Thermalization of boost-invariant plasma from AdS/CFT

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Outline

1. **Motivation**
2. **Key physical questions**
3. **Boost-invariant flow**
4. **AdS/CFT methods for evolving plasma**
5. **Numerical relativity setup**
6. **Main results**
   - Nonequilibrium vs. hydrodynamic behaviour
   - Entropy
   - Characteristics of thermalization
7. **Conclusions**

Motivation

- There are strong indications that the quark-gluon plasma produced at RHIC is a strongly coupled system
- This poses numerous problems for the theoretical description (but also makes it very interesting)
- Static properties:
  - Thermodynamics — entropy/energy density etc.
  - Lattice QCD is an effective tool
  - Directly deals with QCD!
  - Quantitative results
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  - Expansion of the plasma in heavy-ion collisions
  - *Derivation* of hydrodynamic expansion in the later stages of the collision
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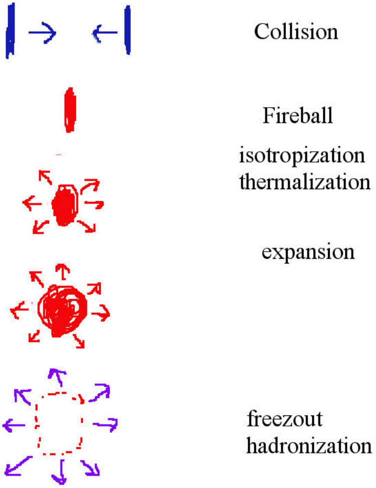
Point of reference: heavy-ion collision at RHIC:

c.f. lectures by Hirano



Key physical questions

- When and how does the transition to hydrodynamics ($\equiv$ thermalization/ isotropization) occur?
- To what extent would higher order (even all-order) viscous hydrodynamics explain plasma dynamics or do we need to incorporate genuine nonhydrodynamic degrees of freedom in the far from equilibrium regime
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- Deconfined phase
- Strongly coupled
- No supersymmetry!

Differences:

- No running coupling $\longrightarrow$ Even at very high energy densities the coupling remains strong
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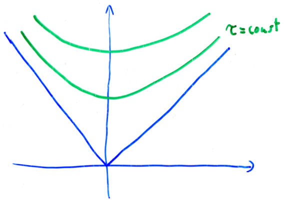
Bjorken '83

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



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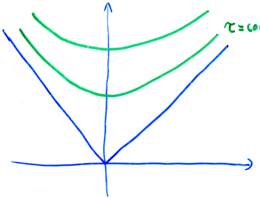

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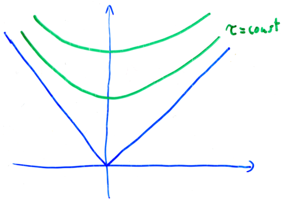

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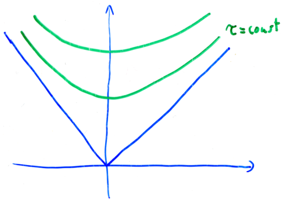

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- Leading term — perfect fluid behaviour
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- As we decrease τ more and more dissipation will start to be important
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- The large τ expansion is completely determined in terms of a single overall scale
- For small τ, in contrast, initial conditions will be very important leading to a dependence on a multitude of scales/parameters... **(this talk)**

Large τ behaviour of $\varepsilon(\tau)$

- Current result for large τ: RJ,Peschanski;RJ;RJ,Heller;Heller

$$\varepsilon(\tau) = \frac{1}{\tau^{\frac{4}{3}}} - \frac{2}{2^{\frac{1}{2}} 3^{\frac{3}{4}}} \frac{1}{\tau^{2}} + \frac{1 + 2\log 2}{12\sqrt{3}} \frac{1}{\tau^{\frac{8}{3}}} + \frac{-3 + 2\pi^2 + 24\log 2 - 24\log^2 2}{324 \cdot 2^{\frac{1}{2}} 3^{\frac{1}{4}}} \frac{1}{\tau^{\frac{10}{3}}} + \ldots$$

- Leading term — perfect fluid behaviour
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Aim: Study the evolution of $\varepsilon(\tau)$ all the way from $\tau = 0$ to large τ starting from various initial conditions...

Questions:

- When and how does the transition to hydrodynamics ($\equiv$ thermalization/ isotropization) occur? (p_L and p_T are determined in terms of $\varepsilon(\tau)$)
- To what extent would higher order (even all-order) viscous hydrodynamics explain plasma dynamics or do we need to incorporate genuine nonhydrodynamic degrees of freedom in the far from equilibrium regime
- Does there exist some physical characterization of the initial state which determines the main features of thermalization and subseqent evolution?
- What is the produced entropy from $\tau = 0$ to $\tau = \infty$ (asymptotically perfect fluid regime)

It is convenient to eliminate explicit dependence on the number of degrees of freedom and use an *effective* temperature T_{eff} instead of $\varepsilon(\tau)$

$$\langle T_{\tau\tau} \rangle \equiv \varepsilon(\tau) \equiv N_c^2 \cdot \frac{3}{8}\pi^2 \cdot T_{eff}^4$$

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Describe it in terms of lightest degrees of freedom on the AdS side which are relevant at strong coupling

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$$ds^2 = \frac{g_{\mu\nu}(x^\rho, z) dx^\mu dx^\nu + dz^2}{z^2} \equiv g^{5D}_{\alpha\beta} dx^\alpha dx^\beta$$

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- The plasma system is described by the geometry

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$$g_{\mu\nu}(x^\rho, z) = \eta_{\mu\nu} + z^4 g^{(4)}_{\mu\nu}(x^\rho) + \ldots$$

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- We will start from some initial geometry on a hypersurface at $\tau = 0$ (more precisely appropriate initial conditions for Einstein's equations)

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- Evolve it in time by solving Einstein's equations

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Initial conditions

- In the work [Beuf, Heller, RJ, Peschanski], we analyzed possible initial conditions in the Fefferman-Graham coordinates

$$ds^2 = \frac{1}{z^2}\left(-e^{a(z,\tau)}d\tau^2 + e^{b(z,\tau)}\tau^2 dy^2 + e^{c(z,\tau)}dx_\perp^2\right) + \frac{dz^2}{z^2}$$

- A typical solution of the constraint equations is

$$a_0(z) = b_0(z) = 2\log\cos z^2 \qquad c_0(z) = 2\log\cosh z^2$$

- There is a *coordinate* singularity at $z = \sqrt{\pi/2}$ where

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- No problem for the approach of [Beuf, Heller, RJ, Peschanski] (power series solutions) but very difficult for numerics...
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- In the ADM formulation we are free to choose how to foliate spacetime into *'equal time'* hypersurfaces
- We use this freedom to ensure that all hypersurfaces end on a single spacetime point in the bulk

- The above choice ensures that we will control the boundary conditions even though they may be in a strongly curved part of the spacetime
- This also ensures that no information flows from outside our region of integration...
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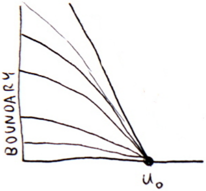

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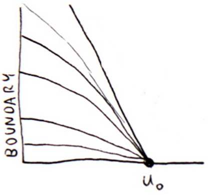

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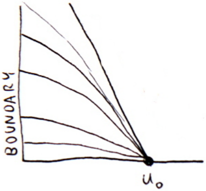

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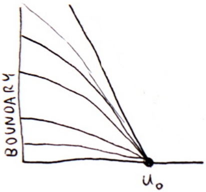

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The Numerical Relativity setup

- Depending on the relation of u_0 to the event horizon we can get quite different behaviours of the numerical simulation
- In order to extend the simulation to large values of τ neccessary for observing the transition to hydrodynamics we need to tune u_0 to be close to the event horizon.
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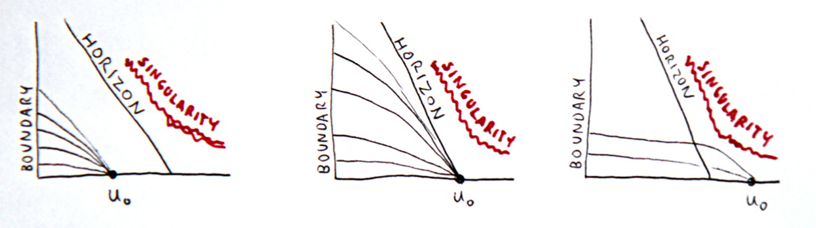

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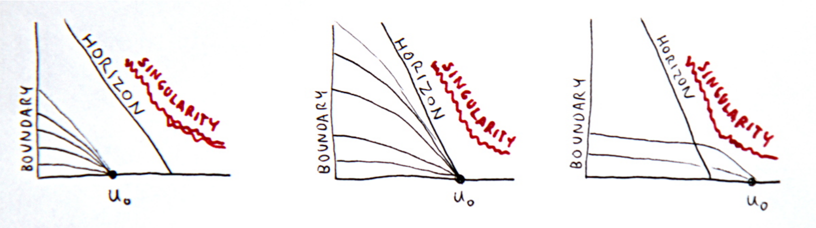

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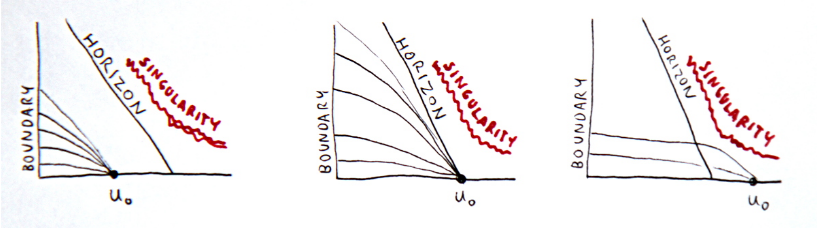

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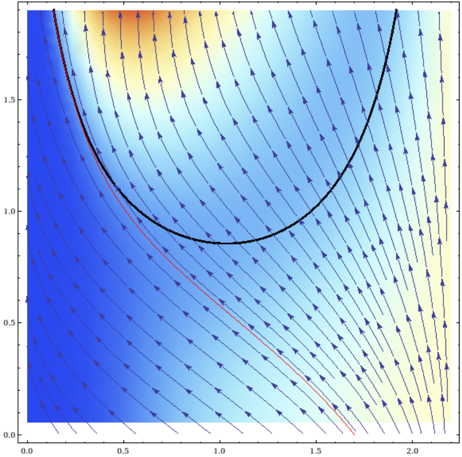

black line – dynamical horizon, arrows – null geodesics, colors represent curvature

Results

- We have considered 20 initial conditions, each given by a choice of the metric coefficient $c(\tau = 0, u)$
- We have chosen quite different looking profiles e.g.

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\begin{aligned}
c_1(u) &= \cosh u \\
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Nonequilibrium vs. hydrodynamic behaviour

- Introduce the dimensionless quantity $w(\tau) \equiv T_{eff}(\tau) \cdot \tau$
- Viscous hydrodynamics (up to any order in the gradient expansion) leads to equations of motion of the form

$$\frac{\tau}{w}\frac{d}{d\tau}w = \frac{F_{hydro}(w)}{w}$$

where $F_{hydro}(w)$ is a *universal function* completely determined in terms of the hydrodynamic transport coefficients (shear viscosity, relaxation time and higher order ones) e.g.

$$\frac{F_{hydro}(w)}{w} = \frac{2}{3} + \frac{1}{9\pi w} + \frac{1-\log 2}{27\pi^2 w^2} + \frac{15 - 2\pi^2 - 45\log 2 + 24\log^2 2}{972\pi^3 w^3} + \ldots$$

- Therefore if plasma dynamics would be given by viscous hydrodynamics (even to arbitrary high order) a plot of $F(w) \equiv \frac{\tau}{w}\frac{d}{d\tau}w$ as a function of w would be a single curve for all the initial conditions
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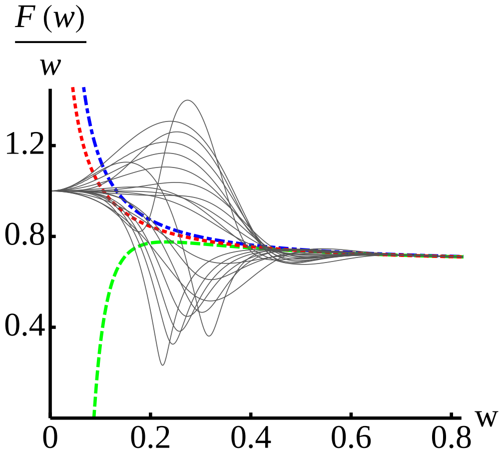

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- An observable sensitive to the details of the dissipative dynamics (e.g. hydrodynamics) is the pressure anisotropy

$$\Delta p_L \equiv 1 - \frac{p_L}{\varepsilon/3} = 12F(w) - 8$$

- For a perfect fluid $\Delta p_L \equiv 0$. For a sample initial profile we get

- For $w = T_{eff} \cdot \tau > 0.63$ we get a very good agreement with viscous hydrodynamics
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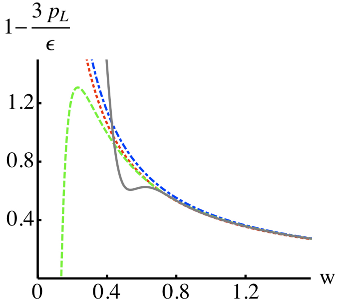

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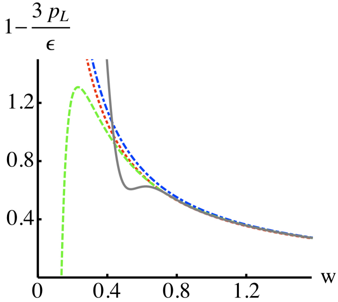

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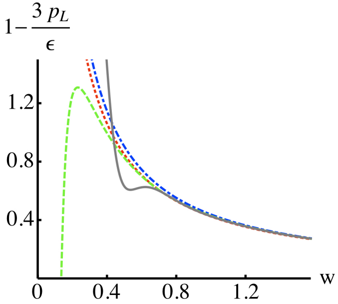

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- We consider the entropy per unit rapidity and unit transverse area in units of initial temperature introducing a dimensionless entropy density s through

$$s = \frac{S}{\frac{1}{2} N_c^2 \pi^2 T_{eff}^2(0)}$$

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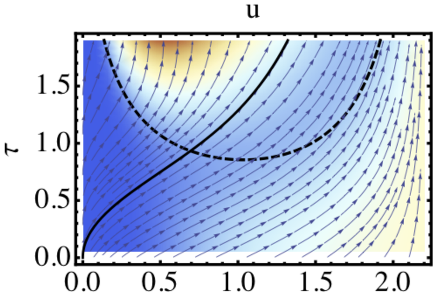

Final entropy

- For large proper-time, the dynamics is given by hydrodynamics, leading to the large τ expansion

$$T_{eff}(\tau)=\frac{\Lambda}{(\Lambda\tau)^{1/3}}\left\{1-\frac{1}{6\pi(\Lambda\tau)^{2/3}}+\frac{-1+\log 2}{36\pi^2(\Lambda\tau)^{4/3}}+\frac{-21+2\pi^2+51\log 2-24\log^2 2}{1944\pi^3(\Lambda\tau)^2+\ldots}\right\}$$

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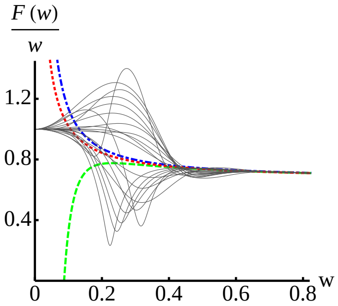

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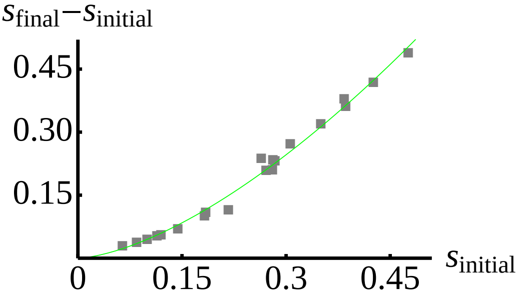

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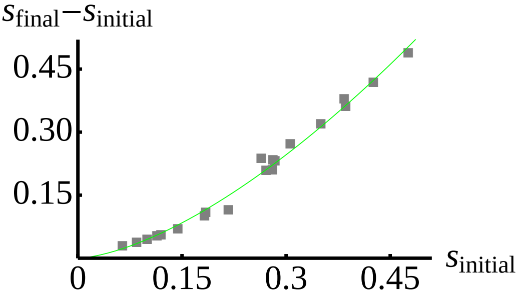

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Observation:

- The initial entropy turns out to be a key characterization of the initial state
- There seems to be a lot of hidden regularity in the nonequilibrium dynamics
- We will show below that the initial entropy also characterizes the characteristics of the transition to hydrodynamics ($\equiv$ thermalization)
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A numerical criterion for thermalization

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- We adopted a numerical criterion for thermalization

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- We looked at the following features of thermalization:
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- We adopted a numerical criterion for thermalization

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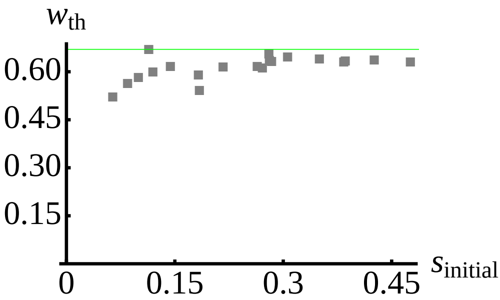
$w = T_{eff} \cdot \tau$ at thermalization

- w at thermalization is approximately constant and for the initial profiles considered does not exceed $w = 0.67$. It seems to decrease for profiles with smaller initial entropy
- N.B. sample initial conditions for hydrodynamics at RHIC ($\tau_0 = 0.25\, fm$, $T_0 = 500\, MeV$) assumed in [Broniowski, Chojnacki, Florkowski, Kisiel] correspond to $w = 0.63$
- The pressure anisotropy at thermalization is still sizable

$$\Delta p_L \equiv 1 - \frac{p_L}{\varepsilon/3} = 12F(w) - 8 \simeq 12F_{hydro}(w) - 8 \sim 0.72 - 0.73$$



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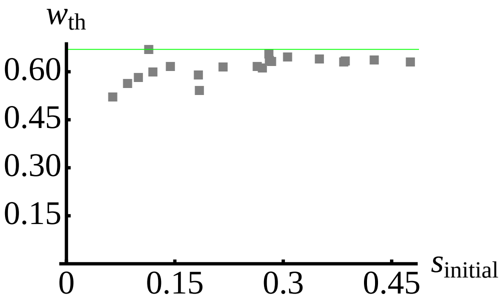

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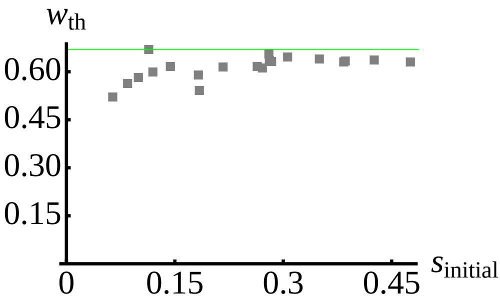

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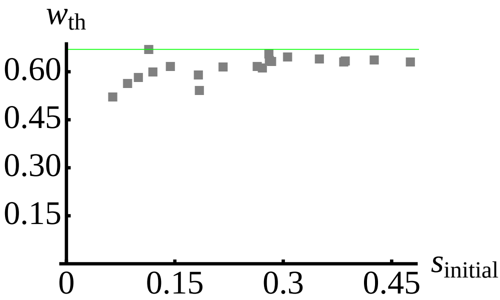

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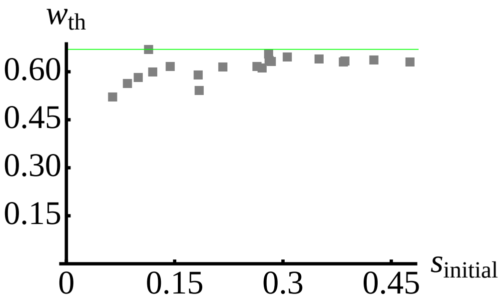

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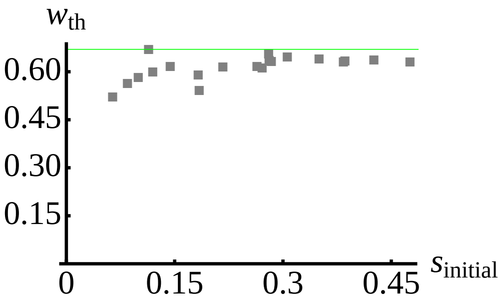

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- Thermalization time in units of the initial *effective* temperature $T_{eff}(0)$

- Again we see a clean dependence on the initial entropy $s_{initial}$
- The data can be fitted by

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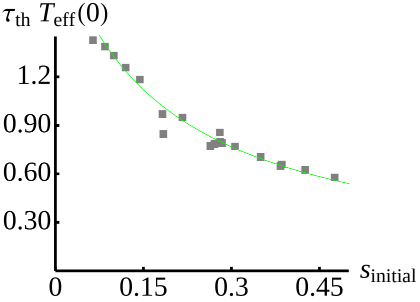

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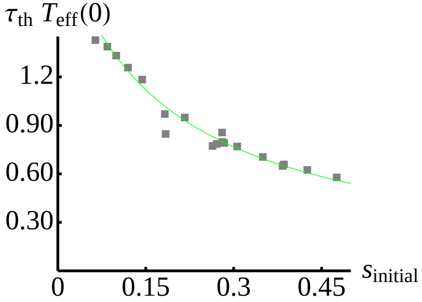

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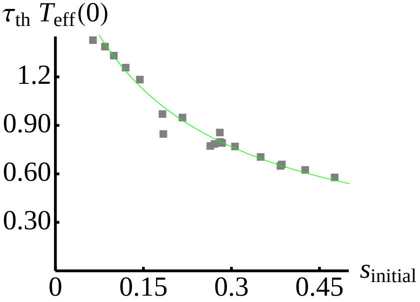

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Temperature at thermalization

- It is interesting to consider the ratio of the temperature at thermalization to the initial effective temperature
- This gives information on which part of the cooling process occurs in the far from equilibrium regime and which part occurs during the hydrodynamic evolution

- Note: for initial profiles with large $s_{initial}$, the energy density initially rises and only then falls $\longrightarrow$ even for $T_{th}/T_{eff}(0) \sim 1$ there is still sizable nonequilibrium evolution
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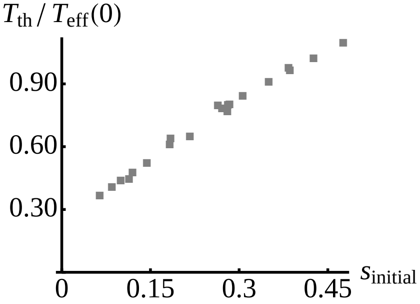

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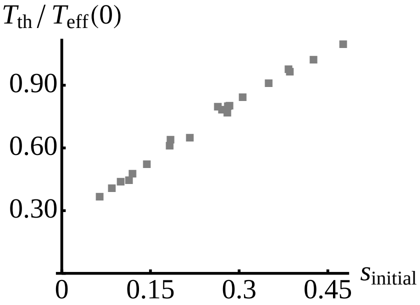

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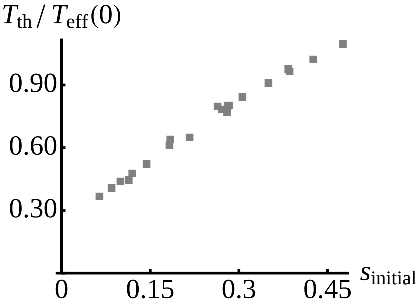

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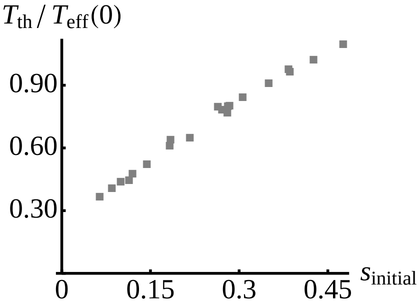

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- The AdS/CFT methods *do not* presuppose hydrodynamics so are applicable even to very out-of-equilibrium configurations
- Even though genuine nonequilibrium dynamics is very complicated, we observed surprising regularities
- Initial entropy seems to be a key physical characterization of the initial state determining the total entropy production and thermalization time and temperature
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