Can AdS/CFT be useful for heavy-ion physics?

Pavel Kovtun

KITP, University of California, Santa Barbara

A review of many people's work

seminar at KITP, UCSB

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What is heavy-ion physics?

Heavy-ion collisions — study QCD at high energy density

Experiment: **RHIC** (Brookhaven, NY)

- Started in year 2000
- Collides *Au* nuclei
- CM energy $\sqrt{s}$=200 GeV per nucleon

Quest: find and study QGP [deconfined state of QCD] → field theory at finite temperature and density. Not obvious *a priori* that a thermal state will be produced.

Evidence for thermalization [lots of data and non-trivial calculations] :

Particle abundances and ratios — reproduced by statistical models

Elliptic flow — reproduced by hydrodynamic models

Jet quenching — indication of short mean free path

Optimistically, QGP is hidden in the collision

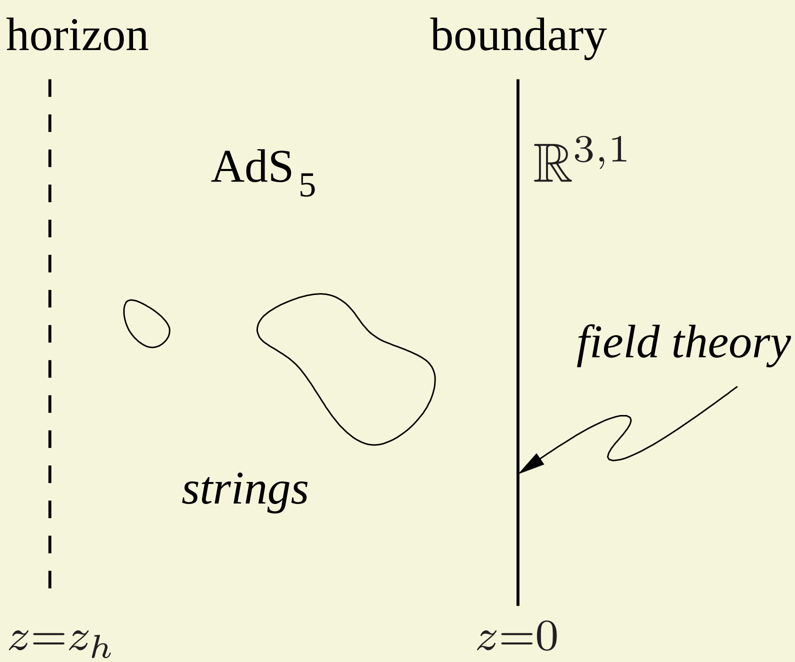
What is AdS/CFT

(J.Maldacena hep-th/9711200, review: hep-th/9905111)

large N_c, $d{=}4$, $\mathcal{N}{=}4$ SYM $=$ IIB strings on $AdS_5 \times S^5$

$$\lambda \leftrightarrow \left(\frac{R^2}{\alpha'}\right)^2 \quad \text{string corrections to SUGRA}$$

$$\frac{\lambda}{4\pi N_c} \leftrightarrow g_s \quad \text{string loops}$$



$$\langle e^{\int h(x) T(x)} \rangle_{\text{field}} = Z_{\text{string}}[g(x, z{\to}0) = h(x)]$$

$$T_{\mu\nu}(x) \leftrightarrow h_{\mu\nu}(x, z{\to}0)$$

$$J_\mu(x) \leftrightarrow A_\mu(x, z{\to}0)$$

$$\text{tr}F^2(x) \leftrightarrow \varphi(x, z{\to}0)$$

$$\vdots$$

$$\therefore \langle T_{\mu\nu} T_{\alpha\beta} \rangle \sim \frac{\delta^2 \ln Z_{\text{string}}[h]}{\delta h_{\mu\nu} \delta h_{\alpha\beta}} \sim \frac{\delta^2}{\delta h_{\mu\nu} \delta h_{\alpha\beta}} S_{\text{cl}}[h]$$

AdS/CFT is a **tool** to define/perform calculations in field theory

Applies to field theories beyond $\mathcal{N}{=}4$ SYM

RHIC + AdS/CFT = ♡ ?

Modest: Can AdS/CFT be useful to understand finite-tempearture QCD?

Bold: Can AdS/CFT be useful to understand the dynamics of the collision?

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Modest: Can AdS/CFT be useful to understand finite-tempearture QCD?

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Comments

- $\mathcal{N}$=4 SYM is the simplest example. Theories which are more similar to QCD can be treated by AdS/CFT methods.
- Application of AdS/CFT to thermal QCD is not exhausted. How far can we push this program?
- It is not a waste of time to do these calculations. Results are relatively easy to derive compared to the conventional methods.
- If there were an effective tool to do real-time computations in strongly coupled QCD at finite T and μ — no need to invoke AdS/CFT. In the absense of such a tool, AdS/CFT is the best we have (for some questions).
- Understanding finite-temperature field theory is an interesting question by itself. AdS/CFT can be useful in searching for universal properties (shear viscosity example is encouraging).

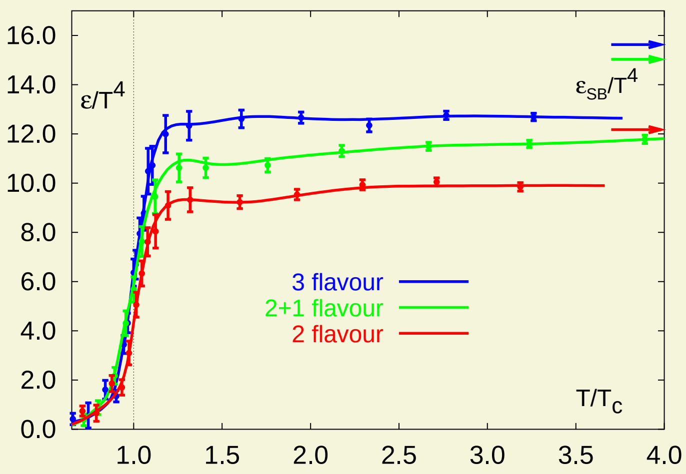
Why $\mathcal{N}$=4 SYM may have something to do with thermal QCD

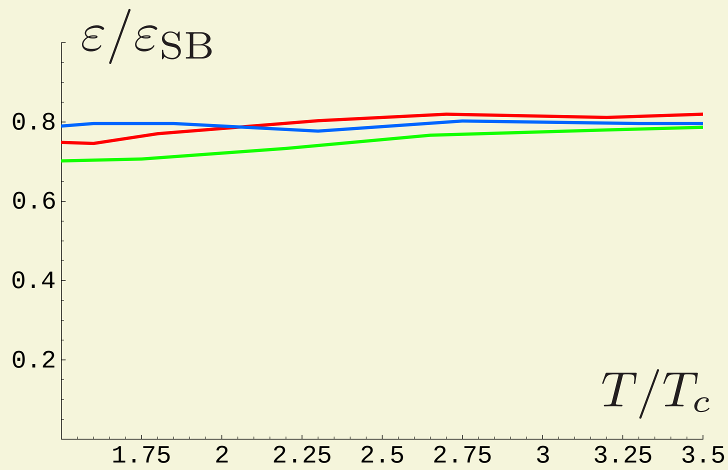
Q: $\mathcal{N}$=4 SYM is supersymmetric, while QCD is not

A: At finite temperature, supersymmetry is broken anyway

Q: $\mathcal{N}$=4 SYM is conformal, while QCD is asymptotically free

A: Let's look at the thermodynamics of QCD (e.g. F.Karsch, hep-lat/0106019)





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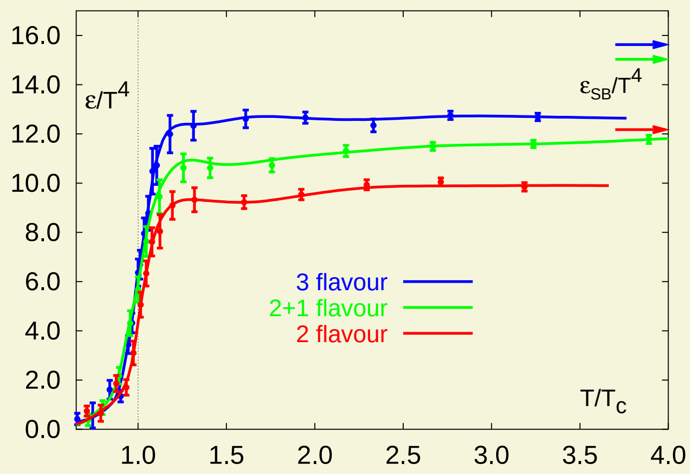

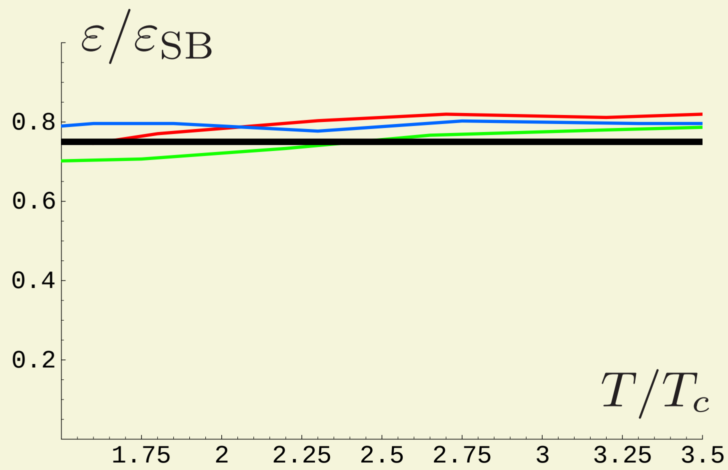

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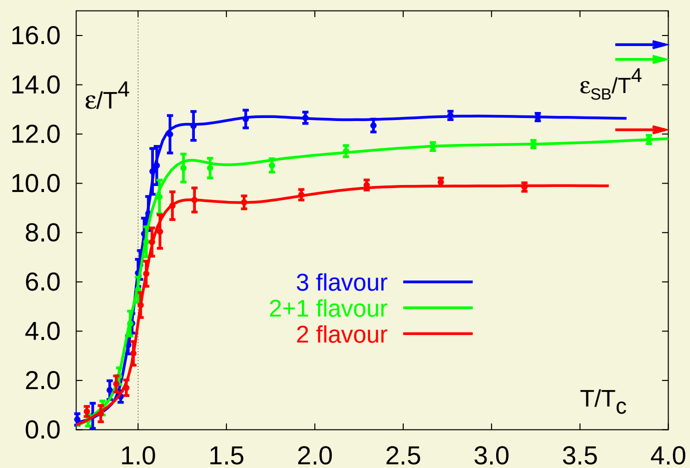
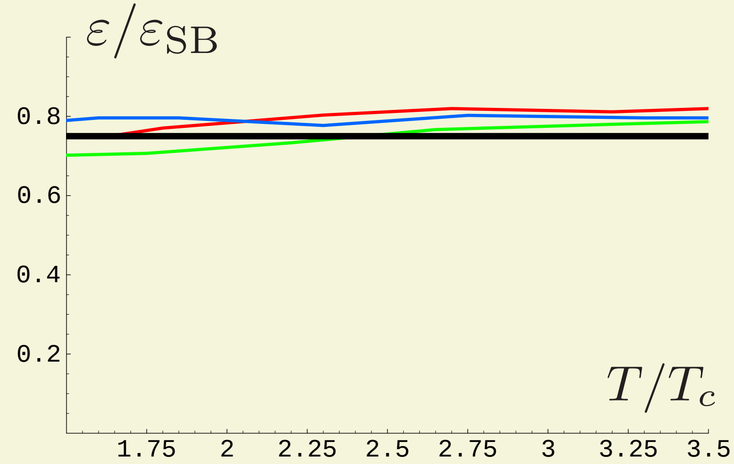




$T_c \approx 170$ MeV $\therefore$ QCD perturbation theory is not to be trusted for $T \gtrsim T_c$

When depart from thermodynamics — real-time on the lattice is hard

> Use strongly coupled $\mathcal{N}$=4 SYM as a model for QCD at $T \gtrsim T_c$

Will discuss application of AdS/CFT to:

- Momentum transport
- Electromagnetic response
- Energy loss by a heavy probe
- Thermalization

- AdS/CFT has more to say!

Momentum transport

- Conservation laws: $\partial_\mu T^{\mu\nu}=0 \quad \Rightarrow \quad \begin{cases} \partial_t \epsilon = -\boldsymbol{\nabla}\cdot\boldsymbol{\pi} \\ \partial_t \pi^i = -\boldsymbol{\nabla}_j T^{ij} \end{cases}$
- Constitutive relations:

$$\begin{cases} T^{ij} = \delta^{ij}\left[\langle P\rangle + v_s^2\delta\epsilon - \gamma_\zeta \boldsymbol{\nabla}\boldsymbol{\pi}\right] - \gamma_\eta\left(\boldsymbol{\nabla}^i\pi^j + \boldsymbol{\nabla}^j\pi^i - \frac{2}{3}\delta^{ij}\boldsymbol{\nabla}\boldsymbol{\pi}\right) + \dots \\ \gamma_\eta \equiv \dfrac{\eta}{\langle\epsilon+P\rangle}\,,\ \gamma_\zeta \equiv \dfrac{\zeta}{\langle\epsilon+P\rangle}\,,\ v_{\rm s}^2 = \partial P/\partial\epsilon \end{cases}$$

- Viscosities η, ζ — input from microscopic physics

Two eigenmodes:

Shear mode: $\pi_\perp(t,\boldsymbol{k}) = e^{-\gamma_\eta \boldsymbol{k}^2 t}\,\pi_\perp(0,\boldsymbol{k})$

Sound mode: $\boldsymbol{\pi}_\parallel(t,\boldsymbol{k}) = e^{-\frac{1}{2}(\gamma_\zeta+\frac{4}{3}\gamma_\eta)\boldsymbol{k}^2 t}\times$

$$\times\left[\boldsymbol{\pi}_\parallel(0,\boldsymbol{k})\cos(kv_st) - i\hat{k}v_s\sin(kv_st)\delta\epsilon(0,\boldsymbol{k})\right]$$

Long-wavelength response is controlled by a small number of kinetic coefficients

Correlation functions in the hydrodynamic limit

Hydrodynamic modes $\Rightarrow$ hydrodynamic singularities at small ω, k.

Example: $S_{tx,tx}(\omega,k) = \dfrac{2\gamma_\eta k^2}{\omega^2 + (\gamma_\eta k^2)^2}(\epsilon + P)T$ relaxation of transverse momentum

Kubo formulas
$$\eta = \lim_{\omega\to 0}\frac{1}{2\omega}\int dt\, e^{i\omega t}\int d^3x\, \langle [T_{xy}(t,\boldsymbol{x}), T_{xy}(0)]\rangle$$

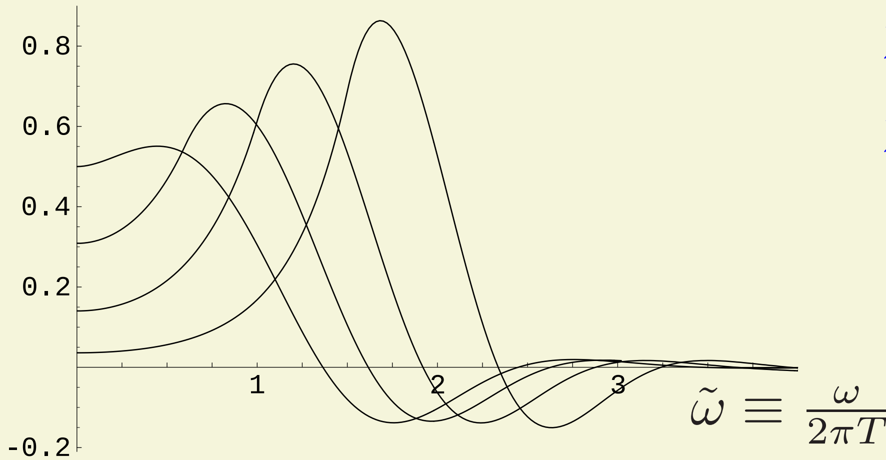
$$\frac{4}{3}\eta + \zeta = \lim_{\omega\to 0}\frac{1}{2\omega}\int dt\, e^{i\omega t}\int d^3x\, \langle [T_{xx}(t,\boldsymbol{x}), T_{xx}(0)]\rangle$$

Connection to microscopic physics: Viscosities can be extracted from (small-frequency limits of) real-time correlation functions

Spectral function for stress

(PK, A.Starinets hep-th/0602059, D.Teaney hep-ph/0602044)

$$\frac{1}{\tilde{\omega}}\left(\chi(\tilde{\omega}) - \chi^{T=0}(\tilde{\omega})\right)\ \left[\frac{1}{\pi^2 N_c^2 T^4}\right]$$



$$\chi(\omega, k) = -2\,\mathrm{Im}\,G^{\mathrm{ret}}_{xy,xy}(\omega, k)$$

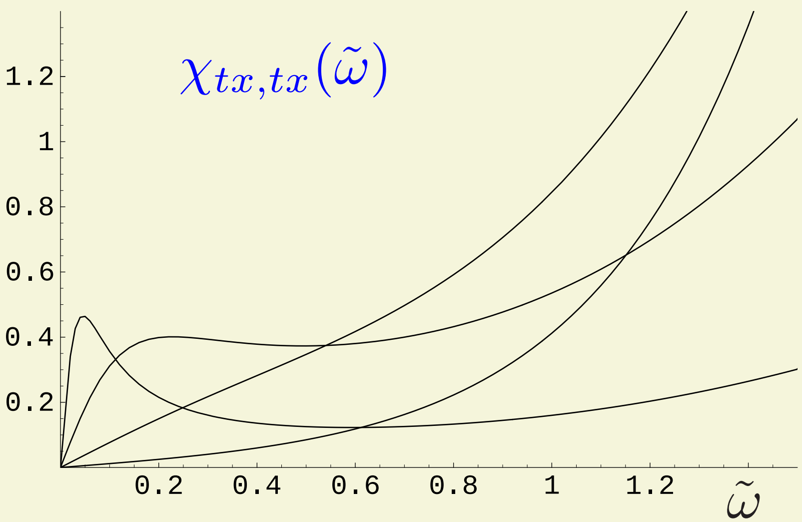
$$\chi(\omega) \sim \omega, \quad \omega \ll 2\pi T$$

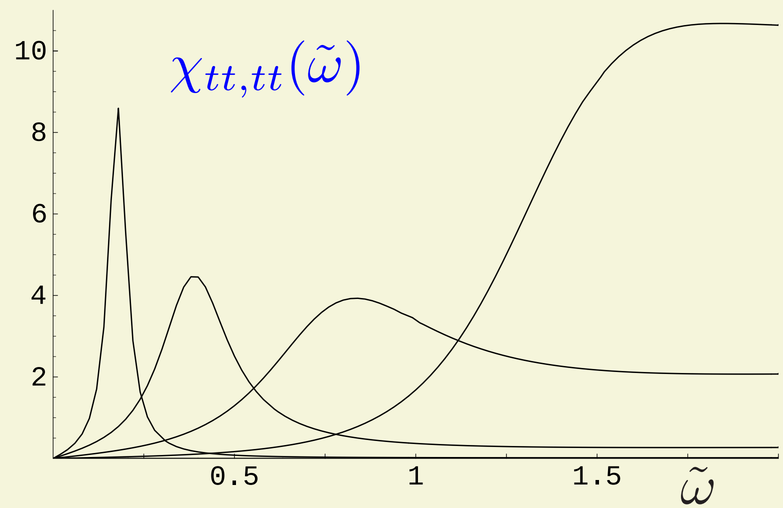
$$\chi(\omega) - \chi^{T=0}(\omega) \sim e^{-\gamma\omega}, \quad \omega \gg 2\pi T$$

$$\boxed{\eta = \frac{\pi}{8} N_c^2 T^3}$$

T^3 by conformal invariance, N_c^2 counts d.o.f.

Spectral function for conserved energy-momentum

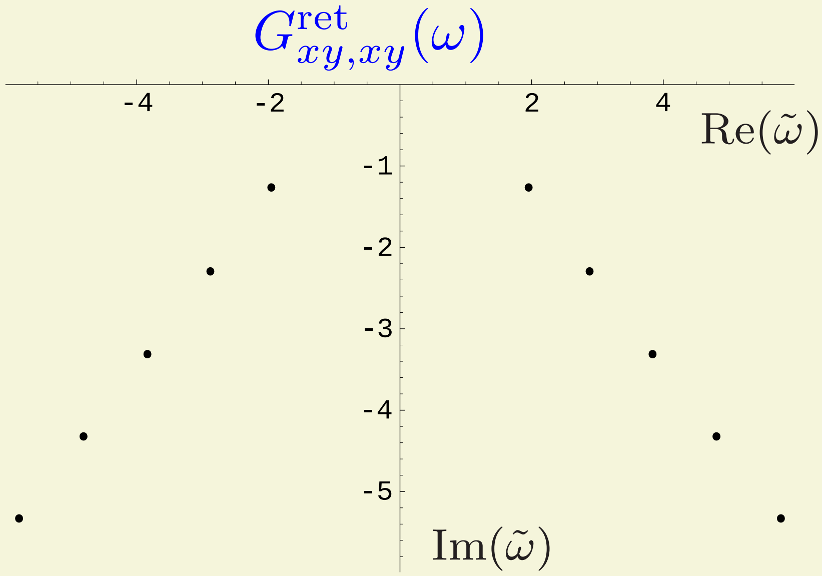




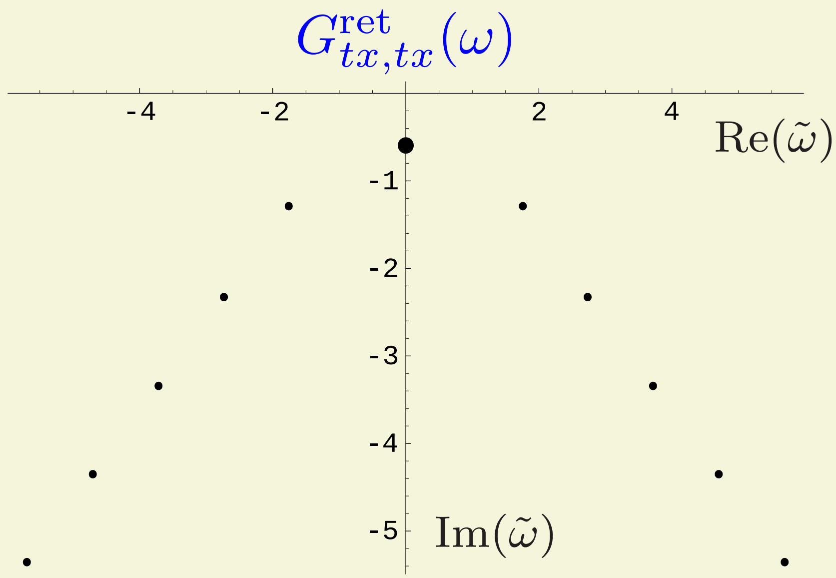
Hydrodynamic peaks clearly visible in dual classical gravity

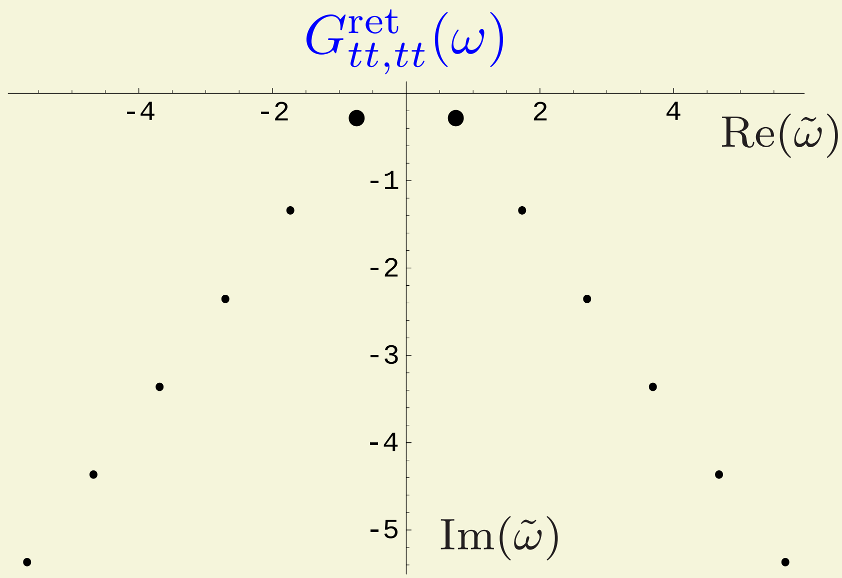
Singularities of $G^{\rm ret}(\omega, k)$

(A.Nunez, A.Starinets hep-th/0302026, PK, A.Starinets hep-th/0506184)



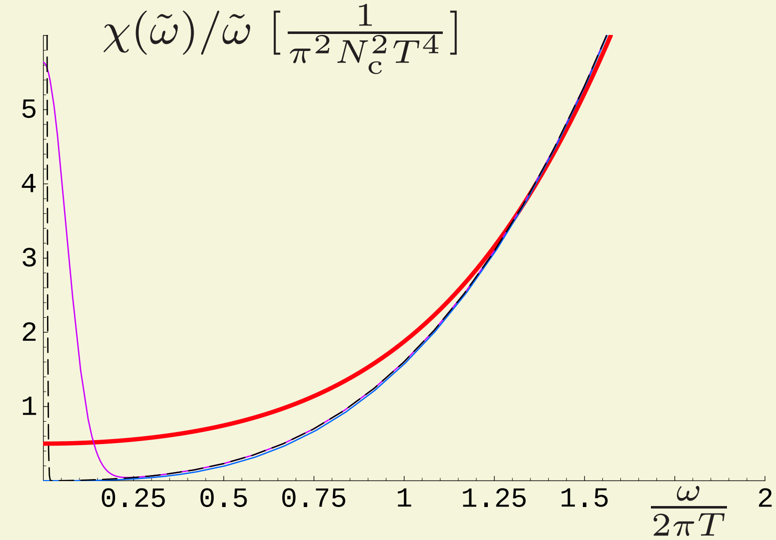
- Infinite series of poles
- $\omega_n = 2\pi n T(\pm 1 - i)$ as $n\to\infty$
- For conserved densities, $\omega_0\to 0$ as $k\to 0$
- Hydro poles agree with Kubo formula





Singularities of $G^{\rm ret}(\omega, k)$ are (quasi)normal modes of the dual gravity background

Real-time correlators are very different at strong and weak coupling

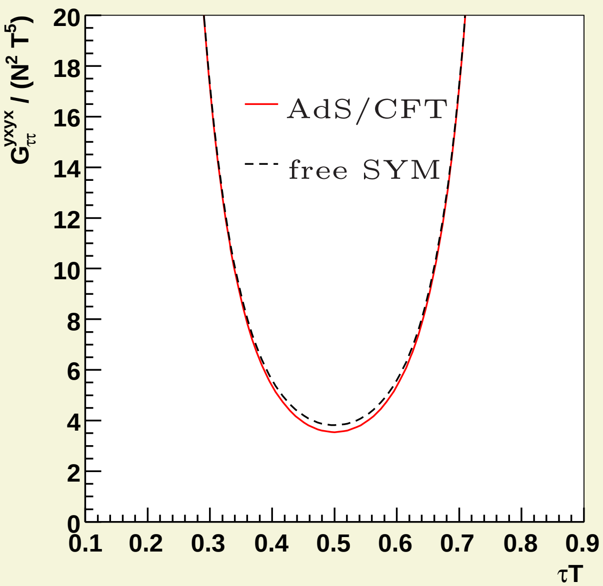


Red — strongly coupled SYM, $\eta = O(1)$

Dashed — free SYM, $\eta = \infty$

Purple — weakly coupled SYM, $\eta \sim \frac{1}{\lambda^2}$

Blue — SYM, $T = 0$



Euclidean correlators are almost the same!

(picture from D.Teaney, hep-ph/0602044)

$$G_{\rm E}(\tau) = \int_0^\infty d\omega\ \chi(\omega)\,\frac{\cosh[\omega(\tau-\beta/2)]}{\sinh(\beta\omega/2)}$$

Lattice $G_{\rm E}(\tau)$ has errorbars ~500% (hep-lat/0406009)

∴ Lattice determination of shear viscosity has no chance

Universality: Lower bound on shear viscosity?

(PK, D.Son, A.Starinets hep-th/0405231)

Life at low Reynolds number

E. M. Purcell
Lyman Laboratory, Harvard University, Cambridge, Massachusetts 02138

(Received 12 June 1976)

Editor's note: This is a reprint (slightly edited) of a paper of the same title that appeared in the book *Physics and Our World: A Symposium in Honor of Victor F. Weisskopf*, published by the American Institute of Physics (1976). The personal tone of the original talk has been preserved in the paper, which was itself a slightly edited transcript of a tape. The figures reproduce transparencies used in the talk. The demonstration involved a tall rectangular transparent vessel of corn syrup, projected by an overhead projector turned on its side. Some essential hand waving could not be reproduced.

This is a talk that I would not, I'm afraid, have the nerve to give under any other circumstances. It's a story I've been saving up to tell Viki. Like so many of you here, I've enjoyed from time to time the wonderful experience of exploring with Viki some part of physics, or anything to which we can apply physics. We wander around strictly as amateurs equipped only with some elementary physics, and in the end, it turns out, we improve our understanding of the elementary physics even if we don't throw much light on the other subjects. Now this is that kind of a subject, but I have still another reason for wanting to, as it were, needle Viki with it, because I'm going to talk for a while about viscosity. Viscosity in a liquid will be the dominant theme here and you know Viki's program of explaining everything, including the heights of mountains, with the elementary constants. The viscosity of a liquid is a very tough nut to crack, as he well knows, because when the stuff is cooled by merely 40 degrees, its viscosity can change by a factor of a million. I was really amazed by fluid viscosity in the early days of NMR, when it turned out that glycerine was just what we needed to explore the behavior of spin relaxation. And yet if you were a little bug inside the glycerine, looking around, you wouldn't see much change in your surroundings as the glycerine cooled. Viki will say that he can at least predict the *logarithm* of the viscosity. And that, of course, is correct because the reason viscosity changes is that it's got one of these activation energy things and what he can predict is the order of magnitude of the exponent. But it's more mysterious than that, Viki, because if you look at the Chemical Rubber Handbook table you will find that there is almost no liquid with viscosity much lower than that of water. The viscosities have a big range *but they stop at the same place*. I don't understand that. That's what I'm leaving for him.[1]

Now, I'm going to talk about a world which, as physicists, we almost never think about. The physicist hears about viscosity in high school when he's repeating Millikan's oil drop experiment and he never hears about it again, at least not in what I teach. And Reynolds's number, of course, is something for the engineers. And the *low* Reynolds number regime most engineers aren't even interested in—except possibly chemical engineers, in connection with fluidized beds, a fascinating topic I heard about from a chemical engineering friend at MIT. But I want to take you into the world of very low Reynolds number—a world which is inhabited by the overwhelming majority of the organisms in this room. This world is quite different from the one that we have developed our intuitions in.

I might say what got me into this. To introduce something that will come later, I'm going to talk partly about how microorganisms swim. That will not, however, turn out to be the only important question about them. I got into this through the work of a former colleague of mine at Harvard, Howard Berg. Berg got his Ph.D. with Norman Ramsey, working on a hydrogen maser, and then he went back into biology which had been his early love, and into cellular physiology. He is now at the University of Colorado at Boulder, and has recently participated in what seems to me one of the most astonishing discoveries about the questions we're going to talk about. So it was partly Howard's work, tracking *E. coli* and finding out this strange thing about them, that got me thinking about this elementary physics stuff.

Well, here we go. In Fig. 1, you see an object which is moving through a fluid with velocity v. It has dimension a. In Stokes's law, the object is a sphere, but here it's anything; η and ρ are the viscosity and density of the fluid. The ratio of the inertial forces to the viscous forces, as Osborne Reynolds pointed out slightly less than a hundred years ago, is given by $av\rho/\eta$ or av/ν, where ν is called the *kinematic* viscosity. It's easier to remember its dimensions: for water, $\nu \approx 10^{-2}$ cm^2/sec. The ratio is called the Reynolds number and when that number is small the viscous forces dominate. Now there is an easy way, which I didn't realize at first, to see who should be interested in small Reynolds numbers. If you take the viscosity η and square it and divide by the density, you get a force (Fig. 2). No other dimensions come in at all. η^2/ρ is a force. For water, since $\eta \approx 10^{-2}$ and $\rho \approx 1$, $\eta^2/\rho \approx 10^{-4}$ dyn. That is a force that will tow *anything*, large or small, with a Reynolds number of order of magnitude 1. In other words, if you want to tow a submarine with Reynolds number 1 (or strictly speaking, $1/6\pi$ if it's a spherical submarine) tow it with 10^{-4} dyn. So it's clear in this case that you're interested in small Reynolds number if you're interested in *small forces* in an absolute sense. The only other people who are interested in low Reynolds number, although they usually don't have to invoke it, are the geophysicists. The Earth's mantle is supposed to have a viscosity of 10^{21} P. If you now work out η^2/ρ, the force is 10^{41} dyn. That is more than 10^9 times the gravitational force that half the Earth exerts on the other half! So the conclusion is, of course, that in the flow of the mantle of the Earth the Reynolds number is *very* small indeed.

Now consider things that move through a liquid (Fig. 3). The Reynolds number for a man swimming in water might be 10^4, if we put in reasonable dimensions. For a goldfish or a tiny guppy it might get down to 10^2. For the animals that we're going to be talking about, as we'll see in a mo-

he can predict is the order of magnitude of the exponent. But it's more mysterious than that, Viki, because if you look at the Chemical Rubber Handbook table you will find that there is almost no liquid with viscosity much lower than that of water. The viscosities have a big range *but they stop at the same place*. I don't understand that. That's what I'm leaving for him.[1]

!!

- $\eta/s \gg 1$ at small coupling
- $\eta/s = \frac{1}{4\pi}$ is finite at large coupling
- Natural to assume $\eta/s \geqslant \frac{1}{4\pi}$ in SYM

Is $\frac{\eta}{s} \geqslant \frac{1}{4\pi}$ universal?

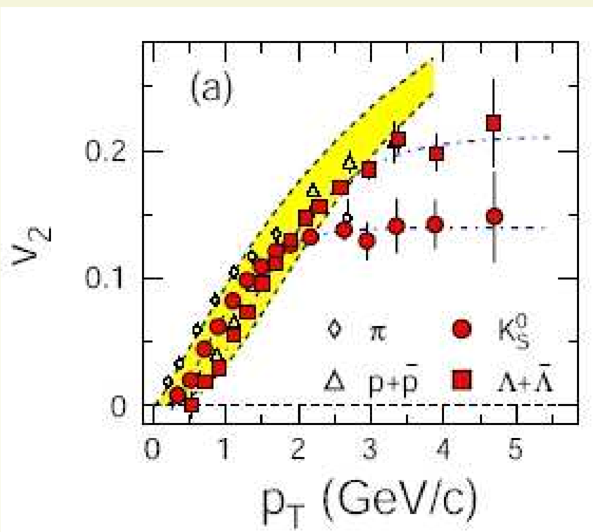
We know $\frac{\eta}{s} = \frac{1}{4\pi}$ **is** universal — proven for a large class of (but not all) field theories with gravity duals. Prove from first principles?

What is the viscosity measured at RHIC?

Of course, RHIC does not "measure" viscosity. Rather, measured angular distributions of particles are confronted with hydrodynamic models of the "fireball" evolution. Quantitatively: lentil-shaped reaction region ⇒ azimuthal anisotropy of particle distribution

$$\frac{d^2N}{dp_T d\phi} = N_0 \left[1 + 2\, v_2(p_T) \cos(2\phi) + \ldots\right]$$

↖ "elliptic flow"



Elliptic flow from PHENIX and STAR (figure from nucl-ex/0501009). Yellow band — hydro calculations. To reproduce elliptic flow from hydro, η/s must be small, within a factor of 4 of the conjectured bound. Perturbative η/s is too high.

Hydro works well at low p_T, but not at high p_T

Optimistically: $\mathcal{N}$=4 SYM does very well with η/s

Will discuss application of AdS/CFT to:

Momentum transport

→ Electromagnetic response

Energy loss by a heavy probe

Thermalization

AdS/CFT has more to say!

How brightly does a plasma glow?

Γ — number of photons per unit time per unit volume

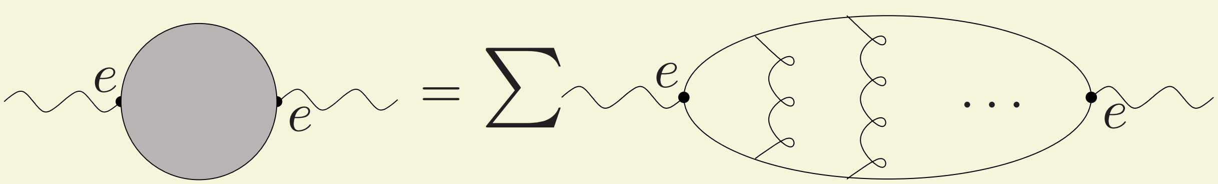
Photon interaction: $e\, J_\mu^{\mathrm{EM}} A^\mu$

e small $\Rightarrow$ photons do not thermalize

$$d\Gamma = \frac{d^3k}{(2\pi)^3}\frac{e^2}{2|\boldsymbol{k}|}\,\eta^{\mu\nu} C^<_{\mu\nu}(k)\Big|_{\omega=|\boldsymbol{k}|} \quad \text{where } C^<_{\mu\nu}(x) = \langle J_\mu^{\mathrm{EM}}(0) J_\nu^{\mathrm{EM}}(x)\rangle$$

Wightman function: $C^<_{\mu\nu}(k) = -2n_B(\omega)\,\mathrm{Im}C^{\mathrm{ret}}_{\mu\nu}(k)$

$\therefore$ Photon spectrum is determined by EM current-current spectral function



true to leading order in e, but to all orders in g

Perturbative evaluation of $\dfrac{d\Gamma}{d^3k}$ is not easy, see e.g. P.Arnold, G.Moore, L.Yaffe, hep-ph/0111107

How brightly does $\mathcal{N}$=4 plasma glow?

(PK, A.Starinets, to appear)

But wait... $\mathcal{N}$=4 SYM does not have a photon

[$U(1)$ gauge field coupled to a conserved current]

Let's introduce one! To do so:

Gauge a $U(1)$ subgroup of $SU(4)$ R-symmetry with coupling e

Add spectators ψ_s to cancel the anomaly

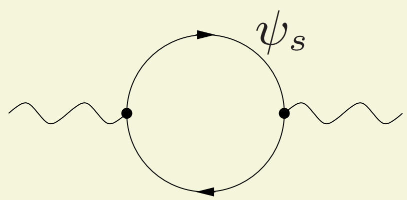
Take e to be small

$$J_\mu^{\mathrm{EM}} = J_\mu^{\mathrm{R}} + \sum \bar{\psi}_s \gamma_\mu \gamma_5 \psi_s$$

conserved
non-anomalous
couples to a $U(1)$ gauge field

To lowest order in e:

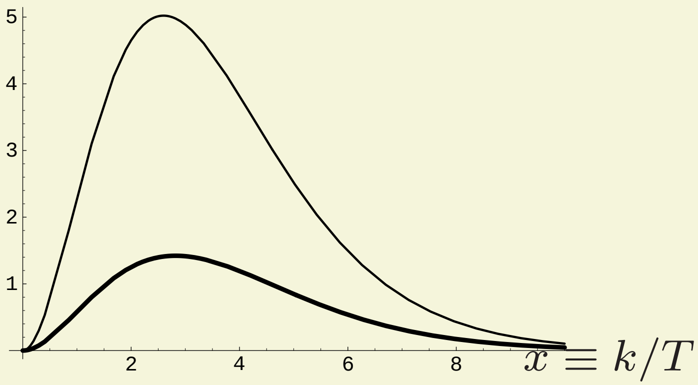
$$\langle J_\mu^{\mathrm{EM}} J_\nu^{\mathrm{EM}} \rangle = \langle J_\mu^{\mathrm{R}} J_\nu^{\mathrm{R}} \rangle +$$



spectator loop does not contribute to photon production (one-photon emission kinematically forbidden in a free theory)

Photon emission rate is given by R-current spectral function

Photon emission spectrum of $\mathbf{SYM_{EM}}$



Thick line: $\dfrac{x^3}{e^x - 1}$ Thin line: $\dfrac{x^3}{e^x - 1} f_{\mathrm{SYM}}(x)$

At small x: $f_{\mathrm{SYM}}(x) \to \text{const}$, $\mathrm{Im}\, \Pi^{\mu}{}_{\mu}(\omega{=}k) \sim k$,
consistent with hydrodynamics

At large x: decays as $f_{\mathrm{SYM}}(x) \sim \ln(1/x)$

Emission rate is finite and λ-independent at strong coupling

Photon emission spectrum of $\mathrm{SYM}_{\mathrm{EM}}$

$x \equiv k/T$

Thick line: $\dfrac{x^3}{e^x - 1}$ Thin line: $\dfrac{x^3}{e^x - 1} f_{\mathrm{SYM}}(x)$

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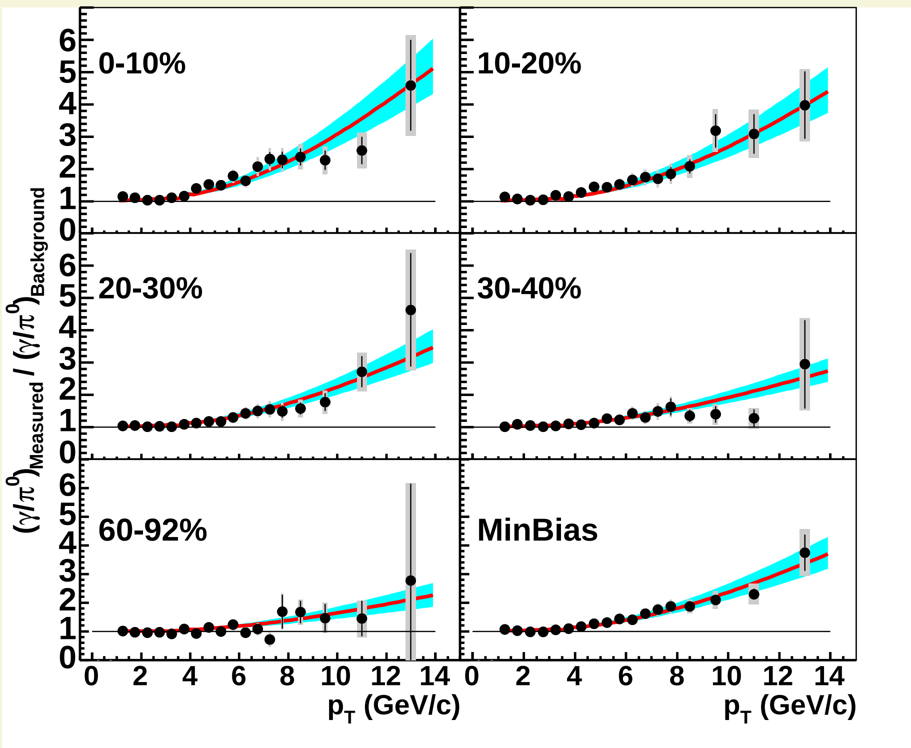

PHENIX data for photon production (nucl-ex/0410003)

$\therefore$ Not much room left for thermal QGP photons — but more precise measurements are planned

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→ Energy loss by a heavy probe

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AdS/CFT has more to say!

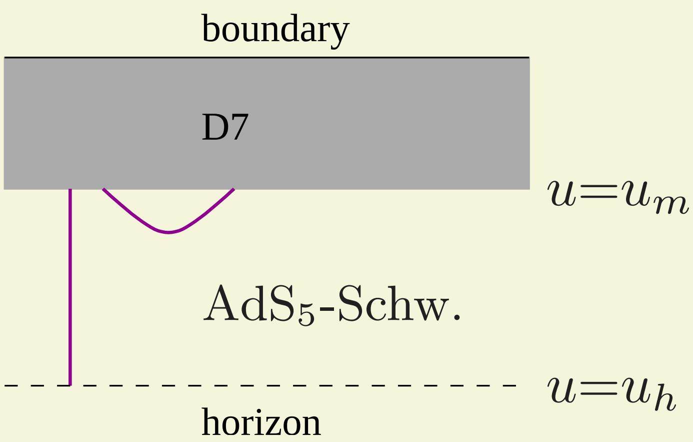
Heavy probe energy loss

(C.Herzog, A.Karch, PK, C.Kozcaz, L.Yaffe, to appear)

Probe of mass M, moving through a thermal medium with $T \ll M$

(think about charm quark $M \approx 1.3\,\mathrm{GeV}$, moving in a plasma at $T = 200\,\mathrm{MeV}$)

Model: $\mathcal{N}$=4 SYM + fundamental matter $N_{\mathrm{f}} \ll N_{\mathrm{c}}$ (A.Karch, A.Katz, hep-th/0205236)



Static string:

$$E = \frac{\sqrt{\lambda}}{2\pi} u_m, \quad T = 0$$

$$E = \frac{\sqrt{\lambda}}{2\pi} (u_m - u_h), \quad T \neq 0$$

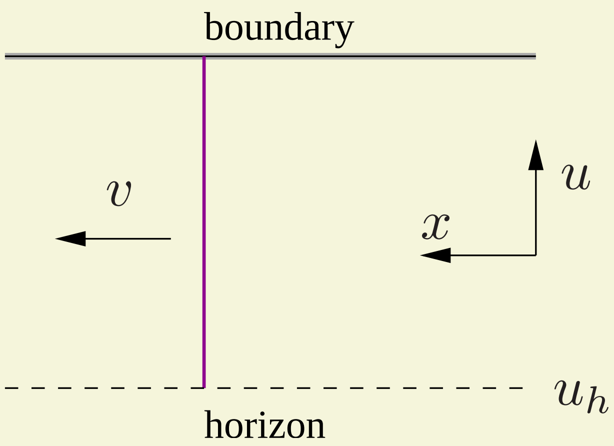
thermal mass

Heavy quark $E \gg T$ — string is classical

To analyze energy loss, solve classical equations of motion for a moving string

Stationary analytic solution

Take infinitely heavy "quark" ($u_m \to \infty$), move it at constant speed

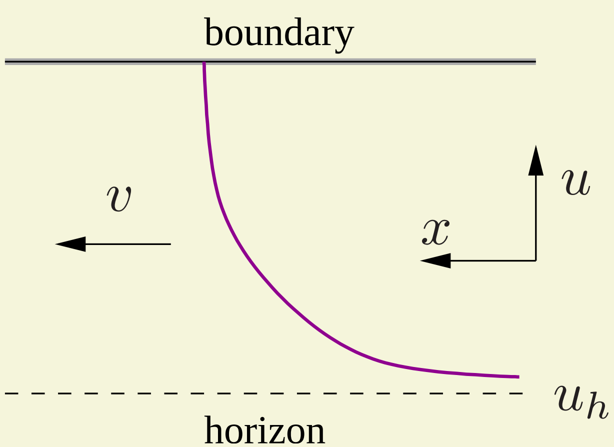


String profile: $x(u,t) = vt$ solves e.o.m.

however:

$-g$ flips sign at $u^4 = \frac{u_h^4}{1-v^2} > u_h^4$

E, P become complex — solution unphysical



$x(u,t) = X(u) + vt$

Can find $X(u)$ s.t. $-g$ is positive everywhere

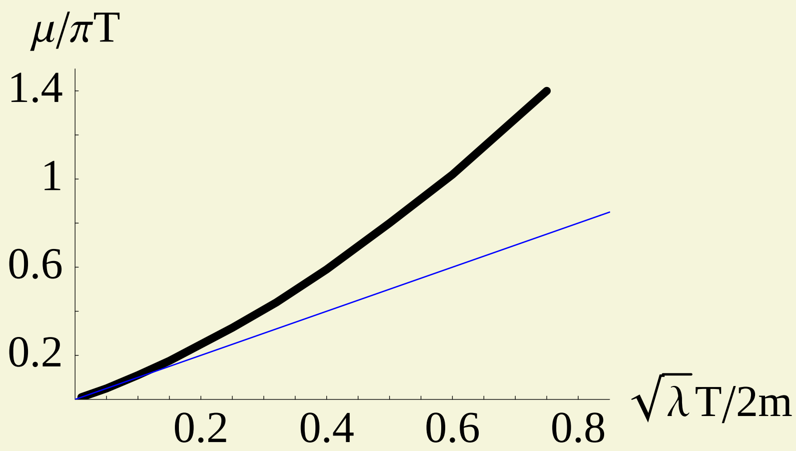
Source moves at constant speed

Momentum pumped in at the boundary

Momentum leaks off at the horizon

$$\frac{dP}{dt} = -\pi_x^1\Big|_{u=u_h} = -\frac{\sqrt{\lambda}}{2\pi}\frac{v}{\sqrt{1-v^2}}(\pi T)^2 = -\left(\frac{\sqrt{\lambda}T^2\pi}{2M}\right)\left(\frac{Mv}{\sqrt{1-v^2}}\right) = -\mu\, P$$

Numerical solution



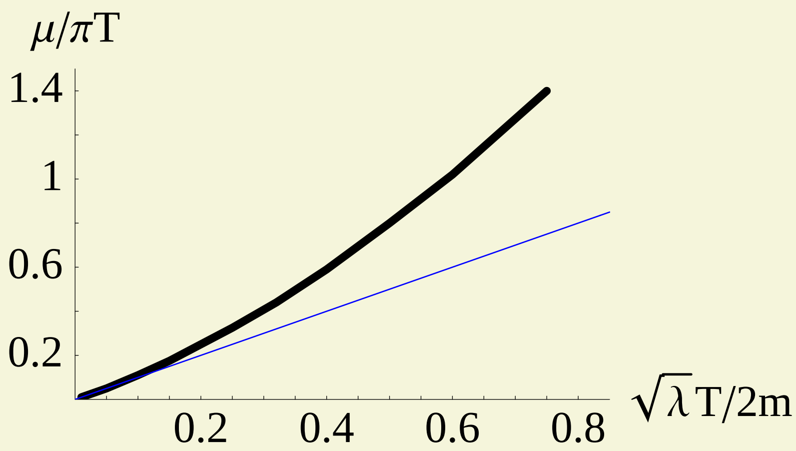
$dP/dt = -\mu P$

- Both non-relativistic and relativistic quarks
- Drag coefficient independent of momentum
- Does not have a finite $\lambda \to \infty$ limit

Rough estimate: $M/T \approx 7$, $\alpha_s \approx 0.5$, $\lambda \approx 20$ gives drag coefficient $\mu \approx T$

Perturbative μ, see e.g. G.Moore, D.Teaney, `hep-ph/0412346`, $\mu \approx T/7$

Numerical solution



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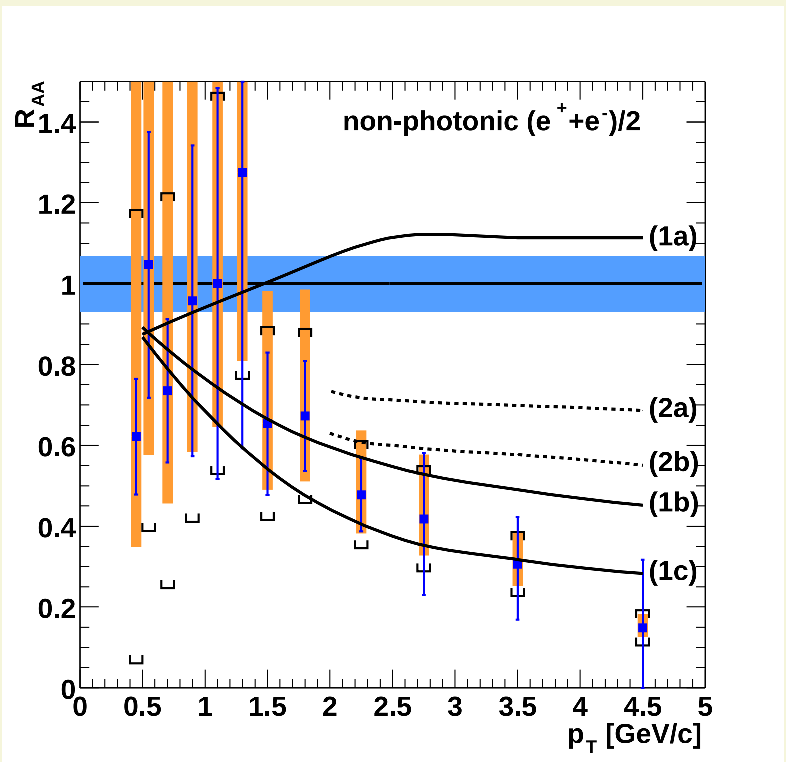

PHENIX data for electrons from heavy quark decay (`nucl-ex/0510047`)

Perturbative gluon radiation under-estimates energy loss for heavy quarks (but does well for light quarks)

Currently active area of research

Will discuss application of AdS/CFT to:

Momentum transport

Electromagnetic response

Energy loss by a heavy probe

→ Thermalization

AdS/CFT has more to say!

Thermalization

Thermal equilibrium in a collision established? If so:
On the partonic level at early stage, or on the hadronic level at a later stage?
At what temperature? How does the state evolve?

From AdS/CFT perspective [both solid results and speculations] :

H.Nastase, hep-th/0501068, hep-th/0603176, O.Aharony, S.Minwalla, T.Wiseman, hep-th/0507219, E.Shuryak, S.Sin, I.Zahed, hep-th/0511199, R.Janik, R.Peschanski, hep-th/0512162

however:

Any attempt to understand thermalization in heavy-ion collisions from AdS/CFT must:

- be able to distinguish between hadron-hadron and Au+Au collisions
- quantitatively understand the role of finite N_c

AdS/CFT is not (currently) useful for understanding thermalization

Will discuss application of AdS/CFT to:

Momentum transport

Electromagnetic response

Energy loss by a heavy probe

Thermalization

$\rightarrow$ AdS/CFT has more to say!

A sample of challenges for AdS/CFT

(both easy and hard)

- Deformations of thermal $\mathcal{N}=4$ SYM [more realistic models for QCD]
- Finite 't Hooft coupling corrections to $\mathcal{N}=4$ SYM [quasiparticle dynamics]
- Real-time dynamics with flavor [heavy-quark resonances]
- Finite N_c corrections to $\mathcal{N}=4$ SYM [relaxation timescales]
- Non-linear hydrodynamics [classical gravity not enough]
- Gauge-field dynamics [effective theories]
- Partonic structure [initial state for the collision]
- Reason for universality of η/s [or any other strong-coupling universality]
- Membrane paradigm and AdS/CFT [project for a GR raduate student]
- Black hole singularity [power vs exp decay of correlators at large ω]

Can AdS/CFT be useful for heavy-ion physics?