# AdS/CFT and nonequilibrium QCD

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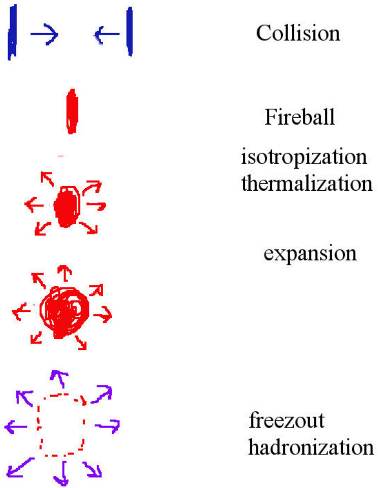
# Outline

1. **Motivation**
   - The AdS/CFT correspondence
   - $\mathcal{N} = 4$ plasma versus QCD plasma
   - Why study $\mathcal{N} = 4$ plasma?
2. **The AdS/CFT methods**
3. **Boost-invariant flow**
4. **Large proper time regime**
5. **Small proper time regime**
6. **Other nonequilibrium processes**
7. **Conclusions**

## Motivation

**Point of reference:** heavy-ion collision at RHIC:



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- Study properties of the expanding plasma system
- Initially focus on late stages of expansion
- Derive hydrodynamic expansion in its fully nonlinear regime
- Proceed to earlier times...
- Dissipative effects start to be important
- Consider far from equilibrium behaviour at very early times
- Understand early thermalization/isotropization

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# The AdS/CFT correspondence

| $\mathcal{N} = 4$ Super Yang-Mills theory | $\equiv$ | Superstrings on $AdS_5 \times S^5$ |
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| strong coupling | | (semi-)classical strings |
| nonperturbative physics | | or supergravity |
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- Deconfined phase
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Differences:

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- (Exactly) conformal equation of state
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- Try to build some new physical intuitions within this new language
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# The AdS/CFT setup

EMPTY SPACE

(VACUUM)


$AdS_5$ $(\times S^5)$

$$ds^2 = \frac{\eta_{\mu\nu} dx^\mu dx^\nu + dz^2}{z^2}$$

| GAUGE THEORY SIDE | | STRING THEORY SIDE |
|---|---|---|
| STATE WITH GIVEN EXPECTATION VALUES OF THE CORRESPONDING OPERATOR | | |


| | | | |
|---|---|---|---|
| $\langle T_{\mu\nu} \rangle \neq 0$ | $\longleftrightarrow$ | GRAVITON | $g_{\mu\nu}$ |
| $\langle \mathrm{tr}\, F^2 \rangle \neq 0$ | $\longleftrightarrow$ | DILATON | $\phi$ |
| GENERIC OPERATOR | $\longleftrightarrow$ | GENERIC STRING STATE | |

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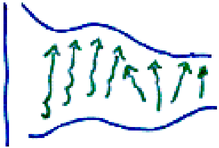

DESCRIBED BY SOME BACKGROUND GEOMETRY:

$$\langle T_{\mu\nu} \rangle = \ldots \quad \longleftrightarrow \quad ds^2 = \frac{g_{\mu\nu}(x^\mu, z)\, dx^\mu dx^\nu + dz^2}{z^2}$$

MACROSCOPIC SPACETIME PROFILE OF ENERGY MOMENTUM TENSOR

# Basic strategy

1. Pick some family of $\langle T_{\mu\nu}(x^\rho) \rangle$'s
2. Solve *5-dimensional* Einstein's equations to obtain the geometry

$$ds^2 = \frac{g_{\mu\nu}(x^\rho, z)dx^\mu dx^\nu + dz^2}{z^2}$$

3. Generically the above geometry will be singular.
   The $\langle T_{\mu\nu}(x^\rho) \rangle$ leading to nonsingular geometry will be singled out as physical...

**or**

1. Start from some (nonsingular!) initial data ($\equiv$ initial geometry in the bulk)
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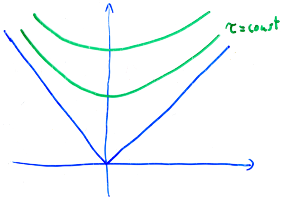
Bjorken '83

Assume a flow that is invariant under longitudinal boosts and does not depend on the transverse coordinates.




- Pass to proper-time/spacetime rapidity coordinates $(\tau, y, x_1.x_2)$.
- In a conformal theory, $T^\mu_\mu = 0$ and $\partial_\mu T^{\mu\nu} = 0$ determine, under the above assumptions, the energy-momentum tensor completely in terms of a single function $\varepsilon(\tau)$.
- $\varepsilon(\tau)$ is the energy density at mid-rapidity.

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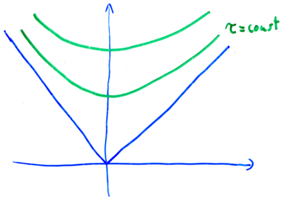


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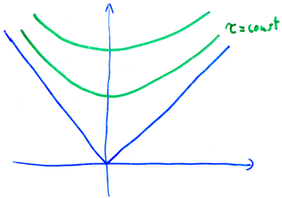


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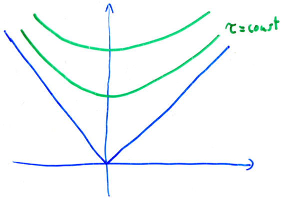


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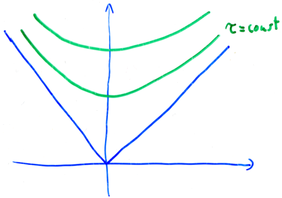
- In a conformal theory, $T^\mu_\mu = 0$ and $\partial_\mu T^{\mu\nu} = 0$ determine, under the above assumptions, the energy-momentum tensor completely in terms of a single function $\varepsilon(\tau)$.
- $\varepsilon(\tau)$ is the energy density at mid-rapidity.

We will be now interested in the late-time asymptotics of $\varepsilon(\tau)$.

Bjorken '83

Assume a flow that is invariant under longitudinal boosts and does not depend on the transverse coordinates.

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## What is the physics of $\varepsilon(\tau)$?

- Weak coupling – free streaming

$$\varepsilon(\tau) = \frac{1}{\tau}$$

- Perfect fluid assumption

$$\varepsilon(\tau) = \frac{1}{\tau^{\frac{4}{3}}}$$

- Fluid with viscosity $\eta = \frac{\eta_0}{\tau}$

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# How to determine $\varepsilon(\tau)$?

- Consider some $\varepsilon(\tau)$ RJ,Peschanski
- Construct the dual geometry

$$\boxed{\varepsilon(\tau)} \longrightarrow \boxed{ds^2 = \frac{g_{\mu\nu}(z,\tau)dx^\mu dx^\nu + dz^2}{z^2}}$$

- Require that the dual geometry is **nonsingular**
- This requirement will pick out physically allowed $\varepsilon(\tau)$...

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- The resulting geometry looks like a black hole with the horizon moving into the bulk ≡ Hawking temperature falls ≡ the plasma expands and cools
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- Dissipative effects become more and more important
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- Recent studies:

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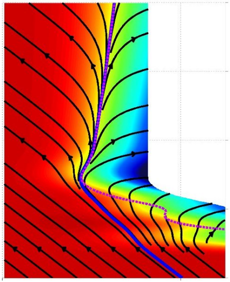

Beuf, Heller, RJ, Peschanski

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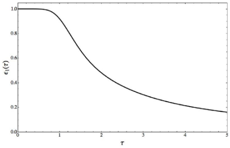

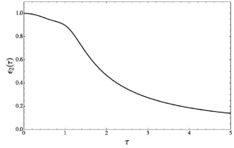

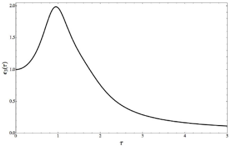


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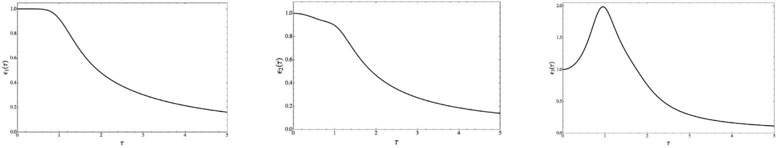


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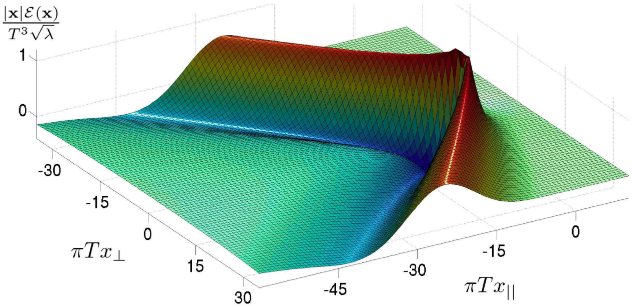
Chesler, Yaffe 0706.0368

- Consider a heavy quark moving through infinite static plasma with velocity greater than the speed of sound



# Conclusions

- AdS/CFT is an effective tool to study real time dynamics of strongly coupled plasma
- Apart from the most developed case of $\mathcal{N} = 4$ theory discussed here there are refinements for more realistic theories
- AdS/CFT predicts hydrodynamics in its fully nonlinear regime
- Very general framework for studying time-dependent dynamical processes or out-of-equilibrium configuration
- Investigate early time dynamics...
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