

Heavy ion collisions

String theory

Condensed
Matter
Physics



11th Workshop on Non-perturbative QCD @ Paris, 9 June 2011

Rapid Thermalization by Baryon Injection in Gauge/Gravity Duality

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w/ N.Iizuka (CERN), T.Oka (Tokyo) arXiv:1012.4463

(1)

Problem

Derivation of the Rapid thermalization at Heavy ion collision?

(2)

Cause

QCD : strongly coupled, & confined \rightarrow deconfined

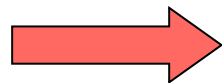
Thermalization : non-equilibrium & time-dependent process

(3)

Our solution

AdS/CFT can treat all the causes.

+ Initial condition mimicking the collision

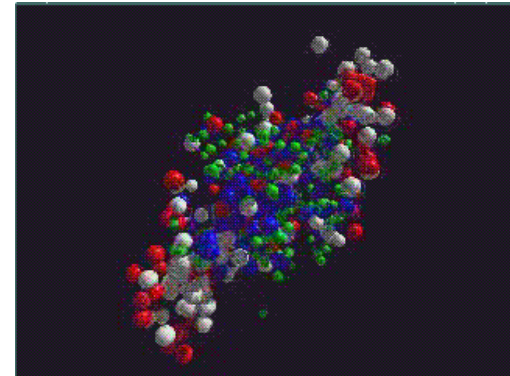
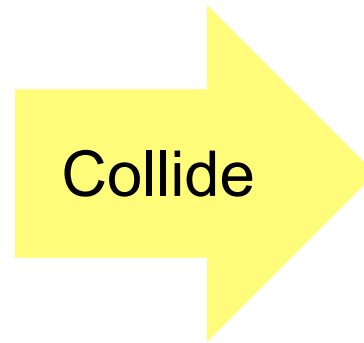
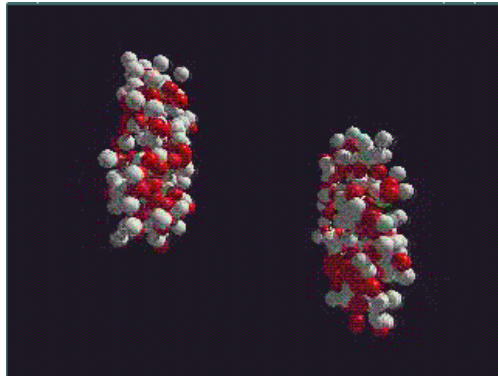


Rapid thermalization

(1)

Problem

Derivation of the Rapid thermalization at Heavy ion collision?



Hydrodynamic simulation suggests rapid thermalization :

$$t_{\text{th}} < 2 \text{ [fm/c]}$$

[Kolb, Huovinen, Heinz, Heiselberg ('00)],

[Hirano ('01)], [Huovinen ('01)],

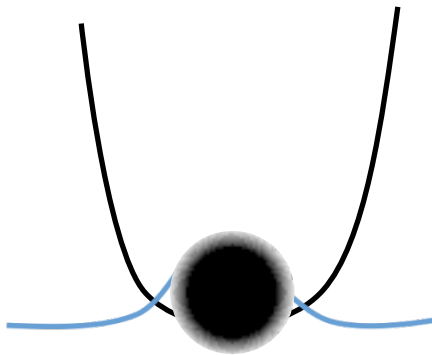
[Teaney, Lauret, Shuryak ('01)], [Heinz, Kolb ('02)], ...

(2)

Cause

QCD : strongly coupled, & confined \rightarrow deconfined

Thermalization : non-equilibrium & time-dependent process



AdS

/

CFT

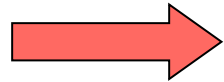
Formation of
Black Hole Horizon = Thermalization
+ deconfinement

(3)

Our solution

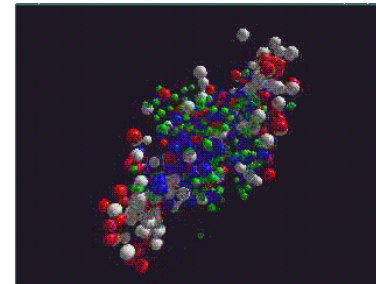
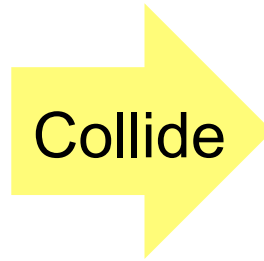
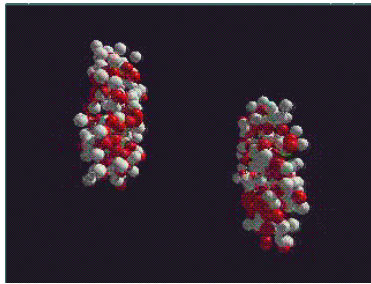
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+ Initial condition mimicking the collision



Rapid thermalization

Initial condition ?



- Bjorken expansion [Janik, Peschanski ('06)], [Chesler, Yaffe ('08)],
[Bhattacharyya, Minwalla ('09)], ...
[Muller, et.al ('10)]

- Sudden change of Baryon number density [Ours]

Both should give the rapid thermalization

Plan of this talk

Our idea: Collision = a time dep. baryon density

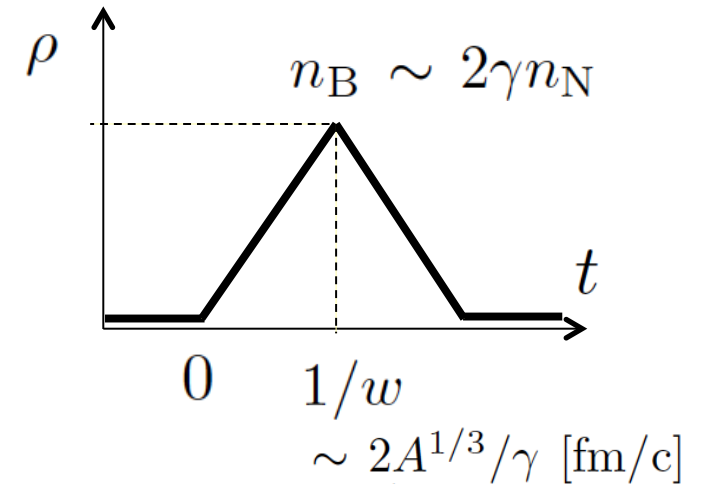
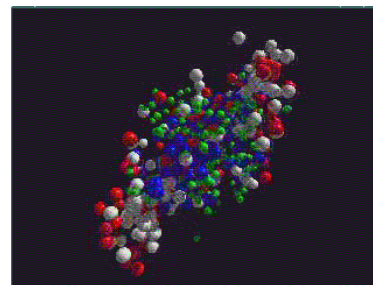
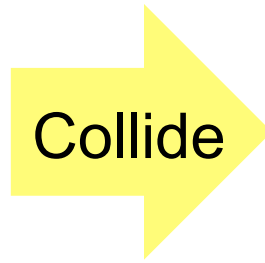
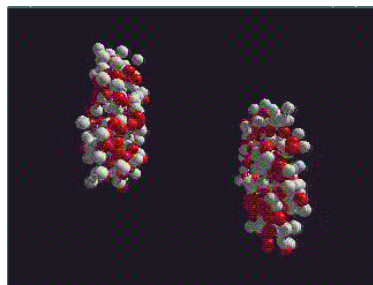
Time dependence, solved

Nonlinearity \rightarrow Effective horizon

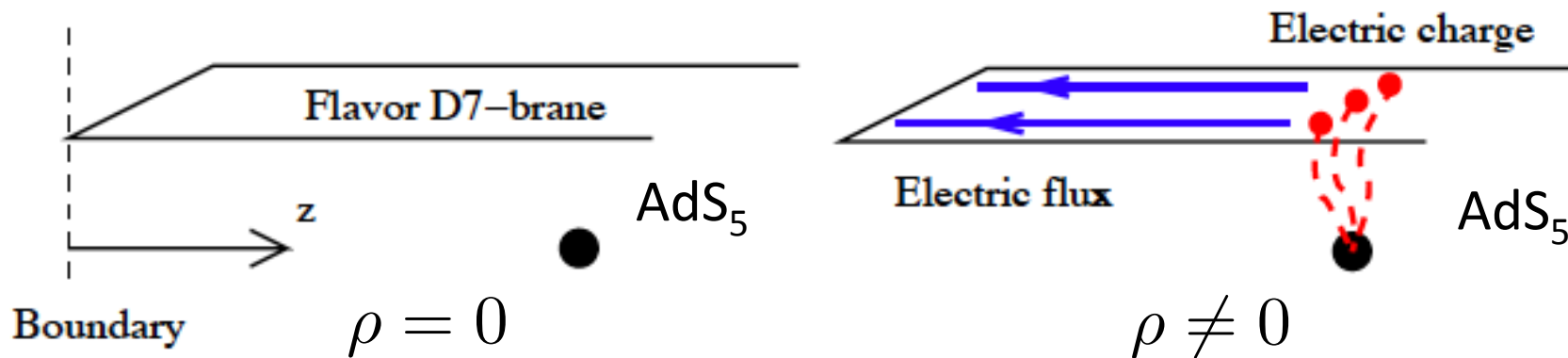
Thermalization timescale, a fun part

Universality?

Our idea : Collision = a time-dep. baryon density

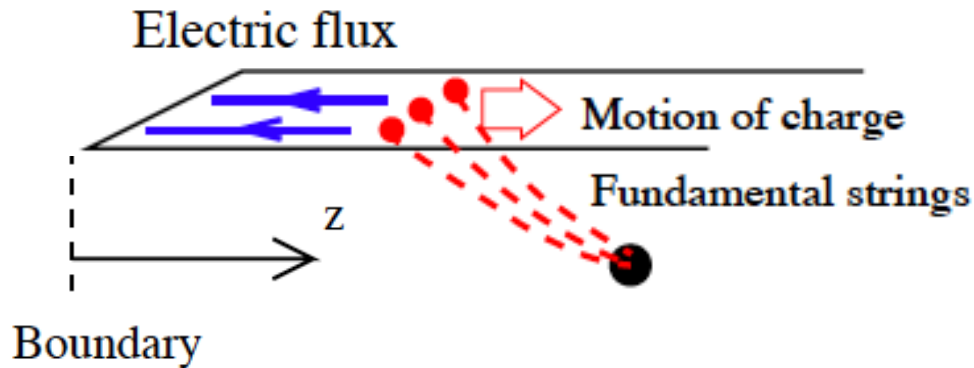


$N=2$ SQCD: D3-D7



[Apreda, Erdmenger, Evans, Fralnik ('05)], [Kim, Sin, Zahed ('06)],
 [Horigome, Tanii ('06)], [Parnachev, Sahakyan ('06)],
 [Kobayashi, Mateos, Matuura, Myers, Thomson ('06)], ...

Time dependence, solved



On the Flavor D-brane in curved geometry,
solve nonlinear Maxwell with source motion

$$S = -\mu_7 \int d^8 \xi \sqrt{-\det (G_{ab} + 2\pi\alpha' F_{ab})}$$

$$\delta S = \mu_7 V_3 \text{Vol}(S^3) \int dt dz (A_t j^t + A_z j^z)$$

$$j^t = j^z = g'(t - z) \quad g(t) = (2/\pi)(2\pi\alpha')^4 \lambda n_B(t)$$

“Holographic Quantum Quench” [Das, Nishioka, Takayanagi (‘10)]

Details

D7-brane action in AdS₅ background, for massless quark :

$$S = -\mu_7 V_3 \text{Vol}(S^3) \int dt dz \frac{R^8}{z^5} \sqrt{1 - \frac{z^4}{R^4} (2\pi\alpha')^2 F_{tz}^2}$$

Solution :

$$(2\pi\alpha') F_{tz} = \frac{R^2 z g(t-z)}{\sqrt{(2\pi\alpha')^2 R^{12} + z^6 (g(t-z))^2}}$$

Check :

$$g(t-z) = \text{constant} \quad \rightarrow \text{Previously known solutions used for phase diagrams}$$

Nonlinearity → Effective Horizon

Small fluctuation on the flavor D-brane (meson modes) feels emergence of **effective horizon** in this background solution

→ **Thermalization**

D7 scalar fluctuation:

$$S = - \int dt dz d^3 x^i d^3 \theta^I \frac{\sqrt{-\tilde{g}}}{2} \tilde{g}^{MN} \partial_M \delta \eta \partial_N \delta \eta + \mathcal{O}(\delta \eta^3)$$
$$- \tilde{g}_{tt} = \tilde{g}_{zz}$$
$$= \mu_7^{1/3} R^{4/3} z^{-4/3} (1 - z^4 R^{-4} (2\pi \alpha'^2) F_{tz}^2)^{5/6},$$
$$\tilde{g}_{ij} = \mu_7^{1/3} R^{4/3} z^{-4/3} (1 - z^4 R^{-4} (2\pi \alpha'^2) F_{tz}^2)^{-1/6} \delta_{ij},$$
$$\tilde{g}_{IJ} = \mu_7^{1/3} R^{4/3} z^{2/3} (1 - z^4 R^{-4} (2\pi \alpha'^2) F_{tz}^2)^{-1/6} G_{IJ},$$

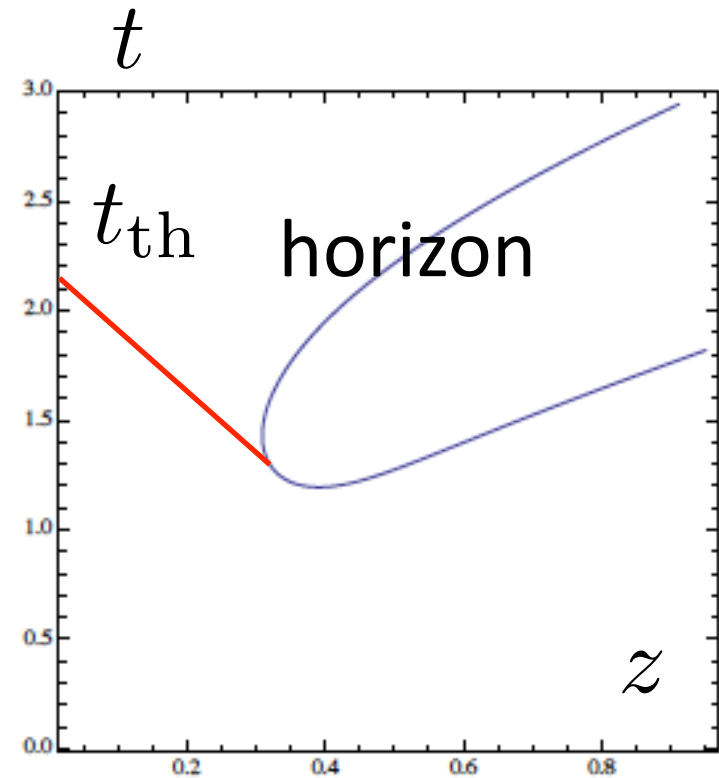
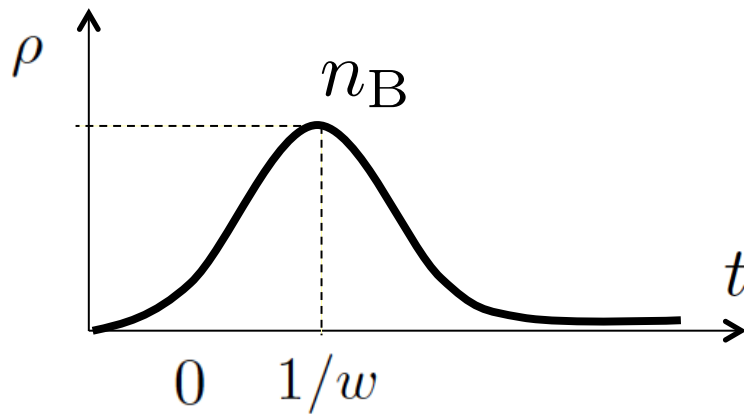
Apparent horizon is located at:

$$(\partial_z - \partial_t) \left[z^2 (1 - z^4 R^{-4} (2\pi \alpha'^2) F_{tz}^2) \right] = 0$$

Thermalization timescale

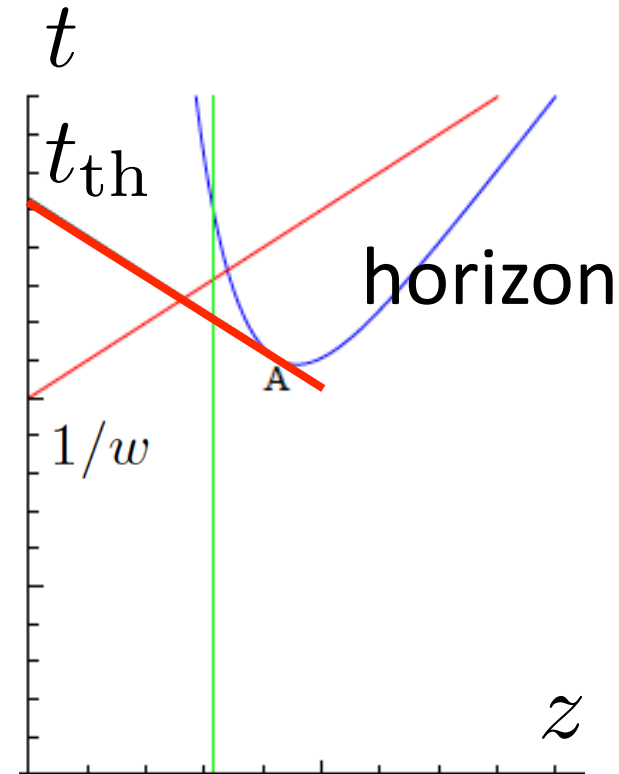
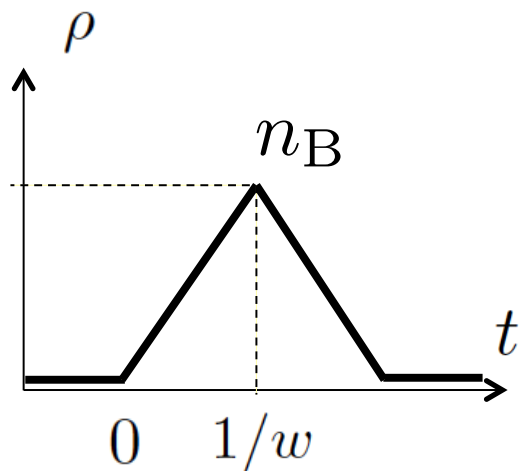
Example: gaussian change

$$\rho(t) = n_B \exp \left[-(2w)^2 (t - 1/w)^2 \right]$$



Thermalization timescale

Example: linear change




$$t_{th} \sim \min_{\{k=0,1,2\}} \left\{ \left(\frac{\lambda}{n_B^2 w^k} \right)^{1/(6+k)} \right\}$$

Fun : physical parameters

$$t_{\text{th}} \sim \min_{\{k=0,1,2\}} \left\{ \left(\frac{\lambda}{n_{\text{B}}^2 w^k} \right)^{1/(6+k)} \right\}$$

RHIC Au Collision:

$$n_{\text{B}} \sim 2\gamma n_{\text{N}}$$
$$1/w \sim 2A^{1/3}/\gamma \text{ [fm/c]}$$
$$\gamma = E/m_{\text{Au}} \sim 100$$

 $t_{\text{th}} < 1 \text{ [fm/c]}$

**Rapid thermalization,
consistent with hydrodynamics**

$$t_{\text{th}} \lesssim \mathcal{O}(0.1) \text{ [fm/c]} \quad \text{for LHC}$$

Universality?

- Effect of quark mass? Little. $\eta(z=0) = 2\pi\alpha' m_q$

$$R^2/z^2 \rightarrow (R^2/z^2 + \eta^2/R^2)$$

Small mass does not change the story: $m_q \ll (\sqrt{2}\lambda n_B/\pi)^{1/3}$

- Confining gauge theory? Still applicable.

IR modification does not change the story, since horizon formation is around UV region.

Ex) Liu-Tseytlin background, valid for $\tau_{\text{QCD}} < 2^{5/3} \lambda^{1/6} n_B^{2/3}$

- Supersymmetry? Not so relevant.

We have not used any fermions.

- Other models with no asymptotic AdS₅? Significantly altered.
- What is thermalized? Quarks and mesons

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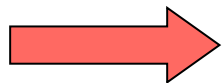
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