Spinodal instability with varying criticality in holography

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Introduction

An outstanding question in the QCD phase diagram is the location (or even existence) of a **critical point** as the end-point of a **first-order phase transition**.

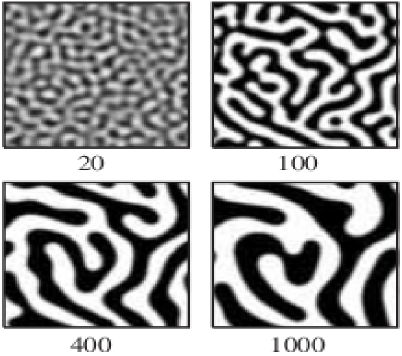
A smoking gun signature for a first-order phase transition with negative speed of sound squared c_s^2 is the occurrence of a **spinodal instability**.

The gauge/gravity duality allows to explore such strong coupling non-perturbative out-of-equilibrium dynamics for almost perfect fluids. The spinodal instability of the fluid gets mapped to a Gregory-Laflamme type instability of a holographically dual system of black branes. This dual gravitational picture is amenable to numerical general relativity computations.

Now we explore dynamics near and far from a critial point with single parameter ϕ_{M} for possible implications of the searches of the QCD critical point.

Holographic setup

spinodal instability:



spinodal decomposition in a two phase system

[Onuki 1987]

Gregory-Laflamme instability:

thin black ring pinching off

[Figueras, Kunesch, Tunyasuvunakool 2015]

gauge/gravity correspondence:

bridge between physical phenomena in gauge theories and gravity.

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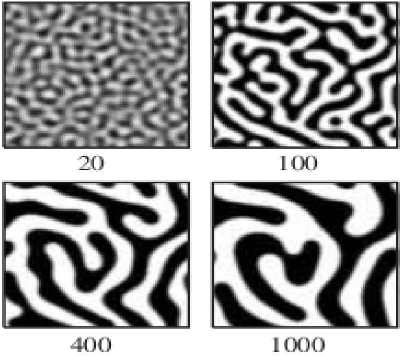

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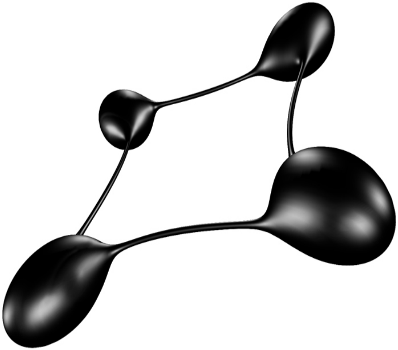

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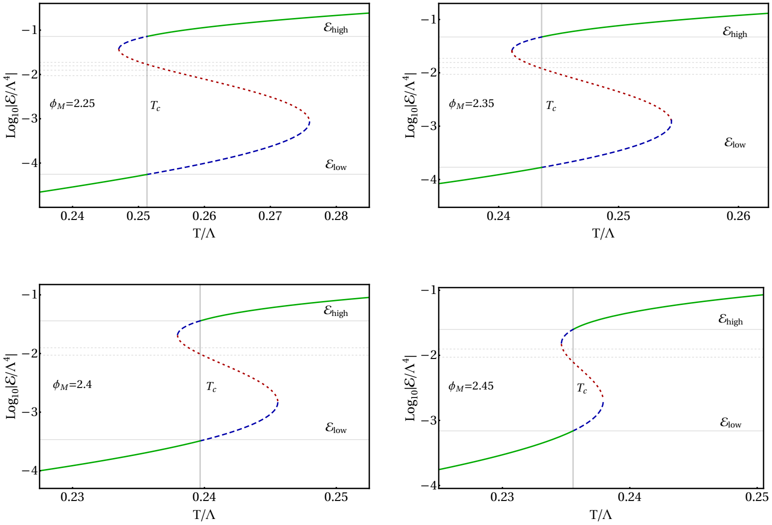
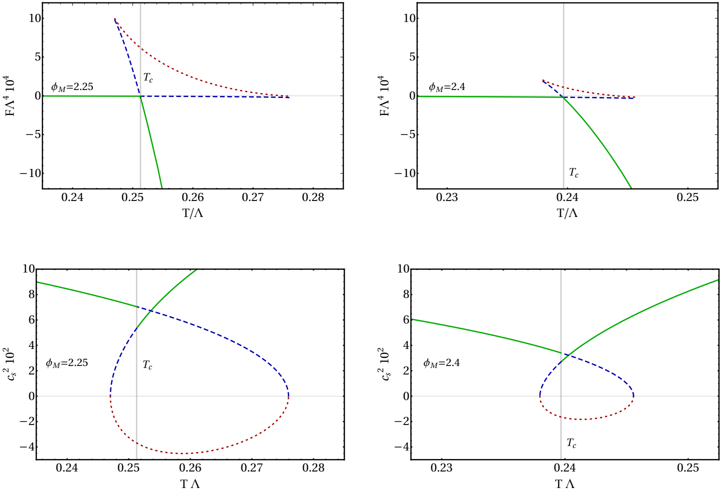


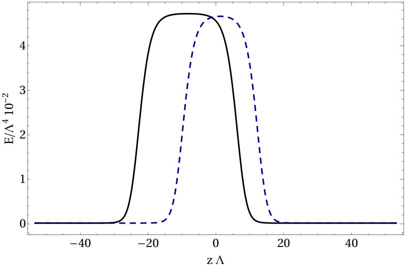
Energy density over T for theories with first order phase transition (blue) metastable (red) spinodal region (green) stable phases

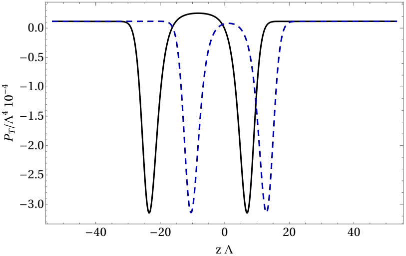
Bottom-up model: tuning criticality II



Thermodynamical properties of hard/soft transition:
(top row) Free energy over temperature
(bottom row) Speed of sound squared over temperature

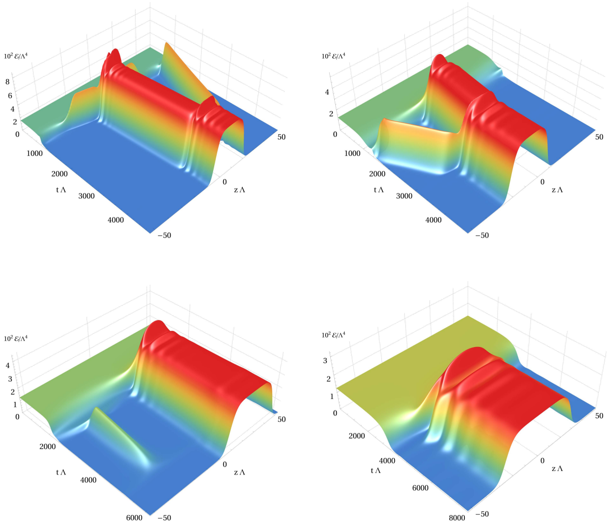
New criterium plateau (full black) where $P_T \geq 0.8 P_c$ versus peak (dashed blue) where $P_T < 0.8 P_c$





Longitudinal profiles of (left) local energy density (right) transverse pressure PT

Spinodal instability evolution



Phase separated final solution seen in the evolution of the local energy density of harder/softer phase transitions

Spinodal instability - formation time

The formation time is defined as the time from the start of the evolution to when the system first reaches one of the two stable phases.

Formation time of the spinodal instability with varying criticality:

ϕ_{M}	2.25	2.35	2.4	2.45
$t_{\mathrm{f}ormation}\Lambda$	880	1380	1725	2660

The formation time correlates with the strength of the first order phase transition: the strongest phase transition with the largest spinodal region shows the fastest formation time.

Summary: spinodal instability approaching a critical point

Demonstration that mergers of equilibrated peaks and unstable plateaux lead to the preferred final single phase separated solution with different first order phase transitions.

Near a critical point the interface between cold and hot stable phases, given by its width and surface tension, features

- a **wider phase separation**,
- a **smaller surface tension** and
- a **longer formation time**.

Hence the spinodal instability is easier to detect far from a critical point along the first order phase transition.

New discovery of a atypical setup with dissipation of a peak into a plateau.

Literature

1) "Holographic approach of the spinodal instability to criticality" By Maximilian Attems arXiv:2012.15687 [hep-th].

2) "Dynamics near a first order phase transition" By Loredana Bellantuono, Romuald A. Janik, Jakub Jankowski, Hesam Soltanpanahi arXiv:1906.00061 [hep-th], JHEP 10 (2019) 146.

3) "Dynamics of Phase Separation from Holography" By Maximilian Attems, Yago Bea, Jorge Casalderrey-Solana, David Mateos, Miguel Zilhao, arXiv:1905.12544 [hep-th], JHEP 01 (2020) 106.

Backup: setup bottom-up model

Dual field theory: 'mimics'a deformation of N=4 SYM with a dimension 3 operator O and source Λ as 'mass'

$$S_{\text{GaugeTheory}} = S_{\text{conformal}} + \int d^4x \Lambda O$$

Einstein-Hilbert action coupled to a scalar with non-trivial potential in five-dimensional bottom-up model:

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

We derive the potential from the superpotential [Bianchi, Freedman, Skenderis 2002]: $V(\phi) = -\frac{4}{3} W(\phi)^2 + \frac{1}{2} W'(\phi)^2$

$$\ell^2 W(\phi) = -\frac{3}{2} - \frac{\phi^2}{2} - \frac{\phi^4}{4\phi_M^2}$$

using a single parameter with critical value $\phi_M = 2.521$

$$\ell^2 V(\phi) = -3 - \frac{3\phi^2}{2} - \frac{\phi^4}{3} - \frac{\phi^6}{3\phi_M^2} + \frac{\phi^6}{2\phi_M^4} - \frac{\phi^8}{12\phi_M^4}$$

Backup: thermodynamics bottom-up model

Dual field theory: 'mimics'a deformation of N=4 SYM with a dimension 3 operator O and source Λ as 'mass'

$$S_{\mathrm{GaugeTheory}} = S_{\mathrm{conformal}} + \int d^4x \Lambda O$$

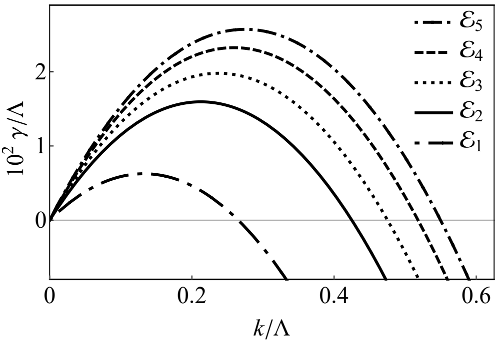
Growth rate

$$\gamma(k) = |c_s|\, k - \Gamma k^2$$

sound attenuation constant

$$\Gamma = \frac{1}{2T}\left(\frac{4}{3}\frac{\eta}{s} + \frac{\zeta}{s}\right)$$

raise dynamical instability



Backup: pinodal instability - stages

four generic stages:

1. linear stage
2. reshaping
3. merger
4. final:
   static + phase-separated

Homogeneous initial state in periodic unstable region, initial instability triggered by $n = 3$

endstate:
phase-separated configuration

conjecture:
all static, non-phase separated configurations are dynamically unstable