Strongly coupled dynamics with a phase transition – some surprises

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RJ, M. Järvinen, H. Soltanpanahi, J. Sonnenschein, PRL '22 [2205.06274]
RJ, M. Järvinen, J. Sonnenschein, to appear...

Outline

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Long term motivation

Domain wall velocities
- Conventional picture and a key question
- Results of holographic simulations
- A simple formula for domain wall velocity

Boost-invariant expansion and hot remnants
- Boost-invariant expansion and cooling
- Reheating of plasma remnants
- Entropy considerations

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Question: How to understand phase transitions in real time within holography?

- Phase transitions in equilibrium in holography correspond to switching between **two spacetime geometries**
- It is nontrivial what happens in real time...
- In some cases there is a classical gravity description, in others probably not...

Theoretically interesting even for its own sake!

But also interesting real-world applications:

- What does holography tell us about hadronization??

  caution for $N_c = 3$: crossover!
- 1^{st} order phase transition reappears at nonzero density...
- Some physics in early universe??

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1. Bubble wall velocities

Introduction

- At a 1^{st} order phase transition $T = T_c$, we can have domains of coexisting phases separated by domain walls
- The pressures on both sides are balanced and the domain wall can be static...

Question: What happens when we move away from $T = T_c$?

- This can occur for nucleated bubbles of a stable phase within an supercooled medium
- At an interface between phases away from $T = T_c$
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Domain walls start to move...

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Goal:

Understand bubble wall velocities at strong coupling...

- The pressures on both sides are not balanced so one would expect accelerated motion...

- ...but this does not happen — the domain wall ultimately moves with a constant velocity...

- **Common lore:** friction in the second phase balances the net force — challenging to calculate...

Our claim: At strong coupling (+ some entropy ratio assumptions), the domain wall velocity can be understood in a much simpler way using essentially only the equation of state...

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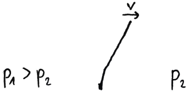

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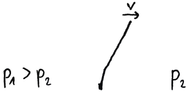

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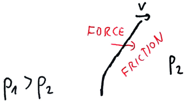

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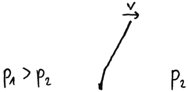

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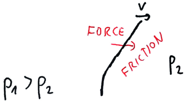

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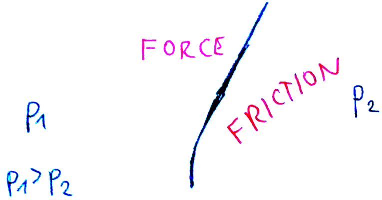

- The net force across the domain wall implies that the pressure difference is localized close to the domain wall...
- It is not obvious *a-priori* if this is always the case...

Perform holographic simulation and read off the pressure profile...

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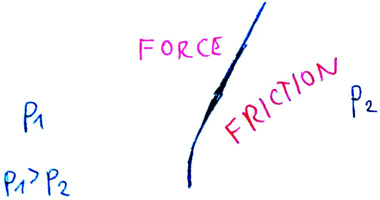

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1. Witten model in 3D – confinement/deconfinement transition
   use simplified hydrodynamics+scalar field fitted to holography

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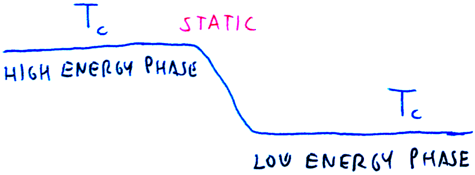

- We increase the temperature of the high energy phase...
- We perform time evolution from the above static initial conditions...
- The pressure in each phase may be read off from the T^{yy} component of the energy-momentum tensor

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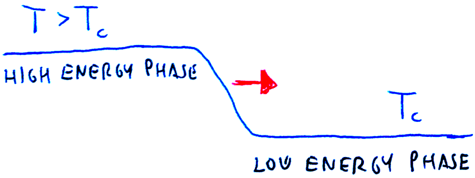

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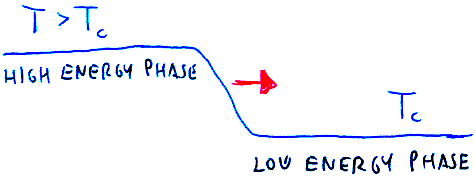

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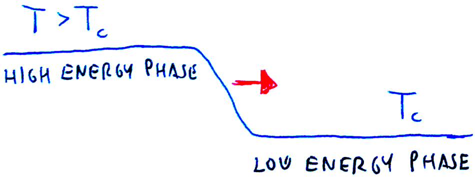

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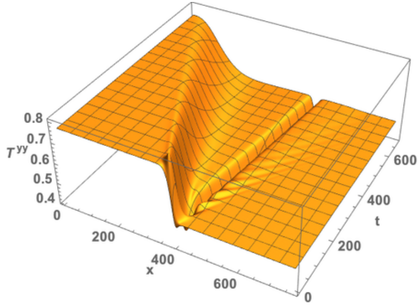

Key features:

- The large pressure difference appears **away** from the domain wall
- The change in pressures occurs in the high energy density phase
  $\longrightarrow$ **hydrodynamic description**
- The pressure is essentially constant across the domain wall, and very close to $p(T_c)$...

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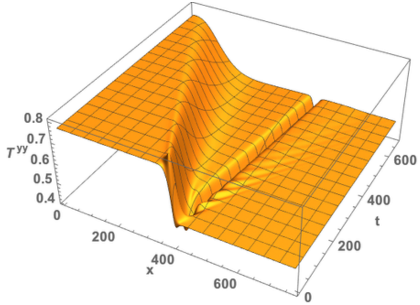

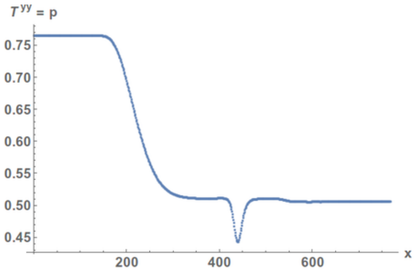

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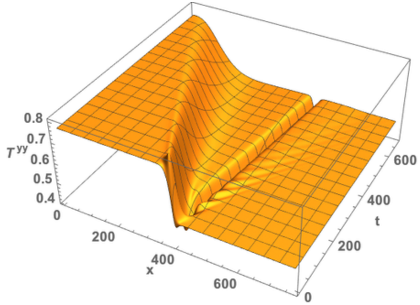

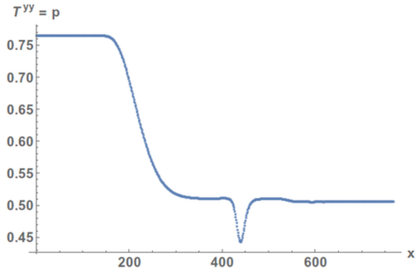

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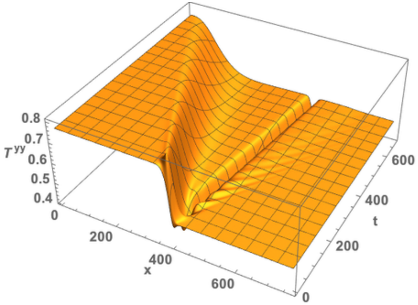

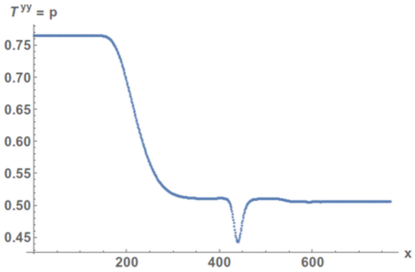

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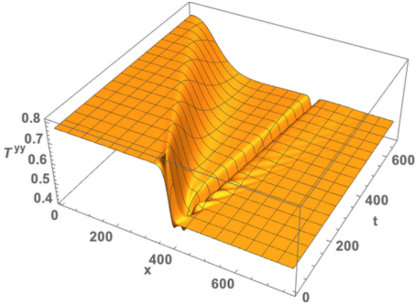

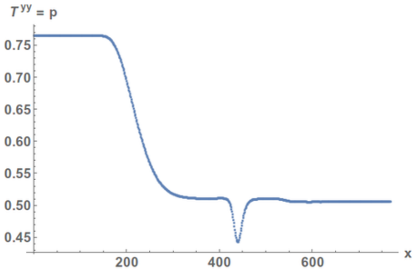

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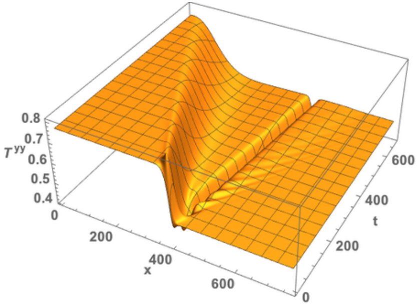

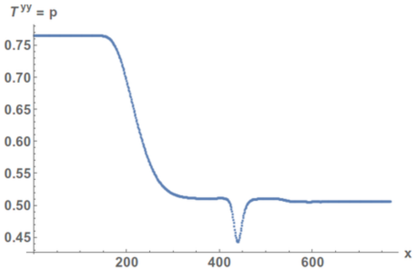

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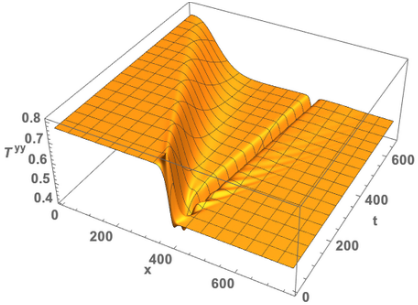

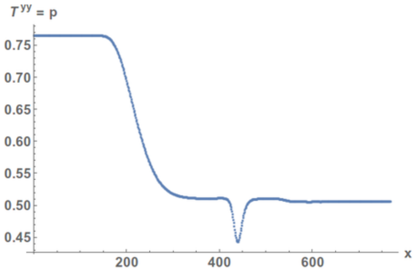

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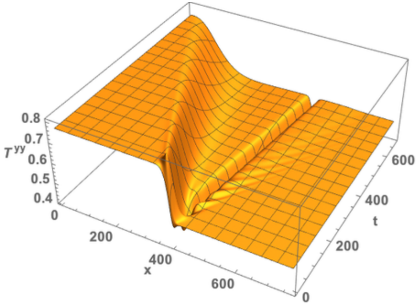

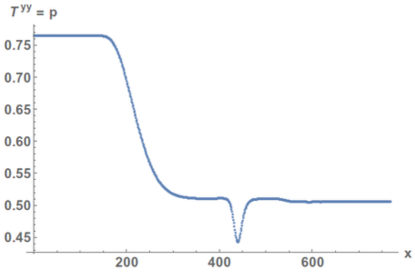

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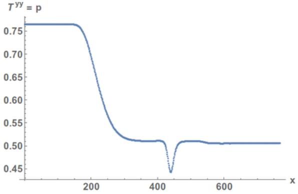
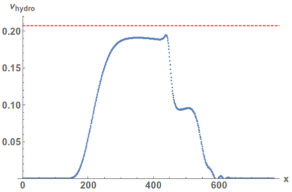
We can extract the hydrodynamic velocity from T^{xt}





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- This gets better with increasing ratio of entropies in the two phases...
- We can fomulate finding v_{dw} as a hydrodynamic problem:

This leads to the formula:

$$v_{dw} = \tanh \int_{p_c}^{p_A} \frac{1}{(\varepsilon + p)c_s} dp$$

requires only EOS!

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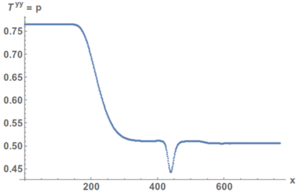

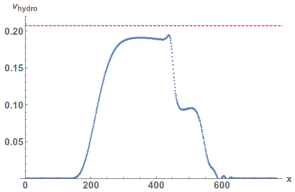

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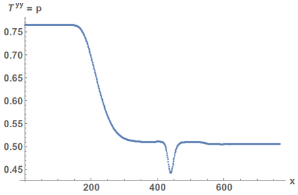

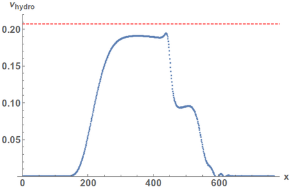

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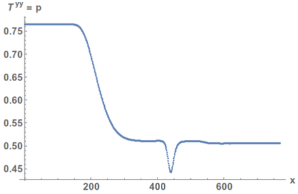

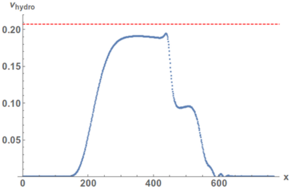

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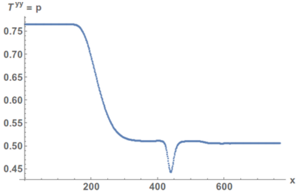

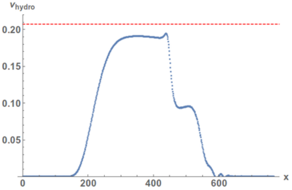

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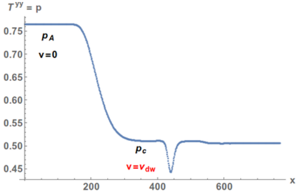

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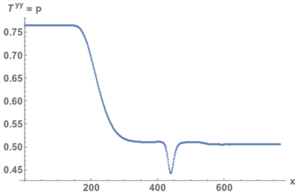

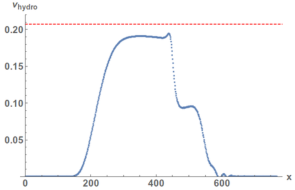

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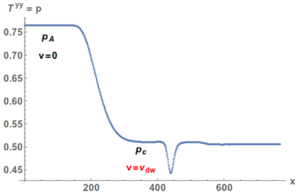

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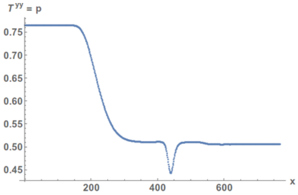

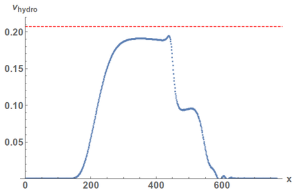

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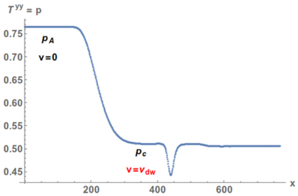

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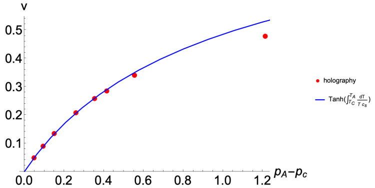

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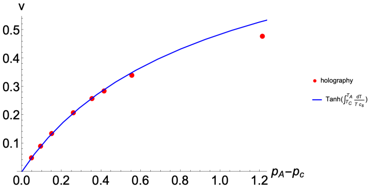

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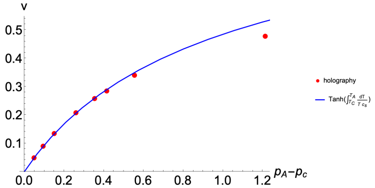

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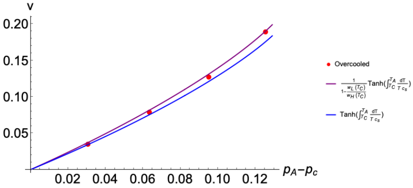

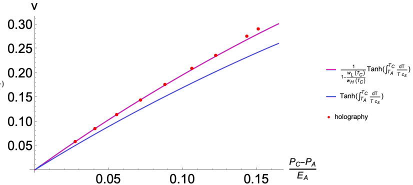

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Key takeaways:

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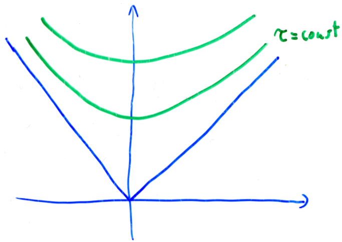
2. Boost-invariant expansion and hot remnants

Boost-invariance and 1^{st} order phase transition



- The plasma undergoes boost-invariant expansion in the longitudinal direction
- The expansion induces generically cooling and thus naturally pushes the system across the phase transition

- A scale invariant plasma cools as $T(\tau) \sim 1/\tau^{\frac{1}{3}}$
- Entropy per unity rapidity is preserved

$$S \propto \tau V_\perp T^3 \sim const$$

- We would expect the expanding plasma to be more and more supercooled and transitioning to the other phase through nucleating more and more bubbles...

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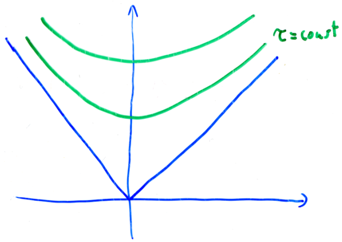

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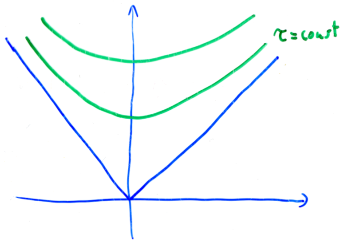

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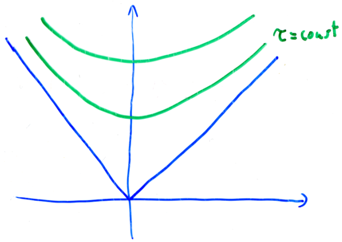

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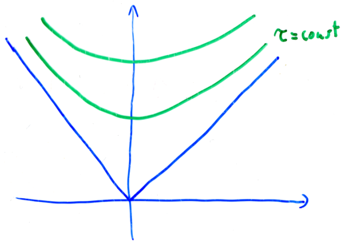

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  (3D Witten model in a simplified hydro+scalar field description)

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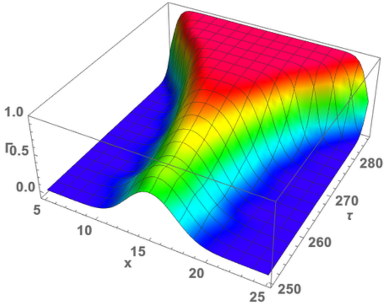

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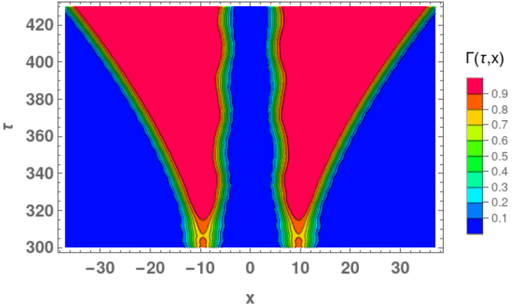

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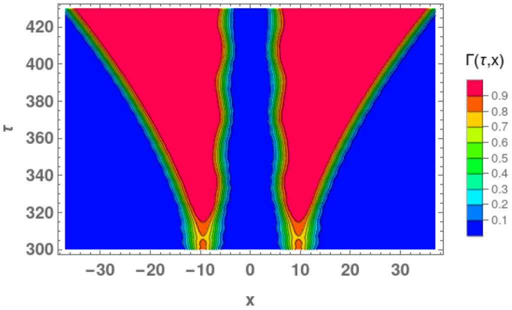

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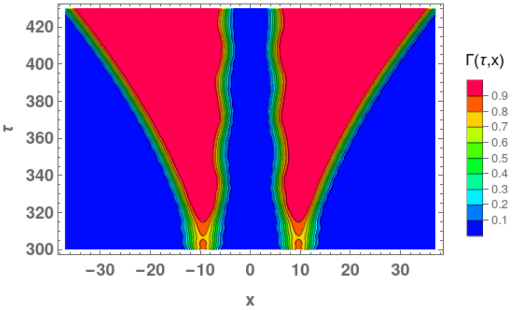

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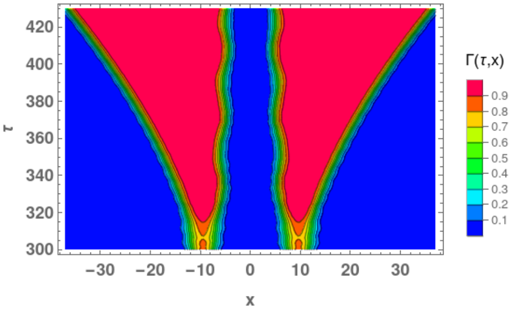

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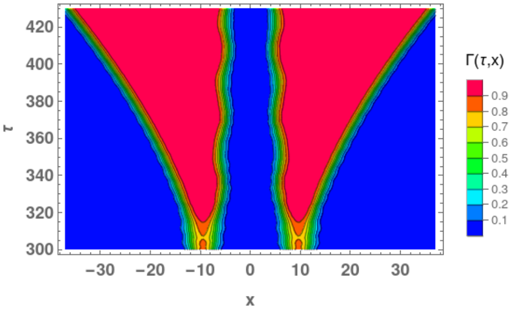

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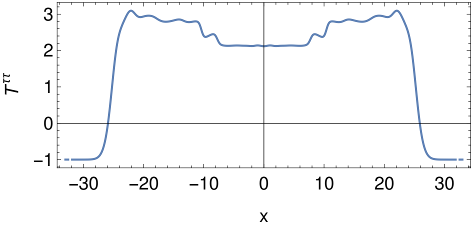

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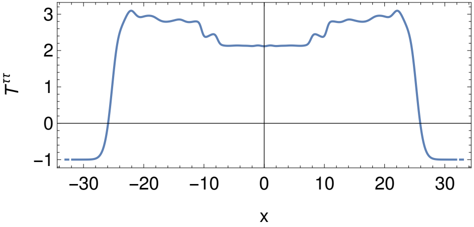

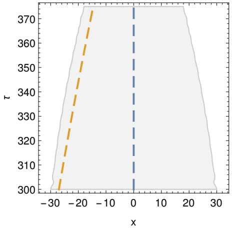

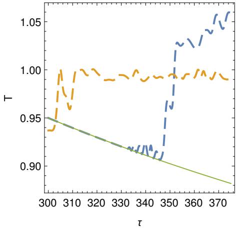

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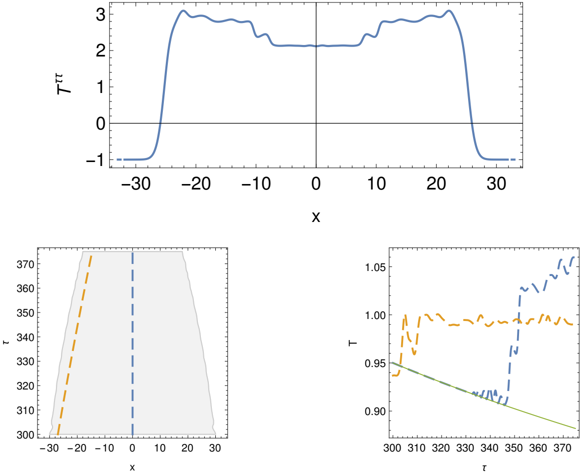

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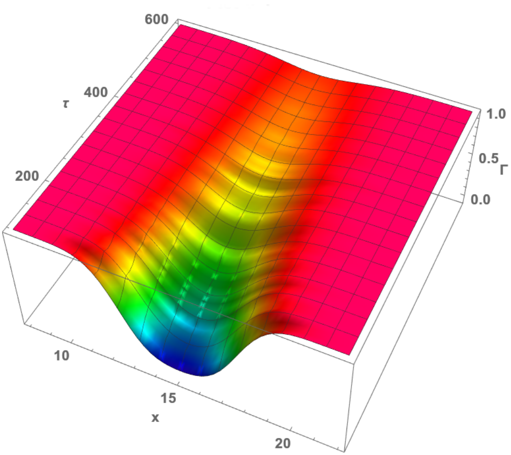

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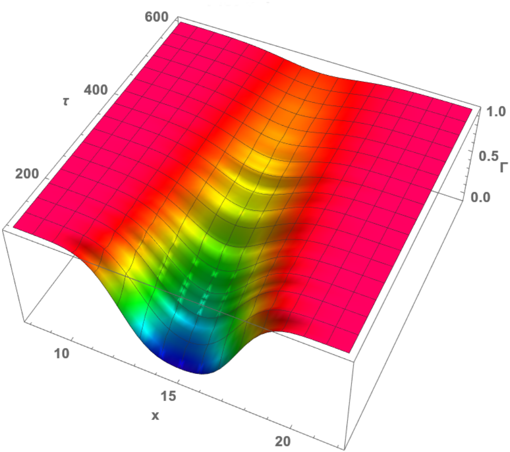

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