Relaxation rates and phase transitions

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arXiv:1603.05950
arXiv:1512.06871

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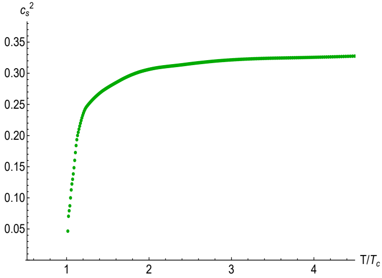
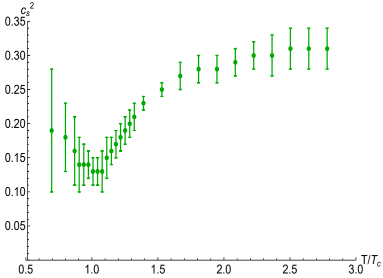
Phase structure at strong coupling

- Systems at strong coupling exhibit various phase structures
- Pure gluon system $\longrightarrow$ 1^{st} order phase transition (left)
- Gluons + quarks $\longrightarrow$ smooth crossover (right)



G. Boyd *et.al.* Nucl. Phys. B **469**, 419 (1996)



S. Borsanyi *et al.* JHEP **1009**, 073 (2010)

Phase structure at strong coupling

- Real time dynamics is not easy reachable with lattice methods
- Use other methods to model strongly coupled phase transitions
- Compute the spectrum of linearized perturbations
- Compute transport coefficients and non-hydrodynamic modes
- Check linear stability

Method:

Use string theory based methods to formulate models at strong coupling!

Questions

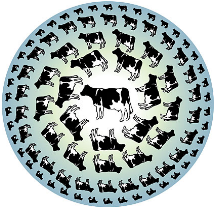
- Does spinodal instability appear for a system with a 1^{st} order phase transition?
- Does dynamical instability has to be accompanied by a thermodynamical instability?
- How non-hydrodynamic degrees of freedom behave in the critical region?
- Do diffusive modes appear?

Method:

Use string theory based methods to formulate models at strong coupling!

Holography and Quantum Field Theory

- Holographic principle
  Quantum gravity in d dimensions must have a number of DOF which scales like that of QFT in $d-1$ dimensions
  't Hooft and Susskind '93



- String Theory realization: *AdS/CFT correspondence*
  Theory is *conformal* and *supersymmetric* Maldacena '97
- Extensions to *non-supersymmetric* and *non-conformal* field theories are possible
- Applications: elementary particle physics and condensed matter physics

Classical gravity limit

- Limit $N \to \infty$ and $\lambda = g_{YM}^2 N \to \infty$
- Lattice simulation for $N = 3, 4, 5, 6, 8$ colours

  M. Panero, Phys. Rev. Lett. **103**, 232001 (2009)
- Equilibrium state in QFT $\longleftrightarrow$ black hole in dual spacetime
  Field theory temperature $\longleftrightarrow$ Hawking temperature
  Field theory entropy $\longleftrightarrow$ Bekenstein-Hawking entropy

  E. Witten, Adv. Theor. Math. Phys. **2**, 505 (1998)

- Gravity-scalar field model in $d = 5$

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

with the potential

$$V(\phi) = -12 \left(1 + a\,\phi^2\right)^{1/4} \cosh(\gamma\,\phi) + b_2\,\phi^2 + b_4\,\phi^4 + b_6\,\phi^6$$

- Scalar field generically adds energy scale to the system
- Modeling of some aspects of QCD e.g. equations of state, meson spectra, colour confinement

U. Gursoy, *et.al.* JHEP **0905**, 033 (2009)
S. S. Gubser, A. Nellore, Phys. Rev. D **78** (2008) 086007

Phase transitions in holography

- Phase structure is determined by the bulk scalar field interactions quantified by a potential $V(\phi)$

- It is possible to tune parameters to mimic
  $\rightarrow$ crossover e.g. QCD
  $\rightarrow$ 1^{st} order phase transition e.g. pure gluon systems
  $\rightarrow$ 2^{nd} order phase transition

U. Gursoy, *et.al.* JHEP **0905**, 033 (2009)
S. S. Gubser, A. Nellore, Phys. Rev. D **78** (2008) 086007

Linear response and Quasinormal modes

- Perturb the system $\mathcal{L} = \mathcal{L}_0 + h_{ij}\delta^3(x)\delta(t)T^{ij}(x)$ the response is the *retarded Green's* function

$$G_R(\omega, k) \propto i \int dt d^3x \; \theta(t) e^{ikx - i\omega t} \langle [T_{ij}(x,t), T_{kl}(0)] \rangle$$

- *Quasinormal modes*, i.e., solutions of linearized fluctuation equations correspond to poles of holographic retarded Green's functions. In general

$$\omega_n(k) = \Omega_n(k) - i\Gamma_n(k)$$

where $n = 1, 2, 3, \ldots$ $\Omega_n(k)$—oscillation frequency, $\Gamma_n(k)$—damping rate. Stable modes have $\Gamma_n(k) > 0$.

P. K. Kovtun, A. O. Starinets, Phys. Rev. D **72**, 086009 (2005)

- Hydrodynamic mode is defined by

$$\lim_{k\to 0} \omega_{\mathrm{H}}(k) = 0$$

- The sound mode

$$\omega(k) = \pm\, c_s\, k - \frac{i}{2\,T} \left(\frac{4}{3} \frac{\eta}{s} + \frac{\zeta}{s} \right) k^2 + O(k^3)$$

η−shear viscosity, ζ−bulk viscosity, s−entropy density, c_s−speed of sound, T−temperature

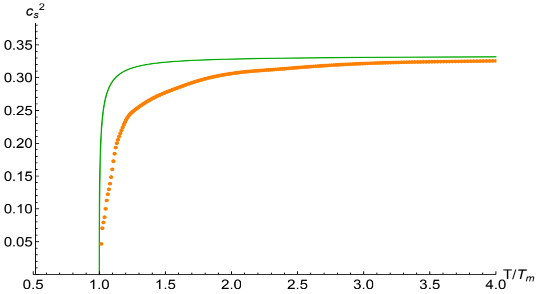
- In holographic models also *non-hydrodynamic* modes are present

P. K. Kovtun, A. O. Starinets, Phys. Rev. D **72**, 086009 (2005)

The first example

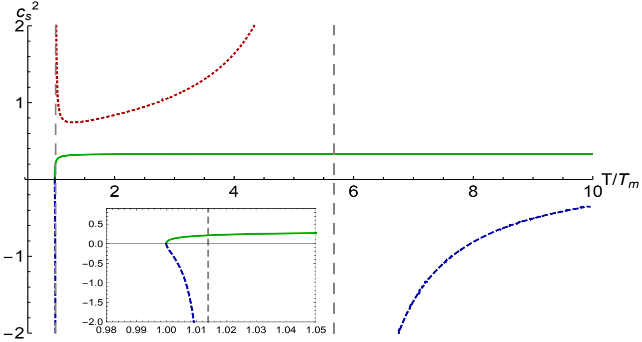
- Holographic model motivated by gluon dynamics
- Transition between black hole and horizon-less geometry

  S. W. Hawking, D. N. Page, Commun. Math. Phys. **87**, 577 (1983)
- Holographic 1^{st} order phase transition



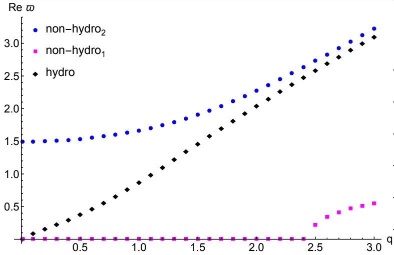
G. Boyd *et.al.* Nucl. Phys. B **469**, 419 (1996)

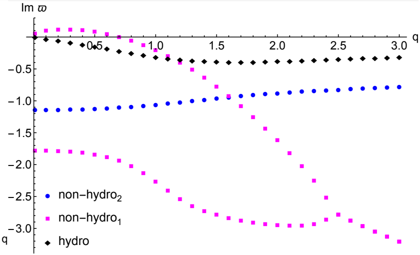
Full holographic scan



- Below T_m no black hole solution exists
- Various lines represent different black hole phases with different properties

Dynamical instability





- Quasinormal modes at $T = 1.027\, T_m$
- System displays dynamical instability despite thermodynamical stability!

Spinodal instability

- When $c_s^2 < 0$ we have purely damped hydro-modes

$$\omega \approx \pm i|c_s|\, k - \frac{i}{2\,T}\left(\frac{4}{3}\frac{\eta}{s} + \frac{\zeta}{s}\right) k^2$$

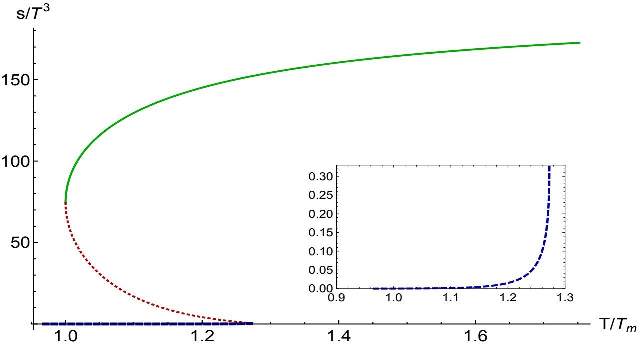
so for small enough k we have $\mathrm{Im}\ \omega > 0$

- For a finite range of momenta this mode is present
- This appears for systems with a 1^{st} order phase transition; *spinodal* instability
- This phenomenon occurs e.g. in nuclear matter

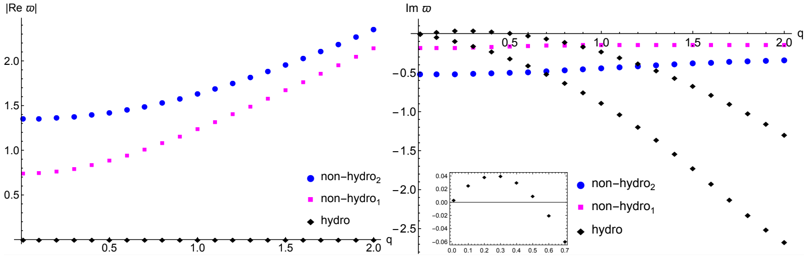
P. Chomaz, M. Colonna, J. Randrup, Phys. Rept. **389**, 263 (2004)

The second example

- Transition between two different black hole solutions
- Other example of holographic 1$^{\mathrm{st}}$ order phase transition
- As in the previous case there exists minimal temperature T_m
- For the unstable region (red-dashed line) we have $c_s^2 < 0$



Holographic spinodal instability



- Modes for $T \simeq 1.06\, T_m$ where $c_s^2 \simeq -0.1$
- Hydrodynamic mode follows the thermodynamic instability
- Non-hydrodynamic modes have weak momentum dependence

Summary

- Thermodynamic instability $\longrightarrow$ dynamical instability
- Converse seems not to be true!

  U. Gursoy, A. Jansen, W. van der Schee, arXiv:1603.07724 [hep-th]
- Non-trivial phase structure limits the applicability of hydrodynamics
- In most cases non-hydro degrees of freedom have very weak dependence on k $\longrightarrow$ *„ultralocality"*
- Extensions to lower couplings and comparison to kinetic theory

  S. Grozdanov, N. Kaplis, A. O. Starinets, arXiv:1605.02173 [hep-th]
- Experimental evidences in cold atoms systems

  J. Brewer, P. Romatschke, Phys. Rev. Lett. **115**, no. 19, 190404 (2015)

Question:

What is field theory interpretation of non-hydrodynamic quasinormal modes?