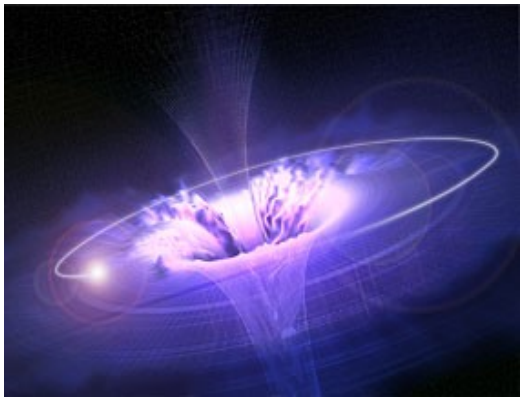
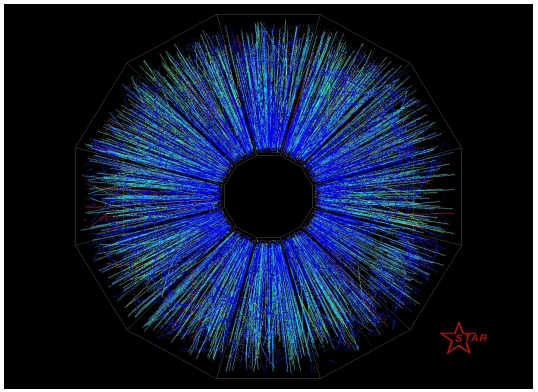
COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

Can  Correlate Soft and Hard

Phenomena at  ??????

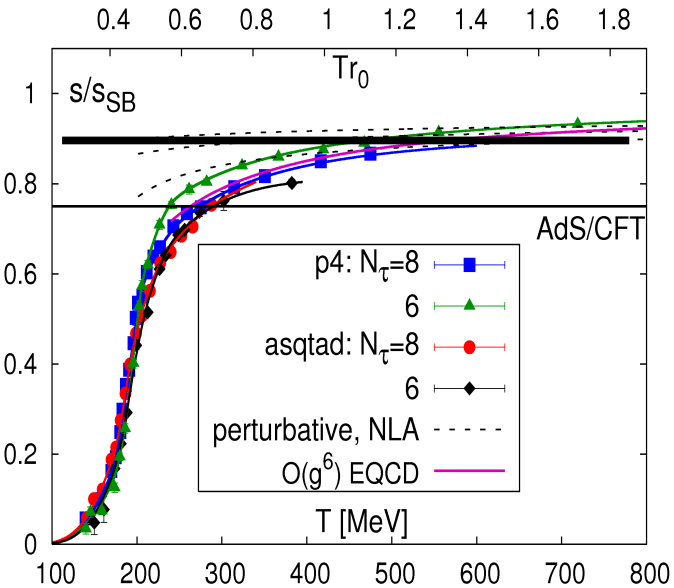
Jorge Noronha

Based on JN, M. Gyulassy, G. Torrieri, to appear soon

RHIC-AGS Users' Meeting 2009

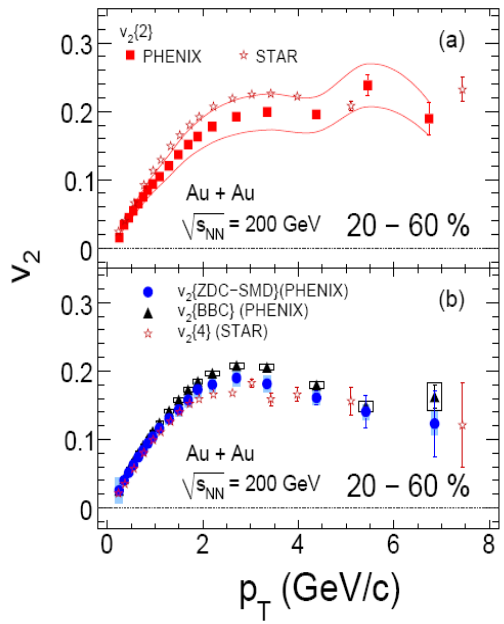
AdS/CFT

Thermodynamics



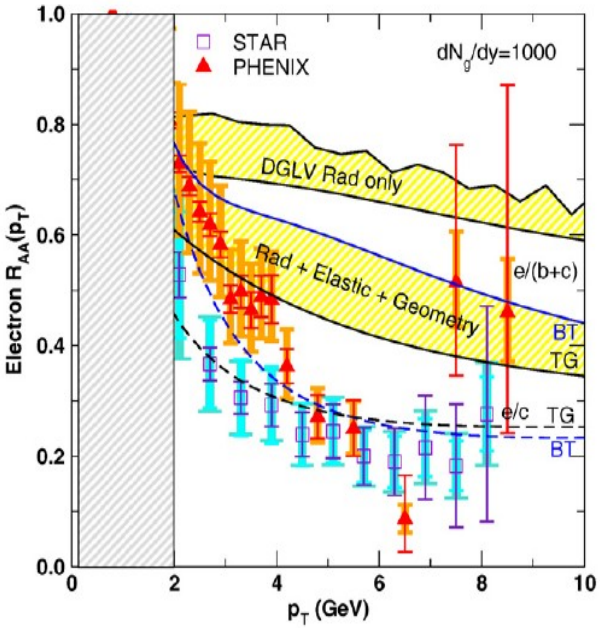
From P. Petreczky, QM09

Soft



From PHENIX, 2009

Hard



From WHDG, 2007

Outline

I A Glimpse into AdS/CFT

II How Perfect can a Fluid be ?

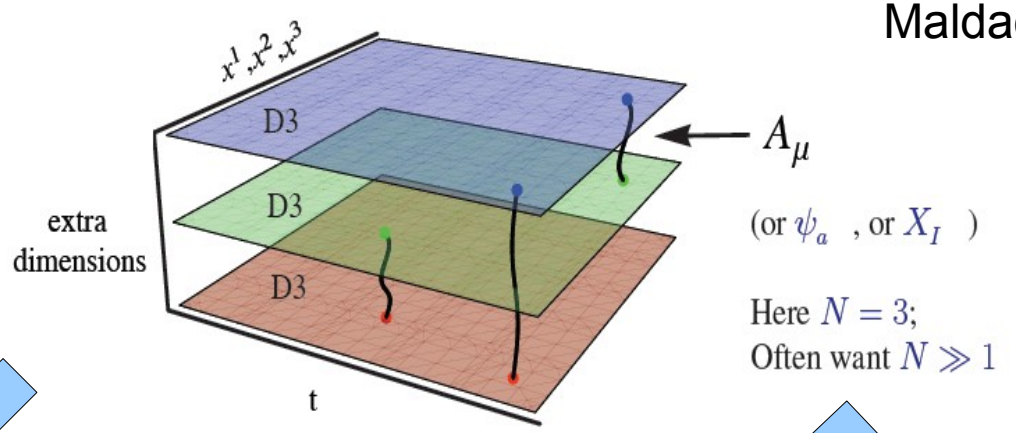
III Connecting Hard and Soft Phenomena @ RHIC

Summary

I A Glimpse into AdS/CFT

Figure from S. Gubser, QM09

Maldacena, 1998



LOW ENERGY

LOW ENERGY

4d CFT

$$\int dx^4\, Tr\left[F^2 + \ldots\right]$$

$$N_c,\ \lambda \gg 1$$

DUAL TO

5d Theory of gravity in AdS

$$\frac{1}{16\pi G_5}\int dx^5 \sqrt{-G}\,(R + \Lambda + \ldots)$$

$$1/g_s,\ L^2/\alpha' \gg 1$$

How does one compute the entropy density?

Hawking, Page (1983)

$$Z = e^{-I} = e^{-F/T}$$

Free energy

$$F(T)$$

Entropy

$$s = -\frac{\partial F}{\partial T}$$

For the most simple cases ...

Bekenstein-Hawking formula: $$s_{BH} = \frac{A}{4G_5}$$

A = horizon area

For $\mathcal{N} = 4$ SYM

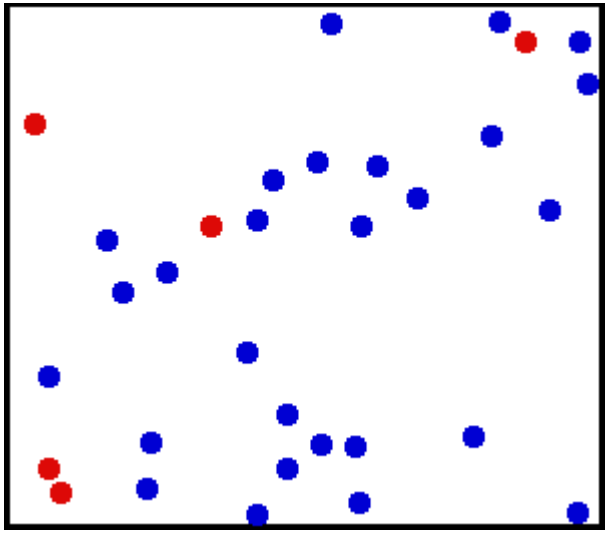
$$s_{BH} = \frac{\pi}{2} N_c^2 T^3 = \frac{3}{4} s_{SB}$$

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

II How Perfect can a Fluid be?

The answer depends on what the relevant degrees of freedom are like ...

Weakly-interacting quasiparticles



$\epsilon\,,\ p,\ T$

According to kinetic theory

$$\eta \sim l\,\rho\,\langle p\rangle \qquad l \sim 1/\sigma \gg 1$$

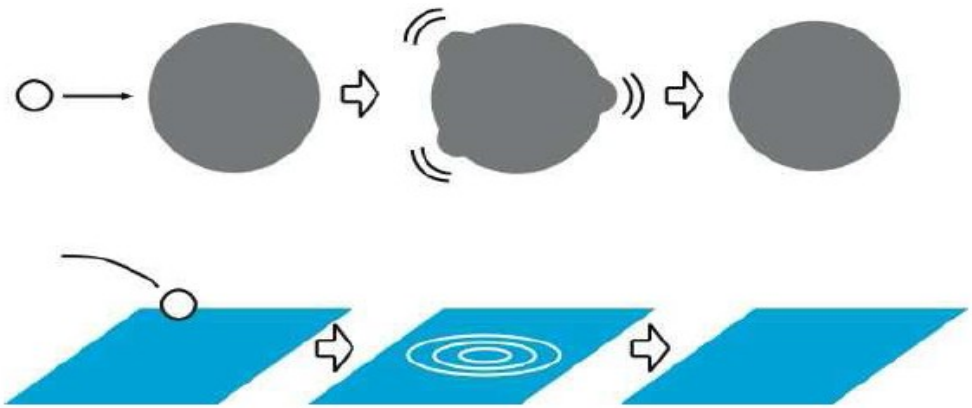
Using the uncertainty principle

$$\frac{\eta}{s} \gtrsim \frac{1}{12}$$

Danielewicz, Gyulassy, 1985

What happens at strong coupling?

The AdS black brane geometry fluctuates like a nearly perfect fluid !!!!



$$\frac{\eta}{s} \sim \frac{1}{4\pi}$$

Figure from Natsuume, 2008

Universal lower bound on viscosity for all substances in nature?

Kovtun, Son, Starinets, 2005.

$$\frac{\eta}{s} \geq \frac{1}{4\pi}$$

Is this universal at least in string theory? In supergravity, yes! However, deviations from this limit can lead to extra terms that can violate the bound. For instance,

$$S = \frac{1}{16\pi G_5} \int d^5x \sqrt{-G} \left[\mathcal{R} + \frac{12}{L^2} + \frac{\lambda_{GB}}{2} L^2 \left(\mathcal{R}^2 - 4\mathcal{R}_{\mu\nu}\mathcal{R}^{\mu\nu} + \mathcal{R}_{\mu\nu\lambda\rho}\mathcal{R}^{\mu\nu\lambda\rho} \right) \right]$$

Brigante et al., 2008
Petrov and Kats, 2007
Buchel, Myers, Sinha, 2009

$$\lambda_{GB} \sim 1/N_c$$

$$\frac{\eta}{s} = \frac{1}{4\pi} \left(1 - 4\lambda_{GB} \right)$$

Small violation!!

III Connecting Hard and Soft Phenomena @ RHIC

JN, M. Gyulassy, G. Torrieri, (2009), to appear

The idea is to use the $\mathcal{R}^2 \to \lambda_{GB} \sim 1/N_c$ **and** $\mathcal{R}^4 \to 1/\lambda^{3/2}$ **corrections**

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

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

Heavy quark energy loss

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

To compute

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

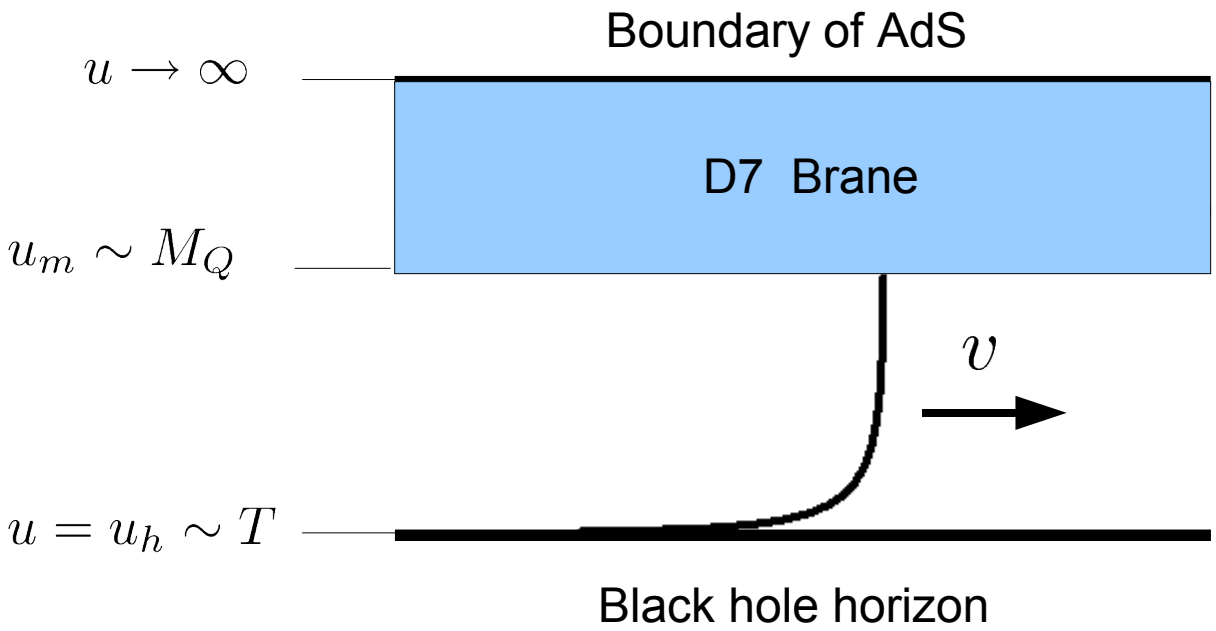
with

$$s/s_{SB} \sim 0.85$$

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

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

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

Heavy Quark Stopping Time

$$\frac{dp}{dt} = -\mu_Q\, p = -\frac{p}{\tau_Q}$$

Equal density condition

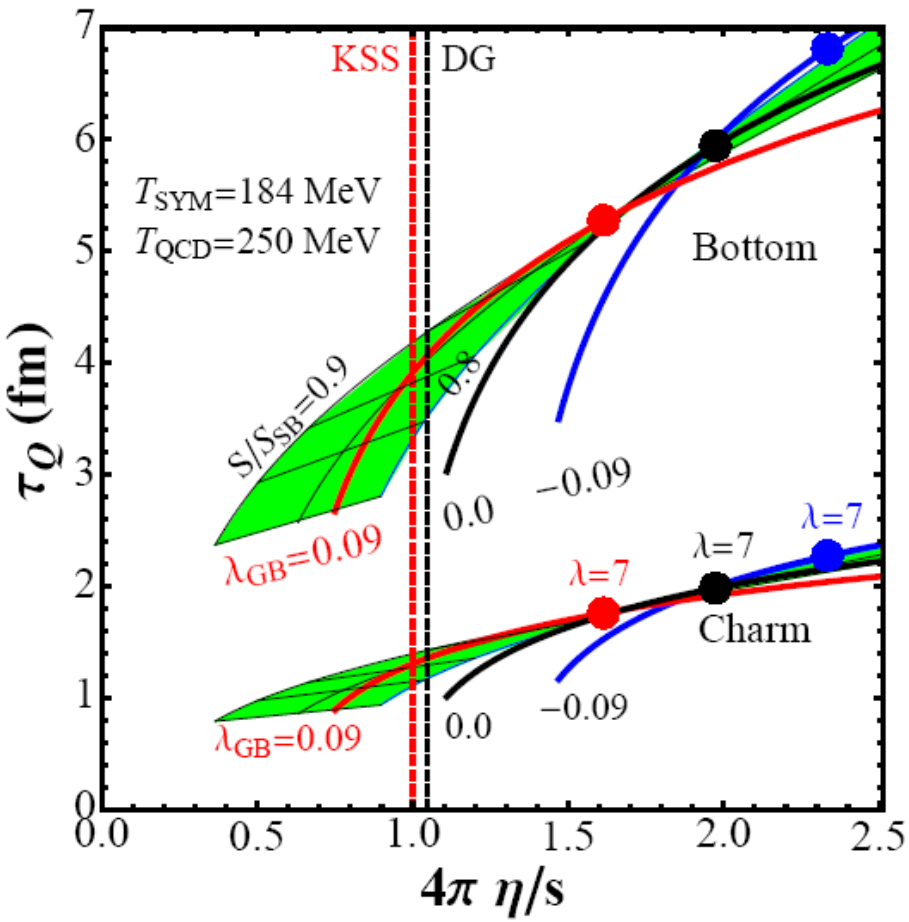
$$T_{SYM} = 0.736\, T_{QCD}$$

Causality constraint

$$\lambda_{GB} < 0.09$$

LQCD (green) + causality (red)

Imply that $\lambda_{GB} > 0$



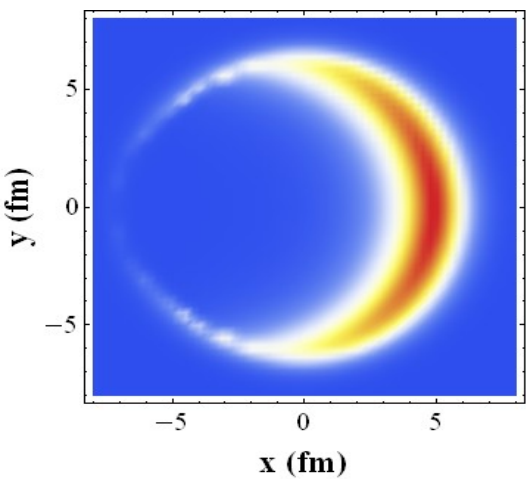
Computing the nuclear modification factor of non-photonic electrons R^e_{AA}

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

CGC ~ Glauber → Adil et al, 2006

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

Charm surface bias



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

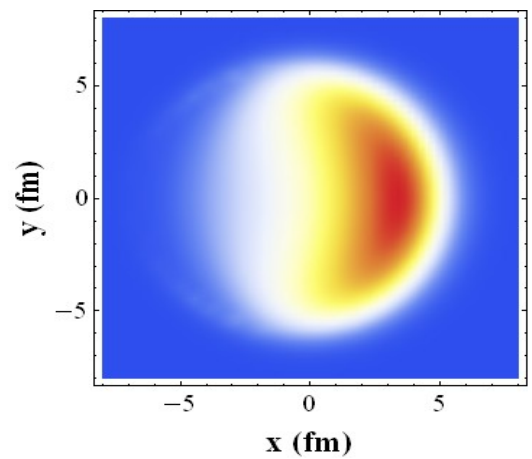
$$\phi = 0$$

$$\lambda = 7$$

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

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

Bottom surface bias

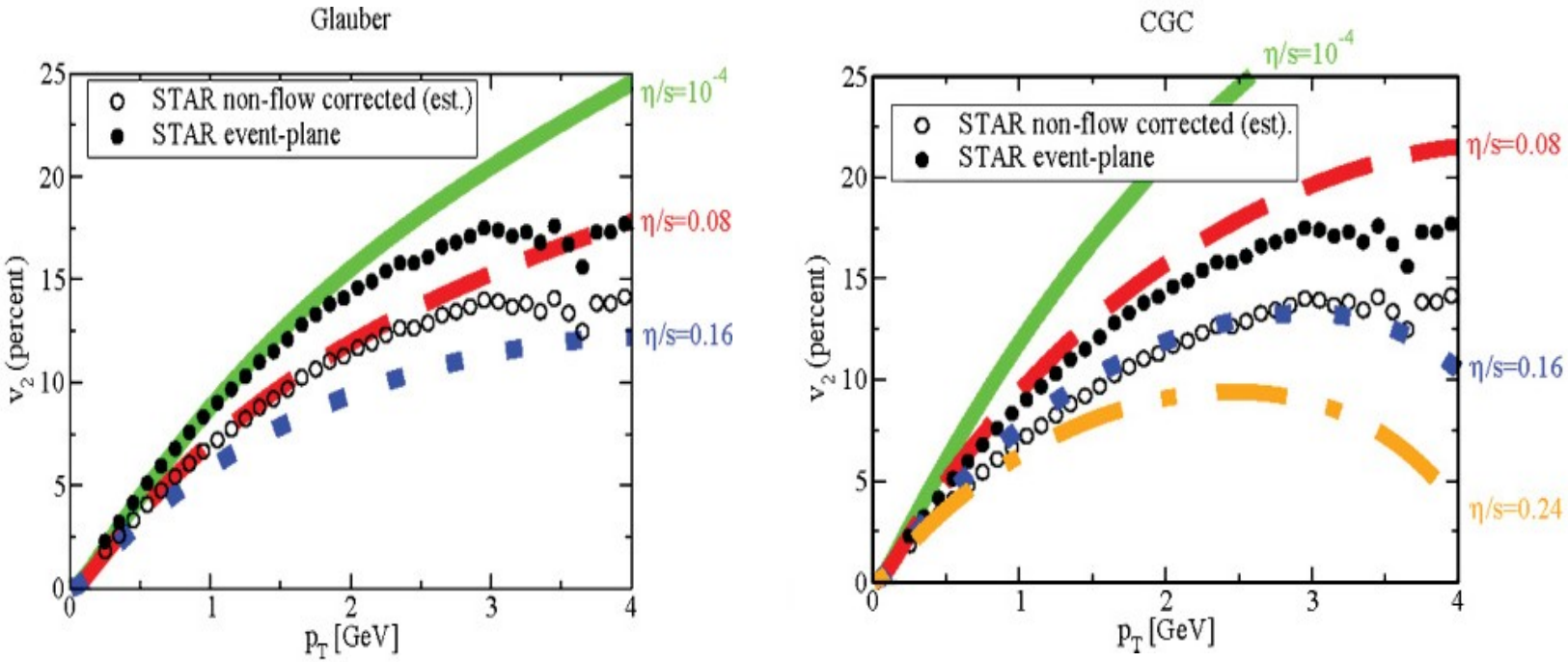


We use results for v2 of charged particles from viscous hydrodynamic simulations to obtain (low pT)

$$v_2(p_T, \eta/s) = v_2(p_T, \lambda, \lambda_{GB})$$

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

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



Summary: 5 fold AA observable correlations with 2 (AdS+GB)/CFT couplings

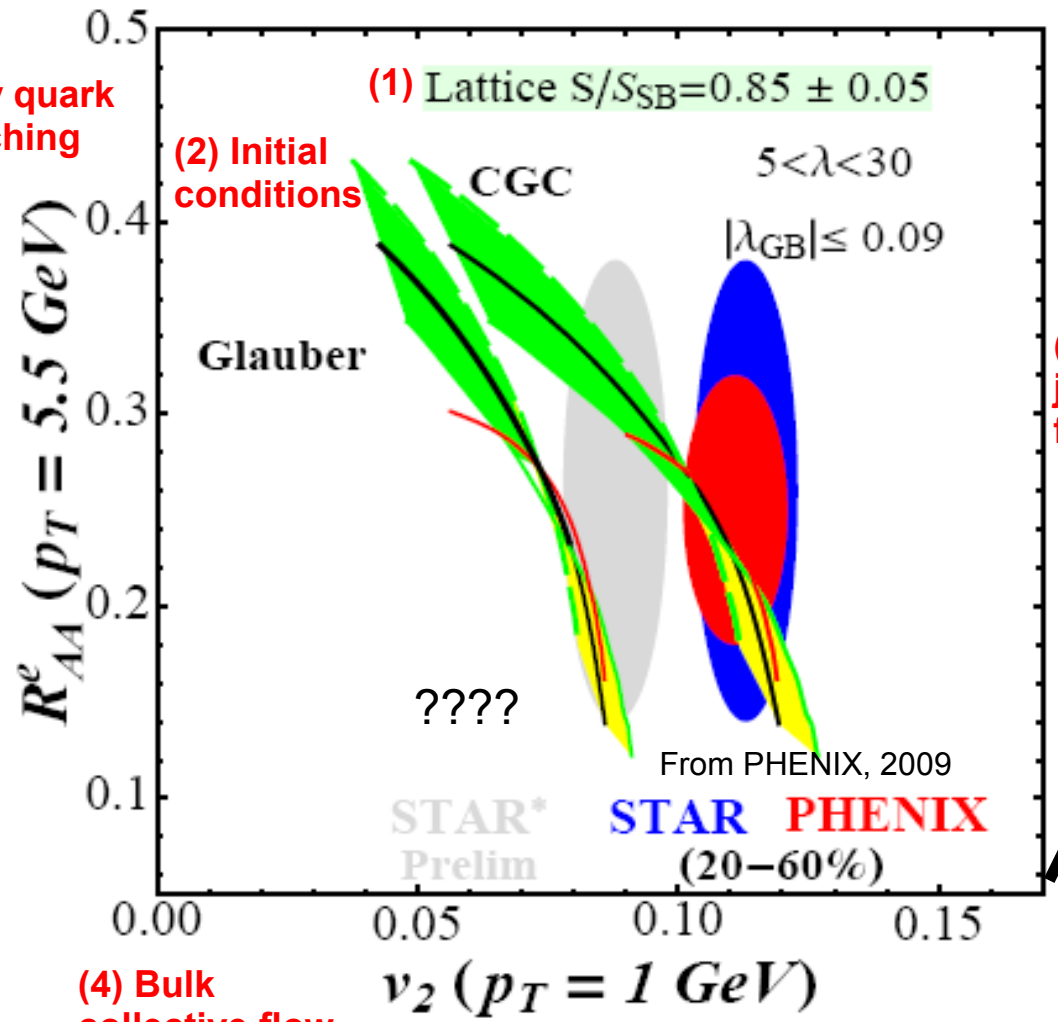
$$p_T^e \sim 0.7 p_T^Q$$

e = 0.4 c + 0.6 b

0-10%

$$dN/dy = 1000$$

$$\tau_0 = 1\, fm/c$$



(5) Heavy quark jet induced collective flow

Future

From Luzum, Romatschke, 2008.

Back up Slides