

Holographic Model in Anisotropic Hot Dense QGP with External Magnetic Field

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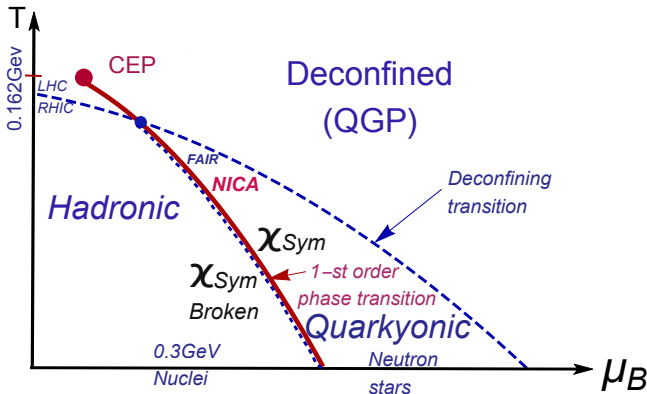
with I.Ya. Aref'eva and P. Slepov
JHEP 07(2021)161 [arXiv:2011.07023]

The Expected QCD Phase Diagram

Goal of Holographic QCD — describe QCD phase diagram

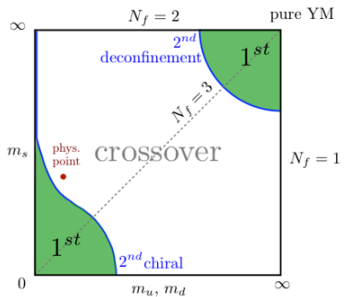
Requirements:

- reproduce the QCD results from perturbative theory at short distances
- reproduce Lattice QCD results at large distances (~ 1 fm) and **small** μ_B



QCD Phase Diagram: Lattice

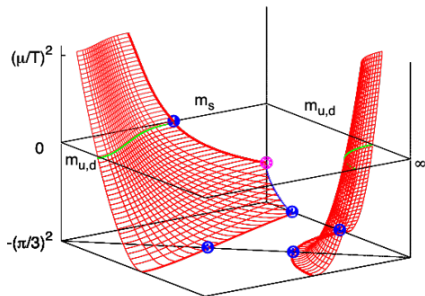
Phase diagram
on quark mass



Columbia plot

Brown et al., PRL (1990)

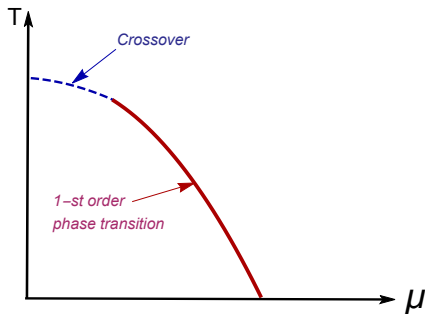
Main problem with $\mu \neq 0$
Imaginary chemical potential method



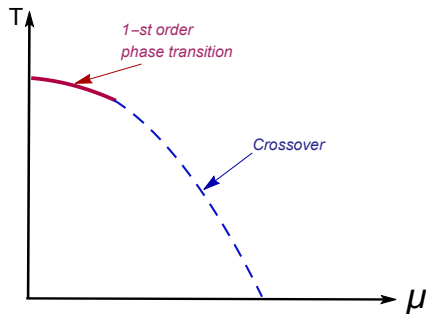
Philipsen, Pinke, PRD (2016)

“Heavy” and “Light” Quarks from Columbia Plot

Light quarks



Heavy quarks



Anisotropy in QGP

- Origins of anisotropy

- Longitudinal and 2 transversal directions

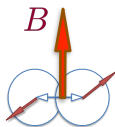
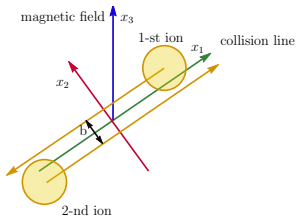
- Multiplicity dependencies *ALICE*

$$\mathcal{M}(s) \sim s^{0.155(4)}$$

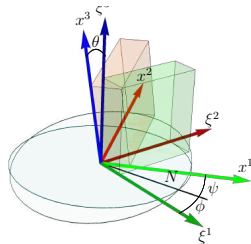
- *Aref'eva, Golubtsova, JHEP (2014)*

$$\mathcal{M}(s) \sim s^{1/(\nu+2)} \Rightarrow \nu = 4.5$$

- Full anisotropy (in strong magnetic field, $eB \sim 5 - 10 m_\pi^2$, m_π – pion mass)



Peripheral HIC



Fully Anisotropic Background

$$\mathcal{L} = R - \frac{f_1(\phi)}{4} F_{(1)}^2 - \frac{f_2(\phi)}{4} F_{(2)}^2 - \frac{f_B(\phi)}{4} F_{(B)}^2 - \frac{1}{2} \partial_\mu \phi \partial^\mu \phi - V(\phi)$$

$$A_\mu^{(1)} = A_t(z) \delta_\mu^0 \quad F_{\mu\nu}^{(2)} = q \, dy^1 \wedge dy^2 \quad F_{\mu\nu}^{(B)} = q_B \, dx \wedge dy^1$$

$$A_t(0) = \mu \quad g(0) = 1 \quad \text{Dudal et al., (2019)}$$

$$A_t(z_h) = 0 \quad g(z_h) = 0 \quad \phi(z_0) = 0 \rightarrow \sigma_{\text{string}}$$

$$ds^2 = \frac{L^2}{z^2} \mathbf{b}(z) \left[-g(z) dt^2 + dx^2 + \left(\frac{z}{L}\right)^{2-\frac{2}{\nu}} dy_1^2 + e^{c_B z^2} \left(\frac{z}{L}\right)^{2-\frac{2}{\nu}} dy_2^2 + \frac{dz^2}{g(z)} \right]$$

I.A., A.G. (2014), Giataganas (2013)

Gürsoy, Järvinen et al., (2019)

$$\mathbf{b}(z) = e^{2\mathcal{A}(z)} \rightarrow \text{quarks mass}$$

“Bottom-up approach”

$$\mathcal{A}(z) = -cz^2/4 \rightarrow \text{heavy quarks background (b, t)} \quad \text{Andreev, Zakharov (2006)}$$

$$\mathcal{A}(z) = -a \ln(bz^2 + 1) \rightarrow \text{light quarks background (d, u)} \quad \text{Li, Yang, Yuan (2020)}$$

Anisotropic Solution for “Heavy” Quarks

$$A_t = \mu \frac{e^{(c-2c_B)z^2/4} - e^{(c-2c_B)z_h^2/4}}{1 - e^{(c-2c_B)z_h^2/4}}, \quad \rho = -\frac{\mu(c-2c_B)}{4\left(1 - e^{(c-2c_B)z_h^2/4}\right)}$$

$$f_B = -\frac{2c_B z^{1-\nu/2} g}{q_B^2 e^{cz^2/2}} \left(\frac{3cz}{2} + \frac{2}{\nu z} - c_B z - \frac{g'}{g} \right)$$

$$g = e^{c_B z^2} \left\{ 1 - \frac{\Gamma\left(1 + \frac{1}{\nu}\right) - \Gamma\left(1 + \frac{1}{\nu}; \frac{3}{4}(2c_B - c)z^2\right)}{\Gamma\left(1 + \frac{1}{\nu}\right) - \Gamma\left(1 + \frac{1}{\nu}; \frac{3}{4}(2c_B - c)z_h^2\right)} - \frac{\mu^2 (2c_B - c)^{-\frac{1}{\nu}}}{4\left(1 - e^{(c-2c_B)\frac{z_h^2}{4}}\right)^2} \left(\Gamma\left(1 + \frac{1}{\nu}\right) - \Gamma\left(1 + \frac{1}{\nu}; \frac{3}{4}(2c_B - c)z^2\right) \right) \times \right. \\ \left. \times \left[1 - \frac{\Gamma\left(1 + \frac{1}{\nu}\right) - \Gamma\left(1 + \frac{1}{\nu}; \frac{3}{4}(2c_B - c)z^2\right)}{\Gamma\left(1 + \frac{1}{\nu}\right) - \Gamma\left(1 + \frac{1}{\nu}; \frac{3}{4}(2c_B - c)z_h^2\right)} \frac{\Gamma\left(1 + \frac{1}{\nu}\right) - \Gamma\left(1 + \frac{1}{\nu}; (2c_B - c)z_h^2\right)}{\Gamma\left(1 + \frac{1}{\nu}\right) - \Gamma\left(1 + \frac{1}{\nu}; (2c_B - c)z^2\right)} \right] \right\}$$

$$\phi = \int_{z_0}^z \frac{1}{\nu \xi} \sqrt{4\nu - 4 + (4\nu c_B + 3(3c - 2c_B)\nu^2) \xi^2 + \left(\frac{3}{2} \nu^2 c^2 - 2c_B^2\right) \xi^4} d\xi, \quad z_0 \neq 0$$

Thermodynamics in Holography

$$T = \frac{|g'|}{4\pi} \Big|_{z=z_h} \quad \longrightarrow \quad \text{QGP temperature (Maldacena)}$$

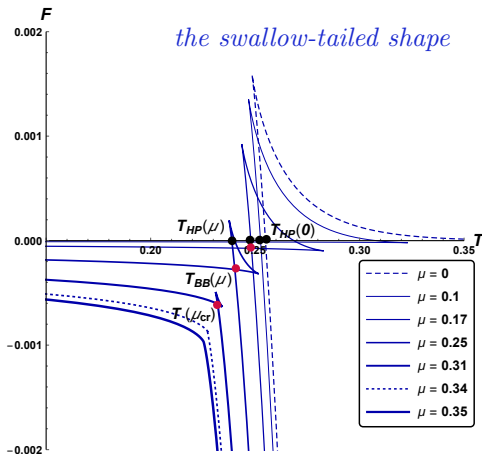
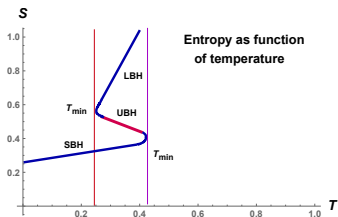
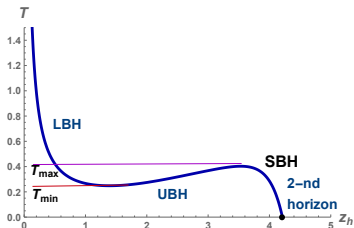
$$s = \frac{1}{4} \sqrt{\prod_{i=1}^3 g_{ii}} \Big|_{z=z_h} \quad \longrightarrow \quad \text{multiplicity of process (Landau)}$$

$$F = \int_{z_h}^{\infty} s \, dT \quad \longrightarrow \quad \text{background BH-BH phase transition}$$

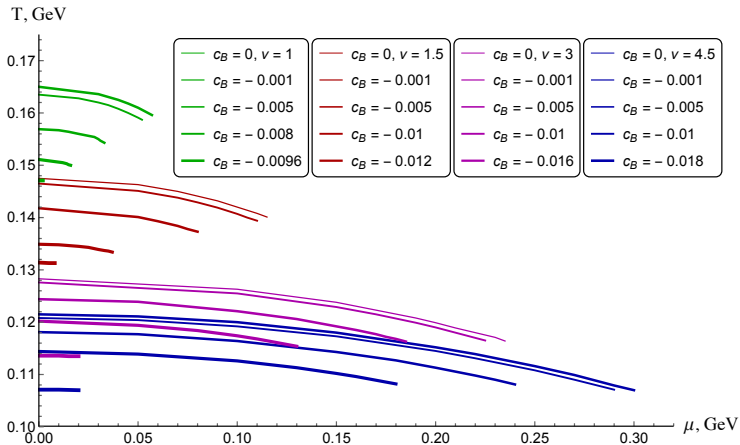
$$A_t = \mu - \rho z^2 + \dots \quad \longrightarrow \quad \text{chemical potential, density}$$

BH-BH Phase Transition

BH-BH describes transition from small black holes \rightarrow large black holes



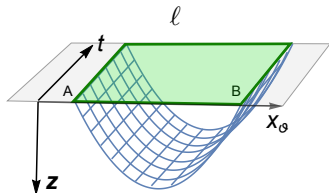
BH-BH Phase Transition: “Heavy” Quarks in Magnetic Field



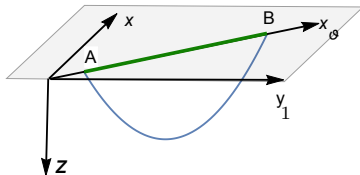
Light quarks *Aref'eva, K.R., Slepov, JHEP 06 (2021) 090 [arXiv:2009.05562]*

Temporal Wilson Loop

$$W[C_\vartheta] = e^{-S_\vartheta, t} \quad \vec{n}: \quad n_x = \cos \vartheta, \quad n_{y_1} = \sin \vartheta, \quad n_{y_2} = 0$$



x - collision axes



Two special cases:

- $\vartheta = 0$ WL (longitudinal)
- $\vartheta = \pi/2$ WT (transversal)

$$l \rightarrow \infty \quad S \sim \sigma_{DW} l$$

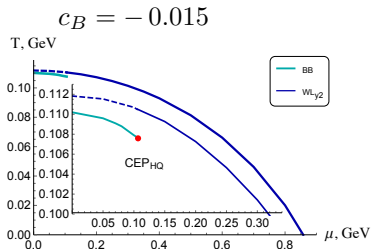
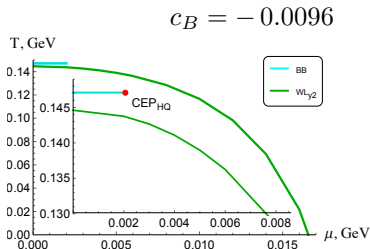
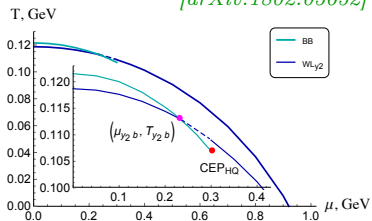
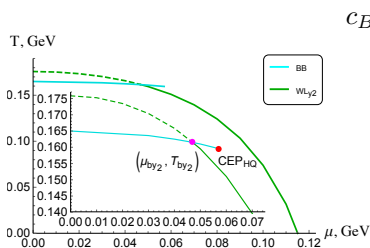
the string tension

$$\sigma_{DW} = \frac{b(z)e^{\sqrt{\frac{2}{3}}\phi(z, z_0)}}{z^2} \sqrt{g(z) \left(z^2 - \frac{2}{v} \sin^2(\vartheta) + \cos^2(\vartheta) \right)} \Big|_{z=z_{DW}}, \quad \frac{\partial \sigma}{\partial z} \Big|_{z=z_{DW}} = 0$$

Aref'eva, K.R., Slepov, *PLB* **792** (2019) 470 [arXiv:1808.05596]

Phase Transition for “Heavy” Quarks

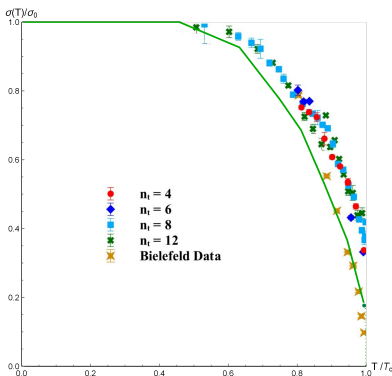
JHEP 05(2018)206
[arXiv:1802.05652]



- We see the **inverse** magnetic catalysis

Our String Tension vs Lattice

- We take $z_0 = 10 \exp(-z_h/4) + 0.1$ (#)



- The green curve shows the string tension as function of temperature for $z_0 = (\#)$, $\mu = 0$, $\nu = 1$, $a = 4.046$, $b = 0.01613$, $c = 0.227$
- The dots with different decorations Lattice *Cardoso, Bicudo, PRD (2012)*
- The thin green dotted line shows the WL phase transition

Spatial Wilson Loops

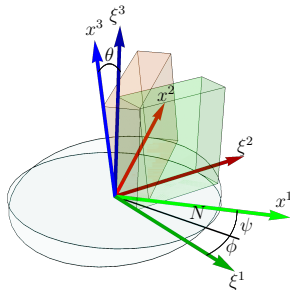
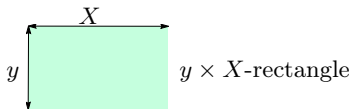
Nesting of the 2-dimensional world sheet in 5-dimensional space-time

$$X^0(\xi) = \text{const}$$

$$X^i(\xi) = \sum_{\alpha=1,2} a_{i\alpha}(\phi, \theta, \psi) \xi^\alpha, \quad i = 1, 2, 3, \quad \alpha = 1, 2$$

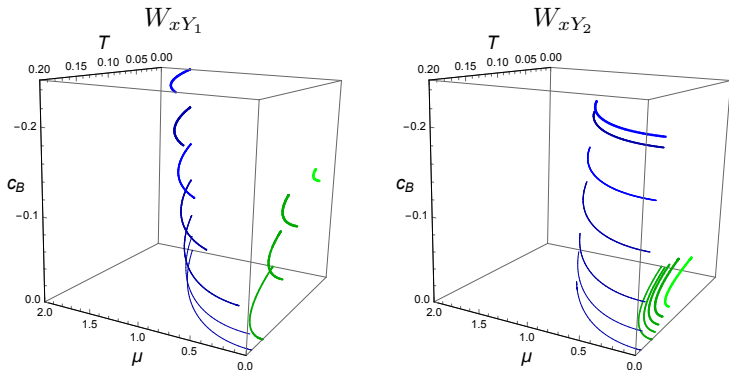
$$X^4(\xi) = z(\xi^1)$$

- x^i – spatial coordinates
- $a_{ij}(\phi, \theta, \psi)$ – entries of the rotation matrix



*brick's orientation is equivalent
to rectangle's orientation*

Drag Forces Phase Transitions



Phase transition surfaces – surfaces stretched on blue/green curves

- Under variation of (T , μ , magnetic field) the spatial string tension undergoes the phase transition *Aref'eva, K.R., Slepov [arXiv:2012.05758]*
- The light green and blue lines represent to the end of the phase transitions
- Drag forces and **energy losses** undergo the phase transition as well

Conclusion

- We have an interplay between two types of phase transitions
 - Crossover
 - 1-st order phase transition
- Magnetic field influences the phase diagram for “heavy” quarks model
 - Inverse magnetic catalysis
 - External magnetic field suppresses BH-BH transition
 - For larger anisotropy $\nu > 1$ this suppression weakens
 - Drag forces and energy losses undergo the phase transition depending on anisotropy and magnetic field
- What to do next
 - “Light” quarks model in magnetic field
 - “Hybrid” model corresponding to realistic quark masses
 - Other characteristics (susceptibility, transport coefficients, η/s , direct-photon spectra, jet quenching, thermalization time, etc)

Thank you
for your attention