A Thermal Quench Induces Spatial Inhomogeneities in a Holographic Superconductor

Hai-Qing Zhang

(Instituto Superior Técnico, Lisboa)

INI, Cambridge, 17/09/2013

Coauthor: Antonio M. García-García & Hua-Bi Zeng, arXiv:1308.5398

TÉCNICO LISBOA

Introduction

- **Static homogeneous** holographic superconductor (HSC)
- **Dynamical homogeneous** HSC
- **Static inhomogeneous** HSC

- **Static homogeneous** HSC:

  Gubser, Phys. Rev. D 78 (2008) 065034

  Hartnoll, Herzog, & Horowtiz, Phys.Rev.Lett. 101 (2008) 031601

✓ Einstein-Maxwell-charged scalar action with negative cosmological constant

✓ $T>T_c$ (or $\mu< \mu_c$, since $T\sim1/\mu$): $\psi=0$;

$T<T_c$: two available solutions

$\psi=0$ $>$ $\psi\neq0$ superconducting solution

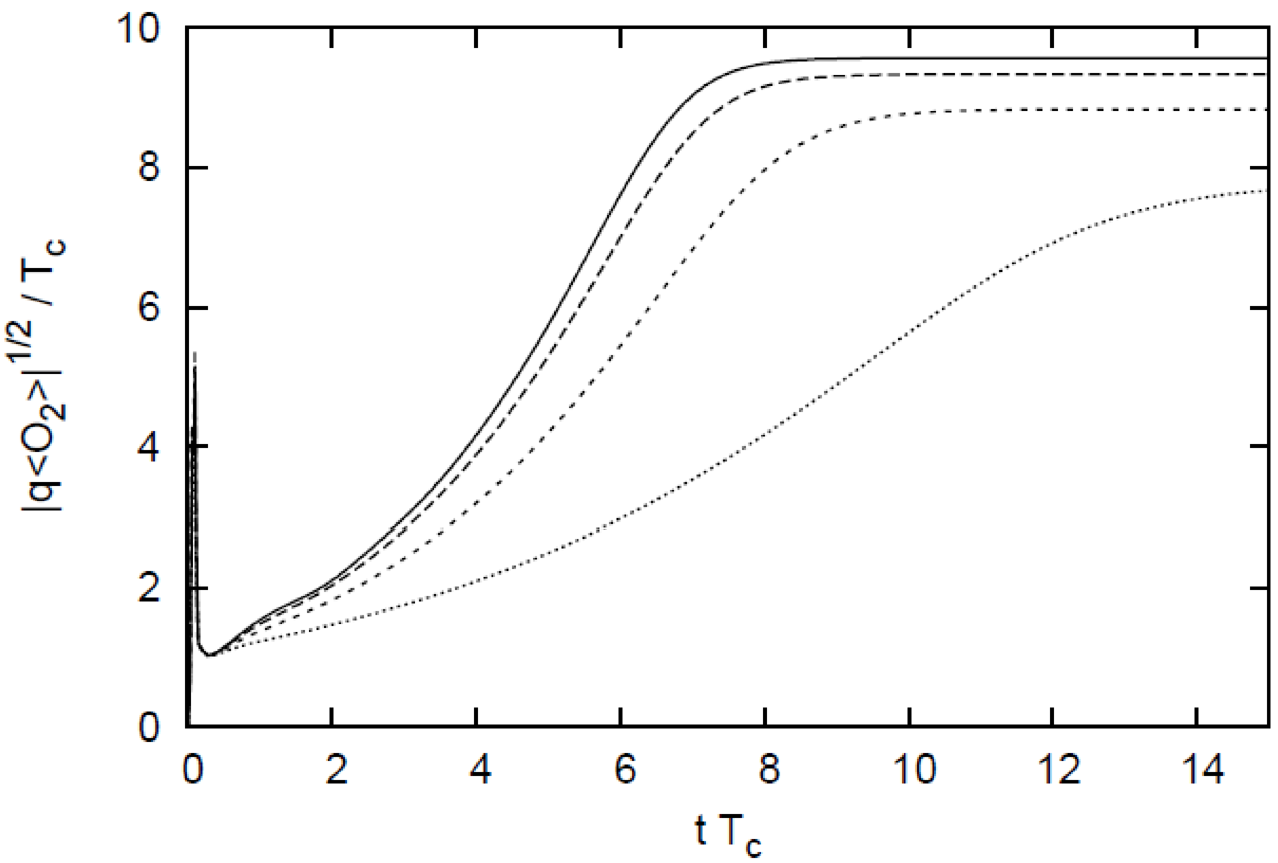
free energy

- **Dynamical homogeneous** HSC after a quench:

✓ Murata, Kinoshita & Tanahashi, JHEP 1007 (2010) 050

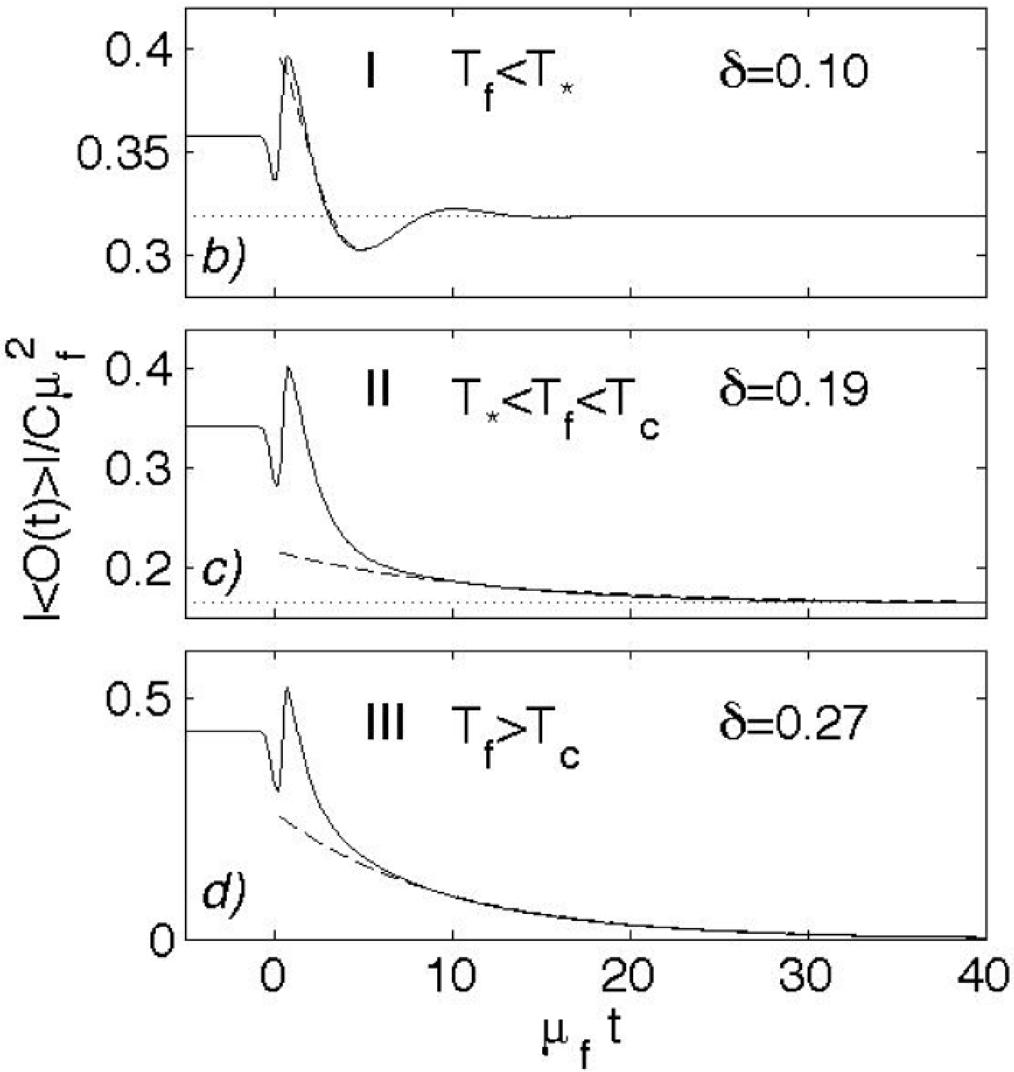
T<Tc, RN-AdS → (Gaussian quench) → static hairy black hole;

normal phase → superconducting phase



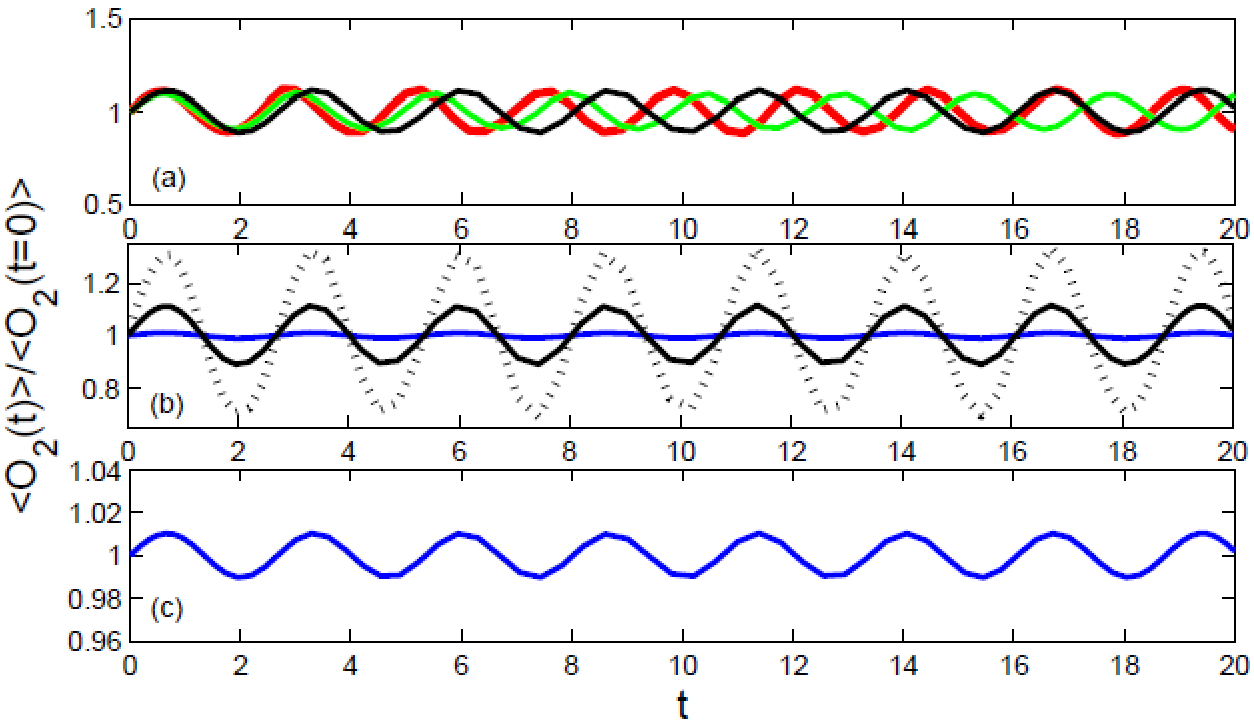
✓ Bhaseen, Gauntlett, Simons, Sonner & Wiseman, Phys.Rev.Lett. 110 (2013) 015301

three kinds of decays are found, consistent with QNMs



✓ Gao, Garcia-Garcia, Zeng & **Zhang**: arXiv:1212.1049

AdS soliton background, undamped oscillation modes are found; lack of thermalization in CFT



✓ Polkovnikov, Sengupta, Silva, Vengalattore, Rev.Mod.Phys. 83 (2011) 863

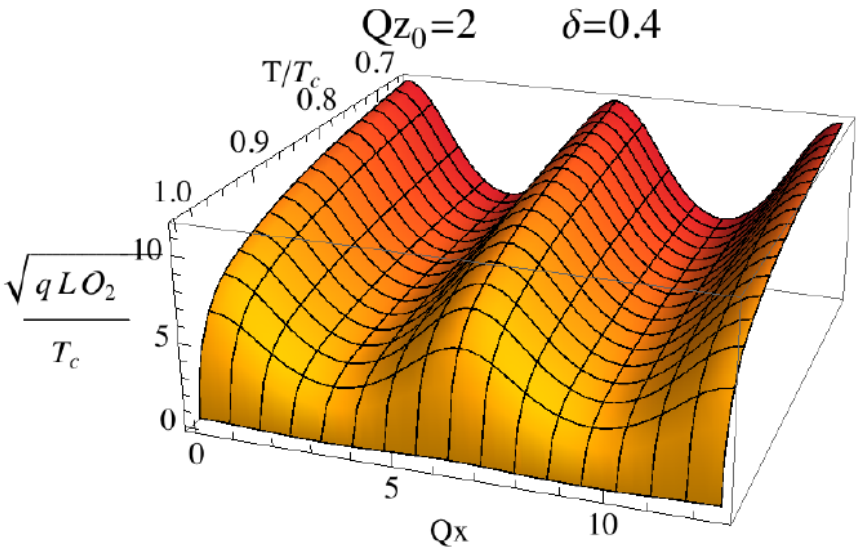
CMT: lack of thermalization comes from integrability.

Question: what is the relation between a gravity without horizon and the integrable field theory on boundary?

- **Static inhomogeneous** HSC:

Flauger, Pajer & Papanikolaou, Phys.Rev. D83 (2011) 064009

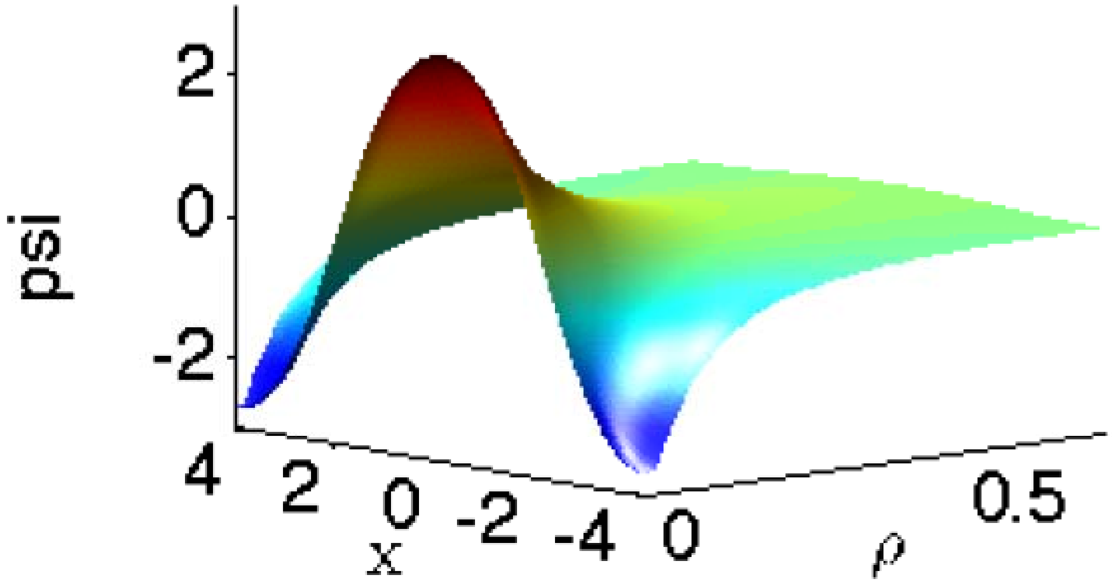
Einstein- Maxwell-scalar action, modulated chemical potential, striped superconductor, *explicitly* break translational symmetry, free energy is lower than the homogeneous case



Donos & Gauntlett, JHEP 1108, 140 (2011)

Rozali, Smyth, Sorkin & Stang, Phys.Rev.Lett. 110, (2013) 201603

Einstein-Maxwell-axion action, *spontaneously* break the translational symmetry, striped order parameter



Liu, Ooguri, Stoica & Yunes, Phys. Rev. Lett. 110, (2013) 211601

Chern-Simons term , *spontaneously* generate angular momentum

- Other references:

✓ dynamical studies :

I. Amado, M. Kaminski & K. Landsteiner, JHEP, 0905021 (2009)

S. Bhattacharyya, and S. Minwalla, JHEP 0909:034, (2009)

P. Bizon, and A. Rostworowski, Phys. Rev. Lett. 107, 031102 (2011)

O. Dias, G. Horowitz, D. Marolf and J. Santos, Class. Quant. Grav. 29, 235019 (2012)

P. Basu, D. Das, S. Das and T. Nishioka, arXiv:1211.7076

...

✓ inhomogeneous studies:

S. Nakamura, H. Ooguri and C. -S. Park, Phys. Rev. D 81, 044018 (2010)

G. T. Horowitz, J. E. Santos and D. Tong, JHEP 1211, 102 (2012)

...

Motivation to Dynamical Inhomogeneous HSC

- Kibble-Zurek mechanisms:

  Zel'dovich, Kobzarev & Okun, Zh. eksp. teor. Fiz. 67, 3 (1974);
  Soviet Phys. JETP 67, 401 (1975)

  Kibble, J. Phys. A 9, 1387 (1976)
  Zurek, Nature 317, 505 (1985)

  topological defects generated from a sudden quench

Dzero, Yuzbashyan & Altshuler, Eur. Phys. Lett. 85 (2009) 20004

system size larger than superconducting coherence length, quench can excite finite momentum states, results in spatial inhomogeneities

- From holography:

  Donos & Gauntlett, JHEP 1108, 140 (2011)

  Rozali, Smyth, Sorkin & Stang, Phys.Rev.Lett. 110, (2013) 201603

✓ axion fields, spontaneously break the translational symmetry.

  Liu, Ooguri, Stoica & Yunes, Phys. Rev. Lett. 110, (2013) 211601

✓ angular momentum generation from Chern-Simons terms.

- How about a quench depending on time?

Dynamical inhomogeneous HSC

- Einstein-Maxwell-complex scalar action:

$$S = \int d^4x\sqrt{-g}\left[R - 2\Lambda - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - |\nabla\psi - iqA\psi|^2 - m^2|\psi|^2\right].$$

in which $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$

- AdS-Schwarzschild black hole:

$$ds^2 = -f(r)dt^2 + \frac{dr^2}{f(r)} + r^2(dx^2 + dy^2)$$

with

$$f(r) = r^2/L^2(1 - r_0^3/r^3)$$

- ✓ Fields depend on *t,r* & *x.*
- ✓ Ansatz:

$$\psi(t,r,x) = \rho(t,r,x)e^{i\varphi(t,r,x)}, \ \psi^*(t,r,x) = \rho(t,r,x)e^{-i\varphi(t,r,x)}.$$

$$A_i(t,r,x) = M_i(t,r,x) + \partial_i\varphi(t,r,x), \quad i = t,r,x.$$

- ✓ 4 independent EoMs, 1 constraint equation
- ✓ Boundary conditions:
- ✓ At horizon: $Mt(t, x)|_{rh}=0$;
- ✓ Other fields are finite

✓ For m^2=-2, expansions near boundary:

$$\begin{aligned}\rho &= \rho_1(t,x)/r + \rho_2(t,x)/r^2 + \dots,\\ M_t &= \mu(t,x) - \tilde{\rho}(t,x)/r + \dots,\\ M_r &= M_r^{(2)}(t,x)/r^2 + \dots,\\ M_x &= v(t,x) + J(t,x)/r + \dots.\end{aligned}$$

$\tilde{\rho}(t,x)$-charge density;

$\mu(t,x)$-chemical potential;

source $\rho_1 = 0$;

order parameter $\langle\mathcal{O}(x,t)\rangle \equiv \rho_2(x,t)$

$v(t,x)$ - superfluid velocity;

supercurrent $J = 0$.

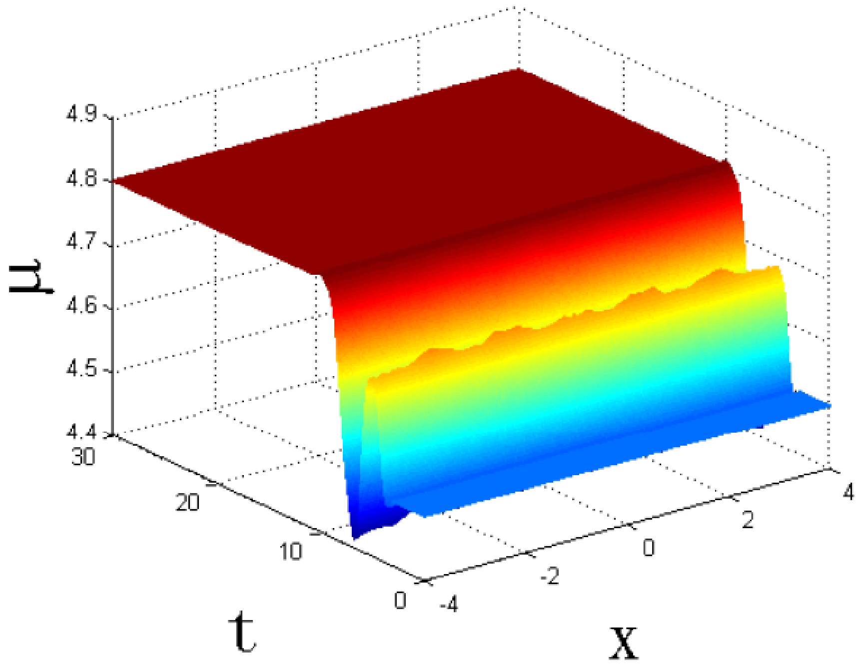
- Thermal quench, since $T \sim 1/\mu$, it is equal to quench chemical potential.
- Quench A:

$\mu_i=4.5$, $\mu_f=4.8$, corresponding to

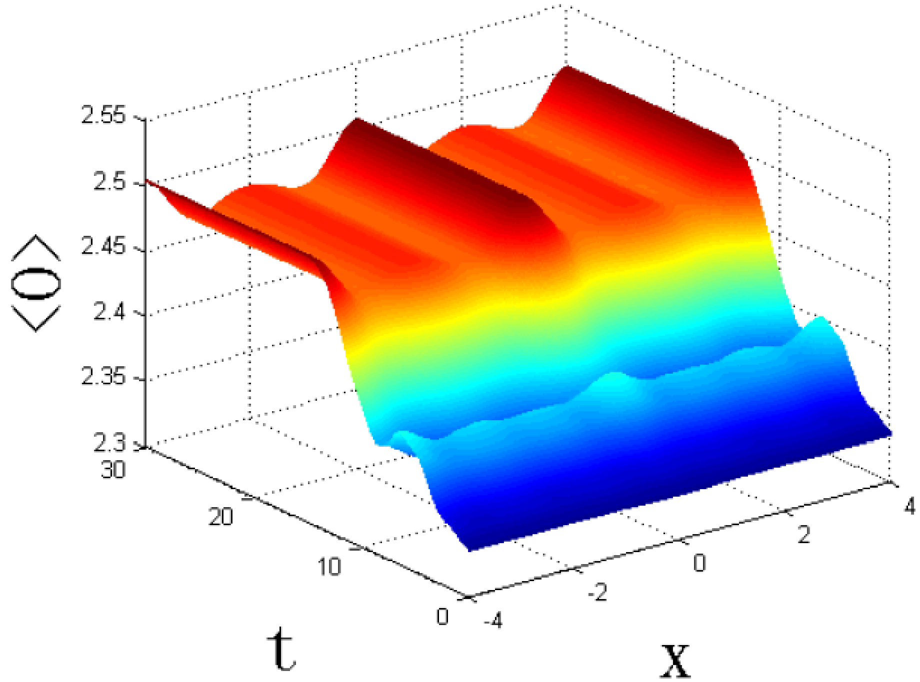
$T_i=0.903T_c$, $T_f=0.846T_c$

since for homogeneous case $\mu_c=4.063$ (m^2=-2)

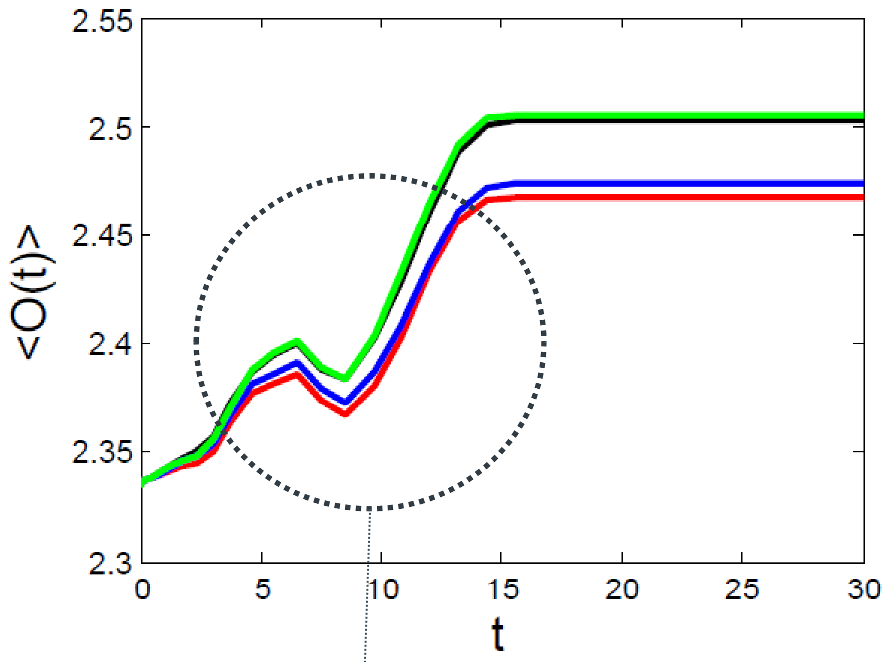
Hartnoll, Herzog, & Horowtiz, Phys.Rev.Lett. 101 (2008) 031601

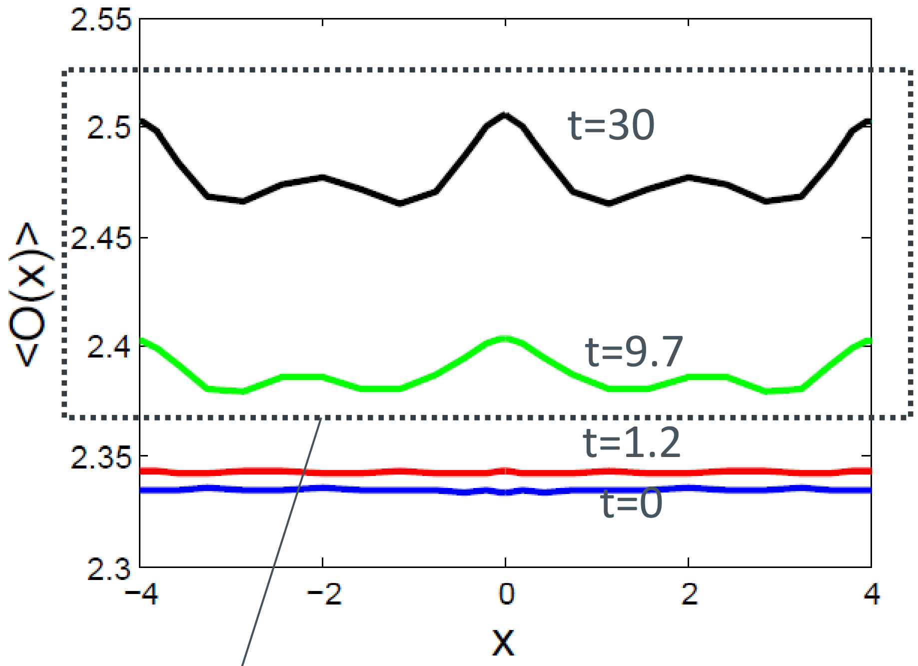


chemical potential



expectation value





oscillations in time

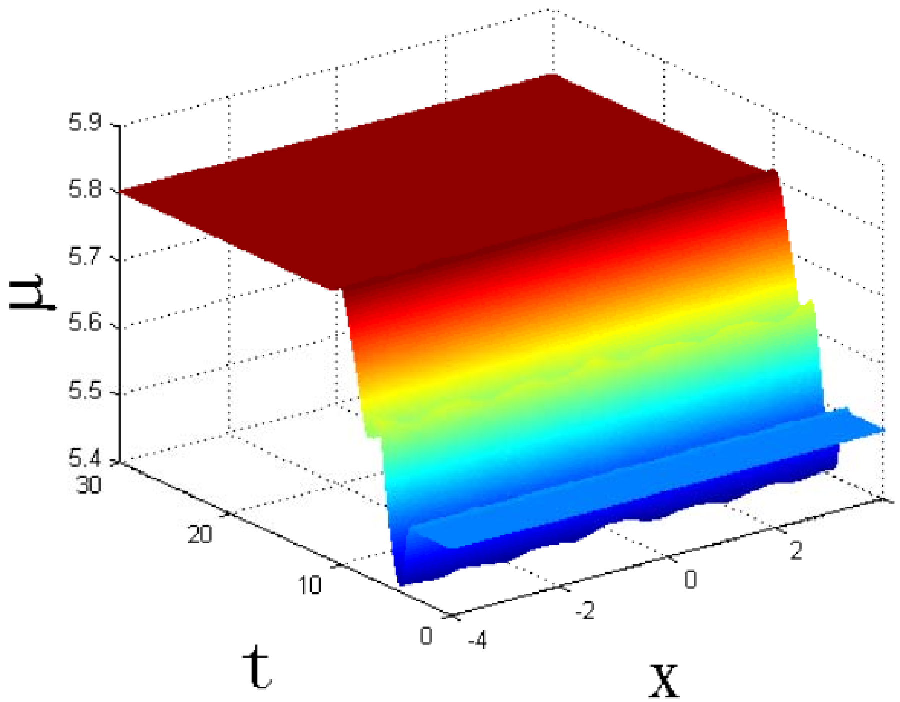
inhomogeneous order parameter

Physical meaning: quench will excite finite momentum

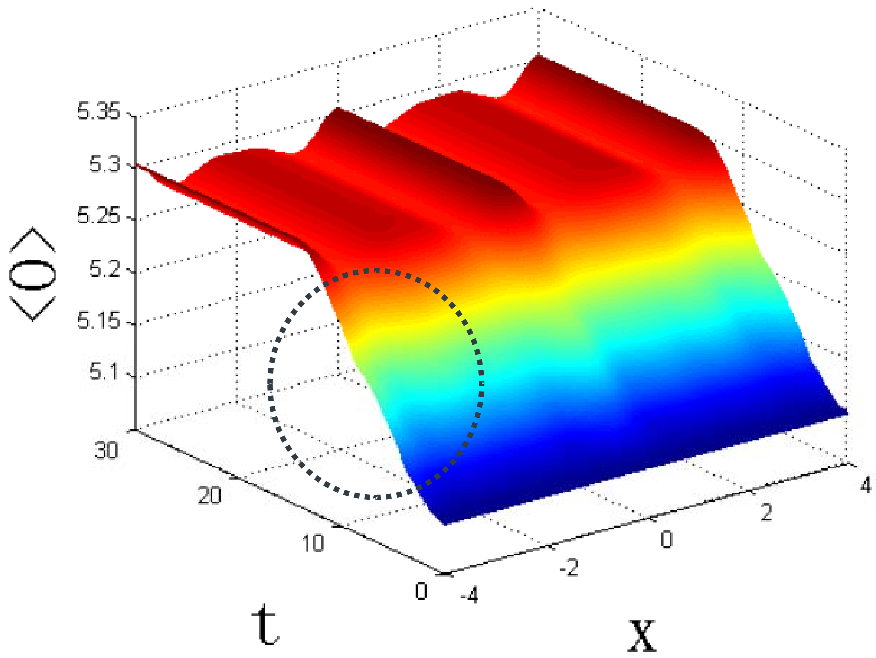
- Quench B:

  μ_i=5.5, μ_f=5.8, corresponding to

  T_i=0.738 T_c, T_f=0.700 T_c.



chemical potential



expectation value

- Free energy, grand canonical ensemble,

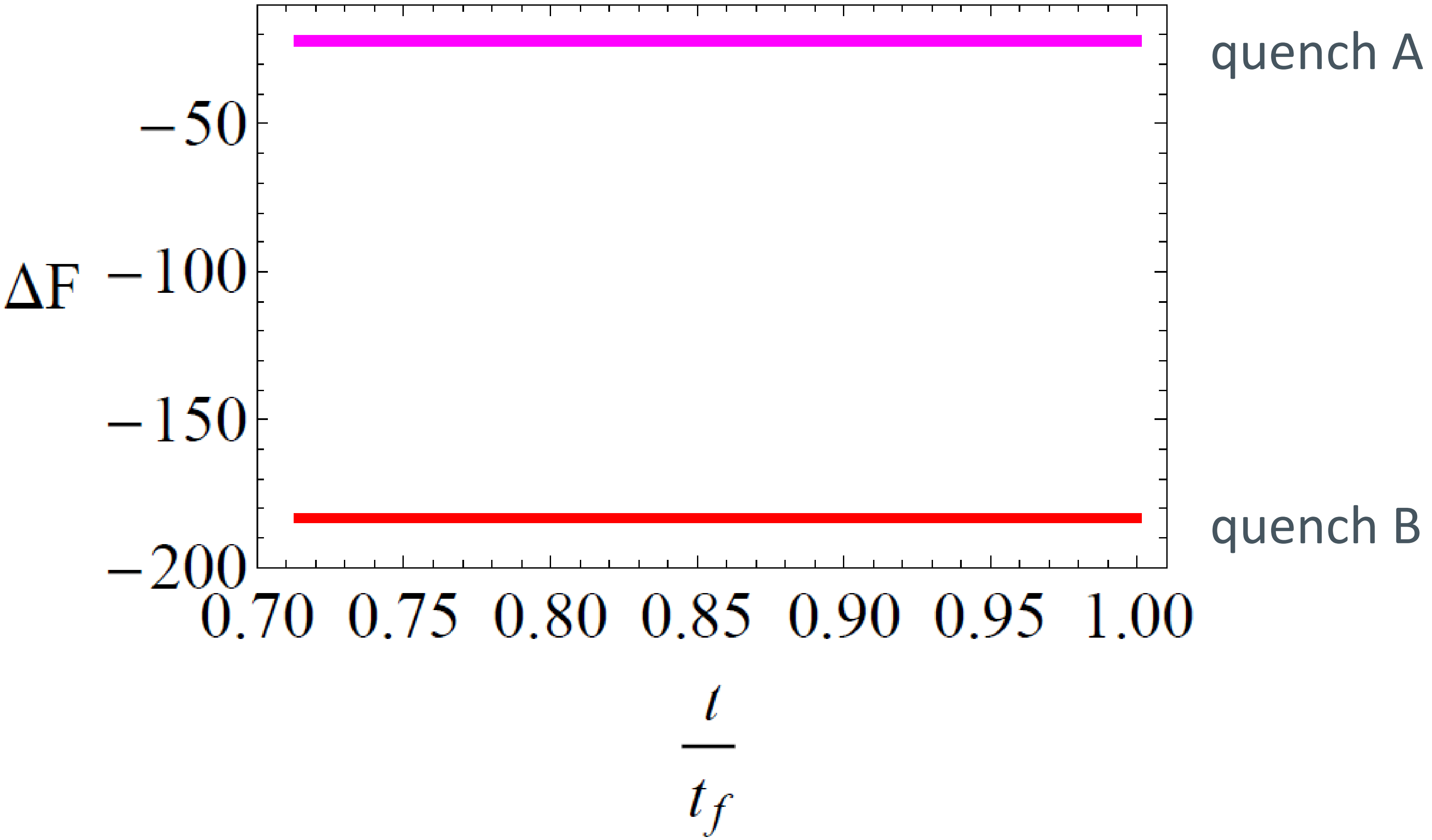
  F=-TSos

$$S_{os} = \int_{z=0} d^3x \left[\frac{h}{z^2}\psi\partial_z\psi - M_t\partial_z M_t + hM_x\partial_z M_x + h^2 M_r\partial_z M_r \right] - \int d^4x \left[\frac{M_t^2}{hz^2}\psi - \frac{M_x^2\psi^2}{z^2} + \frac{h}{z^2}M_r^2\psi^2 \right]$$

where z=1/r, h=1-z^3

$$F \propto \int_{z=0} d^3x M_t\partial_z M_t + \int d^4x \left[\frac{M_t^2}{hz^2}\psi - \frac{M_x^2\psi^2}{z^2} + \frac{h}{z^2}M_r^2\psi^2 \right]$$

- at late times



Summaries

- Developments in HSC: static homogeneous, dynamical homogeneous, static inhomogeneous.
- Motivation: spontaneous symmetry breaking
- Dynamical inhomogeneous HSC, a quench induces translational symmetry breaking

Thanks for your attention!