The Dicke Quantum Phase Transition with Ultracold Atoms

QO Group Meeting

Nov 9th, 2010

Nathan Cheng

Vol 464 | 29 April 2010 | doi:10.1038/nature09009 nature

ARTICLES

Dicke quantum phase transition with a superfluid gas in an optical cavity

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Exploring Symmetry Breaking at the Dicke Quantum Phase Transition

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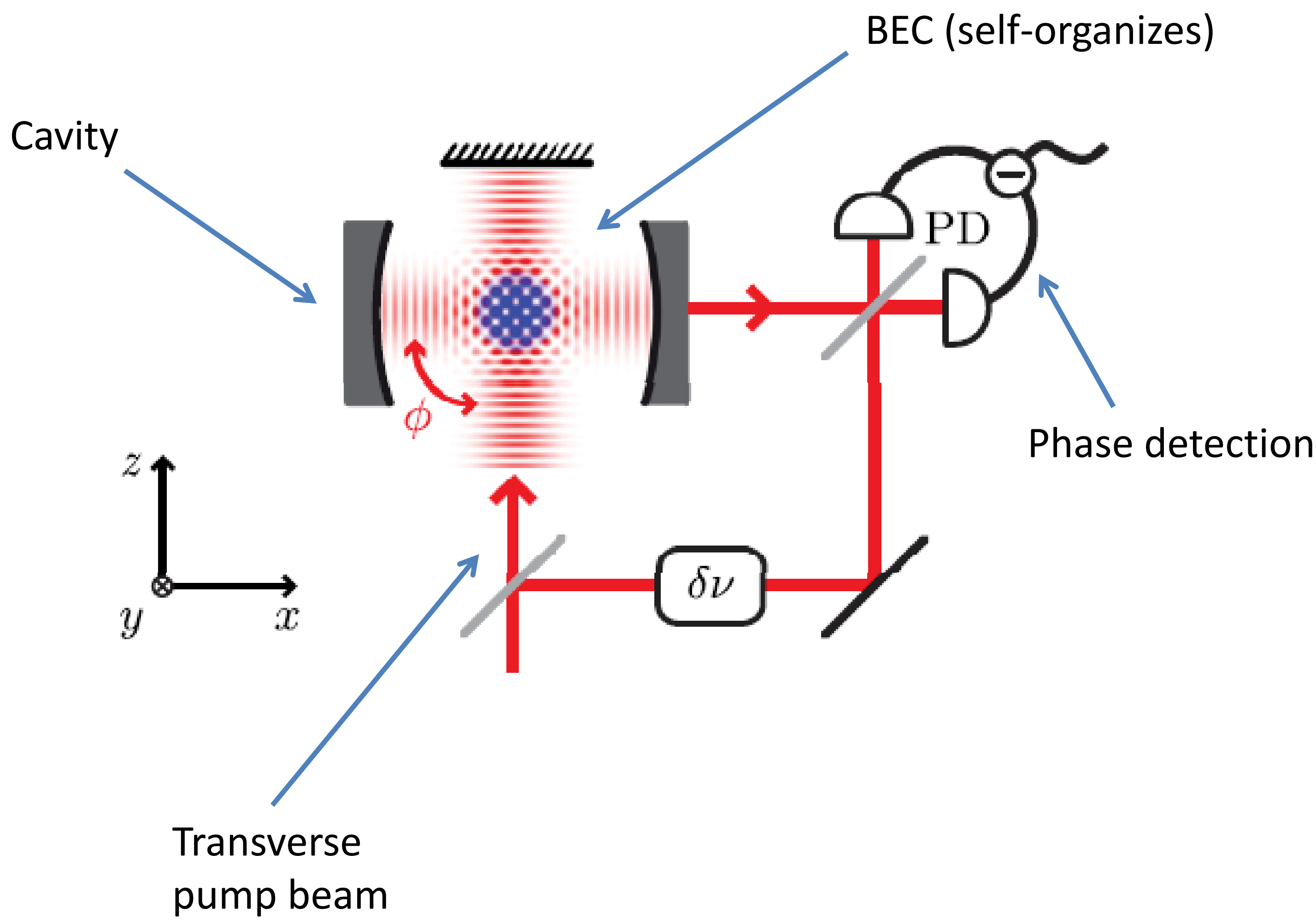
(Received 29 April 2011; revised manuscript received 18 July 2011; published 30 September 2011)

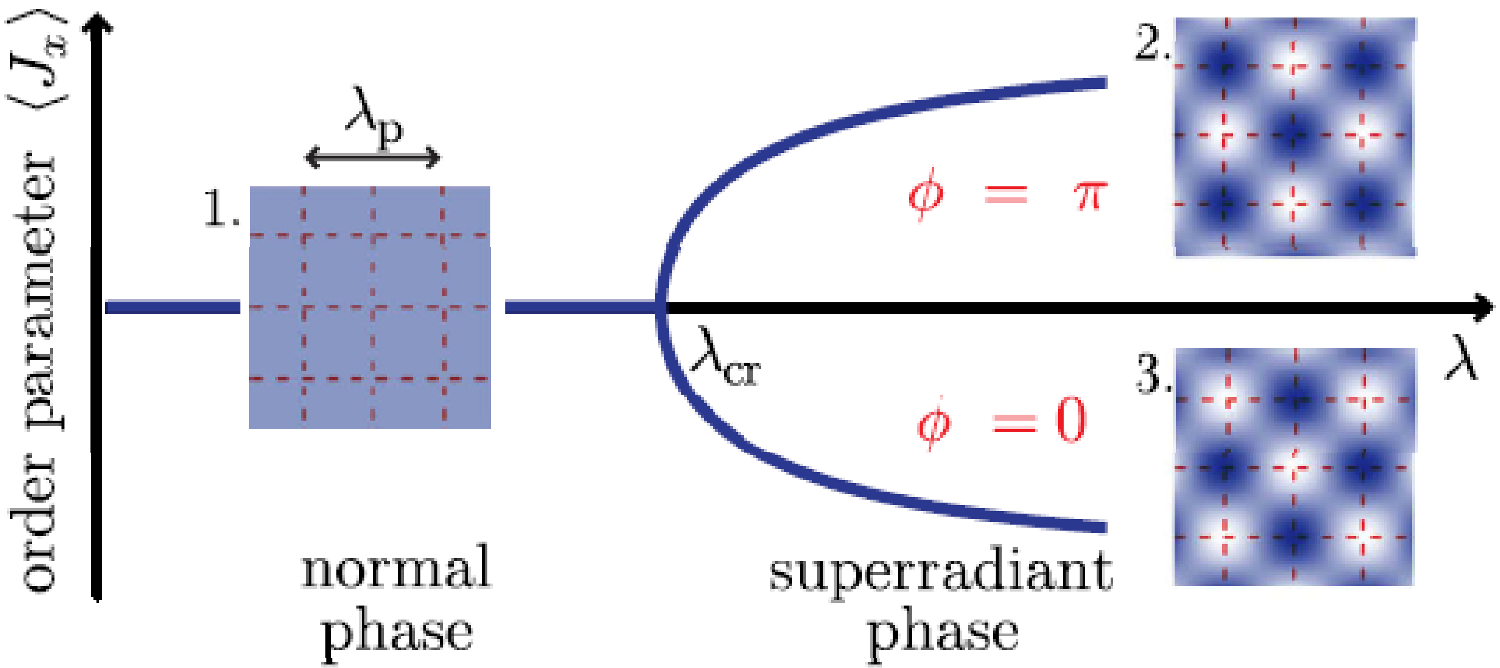
We study symmetry breaking at the Dicke quantum phase transition by coupling a motional degree of freedom of a Bose-Einstein condensate to the field of an optical cavity. Using an optical heterodyne detection scheme, we observe symmetry breaking in real time and distinguish the two superradiant phases. We explore the process of symmetry breaking in the presence of a small symmetry-breaking field and study its dependence on the rate at which the critical point is crossed. Coherent switching between the two ordered phases is demonstrated.

The Punchline
(while you are still awake)



The Punchline

$$\hat{H} = \hbar\omega_0 \hat{J}_z + \hbar\omega \hat{a}^\dagger \hat{a} + \frac{2\hbar\lambda}{\sqrt{N}}(\hat{a}^\dagger + \hat{a})\hat{J}_x.$$



Agenda

- Atoms in a Cavity
  - Theory
  - BEC in a cavity: Dicke Model
  - Quantum Phase Transition
  - Coupled Momentum State
- Experimental Apparatus
- Results
- Conclusion

Theory of atoms in a cavity

Single atom Hamiltonian

- Atoms
- Quantized EM Field
- Interaction (electric dipole)

Jaynes-Cummings

- Single atom
- Neglect counter rotating terms
- Analytically solveable

Dicke Model

- N two-level atoms interacting identically with a single EM mode
- 2^{nd} order phase transition (strong coupling)

Simple but hard to realize

Single-atom Hamiltonian

Dipole interaction

$$\hat{\mathcal{H}} = \hat{\mathcal{H}}_{\mathrm{a}} + \hat{\mathcal{H}}_{\mathrm{c}} + \hat{\mathcal{H}}_{\mathrm{int}}$$
$$= \hbar\omega_{\mathrm{a}}\hat{\sigma}_{+}\hat{\sigma}_{-} + \hbar\omega_{\mathrm{c}}\hat{a}^{\dagger}\hat{a} + \hbar g_{0}\left(\hat{\sigma}_{+} + \hat{\sigma}_{-}\right)\left(\hat{a} + \hat{a}^{\dagger}\right).$$

Eg = 0

$$\hat{E} = \mathcal{E}_{\max}(\hat{a} + \hat{a}^{\dagger}).$$

Single-atom coupling
strength to electric field

Jaynes-Cummings

$$\hat{\mathcal{H}} = \hbar\omega_{\mathrm{c}}\hat{a}^{\dagger}\hat{a} + \hbar\omega_{\mathrm{a}}\hat{\sigma}_{+}\hat{\sigma}_{-} + \hbar g_0\left(\hat{\sigma}_{+}\hat{a} + \hat{\sigma}_{-}\hat{a}^{\dagger}\right).$$

Neglected the counter-rotating terms

Dicke Model

Coupling strength

$$\hat{H} = \hbar\omega_0 \hat{J}_z + \hbar\omega \hat{a}^\dagger \hat{a} + \frac{2\hbar\lambda}{\sqrt{N}}(\hat{a}^\dagger + \hat{a})\hat{J}_x.$$

Keeping the counter-rotating terms

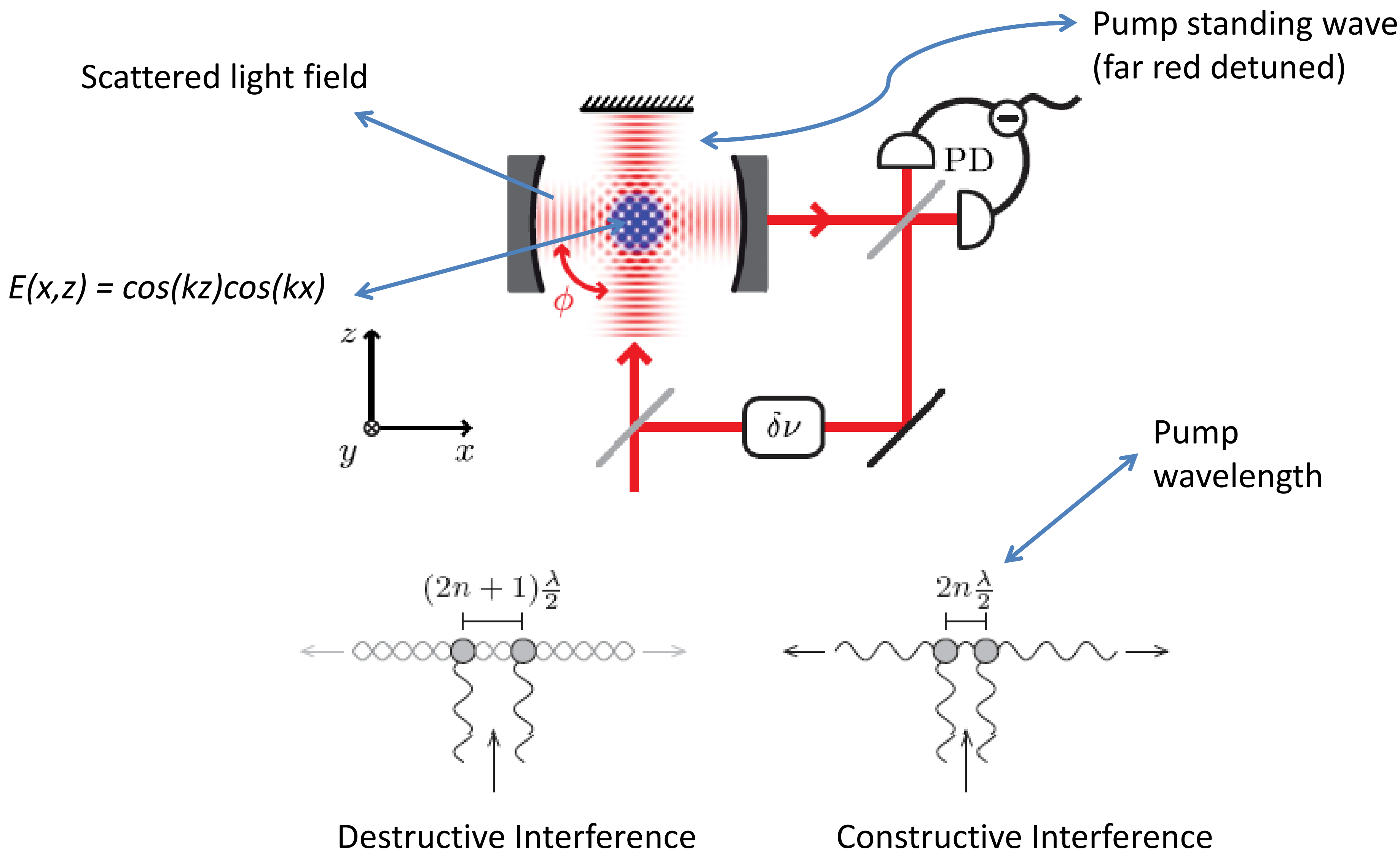
Atom Hamiltonian

Cavity Hamiltonian

Interaction Hamiltonian

Later: Can be realized by considering the two motional states of a BEC as “Ground” and “Excited” states!

Dicke Phase Transition for a BEC



Ordered Phase

Normal phase

Ordered phases (sub-lattices)

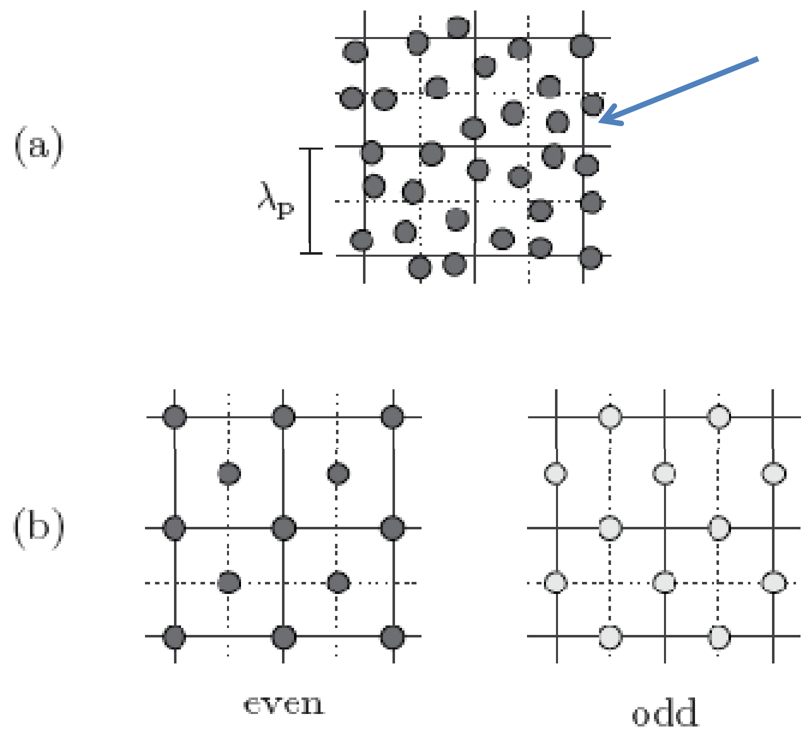
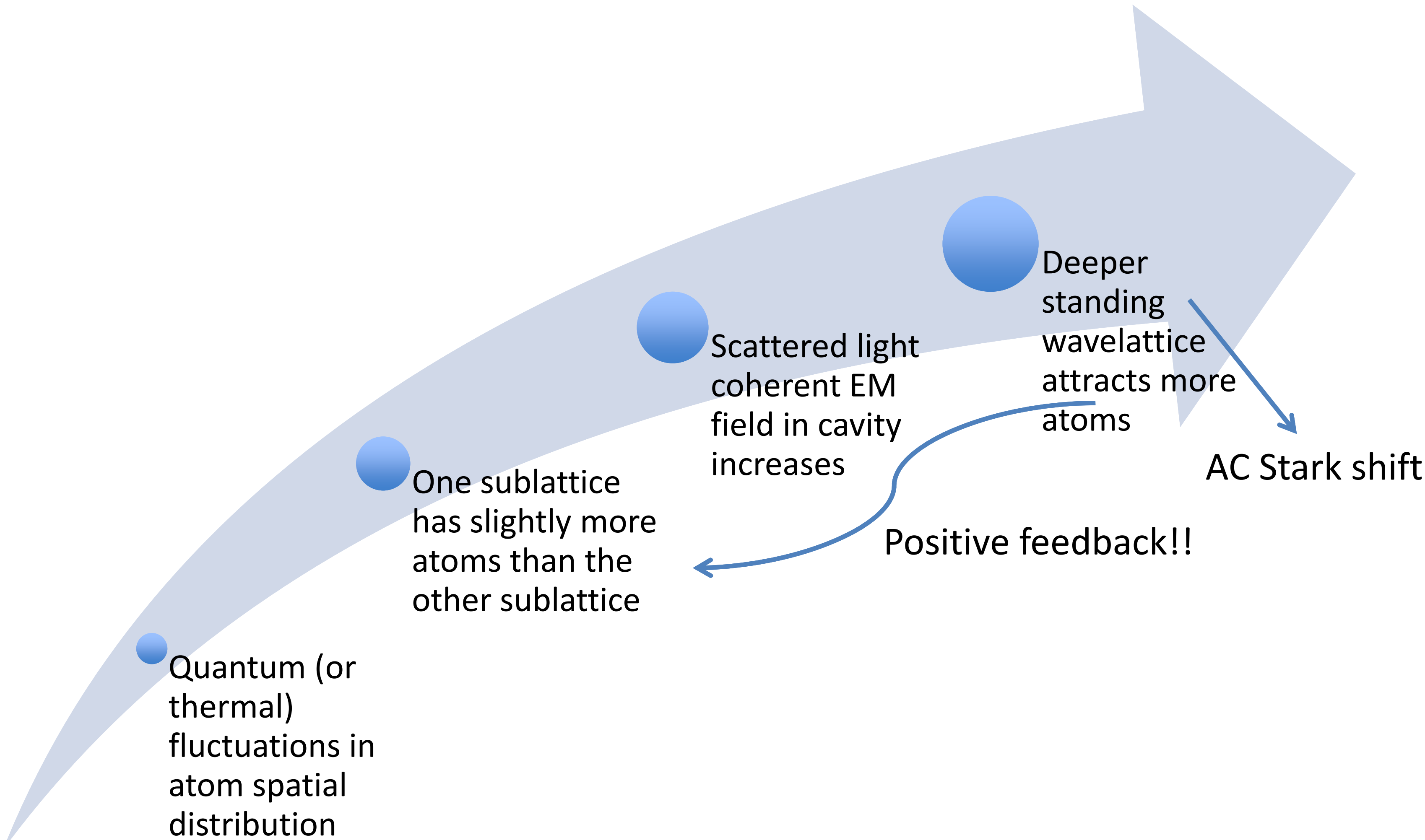


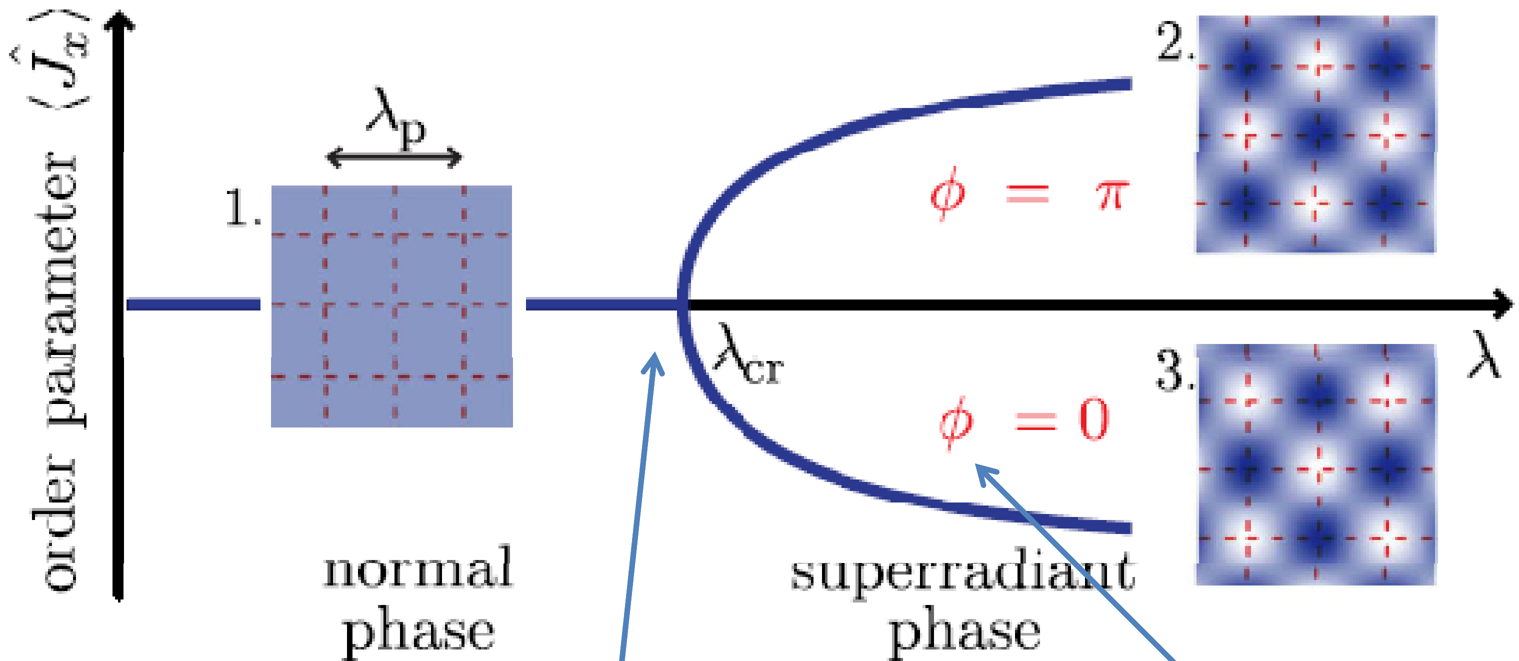
FIGURE 2.3.: The distribution of atoms with respect to the combined mode of the cavity and pump fields. (i) The atoms are distributed equally over all sites suppressing the scattering due to destructive interference. (ii) The atoms are distributed on either the even or odd sub-lattice, thereby maximizing the scattering of pump light into the cavity.

Fluctuations and spontaneous symmetry breaking



Order Parameter

= Difference between sublattice populations



Spontaneous symmetry breaking

Relative phase between

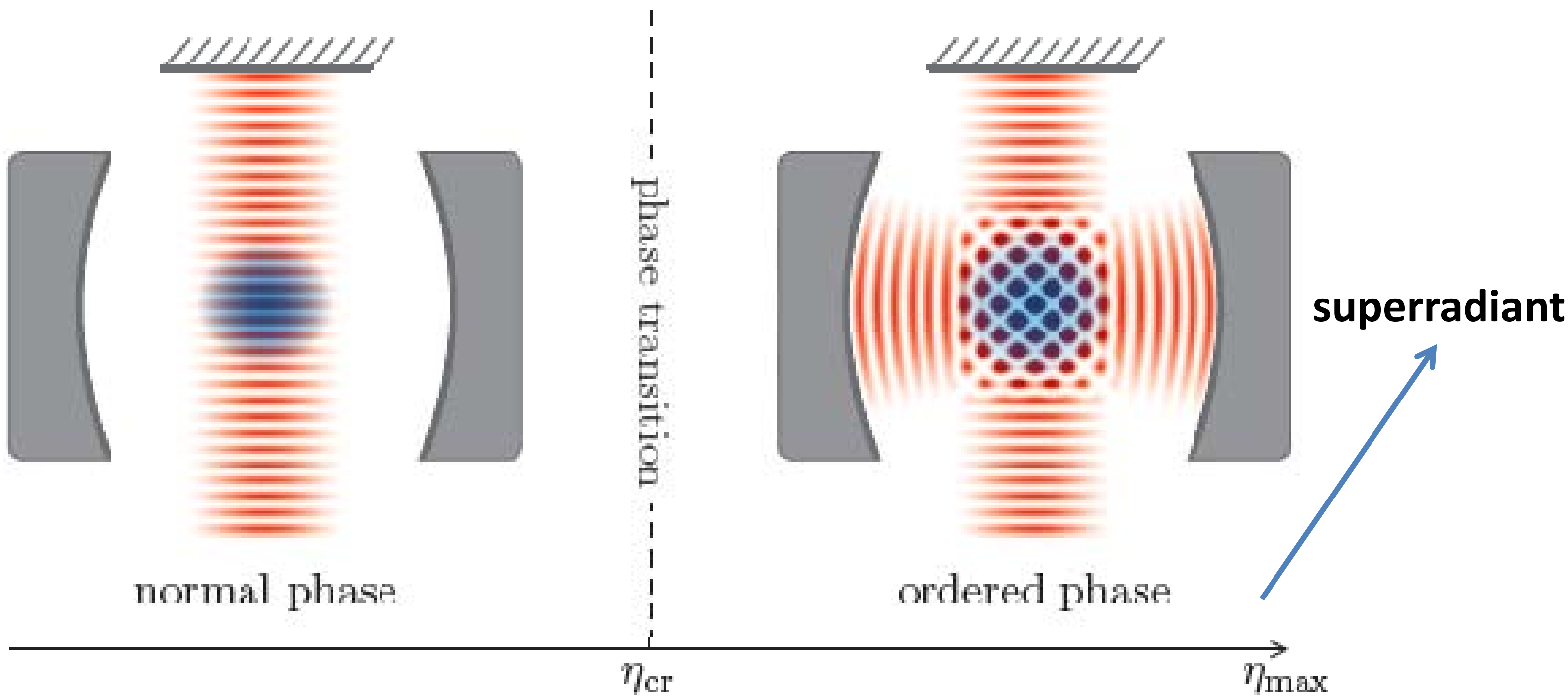
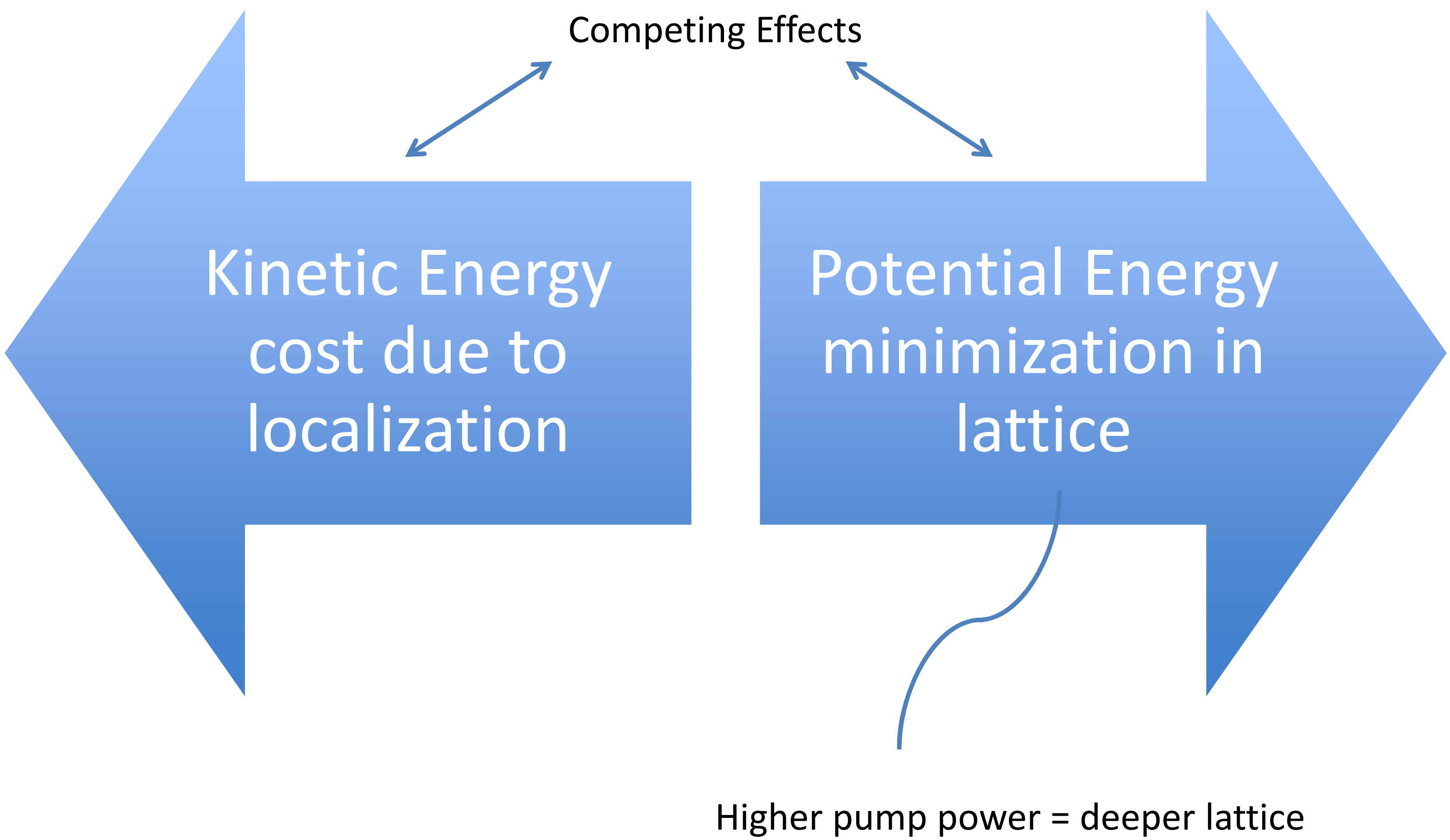


FIGURE 2.4.: Ground state below and above the critical pump amplitude η_{cr}. The normal phase is characterized by no coherent cavity-field population and a constant atomic density. A coherent population of the cavity-light field and a modulated atomic field characterize the ordered phase.

Driving the phase transition



So how is this the Dicke Model?

$$\hat{H} = \hbar\omega_0 \hat{J}_z + \hbar\omega \hat{a}^\dagger \hat{a} + \frac{2\hbar\lambda}{\sqrt{N}}(\hat{a}^\dagger + \hat{a})\hat{J}_x.$$

Motional states!

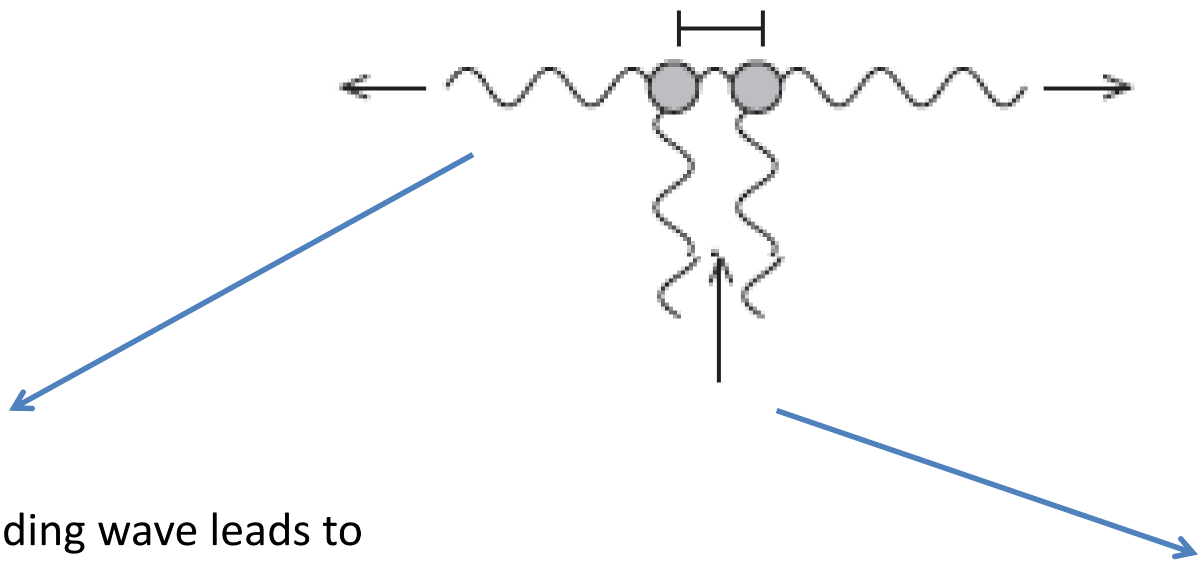
Controlled by pump power

$|p_x, p_z\rangle = |0, 0\rangle$ (Ground)

$|\pm\hbar k, \pm\hbar k\rangle = \sum_{\mu,\nu=\pm 1} |\mu\hbar k, \nu\hbar k\rangle/2.$ (Excited)

$\omega_r \equiv E_r/\hbar = \hbar k^2/(2m)$ Effective transition frequency (controlled by pump frequency)

More Intuitively…



Standing wave leads to ambiguity in momentum sign

Pump standing wave

Coupled Momentum States

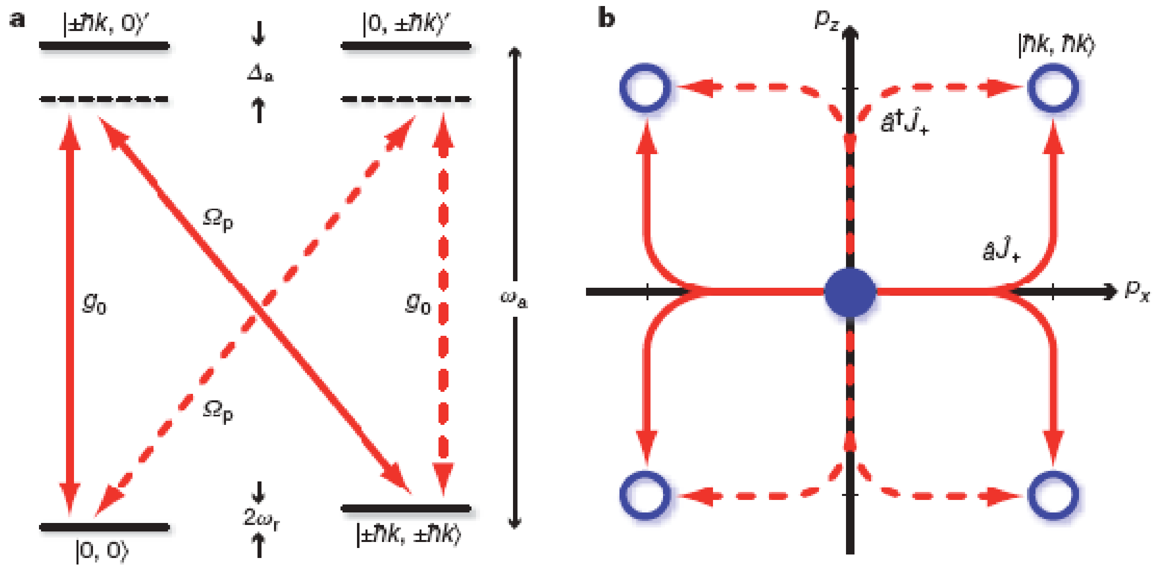
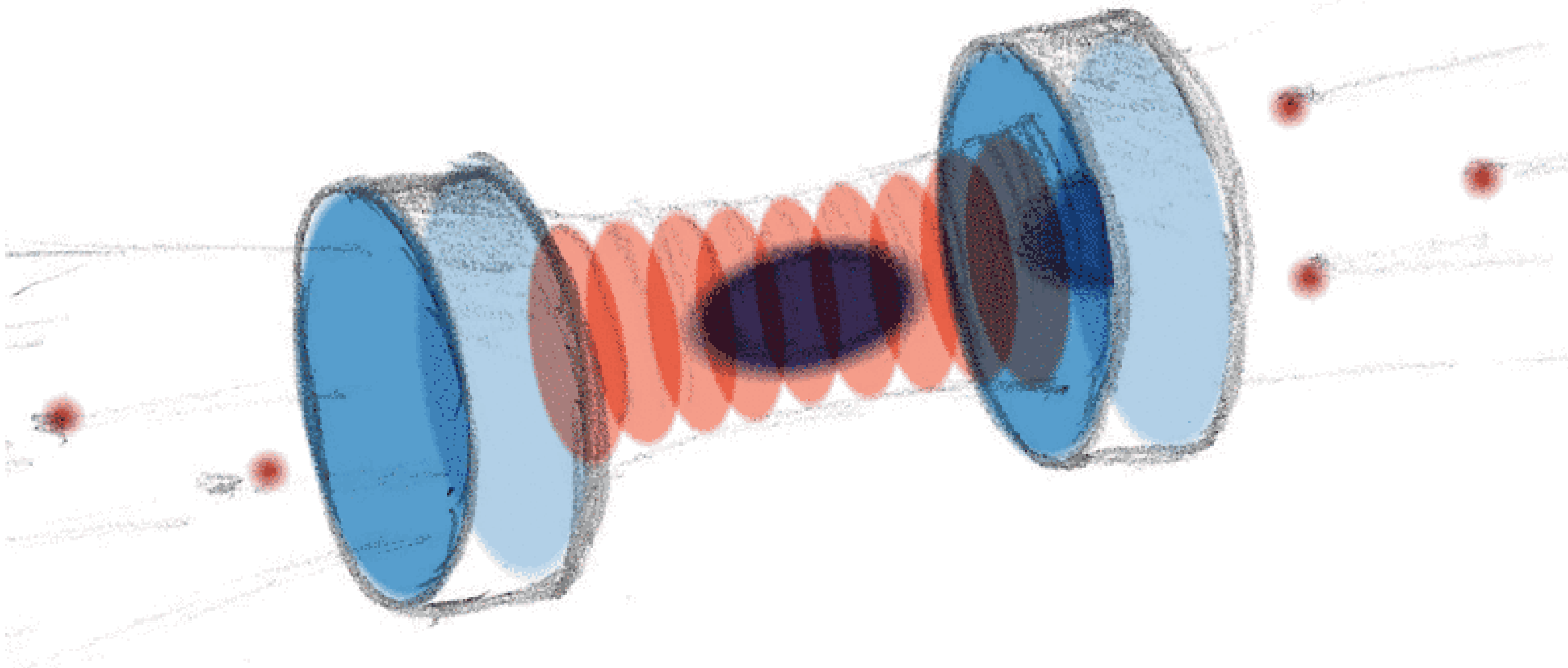


Figure 2 | Analogy to the Dicke model. In an atomic two-mode picture, the pumped BEC–cavity system is equivalent to the Dicke model including counter-rotating interaction terms. **a**, Light scattering between the pump field and the cavity mode induces two balanced Raman channels between $|p_x, p_z\rangle = |0,0\rangle$, the atomic zero-momentum state, and $|\pm\hbar k, \pm\hbar k\rangle$, the symmetric superposition of states with an additional unit of photon momentum along the x and z directions. Primes indicate electronically excited momentum states. **b**, The two excitation paths (dashed and solid) corresponding to the two Raman channels are illustrated in a momentum diagram.

Experiment



Birth of a BEC

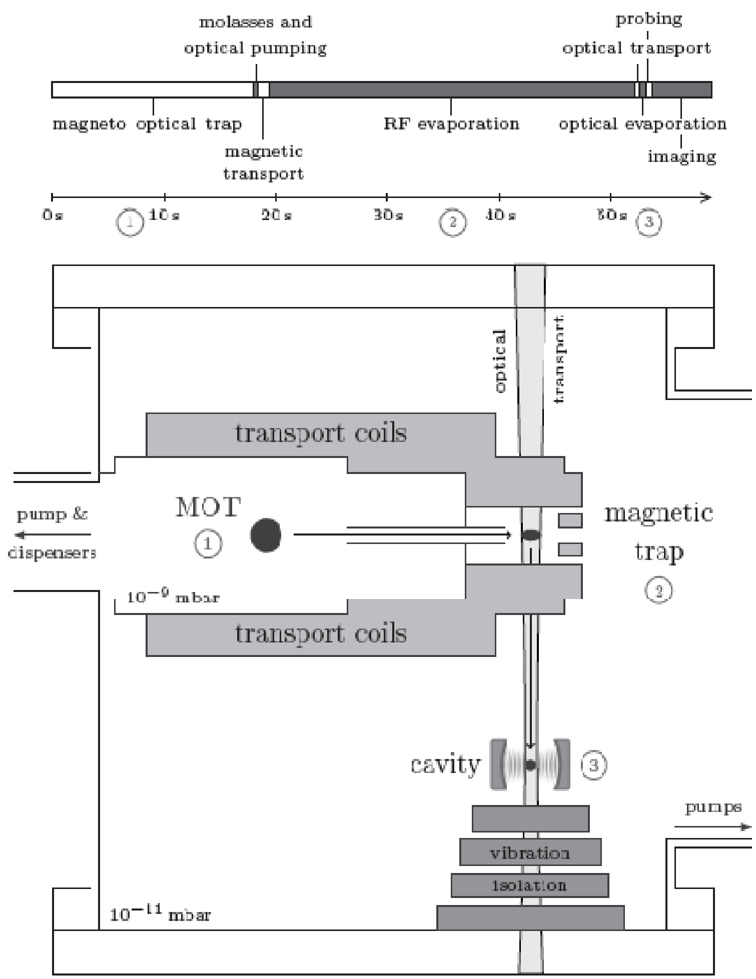
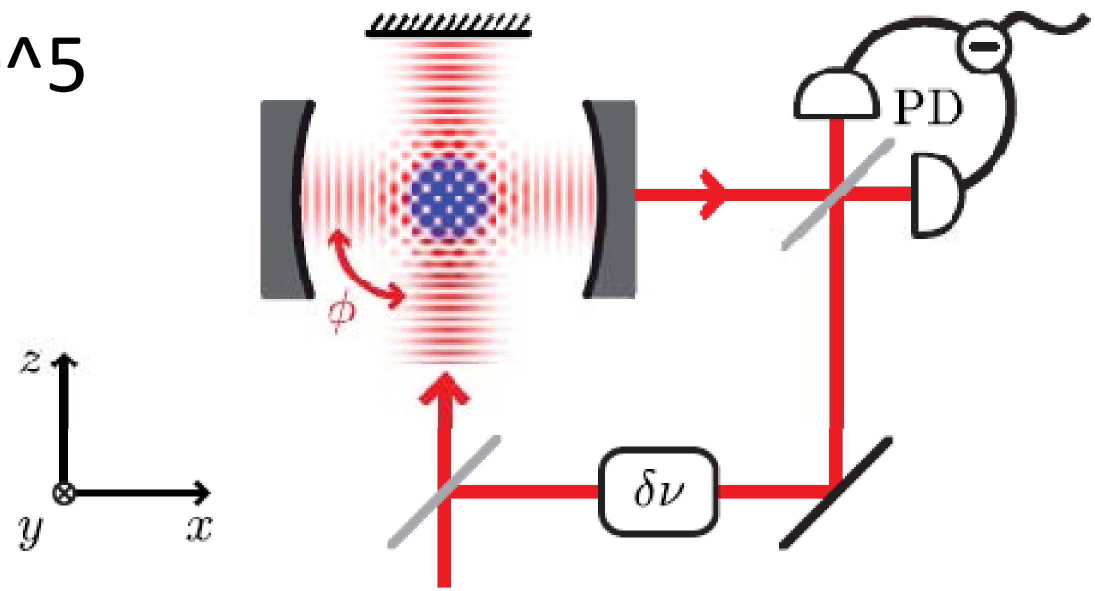


FIGURE 3.1.: Timing sequence and sketch of the experimental apparatus. The atoms are pre-cooled in a magneto-optical trap, transported into an ultra-high vacuum chamber and evaporatively cooled to near quantum degeneracy. After optical transportation, the atoms are trapped in the cavity by a crossed-beam dipole trap where a last step of evaporative cooling yields a BEC.

More experimental details

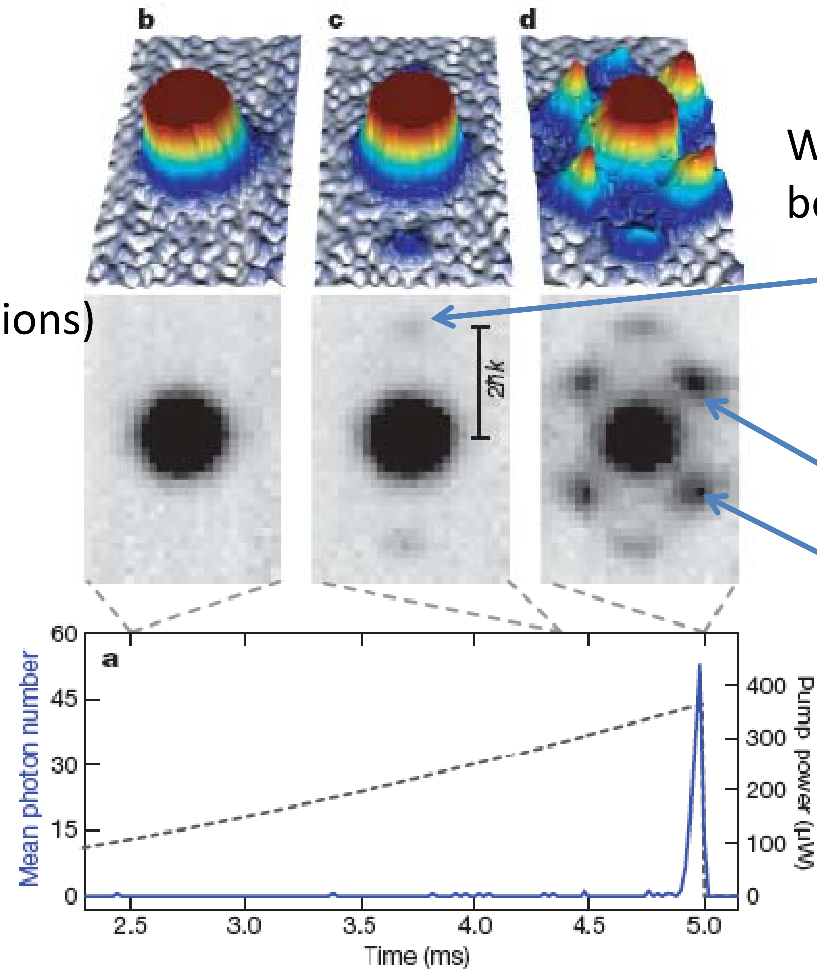
- 200,000 Rb-87 atoms in the cavity
- Pump = 784.5 nm, red detuned 10 cavity linewidths (from cavity)
- Pump is far detuned from atomic resonance
- Cavity finesse ~ 10^5



Observations

Time of flight images
(i.e momentum distributions)

Weak momentum from pump
beam standing wave



Coupled
momentum
states

Figure 3 | Observation of the phase transition. a–d, The pump power (dashed) is gradually increased while the mean intracavity photon number (solid; 20-μs bins) is monitored. After the sudden release of the atomic cloud and its subsequent ballistic expansion for 6 ms, absorption images (clipped equally in atomic density) are made for pump powers corresponding to lattice depths of $2.6E_r$ (**b**), $7.0E_r$ (**c**) and $8.8E_r$ (**d**). Self-organization is manifested by an abrupt build-up of the cavity field accompanied by the formation of momentum components at $(p_x, p_z) = (\pm\hbar k, \pm\hbar k)$ (**d**). The weak momentum components at $(0, \pm 2\hbar k)$ (**c**) result from loading the atoms into the one-dimensional standing-wave potential of the pump laser. The pump–cavity detuning was $\Delta_c = -2\pi \times 14.9(2)$ MHz and the atom number was $N = 1.5(3) \times 10^5$ (parentheses show uncertainty in last digit).

Symmetry Breaking

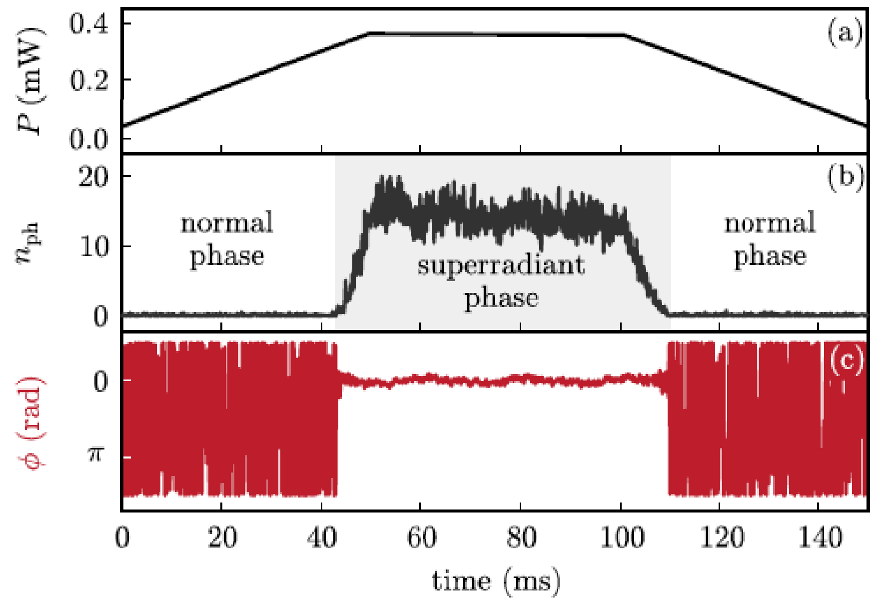


FIG. 2 (color online). Observation of symmetry breaking and steady-state superradiance. Shown are simultaneous traces of (a) the coupling laser power P, (b) the mean intracavity photon number n_{ph}, and (c) the relative time phase ϕ between the coupling laser and cavity field (both averaged over 150 μs). The coupling laser frequency is red-detuned by 31.3(2) MHz from the empty cavity resonance, and the atom number is $2.3(5) \times 10^5$. Residual atom loss causes a slight decrease of the cavity photon number in the superradiant phase.

Phase Diagram

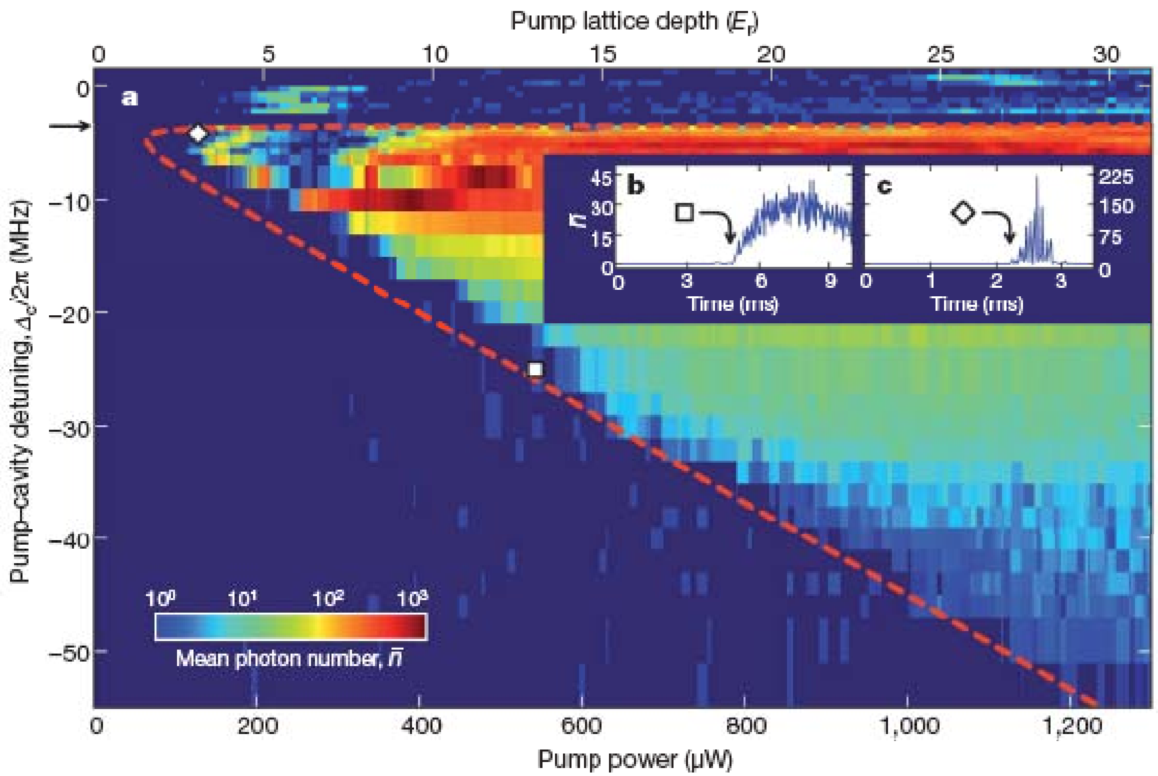


Figure 5 | Phase diagram. **a**, The pump power is increased to 1.3 mW over 10 ms for different values of the pump-cavity detuning, Δ_c. The recorded mean intracavity photon number, $\bar{n}$, is displayed (colour scale) as a function of pump power (and corresponding pump lattice depth) and pump–cavity detuning, Δ_c. A sharp phase boundary is observed over a wide range of Δ_c values; this boundary is in very good agreement with a theoretical mean-field model (dashed curve). The dispersively shifted cavity resonance for the non-organized atom cloud is marked by the arrow on the vertical axis. **b**, **c**, Typical traces showing the intracavity photon number for different pump–cavity detunings: $\Delta_c = -2\pi \times 23.0(2)$ MHz, 20-μs bins (**b**); $\Delta_c = -2\pi \times 4.0(2)$ MHz, 10-μs bins (**c**). The atom number was $N = 1.0(2) \times 10^5$. In the detuning range $-2\pi \times 7\,\text{MHz} \geq \Delta_c \geq -2\pi \times 21\,\text{MHz}$, the pump power ramp was interrupted at 540 μW. Therefore, no photon data was taken in the area of **a** under the insets.

Conclusions

- Realization of the Dicke model via motional states of a BEC coupled to a cavity
- Observation of 2^{nd} order phase transition
- Exploration of spontaneous symmetry breaking

Questions?