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2164-5

Workshop on Nano-Opto-Electro-Mechanical Systems Approaching the Quantum Regime

6 - 10 September 2010

From Cavity Opto-Mechanics to Quantum Phase-Transitions

Tilman ESSLINGER

ETH Zurich, Instit. for Quantum Electronics
Schafmattstr. 16, CH-8093
Zurich
SWITZERLAND

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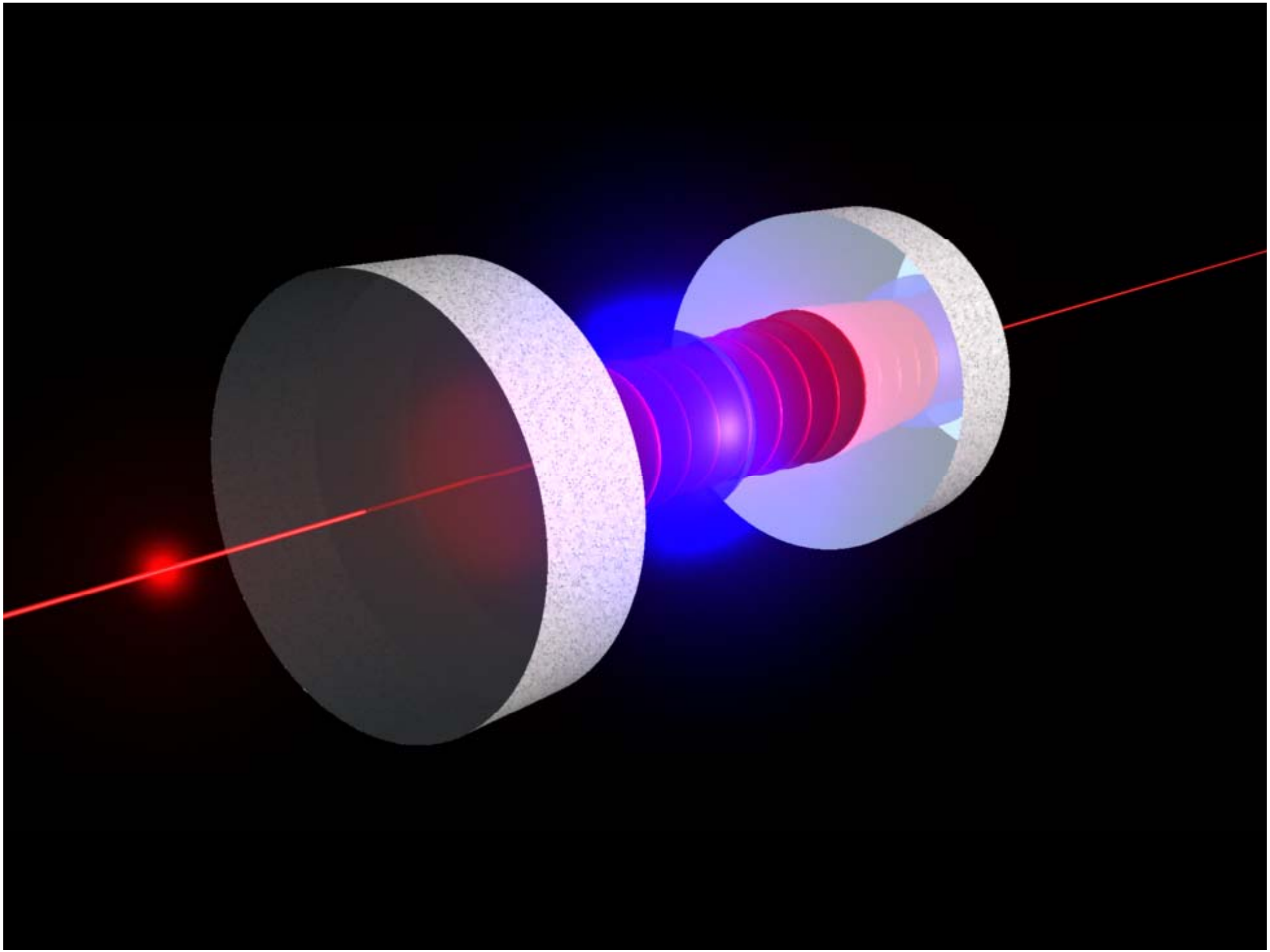
Tilman Esslinger ETH Zürich

Funding: ETH, EU (ERC, NameQuam, Scala), QSIT, SNF

www.quantumoptics.ethz.ch

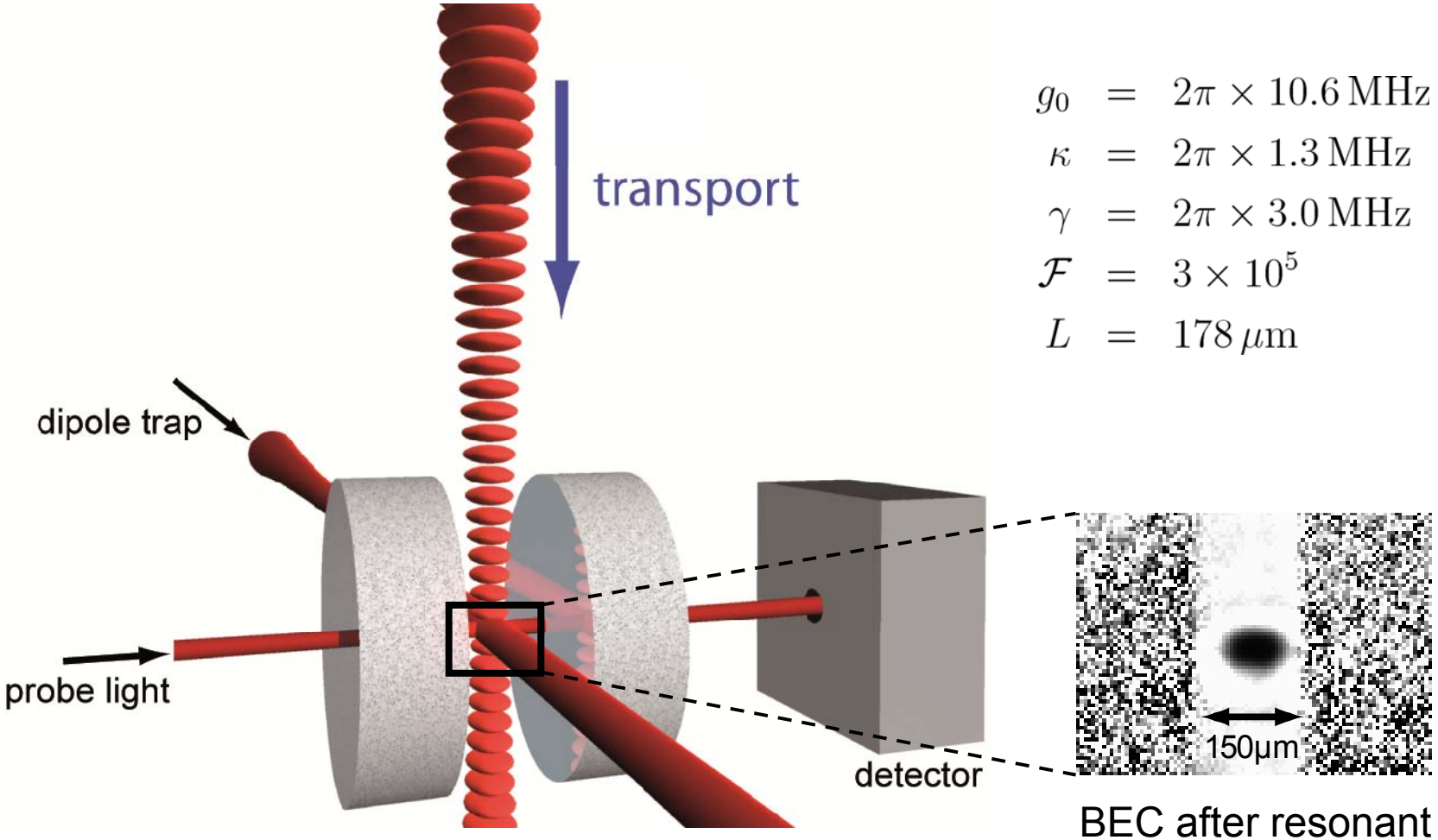
Quantum Gases  Quantum Optics



Cavity opto-mechanics

Dicke Quantum Phase Transition

Experimental setup

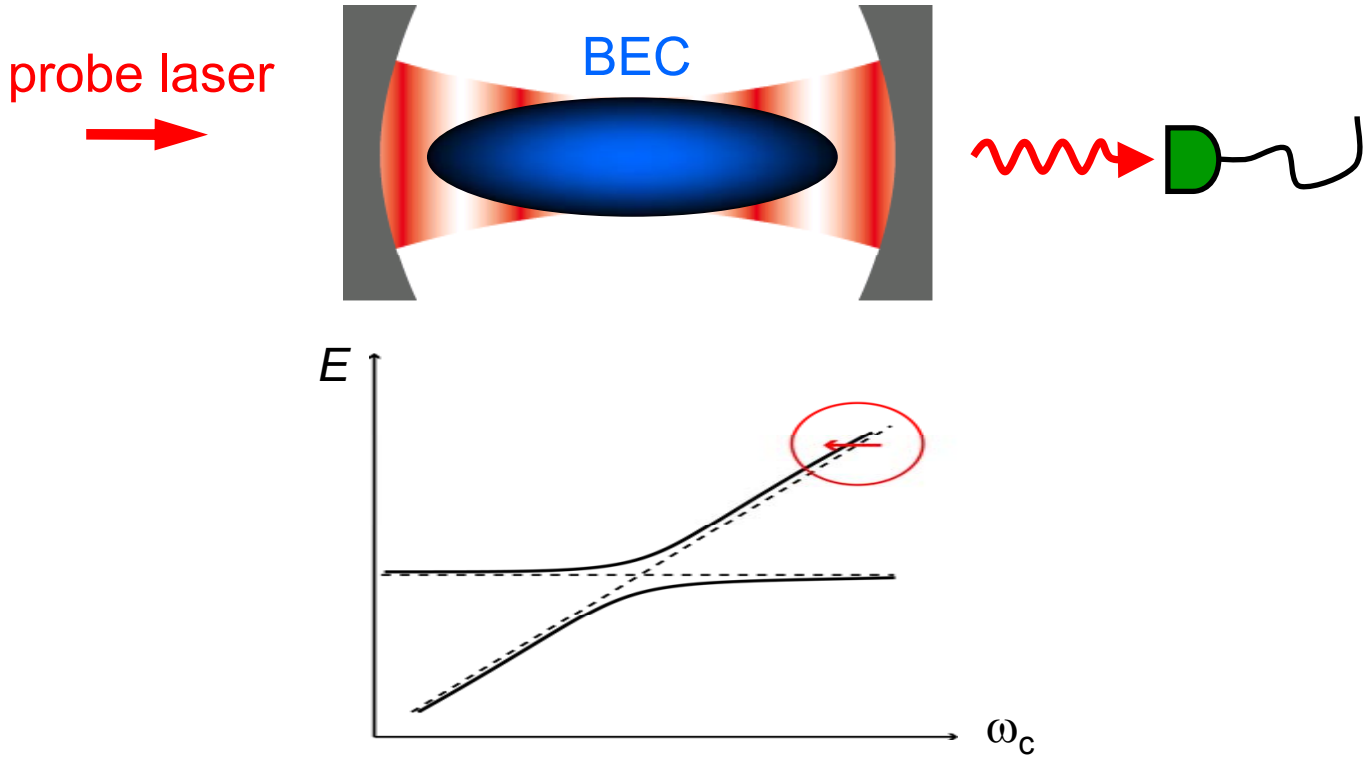


$$
\begin{aligned}
g_0 &= 2\pi \times 10.6\,\mathrm{MHz} \\
\kappa &= 2\pi \times 1.3\,\mathrm{MHz} \\
\gamma &= 2\pi \times 3.0\,\mathrm{MHz} \\
\mathcal{F} &= 3 \times 10^5 \\
L &= 178\,\mu\mathrm{m}
\end{aligned}
$$

BEC after resonant probing and free expansion

See also: Zimmermann, Hemmerich, Stamper-Kurn, Reichel

Spectroscopy

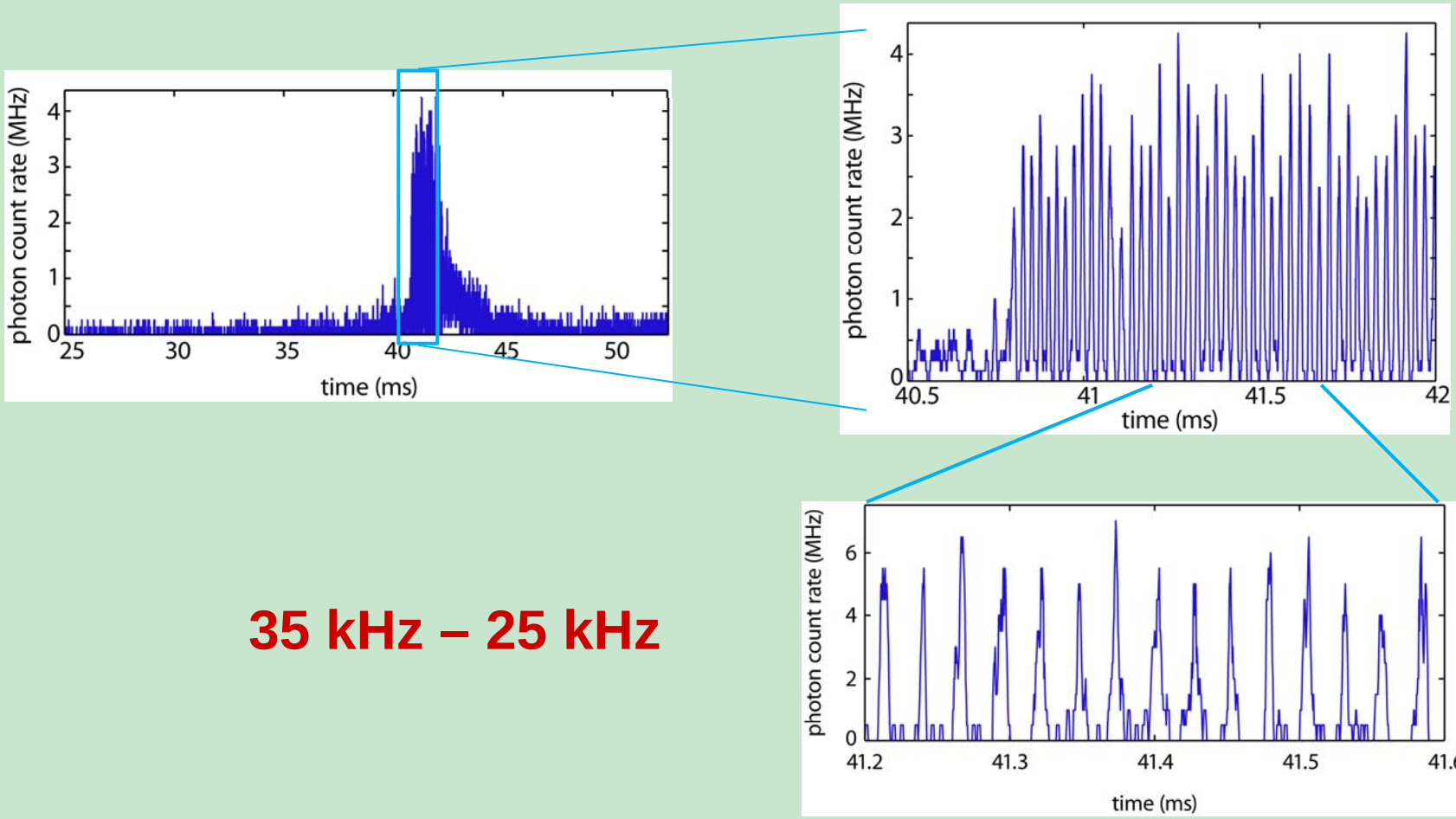


The bare cavity resonance frequency is refractively shifted by BEC

See also: D. Stamper-Kurn group: PRL 99, 213601 (2007), Nat. Phys. 4, 561 (2008)

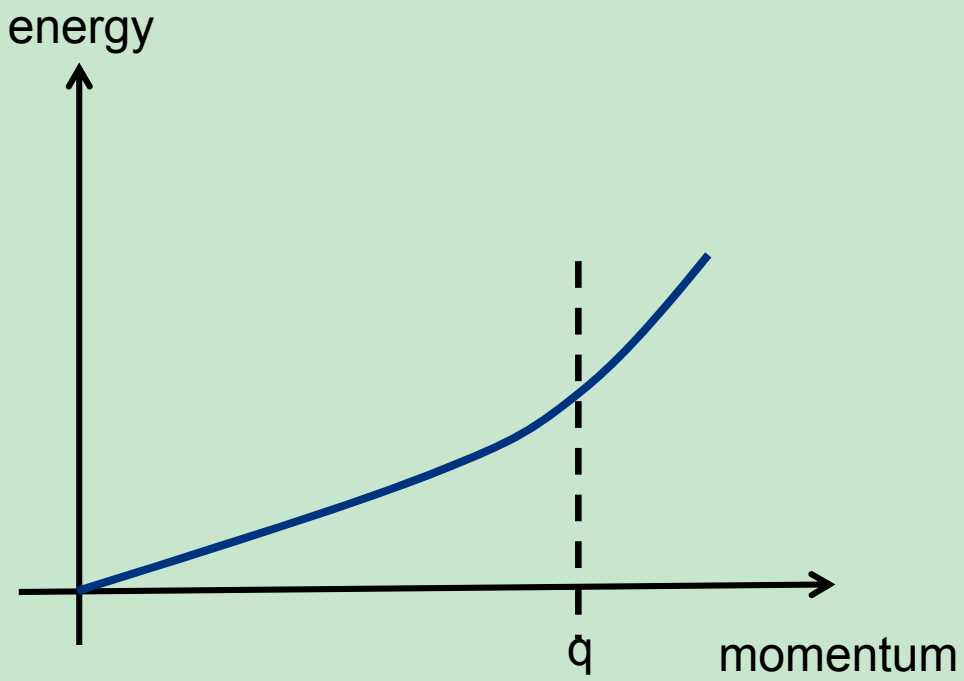
BEC Cavity Dynamics

BEC

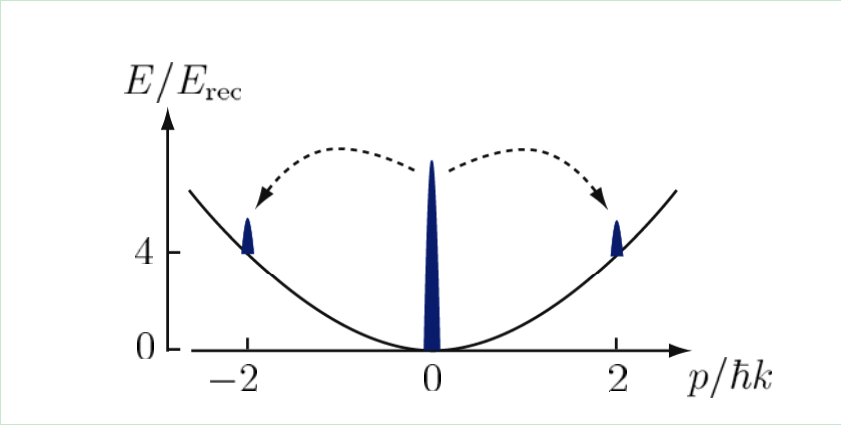


35 kHz – 25 kHz

Coupling BEC-Cavity



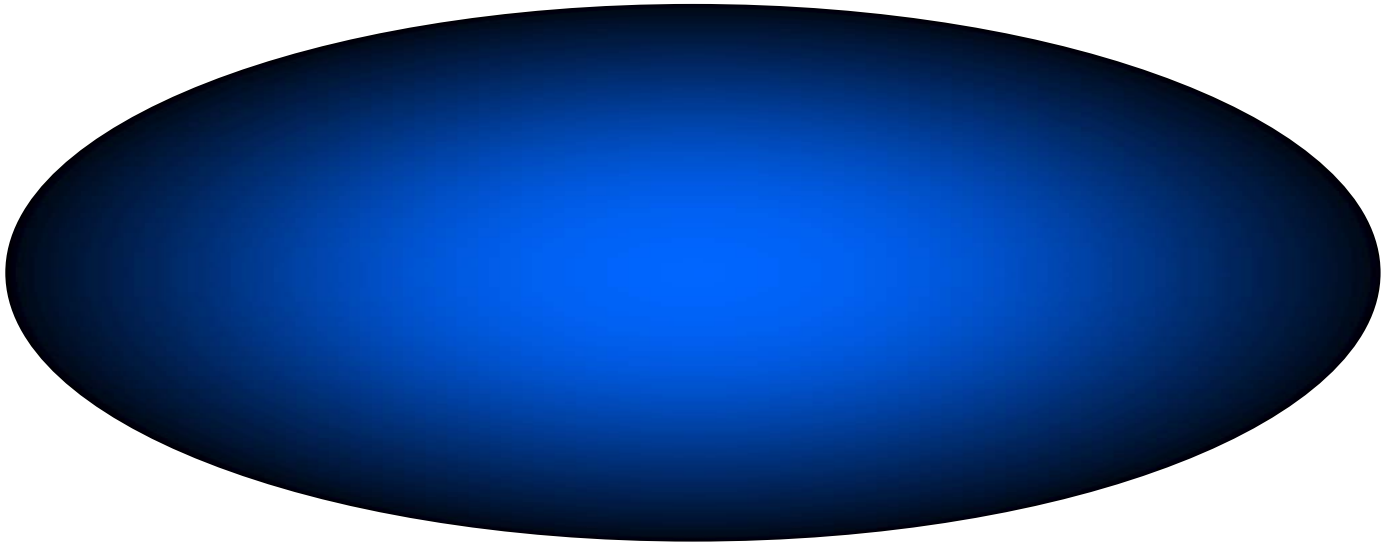
BEC as a mechanical oscillator



$$\Psi(x,t) = c_0(t)\left|\, p = 0\right\rangle + c_2(t)\left|\, p = \pm 2\hbar k\right\rangle$$

$$\left|\Psi(x,t)\right|^2 \approx N + c_2\sqrt{N}\cos(2kx)\cos(4\omega_r t)$$

BEC as a mechanical oscillator



Cavity opto-mechanics with a BEC

$$H = \int \hat{\Psi}^{\dagger}(x)\left(\frac{-\hbar^2}{2m}\frac{d^2}{dx^2} + \hbar U \cos^2(kx)\hat{a}^{\dagger}\hat{a}\right)\Psi(x)dx - \Delta\hbar\hat{a}^{\dagger}\hat{a} - H_{in/out}$$

$$\Psi(x) = \sqrt{N}\,|p=0\rangle + \hat{c}_2\,|\pm 2\hbar k\rangle$$

$$H = 4\hbar\omega_{rec}\hat{c}^{\dagger}\hat{c} - \Delta\hbar\hat{a}^{\dagger}\hat{a} + \hbar g\left(\hat{c}+\hat{c}^{\dagger}\right)\hat{a}^{\dagger}\hat{a} - H_{in/out}$$

Cavity opto-mechanics with a BEC

Full Hamiltonian

two mode description

$$H = 4\hbar\omega_{rec}\hat{c}^{\dagger}\hat{c} - \Delta\hbar\hat{a}^{\dagger}\hat{a} + \hbar g\left(\hat{c} + \hat{c}^{\dagger}\right)\hat{a}^{\dagger}\hat{a} - H_{in/out}$$

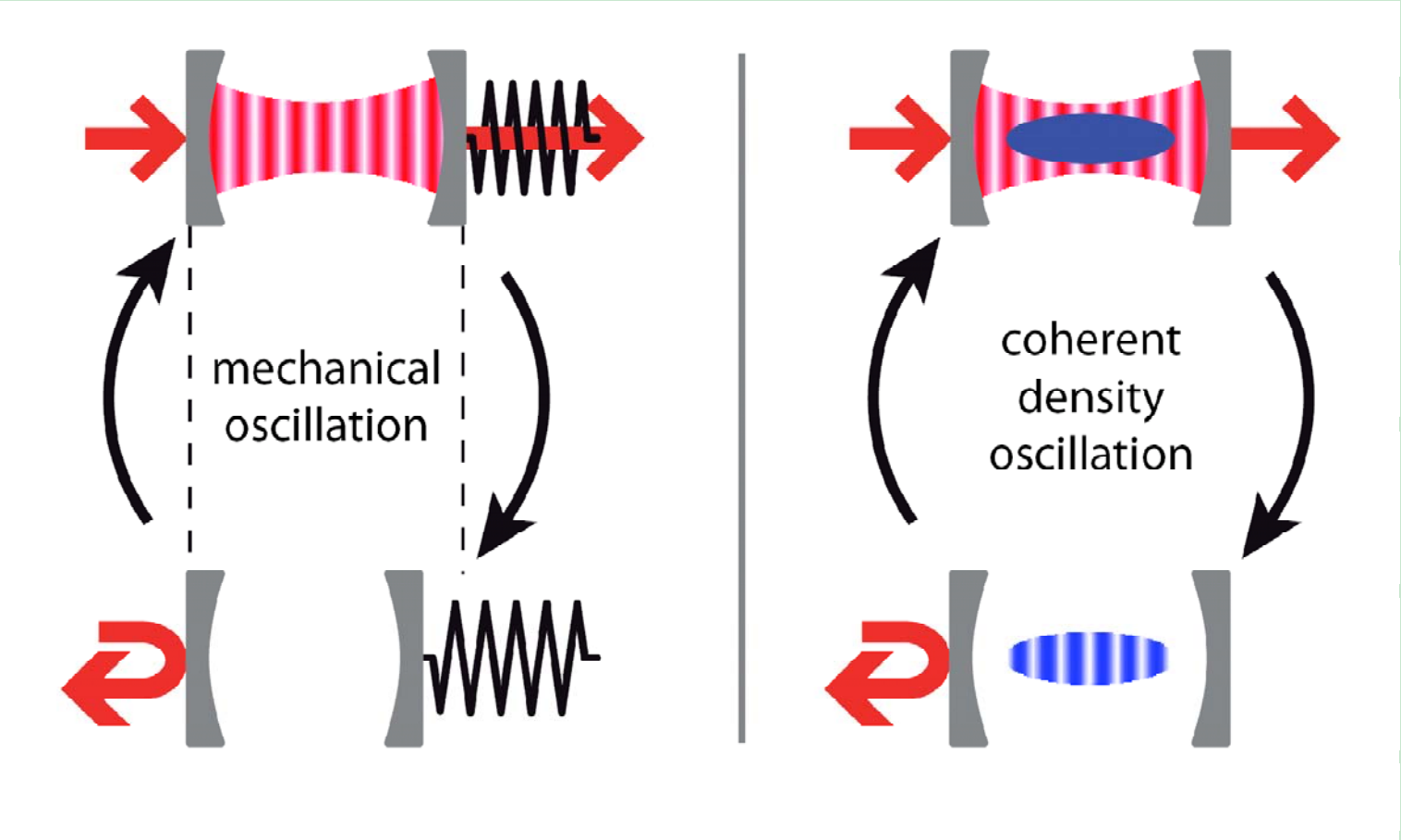
mechanical mode

optical mode

strong coupling: $g \approx 0.3\ \kappa$

pump/decay

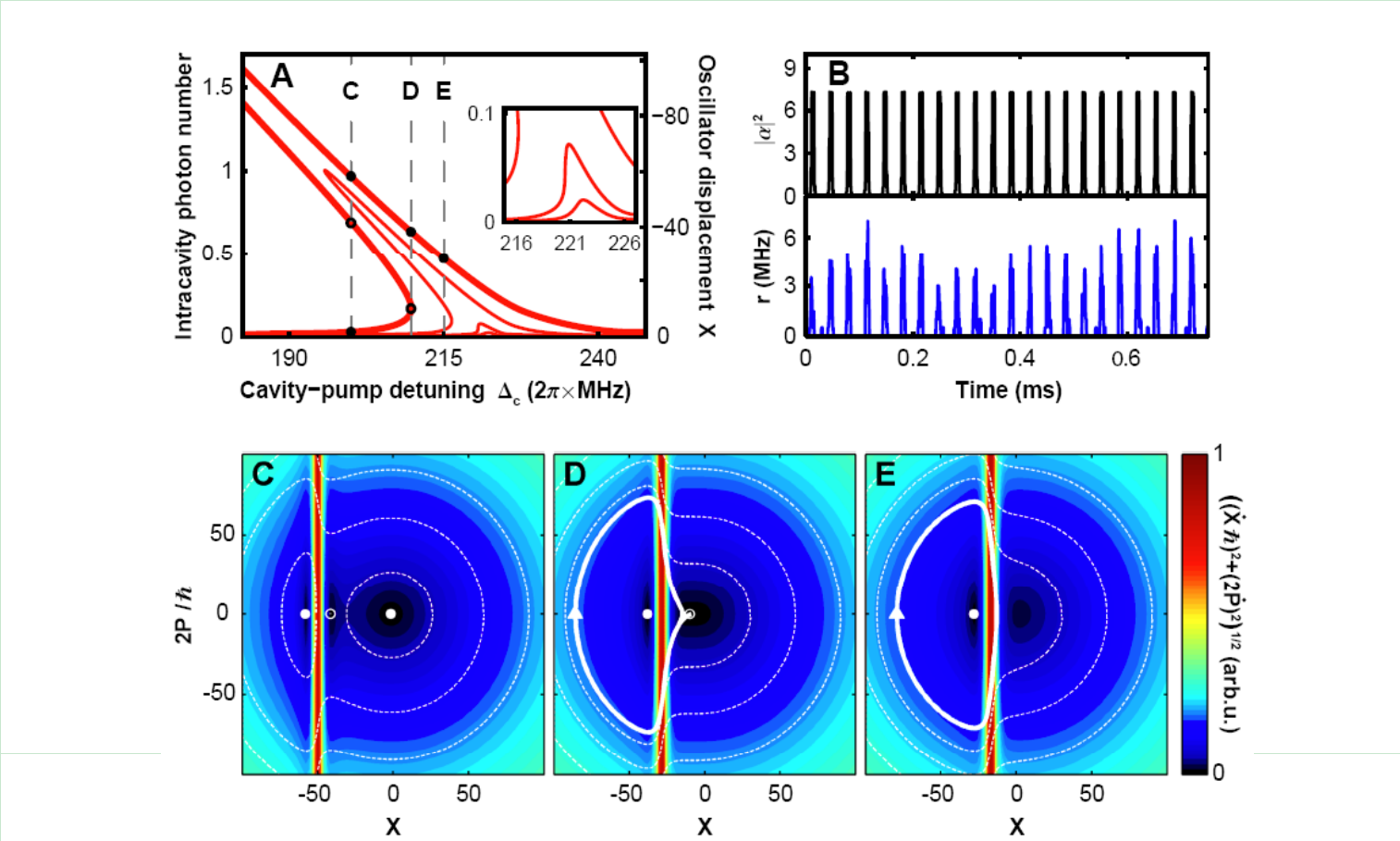
Cavity opto-mechanics with a BEC



F. Brennecke, S. Ritter, T. Donner, T. Esslinger, Science 322, 235 (2008)

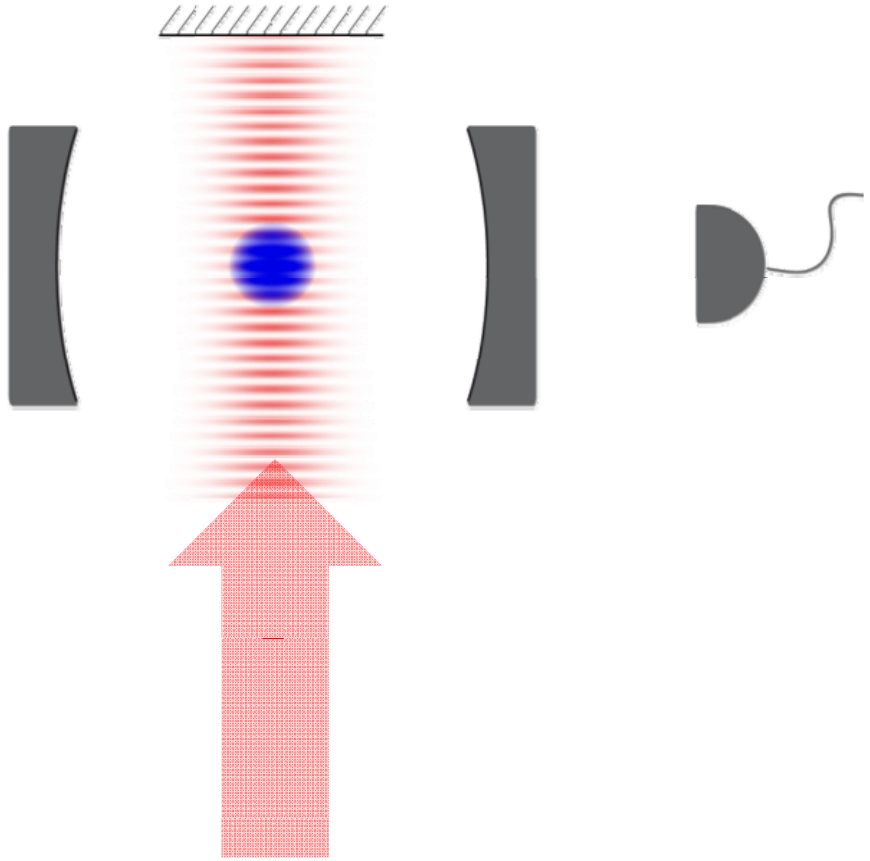
See also: Stamper-Kurn (Berkeley), Nature Physics 2008

Dynamics of BEC cavity system



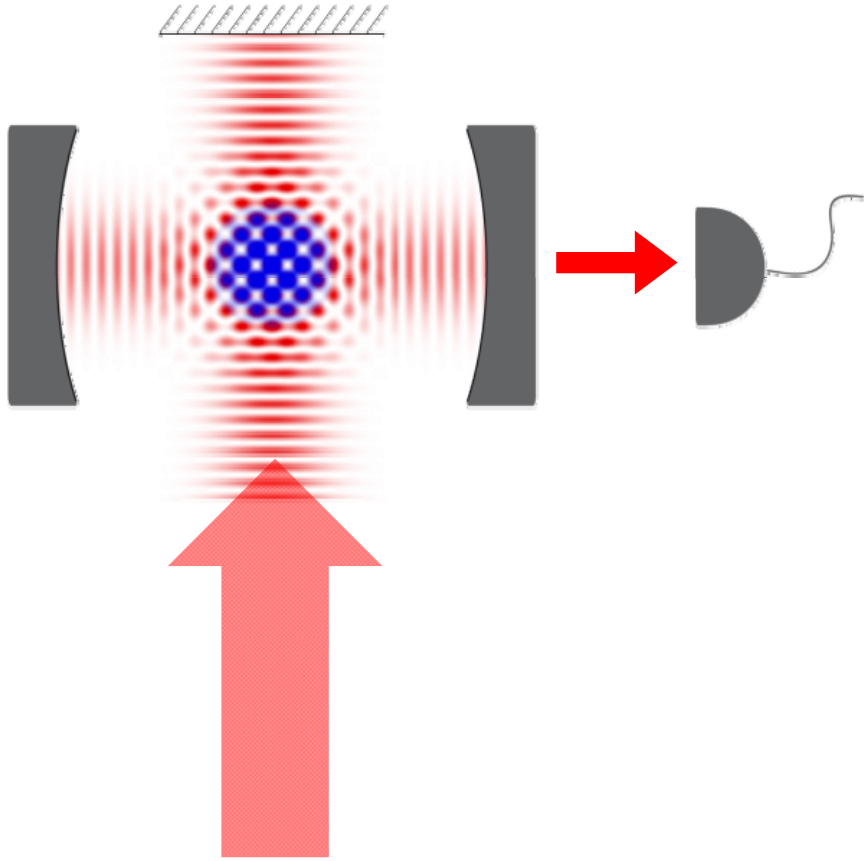
F. Brennecke, S. Ritter, T. Donner, T. Esslinger, Science 322, 235 (2008)

Transverse Pumping



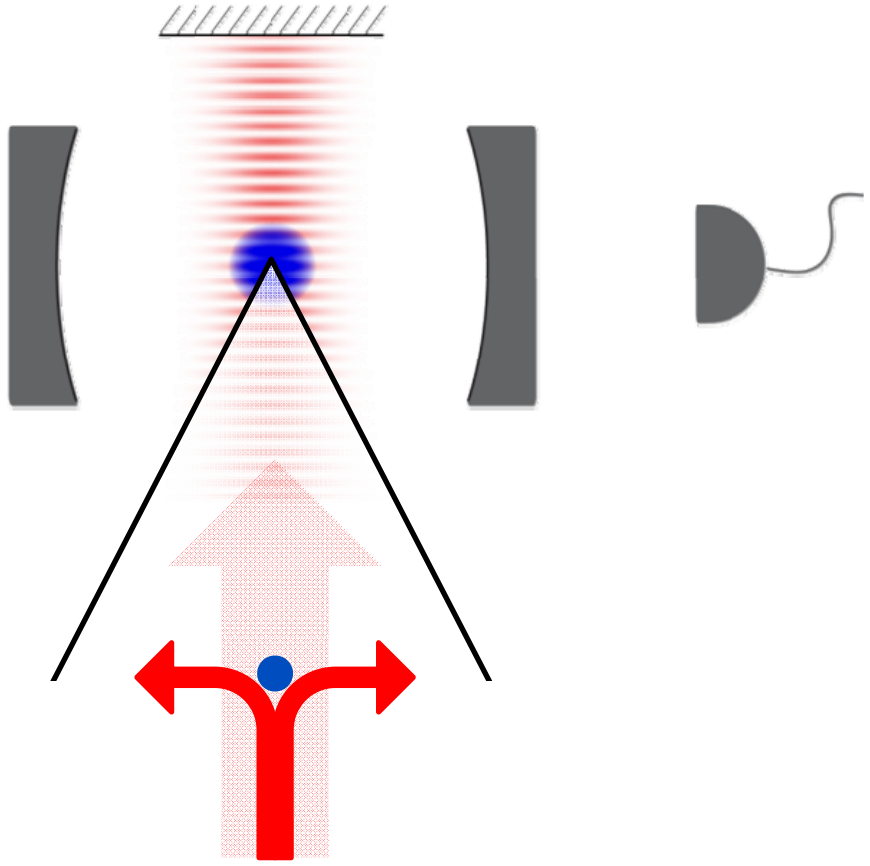
Theory: H. Ritsch, P. Domokos, Exp. with thermal atoms: V. Vuletic

Phase Transition

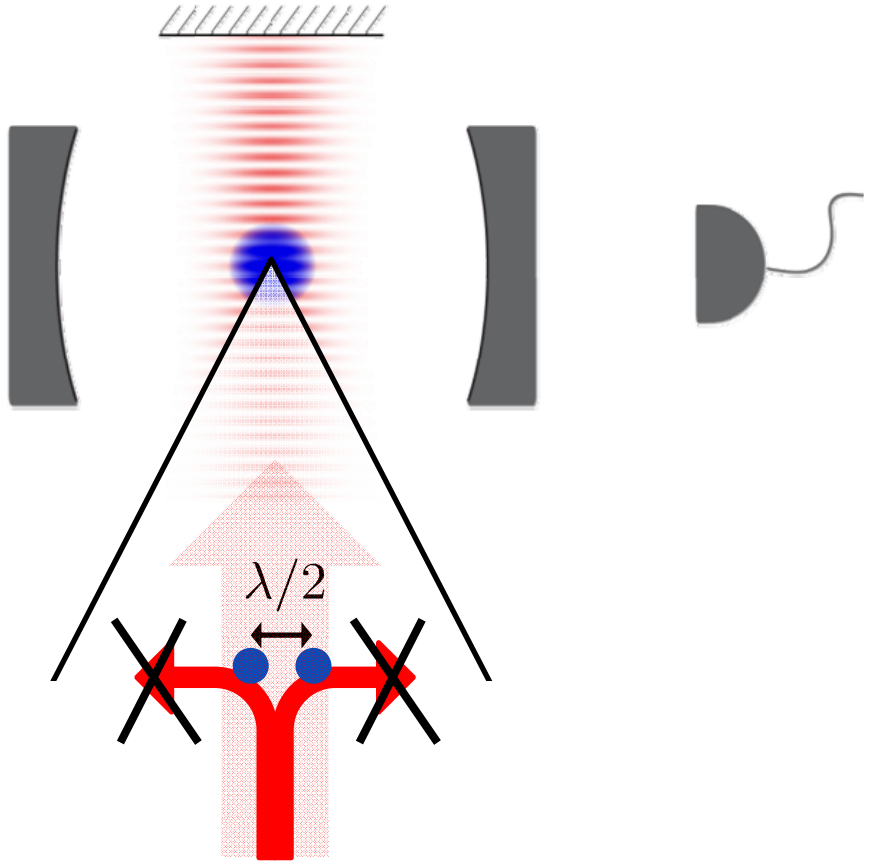


Theory: H. Ritsch, P. Domokos, Exp. with thermal atoms: V. Vuletic

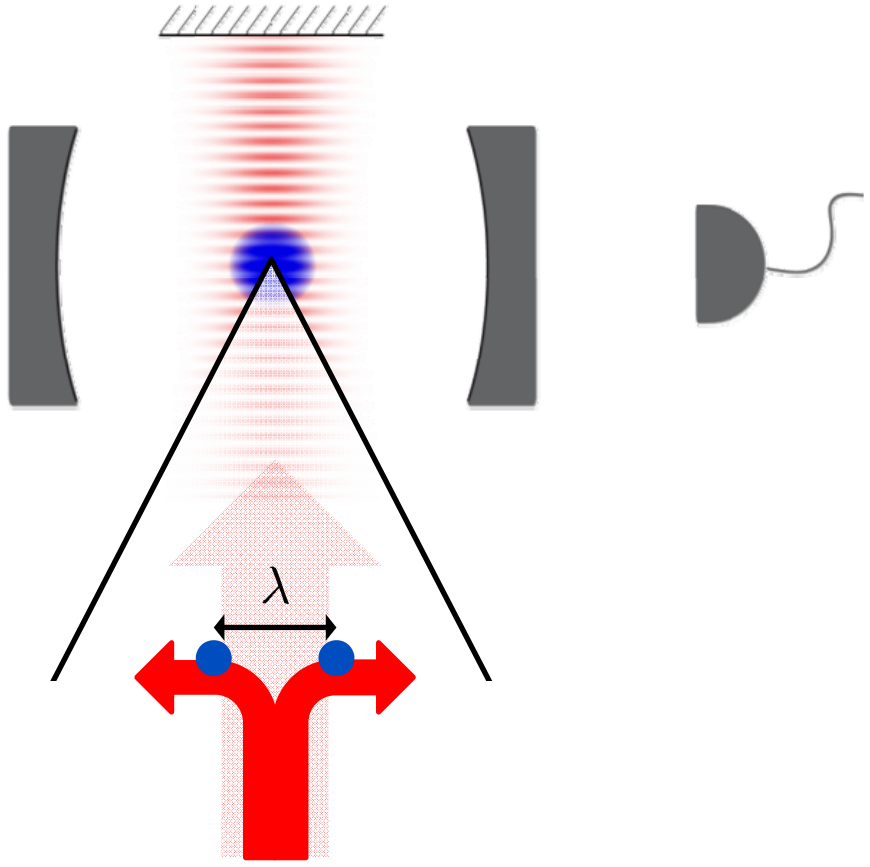
Scattering from a single atom



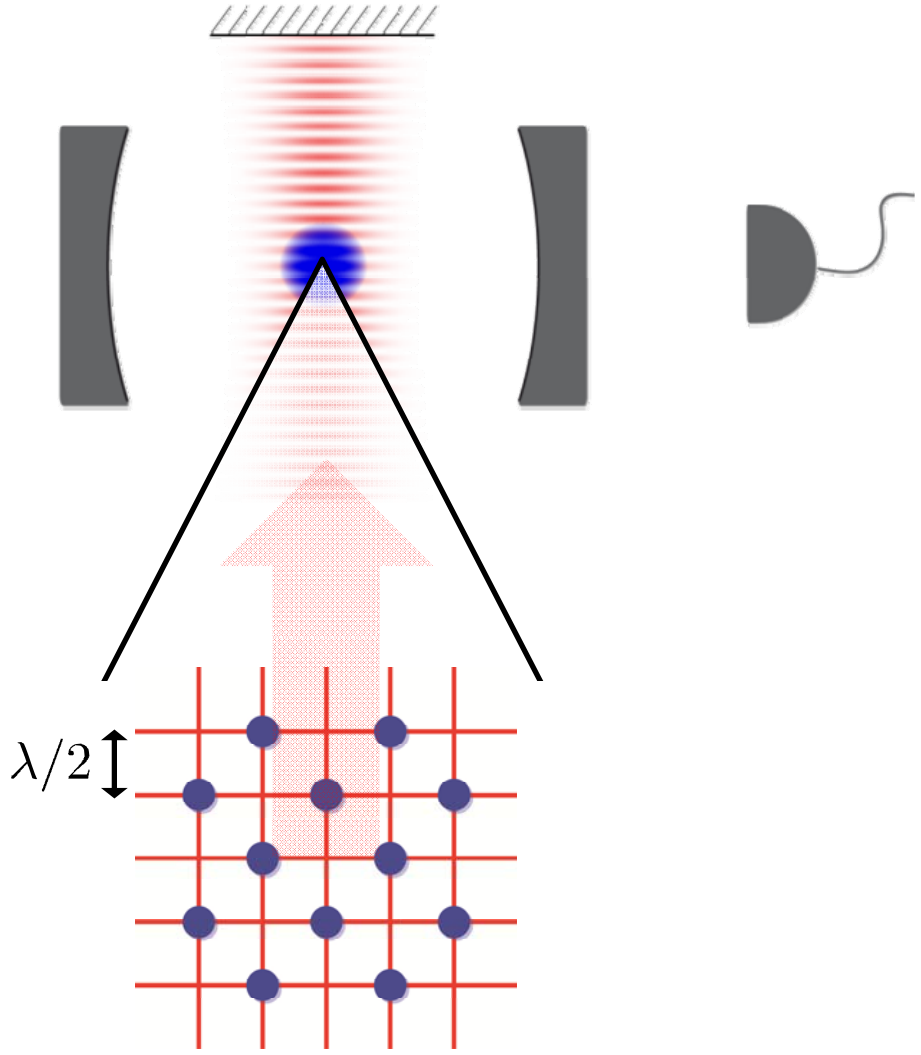
Scattering from two atoms: Interference



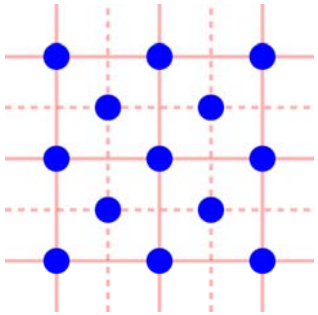
Scattering from two atoms: Interference



Self-organization

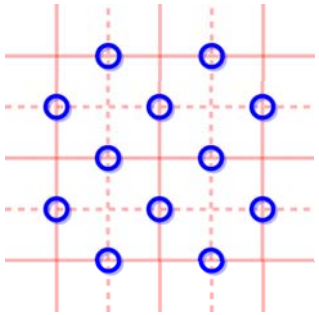


Symmetry-breaking



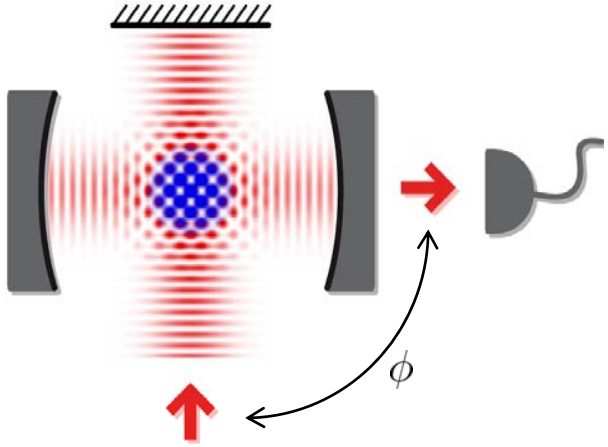
even

$\phi = 0$

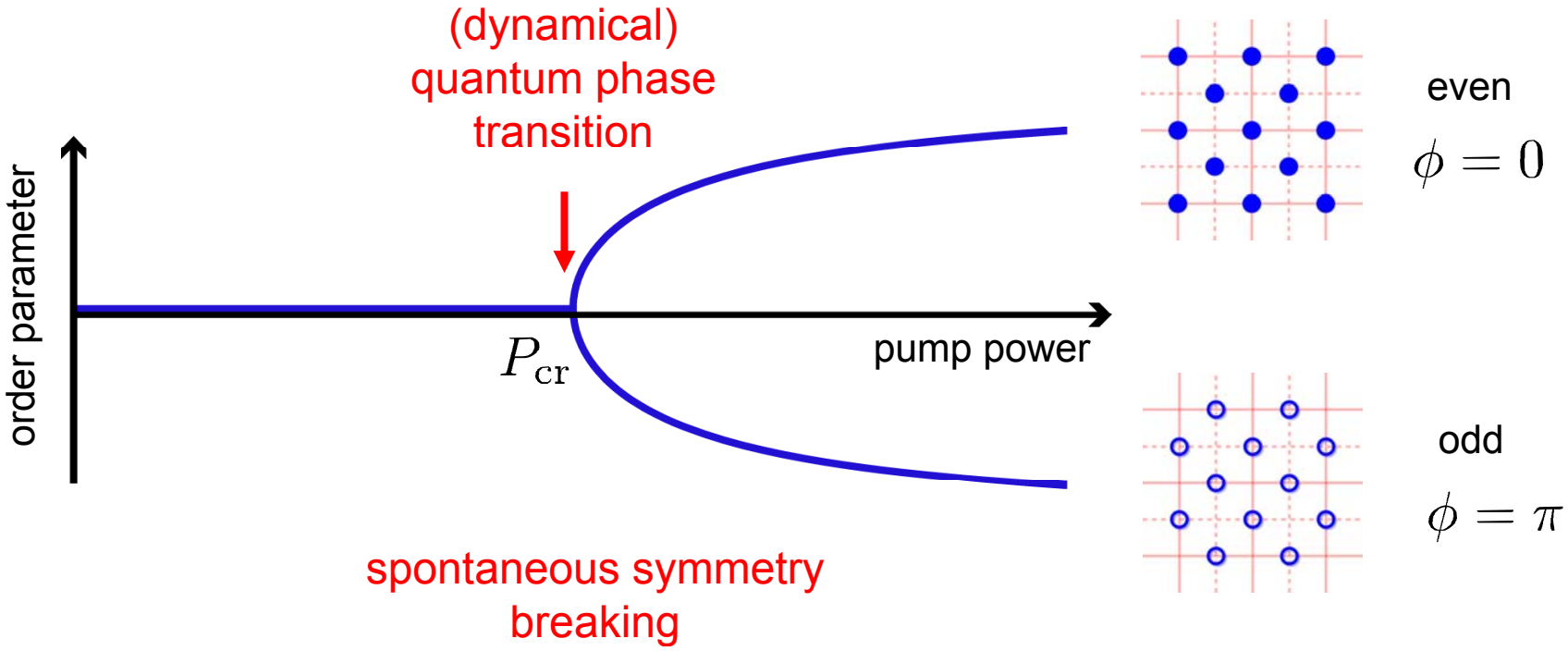


odd

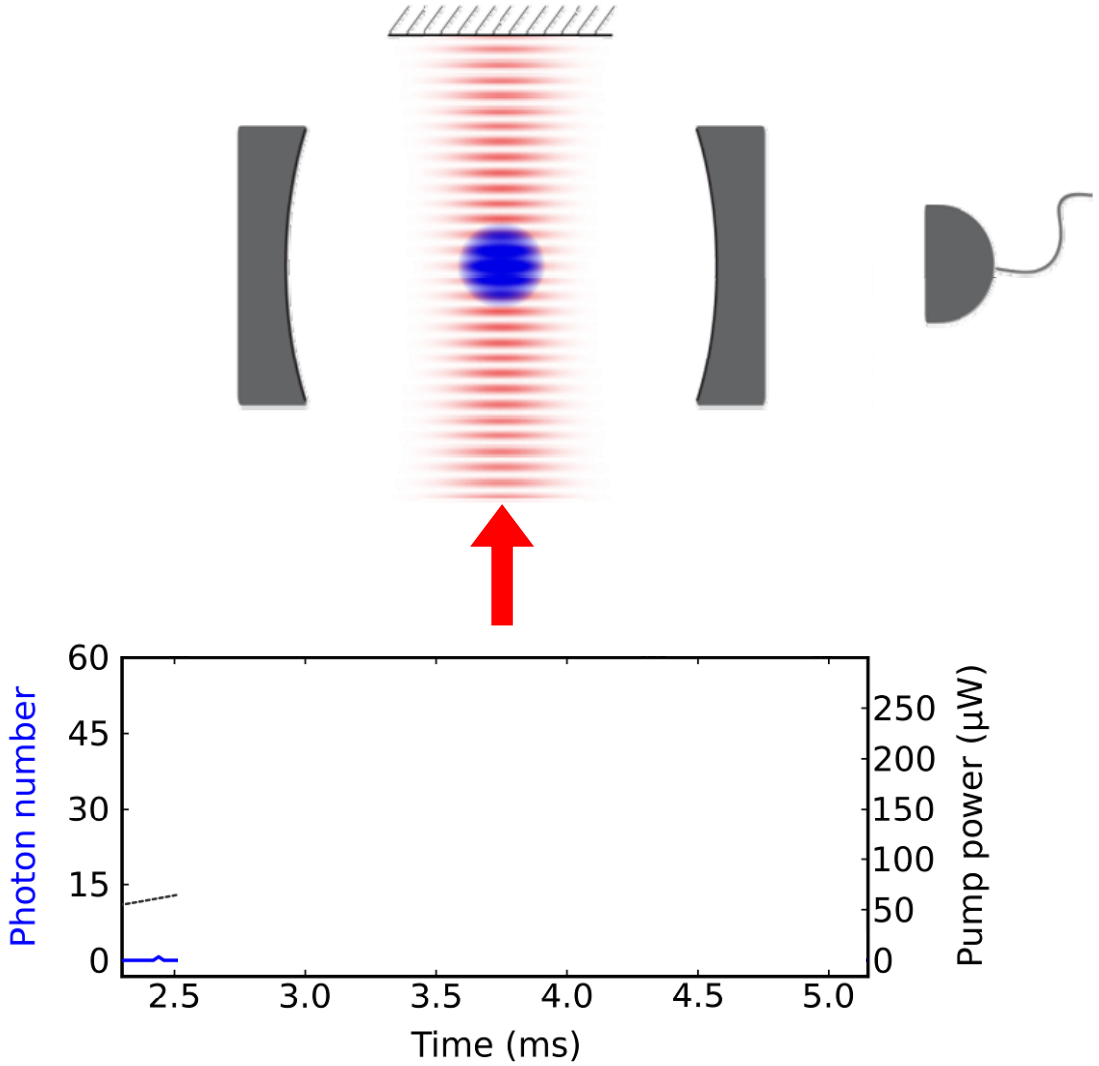
$\phi = \pi$



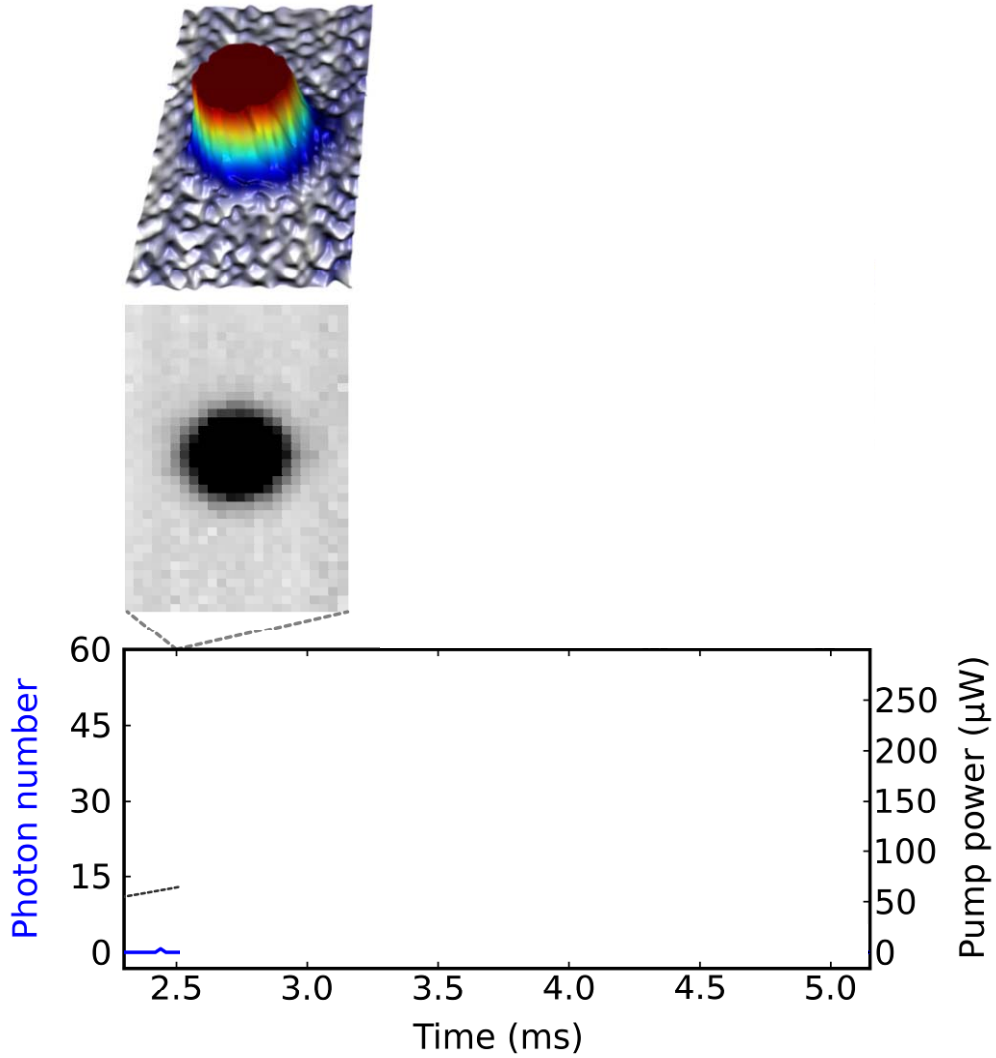
Self-organization



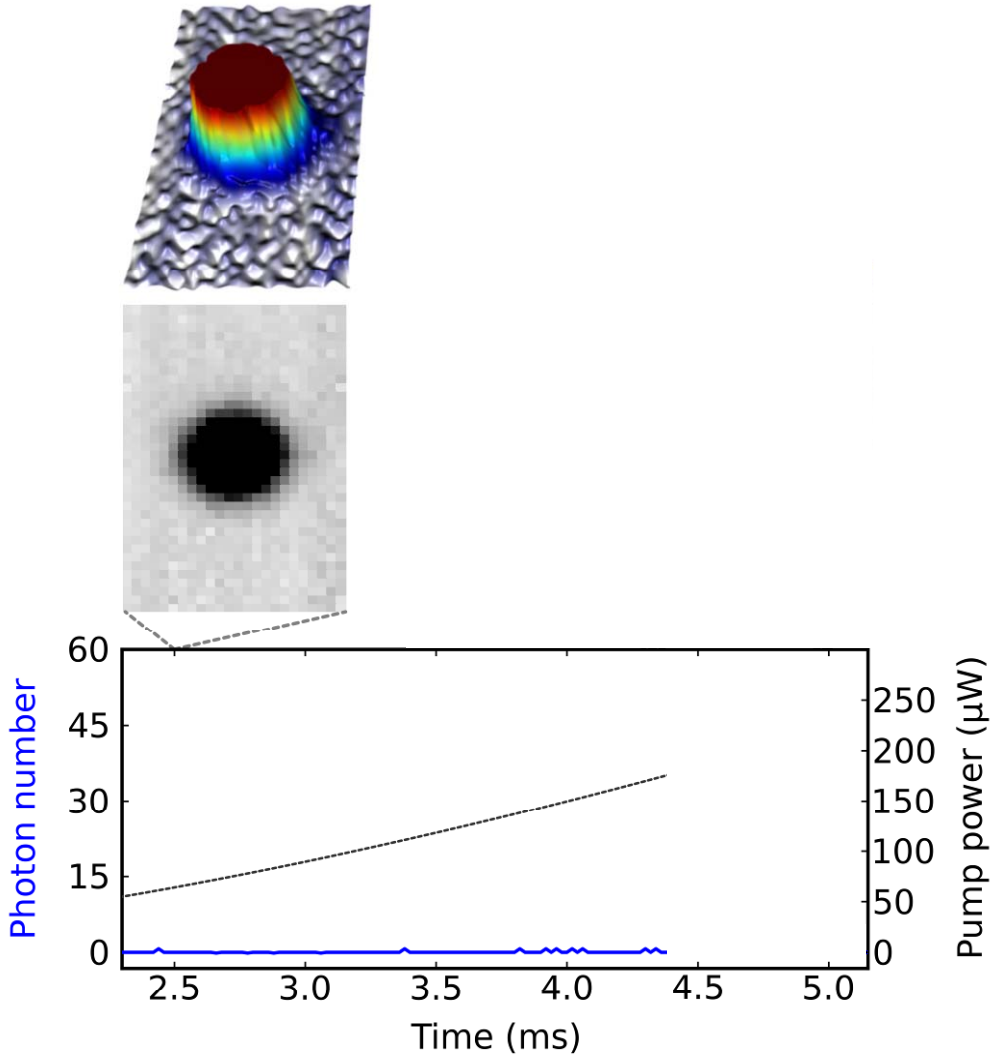
Observing Self-Organization



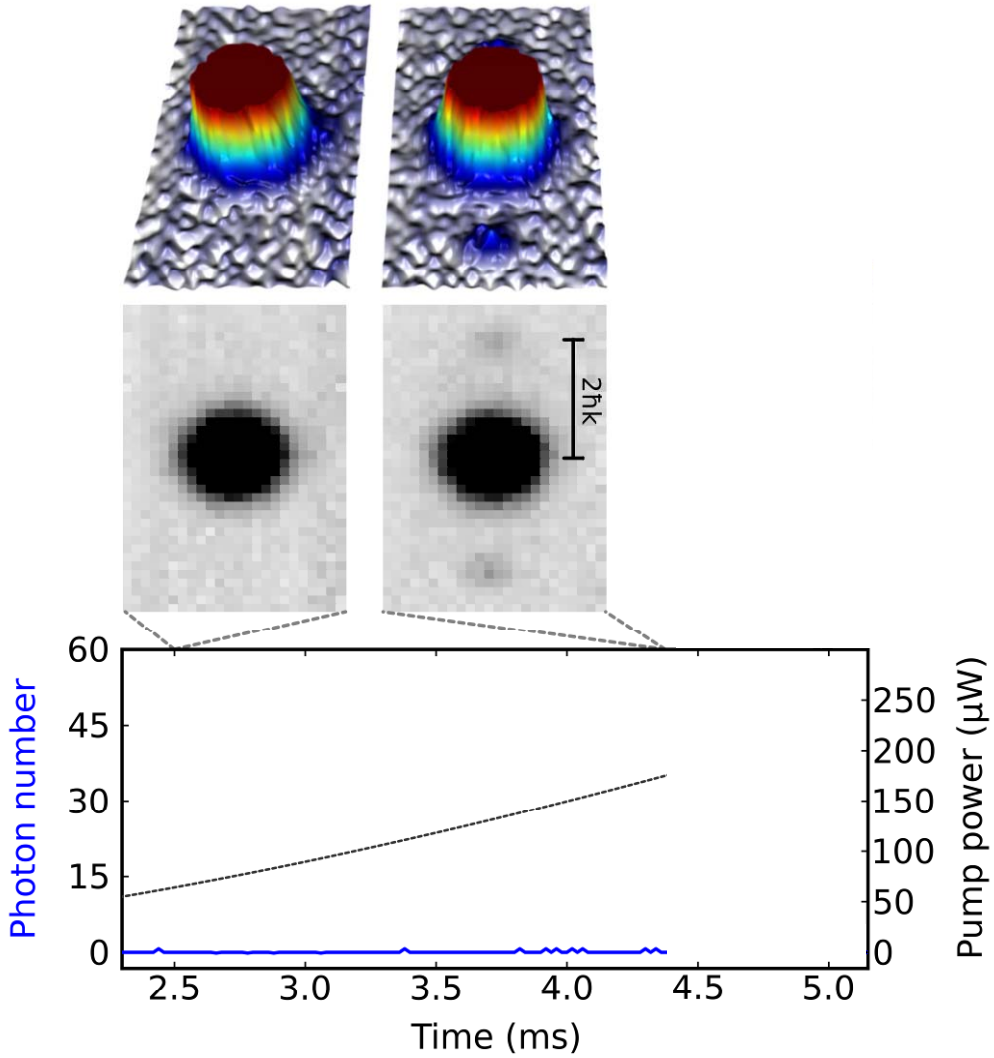
Observing Self-Organization



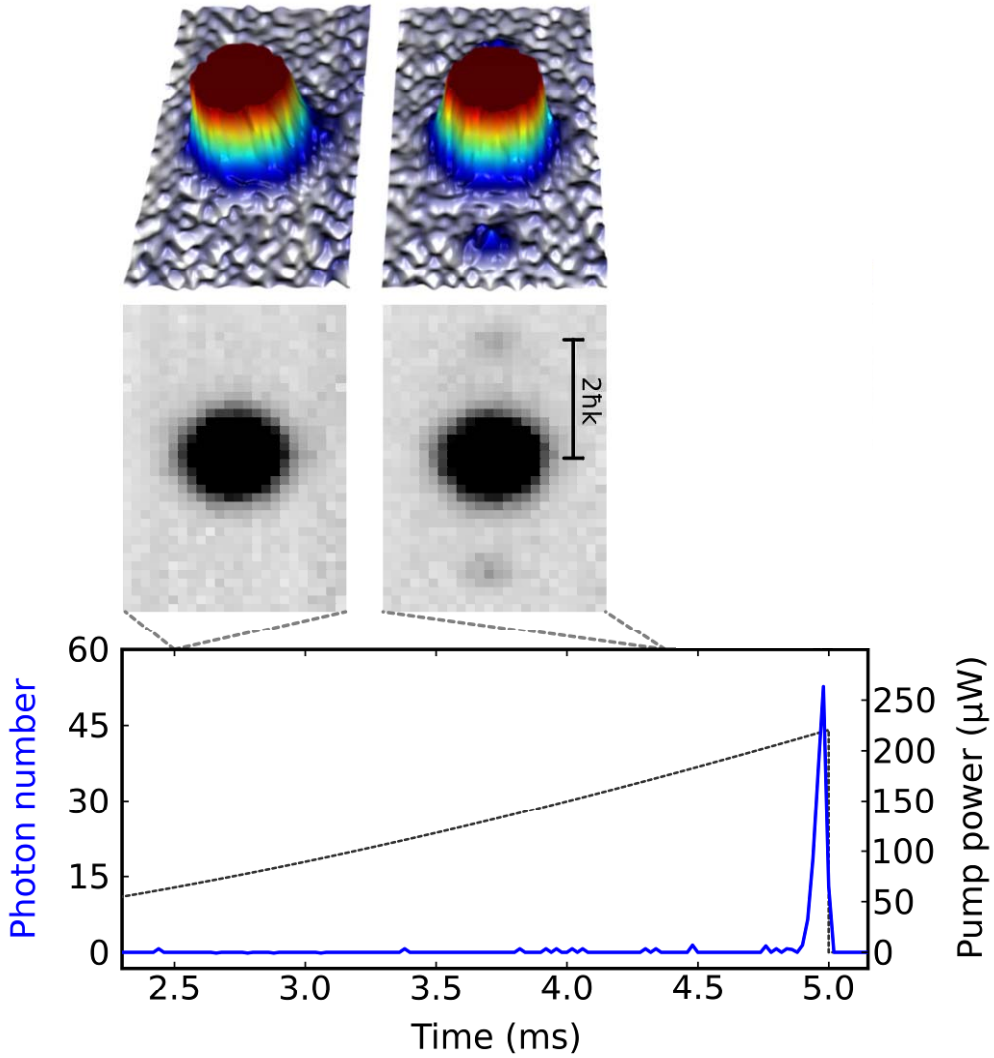
Observing Self-Organization



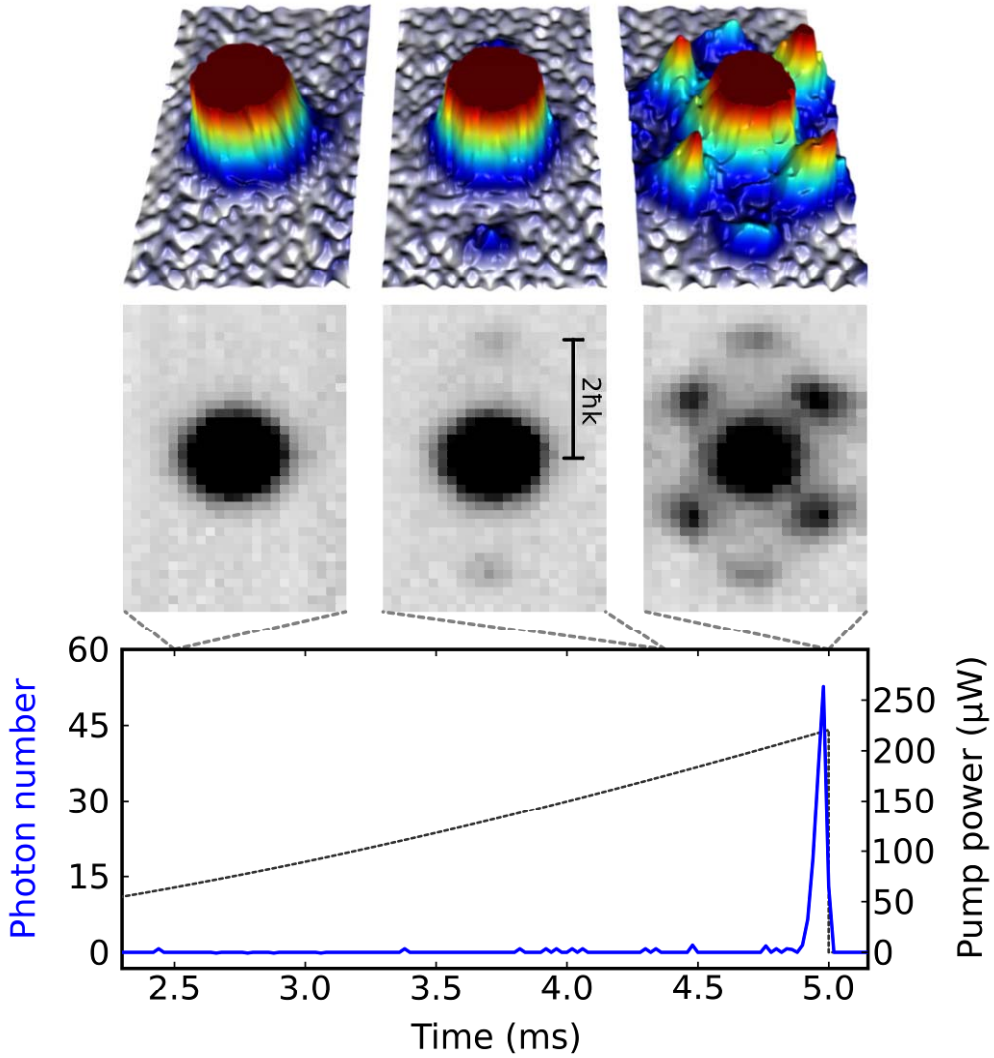
Observing Self-Organization



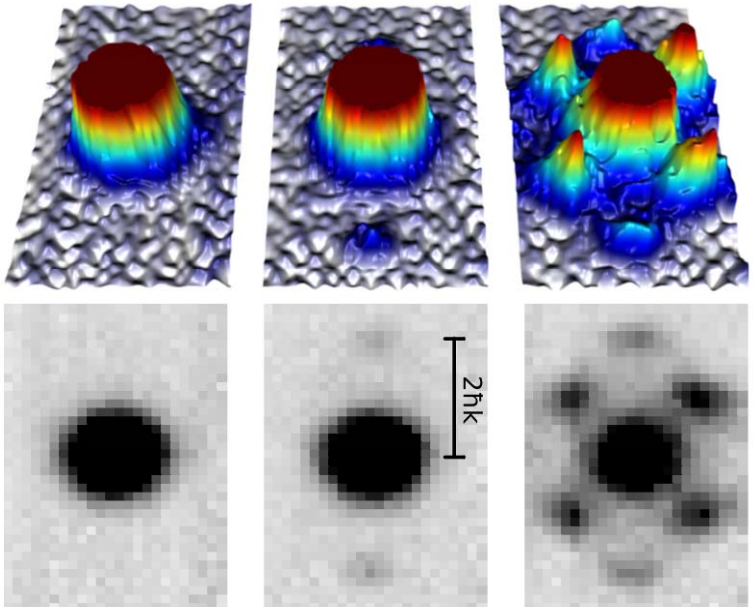
Observing Self-Organization



Observing Self-Organization



Observing Self-Organization

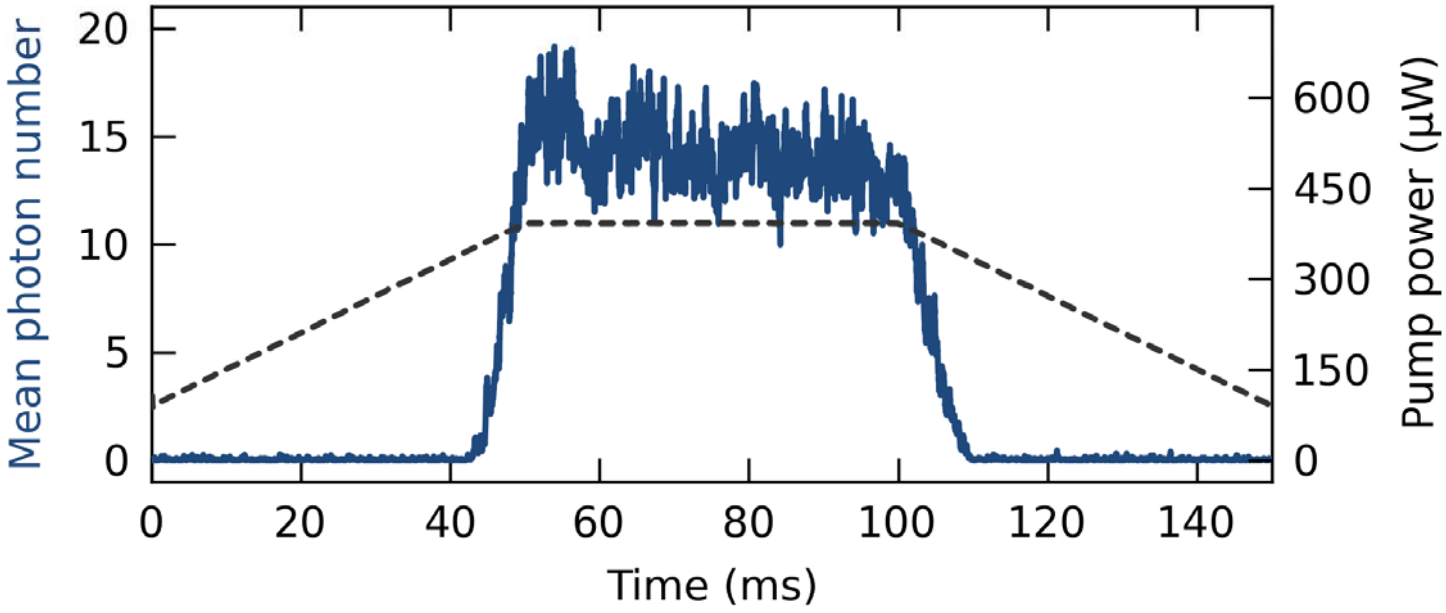


Coexistence of:
- non-trivial diagonal long-range order
- off-diagonal long-range order

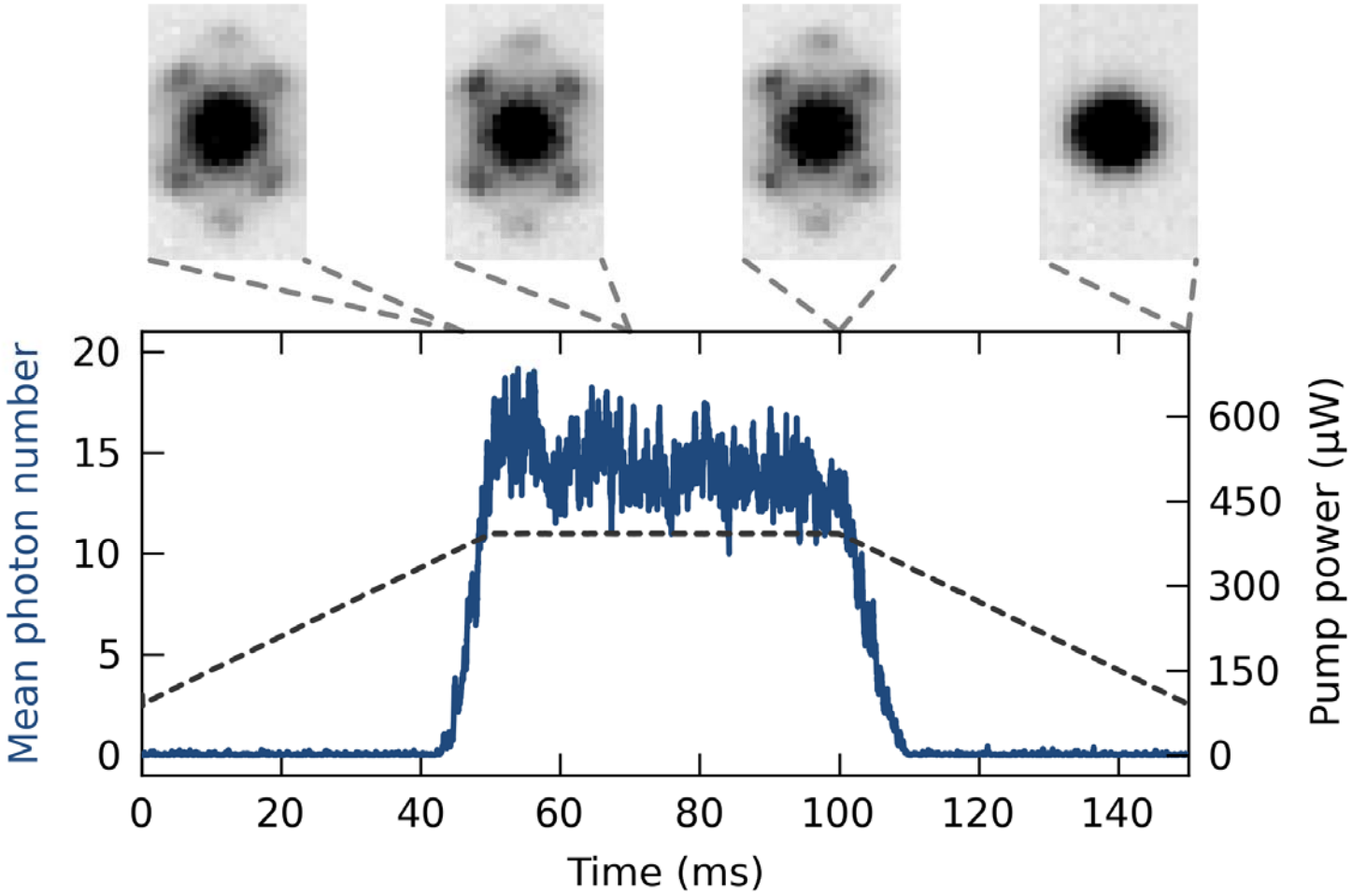
⬇

The atoms can be regarded as a Supersolid

Stability


Mean photon number
20
15
10
5
0
0
20
40
60
80
100
120
140
Time (ms)
600
450
300
150
0
Pump power (μW)

Stability and Dephasing



PHYSICAL REVIEW A **75**, 013804 (2007)

Proposed realization of the Dicke-model quantum phase transition in an optical cavity QED system

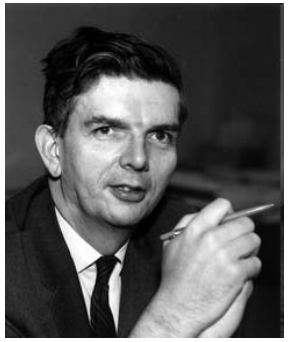
F. Dimer,[1] B. Estienne,[2] A. S. Parkins,[3,*] and H. J. Carmichael[1]

[1]*Department of Physics, University of Auckland, Private Bag 92019, Auckland, New Zealand*

[2]*Laboratoire de Physique Théorique et Hautes Energies, Université Pierre et Marie Curie, 4 place Jussieu, F-75252 Paris Cedex 05, France*

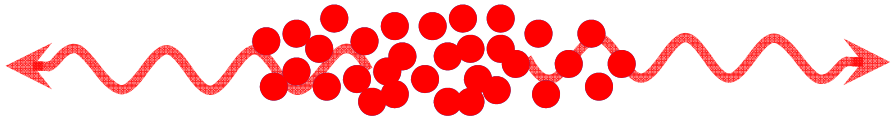
[3]*Norman Bridge Laboratory of Physics 12-33, California Institute of Technology, Pasadena, California 91125, USA*

(Received 18 July 2006; published 8 January 2007)

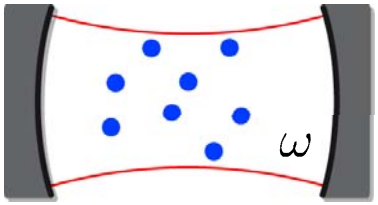


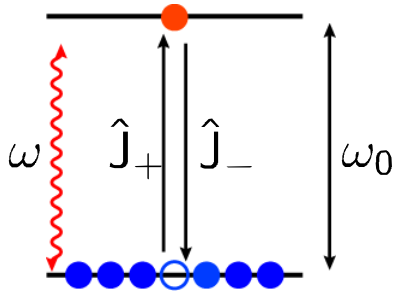
“molecules interacting with a common radiation field cannot be treated as independent”
R.H. Dicke (1953)

Super-radiance



Dicke Model





$$\hat{H}_{\text{Dicke}} = \omega \hat{a}^\dagger \hat{a} + \omega_0 \hat{J}_z + \frac{\lambda}{\sqrt{N}}(\hat{a} + \hat{a}^\dagger)(\hat{J}_+ + \hat{J}_-)$$

On the Superradiant Phase Transition for Molecules in a Quantized Radiation Field: the Dicke Maser Model

KLAUS HEPP

Physics Department, ETH, Zürich, 8049 Switzerland

AND

ELLIOTT H. LIEB*

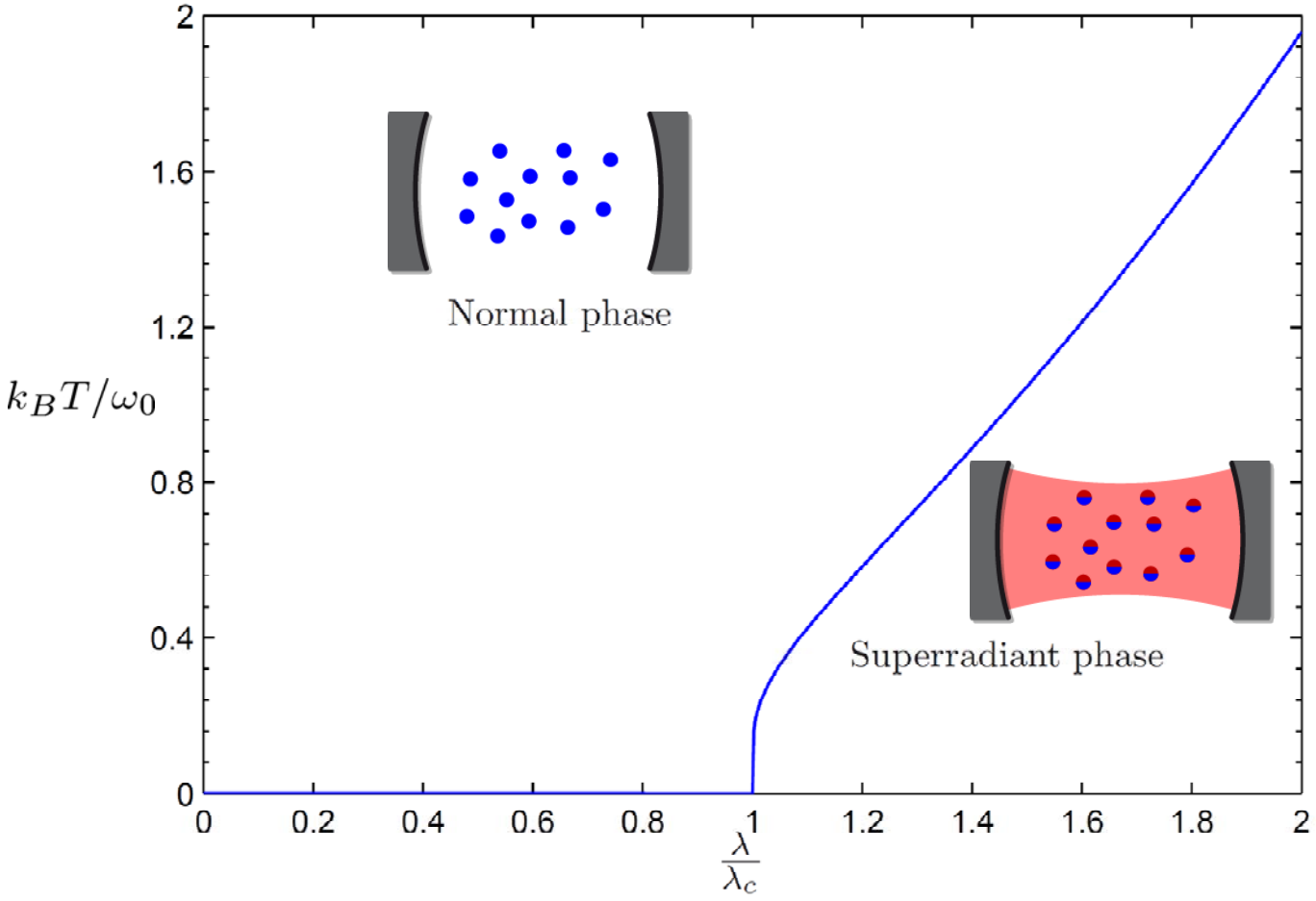
Mathematics Department, MIT, Cambridge, Mass. 02139, USA

A system of N two-level molecules coupled to finitely many modes of a quantized radiation field via a truncated dipolar interaction is investigated. The thermodynamic and correlation functions can be exactly computed in the limit $N \to \infty$. The system exhibits a second order phase transition from normal to superradiance. Different effective Hamiltonians with linear Heisenberg equations of motion become asymptotically exact in the limit $N \to \infty$.

ANNALS OF PHYSICS: 76, 360–404 (1973)

Super-radiant phase transition

$$\hat{H}_{\mathrm{Dicke}} = \omega \hat{a}^\dagger \hat{a} + \omega_0 \hat{J}_z + \frac{\lambda}{\sqrt{N}}(\hat{a} + \hat{a}^\dagger)(\hat{J}_+ + \hat{J}_-)$$



$$\lambda_c = \sqrt{\omega\omega_0}/2$$

Recent work: T. Brandes, …

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Proposed realization of the Dicke-model quantum phase transition in an optical cavity QED system

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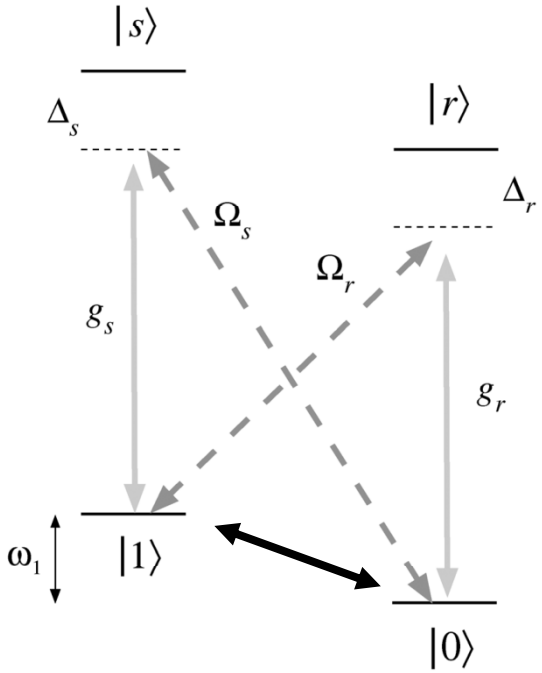
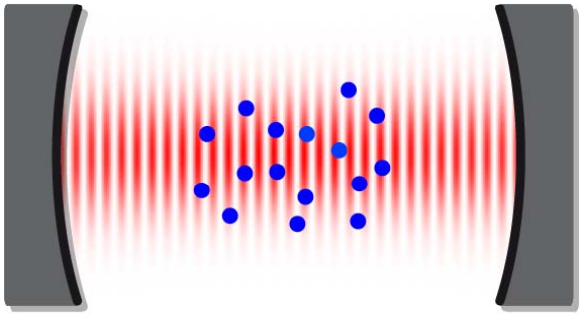
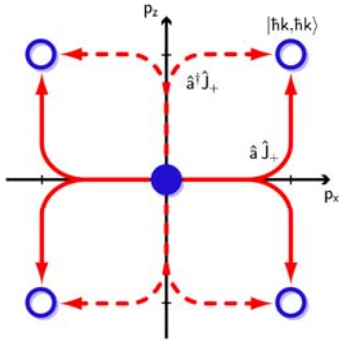


described by the Dicke Hamiltonian

Dicke Model

$$\hat{H}_{\mathrm{Dicke}} = \omega \hat{a}^\dagger \hat{a} + \omega_0 \hat{J}_z + \frac{\lambda}{\sqrt{N}}(\hat{a} + \hat{a}^\dagger)(\hat{J}_+ + \hat{J}_-)$$





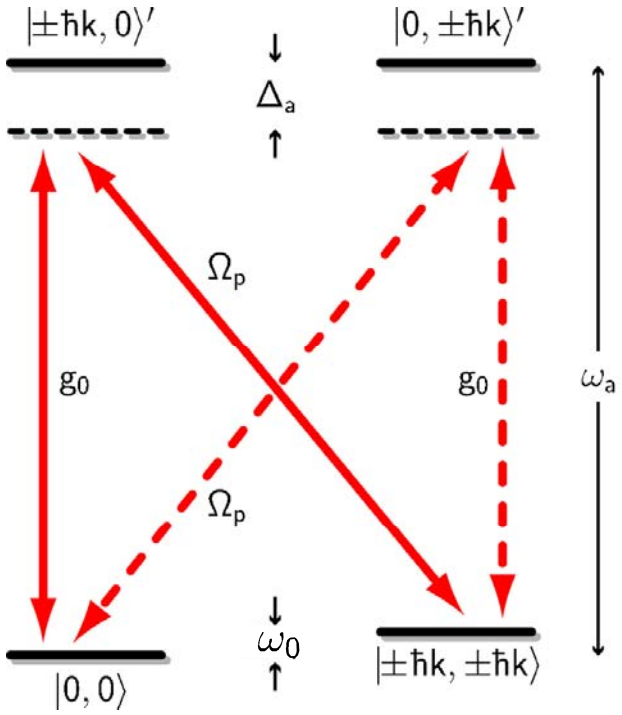
K. Baumann, C. Guerlin, F. Brennecke, and T. Esslinger, Nature 464, 1301 (2010)

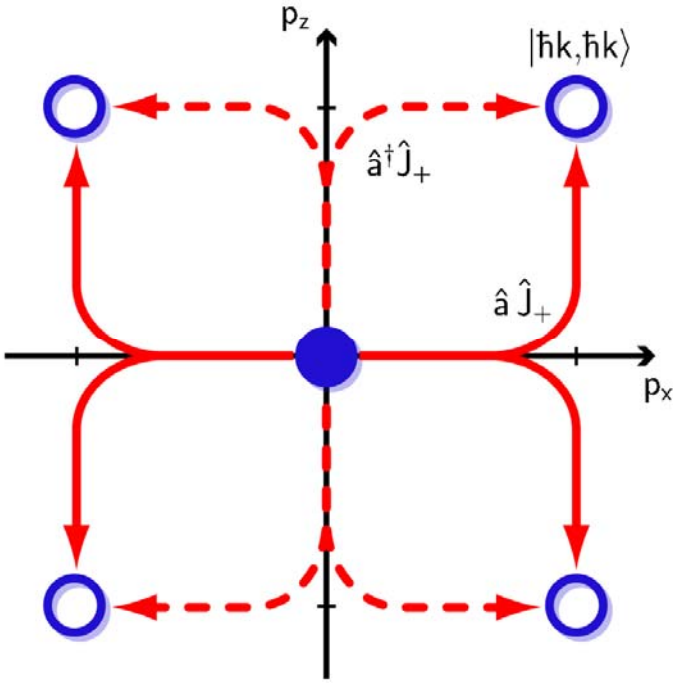
1D theory: D. Nagy, G. Ko´nya, G. Szirmai, P. Domokos, PRL 104, 130401 (2010).

Two-Mode Description

energy diagram

momentum diagram

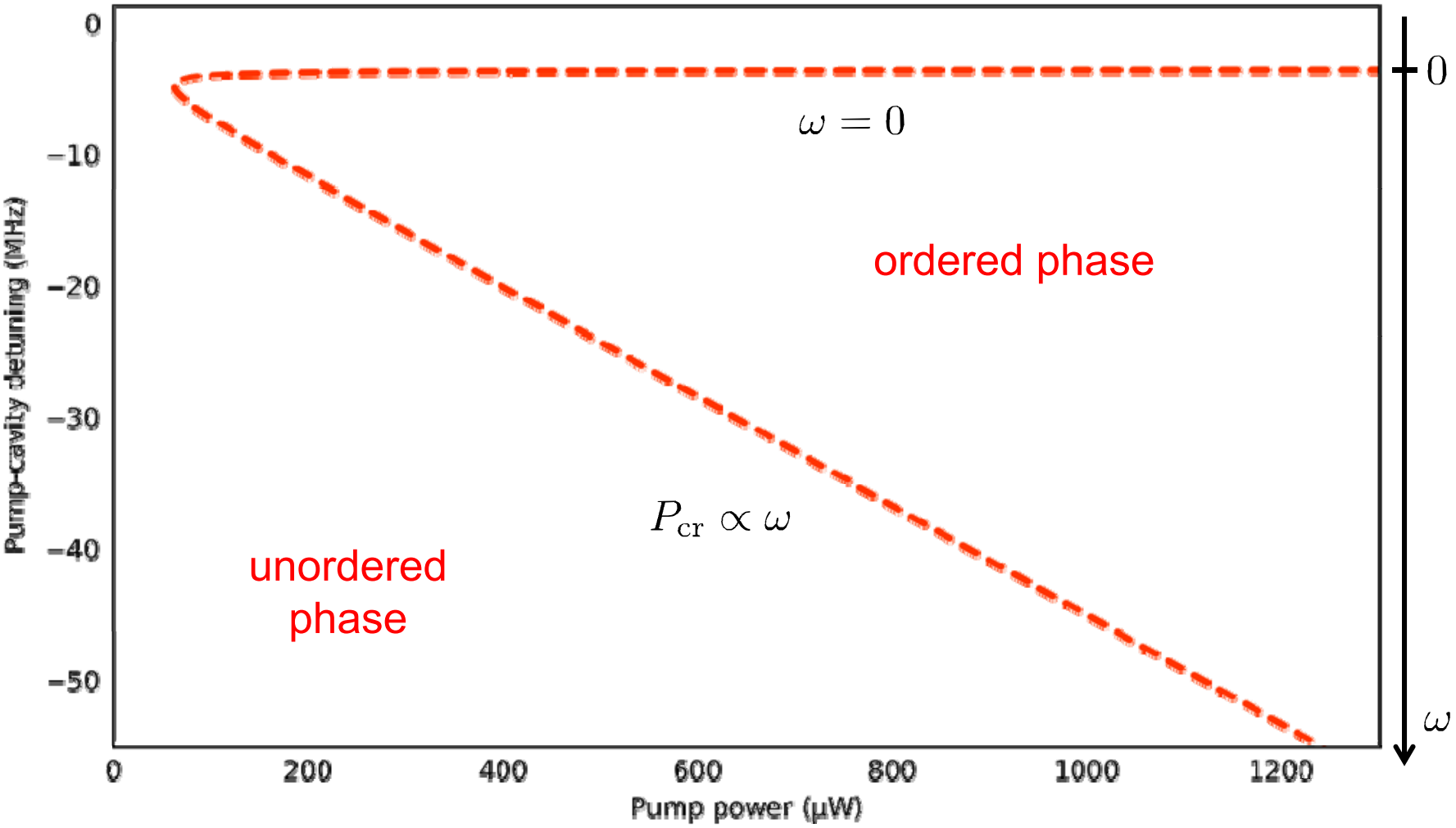




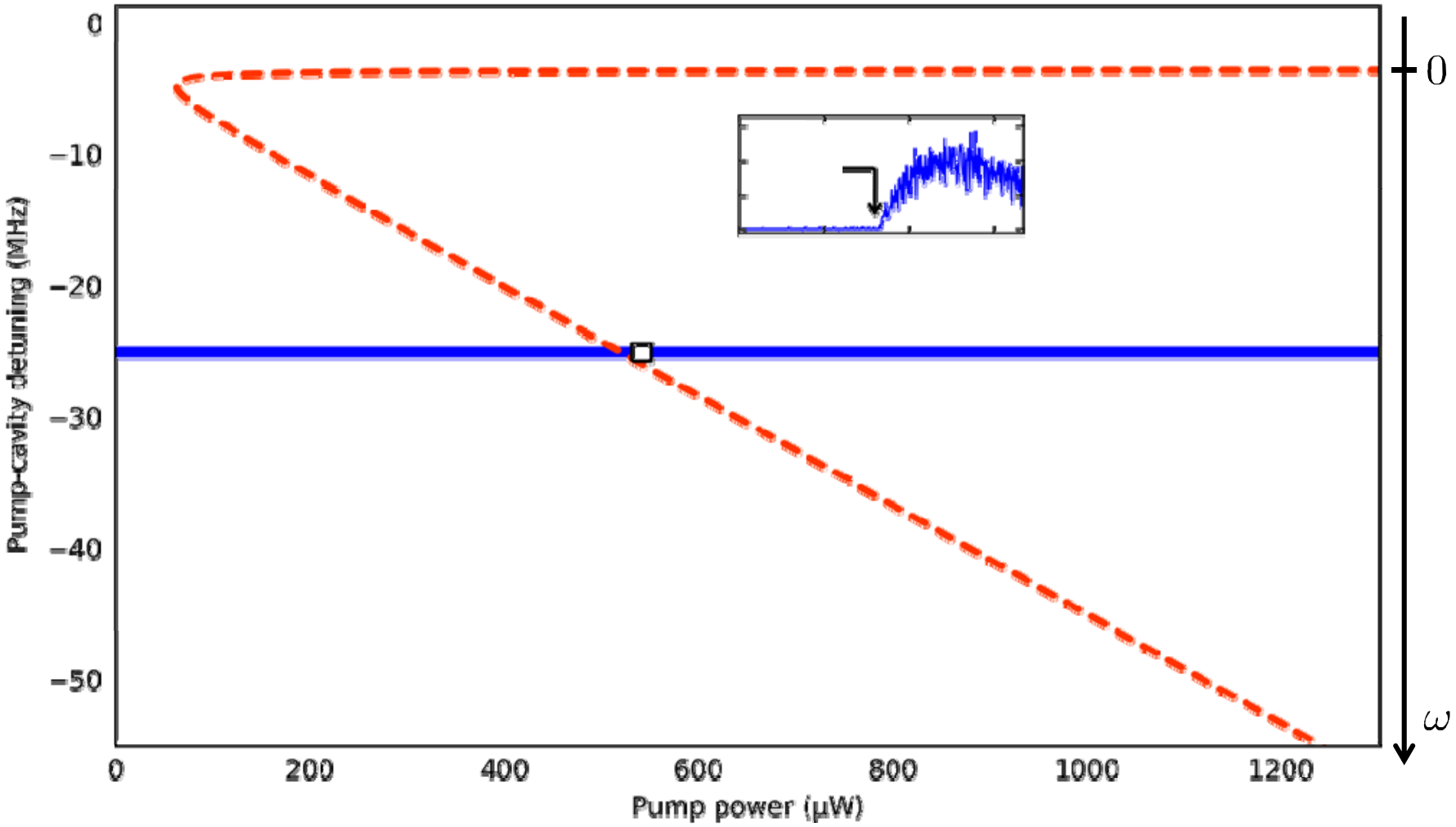
$$\hat{J}_+ = \sum_i |\pm\hbar k, \pm\hbar k\rangle_{i\,i}\langle 0, 0| = \hat{J}_-^\dagger$$

Zero Temperature Phase Diagram

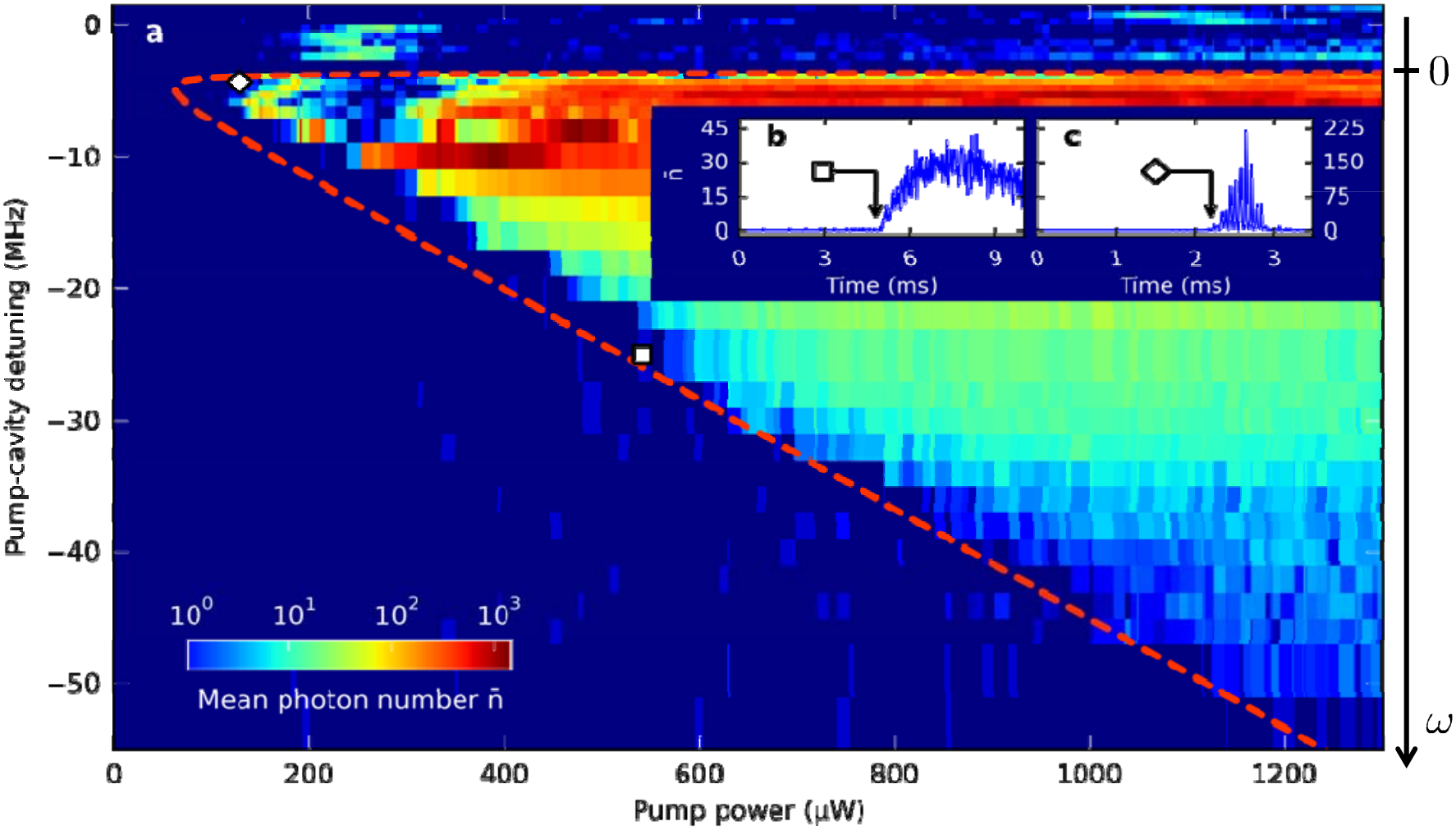
$$\lambda_{\mathrm{cr}} = \sqrt{\omega\omega_0}/2 \qquad P_{\mathrm{cr}} \propto \lambda_{\mathrm{cr}}^2$$



Zero Temperature Phase Diagram

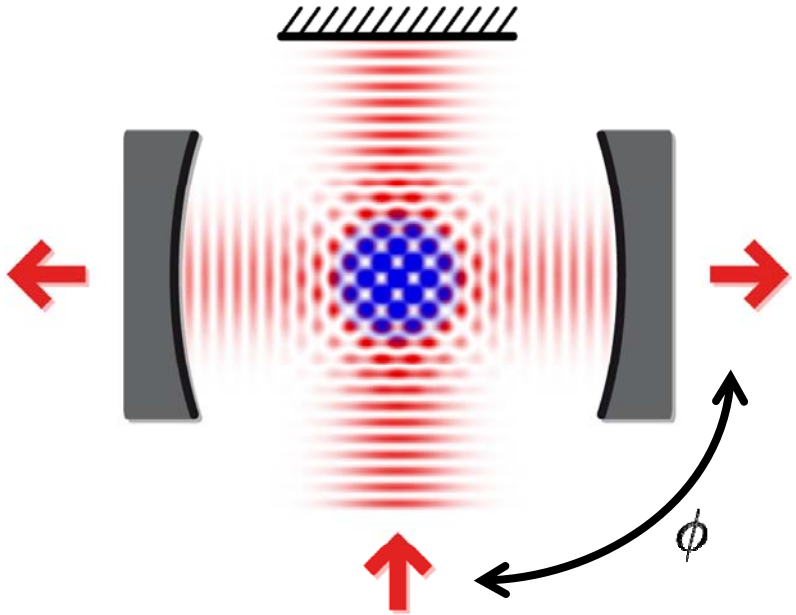


Zero Temperature Phase Diagram



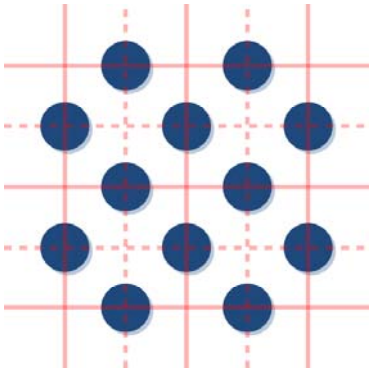
K. Baumann, C. Guerlin, F. Brennecke, and T. Esslinger. Nature 464, 1301 (2010)

Phase Sensitive Detection



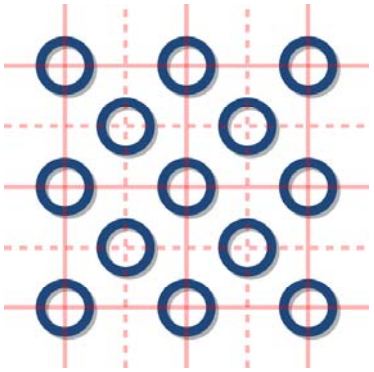
even

$\phi = 0$

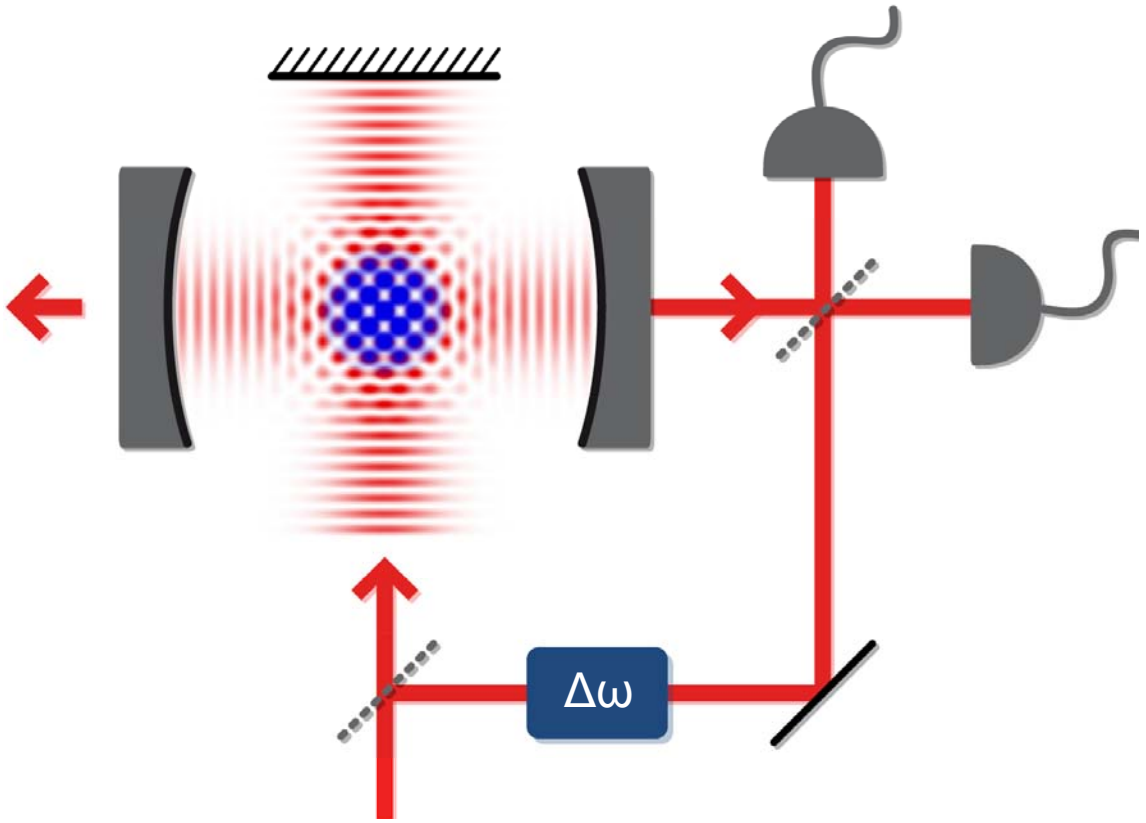


odd

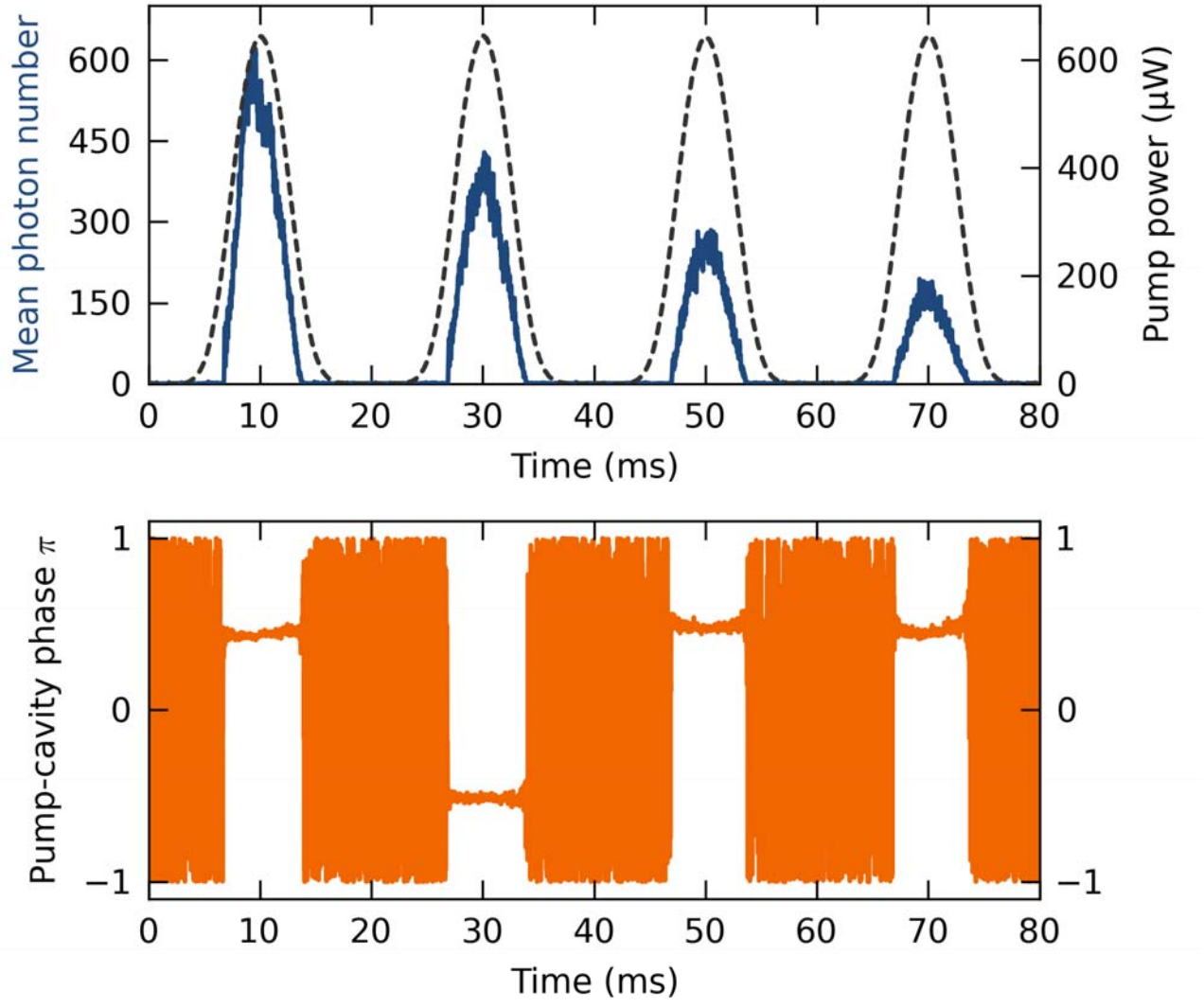
$\phi = \pi$

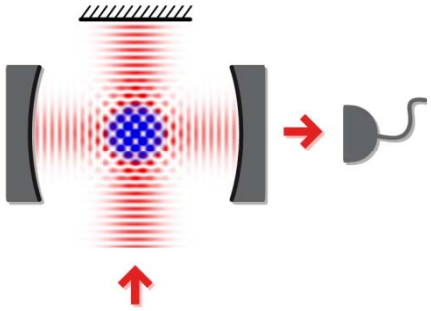


Phase Sensitive Detection



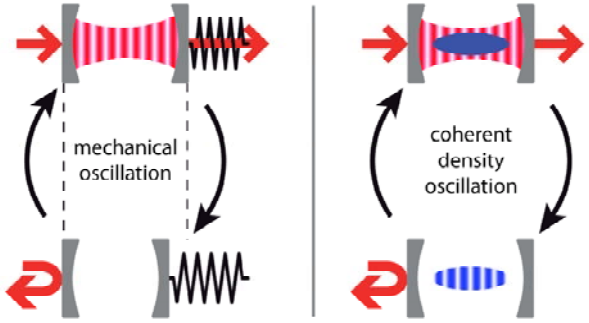
Phase Sensitive Detection

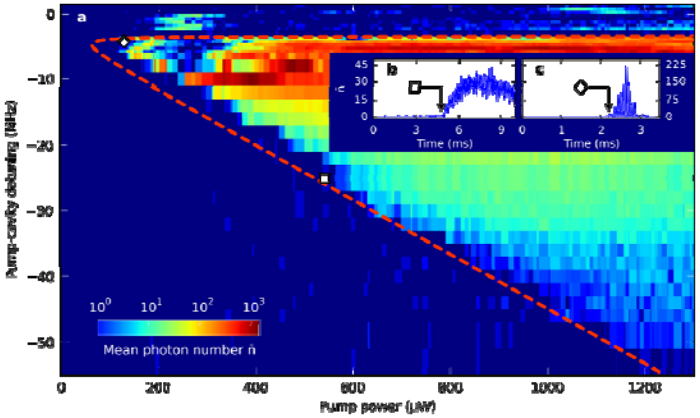




$$\Rightarrow \quad |\text{even}, \alpha\rangle \pm |\text{odd}, -\alpha\rangle$$

Summary


mechanical
oscillation
coherent
density
oscillation


a
b
c
Time (ms)
Time (ms)
Mean photon number n̄
Pump power (μW)

Thanks !

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Quantum Gases in Optical Lattices

Leticia Tarruell
Daniel Greiff
Thomas Uehlinger
Robert Jördens

Lithium Microscope

Torben Müller
Jakob Meineke
Jean-Philippe Brantut
Bruno Zimmermann
Henning Moritz

BEC and Cavity

Ferdinand Brennecke
Kristian Baumann
Raphael Mottl
Silvan Leinss

Electronics

Alexander Frank

Administration

Veronica Bürgisser

Former Members: Christine Guerlin (Thales), Niels Strohmaier (Hamburg),Thomas Bourdel (Orsay), Tobias Donner (Boulder), Kenneth Günter (ENS, Paris), Michael Köhl (Cambrigde), Anton Öttl (Berkeley), Stephan Ritter (MPQ), Thilo Stöferle (IBM), Yosuke Takasu (U Kyoto)

Discussions: Eugene Demler, Lode Pollet, Vito Scarola, Sebastian Huber, Matthias Troyer, Hans-Peter Büchler, J. Blatter, E. Altman, …