Holography for quark-gluon plasma formation in heavy-ions collisions

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3 keys points

Outlook

Quark-gluon plasma (QGP)

14'th Ginzburg's problem,

UFN, 2002

Holography

Heavy-ions collisions (HIC)

- New formula for multiplicity
- New phase transition

Февраль 2002 г.

УСПЕХИ ФИЗИЧЕСКИХ НАУК

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On some advances in physics and astronomy over the past three years

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In 1999 the author published a paper "What problems of physics and astrophysics seem now to be especially important and interesting (thirty years later, already on the verge of XXI century?" [1]. By its very nature and intention, the content of this paper should be modified on a continuous basis to keep up with advances in science. In the last three years important results of a fundamental nature have been obtained which the author finds appropriate to summarize briefly in this article not least because of the great readers' interest generated by Ref. [1].

PACS numbers: **01.55. + b**, **01.90. + g**
Bibliography 69 references
Received 16 January 2002

Ginzburg V L *About Science, Myself, and Others*

12. **Разеры, гразеры, сверхмощные лазеры.**
13. **Сверхтяжелые элементы. Экзотические ядра.**
14. **~~Спектр масс. Кварки и глюоны.~~ Квантовая хромодинамика. Кварк-глюонная плазма.**
15. **Единая теория слабого и электромагнитного взаимодействия. $W^{\pm}$- и Z^0-бозоны. Лептоны.**
16. **Стандартная модель. Великое объединение. Суперобъединение. Распад протона. Масса нейтрино. Магнитные монополи.**

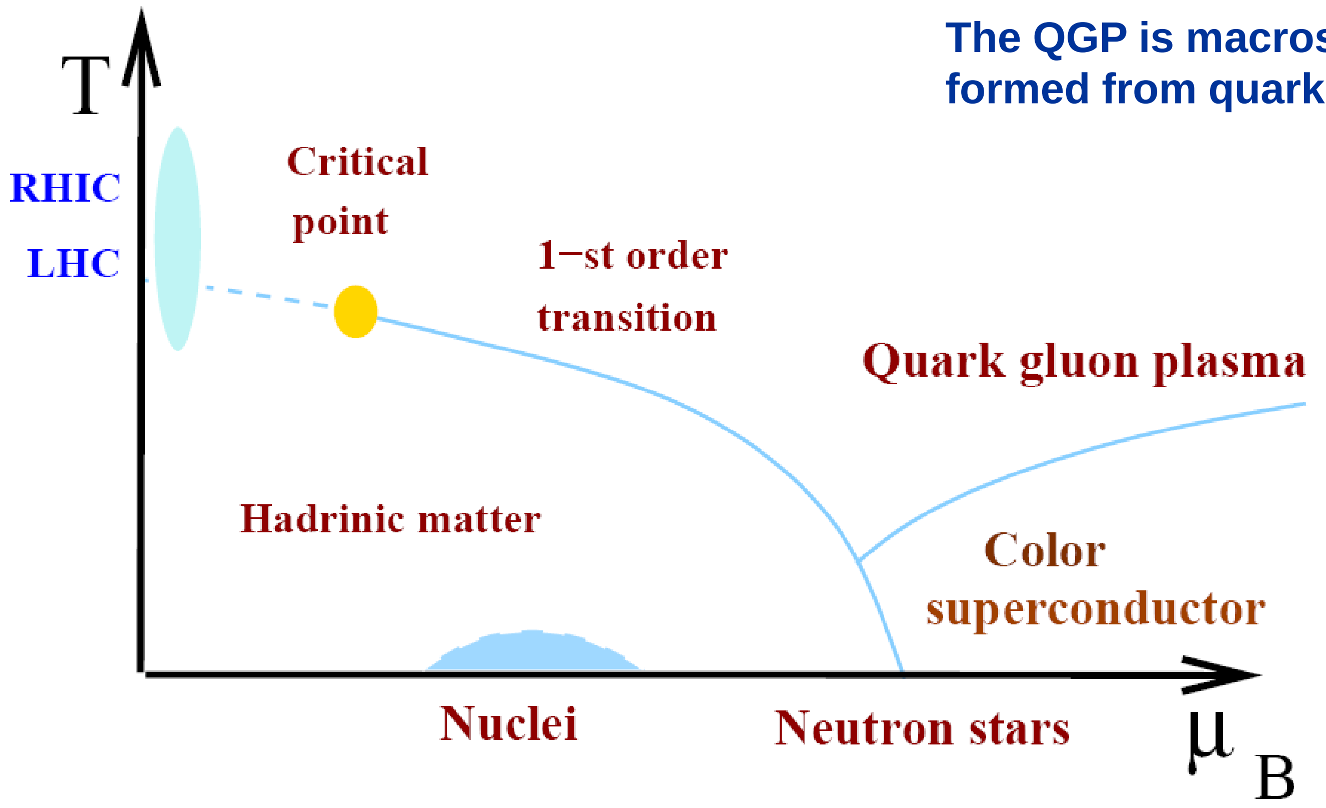
стве металлов [12]. В этой связи особенно интересны результаты [13], опубликованные в самом конце 2001 г., и быть может свидетельствующие о том, что в купратах "элементарные возбуждения", переносящие ток и тепло, довольно существенно отличны от электронов и дырок. Мне, однако, осталась неясной роль присутствующего в этих экспериментах сильного магнитного поля. Несомненно, опыты [13] должны быть (и будут!) повторены и

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

Asymptotic freedom

T increases, or
density increases

nuclear matter → Deconfinded phase



The QGP is macroscopic matter formed from quarks and gluons

Heavy Ions collisions

Experiments

- started in the 1990's at the Brookhaven Alternating Gradient Synchrotron (AGS),
- the CERN Super Proton Synchrotron (SPS)
- the Brookhaven Relativistic Heavy-Ion Collider (RHIC)
- the LHC collider at CERN.

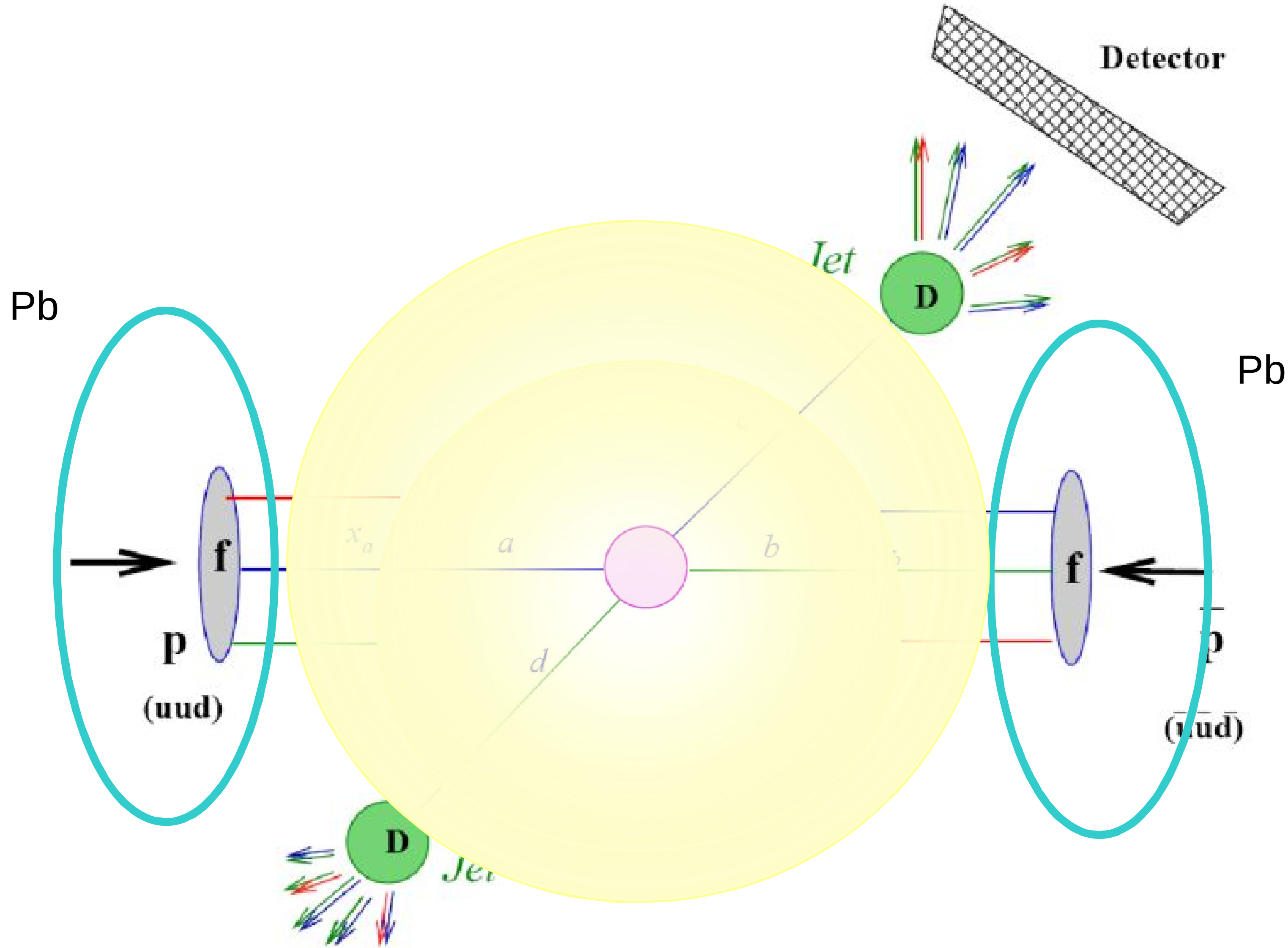
$$\sqrt{s_{NN}} = 4.75\, GeV$$
$$\sqrt{s_{NN}} = 17.2\, GeV$$
$$\sqrt{s_{NN}} = 200\, GeV$$
$$\sqrt{s_{NN}} = 2.76\, TeV$$

Theory (macroscopic: thermodynamics, hydrodynamics, …

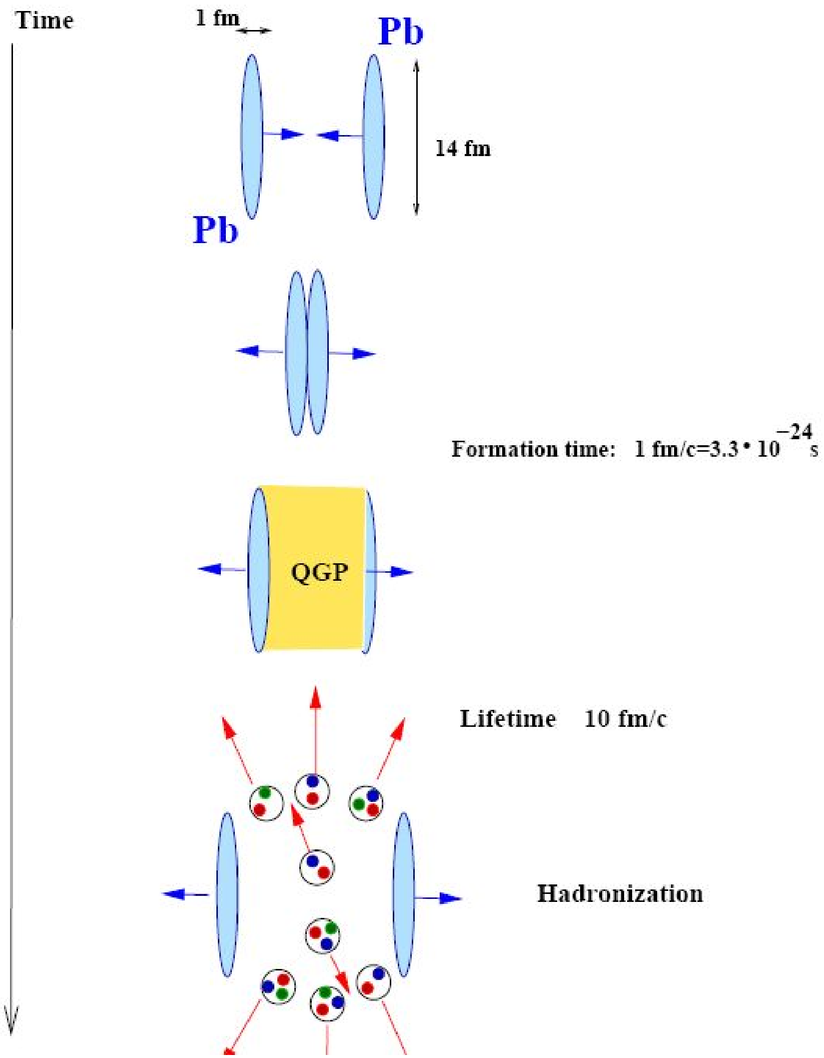
microscopic - QCD, holographic)

Landau(1953); Fermi(1950); Pomeranchuk; Rozental, Cernavskij (UFN,1954);
Landau, Bilenkij (UFN,1955); Cernavskij, Feiberg (1972);
Cooper,…(1975); Bjorken(1983);
Kolb, Heinz (2003); Janik, Peschansky (2006); Shuryak(2009); Peigne, Smilga (UFN, 2009)
Dremin, Leonidov (UFN, 2010); Muller, Schafer(2011),….

pp collisions vs heavy Ions collisions



Heavy Ions collisions

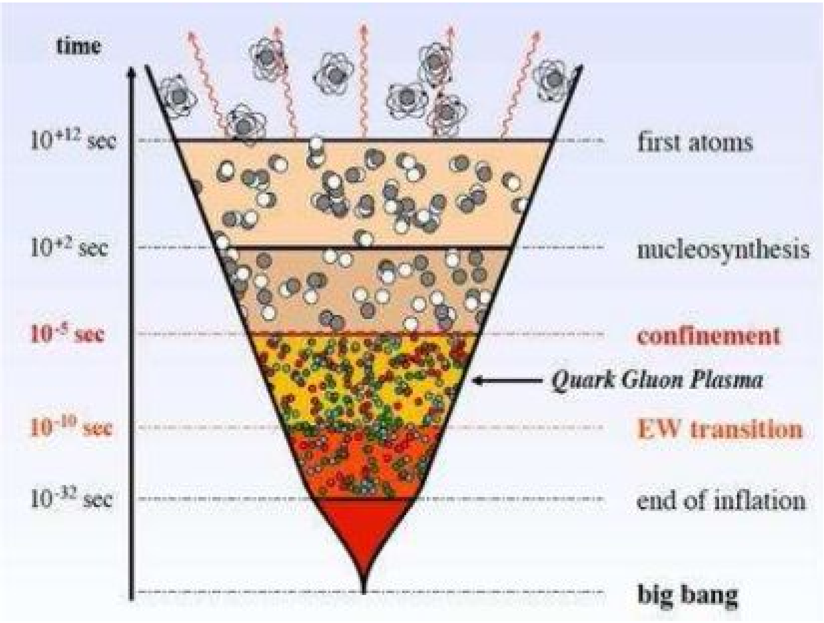


- **Due to multiple interactions the system will thermalize and form the QGP**
- **QGP undergoes a collective expansion and eventually becomes so dilute that it hadronizes.**

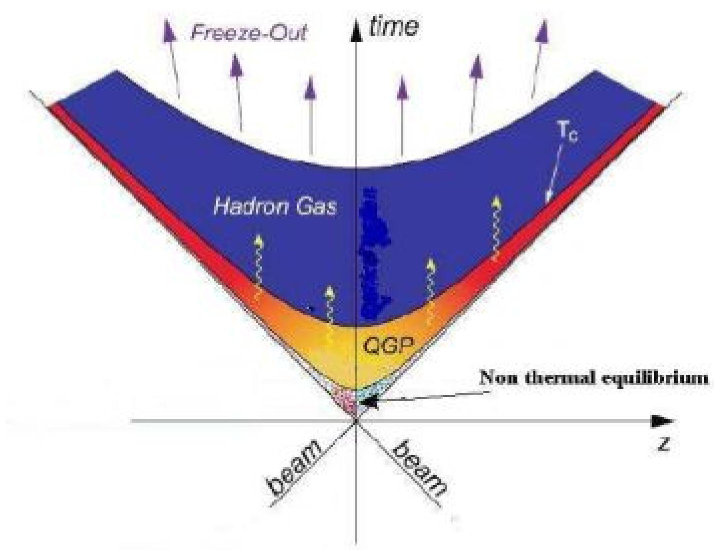
We can "see" this collective expansion ("elliptic flow")

QGP in Heavy Ion Collision and Early Universe

- **One of the fundamental questions in physics is: what happens to matter at extreme densities and temperatures as may have existed in the first microseconds after the Big Bang**
- **The aim of heavy-ion physics is to collide nuclei at very high energies and create such a state of matter in the laboratory.**



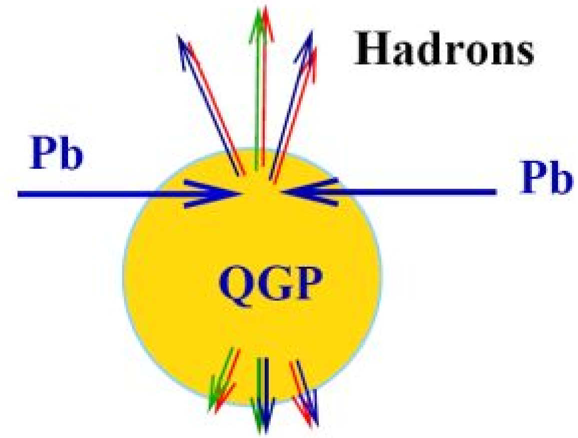
Evolution of the Early Universe



Evolution of a Heavy Ion Collision

QGP in heavy-ions collisions

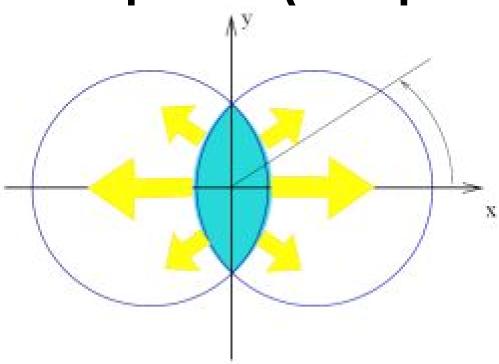
There are strong experimental evidences that RHIC or LHC have created some medium which behaves collectively:



suppression of back-to-back jet correlations (signals that some jets are "lost" going through the medium)

modification of particle spectra (compared to p+p)

Elliptic flow



Hydrodynamics simulations can give estimations for V_2.

more pressure along the small axis

QGP and Relativistic Hydrodynamics

Hydrodynamics appears as an effective description, valid on

length scales >>mean free path

Fermi,
L.D.Landau (1953),
J.D.Bjorken (1982)

Energy-Momentum tensor (**perfect fluid**)

$$T^{\mu\nu} = (\epsilon + p)u^{\mu}u^{\nu} - p\eta^{\mu\nu} \; ; \; u^{\mu}u^{\mu} = -1$$

Hydrodynamics

$$\boxed{\partial_{\mu}T^{\mu\nu} = 0} \; ; \; \frac{\partial p}{\partial \epsilon} = c_s^2 (= 1/g) \; ; \; \boxed{T^{\mu\mu} = 0} \Rightarrow g = 3$$

Fluid with viscosity

η - **shear viscosity**

ς - **bulk viscosity**

$$T^{\mu\nu} = (\varepsilon + p)u^{\mu}u^{\nu} - p\eta^{\mu\nu}$$

$$+ P^{\mu\alpha}P^{\nu\beta}[\eta(\partial_{\alpha}u_{\beta} + \partial_{\beta}u_{\alpha} - \frac{2}{3}g_{\alpha\beta}\partial \cdot u) + \varsigma g_{\alpha\beta}\partial \cdot u]$$

$$P^{\mu\nu} = g^{\mu\nu} + u^{\mu}u^{\nu}$$

QCD as a strongly coupled fluid

- **A remarkable conclusion from the RHIC and LHC experiments is that the QGP does not behave as a weakly coupled gas of quarks and gluons, but rather as a strongly coupled fluid.** **Shuryak, 04**

- 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 strong motivation for understanding the dynamics of strongly coupled QGP through the gauge/string duality

Dual description of QGP (Quark Gluon Plasma) as a part of Gauge/string duality

(Maldacena '97):

- **The Gauge/Gravity duality gives an correspondence between the 4-dim physical space where the gauge theory lives and the 5-dimensional space where the supergravity (weak curvature) approximation of the 10-dimensional string theory is valid.**

- **Or in others words, the properties of the gauge theory in (physical) Minkowski space in3+1 dimensions are in one-to-one relation with properties of the bulk theory.**

- **The best known example of such theories is N = 4 super Yang-Mills, a superconformal field theory with matter in the adjoint representation of the gauge group SU(Nc).**

Dual description of QGP (Quark Gluon Plasma) as a part of Gauge/string duality

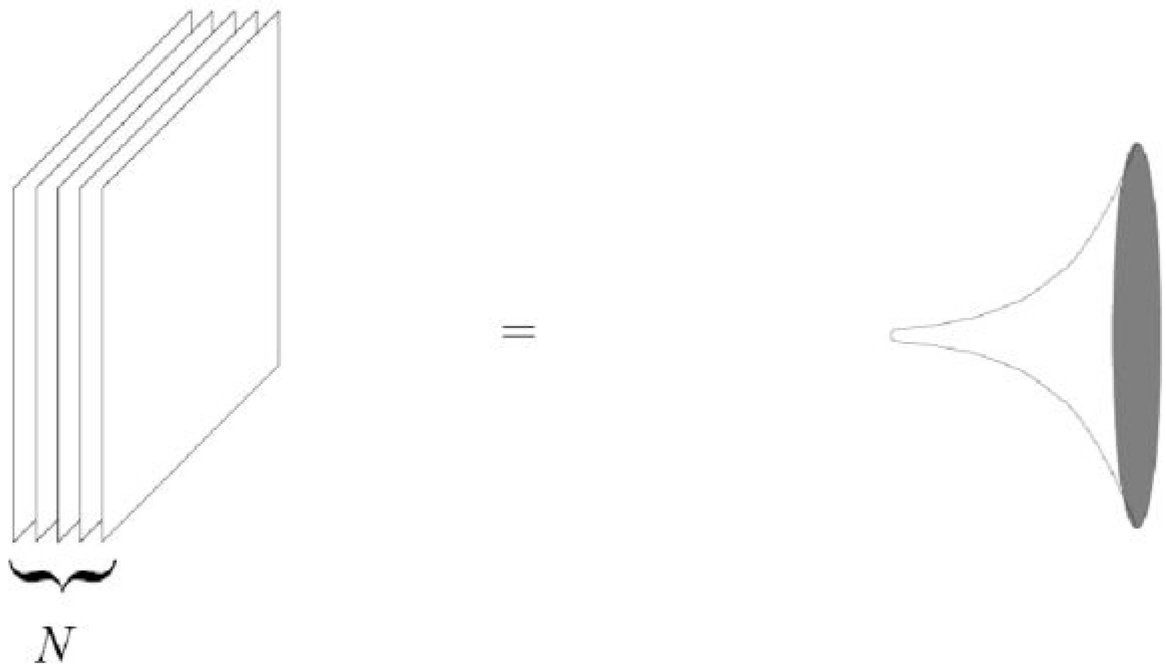
- However, there is not yet exist a gravity dual construction for QCD.
- Differences between N = 4 SYM and QCD are less significant, when quarks and gluons are in the deconfined phase (because of the conformal symmetry at the quantum level N = 4 SYM theory does not exhibit confinement.)

- Lattice calculations show that QCD exhibits a quasi-conformal behavior at temperatures T >300 MeV and the equation of state can be approximated by $\varepsilon = 3p$ (a traceless conformal energy-momentum tensor).

- The above observations, have motivated 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 quark-gluon plasma, in particular in the evaluation of η/s [Policastro,Son, Starinec, 01]

The Gauge/Gravity Duality



SUGRA $AdS_5 \times S_5$

N = 4 SYM

Relation between parameters:

$$g^2 = 4\pi g_{\rm st}$$

$$g^2 N_c = \frac{R^4}{\ell_s^4}$$

Dual description of QGP (Quark Gluon Plasma) as a part of Gauge/string duality

In the phenomenological hydrodynamical (Landau or Bjorken models of QGP),

the plasma is characterized by a space-time profile of the energy-momentum tensor

$$T_{\mu\nu} \quad , \mu, \nu = 0, \dots 3$$

$$T_{\mu\nu} = < \hat{T}_{\mu\nu} >$$

ADS/CFT: operators in the gauge theory correspond to fields in SUGRA

$$< \mathcal{O} > \Leftrightarrow \mathcal{A},$$

$$If \quad \hat{T}_{\mu\nu} \quad then \quad g_{MN}$$

.

In the case of the energy-momentum tensor, the corresponding field is the 5D metric.

Dual description of QGP (Quark Gluon Plasma) as a part of Gauge/string duality

Janik, 05

Static uniform plasma

$$\langle T_{\mu\nu}\rangle \propto g^{(4)}_{\mu\nu} = \begin{pmatrix} 3/z_0^4 & 0 & 0 & 0 \\ 0 & 1/z_0^4 & 0 & 0 \\ 0 & 0 & 1/z_0^4 & 0 \\ 0 & 0 & 0 & 1/z_0^4 \end{pmatrix}.$$

$$G_{MN} = \Lambda g_{MN}, \quad g_{\mu\nu}\,|_{boundary} = g^{(4)}_{\mu\nu}$$

Solution: $$ds^2 = -\frac{(1-z^4/z_0^4)^2}{(1+z^4/z_0^4)z^2}dt^2 + (1+z^4/z_0^4)\frac{dx^2}{z^2} + \frac{dz^2}{z^2}$$

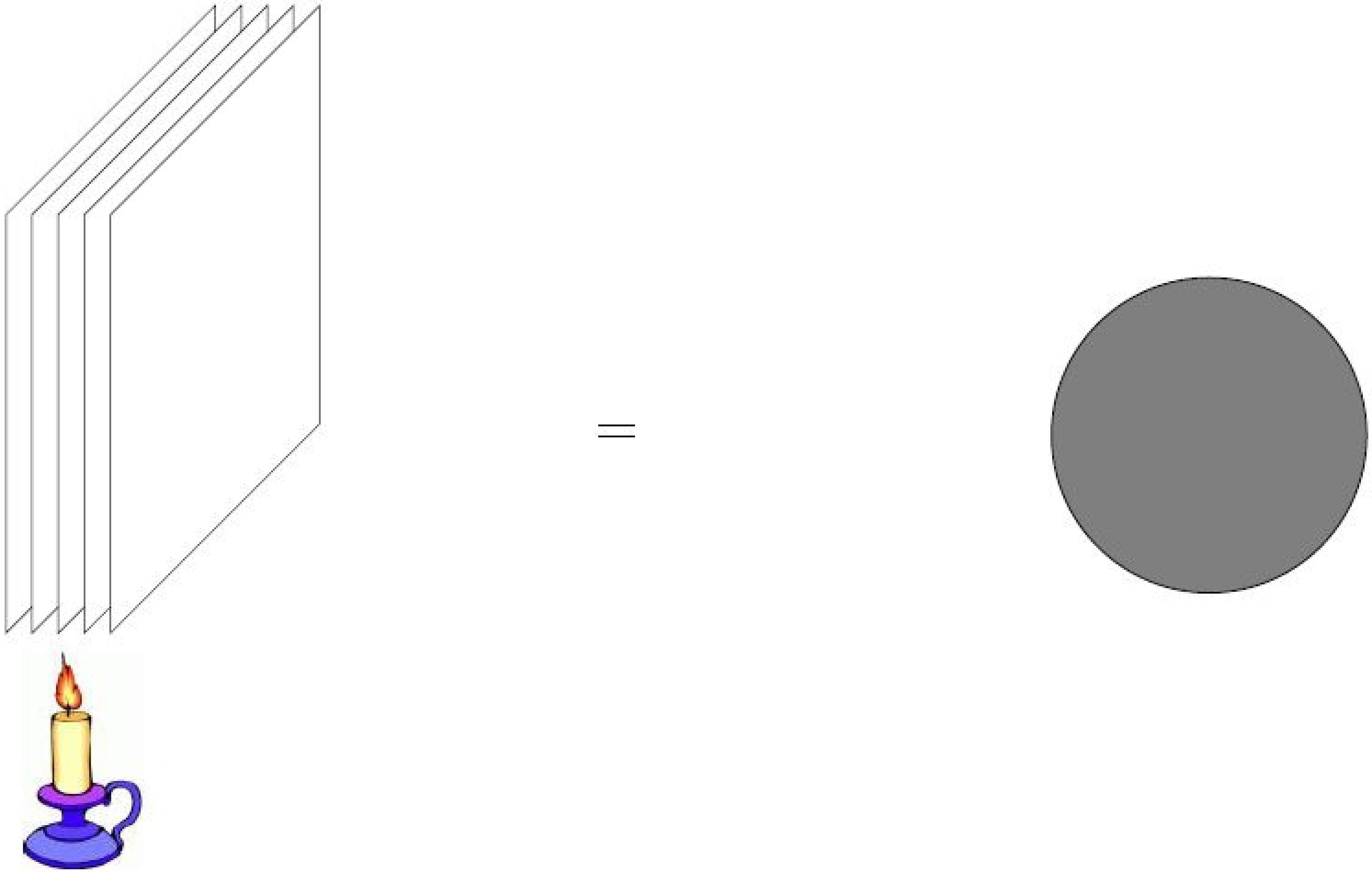
Performing a change of coordinates $$\tilde{z} = \frac{z}{\sqrt{1+\frac{z^4}{z_0^4}}}$$

The standard AdS static black hole

$$ds^2 = -\frac{1-\tilde{z}^4/\tilde{z}_0^4}{\tilde{z}^2}dt^2 + \frac{dx^2}{\tilde{z}^2} + \frac{1}{1-\tilde{z}^4/\tilde{z}_0^4}\frac{d\tilde{z}^2}{\tilde{z}^2}$$

with $\tilde{z}_0 = z_0/\sqrt{2}.$

Dual description of QGP (Quark Gluon Plasma)



“Quark gluon plasma” = black hole (in anti de-Sitter space)

Dual description of formation of QGP

CONJECTURE:

Black Hole formation in AdS_5

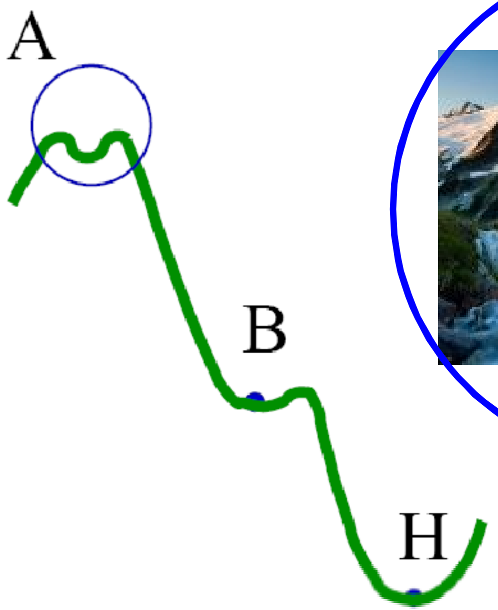
= thermalization (formation of QGP) of 4-dim QCD

BH formation in AdS (or holographic thermalization)

Thermalization of some class of space-time geometries =
space-time geometries without an event horizon (EH) evolve to space-times with EH.

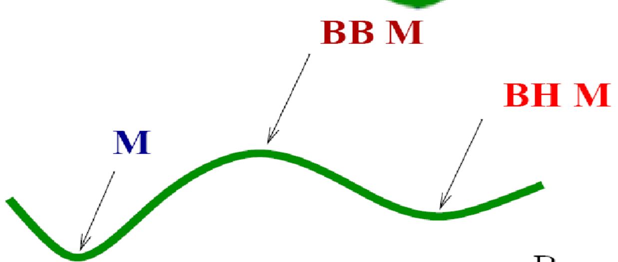
Take deformed AdS space-times (asymptotical AdS) and ask under which conditions they evolve to the AdS space with a BH, or black branes.

.



- H **Sch AdS is an equilibrium "point"**
- B Black branes AdS
- A AdS is stable under small fluctuations and is unstable under large nonlinear fluctuations

Bizon and Rostworowski, PRL, 2011;
Dias, Horowitz and Santos, 1109.1825



Circle A - large chaotic deformations

After a sufficiently long time, any finite excitation of AdS eventually finds itself inside its Schw. radius and collapses to a BH

Deformations of AdS metric

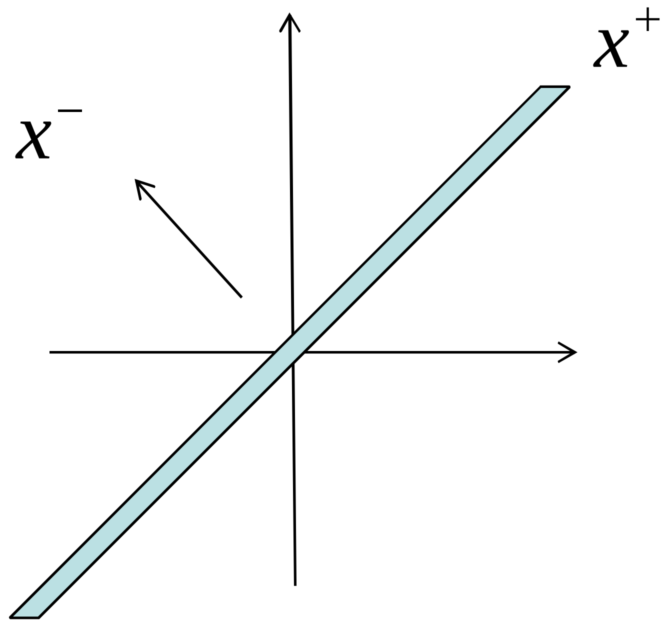
- colliding gravitational shock waves
- drop of a shell of matter with vanishing rest mass ("null dust"), Balasubramanian at all, PRL “11
  infalling shell geometry = Vaidya metric

- sudden perturbations of the metric near the boundary that propagate into the bulk Chesler, Yaffe, PRL “09

Single Nucleus in AdS/CFT

An ultrarelativistic nucleus is a shock wave in 4d with the energy-momentum tensor

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



The metric of a shock wave in AdS corresponding to the ultrarelativistic nucleus in 4d is

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

Janik, Peschanksi '05

Ultrarelativistic particle = shock wave

- Aichelburg-Sexl shock wave

$$ds^2 = -dUdV + dx^{i2} + F(x^i)\delta(U)\, dU^2,$$

$$F(x^i) = \frac{c_k}{|\sum (x^i - x_{k0}^i)^2|^{(D-4)/2}}, \quad U = x$$

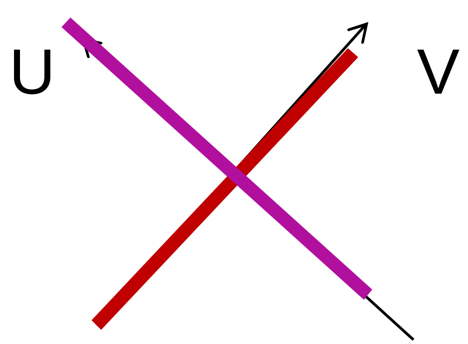
Smooth coordinates: P.D'Eath coordinates, Dray and 't Hooft

2 Ultrarelativistic particles = 2 shock waves

- 2 Aichelburg-Sexl shock waves

$$ds^2 = -dUdV + dX^{i2} + F_1(X^i)\delta(U)\, dU^2 + F_2(V^i)\delta(V)\, dV^2,$$

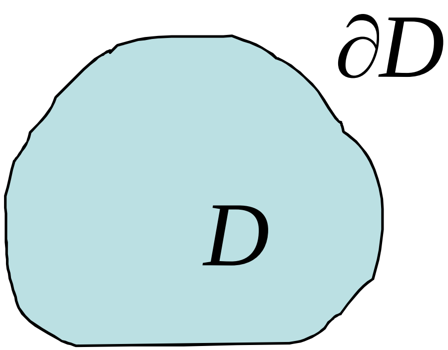
$$F_k(X^i) = \frac{c_k}{|\sum (X^i - X_{k0}^i)^2|^{(D-4)/2}}$$



BLACK HOLE FORMATION = $\exists$ Trapped Surface(TS)

- Theorem (Penrose): **BH Formation = $\exists$ TS**

- **Theorem. $\exists$ TS for two shock waves =**
  . $\exists$ solution to the following Dirichlet problem



- $\Psi_{1,2} > 0, \; X \in D, \;\; \Psi_{1,2} = 0, \quad X \in \partial D$
- $\nabla^2 \Psi_{1,2} = \delta^{(D-2)}(X - X_{(1,2)}), \quad X \in D,$

  the outer null normals have zero convergence

- $\nabla\Psi_1 \cdot \nabla\Psi_2 = 4, \;\; X \in \partial D$

  no $\delta -$ function in convergence

Eardley, Giddings; Kang, Nastase,….

Different profiles ----- different multiplicities

An arbitrary gravitational shock wave in *AdS*5

$$ds^2 = \frac{L^2}{z^2}\left(-dx^+dx^- + dx_\perp^2 + \phi(x_\perp, z)\delta(x^+)dx^{+2} + dz^2\right)$$

$$\Phi(z, x_\perp) \equiv \frac{L}{z}\phi(z, x_\perp) \qquad \left(\Box_{H_3} - \frac{3}{L^2}\right)\Phi(z, x_\perp) = -16\pi G_5 \frac{z}{L} J_{uu}(z, x_\perp)$$

- **Point sourced shock waves**

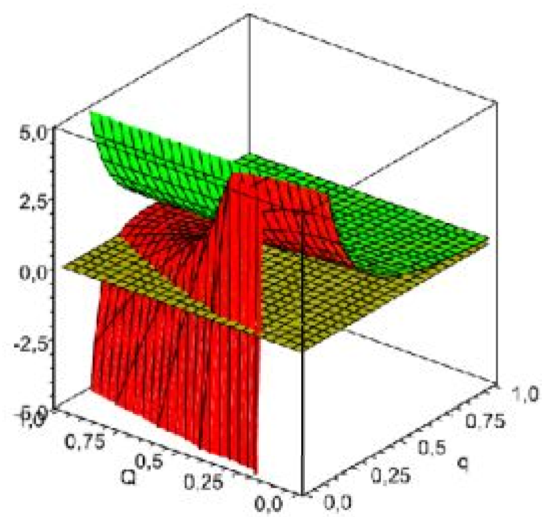
Hotta,Tanaka, 93

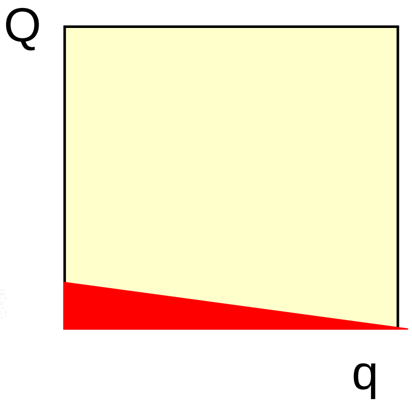
$$J_{uu} = E\delta(u)\delta(z-L)\delta(x^1)\delta(x^2) \qquad \Phi(z, x_\perp) = \Phi^{p}(q) \qquad q = \frac{x_\perp^2 + (z-L)^2}{4zL}$$

The chordal coordinate

- **Point charged shock waves**

$$\Phi(z, x_\perp) = \Phi^{p}(q) + \Phi^{Q}(q)\Theta(q - q_{Th})$$





Dual description of QGP (Quark Gluon Plasma)

- QGP formation for heavy ions collisions in M_4

  in dual description:

  BH formation in shock waves collisions in AdS_5

- Trapped surface area ------ multiplicity

- BH charge ------- chemical potential

Multiplicity=Entropy=area of trapped surface

$$S_{\text{trapped}} \approx \pi\left(\frac{L^3}{G_5}\right)^{1/3}(2EL)^{2/3}$$

Gubser, Pufu, Yarom, 0805.1551,
Alvarez-Gaume, C. Gomez, Vera,
Tavanfar, Vazquez-Mozo, 0811.3969
IA, Bagrov, Guseva, 0905.1087

Lattice calculations $E\,T^4 \approx 11$

Hawking-Page relation $\frac{L^3}{G_5} = \frac{16\,E\,T^4}{3\pi^3}$

$$\frac{L^3}{G_5} \approx 1.9$$

From a Woods-Saxon profile for the nuclear density

$$Au: \quad L \approx 4.3\,fm = 4.3\cdot 5\frac{1}{GeV}; \qquad Pb: \quad L \approx 4.4\,fm$$

$$EL\Big|_{\text{Au}-\text{Au},\sqrt{s_{NN}}=200\,\text{GeV}} \approx 4.3\times 10^5 \qquad EL\Big|_{\text{Pb}-\text{Pb},\sqrt{s_{NN}}=5.5\,\text{TeV}} \approx 1.27\times 10^7$$

$$S \geq S_{\text{trapped}} \approx 35000\left(\frac{\sqrt{s_{NN}}}{200\text{ GeV}}\right)^{2/3}$$

Multiplicity: Experimental data, Landau, AdS-estimation

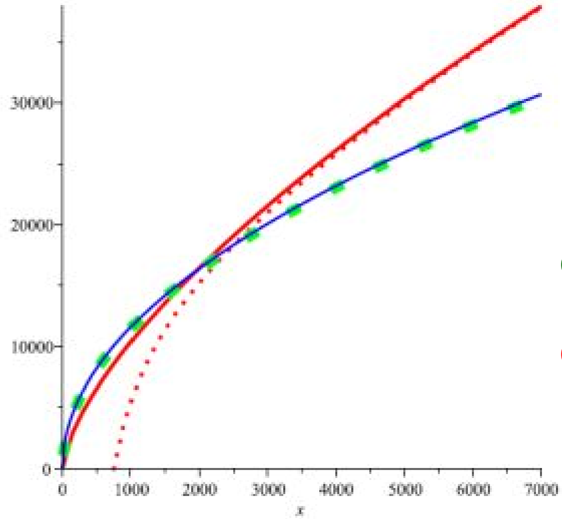
Phenomenological estimation: total multiplicity and the number of charged particle

$$S_{\text{trapped}} \leq S_{\text{AdS}} = S_{\text{QGP}} \approx 7.5 N_{\text{ch}}$$

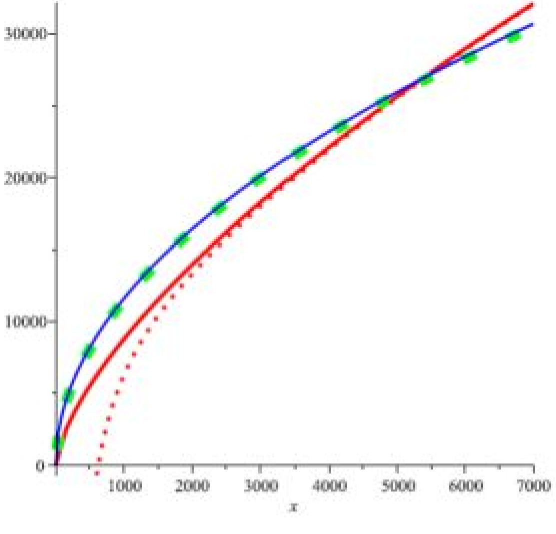
$$\mathcal{M} \cdot S_{\text{trapped}} < N_{\text{ch}}$$

$$S_{trapped} \propto s_{NN}^{1/3}$$

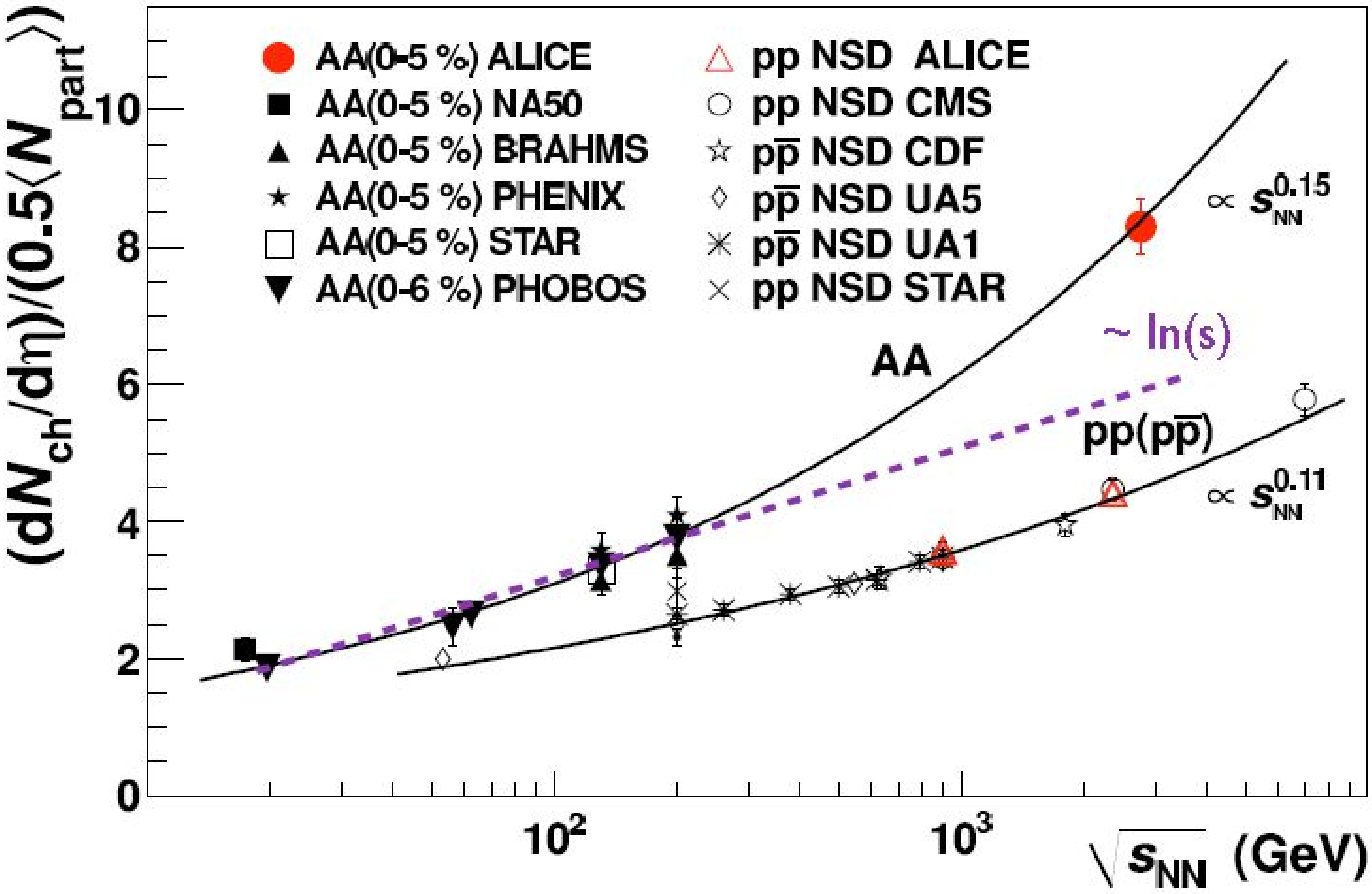
$$S_{Landau} \propto s_{NN}^{1/4}$$



red line - TS estimation
blue line - Landau model
dotted green - the experimental data
dashed line red line - TS estimation with a chemical potential

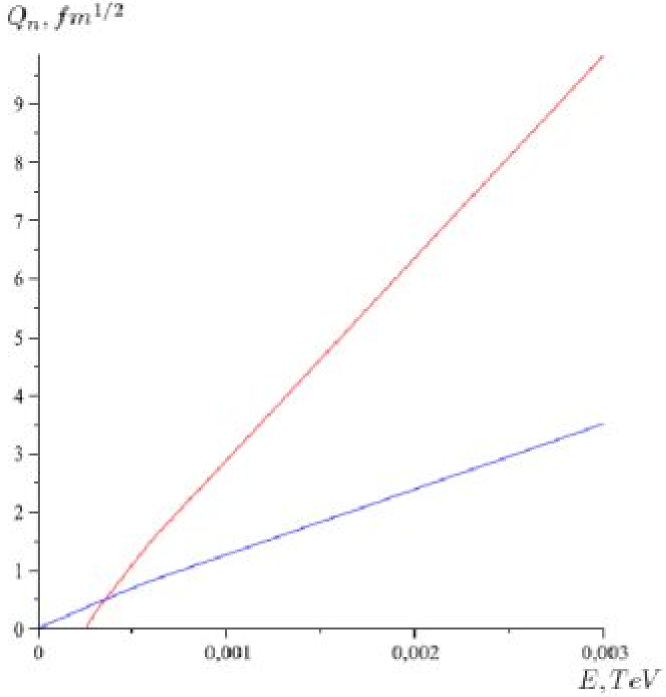


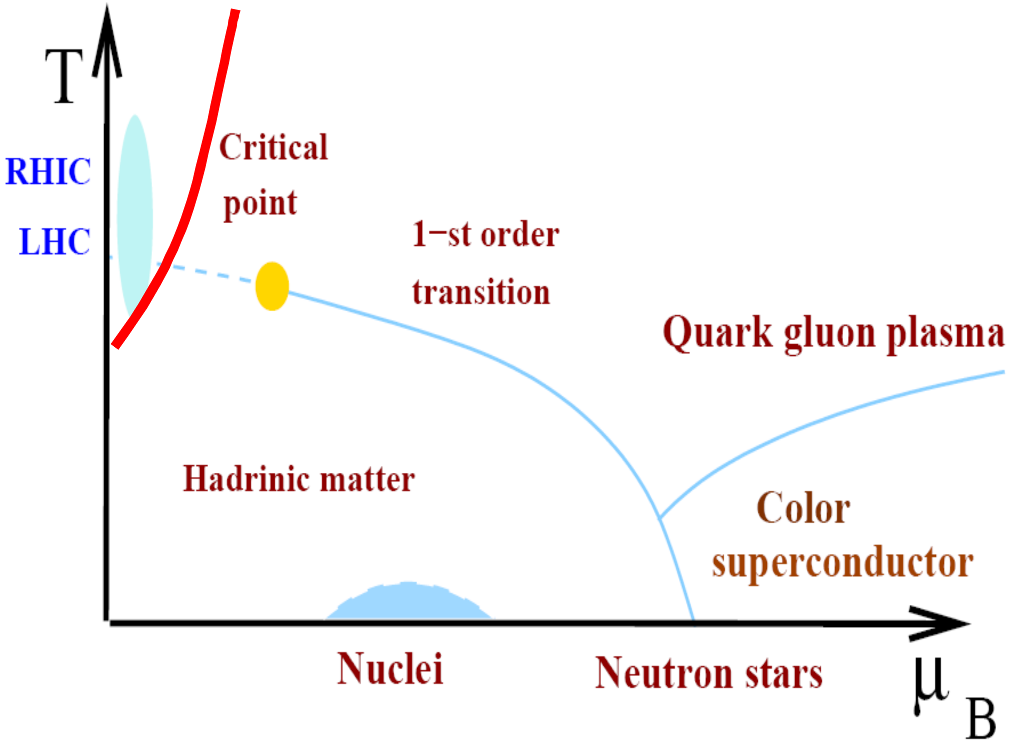
Multiplicity: Experimental data



Phase diagram from dual approach

Formation of trapped surfaces is only possible when Q<Qcr





Red for smeared matter
Blue for point-like

I.A., A.Bagrov, Joukovskaya, 0909.1294
I.A., A.Bagrov, E.Pozdeeva, 1201.6542

Different profiles ----- different multiplicities

Goal: try to find a profile to fit experimental data

Cai, Ji, Soh, gr-qc/9801097

- **Dilaton shock waves**

IA, 0912.5481

Multiplicity very closed to LHC data

Kiritsis,Taliotis, 1111.1931

Further directions

- Anysotropic thermalisation
- Isotropisation time
(isotropisation due to instability in anisotropic plasma)

Janik, Witaszczyk, 08

$$\tau_{isotr} \sim 0.1\, fm$$

$$\langle T^{\mu\nu} \rangle = diag(\varepsilon, P_{\perp}, P_{\perp}, P_{L})$$

Mateos,Trancanelli, PRL, '11
PRL, '12

a conformal anomaly $\langle T^{\mu}_{\mu} \rangle \propto a^4$

5-dimensional axion-dilaton gravity

$$\chi = a\, x_L$$

Conclusion

Using conjecture that BH production in AdS5 gives QGP formation in 4-dim QCD we have got:

- Multiplicity
- New phase transition (T vs μ)