Holography, hydrodynamics and phase transitions

Romuald A. Janik

Jagiellonian University
Kraków

60^{th} Jubilee Cracow School of Theoretical Physics
Panorama of Hadronic Physics

Outline

Holography

Holography and Hydrodynamics

Holography beyond Hydrodynamics

Holography and Phase Transitions

Conclusions and outlook

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The AdS/CFT correspondence

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

- The claim is that the two theories are **equivalent**
- Gauge theory degrees of freedom are (somehow) reorganized into string degrees of freedom
- String theory contains gravity, but also an infinite set of other fields... **very complicated theory...**

What happens at strong coupling?

The infinite set of non-gravitational fields become very heavy and effectively decouple!

We reduce gauge theory dynamics to gravity... **tractable!**

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Holography – dictionary at strong coupling

$\langle T_{\mu\nu}(x)\rangle$	$\longleftrightarrow$	(5D) geometry $g_{\mu\nu}(x,z)$
evolution	$\longleftrightarrow$	5D Einstein's equations
$\langle T_{\mu\nu}\rangle = \begin{pmatrix} E & 0 & 0 & 0 \\ 0 & p & 0 & 0 \\ 0 & 0 & p & 0 \\ 0 & 0 & 0 & p \end{pmatrix}$	$\longleftrightarrow$	black hole geometry
Temperature	$\longleftrightarrow$	Hawking temperature
Entropy	$\longleftrightarrow$	Area of the horizon
Hydrodynamics		$\eta/s = \frac{1}{4\pi}$
$T^{\mu\nu} = (\varepsilon + p)u^\mu u^\nu + p\eta^{\mu\nu} + \ldots$	$\longleftrightarrow$	geometry in a gradient expansion

Important: There is a lot more than hydrodynamics on the gravity side...

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

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

- Dispersion relation $\omega(k)$ fixed by linearized Einstein's equations.
(perturbations corresponding to the sound channel in hydrodynamics)

from Kovtun,Starinets hep-th/0506184

- This is equivalent to summing contributions from *all-order* viscous hydrodynamics
- But, **in addition**, there is an infinite set of higher QNM — effective degrees of freedom not contained in the hydrodynamic description at all!

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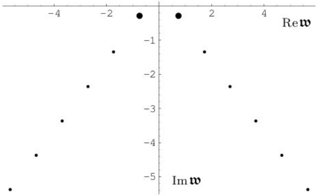

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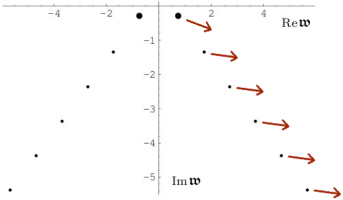

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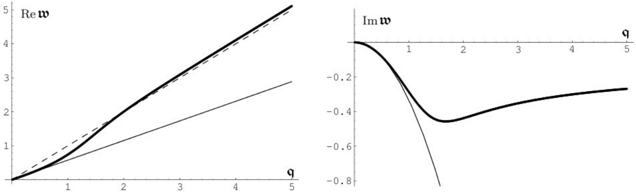

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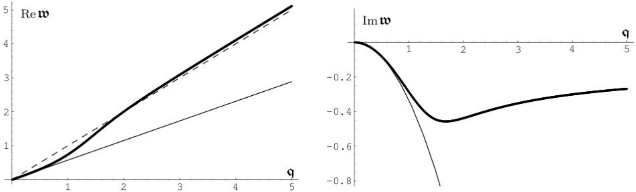

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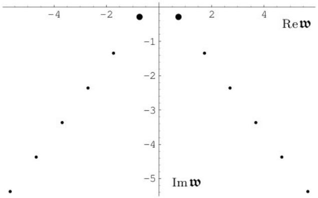

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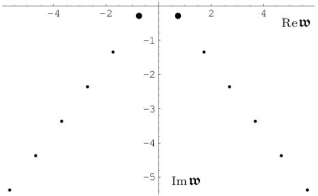
Recall the independent modes in the sound channel (at some small k)



- the higher non-hydrodynamic modes have $Im\,\omega < 0$ even at $k = 0$, hence are **damped**
- the hydrodynamic geometry is stable under non-hydrodynamic perturbations – it is **an attracting geometry**
- The transition to hydrodynamics can be understood as approaching **an attractor** RJ, Peschanski '06
- Far away from equilibrium, the nonhydrodynamic degrees of freedom are as important (or more) as hydrodynamics...
- It is then a strongly interacting system – need to solve (numerically) the full nonlinear Einstein's equations in 5D

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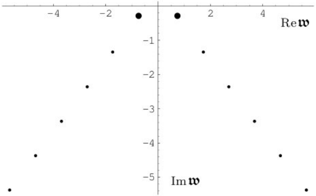

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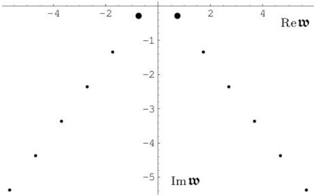

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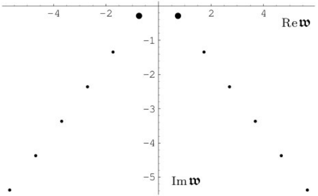

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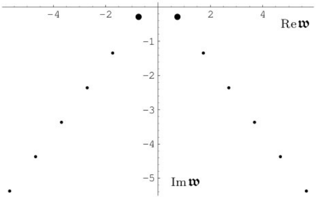

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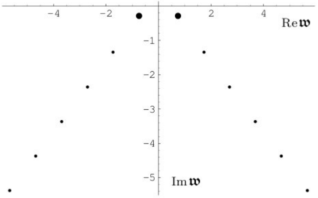

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What can we learn about the transition to hydrodynamics?

Sample numerical evolution (gray)

$w \equiv T \cdot \tau$

Key takeaways:

1. Hydrodynamics works quite well for $w \equiv T\tau \sim 0.6 - 0.7$
2. At the transition to hydrodynamics, the pressure anisotropy is sizeable! **(hydrodynamization and not thermalization)**

Further developments

- Shock wave collisions have been studied — Chesler, Yaffe
- Extended to asymmetric shock waves — Heller, Mateos, v der Schee

  and off-center — Chesler, Yaffe

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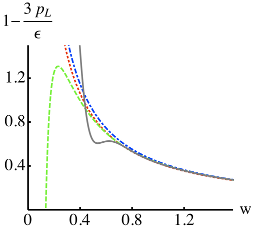

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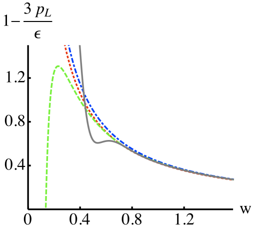

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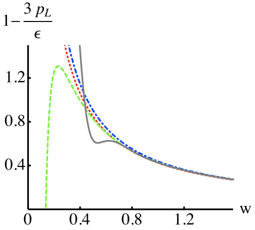

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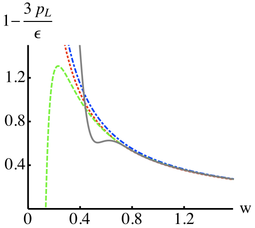

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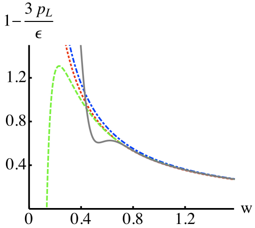

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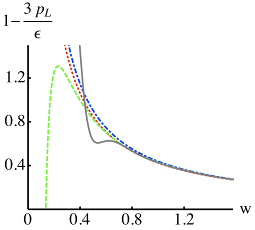

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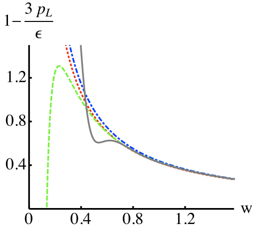

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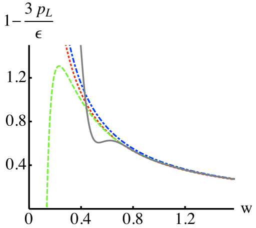

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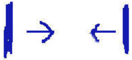

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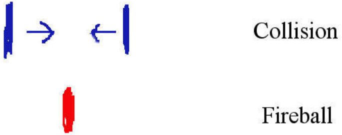

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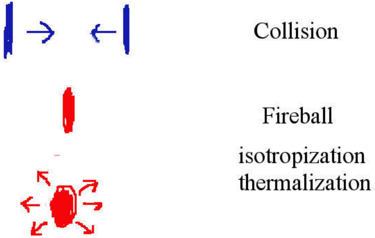

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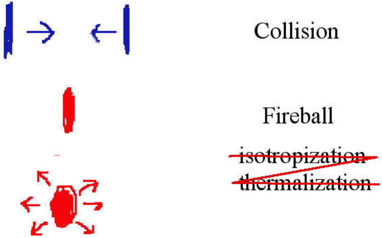

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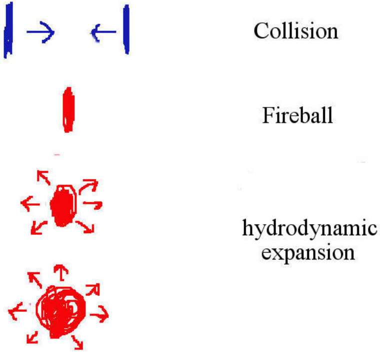

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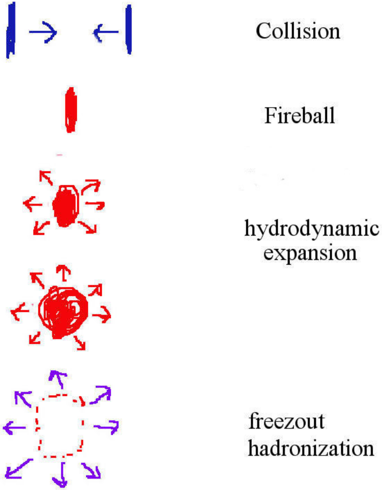

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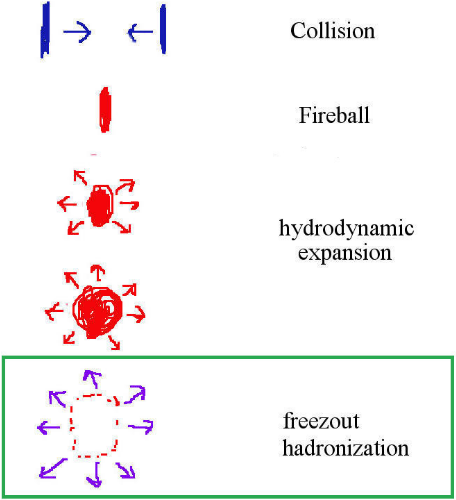

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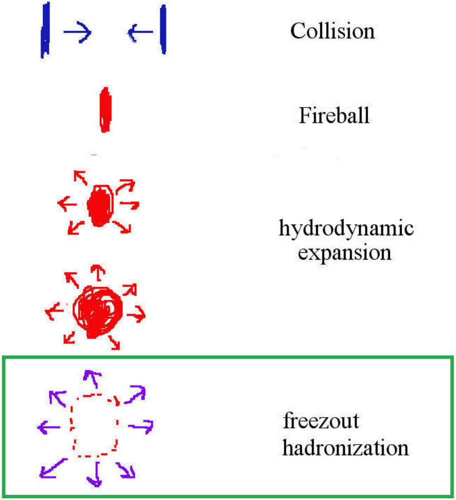

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We need to describe a nonconformal plasma

- We use **a bottom-up** approach: use a gravity+scalar field model and choose scalar potential to model the physics we want (1^{st} order phase transition)

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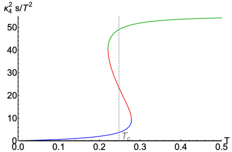

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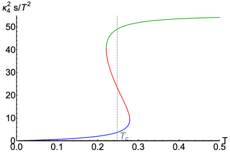

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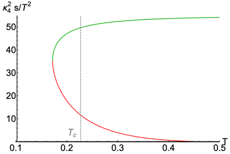

Look at the easier case first...

RJ, Jankowski, Soltanpanahi PRL '17 [1704.05387]

Energy density as a function of temperature

- $\phi_H = 1$ is in the overcooled phase
- $\phi_H = 2, 3$ are in the unstable spinodal phase

Results:

- In the overcooled phase we find no trace of **nonlinear** instability...
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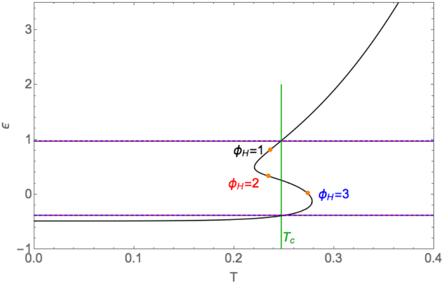

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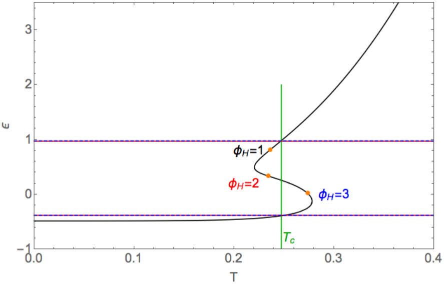

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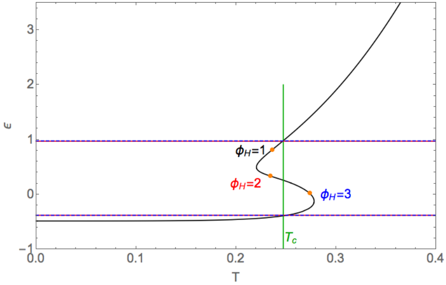

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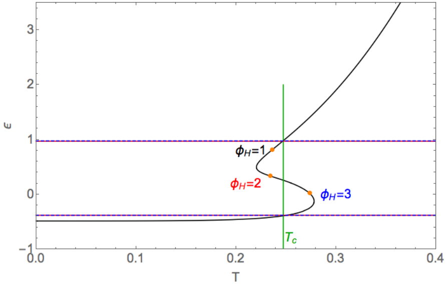

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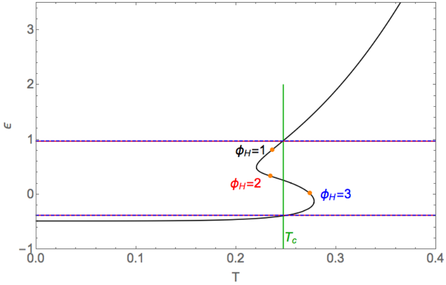

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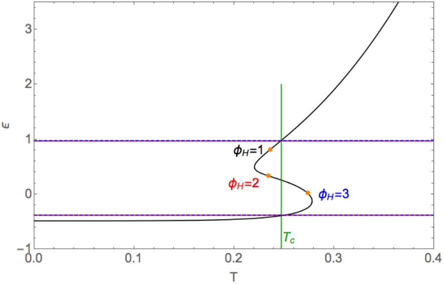

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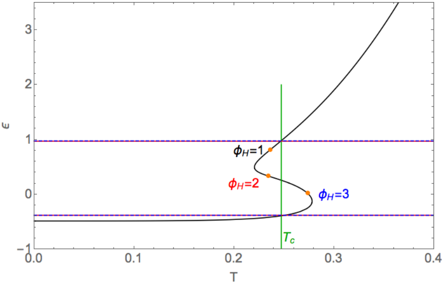

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(with a gaussian perturbation)

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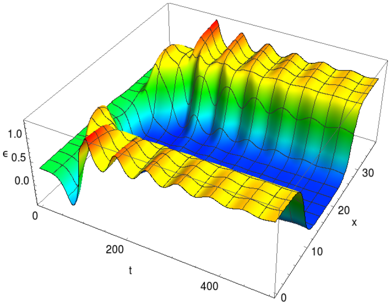

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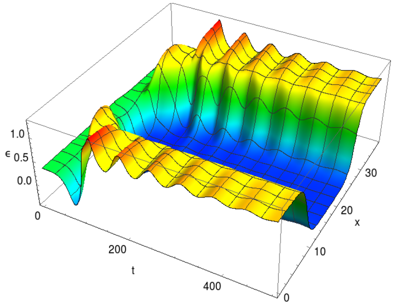

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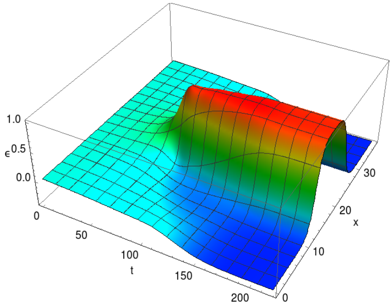

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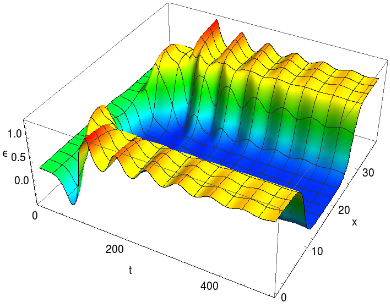

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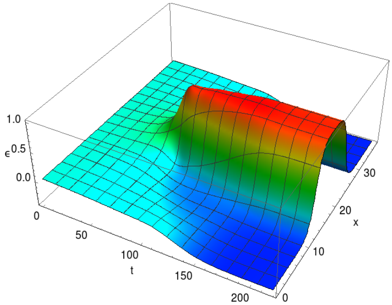

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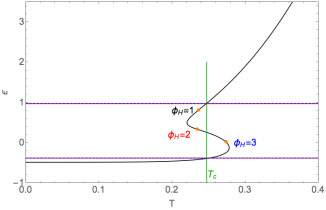

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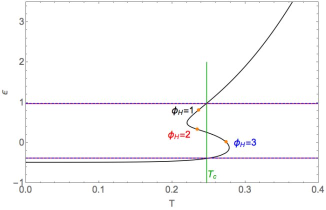

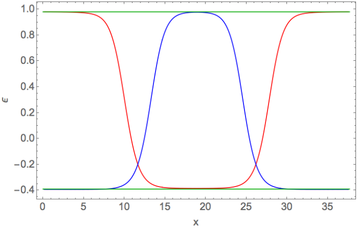

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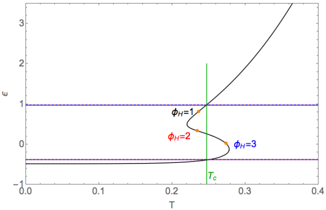

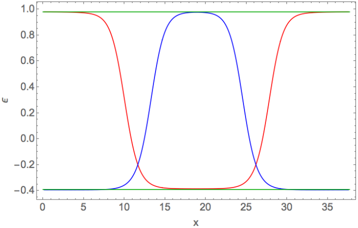

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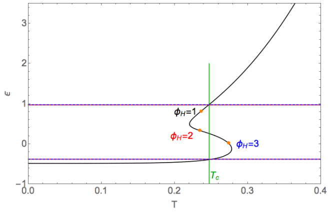

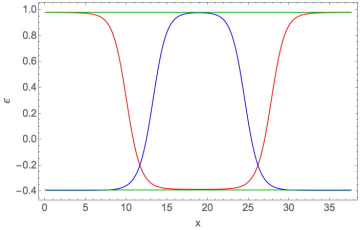

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The preceding results lead to several questions...

L. Bellantuono, RJ, J. Jankowski, H. Soltanpanahi '19

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- Do we get multiple domains in the final state, or do their merge (how?) to reach a minimal number?
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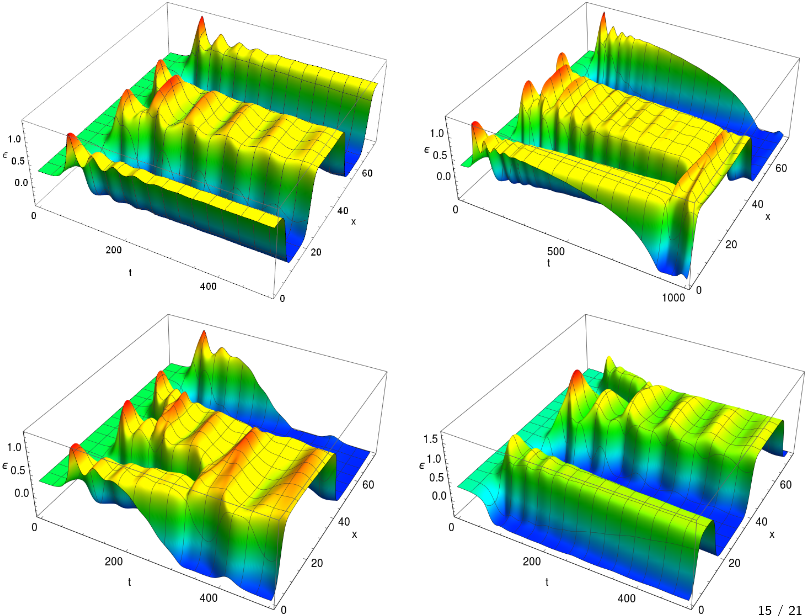

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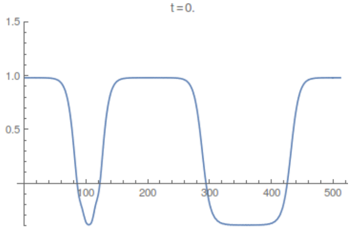

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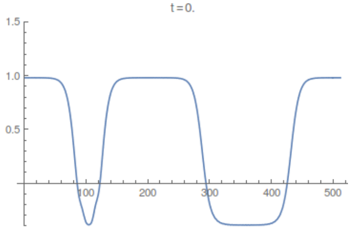

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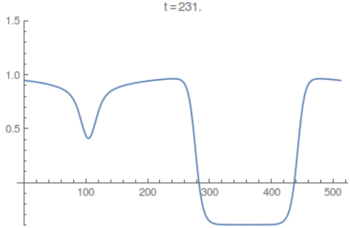

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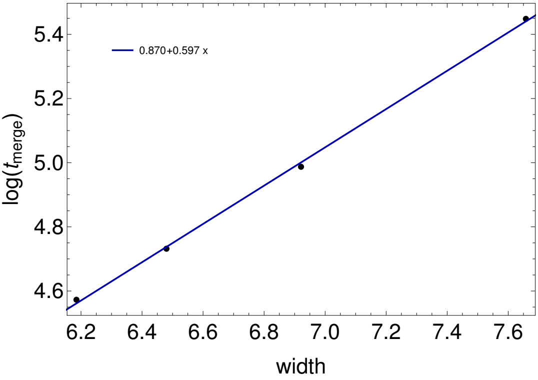

- We see an exponentially long life time

$$\log(t_{merge}) = 0.870 + 0.597\, width$$

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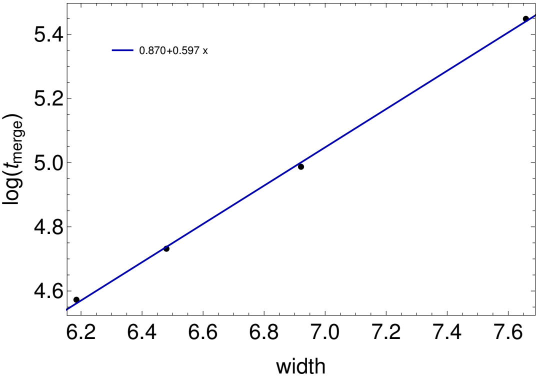

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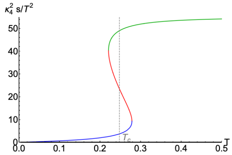

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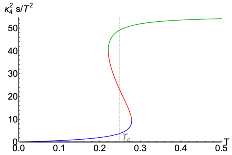

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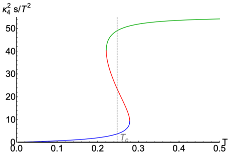

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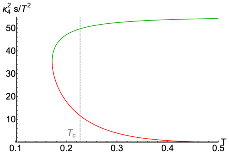

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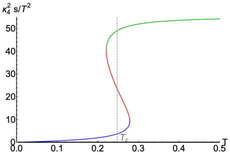

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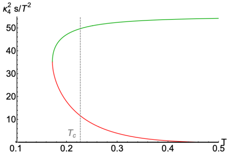

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work in progress with M. Jarvinen, J. Sonnenschein
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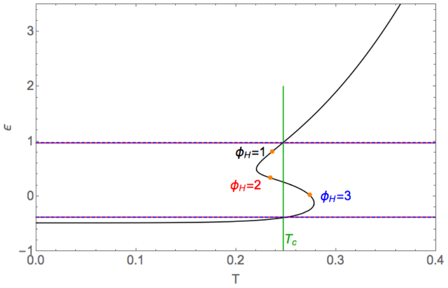

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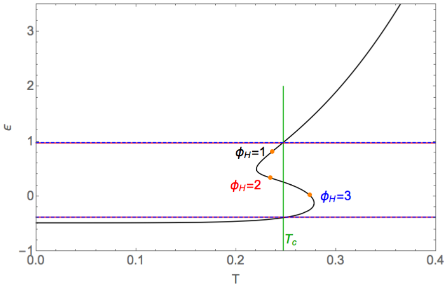

- $\phi_H = 1$ is in the overcooled phase
- Infinitesimal perturbation does not lead to a transition...
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with H. Soltanpanahi

Need to explicitly model tunneling phenomena on the gravity side in order to pass to the deconfined phase!

work in progress with M. Jarvinen, J. Sonnenschein
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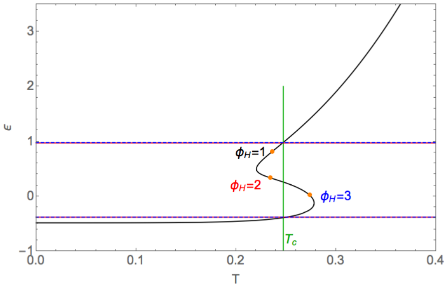

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Conclusions and outlook

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- Hydrodynamics emerges as a limiting case of the dynamics, but holography includes other dynamics relevant for far from equilibrium physics...
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