Quark-Gluon Plasma Formation in Heavy Ion Collisions in Holographic Description

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Outlook

- Quark-Gluon Plasma(QGP) in heavy-ions collisions(HIC)
- Holography description of QGP in equilibrium
- Holography description of formation of

  QGP in HIC <=> Black Holes formation in AdS
- Thermalization time/Dethermalization time
- Non-central collisions in holography description

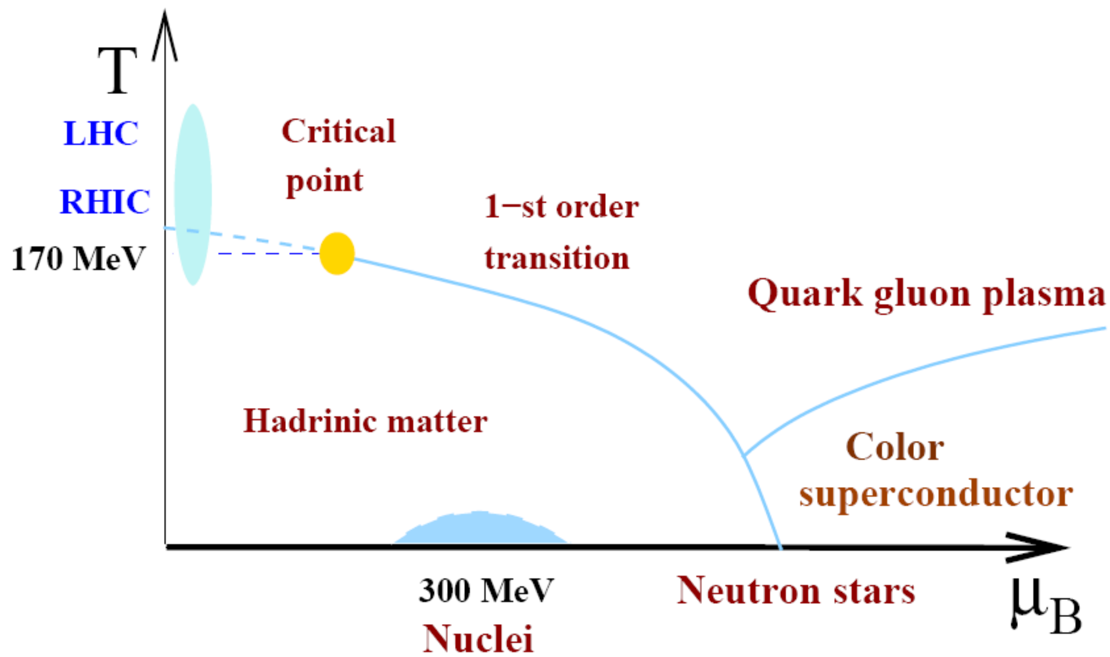
Quark-Gluon Plasma (QGP): a new state of matter

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

HIC are studied in several **experiments:**

- started in the 1990's at the Brookhaven Alternating Gradient Synchrotron (AGS), $\sqrt{s_{NN}} = 4.75 GeV$
- the CERN Super Proton Synchrotron (SPS) $\sqrt{s_{NN}} = 17.2 GeV$
- the Brookhaven Relativistic Heavy-Ion Collider (RHIC) $\sqrt{s_{NN}} = 200 GeV$
- the LHC collider at CERN. $\sqrt{s_{NN}} = 2.76 TeV$

Fireball at the LHC is denser, larger and longer lived than at RHIC.

$$\epsilon \sim 10 GeV/fm^3, V \sim 4800 fm^3, \tau_{life} \sim 10 fm/c$$

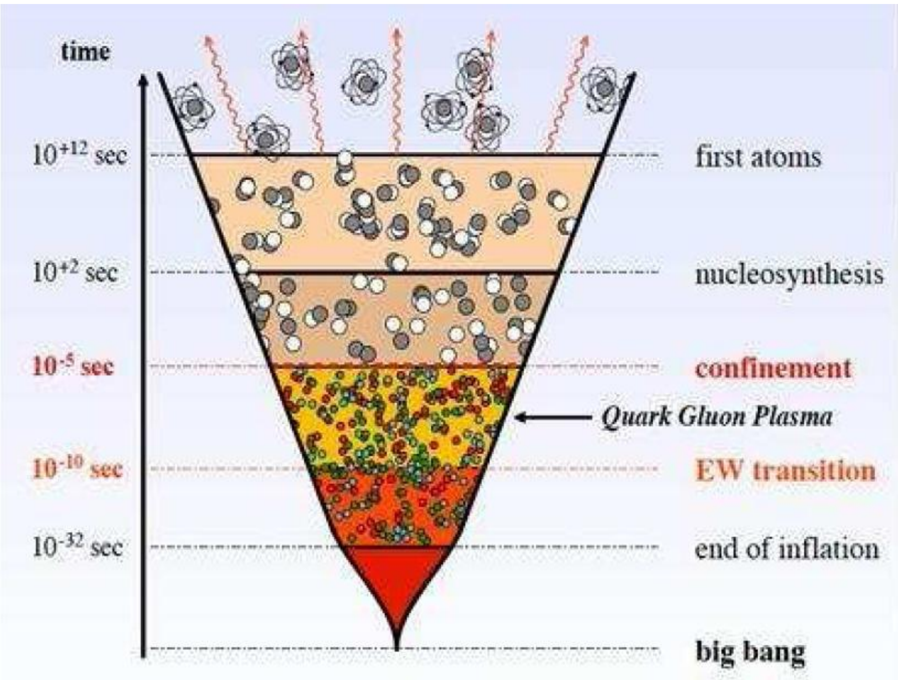
There are strong experimental evidences that RHIC or LHC have created some medium which behaves collectively:

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

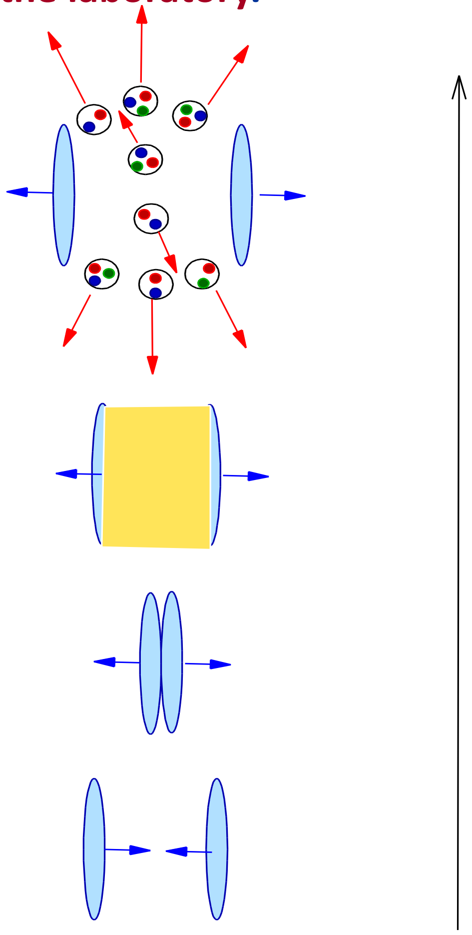
Study of this medium is also related with study of Early Universe

QGP 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 create such a state of matter in the laboratory.

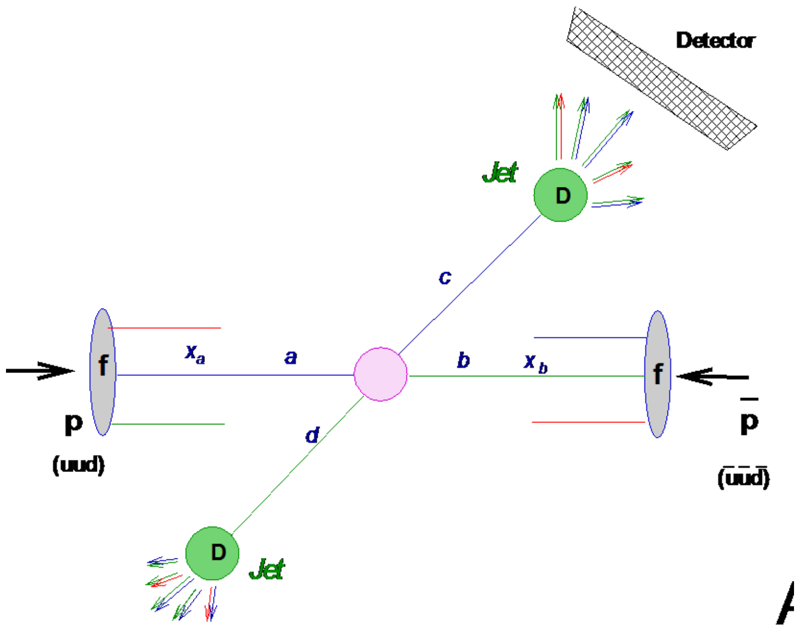


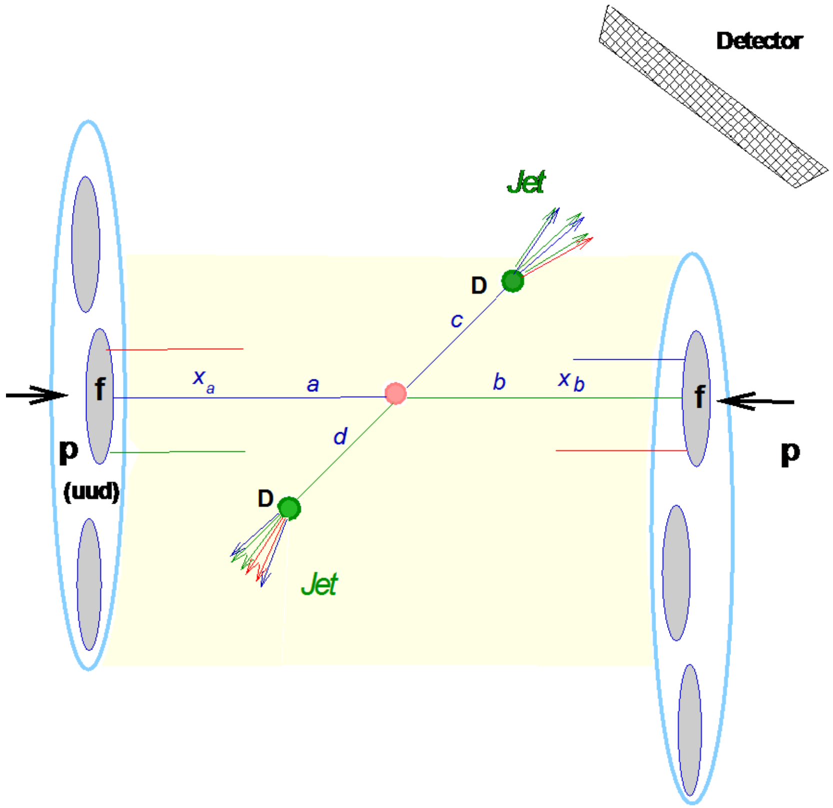
Evolution of the Early Universe



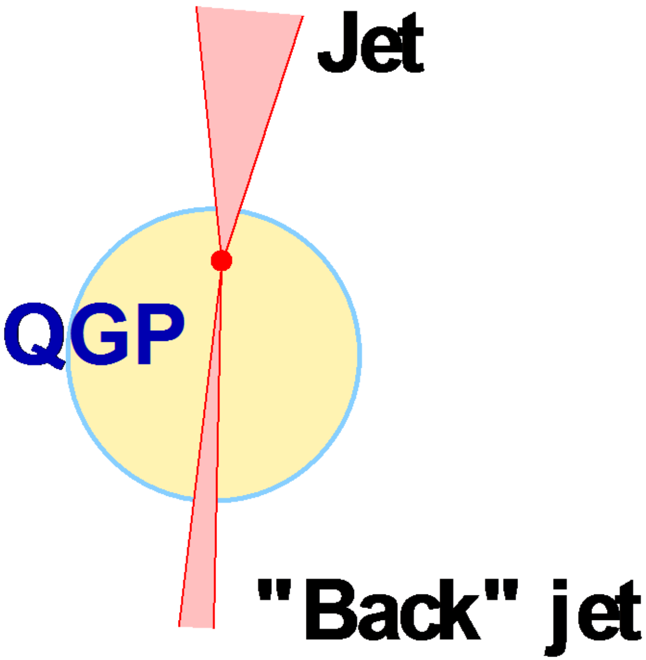
Evolution of a Heavy Ion Collision

pp collisions vs heavy ions collisions

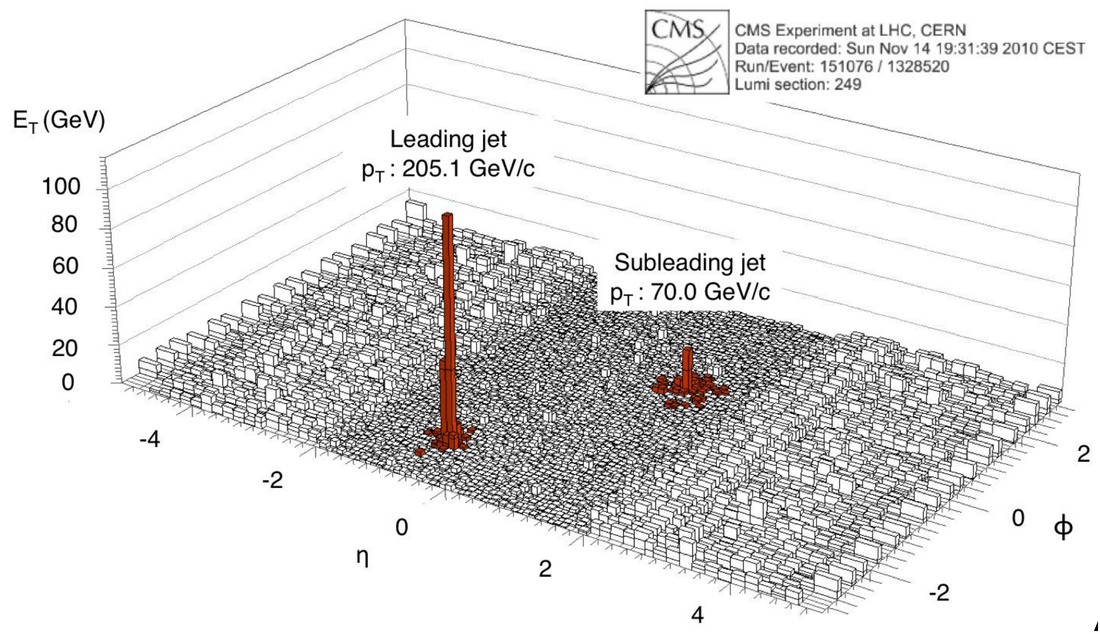




Jet quenching



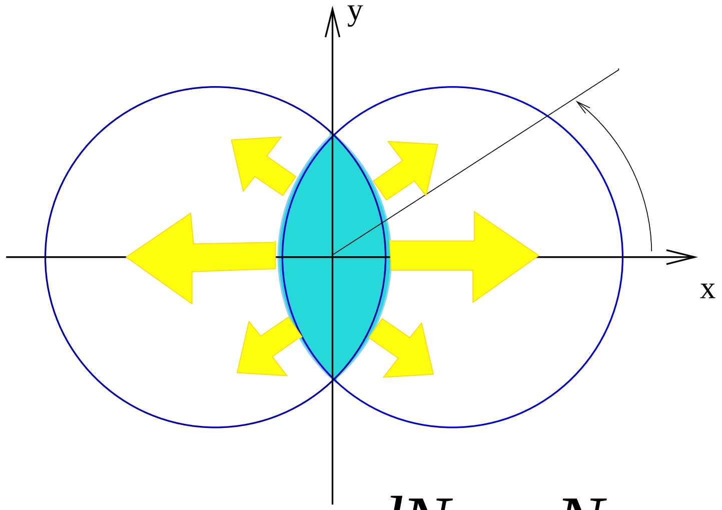
Central collision



P. Sorensen, Highlights from Heavy Ion Collisions at RHIC….., 1201.0784[nucl-ex]

I.A., Holographic Description of Heavy Ion Collisions, PoS ICMP2012 (2012) 025

Elliptic flow



Non-central collision

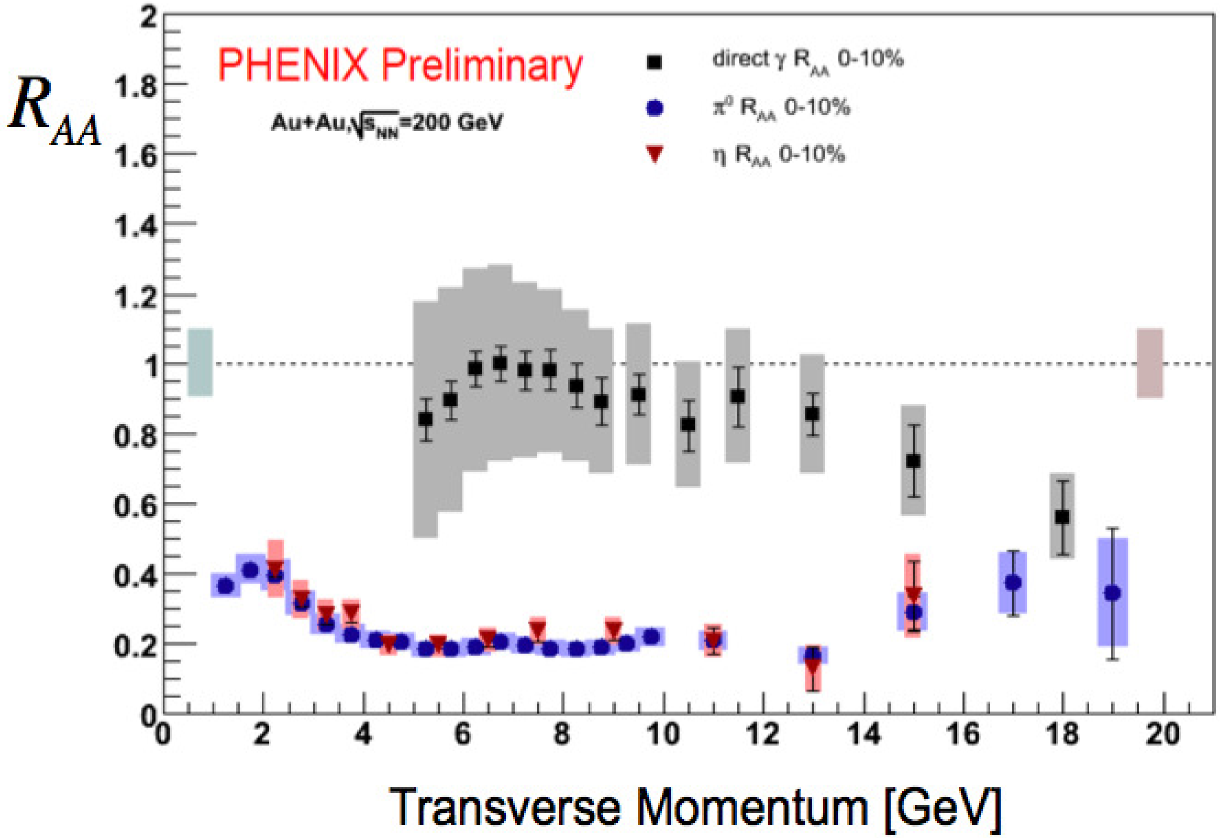
$$\frac{dN}{d\varphi} = \frac{N}{2\pi}(1 + v_2(p_\perp, b)\cos(2\varphi) + \ldots)$$

Imprints of anisotropies are more essential for small shear viscosity,
since usually large viscosity erases stronger irregularity

$$\eta/s \approx 0.03 - 0.15$$

The nuclear modification factor

$$R^h_{AB}(p_T, \eta, \text{centrality}) = \frac{\frac{\mathrm{d}N^{AB\to h}_{\text{medium}}}{\mathrm{d}p_T\,\mathrm{d}\eta}}{\langle N^{AB}_{\text{coll}}\rangle \frac{\mathrm{d}N^{pp\to h}_{\text{vacuum}}}{\mathrm{d}p_T\,\mathrm{d}\eta}}$$

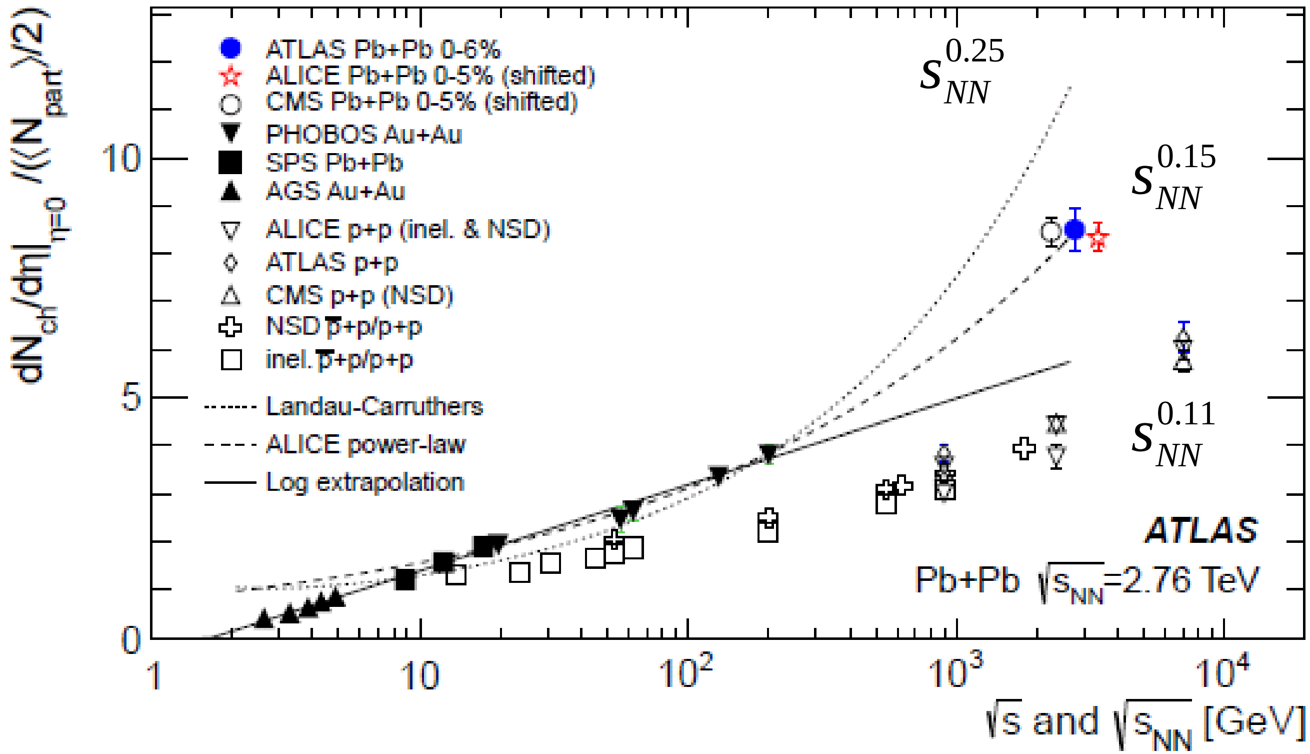


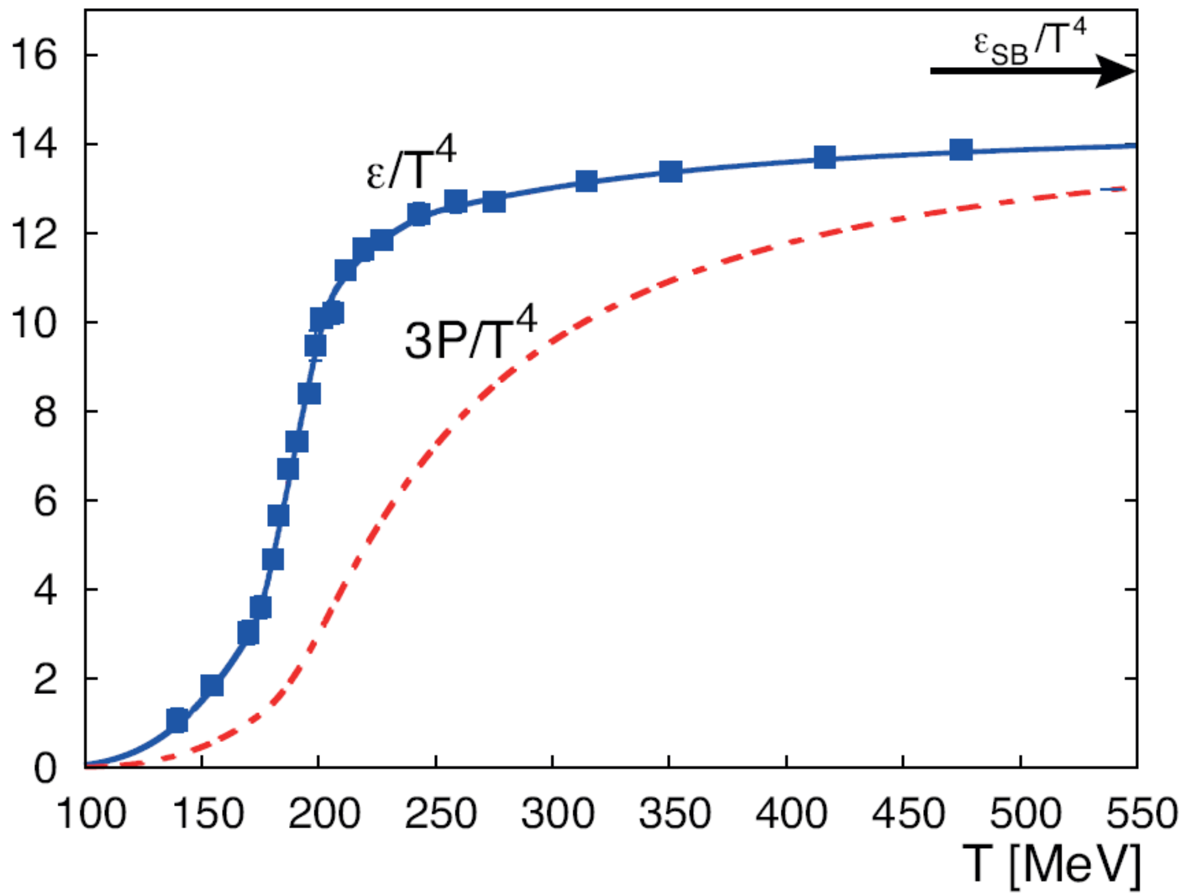
Multiplicity: Landau's/Hologhrapic formula vs experimental data

Landau formula

$$\mathcal{M} \sim s_{NN}^{1/4}$$

Plot from: ATLAS Collaboration 1108.6027





lattice calculation of QCD thermodynamics $N_f = 3$

S. Borsanyi et al., ”The QCD equation of state with dynamical quarks,” arXiv:1007.2580

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 $E = 3P$ (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 QGP.

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

"Holographic description of quark-gluon plasma"

- Holographic description of quark-gluon plasma in equilibrium

- Holography description of quark-gluon plasma formation
  in heavy-ions collisions

Hologhraphic description of QGP

(QGP in equilibruum)

Holography for thermal states

TQFT in M_D-spacetime	=	Black hole in AdS_{D+1}-space-time

TQFT = QFT with temperature

AdS/CFT correspondence in Euclidean space. $T\neq 0$

To compute the Matsubara correlator at finite temperature

$$G^E(k_E) = \int d^4x_E\, e^{-ik_E\cdot x_E} \langle T_E \hat{\mathcal{O}}(x_E)\hat{\mathcal{O}}(0)\rangle$$

Here T_E denotes Euclidean time ordering

Euclidean time coordinate τ is periodic, $\tau \sim \tau + T^{-1}$

$$< e^{\int_{\partial M} \phi_0 \mathcal{O}} > \; = e^{S_g[\phi_c(\phi_0)]}$$

$$\underbrace{\phi(\tau,\vec{x}}_{x_E},z), \quad S_g[\phi], \quad \delta S_g[\phi_c]=0 \quad \phi_c|_{\partial M}=\phi_0 \quad \phi_c=\phi_c(\phi_0)$$

boundary condition $\phi|_{z=0} = \phi_0$ + requirement of regularity at horizon

g: $$ds^2 = \frac{R^2}{z^2}\left(f(z)d\tau^2 + d\mathbf{x}^2 + \frac{dz^2}{f(z)}\right) + R^2 d\Omega_5^2$$

$$f(z) = 1 - z^4/z_H^4 \qquad z_H = (\pi T)^{-1}$$

T is the Hawking temperature

$0 < z < z_H$

Correlators with T≠0 AdS/CFT

Example. D=2

$$\langle \mathcal{O}(t,\mathbf{x})\mathcal{O}(t,\mathbf{x}')\rangle_{ren} \sim e^{-\Delta\delta\mathcal{L}}$$

x-x'= ℓ

$$\delta\mathcal{L} \equiv \mathcal{L} + 2\ln(z_0/2)$$

Vacuum correlators M=AdS

$$\delta\mathcal{L}_{\mathrm{vacuum}}(\ell) = 2\ln\frac{\ell}{2}$$

Temperatute M=BHAdS with r_H

t $\geq \ell/2$

$$\delta\mathcal{L}_{\mathrm{thermal}}(\ell) = 2\ln\frac{\sinh\frac{r_H\ell}{2}}{r_H}$$

Bose gas

Hologhraphic Description of Formation of QGP

Hologhraphic thermalization

Thermalization of QFT in Minkowski D-dim space-time

⟷

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

Profit:

Studies of BH formation in AdS_{D+1}

Time of thermalization in HIC

Multiplicity in HIC

Formation of BH in AdS. Deformations of AdS metric leading to BH formation

- **colliding gravitational shock waves**

Gubser, Pufu, Yarom, Phys.Rev. , 2008 (I)
Gubser, Pufu, Yarom, JHEP , 2009 (II)
Alvarez-Gaume, C. Gomez, Vera,
Tavanfar, Vazquez-Mozo, PRL, 2009
IA, Bagrov, Guseva, Joukowskaya, E.Pozdeeva
2009, 2010,2012 JHEP
Kiritsis, Taliotis, 2011 JHEP

- **drop of a shell of matter with vanishing rest mass**

  ("null dust"),

  infalling shell geometry = Vaidya metric

Danielsson, Keski-Vakkuri , Kruczenski, 1999
……
Balasubramanian +9. PRL, 2011, Phys.Rev.2011

- **sudden perturbations of the metric near the boundary that propagate into the bulk**

Chesler, Yaffe, PRL, 2011

Deformations of AdS metric by infalling shell

d+1-dimensional infalling shell geometry is described in Poincar'e coordinates by the Vaidya metric

Danielsson, Keski-Vakkuri and Kruczenski

$$ds^2 = \frac{1}{z^2}\left[-\left(1 - m(v)z^d\right)dv^2 - 2dz\,dv + d\mathbf{x}^2\right] \qquad ★$$

v labels ingoing null trajectories

1) For constant $m(v) = M$, the coordinate transformation $dv = dt - \dfrac{dz}{1 - M\,z^d}$

brings ★ in the form

$$ds^2 = \frac{1}{z^2}\left[-\left(1 - Mz^d\right)dt^2 + \frac{dz^2}{1 - Mz^d} + d\mathbf{x}^2\right]$$

2) $$m(v) = \frac{M}{2}\left(1 + \tanh\frac{v}{v_0}\right)$$

★ interpolates between vacuum AdS inside the shell and an AdS black brane

Correlators via Geodesics in AdS/CFT

$$< \mathcal{O}_\Delta(\tau_1, \vec{x}_1)\mathcal{O}_\Delta(\tau_2, \vec{x}_2) > = \int \mathcal{D}\mathcal{P}\ e^{i\Delta\, L(\mathcal{P})}$$

$$\mathcal{P} \in M$$

$$(\tau_1, \vec{x}_1) \in \partial M$$

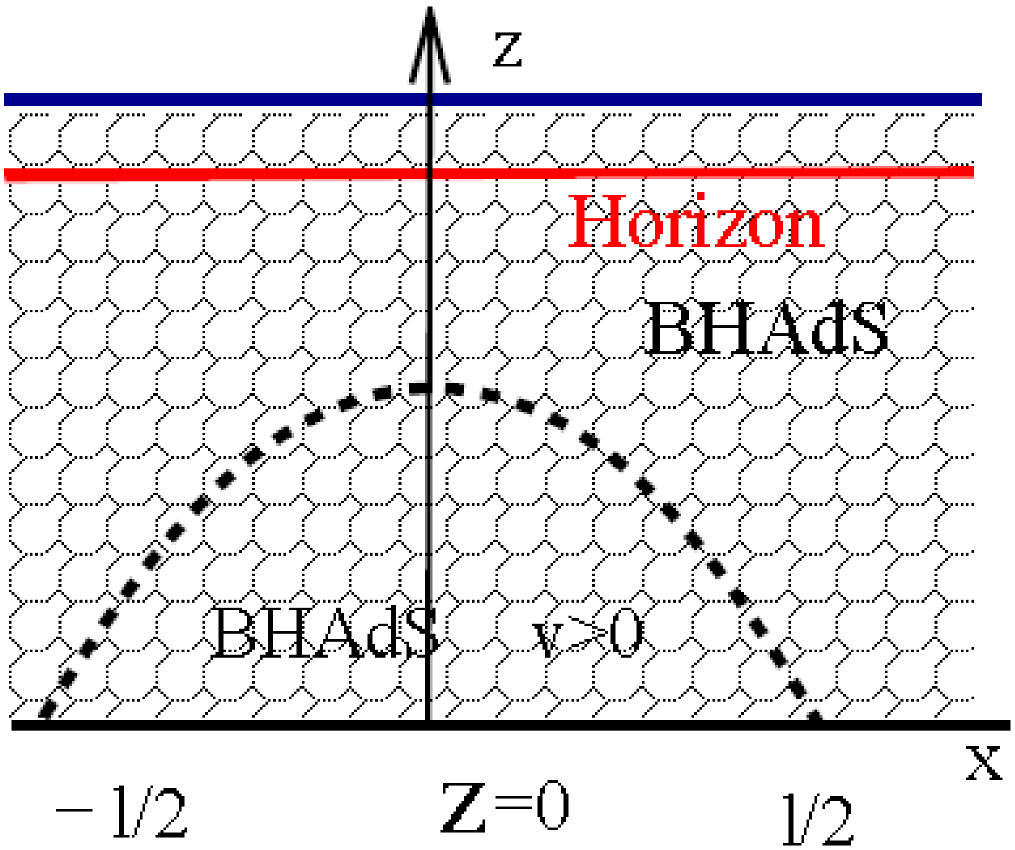
$$L(\mathcal{P}) = \int (-g_{\mu\nu} \dot{X}^\mu \dot{X}^\nu)^{1/2}$$

$$(\tau_2, \vec{x}_2) \in \partial M$$

Vacuum correlators: M=AdS

Temperatute: M=BHAdS

Thermalization with Vadya AdS

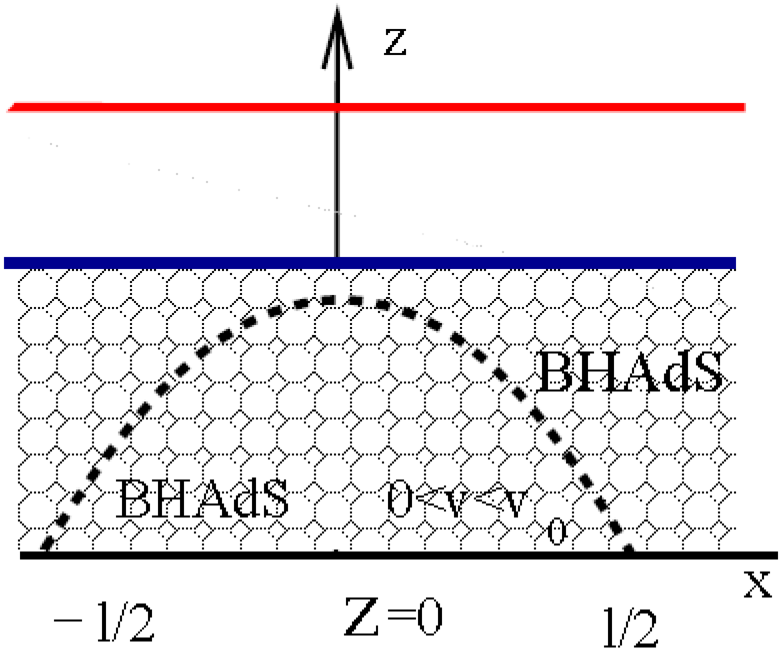


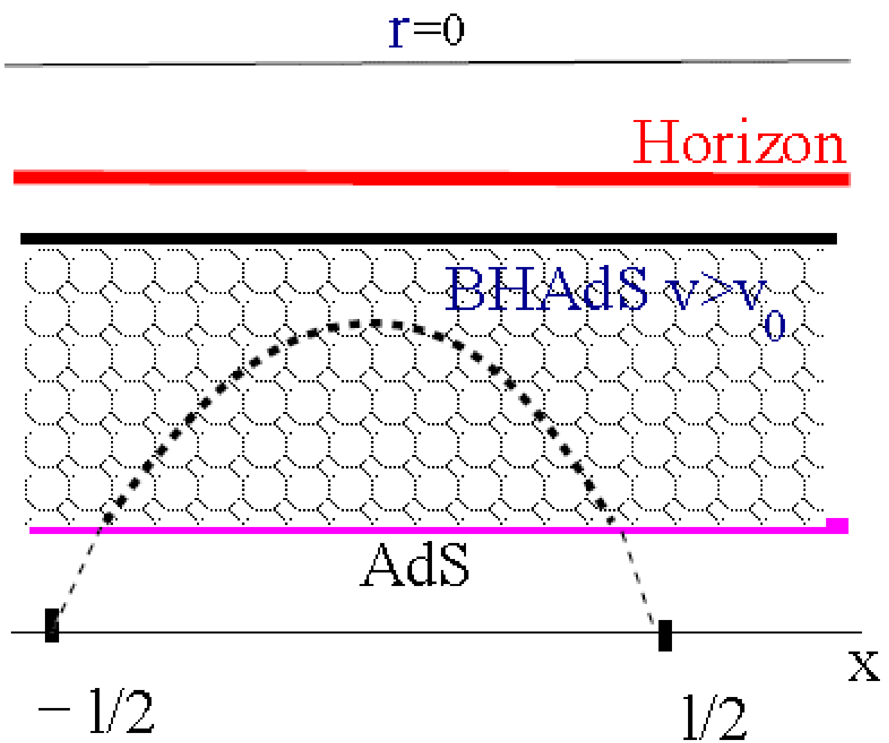
Equal-time correlators

Evaporation vs thermalization

$$m(v) = M\theta(v) - M_1\theta(v - v_1)$$

$$M = M_1$$





No thermalization for large l

$t_{dethermalization}$ / $t_{thermalization}$

$$\tau_{therm} = \int_J^\infty \frac{dr}{r^2(1 - \frac{M}{r^d})}$$

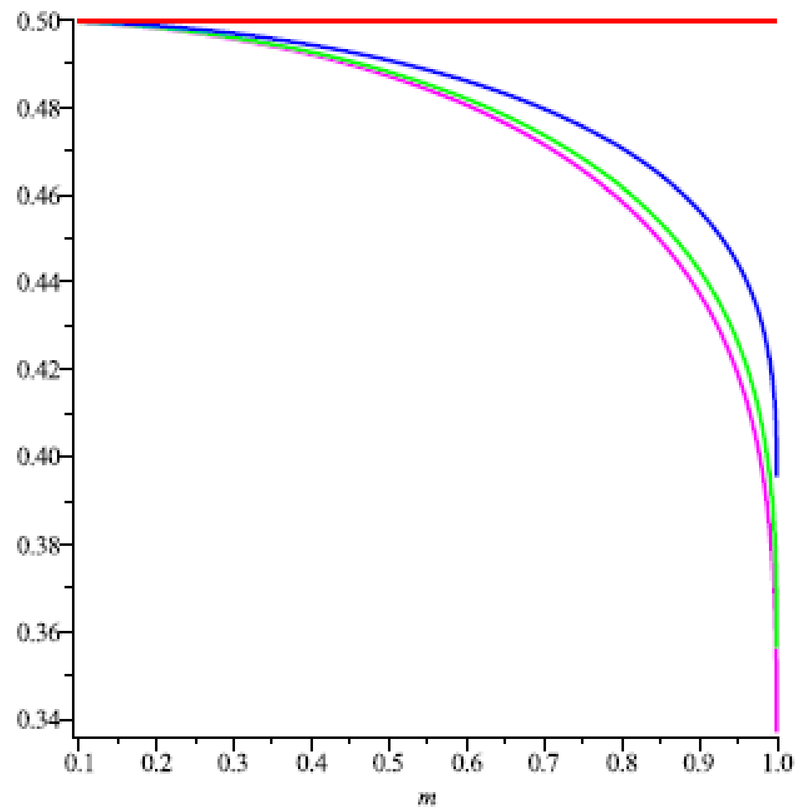
$$\ell = 2J \int_J^\infty \frac{dr}{r^2\sqrt{(r^2 - J^2)\,(1 - \frac{M}{r^d})}}.$$

$$\frac{\tau_{ther}}{\tau_{dether}} = F(m^2, d) \qquad F(m^2, d) = \frac{\int_1^\infty \frac{d\rho}{\rho^2(1 - \frac{m^2}{\rho^d})}}{2\int_1^\infty \frac{d\rho}{\rho^2\sqrt{(\rho^2 - 1)\,(1 - \frac{m^2}{\rho^d})}}}.$$

$t_{dethermalization}$ / $t_{thermalization}$

$$\frac{\tau_{ther}}{\tau_{dether}} = F(m^2, d)$$

$$0.78 < \frac{\tau_{ther}}{\tau_{det}} < 1$$



Data: $\tau_{ther}/\tau_{det} \sim 0.1 - 0.05$

$t_{thermalization}$

Data: $\tau_{ther} \sim 1 \text{ fm/c}$

Balasubramanian +9,PRL, 2011,Phys.Rev.2011

thermal scale $l \sim \hbar/T$ $\quad T \sim 300 - 400 MeV$

$\tau_{therm} \sim 0.3\text{fm/c},$

$l \sim 2 \text{ fm}$

I.A., I.Volovich,1211.6041

$r_{Pb} \approx 7 \text{ fm}$ can pack 208 (A=208 for Pb) balls with radius

$$r_n = \sqrt[3]{\frac{\eta_K}{208}}\, r_{Pb} \approx 1.07 \, \text{fm} \qquad l \sim r_n$$

η_K is the Kepler number $\eta_K = \pi/\sqrt{18} \approx 0.74$

$t_{dethermalization}$ /$t_{thermalization}$

Data: $\tau_{ther}/\tau_{det} \sim 0.1 - 0.05$

$l_{det} \sim 2r_{Pb} \sim 14$ fm. $\qquad l_{therm} \sim 2\, fm$

$\tau_{det} \sim 7\text{fm/c}$

$$\frac{\tau_{ther}}{\tau_{det}} = \frac{\tau_{ther}}{0.5 \cdot l_{ther}} \cdot \frac{l_{ther}}{l_{det}} = 0.39 \cdot \frac{2}{14} \approx 0.056$$

Thermalization Time and Centricity

In progress with A.Koshelev, A.Bagrov

Non-centricity

Kerr-ADS-BH

$$ds^2 = -(N^{\perp}(r))^2 dt^2 + \frac{1}{(N^{\perp}(r))^2} dr^2 + r^2 (N^{\phi}(r) dt + d\phi)^2$$

$$N^{\perp} = \left(-M + \left(\frac{r}{l}\right)^2 + \frac{a^2}{r^2} \right)^{1/2}, \quad N^{\phi}(r) = -\frac{a}{r^2}$$

$$ds^2 = -\left(-M + \frac{r^2}{l^2} \right) dv^2 + 2dvdr - 2advd\hat{\phi} + r^2 d\hat{\phi}^2$$

$$dv = dt + \frac{dr}{(N^{\perp})^2}$$

$$d\hat{\phi} = d\phi - \frac{N^{\phi}}{(N^{\perp})^2} dr$$

$$M(v) = M\theta(v),$$

$$j(v) = 2a\theta(v)$$

Kerr-ADS-BH Geometry

$$\beta_{1,2} = \frac{l^2 M}{2}\left(1 \pm \sqrt{1 - \frac{4a^2}{l^2 M^2}}\right)$$

Geodesics

$$t(r) = t_0 - \frac{\mathcal{E} l^3}{2} I_{\pm}|_{\alpha=-\frac{\mathcal{J} a}{\mathcal{E}}}, \quad \phi(r) = \phi_0 + \frac{\mathcal{J} l}{2} I_{\pm}|_{\alpha=\frac{\mathcal{E} a + \mathcal{J} M}{\mathcal{J}/l^2}}$$

$$-I_+ = \frac{1}{(\beta_1 - \beta_2)}\left[\frac{\alpha - \beta_1}{\sqrt{B_1}} \ln(X_1 - \mathrm{sign}(x - \beta_1)\sqrt{X_1^2 - (\gamma_1 - \gamma_2)^2}) - \right.$$
$$\left. - \frac{\alpha - \beta_2}{\sqrt{B_2}} \ln(X_2 - \mathrm{sign}(x - \beta_2)\sqrt{X_2^2 - (\gamma_1 - \gamma_2)^2})\right] + C = I_- + C$$

$$X_i = (2\beta_i - \gamma_1 - \gamma_2) + \frac{2B_2}{x - \beta_i}$$

$$\gamma_1 + \gamma_2 = Ml^2 - l^2\mathcal{E}^2 - +J^2$$
$$\gamma_1 \gamma_2 = l^2 a^2 - l^2 J(MJ + 2a\mathcal{E})$$

$$x \equiv r^2$$

$$C = -\frac{2}{(\beta_1 - \beta_2)}\left[\frac{\alpha - \beta_1}{\sqrt{B_1}} - \frac{\alpha - \beta_2}{\sqrt{B_2}}\right] \ln(\gamma_1 - \gamma_2)$$

Geodesics which start and finish at $r = \infty$

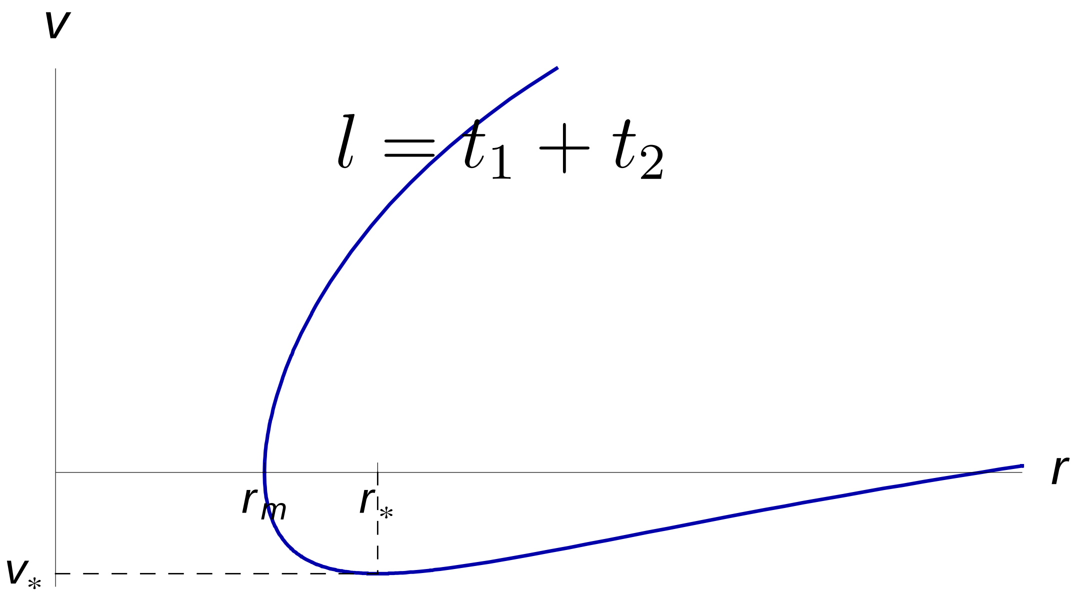
$$t_1 \equiv t_-(\infty) \qquad t_2 \equiv t_+(\infty)$$

$$t_1 = t_0 - \frac{\mathcal{E}}{2} I_-(\infty)\big|_{\alpha = -\frac{\mathcal{J} a}{\mathcal{E}}}$$

$$t_2 = t_0 - \frac{\mathcal{E}}{2} I_+(\infty)\big|_{\alpha = -\frac{\mathcal{J} a}{\mathcal{E}}}$$

$$\phi_1 = \phi_-(\infty) = \phi_0 + \frac{\mathcal{J}}{2} I_-(\infty)\big|_{\alpha = \frac{\mathcal{E} a + \mathcal{J} M}{\mathcal{J}}}$$

$$\phi_2 = \phi_+(\infty) = \phi_0 + \frac{\mathcal{J}}{2} I_+(\infty)\big|_{\alpha = \frac{\mathcal{E} a + \mathcal{J} M}{\mathcal{J}}}$$



Thermal point

$$\dot{v}_* = 0$$

a=0

$$l = t_1 + t_2 - 2 v_*$$

Conclusion

Formation of QGP of 4-dim QCD ⇔ Black Hole formation in AdS_5

- **Multiplicity: AdS-estimations fit experimental data**

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

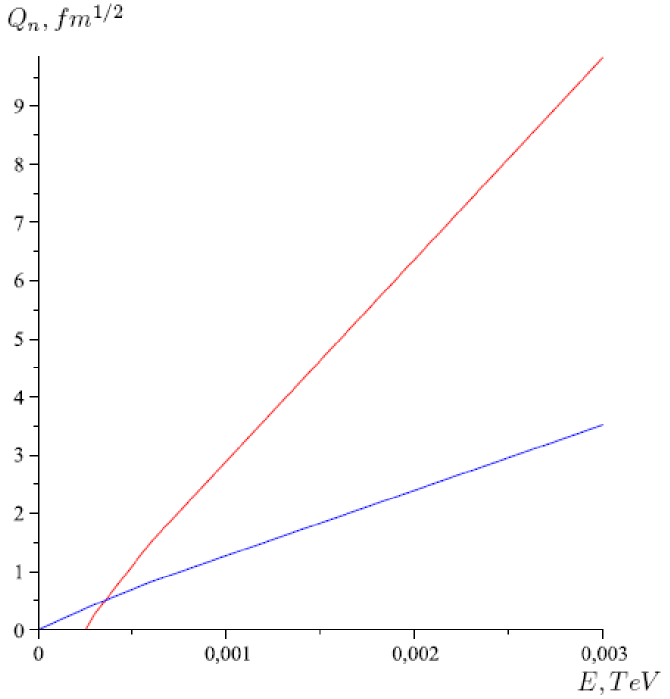
- $\tau_{ther}/\tau_{det} \sim 0.1 - 0.05$

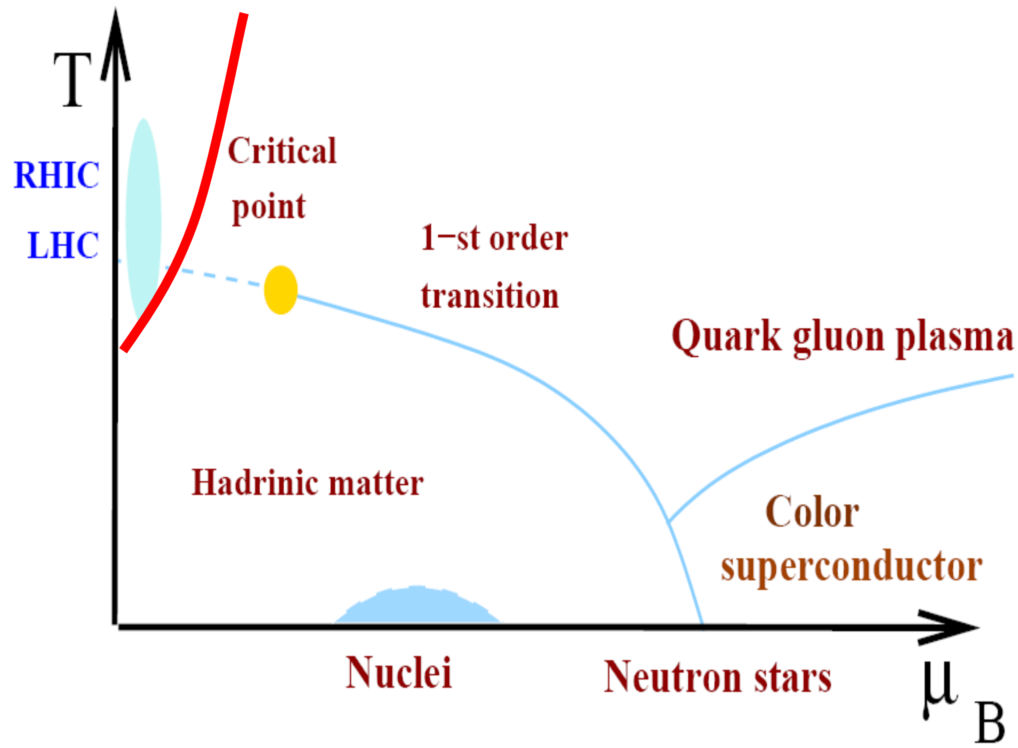
- **Non-centricity decreases thermalization time.**

- **New phase transition (T vs μ_B)**

BACKUP: Phase diagram from dual approach

Formation of trapped surfaces is only possible when Q<Qcr





Red for a smeared matter
Blue for a point-like source

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