Holograms of Strings

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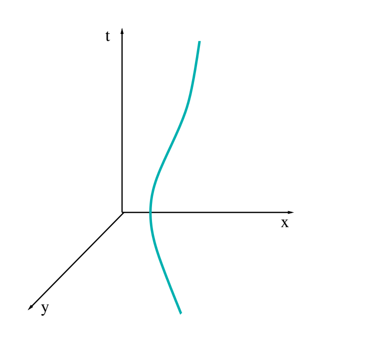
Outline

- Introduction to String Theory and AdS/CFT
- Holograms of strings
- Applications to strongly coupled hot plasmas
  - Jet quenching
  - Hydrodynamic expansion coefficients: first and second order coefficients
- Building holography for aging systems bottom-up

Introduction to String Theory



Point particle evolution : worldine

$$S = -m \int d\tau \sqrt{-\dot{X}^\mu \dot{X}^\nu g_{\mu\nu}(X)} \sim Length$$

$$p^\mu p_\mu = -m^2$$

Introduction to String Theory

String evolution : worldsheet

$$S = -T \int d\tau d\sigma \sqrt{-(\dot{X}\cdot\dot{X})(X'\cdot X') + (X'\cdot\dot{X})^2} \sim Area$$

$$S = -\frac{T}{2} \int d\tau d\sigma \sqrt{-\det h} h^{\alpha\beta} \partial_\alpha X \cdot \partial_\beta X$$

$$T = \frac{1}{2\pi\alpha'} \qquad \alpha' = \text{Regge slope} = l_s^2 = \text{string length}^2$$

Introduction to String Theory

String equations of motion = Wave equations

$$\Box X = \ddot{X} - X'' = 0$$

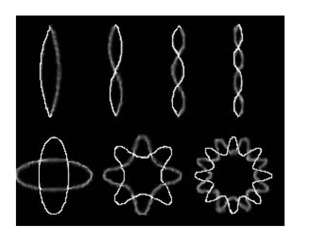
Same as for a vibrating violin string!

$$S_{violin} = \int dt \int dx \left[\frac{\mu}{2} (\dot{y})^2 - \frac{T}{2} (y')^2 \right]$$

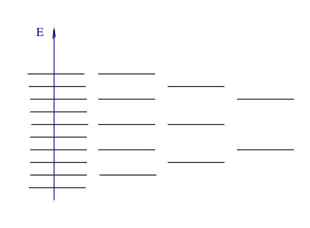
Also, same as for a violin string, two types on endpoint conditions: free (Neumann) or fixed (Dirichlet).

Introduction to String Theory

Modes of vibrations for the open and closed strings:



Energy levels for the quantum violin string



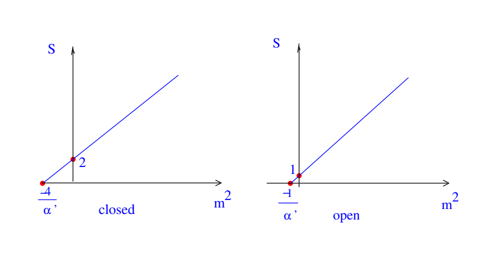
Just an infinite bunch of harmonic oscillators.

Introduction to String Theory

But, the relativistic string is more constrained: invariance under reparametrizations of the worldsheet means that the energy as measured on the worldsheet (and the stress tensor in general) is zero:

$$\dot{X} \cdot \dot{X} + X' \cdot X' = 0, \qquad \dot{X} \cdot X' = 0$$

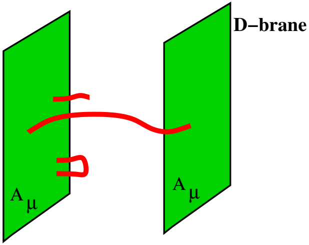
The string spectrum is an infinite tower of particles, with arbitrarily high spin classified by the Lorentz group



And, the number of space-time dimensions is fixed (26 or 10).

Introduction to String Theory

Open string with Neumann (free) and Dirichlet (fixed) boundary conditions:



$X_{||}$: Neumann b.c. and $X_{\perp}$: Dirichlet b.c.

At the massless level find a spin one particle (photon) and several (as many as transverse directions to the D-brane) scalar particles.
The D-brane is dynamical (it fluctuates). Its action is derived by requiring one-loop conformal invariance for the open string. Conformal invariance: scaling symmetry (the theory looks the same at any scale).

For a space-time filling D-brane

$$S = -\frac{1}{4\pi\alpha'}\int_{ws} d\tau d\sigma\, \partial^\alpha X^\mu \partial_\alpha X_\mu + \int_{bdy\ ws} d\tau\, A_\mu \partial_\tau X^\mu$$

$$\beta = 0 \longrightarrow \text{EOM of Born} - \text{Infeld action}: \ \mathcal{L} = \sqrt{\det(\eta_{\mu\nu} + 2\pi\alpha' F_{\mu\nu})}$$

For small α', get the Maxwell action

$$\mathcal{L} = \frac{1}{4} F_{\mu\nu} F^{\mu\nu} \sim \vec{E}^2 - \vec{B}^2$$

For closed strings, conformal (scale) invariance

$$S = -\frac{1}{4\pi\alpha'}\int_{ws} d\tau d\sigma \Big[\partial^\alpha X^\mu \partial_\alpha X^\nu g_{\mu\nu}(X) + i\partial^\alpha X^\mu \partial^\beta X^\mu \epsilon_{\alpha\beta} B_{\mu\nu}(X) + \alpha' \Phi(X) R_{ws}\Big]$$

requires that the space-time metric satisfies Einstein equations

$$R_{\mu\nu} = \mathrm{B},\Phi-\mathrm{sources}, \qquad R_{\mu\nu} = 0 \ \text{ in } \ \text{vacuum}$$

In general, conformal invariance implies the EOM of Einstein action (+more)

$$\mathcal{L} = \tfrac{1}{G_N}\sqrt{-\det g}\, e^{-2\Phi}\Big[R - \tfrac{1}{2} H_{\mu\nu\rho} H^{\mu\nu\rho} + 4\partial^\mu \Phi \partial_\mu \Phi\Big]$$

It's the tail wagging the dog! the string cannot exist in other spacetimes than those compatible with general relativity.

Superstrings

Supersymmetry relates particles with different spin-statistics:

supermultiplet=(bosons, fermions)
Infinitesimal transformation

$$\delta f = \epsilon \partial b \qquad \delta b = \epsilon f \quad "\delta^2" b = "\epsilon^2" \partial b$$

Superstrings live in 10 dimensions. At the massless level (or $\alpha' \to 0$) find

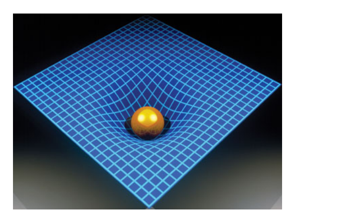
- open strings: superMaxwell multiplet (A_μ and a spin 1/2 field, gaugino)
- closed strings: supergravity multiplet ($g_{\mu\nu}$, a spin 3/2 field, gravitino, plus a bunch of other fields)

D-branes in supergravity

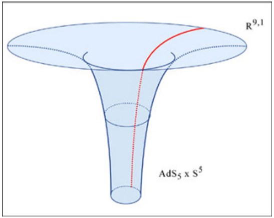
D-branes have energy, they gravitate, and curve the space around them.

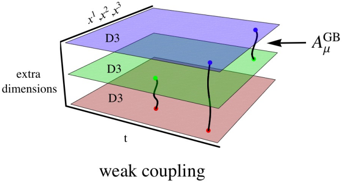
Mass/Energy $\leftrightarrow$ Geometry/Metric.

This is much like having an object with a mass M source the Einstein equation. In the limit of weak gravitational field, the geodesic motion of some test particle yields Newtonian dynamics and gravity.

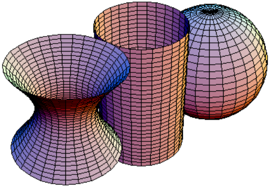


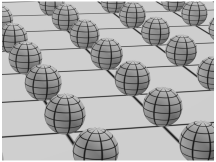
For flat D3-branes (extended in space-time) we have a dual description





How to think of $AdS_5 \times S^5$?





S^5 is a 5-dimensional constant positive curvature space (sphere):

$$Y_1^2 + Y_2^2 + Y_3^2 + Y_4^2 + Y_5^2 + Y_6^2 = R^2$$

AdS_5 is a 5-dimensional constant negative curvature space:

$$-X_{-1}^2 - X_0^2 + X_1^2 + X_2^2 + X_3^2 + X_4^2 = -R^2$$

Back to D3's

Dual perspective in the low energy limit ($\alpha' \to 0$):

- Solutions of supergravity

$$ds^2 = \sqrt{h(r)}dx^\mu dx_\mu + \frac{1}{\sqrt{h(r)}}(dr^2 + r^2 d\Omega_5^2)$$

$$h(r) = 1 + \frac{4\pi N g_s \alpha'^2}{r^4} \equiv 1 + \frac{R^4}{r^4}$$

$$ds^2 = \frac{R^2}{z^2}(dx^\mu dx_\mu + dz^2) + R^2 d\Omega_5^2 = ds^2_{AdS} + ds^2_S$$

- 4d field theory = maximally supersymmetric extension of QCD or $\mathcal{N} = 4$ superYang Mills

SU(N) gauge field A_μ, 4 spin 1/2 fields, and 6 scalars
All fields transform as in the adjoint representation of SU(N).

Holography

Maldacena: The 4d maximally susy gauge theory with gauge group SU(N), at strong coupling, is dual to superstring theory on the curved background $AdS_5 \times S^5$.

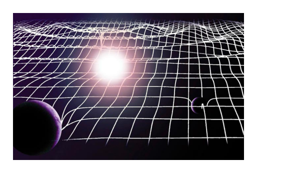
- Identification of symmetries:
  -conformal symmetry $SO(4,2)$ is a(n) symmetry (isometry) of the AdS_5 background
  -R-symmetry $SO(6)$ is a(n) symmetry (isometry) of the S^5 background
- Identification of couplings

$$\frac{g_{YM}^2}{4\pi} = g_s, \qquad g_{YM}^2 N = \frac{R^2}{\alpha'^2}, \qquad \alpha' \to 0, \qquad R \gg \sqrt{\alpha'}$$

- This is a strong/weak duality. Difficult to prove, but powerful in its applications. Simply replace the strongly coupled system by a gravitational weakly coupled one.

Holograms of strings

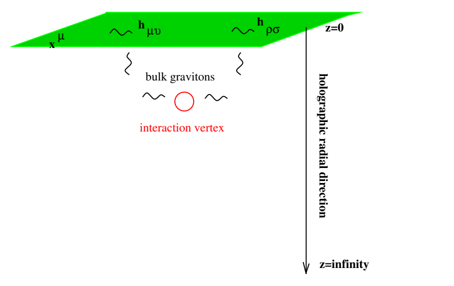
Consider the field theory, and imagine that it interacts with a gravitational wave. This coupling involves the metric fluctuation $h_{\mu\nu}$ with the energy-stress tensor $T_{\mu\nu}$ (recall that the energy density is $\sim \vec{E}^2 + \vec{B}^2$).



This metric fluctuation on the boundary of AdS propagates in the bulk. Expectation values of the energy-stress tensor are computed by evaluating the supergravity action on AdS_5, pertubed by the boundary fluctuation $h_{\mu\nu}$.

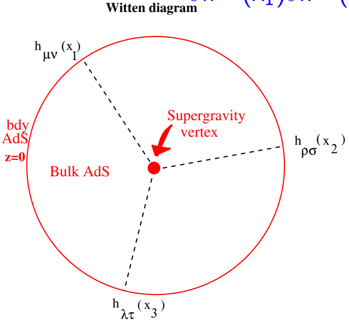
Similarly, a background field A_μ will source a current $\bar{\psi}\gamma^\mu\psi$ in the field theory.

Expectation values of the current are computed by evaluating the supergravity action, perturbed by the boundary fluctuation A_μ.

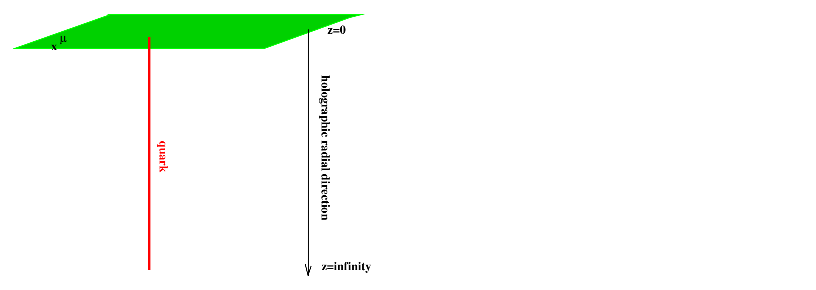


More concretely,

$$\langle T_{\mu\nu}(x_1)\, T_{\rho\sigma}(x_2)\, T_{\lambda\tau}(x_3)\rangle = \frac{\delta^3 S_{sugra}}{\delta h^{\mu\nu}(x_1)\delta h^{\rho\sigma}(x_2)\delta h^{\lambda\tau}(x_3)}$$

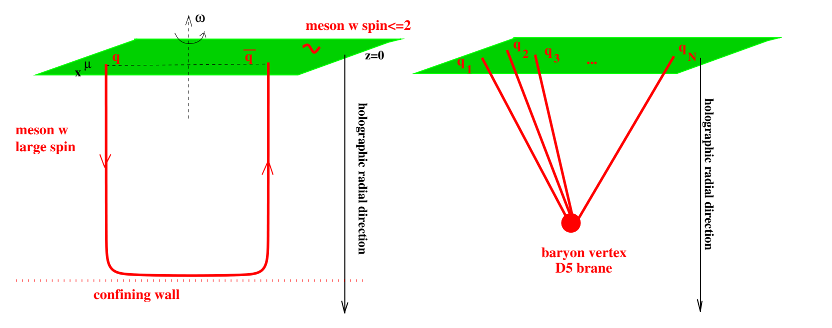


- bulk gravitons - holograms of stress-energy tensor
- bulk gauge fields - holograms of currents
- other operators: bulk scalars with mass m - holograms of scalar operators with conformal dimension $\Delta = 2 + \sqrt{4 + m^2 R^2}$ etc.
- quarks? these particles transform in the fundamental representation of SU(N) [In QCD there are 3 quarks, and 8 gluons, and the gauge field is SU(3).] Need strings with one end on the D3's and one end on some other ("flavor") D-brane:



Still, this is not the holographic dual of a confining gauge theory. For that, the AdS geometry needs to be replaced by something else.

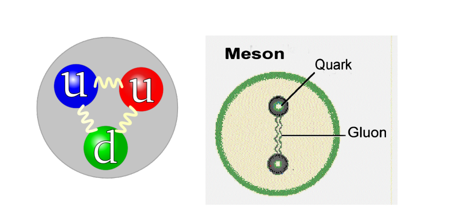
- mesons? these are $q\bar{q}$ bound states. holographic dual?
  - for small spin - fluctuations of the flavor D-brane
  - for large spin - open spinning strings
- baryons? these are qqq bound states. holographic dual? A baryon vertex (wrapped D-brane on S^5) with N open strings connecting the boundary to it.



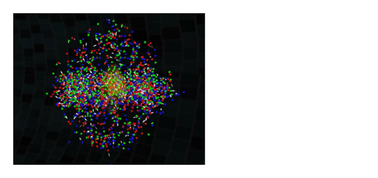
Applications to strongly coupled hot plasmas

Quark-Gluon Plasma

- At room temperature, quarks and gluons are always confined inside colorless objects (hadrons: baryons, mesons).



- At very high temperature, quarks and gluons deconfine and form a QG plasma.



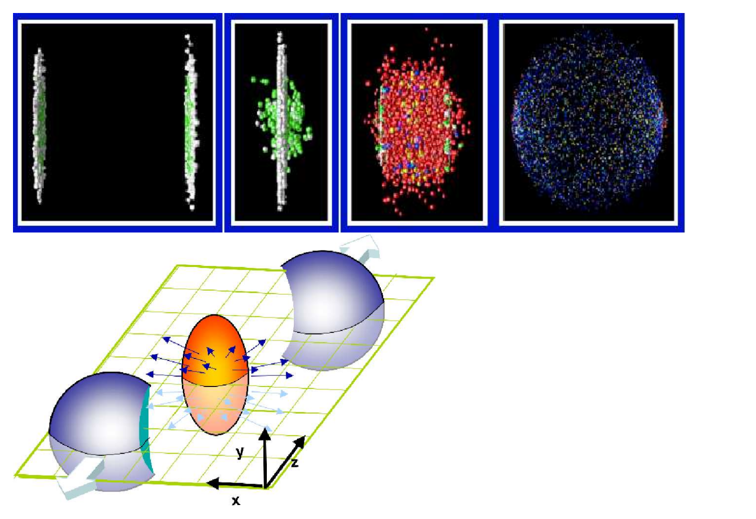
At $T \to \infty$ the interactions vanish and the quarks and gluons are free, non-interacting particles (QGP gas).

In the lab, QGP is created in relativistic heavy ion collisions at RHIC (Brookhaven National Lab) and LHC (Geneva, CERN).

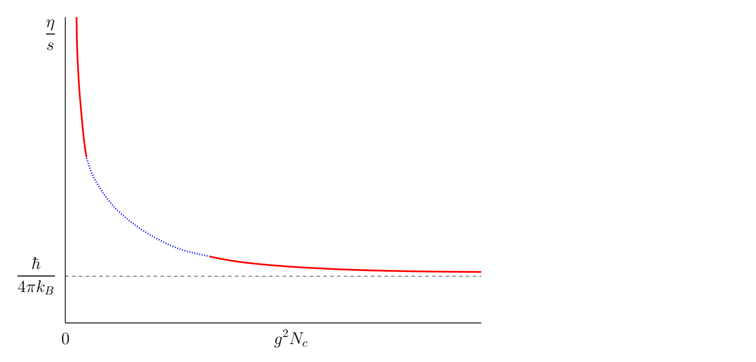
RHIC: Au-Au collisions $\sqrt{s_{NN}} \sim 200 GeV$, $T \sim 300 MeV$

LHC Pb-Pb collisions $\sqrt{s_{NN}} \sim 2.76 TeV$, $T \sim 450 MeV$

Cartoon of a collision event

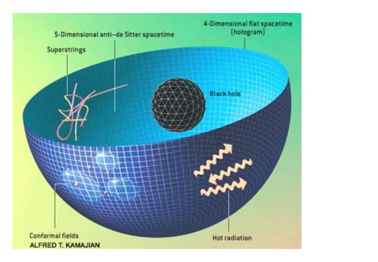


- Properties of the QGP: weakly or strongly coupled?
  Collective behavior of the observed final-state hadrons (anisotropy of the momenta distribution in the ellipse angle): suggests that RHIC and LHC QGP is a fluid, which moreover exhibits a very small viscosity (ideal, strongly coupled fluid).



  [Kovtun, Son, Starinets 2004]
- Probes of QGP? it exists for $5fm$ (or, in proper units, $10^{-23}s$), so external probes cannot be used. Use hard probes created during the collision - jet quenching.

If the deconfined quarks and gluons interact strongly, this is a strongly coupled plasma. In a range of temperatures above T_c, hot QCD is similar to hot superYang-Mills: non-supersymmetric, almost conformal.
So, its holographic dual is not unlike AdS at finite temperature, that is AdS with a black hole in it.
Black holes radiate, and the (Hawking) radiation has a thermal spectrum, with a temperature which can be computed from geometry.
Holographically, identify the Hawking temperature and the dual field theory temperature.

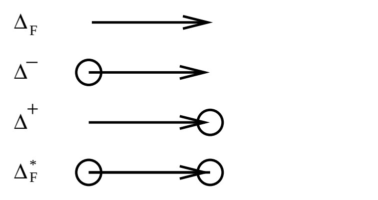


Real-time AdS/CFT

We are interested in dynamical processes which happen near equilibrium. Develop real-time AdS-CFT tools. In real-time (as opposed to Euclidean/imaginary time) there is the issue of time-ordering:

$$
\begin{aligned}
\text{Feynman correlator} \quad G_F &\sim \langle \mathcal{T}\phi(x_1)\phi(x_2)\rangle \\
&\sim \frac{1}{(\vec{x}_1-\vec{x}_2)^2-(t_1-t_2)^2+i\epsilon} \\
\text{Wightman correlator} \quad G_W^+ &\sim \langle \phi(x_1)\phi(x_2)\rangle \\
&\sim \frac{1}{(\vec{x}_1-\vec{x}_2)^2-(t_1-t_2-i\epsilon)^2} \\
\text{Causal Retarded correlator} \quad G_R &\sim G_F - G_W^- \\
&\quad \text{support on the forward light} - \text{cone}
\end{aligned}
$$

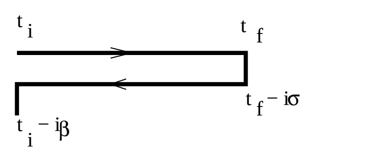
Veltman's circling rules can be transplanted to gravity on AdS



Properties:

- Largest time identity: Sums of all diagrams with all vertices circled or uncircled is zero
- Retarded n-point function: Assume that external leg 1 has the largest time. Then the retarded n-point function is the sum of all diagrams with vertices circled or un-circled, with the exception of 1 which remains uncircled.

In real-time finite temperature formalism, use Schwinger-Keldysh path integration contour



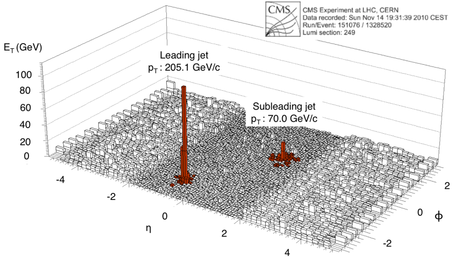
Kobes & Semenoff: Trade the Schwinger-Keldysh propagator for circling rules, which are the same as at zero temperature.
The retarded propagator determines completely all other components of the SK propagator

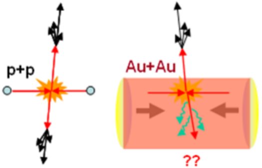
$$
\begin{aligned}
G_R =& \theta(t)\langle e^{-\beta H}[\phi_1(x), \phi_1(0)]\rangle \\
G_F =& Re(G_R) + iIm(G_R)\coth(E/2T)
\end{aligned}
$$

In AdS-CFT, causal propagators have specified incoming/outgoing boundary conditions at the black hole horizon; the others can be determined from them; also, one more prescription applies: the bulk region is integrated only up to horizon.
Real-time 2-point functions known since 2002 [Son and Starinets, Son and Herzog].
Real-time higher n-point functions known since 2010 [Arnold, Barnes, DV, Wu].
Applications? Beyond linear response.

Jet quenching

Jet: a colimated spray of hadrons resulted from the QCD branching of a hard parton.
Jet (here): the hard parton moving through the hot medium.
Jet quenching: jet interacts with the medium, leading to a marked decrease in its energy.



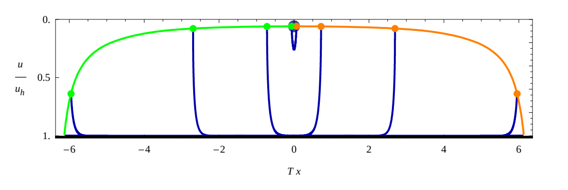


Possibilities:

- the jet interacts weakly with the medium and with the emitted radiation.
- the jet interact strongly with the medium, and weakly with the emitted radiation.
- all interactions are strong.

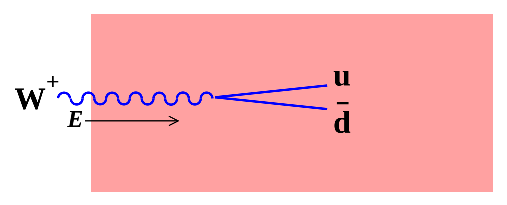
Different kinds of jets:

- - heavy quarks and the drag force experienced due to medium interactions - open strings with one end-point on the horizon, dragged by an invisible hand such that it moves with constant velocity, the other endpoint trailing behind, approaching the horizon
- - gluon-like jets - holograms of closed folded-back strings with both ends through the horizon [Gubser et al 2008]
- - two light-quark jets moving in opposite directions - holograms of open strings with the endpoints moving farther from each other, falling in the black hole [Chesler et al 2008]

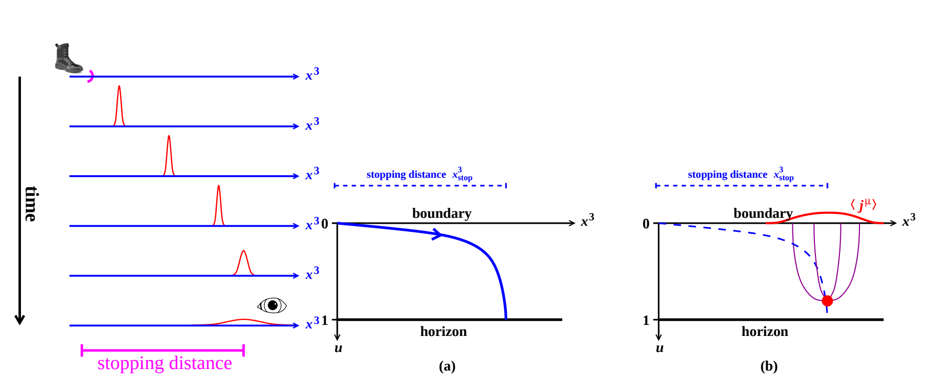


All these scenarios begin by setting up the initial problem on the gravity side. Not an easy translation to an initial condition on the field theory side.

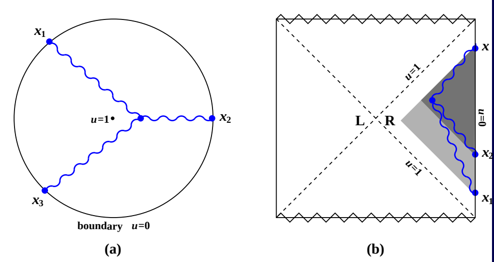
The question: how far does a localized, highly energetic excitation travel through the hot plasma, before coming to a stop and thermalizing?
Answer: it depends. For a weakly coupled plasma, the stopping distance dependence with the energy E is $l_{stop} \sim E^{1/2}$. [Arnold, Moore, Yaffe]
For a strongly coupled plasma, with long strings as the duals of the jet, $l_{stop} \sim [E/(T\sqrt{\lambda})]^{1/3}$.
What about jets whose duals are short strings (supergravity fluctuations)? [Arnold, Vaman 2010,2011] These are easily amenable to an initial problem on the field theory side.
Example: perturb the boundary theory by some classical field, sourcing a current.
Analogy



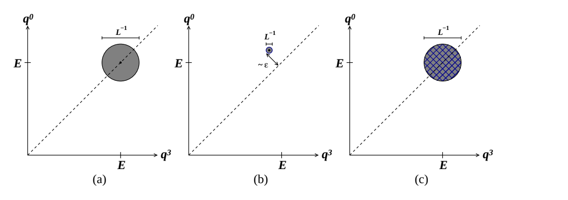
The $q\bar{q}$ pair move to right, carrying conserved charges, isospin. Track their location by doing an isospin measurement!



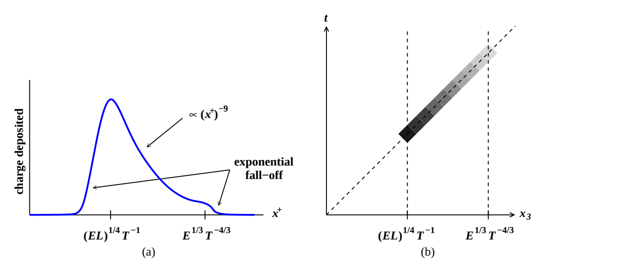
The problem reduces to a computation of a 3-point current correlator "$\langle \mathrm{boot}|\mathrm{eye}|\mathrm{boot}\rangle$".



The source



The result

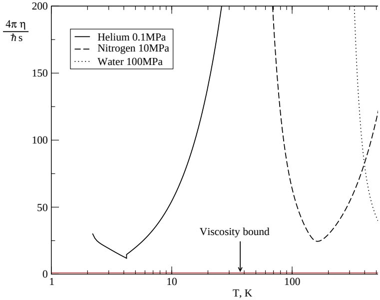


Typical $l_{stop} \sim E^{1/4}$. Maximal $l_{stop} \sim E^{1/3}$.
Source (b) wavepacket localized in the bulk. Amenable to a classical treatment: point particle following a geodesic trajectory

$$l_{stop} \sim \left(\frac{E^2}{-q^\mu q_\mu} \right)^{1/4} .$$

Hydrodynamics of the strongly coupled plasma

The QCD plasma at RHIC and LHC is a "perfect fluid".



[Kovtun,Son,Starinets, 2004]

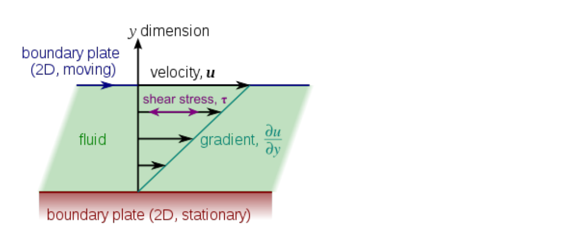
Hydrodynamics- long wavelength/long distance effective description of a classical or quantum many-body system at finite T.

Relativistic hydro - the quantum fluid is constrained by Lorentz (think QGP)

Long wavelength modes - $\omega, k \ll T$

Hydrodynamic equations - EOS and conservation laws (e.g. energy-momentum tensor is conserved: $\nabla_\mu T^{\mu\nu} = 0$) plus an expansion in small gradients (small ω, k). The coefficients of this expansion are called hydro coefficients.

At linear order - viscosity (shear + bulk).



Holographic bound (which later it was found to be violated by $1/N$ terms in a large class of examples) for the shear viscosity $\eta/s = 1/(4\pi)$. [Kovtun, Son, Starinets].

QGP: $\eta/s \sim (1-2) \times 1/(4\pi)$.

Decompose the stress tensor of a CFT into an equilibrium piece and a non-equilibrium part, with the latter expanded in gradients, which are taken to be small:

$$T^{\mu\nu} = T^{\mu\nu}_{\text{eq}} + \Pi^{\mu\nu}, \qquad T^{\mu\nu}_{\text{eq}} = (\epsilon + P)U^\mu U^\nu + Pg^{\mu\nu}$$

$$\Pi^{\mu\nu} = -\eta\sigma^{\mu\nu} + \eta\tau_\Pi\left({}^{\langle}U\cdot\nabla\sigma^{\mu\nu\rangle} + \tfrac{1}{3}\nabla\cdot U\sigma^{\mu\nu}\right)$$
$$+\kappa\left(R^{\langle\mu\nu\rangle} - 2U_\rho U_\sigma R^{\rho\langle\mu\nu\rangle\sigma}\right)$$
$$+\lambda_1\sigma^{\langle\mu}{}_\rho\sigma^{\nu\rangle\rho} + \lambda_2\sigma^{\langle\mu}{}_\rho\Omega^{\nu\rangle\rho} + \lambda_3\Omega^{\langle\mu}{}_\rho\Omega^{\nu\rangle\rho} + \dots$$

where σ and Ω are the fluid's shear and vorticity tensors:

$$\sigma^{\mu\nu} = 2\nabla^{\langle\mu}U^{\nu\rangle} \equiv \tfrac{1}{2}\Delta^{\mu\rho}\Delta^{\nu\sigma}(2\nabla_\rho U_\sigma + 2\nabla_\sigma U_\rho) - \tfrac{1}{3}\Delta^{\mu\nu}\Delta^{\rho\sigma}2\nabla_\rho u_\sigma$$
$$\Omega^{\mu\nu} = \tfrac{1}{2}\Delta^{\mu\rho}\Delta^{\nu\sigma}(\nabla_\rho U_\sigma - \nabla_\sigma U_\rho)$$

and where $\Delta^{\mu\nu}$ are transverse (to the fluid's velocity) projectors.

- Compute the fluid's response to a small, slowly varying gravitational perturbation, and derive Kubo-type formulae for 2nd order hydro coefficients. [Moore, Sohrabi 2010]

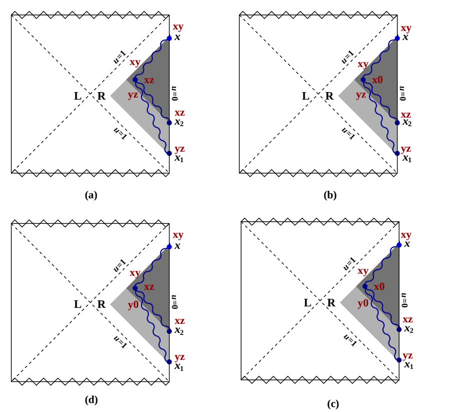
$$\begin{aligned}\langle T^{\mu\nu}(z)\rangle_h &= \langle T^{\mu\nu}\rangle_{h=0} - \frac{1}{2}\int d^4x\, G_{ra}^{\mu\nu\,\rho\sigma}(z;x)h_{\rho\sigma}(x) \\ &+ \frac{1}{8}\int d^4x \int d^4y\, G_{raa}^{\mu\nu\,\rho\sigma\,\tau\zeta}(z;x,y)h_{\rho\sigma}(x)h_{\tau\zeta}(y) + \dots\end{aligned}$$

- Solve the conservation law $\nabla_\mu T^{\mu\nu} = 0$, iteratively, in the fluid's velocity U^μ, and order-by-order in the metric fluctuations $\Longrightarrow$ get Kubo-type formulae! [Arnold, DV, Wu, Xiao, 2011]

$$\lim_{\substack{\omega_1\to 0\\ \omega_2\to 0}} \partial_{\omega_1}\partial_{\omega_2} \lim_{\substack{k_1\to 0\\ k_2\to 0}} G^{xy\,xz\,yz} = -\lambda_1 + \eta\tau_\Pi$$

$$\lim_{\substack{\omega_2\to 0\\ k_1\to 0}} \partial_{k_2}\partial_{\omega_1} \lim_{\substack{\omega_2\to 0\\ k_1\to 0}} G^{xy\,yz\,tx} = -\tfrac{1}{4}\lambda_2 + \tfrac{1}{2}\eta\tau_\Pi$$

$$\lim_{\substack{k_1\to 0\\ k_2\to 0}} \partial_{k_1}\partial_{k_2} \lim_{\substack{\omega_1\to 0\\ \omega_2\to 0}} G^{xy\,0x\,0y} = -\tfrac{1}{4}\lambda_3$$



$$\lim_{\substack{k_1\to 0\\ k_2\to 0}} G^{xy\,yz\,xz}_{AdS} = \frac{N_c^2}{2^4\pi^2}\left[\frac{1}{2^3} - i\frac{\omega_1+\omega_2}{2^2} - \frac{(\omega_1\omega_2+\omega_1^2+\omega_2^2)(\ln 2-1)}{2^2} + \dots\right]$$

$$\lim_{\substack{k_1\to 0\\ k_2\to 0}} G^{xy\,yz\,xz}_{\text{hydro}} = \frac{N_c^2}{2^4\pi^2}\left[\tfrac{1}{3}\bar{\epsilon} - i\eta(\omega_1+\omega_2) + \eta\tau_\Pi(\omega_1^2+\omega_2^2+\omega_1\omega_2) - \tfrac{1}{2}\kappa(\omega_1^2+\omega_2^2) - \lambda_1\omega_1\omega_2 + \dots\right]$$

- λ_1: $\lambda_1 = \frac{N_c^2}{2^6\pi^2}, \Rightarrow \lambda_1 = \frac{N_c^2 T^2}{16}.$

$$\lim_{\substack{\omega_1\to 0\\ \omega_2\to 0}} G^{xy\,ty\,tx}_{AdS} = \frac{N_c^2}{2^6\pi^2}\left[-\frac{1}{2} + (k_1^2+k_2^2) + \dots\right]$$

$$\lim_{\substack{\omega_1\to 0\\ \omega_2\to 0}} G^{xy\,ty\,tx}_{\text{hydro}} = -\tfrac{1}{3}\bar{\epsilon} + \tfrac{1}{2}\kappa(k_2^2+k_1^2) - \tfrac{1}{4}\lambda_3 k_1 k_2 + \dots$$

- λ_3: $\lambda_3 = 0.$

$$\lim_{\substack{k_1\to 0\\ \omega_2\to 0}} G^{xy\,yz\,tx}_{AdS} = \frac{N_c^2}{2^6\pi^2}\omega_1 k_2 + \dots$$

$$\lim_{\substack{k_1\to 0\\ \omega_2\to 0}} G^{xy\,yz\,tx}_{\text{hydro}} = (-\tfrac{1}{4}\lambda_2 + \tfrac{1}{2}\eta\tau_\Pi)\omega_1 k_2 + \dots$$

- λ_2: $\lambda_2 = -\frac{N_c^2}{2^5\pi^2}\ln 2 \Rightarrow \lambda_2 = -\frac{1}{8}N_c^2 T^2 \ln 2.$

Building AdS/CFT bottom-up: Aging Dynamics

Non-equlibrium criticality/ Aging
Hankel, Pleimling: A physical many-body system will undergo aging if the relaxation process towards its stationary state(s) exhibits
-slow dynamics (non-exponential relaxation)
-breaking of time-translation invariance
-dynamical scaling.
Example: take a feromagnetic spin system, which is prepared in a high temperature state, then quenched below its critical temperature and left to evolve freely. The size of the clusters of ordered spins, which form and grow, is time-dependent: $L \sim t^{1/z}$.
Features: two-point correlation functions depend on both times, not only on their difference.

Start with the symmetries.
Schrodinger group

$$t \to t' = \frac{\alpha t + \beta}{\gamma t + \delta} \qquad , \vec{r} \to \vec{r}' = \frac{R\vec{r} + \vec{v}t + \vec{a}}{\gamma t + \delta}$$
$$\alpha\delta - \beta\gamma = 1$$

where R is a rotation matrix. The various Schrodinger group transformations are: time and spatial-translation $(\beta, \vec{a})$, spatial rotations (R), Galilei transformations $(\vec{v})$, dilatations (δ) and special Schrodinger transformation (γ).
For Aging, eliminate time-translations. Compute 2 and 3-point correlation functions (for scalar operators they are left invariant by the Aging algebra generators). [Minic, DV, Wu].
To construct the holographic dual, ask that the algebra of the Age generators is the algebra of the Killing vectors (generators of metric symmetries). Reverse-engineer the algebra to give you a metric. Ask if the metric derived yields compatible expressions for 2 and 3-point correlators.

Conclusions

AdS/CFT and its various extensions AdS/QCD, gauge/string duality, AdS/CMT have given us an analytic window into strongly coupled systems. There are many string theory constructions dual to confining gauge theories, but none is yet hailed as the QCD holographic dual.

However, the strongly coupled plasma studied at RHIC and LHC and finite temperature AdS/CFT have similar characteristics. Therefore calculations performed using AdS/CFT techniques (e.g. hydrodynamic coefficients, jet quenching) are in fairly good agreement with experimental results.

Currently, many people are exploring and extending these techniques to various condensed matter systems.

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