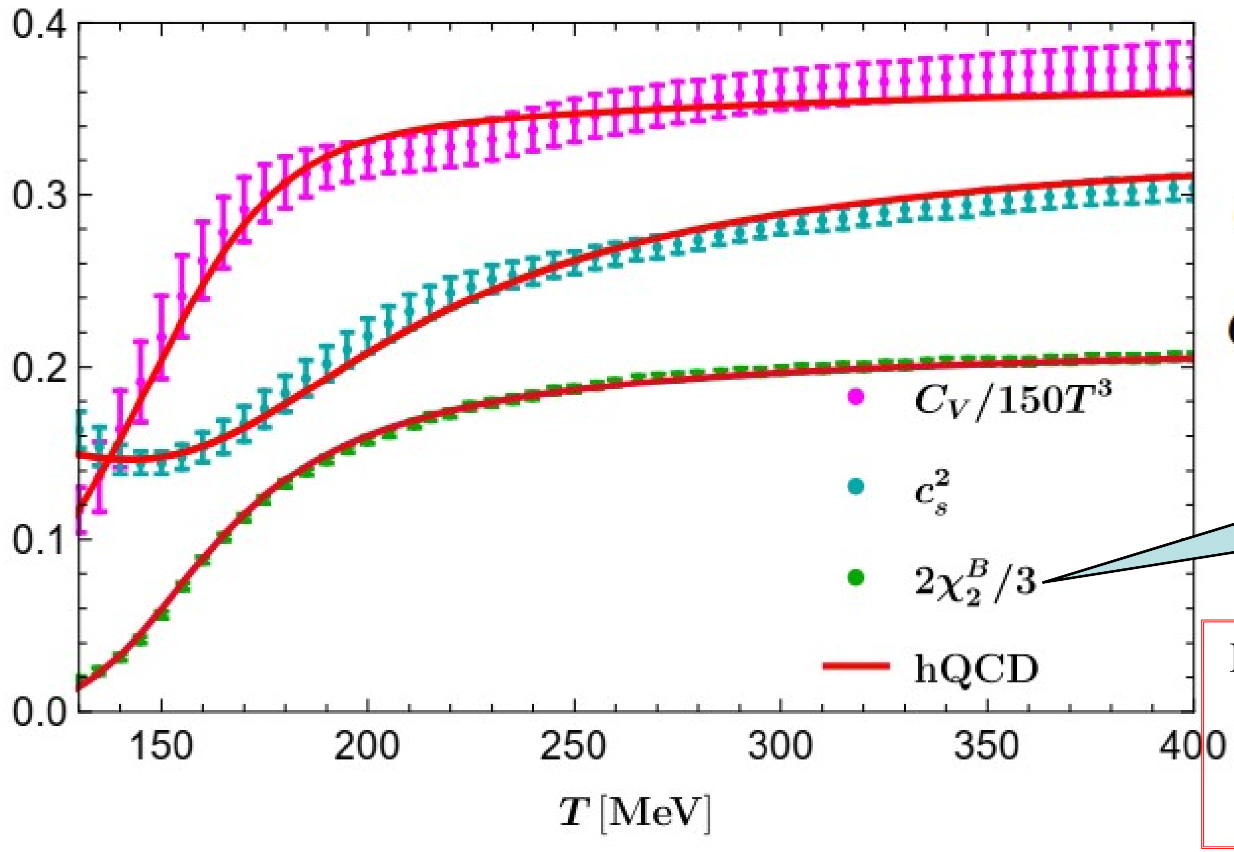
A. Bazavov *et al.* [HotQCD], Phys. Rev. D 90 (2014), 094503[arXiv:1407.6387 [hep-lat]].

To fix model parameters by thermal dynamics

Rong-Gen Cai, Song He, Li Li, Yuan-Xu Wang, 2201.02004

c_1, c_2, c_3, c_4, c_5 Effective Newton constant κ_N^2 Scalar source ϕ_s+Renormalization **b**

Sound speed,specific heat, second-order baryon susceptibility **at vanishing chemical potential**



$$c_s = \sqrt{(dP/d\epsilon)_{\mu_B}}$$

$$C_V = (d\epsilon/dT)_{\mu_B}$$

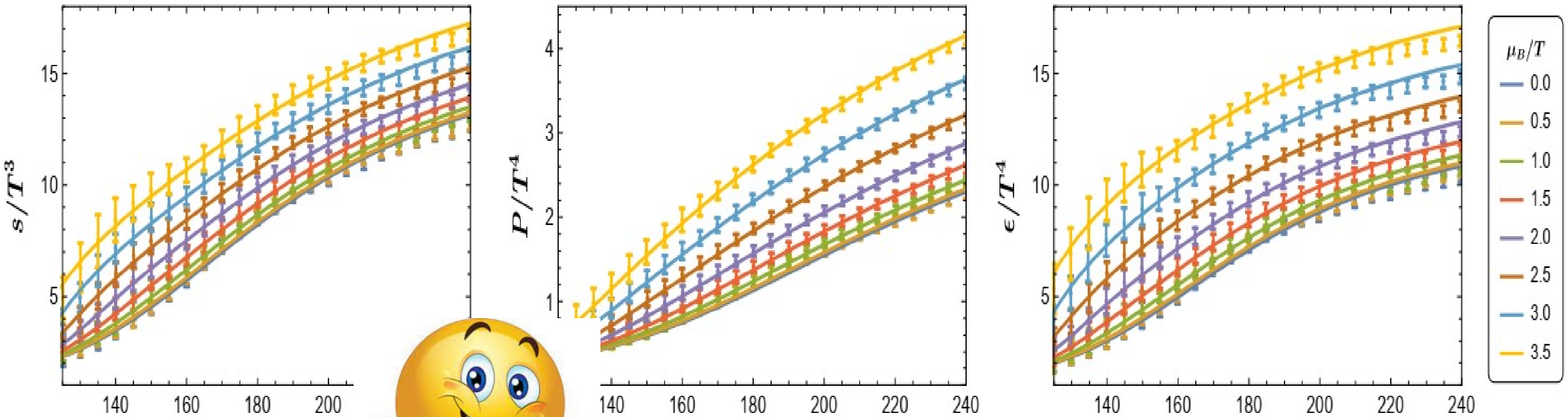
$$\chi_2^B = (d\rho_B/d\mu_B)_T$$

Bazavov *et al.* [HotQCD], Phys.Rev. D 90 (2014), 094503[arXiv:1407.6387 [hep-lat]].

Prediction of hQCD model

Predictions of thermal dynamical quantities at finite chemical potential

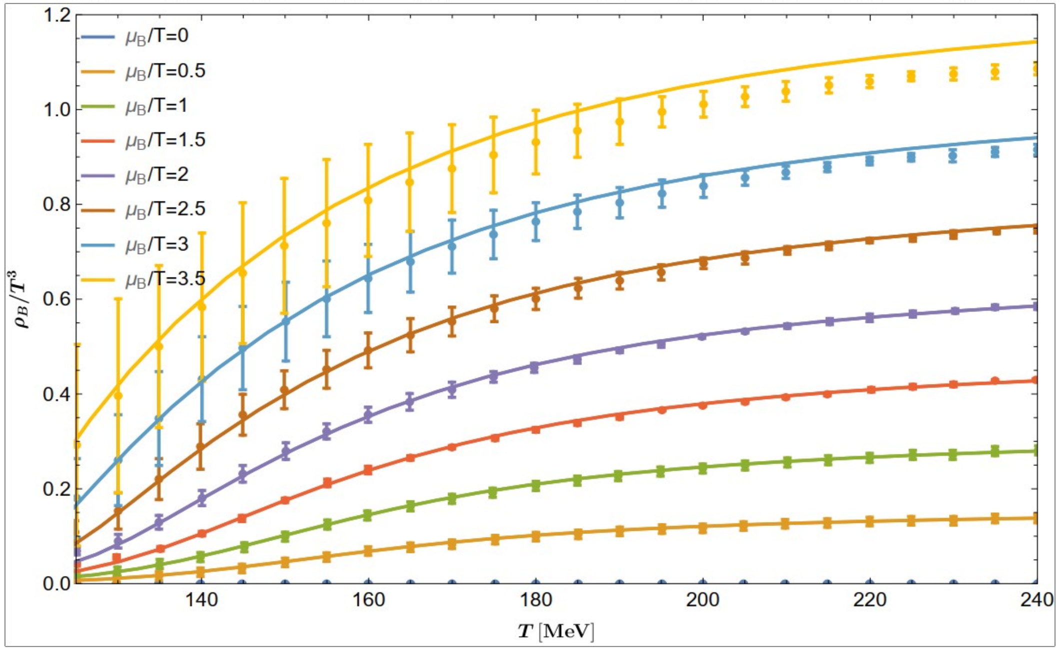
S. Bors´anyi, etc., Phys. Rev. Lett. 126 (2021) no.23, 232001 [arXiv:2102.06660 [hep-lat]]



More challenging fitting

Rho_B

Rong-Gen Cai, Song He, Li Li, Yuan-Xu Wang, 2201.02004

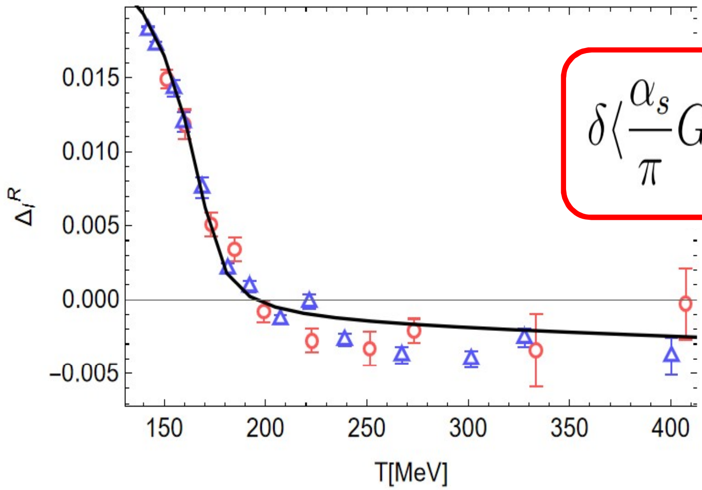


Condensation

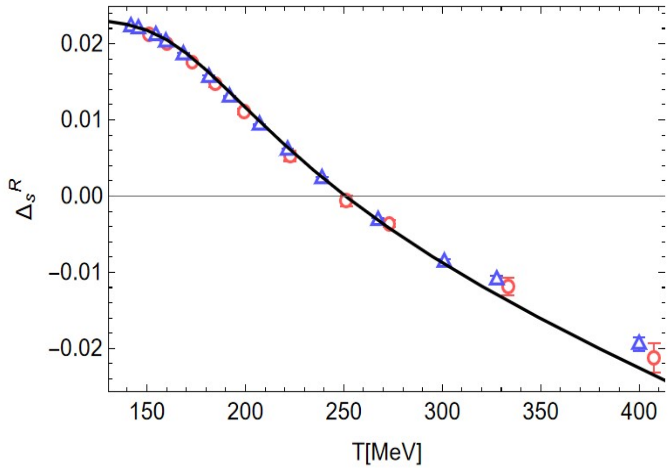
$$S_\sigma = -\frac{1}{2\kappa_N^2}\int d^5x\sqrt{-g}\,Z_\sigma(\phi)\left[\frac{1}{2}\nabla_\mu\sigma\nabla^\mu\sigma + V_\sigma(\sigma)\right]$$

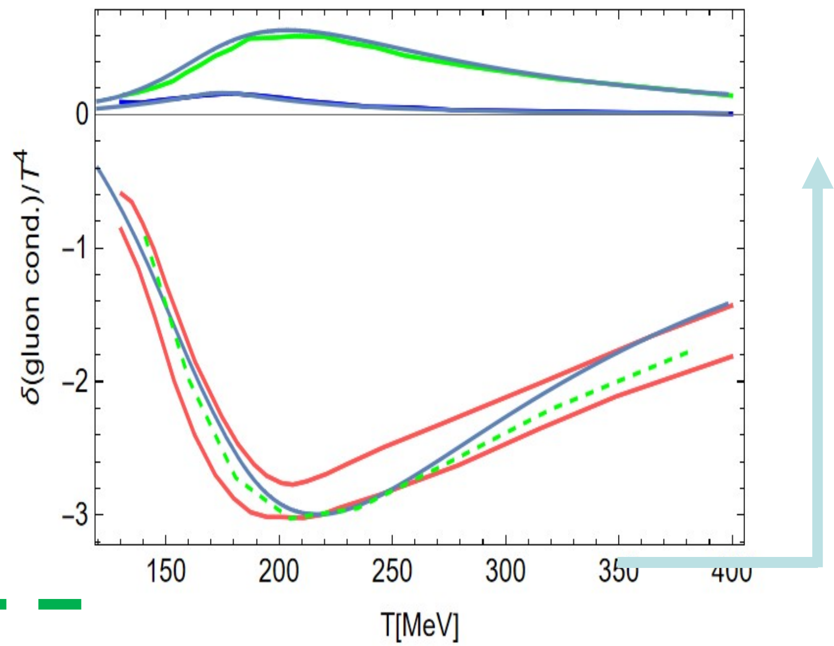
$$V_\sigma(\sigma) = \frac{1}{2}m^2\sigma^2 + a_0\sigma^4,$$

$$Z_\sigma(\phi) = a_1\, e^{a_2\,\phi^2} + a_3 e^{a_4\,\phi}$$



$$\delta\langle\frac{\alpha_s}{\pi}G^a_{\mu\nu}G^{a\mu\nu}\rangle_T = -\frac{8}{9}\Big[\delta T^\mu_\mu(T) - m_u\delta\langle\bar{u}u\rangle_T - m_d\delta\langle\bar{d}d\rangle_T - m_s\delta\langle\bar{s}s\rangle_T\Big].$$



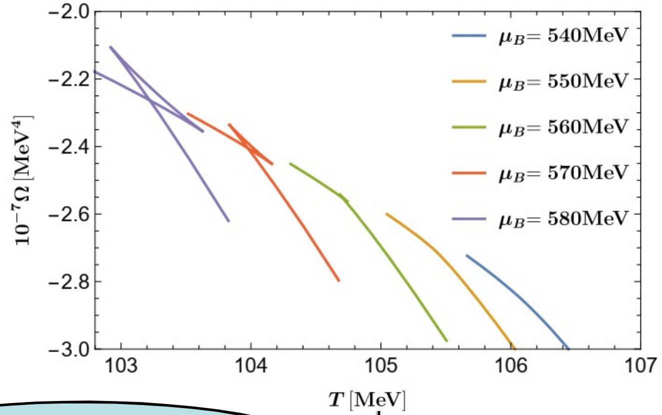


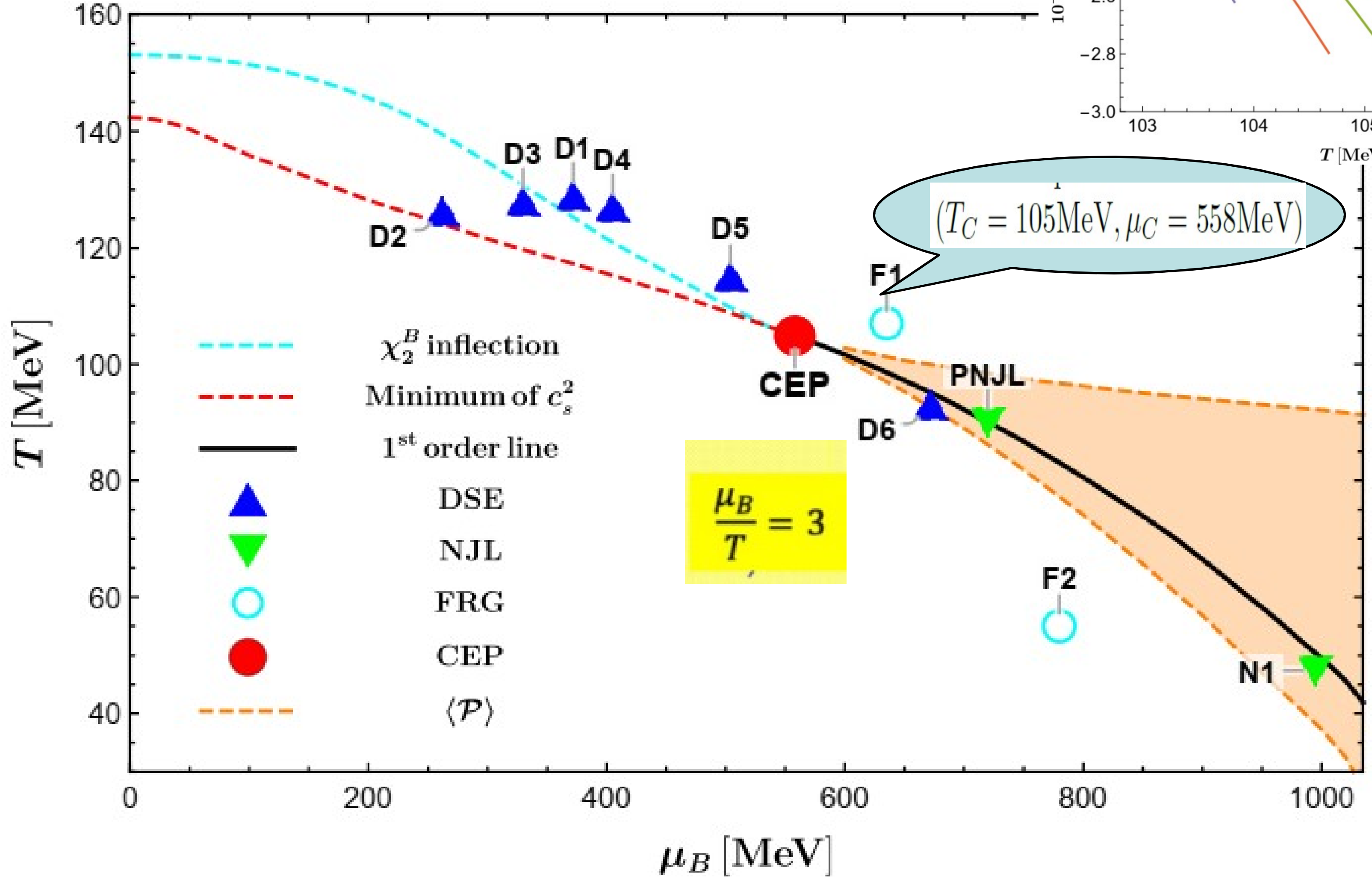
***[1812.00385v2]: Gubler P, Satow D. Recent progress in QCD condensate evaluations and sum rules.**

Predictions of QCD phase diagram

mu_B/T<=3 & mu_B< 300 MeV excluded by lattice simulation

A. Bazavov, etc.Phys. Rev. D 95 (2017) no.5, 054504 [arXiv:1701.04325 [hep-lat]].





Induced gravitational wave

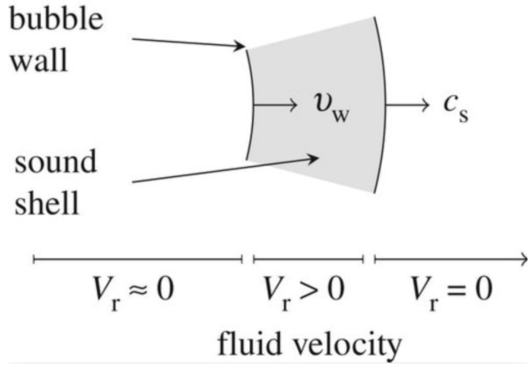
Strong first order phase transition will result in the production of GWs:

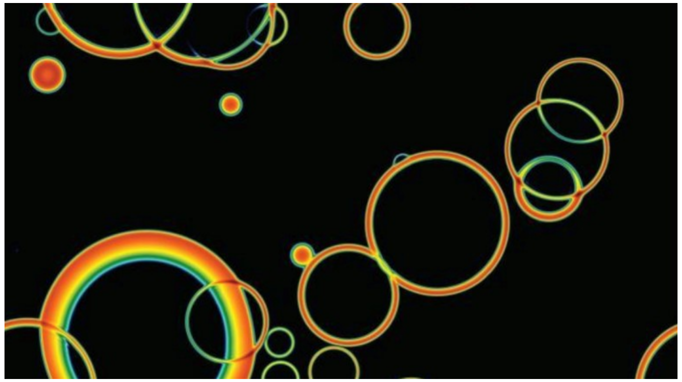
bubble collision + sound wave + MHD turbulence

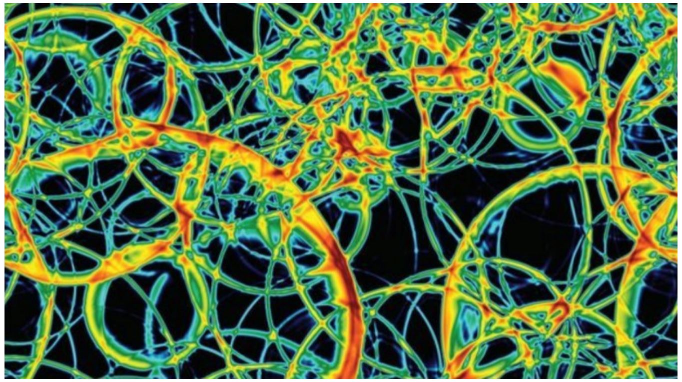
GWs are dominated by **sound waves** with energy spectrum

$$h^2\Omega_{GW}(f) = 8.5\times 10^{-6}\left(\frac{100}{g_n}\right)^{1/3}\left(\frac{\kappa\alpha}{1+\alpha}\right)^2 \times\left(\frac{H_n}{\beta}\right) v_w S_{SW}(f)\,.$$

α: phase transition strength parameter
v_w: bubble wall terminal velocity
$\frac{\beta}{H_n}$: the inverse time duration of the phase transition
H_n: Hubble rate at the nucleation temperature T_n
g_n: the number of degrees of freedom
κ: the fraction of bulk kinetic energy relative to the available vacuum energy.







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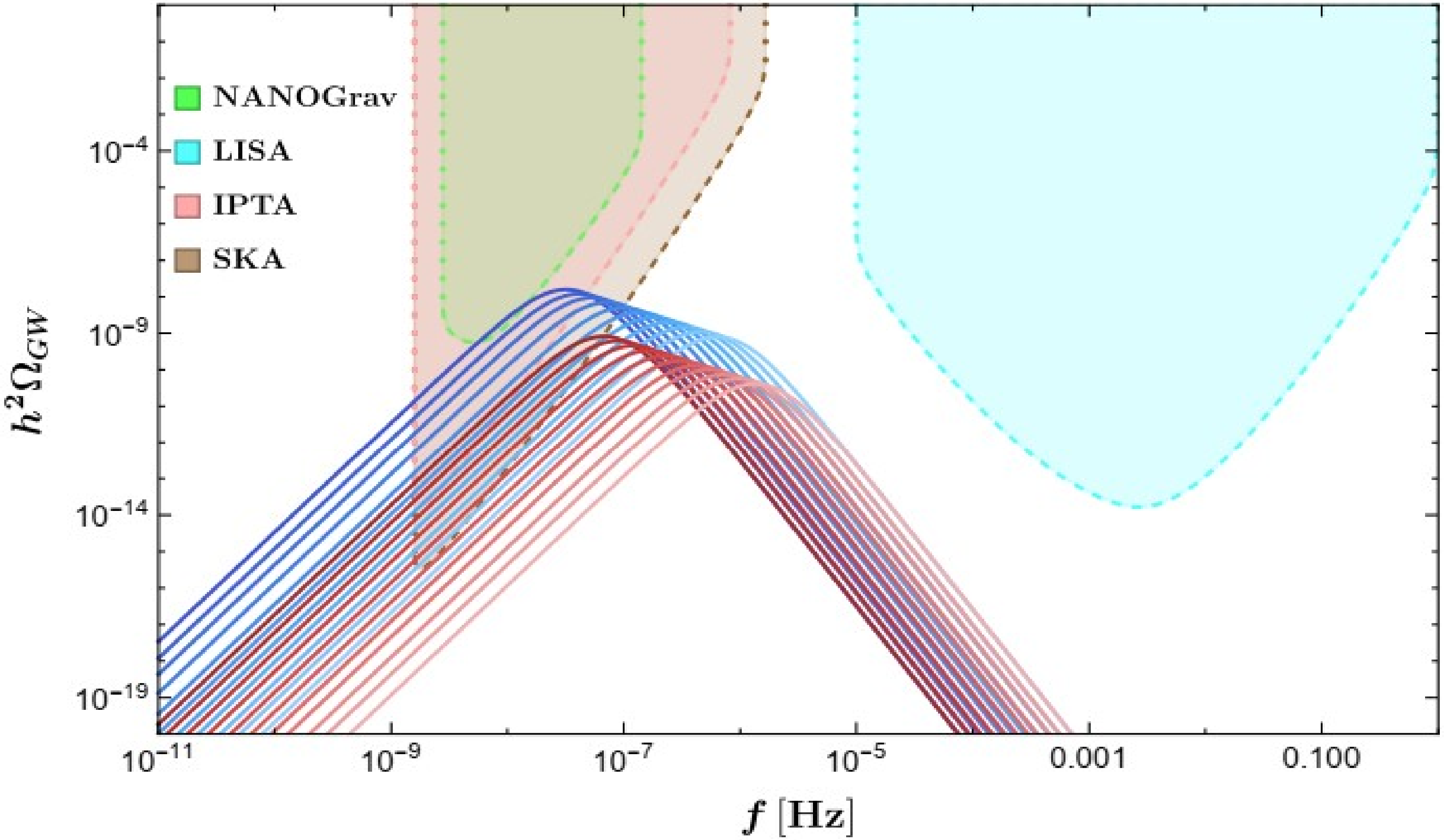
Stochastic GW spectrum from the first order QCD phase transition



(μ, T, α) = (560 MeV, 104.71 MeV, 0.13) (red band) and (1000 MeV, 49.53 MeV, 0.33) (blue band).
The upper curve in each band is for $\beta/Hn = 4$ and the lower curve is for $\beta/Hn = 80$.

The GW energy spectrum from our hQCD model is within the projected sensitivity of IPTA and SKA, thus can be potentially detected in the near future.

Summary

I. Propose a hQCD model on quantitative level to describe QCD phase diagram.

II. EOS confront with lattice simulations at zero/non-zero chemical potential.

III. Realize QCD CEP and quantitatively agrees with effective field results.

IV. Stochastic GW spectrum induced by QCD phase transition predicted.

Thank you！