Holographic thermalization in heavy ion collsions

Based on works

I. Arefeva, Holographic approach to quark-gluon plasma in heavy ion collisions, Phys. Usp. 57, 527 (2014).

D. Ageev, I. Arefeva, Holographic Thermalization in Quark Confining Background, arXiv:1409.7558

I. Arefeva, A. Golubtsova, Shock waves in Lifshitz-like spacetimes, arXiv:1410.4595

Outlook

- Physical picture of formation of Quark-Gluon Plasma in Heavy-Ions Collisions (HIC)
- Why holography?
- Results from holography

  (fit of experimental data via holography: top-down, bottom-up)

- Holography description of static QGP
  - qq-potential, …… thousands of papers
- Holography description of QGP formation in HIC
  - 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 <u>strong experimental evidences</u> that RHIC or LHC have created <u>some medium which behaves collectively</u>:

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

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

- ***<u>There is not yet exist a gravity dual construction for QCD.</u>***
- **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 ☜ = 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 <u>static QGP</u>.**

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

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

Holography and AdS/CFT correspondence

$$\boxed{\begin{aligned}&\left\langle \exp\left(\int_{\partial M} \phi_0 \mathcal{O}\, \mathrm{d}^D x\right)\right\rangle \\ &= \exp\left\{-S\left[\phi_{\rm cl}(\phi_0)\right]\right\}\end{aligned}}$$

Maldacena, 1997
Gubser,Klebanov,Polyakov
Witten, 1998

M=AdS, BHAdS,…

$$\phi(t,\vec{x},z), \quad S_g[\phi], \quad \delta S[\phi_{\rm cl}] = 0$$

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

+ requirement of regularity at horizon

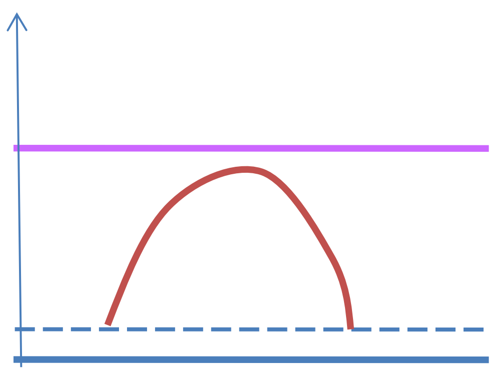
Correlators with/without Temperature via AdS/CFT

Example I. AdS, D=2+1

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

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

Example II. BHAdS, D=2+1



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

$$\mathrm{f(z) = 1 - Mz^2}$$

$$r_H = 2\pi T$$

Temperatute

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

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	$\Longleftrightarrow$	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**

$$Z_{ren}(z_0)\; g_{\mu\nu}^{(1)} \Big|_{\substack{boundary \\ z_0 \to 0}} = T_{\mu\nu}$$

Main idea: make some perturbations of AdS metric that near the boundary “mimic” the mater (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

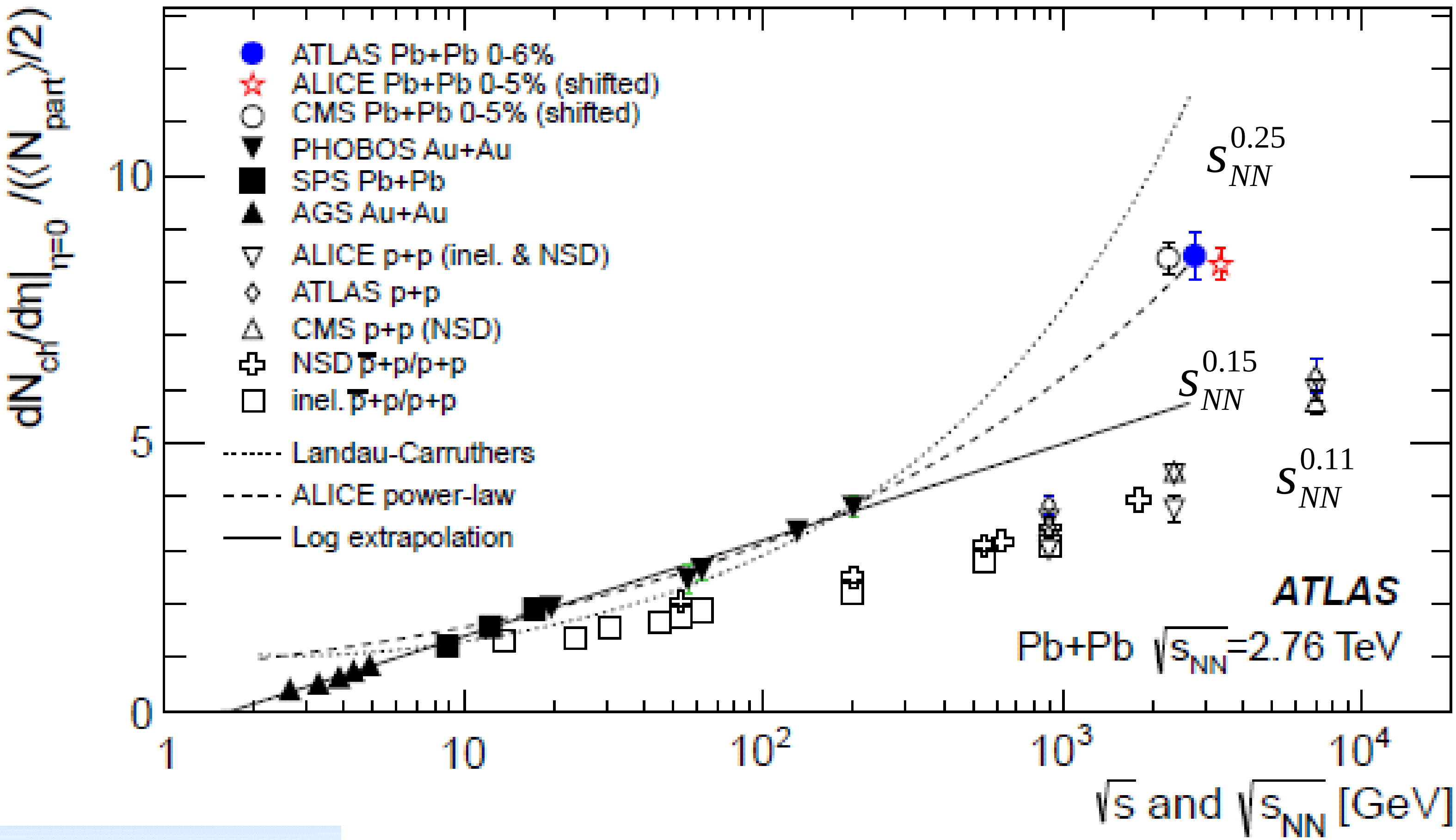
Physical quantities that we expect to estimate:

D=5 AdS		D=4 Minkowski
• Black hole formation time	⟺	• Thermalization time
• Entropy		• Multiplicity

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

$$\mathcal{M}_4 \sim \mathcal{S}_5$$

Gubser et al: 0805.1551

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

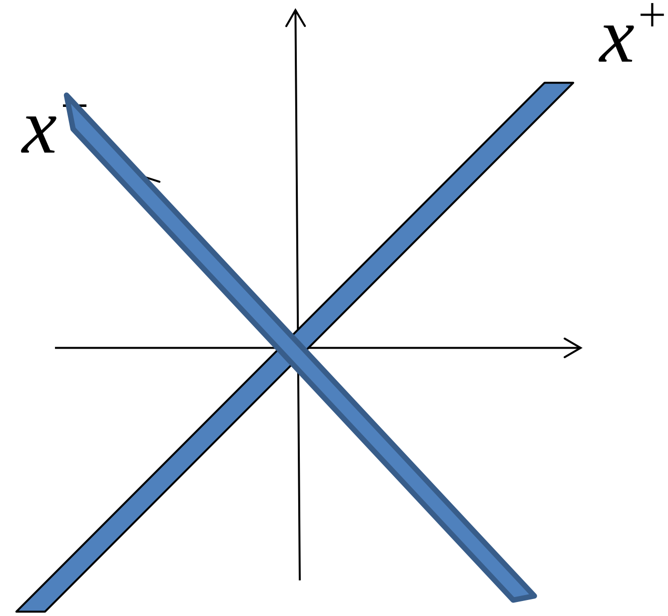
$$S \geq S_{trapped} = A_{trapped} / 4\mathrm{G}_N$$

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

Nucleus collision in AdS/CFT

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

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



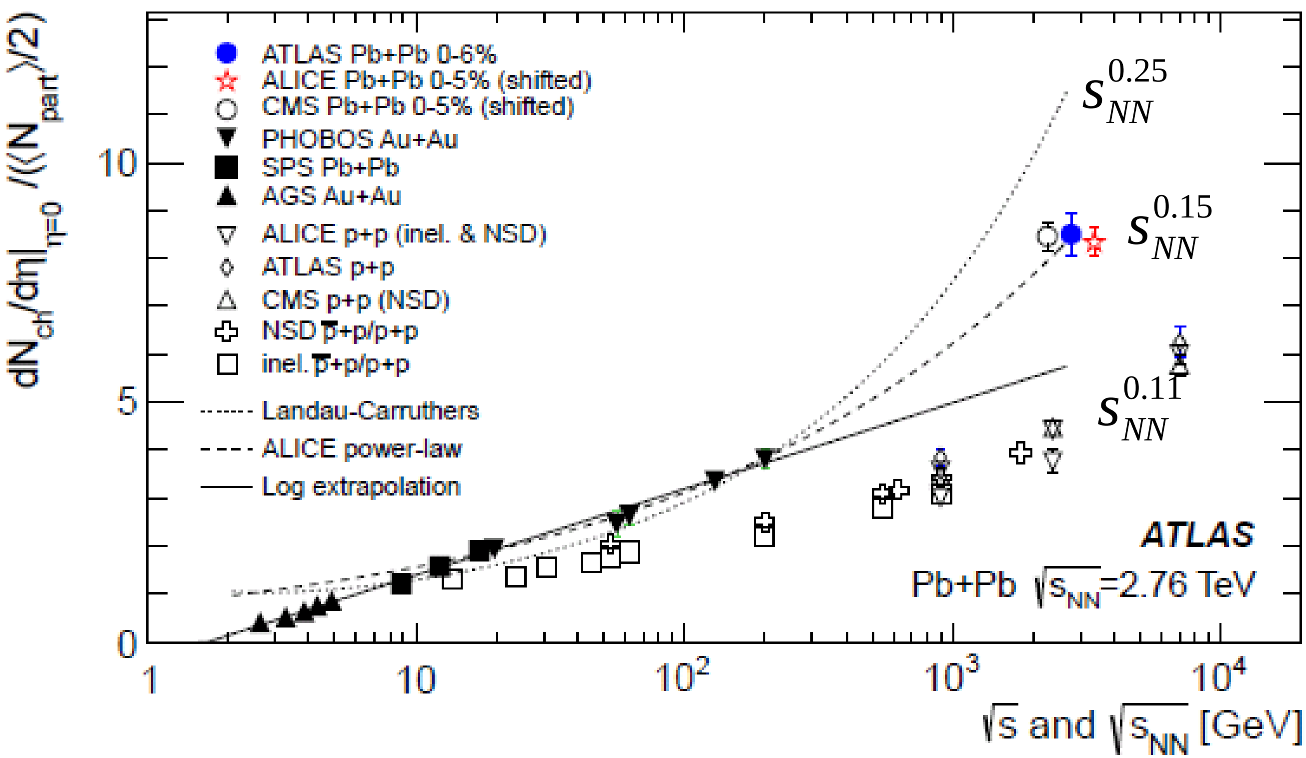
$$ds^2 = \frac{L^2}{z^2}\left[-2\, dx^+ dx^- + \frac{2\pi^2}{N_C^2}\langle T_{--}(x^-)\rangle z^4\, dx^{-2} + \frac{2\pi^2}{N_C^2}\langle T_{++}(x^+)\rangle z^4\, dx^{+2} + dx_\perp^2 + dz^2 \right]$$

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

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

Typical behavour

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

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

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

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. Arefeva., Bagrov and E.Pozdeeva, JHEP(2012)

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

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

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

$s_{points} \sim s_{walls}$

Power-law b-factor

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

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

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

Power-law b-factor coinsides with experimental data at *a*≈0.47.

We consider

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

Price: non standard kinetic term !?

Question: can we fit this background with other data?

Multiplicity vs. quark potential

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

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

$$h = e^{\frac{a z^2}{2}}$$

AdS with soft-wall

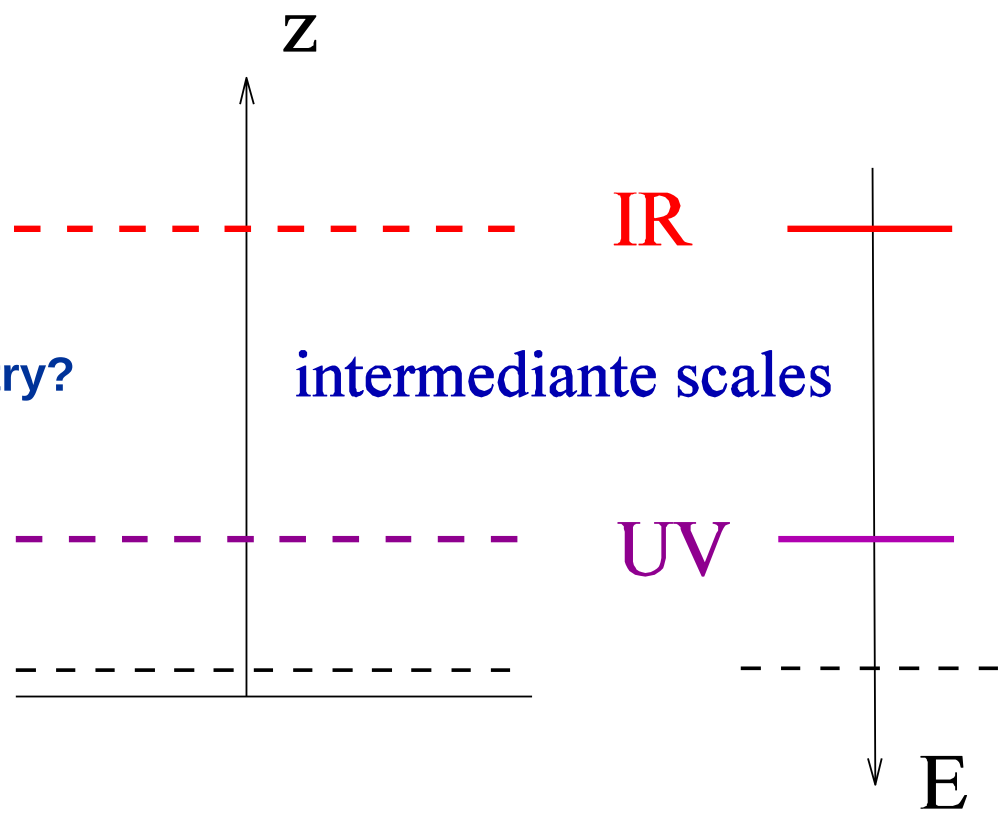
O. Andreev and V. Zakharov
hep-ph/0604204
R.Galow at al, 0911.0627
S.He, M.Huang, Q.Yan
1004.1880

Multiplicity vs quark potential

Soft/hard wall

Interpolating geometry?

AdS_5



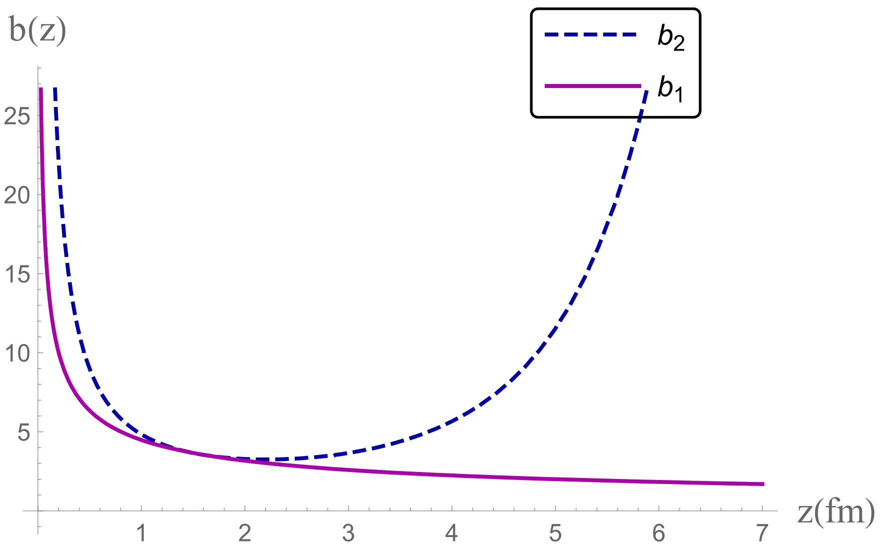
Multiplicity and quark potential

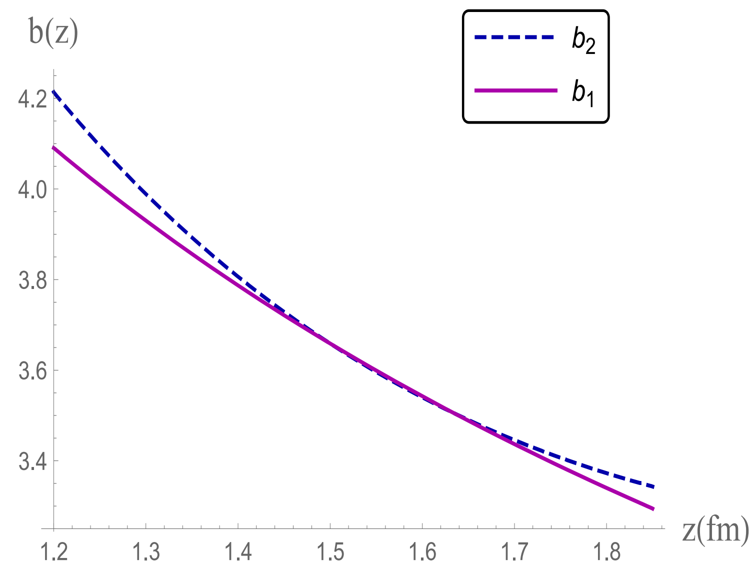
D.Ageev, I. Arefeva
arXiv:1409.7558

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

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

Intermediate scale!





Multiplicity and quark potential

Restriction on energy !!!!!!!

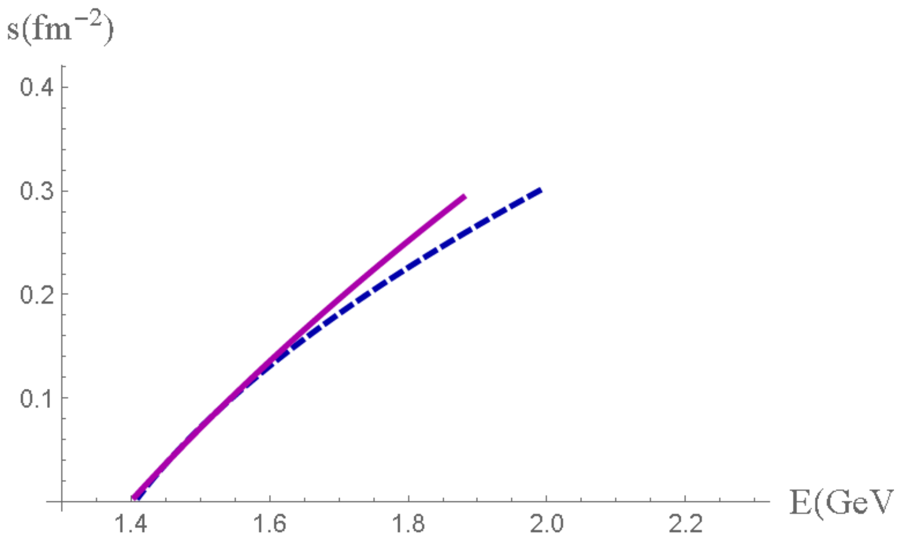
Pack the trapped surface in the intermediate scale.

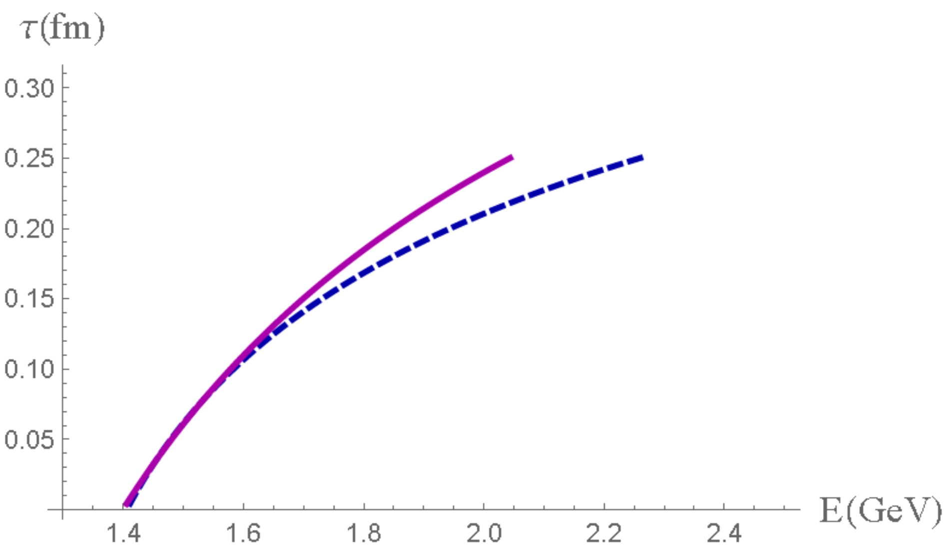
$$\frac{C}{2} = b^3(z_a) + b^3(z_b) \qquad C = \frac{16\pi G_5 E}{L^2}$$

$$s = \frac{S_{\rm trap}}{\int d^2x_\perp} = \frac{1}{2G_5}\int_{z_a}^{z_b} b^3\, dz$$

Multiplicity and quark potential.

Restriction on energy !!!!!!!





Estimation of the termalization time

Small energies!

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

Anisotropy during thermalization

In the past: it has been claimed that the pre-equilibrium period can only exist for up to 1 fm/c and after that, the QGP becomes isotropic

Now: corrections to ideal isotropic behavior even at times ~2 fm/c

Anisotropy after thermalization

- Experimental evidence for anisotropies:

jet quenching, changes in R-mod.factor, photon and dilepton,yields,

- QGP is anisotropic for a short time after collision

$$0 < \tau_{therm} < \tau < \tau_{iso}$$

$$\tau_{therm} \approx 0.1 \div 0.3[fm]$$

- The time of locally isotropization is about

$$\tau_{iso} \sim 2fm$$

This gives a reason to consider BH formation in anizotropic background

Multiplicity with anisotropic Lifshitz background

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

I. Arefeva, A. Golubtsova
arXiv:1410.4595

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

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

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

Shock wave

$$z = 1/\rho$$

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

Solves E.O.M. if

$$\Box_3$$

$$\left[\Box_3 - \left(1 + \frac{2}{\nu} \right) \right] \frac{\phi(y_1, y_2, z)}{z} = -2zT_{uu}$$

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

Multiplicity with anisotropic Lifshitz background

Domain wall

$$\left[\Box_3 - \left(1 + \frac{2}{\nu}\right)\right]\frac{\phi(z)}{z} = -16\pi G_5 z J_{uu} \qquad J_{uu} = z^{1+2/\nu}\delta(z - z_*)$$

$$\phi = \phi_a \Theta(z_* - z) + \phi_b \Theta(z - z_*),$$

$$\phi_a(z) = C_0 z_a z_b \left(\frac{z_*^{(2\nu+1)/\nu}}{z_b^{(2\nu+1)/\nu}} - 1\right)\left(\frac{z^{(2\nu+1)/\nu}}{z_a^{(2\nu+1)/\nu}} - 1\right),$$

$$\phi_b(z) = C_0 z_a z_b \left(\frac{z_*^{(2\nu+1)/\nu}}{z_a^{(2\nu+1)/\nu}} - 1\right)\left(\frac{z^{(2\nu+1)/\nu}}{z_b^{(2\nu+1)/\nu}} - 1\right),$$

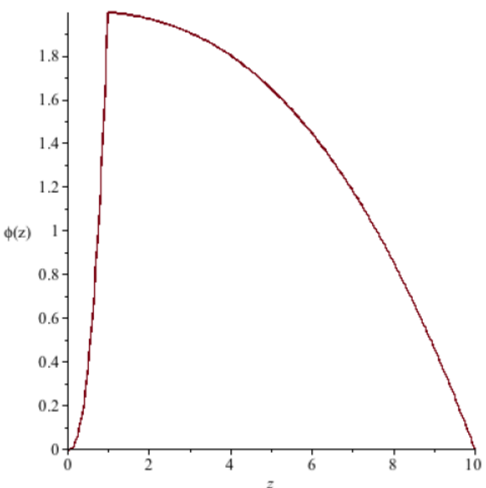
$$C_0 = -\frac{16\nu\pi G_4 E {z_a}^{1+1/\nu} {z_b}^{1+1/\nu}}{(2\nu+1)L^{\frac{1}{\nu}+3}(z_b^{(2\nu+1)/\nu} - z_a^{(2\nu+1)/\nu})}.$$

Multiplicity with anisotropic Lifshitz background

Colliding Domain Walls

$$ds^2 = -\frac{1}{z^2}dudv + \frac{1}{z^2}\phi_1(y_1, y_2, z)\delta(u)du^2 + \frac{1}{z^2}\phi_2(y_1, y_2, z)\delta(v)dv^2$$

$$+ \frac{1}{z^{2/\nu}}\left(dy_1^2 + dy_2^2\right) + \frac{dz^2}{z^2}$$



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

To get $s \sim E^{0.3}$

$$\boxed{\nu = 4}$$

Anisotropic solutions in D3D7

Takayanagi et. al., Mateos et. al., : Anis. Deform. of AdS_5 in UV
Lif –like in IR

Axion-dilaton-gravity action (in the Einstein frame)

$$S_{bulk} = \frac{1}{2\kappa^2}\int_{\mathcal{M}}\sqrt{-g}\left(R + 12 - \frac{1}{2}(\partial\phi)^2 - \frac{1}{2}e^{2\phi}(\partial\chi)^2\right)$$ +Bnd.trm

$$ds^2 = \frac{e^{-\frac{1}{2}\phi}}{u^2}\left(-\mathcal{F}\mathcal{B}\,dt^2 + dx^2 + dy^2 + \mathcal{H}dz^2 + \frac{du^2}{\mathcal{F}}\right)$$

$$\chi = az, \quad \phi = \phi(u)$$

Lif –like in IR

$$ds^2 = -\rho^2 dudv + \rho^2 dy^2 + \rho^{4/3}dw^2 + \frac{d\rho^2}{\rho^2}$$

One SW

$$ds^2 = \frac{1}{z^2}\left(\phi\delta(u)du^2 - dudv + z^{-2}dy^2 + z^{2/3}dw^2 + \frac{dz^2}{z^2}\right)$$

Conclusion

Formation of QGP of 4-dim QCD ⇔ BH formation in 5-dim

- **BH formation in isotropic 5-dim models (AdS, b-factors)**

  1) Multiplicity $$S_{data} \propto s_{NN}^{0.15}$$

  2) Cornell qq-potential

Restriction on energy!

- **BH formation in anisotropic 5-dim models:**

  1) **in Lif-like (Multiplicity – OK!)**
  2) **in background with a flow from AdS to Lif-like (work in progress ?).**