Holography for heavy ions collisions

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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: the energy losses, quenching coefficient of jets, the emission rate of direct photons
    - **New in the last years** - **more detailed structure of phase transitions**

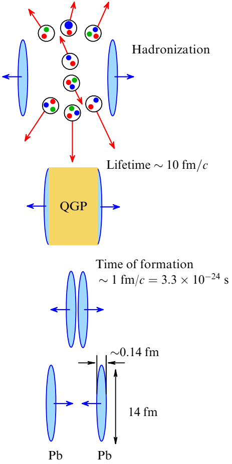
Outlook

The latest results have already been presented at this conference

in the reports of my collaborators:

- A.Hajilou, *Magnetic catalysis in holographic model with two types of anisotropy for heavy quarks*
- P.Slepov, *Energy loss for heavy quarks in strong magnetic field*
- K.Rannu, *On the role of the* z^5 *term in the metric strain coefficient for the holographic description of magnetic catalysis in a quark-gluon plasma*
- M.Usova, *Holographic RG flows for light and heavy quarks models*

Evolution during heavy ion collision



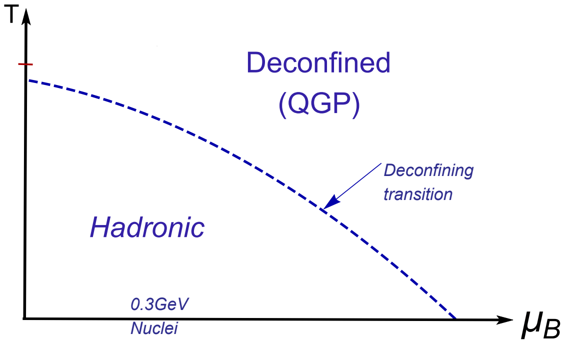
- QGP is a state of matter of free quarks, antiquarks and gluons at high temperature. QGP was discovered at RHIC in 2005.
- QGP behaves (RHIC, LHC) like a strongly interacting fluid (collective effects)

QGP - strongly interacting liquid

- **Two questions:**
  1. How was it formed?
  2. what properties does it have?
  - **The main property is the structure of the phase diagram**

QCD Phase Diagram: Early Conjecture

Cabibbo and Parisi, 1975



- μ a measure of the imbalance between quarks and antiquarks in the system

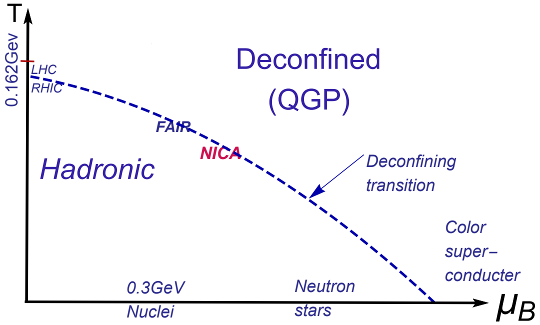
QCD Phase Diagram: Experiments

- LHC, RHIC (2005);
- FAIR (Facility for Antiproton and Ion Research),

  NICA (Nuclotron-based Ion Collider fAcility)

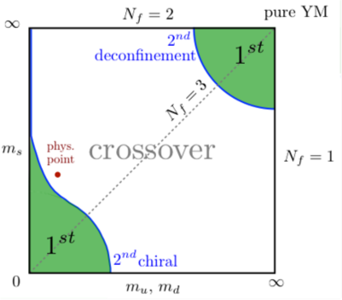
Main goals

- search for signs of the phase transition between hadronic matter and QGP;
- search for new phases of baryonic matter



QCD Phase Diagram: Lattice

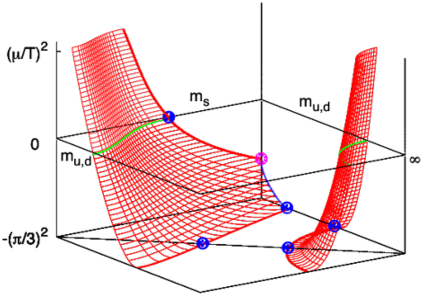
Phase diagram
on quark mass



Columbia plot

Brown et al., PRL (1990)

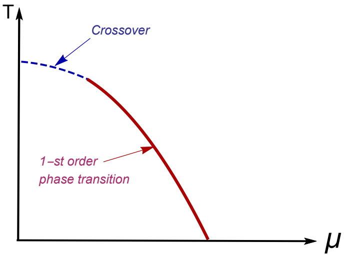
Main problem with $\mu \neq 0$
Imaginary chemical potential method



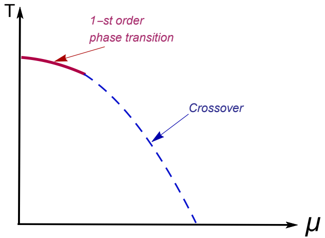
Philipsen, Pinke, PRD (2016)

“Heavy” and “light” quarks from Columbia plot

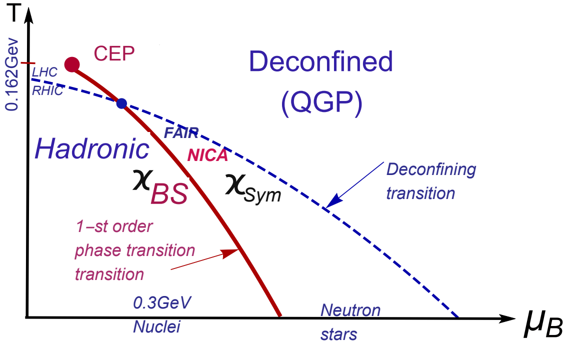
Light quarks



Heavy quarks

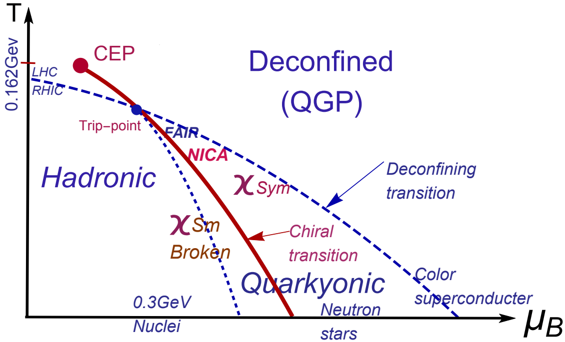


The expected QCD phase diagram



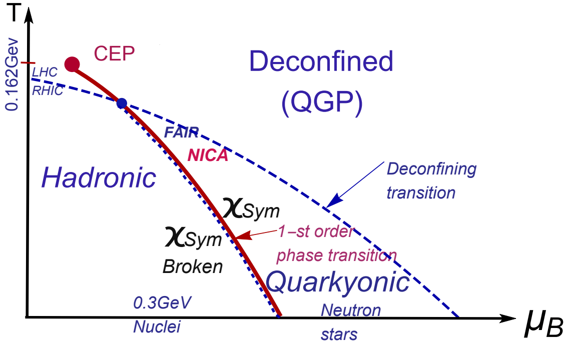
- Parameter of the chiral symmetry breaking $< \bar{\psi}\psi >$
  - $< \bar{\psi}\psi > = 0 \Longleftrightarrow \chi$-symmetry
  - $< \bar{\psi}\psi > \neq 0 \Longleftrightarrow$ broken χ-symmetry

The expected QCD phase diagram



- Quarkyonic phase: baryon free ⇒ dense baryons *McLerran, Pisarski 0706.2191*
  - Baryon density jumps

The expected QCD phase diagram



Holographic QCD

- Perturbation methods are **not applicable** to describe QCD phase diagram
- Lattice methods **do not work**, because of problems with the chemical potential.
- **Holographic QCD - phenomenological model(s)**
- One of goals 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

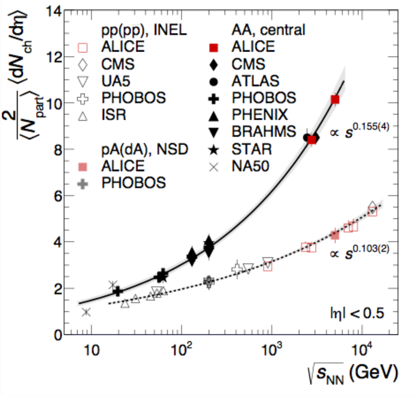
Holographic method - phenomenological approach

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

Total multiplicity produced in heavy ions collision

- Results of applying the holographic approach to the description of collisions between heavy ions and quark-gluon plasma should be explanation of experimental data. As an example of such explanation of experimentally data - calculation of **the total multiplicity**



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

$$\mathcal{M}_\nu \sim s^{\frac{1}{2+\nu}}, \qquad \textbf{I.A., Golubtsova, JHEP, 2014}$$

$$\mathcal{M}_{LHC} \sim s^{0.155} \qquad \nu = 4.45$$

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

I.A, K. Rannu, P.Slepov, JHEP, 2021

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

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

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

Giataganas'13; IA, Golubtsova'14; Gürsoy, Järvinen '19; Dudal et al.'19

$\mathfrak{b}(z)=e^{2\mathcal{A}(z)}\ \Leftrightarrow$ quarks mass

"Bottom-up approach"

Heavy quarks background (b, t):

$\mathcal{A}(z)=-\ cz^2/4$ — *Andreev, Zakharov'06*

$\mathcal{A}(z)=-\ cz^2/4+pz^4$ — *IA, Hajilou, Rannu, Slepov, 2305.06345*

$\mathcal{A}(z)=-\ cz^2/4+dB^2z^5$ — *Bohra, Dudal, Hajilou, Mahapatra, PRD 21; Rannu's talk*

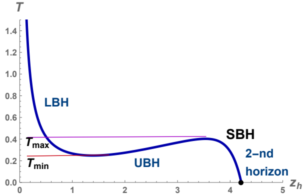
Light quarks background (d, u)

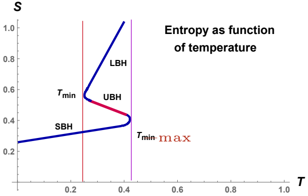
$\mathcal{A}(z)=-\,a\ln(bz^2+1)$ — *Li, Yang, Yuan'17*

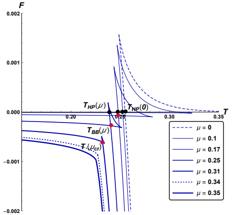
Origin of 1-st order phase transition in HQCD

- $g(z)$ blackenning function. The form of $g(z)$ depends on $\mathcal{A}(z)$.
- Due **non-monotonic** dependence of $T = T(z_h) = g'(z)/4\pi\Big|_{z=z_h}$ on z_h, the entropy $s = s(T)$ is **not monotonic**
- As a consequence the free energy $F = -\int s dT$ undergoes the phase transition

1-st order phase transition describes transition
from **small black holes → large black holes**





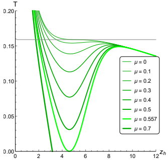


The swallow-tailed shape

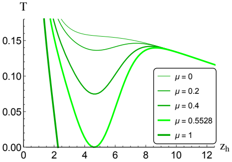
- Physical quantities that probe backgrounds are smooth relative to z_h
  $\Rightarrow$ their dependence on T **should be taken from stable region**
- Non-monotonic dependence of $T = T(z_h)$ gives the 1-st PT for corresponding characteristic of QCD

Origin of 1-st order phase transition in HQCD

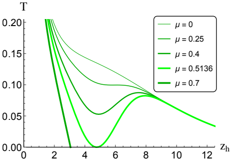
Light quarks, $\nu = 1$ IA, Ermakov, Rannu, Slepov, Eur.Phys.J. C'23



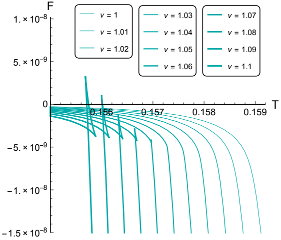
$c_B = 0$



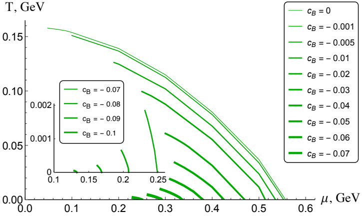
$c_B = 0.001$



$c_B = 0.01$

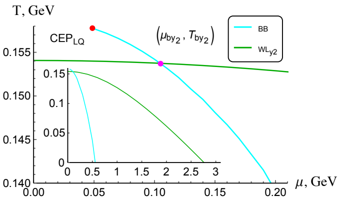


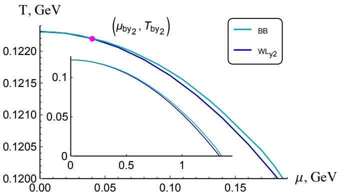
$\mu = 0$



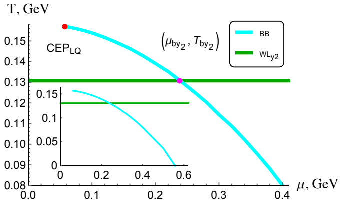
Phase transitions for light quarks

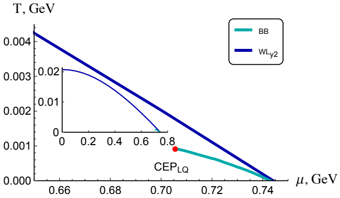
isotropic, $\nu = 1$ **anisotropic, $\nu = 4.5$**





$c_B = 0$ Quarkyonic phase (QP) appears during isotropization



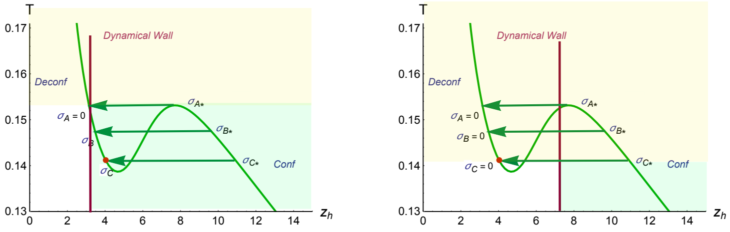


$c_B = -0.0000985$ $c_B = -0.0858$

For $\nu = 4.5$ QP appears at large magnetic field and large μ

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**
- Non-monotonic dependence of $T = T(z_h)$ gives the 1-st PT for corresponding characteristic of QCD



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

Conclusion

- QCD phase diagram
  - Anisotropy leads to smearing of the confinement/deconfinement phase transition
  - **Effect of inverse (IMC)/direct magnetic (MC) catalysis**
    [critical T decreases/increases with increasing of B]

    dependents on quark mass:

    for heavy quarks — MC
    for light quarks — IMC
  - we expect an influence of isotropization on MC/IMC

Conclusion

- **The hadronic matter - quarkyonic matter** phase transition $\Longleftrightarrow$ the first order phase transition for HQCD with light quarks.
- A characteristic feature of quarkyonic matter is a small, compared with the confinement potential, a linear potential between quarks, which is not sufficient to keep quarks inside hadrons.
- Transverse-longitudinal anisotropy and magnetic field essentially influence on location of the quarkyonic phase
- We expect **a jump of jet quenching** on the hadronic - quarkyonic phase transition

Main refs

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- I.A., K. Rannu, P. S. Slepov, "Anisotropic solutions for a holographic heavy-quark model with an external magnetic field", TMPh **206** (2021) 400
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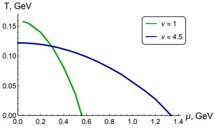
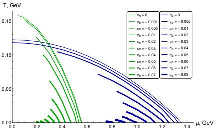
Backup. Comparison of the 1st order phase transition for light and heavy quarks

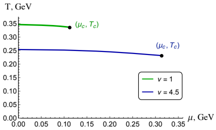
Phase transitions of the 1st order in isotropic (green lines $\nu = 1$) and anisotropic (blue lines $\nu = 4.5$) models

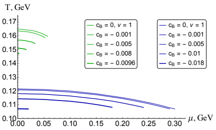




light quarks

$B = 0$ $\qquad$ $B \neq 0$





heavy quarks

$B = 0$ $\qquad$ $B \neq 0$

- 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