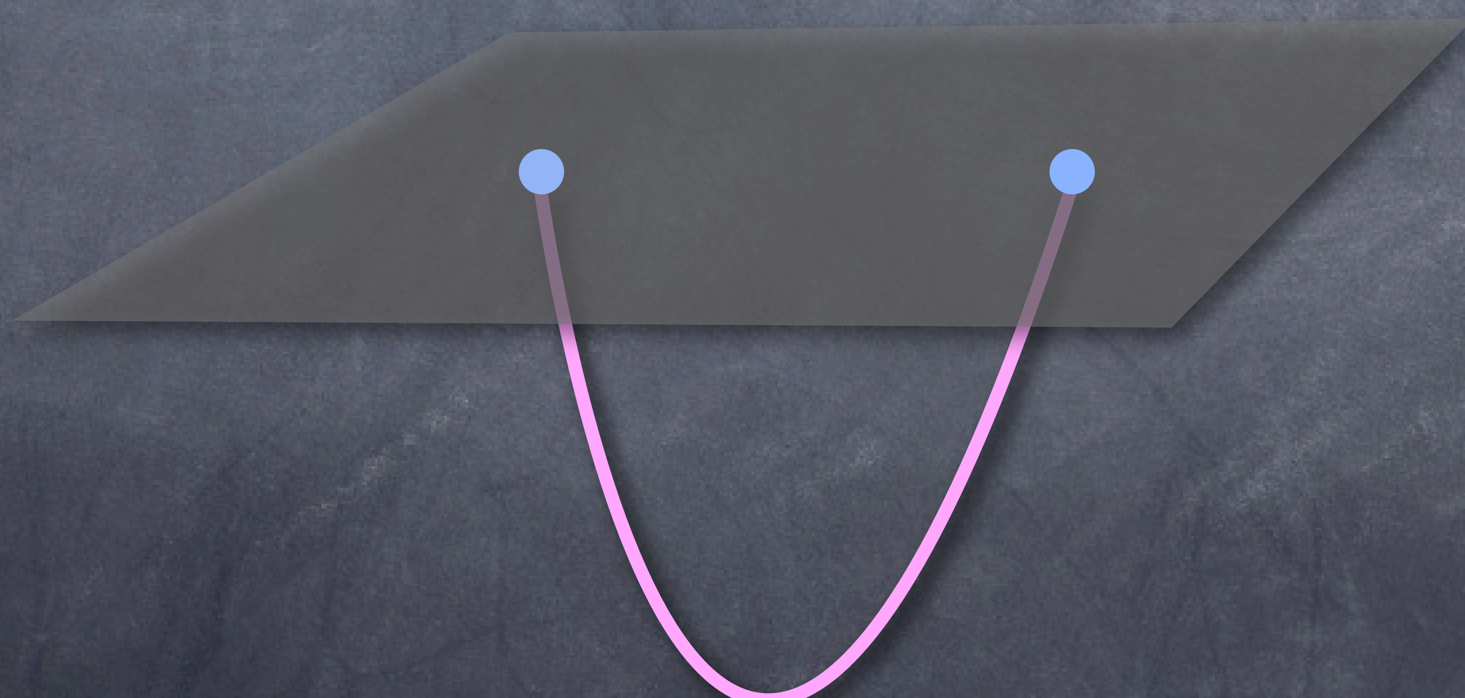
AdS/CFT/RHIC

(or)

What the Anti-de Sitter/Conformal Field Theory correspondence can tell us about Relativistic Heavy Ion Collisions



Introductions...

AdS/CFT/RHIC is exciting!

Potential string theory connection with experiment, produced matter may be 'strong' enough for description via gauge-gravity duals.

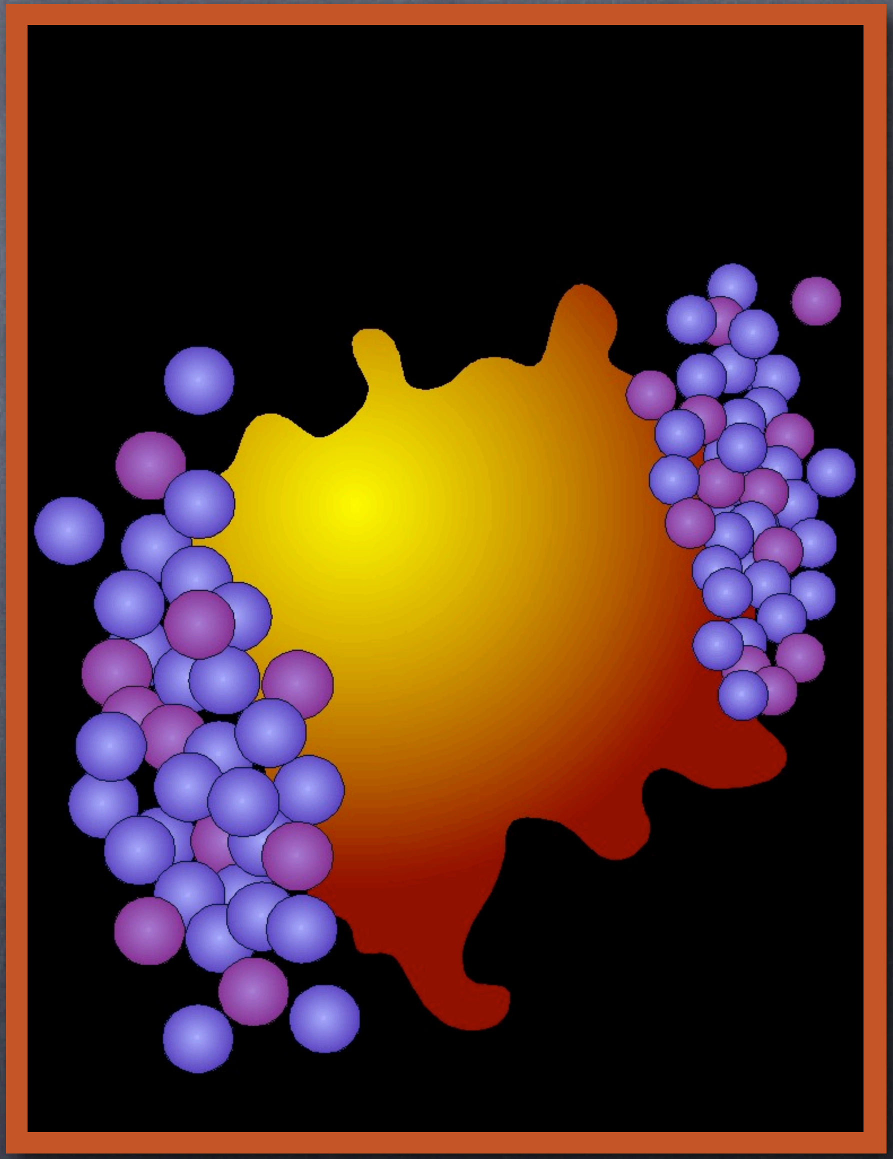
What's been done?

An unusual correspondence

A Long Island Laboratory

Exploiting the dual

Where can we go?



Viscosity Primer

What would we expect from a study of viscosity in strongly interacting systems?

Viscosity measures the rate of momentum transport:

$$T_{zx} = -\eta\,\partial_z u_x$$

In standard kinetic theory, easy to show that

$$\boxed{\eta \sim n\bar{p}\lambda \sim \frac{\bar{p}}{\sigma} \sim \frac{\sqrt{T}}{\sigma}}$$

in weakly coupled thermal ϕ^4 we find $\sigma \sim g^2/T^2$

Somewhat counterintuitive: strongly coupled systems generally characterized by lower viscosity...

Viscosity Primer

What would we expect from a study of viscosity in strongly interacting systems?

Quantum mechanics anticipates a lower bound on η/s

$$\eta \sim \frac{1}{3} n \bar{p} \lambda = \epsilon \tau = n \frac{E}{N} \tau$$

and for relativistic systems,

$$s \sim 4n \qquad \text{so} \qquad \frac{\eta}{s} \approx \frac{1}{12} \cdot \frac{E}{N} \tau$$

from the uncertainty principle, product of average energy and mean free time cannot be less than 1:

$$\boxed{\frac{\eta}{s} \geq \frac{1}{12}}$$

Bounded From Below

Son et. al study this bound in strongly interacting systems

Motivation:

The AdS/CFT duality provides a map between interesting parameters on either side of the '/'...

AdS	CFT
$\frac{R^4}{l_s^4}$	$g^2 N_c$

In the limit $R \gg l_s$, string theory approaches classical supergravity.

So, AdS/CFT is a practical way to probe strongly coupled gauge theories

Bounded From Below

Son et. al study this bound in strongly interacting systems

In field theories (and quantum mechanics), well known techniques for computing dissipations, like Kubo's formula.

$$\eta = -\lim_{\omega \to 0} \frac{1}{\omega} \Im G_R(\omega, 0)$$

what can gravity tell us about the right hand side?

Quite a bit!

The energy momentum tensor couples to the graviton field. From the correspondence...

$$\sigma_a = -\frac{16\pi G}{\omega} \Im G_R(\omega)$$

where

$$\Im G_R(\omega) = -\frac{1}{2} \int dt\, dx\, e^{i\omega t} \langle [T_{xy}(t,x), T_{xy}(0,0)] \rangle$$

Bounded From Below

Son et. al study this bound in strongly interacting systems

Rearranging some terms leads to central identity:

$$\boxed{\eta = \frac{\sigma_a(0)}{16\pi G}}$$

problem reduced to finding the absorption cross section in classical supergravity, reduced again to finding absorption cross section for massless scalar.

From Das, Gibbons and Mathur, low frequency cross section is just

$$\sigma_a = A\,!$$

Bekenstein-Hawking says

$$s = \frac{A}{4G}$$

Bounded From Below

Son et. al study this bound in strongly interacting systems

Hence, one finds

$$\frac{\eta}{s} = \frac{\sigma_a(0)}{16\pi G} = \frac{4GA}{16\pi GA} = \frac{1}{4\pi}$$

or, with dimensions, (drum-roll)...

$$\boxed{\frac{\eta}{s} = \frac{\hbar}{4\pi k_B}}$$

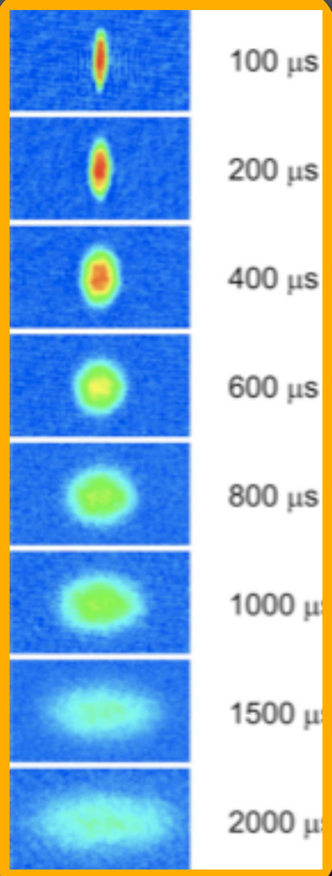
(about 400 times smaller than water)

This result holds certainly for N=4 SYM--but more too! Conjectured to bound all finite temperature relativistic field theories with vanishing chemical potential from below. Looks promising for N=4 SYM where

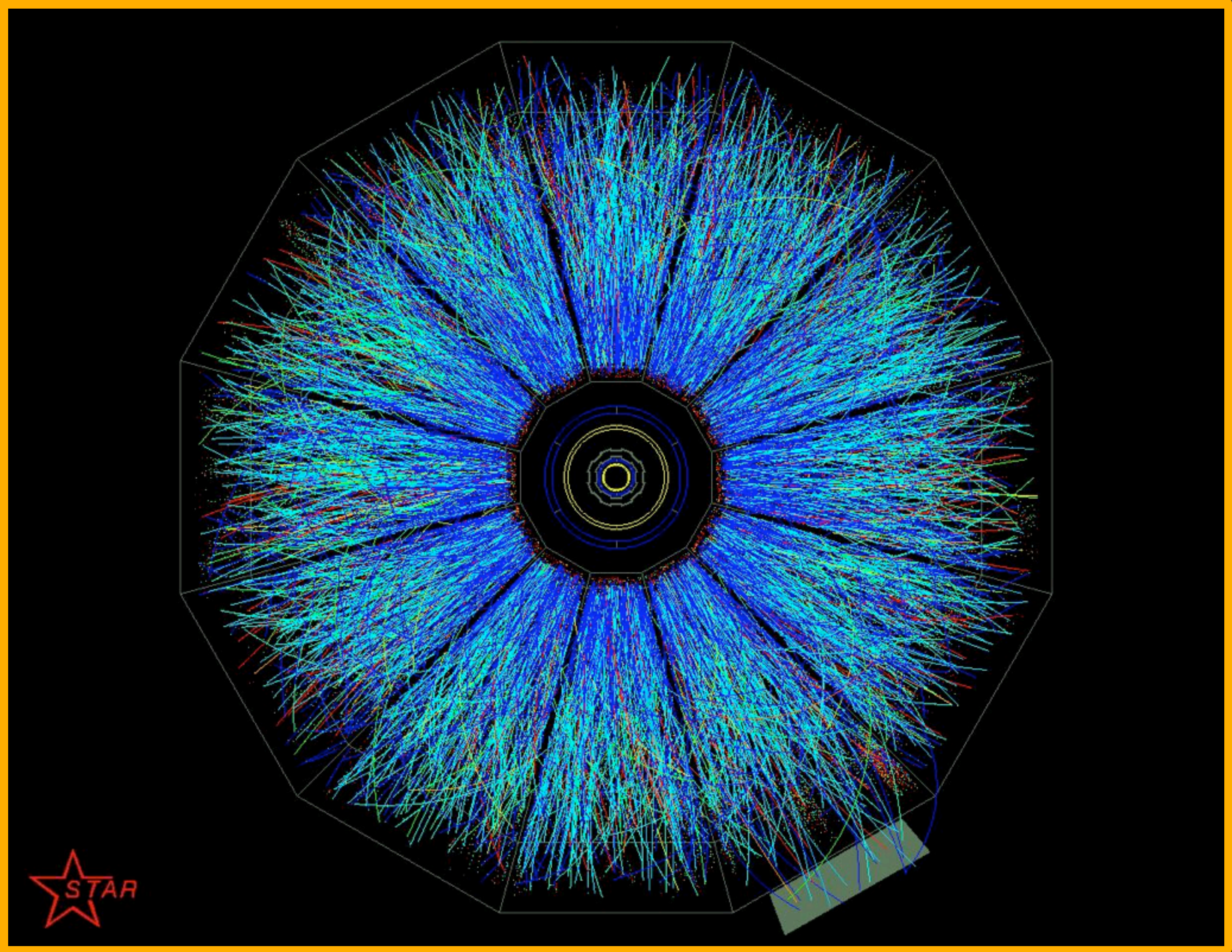
$$\frac{\eta}{s} = \frac{\hbar}{4\pi k_B}\left(1 + \frac{135\,\zeta(3)}{8(2g^2 N_c)^{3/2}} + \dots\right)$$

In practice, make perfect

"The bound is most useful for strongly interacting systems where reliable theoretical estimates of viscosity are not available"



VS



In practice, make perfect

Backyard bangs at the Relativistic Heavy Ion Collider

RHIC Basics:

The Experiment

Collide variety of species, produce extremely hot (10^12 eV!) dense matter

Huge on all scales...

Early theoretical work

Focus on relativistic gas of light quarks

weakly interacting picture explored with pQCD--not that great

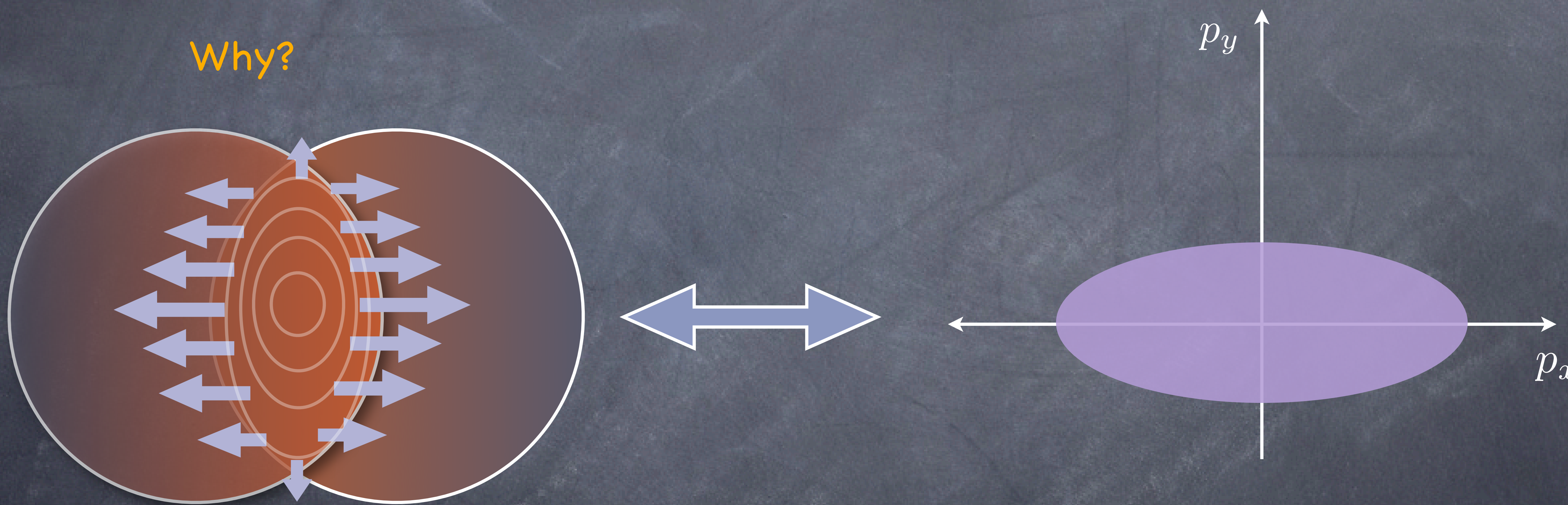
Many properties realized via hydrodynamic calculations!

In practice, make perfect

Relativistic heavy ion collisions as a QCD playground

In 2005, Brookhaven National Labs issues press release, suggest produced matter is "most nearly perfect fluid ever observed"

Why?



Can quantify angular anisotropy of particle distributions by Fourier expansion coefficients

$$f(\varphi) \sim 1 + 2v_2 \cos 2\varphi$$

In practice, make perfect

Relativistic heavy ion collisions as a QCD playground

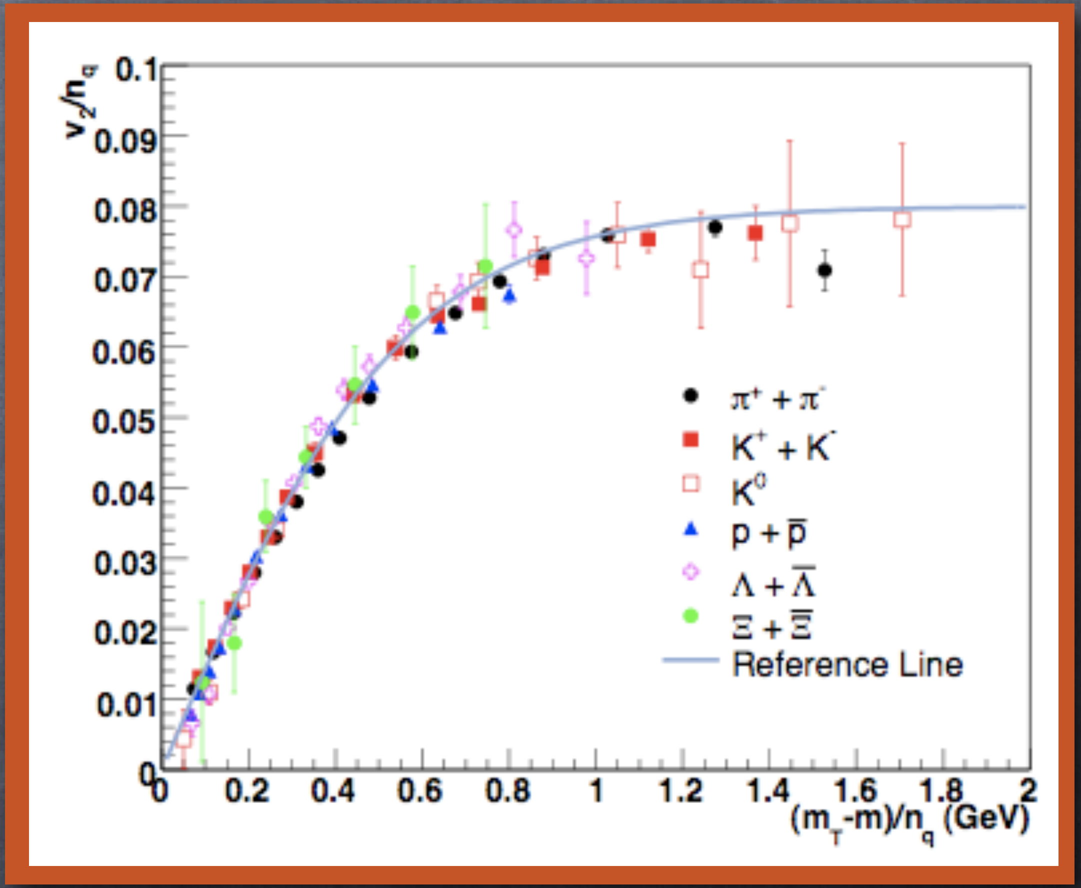
In general, v2 depends on centrality, transverse momentum (pT), etc.

Studies of these dependencies have led to estimates of the viscosity to entropy density ratio in the QGP:

Most such estimate uses observed scaling behaviors, like right, find

$$\frac{\eta}{s} \sim 0.1$$

not too far from 0.08...

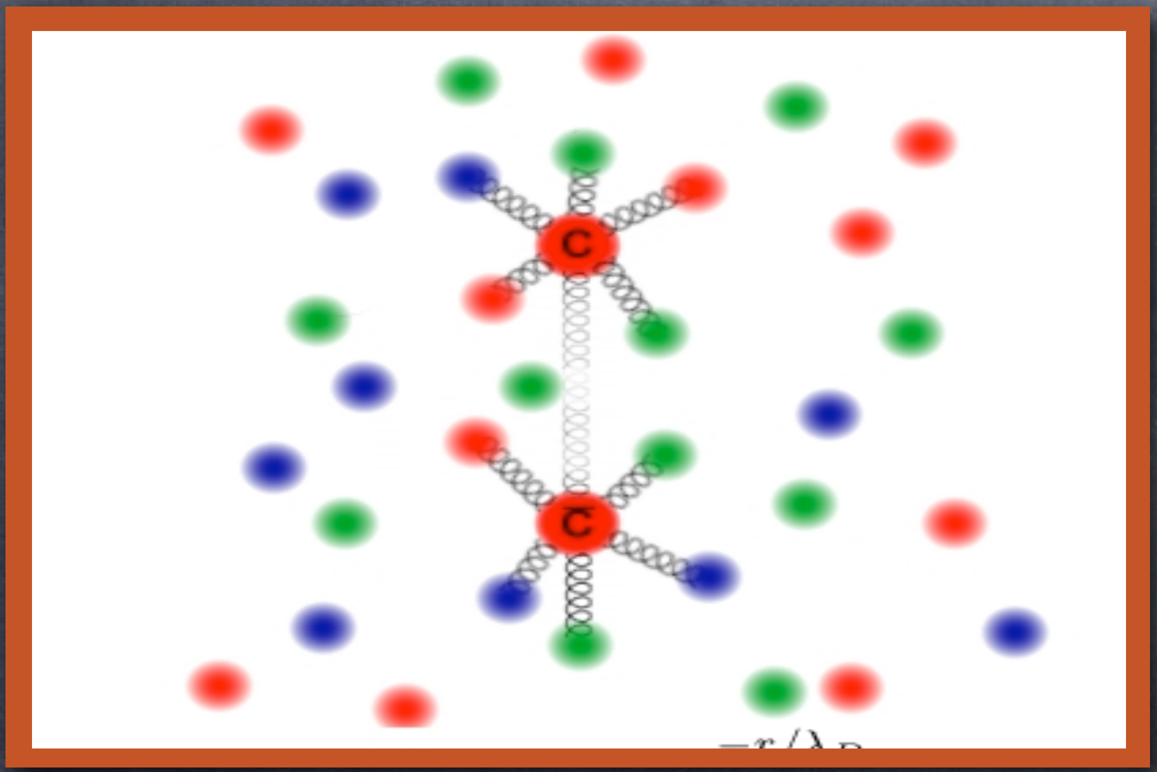


In practice, make perfect

Relativistic heavy ion collisions as a QCD playground

What else is experimentally accessible?

Quarkonia Suppression and Quenched Jets



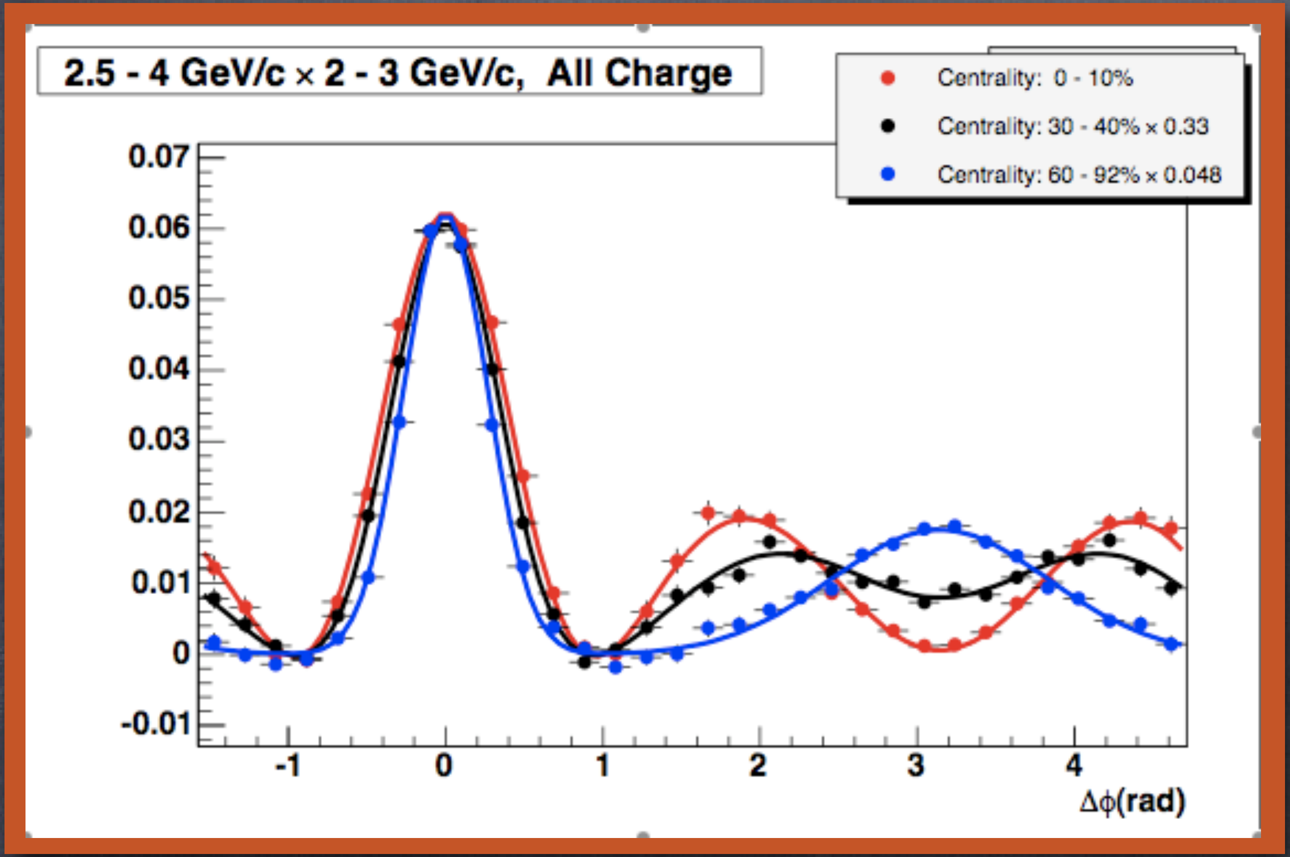
Quark anti-quark states (J/Psi) produced in initial hard scatterings may melt in the QGP. Potential to learn about deconfinement?

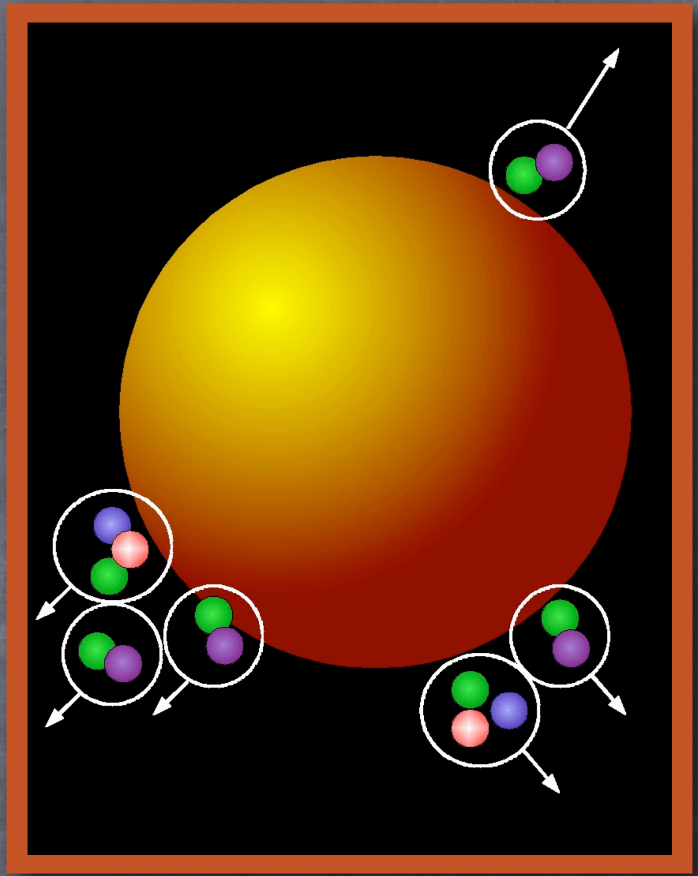
Jets as probes: auto-generated on relevant time scale, interact with produced medium in characteristic ways?

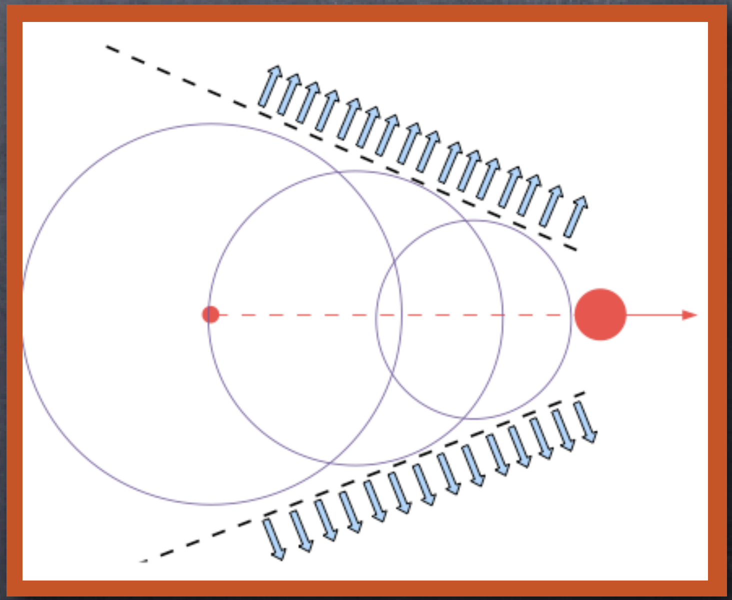
In practice, make perfect

Relativistic heavy ion collisions as a QCD playground

What else is experimentally accessible?







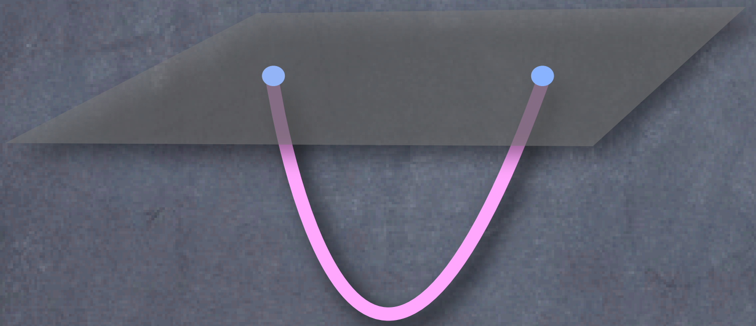
partons traversing the fireball deposit energy in the form of sound waves--a sort of sonic boom

AdS/CFT Returns!

How can we understand such phenomena in guage-gravity duals?

Quarkonia

Early on, Maldecena computes quark anti-quark potential:



$$U = -\frac{4\pi^2\sqrt{2g_{ym}^2 N}}{\gamma(\frac{1}{4})^4 L}$$

Recently, Rajagopal, others compute screening lengths for 'hadrons' moving through strongly coupled N=4 SYM plasmas. Find free quarks beyond

$$l_{max} \sim \frac{(1-v^2)^{1/4}}{T} \sim \left(\frac{1-v^2}{\epsilon}\right)^{1/4}$$

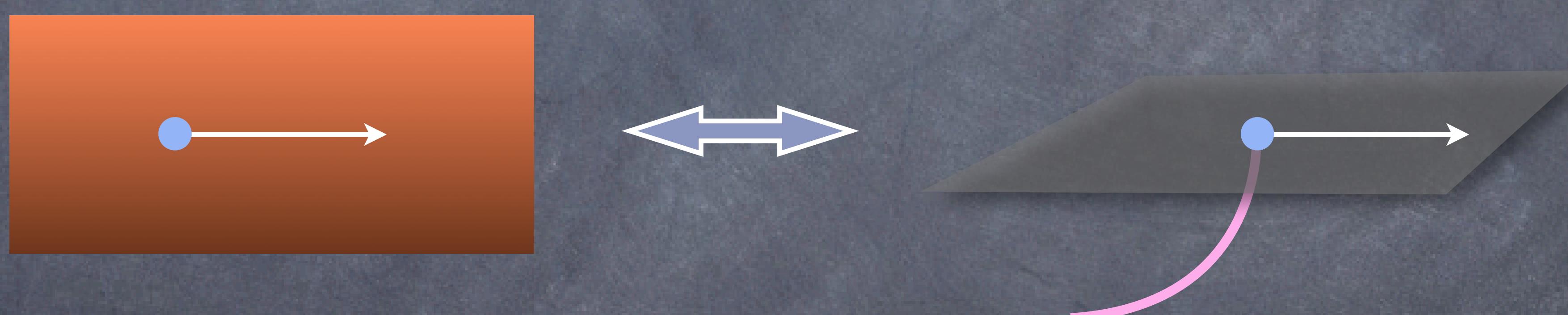
AdS/CFT Returns!

How can we understand such phenomena in gauge-gravity duals?

Jet Quenching

Gubser pioneered energy loss studies. Most works follow similar prescription:

1) Create an infinitely massive test quark in the N=4 plasma



2) Trailing string dangles from boundary into Ads5, exerts drag force on quark. Calculate dynamics from classical gravity.

3) Translate via AdS/CFT dictionary.

AdS/CFT Returns!

How can we understand such phenomena in gauge-gravity duals?

Jet Quenching

N=4 SYM corresponds to near horizon limit of near extremal D3-brane, so relevant metric is

$$ds^2 = \frac{r^2}{L^2}(-hdt^2 + d\vec{x}^2) + \frac{L^2}{r^2}\frac{dr^2}{h}$$

(AdS5-Schwarzschild)

where

$$h = 1 - \frac{r_0^4}{r^4}$$

Describe string here with Nambu-Goto action, work in static gauge, where

$$S = -\frac{1}{2\pi\alpha'}\int dt\, dr\sqrt{1 + \frac{hr^4}{L^4}(\partial_r x)^2 - \frac{(\partial_t x)^2}{h}}$$

AdS/CFT Returns!

How can we understand such phenomena in gauge-gravity duals?

Jet Quenching

Gubser suggests an ansatz,

$$x^1(t,r) = vt + \xi(r) + \text{transients}$$

inserts into Lagrangian,

$$\mathcal{L} = -\sqrt{1 - \frac{(\partial_t x)^2}{h} + \frac{hr^4}{L^4}(\partial_r x)^2} \to -\sqrt{1 - \frac{v^2}{h} + \frac{hr^4}{L^4}(\partial_r \xi)^2}$$

and computes equation of motion. From here compute canonical momentum,

$$\pi_\xi \equiv \frac{\partial \mathcal{L}}{\partial(\partial_r \xi)}$$

rearrange to find $\xi(r)$.

AdS/CFT Returns!

How can we understand such phenomena in gauge-gravity duals?

Jet Quenching

Quantity of interest is flow of momentum down the string. "Tedious" calculation shows

$$\frac{dp_1}{dt} = \sqrt{-g}P^r_{x_1} = -\frac{r_0^2}{2\pi\alpha' L^2}\frac{v}{\sqrt{1-v^2}}$$

from the dictionary,

$$L^4 \rightarrow g^2 N\alpha' \quad \text{and} \quad T \rightarrow \frac{r_0}{\pi L^2}$$

so

$$\boxed{\frac{dp_1}{dt} = -\frac{\pi\sqrt{g^2 N}}{2}T^2\frac{p_1}{m}}$$

AdS/CFT Returns!

How can we understand such phenomena in gauge-gravity duals?

Jet Quenching

Notice that this differential equation is easily solvable, yields a characteristic time for heavy quark momentum dissipation:

$$\frac{dp_1}{dt} = -\frac{\pi\sqrt{g^2 N}}{2} T^2 \frac{p_1}{m} \rightarrow \tau = \frac{2}{\pi\sqrt{g^2 N}} \frac{m}{T^2}$$

Is this measurable? Turns out that

$$\tau_c \approx 0.6\,\mathrm{fm/c} \cdot \epsilon_{\mathrm{YM}}$$

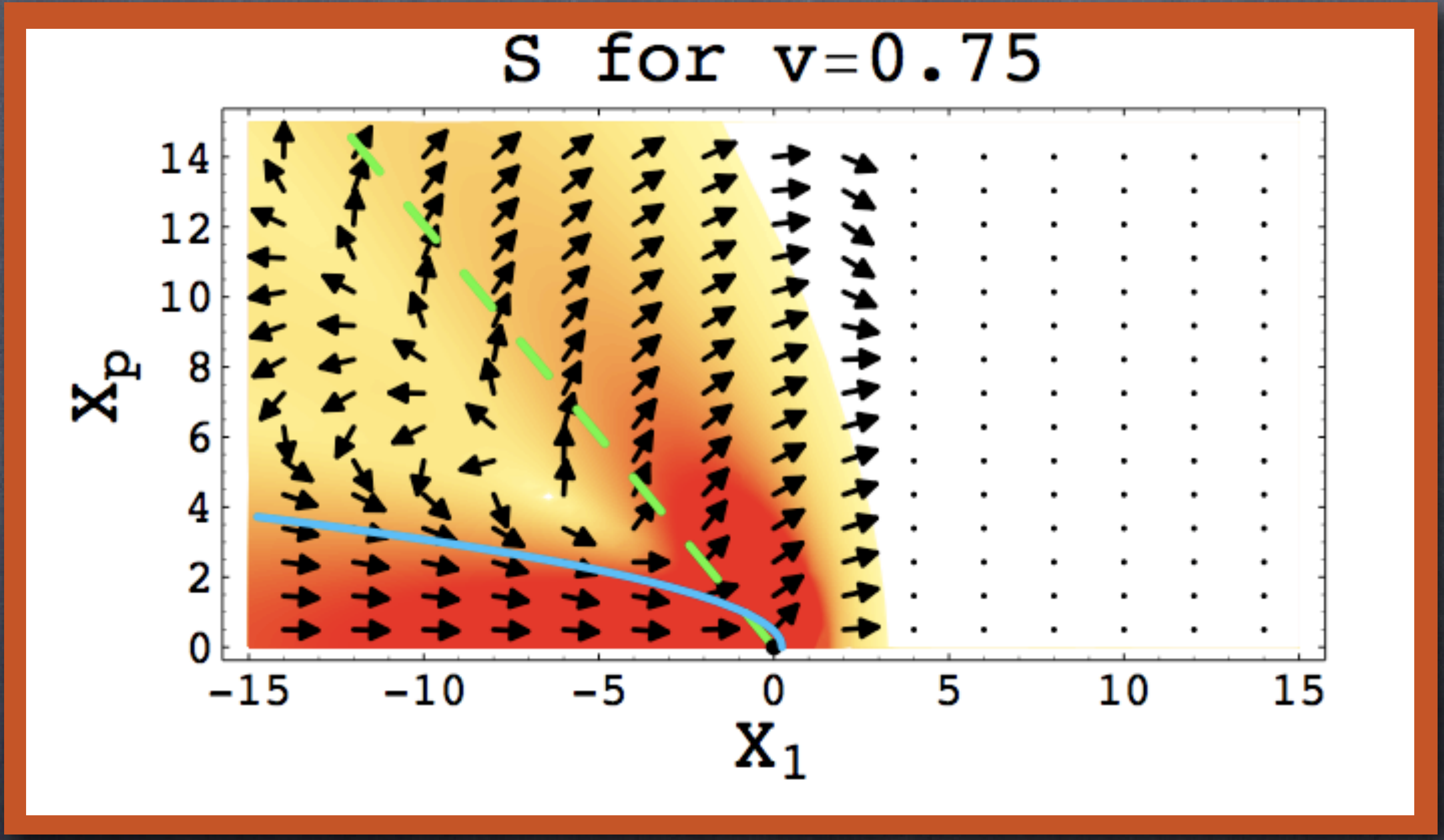
nominally encompassed by QGP time scales...

AdS/CFT Returns!

How can we understand such phenomena in gauge-gravity duals?

Jet Quenching

In a numerical tour de force, computes Poynting vector for heavy quark traversing N=4 plasma. Finds



These quarks deposit energy in Mach cones!

Conclusions...

AdS/CFT/RHIC is exciting!

- Potential string theory connection with experiment, produced matter may be 'strong' enough for description via gauge-gravity duals.

The Latest

- Most current calculations still address 'big three' (flow, quarkonia, jet quenching).
- Emphasis shifting to higher order corrections, light(er) mesons, even 'baryons'!
- More attempts towards parameters attainable at RHIC.

The Longview

- Can we learn anything about QGP degrees of freedom? What about quasi-particle states??
- QGP is phenomenologically very rich--until whistle blows, play ball!