The phase diagram of holographic QCD and the properties of heavy quarkonium with rotation

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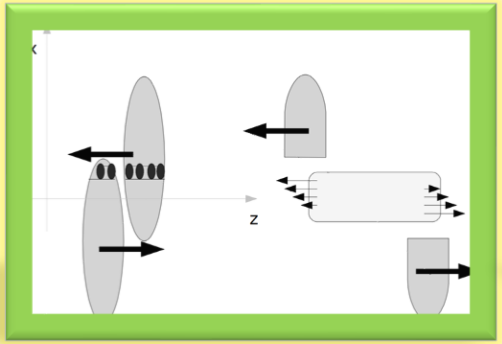
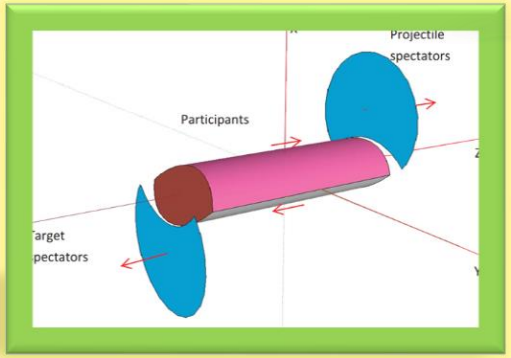
Zhibin Li(李志镔)

Motivation





- **Off-Central Heavy Ion Collision**

  ⟹ Quark-gluon plasma (QGP) carrying vorticity

- **Neutron star**

  ⟹ Quark matter in rotation.

- **Theoretical approaches:**

  ✓ Lattice simulation;

  ✓ Holography: gauge/gravity dual or AdS/QCD correspondence

  ✓ Other low energy effective model. eg. HRG, NJL , PNJL, fRG, ...

- **Phenomenological issues:**

  1. Phase structure 2. Spectral function 3. Configuration entropy 4.Energy loss 5. Spin alignment.............

Holography

AdS/CFT dual: The string theory or gravitational theory in the d-dimensional anti De Sitter space (AdS) corresponds to a conformal field theory (CFT) defined on the d-1-dimensional boundary of the space.

The Large N limit of superconformal field theories and supergravity. Juan Martin Maldacena. Int.J.Theor.Phys. 38 (1999) 1113-1133 (reprint), Adv.Theor.Math.Phys. 2 (1998) 231-252 • e-Print: hep-th/9711200

Anti-de Sitter space and holography. Edward Witten. Adv.Theor.Math.Phys. 2 (1998) 253-291 • e-Print: hep-th/9802150

Non gravitational system at strong coupling = Gravitational theory at weak coupling

Content

Part I: Holographic model

Action: *R.-G. Cai, S. He, L. Li and Y.-X. Wang, Probing QCD critical point and induced gravitational wave by black hole physics, Phys. Rev. D 106 (2022) L121902 [arXiv:2201.02004]*

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

$$\boxed{V(\phi) = -12\cosh[c_1\phi] + \left(6c_1^2 - \frac{3}{2}\right)\phi^2 + c_2\phi^6,} \quad \boxed{Z(\phi) = \frac{1}{1+c_3}\mathrm{sech}[c_4\phi^3] + \frac{c_3}{1+c_3}e^{-c_5\phi}.}$$

where c_1, c_2, c_3, c_4, c_5 are free parameters of the model, which capture the physical properties of realistic QCD.

Background:

$$ds^2 = -e^{-\eta(r)}f(r)dt^2 + \frac{dr^2}{f(r)} + r^2(dx_1^2 + dx_2^2 + dx_3^2),$$
$$\phi = \phi(r), \qquad A_t = A_t(r),$$

Equations of motion:

$$\nabla_\mu\nabla^\mu\phi - \frac{\partial_\phi Z}{4}F_{\mu\nu}F^{\mu\nu} - \partial_\phi V = 0\,,$$
$$\nabla^\nu(ZF_{\nu\mu}) = 0\,,$$
$$\mathcal{R}_{\mu\nu} - \frac{1}{2}\mathcal{R}g_{\mu\nu} = \frac{1}{2}\partial_\mu\phi\partial_\nu\phi + \frac{Z}{2}F_{\mu\rho}F_\nu{}^\rho$$
$$+\frac{1}{2}\left(-\frac{1}{2}\nabla_\mu\phi\nabla^\mu\phi - \frac{Z}{4}F_{\mu\nu}F^{\mu\nu} - V\right)g_{\mu\nu}\,.$$

Hawking temperature and entropy density:

$$T = \frac{1}{4\pi}f'(r_h)e^{-\eta(r_h)/2}, \qquad s = \frac{2\pi}{\kappa_N^2}r_h^3.$$

Part I: Holographic model

Boundary conditions:

IR (The smoothness of the event horizon):

$$
\begin{aligned}
f &= f_h(r-r_h)+\dots\,,\\
\eta &= \eta_h^0+\eta_h^1(r-r_h)+\dots\,,\\
A_t &= a_h(r-r_h)+\dots\,,\\
\phi &= \phi_h^0+\phi_h^1(r-r_h)+\dots\,.
\end{aligned}
$$

UV (asymptotic AdS):

$$\phi(r)=\frac{\phi_s}{r}+\frac{\phi_v}{r^3}-\frac{\ln(r)}{6r^3}(1-6c_1^4)\phi_s^3+\mathcal{O}(\frac{\ln(r)}{r^5})\,.$$

$$f(r)=r^2\left[1+\frac{\phi_s^2}{6r^2}+\frac{f_v}{r^4}-\frac{\ln(r)}{12r^4}(1-6c_1^4)\phi_s^4+\mathcal{O}\left(\frac{\ln(r)^2}{r^6}\right)\right]\,.$$

$$
\begin{aligned}
A_t(r) = \mu_B &- \frac{2\kappa_N^2 n_B}{2r^2} - \frac{2\kappa_N^2 n_B\, c_3\, c_5\, \phi_s}{3(1+c_3)\, r^3}\\
&+ \frac{2\kappa_N^2 n_B\, \phi_s^2\, ((1+c_3)^2-6(-1+c_3)\, c_3\, c_5^2)}{48(1+c_3)^2\, r^4}\\
&+ \frac{2\kappa_N^2 n_B\, c_3\, c_5\, (-10\, c_5^2\, (1+(-4+c_3)\, c_3))\, \phi_s^3}{300(1+c_3)^3\, r^5}\\
&+ \frac{2\kappa_N^2 n_B\, c_3\, c_5\, ((7-12\, c_1^4)\, \phi_s^3-60\, \phi_v)}{300(1+c_3)\, r^5}\\
&- \frac{2\kappa_N^2 n_B\, c_3\, c_5\, \phi_s^3(-1+6\, c_1^4)\ln(r)}{30(1+c_3)\, r^5} + \mathcal{O}(\frac{\ln(r)}{r^6})\,.
\end{aligned}
$$

$$
\begin{aligned}
\eta(r) = 0 &+ \frac{\phi_s^2}{6r^2} + \frac{(1-6c_1^4)\phi_s^4+72\phi_s\phi_v}{144r^4}\\
&- \frac{\ln(r)}{12r^4}(1-6c_1^4)\phi_s^4 + \mathcal{O}(\frac{\ln(r)^2}{r^6})\,.
\end{aligned}
$$

$\boldsymbol{\phi_s}$ is the **source of the scalar operator** of the boundary theory, which essentially breaks the conformal symmetry and plays the role of the energy scale.

Part I: Holographic model

EOM have two independent scaling symmetries:

$$
\boxed{\begin{aligned} &t \to \lambda_t\, t\,, \quad e^{\eta} \to \lambda_t^2\, e^{\eta}\,, \quad A_t \to \lambda_t^{-1} A_t\,, \\ &r \to \lambda_r\, r\,, \qquad f \to \lambda_r^2\, f\,, \quad A_t \to \lambda_r\, A_t\,, \end{aligned}}
$$

$$
\begin{aligned}
\nabla_\mu \nabla^\mu \phi - \frac{\partial_\phi Z}{4} F_{\mu\nu}F^{\mu\nu} - \partial_\phi V &= 0\,, \\
\nabla^\nu (Z F_{\nu\mu}) &= 0\,, \\
\mathcal{R}_{\mu\nu} - \frac{1}{2}\mathcal{R} g_{\mu\nu} = \frac{1}{2}\partial_\mu\phi\partial_\nu\phi &+ \frac{Z}{2}F_{\mu\rho}F_\nu{}^\rho \\
+\frac{1}{2}\Big(-\frac{1}{2}\nabla_\mu\phi\nabla^\mu\phi - \frac{Z}{4}F_{\mu\nu}F^{\mu\nu} &- V\Big)g_{\mu\nu}\,.
\end{aligned}
$$

with λ_t and λ_r constants.

Setting $\eta_h^0 = 0$ and $r_h = 1$ for performing numerics.

Using the first symmetry to satisfy the asymptotic condition $\eta(r \to \infty) = 0$;

Using the second one to fix the energy scale ϕ_s.

Part I: Holographic model

Thermodynamics:

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

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

with $V = \int dxdydz$ and $t \in [1, 1/T]$.

Free energy density :

$$\begin{aligned} \Omega = \lim_{r\to\infty}\Big[&2e^{-\eta/2}r^2 f - e^{-\eta/2}r^3\sqrt{f}\Big(2K - 6 \\ &- \frac{1}{2}\phi^2 - \frac{6c_1^4-1}{12}\phi^4\ln(r) - b\phi^4\Big)\Big]\,, \\ = \frac{1}{2\kappa_N^2}&\left(f_v - \phi_s\phi_v - \frac{3-48b-8c_1^4}{48}\phi_s^4\right)\,. \end{aligned}$$

Energy-momentum tensor:

$$\begin{aligned} T_{\mu\nu} &= \lim_{r\to\infty}\frac{2\,r^2}{\sqrt{-\det h}}\frac{\delta(S+S_\partial)_{on-shell}}{\delta h^{\mu\nu}}\,, \\ &= \frac{1}{2\kappa_N^2}\lim_{r\to\infty} r^2\Big[2(Kh_{\mu\nu} - K_{\mu\nu} - 3h_{\mu\nu}) \\ &- (\frac{1}{2}\phi^2 + \frac{6c_1^4-1}{12}\phi^4\ln[r] + b\,\phi^4)h_{\mu\nu} \\ &- (F_{\mu\rho}F_\nu{}^\rho - \frac{1}{4}h_{\mu\nu}F_{\rho\lambda}F^{\rho\lambda})\ln[r]\Big]\,, \end{aligned}$$

Energy density:

$$\epsilon := T_{tt} = \frac{1}{2\kappa_N^2}\left(-3f_v + \phi_s\phi_v + \frac{1+48b}{48}\phi_s^4\right)\,,$$

Pressure:

$$\begin{aligned} P &:= T_{xx} = T_{yy} = T_{zz} \\ &= \frac{1}{2\kappa_N^2}\left(-f_v + \phi_s\phi_v + \frac{3-48b-8c_1^4}{48}\phi_s^4\right)\,, \end{aligned}$$

Trace anomaly:

$$\epsilon - 3P = \frac{1}{2\kappa_N^2}\left(2\phi_s\phi_v + \frac{1-24b-3c_1^4}{6}\phi_s^4\right)$$

<u>ϕ_s **breaks the conformal symmetry**</u>.

Part I: Holographic model

E. Kiritsis and L. Li, "Holographic Competition of Phases and Superconductivity," JHEP 01, 147 (2016) [arXiv:1510.00020].

R. G. Cai, L. Li and R. Q. Yang, "No Inner-Horizon Theorem for Black Holes with Charged Scalar Hairs," JHEP 03 (2021), 263 [arXiv:2009.05520]

Baryon number density:

$$\frac{1}{2\kappa_N^2} e^{\eta/2} r^3 Z A_t' = n_B \,,$$

Conserved quantity(radial):

$$\boxed{\mathcal{Q} = \frac{1}{2\kappa_N^2} r^3 e^{\eta/2} \left[r^2 \left(\frac{f}{r^2} e^{-\eta} \right)' - Z A_t A_t' \right],}$$

At the horizon: $\boxed{\mathcal{Q} = T s,}$

At the boundary: $\boxed{\mathcal{Q} = \epsilon + P - \mu_B n_B \,.}$

Thermodynamical relation:

$$\boxed{\Omega = \epsilon - T s - \mu_B n_B = -P,}$$

Sound speed:

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

Specific heat:

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

Second-order baryon susceptibility:

$$\chi_2^B = (dn_B/d\mu_B)_T/T^2$$

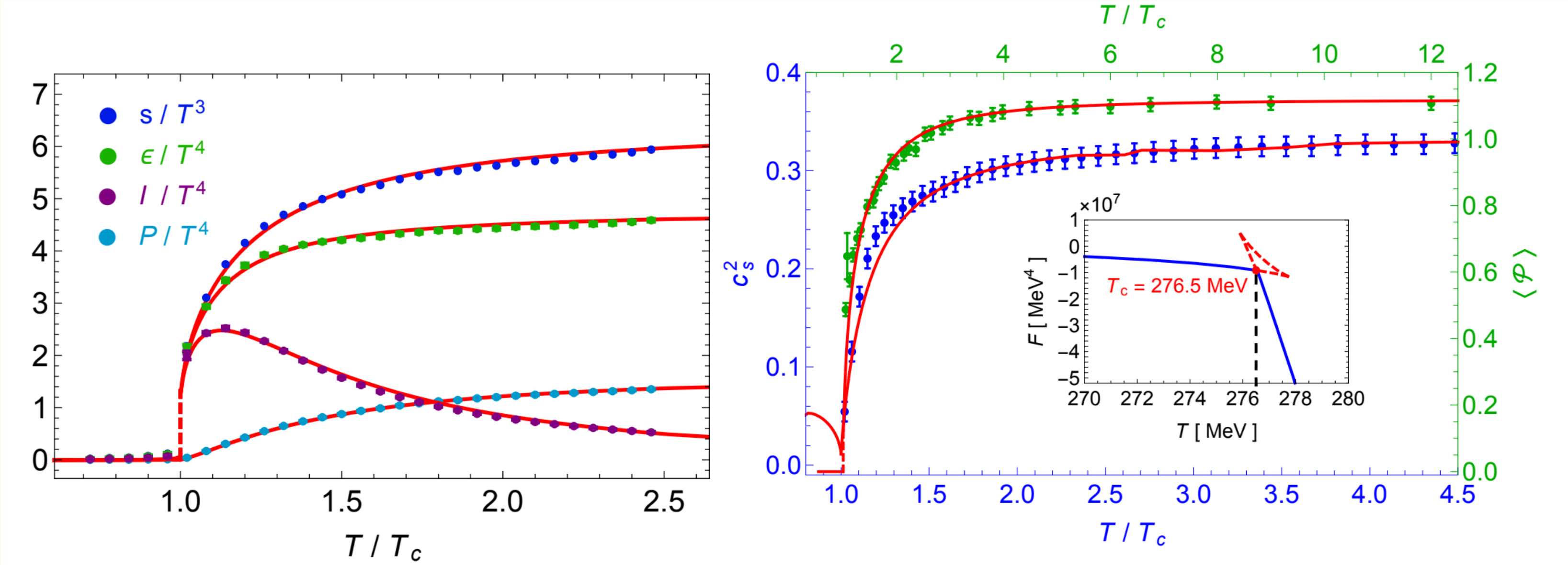
Part II: Phase Structure

Pure gluon: ***S. He, L. Li, Z. Li and S.-J. Wang, Gravitational Waves and Primordial Black Hole Productions from Gluodynamics, 2210.14094.***

model	c_1	c_2	c_3	c_4	c_5	κ_N^2	ϕ_s(GeV)	b
pure $SU(3)$	0.735	0				$2\pi(4.88)$	1.523	-0.36458

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

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



Part II: Phase Structure

2 flavor: *Y.-Q. Zhao, S. He, D. Hou, L. Li and Z. Li, Phase structure and critical phenomena in 2-flavor QCD by holography, 2310.13432.*

model	c_1	c_2	c_3	c_4	c_5	κ_N^2	ϕ_s(GeV)	b
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2 flavor	0.710	0.0002	0.530	0.085	30	$2\pi(3.72)$	1.227	-0.25707

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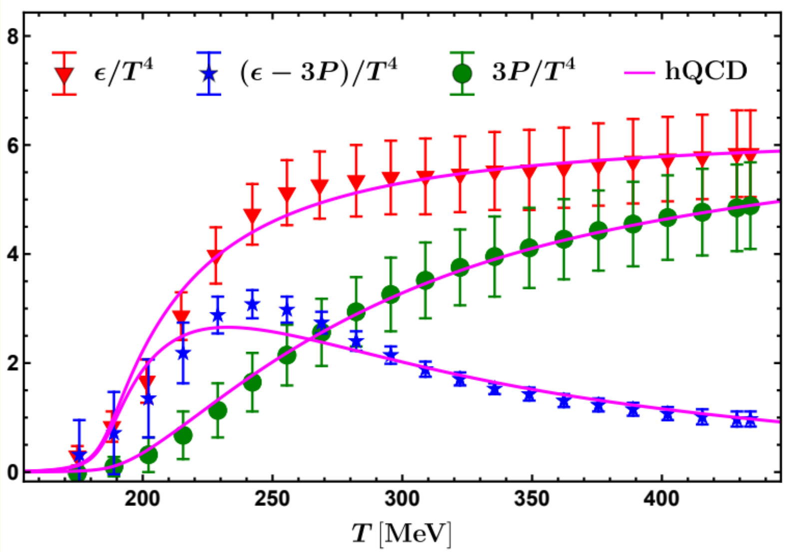

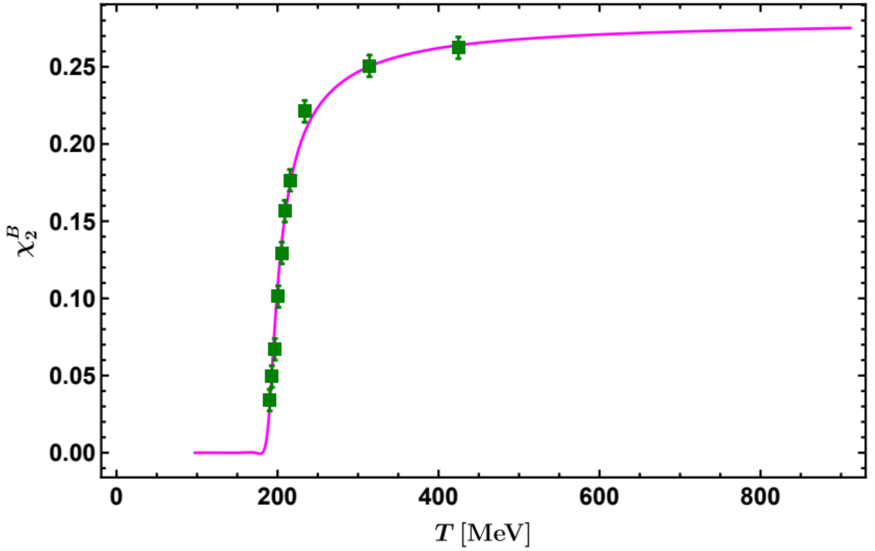

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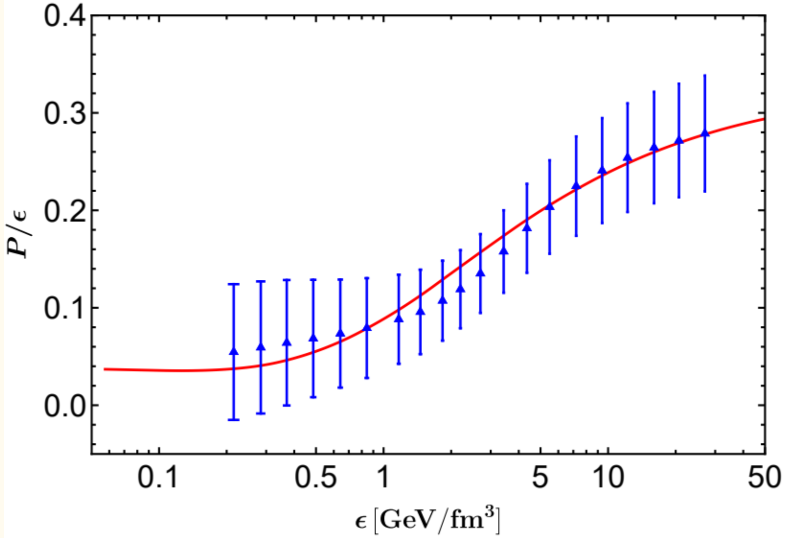

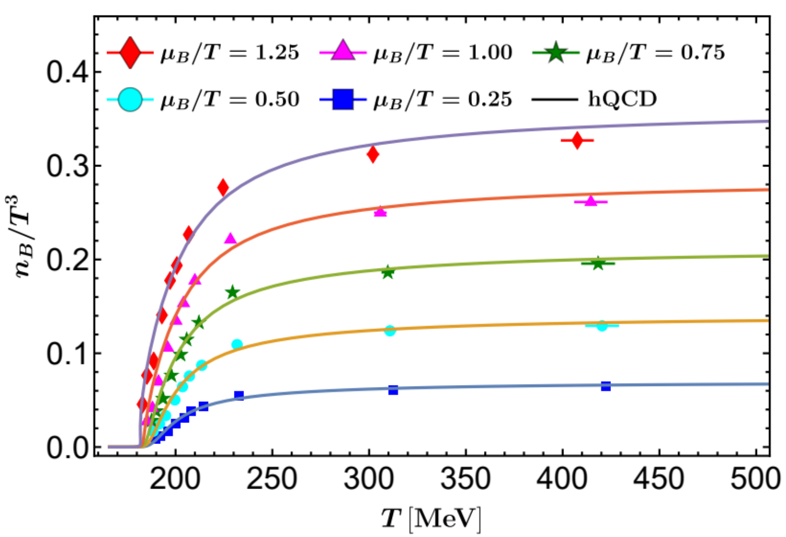

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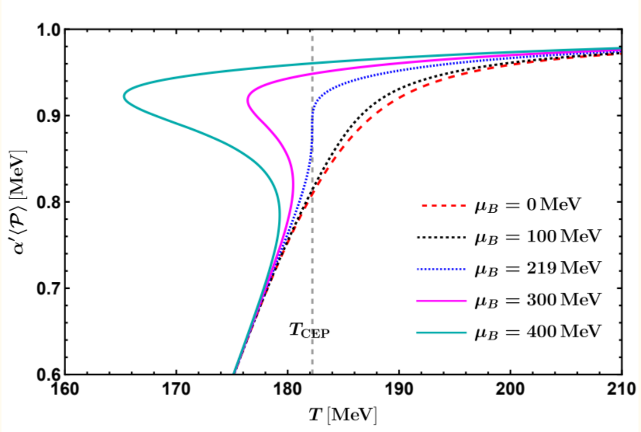
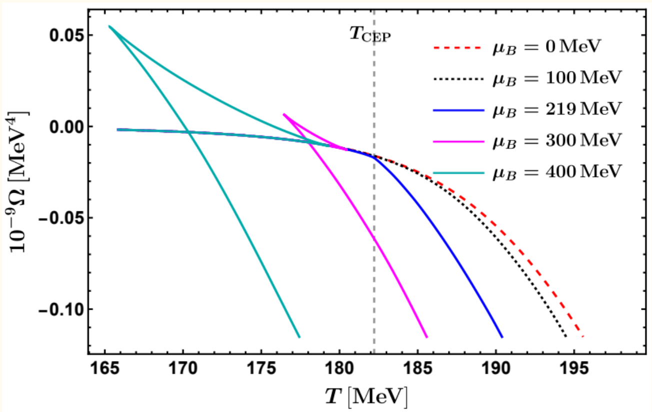
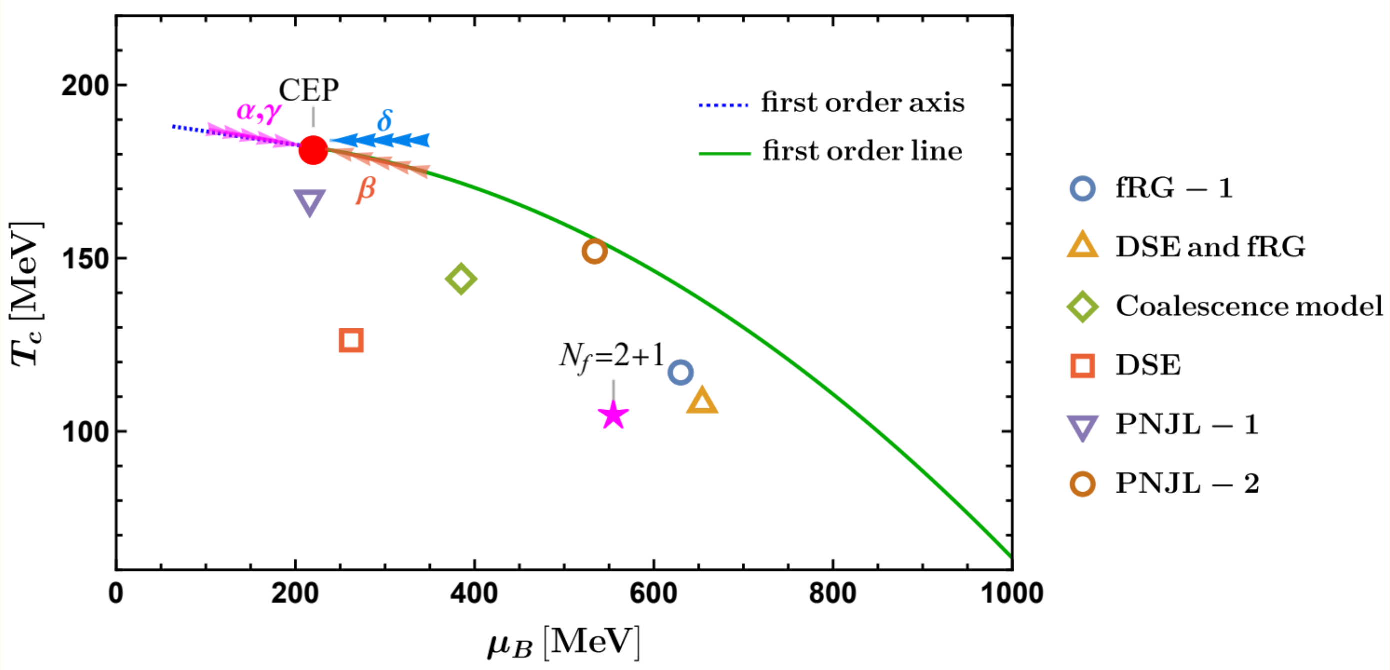




$(T_{CEP}, \mu_{CEP}) = (182, 219)$MeV

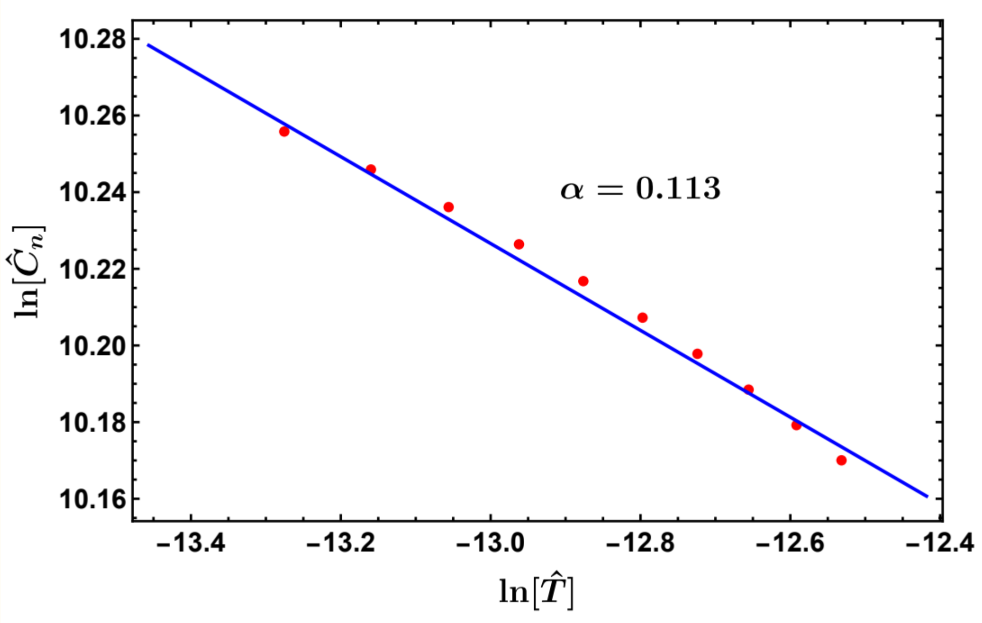


Part II: Phase Structure

2 flavor: *Y.-Q. Zhao, S. He, D. Hou, L. Li and Z. Li, Phase structure and critical phenomena in 2-flavor QCD by holography, 2310.13432.*

$$C_n \equiv T\left(\frac{\partial s}{\partial T}\right)_{n_B} = -T\left(\frac{\partial^2\Omega}{\partial T^2} - \frac{(\partial^2\Omega/\partial T\partial\mu)^2}{(\partial^2\Omega/\partial\mu^2)}\right) \sim |T - T_{\mathrm{CEP}}|^{-\alpha}.$$

Critical exponent-α:
along first order axis

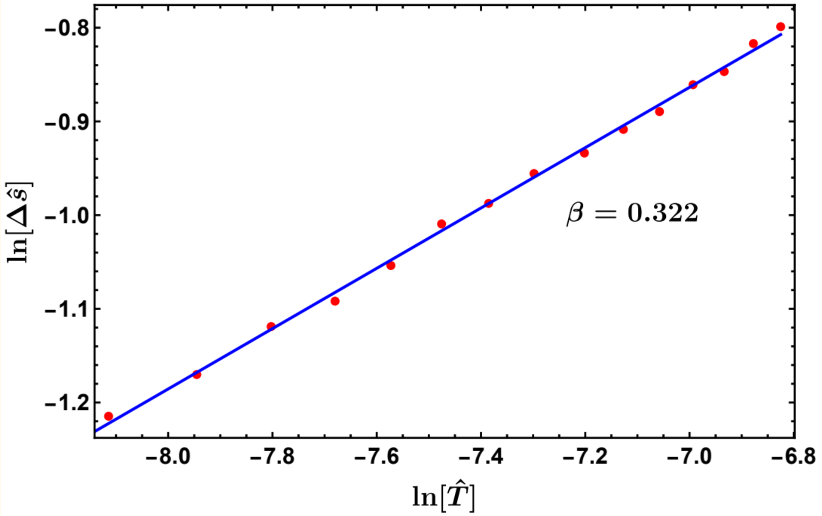


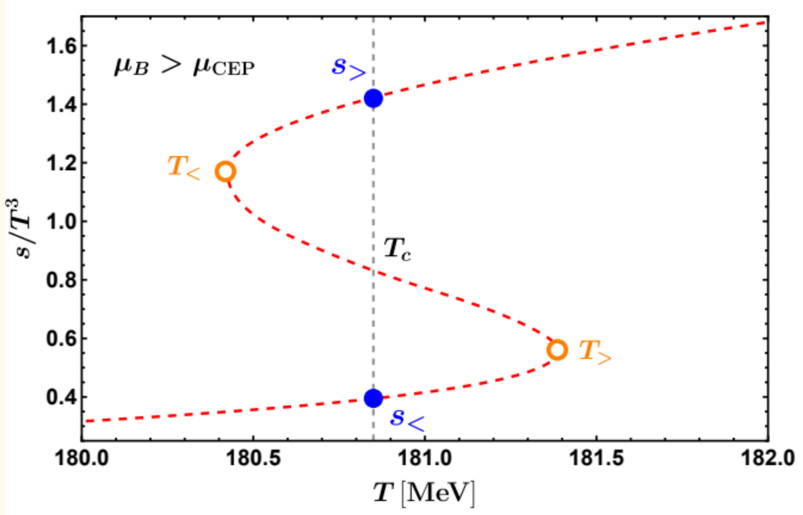
Part II: Phase Structure

2 flavor: *Y.-Q. Zhao, S. He, D. Hou, L. Li and Z. Li, Phase structure and critical phenomena in 2-flavor QCD by holography, 2310.13432.*

Critical exponent-β:
along first order line

$$\Delta s = s_> - s_< \sim (T_{\rm CEP} - T)^{\beta}.$$



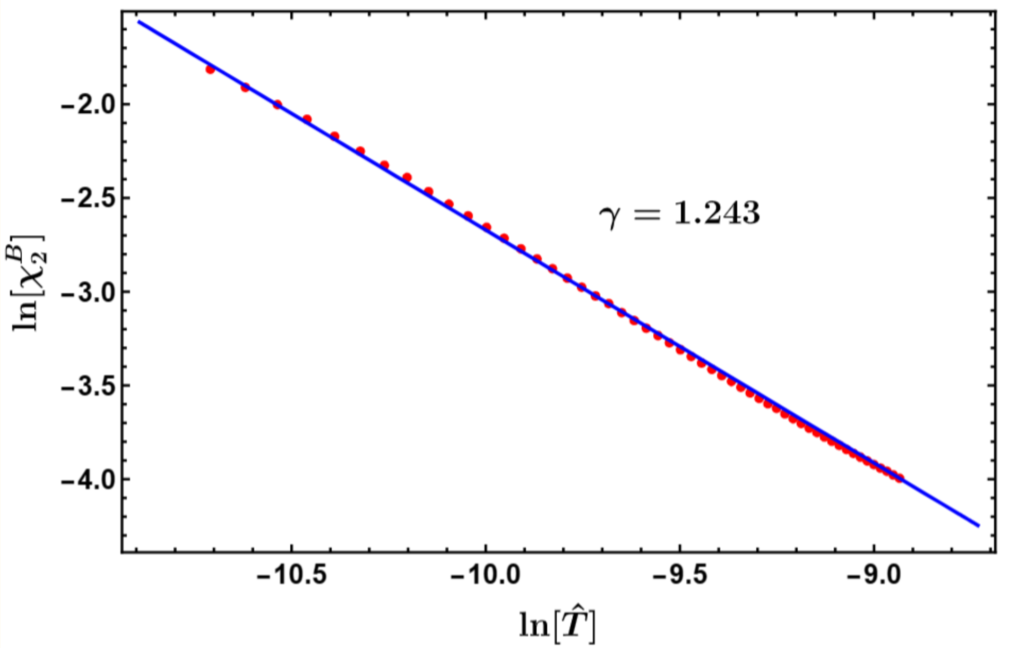


Part II: Phase Structure

2 flavor: *Y.-Q. Zhao, S. He, D. Hou, L. Li and Z. Li, Phase structure and critical phenomena in 2-flavor QCD by holography, 2310.13432.*

$$\chi_2^B = \frac{1}{T^2}\left(\frac{\partial n_B}{\partial \mu_B}\right)_T \sim |T - T_{\rm CEP}|^{-\gamma}.$$

Critical exponent-γ:
along first order axis

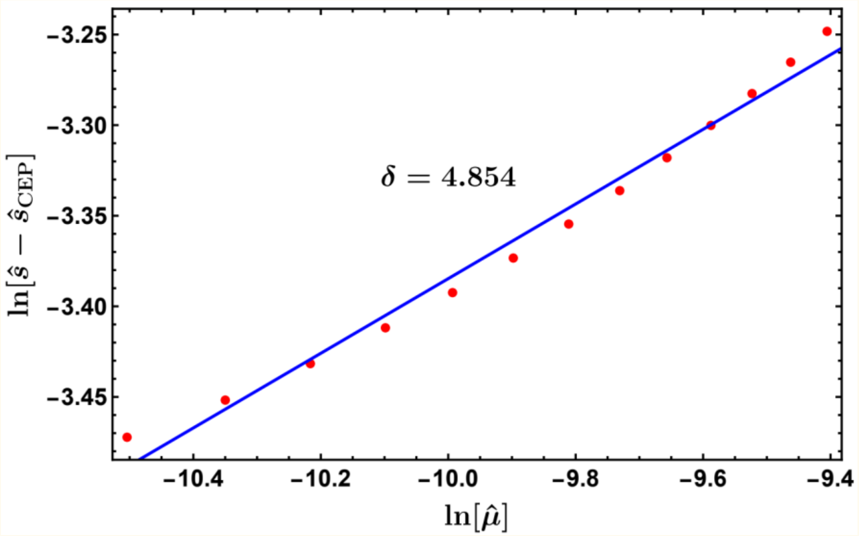


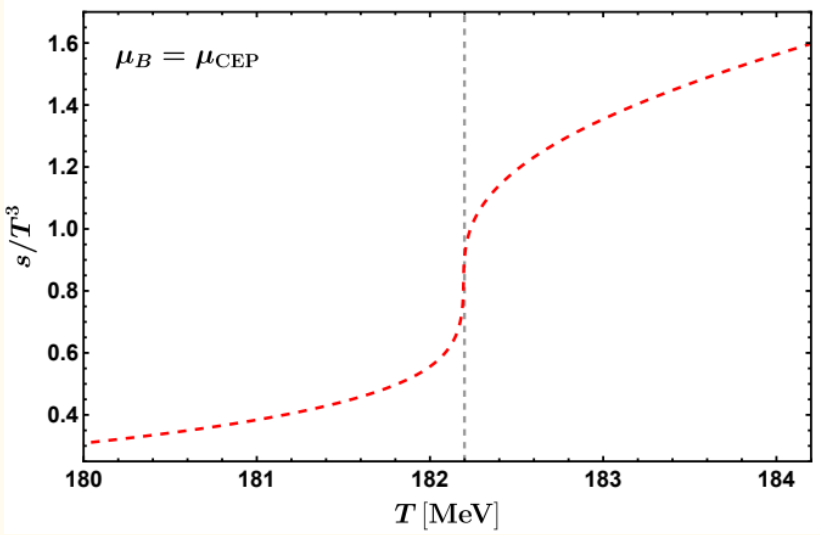
Part II: Phase Structure

2 flavor: *Y.-Q. Zhao, S. He, D. Hou, L. Li and Z. Li, Phase structure and critical phenomena in 2-flavor QCD by holography, 2310.13432.*

Critical exponent-δ:
along critical isotherm

$$s - s_{\mathrm{CEP}} \sim \left|\mu_B - \mu_{\mathrm{CEP}}\right|^{1/\delta}$$





Part II: Phase Structure

2 flavor: *Y.-Q. Zhao, S. He, D. Hou, L. Li and Z. Li, Phase structure and critical phenomena in 2-flavor QCD by holography, 2310.13432.*

Scaling relation: $$\alpha + 2\beta + \gamma = 2, \quad \alpha + \beta(1+\delta) = 2\,.$$

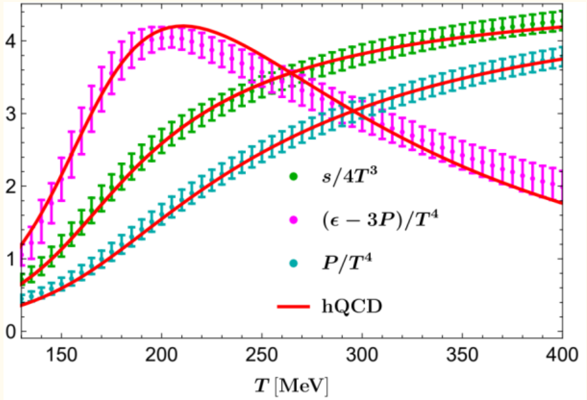
O. DeWolfe, S.S. Gubser and C. Rosen, A holographic critical point, Phys. Rev. D 83 (2011) 086005 [1012.1864].

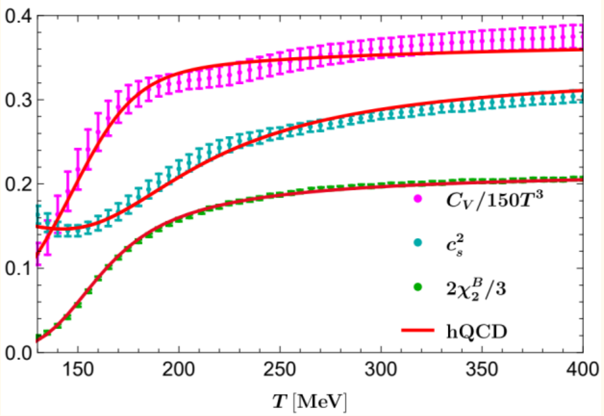
	Experiment	3D Ising	Mean field	DGR model	Ours
α	0.110-0.116	0.110(5)	0	0	0.113
β	0.316-0.327	0.325±0.0015	1/2	0.482	0.322
γ	1.23-1.25	1.2405±0.0015	1	0.942	1.243
δ	4.6-4.9	4.82(4)	3	3.035	4.854

N. Goldenfeld, Lectures on phase transitions and the renormalization group (1992).

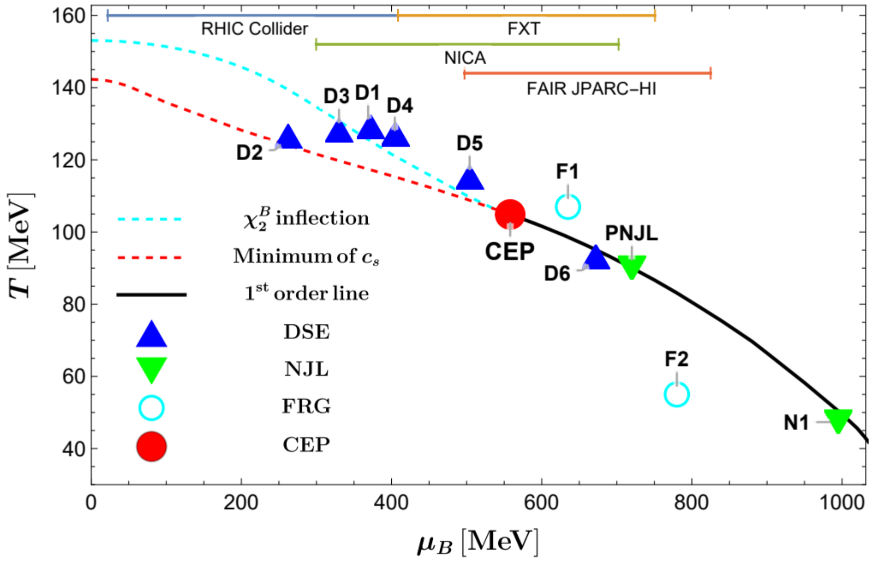
Part II: Phase Structure

2+1 flavor: *R.-G. Cai, S. He, L. Li and Y.-X. Wang, Probing QCD critical point and induced gravitational wave by black hole physics, Phys. Rev. D 106 (2022) L121902 [arXiv:2201.02004].*





model	c_1	c_2	c_3	c_4	c_5	κ_N^2	ϕ_s(GeV)	b
pure $SU(3)$	0.735	0				$2\pi(4.88)$	1.523	-0.36458
2 flavor	0.710	0.0002	0.530	0.085	30	$2\pi(3.72)$	1.227	-0.25707
2+1 flavor	0.710	0.0037	1.935	0.085	30	$2\pi(1.68)$	1.085	-0.27341



$(T_{CEP}, \mu_{CEP}) =$
$(105, 555)$MeV

Part II: Phase Structure

Background without rotation: *Y.-Q. Zhao, S. He, D. Hou, L. Li and Z. Li, Phase diagram of holographic thermal dense QCD matter with rotation, JHEP 04 (2023) 115 [2212.14662].*

$$ds^2 = -e^{-\eta(r)} f(r) dt^2 + \frac{dr^2}{f(r)} + r^2 (dx_1^2 + dx_2^2 + dx_3^2),$$
$$\phi = \phi(r), \qquad A_t = A_t(r),$$

Background with rotation: $\mathcal{M}_3 = \mathbb{R} \times \Sigma_2.$

$$ds^2 = -f(r) e^{-\eta(r)} dt^2 + \frac{dr^2}{f(r)} + r^2 \ell^2 d\theta^2 + r^2 d\sigma^2 ,$$

Local Lorentz boost:

$$\boxed{t \to \frac{1}{\sqrt{1-\omega^2\ell^2}}(\hat{t} + \omega\ell^2\hat{\theta}), \qquad \theta \to \frac{1}{\sqrt{1-\omega^2\ell^2}}(\hat{\theta} + \omega\hat{t}) .}$$

$$N(r) = \frac{r^2 f(r) \left(1-\omega^2\ell^2\right)}{r^2 e^{\eta(r)} - \omega^2\ell^2 f(r)} ,$$
$$R(r) = \frac{r^2\ell^2 - \omega^2\ell^4 f(r) e^{-\eta(r)}}{1-\omega^2\ell^2} ,$$
$$Q(r) = \frac{\omega\left(f(r) - r^2 e^{\eta(r)}\right)}{\omega^2\ell^2 f(r) - r^2 e^{\eta(r)}} .$$

Rotating Metric:

$$d\hat{s}^2 = g_{\mu\nu} d\hat{x}^\mu d\hat{x}^\nu = -N(r) d\hat{t}^2 + \frac{dr^2}{f(r)} + R(r)(d\hat{\theta} + Q(r) d\hat{t})^2 + r^2 d\sigma^2 ,$$

Part II: Phase Structure

The null generator of the horizon: $\xi = \partial_{\hat{t}} - \omega\partial_{\hat{\theta}}$

Y.-Q. Zhao, S. He, D. Hou, L. Li and Z. Li, Phase diagram of holographic thermal dense QCD matter with rotation, JHEP 04 (2023) 115 [2212.14662].

Gauge field: $\hat{A}_\mu = \frac{1}{\sqrt{1-\omega^2\ell^2}} A_t \delta^t_\mu + \frac{\omega\ell^2}{\sqrt{1-\omega^2\ell^2}} A_t \delta^\theta_\mu \,.$

Baryon chemical potential: $\hat{\mu}_B = A_\mu \xi^\mu|_{r=\infty} - A_\mu \xi^\mu|_{r=r_h} = \mu_B \sqrt{1-\omega^2\ell^2}\,,$

Baryon number density: $\hat{\rho}_B = \rho_B / \sqrt{1-\omega^2\ell^2}.$

Hawking temperature and entropy density:

$$\hat{T} = T\sqrt{1-\omega^2\ell^2} = \frac{1}{4\pi} f'(r_h) e^{-\eta(r_h)/2} \sqrt{1-\omega^2\ell^2}, \qquad \hat{s} = \frac{s}{\sqrt{1-\omega^2\ell^2}} = \frac{2\pi}{\kappa_N^2} r_h^3 \frac{1}{\sqrt{1-\omega^2\ell^2}}\,,$$

Energy-momentum tensor:

$$\hat{T}_{\mu\nu} = \lim_{r\to\infty} \frac{2}{\sqrt{-\hat{g}}} \frac{\delta(\hat{S}+\hat{S}_\partial)_{on-shell}}{\delta \hat{g}^{\mu\nu}} = \frac{1}{2\kappa_N^2} \lim_{r\to\infty} r^2 \left[2(\hat{K}\hat{h}_{\mu\nu} - \hat{K}_{\mu\nu} - 3\hat{h}_{\mu\nu}) - \left(\frac{1}{2}\phi^2 + \frac{6c_1^4 - 1}{12}\phi^4 \ln[r] + b\phi^4\right)\hat{h}_{\mu\nu} - \left(F_{\mu\rho}F^\rho_\nu - \frac{1}{4}\hat{h}_{\mu\nu}F_{\rho\lambda}F^{\rho\lambda}\right)\ln[r] \right].$$

Part II: Phase Structure

Free energy density: $\hat{\Omega} = -\frac{1}{2\kappa_N^2}\left(-f_v + \phi_s\phi_v + \frac{3-48b-8c_1^4}{48}\phi_s^4\right)$

Y.-Q. Zhao, S. He, D. Hou, L. Li and Z. Li, Phase diagram of holographic thermal dense QCD matter with rotation, JHEP 04 (2023) 115 [2212.14662].

Energy density: $\hat{\epsilon} := \hat{T}_{00} = \frac{\epsilon + \omega^2\ell^2 P}{1-\omega^2\ell^2}\,,$

Pressure: $\hat{P}_1 := \hat{T}_{11} = \frac{1}{\ell^2}\hat{T}_{\theta\theta} = \frac{P+\omega^2\ell^2\epsilon}{1-\omega^2\ell^2}$ $\quad \hat{P}_2 := \hat{T}_{22} = P\,,$ $\quad \hat{P}_3 := \hat{T}_{33} = P\,,$

Angular momentum: $\boxed{J = \hat{T}_{\theta t} = \frac{\omega\ell^2(\epsilon+P)}{1-\omega^2\ell^2}}$

Thermodynamic relation: $\hat{\Omega} = \hat{\epsilon} - \hat{T}\hat{s} - \hat{\mu}_B\hat{\rho}_B - \omega J = -P\,.$

Trace anomaly: $\hat{I} = -\hat{T}^{\mu}_{\mu} = -T^{\mu}_{\mu} = I = \epsilon - 3P$

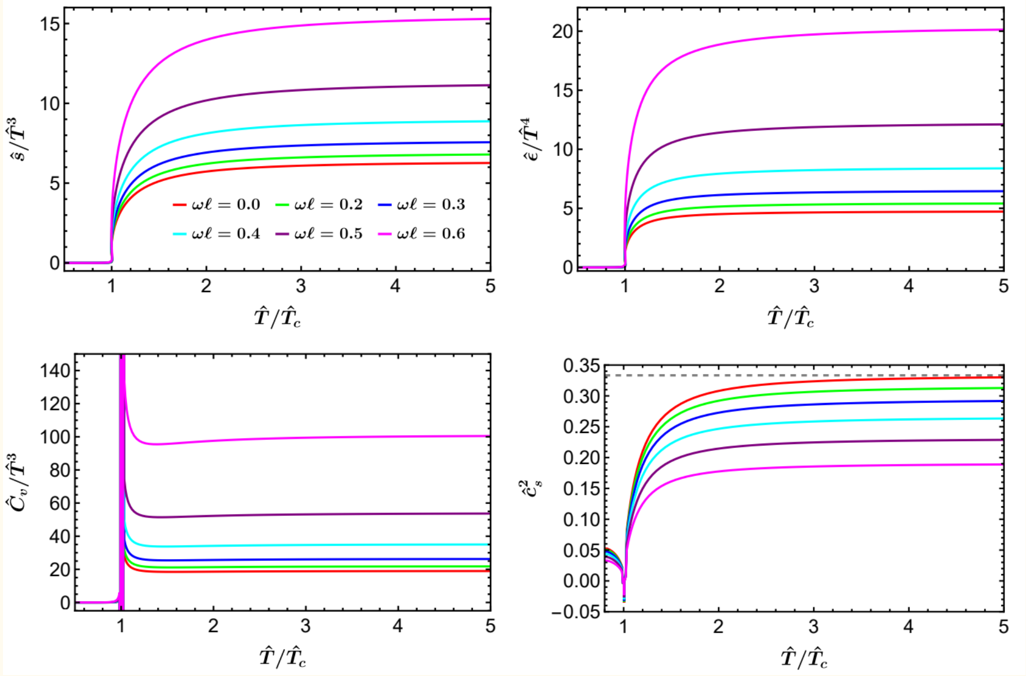
Squared speed of sound: $\hat{c}_s^2 = \frac{dP}{d\hat{\epsilon}}\Big|_{\hat{\mu}_B,\omega}\,.$

Specific heat: $\hat{C}_v = \frac{d\hat{\epsilon}}{d\hat{T}}\Big|_{\hat{\mu}_B,\omega}\,,$

Second-order baryon susceptibility: $\hat{\chi}_2^B = \frac{1}{\hat{T}^2}\frac{\partial\,\hat{\rho}_B}{\partial\,\hat{\mu}_B}\Big|_{\hat{T},\omega} = -\frac{1}{\hat{T}^2}\frac{\partial^2\,\hat{\Omega}}{\partial\,\hat{\mu}_B^2}\Big|_{\hat{T},\omega}$

Part II: Phase Structure

Pure gluon: *Y.-Q. Zhao, S. He, D. Hou, L. Li and Z. Li, Phase diagram of holographic thermal dense QCD matter with rotation, JHEP 04 (2023) 115 [2212.14662].*



Part II: Phase Structure

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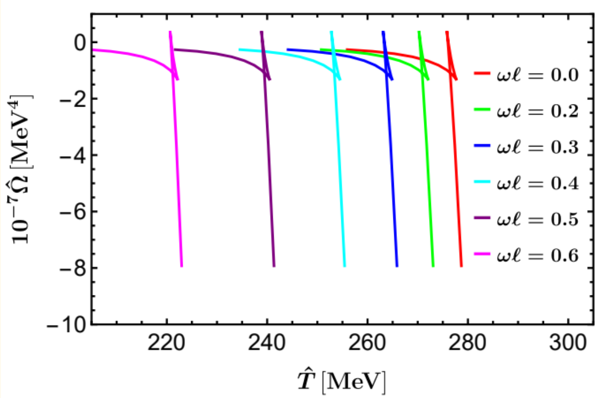
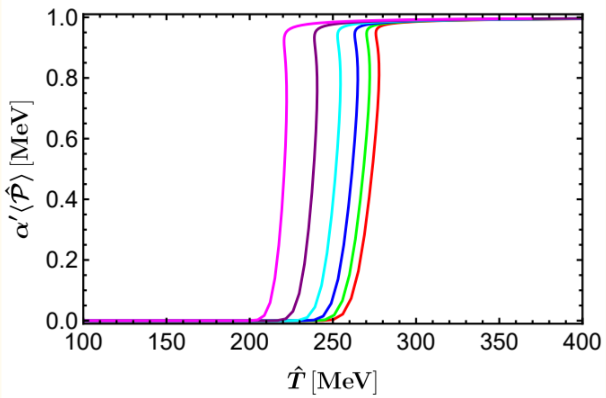
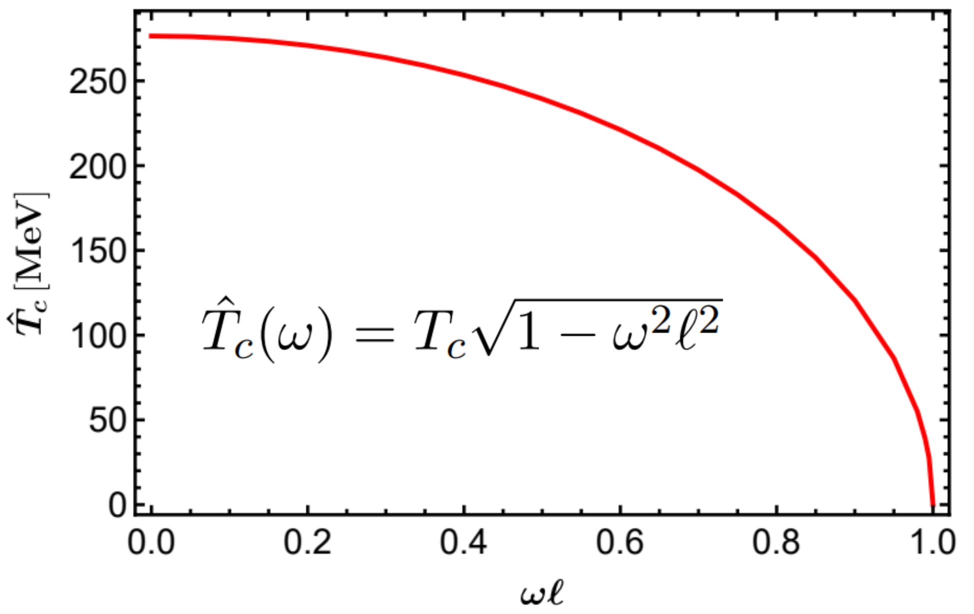


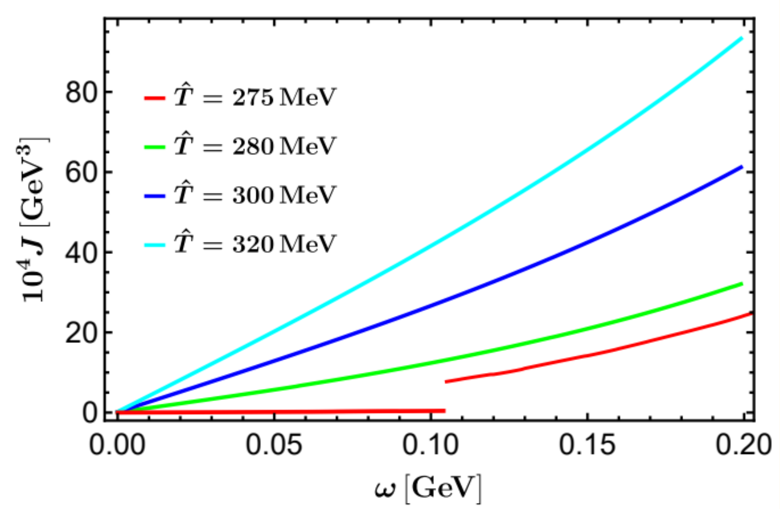


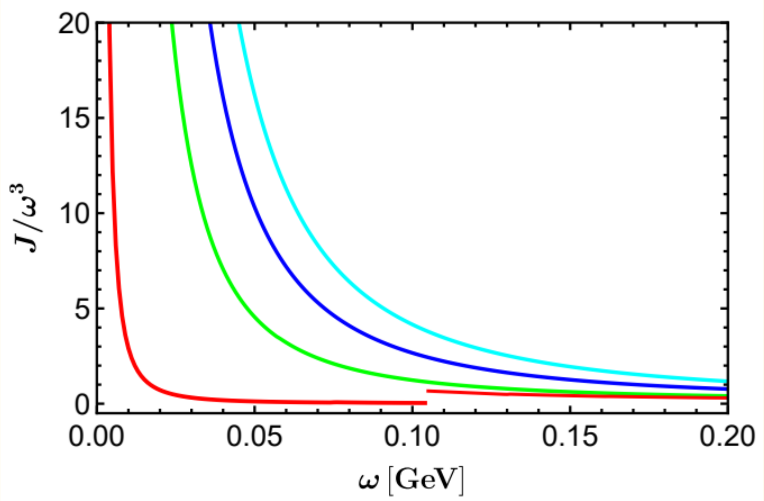


Part II: Phase Structure

Pure gluon: *Y.-Q. Zhao, S. He, D. Hou, L. Li and Z. Li, Phase diagram of holographic thermal dense QCD matter with rotation, JHEP 04 (2023) 115 [2212.14662].*

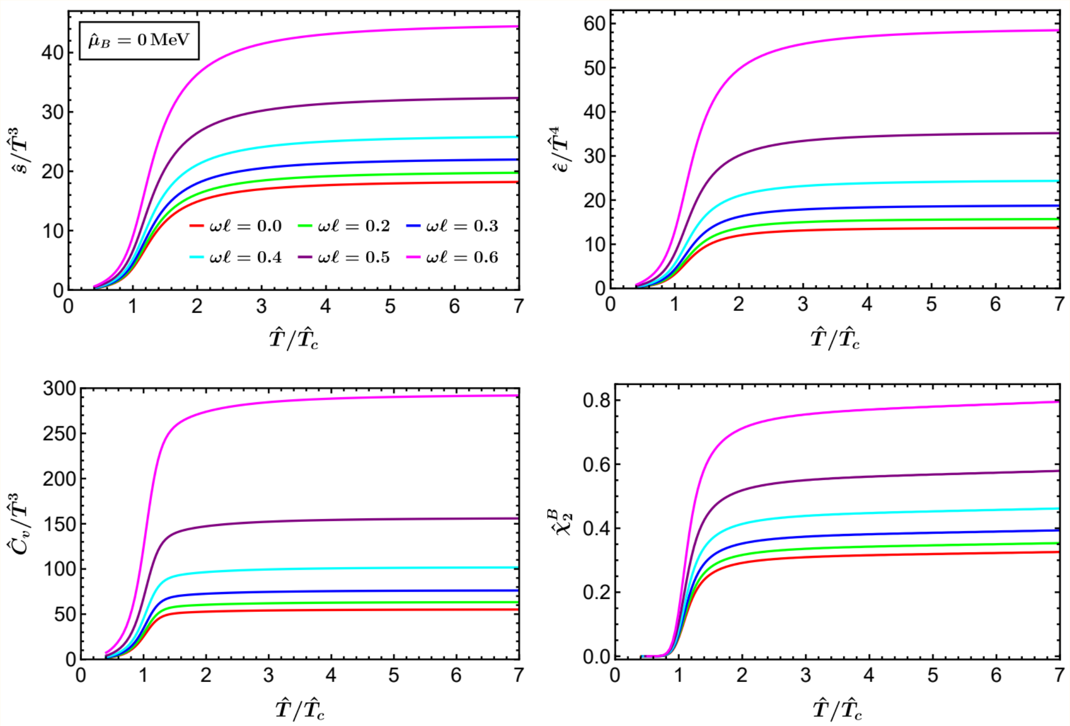
$$\boxed{J = \hat{T}_{\theta t} = \frac{\omega \ell^2 (\epsilon + P)}{1 - \omega^2 \ell^2}}$$

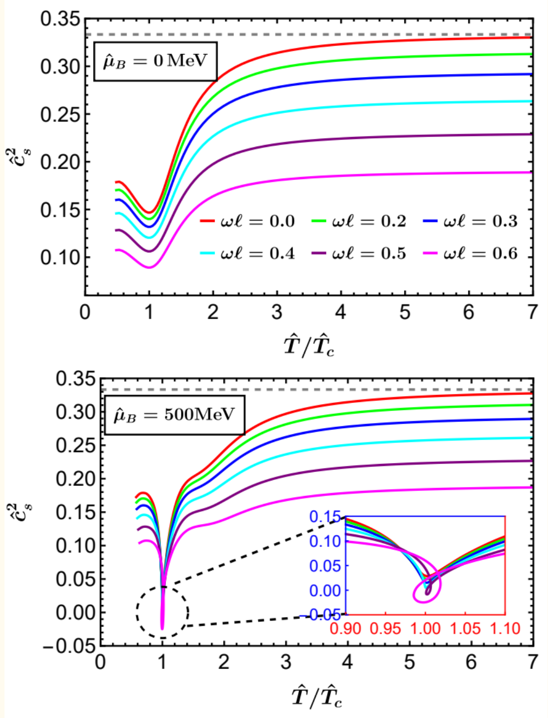




Part II: Phase Structure

2+1 flavor: *Y.-Q. Zhao, S. He, D. Hou, L. Li and Z. Li, Phase diagram of holographic thermal dense QCD matter with rotation, JHEP 04 (2023) 115 [2212.14662].*





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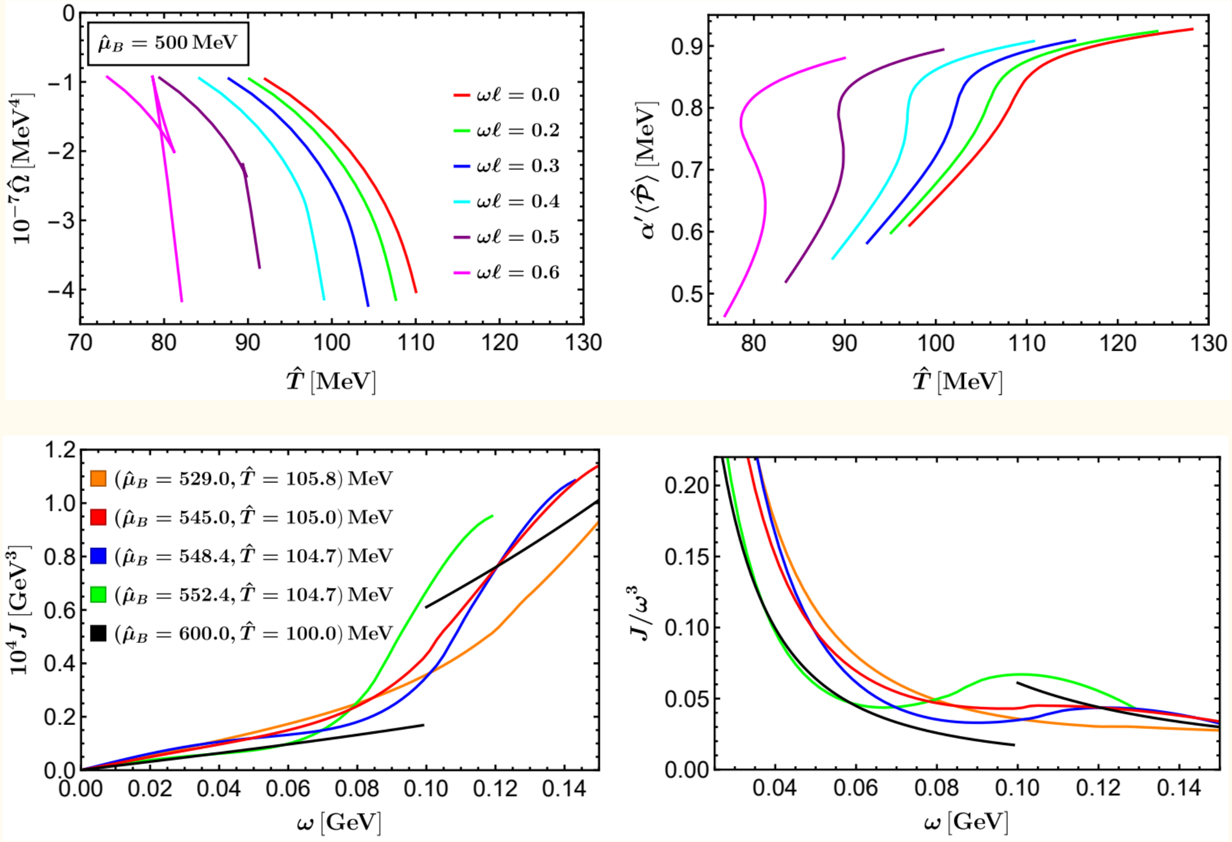


$$J = \rho_m \ell^2 \omega = (\epsilon + P)\ell^2\omega + \mathcal{O}(\omega^3)\,.$$

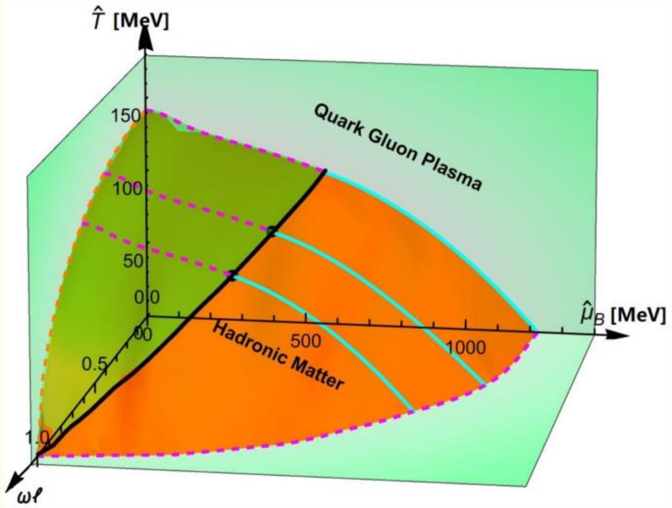
In the non-relativistic limit :

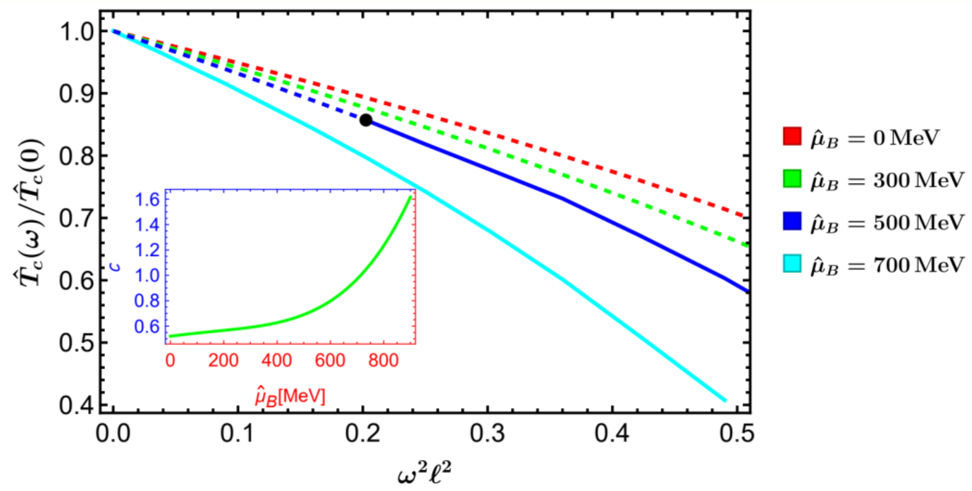
$$\epsilon + P \approx \rho_m$$

Part II: Phase Structure

2+1 flavor: *Y.-Q. Zhao, S. He, D. Hou, L. Li and Z. Li, Phase diagram of holographic thermal dense QCD matter with rotation, JHEP 04 (2023) 115 [2212.14662].*

$$\boxed{\hat{T}_c(\omega)/\hat{T}_c(0) \approx 1 - c\,\omega^2}$$





Part I: Holographic model

Part II: Phase structure (with rotation)

Part III: Spectral function

Part IV: Configuration entropy

Part V: Summary and Outlook

Part III: Spectral function

Lagrangian for background:

Y.-Q. Zhao and D. Hou, Vector meson spectral function in a dynamical AdS/QCD model, Eur. Phys. J. C 82, 1102 (2022), arXiv:2108.08479.

$$\mathcal{L} = \sqrt{-g}\left(R - \frac{g_1(\phi_0)}{4}F_{(1)\mu\nu}F^{\mu\nu} - \frac{g_2(\phi_0)}{4}F_{(2)\mu\nu}F^{\mu\nu} - \frac{1}{2}\partial_\mu\phi_0\partial^\mu\phi_0 - V(\phi_0)\right).$$

Metric:

$$ds^2 = \frac{R^2 S(z)}{z^2}\left(-f(z)dt^2 + dx_1^2 + e^{B^2z^2}(dx_2^2 + dx_3^2) + \frac{dz^2}{f(z)}\right),$$

$$\phi_0 = \phi_0(z), \quad A_{(1)\mu} = A_t(z)\delta_\mu^t, \quad F_{(2)} = B dx_2 \wedge dx_3,$$

J/ψ

Five-dimensional Maxwell action for vector meson:

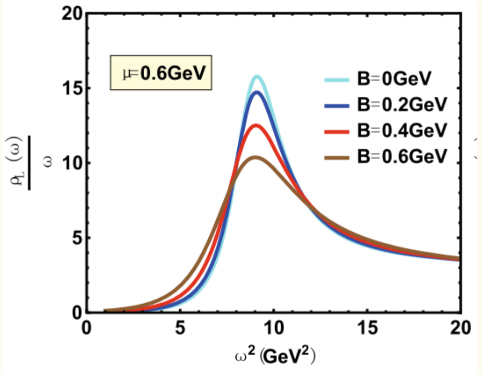
$$S = \int d^4x dz \sqrt{-g} e^{-\phi(z)}\left[-\frac{1}{4g_5{}^2}F_{mn}F^{mn}\right],$$

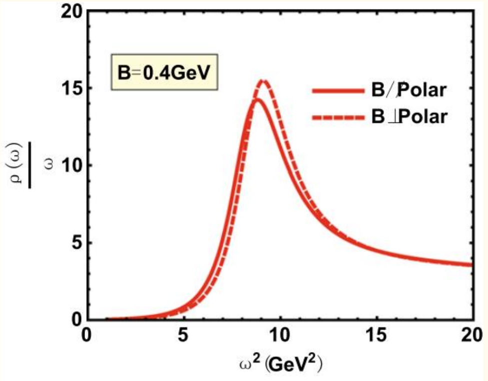
$$\phi(z) = \kappa^2 z^2 + Mz + \tanh\left(\frac{1}{Mz} - \frac{\kappa}{\sqrt{\Gamma}}\right),$$

$$\kappa_c = 1.2\,\mathrm{GeV}, \quad \sqrt{\Gamma_c} = 0.55\,\mathrm{GeV}, \quad M_c = 2.2\,\mathrm{GeV},$$

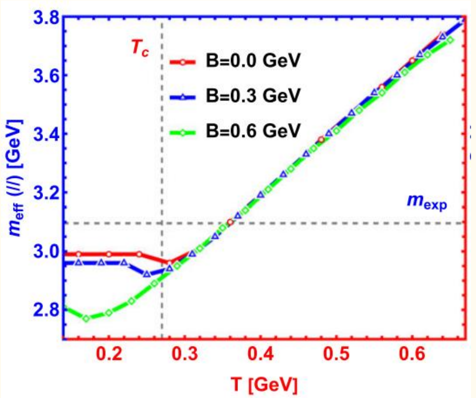
Part III: Spectral function

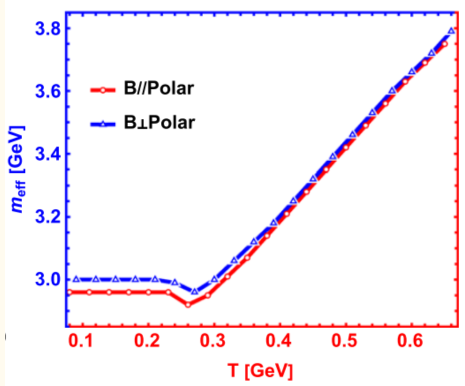
Mass Spectra: *Y.-Q. Zhao and D. Hou, Vector meson spectral function in a dynamical AdS/QCD model, Eur. Phys. J. C 82, 1102 (2022), arXiv:2108.08479.*





J/ψ





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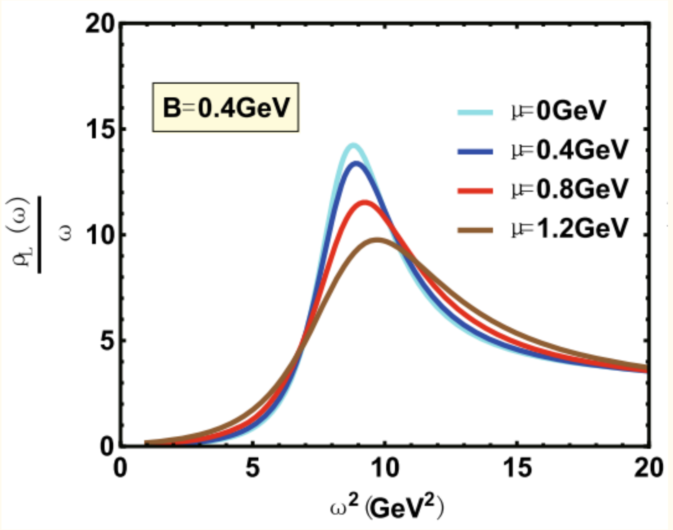
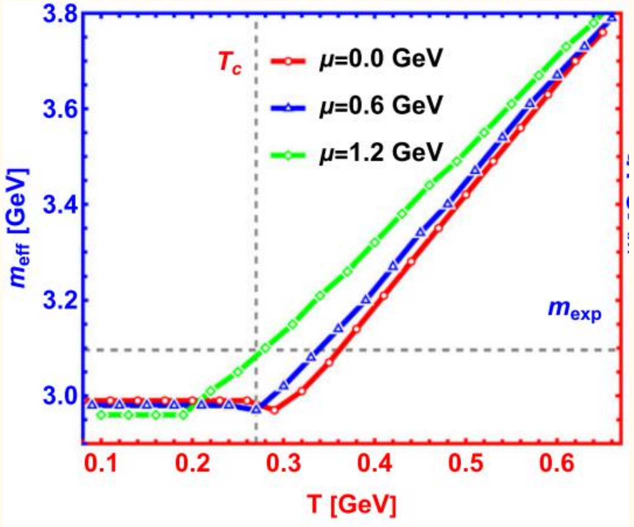
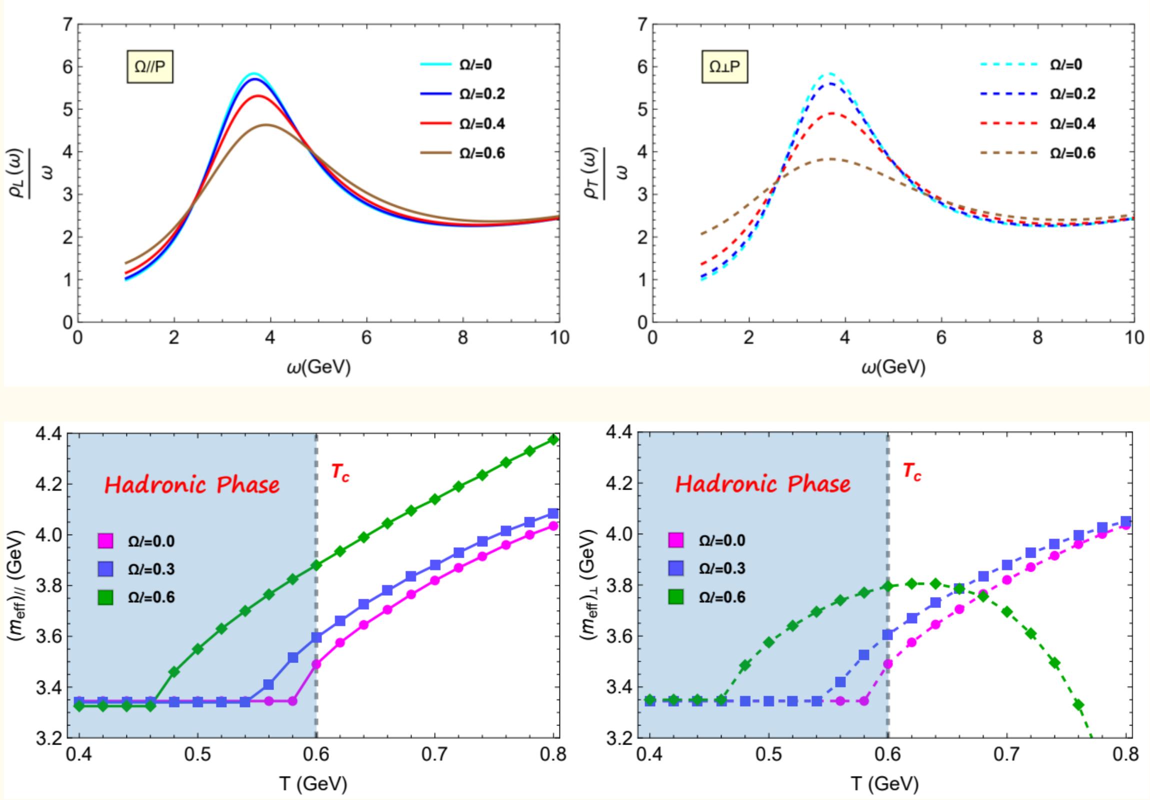




J/ψ

Part III: Spectral function

Mass Spectra: *Y.-Q. Zhao and D. Hou, J/Ψ suppression in a rotating magnetized holographic QGP matter, arXiv 2306.04318.*



Part IV: Configuration entropy

Gauss-Bonnet(GB) gravity: *Y.-Q. Zhao and D. Hou, "Configuration entropy of Υ(1S) state in strong coupling plasma," Phys.Lett.B 847 (2023) 138271, arXiv:2305.07087.*

$$\boxed{S = \frac{1}{16\pi G_5}\int d^5x\sqrt{-G}[(\mathcal{R}+\frac{12}{R^2})+\frac{\lambda_{GB}R^2}{2}\mathcal{L}_{GB}],}$$

$$\mathcal{L}_{GB} = \mathcal{R}^2 - 4\mathcal{R}_{\mu\nu}\mathcal{R}^{\mu\nu} + \mathcal{R}_{\mu\nu\rho\sigma}\mathcal{R}^{\mu\nu\rho\sigma}.$$

Metric:

$$\boxed{ds^2 = \frac{R^2}{z^2}(-af_{GB}(z)dt^2 + dx^2 + \frac{1}{f_{GB}(z)}dz^2)}$$

$$a = \frac{1}{2}(1+\sqrt{1-4\lambda_{GB}}),$$

$$f_{GB}(z) = \frac{1}{2\lambda_{GB}}(1-\sqrt{1-4\lambda_{GB}(1-\frac{z^4}{z_h^4})}).$$

Hawking temperature:

$$T = \left|\frac{\kappa}{2\pi}\right| = \frac{\sqrt{a}}{\pi z_h},$$

$$\kappa = \sqrt{-g_{tt}/g_{zz}}(\log(\sqrt{-g_{tt}}))'|_{z=z_h}$$

Ratio of the shear viscosity *η* and the entropy density *s*

$$\frac{\eta}{s} = \frac{1}{4\pi}(1-4\lambda_{GB}).$$

Part IV: Configuration entropy

Action for vector matter:

Y.-Q. Zhao and D. Hou, "Configuration entropy of Υ(1S) state in strong coupling plasma," Phys.Lett.B 847 (2023) 138271, arXiv:2305.07087.

$$S_{\rm matter} = \int d^4x dz \sqrt{-g} e^{-\phi(z)} [-\frac{1}{4{g_5}^2} F_{mn}F^{mn}],$$

$$\phi(z) = m_b^2 z^2 + M_b z + \tanh\left(\frac{1}{M_b z} - \frac{m_b}{\sqrt{\Gamma_b}}\right).$$

with

$$m_b = 2.45GeV, \ \sqrt{\Gamma_b} = 1.55GeV, \ M_b = 6.2GeV.$$

Υ(1S)

Energy tensor:

$$T_{\mu\nu} := -\frac{2}{\sqrt{-g}} \frac{\delta S_{\rm matter}}{\delta g^{\mu\nu}}.$$

Energy density:

$$\rho(z) = T_{00}(z) = \frac{z^2 e^{-\phi(z)}}{2g_5^2} (|E_\alpha|^2 + \frac{af^2(z)}{|\omega|^2} |E'_\alpha|^2).$$

Differential configuration entropy:

$$\boxed{S_{DCE} = -\int_{-\infty}^{\infty} \epsilon(k) \log[\epsilon(k)] dk.}$$

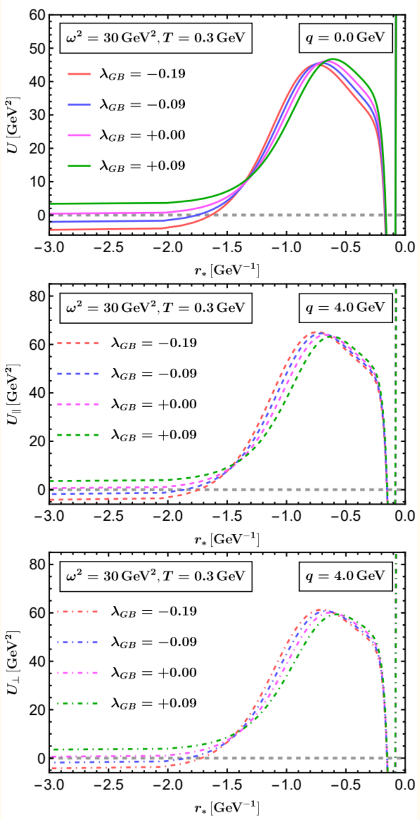
Modal fraction:

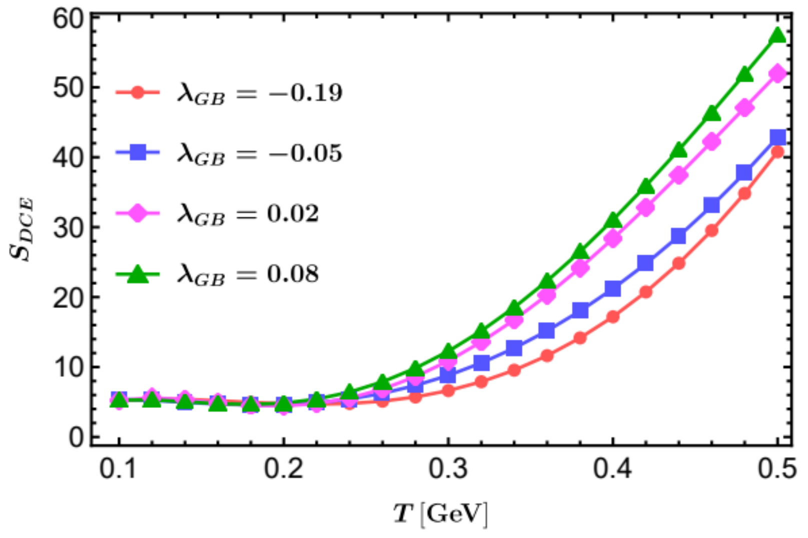
$$\epsilon(k) = \frac{S^2(k) + C^2(k)}{[S^2(k) + C^2(k)]_{max}}.$$

$$\begin{aligned} \rho(k) &= (C(k) - iS(k))/\sqrt{2\pi}, \\ C(k) &= \int_0^{z_h} \rho(z) \cos(kz) dz, \\ S(k) &= \int_0^{z_h} \rho(z) \sin(kz) dz, \end{aligned}$$

Part IV: Configuration entropy

Gauss-Bonnet(GB) gravity: *Y.-Q. Zhao and D. Hou, "Configuration entropy of Υ(1S) state in strong coupling plasma," Phys.Lett.B 847 (2023) 138271, arXiv:2305.07087.*



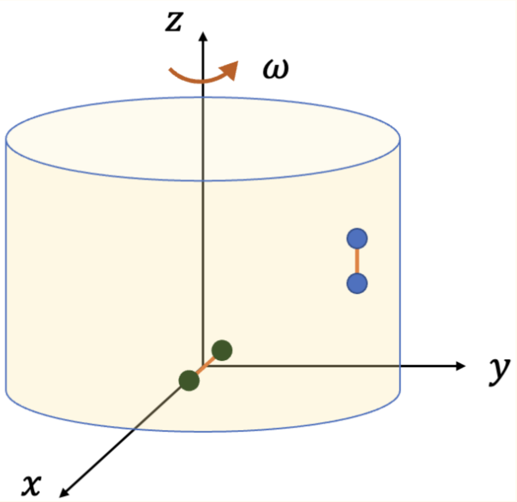


Υ(1S)

Appendix

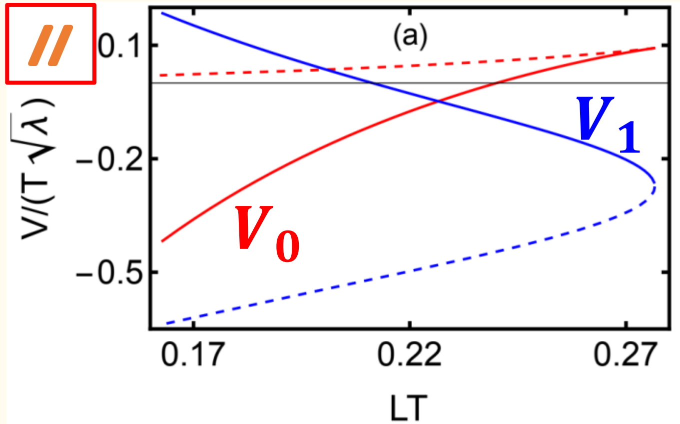
Global rotation:

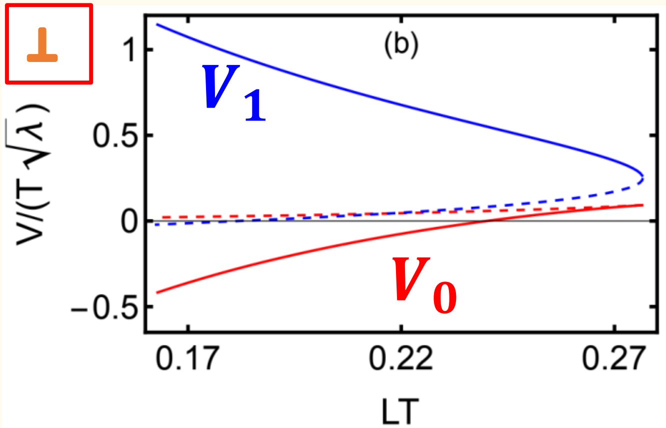
J.-X. Chen, D. –F. Hou and H.-C. Ren, "Drag force and heavy quark potential in a rotating background," arXiv:2308.08126.



In the non-relativistic limit: $(t, l, \phi, z, r) \to (t, l, \phi + \omega t, z, r)$

Heavy quark potential : $V(L) = V_0(L) + \omega^2 l^2 V_1(L) + O(\omega^4),$





Appendix

In the UV limit:

J.-X. Chen, D. –F. Hou and H.-C. Ren, "Drag force and heavy quark potential in a rotating background," arXiv:2308.08126.

$$L \to 0,\ r_c \to \infty$$

$V_0(L)$ **approaches to the heavy quark potential at zero temperature.**

$$V_1(L) \simeq -\frac{1}{2}V_0(L)$$

$$V(L) \simeq -\frac{4\pi^2\sqrt{\lambda}}{\Gamma^4\left(\frac{1}{4}\right)L}\left(1-\frac{1}{2}\omega^2 l^2+O(\omega^4)\right)$$

The rotation effect reduce the depth of the potential well.

Part I: Holographic model

Part II: Phase structure (with rotation)

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Part V: Summary and Outlook

Part V: Summary and Outlook

- Dimensionless angular momentum may serve as an order parameter for CEP.
- The appearance of rotation reduces the phase transition temperature.
- The appearance of rotation promotes the dissociation effect of heavy vector meson.
- The dissociation effect is stronger when the direction of angular velocity is transverse to the direction of polarization.
- The rotation effect reduce the depth of the potential well.
- Considering the effect of rotation on the critical dynamics.
- Studying the differential rotation to simulate the realistic QCD.
- Considering the global rotation in the case of relativity.

Thanks !