

Holographic approach for quark-gluon plasma formation in heavy ion collisions

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Outlook

- Physical picture of formation of Quark-Gluon Plasma in heavy-ions collisions
- **Why holography?**
- **Results from holography** (fit of experimental data via holography:
top-down
bottom-up)
- **Holography description of static QGP**
- **Holography description of QGP formation in heavy ions collisions**
 - **Thermalization time**
 - **Multiplicity**

Quark-Gluon Plasma (QGP): a new state of matter

QGP is a state of matter formed from deconfined quarks, antiquarks, and gluons at high temperature

QCD: asymptotic freedom, quark confinement

**T increases, or
density increases**

**nuclear
matter**



**Deconfined
phase**

Experiments: Heavy ions collisions produced a medium



There are strong experimental evidences that RHIC or LHC have created some medium which behaves collectively:

- modification of particle spectra (compared to p+p)
- jet quenching
- high p_T -suppression of hadrons
- elliptic flow
- suppression of quarkonium production

Study of this medium is also related with study of Early Universe

QGP as a strongly coupled fluid

- Conclusion from the RHIC and LHC experiments: appearance of QGP (not a weakly coupled gas of quarks and gluons, but **a strongly coupled fluid**).
- This makes perturbative methods inapplicable
- The lattice formulation of QCD does not work, since we have to study real-time phenomena.
- This has provided a motivation to try to understand the dynamics of QGP through the **gauge/string duality**

Dual description of QGP as a part of Gauge/string duality

- There is not yet exist a gravity dual construction for QCD.
- Differences between $N = 4$ SYM and QCD are less significant, when quarks and gluons are in the deconfined phase (because of the conformal symmetry at the quantum level $N = 4$ SYM theory does not exhibit confinement.)
- Lattice calculations show that QCD exhibits a quasi-conformal behavior at temperatures $T > 300$ MeV and the equation of state can be approximated by $E = 3 P$ (a traceless conformal energy-momentum tensor).
- This motivates to use the AdS/CFT correspondence as a tool to get non-perturbative dynamics of QGP.
- There is the considerable success in description of the static QGP.

Review: Solana, Liu, Mateos, Rajagopal, Wiedemann, 1101.0618

I.A., Holographic approach for quark-gluon plasma in heavy ion collisions,
UFN, v184, 2014

Holography and AdS/CFT correspondence

$$\langle e^{\int_{\partial M} \phi_0 \mathcal{O}} \rangle$$

$$= e^{S_g[\phi_c(\phi_0)]}$$

Maldacena, 1997
Gubser, Klebanov, Polyakov
Witten, 1998

M=AdS, BAdS, ...

$$\phi(t, \vec{x}, z), \quad S_g[\phi], \quad \delta S_g[\phi_c] = 0$$

$$\phi_c|_{\partial M} = \phi_0$$

+ requirement of regularity at horizon

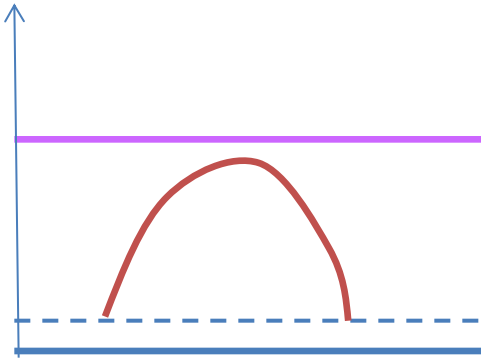
Correlators with/without Temperature via AdS/CFT

Example I. AdS, D=2+1

$$ds^2 = \frac{-dt^2 + dx^2 + dz^2}{z^2}$$

$$\langle O_{\Delta}(t, x) O_{\Delta}(t, x') \rangle \sim \frac{1}{|x - x'|^{2\Delta}}$$

Example II. BHAdS, D=2+1



$$ds^2 = \frac{1}{z^2} (f(z) dt^2 + \frac{dz^2}{f(z)} + d\vec{x}^2)$$

$$f(z) = 1 - Mz^2$$

$$r_H = 2\pi T$$

Temperature

$$\langle O_{\Delta}(t, x) O_{\Delta}(t, x') \rangle_T \sim \frac{1}{|\sinh(\pi T |x - x'|)|^{2\Delta}}$$

Bose gas

Holography for thermal states



TQFT in
 M_D -spacetime

=

Black hole
in AdS_{D+1} -space-time

TQFT = QFT with temperature

Holographic Description of Formation of QGP

(Holographic thermalization)



Thermalization of QFT in
Minkowski D -dim space-
time



Black Hole formation
in Anti de Sitter
 $(D+1)$ -dim space-time

Models of BH creation in D=5 and their meaning in D=4

$$g_{MN} \Rightarrow g_{MN}^{(0)} + g_{MN}^{(1)}$$

- **AdS/CFT correspondence**

$$Z_{ren}(z_0) \left. g_{\mu\nu}^{(1)} \right|_{\substack{\text{boundary} \\ z_0 \rightarrow 0}} = T_{\mu\nu}$$

Main idea: make some perturbation of AdS metric that near the boundary “mimic” the matter (heavy ions) collisions and see what happens.

Holographic thermalization



How to “mimic” the heavy ions collision

Models:

shock waves collision in AdS

colliding ultrarelativistic particles in AdS_3 (toy model)

infalling shell

Holographic thermalization

Physical quantities that we expect to estimate:

D=5 AdS

- Black hole formation time
- Entropy

D=4 Minkowski

- Thermalization time
- Multiplicity



Thermalization time

Experimental data (just estimations)

Bjorken, 1983

$$\epsilon(y) = \frac{1}{A\tau_{therm}} \frac{N}{dy} \langle m_{tr} \rangle, \quad m_{tr} = \sqrt{m_{\pi}^2 + k_{tr}}$$

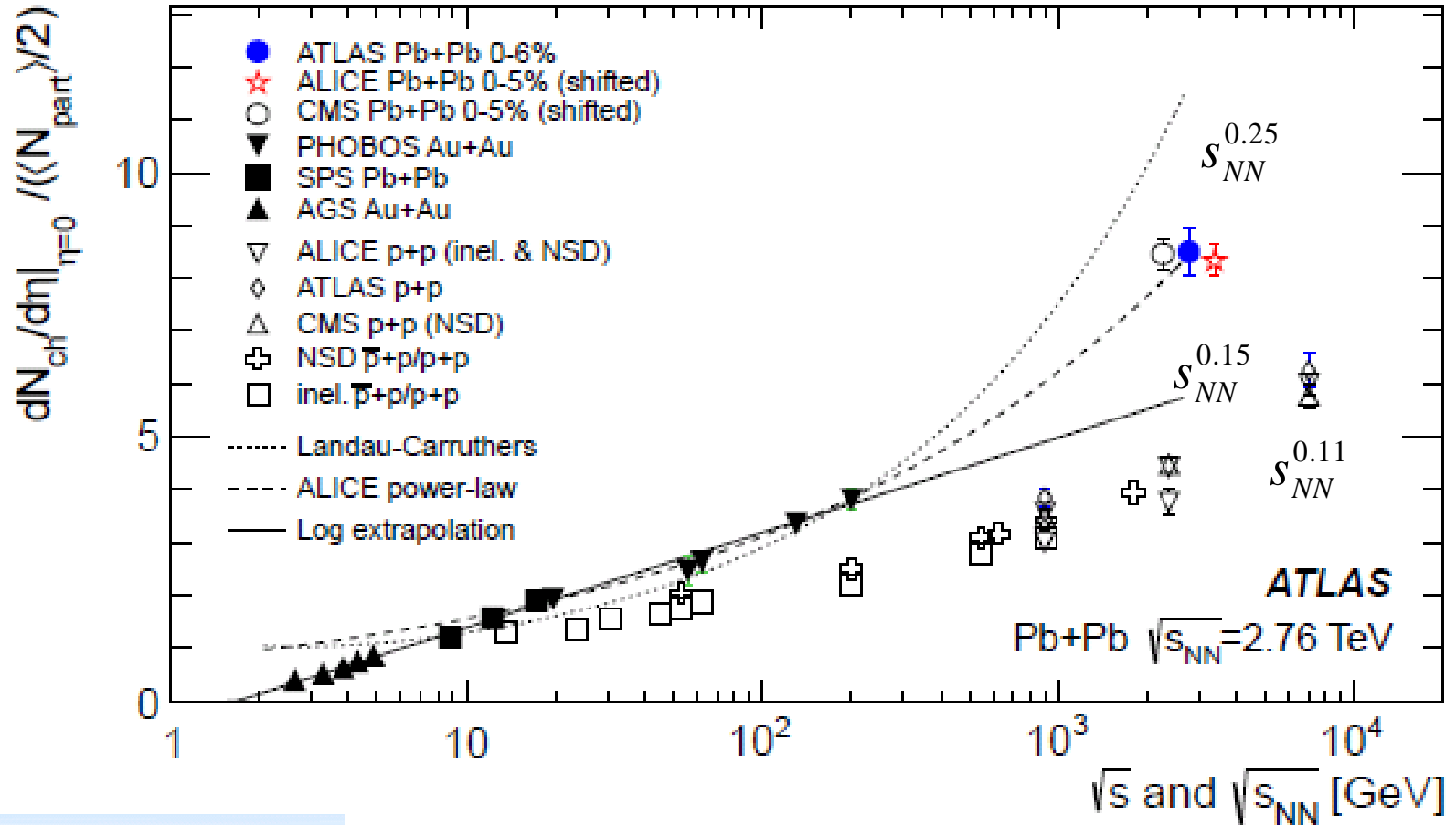
Holographic estimations

Position of horizon ~ size of the trapped surface

Multiplicity

Experimental data

Plot from: ATLAS Collaboration 1108.6027



PbPb

$$dN_{ch}/d\eta \propto s_{NN}^{0.15}$$

pp:

$$dN_{ch}/d\eta \propto s_{NN}^{0.11}$$

Multiplicity as entropy

D=4. Macroscopic theory of high-energy collisions

Landau(1953); Fermi(1950)

thermodynamics, hydrodynamics, kinetic theory, ...

D=5. Holographic approach

Main conjecture: multiplicity is proportional to entropy of produced D=5 Black Hole

$$\mathcal{M} \sim S$$

Gubser et al: 0805.1551

The minimal black hole entropy can be estimated by trapped surface area

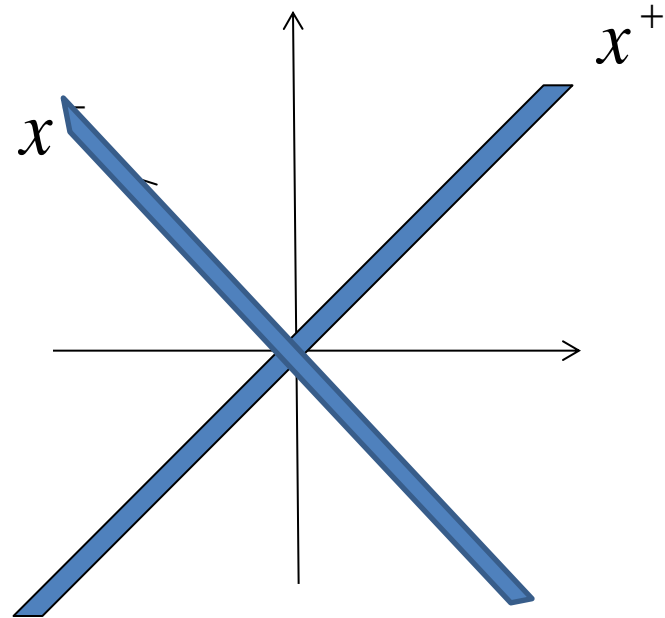
$$S \geq S_{trapped} = A_{trapped} / 4G_N$$

Gubser, Pufu, Yarom, JHEP , 2009
Alvarez-Gaume, C. Gomez, Vera,
Tavanfar, Vazquez-Mozo, PLB, 2009
IA, Bagrov, Guseva, JHEP, 2009
Kiritsis, Taliotis, JHEP, 2011

Nucleus collision in AdS/CFT

$$\langle T_{--} \rangle \sim \mu \delta(x^-)$$

$$\langle T_{++} \rangle \sim \mu \delta(x^+)$$



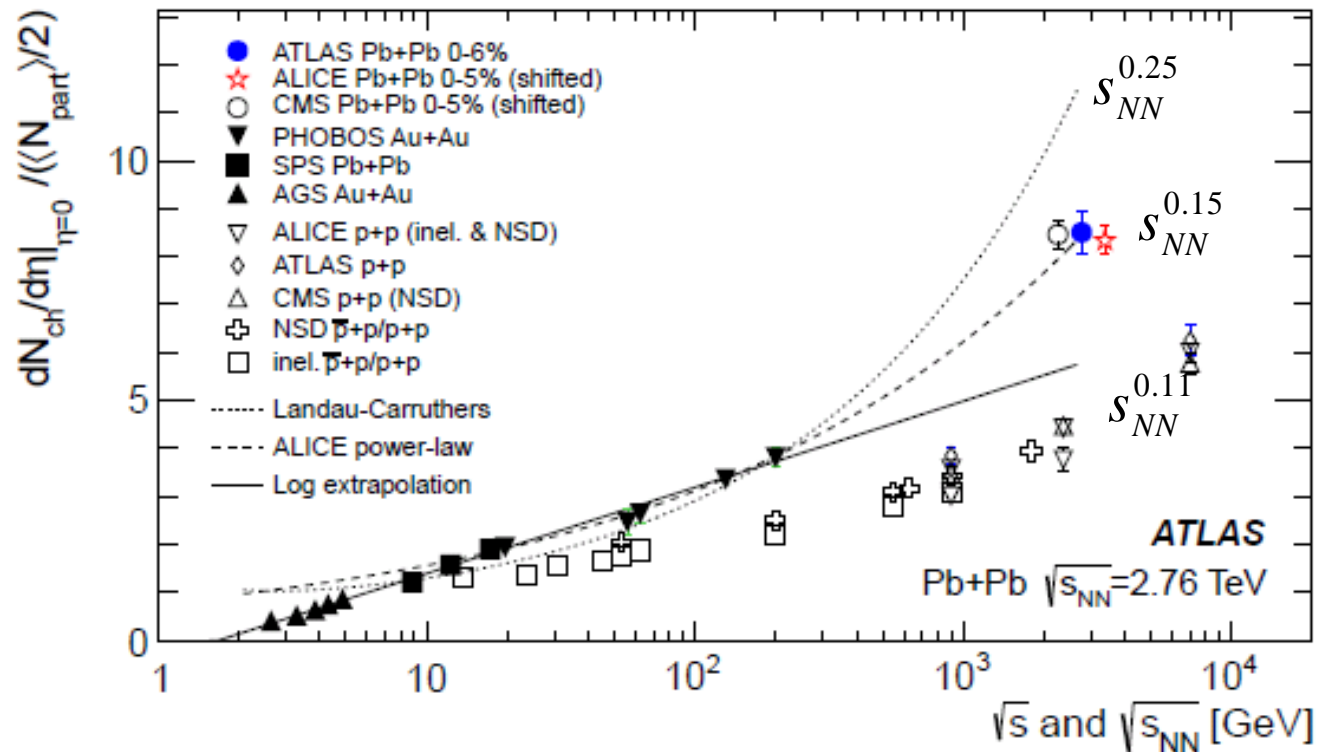
$$ds^2 = \frac{L^2}{z^2} \left[-2 dx^+ dx^- + \frac{2\pi^2}{N_C^2} \langle T_{--}(x^-) \rangle z^4 dx^{-2} + \frac{2\pi^2}{N_C^2} \langle T_{++}(x^+) \rangle z^4 dx^{+2} + dx_{\perp}^2 + dz^2 \right]$$

The metric of two shock waves in AdS corresponding to collision of two ultrarelativistic nucleus in 4D

Multiplicity: Holographic formula vs experimental data

The simple holographic model gives

$$dN_{ch}/d\eta \sim s_{NN}^{1/3}$$



Search for models with suitable entropy

Metric with modified b-factor

IHQCD

Gursoy, Kiritsis, Nitti

$$S_5 = -\frac{1}{16\pi G_5} \int \sqrt{-g} \left[R + \frac{d(d-1)}{L^2} - \frac{4}{3}(\partial\Phi)^2 + V(\Phi_s) \right] dx^5$$

$$ds^2 = b^2(z)(-dt^2 + dz^2 + dx_i^2)$$

Reproduces 2-loops QCD beta-function

Reproduce an asymptotically-linear glueball spectrum

Search for models with suitable entropy

Kiritsis, Taliotis, **JHEP(2012)**

Shock wave metric with modified b-factor

$$ds^2 = b^2(z)(dz^2 + dx^i dx^i - dx^+ dx^- + \phi(z, x^1, x^2)\delta(x^+)(dx^+)^2)$$

Typical behaviour

$$b(z) = \frac{L}{z} e^{-z^2/z_0^2}$$

$$s_{NN}^{\delta_1} \ln^{\delta_2} s_{NN}$$

$$\delta_1 \approx 0.225, \quad \delta_2 \approx 0.718$$

not 0.15

Shock wall with modified by b-factor

Description of HIC by the wall-wall shock wave collisions

S. Lin, E. Shuryak, 0902.1508

I. A., Bagrov and E.Pozdeeva, JHEP(2012)

$$ds^2 = b^2(z)(dz^2 + dx^i dx^i - dx^+ dx^- + \phi^w(z, x^1, x^2) \delta(x^+) (dx^+)^2)$$

$$\left(\partial_z^2 + \frac{3b'}{b} \partial_z \right) \phi^w(z) = -16\pi G_5 \frac{E^*}{b^3} \delta(z_* - z)$$

I. A., E.Pozdeeva, T.Pozdeeva (2013, 2014)

$$S_{\text{points}} \sim S_{\text{walls}}$$

Power-law b-factor

$$b = (L/z)^a$$

$$S_{\text{walls}} = \frac{L}{2G_5} \left(\frac{8\pi G_5}{L^2} \right)^{\frac{3a-1}{3a}} E^{\frac{3a-1}{3a}}$$

The multiplicity depends as $s^{0.15}_{\text{NN}}$ in the range $10\text{-}10^3$ GeV

Power-law b-factor coincides with experimental data at $a \approx 0.47$.

We consider

$$b(z) = \frac{L}{z^{1/2}}$$

Price: non standard kinetic term !?

Multiplicity with anisotropic Lifshitz background

$$S = \frac{1}{2\kappa^2} \int d^5x \sqrt{|g|} \left[R - 2\Lambda - \frac{1}{12} H_3^2 - \frac{m_0^2}{2} B_2^2 \right]$$

IA, A. Golubtsova

$$H_3 = 2\sqrt{\frac{\nu-1}{\nu}} \rho d\rho \wedge dt \wedge dx, \quad B_2 = \sqrt{\frac{\nu-1}{\nu}} \rho^2 dt \wedge dx$$

$$\Lambda = 5 + \frac{6}{\nu} + \frac{3}{\nu^2}$$

$$ds^2 = \rho^2 (-dt^2 + dx^2) + \rho^{2/\nu} (dy_1^2 + dy_2^2) + \frac{d\rho^2}{\rho^2}$$

Shock wave

$$z = 1/\rho$$

$$ds^2 = \frac{\phi(y_1, y_2, z)\delta(u)}{z^2} du^2 - \frac{1}{z^2} dudv + z^{-2/\nu} (dy_1^2 + dy_2^2) + \frac{dz^2}{z^2}$$

Solves E.O.M. if

$$\delta(u) \left[\square_3 - \left(1 + \frac{2}{\nu} \right) \right] \frac{\phi(y_1, y_2, z)}{z} = -2zT_{uu}$$

\square_3

$$ds^2 = \rho^{2/\nu} (dy_1^2 + dy_2^2) + \frac{d\rho^2}{\rho^2}$$

Multiplicity with anisotropic Lifshitz background

Domain wall

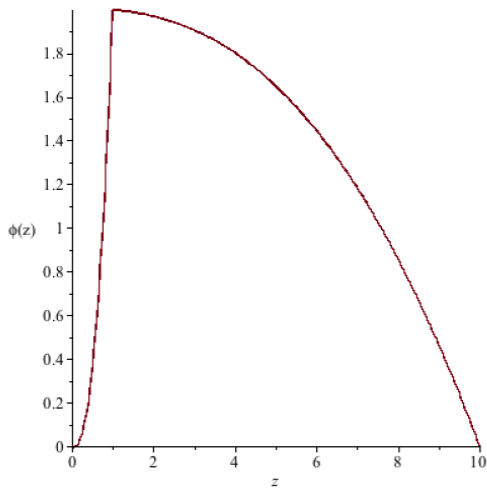
$$\left[\square_3 - \left(1 + \frac{2}{\nu} \right) \right] \frac{\phi(z)}{z} = -16\pi G_5 z J_{uu} \quad J_{uu} = z^{1+2/\nu} \delta(z - z_0)$$

$$\phi(z) = -\frac{8\nu\pi G_5 E}{\nu + 1} z_0^{2(\nu+1)/\nu} \Theta(z - z_0) \left(\frac{z^{2(\nu+1)/\nu}}{z_0^{2(\nu+1)/\nu}} - 1 \right) + C_1 z^{2(\nu+1)/\nu} + C_2,$$

Multiplicity with anisotropic Lifshitz background

Colliding Domain Walls

$$ds^2 = -\frac{1}{z^2}dudv + \frac{1}{z^2}\phi_1(y_1, y_2, z)\delta(u)du^2 + \frac{1}{z^2}\phi_2(y_1, y_2, z)\delta(u)dv^2 .$$
$$+ \frac{1}{z^{2/\nu}}(dy_1^2 + dy_2^2) + \frac{dz^2}{z^2}$$



$$\mathcal{S} \sim \frac{\nu}{4G_5} (8\pi G_5)^{2/(\nu+2)} E^{2/(\nu+2)}$$

To get $\mathcal{S} \sim E^{0.3}$

$$\nu = 4$$

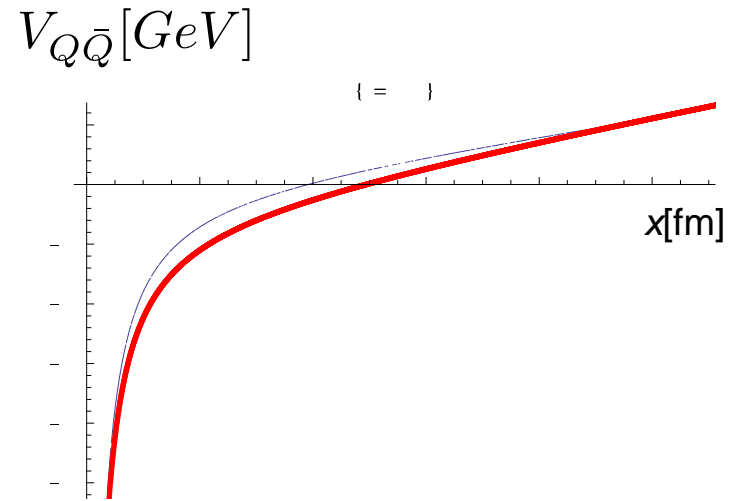
Question: can we fit this background with other data?

Multiplicity VS quark potential

$$ds^2 = b^2(z)(-dt^2 + dz^2 + dx_i^2)$$

$$b^2(z) = \frac{L^2 h(z)}{z^2}$$

$$h = e^{\frac{az^2}{2}}$$



AdS with soft-wall

$$V_{Cornell}(x) \equiv V_{Q\bar{Q}}(x) = -\frac{\kappa}{x} + \sigma_{str}x + V_0$$

$$\kappa \approx 0.48, \quad \sigma_{str} = 0.183 \text{ GeV}^2, \quad C = -0.25 \text{ GeV}$$

Coulomb term

Confinement
linear potential

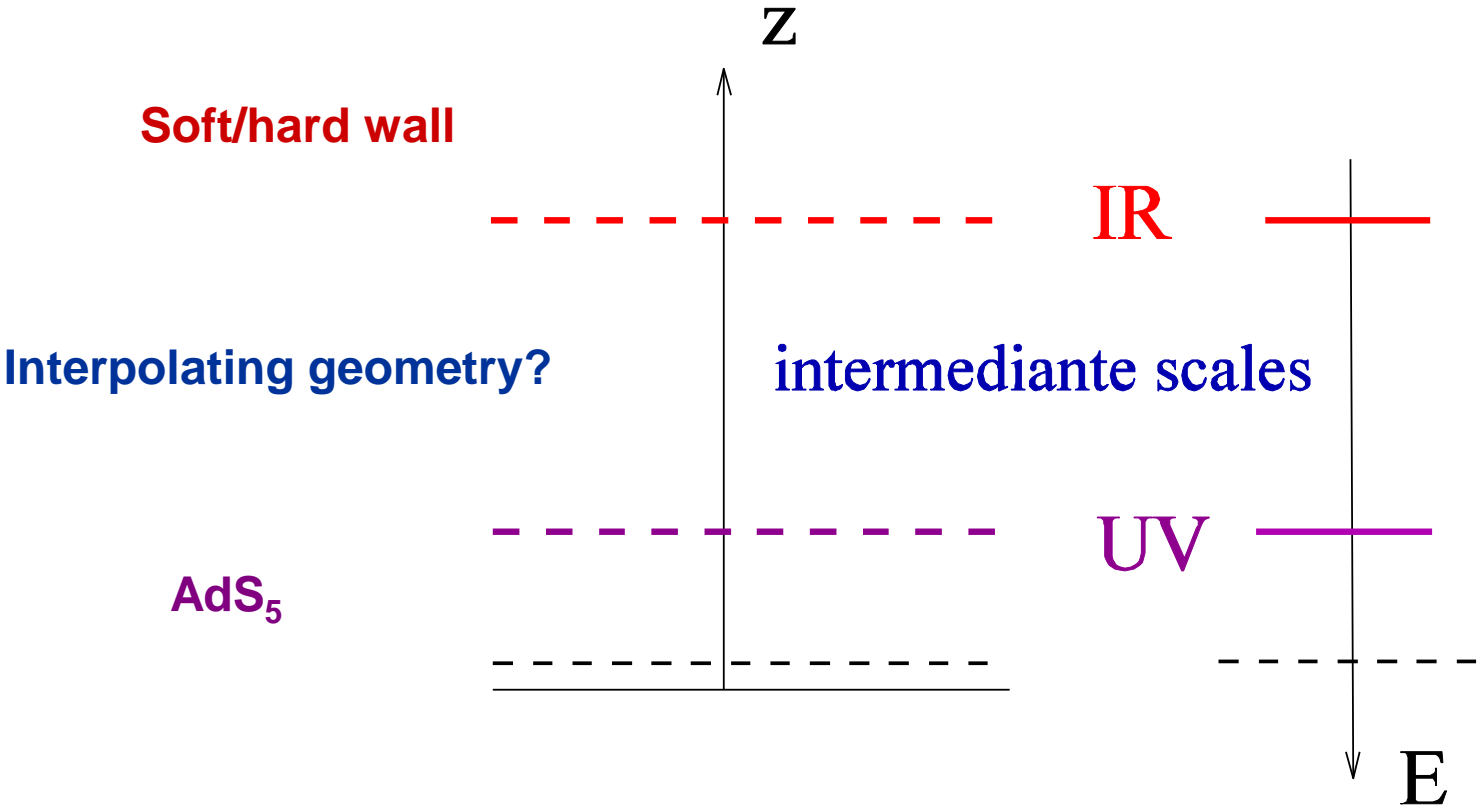
O. Andreev and V. Zakharov
hep-ph/0604204

R.Galov et al, 0911.0627

S.He, M.Huang, Q.Yan

1004.1880

Multiplicity **VS** quark potential



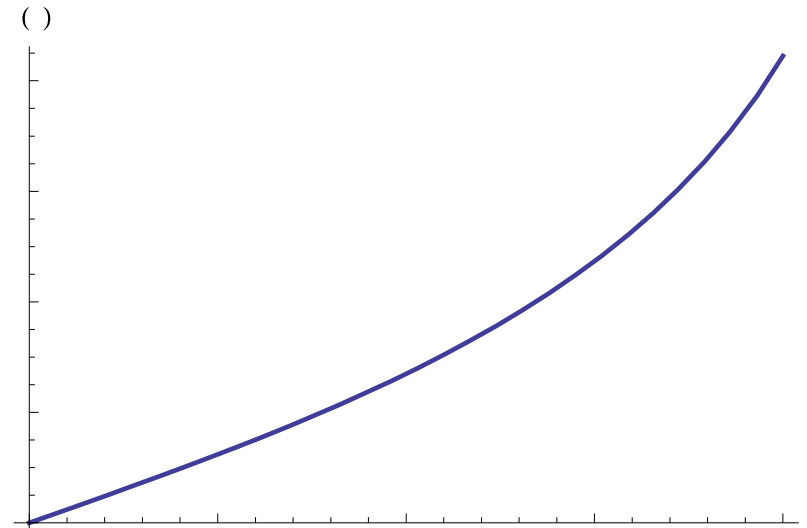
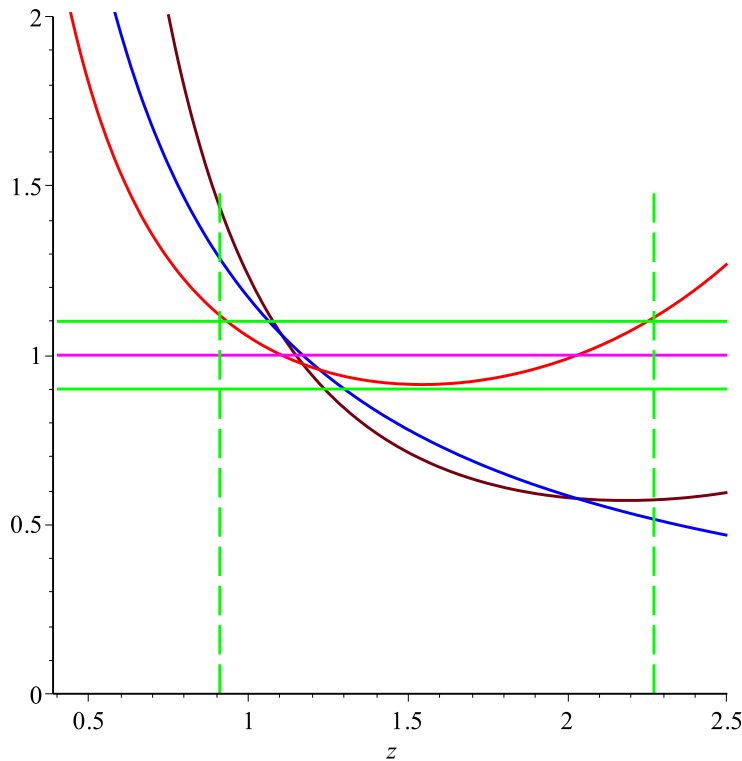
Multiplicity and quark potential

with D.Ageev

$$\frac{L^2 e^{\frac{az^2}{2}}}{z^2} \approx \frac{L^2}{z L_{eff}}$$

$$z_{UV} < z < z_{IR}$$

$$L_{eff} = 0.95$$



Multiplicity and quark potential

Quark potential in string frame

$$ds_s^2 = e^{2\mathcal{A}(z)} (-dt^2 + d\vec{x}^2 + dz^2)$$

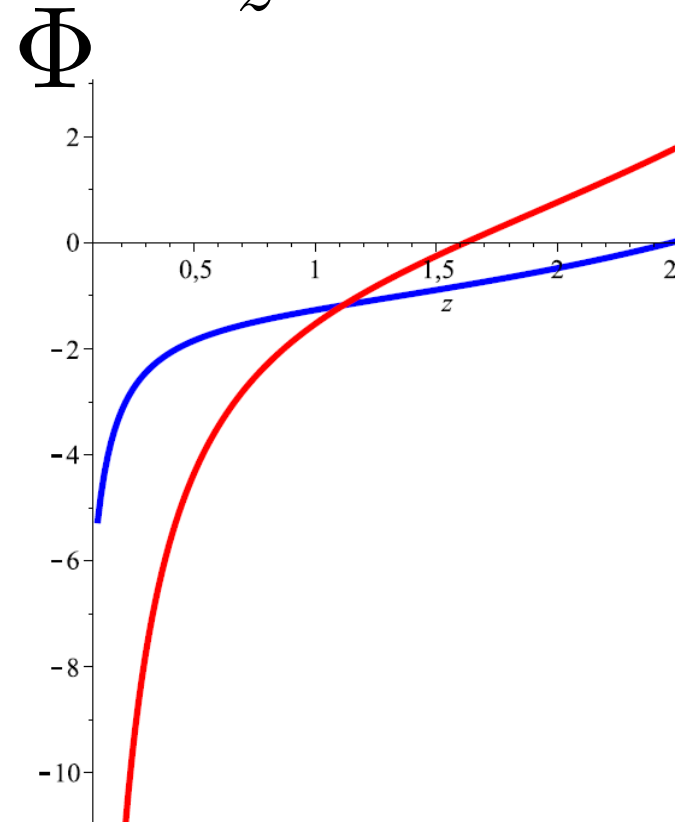
$$\frac{L^2 e^{\frac{az^2}{2}}}{z^2} = e^{2\mathcal{A}}$$

Trapped surface in Einstein frame

$$ds_E^2 = e^{2A(z)} (-dt^2 + d\vec{x}^2 + dz^2)$$

$$A(z) = -\frac{2}{3}\Phi + \mathcal{A}$$

$$\Phi'' - 2\mathcal{A}'\Phi' = \frac{3}{2}(\mathcal{A}'' - \mathcal{A}'^2)$$



Multiplicity and quark potential

$$\frac{e^{-\frac{3}{4}\Phi + \frac{az^2}{2}}}{z^2} \approx \frac{L_{eff}}{z}$$

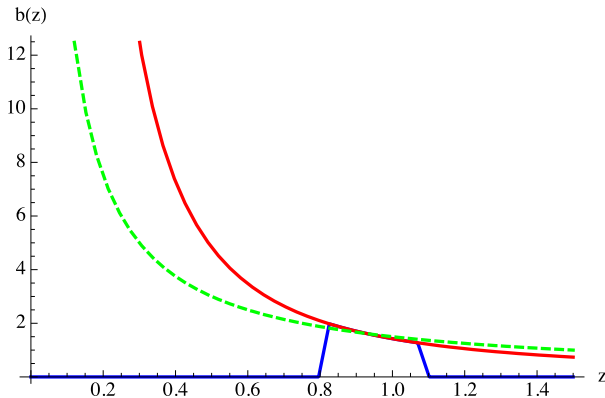
Trapped surface

$$z_{UV} < z < z_{IR}$$

$$z_a < z < z_b$$

Pack the trapped surface in the interval

$$z_{UV} < z < z_{IR}$$



$$E_{IR} < E < E_{UV}$$

$$E_{IR,UV} = \frac{L_{eff}^{7/2}}{8\pi G_5} \cdot \frac{1}{z_{IR,UV}^{3/2}}$$

Estimation of the thermalization time!

$$\tau \sim \frac{z_{UV} + z_{IR}}{4}$$

$$s \sim (L_{eff} E)^{1/3}$$

RG flow to anisotropic solutions and multiplicity



We would like to have a flow from AdS_5 to Lif_5 (with $b^2=L_{eff}/z$)

Known

AdS_5 to Lif_5

Dey,Roy, 1406.5992

but not Lif_5 admitting SW

AdS_5 to $AdS_3 \times H_2$ $Lif_3 \times H_2$

Burda, Gregory, Ross, 1408.3271

Colliding ultrarelativistic particles or to AdS_3 or Lif_3 ?

Conclusion

Formation of QGP of 4-dim QCD \Leftrightarrow Black Hole formation in AdS₅

- **b-factor that fits experimental data:**

1) Multiplicity

$$S_{data} \propto S_{NN}^{0.15}$$

2) Cornell qq-potential

- **attempts to get a top-down model for this b-factor (work in progress)**