Far-from-equilibrium dynamics near a critical point

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1. Introduction

- The phase diagram of the strong interactions, i.e. the (T, μ_B) plane, remains vastly uncharted. Nonetheless, it is conjectured the existence of a critical point.
- One cannot apply perturbative methods of QCD since the quark-gluon plasma (QGP) formed in the vicinity of phase transitions is in a strongly coupled regime. Furthermore, lattice QCD is severely restricted at finite chemical potential due to the fermionic sign problem.
- Holography, as detailed below, offers a unique opportunity to study far-from-equilibrium dynamics in strongly coupled plasmas. Additionally, one can study non-equilibrium processes in the vicinity of a critical point.

2. Holography

Holography is the idea that a quantum field theory has an equivalent dual description in terms of a classical gravitational theory in higher dimensions. For instance, the AdS/CFT correspondence is a realization of such duality.

AdS/CFT = A superstring theory (type IIB) in $AdS_5 \times S^5$ is equivalent to a conformal field theory in 4 dimensions, the so-called SU(N) N=4 Super Yang-Mills.

The usefulness of the correspondence is that it maps a strongly coupled theory (N=4 SYM at infinite coupling) to a weakly coupled theory (general relativity in AdS5). Then, this duality may provide insights on the strongly coupled QGP. For instance, the celebrated result for the shear viscosity $\eta/s = 1/4\pi$ seems to be in the ballpark of what is found in heavy ion collisions.

Moreover, through the holographic dictionary, it is possible to extract one-point functions such as $\langle T^{\mu\nu}\rangle$ and $\langle J^{\mu}\rangle$. Hence, by disturbing the geometry of the dual space, it is possible to study the thermalization process of a strongly coupled plasma [1].

3. 1-R charge black hole (1RCBH) [2]

The gravitatonal background to investigate the N=4 SYM plasma with chemical potential (μ) and a critical point is the 1-R charge black hole (1RCBH), which is a "top-down" model obtained via compactifications of the supergravity action [2].

The bulk Lagrangian of the 1RCBH is:

$$2\kappa_5^2\mathcal{L} = R - \frac{(\partial_\mu\phi)^2}{2} - V(\phi) - \frac{f(\phi)(F_{\mu\nu})^2}{4}, \qquad (1)$$

$$V(\phi) = -\frac{1}{L^2}\left(8e^{\frac{\phi}{\sqrt{6}}} + 4e^{-\sqrt{\frac{2}{3}}\phi}\right), \qquad f(\phi) = e^{-2\sqrt{\frac{2}{3}}\phi},$$

1RCBH Thermodynamics:

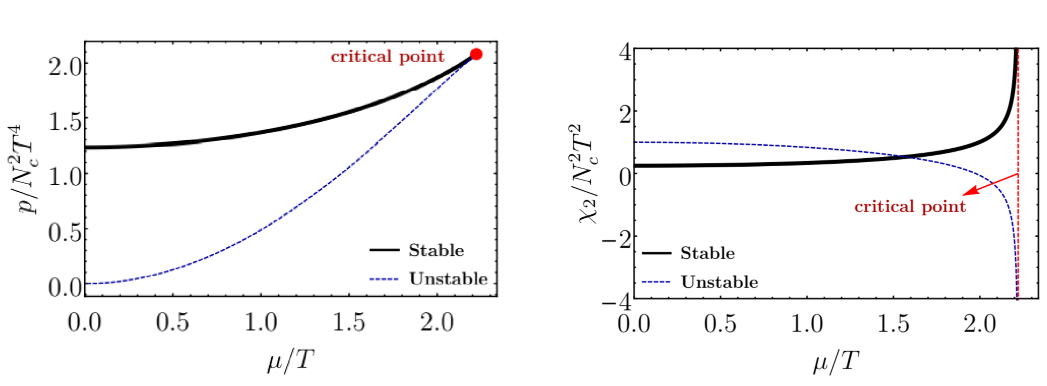


Fig. 1. (*Left*) Pressure as function of the chemical potential. (*Right*) 2nd order susceptibility as function of the chemical potential. Since the 1RCBH is a conformal model, the phase diagram is a line, i.e. it begins at $\mu/T = 0$ and ends at $\mu/T = \pi/\sqrt{2}$ (critical point).

Once the Lagrangian is specified, one may solve the Einstein's equations with different initial conditions to understand non-equilibrium processes near the critical point.

More specifically, we have considered the **homogeneous isotropization [3]** and the holographic **bjorken flow [4]** in the vicinity of the critical point of the 1RCBH.

References and Aknowledgements

[1] P. M. Chesler and L. G. Yaffe. JHEP **12** (2014) 086.
[2] S. S. Gubser. *Nucl. Phys.* **B551** (1999) 667.
[3] R. Critelli, R. Rougemont, J. Noronha. JHEP **12** (2017) 029.
[4] R. Critelli, R. Rougemont, J. Noronha. ArXiv: 1805.00882.
[5] Finazzo, Rougemont, Zaniboni, Critelli, Noronha. JHEP **01** (2017) 137.

3. Homogeneous isotropization [3]

- **GOAL:** Study the isotropization and equilibration of a strongly coupled non-Abelian plasma near a critical point using the the 1RCBH background.
- **RESULTS**: Pressure anisotropy (Δp) and the scalar condensate ($\langle O_\phi\rangle$)

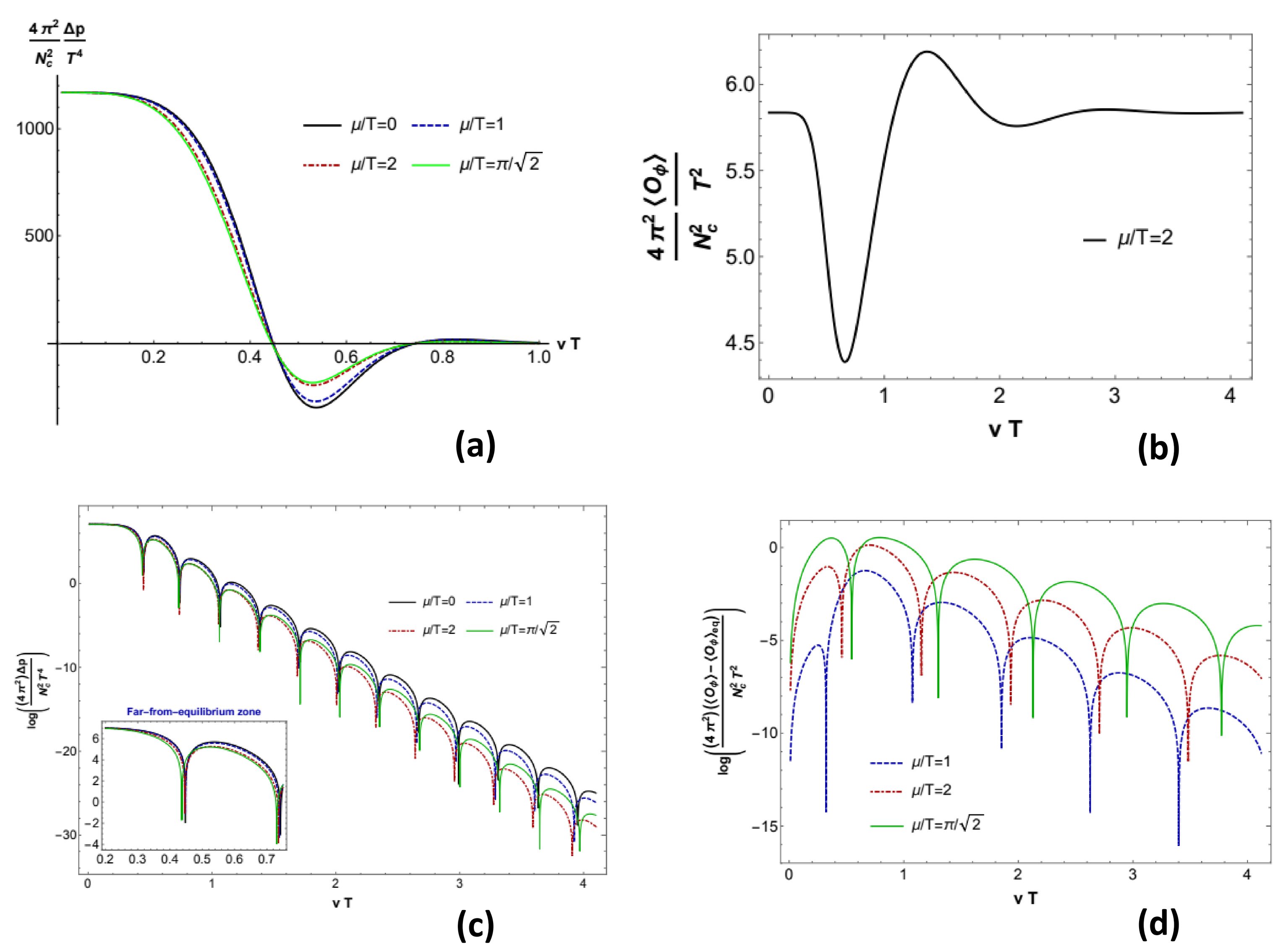


Fig. 2. (a) Time evolution of the pressure anisotropy normalized by the temperature for some values of chemical potential. (b) Time evolution of the scalar condensate for. (c) Late time behavior of the isotropization. (d) Subtracted late time behavior of the scalar condensate. The late time behavior of (c) and (d) matches the quasinormal modes (QNM's) of the linear analysis [5].

- **DISCUSSION**: Early time dynamics depends on the initial conditions but late time behavior agrees with linear analysis [5]. Regarding the isotropization, fig. 1 shows that the chemical potential does not change the isotropization time significantly, even near the critical point. With respect to the scalar condensate, its time evolution is more sensitive as one increases the chemical potential.

4. Bjorken flow [4]

- **GOAL:** Study the effect of a critical point (CP) in the holographic bjorken flow. More specifically, what is the influence of the CP on the onset of hydrodynamics (hydrodynamization)?
- **RESULTS:** Pressure anisotropy (Δp), charge density (ρ), scalar condensate ($\langle O_\phi\rangle$), and hydrodynamization time (w_{hydro}). In particular, the hydrodynamization time is defined when the inequality below begins to hold

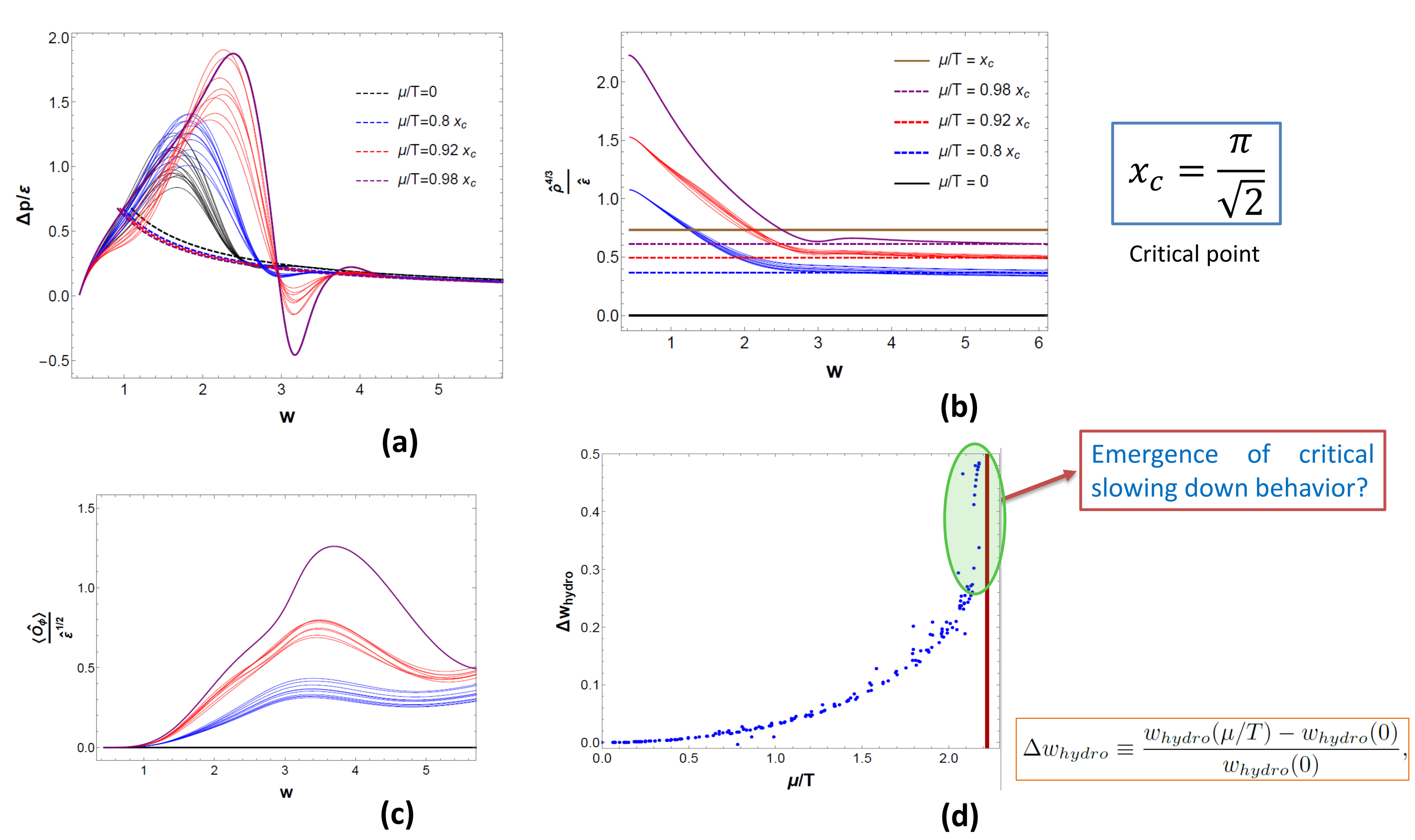
$$\left|\left(\frac{\Delta p}{\varepsilon}\right)_{numerical} - \left(\frac{\Delta p}{\varepsilon}\right)_{hydro}\right| \le 0.01\left(\frac{\Delta p}{\varepsilon}\right)_{hydro} \qquad (2)$$

where *hydro* denotes the **Navier-Stokes** solution.

$$w \equiv \varepsilon^{1/4}\tau$$

$$x_c = \frac{\pi}{\sqrt{2}}$$

Critical point



$$\Delta w_{hydro} \equiv \frac{w_{hydro}(\mu/T) - w_{hydro}(0)}{w_{hydro}(0)},$$

Fig. 3. (a) Time evolution of the pressure anisotropy for some values of μ/T; the dashed line is the Navier-Stokes solution. (b) Time evolution of the charge density. (c) Time evolution of the scalar condensate. (d) Variation of the hydrodynamization time with respect the chemical potential.

- DISCUSSION: From Fig. 3. (a) we see an apparent enhancement of the hydrodynamization time for large values of μ/T. This behavior is confirmed in Fig. 3. (d), which shows how the hydrodynamization time increases with μ/T. Indeed, in the vicinity of the critical point we observe some kind of critical slowing down of the hydrodynamization time.

5. Conclusions

Holography provides a way to determine the non-equilibrium behavior of strongly coupled systems near a critical point.

We showed, for the first time, that the time that it takes for hydrodynamics to be valid (hydrodynamization time) significantly increases near the critical point.