Universidade de São Paulo

Hard Probes and AdS/CFT: Theory and Predictions

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PANIC, MIT, July 2011

Outline

1) **Hard Probes and the QGP**

2) **Hard Probes and the AdS/CFT Correspondence: Universal (as well as some specific) predictions for energy loss in a strongly-coupled plasma that "looks like" the QGP**

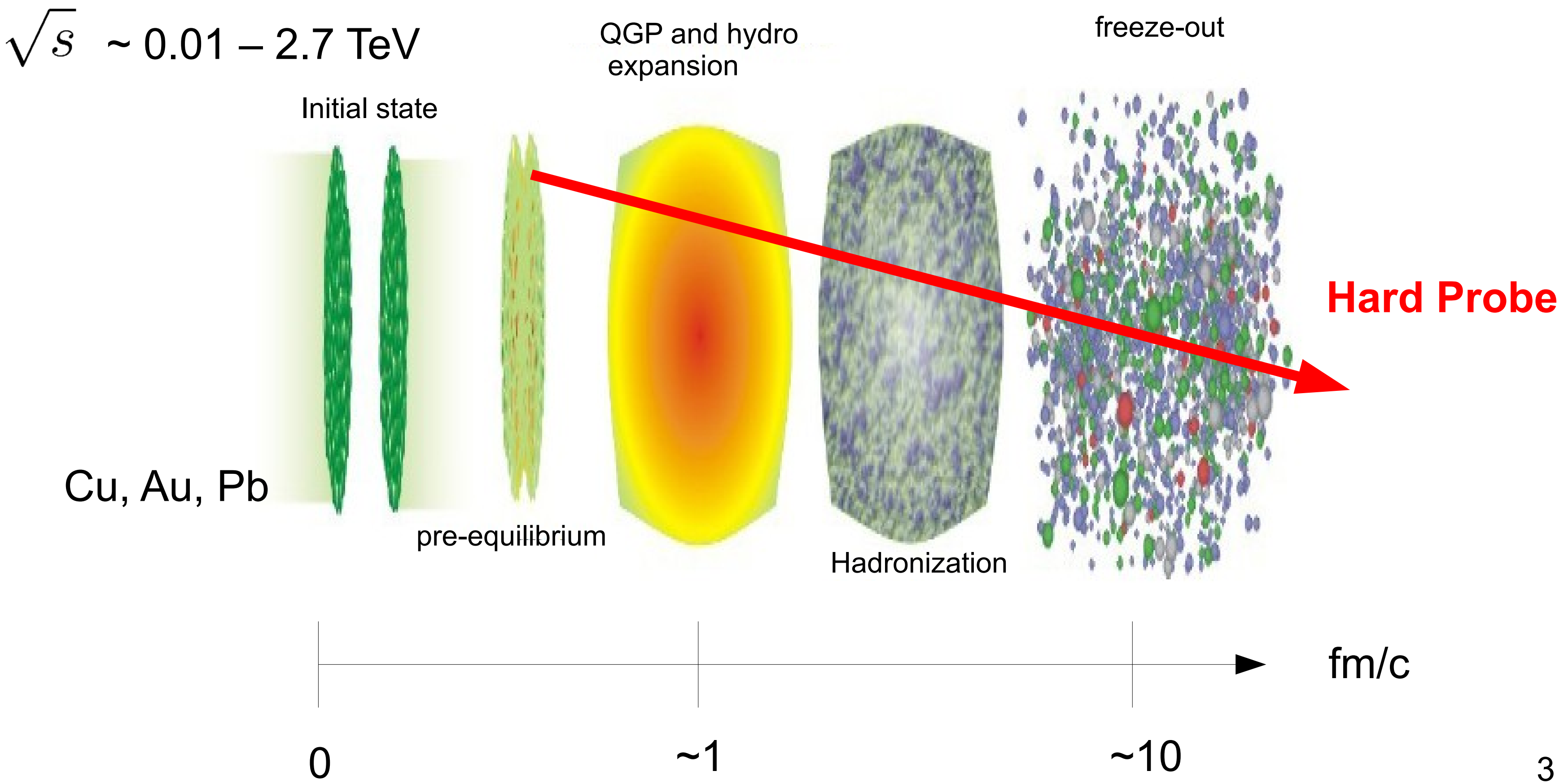
- Heavy Quarks

- Light Quarks

- Jet Quenching Parameter

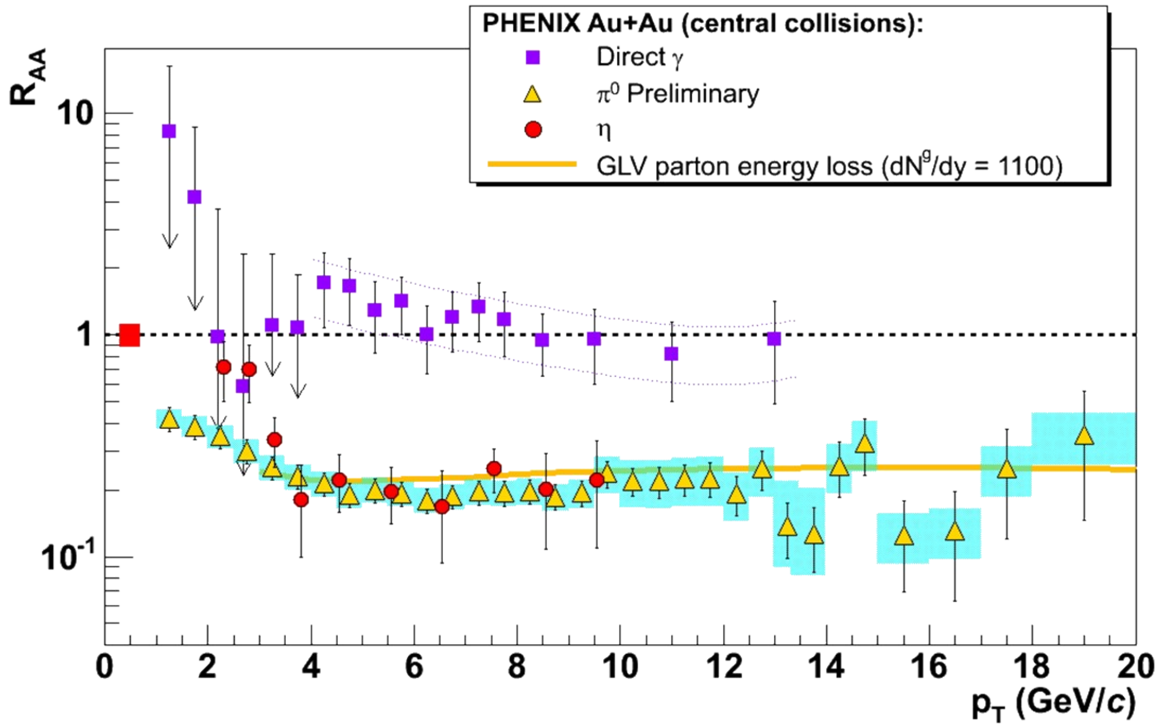
3) **Conclusions and Outlook**

Hard Probes and the QGP



Strong Jet Suppression: Highly Opaque Medium to Colored Objects!!!

$$R_{AA} = \frac{\frac{dN_{AA}}{dy}}{N_{bin}\,\frac{dN_{pp}}{dy}}$$

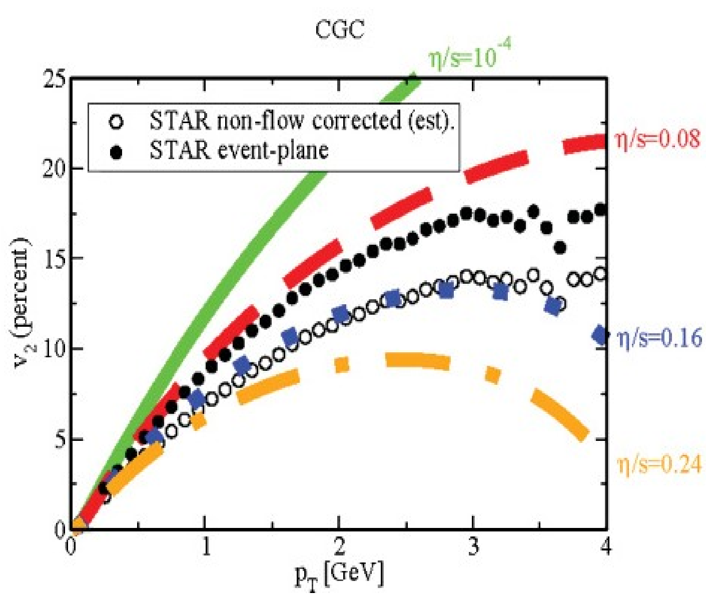


Some facts:

- In very central heavy ion collisions hadrons with high momentum are strongly suppressed.

- The large azimuthal anisotropy of low momentum hadrons can be described within “nearly perfect” relativistic hydrodynamics.

Luzum, Romatschke, 2008



$$\frac{\eta}{s} \sim (1-3)\frac{1}{4\pi}$$

Close to the magical KSS value!

Does this very small η/s imply that the QGP d.o.f. interact strongly at the temperature scale?

The straightforward answer is yes.

Jet quenching is more complicated, though, because

(1) Production process: large momentum transfer → small coupling.

(2) Interaction between jet and medium: involves evaluating the coupling at different scales including the T scale, where the system seems to behave as a strongly coupled system.

(3) Fragmentation: non-perturbative but under control (if in vacuum).

There are at least 3 different ways to address issue number (2):

(a) Assume weak coupling at all scales (not discussed in this talk)

(b) Assume strong coupling at all scales via AdS/CFT (Gubser, HKKKY 2006)

(c) “Hybrid” idea (LRW 2006): assume that strongly coupled medium interactions are encoded in at least one parameter (the jet quenching coefficient or qhat)

The AdS/CFT correspondence is the tool used in (b) and (c)

Maldacena's conjecture (1998)

$\mathcal{N} = 4$ SYM is equivalent to type IIB string theory on $AdS_5 \otimes S_5$

$N_c \gg 1$ **Duality dictionary** Witten, 1998; Gubser, Klebanov, Polyakov, 1998

Gauge theory $\sim$ Type IIB supergravity

t'Hooft coupling $\lambda = \dfrac{R^4}{\alpha'^2} \gg 1$

gravitational coupling $\kappa^2 \sim g_s^2 \ell_s^8 \ll 1$

$$-\ln\langle e^{\int d^4x\, \mathcal{O}(x)\phi_0(x)}\rangle_{CFT} = Z_{string} \simeq \sum_{extrema} S_{sugra}[\phi]\Big|_{\substack{\phi_{x,\epsilon}=\phi_0 \\ \epsilon \to 0}}$$

Generating functional for gauge theory

Near an **UV trivial fixed point** (where coupling vanishes)

- Main analytical tool is **perturbation theory.**

Near a **nontrivial fixed point** (where coupling is nonzero and large)

- The **AdS/CFT correspondence** can be used to understand how the theory flows to the IR. This is the general idea we are going to use in this talk.

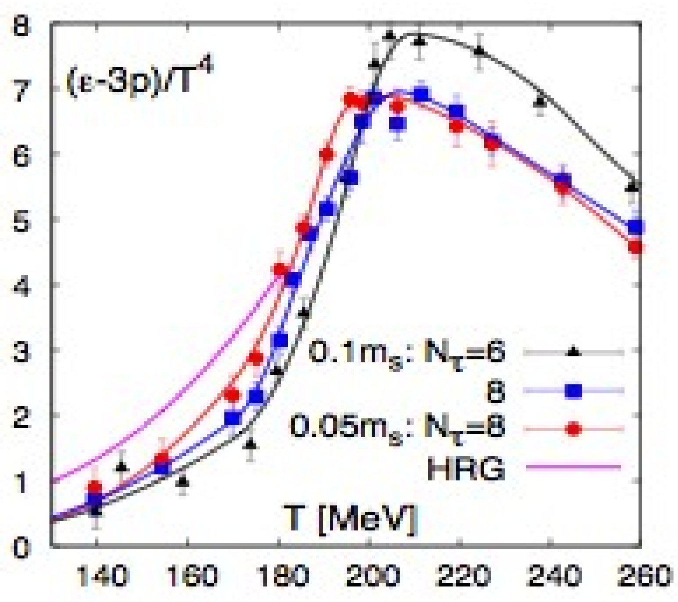
However, QCD has a trivial UV fixed point. The hope is that at scales of

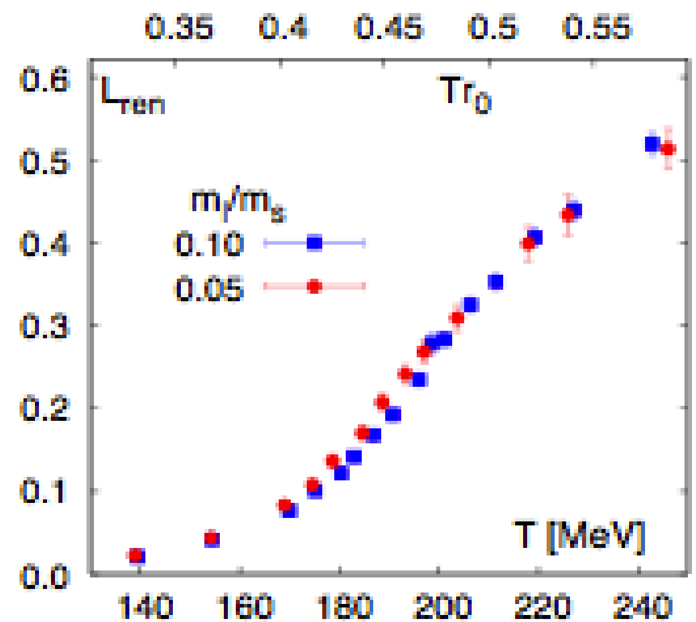
$\mathcal{O}(T)$ where T ~ 200 MeV

there is some gravity dual construction that can be used to mimic a given set of features displayed by the QGP at that scale (the near Tc region).

What are the QGP properties that we are interested in?

Trace anomaly HotQCD 2010 **Polyakov loop**





In the near Tc region, the **QGP is not conformal** (but it could still be sufficiently strong interacting for our purposes here)

I would like to understand how the large trace anomaly near Tc affects the energy loss of hard probes.

Currently, the only way one can address this question at strong coupling is via the gauge/string duality.

So, I'm going to show you now the simplest bottom-up 5d gravity dual model that can describe the large trace anomaly and the nontrivial Polyakov loop predicted by lattice near Tc.

Once this gravity dual model is fixed, the idea is to see what kind of universal and specific model predictions can be obtained for the energy loss in a strongly-coupled plasma.

Minimal Non-Conformal Model (**a bottom-up approach**)

Gubser, 2008
Kiritsis et al., 2008

Idea: Replace asymptotic freedom by conformal invariance above a given scale

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

Scalar potential

$$V(\phi)$$

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

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

Lead to relevant deformation of a 4d CFT

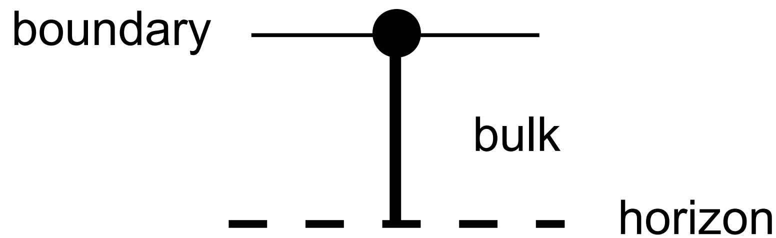
$$\mathcal{L}_{CFT} + \Lambda_\phi^{4-\Delta}\mathcal{O}_\phi$$

Δ = UV scaling dimension

Plasma's pressure ~ On shell gravity action

Infinitely massive heavy quark ~ fundamental string in the bulk

Dual description
of the Polyakov loop



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

Polyakov loop $L_R \sim e^{-S_{NG}(\mathcal{D})}$

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

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

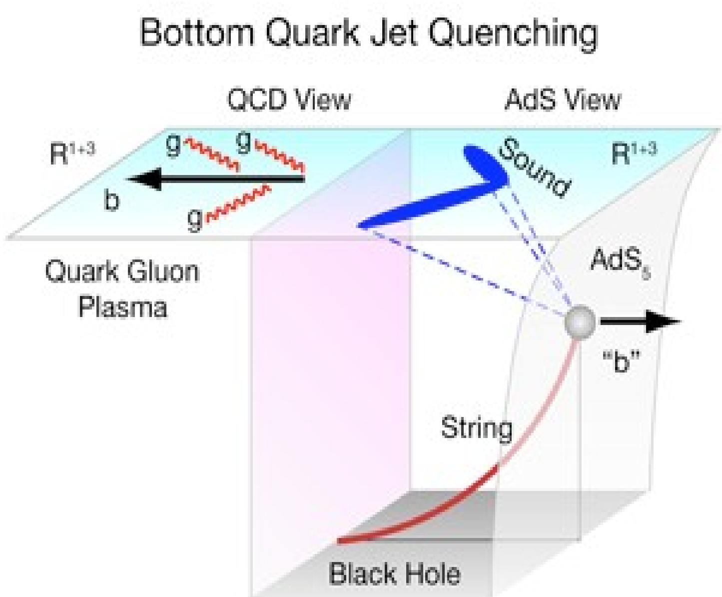
$q(\phi)$ coupling between string and the scalar field

JN, PRD (2010)

Assuming strong coupling at all scales:

Trailing String Model for Heavy Quark Energy Loss

Gubser, HKKKY, Teaney, CasadeIrrey-Solana, 2006.



$M_Q/T \gg 1$

From the Nambu-Goto action for the moving string in the bulk one obtains the drag force

$$\boxed{\left.\frac{dp}{dt}\right|_{CFT} \sim -\frac{R^2}{\alpha'} T^2 \frac{p}{M_Q}}$$

Universal properties:

- The energy loss always increases with T and quark momentum p.

- One can prove analytically that for **any scalar single scalar potential**

Ficnar, JN, Gyulassy, to appear

When $v \rightarrow 1$

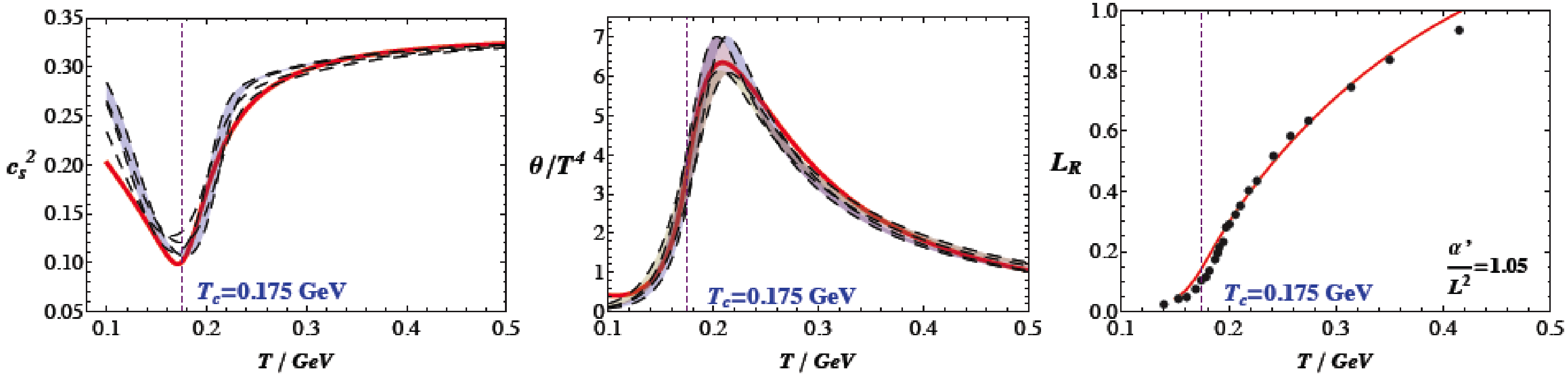
$$\frac{dp}{dt} = \# \left(\frac{dp}{dt}\right)\Big|_{CFT} \left(\frac{S}{T^3}\right)^{1/2}$$

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

Ultrarelativistic heavy quarks are directly sensitive to the QCD phase transition !!!!

Fixing the parameters to fit HotQCD data $\gamma = 0.606, \; b_2 = 0.703, \; b_4 = -0.12, \; b_6 = 0.00325$

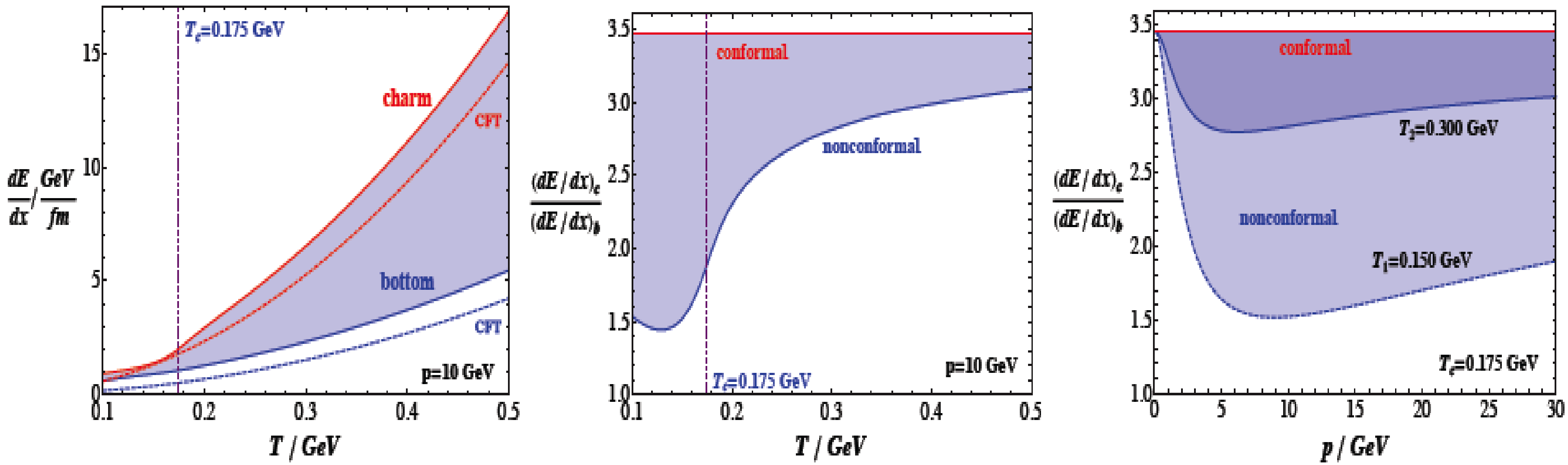
$$V(\phi) = -\frac{12}{R^2}\cosh\gamma\phi + b_2\phi^2 + b_4\phi^4 + b_6\phi^6$$



Once all the parameters are fixed, we can now use the model to compute the energy loss ...

Specific model predictions: Magnitude of heavy quark energy loss

Ficnar, JN, Gyulassy, 2010

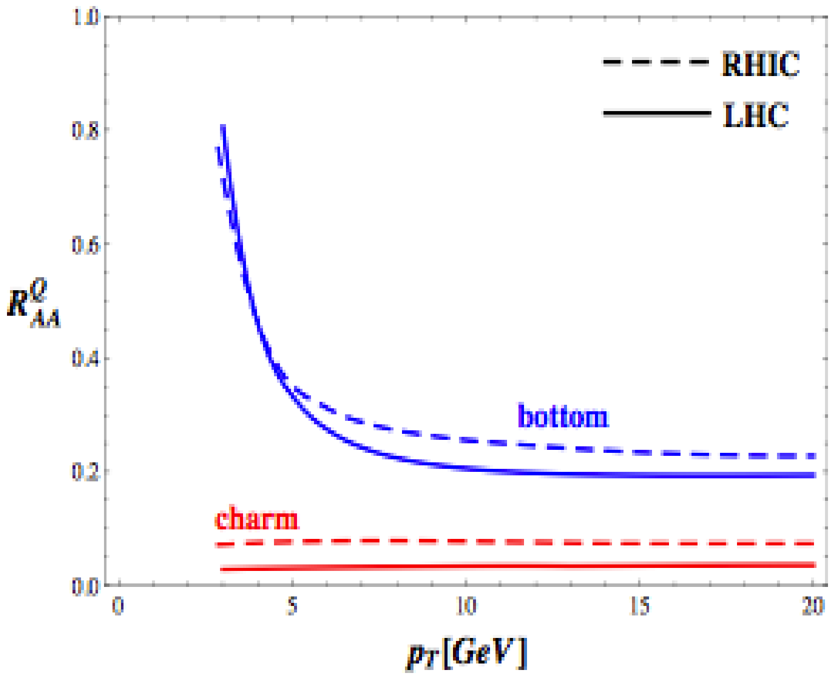


- Charm to bottom ratio at low momentum is sensitive to the trace anomaly although it converges to the simple Mb/Mc ratio discussed by Horowitz and Gyulassy (2008).

Specific model predictions: Heavy quark nuclear modification factor

Ficnar, JN, Gyulassy, 2011

$$\langle R_{AA}\rangle(p_f) = \int d^2\vec{x}_\perp \frac{T_{AA}(\vec{x}_\perp)}{N_{bin}} \int \frac{d\phi}{2\pi} \times \frac{(dN/dp_f^2)_{quenched}(p_i(p_f, \vec{x}_\perp, \phi))}{(dN/dp_f^2)_{unquenched}(p_f)}$$



Includes:

- Bjorken expansion
- Full Glauber geometry

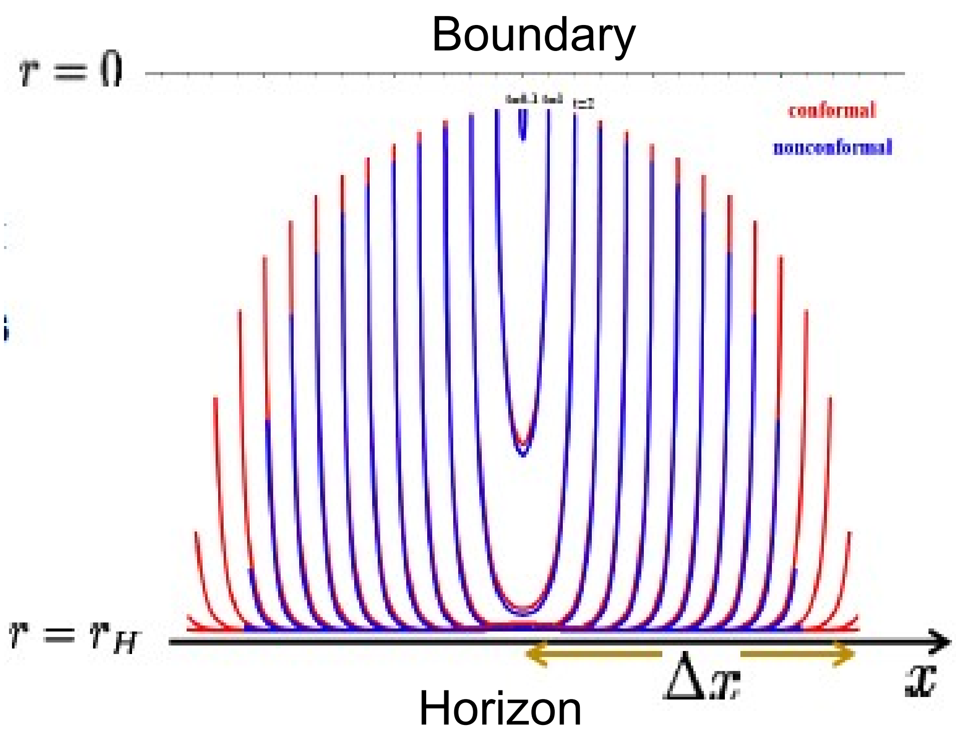
- Charm quark may be already too light to be described by a trailing string. Bottom quark prediction more reliable.

- **UNIVERSAL prediction:** Heavy quark R_AA monotonically decreases with momentum (due to asymptotic conformal invariance)!!!

Assuming strong coupling at all scales:

Falling String Model for Light Quark Energy Loss

Chesler et al., 2009



Ficnar, JN, Gyulassy, 2011

For a CFT, the maximum penetration distance traveled by the quark with energy E

$$\Delta x_{max}^{CFT} \sim E^{1/3}$$

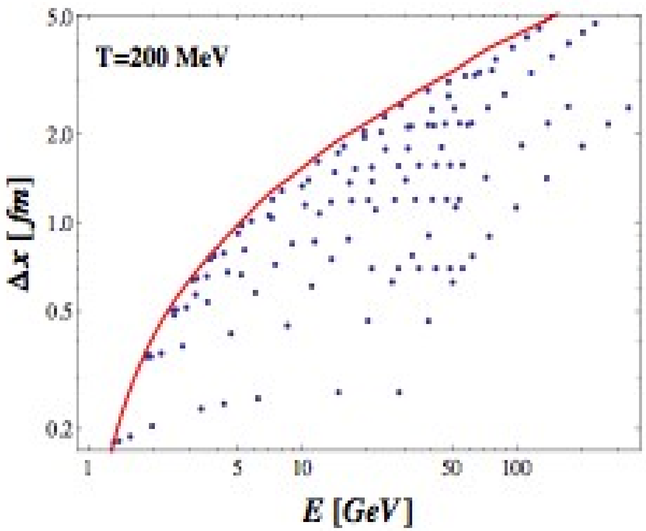
Chesler et al., 2009

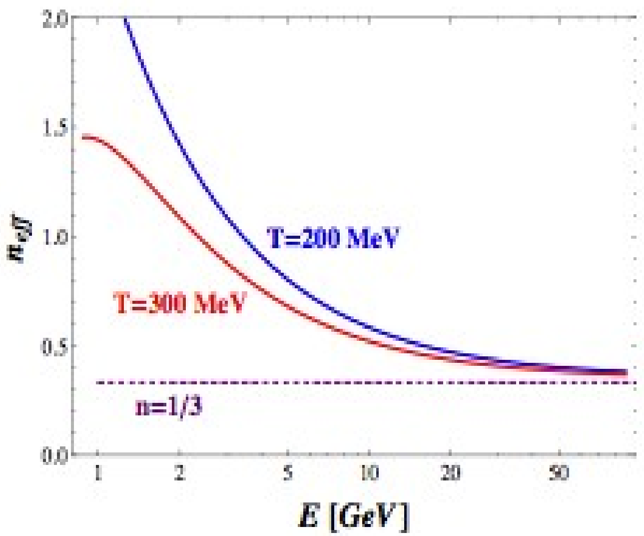
Taking into account the strong trace anomaly near Tc we obtain

Ficnar, JN, Gyulassy, 2011

$$\Delta x_{max} \sim E^{n_{eff}(E,T)}$$

$$n_{eff}(T,E) \geq 1/3$$





“Hybrid” idea: The Jet Quenching Parameter at Strong Coupling

Liu, Rajagopal, Wiedemann, 2006

Light-like Wilson loop:

$$\langle W(C)\rangle_T \sim e^{-\hat{q}\, x_\perp^2\, L_-/4\sqrt{2}+\ldots}$$

$$\hat{q} \equiv \frac{< k_\perp^2 >}{L_-}$$

(non-perturbative definition of qhat that can be computed using the gauge/string duality)

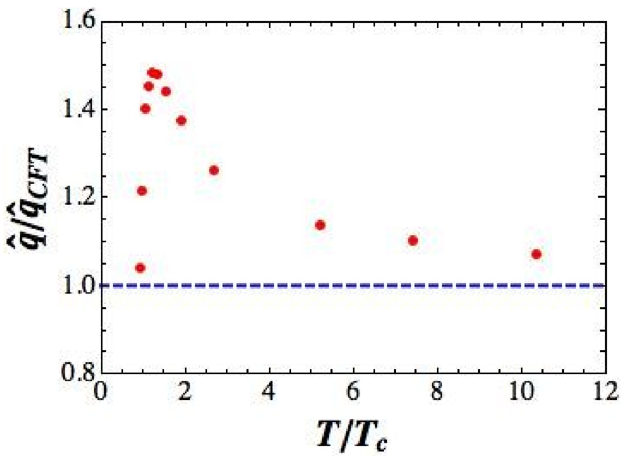
For strongly-coupled conformal plasmas:

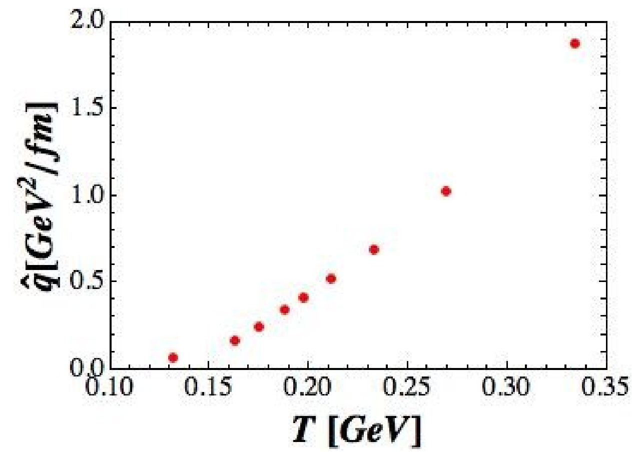
$$\hat{q}_{CFT} \sim \frac{R^2}{\alpha'}\, T^3$$

“Hybrid” idea: Liu, Rajagopal, Wiedemann, 2006

Specific model predictions for qhat: Sensitivity to the QCD phase transition

Ficnar, JN, Gyulassy, to appear





- $\hat{q}/T^3$ is strongly enhanced near Tc.

- $\hat{q}(T)$ is relatively small.

Conclusions and Outlook

- Gauge/string duality gives us means to address the violation of conformal invariance near Tc and see how the trace anomaly affects the energy loss.

- **General prediction: Ultrarelativistic heavy quarks** are extremely sensitive to the **QCD phase transition**.

$$\lim_{v\to 1} \frac{dE}{T^2\, dx} \sim \left(\frac{S}{T^3}\right)^{1/2}$$

- **General prediction:** Heavy quark R_AA monotonically decreases with pT.

- **Light quarks:** $\Delta x_{max} \sim E^{n_{eff}(E,T)}$ $\quad n_{eff}(T, E > 50\, GeV) \to 1/3$

$\hat{q}/T^3$: Strongly enhanced near Tc although absolute value at

300 MeV ~ 1 GeV/fm^2.

Back up Slides

The Duality at Finite Temperature

- Black branes are solutions of the equations of motion of these higher dimensional theories of gravity. These objects possess (Hawking) temperature and they are used in the description of a thermal equilibrium state in the 4D gauge theory.

Plasma's temperature

= Black brane temperature

Near equilibrium fluctuations in the 4D plasma ~ black brane horizon fluctuations !!!!

The Advent of String Theory

The gauge/string duality gives us nice (infinite number of) examples where (infinitely) strong coupling (at all energy scales) indeed leads to a small

$$\boxed{\frac{\eta}{s} = \frac{1}{4\pi}}$$

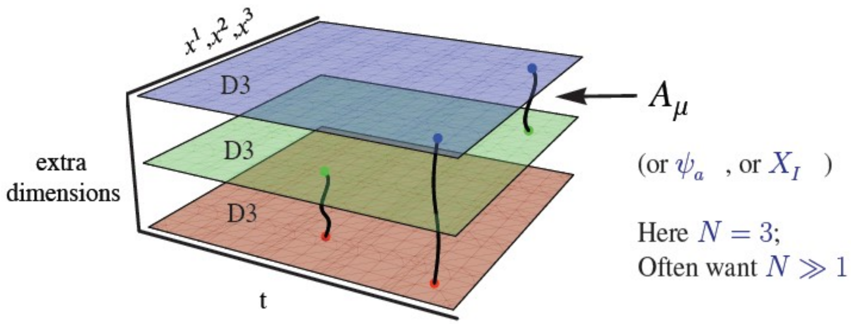
Universal value for any sufficiently strongly coupled large Nc gauge theory with a gravity dual

KSS, 2005, Buchel and Liu, 2005

- It is reasonable to investigate how hard probes lose energy in these strongly coupled theories to see if we can extract some type of general behavior that could be relevant to jet quenching in the QGP.

STANDARD EXAMPLE

$\mathcal{N} = 4$ SU(Nc) Supersymmetric Yang-Mills



Fields in the adjoint rep. of SU(Nc)

- 16 + 16 supercharges
- SU(4) R-symmetry
- SO(6) global symmetry

$\beta = 0$ **CFT !!!!**

Maldacena, 1998: This theory is dual to Type IIB string theory on AdS5 x S5

Strongly-coupled, large Nc gauge theory

$$N_c \to \infty$$

$$\lambda = L^4/\ell_s^4 \to \infty$$

T'Hooft coupling in the gauge theory

Weakly-coupled, low energy string theory

$$g_s \to 0$$

$$\ell_s/L \to 0$$

Type IIB supergravity

10d low energy action

$$S_{sugra} = -\frac{1}{2\kappa_{10}^2}\int d^{10}x\sqrt{-G}\left[\mathcal{R} - \frac{(\partial\phi)^2}{2} - \frac{1}{4.5!}F_5^2 \ldots\right]$$

$$\int_{S_5} F_5 = N_c$$

D3-brane flux

Compactify over S_5

$$S = -\frac{1}{2\kappa_5^2}\int d^5x\sqrt{-G}\left[\mathcal{R} + \frac{12}{R^2} + \ldots\right]$$

$\kappa_5^2 \sim 1/N_c^2$

This is the basic starting point in most of the gravity calculations

Low energies $E \ll 1/\ell_s$

Second description

Observer at infinity sees 2 types of low energy $\omega \longrightarrow 0$ excitations:

1) Decoupled bulk massless particles with very long wavelengths (free gravity)

Low energy graviton cross section $\sigma_{abs} \sim \omega^3 R^8 \longrightarrow 0$

2) Near u → 0 excitations $f \sim R^4/u^4$

$$ds^2 = \frac{u^2}{R^2}(-dt^2 + d\vec{x}^2) + R^2 \frac{du^2}{u^2} + R^2 d\Omega_5^2 \quad \Longrightarrow \quad AdS_5 \otimes S_5$$

Type IIB in

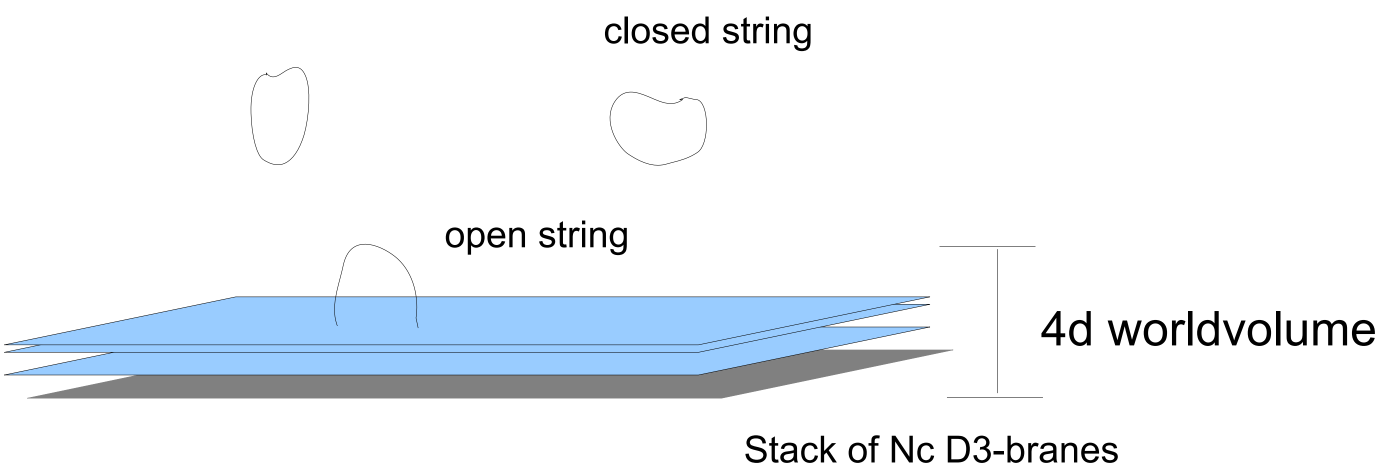
AdS/CFT in a Nutshell

Type IIB string theory

$$G_{\mu\nu},\ \Phi,\ B_{\mu\nu},\ C,\ C_{\mu\nu}, C_{\mu\nu\lambda\rho},\ \ldots$$

$\mathcal{N}=2$ 32 supercharges

The slide is a 10d spacetime

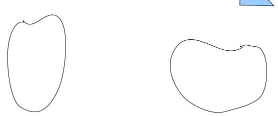


Low energies $E \ll 1/\ell_s$

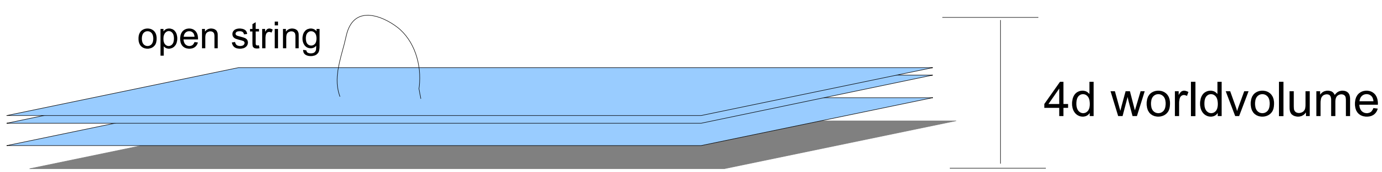
First description

Effective action for massless modes

$$S = S_{Bulk} + S_{brane} + S_{int}$$



Closed strings



Stack of Nc D3-branes

Low energies $E \ll 1/\ell_s$

$\boxed{\text{First description}}$

Expansion around flat space $G = \eta + \kappa\, h$

$\ell_s \longrightarrow 0$ $\kappa \longrightarrow 0$ Gravitational coupling

$$S_{Bulk} \sim \frac{1}{2\kappa^2} \int d^{10}x \sqrt{-G}\,\mathcal{R} \sim \int d^{10}x\,(\partial h)^2 + \cancel{\kappa(\partial h)^2 h} + \ldots$$ Free gravity

$S_{int} \longrightarrow 0$ No interactions between branes and bulk

S_{brane} Non-Abelian Dirac-Born-Infeld → $\mathcal{N} = 4$ SYM in 4d + ~~higher derivative corrections~~

Low energies $E \ll 1/\ell_s$

$\boxed{\text{Second description}}$

D3-branes are sources for $C_{\mu\nu\lambda\rho}$

Supergravity solution for the 10d metric

$$ds^2 = f^{-1/2}(-dt^2 + d\vec{x}^2) + f^{1/2}(du^2 + u^2 d\Omega_5^2)$$

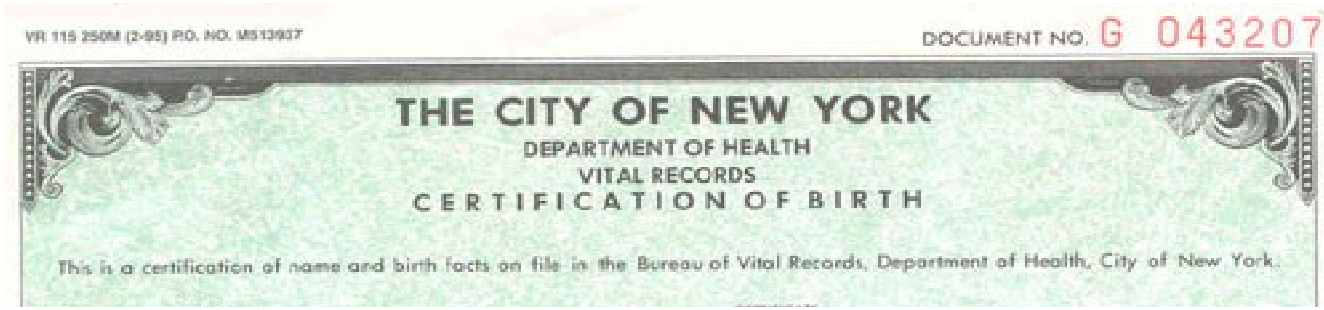
$$R^4/\ell_s^4 \sim g_s N_c$$

$$f = 1 + \frac{R^4}{u^4}$$

Redshift $\quad E_\infty = f^{-1/4} E_u \sim u\, E_u / R$

Objects brought close and closer to u = 0 have lower and lower energies at infinity

Strong Jet Suppression: Highly Opaque Medium to Colored Objects!!!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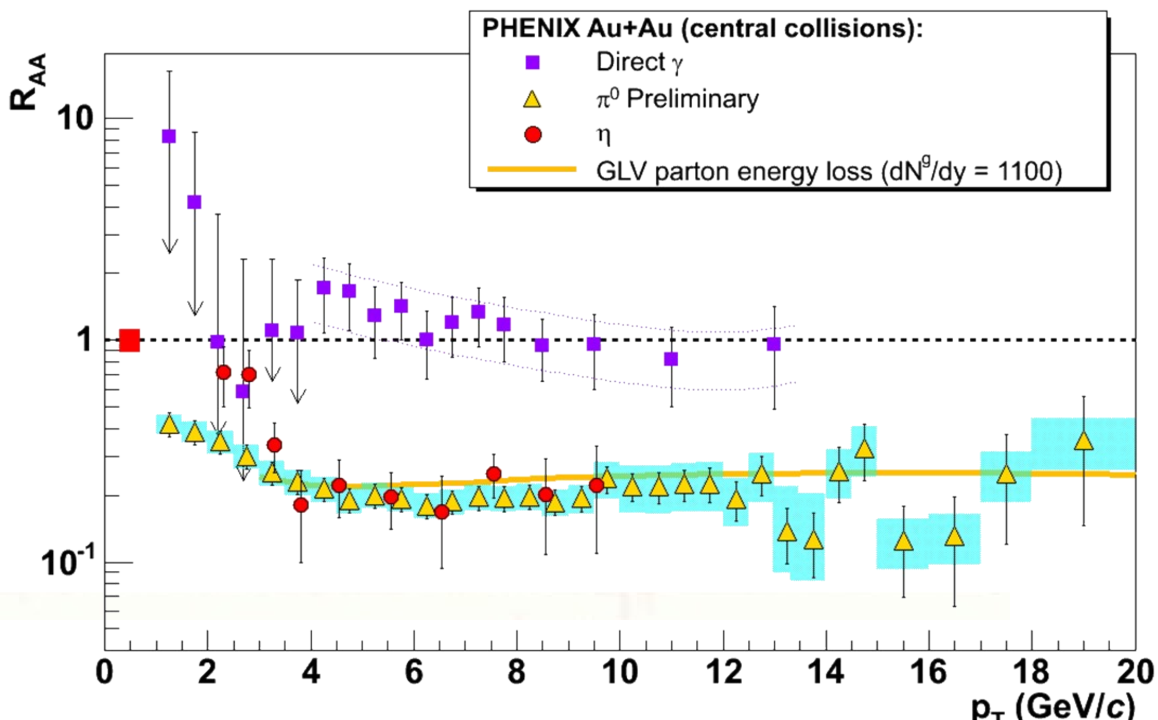
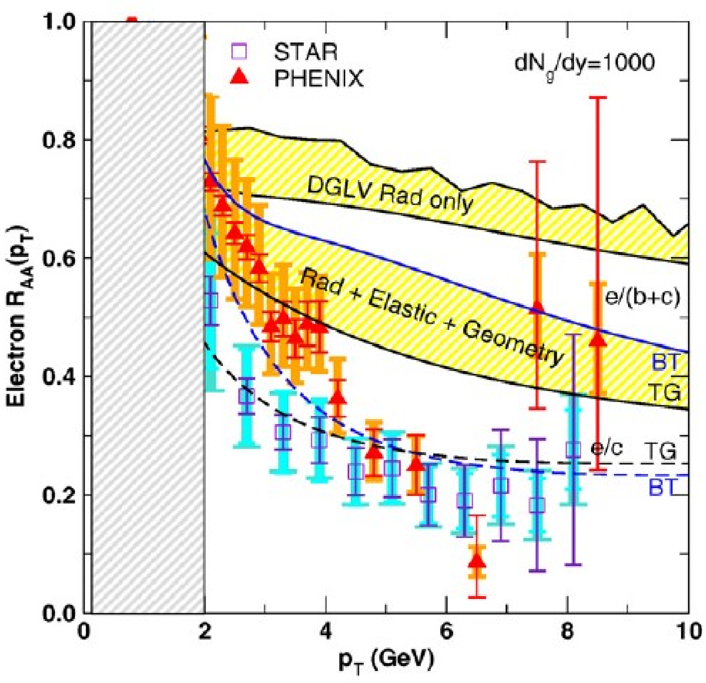
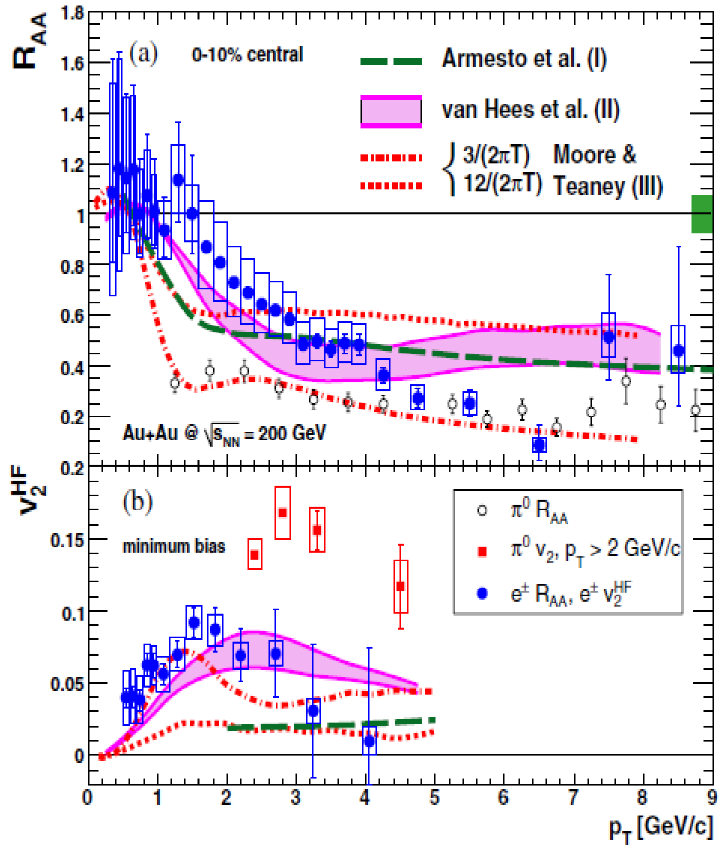
$$R_{AA} = \frac{A+A}{T_{AA}\ p+p}$$



Strong Quenching and Flow of Heavy Quarks

Heavy Quark Nuclear Modification Factor





WHDG, 2007

Mathematical Definition of the Gauge/String Duality

$$Z_{string}\left[\Phi(x^\mu, y)\Big|_{y\to\infty} = \phi_0(x^\mu)\right] = \langle e^{\int d^4x \mathcal{O}(x^\mu)\phi_0(x^\mu)}\rangle_{GaugeTheory}$$

Gubser, Polyakov, Klebanov; Witten 1998

- The source term $\phi_0(x^\mu)$ for the gauge invariant operator $\mathcal{O}(x^\mu)$ in the 4D gauge theory corresponds to a dynamical field $\Phi(x^\mu, y)$ defined in the 5D bulk gravity (or 10D string) theory.

- Ex: Metric in 5D $G_{MN}(x^\mu, y)$ is dual to $T^{\mu\nu}(x^\lambda)$ in 4D gauge theory.

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

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

$a = 1$ $\qquad b_4 = 0.4$

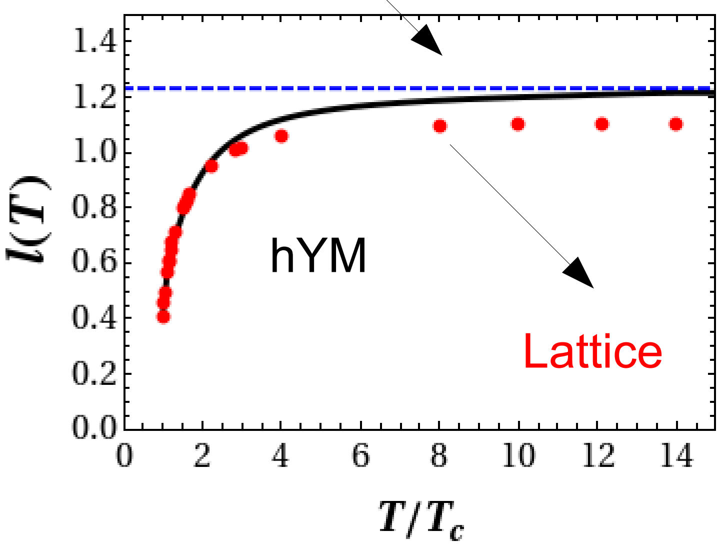
$b_2 = 5$ $\qquad b_6 = 0.0098$ $\qquad \Delta = 2$

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



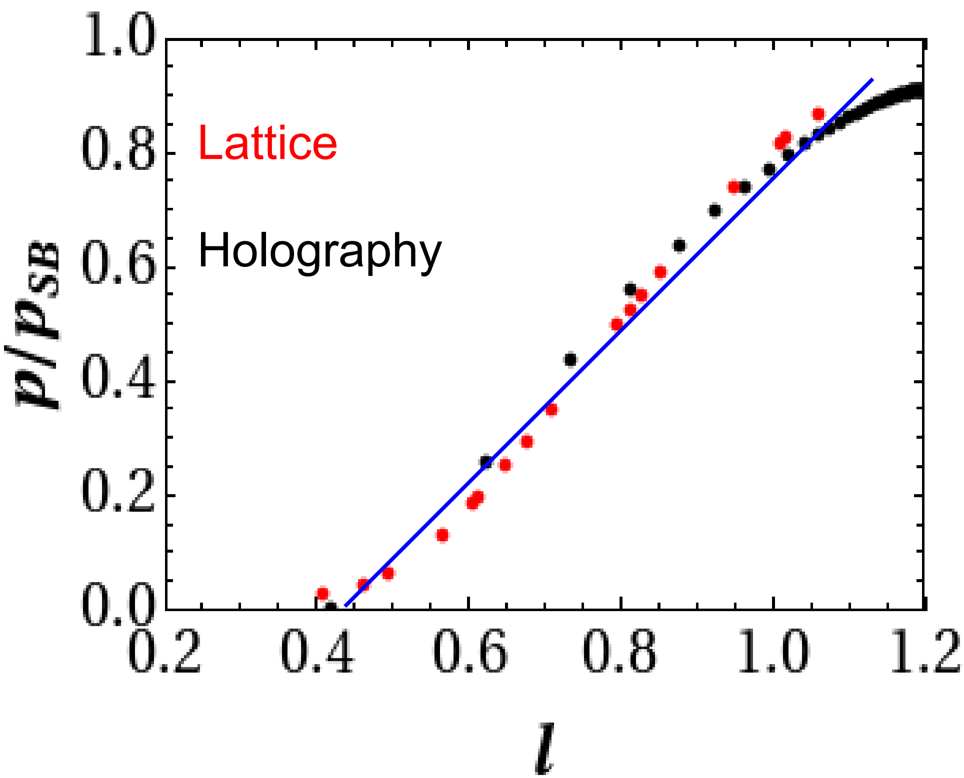
Good agreement below 4Tc …

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 ...

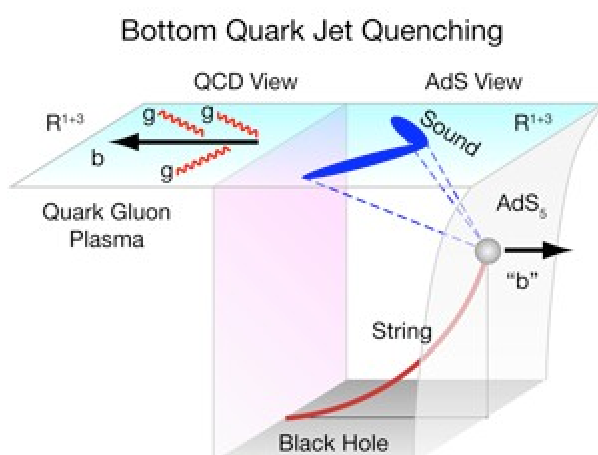
- $\eta/s = 1/(4\pi)$ above Tc. Below Tc one should expect $\eta/s \sim N_c^2$

JN, arXiv:0912.4824 [hep-th]

- ζ/s has a peak at Tc.

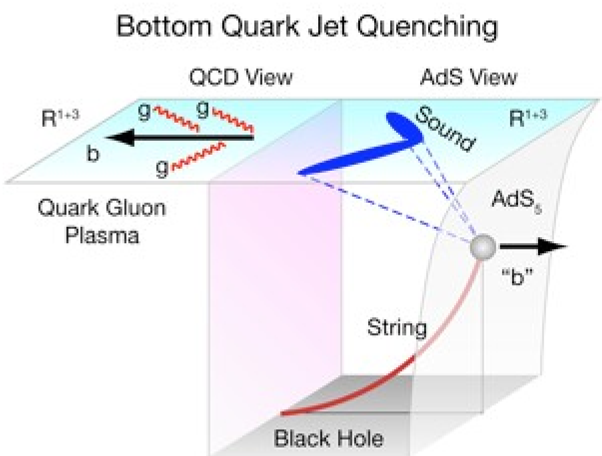
Gubser et al (2008).

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 !!!

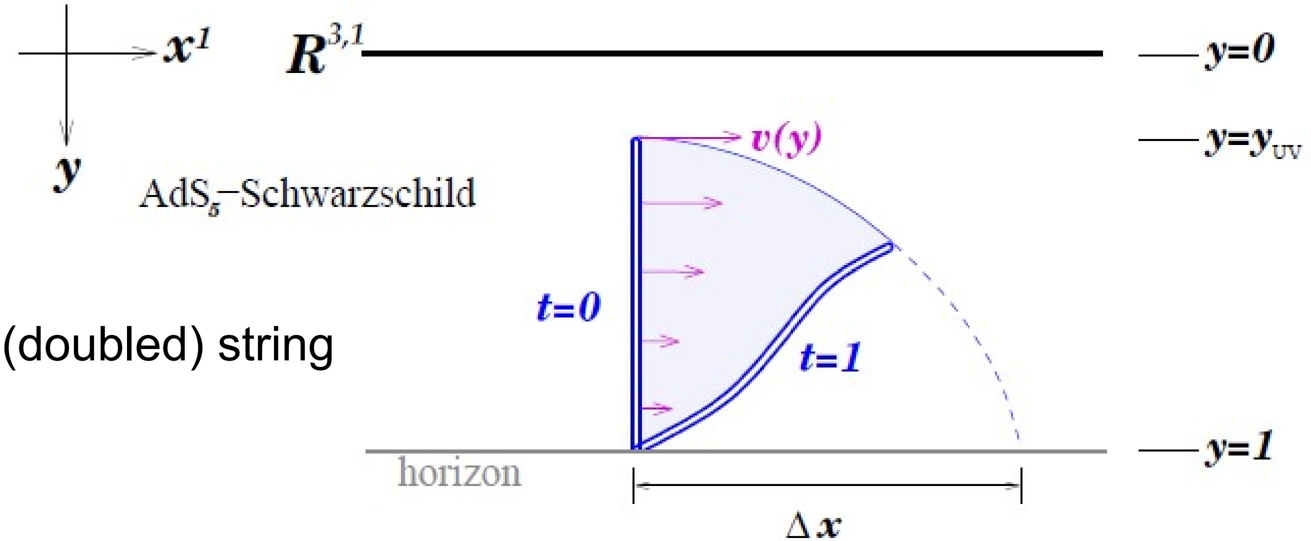
Here we know exactly how confinement affects the heavy quark energy loss ...

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

The Advent of String Theory

The gauge/string duality gives us nice (infinite number of) examples where (infinitely) strong coupling (at all energy scales) indeed leads to a small

$$\boxed{\frac{\eta}{s} = \frac{1}{4\pi}}$$

Universal value for any sufficiently strongly coupled large Nc gauge theory with a gravity dual

KSS, 2005, Buchel and Liu, 2005

- It is reasonable to investigate how hard probes lose energy in these strongly coupled theories to see if we can extract some type of general behavior that could be relevant to jet quenching in the QGP.

Other interesting properties that I have no time to discuss here in detail ...

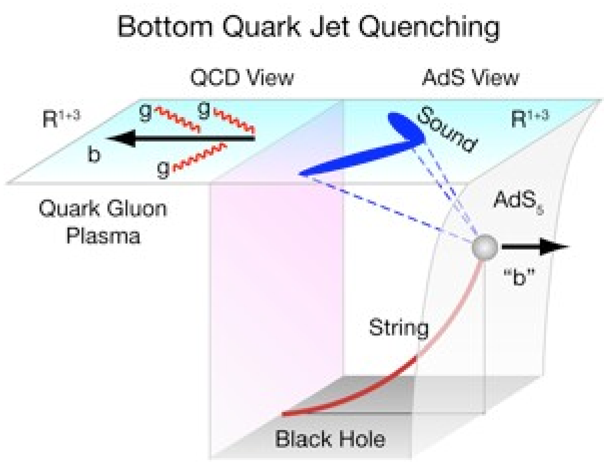
- $\eta/s = 1/(4\pi)$ above Tc. Below Tc one should expect $\eta/s \sim N_c^2$

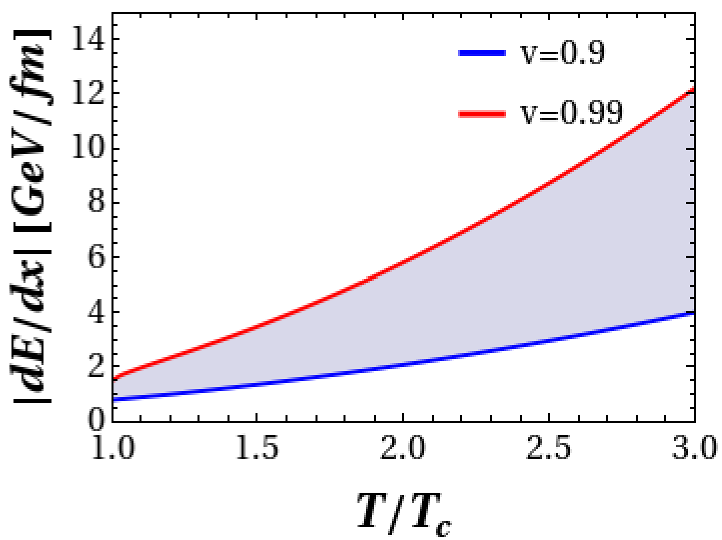
Noronha, arXiv:0912.4824 [hep-th]

- ζ/s has a peak at Tc.

Gubser, Nellore, Pufu, Rocha, PRL (2008).

What about heavy quark energy loss?



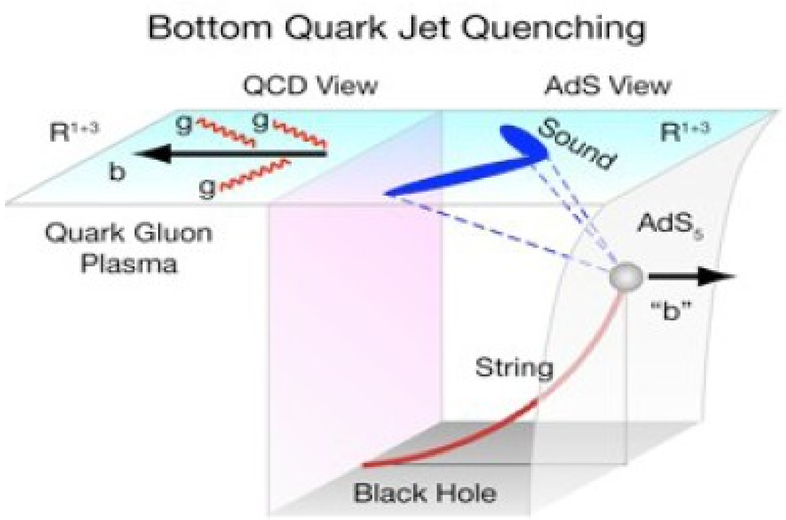


What does that imply?????

- RHIC plasma exhibits is a hologram (in the sense of the gauge/string duality) !!!!!

- The d.o.f. in this limit cannot be described using quasiparticles (no branch cuts).

- What happens to jet quenching????



Gubser; Herzog et al., Teaney, CasadeIrrey-Solana (2006)

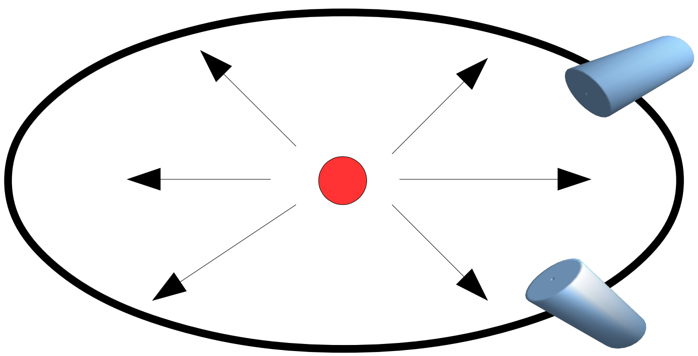
Jets in Strongly-Coupled Plasmas

First of all, are there jets in strongly-coupled plasmas?

Energy correlators

Hofman, Maldacena (2008)

$$\langle \mathcal{E}(\Omega_1)\ldots\mathcal{E}(\Omega_n)\rangle = \frac{\langle 0|O^\dagger \mathcal{E}(\Omega_1)\ldots\mathcal{E}(\Omega_n) O|0\rangle}{\langle 0|O^\dagger O|0\rangle}$$



Calorimeters

Basham, L.S. Brown, S.D. Ellis and S.T. Love, 1978.

This observable was used to test QCD and measure the running coupling constant

Energy correlators provide a way to define jets which is independent of the notion of quasiparticles because one only needs to know n-point functions of gauge invariant observables such as the energy-momentum tensor.

Leading order QCD: Collinear radiation -> singular behavior of 2-point functions

$$\langle \mathcal{E}(\theta_1)\mathcal{E}(\theta_2)\rangle \sim \frac{C\lambda}{\theta_{12}^2}$$

1-point function: “Antenna” behavior

$$\langle \mathcal{E}(\theta)\rangle \sim 1 + a_2(\cos^2\theta - 1/3)$$

$$a_2 = -\frac{3}{2} + \frac{9\alpha_s}{2\pi}$$

What about happens at strong coupling???

1-point functions

$$\langle \mathcal{E}(\theta) \rangle \sim 1 + 3\frac{c-a}{c}\left(\cos^2\theta - \frac{1}{3}\right)$$

For $\mathcal{N}=4$ SYM $a=c$ Spherically symmetric distribution !!!!

Higher-order derivatives in the gravity dual should affect both soft and hard phenomena (more about that later) !!!

There are no excitations carrying large fractions of longitudinal hadronic momentum !!!

Hatta, Mueller, Iancu (2007)

In fact, checking the details one finds ...

Hofman, Maldacena (2008)

$$\langle \mathcal{E}(\Omega_1)\mathcal{E}(\Omega_2)\rangle \sim \frac{1}{|\theta_{12}|^{2-\gamma}}$$

Weak-coupling

$$\gamma \sim \mathcal{O}(\lambda) \ll 1$$

Jets!!!!

Strong-coupling

$$\gamma = \sqrt{2}\,\lambda^{1/4} - 4 + \ldots$$

No Jets when $\lambda \to \infty$

Jets ???

$$\lambda \sim 10$$

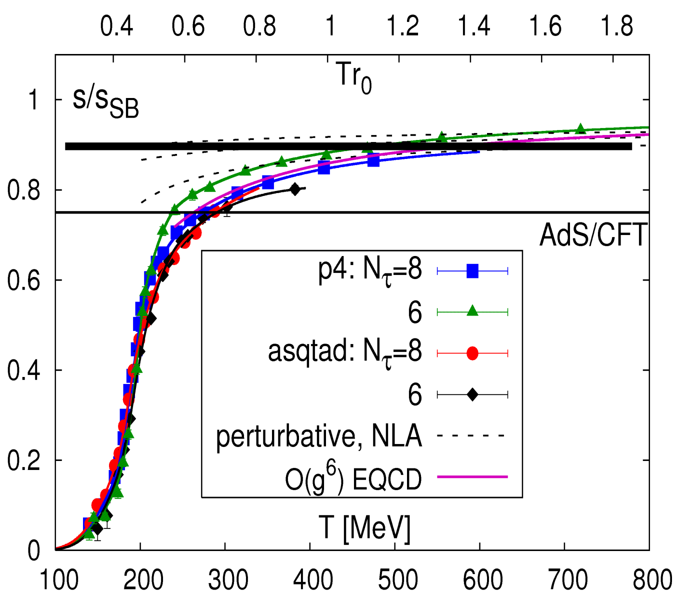
Soft and Hard Correlations at RHIC and Holography

AdS/CFT

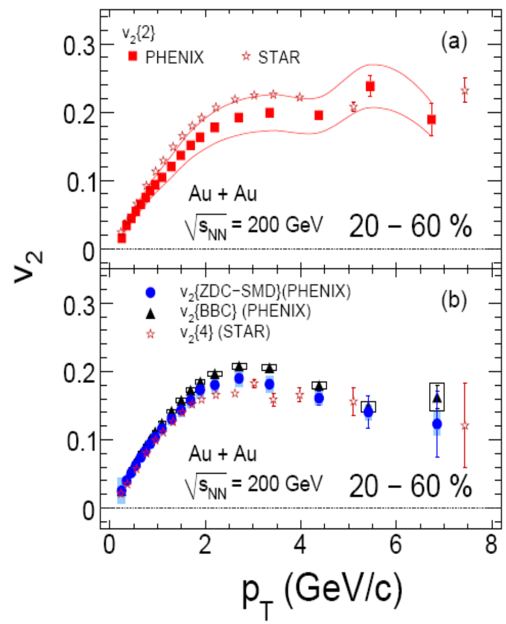
Thermodynamics

Soft

Hard



From P. Petreczky, QM09



From PHENIX, 2009

From WHDG, 2007

Conjecture

$$\boxed{\mathcal{N}=4 \text{ SYM is equivalent to type IIB string theory on } AdS_5 \otimes S_5}$$

Realization of the holographic principle!!!!
End of the black hole information paradox?

Maldacena, 1998

Witten, 1998;
Gubser, Klebanov, Polyakov, 1998

Duality dictionary

$$Z_{string}\left[\Phi(x^\mu, y)\Big|_{y\to\infty} = \phi_0(x^\mu)\right] = \langle e^{\int d^4x \mathcal{O}(x^\mu)\phi_0(x^\mu)}\rangle_{GaugeTheory}$$

- Lorentz invariance
- Match conformal dimension
- Use conserved quantities
- Gauge invariant observables
- Euclidean space

Bulk		Boundary
G_{MN}	$\Longleftrightarrow$	$T^{\mu\nu}$
Dynamical gravity		Translational invariant gauge theory

Entropy density: The Stefan-Boltzmann limit for $\mathcal{N}=4$ SYM

$$\lambda \ll 1 \qquad s_{SB} = \frac{2}{3}\pi^2 N_c^2 T^3$$

What about the limit $N_c \to \infty$ $\lambda \gg 1$?

Bekenstein-Hawking formula: $s_{BH} = \dfrac{A}{4G_{10}}$

$$A = \int d^3\vec{x} \int_{S_5} d^5\Omega \sqrt{-det\, G_{\mu\nu}}$$

$$\boxed{s_{BH} = \frac{\pi}{2} N_c^2 T^3 = \frac{3}{4} s_{SB}}$$

One cannot really know, using only thermodynamic quantities, whether a plasma is strongly or weakly-coupled

Similar to lattice QCD data above “Tc”

When $N_c \to \infty$ $\lambda \gg 1$ we have that

$$\boxed{\frac{\eta}{s} = \frac{1}{4\pi}}$$

Universal for all gravity dual theories in the supergravity approximation Buchel, Liu, 2005; KSS, 2005

- Conformal and non-conformal theories
- Non-zero chemical potential
- Presence of fundamental matter

λ - corrections for $\mathcal{N} = 4$ SYM / Type IIB $\Rightarrow$ $\alpha'^3 \mathcal{R}^4$

added to the bulk action

Gubser, Klebanov, Tseytlin, 2005

$$\frac{L^2}{\alpha'} = \sqrt{\lambda}$$

$$\frac{\eta}{s} = \frac{1}{4\pi}\left(1 + \frac{15\zeta(3)}{\lambda^{3/2}} + \dots\right) \geq \frac{1}{4\pi}$$

Buchel, Liu, Starinets, 2005

Universidade de São Paulo

Connecting Hard and Soft Phenomena @ RHIC

JN, M. Gyulassy, G. Torrieri, arXiv:1009.2286

The idea is to use the the known finite coupling corrections to N=4 SYM

$$\frac{s}{s_{SB}} = \frac{3}{4}\left(1 + \frac{15}{8}\frac{\zeta(3)}{\lambda^{3/2}}\right)$$

$$\frac{\eta}{s} = \frac{1}{4\pi}\left(1 + 15\frac{\zeta(3)}{\lambda^{3/2}}\right)$$

Heavy quark energy loss

$$\frac{dp}{dt} = -\frac{\sqrt{\lambda}\,\pi T^2}{2M_Q}\left(1 + \boxed{\frac{15}{16}\frac{\zeta(3)}{\lambda^{3/2}}}\right)p$$

Can a large $\lambda_{t'Hooft}$

describe

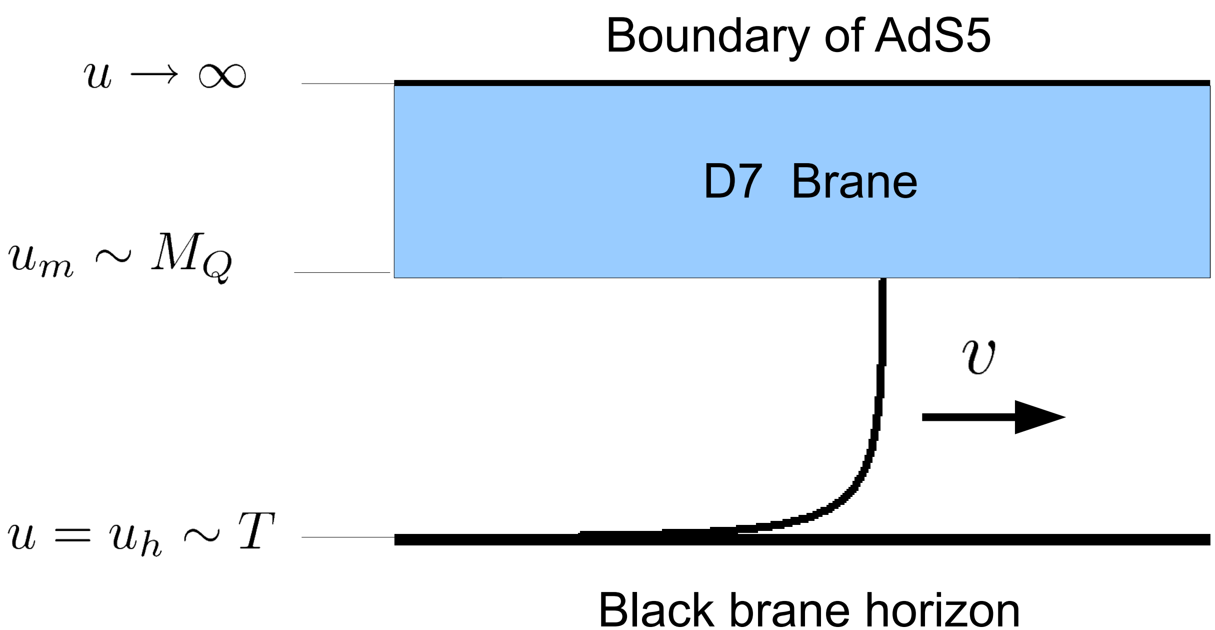
$R^e_{AA} \times v_2$????

Makes three fold *analytic* correlation between soft thermo, transport, *and* hard nonequilib dynamics possible for the first time !

Universidade de São Paulo

The holographic description of a heavy quark involves a string that connects the bottom of a D7-brane and the black hole horizon.

Herzog et al., 2006; Gubser, 2006



Drag force

$\mathcal{N} = 4$ SYM

$$\frac{dp}{dt} \sim -\sqrt{\lambda} T^2$$

We included the finite t'Hooft corrections to this scenario !!!!

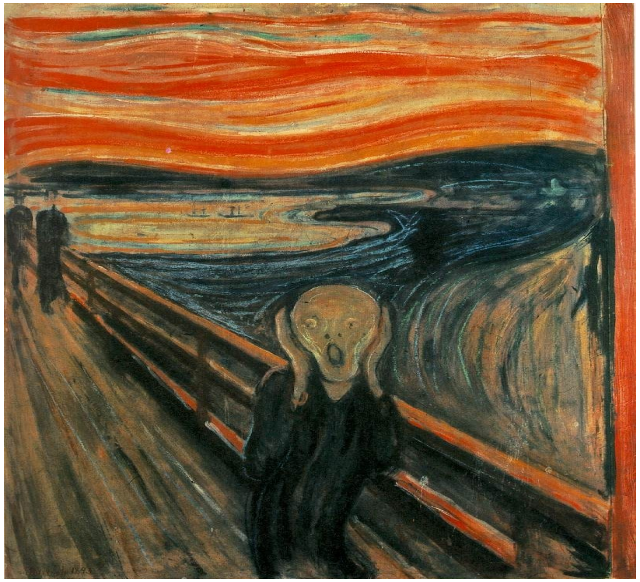
- There will be $\lambda^{-3/2}$ corrections to the energy loss from beyond sugra corrections to black brane background (easy – we just did that).

- However, fluctuations of the string worldsheet lead already to corrections

$$\mathcal{O}(\lambda^{-1/2})$$

Very hard to compute!!!!

Are the predictions computed using this trailing string model reliable???



Correction only computed for the heavy quark potential at T = 0

Liu, H-c. Ren (2009).

Best guess: Include

$$\frac{\mathcal{O}(1)}{\lambda^{1/2}}$$ and check!

Assuming that the typical timescale for the build up of v2 is ~ 4 fm, one then sees that charm quarks would “feel” the flow much more than bottom quarks. However, bottom flow should be seen to some extent. This is very different than at weak coupling

$$\tau_c \sim 7\, fm$$

Moore, Teaney, 2005.

Now we can concentrate on R^e_{AA}

The idea here is to assume that back-to-back ccbar or bbar pairs are produced according to pQCD but their subsequent interaction with the medium can be described using a strong coupling expansion a la AdS/CFT in N=4 SYM.

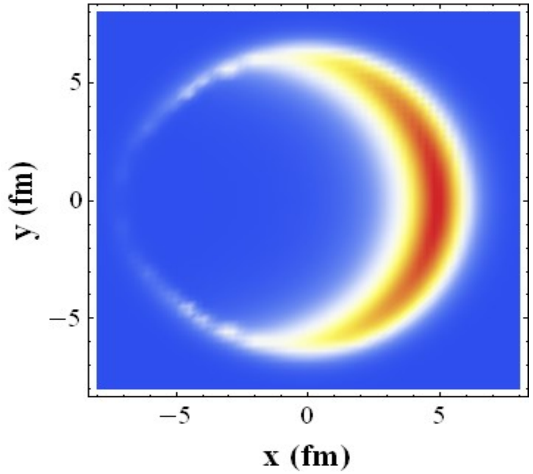
Computing the nuclear modification factor of non-photonic electrons R^e_{AA}

b = 3 (0-10% more central collisions)

CGC ~ Glauber $\longrightarrow$ Dumitru et al 2006

$$T_{AA}\, e^{-n_Q \int d\tau \mu_Q}$$

Charm surface bias



$$p_T = 15\,\mathrm{GeV}$$

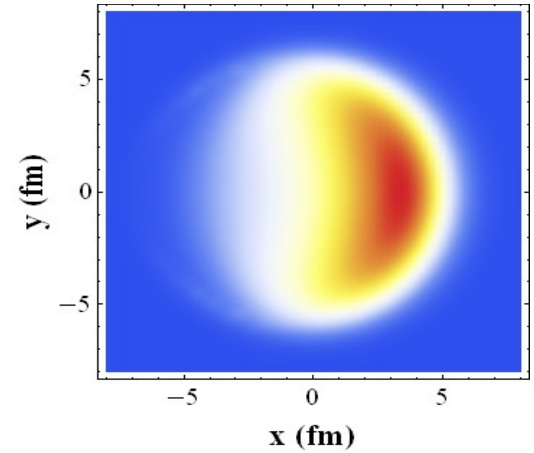
$$\phi = 0$$

$$\lambda = 7$$

$$s/s_{SB} = 0.85$$

$$4\pi\,\eta/s = 1.92$$

Bottom surface bias

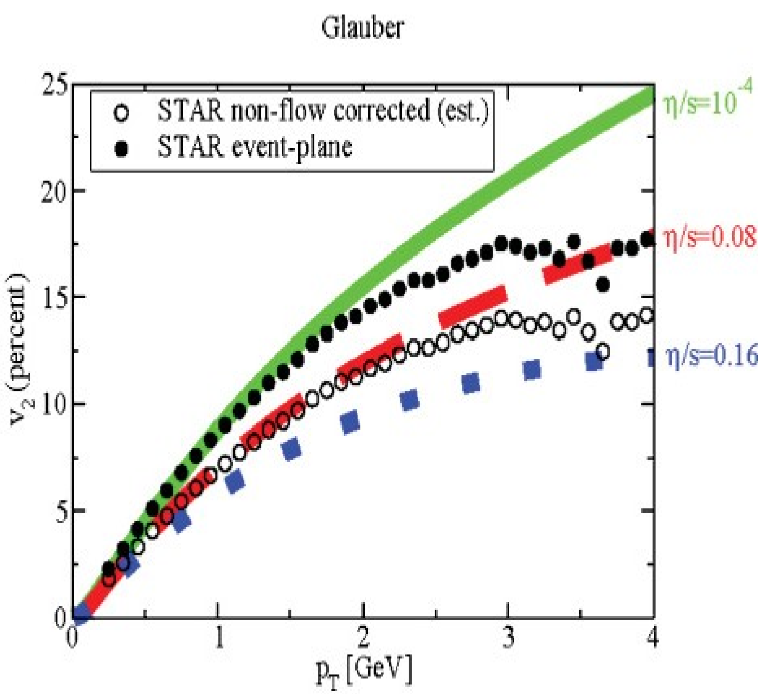


We use results for v2 of charged particles from viscous hydrodynamic simulations to obtain (low pT)

$$v_2(p_T, \eta/s) = v_2(p_T, \lambda)$$

for a given set of initial conditions (Glauber ou CGC)

We take Luzum and Romatschke's (2008) results for v2 at pT=1 GeV



We assume that, after fragmentation, $p_T^e \sim 0.7 p_T^Q$

$$R_{AA}^e = 0.4\, R_{AA}^c + 0.6\, R_{AA}^b$$

Thus, we can study the connection between hard and soft sectors by plotting

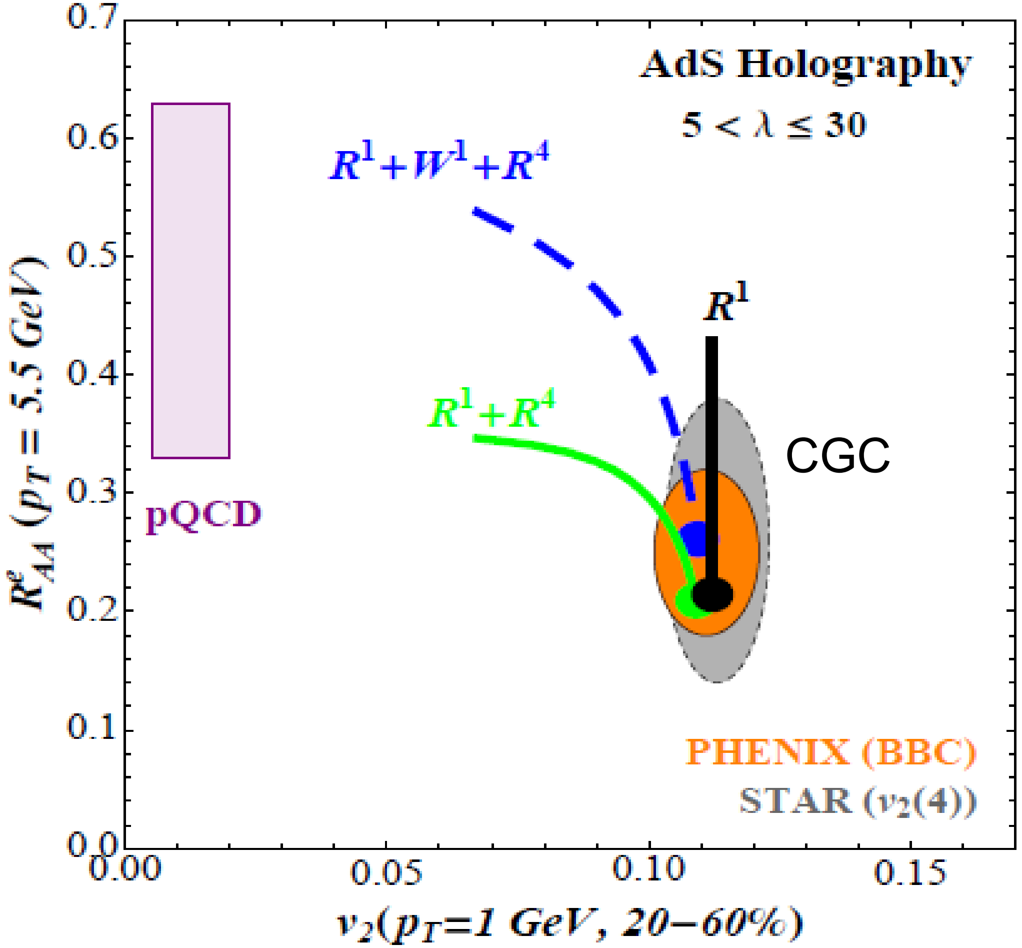
$$R_{AA}^e \times v_2$$

and comparing that to the experimental data. It turned out to be surprisingly difficult to obtain the data points in an unambiguous way. After exchanging lots of emails with

PHENIX and STAR people

We have converged to the following plot

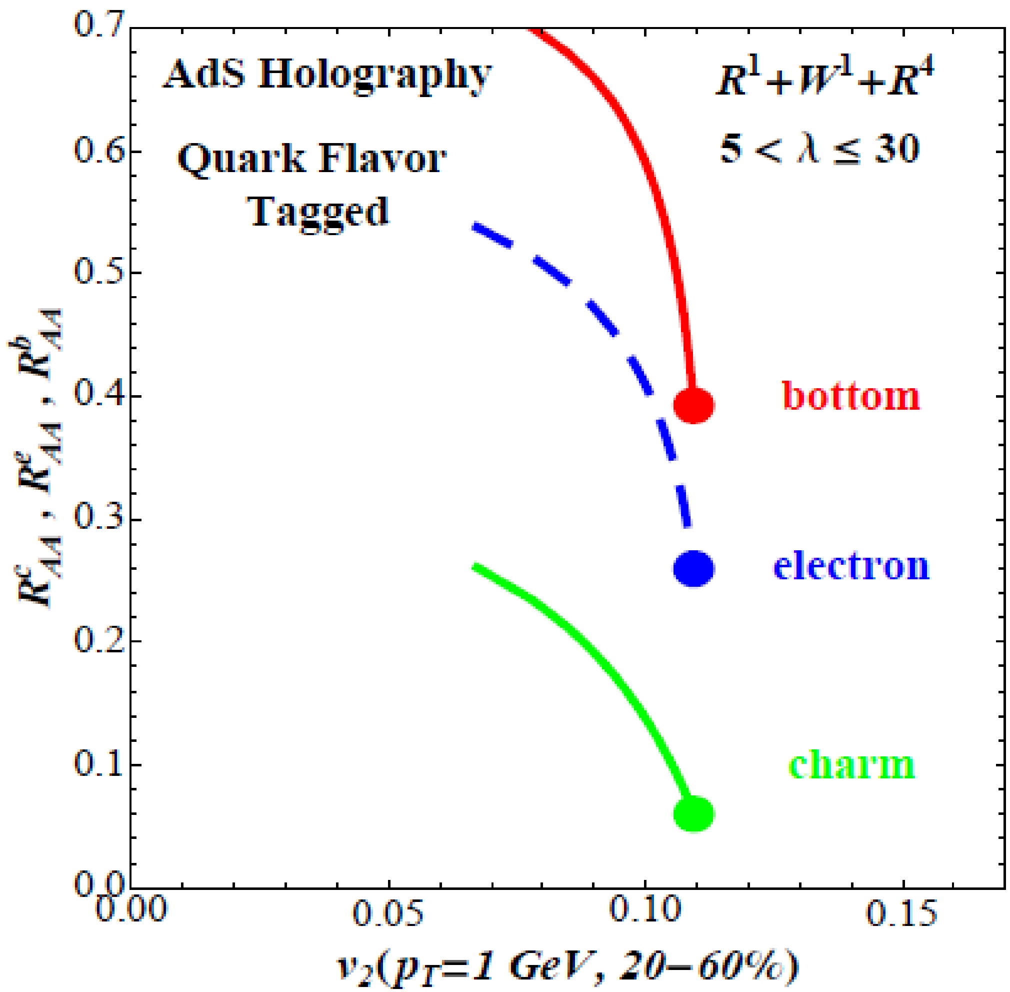
Wordsheet Fluctuations do not matter much!



EVIDENCE FOR STRONGLY COUPLED BEHAVIOR ???

Glauber I.C. cannot describe correlations!!!

Prediction that can be killed on DAY ONE AT LHC !!!!!!



How far are we from finding the exact dual theory of pure glue with Nc = 3??

- Lattice says that, for pure glue, Nc = 3 = infinity is a good approximation.

- This means that the planar limit can be used → enormous simplification!!!!

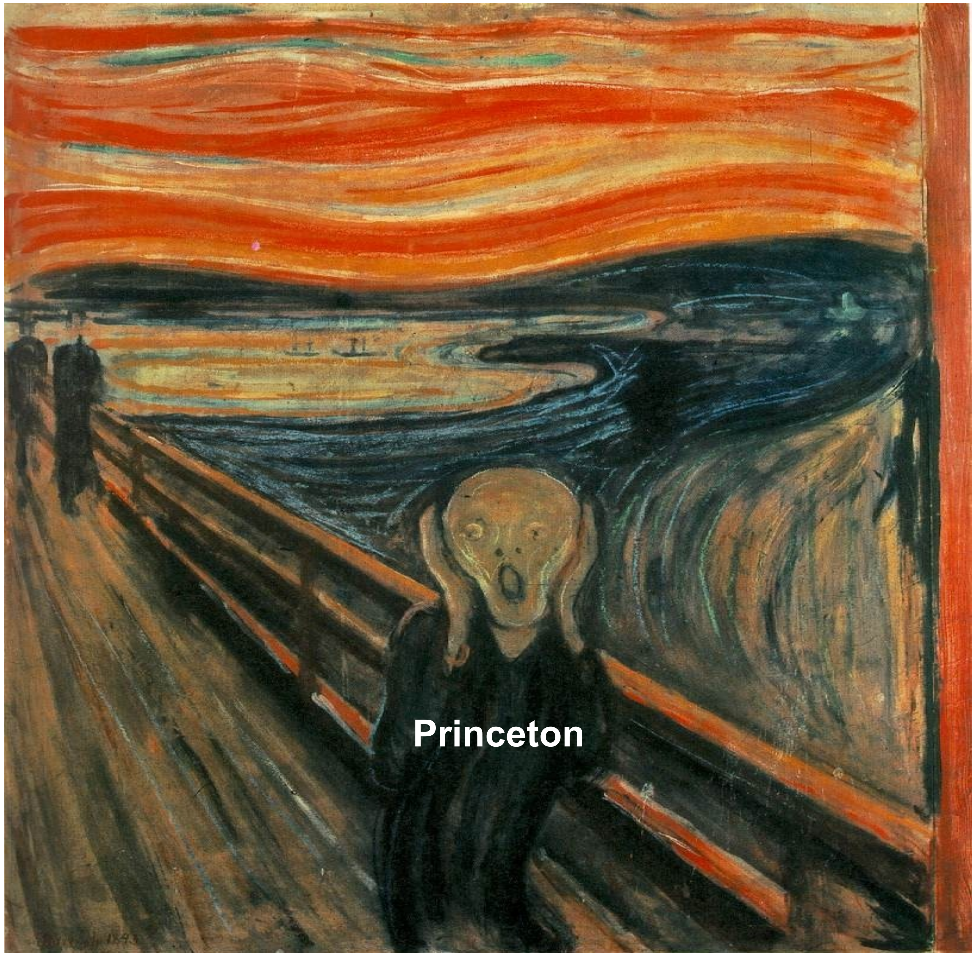
The devil lies in the (ultraviolet) details ...

- Pure glue has a trivial UV fixed point (known since 1973).

- In this talk you will see that, quite generally, SUGRA-like theories

CANNOT BE ASYMPTOTICALLY FREE

Asymptotic freedom may truly require a non-perturbative description of string theory near a curvature singularity!!!!



$$\frac{R^2}{\alpha'} \sim 1$$

Infinite number of corrections!

New ideas are necessary ...

But what can be
done at the moment?

Lattice is going to be our guide ...

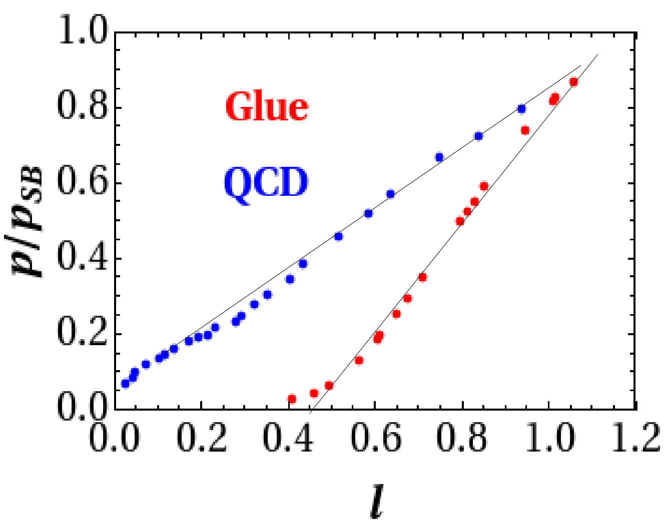
Lattice data suggests that in the temperature region relevant for heavy ion experiments (1 - 3 Tc), QCD at finite T (and zero chemical potential)

- sQGP far from being conformal (sizable trace anomaly)

- Dominated by power-like terms that are beyond the reach of perturbation theory (this could make a big difference in qhat calculations …)

- Thermodynamics looks like pure glue (more on that later).

- Even though the Polyakov loop is not a real order parameter in QCD, the current lattice data suggests that it may be possible to find an effective theory where



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

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

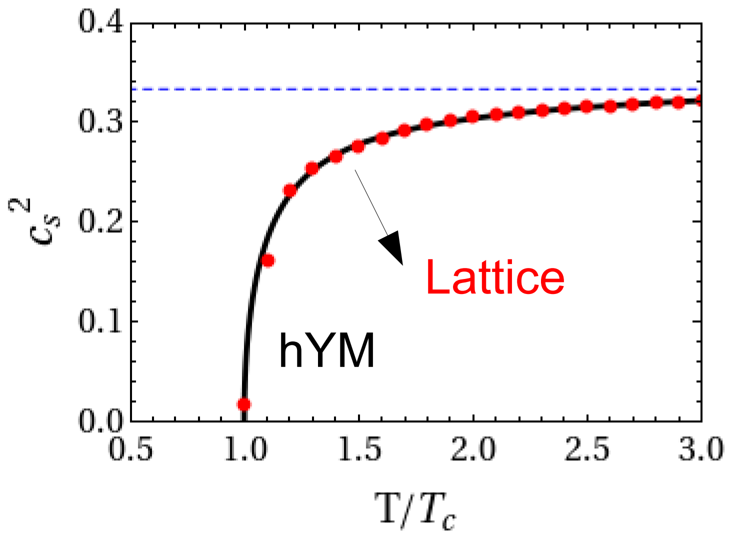
What is this effective theory ???

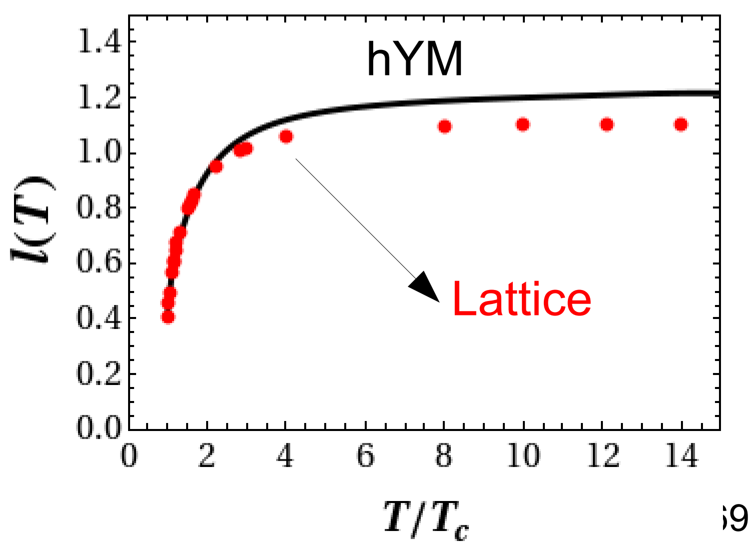
The main idea of this talk is to show you that such an effective theory can be obtained holographically using the gauge/string duality.

This theory will be able to describe the strongly-coupled properties of pure glue ...

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

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





Outline

Pure Glue and QCD – According to lattice

Holographic Description of Pure Glue

Conclusions and Outlook

What is observed on the lattice?

Pure glue SU(NC) gauge theory

About the order of the transition

- Nc = 2 is 2nd order

- Nc = 3 is weak 1st order

- Nc > 3 is strong 1st order

$$\frac{T_c}{\sqrt{\sigma}} = 0.5970(38) + \mathcal{O}(1/N_c^2)$$

$$T_c \simeq 260\mathrm{MeV}$$

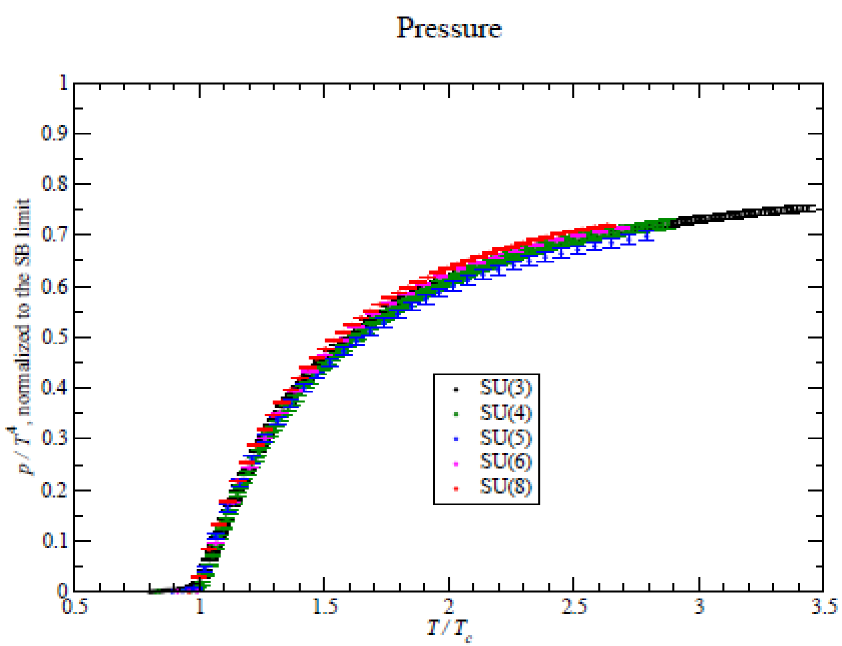
Latent heat

$$\frac{\mathcal{L}_h^{1/4}}{N_c^{1/2} T_c} = 0.766(40) + \mathcal{O}(1/N_c^2)$$

Lucini, Teper, Wenger, hep-lat/0502003

What is observed on the lattice?

Gluon plasma in equilibrium: Weird math!!!! $N_c = 3 = \infty$



No significant difference between Nc = 3 and Nc = 8.

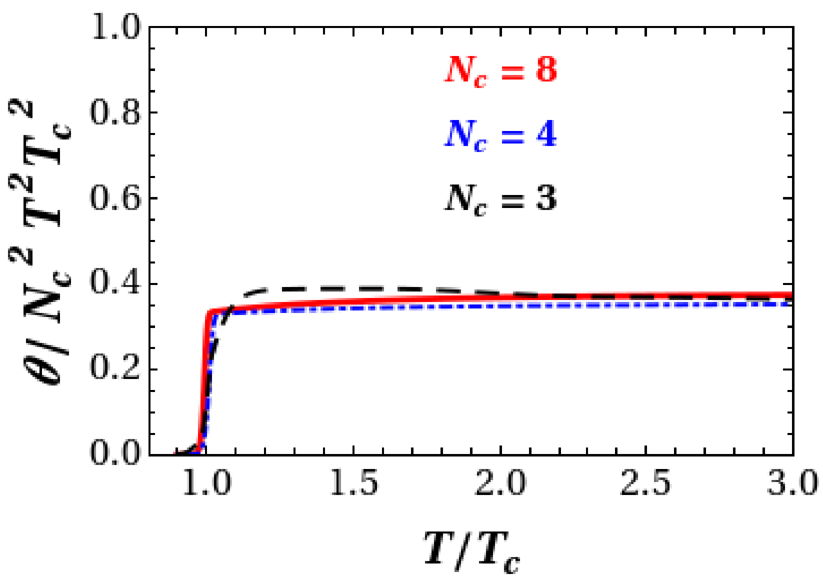
Large Nc approximation is excellent for pure glue theories !!!!

M. Panero, PRL 2009

What is observed on the lattice?

Trace anomaly

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



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

Power like behavior near T_c

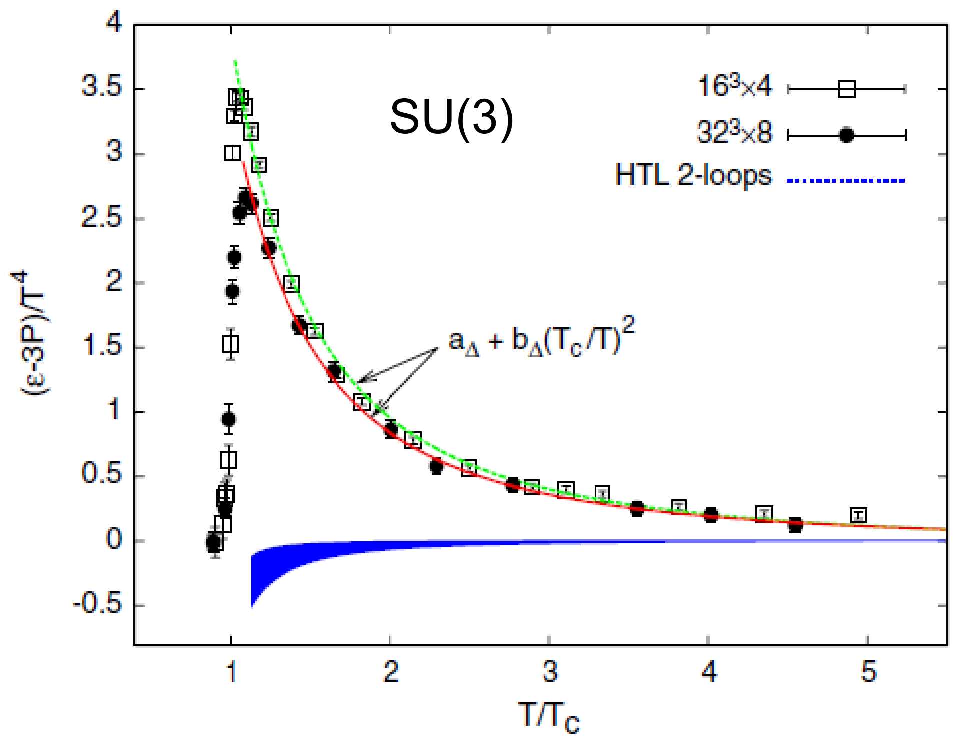
Pisarski, 2006
Megias, Arriola, Salcedo, 2006

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

Qualitatively different from pQCD calculations ...

What is observed on the lattice?

In fact …



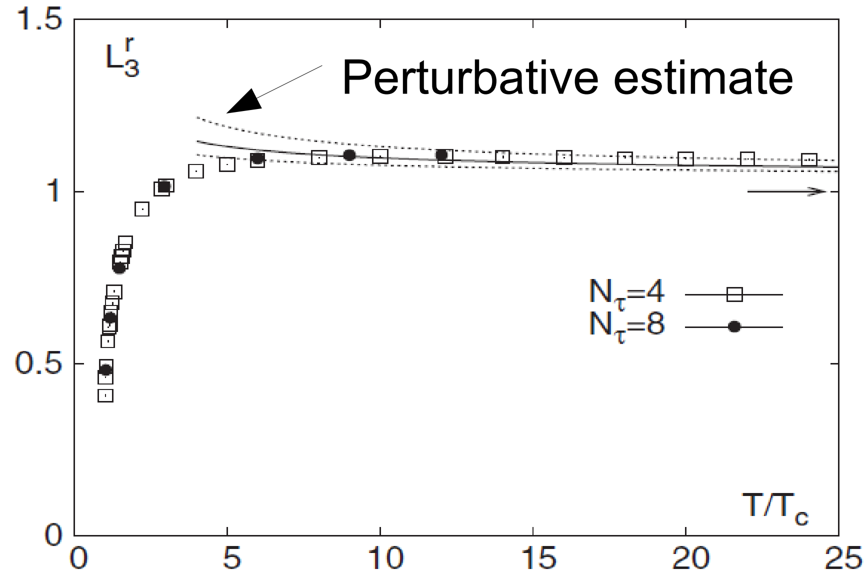
3-loop result looks better, though
Strickland et al., 2009

Megias, Arriola, Salcedo, 2009

What is observed on the lattice?

Renormalized Polyakov loop in the fundamental representation

Pure glue $SU(3)$



Gupta, Huebner, Kaczmarek, 2008.

Large Nc calculations on the lattice haven't been performed yet …

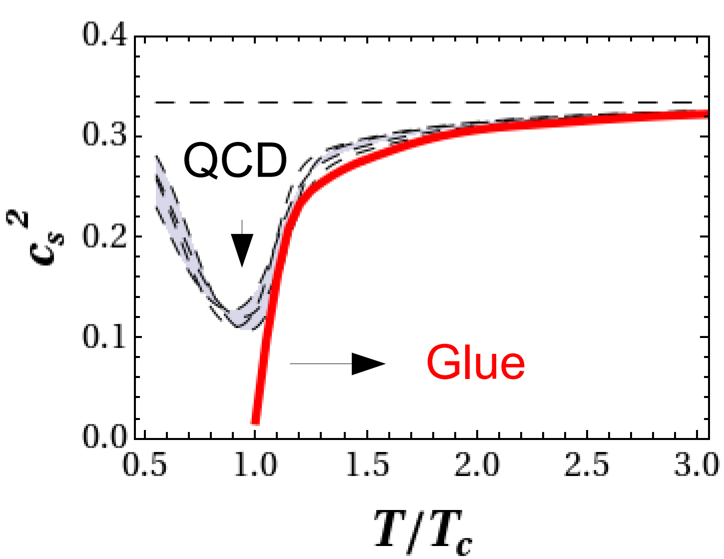
However, one should expect that the loop at large Nc is very similar to the Nc=3 result.

What is observed on the lattice?

QCD with (almost) physical quark masses

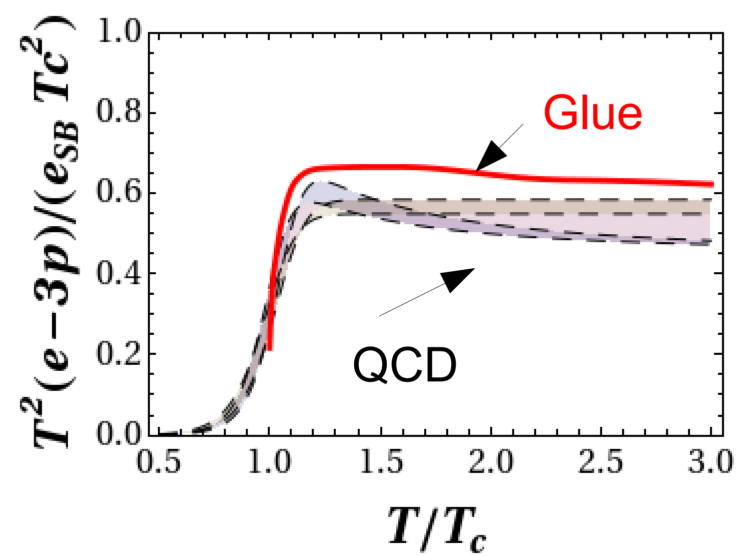
Strange quark mass ms = physical
2 light flavors with 1/10 strange mass

Lattice size: $32^3 \times 8$ Data from A. Bazavov et al , 2009.



QCD is a crossover

(I defined a Tc = 185 MeV
from the dip in the speed of sound)

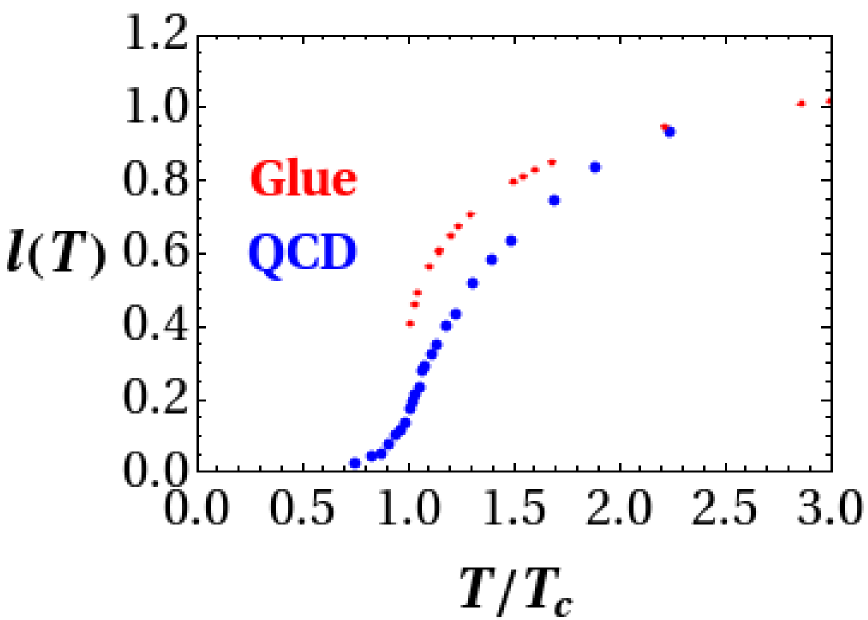


Nonperturbative power-like terms
also present in QCD

What is observed on the lattice?

Renormalized Polyakov loop in the fundamental representation

Data from A. Bazavov et al (MILC Collaboration), 2009.



Mathematical Definitions of the AdS/CFT Correspondence

$$Z_{string}\left[\Phi(x^\mu,u)\Big|_{u\to\infty}=\phi_0(x^\mu)\right]=\langle e^{\int d^4x\mathcal{O}(x^\mu)\phi_0(x^\mu)}\rangle_{GaugeTheory}$$

Gubser, Polyakov, Klebanov; Witten 1998

- The source $\phi_0(x^\mu)$ of the gauge invariant operator $\mathcal{O}(x^\mu)$ in the 4D gauge theory corresponds to a dynamical field $\Phi(x^\mu,u)$ defined in the theory of gravity (or string theory) in D > 4.

- Ex: 5D metric $G_{MN}(x^\mu,u)$ is dual to $T^{\mu\nu}(x^\lambda)$ of the 4D gauge theory

The Supergravity Approximation

- When $g_s \ll 1$ and the AdS radius $R^2/\ell_s^2 \gg 1$ we should recover a theory of supergravity (low energy approximation of superstring theory)

- Action is local and composed of several massless fields (at low energies)

$$\frac{1}{16\pi\, G_{10}} \int d^{10}x \sqrt{-G}\, e^{-2\Phi} \left(\mathcal{R} + 4(\partial\Phi)^2 + \ldots\right)$$

- $G_{10} \sim g_s^2\, \ell_s^8$ where $g_s \sim 1/N_c \ll 1$ is the string coupling.

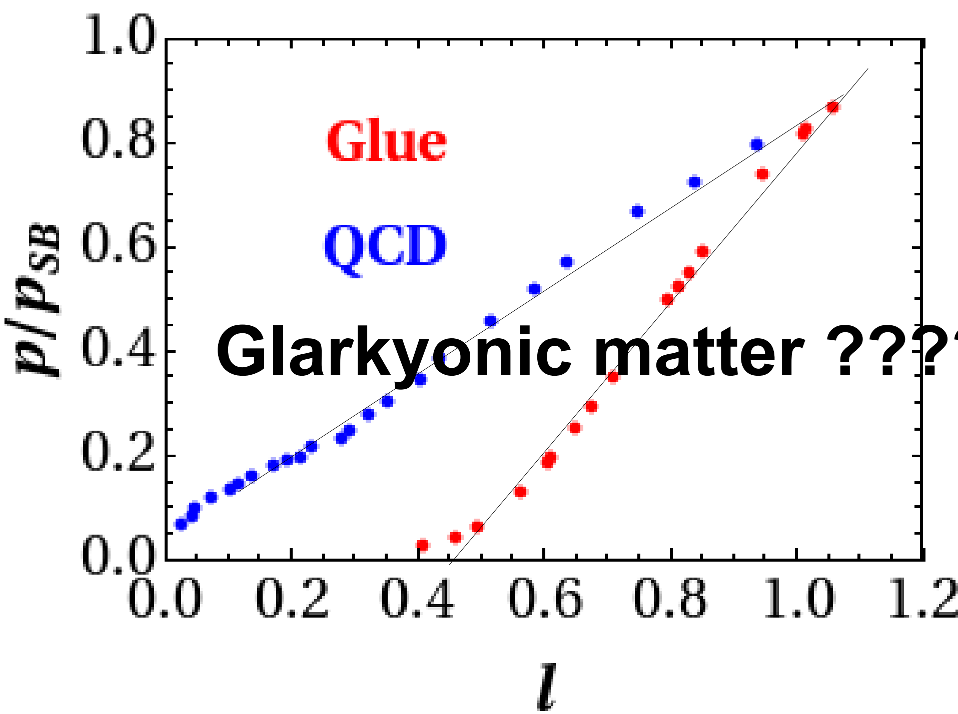
- In this limit, $\lambda = R^4/\ell_s^4 \gg 1,\;\; N_c \to \infty$ and $Z_{string} \sim e^{i\, S_{sugra}}$

T'Hooft coupling in
the gauge theory

What is observed on the lattice?

While both the pressure and the loop vary significantly near Tc, note that

Dumitru, Pisarski, 2010 (to appear); Noronha, 2010 (to appear)



Glarkyonic matter ????

Whatever causes this linear behavior for the glue is also there in QCD

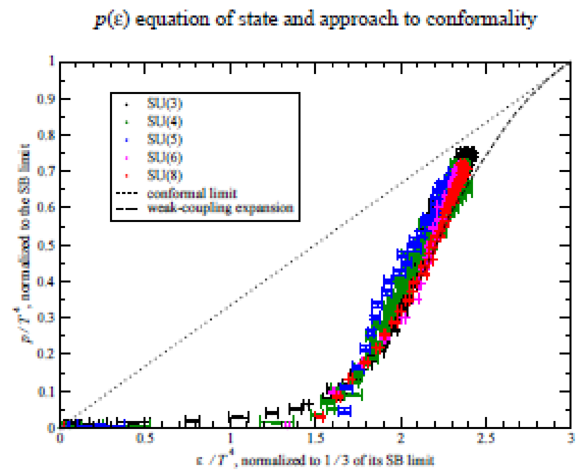
Nf = 0 to Nf =3 → change in the slope!

Glue Quarks

$$\boxed{p/p_{SB} \sim \ell}$$

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: $$N_c = 3 = \infty$$

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 !!!

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.

General assumptions:

Gubser et al. 2008

- Relevant deformation (important in the IR) $\Delta < 4$

- Spacetime is asymptotically AdS_5 with radius R

$$\lim_{\phi \to 0} V(\phi) = -\frac{12}{R^2} + \frac{1}{2R^2}\Delta(\Delta - 4)\phi^2 + \mathcal{O}(\phi^4)$$

- Breitenlohner-Freedman bound $1 \leq \Delta < 4$ $m_\phi^2 < 0$

- Gauge theory is conformal in the UV $E \gg \Lambda_\phi$ (not asymptotically free)

Pure glue at large Nc → Strong 1st order transition

Witten, 1998

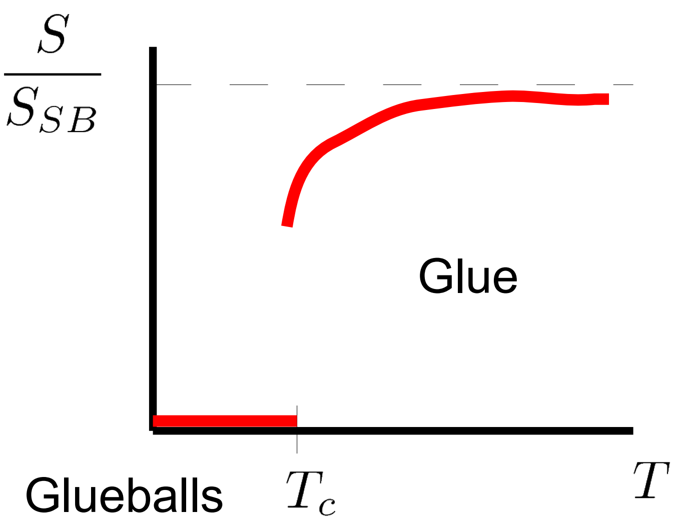
It should be something like this ...

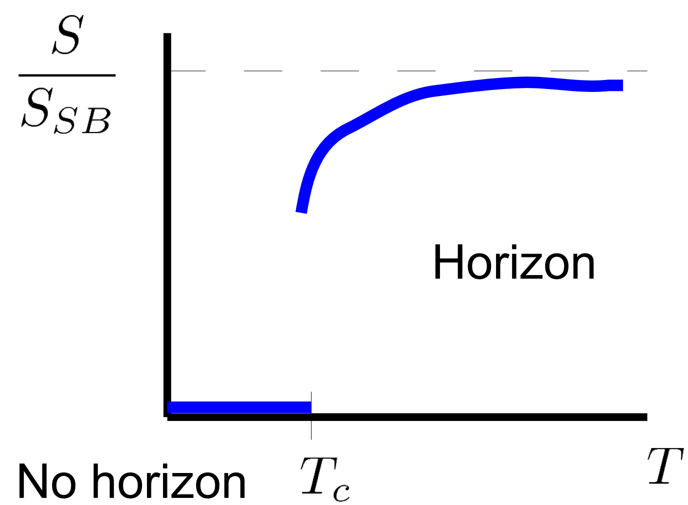
Gauge theory at finite T

Gravity dual with a black brane

T, entropy = T, entropy

$$S = \frac{A}{2k_5^2}$$

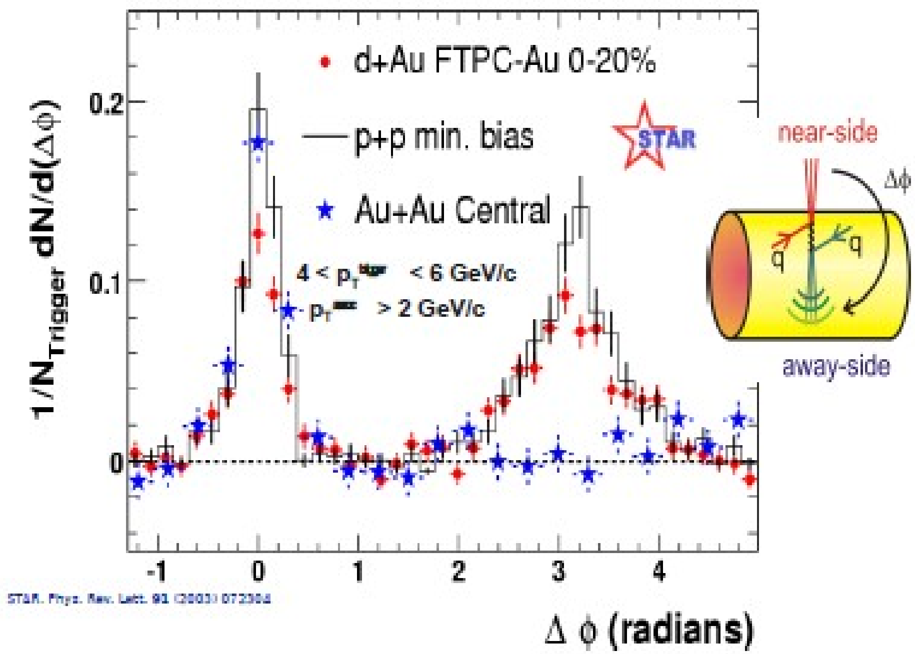




Strong Jet Suppression: Highly Opaque Medium to Colored Objects!!!

Strongly coupled QGP?

Or just a highly dense perturbative medium?



Deconfinement is equivalent to the formation of a horizon in the gravity dual

Hawking-Page transition (1983)

Witten, 1998

$$Z_{sugra} \sim e^{-I_c} + e^{-I_d}$$

Basically, there are two solutions of the supergravity equations (two different metric configurations):

$I_c = \mathcal{F}_c(T)/T$ No horizon

$I_d = \mathcal{F}_d(T)/T$ Horizon

Equal pressure

At T = Tc $p_c(T_c) = p_d(T_c)$ $\rightarrow$ Phase transition

This constraints a lot our choice for $V(\phi)$

Confinement can also be understood via the "area law"

Area law

Heavy quark potential at T = 0

$$\lim_{L\to\infty} \mathcal{V}_{Q\bar{Q}} \sim \sigma\, L$$

Occurs when in the IR

$$\lim_{\phi\gg 1} V(\phi) \sim -\phi^z\, e^{\sqrt{\frac{2}{3}}\phi} \qquad z \geq 0$$

Kiritsis et al, 2008

Such type of potentials (with z=0) may appear in non-critical 5d string theory.

Linear glueball spectrum $M_n^2 \sim n$ appears when z = 1/2.

Kiritsis et al, 2008

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

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

$a = 1$ $\qquad$ $b_4 = 0.4$

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

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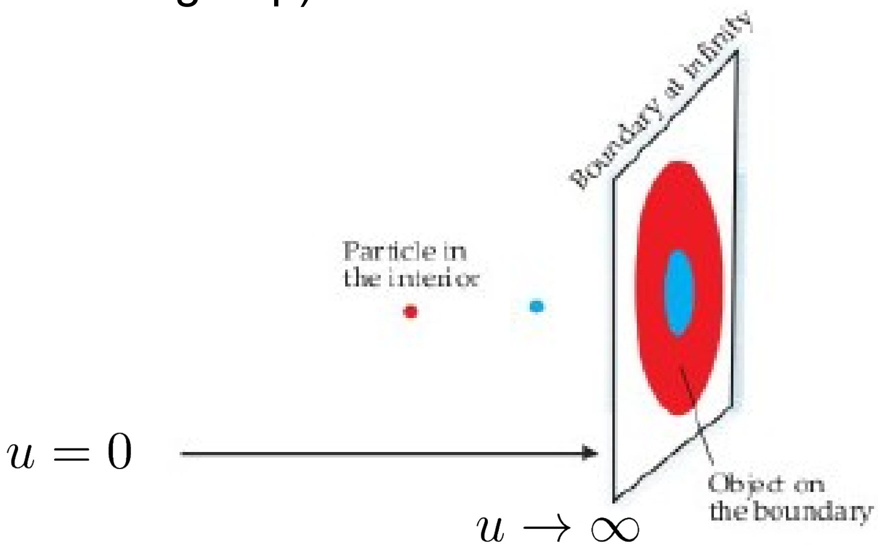
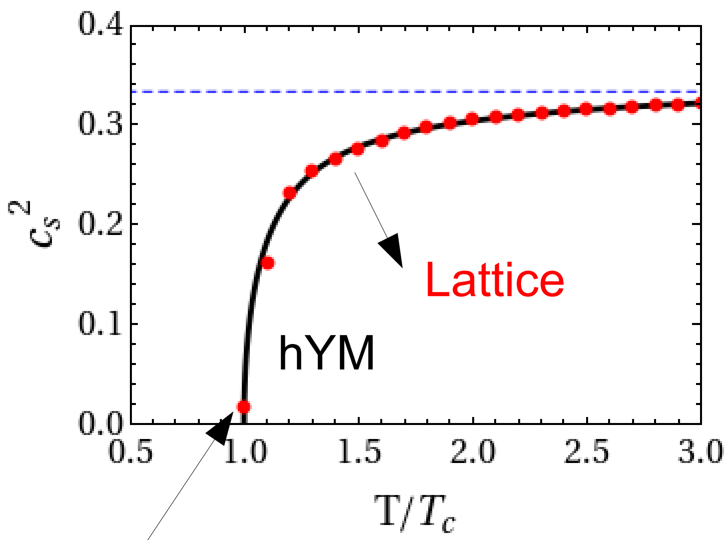
What does this fifth coordinate “u” actually mean ????

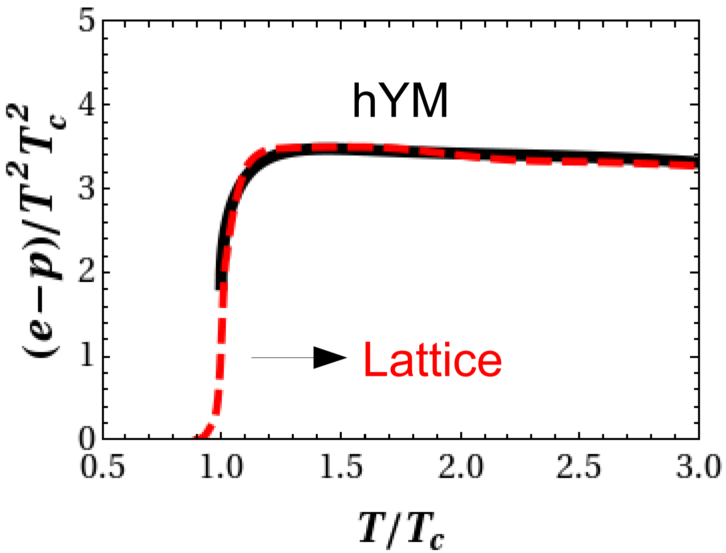
In general, this extra coordinate is related to the energy scale that define the physical processes in the 4D gauge theory (in the sense of the renormalization group)



Main idea: Strongly coupled gauge theories near a nontrivial fixed point can be understood in terms of generalized theories of gravity defined in higher spatial dimensions.

This choice gives an amazing match to the lattice data …





1st order transition

What about the Polyakov loop ????

General Properties of Polyakov Loops in Pure Glue

Polyakov loop
(fundamental rep.)

$$\mathbf{L}(\vec{x}) = P\, e^{i\int_0^{1/T} \hat{A}_0(\vec{x},\tau)d\tau} \qquad \ell \equiv \frac{\mathrm{Tr}\mathbf{L}}{N_c}$$

Below Tc the system is Z(Nc) symmetric

$$\langle \ell(T < T_c)\rangle \sim \sum_{a=0,\ldots,Nc-1} e^{i\,2\pi a/N_c} = 0$$

Above Tc the Z(Nc) symmetry is broken

$$|\langle \ell(T > T_c)\rangle| \neq 0$$

It is more intuitive to think about this the following way

Imagine that the quarks are infinitely heavy and also infinitely far apart (this is well defined above Tc).

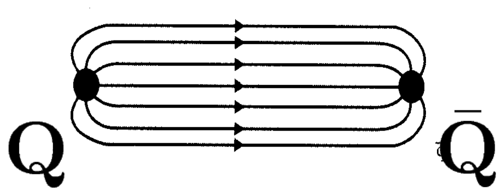
For a single(infinitely massive) quark one could sketch what the partition function is

$$Z \sim \frac{\int \mathcal{D}A\mathcal{D}x\, e^{-S_{glue}(A)+\int dt\left(\frac{M\dot{x}^2}{2}+A\dot{x}\right)}}{\int \mathcal{D}A\, e^{-S_{glue}(A)}} \sim \langle \mathrm{Tr}\, e^{\int_C A} \rangle \sim \langle \ell \rangle$$

$\langle \ell \rangle$ somehow measures what happens to the gluon medium once this heavy quark probe is included

This idea can be made more precise …

McLerran, Svetitsky, 1981



$$= \langle \ell(r)\ell^*(0)\rangle \equiv e^{-F_{Q\bar{Q}}(r,T)/T}$$

Difference between free energy densities

$$F_{Q\bar{Q}}(r,T) \equiv \mathcal{F}(r,T) - \mathcal{F}_{glue}(T)$$

glue+Q pure glue

$$|\langle \ell(T)\rangle| = \lim_{r\to\infty} e^{-F_{Q\bar{Q}}(r,T)/2T} \equiv e^{-F_Q(T)/T}$$

What is $F_Q(T)$??? In general, it is NOT a true free energy !!!

Noronha, 2010

When Nc is large

$$\mathcal{F}_{glue}(T) = N_c^2 F_2^g(T) + F_0^g(T) + \mathcal{O}(1/N_c^2)$$

$$\mathcal{F}(r,T) = N_c^2 F_2(T) + F_0(r,T) + \mathcal{O}(1/N_c^2)$$

Glue + probe quark

$$\lambda_{YM} = g_{YM}^2 N_c$$

$$\lim_{N_c \gg 1} F_Q(T) = (F_0(r \to \infty, T) - F_0^g(T))/2$$

The difference between free energies is not necessarily a free energy

High T properties of the Polyakov Loop

Let's define

$$U_Q(T) \equiv F_Q(T) - T\frac{dF_Q}{dT}$$

One can show that

$$\frac{d\ell(T)}{dT} = U_Q(T)\,\frac{\ell(T)}{T^2}$$

Immediately above Tc one should have $U_Q(T \sim T_c) > 0$

Let's for now assume that $F_Q(T)$ is a true thermodynamic free energy density

Then, in equilibrium one should have a positive specific heat, i.e.,

$$\frac{dU_Q}{dT} > 0 \qquad\qquad T > T_c$$

Since $U_Q(T \sim T_c) > 0$ is always true, in this case one obtains

$$\boxed{\frac{d\ell(T > T_c)}{dT} \geq 0}$$

If $F_Q(T)$ is a true free energy

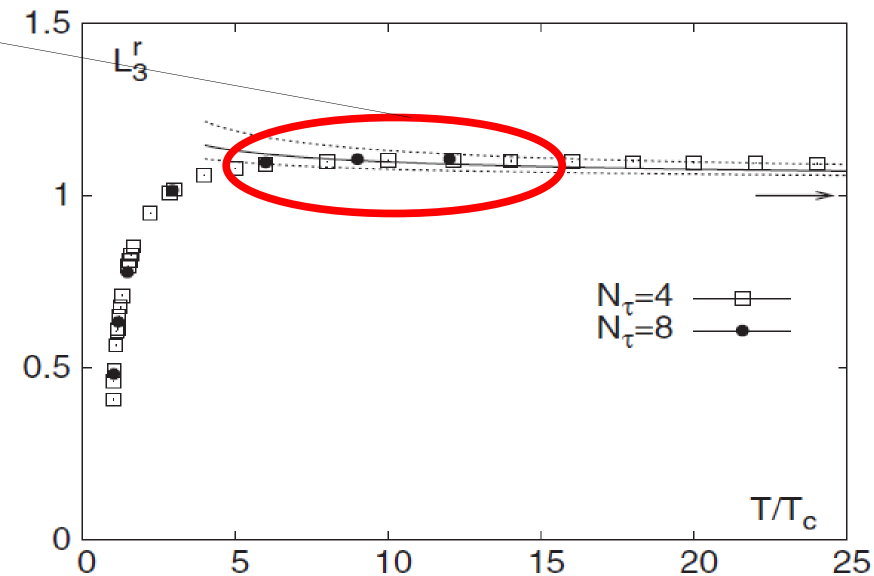
then the Polyakov loop is a monotonic function of T.

Is this true for pure glue with Nc=3 ?

NO!!!!

In this region T ~ 10 Tc

$$\frac{d\ell}{dT} < 0$$



$F_Q(T)$ is not a free energy in pure glue.

Data from Gupta, Huebner, Kaczmarek, 2008.

This should always be true in an asymptotically free theory

Noronha, 2010

At very high temperatures HTL predicts that

$$\ell \sim 1 + \lambda_{YM}(m_D/T) + \ldots$$

$$m_D \sim \sqrt{\lambda_{YM}}T$$

Debye mass

Asymptotic freedom → Loop approaches 1 from above.

$$\frac{d\ell}{dT} < 0 \quad \text{because} \quad \frac{d\lambda_{YM}}{dT} < 0$$

Thus, in any confining theory that is also asymptotically free there must be a value of temperature where

Noronha, 2010

$$\frac{d\ell(T^*)}{dT} = 0$$

I would expect same in QCD although the exact value of T* may be regularization dependent.

What happens in the classes of gravity duals described earlier?

Those theories do not have a trivial UV fixed point (QCD or pure glue do).

Is $F_Q(T)$ a true free energy in this case? Is the loop a monotonic function of T?

In supergravity the loop should be a monotonic function of T because

Noronha, 2010

$$F_0^g(T) = 0$$ in this approximation.

Then,
$$\lim_{N_c \gg 1} F_Q(T) = F_0(r \to \infty, T)/2$$

which implies that $F_Q(T)$ is a free energy and hence

$$\frac{d\ell(T > T_c)}{dT} \geq 0$$

Can this be used to constraint the dual theory of pure glue?

Asymptotic freedom cannot be described by supergravity !!!!!!

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In general, the expectation value of the Polyakov loop is $|\langle \ell(T) \rangle| = e^{-F_Q/T}$

In the deconfined phase the following equation holds for **ANY** $V(\phi)$

$\phi_h = \phi(u_h)$

$$\frac{dF_Q}{dT} = \frac{2}{\alpha'} \frac{q(\phi_h)}{V(\phi_h)} \frac{1}{c_s^2}\,.$$

Speed of sound

- Note that $dF_Q/dT < 0$ in thermodynamic equil. since $V(\phi) < 0$

- This quantity diverges when $c_s \longrightarrow 0$ (phase transition) .

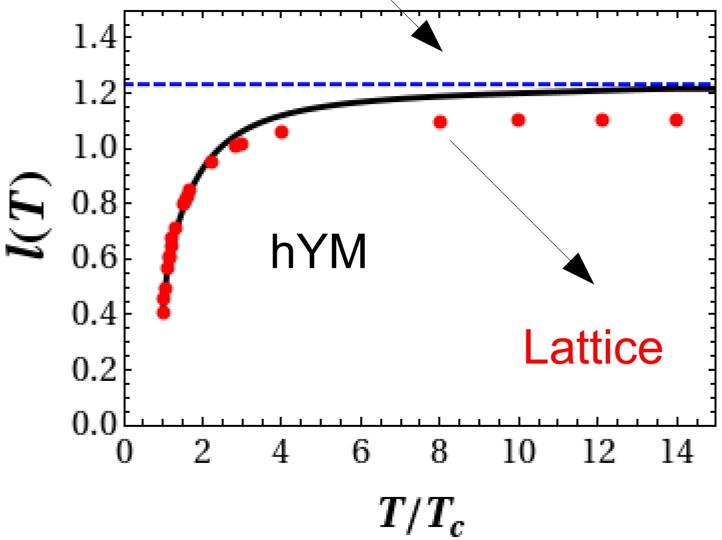
- The jump in the loop at Tc is related to how quickly the speed of sound vanishes at Tc.

Noronha,PRD (2010).

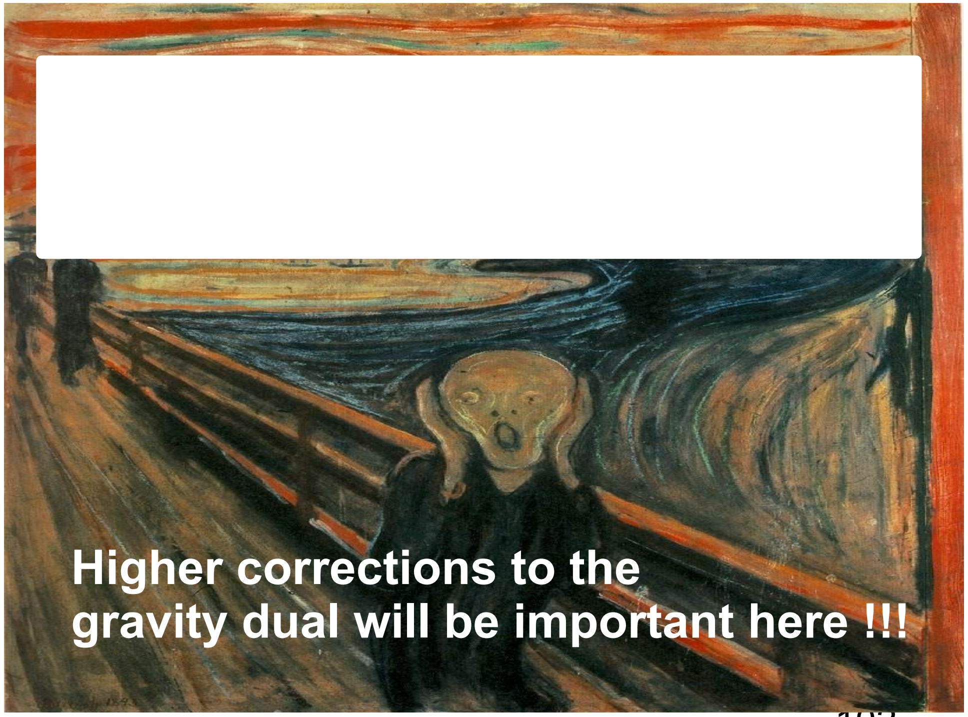
Let's assume a dilaton-like coupling function $q(\phi) = e^{\sqrt{2/3}\phi}$

Kiritsis et al, 2008

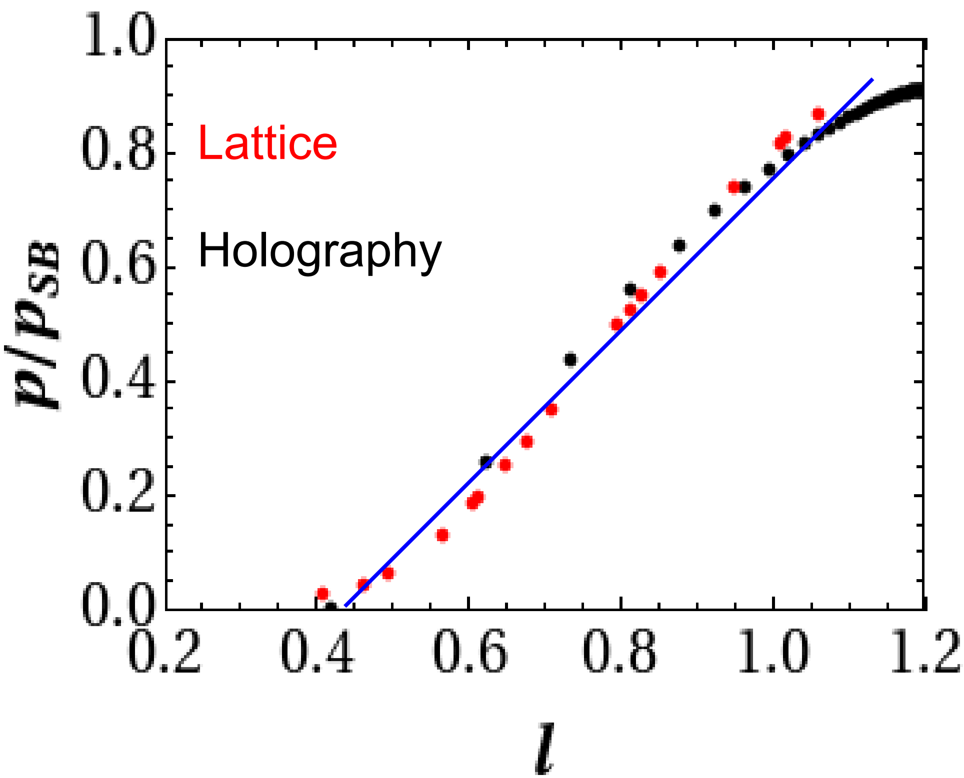
Value at T/Tc >> 1



Good agreement below 4Tc …



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



Other interesting properties that I have no time to discuss here in detail ...

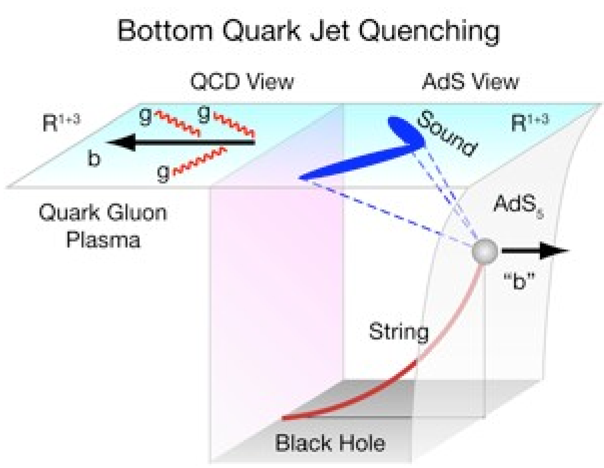
- $\eta/s = 1/(4\pi)$ above Tc. Below Tc one should expect $\eta/s \sim N_c^2$

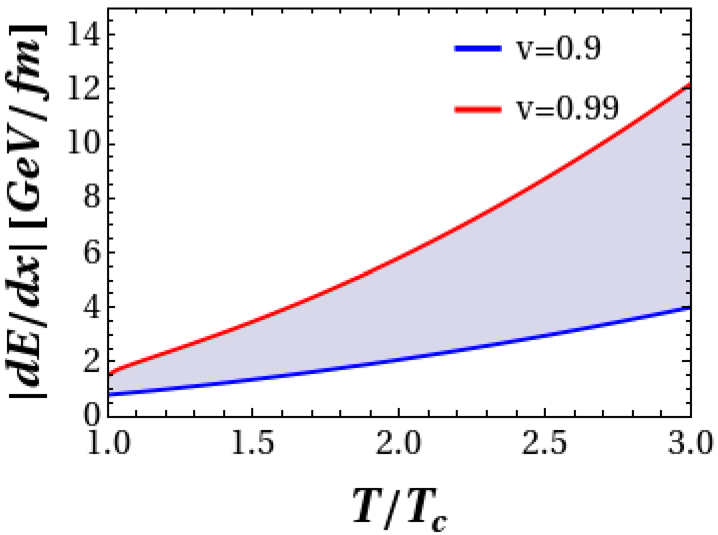
Noronha, arXiv:0912.4824 [hep-th]

- ζ/s has a peak at Tc.

Gubser, Nellore, Pufu, Rocha, PRL (2008).

What about heavy quark energy loss?





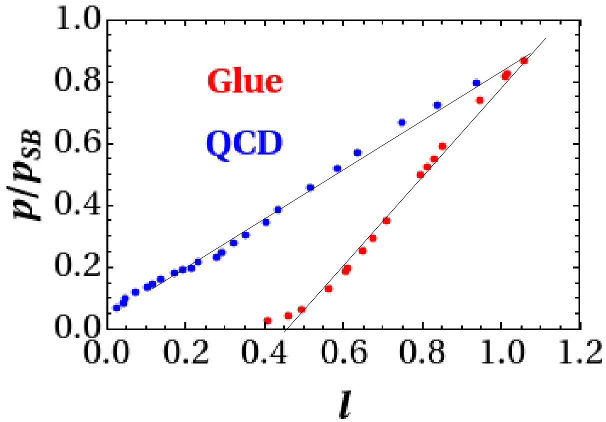
Conclusions and Outlook

- Gauge/string duality can be used to construct a gravity dual that resembles pure glue (linear confinement, are law, deconfinement and etc).

- A similar gravity dual should be able to describe QCD near the crossover transition.

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

- The pressure/SB is roughly a linear function of the Polyakov loop even at low temperatures where main d.o.f. are hadrons in QCD.



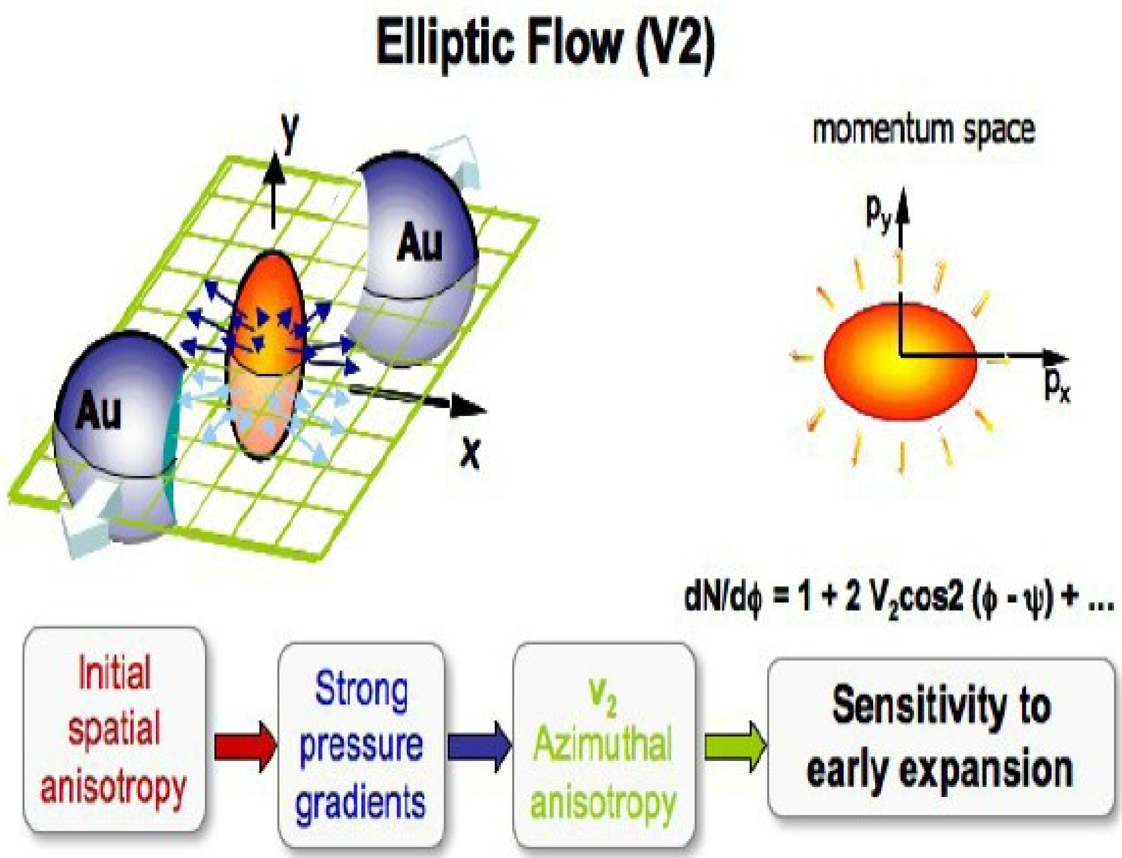
- The Polyakov loop $|\langle \ell(T) \rangle| = e^{-F_Q/T}$

But F_Q is not a free energy in QCD (although it becomes a free energy in gravity duals in the supergravity approximation). The fact that this is not a free energy in QCD directly affects, for instance, the determination of the binding energy of heavy mesons in the plasma (do we understand how these heavy states melt in the plasma ???).

- A good agreement between the holographic calculation for the Polyakov loop and the lattice data near Tc only happens if $R^2/\alpha' \sim 1$

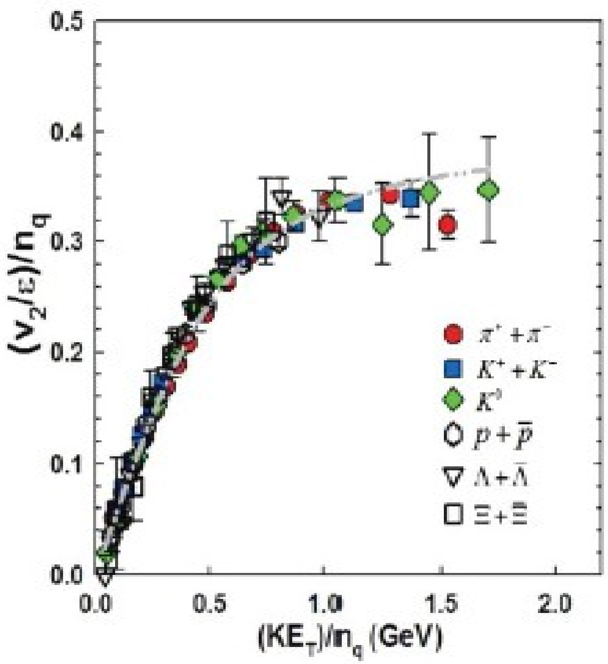
- Would that lead to problems in other observables that have been compared to RHIC data (such as heavy quark energy loss)?

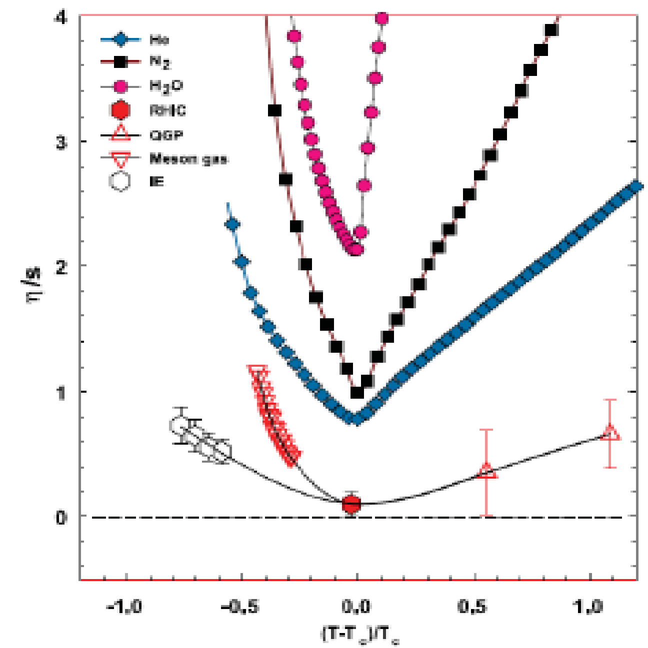
The QGP barometer …



“Nearly Perfect Fluid” of Quarks and Gluons

First big discovery !!!!!





Flow at partonic level?

Better fluid than superfluids!!!

Large elliptic flow → Nearly Ideal Flow → Strong coupling?