Heavy Ion Collisions and QGP: Perturbative QCD vs AdS/CFT

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Introduction

Heavy ion collisions at RHIC $\Rightarrow$

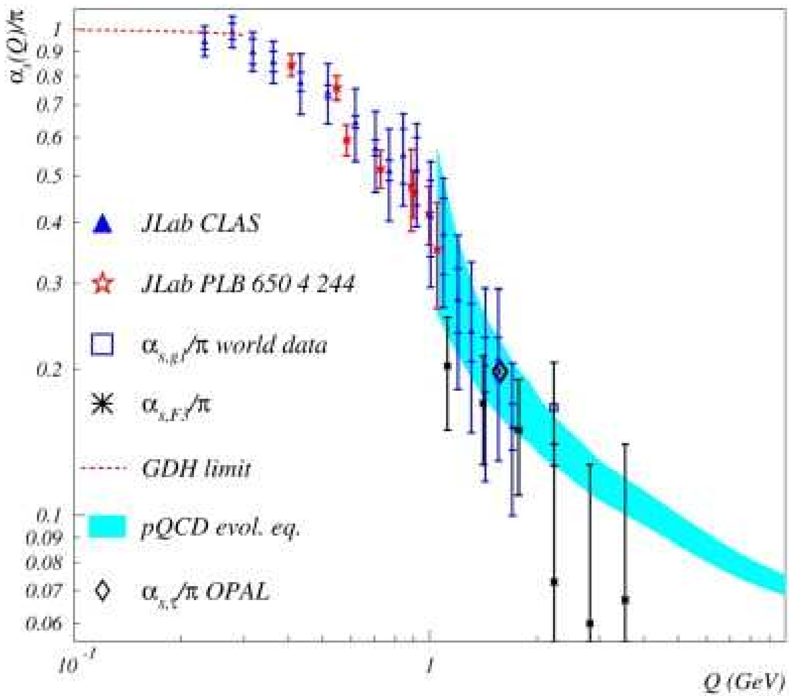
- strong jet quenching $\rightarrow$ deconfined
- large elliptic flow v_2 consistent with hydro evolution and small viscosity $\rightarrow$ perfect fluid

CLAIM: *strongly coupled* QGP $=$ sQGP

$$T_c \sim 200 \text{ MeV} \Rightarrow$$
$$\alpha_s(T \sim 2-3T_c) \sim \mathcal{O}(1)$$

$\alpha_s(T \rightarrow T_c) \gg 1$?? no:

$\alpha_s(Q^2 \rightarrow 0)$ bounded



Deur et al, 0803.4119

How to address $\alpha_s(T) \sim \mathcal{O}(1)$?

- Lattice QCD
- Perturbative QCD (PQCD) $\alpha_s(T) \ll 1 \Leftrightarrow T \gg T_c$

  extrapolated to $\alpha_s(T) \sim 1$

PQCD successful at $T = 0$:

- $Q \gg \Lambda_{\rm QCD} \Rightarrow$ hard processes
- $Q \sim \Lambda_{\rm QCD} \Rightarrow$ jet structure

- AdS/CFT correspondence Maldacena, 1998

$\Rightarrow \lambda \gg 1$ regime of gauge theories extrapolated to $\lambda \sim 1$

- applies to $\mathcal{N} = 4$ SYM with gauge group $\mathrm{SU}(N_c)$, not really to QCD yet...
- assumes $\lambda \gg 1$, $N_c \gg 1$

AdS/CFT correspondence has initiated
strong theoretical activity

- studies of SYM plasma
- unexpected models for confinement

  Karch et al, hep-ph/0602229
- light-front holography

  Brodsky & de Teramond, 0802.0514
- ...

worth keeping informed about it !

Plan

1 Phenomenology: revisit arguments for sQGP

- jet-quenching
- elliptic flow v_2

in fact: PQCD extrapolated to $\alpha_s \sim 1$ consistent with data

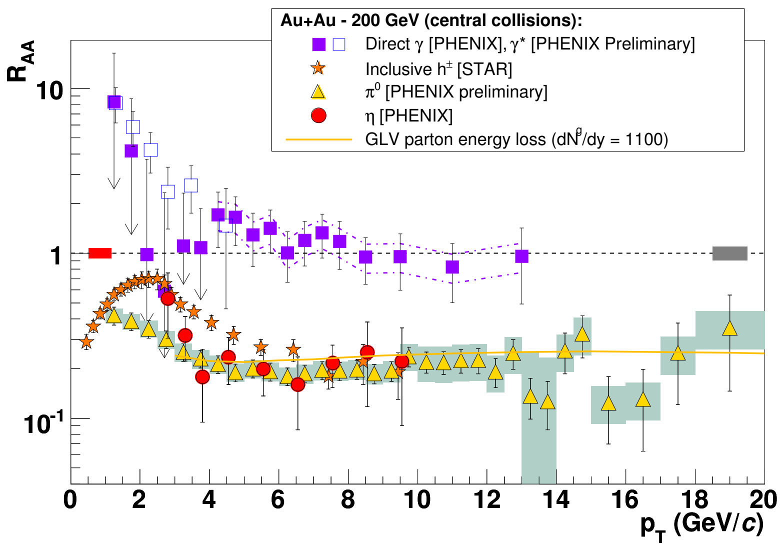
2 Sketch of AdS/CFT correspondence

- heuristic description using D-branes
- application: parton ΔE in SYM plasma

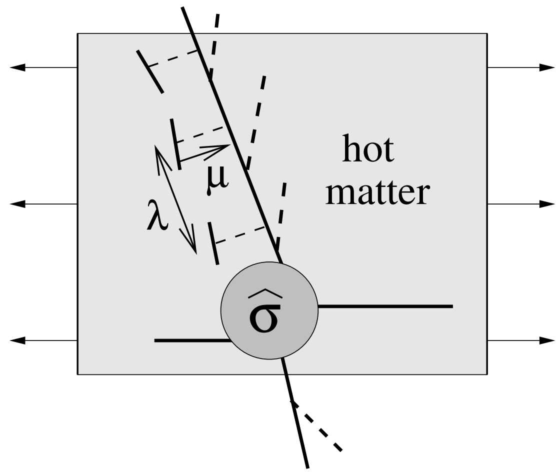
Warning: knowledge under construction

1. Phenomenology

"Jet-Quenching": $R_{\mathrm{AA}}(p_T) = \dfrac{\sharp \text{ particles in central AA } (p_T)}{A^{4/3}\ (\sharp \text{ particles in pp } (p_T))}$



colored particles suffer energy loss

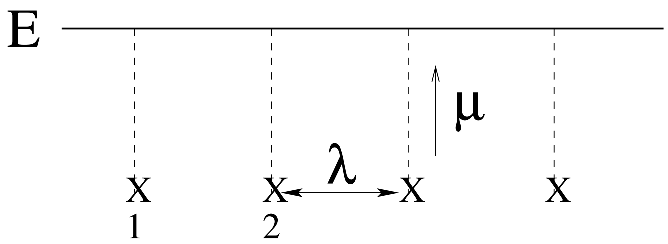


PQCD $\Rightarrow \Delta E_{\mathrm{induced}} \equiv \Delta E_{\mathrm{rad}}^{\mathrm{med}} - \Delta E_{\mathrm{rad}}^{\mathrm{vac}} \sim \alpha_s \hat{q} L^2 \quad (L < L_{cr})$

transport coefficient $\hat{q} = \frac{\mu^2}{\lambda} \sim \alpha_s^2 T^3$

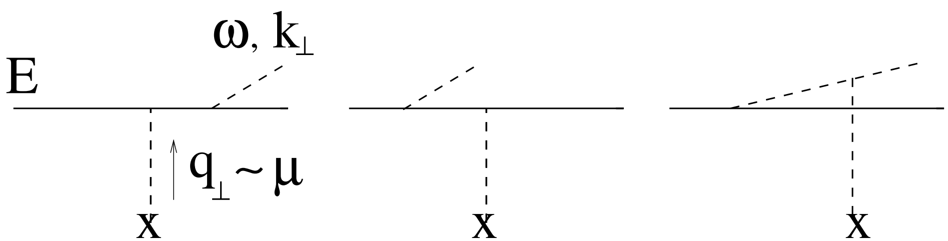
Medium effects on parton propagation in PQCD

- leading order: elastic scattering



$\Rightarrow$ momentum broadening $\quad \langle \Delta p_\perp^2 \rangle_L = \mu^2 \frac{L}{\lambda} = \hat{q} L \qquad \hat{q} \equiv \frac{\mu^2}{\lambda}$

- next order: broadening induces radiation



$\Rightarrow \quad k_\perp \lesssim q_\perp$

$$t_f \sim \frac{\omega}{k_\perp^2} \lesssim L \Rightarrow \frac{dE}{dx} \sim \frac{\omega}{t_f} \cdot \alpha_s \sim \alpha_s \cdot k_\perp^2$$

$$\left.\frac{dE}{dx}\right|_{\text{induced}} \sim \alpha_s \cdot q_\perp^2(L) \sim \alpha_s \cdot \hat{q} L \Rightarrow \Delta E_{\text{induced}} \sim \alpha_s \hat{q} L^2$$

extraction of $\hat{q} = \frac{\mu^2}{\lambda} \sim \alpha_s^2 T^3$ sensitive to α_s, T, and model for AA collision

- In realistic model — B. Zakharov

$$\hat{q} \simeq 1.5\,\mathrm{GeV}^2/\mathrm{fm} \gg \hat{q}_{\mathrm{cold}} \simeq \frac{\Lambda^2_{\mathrm{QCD}}}{(1\,\mathrm{fm})^2} \simeq 0.04\,\mathrm{GeV}^2/\mathrm{fm}$$

$\Rightarrow$ deconfined medium

perturbative QGP or sQGP?

- $\hat{q}$ consistent with PQCD evaluation

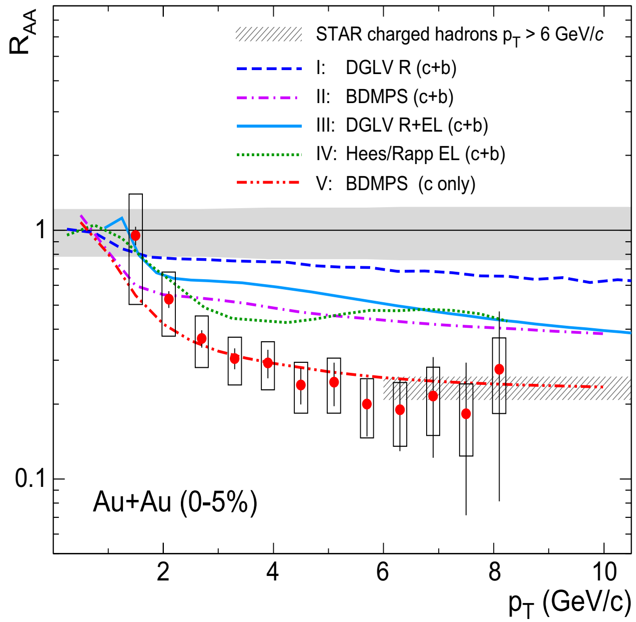
to leading-log: $\hat{q} \simeq 4\pi C_F \alpha_s^2 n \ln\left(\frac{4\pi C_F \alpha_s^2 n L}{\mu^2}\right)$

Arnold, 0810.1026

$\Rightarrow \hat{q} \simeq 1.7\,\mathrm{GeV}^2/\mathrm{fm}$ (for $\alpha_s = 0.5$, $T = 300\,\mathrm{MeV}$)

$e^{\pm}$ from D + B decays

$R_{AA}(Q) \simeq R_{AA}(q,g)$



naively: $\Delta E_Q \ll \Delta E_q$

'dead cone effect'

$\theta_{rad} < M/p_T$ suppressed

$\Rightarrow$ less quenching for heavy flavours

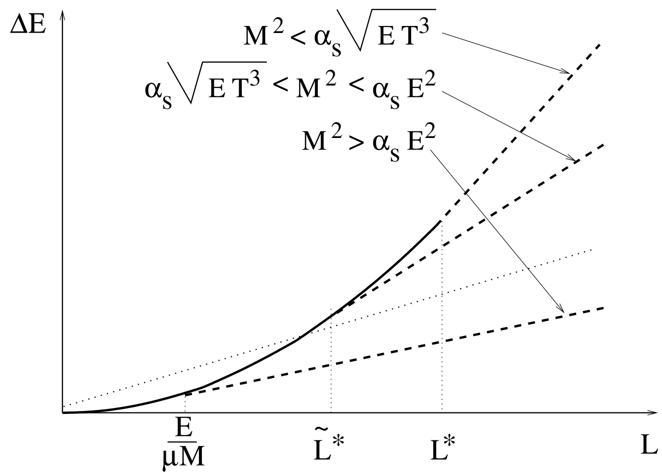
PQCD failure? sQGP?

- explaining $R_{AA}(e^{\pm})$ with ΔE_{rad} still possible

  B. Zakharov

- $\Delta E(E, M, T, L, \alpha_s)$ has a rich structure

  S.P., A.Smilga, 0810.5702

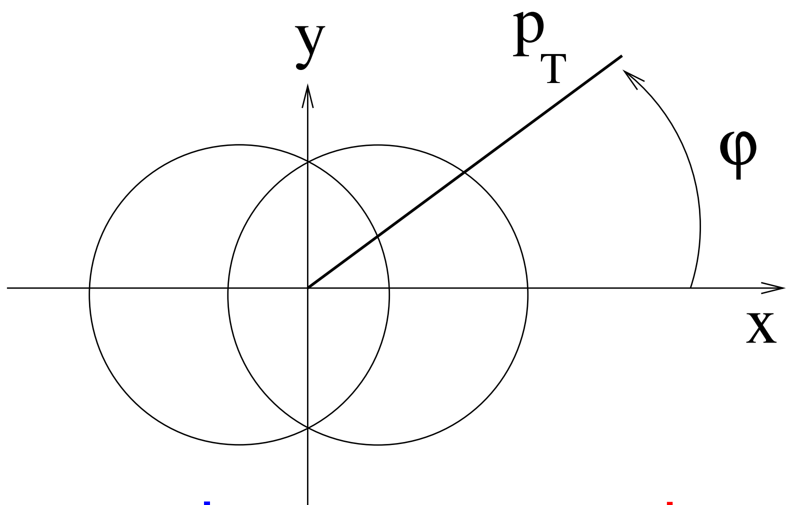


$$L^* = \sqrt{\frac{\lambda E}{\mu^2}} \ ; \ \tilde{L}^* = \left(\frac{\lambda E^2}{\mu^2 M^2}\right)^{\frac{1}{3}}$$

$$L < \tilde{L}^* \Rightarrow \Delta E_Q \simeq \Delta E_q$$

- is deconfined medium in (local) thermal equilibrium?

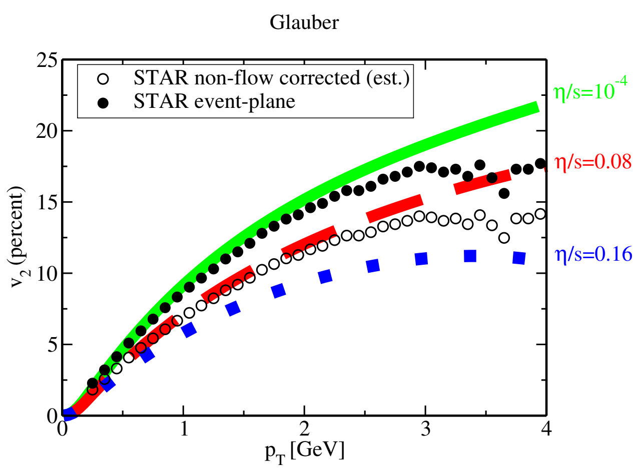
$\rightarrow$ soft particles, anisotropic flow — Ollitrault, 1992



anisotropy in ϕ characterized by elliptic flow

$$v_2 = \frac{\langle p_x^2 - p_y^2 \rangle}{\langle p_x^2 + p_y^2 \rangle}$$

v_2 large $\Rightarrow$ strong interactions in almond $\Rightarrow$ sQGP



$$\frac{\eta}{s} \simeq 0.1 \pm 0.1(\mathrm{th}) \pm 0.1(\mathrm{exp})$$

Luzum & Romatschke, 2008

- PQCD: $\frac{\eta}{s} \sim \frac{1}{\alpha_s^2} \gg 1$
- non-perturbative expectation (AdS/CFT):

$\frac{\eta}{s}(\lambda \to \infty) = \frac{1}{4\pi} \simeq 0.08$ Kovtun, Son, Starinets, 2004

$\Rightarrow$ PQCD apparently ruled out

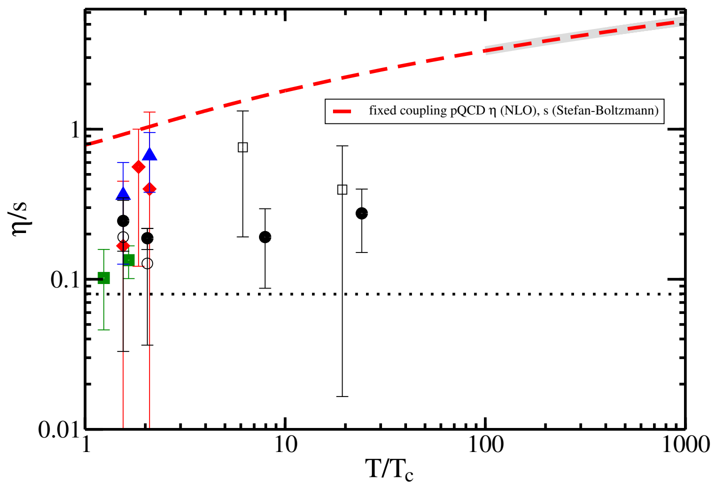
$\Rightarrow$ nearly perfect fluid produced at RHIC = sQGP

What is actual PQCD prediction for η/s?

- fixed coupling:

$$\frac{\eta}{s} = \frac{c_1}{\alpha_s^2 \ln \frac{c_2}{\alpha_s}}$$

(Arnold, Moore, Yaffe hep-ph/0302165)



M. Blühm

- running coupling:

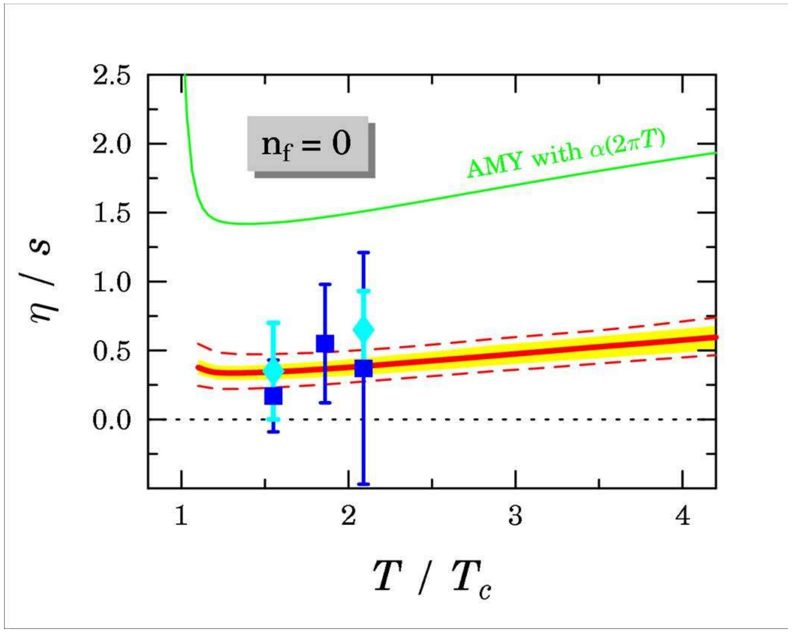
$$\eta^{-1} \sim \lambda^{-1}_{\rm transport} \sim \sigma_{\rm transport} \sim \int dt\, t\, \frac{\alpha_s^2(t)}{t^2}$$

PQCD: $\alpha_s(t) \sim \frac{1}{\ln t}$ $\Rightarrow$ enhances contribution of small t

situation is similar to $\Delta E_{\rm coll}$(parton) S.P & A.Peshier, 2008

PQCD with running α_s consistent with lattice

Peshier, 2009



don't discard perturbative approach!

- PQCD is predictive, successful at $T = 0$, even beyond expected range of validity
  - soft hadron energy and $k_\perp$ distributions within jets
- at $T \neq 0$, PQCD extrapolated to $\alpha_s \sim \mathcal{O}(1)$ works well:
  - jet-quenching (light and heavy flavours)
  - viscosity

$\Rightarrow$ two possible paradigms

- QGP dynamics is perturbative $\rightarrow$ extrapolate $\alpha_s \ll 1$
- QGP dynamics is non-perturbative $\rightarrow$ use AdS/CFT?

2. Sketch of AdS/CFT approach

AdS/CFT correspondence

$\rightarrow$ strong coupling limit of gauge theories

- context: Supersymmetric String Theory

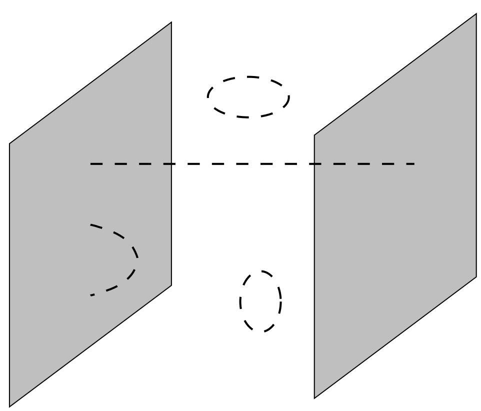
  elementary objects = *strings* $\quad \ell_s \sim \ell_{\text{Planck}}$

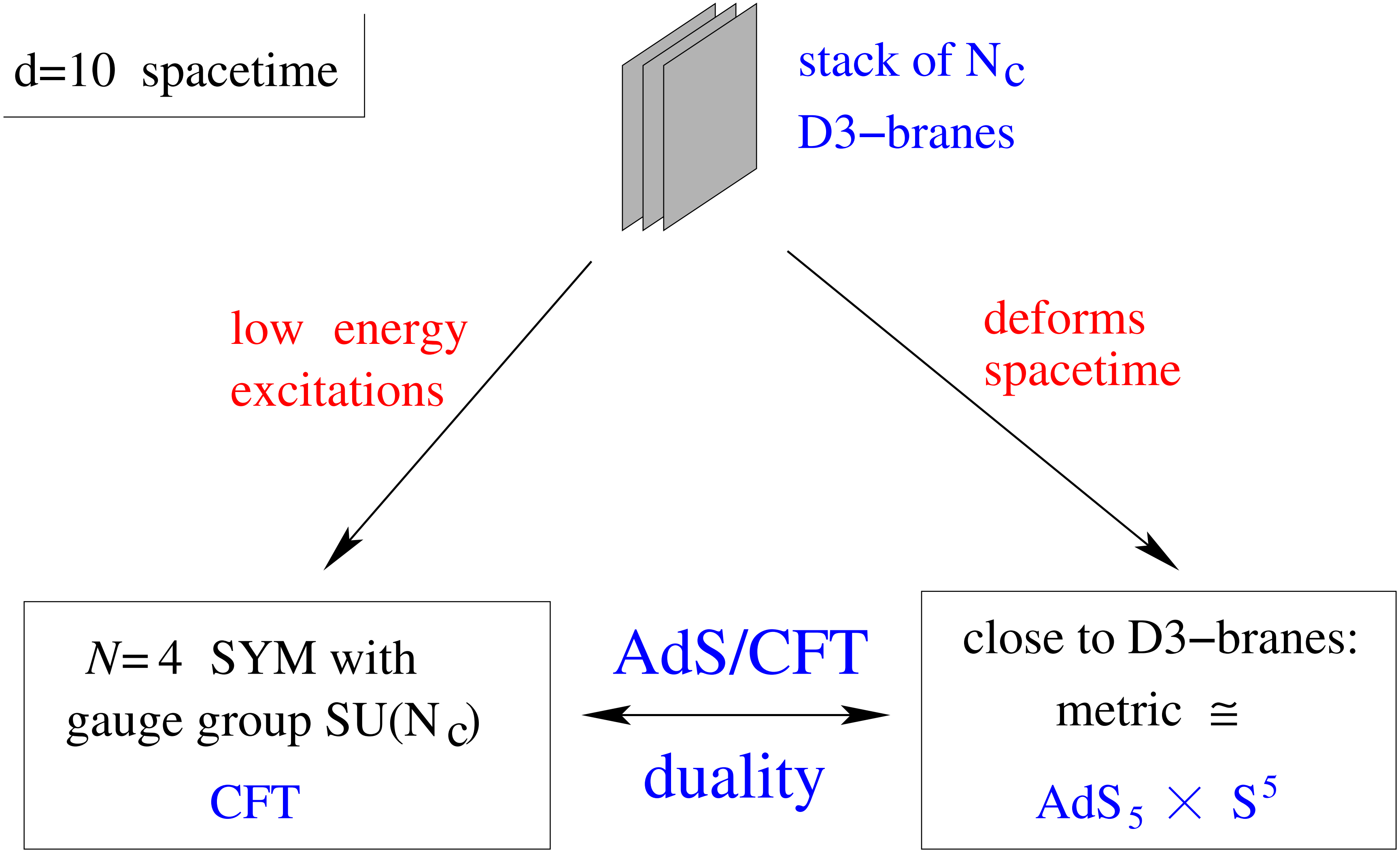
- $\exists$ five consistent SST's (Green & Schwarz, 1985)

- living in $d = 10$ dimensions
- related by dualities (Horava & Witten, 1995)

- string theory includes gravitation

  and D-branes $\equiv p$-dim objects
  where open strings end
  (Polchinski, 1995)




d=10 spacetime
stack of N_c
D3−branes
low energy
excitations
deforms
spacetime
$\mathcal{N}=4$ SYM with
gauge group $SU(N_c)$
CFT
AdS/CFT
duality
close to D3−branes:
metric ≅
$AdS_5 \times S^5$

- Maldacena conjecture (AdS/CFT correspondence):

$\mathcal{N} = 4 \; SU(N_c)$ SYM in $d = 4$ Minkowski spacetime $\Leftrightarrow$ Type IIB SST on $AdS_5 \times S^5$

$$ds^2_{AdS} = \frac{r^2}{R^2}(d\vec{x}^{\,2} - dt^2) + \frac{R^2}{r^2} dr^2$$

theory in $d = 10$ equivalent to theory in $d = 4$!!

Holographic Principle:

a theory containing gravity
must be dual to the boundary theory

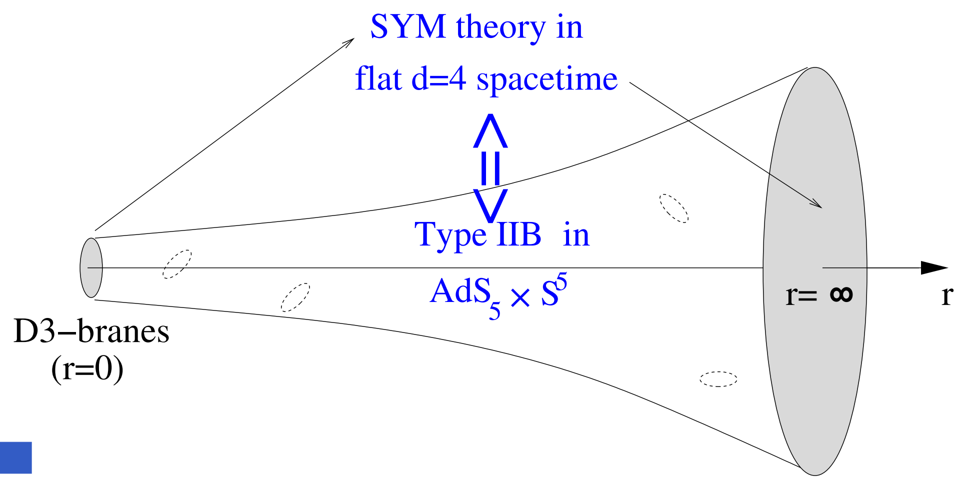
- symmetry of $\mathcal{N} = 4$ SYM = $SO(2,4) \times SO(6)$

= isometry group of $AdS_5 \times S^5$

- parameters:

$$g^2_{\rm YM} = 4\pi g_s \quad ; \quad \lambda = g^2_{\rm YM} N_c = \left(\frac{R}{\ell_s}\right)^4$$

$g_{\rm YM} \to 0,\ N_c \to \infty$ with fixed $\lambda \gg 1$	$\longleftrightarrow$	$g_s \ll 1$ (weakly coupled) $R \gg \ell_s$ (weakly curved)
NP quantum calculation in $d = 4$ boundary SYM theory	$\longleftrightarrow$	*classical* supergravity calculation in $AdS_5 \times S^5$



conformal group $SO(2,4)$ has a mathematical representation on AdS_5

SYM = non-abelian gauge theory
$\Rightarrow$ AdS/CFT might be used to learn about QCD

SYM	QCD
no confinement	confinement
continuous spectrum	discrete spectrum
conformal	running coupling
supersymmetric	not supersymmetric

"AdS/QCD" not guaranteed!!

IR-UV correspondence

- dilatation: $x^\mu = (t, \vec{x}) \to K x^\mu$

$\mathcal{N} = 4$ SYM

$\beta = 0$

scale invariant

string side

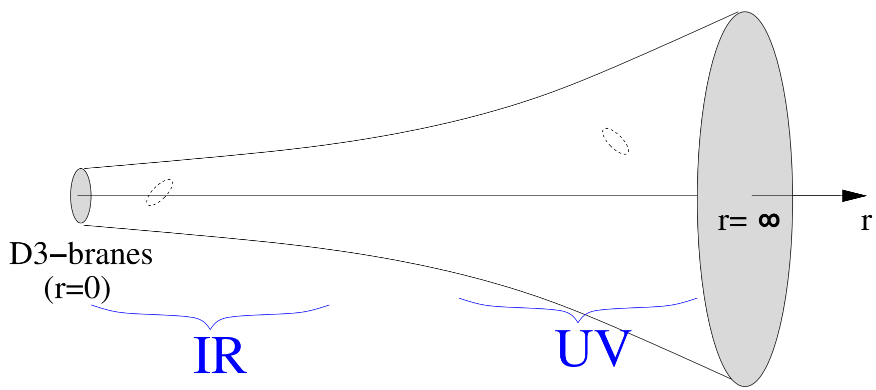
$$ds^2_{AdS} = \frac{r^2}{R^2}(d\vec{x}^2 - dt^2) + \frac{R^2}{r^2}dr^2$$

invariant under

$x^\mu \to K x^\mu$ *and* $r \to r/K$

IR $\leftrightarrow$ large x^μ $\leftrightarrow$ small r

UV $\leftrightarrow$ small x^μ $\leftrightarrow$ large r



in Minkowski space, typical energy scale

$$Q \sim \frac{1}{|x^\mu|} \propto r$$

AdS/CFT at finite T

- $\exists$ another solution: *AdS - Black Hole* metric

$$ds^2_{AdS-BH} = \frac{r^2}{R^2}(d\vec{x}^{\,2} - f\,dt^2) + \frac{R^2}{r^2 f} dr^2 \quad ; \quad f = 1 - \frac{r_0^4}{r^4}$$

$\sim$ black hole singularity at the horizon $r = r_0 = \pi R^2 T_H$

- IR-UV correspondence:

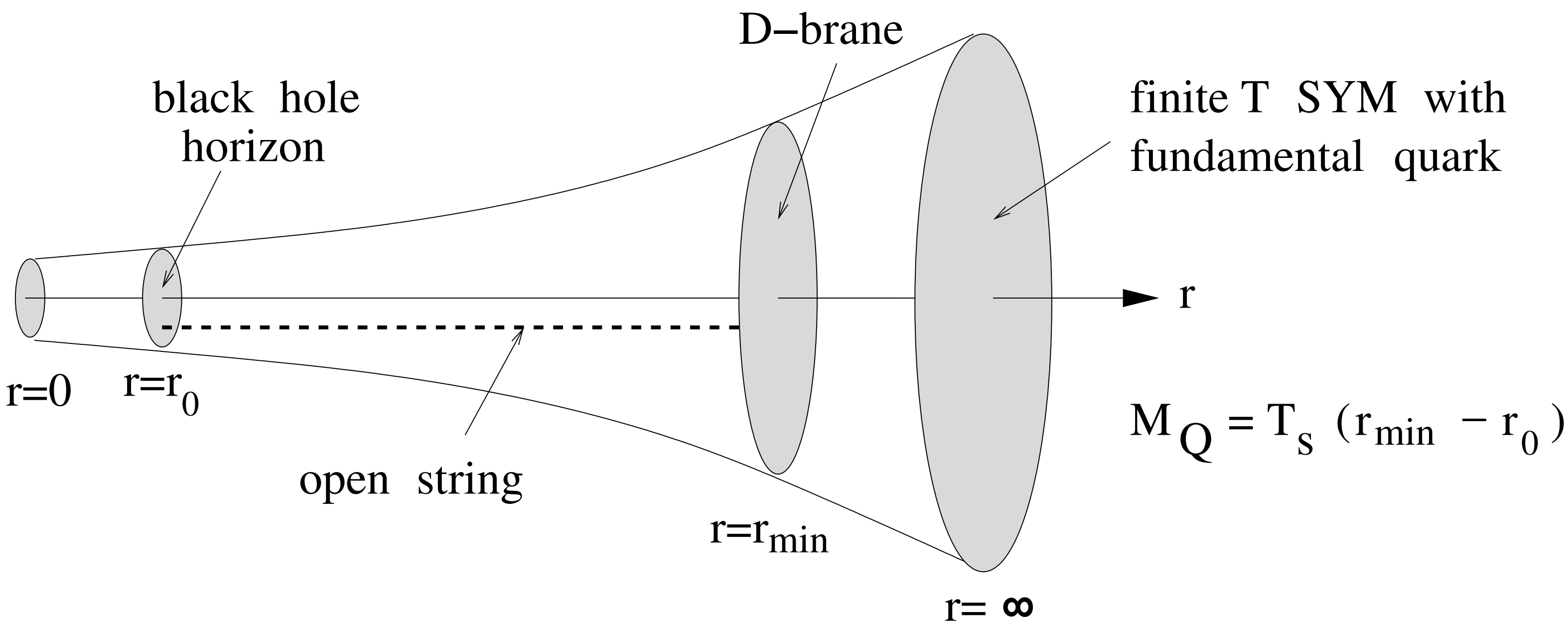
processes at $r \geq r_0 \leftrightarrow$ energy scale $Q \geq \frac{r_0}{R^2} \sim T_H$

AdS-BH metric $\leftrightarrow$ introduce temperature $T = T_H$ in $\mathcal{N} = 4$ SYM

Heavy 'quark' ΔE in SYM plasma

- add quark flavour to the picture (Karch & Katz, 2002)

add fundamental quark in boundary theory $\longleftrightarrow$ add D-brane down to $r = r_{\min}$ in AdS space



heavy quark moving in $\mathcal{N} = 4\ SU(N_c)$ SYM plasma $\longleftrightarrow$ open string endpoint moving on D-brane

The trailing string picture (Herzog et al, 2006)

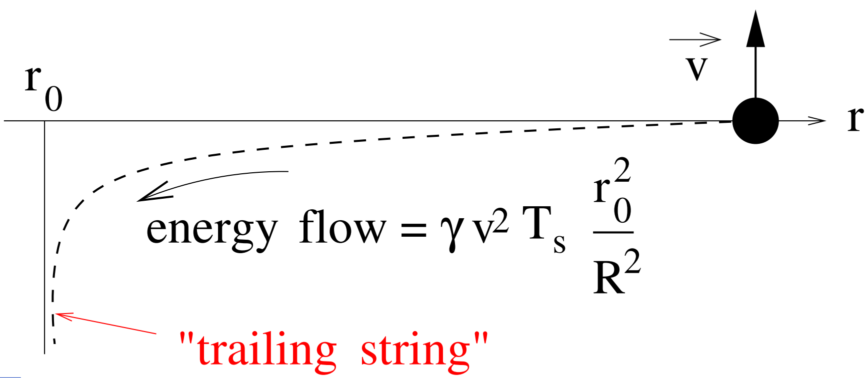
$\rightarrow$ *study classical dynamics of open string in AdS-BH*

Nambu-Goto action

$$S_{\rm NG} = -T_s \int d\sigma d\tau \sqrt{-\det g_{ab}(X^\mu(\sigma,\tau))}$$

- drag quark with velocity v along x-axis
- look for string profile $x(r,t) = x(r) + vt$ minimizing $S_{\rm NG}$

$$\Rightarrow x(r) = \frac{1}{2}\, v\, \frac{R^2}{r_0}\left[\frac{\pi}{2} - \tan^{-1}\left(\frac{r}{r_0}\right) - \coth^{-1}\left(\frac{r}{r_0}\right)\right]$$



$$T_s = \frac{1}{2\pi\ell_s^2} \quad ; \quad r_0 = \pi R^2 T$$

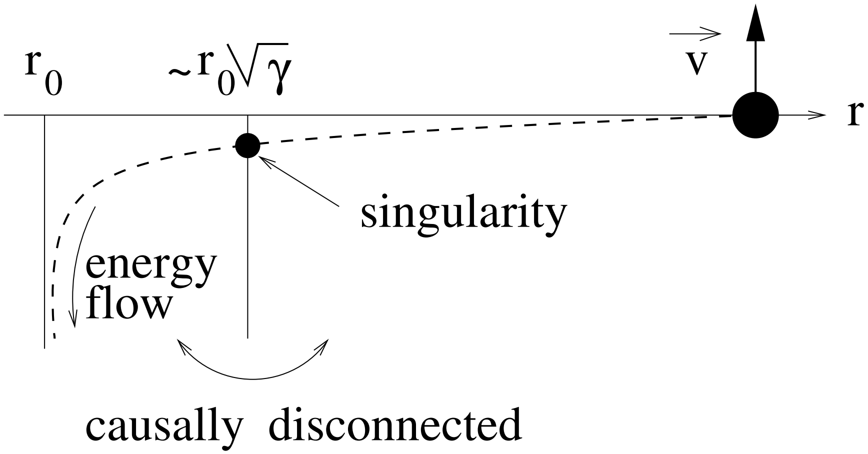
$$\Rightarrow \frac{dE}{dt} = \frac{\pi}{2}\,\gamma v^2 \sqrt{\lambda}\, T^2$$

$$(\lambda \gg 1)$$

A physical interpretation

(Marquet, 2008)
(Giecold, Iancu, Mueller, 2009)

physical process responsible for $\frac{dE}{dx}$ in the SYM plasma?



UV/IR correspondence

$r \leftrightarrow Q = \frac{r}{R^2}$ on boundary

energy loss from

$r \lesssim \sqrt{\gamma}\, r_0 \leftrightarrow Q \lesssim \sqrt{\gamma}\, T$

$\longrightarrow$ suggests energy loss arises from radiation of soft components $Q \lesssim \sqrt{\gamma}\, T$ of heavy quark proper field

purely radiative loss, inducing quark p_T-broadening

Summary

- RHIC data in intermediate region $\alpha_s \sim \mathcal{O}(1)$
- Two theoretical paths to A-A collisions and QGP
  - perturbative QCD ($\alpha_s \ll 1$)
    - only fully predictive approach known
    - not ruled out by heavy-ion data
  - AdS/CFT correspondence ($\lambda \gg 1$)
    - not yet predictive for QCD
    - rich and promising