Holographic Phase Transitions

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Based on work in progress with:

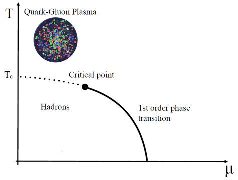
Yago Bea, Jorge Casalderrey-Solana, David Mateos,
Mikel Sánchez, Miguel Zilhão

and arXiv:1905.12544 & arXiv:1807.05175.

Introduction

- **Motivation:** Hot, strongly coupled non-Abelian plasmas can provide insights into properties of QCD matter.

HIC experiments: RHIC, LHC, FAIR, NICA.



Cartoon of QCD phase diagram.

Physical processes:

- Dynamics of the spinodal instability: initially homogeneous system evolves to an inhomogeneous end state.
- Heavy ion collisions through shockwave collisions.

Main result: Applicability of hydrodynamics.

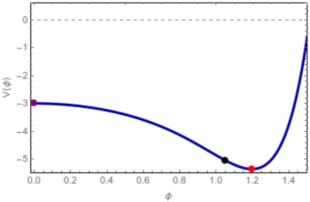
Method: Build gravitational duals of the gauge theory at finite T. Time evolve using Numerical Relativity.

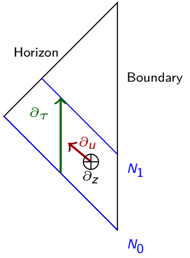
The Setup

Einstein-scalar: $S = \frac{2}{\kappa_5^2}\int d^5x\sqrt{-g}\left[\frac{1}{4}R - \frac{1}{2}(\nabla\phi)^2 - V(\phi)\right]$, where

$V(\phi) = -\frac{4}{3}W(\phi)^2 + \frac{1}{2}W'(\phi)^2$ and $lW(\phi) = -\frac{3}{2} - \frac{\phi^2}{2} - \frac{\phi^4}{4\phi_M^2} + \frac{\phi^6}{\phi_Q}$.

- non-conformal boundary theory.
- 1st, 2nd order phase transitions & crossover.



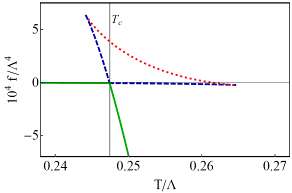


- Ingoing 2+1 Eddington-Finkelstein.
- Initial data on N_0 and boundary conditions.

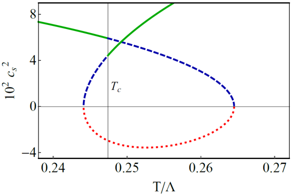
Thermodynamics

Numerically construct homogeneous black brane configurations → thermal states of the boundary theory.

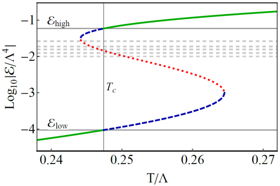
- Λ: source of dim. 3 scalar operator.



Free energy - Temperature.



(Speed of sound)^2 - Temperature.

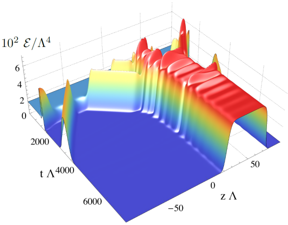


Energy density - Temperature.

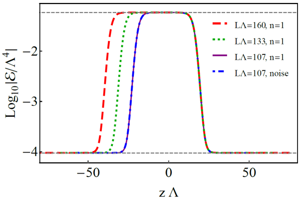
- 1st order phase transition; $c_s^2 < 0$; unstable region.
- Long wavelength, small amplitude sound perturbations grow exponentially.
- Gregory-Laflamme type instability $\longleftrightarrow$ spinodal instability.

Spinodal instability

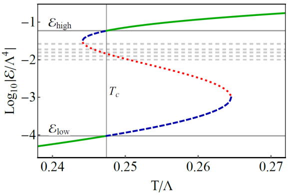
- initiate the system in the unstable region (red dashed).
- periodicity in z direction $\to$ box.
- put a small perturbation (that fits the box).



Energy density.



Final profiles of energy density.



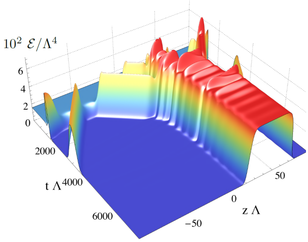
Energy density - Temperature.

- End state: phase separation with 2 domains (high & low energy).
- Interface of separation independent of box size.

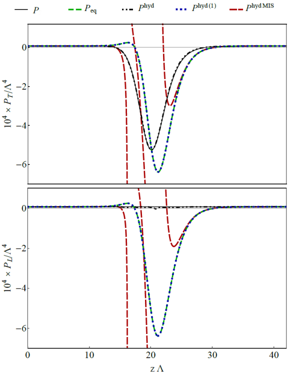
Attems, Bea, Casalderey, Mateos, Zilhão: arXiv:1905.12544.

Spinodal instability: Hydrodynamics

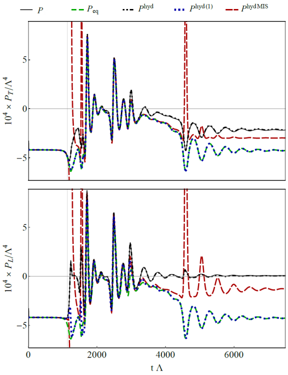
- $T_{\mu\nu} = T^{ideal}_{\mu\nu} + \partial_{spatial} + \partial^2_{spatial}$: not well-posed.
- $T^{MIS}_{\mu\nu} = T^{ideal}_{\mu\nu} + \partial_{spatial} + \partial_{spatial}\partial_{time}$: used in numerical codes.



Energy density.



Final transverse and longitudinal pressures.



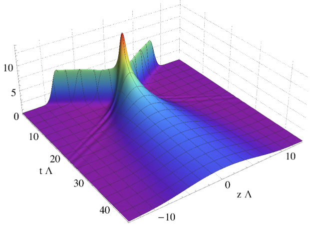
Transverse and longitudinal pressures in time for fixed z.

- @ end state fluid velocity vanishes & $\partial^2_{spatial}$ terms are large.

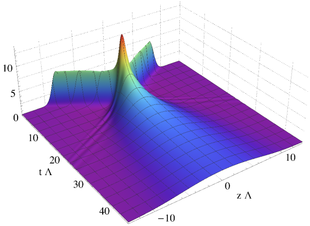
Attems, Bea, Casalderey, Mateos, Zilhão: arXiv:1905.12544.

Shockwave collisions

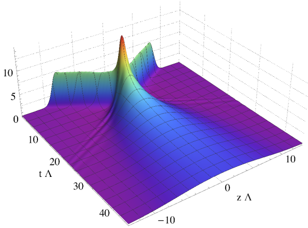
- Collision of 2 identical shockwaves in the bulk moving at the speed of light.
- Model the central region of a head-on HIC.



Energy density: 1st order phase transition.



Energy density: 2nd order phase transition.

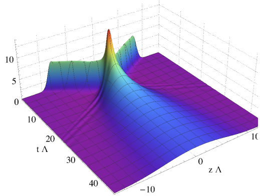


Energy density: crossover.

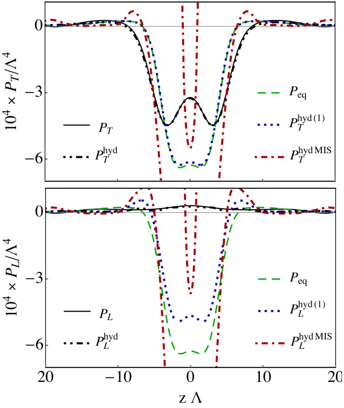
- Quasi-static blob of energy forms; $c_s^2 << 1$.
- No qualitative difference for 1st, 2nd order & crossover.

Attems, Bea, Casalderey, Mateos, Triana, Zilhão: arXiv:1807.05175.

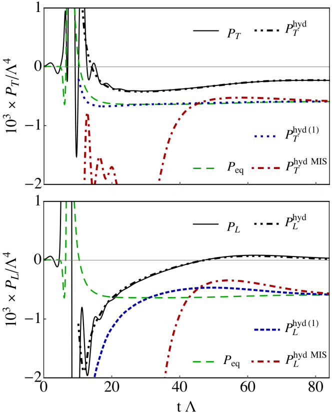
2nd order hydrodynamics describes well the end-state & the blob of energy.



Energy density.



Final transverse and longitudinal pressures.



Transverse and longitudinal pressures in time for fixed z.

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Summary & Future work

Main results:

- Quasi-static blob of energy formed post-collision for all phase transitions.
- Two domains (high & low energy) form at the end of spinodal instability.
- Hydrodynamics with $\partial^2_{spatial}$ describes well collisions and the spinodal instability.

Future work:

- Collisions + spinodal instablity: fast growing instability in the post-collision quasistatic blob.
- Include chemical potential: Einstein-scalar-Maxwell.
- Less symmetric setups: 3+1 bulk equations.

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Thank you!

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