AdS/CFT for the early stages of heavy ion collisions

Quark Matter 2014

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Outline

The AdS/CFT correspondence

$\mathcal{N} = 4$ plasma versus QCD plasma

What physics is captured by the AdS/CFT description?

Recent results

- Another look on boost-invariant equilibration
- Nonhydrodynamic degrees of freedom from a 4D perspective
- Other developments
- Shock wave collisions – thick/thin and with substructure
- A hybrid AdS/CFT – QGP description
- Other AdS/CFT talks in the parallel sessions

Conclusions

The AdS/CFT correspondence

$\mathcal{N} = 4$ **Super Yang-Mills theory** $\equiv$ **Superstrings on** $AdS_5 \times S^5$

- $\mathcal{N} = 4$ Super Yang-Mills theory $\equiv$ gluons + 6 scalars + 4 fermions in the adjoint representation
- At $T = 0$, $\mathcal{N} = 4$ Super Yang-Mills theory is completely different from QCD...
- For $T > T_c$ this is not the case:

A quote from the abstract of
A. Czajka, S. Mrówczyński, *N=4 Super Yang-Mills Plasma*, 1203.1856:

perturbative, Schwinger-Keldysh, collective excitations, collisional processes...

...The N=4 super Yang-Mills plasma is finally concluded to be very similar to the QCD plasma of gluons and light quarks. The differences mostly reflect different numbers of degrees of freedom in the two systems.

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Interpretation:

- The higher dimensional string description is **not** some exotic physics but rather a repackaging of gauge theory degrees of freedom in a novel way
- In *some contexts*, some of these DOF behave like collective hydrodynamic excitations... but there are many more...
- String DOF: **gravity modes** + **massive string modes**
- At large gauge theory coupling the **massive string modes** become very heavy and we are effectively left with the dynamics of **gravity**
- At weak coupling, all those modes are intermingled and we do not have a workable AdS/CFT description for plasma physics..

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$\mathcal{N} = 4$ plasma versus QCD plasma

Similarities:

- Deconfined phase
- Strongly coupled
- **No supersymmetry!**

Differences:

- No running coupling $\longrightarrow$ Even at very high energy densities the coupling remains strong
- (Exactly) conformal equation of state $\longrightarrow$ Perhaps not so bad around $T \sim 1.5 - 2.5\, T_c$
- No confinement/deconfinement phase transition $\longrightarrow$ The $\mathcal{N} = 4$ plasma expands and cools indefinitely

One can pass to more complicated AdS/CFT setups and lift the above differences

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Why use AdS/CFT?

1. We can *compute* what happens in a strongly coupled plasma in some specific gauge theory (here $\mathcal{N} = 4$ SYM)
2. Consider whether this **may** happen in real QGP...
3. Possibly provides some ball-park figures (e.g. η/s)

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What physics is captured by the AdS/CFT description?

Consider the excitations of an infinite uniform static plasma system

- Small disturbances of the uniform static plasma $\equiv$ small perturbations of the black hole metric ($\equiv$ quasinormal modes (QNM))

$$g^{5D}_{\alpha\beta} = g^{5D,black\ \ hole}_{\alpha\beta} + \delta g^{5D}_{\alpha\beta}(z)\, e^{-i\omega t + ikx}$$

- This gets translated on the gauge theory plasma side to

$$T_{\mu\nu} = T^{static}_{\mu\nu} + t_{\mu\nu}\, e^{-i\omega t + ikx}$$

- Dispersion relation fixed by linearized Einstein's equations.

from Kovtun,Starinets hep-th/0506184

- Lowest mode: hydrodynamic sound mode...

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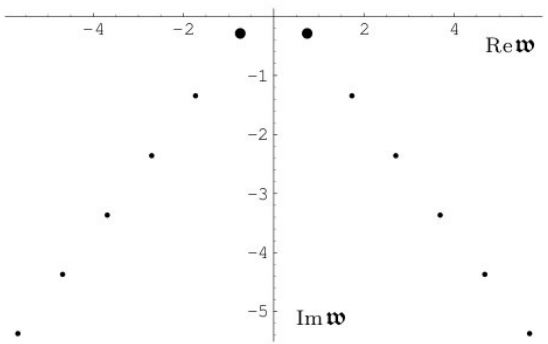
Fix k



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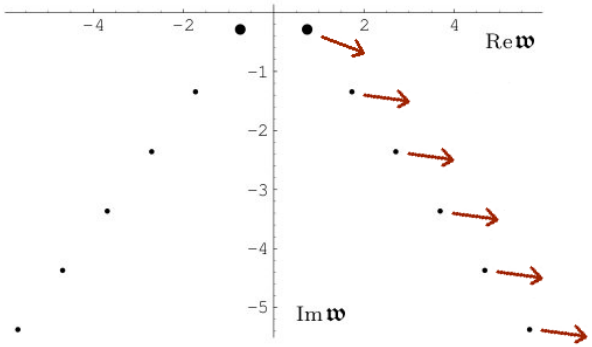

$\longrightarrow$ Determine $\omega_i(k)$

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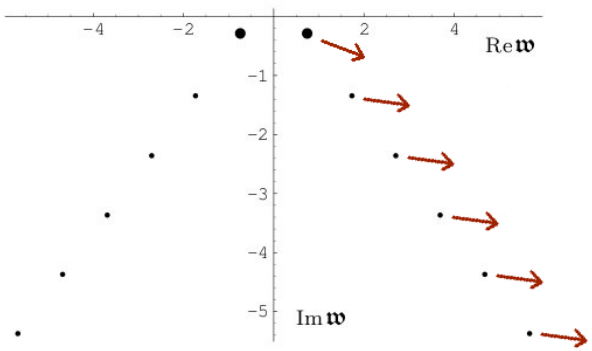

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Einstein's equations in AdS/CFT

- contain all-order viscous hydrodynamic modes (with specific values of all transport coefficients)

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- **in addition** contain the dynamics of genuine nonhydrodynamical modes

$$\omega^{(n)}_{non-hydro} = -i\Gamma_n \pm \Omega_n + \mathcal{O}\left(k^{\#}\right)$$

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Einstein's equations in AdS/CFT

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We have much more degrees of freedom than hydrodynamics.
Is it natural from the gauge theory point of view?

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Question:
When are those nonhydrodynamic degrees of freedom relevant?

- Around equilibrium they are damped — however far from equilibrium nonhydrodynamic degrees of freedom are dominant
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Bjorken '83
Assume a flow that is invariant under longitudinal boosts and does not depend on the transverse coordinates.

- Start from various initial configurations
- Measure local energy density through an *effective temperature* T_{eff}:

$$\varepsilon(\tau) = \frac{3}{8} N_c^2 \pi^2 \, T_{eff}^4(\tau)$$

- Normalize data ($\equiv$ choose units) such that

$$\pi \, T_{eff}(\tau) \sim \frac{1}{\tau^{\frac{1}{3}}} \qquad \text{in the } \tau \to \infty \text{ limit}$$

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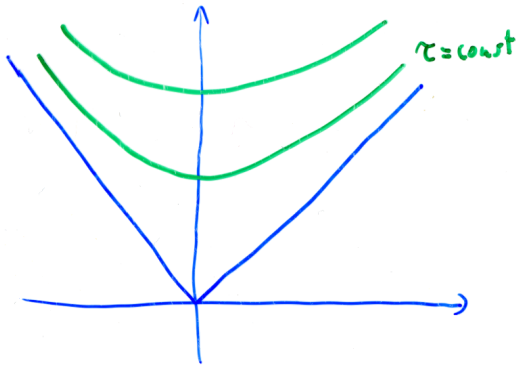

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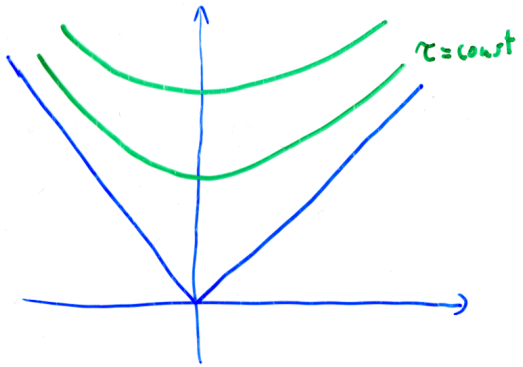

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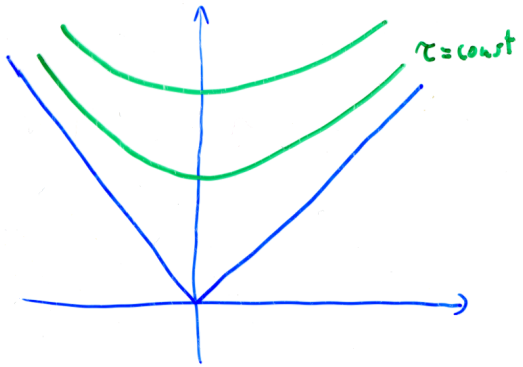

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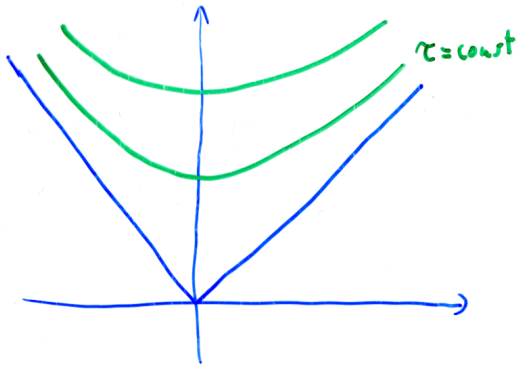

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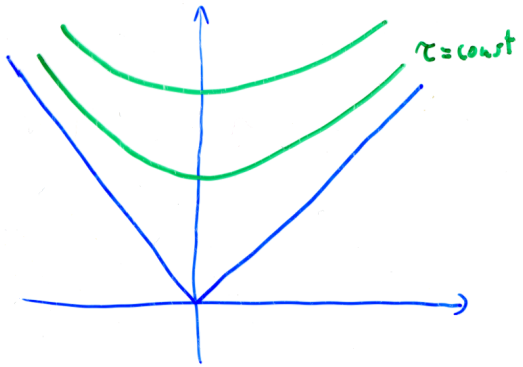

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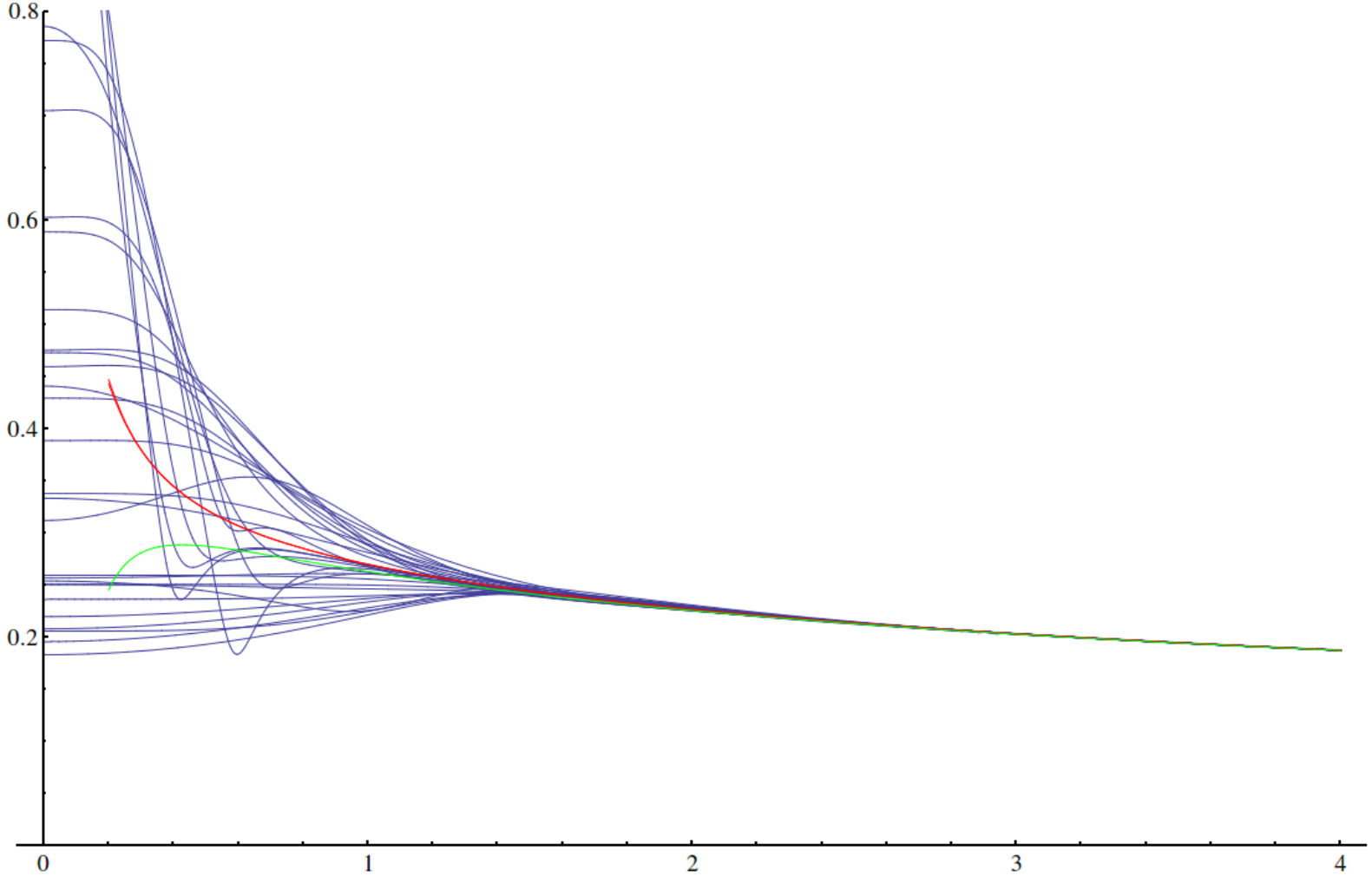

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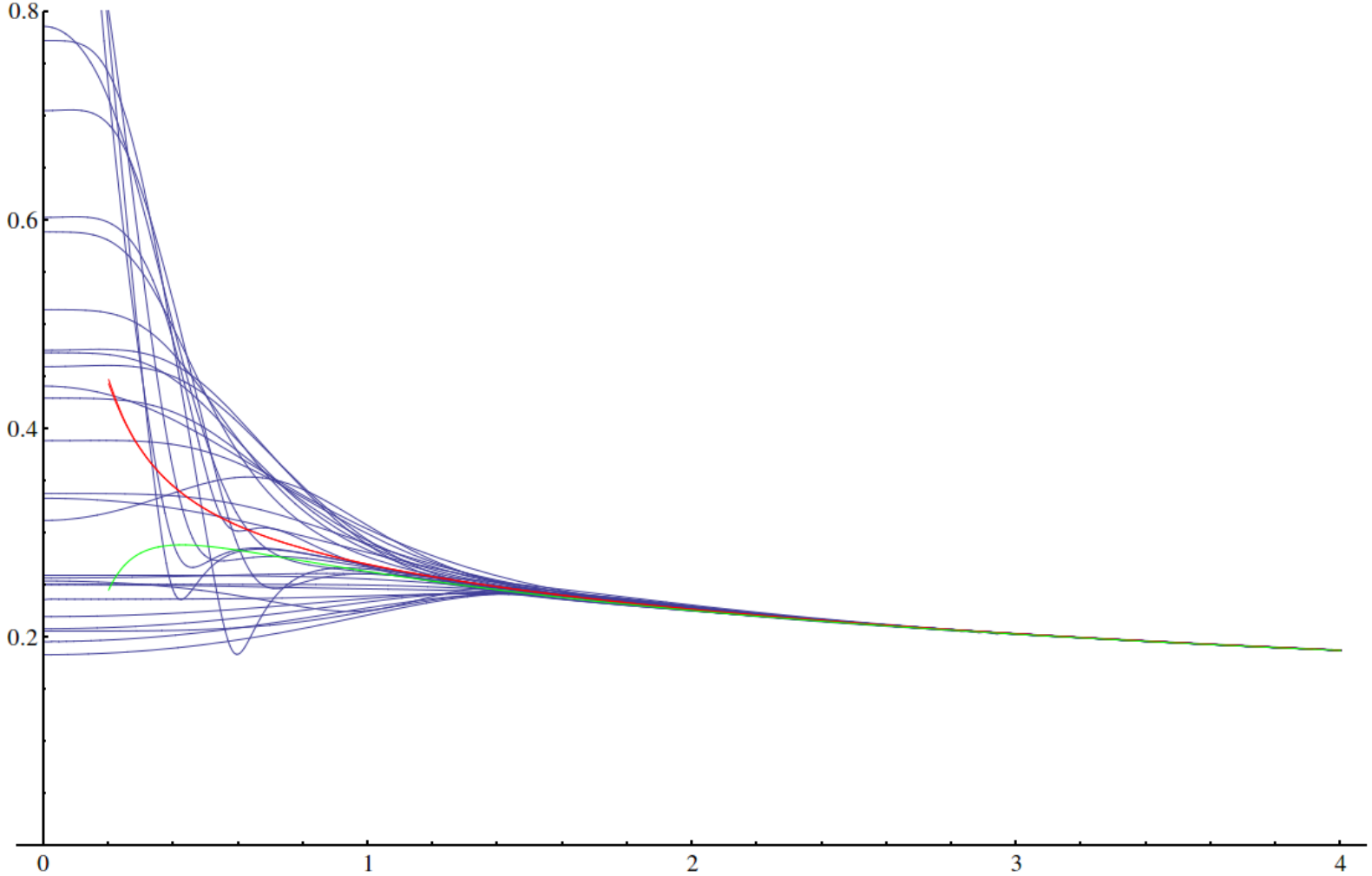

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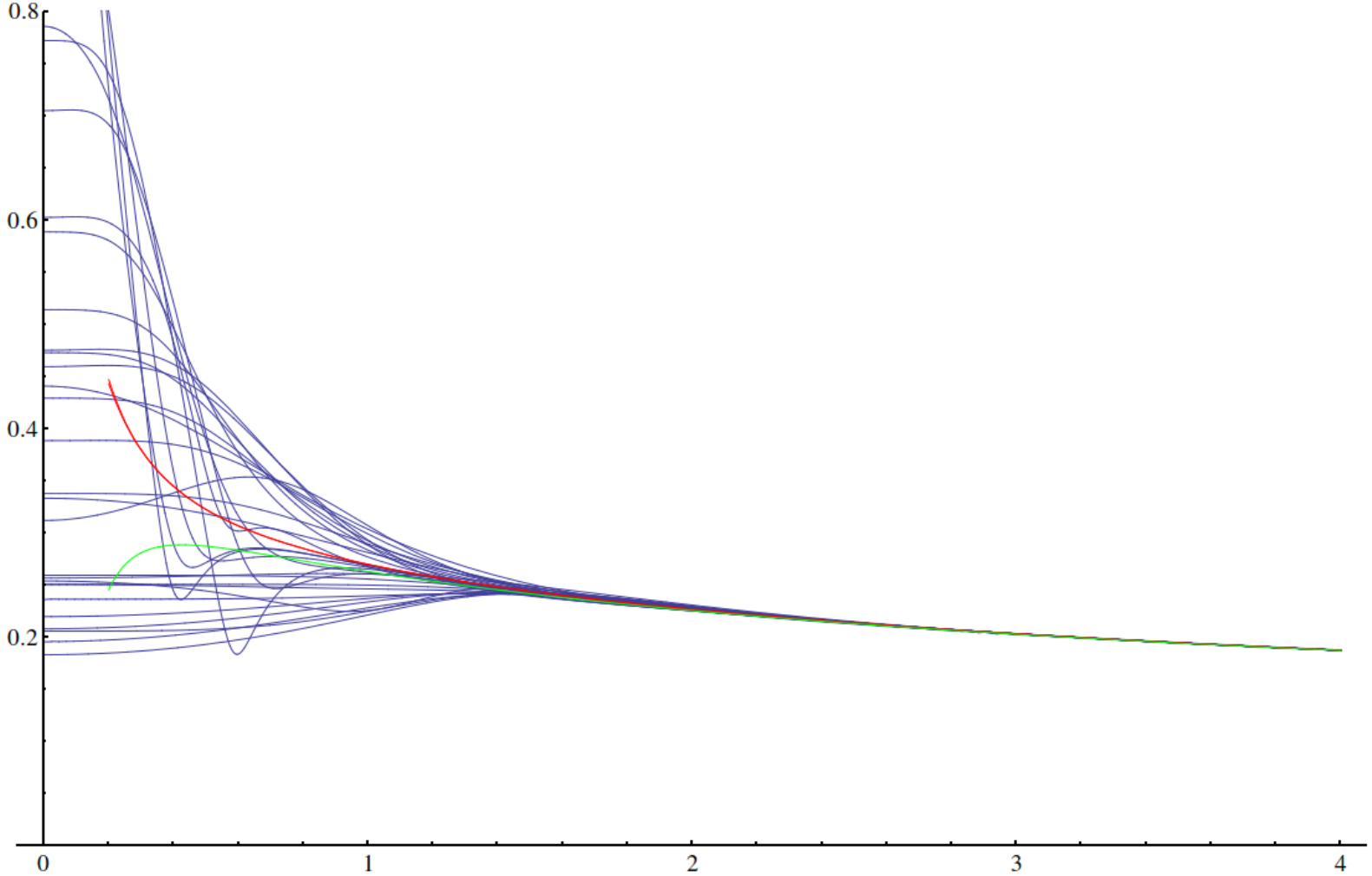

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$$\Delta p_L \equiv 1 - \frac{p_L}{\varepsilon/3} \sim 0.7$$

2. **Hydrodynamization $\neq$ Thermalization**

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(consistent with AdS/CFT analysis)

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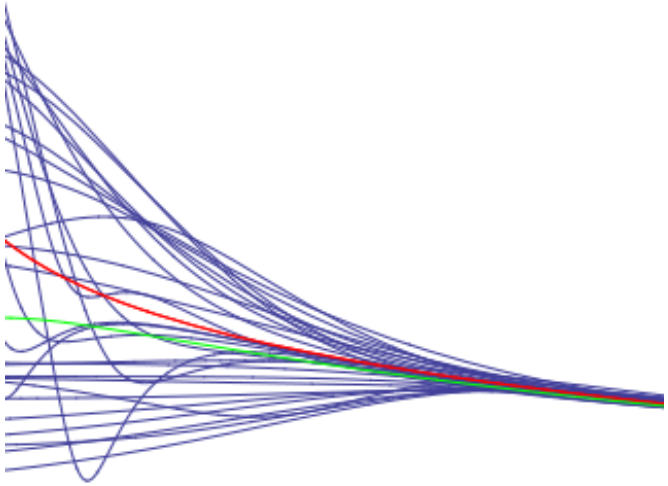

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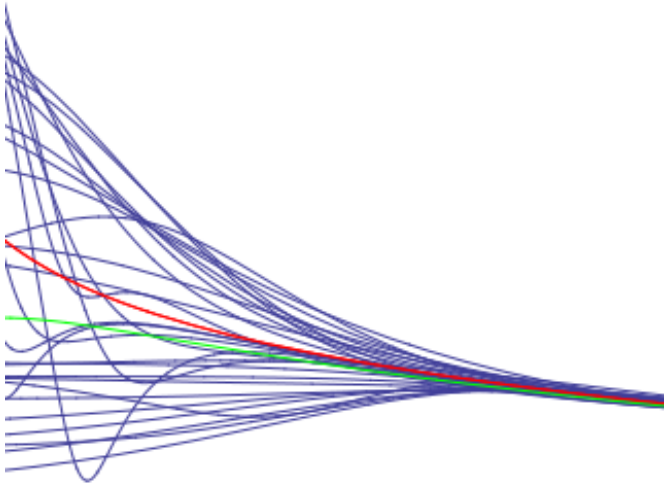

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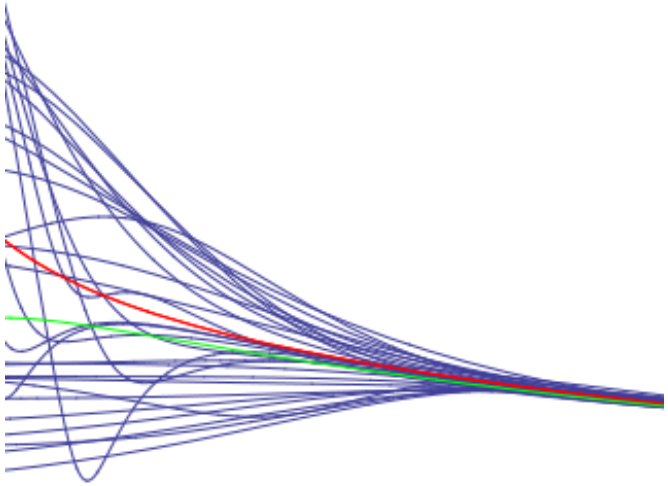

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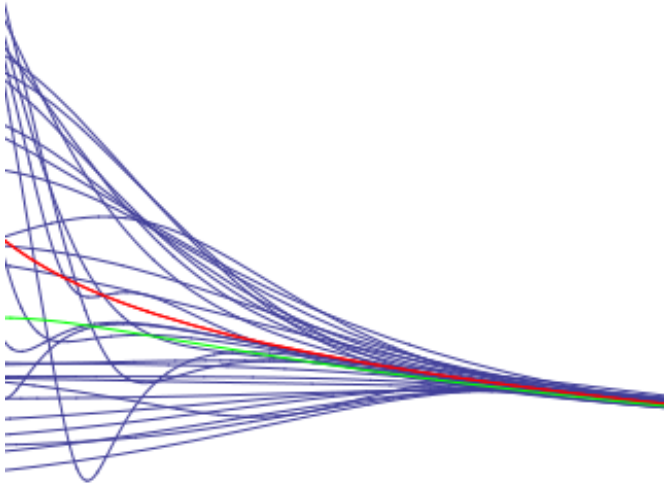

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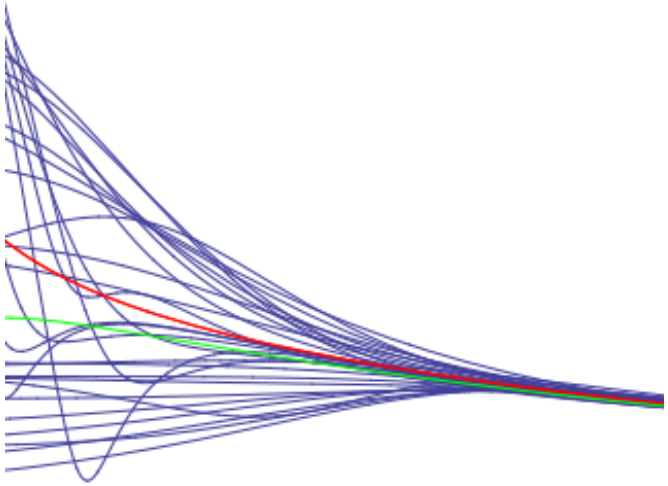
Nonhydrodynamic degrees of freedom from a 4D perspective



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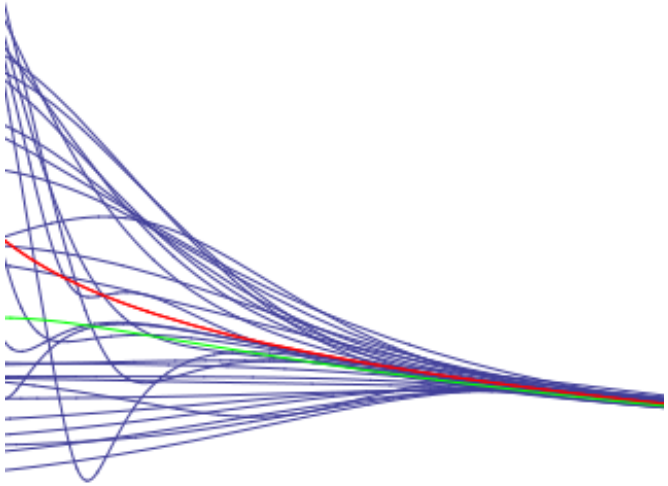

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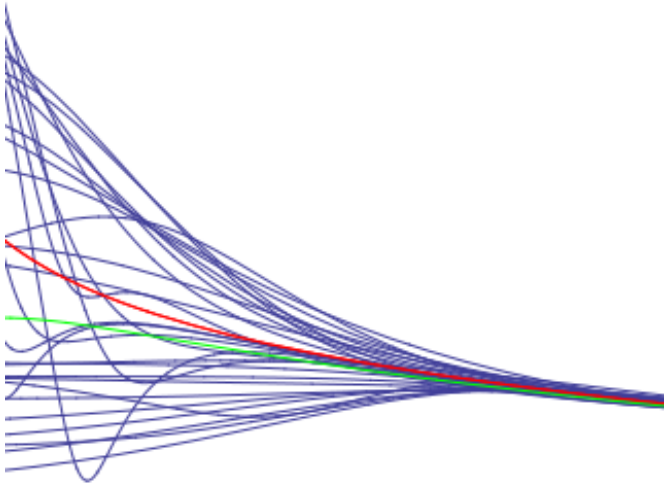

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Other developments

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Heller, RJ, Witaszczyk [PRL 110, 211602 (2013)]

- We now have **very detailed** understanding of high order dissipative hydrodynamics for strongly coupled $\mathcal{N} = 4$ SYM in the boost-invariant context

$$T_{eff}(\tau) = \frac{1}{\tau^{\frac{4}{3}}}\left[1 + \sum_{n=1}^{240} a_n \frac{1}{\tau^{\frac{2n}{3}}}\right]$$

with a_n known numerically to a high accuracy

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- Hydrodynamization of (inhomogeonous) *UV sourced* configurations in a 2+1 theory
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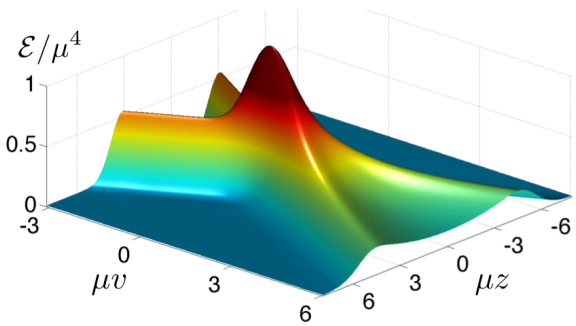

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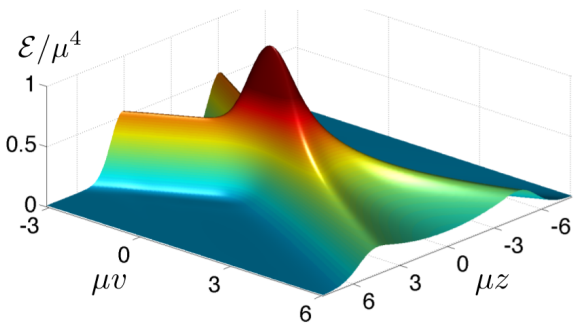

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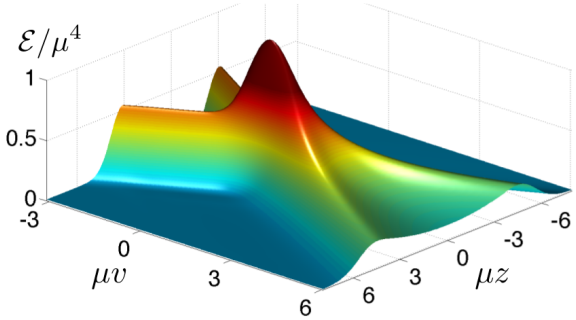

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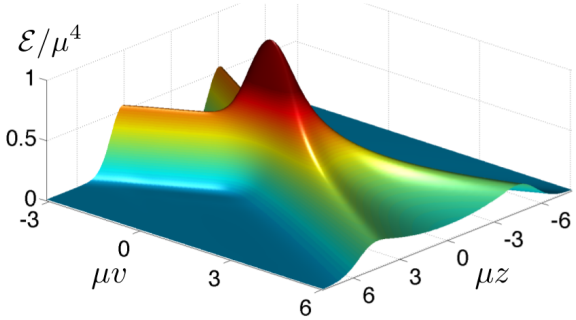

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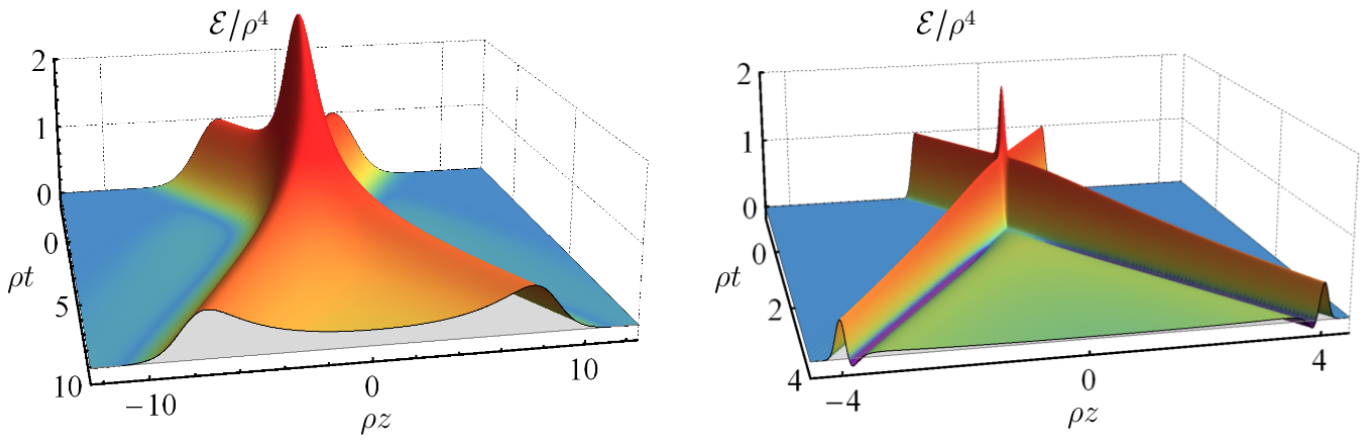

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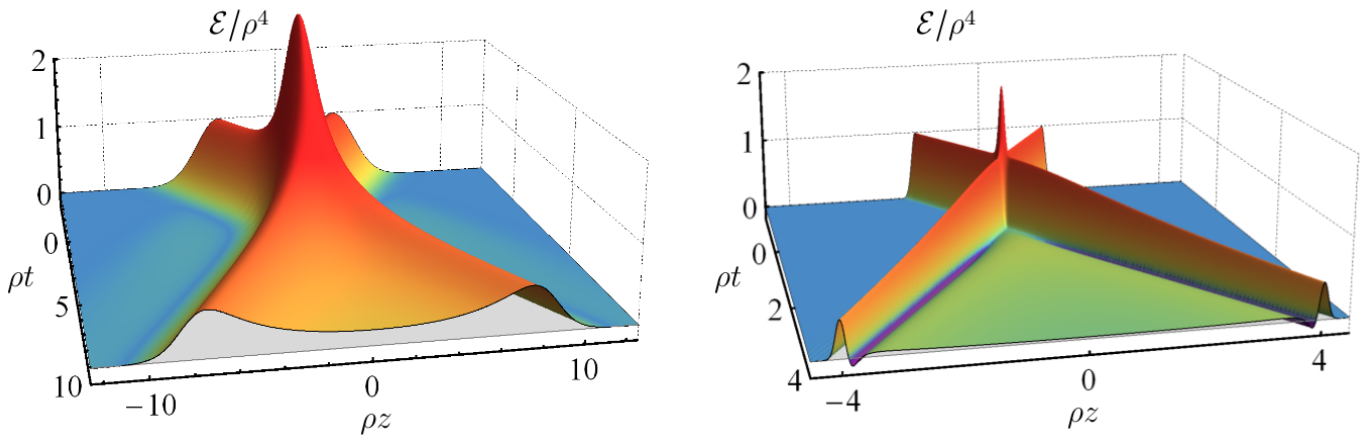

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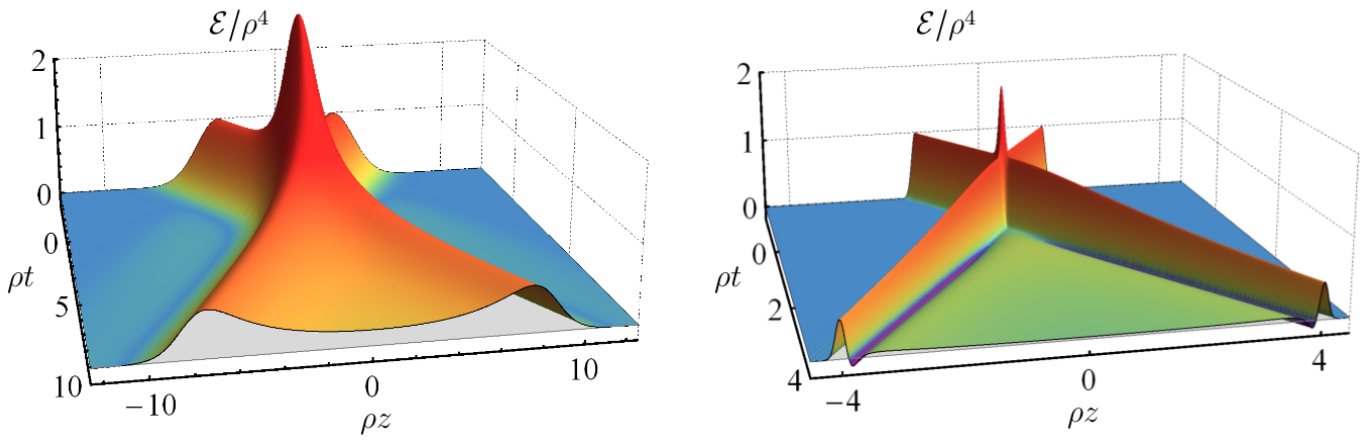

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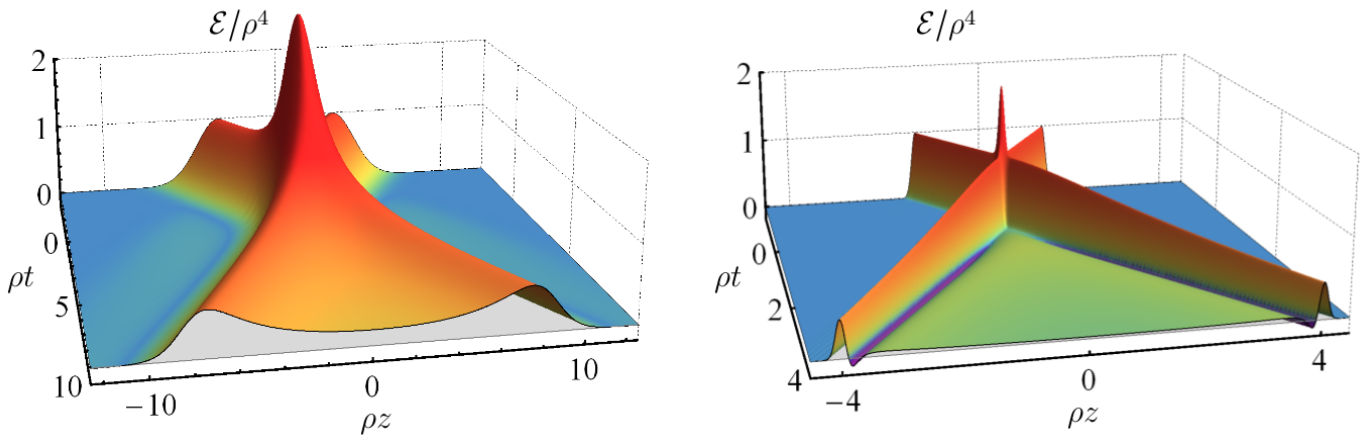

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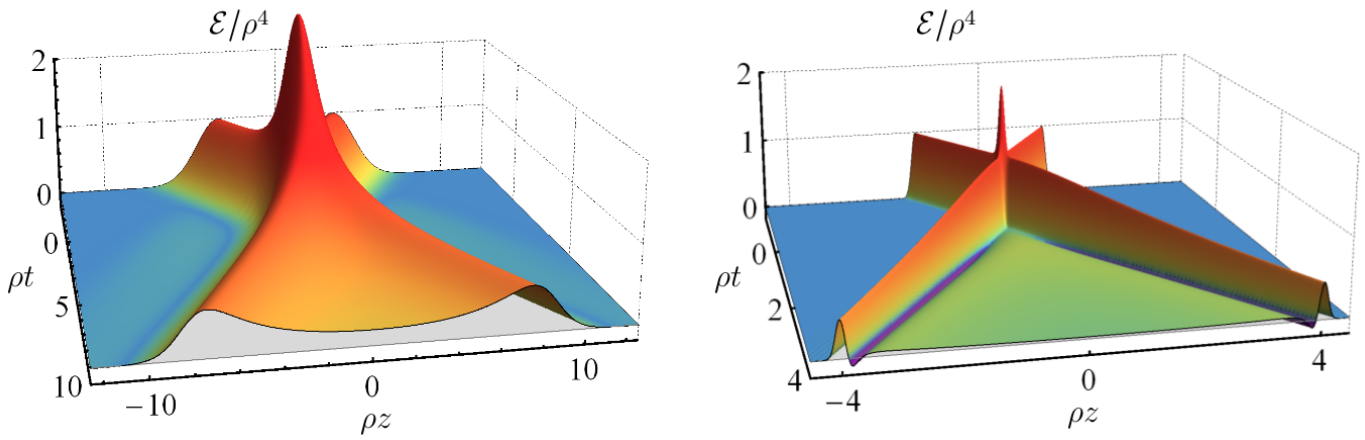

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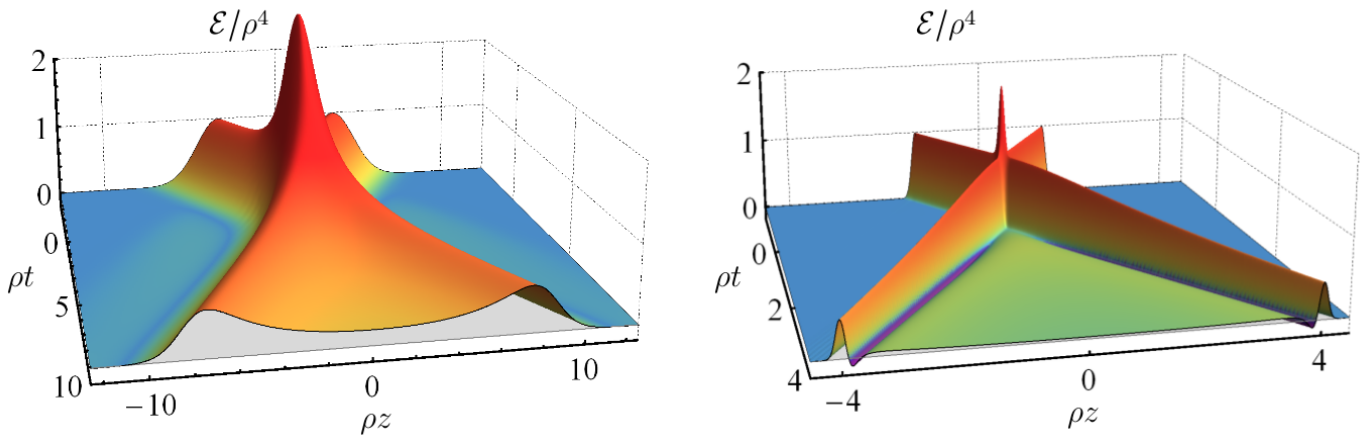

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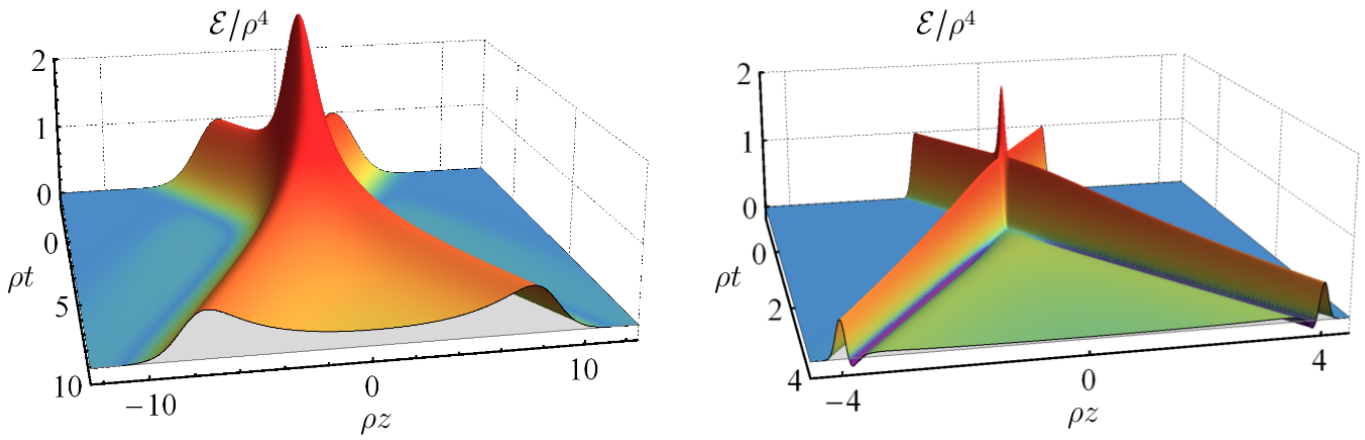

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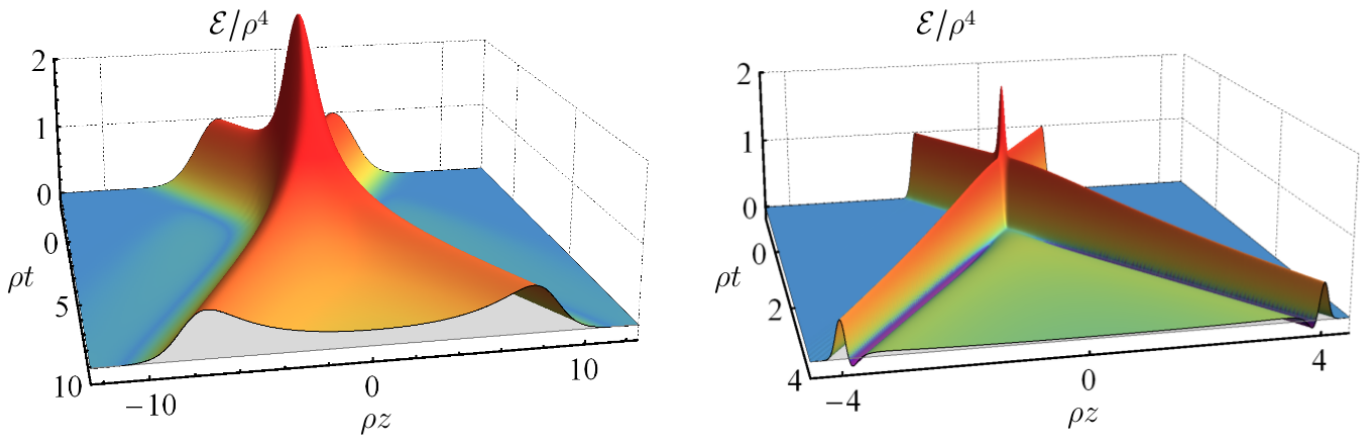

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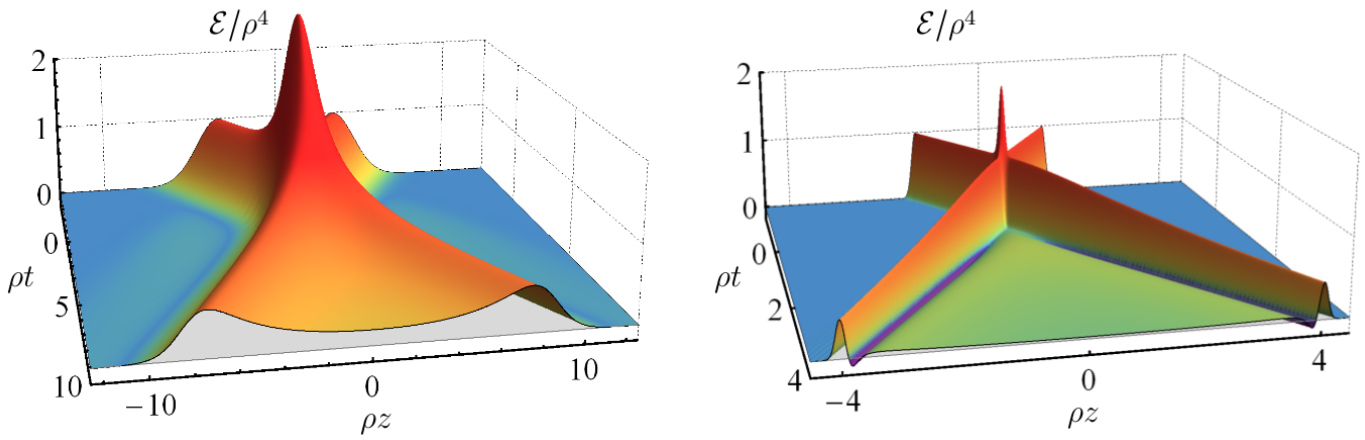

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1312.2956

Study shock wave collisions with nontrivial longitudinal structure

$$T_{++}(x^+) = \frac{N_c^2}{2\pi^2} \cdot \frac{\mu^3}{8\pi\sigma} \left\{ \exp\left[-\frac{(x^+ - L/2)^2}{2\sigma^2} \right] + \exp\left[-\frac{(x^+ + L/2)^2}{2\sigma^2} \right] \right\}$$

Key result:

- The created plasma at midrapidity is **insensitive** to the structure of the initial shock waves if

$$L < \frac{0.26}{T_{hydr}}$$

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1312.2956

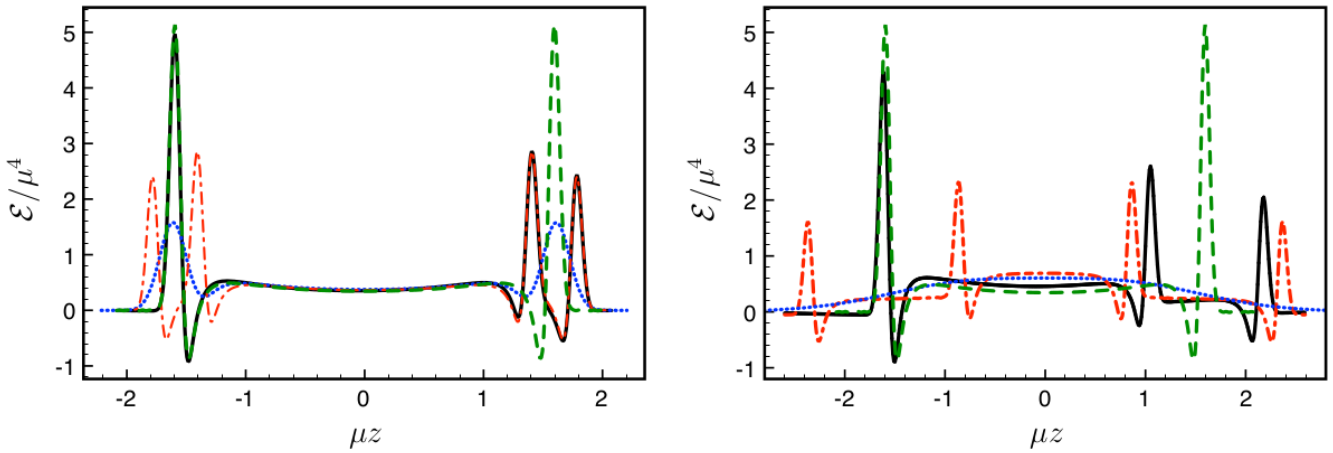
Study shock wave collisions with nontrivial longitudinal structure

$$T_{++}(x^+) = \frac{N_c^2}{2\pi^2} \cdot \frac{\mu^3}{8\pi\sigma} \left\{ \exp\left[-\frac{(x^+ - L/2)^2}{2\sigma^2} \right] + \exp\left[-\frac{(x^+ + L/2)^2}{2\sigma^2} \right] \right\}$$

Key result:

- The created plasma at midrapidity is **insensitive** to the structure of the initial shock waves if

$$L < \frac{0.26}{T_{hydr}}$$



A hybrid study of central nuclear collisions

W. v.d. Schee, P. Romatschke, S. Pratt, [PRL 111, 222302 (2013)]

1. Model a nuclei by a thin shock-wave with *realistic radial size*
2. Use numerical relativity solution in AdS/CFT for the pre-equillibrium stage
3. At the transition to hydrodynamics, this provides initial conditions for subsequent hydrodynamic evolution

   Key point: *initial AdS/CFT evolution generates some specific radial preflow*
4. Use standard **realistic** viscous hydrodynamic code for hydrodynamic flow and kinetic theory for the low-density hadronic stage
5. Excellent agreement of light particle spectra with ALICE results

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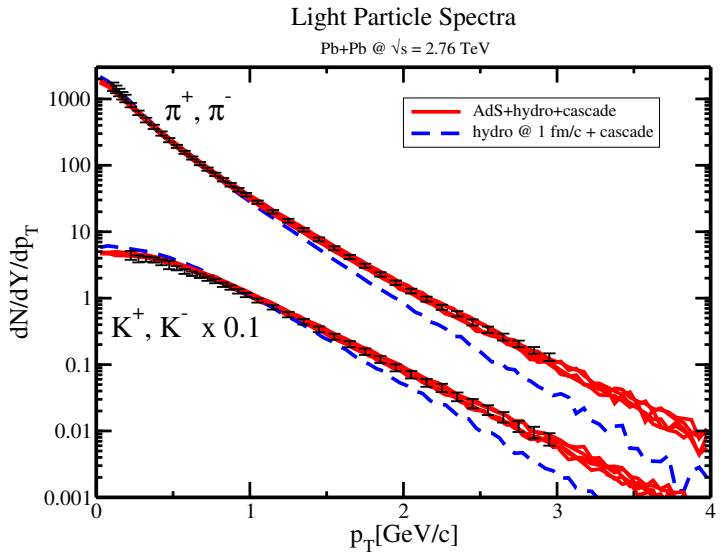

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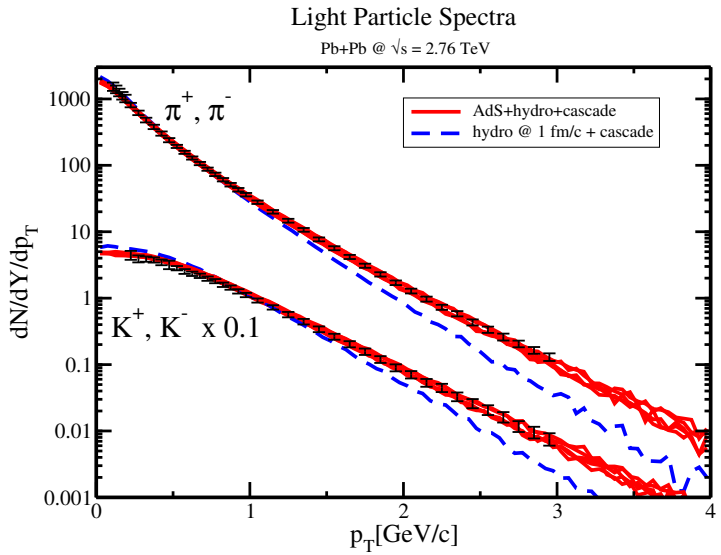

Other AdS/CFT talks in the parallel sessions

W.A. Horowitz
AdS/CFT heavy-quark energy loss beyond the leading order

P. Arnold
Relating classical strings and gravitons in AdS/CFT jet quenching

K. Rajagopal
Jet quenching in strongly coupled plasma

D. Pablos
A hybrid strong/weak coupling approach to jet quenching

Conclusions

- AdS/CFT provides a very general framework for studying time-dependent dynamical processes
- The AdS/CFT methods *do not* presuppose hydrodynamics so are applicable even to very out-of-equilibrium configurations
- AdS/CFT may fill in gaps in our knowledge of the early nonequilibrium stage of plasma evolution
- We can get novel qualitative(/semi-quantitative?) insight into the features of the transition to hydrodynamic behaviour
- A direct handle on non-hydrodynamic behaviour
- Surprising universal features in shock-wave collisions
- Importance of initial preflow for hydrodynamic initial conditions
- Still lots of questions and extensions...
- ... and fascinating interrelations with General Relativity...

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