COLUMBIA UNIVERSITY
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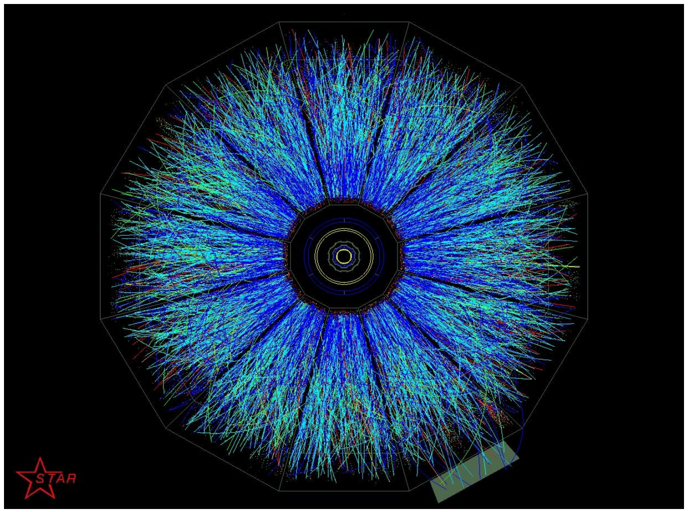
The Strongly-Coupled Semi Quark-Gluon Plasma



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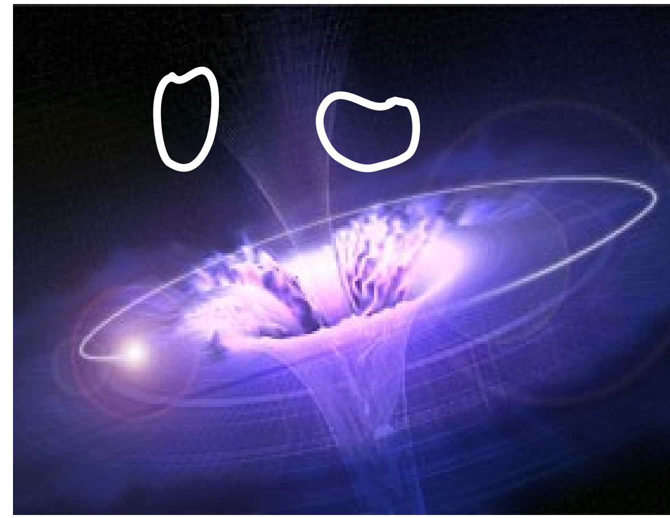


Jorge Noronha

JET Collaboration

Quantifying the Properties of Hot QCD Matter, INT, 2010

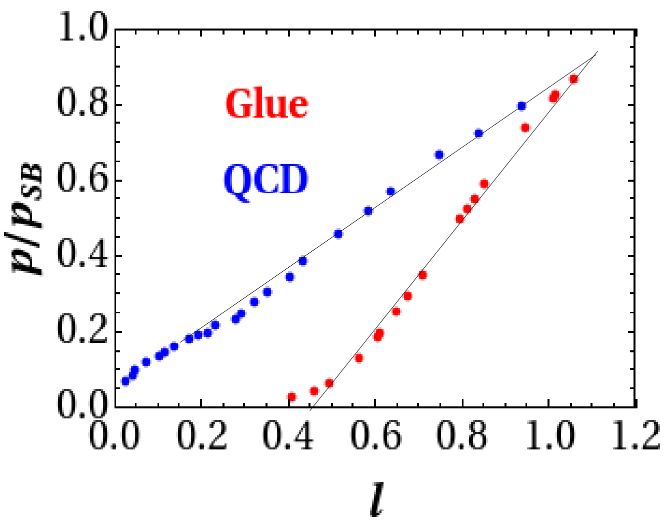
- **The semi QGP corresponds to the QCD state of matter where the Polyakov loop changes significantly with T, i.e., between 0.8 - 2.5 Tc** **(Pisarski, Hidaka, 2008)**

THE SEMI QGP IS NOT APPROXIMATELY CONFORMAL !!!!!!

- Physically this can be seen as a state where ionization of color is not complete.

- According to the lattice, most likely **the QGP created in heavy ions is a semi-QGP.**

- Lattice data suggests that it may be possible to find an effective description of the semi QGP where



Note that $p/p_{SB} \sim \ell$

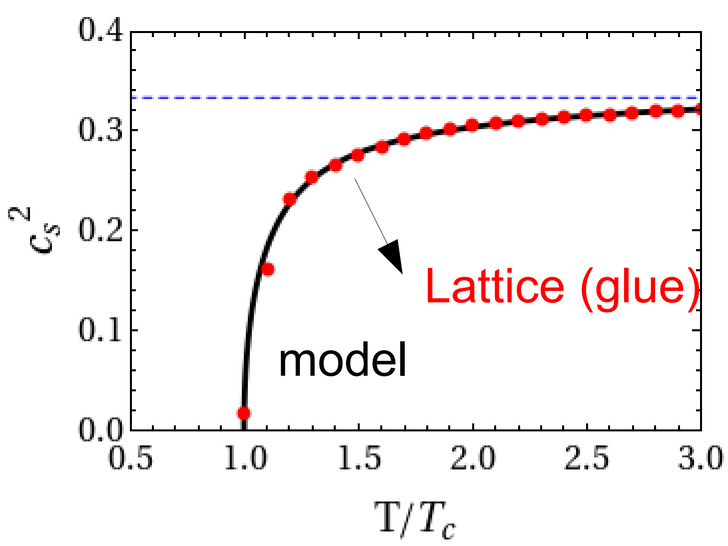
for glue, glue + quarks (even in the "hadronic phase") !!!

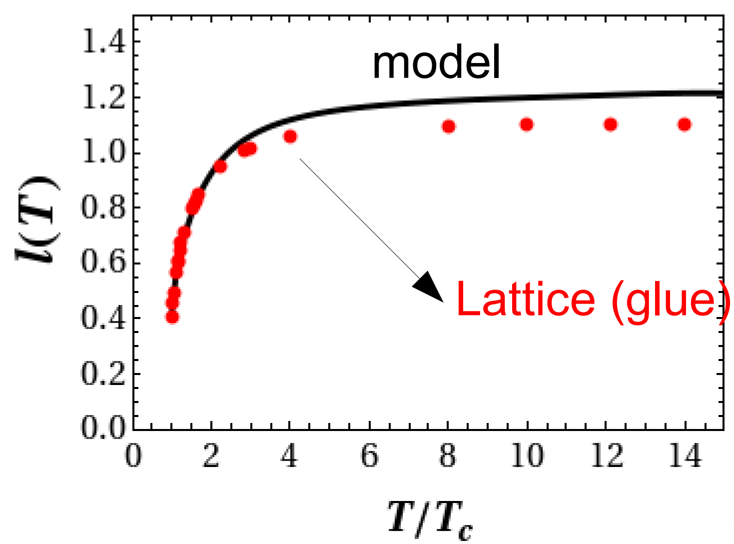
How do we model this semi QGP ???

The **main idea** of this talk is to show you in a few slides that the semi QGP **can be successfully modeled using holography**

In fact, a “simple” 5d gravity dual involving the metric and a scalar field with dynamics given by

$$V(\phi) = -12(1+a\phi^2)^{1/4} \cosh\sqrt{\frac{2}{3}}\phi + \dots$$



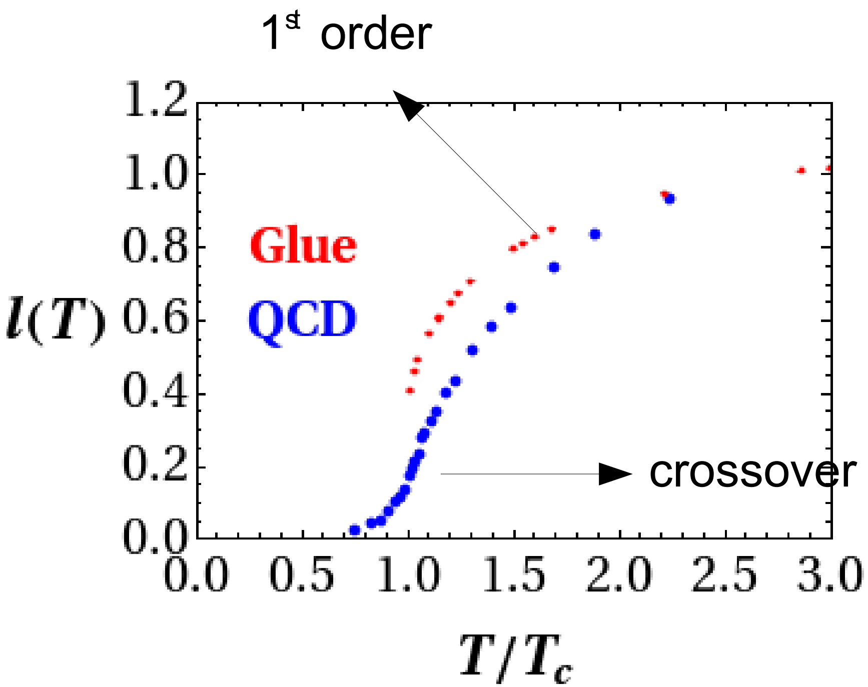


What does the lattice say about the semi Quark-Gluon Plasma?

Renormalized Polyakov loop in the fundamental representation

$$\ell \sim e^{-\mathcal{F}_Q/T}$$

Data from A. Bazavov et al (MILC Collaboration), 2009.
Gupta, Huebner, Kaczmarek, 2008.



In QCD, near Tc one does not have well defined hadrons or quarks and gluons … (at least not in the way we have studied them before)

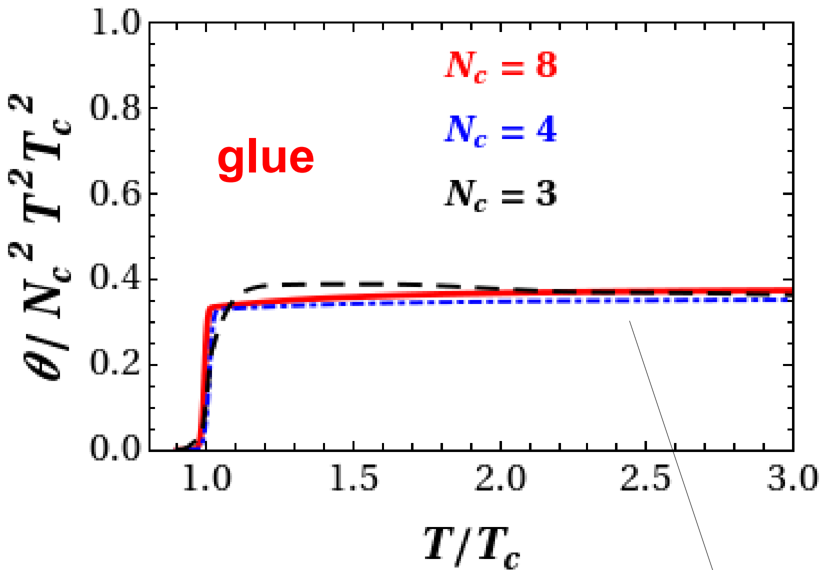
Deconfinement as ionization of color charge

Pisarski, Hidaka, 2008.

What does the lattice say about the semi Quark-Gluon Plasma?

Trace anomaly

$$\theta = \varepsilon - 3p$$



Plot made using the data from M. Panero, PRL 2009

Fuzzy bag?

Power like behavior near T_c

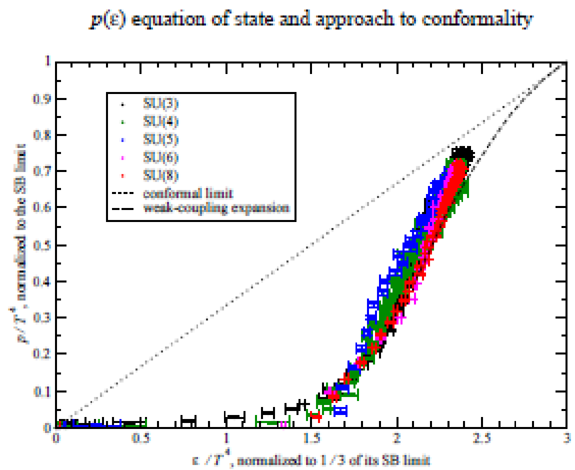
Pisarski, 2006
Megias, Arriola, Salcedo, 2006

$$\frac{e - 3p}{T^4} \sim c\,\frac{T_c^2}{T^2}$$

Qualitatively different than usual pQCD calculations (no logarithms) ...

Holographic Model of Pure Glue at Large Nc

Lattice shows that **conformal invariance is badly violated near Tc**



M. Panero, arXiv:0907.3719 [hep-lat]

Assumption: $1/3 \sim 1/N_c \sim 0$

From the gauge/string duality dictionary

$$\phi \sim Tr\, F_{\mu\nu}^2$$

Bulk — In the gauge theory at the boundary

One should look for gravity duals with a nontrivial scalar field in the bulk !!!

Gubser et al. 2008
Kiritsis et al, 2008

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Minimal extension of the good and old gravity setup (**a bottom-up approach**)

$$S = -\frac{1}{2\kappa_5^2}\int d^5x\,\sqrt{-G}\left[\mathcal{R} - \frac{(\partial\phi)^2}{2} - V(\phi)\right]$$

Scalar potential

$$V(\phi)$$

Nontrivial fields in the 5d bulk: $G_{\mu\nu},\ \phi$

$$k_5^2 = c/\,N_c^2$$

Dual to a relevant deformation of a 4d CFT $\mathcal{L}_{CFT} + \Lambda_\phi^{4-\Delta}\mathcal{O}_\phi$

Here Λ_ϕ is the energy scale of the deformation and Δ is the dimension of $\mathcal{O}_\phi$ in the boundary, which is dual to ϕ in the bulk.

An important property of these theories is that the thermodynamic quantities exhibit a power-like expansion in terms of

$$\left(\frac{\Lambda_\phi}{T}\right)^{2(4-\Delta)}$$

Cherman, Nellore 2009
Hohler, Stephanov, 2009

Thus, the power-like behavior seen on the data should be captured by these models for a convenient choice of parameters.

Here I will require that there is linear confinement below Tc.

A choice for the scalar potential that describes the lattice data is

$$V(\phi) = -12(1+a\phi^2)^{1/4}\ \cosh\sqrt{\frac{2}{3}}\phi + b_2\phi^2 + b_4\phi^4 + b_6\phi^6$$

$a = 1$ $\quad b_4 = 0.4$

$b_2 = 5$ $\quad b_6 = 0.0098$ $\quad \Delta = 2$

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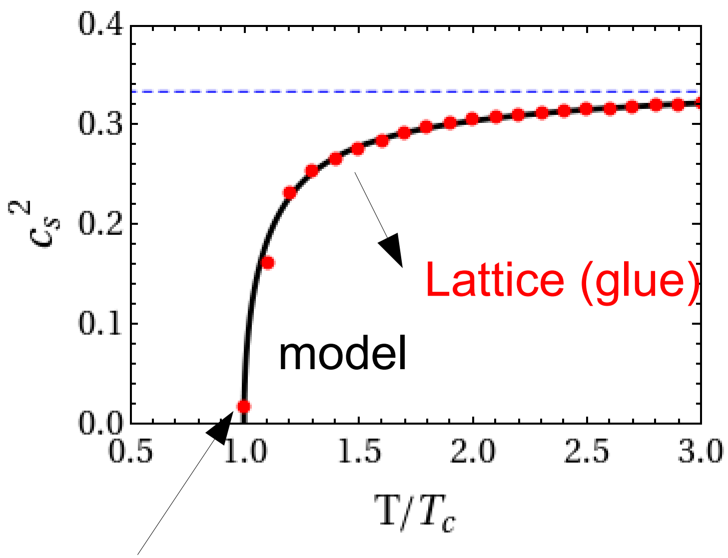
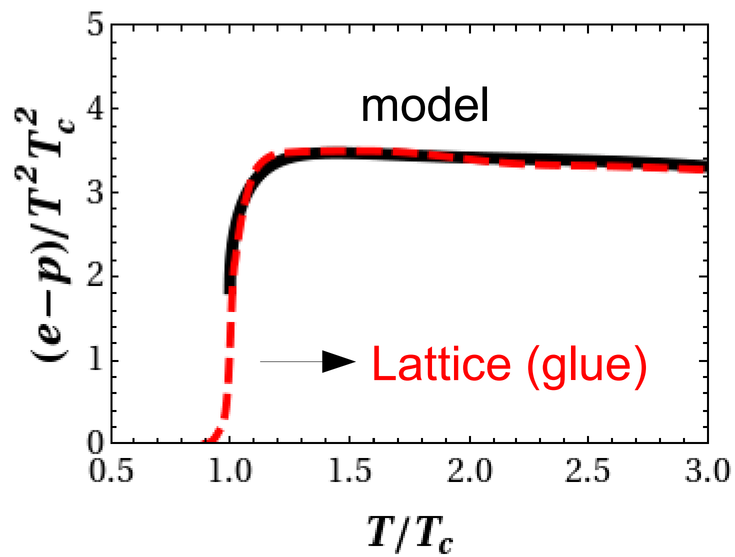
This choice gives an amazing match to the lattice data …



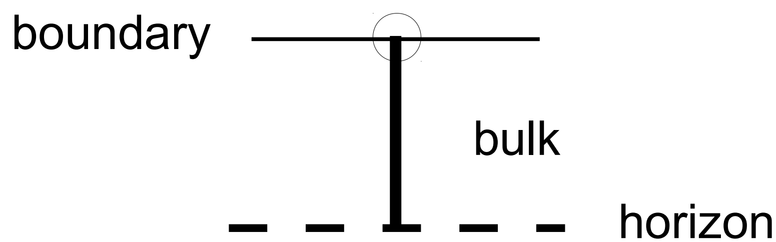
1st order transition



What about the Polyakov loop ???

(**the ionization of color**)

Infinitely massive heavy quark ~ fundamental string in the bulk



Maldacena, 1998
Rey et al. 1998
Brandhuber et al 1998

Assuming

$N_c \gg 1$

$R^2/\alpha' \gg 1$

$$|\langle \ell(T) \rangle| \sim e^{-S_{NG}(\mathcal{D})}$$

$$S_{NG}(\mathcal{D}) = \frac{1}{2\pi\alpha'} \int_{\mathcal{D}} d^2\sigma \, q(\phi) \sqrt{\det h^{ab}}$$

Nambu-Goto action for the string in the bulk

$$h^{ab} = G_{\mu\nu} \partial^a X^\mu \partial^b X^\nu$$

Induced metric on the worldsheet

$q(\phi)$ coupling between string and the scalar field

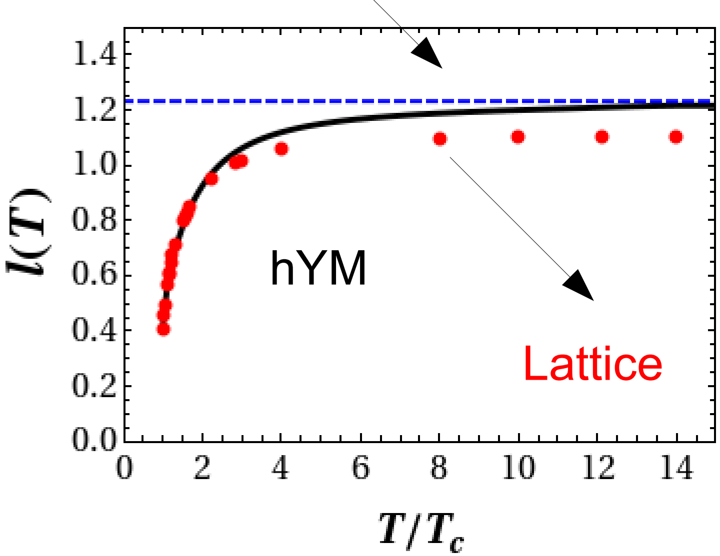
JN, PRD (2010).

JN, PRD (2010).

Let's assume a dilaton-like coupling function $q(\phi) = e^{\sqrt{2/3}\phi}$

Kiritsis et al, 2008

Value at T/Tc >> 1



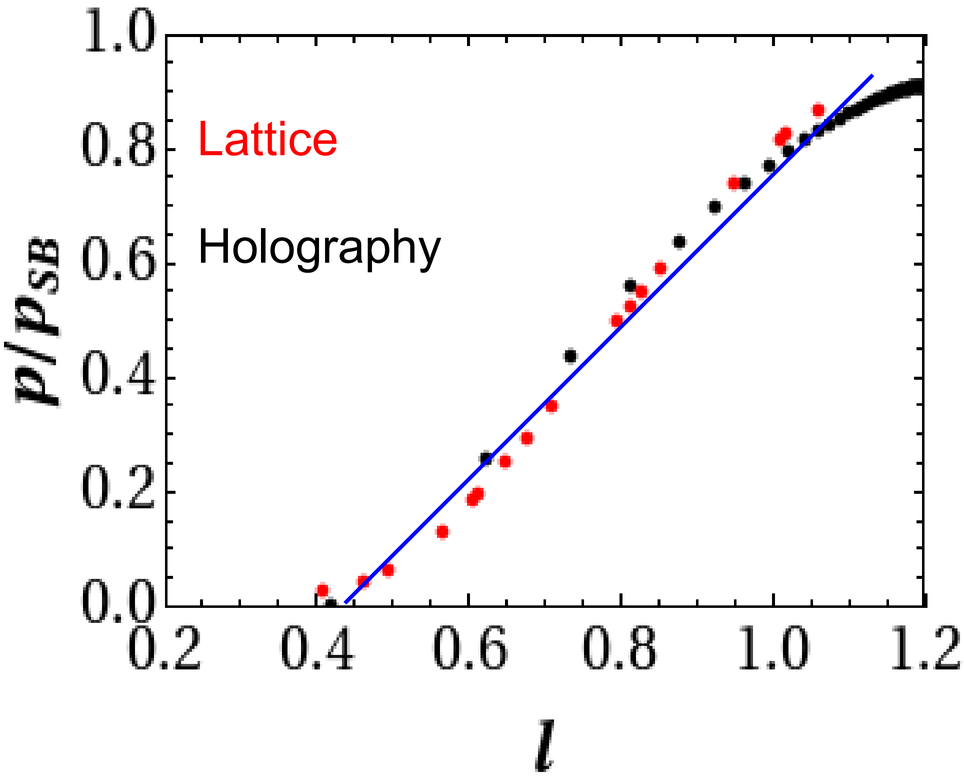
Good agreement below 4Tc …

BUT $R^2/\alpha' \sim 1$

Higher corrections to the gravity dual will be important here !!!

It should be expected because even here $\eta/s = 1/4\pi$ at any T > T_c

In this case the approximate linear relation between P and the loop is reproduced



Other interesting properties, **defined in real time**, that I have no time to discuss here in detail ...

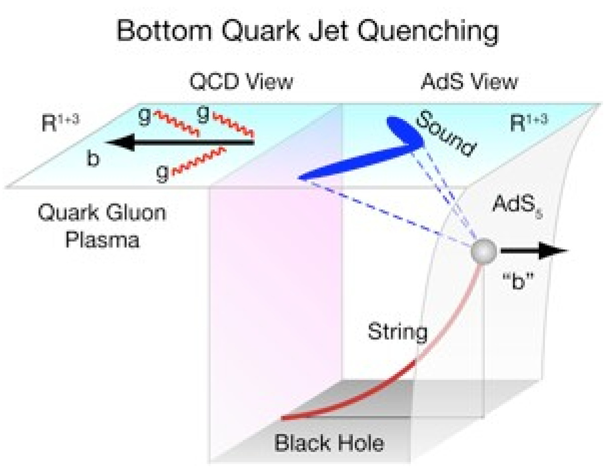
- $\eta/s = 1/(4\pi)$ above Tc. Below Tc one should expect $\eta/s \sim N_c^2$

JN, arXiv:0912.4824 [hep-th]

- ζ/s has a peak at Tc.

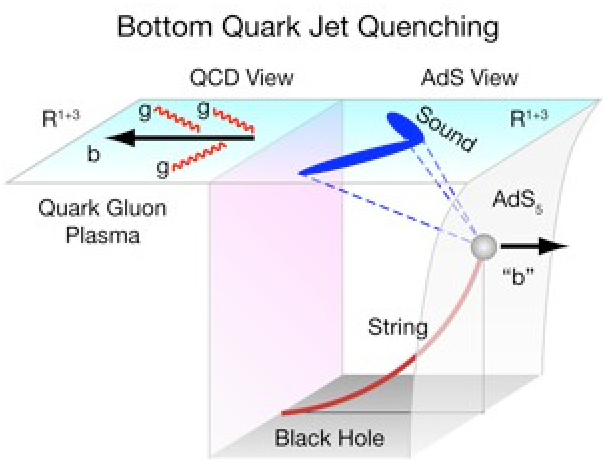
Gubser et al (2008).

What about energy loss????



For the trailing string (heavy quarks) one can show that

Ficnar, JN, Gyulassy, to appear



$v \to 1$ Ultrarelativistic heavy quark

$$\frac{dE}{dx} = \left(\frac{dE}{dx}\right)_{CFT} \left(\frac{S}{S_{CFT}}\right)^{1/2}$$

DIRECT dependence on the medium properties (entropy density) !!!

No Tc enhancement !!!

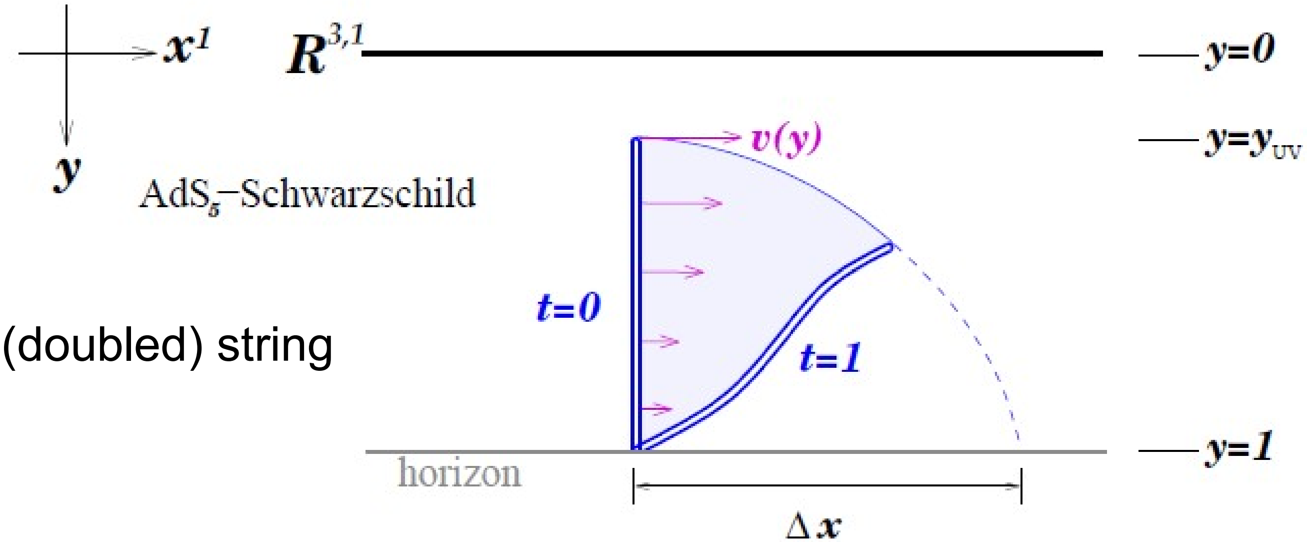
Here we know exactly how confinement affects the heavy quark energy loss ...

What happens to the charm to bottom ratio in R_AA ???

Ficnar, JN, Gyulassy, to appear

What about the glue energy loss ????

Gubser et al, 2008



The "falling (doubled) string problem"

For a CFT one finds $$\Delta x \sim \frac{1}{T}\left(\frac{E}{T}\right)^{1/3}$$

See also Chesler et al, 2009.

BDMPS: $$\Delta E \sim L^2$$

What about the glue energy loss in the semi QGP ????

Ficnar, JN, Gyulassy, to appear

The $\Delta E \sim L^3$ may not survive when conformal invariance is badly broken near Tc. Power of L may be sensitive to the phase transition!

In fact, we know already that in geometries which lead to confinement, such as the Sakai-Sugimoto model,

$$\Delta E \sim L^{2.5}$$ Yi Pang, 2008. **Confinement matters!!!**

The gauge/string duality is the only framework where such questions can be reliably addressed.

Conclusions and Outlook

- The new state of QCD matter created in heavy ions is most likely a semi QGP, which is not conformal and is fundamentally different from the Gedanken free gas (used, for instance, in some jet quenching calculations).

- Gauge/string duality can be used to construct gravity duals that describe a chunk of hot strongly coupled matter that burns and flows like the semi QGP.

- These holographic theories naturally incorporate the non-perturbative power-like temperature terms observed on the lattice (perturbative calculations don't).

- It is possible, using the gauge/string duality, to understand how highly energetic probes lose energy near the deconfinement phase transition (predictions are on the way)

Back-up Slides