LIGHT CONE 2024

Hadron Physics in the EIC era

Exploring QCD Matter: Phase Transitions, Critical Endpoints, and Rotation Effects in Pure Gluon and Multi-Flavor Models

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Based on:

[1]. Y.-Q. Zhao, Song He, Defu Hou, Li Li, Zhibin Li, Phase structure and critical phenomena in two-flavor QCD by holography, Phys. Rev. D 109 (2024) 086015 [arXiv:2310.13432].

[2]. Y.-Q. Zhao , Song He, Defu Hou, Li Li, Zhibin Li, Phase diagram of holographic thermal dense QCD matter with rotation, JHEP 04 (2023) 115 [arXiv:2212.14662] .

Outline

- Static QCD phase structure
  - Pure gluon
  - 2 flavor
  - 2+1 flavor
- Rotating QCD phase structure
  - Pure gluon
  - 2+1 flavor

Static QCD phase structure

Static QCD phase structure

- Holographic QCD model
  - Action:

$g_{\mu\nu}$ corresponds to spacetime geometry

ϕ encodes the running of the gauge coupling

A_μ introduces a finite chemical potential and baryon density.

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

For pure SU(3) theory, there is no quark degree of freedom, so we close the gauge field A_μ by setting $Z(\phi) = 0$.

- Potential and kinetic functions:

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

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

background:

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

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

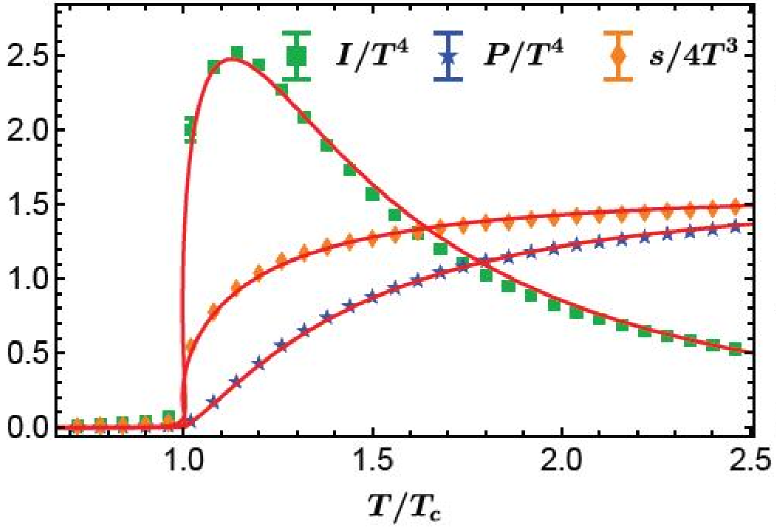
c1, c2, c3, c4, c5 will be fixed by fitting the state-of-the-art lattice QCD data to capture the thermodynamic behavior

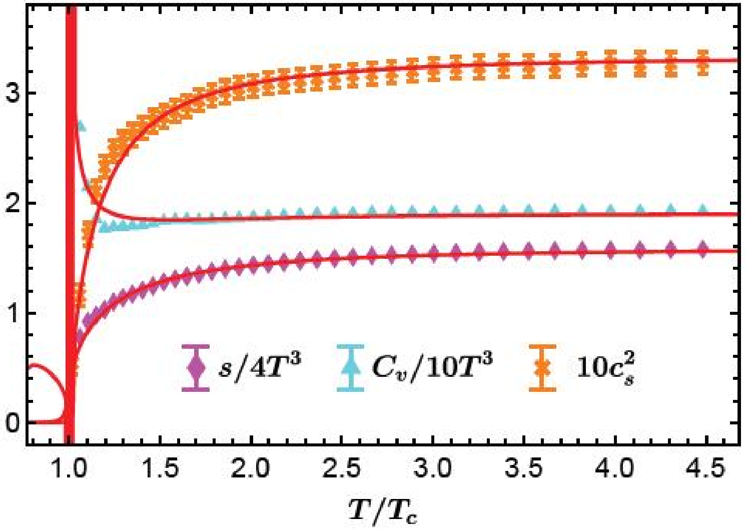
Static QCD phase structure

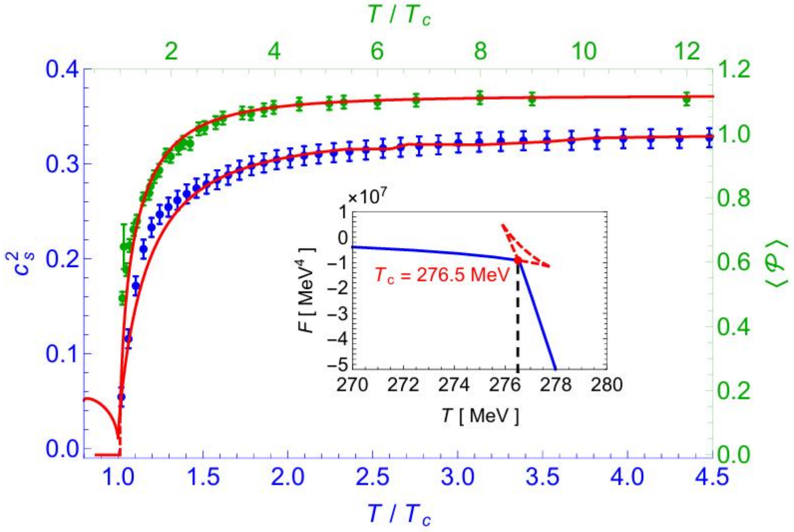
- Fitting the lattice QCD data:

$T_c = 276.5$ MeV

- Pure gluon:







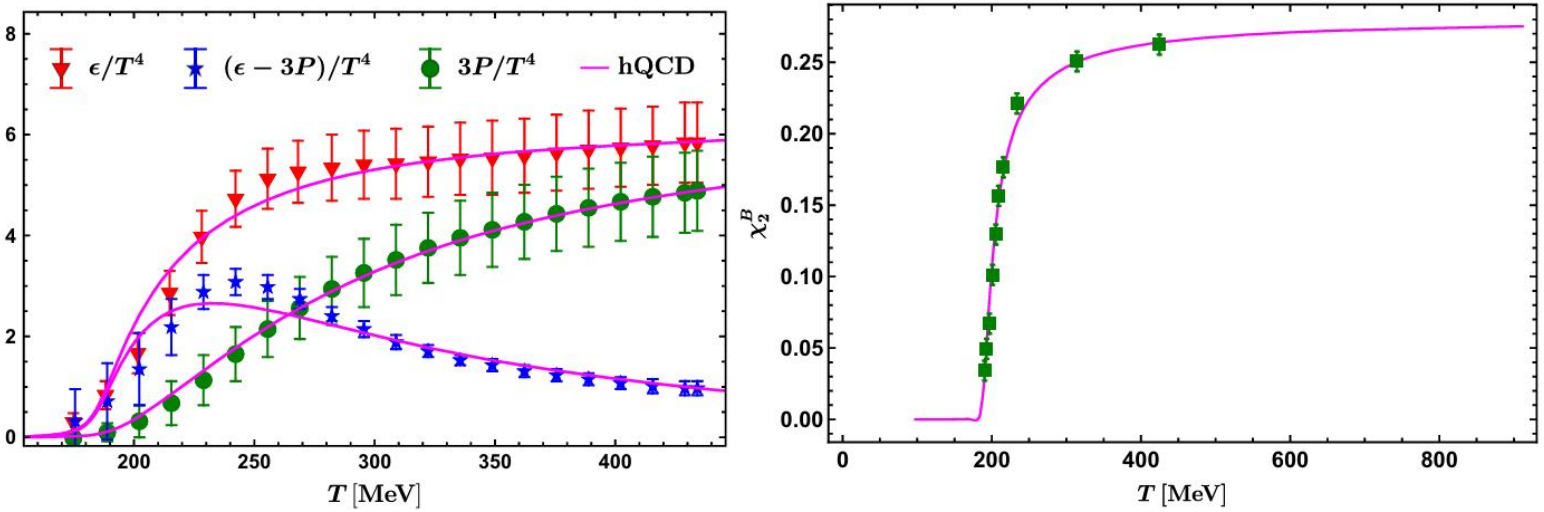
model	c_1	c_2	c_3	c_4	c_5	κ_N^2	ϕ_s(GeV)	b
pure SU(3)	0.735	0				$2\pi(4.88)$	1.523	-0.36458

S. He, L. Li, Z. Li, and S.-J. Wang, Gravitational waves and primordial black hole productions from gluodynamics by holography, Sci. China Phys. Mech. Astron. 67, 240411 (2024).

Y.-Q. Zhao , Song He, Defu Hou, Li Li, Zhibin Li, Phase diagram of holographic thermal dense QCD matter with rotation, JHEP 04 (2023) 115 [arXiv:2212.14662] .

Static QCD phase structure

- Fitting the lattice QCD data:
  - 2 flavor:



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

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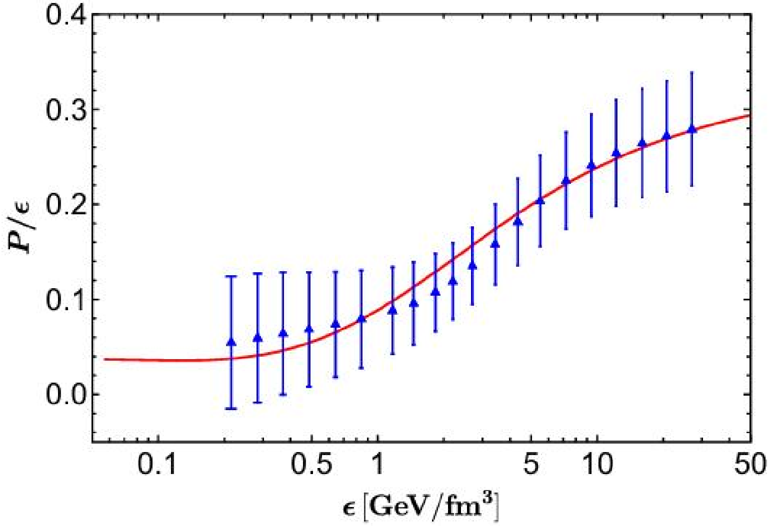
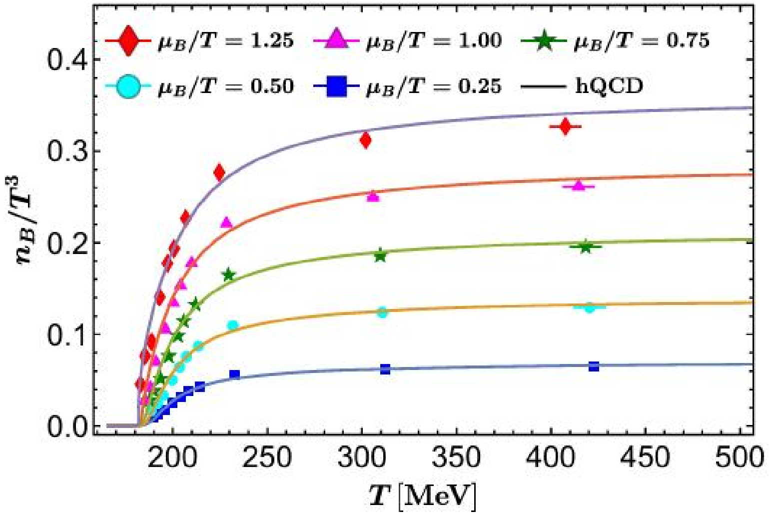
Static QCD phase structure

- Comparing with the lattice QCD data:
  - 2 flavor:





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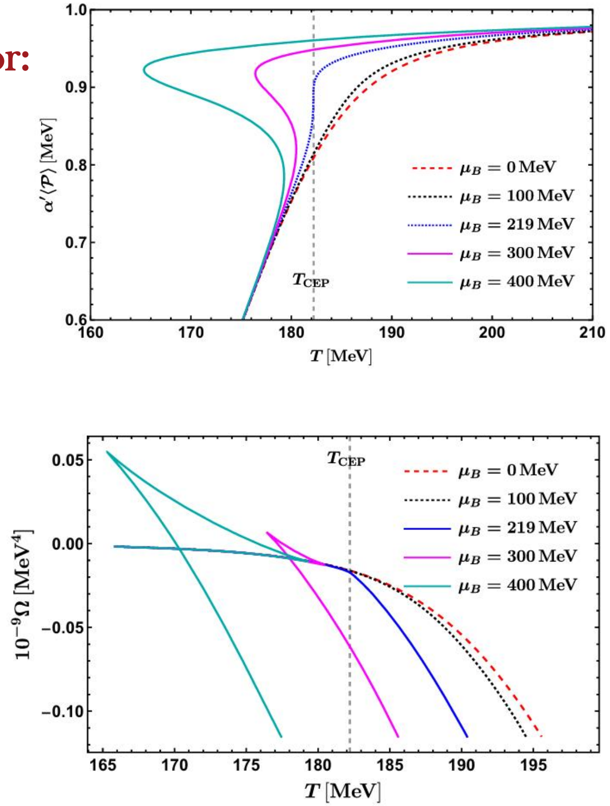
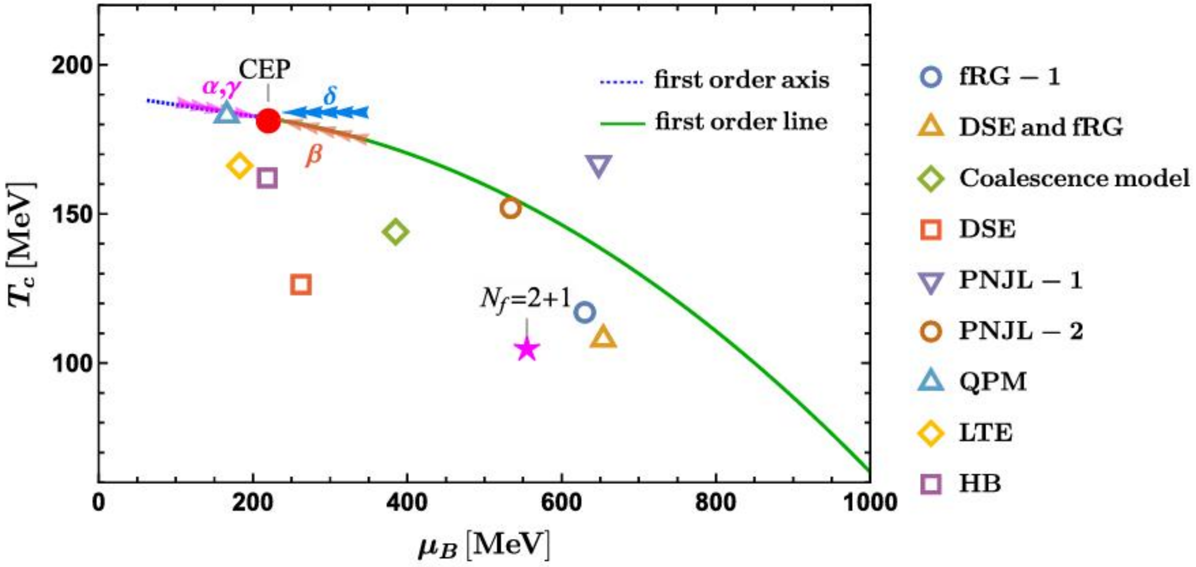
Static QCD phase structure

- Phase structure:
  - 2 flavor:



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



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Static QCD phase structure

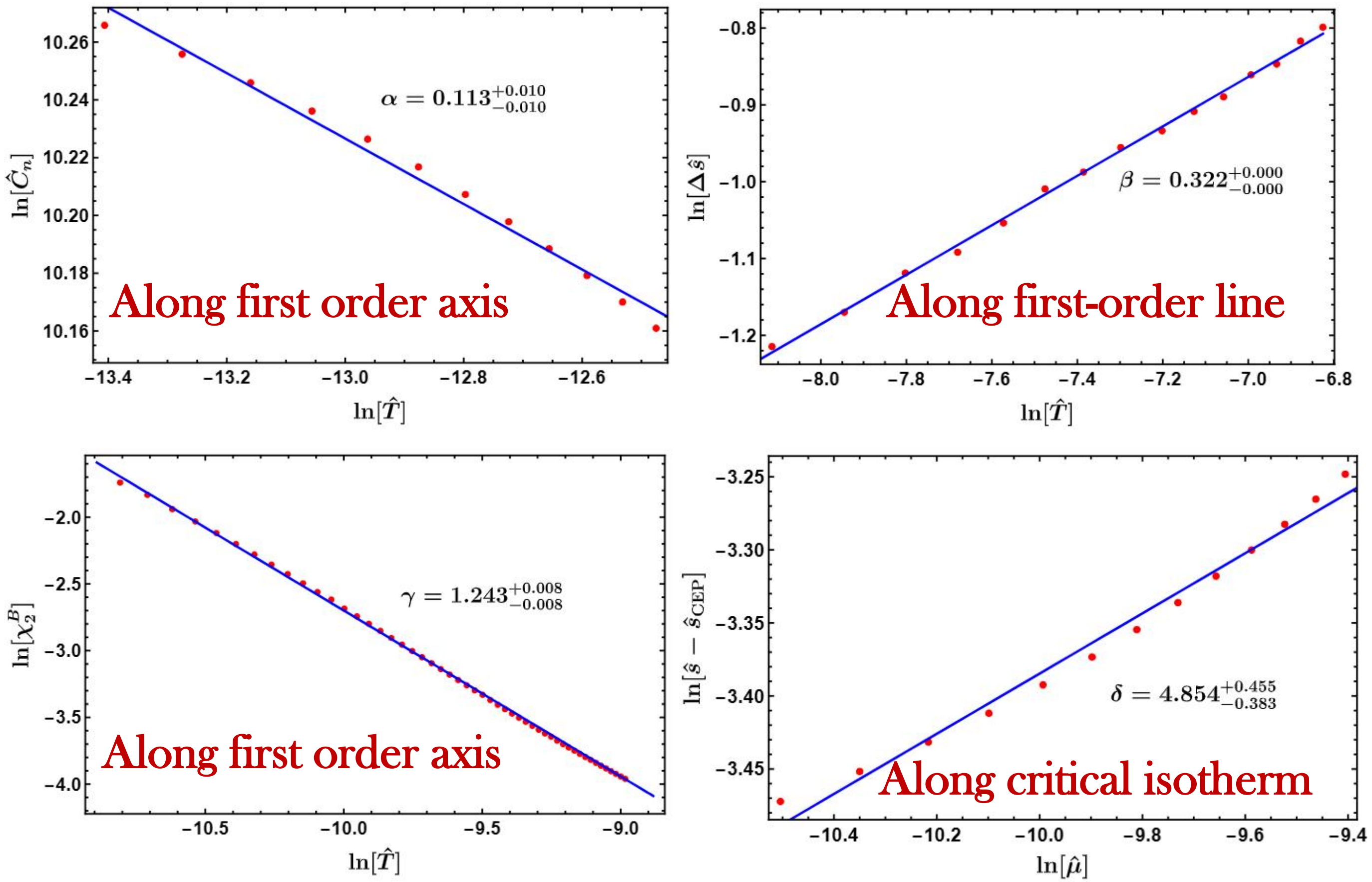
- **Critical exponents:**
  - 2 flavor:

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

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

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

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



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Static QCD phase structure

- **Critical exponents:**
  - 2 flavor:

Scaling relations:

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

	Experiment	3D Ising	Mean field	DGR model	Ours
α	0.110-0.116	0.110(5)	0	0	$0.113^{+0.010}_{-0.010}$
β	0.316-0.327	0.325±0.0015	1/2	0.482	$0.322^{+0.000}_{-0.000}$
γ	1.23-1.25	1.2405±0.0015	1	0.942	$1.243^{+0.008}_{-0.008}$
δ	4.6-4.9	4.82(4)	3	3.035	$4.854^{+0.455}_{-0.383}$

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

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

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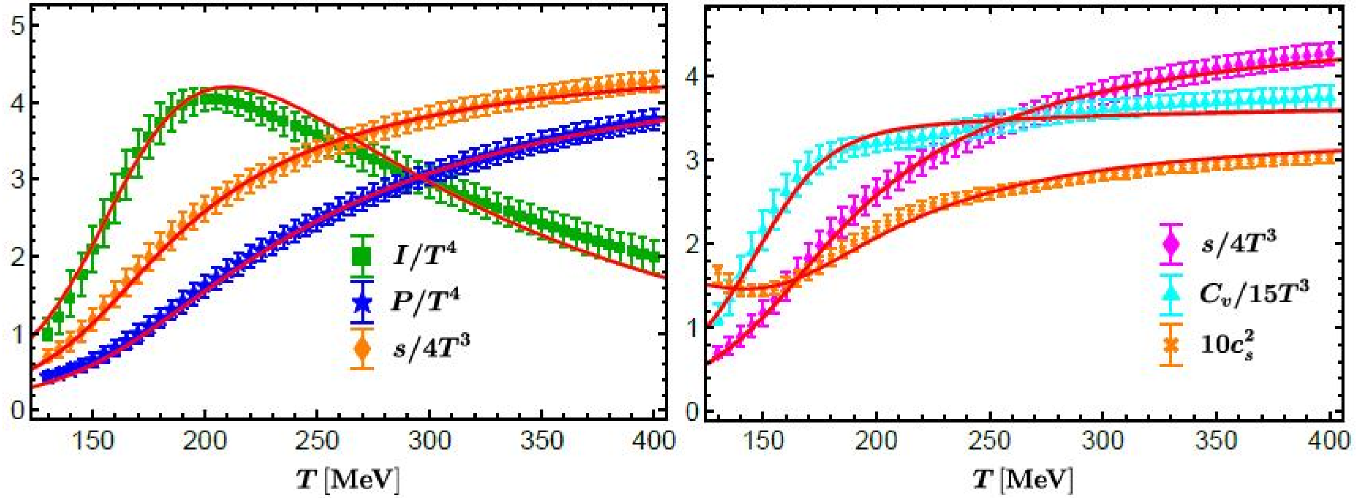
Static QCD phase structure

- Fitting the lattice QCD data:
  - 2+1 flavor:

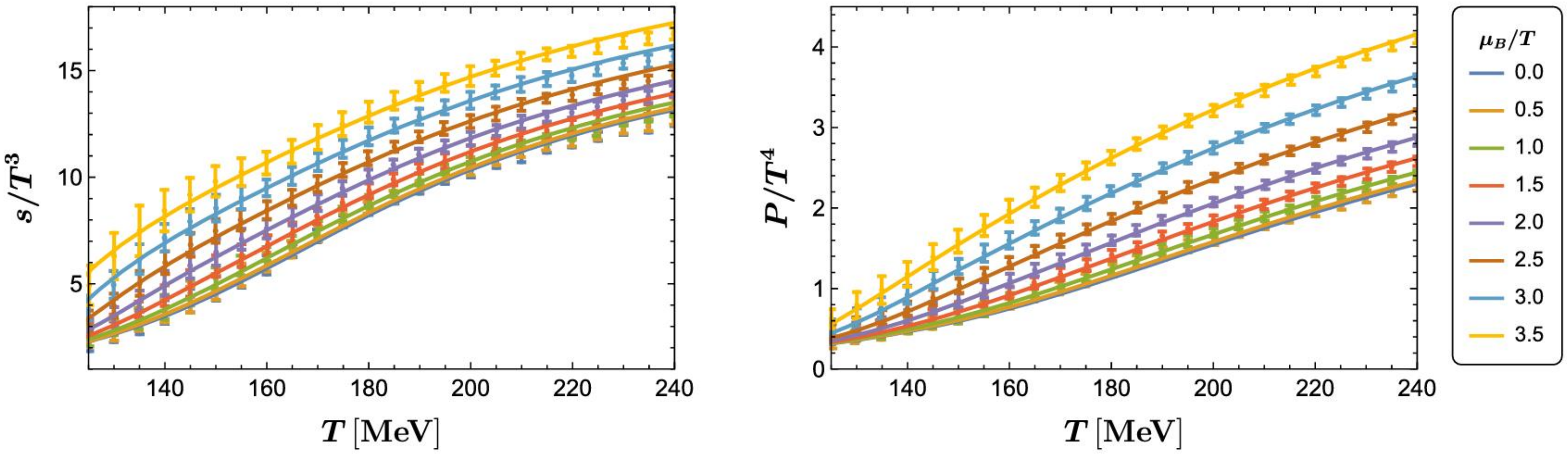


Model	c_1	c_2	c_3	c_4	c_5	κ_N^2	ϕ_s (GeV)	b
2 + 1 flavor	0.710	0.0037	1.935	0.085	30	$2\pi(1.68)$	1.085	−0.27341

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].
Y.-Q. Zhao , Song He, Defu Hou, Li Li, Zhibin Li, Phase diagram of holographic thermal dense QCD matter with rotation, JHEP 04 (2023) 115 [arXiv:2212.14662] .

Static QCD phase structure

- Comparing with the lattice QCD data:
  - 2+1 flavor:



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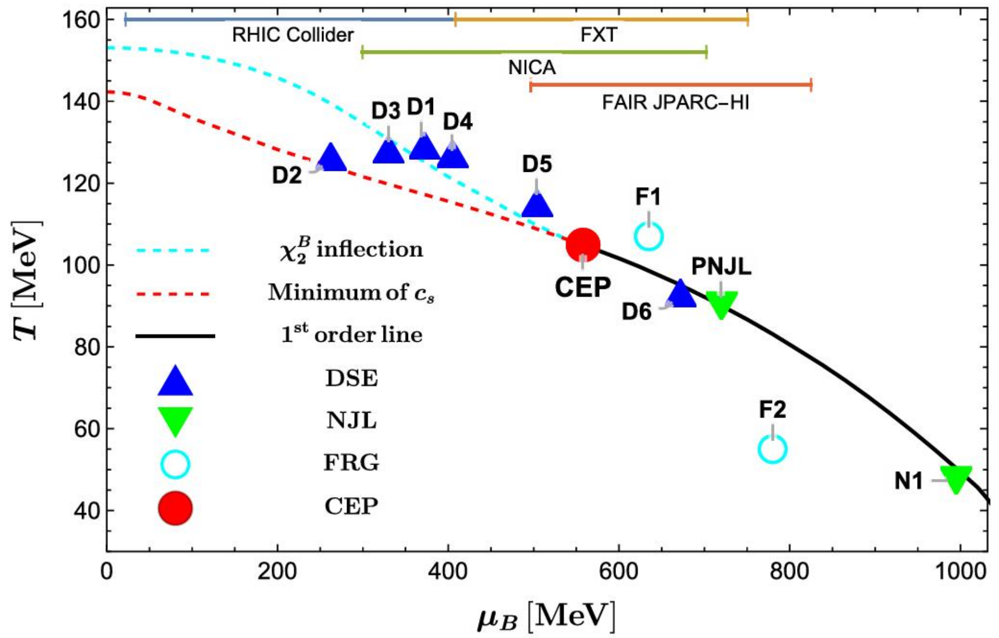
Static QCD phase structure

- **Phase structure:**
  - 2+1 flavor: $(\mu_{\rm CEP}, T_{\rm CEP}) = (555\ {\rm MeV}, 105\ {\rm MeV})$



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Rotating QCD phase structure

Rotating QCD phase structure

Y.-Q. Zhao , Song He, Defu Hou, Li Li, Zhibin Li, Phase diagram of holographic thermal dense QCD matter with rotation, JHEP 04 (2023) 115 [arXiv:2212.14662] .

- Holographic QCD model
  - Static background：

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

  - Splitting the 3-dimensional space into two parts as $\boldsymbol{M_3} = \mathbb{R} \times \boldsymbol{\Sigma_2}$.

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

  - local Lorentz boost:

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

  - Rotating background:

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

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

Rotating QCD phase structure

- Holographic QCD model

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- Hawking temperature and entropy density：

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

- Baryon chemical potential and baryon charge density:

$$\hat{\mu}_B = \mu_B\sqrt{1-\omega^2\ell^2}, \qquad \hat{\rho}_B = \rho_B/\sqrt{1-\omega^2\ell^2}.$$

- Energy density and Pressure density:

$$\hat{\epsilon} := \hat{T}_{00} = \frac{\epsilon + \omega^2\ell^2 P}{1-\omega^2\ell^2}, \quad \hat{P}_1 := \hat{T}_{11} = \frac{1}{\ell^2}\hat{T}_{\theta\theta} = \frac{P + \omega^2\ell^2\epsilon}{1-\omega^2\ell^2}, \quad \hat{P}_2 := \hat{T}_{22} = P, \quad \hat{P}_3 := \hat{T}_{33} = P,$$

- Angular momentum and trace anomaly:

$$J = \hat{T}_{\theta t} = \frac{\omega\ell^2(\epsilon + P)}{1-\omega^2\ell^2}, \qquad \hat{I} = -\hat{T}^\mu_\mu = -T^\mu_\mu = I = \epsilon - 3P$$

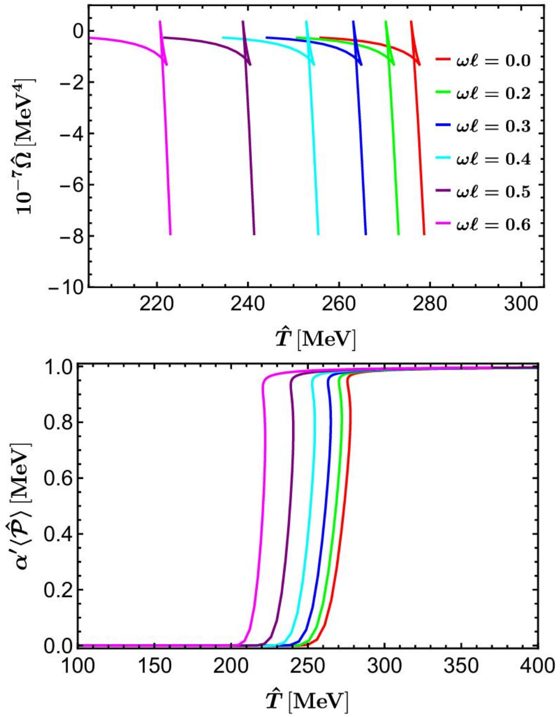
- Thermodynamic relation：

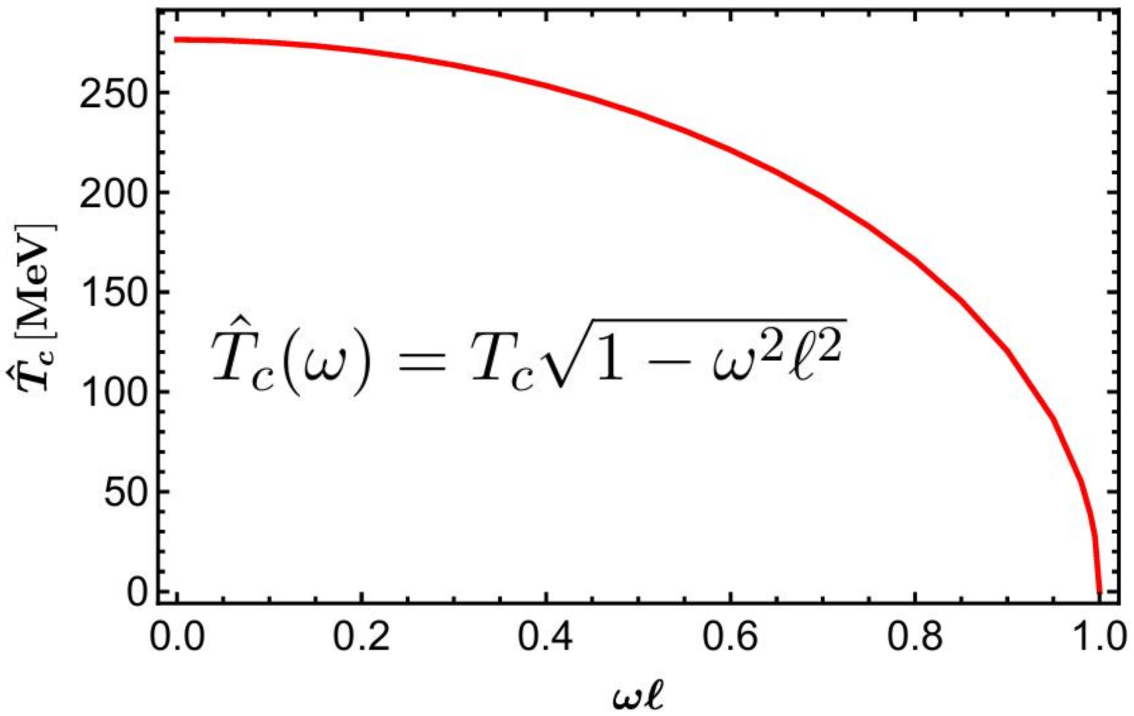
$$\hat{\Omega} = \hat{\epsilon} - \hat{T}\hat{s} - \hat{\mu}_B\hat{\rho}_B - \omega J = -P.$$

Rotating QCD phase structure

➢ Phase structure:

➢ Pure gluon:





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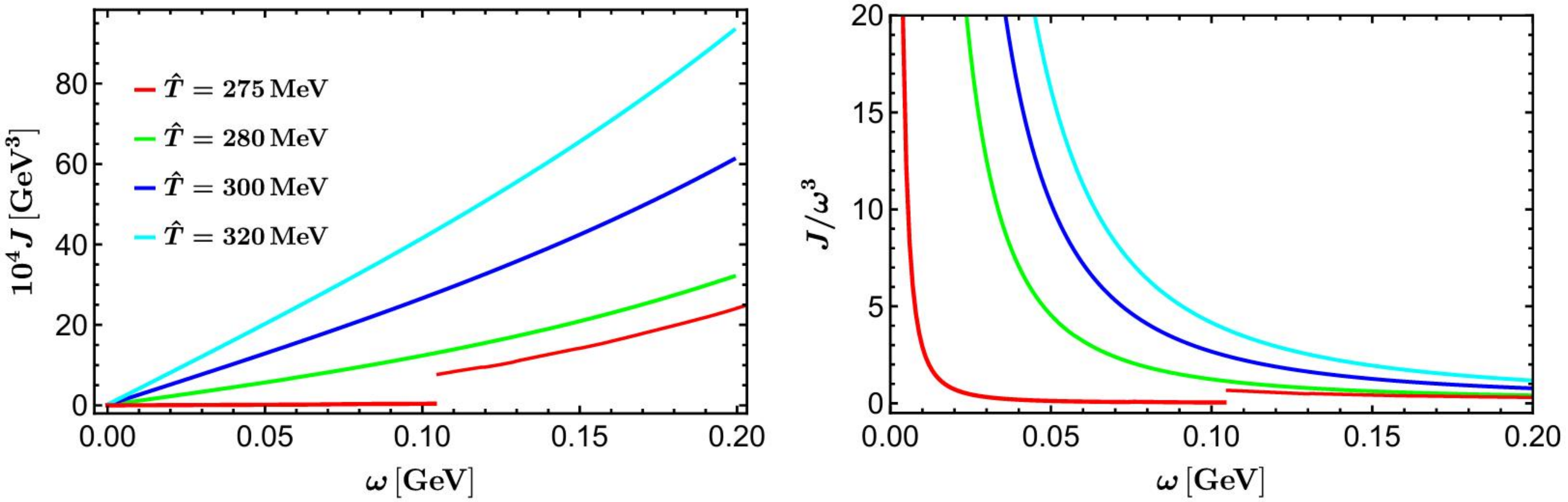
Rotating QCD phase structure

- Angular momentum: **In the non-relativistic limit, classical formula**
  - Pure gluon:

$$J = (\epsilon + P)\ell^2\omega = \rho_m \ell^2 \omega$$



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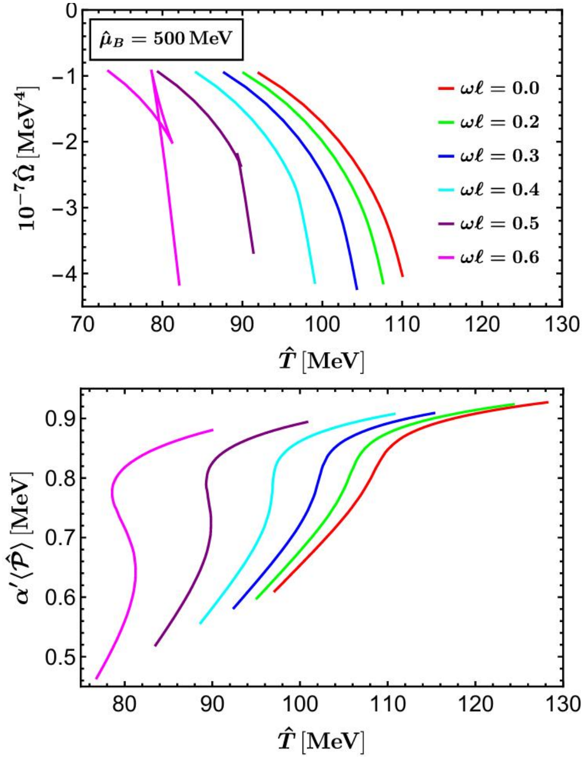
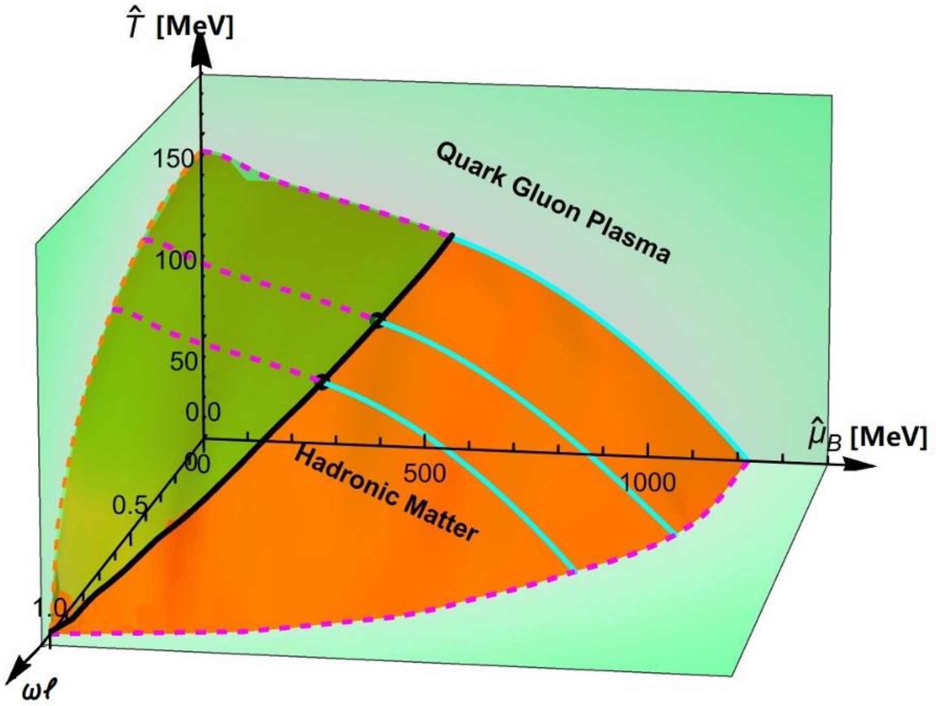
Rotating QCD phase structure

- Phase structure:
  - 2+1 flavor:





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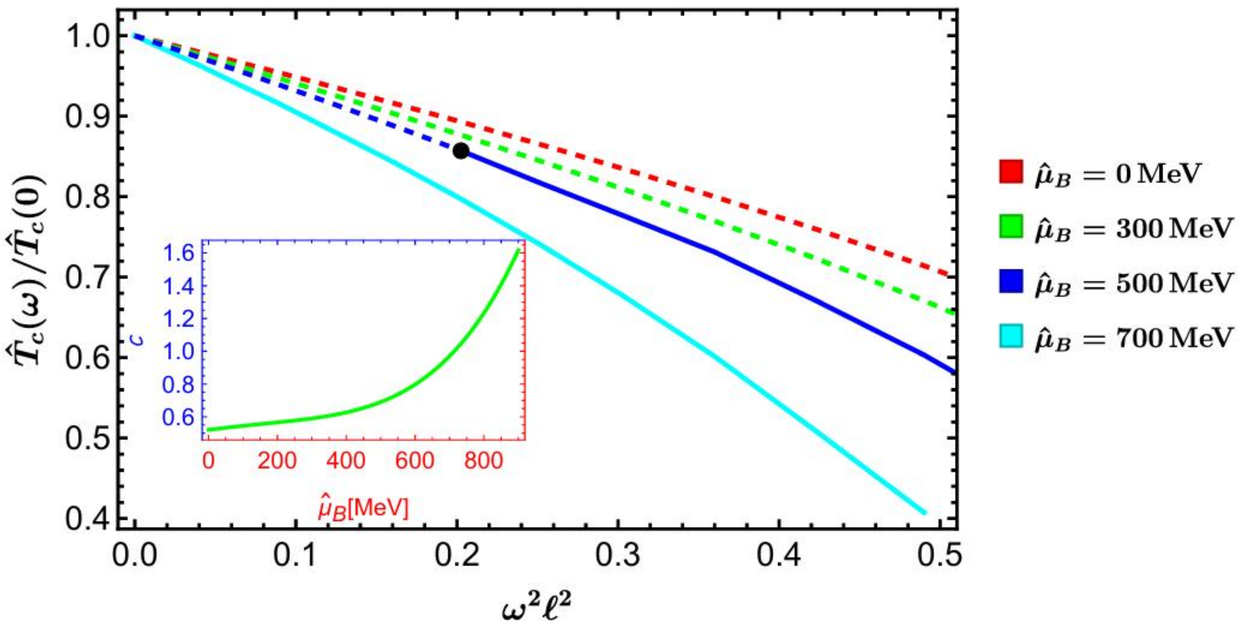
Rotating QCD phase structure

- **Phase structure:**
  - 2+1 flavor:
  - $\mu_B \neq 0$

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

  - $\mu_B = 0$

$$\hat{T}_c(\omega) = \frac{\hat{T}_c(0)}{\sqrt{1-\omega^2\ell^2}} \approx (1 - \frac{\omega^2\ell^2}{2})\hat{T}_c(0)$$



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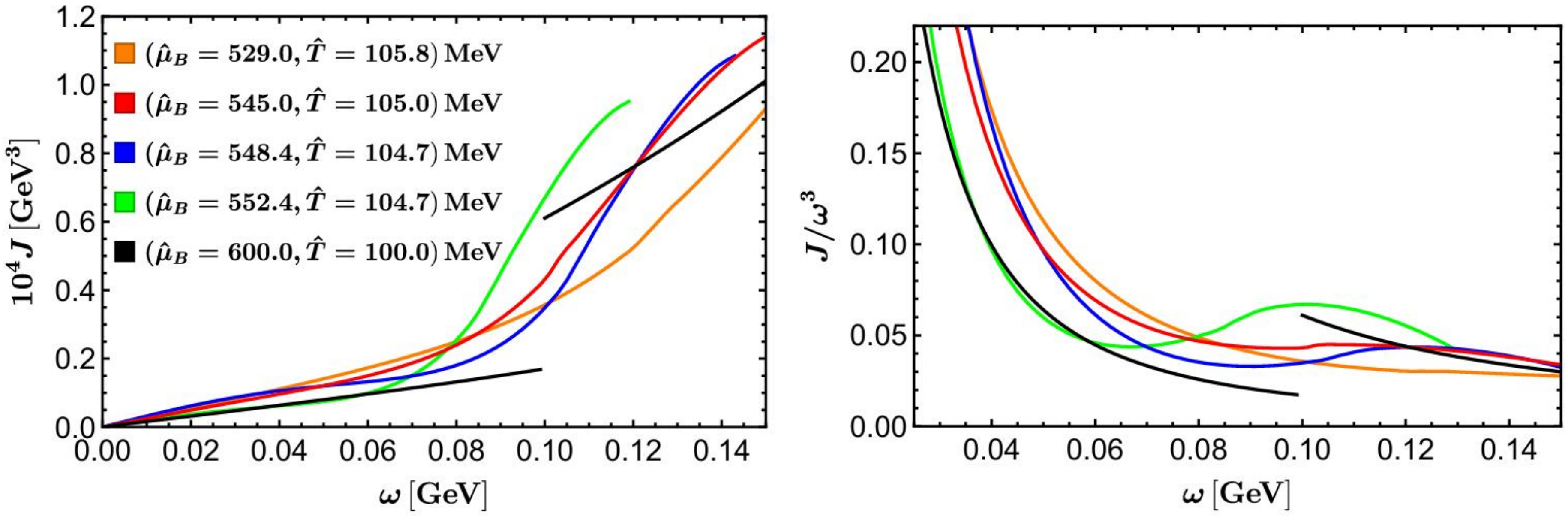

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Thanks!