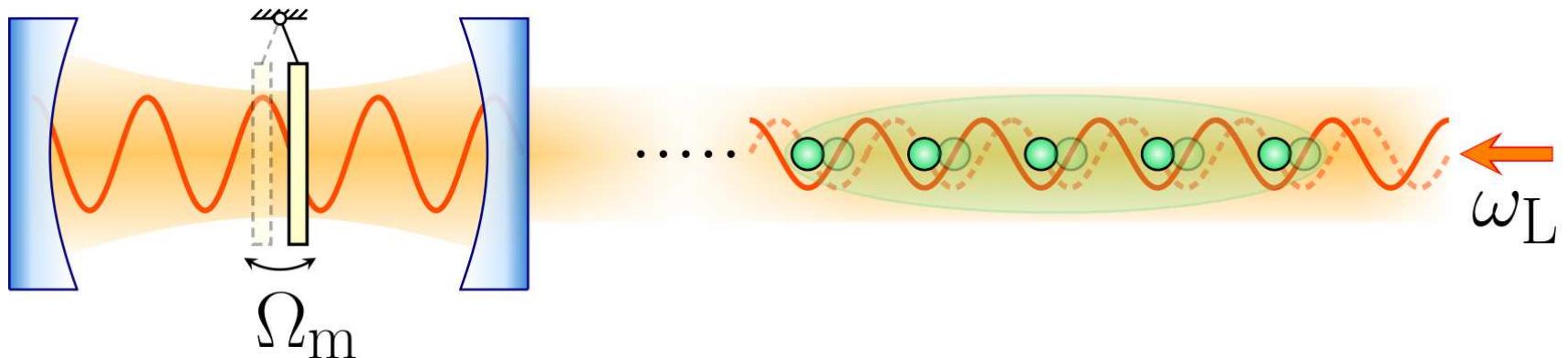


Nonequilibrium Quantum Phase Transition in a Hybrid Atom-Optomechanical System

Axel Pelster



Niklas Mann, M. Reza Bakhtiari, Axel Pelster, and Michael Thorwart,
PRL **120**, 063605 (2018)



SFB/Transregio 49
Frankfurt – Kaiserslautern – Mainz
Condensed matter systems with variable
many-body interactions



1 Effective GPE in Bad Cavity Limit

- **Sympathetic cooling:**

B. Vogell *et al.*, PRA **87**, 023816 (2013)

A. Jöckel *et al.*, Nature Nanotech. **10**, 55 (2015)

- **Collective atomic motion:**

A. Vochezer *et al.*, PRL **120**, 073602 (2018)

- **Mean-field theory:** $\hat{\Psi}(z) \approx \sqrt{N}\psi(z), \quad \hat{a} \approx \sqrt{N}\alpha$

$$i\partial_t\psi = \left[-\omega_R \partial_z^2 + gN|\psi|^2 + V\sin^2(z) - \sqrt{N}\lambda(\alpha + \alpha^*)\sin(2z) \right] \psi$$

$$i\partial_t\alpha = (\Omega_m - i\gamma)\alpha - \sqrt{N}\lambda \int dz \sin(2z)|\psi|^2$$

- **Dynamical competition:** potential terms $\sim \sin^2(z)$ and $\sim \sin(2z)$

- **Two possible approaches:**

- **Numerical solution**

- **Variational solution**

2 Cumulant Expansion

- Gaussian variational ansatz:

$$\psi(z, t) = \left[\frac{1}{\pi\sigma(t)^2} \right]^{1/4} \exp \left[-\frac{[z-\zeta(t)]^2}{2\sigma(t)^2} + i\kappa(t)z + i\beta(t)z^2 \right]$$

e.g. H. Al-Jibbouri and A. Pelster, PRA **88**, 033621 (2013)

- **Projection:** cumulants from equations of motion
- **Ordinary differential equations for variational parameters:**

$$2\Omega_m^{-1} (\ddot{\alpha}' + 2\gamma\dot{\alpha}') = -\partial_{\alpha'} E$$

$$(2\omega_R)^{-1}\ddot{\zeta} = -\partial_{\zeta} E$$

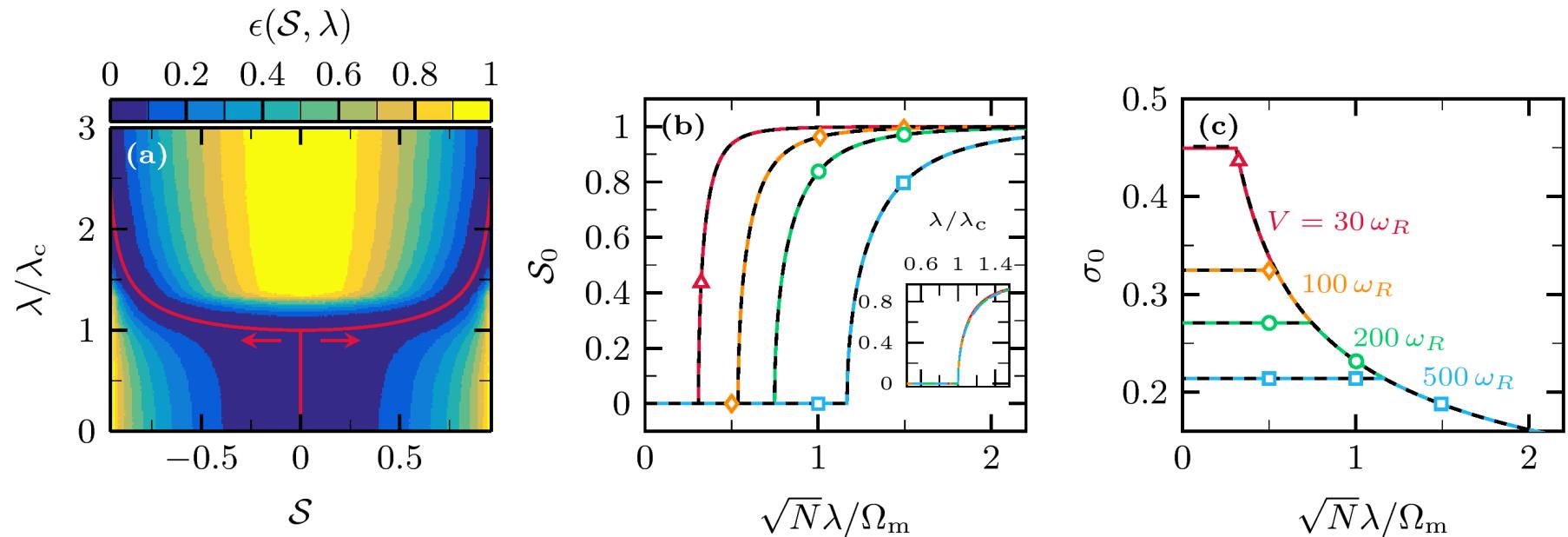
$$(4\omega_R)^{-1}\ddot{\sigma} = -\partial_{\sigma} E$$

potential energy $E = - \int dz \mathcal{L}|_{\dot{\alpha}=\dot{\psi}=0}$

- Other talks using cumulant expansion:
 - V03.00002 by Milan Radonjić, Friday, 10:42 AM, Grand B
 - V03.00005 by Enrico Stein, Friday, 11:18 AM, Grand B

3 Nonequilibrium Quantum Phase Transition

- Order parameter: $S = \sin(2\zeta)$
- Steady state:

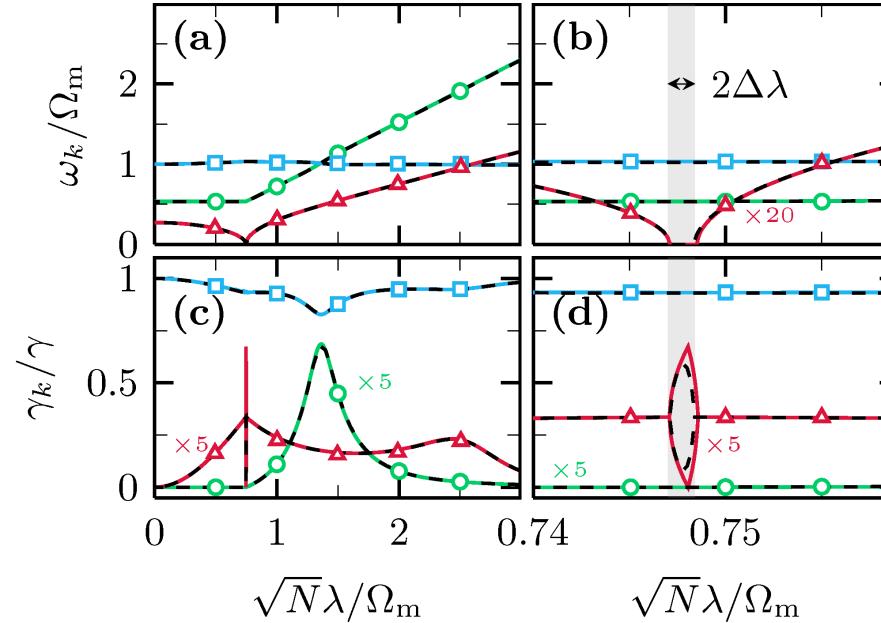


- Critical atom-membrane coupling:

$$\omega_R + \frac{gN}{\sqrt{8\pi}} \sqrt{2 \ln \frac{\lambda_c}{\lambda_{c,V}}} = 4V \left(\frac{\lambda_{c,V}}{\lambda_c} \ln \frac{\lambda_c}{\lambda_{c,V}} \right)^2 ,$$

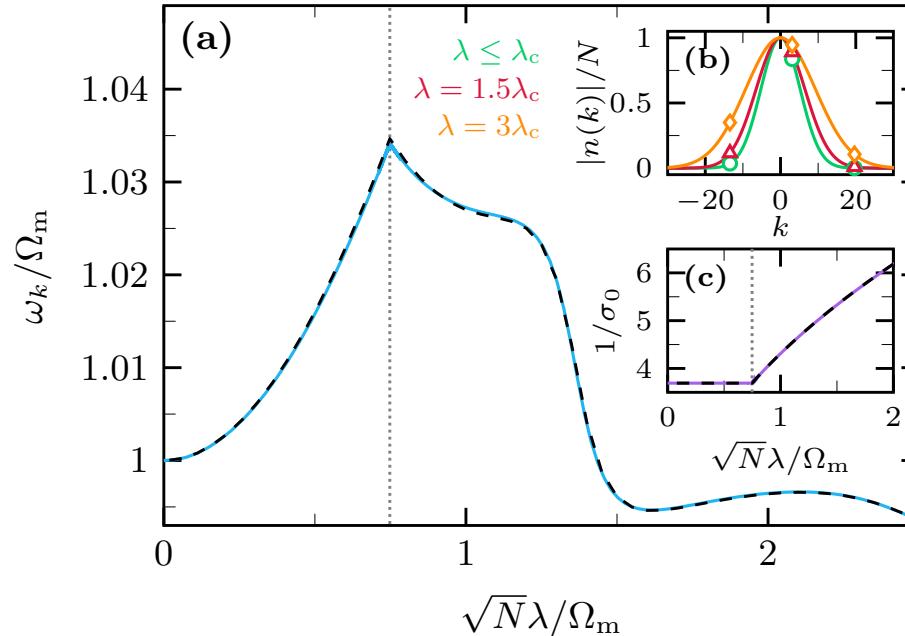
$$\lambda_{c,V}^2 = \frac{(\Omega_m^2 + \gamma^2)V}{4\Omega_m}$$

4 Collective Excitation Spectrum



- **Characterization of critical point:**
 - Mode softening
 - Decay rate maximal
 - **Interval around critical point:**
 - Vanishing of lowest collective frequency
 - Bifurcation of decay rate
- ⇒ **Long-range interactions mediated by membrane**

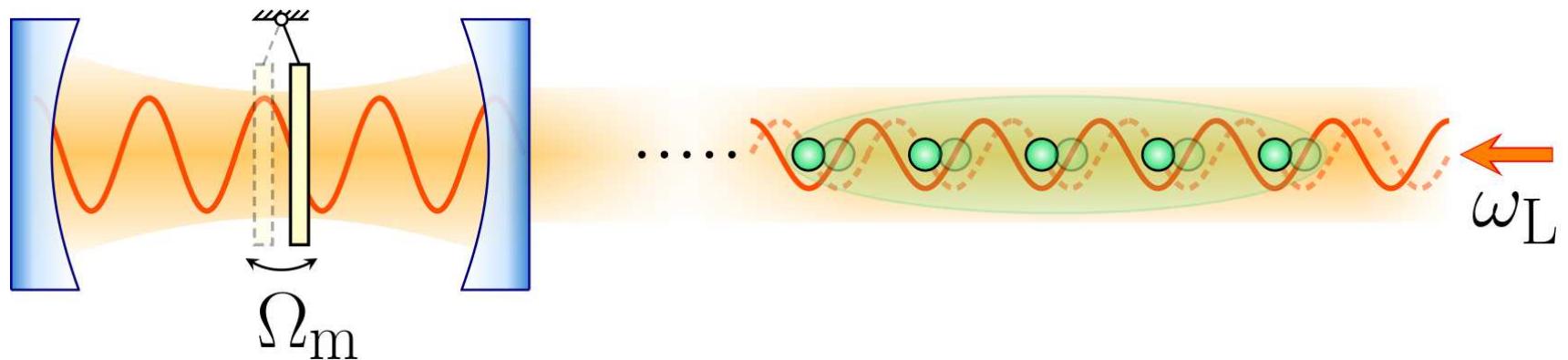
5 Experimental realization



- **Experimental observation possible in existing setups:**
 - Resonant atom-membrane coupling λ : $\omega_\zeta \approx \Omega_m$
H. Zhong *et al.*, Rev. Sci. Instrum. **88**, 023115 (2017)
 - Nonresonant atom-membrane coupling
- **Possible detection schemes:**
 - Spectroscopic measurement of membrane eigenfrequency
 - Atomic momentum distribution: condensate width

6 Summary

- **Vibrational mode of nanomembrane coupled to center of mass motion of atomic gas**
- **NQPT:** critical atom-membrane interaction $\lambda_{c,V}$
 - $\lambda < \lambda_{c,V}$: Atoms symmetrically distributed around lattice sites
 - $\lambda > \lambda_{c,V}$: Finite atomic CoM and membrane displacement
- **Lowest excitation mode shows roton-type characteristics**
- **Strong atom-membrane entanglement at $\lambda = \lambda_{c,V}$**
- **Outlook: Measuring membrane displacement fluctuations**



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8 Announcement

685th Wilhelm and Else Heraeus Seminar Research Frontiers in Ultracold Quantum Gases organized by Carlos Sá de Melo and Axel Pelster Bad Honnef (Germany); December 17 – 21, 2018

Invited Speakers: James Anglin (Germany), Gianni Blatter (Switzerland), Joachim Brand (New Zealand), Gretchen Campbell (USA), Franco Dalfovo (Italy), Leonardo Fallani (Italy), Francesca Ferlaino (Austria), Christian Groß (Germany), Dieter Jaksch (UK), Selim Jochim (Germany), Wolfgang Ketterle (USA), Giovanna Morigi (Germany), Silke Ospelkaus (Germany), Elena Ostrovskaya (Australia), Tilman Pfau (Germany), Arno Rauschenbeutel (Austria), Laurent Sanchez-Palencia (France), Anna Sanpera (Spain), Yoshiro Takahashi (Japan), Letticia Tarruell (Spain), Michael Thorwart (Germany), Masahito Ueda (Japan), Curt von Keyserlingk (USA), Martin Weitz (Germany), Martin Zwierlein (USA)

<http://www-user.rhrk.uni-kl.de/~apelster/Heraeus5/index.html>