HQCD: HIC in holographic approach

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Outlook

- Physical picture of the formation of quark-gluon plasma in collisions of heavy ions.
- Results of applying the holographic approach to the description of collisions between heavy ions and quark-gluon plasma:
  - Explanation of experimental data:
    - multiplicity of particles.
  - Prediction of new effects in anisotropic quark-gluon plasma:
    - smeared of the confinement/deconfinement phase transition;
    - dependence on the anisotropy parameter and the chemical potential of the energy losses (quenching coefficient of jets) and the emission velocity of direct photons

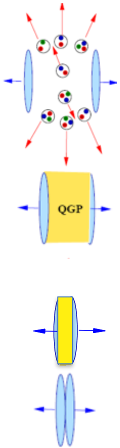
New in the last years

- More detailed structure of phase transitions
  - dependence on the magnitude of the magnetic field
  - detailed account of quark masses

Main refs

- I. Ya. Aref'eva, "Holographic approach to quark–gluon plasma in heavy ion collisions", Phys. Usp., **184:6** (2014)
- И.А., "QGP time formation in holographic shock waves model of heavy ion collisions" TMPh, 184 (2015), 398–417
- I.A., A. Golubtsova, "Shock waves in Lifshitz-like spacetimes," JHEP'04, 011 (2015)
- I.A. and K. Rannu, "Holographic Anisotropic Background with Confinement-Deconfinement Phase Transition," JHEP **05** (2018) 206
- I.A., A. Golubtsova, G. Policastro, "Exact holographic RG flows and the $A_1 \times A_1$ Toda chain," JHEP **05** (2019) 117
- I.A., K. Rannu, P. Slepov, "Orientation Dependence of Confinement-Deconfinement Phase Transition in Anisotropic Media," Phys. Lett. **B 792** (2019) 470
- I. A., A. Patrushev, P. Slepov "Holographic Entanglement Entropy in Anisotropic Background with Confinement-Deconfinement Phase Transition", JHEP **07** (2020) 043
- I.A., K. Rannu, P. S. Slepov, "Anisotropic solutions for a holographic heavy-quark model with an external magnetic field", TMPh **206** (2021) 400
- I.A., A. Golubtsova, E. Gourgoulhon, "Holographic drag force in 5d Kerr-AdS black hole," JHEP **04** (2021) 169
- I. A., K. Rannu, P. Slepov, "Holographic Anisotropic Model for Light Quarks with Confinement-Deconfinement Phase Transition", JHEP **06** (2021) 90
- I.A., K. Rannu, P. Slepov, "Holographic Anisotropic Model for Heavy Quarks in Anisotropic Hot Dense QGP with External Magnetic Field," JHEP **07**(2021) 161
- I.A., A.Ermakov, P.Slepov, "Direct photons emission rate and electric conductivity in twice anisotropic QGP holographic model with first-order phase transition," EPJ C **82** (2022) 85
- I.A., A. Ermakov, K. Rannu and P. Slepov, "Holographic model for light quarks in anisotropic hot dense QGP with external magnetic field," arXiv:2203.12539

Evolution after heavy ion collision

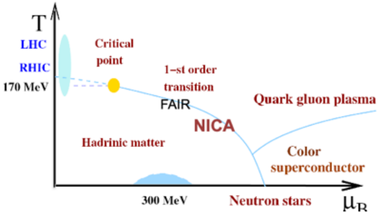


Адронизация

Время жизни:
10fm/c

Время термализации:
$1fm/c = 3.3 \cdot 10^{-24}s$

- QGP is a state of matter of free quarks, antiquarks and gluons at high temperature. QGP was discovered at RHIC in 2005.
- QGP behaves (RHIC, LHC) like a strongly interacting fluid (collective effects)



- Local thermalization. This process is accompanied by a huge production of entropy. The physics is not fully understood. Difficulties arise due to time-dependent non-equilibrium QCD processes.
- Local thermalization creates an initial condition for hydrodynamic evolution

QGP - strongly interacting liquid

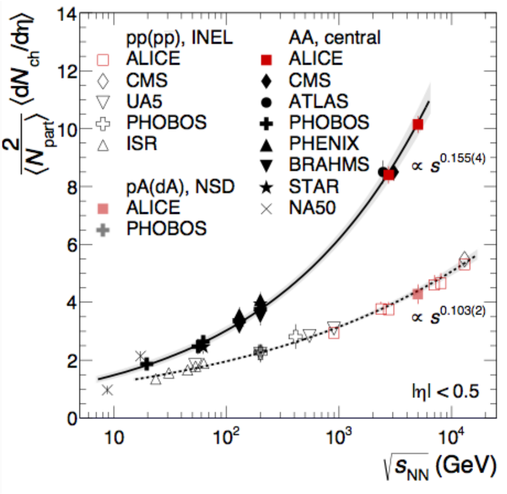
- 2 questions:
    1. How was it formed?
    2. what properties does it have?
- Perturbation methods are not applicable
- Lattice methods do not work, because we consider the process in real time.
- In the stationary case, problems with the chemical potential
- QCD dynamics using holographic description (based on gauge theory/string duality)

Holographic method - phenomenological approach

Motivated by AdS/CFT duality Maldacena,1998

- Temperature in QCD $\Longleftrightarrow$ black hole temperature in (deform.)AdS
- Thermalization in QCD $\Longleftrightarrow$ formation of black hole in (deform.)AdS5
- Thermalization models (black hole formation models):
  - colliding shock waves; the area of the trapped surface determines the multiplicity
  - floating shells
  - collapse of stars

Total multiplicity produced in heavy ions collision



Plot from PRL'16 (ALICE)
PbPb
$\mathcal{M} \sim s_{NN}^{0.15}$

The bulk of the particles are born immediately after the collision of heavy ions

Multiplicity

- Experiment

$$\mathcal{M} \sim s^{0.155}$$

- Macroscopic theory of high-energy collisions

$$Landau: \qquad \mathcal{M} \sim s^{0.25}$$

- Holographic approach
  - The simplest model gives (collision of shock waves)

$$AdS: \qquad \mathcal{M} \sim s^{0.33}$$

  Gubser et al, Phys.Rev. D, 2008; Gubser et al, JHEP, 2009; Alvarez-Gaume et al, PLB; 2009 Aref'eva et al, JHEP, 2009, 2010, 2012; Lin, Shuryak, JHEP, 2009, 2011; Kiritsis, Taliotis, JHEP, 2011
  - Anisotropic Lifshitz type background with exponent ν

$$\begin{aligned} \mathcal{M}_{\nu} &\sim s^{\frac{1}{2+\nu}}, \\ \mathcal{M}_{LHC} &\sim s^{0.155} \qquad \nu = 4.45 \end{aligned}$$

I.A., Golubtsova, JHEP, 2014

Holographic model of an anisotropic plasma in a magnetic field at a nonzero chemical potential

- Action — Aref'eva, Rannu, Slepov, JHEP, 2021

$$\int d^5x\,\sqrt{-g}\left[R-\frac{f_1(\phi)}{4}\,F_{(1)}^2-\frac{f_2(\phi)}{4}\,F_{(2)}^2-\frac{f_B(\phi)}{4}\,F_{(B)}^2-\frac{1}{2}\,\partial_\mu\phi\partial^\mu\phi-V(\phi)\right]$$

  f_1 related to the chemical potential, f_2 with anisotropy, f_B with magnetic field

- metric as a solution to the Einstein equations

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

  The 5-coordinate z plays the role of the energy scale, the behavior of the scalar field ϕ allows one to control the renormalization group properties

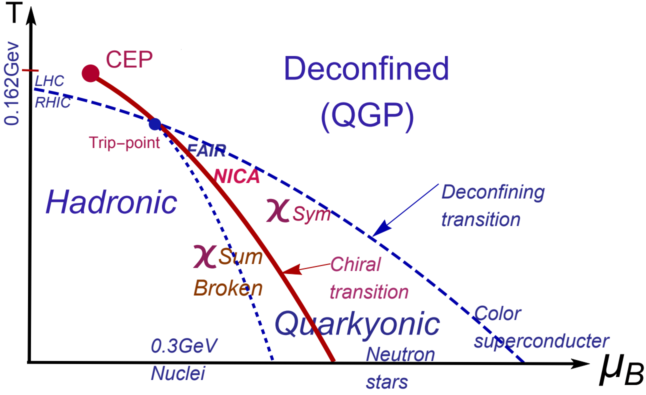
- Phase transition confinement/deconfinement
  - heavy quarks
    - $B=0$
    - $B\neq 0$
  - light quarks
    - $B=0$
    - $B\neq 0$

The Expected QCD Phase Diagram

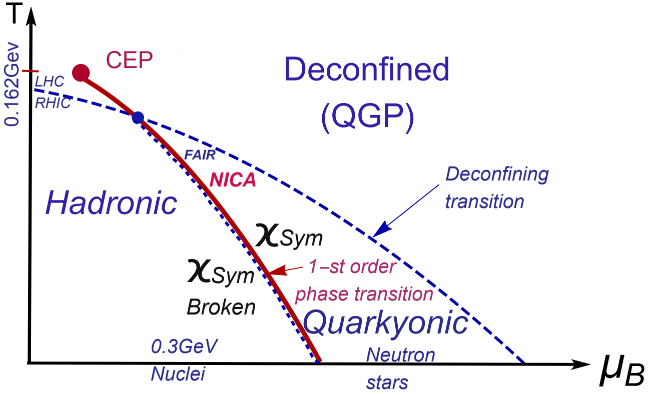
Goal of Holographic QCD — describe QCD phase diagram

Requirements:

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



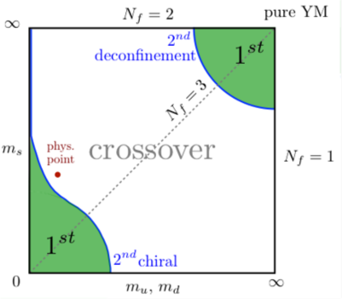
The Expected QCD Phase Diagram

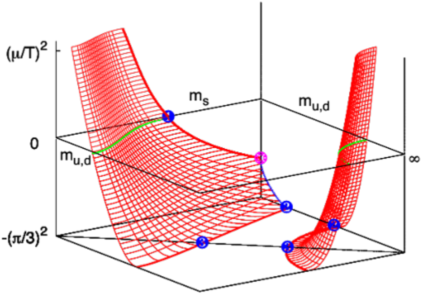


QCD Phase Diagram: Lattice

Phase diagram
on quark mass

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

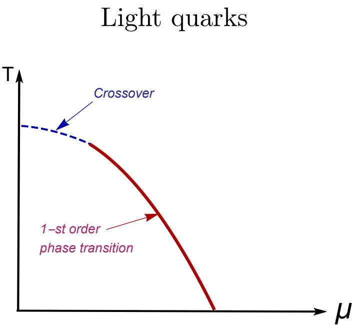


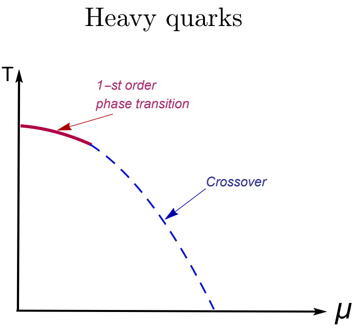


Columbia plot
Brown et al., PRL (1990)

Philipsen, Pinke, PRD (2016)

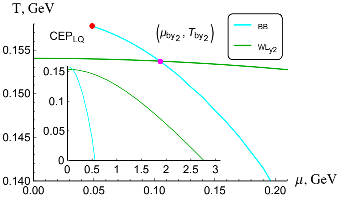
“Heavy” and “Light” Quarks from Columbia Plot

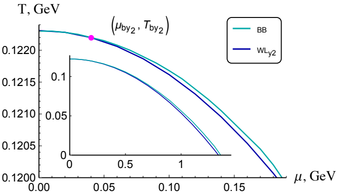




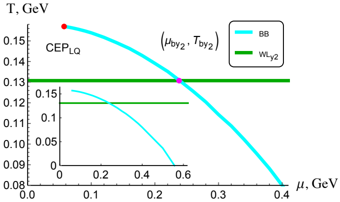
Phase transitions for light quarks

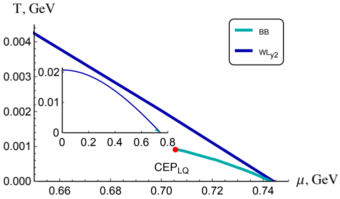
isotropic, $\nu = 1$ **anisotropic, $\nu = 4.5$**





$c_B = 0$ Quarkyonic phase appears during isotropization

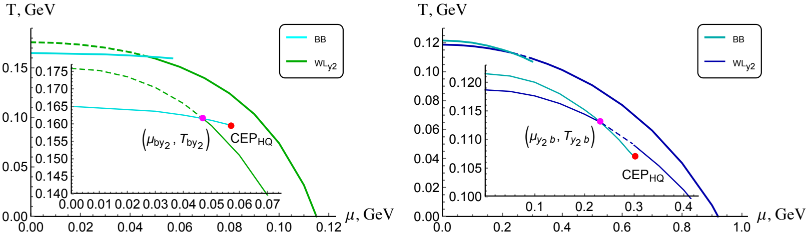




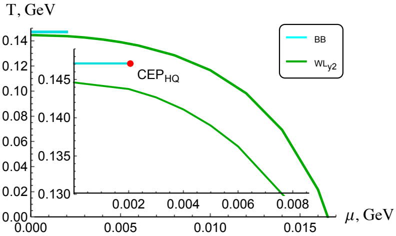
$c_B = -0.0000985$ $c_B = -0.0858$

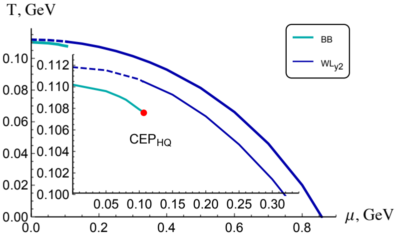
Quarkyonic phase appears during isotropization at large μ

Phase transitions for heavy quarks



$c_B = 0$

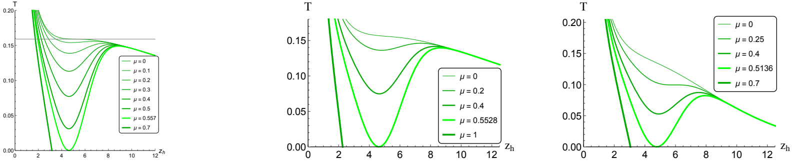




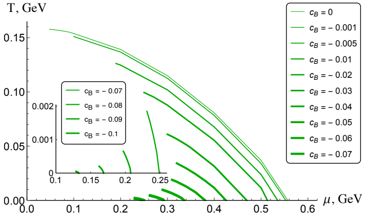
$c_B = -0.0096$ $\qquad$ $c_B = -0.015$

Origin of 1-st order phase transition in HQCD

Light quarks, $\nu = 1$

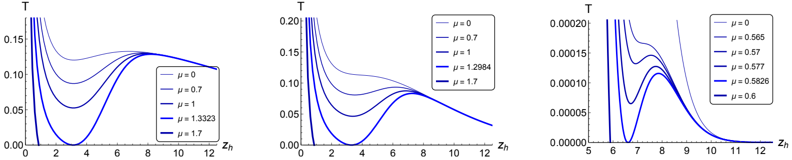


$c_B = 0$ $c_B = 0.001$ $c_B = 0.01$

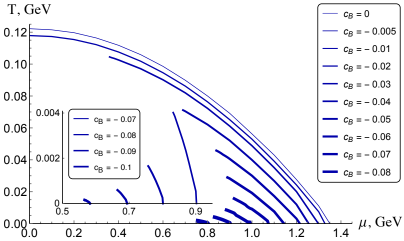


Origin of 1-st order phase transition in HQCD

Light quarks, $\nu = 4.5$

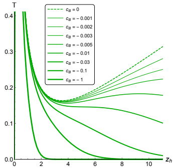


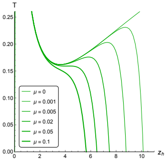
$c_B = 0$ $\qquad$ $c_B = 0.001$ $\qquad$ $c_B = 0.01$

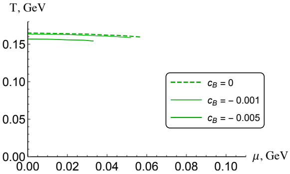


Origin of 1-st order phase transition in HQCD

Heavy quarks, $\nu = 1$

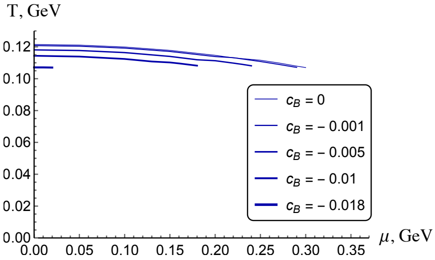






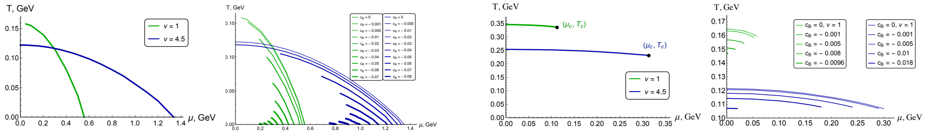
Origin of 1-st order phase transition in HQCD

Heavy quarks, $\nu = 4.5$



Comparison of the 1st order phase transition for light and heavy quarks

Phase transitions of the 1st order in isotropic (green lines $\nu = 1$) and anisotropic (blue lines $\nu = 4.5$) models



light quarks

$B = 0$ $B \neq 0$

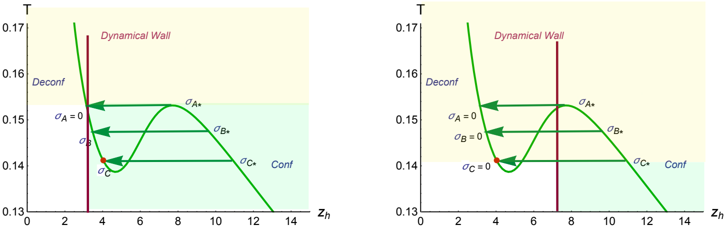
heavy quarks

$B = 0$ $B \neq 0$

- For light quarks, $B = 0$, the onset of the 1st order PTs moves towards $\mu = 0$ as ν increases
- For heavy quarks, $B = 0$, the 1st order PT line becomes longer with increasing ν
- As c_B increases (strong magnetic field) phase transition line lengths decrease

Background 1-st order PT ⇒ 1-st order PT for physical quantities

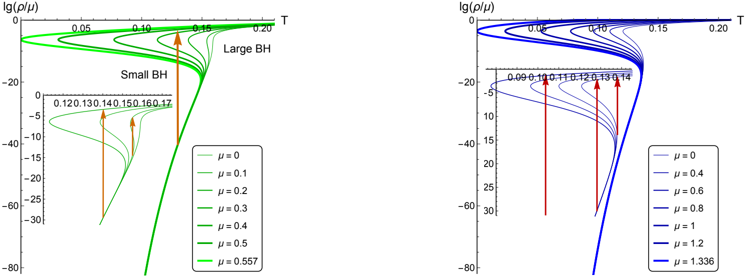
- Physical quantities that probe backgrounds are smooth relative to z_h ⇒ their dependence on T should be taken from stable region
- BB-PT immediately provides the 1-st PT for corresponding characteristic of QCD



The arrows show transitions from the unstable phases to the stable ones

Change of Density across the 1-st Order Transition

$$A_t(z) = \mu - \rho\, z^2 + \ldots$$



$\nu = 1$ $\nu = 4.5$

Density $\rho/\mu(T)$ in logarithmic scale for different μ
$a = 4.046,\ b = 0.01613,\ c = 0.227$
Inner plots show the fragments of main plots zoomed

- At a given T the value of the ratio ρ/μ increases with the transition from unstable to stable state. Quarkionic phase transition?

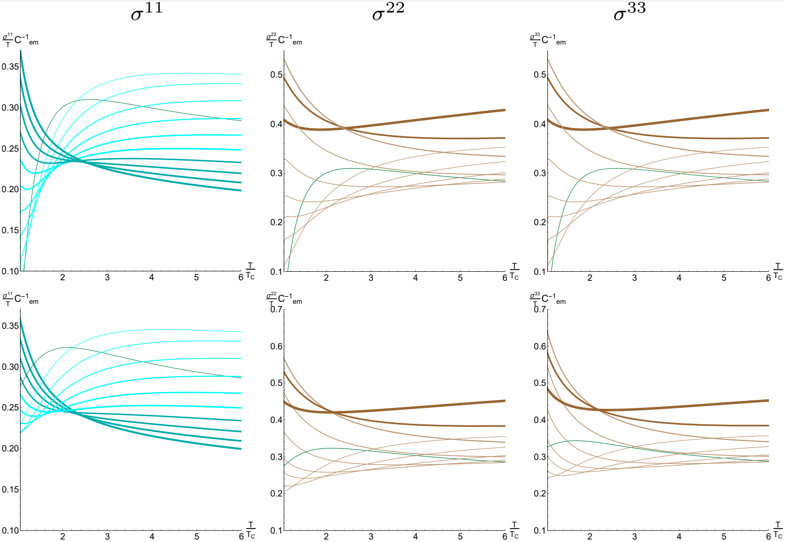
Properties of an anisotropic plasma in a magnetic field at a nonzero chemical potential

- Energy losses $\Longleftrightarrow$ tension of the three-dimensional Wilson loop
  - heavy quarks, $B \neq 0$
    IA., Rannu, Slepov
  - light quarks, $B \neq 0$
    in progress
- Jets quenching $\Longleftrightarrow$ Wilson loop in lightlike direction
  - heavy quarks, $B = 0$
    IA et al, Nucl.Phys.B, 2018
  - light quarks, $B \neq 0$
    in progress
- Photon emission and electrical conduction
  IA, Ermakov, Rannu, Slepov, EPJC22, arXiv:2203.12539

$$d\Gamma \sim \mathrm{Im}\left[\mathrm{tr}\left(\eta_{\mu\nu} G_R^{\mu\nu}\right)\right]_{k^0=|\mathbf{k}|}, \qquad \sigma^{\mu\nu} = -\frac{G_R^{\mu\nu}}{iw}$$

- Entanglement entropy and the number of particles born in a selected volume
  IA, Phys.Part.Nucl.Lett.'19
  IA, Patrushev, Slepov, JHEP'20

Electrical conductivity (light quarks)



$\mu = 0$
$c_B = 0$

$\mu = 0.5$
$c_B = 0.05$

$\nu = 1$(darker green), $\nu = 1.05,\ 1.1,\ 1.15,\ 1.2,\ 1.3,\ 1.5,\ 2,\ 3,\ 4.5$

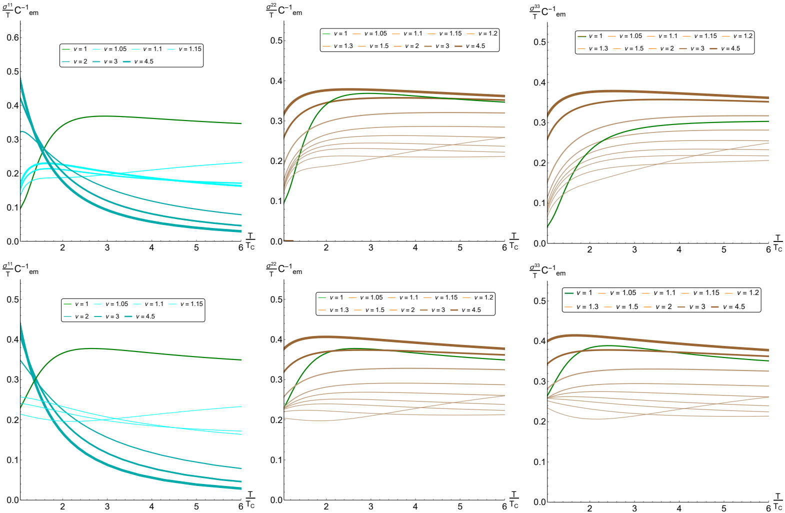
- μ и magnetic field B for all σ^{ii} reduce the "spreading"in anisotropy

Electrical conductivity (heavy quarks)

σ^{11} σ^{22} σ^{33}

$\mu = 0$
$c_B = 0$

$\mu = 0.5$
$c_B = 0.05$



- when changing the mass of quarks no change in σ^{11}, but there is in σ^{22} and σ^{33}

Conclusion

- We have reproduced (using holography) experimental dependence of total particle multiplicity on energy

- QCD phase diagram
  - Anisotropy leads to smearing of the confinement/deconfinement phase transition
  - Magnetic field dependence – effect of inverse/direct magnetic (MC) catalysis: **critical T decreases/increases with increasing of B**
  - Dependence on quark mass: **for heavy quarks should be MC (still not get), for light quarks – IMC (OK)**

- Dependence of electrical conductivity on
  - anisotropy
  - quark masses: σ^{11} **weak,** σ^{22}, σ^{33} **essential dependencies**
  - magnetic field - **reduces anisotropy smearing**

Back-up. Twice Anisotropic Background

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

$A_\mu^{(1)} = A_t(z)\delta_\mu^0$ $\quad$ $F^{(2)} = dy^1 \wedge dy^2$ $\quad$ $F^{(B)} = dx \wedge dy^1$

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

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

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

Giataganas (2013),I.A., A.G. (2014) $\quad$ *Gürsoy, Järvinen et al., (2019)*

$\mathfrak{b}(z) = e^{2\mathcal{A}(z)} \rightarrow$ quarks mass $\quad$ “Bottom-up approach”

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

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

Instead of epigraph

Rephrasing the well known Russian song about Gleb Zheglov
and Volodya Sharapov,

I would say that Gleb Zheglov and his colleagues got up in the morning

not for no reason:

they try to find QGP and Phase Transitions.