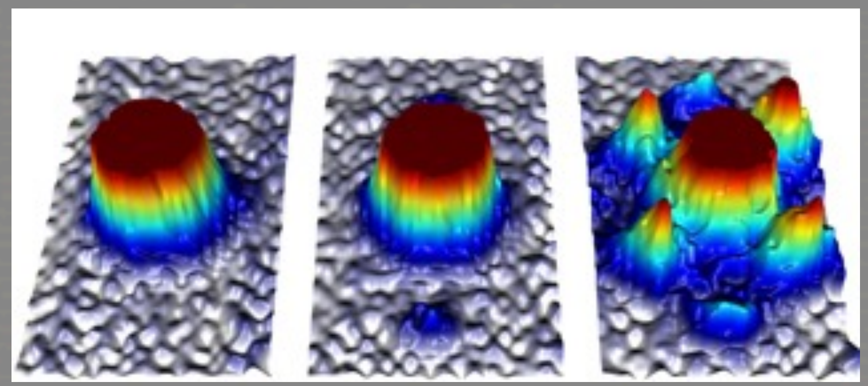
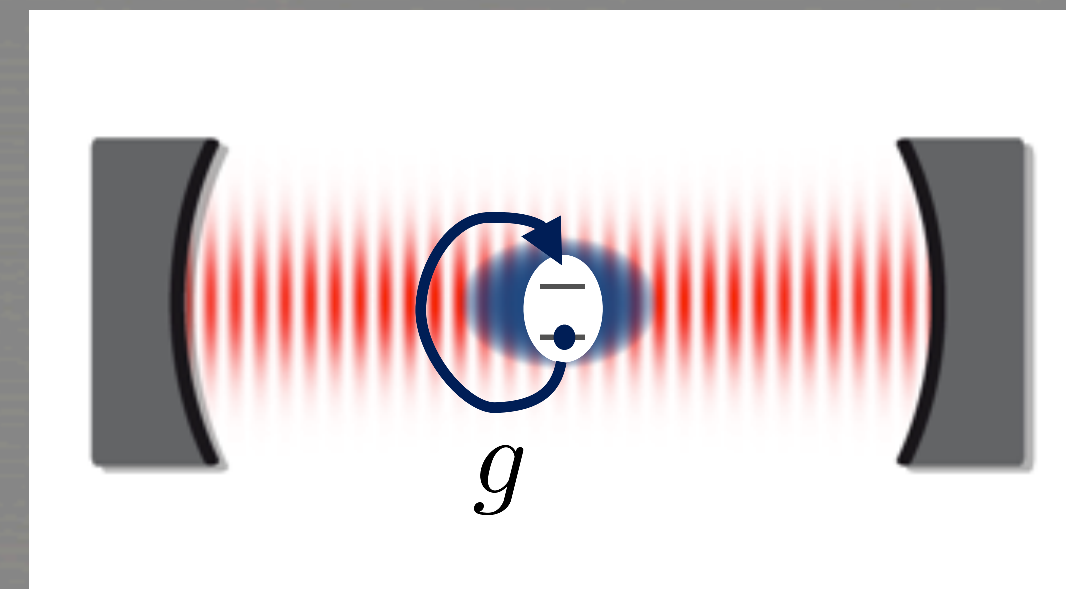
Transition de phase quantique de Dicke dans un gaz superfluide en cavité optique

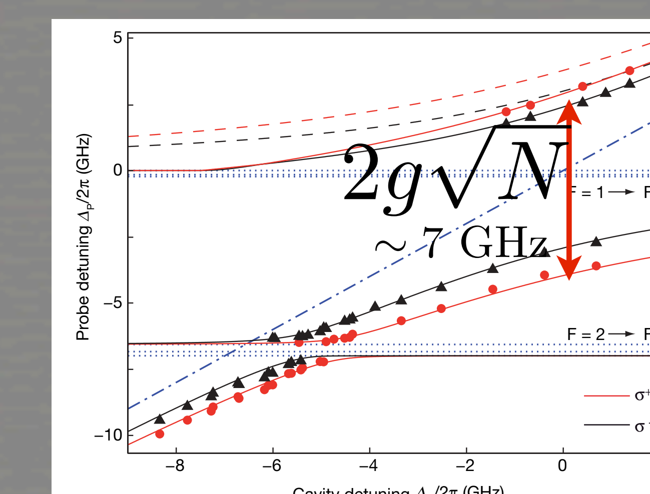


Christine Guerlin

(précédemment à l')
ETH Zürich

Cavity QED meets BEC - why ?





Collective Rabi splitting
ETH Zürich and LKB, 2007
Brennecke et al, & Colombe et al., Nature 450

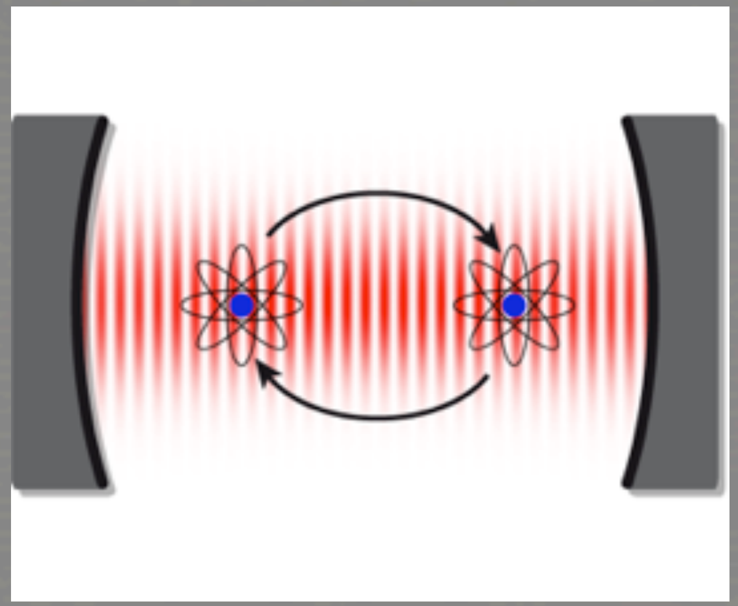
- **As a tool for cavity QED:**
  - collective coupling: $N^{1/2}$ enhancement
  - control of external degrees of freedom:
    quantized external degrees of freedom
    better control of the coupling
    Cavity-based single atom preparation and high-fidelity state read-out, R. Gehr et al, PRL 104 (2010)

- **Combining quantum optics and many-body physics**

⇒ new physical system for many body physics
optical CQED toolbox

Many body physics in cavity

- Particle-particle interactions support collective behavior
- Most drastic collective phenomenon: phase transition



Cavity: mediates effective long-range atom-atom interactions

(if moderate) nonlinearity, instability *@previous experiments*

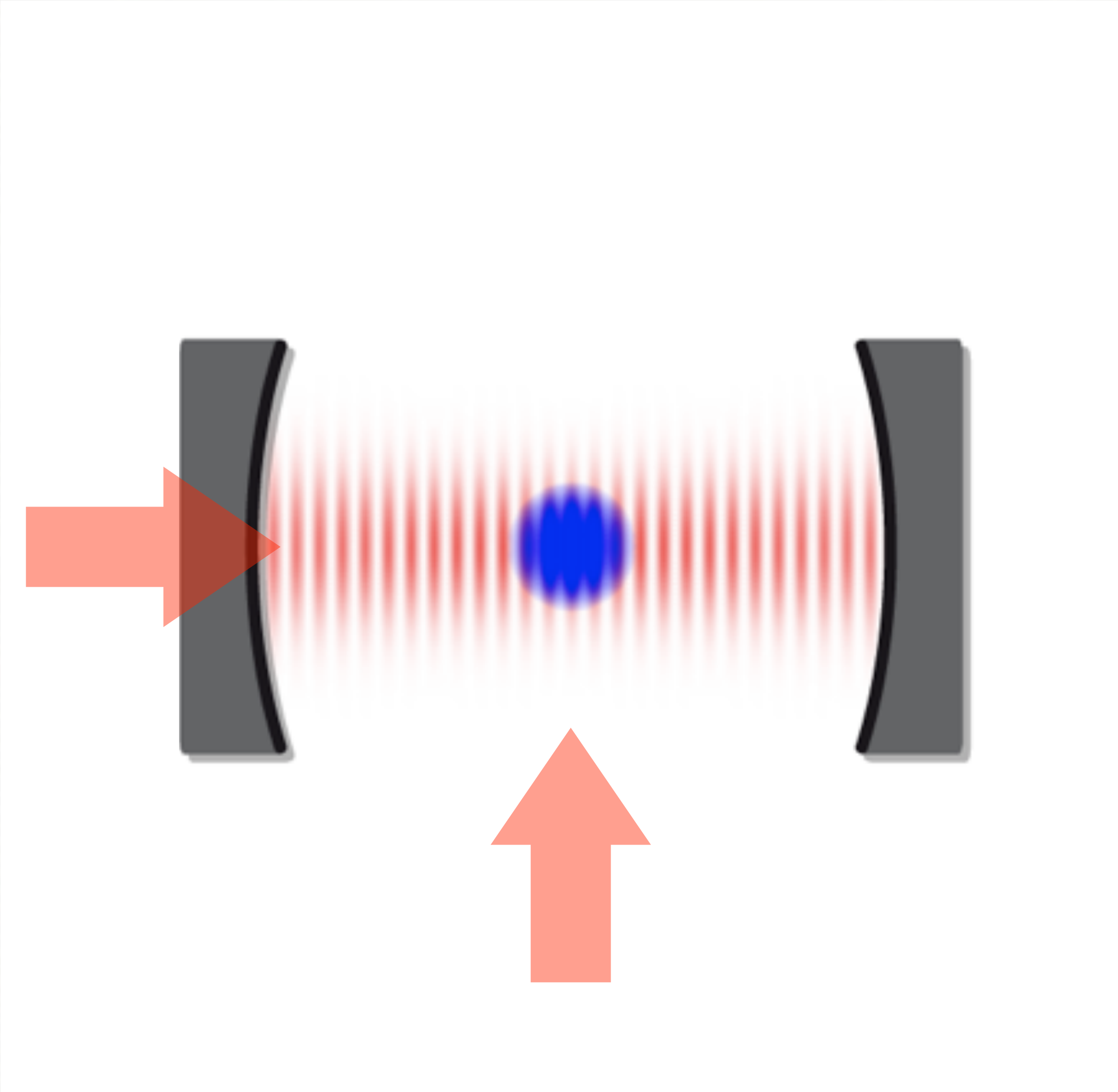
(if strong) novel phase diagram / quantum phase transitions

this talk

theoretical proposals:
M. Lewenstein, H. Ritsch, P. Domokos...

recent review: Cold atoms in cavity-generated dnamical optical lattice potentials, *H. Ritsch et al.*, Rev. Mod. Phys. 85 (2013)

Physical system (on paper)



Bose-Einstein condensate

- ~10^5 atoms (^{87}Rb)
- T ~100nK

$\gamma = 2\pi \times 3$ MHz

High-finesse optical cavity

- length = 178 µm
- finesse = 340 000
- single-atom strong coupling regime

$\kappa = 2\pi \times 1.3$ MHz

$g_0 = 2\pi \times 10.9$ MHz

$$g_0 > \kappa,\ \gamma$$

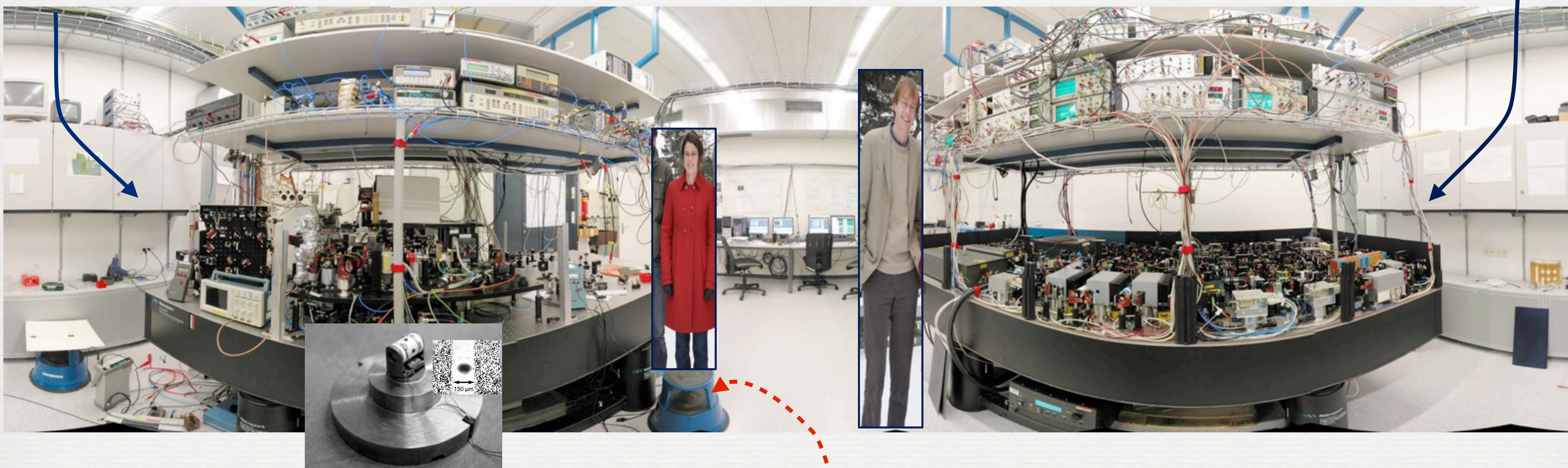
Pump laser field

- close detuned to cavity resonance

Physical system (in 3D)

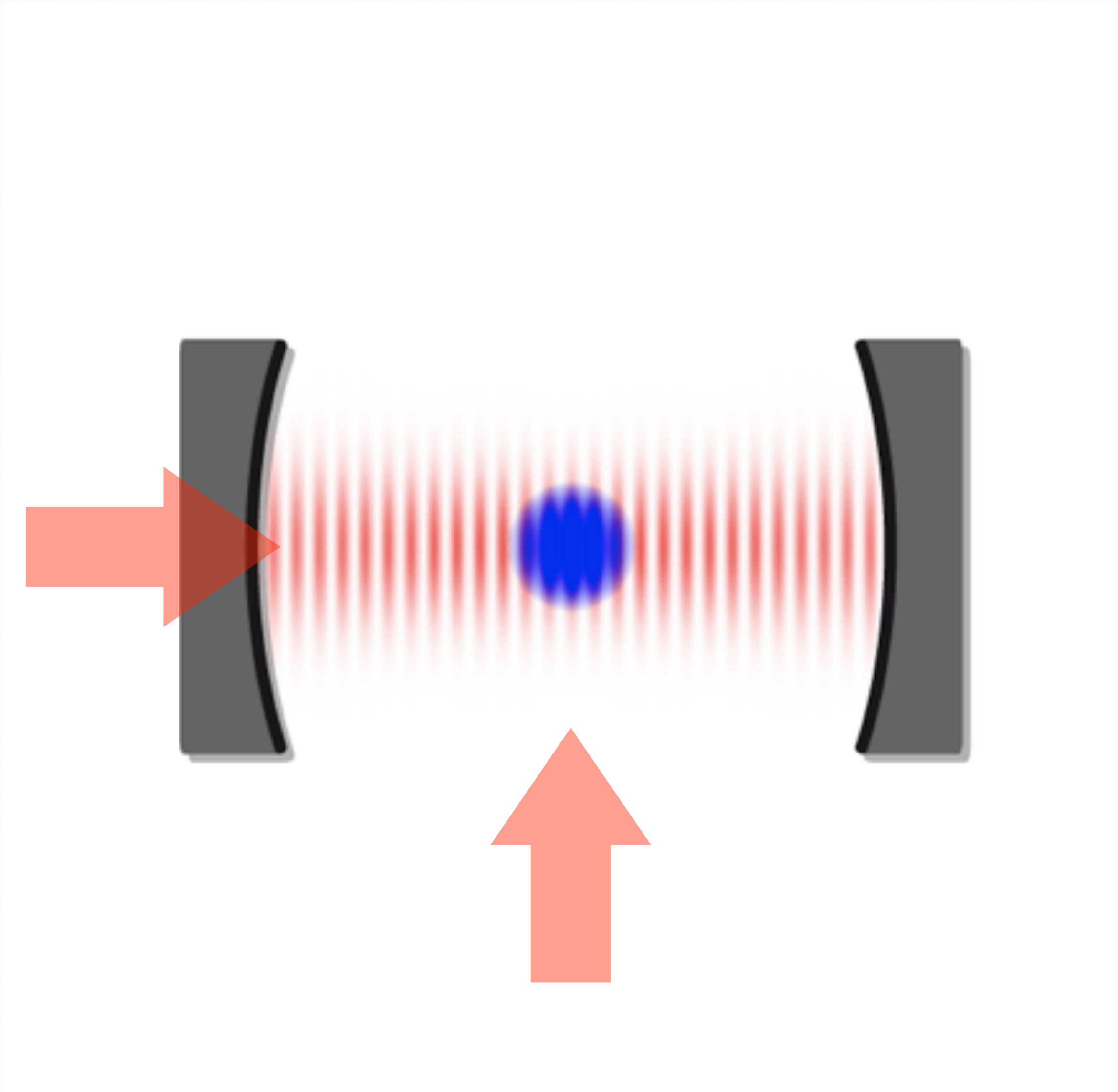
vacuum tank / cavity
beam control and shaping
SPCM

MOT / molasse, dipole trap;
cavity lock and probe chain



operators:
german-french adaptor

Physical system (on paper)



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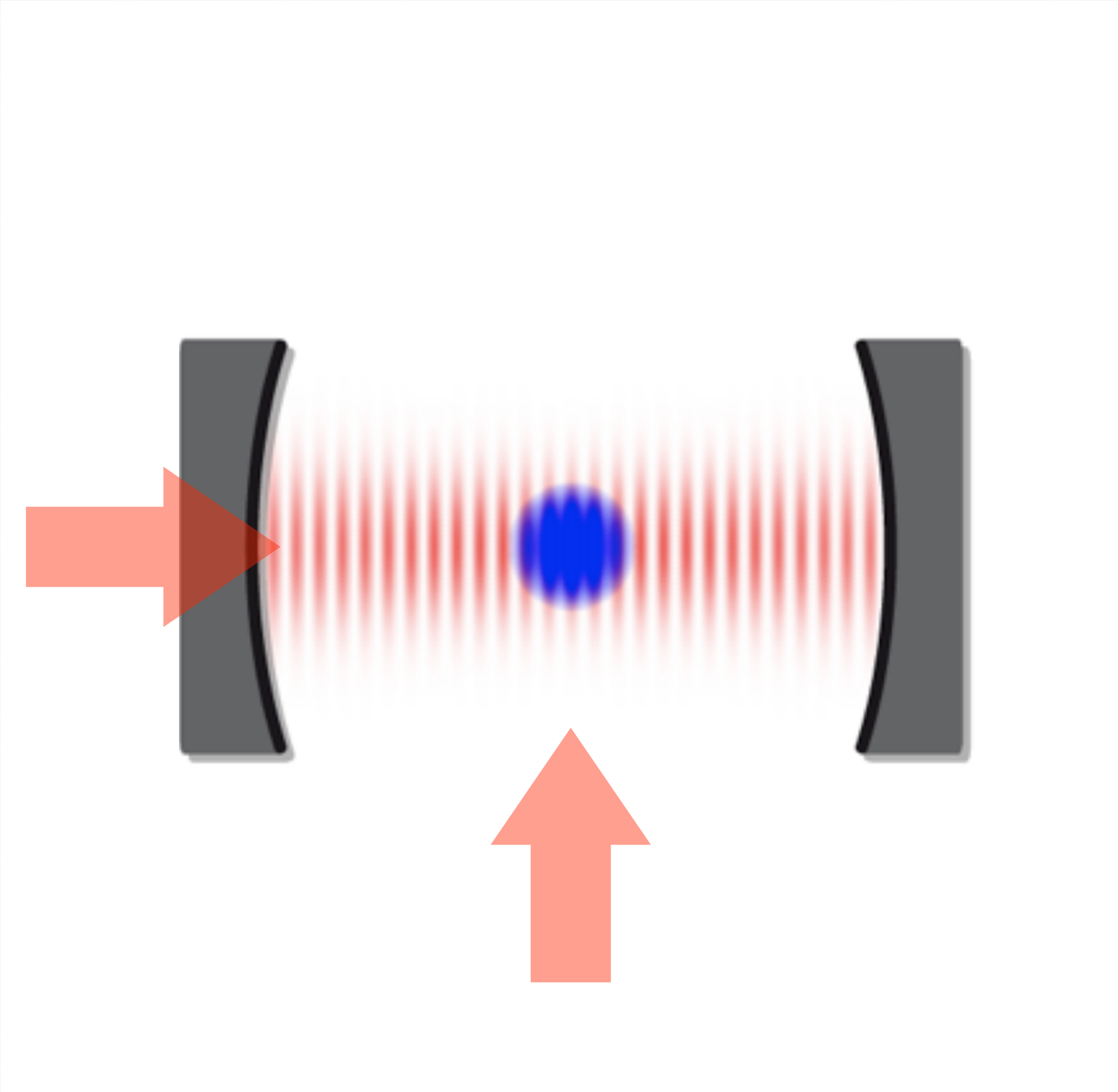
Dispersive interaction



For coupling only to external degrees of freedom: dispersive interaction

Bose-Einstein condensate

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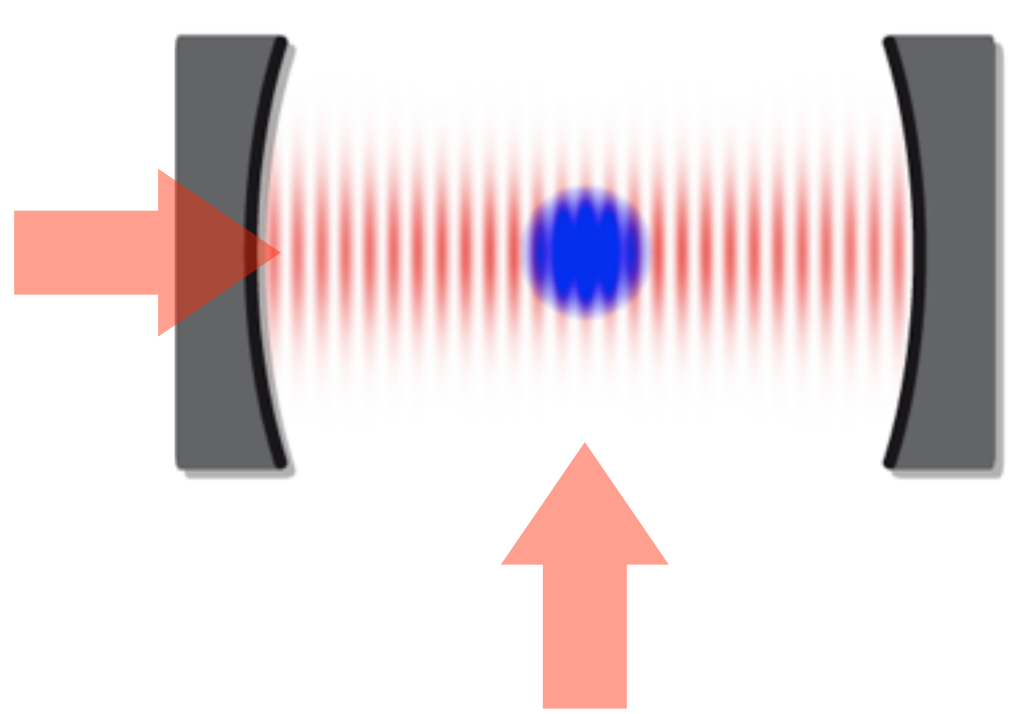
$g_0 > \kappa,\ \gamma$

Pump laser field

- close detuned to cavity resonance
- far detuned from atomic resonance

Dispersive interaction

$$\hat{H}_{(1)} = \hat{H}_a + \hat{H}_c + \hat{H}_{a-c}$$



$\Delta_{a,c} = \omega_p - \omega_{a,c}$

$$\hat{H}_a = \frac{\hat{\mathbf{p}}^2}{2m} + V_{\text{ext}}(\mathbf{r})$$

$$\hat{H}_c = -\hbar\Delta_c \hat{a}^\dagger \hat{a} - i\hbar\eta(\hat{a} - \hat{a}^\dagger) \; + \hbar\eta(\mathbf{r})(\hat{a}^\dagger + \hat{a})$$

$$\boxed{\hat{H}_{a-c} = \hbar U_0 |\phi(\mathbf{r})|^2 \hat{a}^\dagger \hat{a}.}$$

$$U_0 = \frac{g_0^2}{\Delta_a}$$

- shift of atom energy, per photon
  cavity field for atoms: **optical lattice**
- shift of cavity frequency, per photon
  atoms for cavity: index of refraction

$$\psi = f(\alpha)$$

Dispersive interaction

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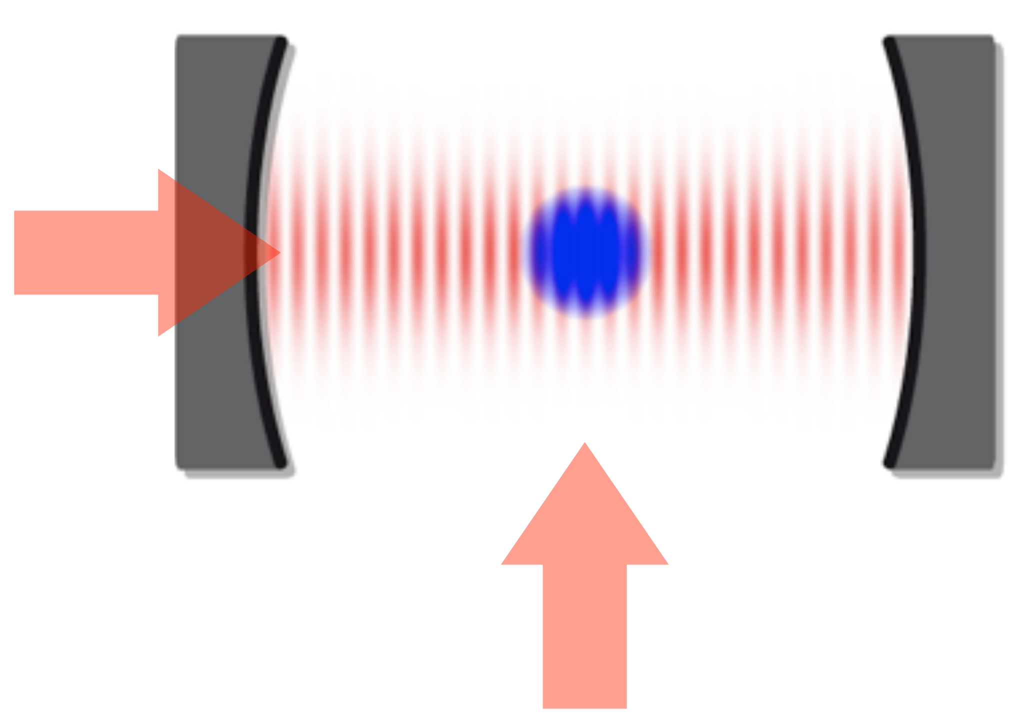

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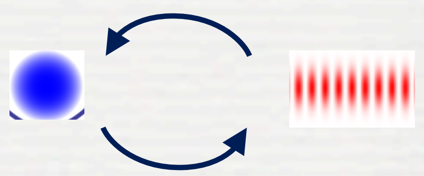


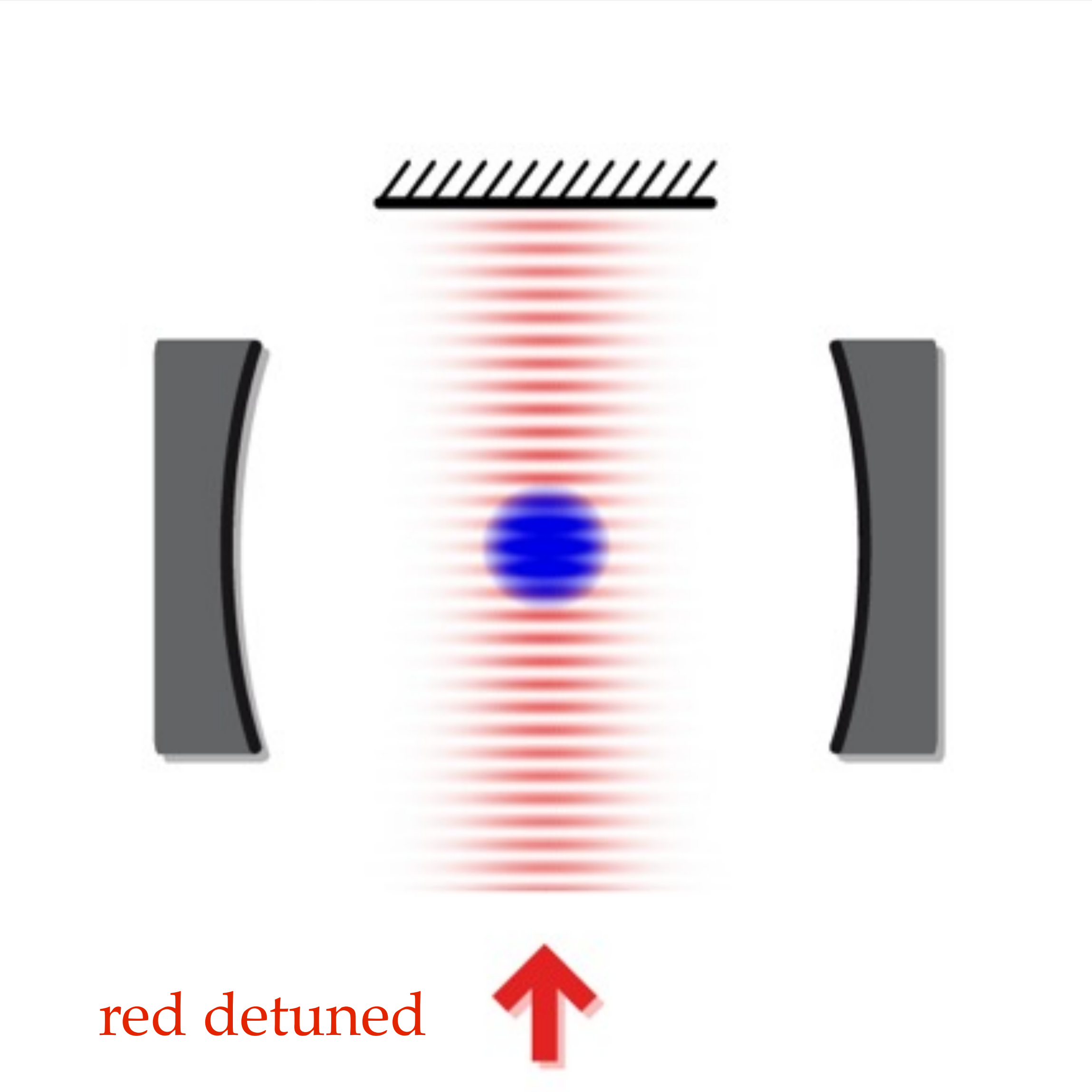
$$\alpha = f(\psi)$$

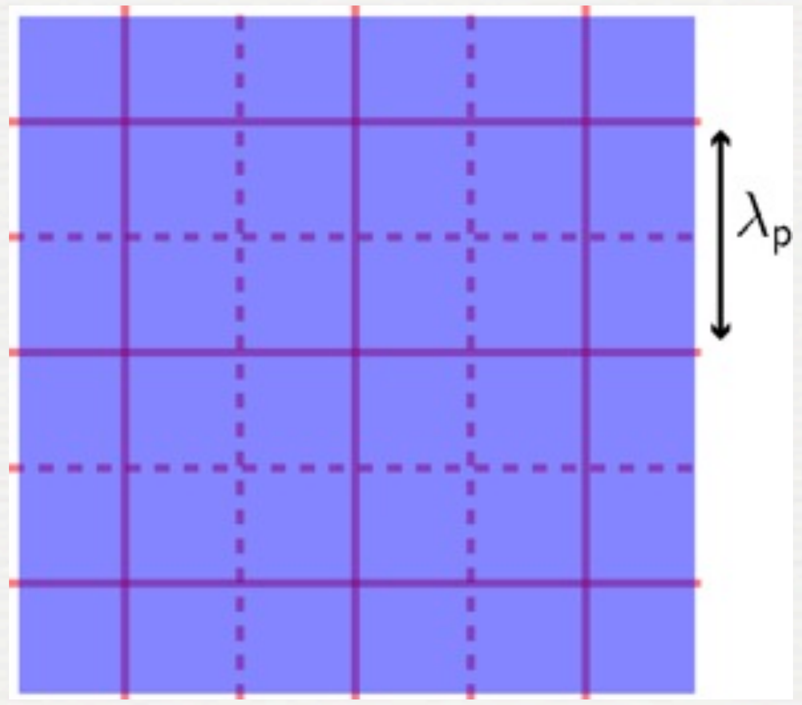
back-action: Cavity field depends on atomic spatial distribution

cavity pumping:	index of refraction
atom pumping:	effective pumping of the cavity

Dynamical optical lattice
Cavity mediates global interaction between atoms !

Atom pumping

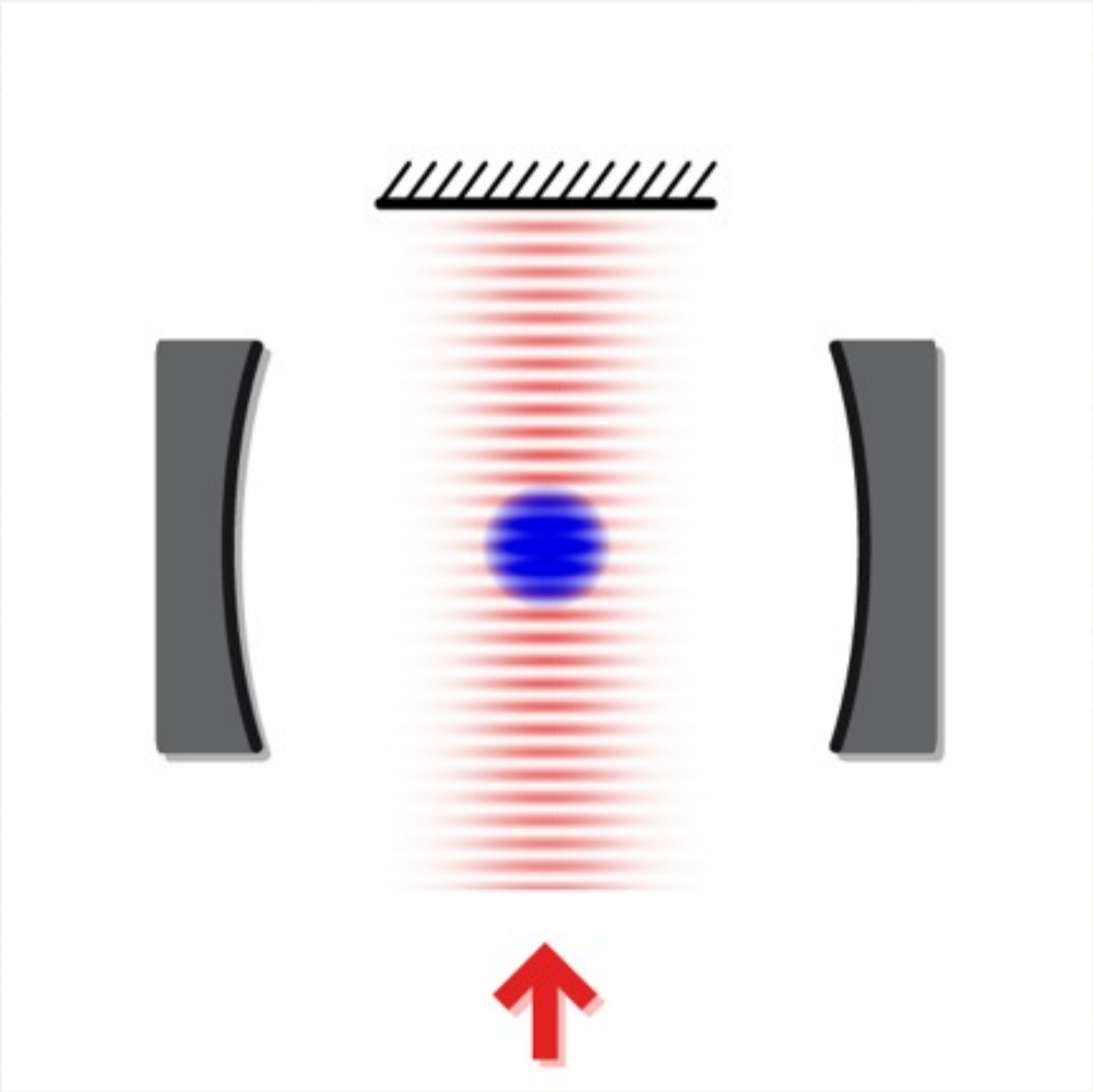


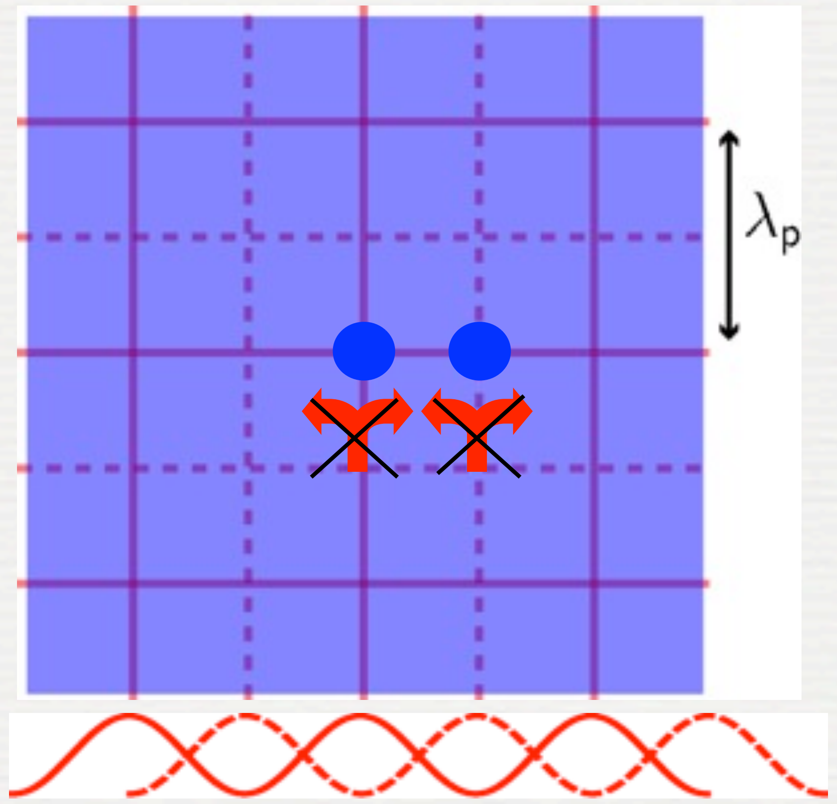


two-photon scattering rate:

$$\eta = \frac{\Omega g_0}{\Delta_a}$$

Atom pumping





destructive interference

two-photon scattering rate:

$$\eta = \frac{\Omega g_0}{\Delta_a}$$

Cavity field buid-up: checkerboard pattern

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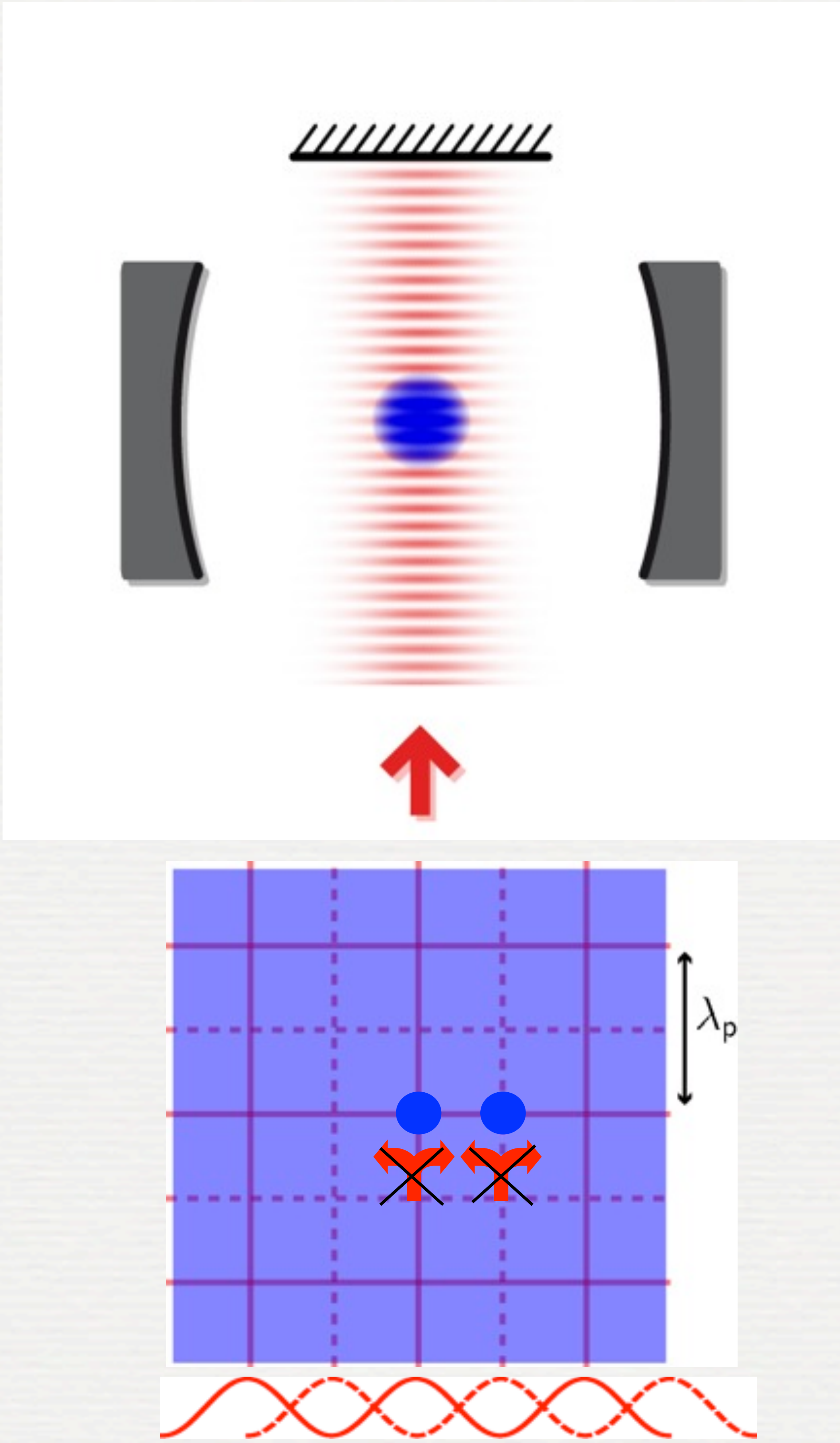

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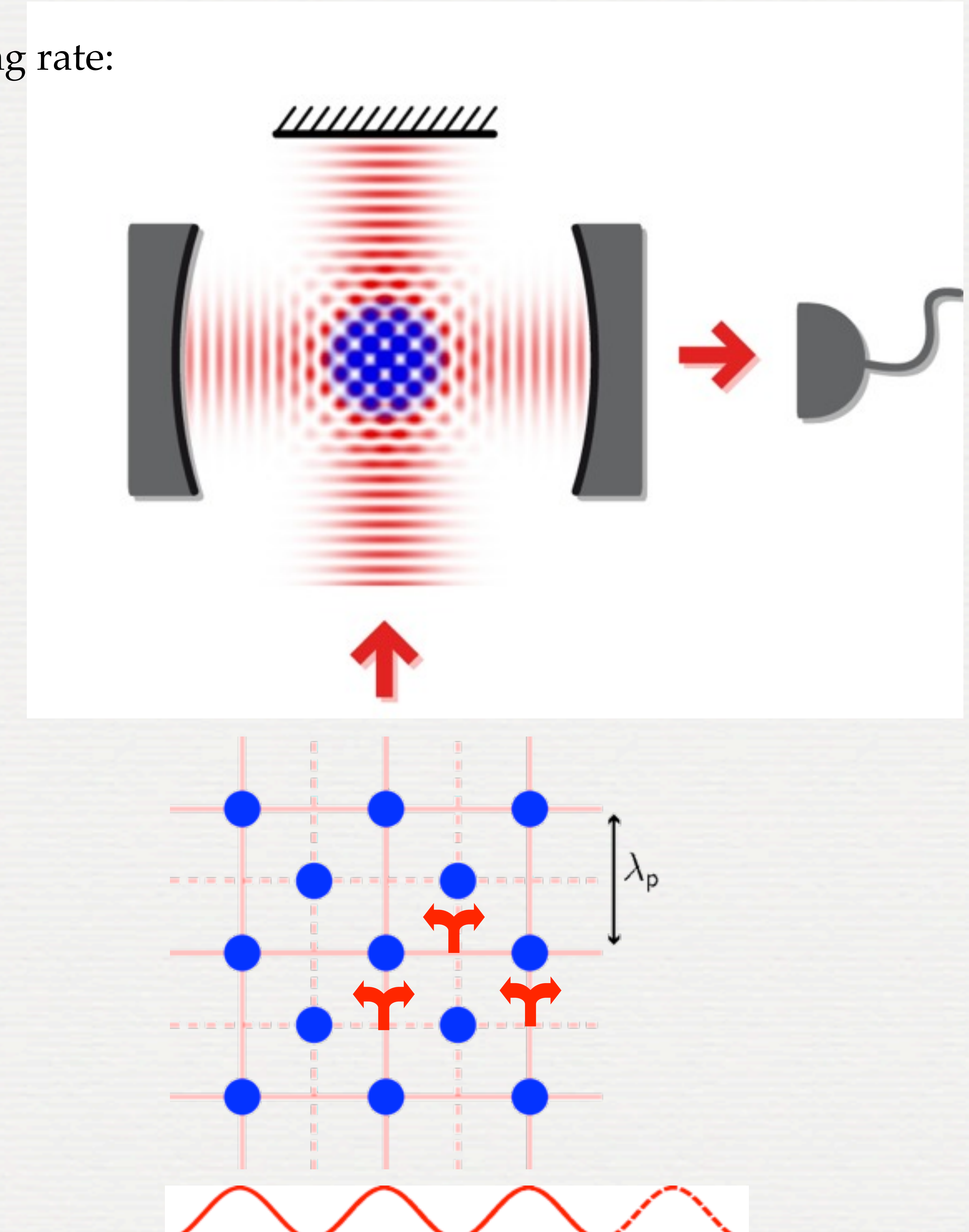


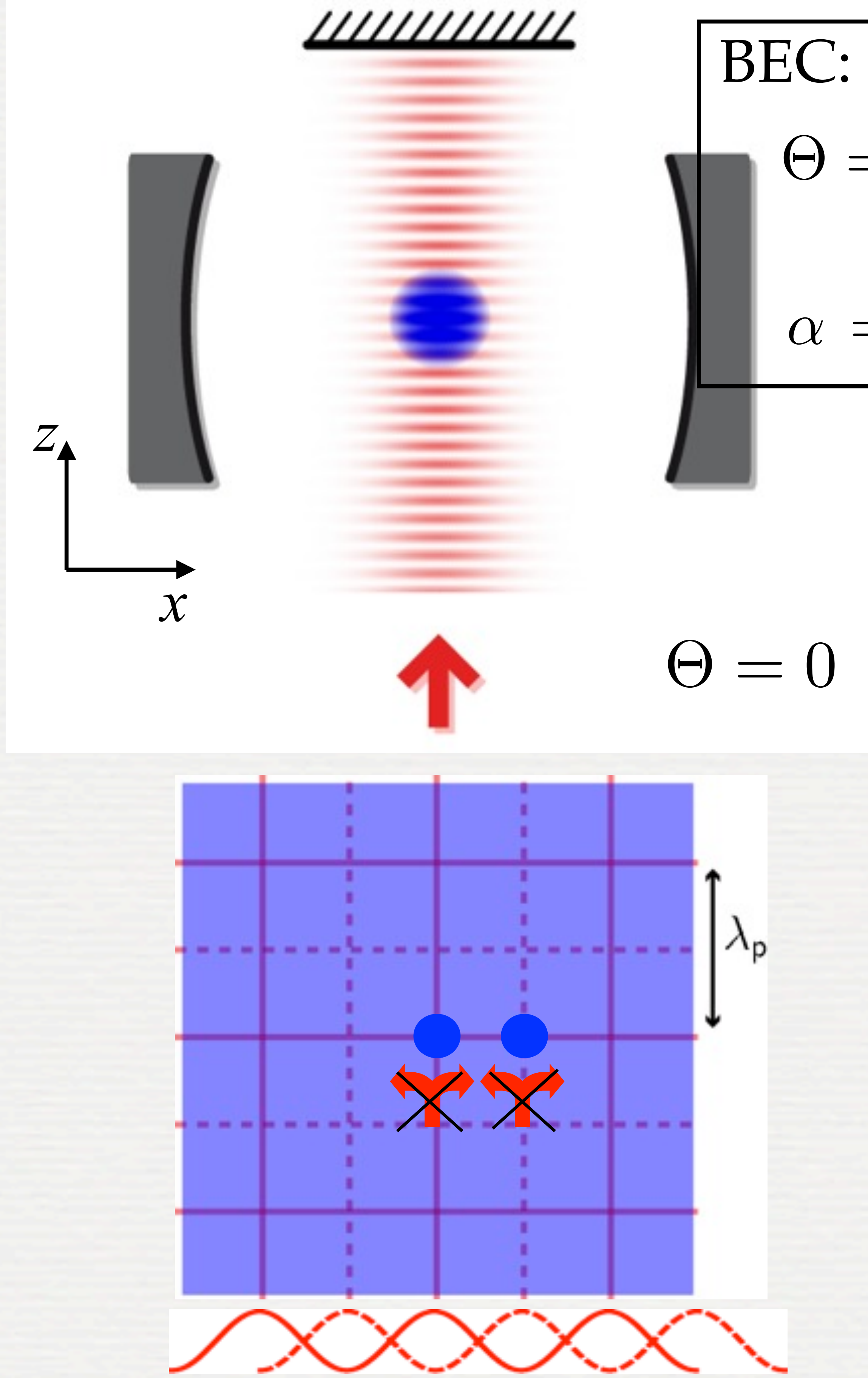
constructive interference

Cavity field buid-up: checkerboard pattern

1 atom: $\eta(\mathbf{r}) = \eta\cos(kx)\cos(kz)$

$$\boxed{\begin{array}{l}\text{BEC:}\quad \eta_{\text{eff}} = \langle\eta(\mathbf{r})\rangle = \eta\Theta \quad \text{with} \\ \Theta = \langle\psi|\cos(kx)\cos(kz)|\psi\rangle \\ \Downarrow \\ \alpha = \eta\Theta/(\Delta_c - U_0\mathcal{B} + i\kappa)\end{array}}$$

mean-field
$\alpha = f(\psi)$



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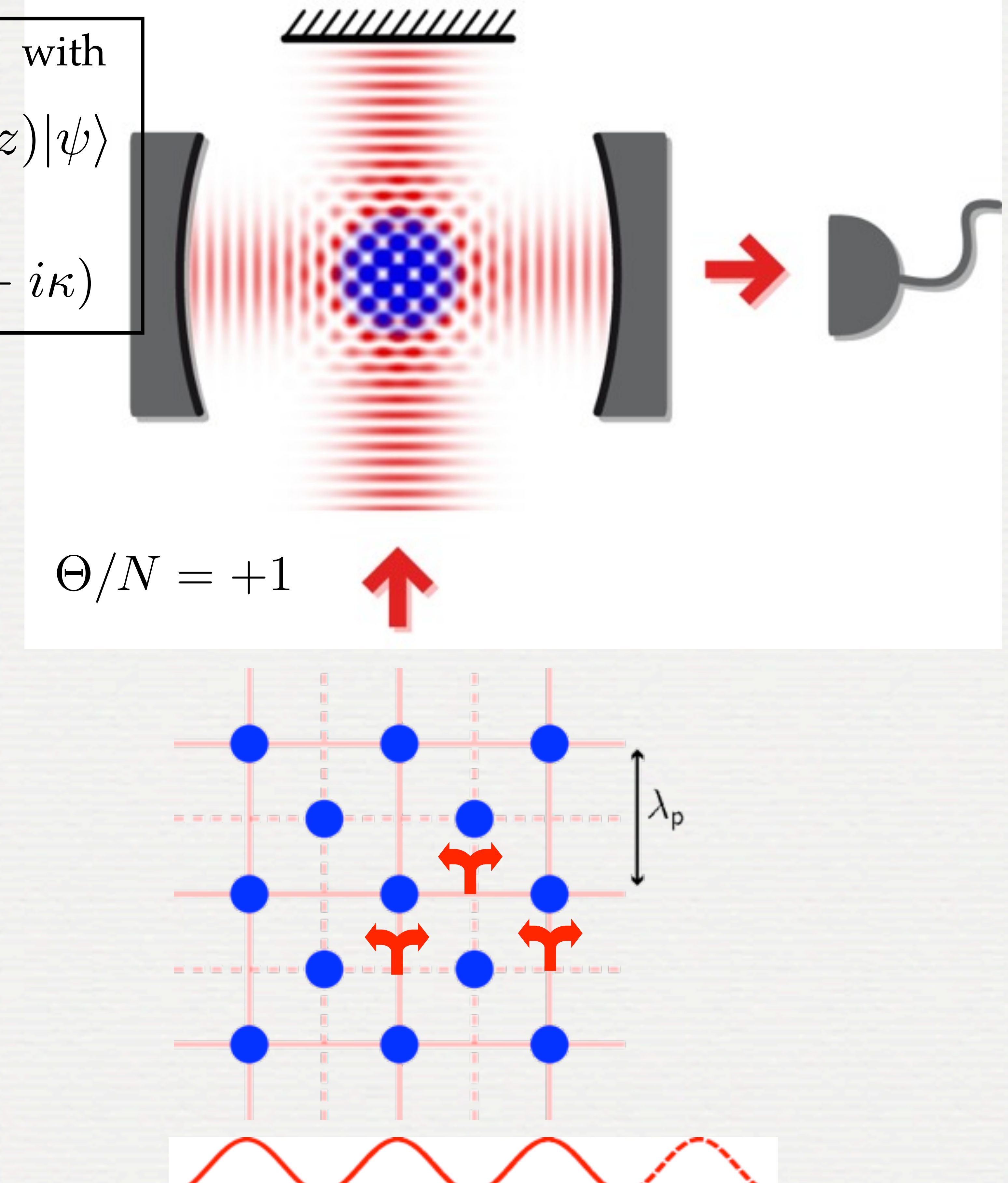


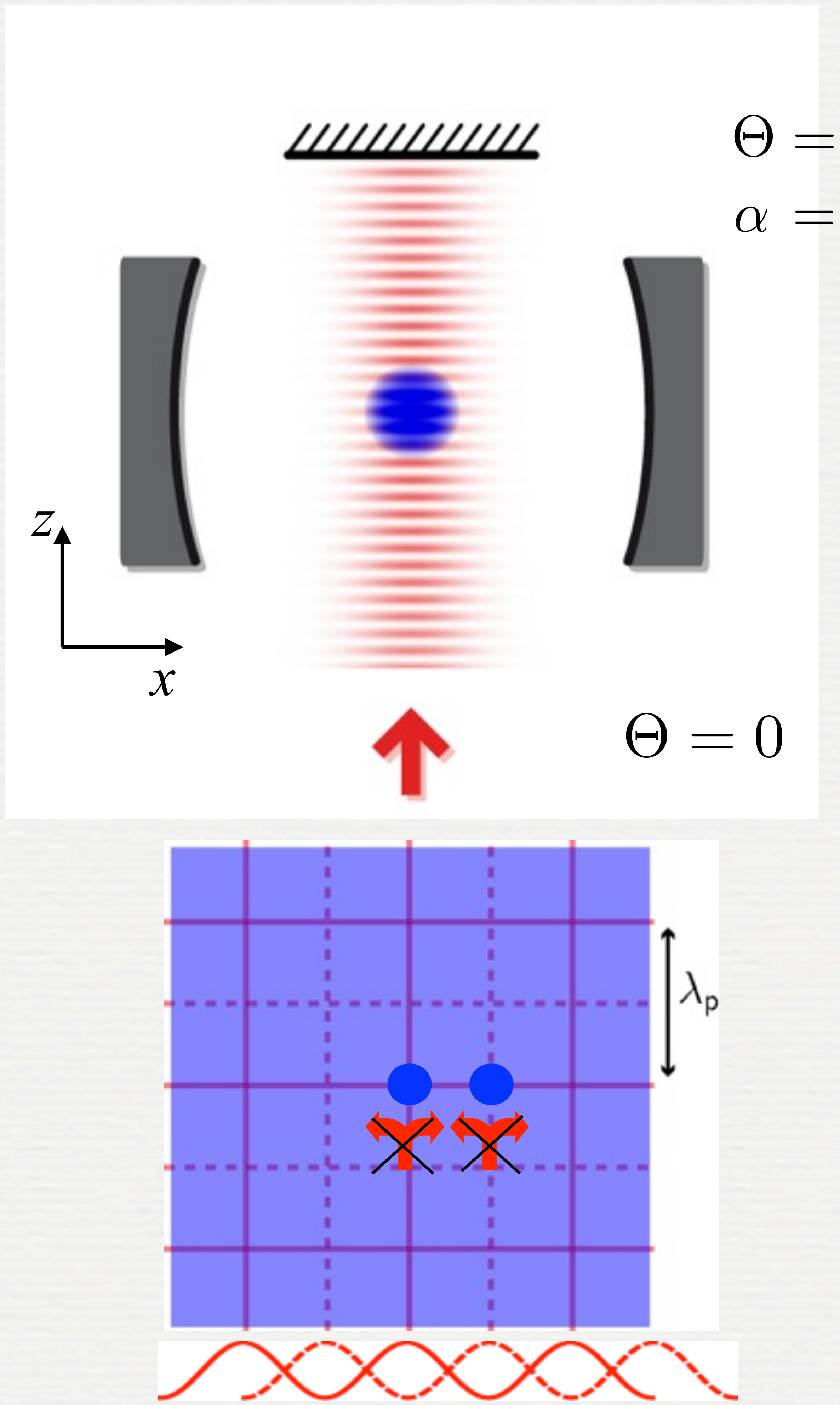
constructive interference

Cavity field buid-up: checkerboard pattern

$$\Theta = \langle\psi|\cos(kx)\cos(kz)|\psi\rangle$$
$$\alpha = \eta\Theta/(\Delta_c - U_0\mathcal{B} + i\kappa)$$

mean-field

$$\alpha = f(\psi)$$
$$\psi = f(\alpha)$$



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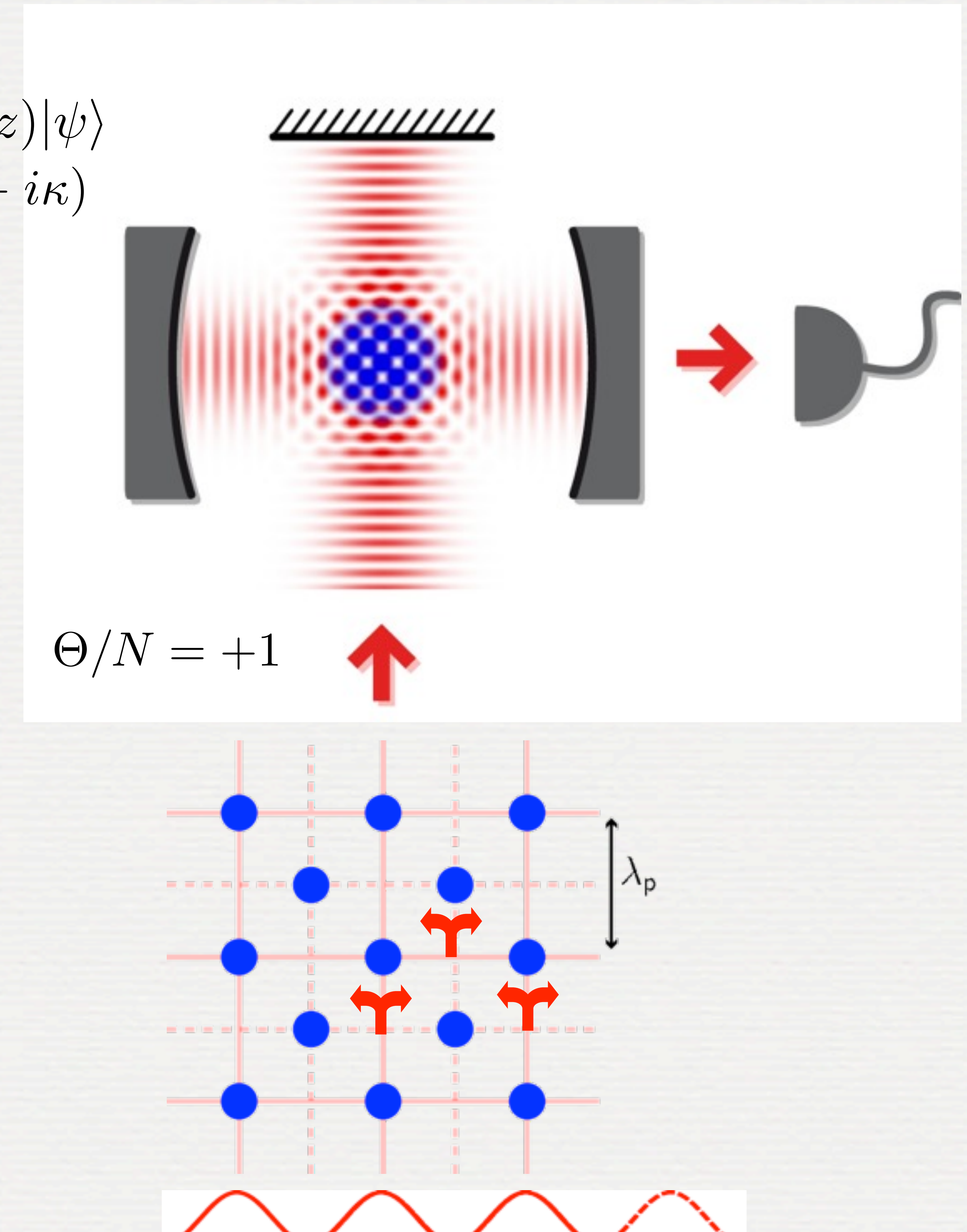

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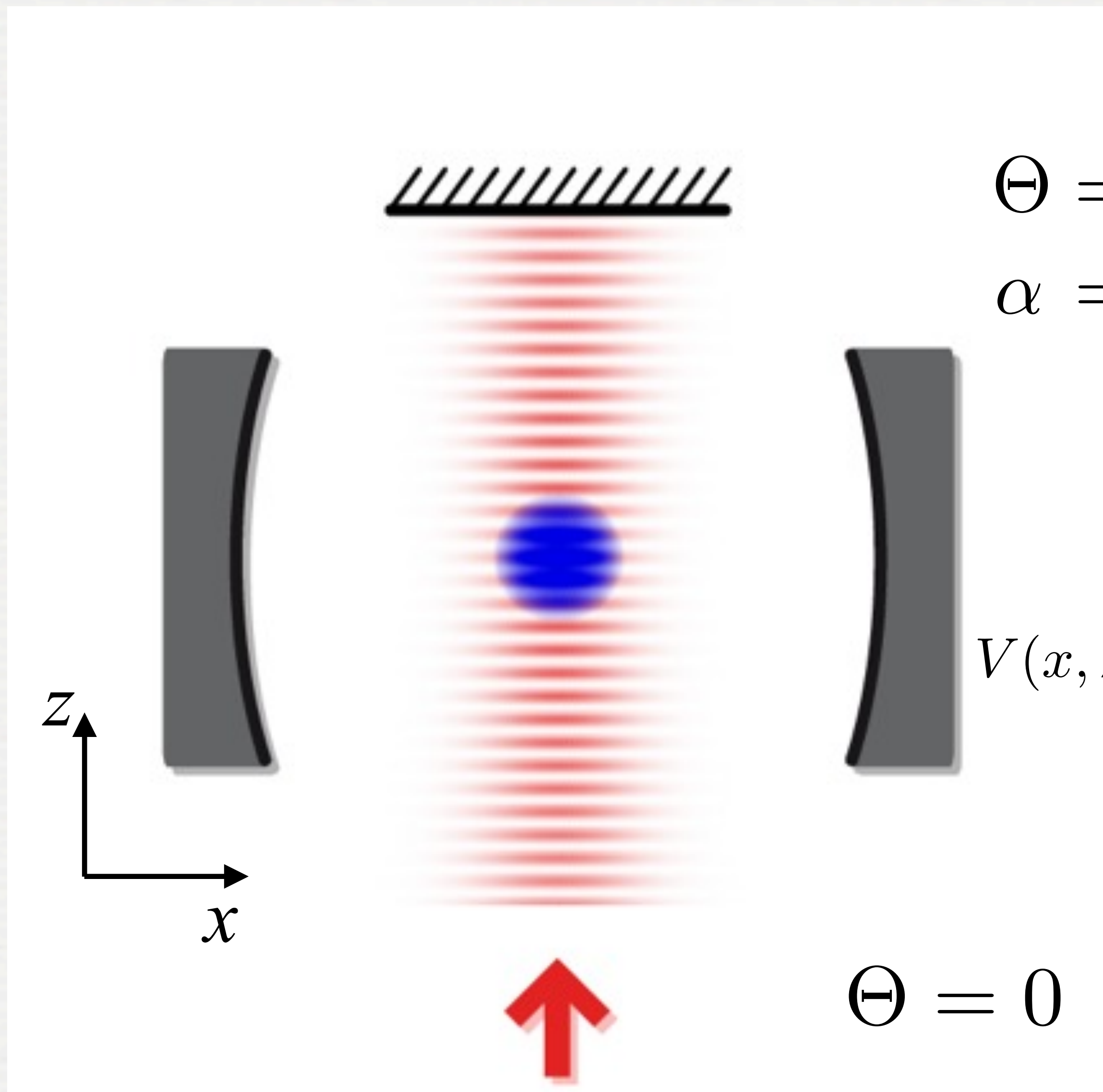
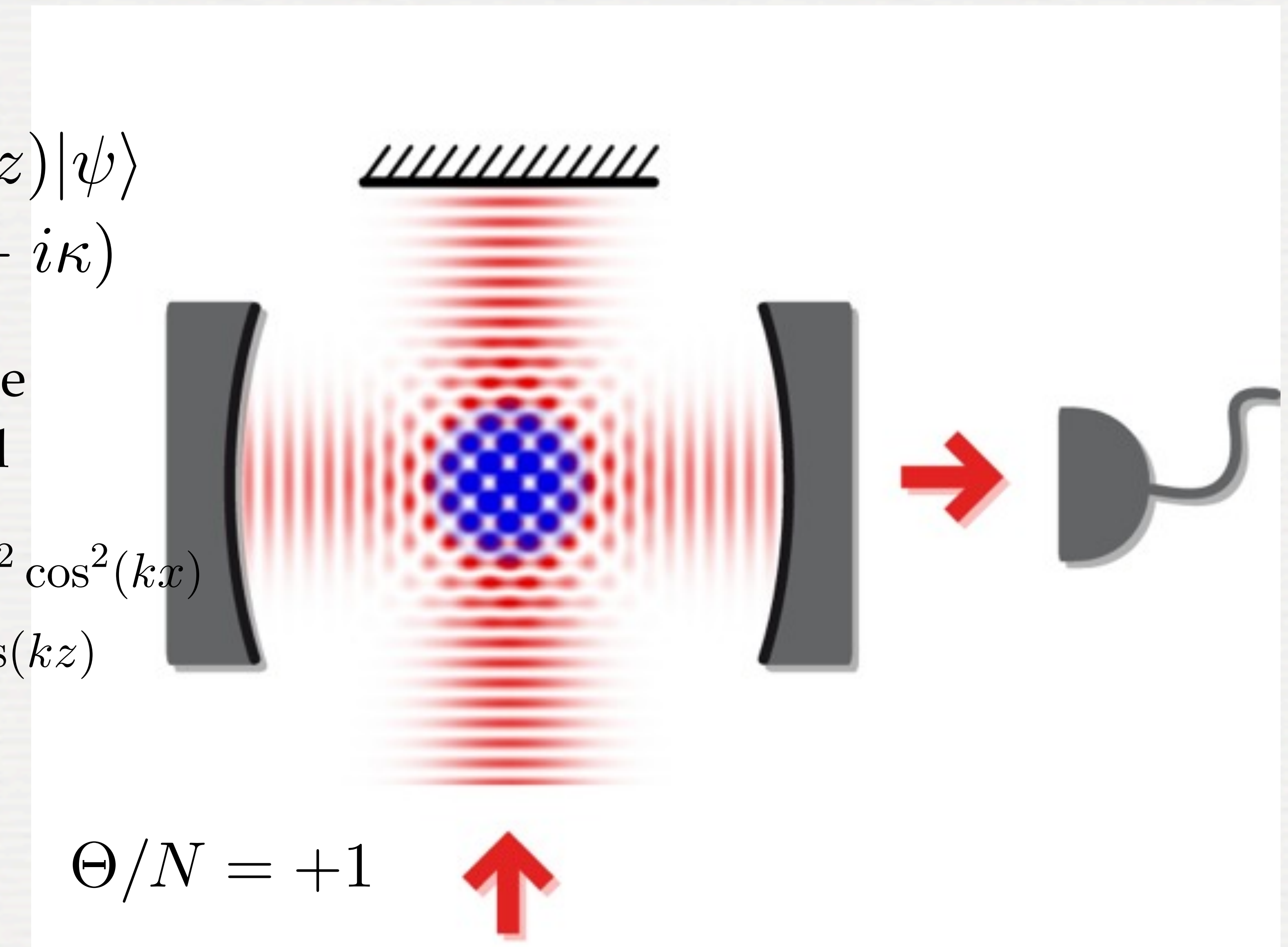


$$\Theta = \langle\psi|\cos(kx)\cos(kz)|\psi\rangle$$
$$\alpha = \eta\Theta/(\Delta_c - U_0\mathcal{B} + i\kappa)$$

fluctuations of Θ can be amplified by potential

$$V(x,z) = V_0\cos^2(kz) + \hbar U_0|\alpha|^2\cos^2(kx) + \hbar\eta(\alpha+\alpha^*)\cos(kx)\cos(kz)$$



mean-field

$$\alpha = f(\psi)$$
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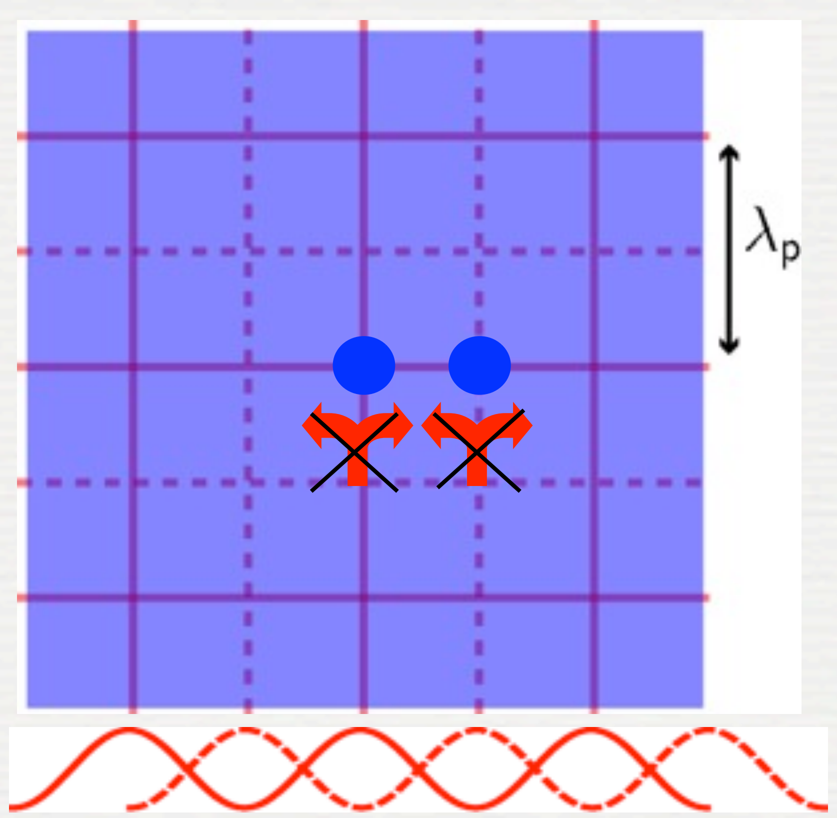
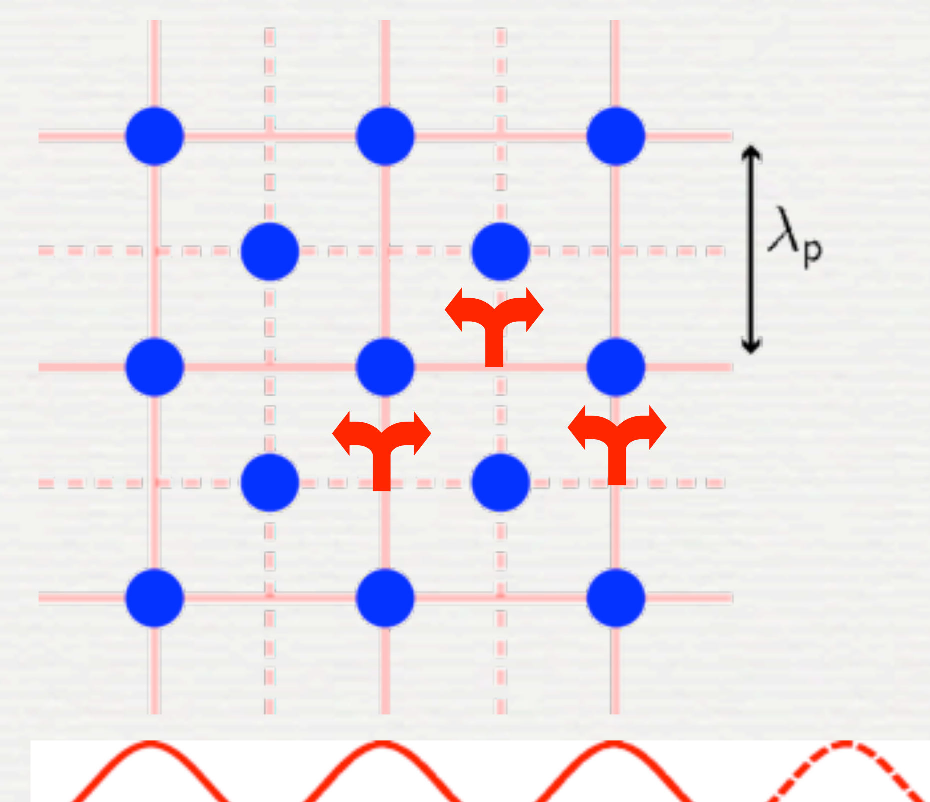


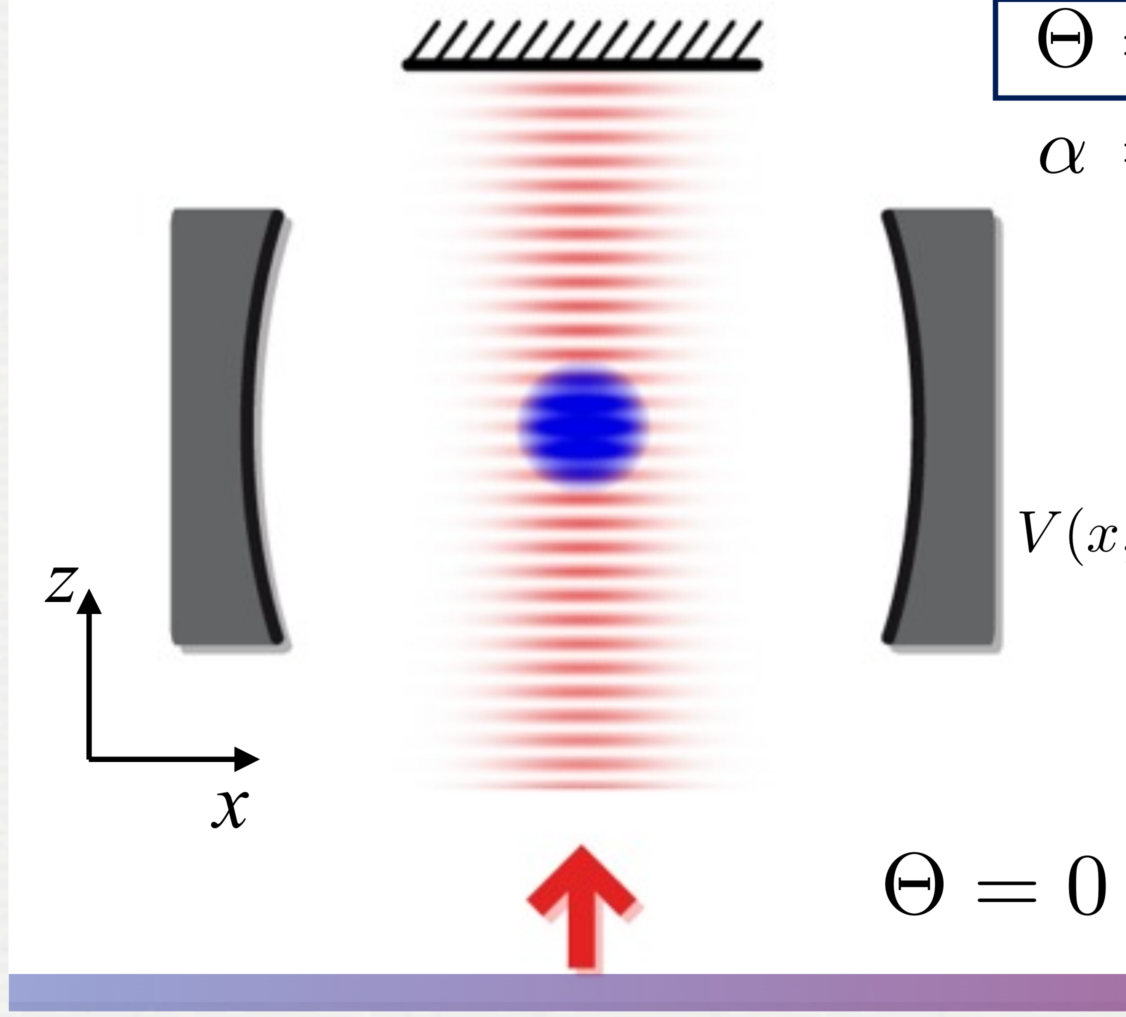
destructive interference



constructive interference

Phase transition

Normal phase



order parameter:

$$\boxed{\Theta = \langle\psi|\cos(kx)\cos(kz)|\psi\rangle}$$

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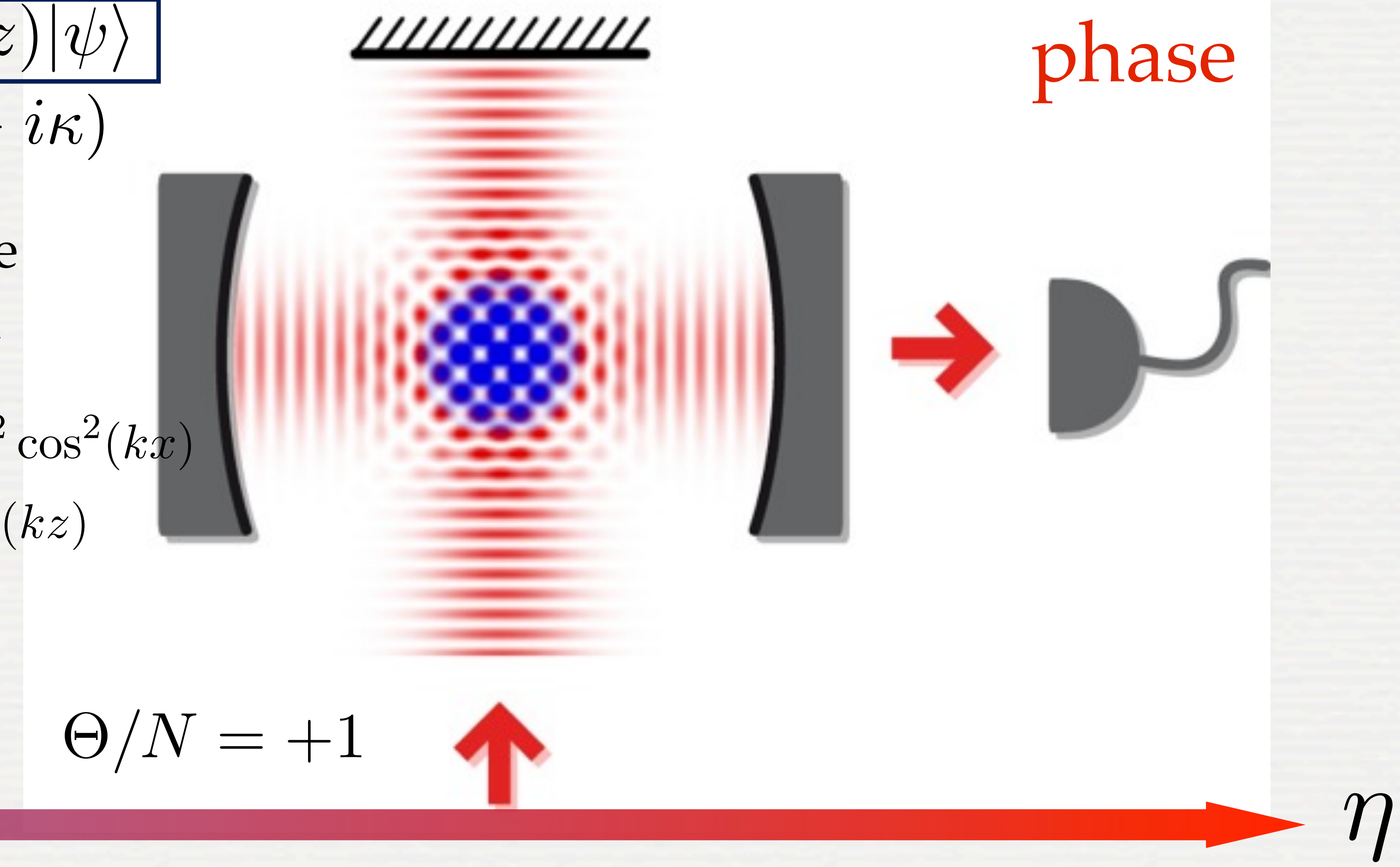
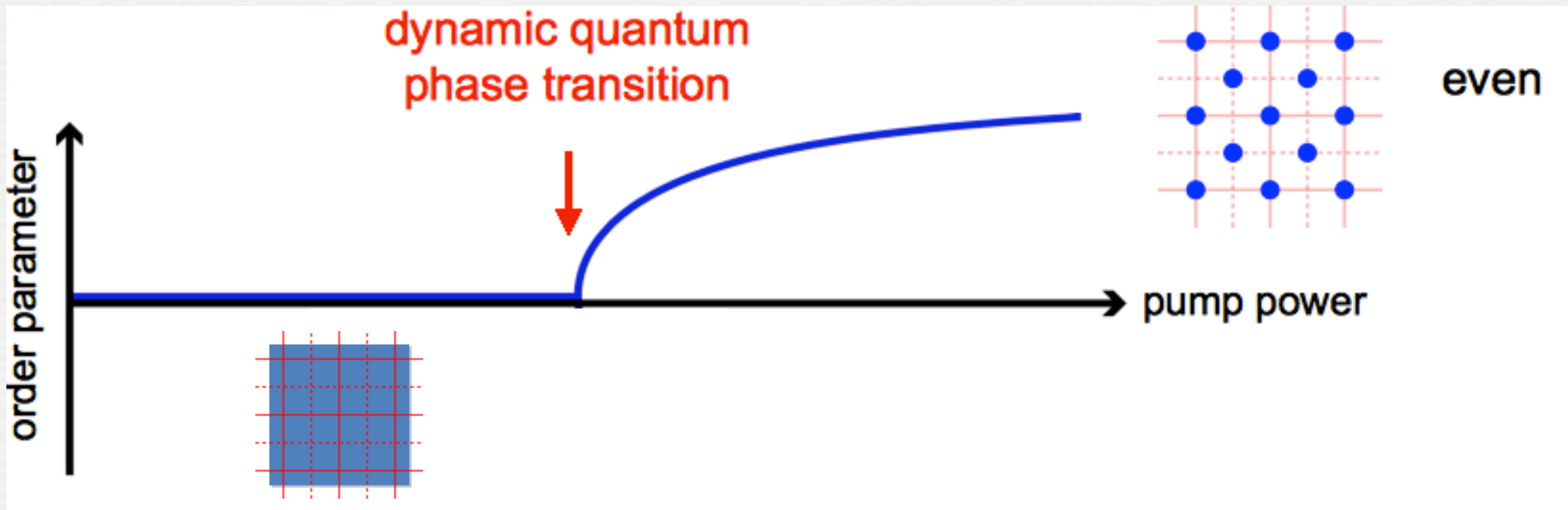
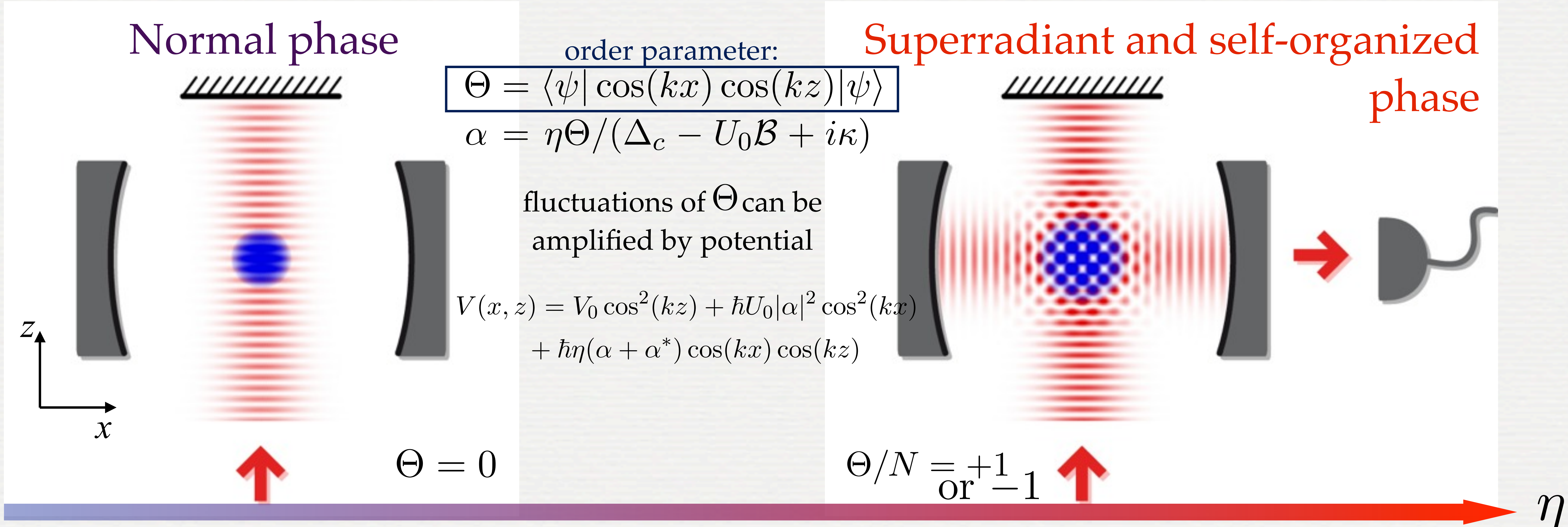
Superradiant and self-organized phase





Phase transition



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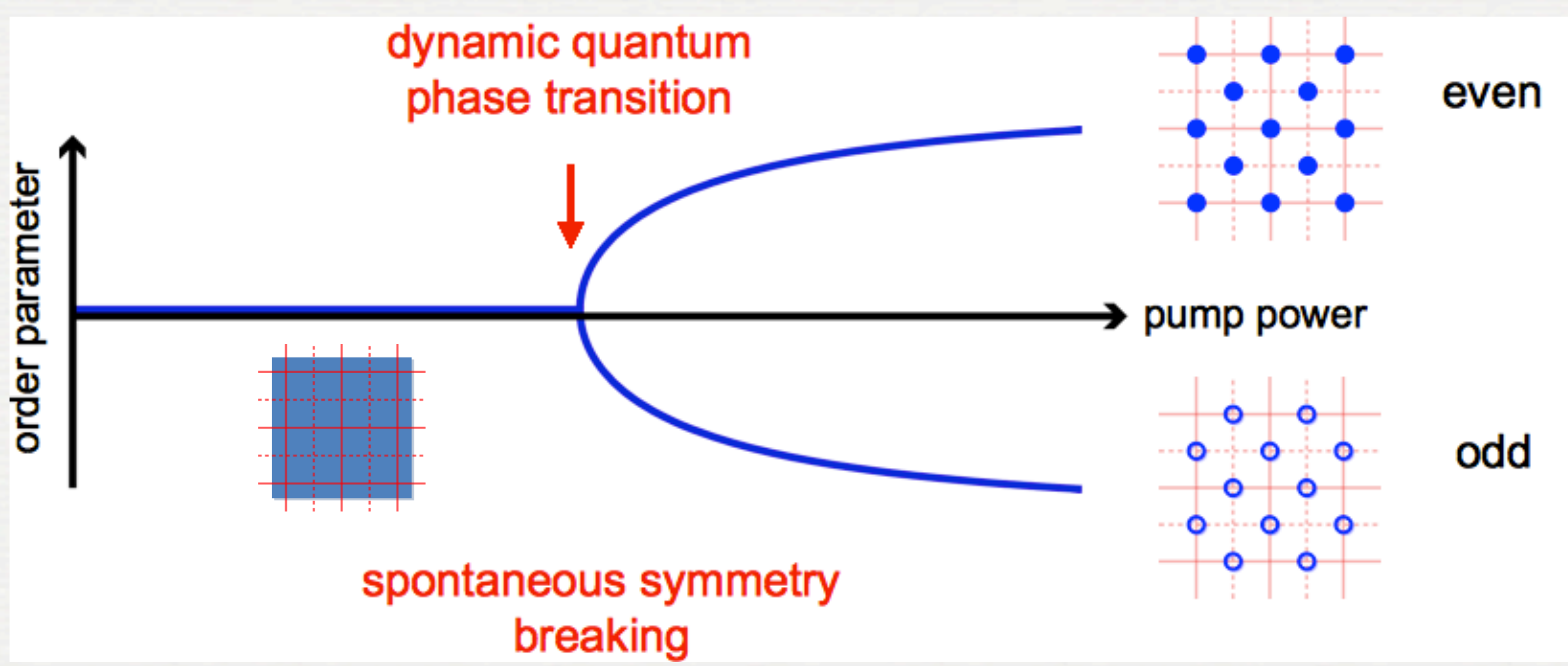
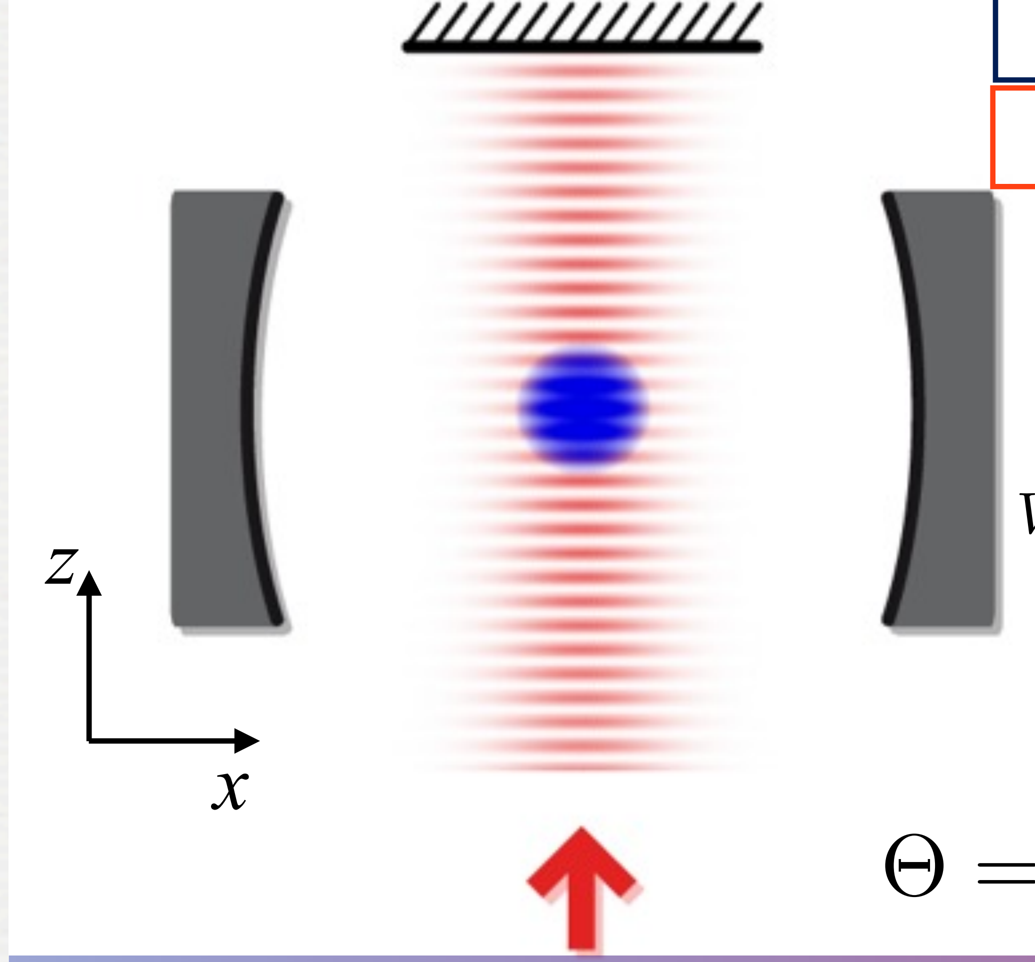


Phase transition

Normal phase



$\Theta = 0$

order parameter:

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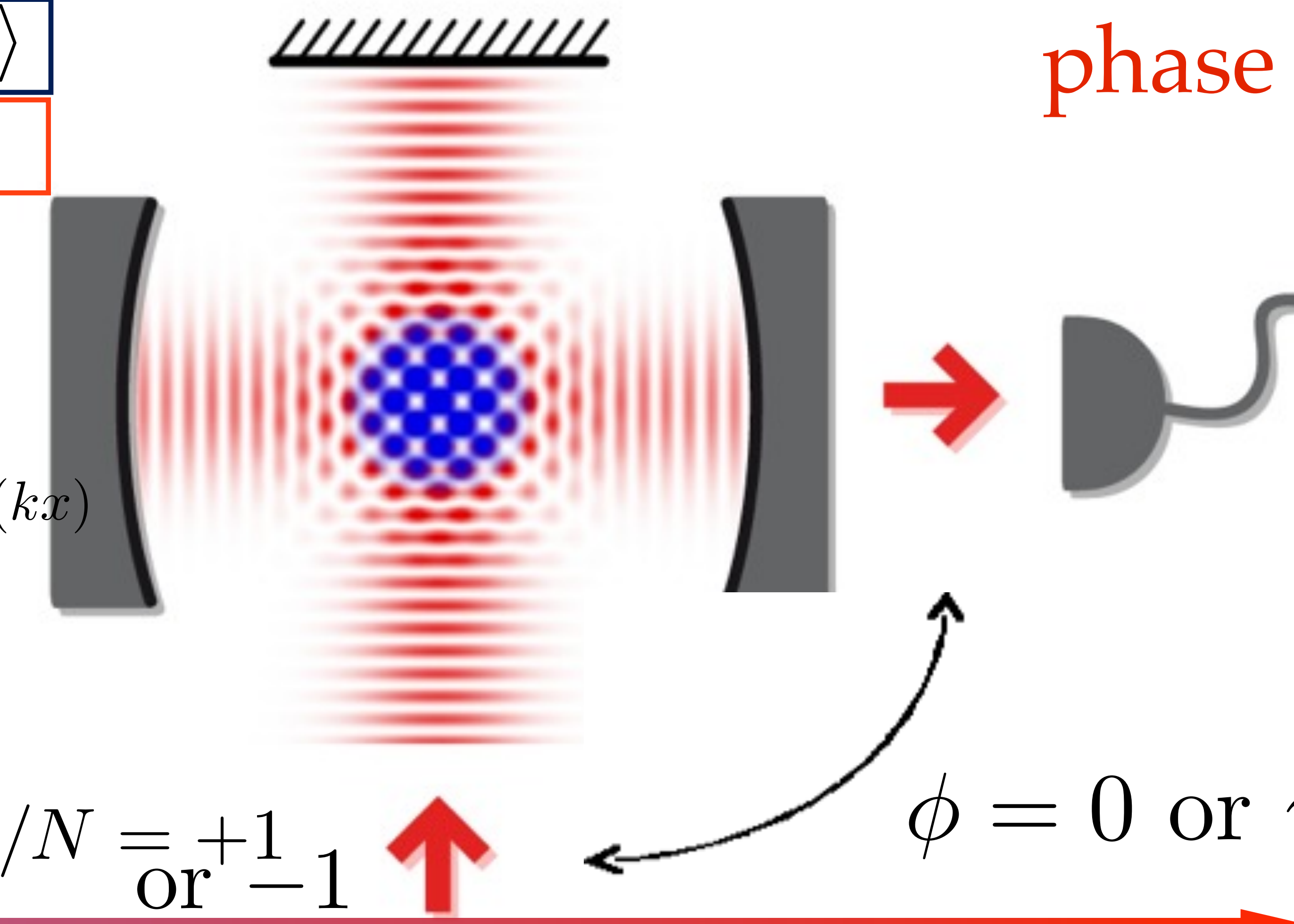
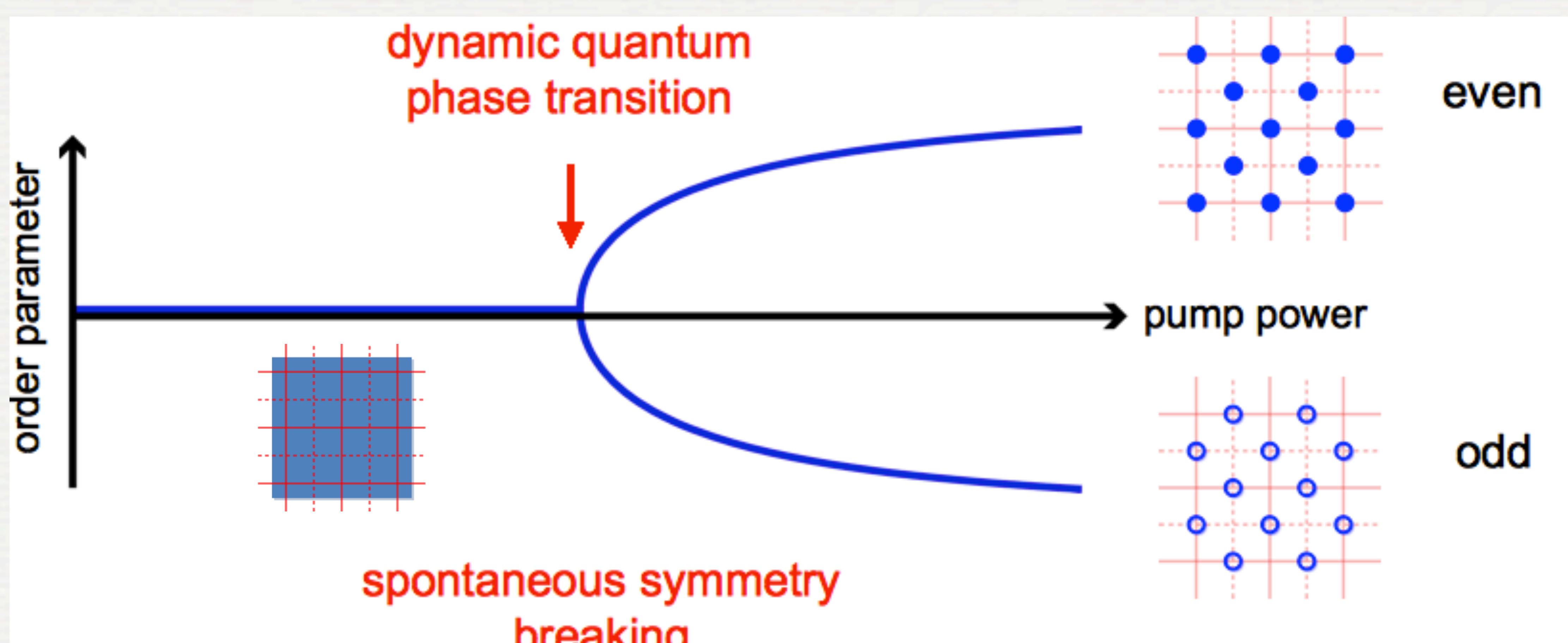


$$\alpha/\eta \simeq -\frac{\Theta}{\tilde{\Delta}_c}$$

$\Theta/N = +1$ or -1

$\phi = 0$ or π

η

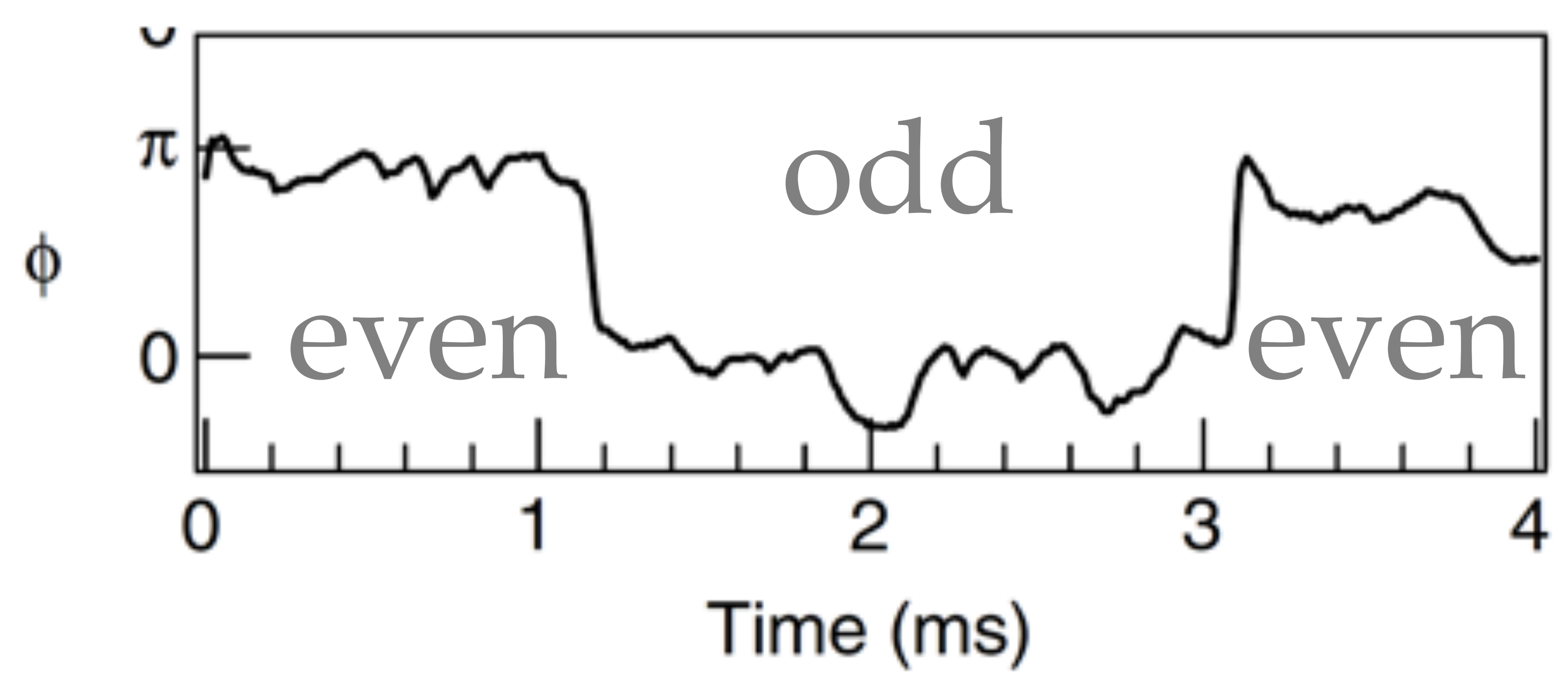


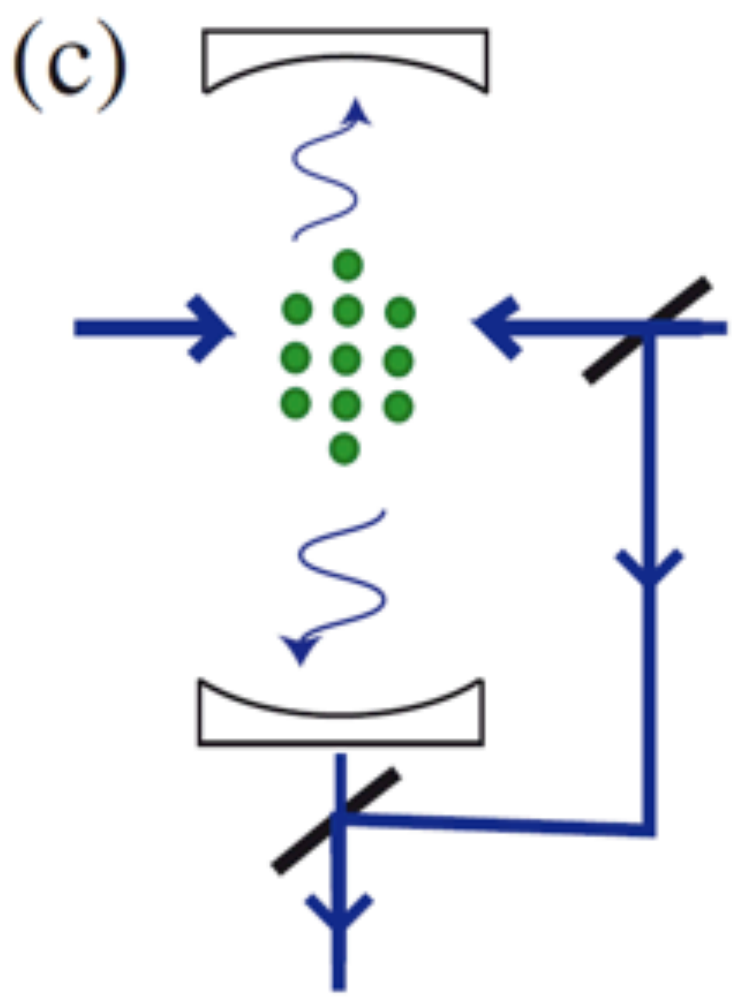
predicted by: H. Ritsch (Innsbruck), P. Domokos (Budapest)

Phase transition with thermal atoms

Observation of Collective Friction Forces due to Spatial Self-Organization of Atoms: From Rayleigh to Bragg Scattering

Adam T. Black, Hilton W. Chan, and Vladan Vuletić
Department of Physics, Stanford University, Stanford, California 94305-4060, USA
(Received 23 April 2003; published 11 November 2003)



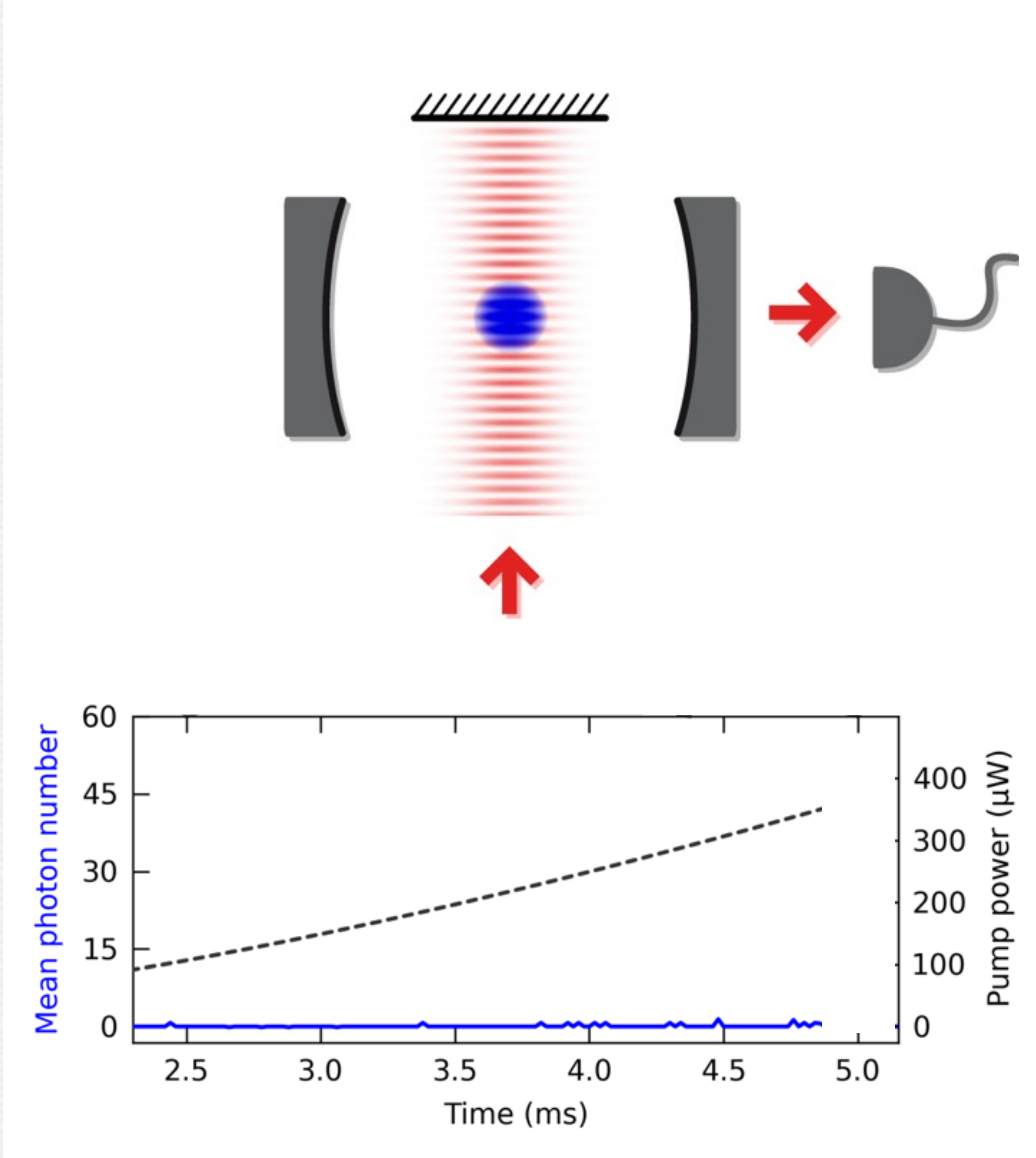


We experimentally confirm the predicted stochastic lattice formation by observing random π jumps in the time phase of the Bragg-scattered intracavity light.

Driven by thermal fluctuations

+ self-organization not directly measured

Phase transition with a BEC



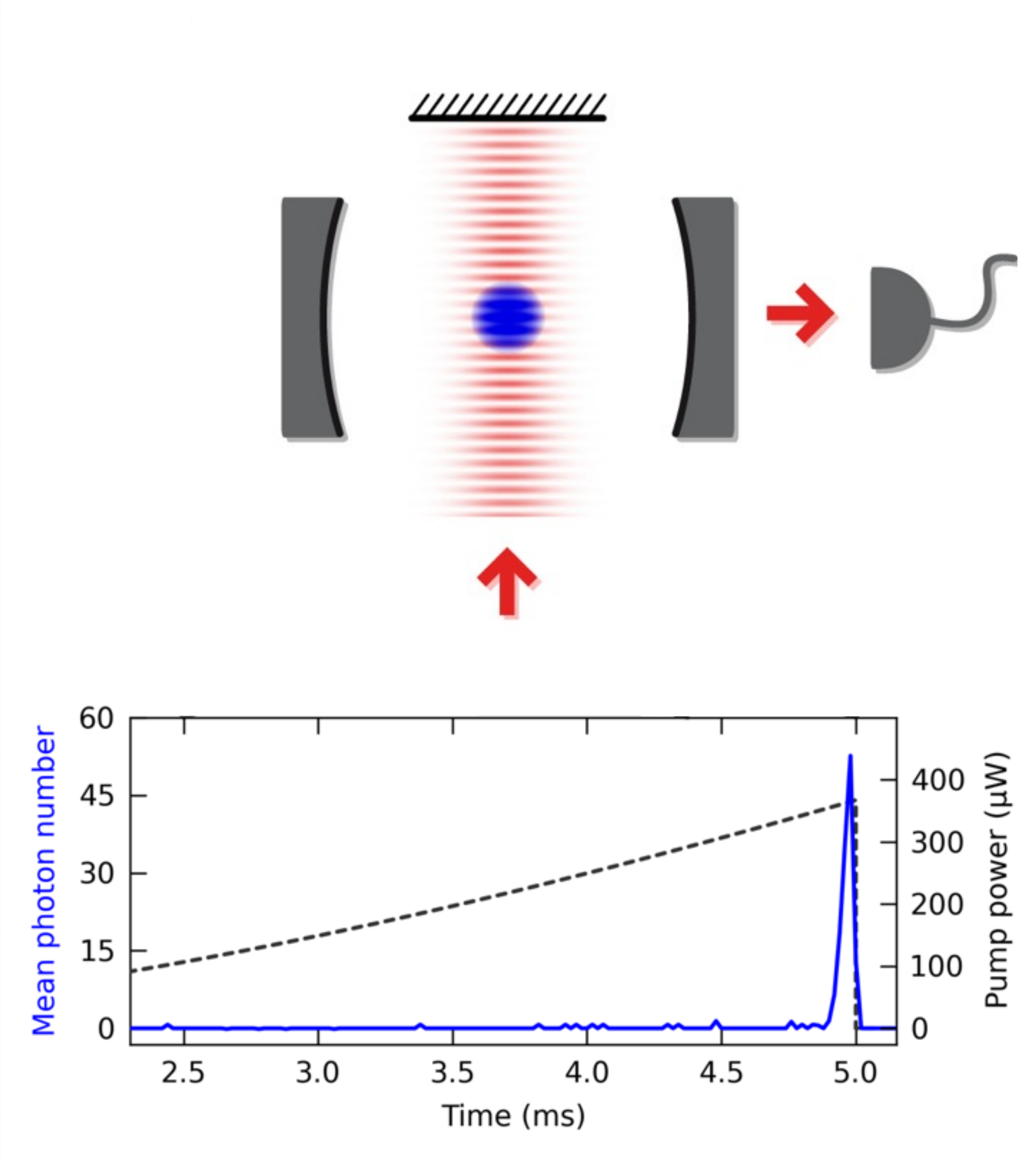
single-photon counter

K. Baumann, C. Guerlin,

F. Brennecke & T. Esslinger,

Nature 464, 1301 (2010)

Phase transition with a BEC



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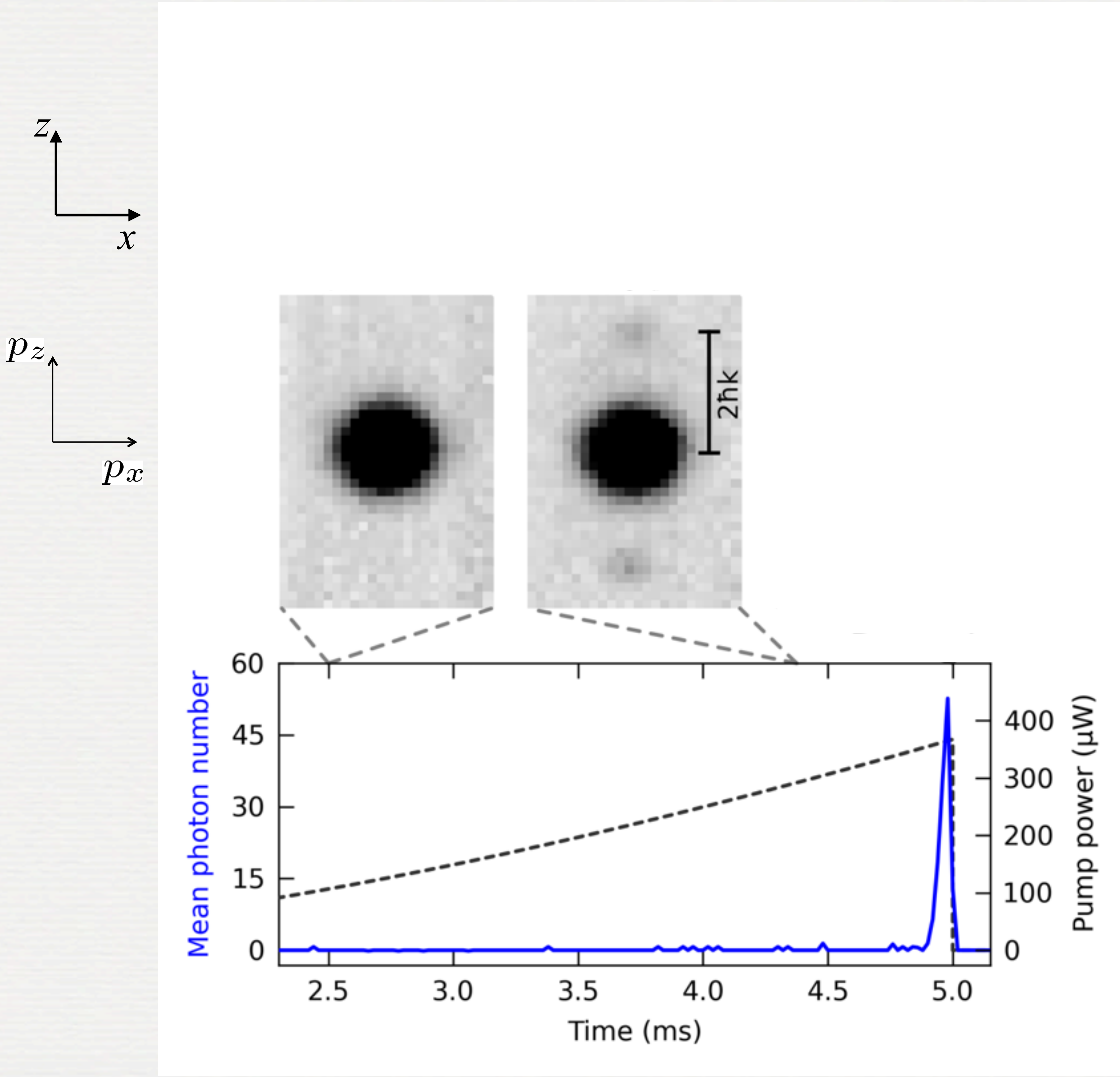
Checkerboard self-organization



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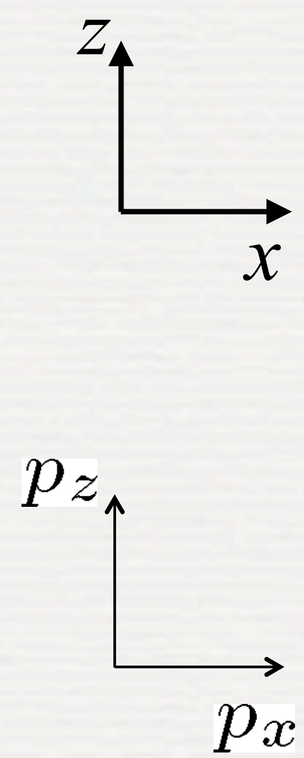

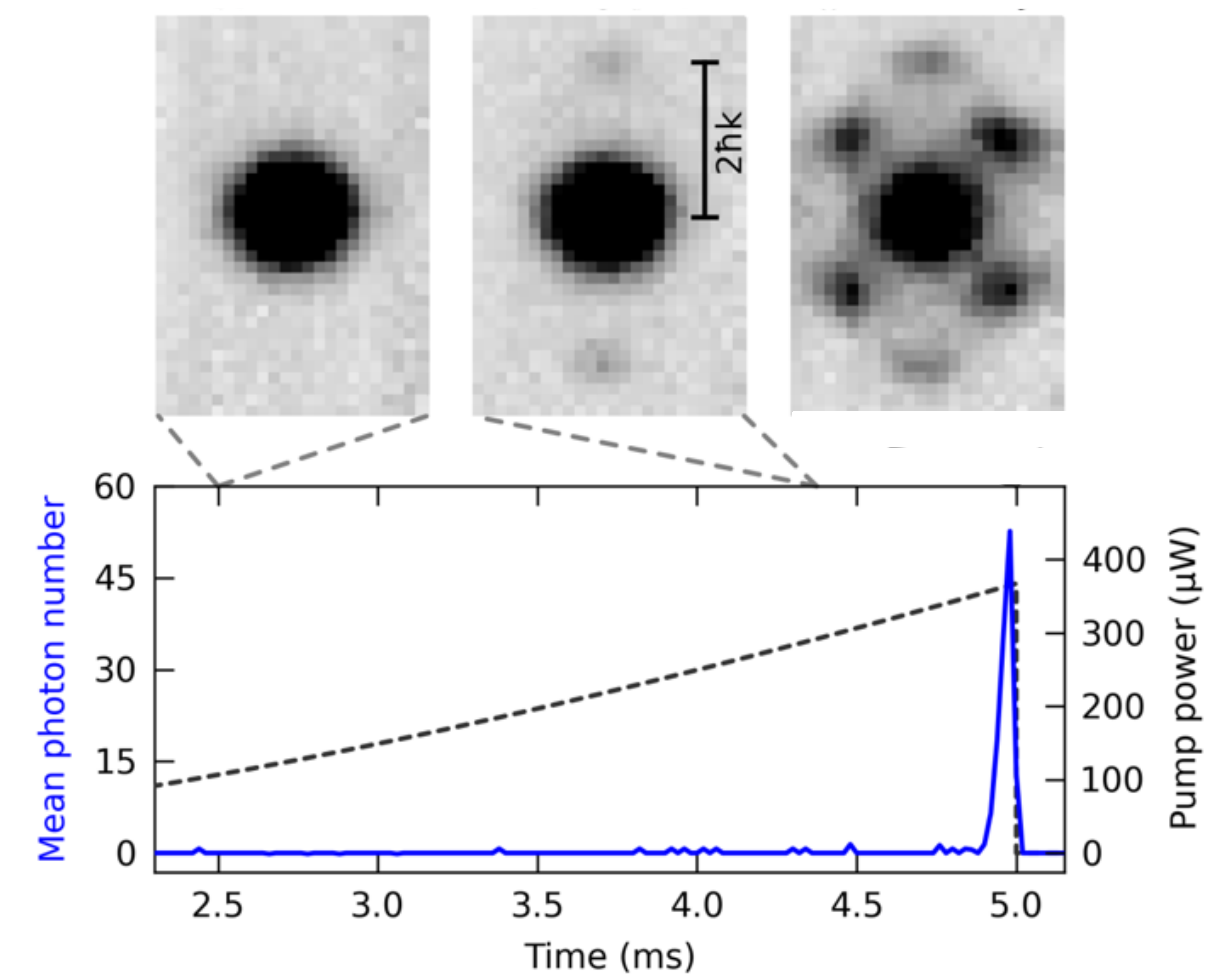

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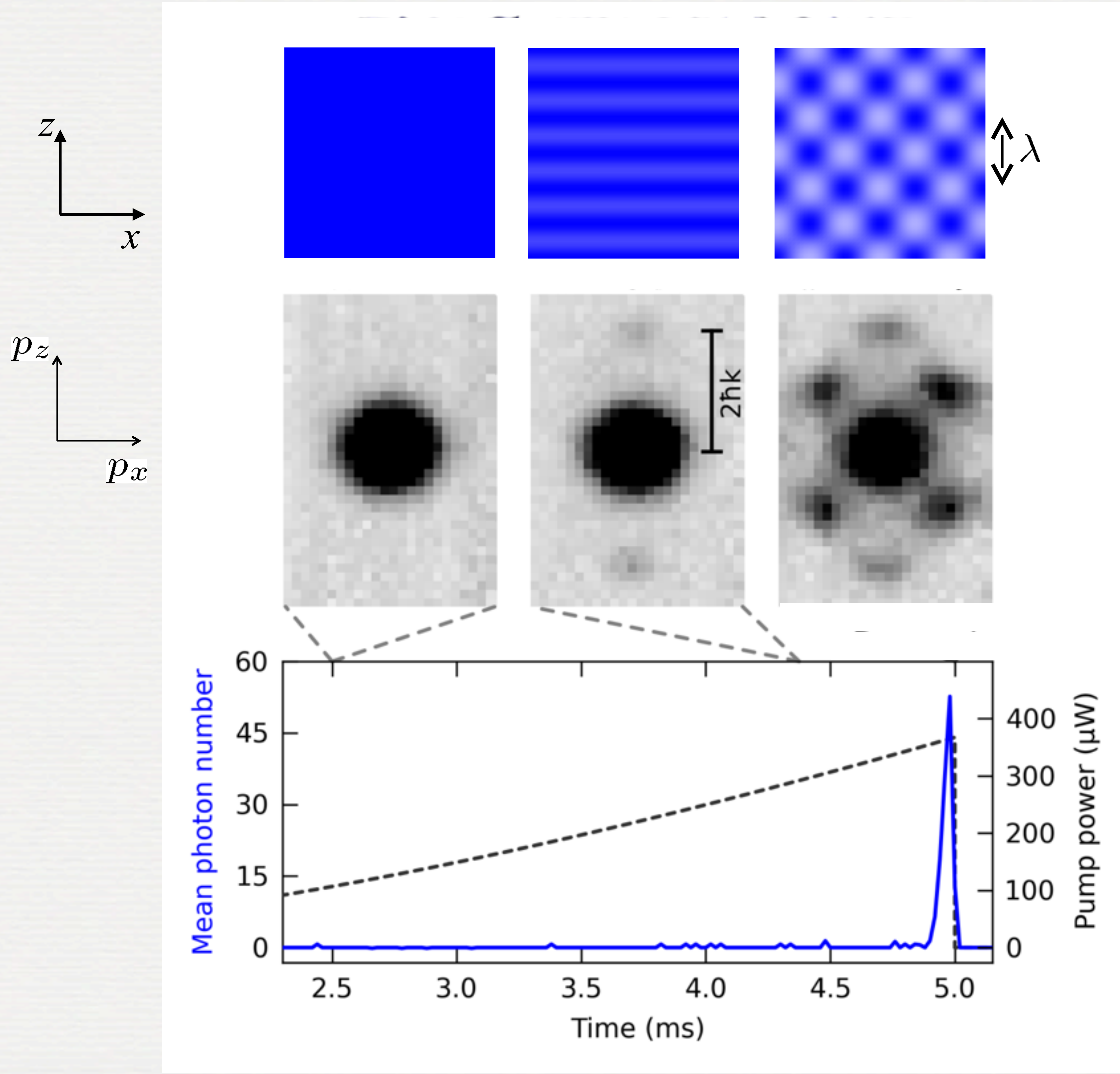

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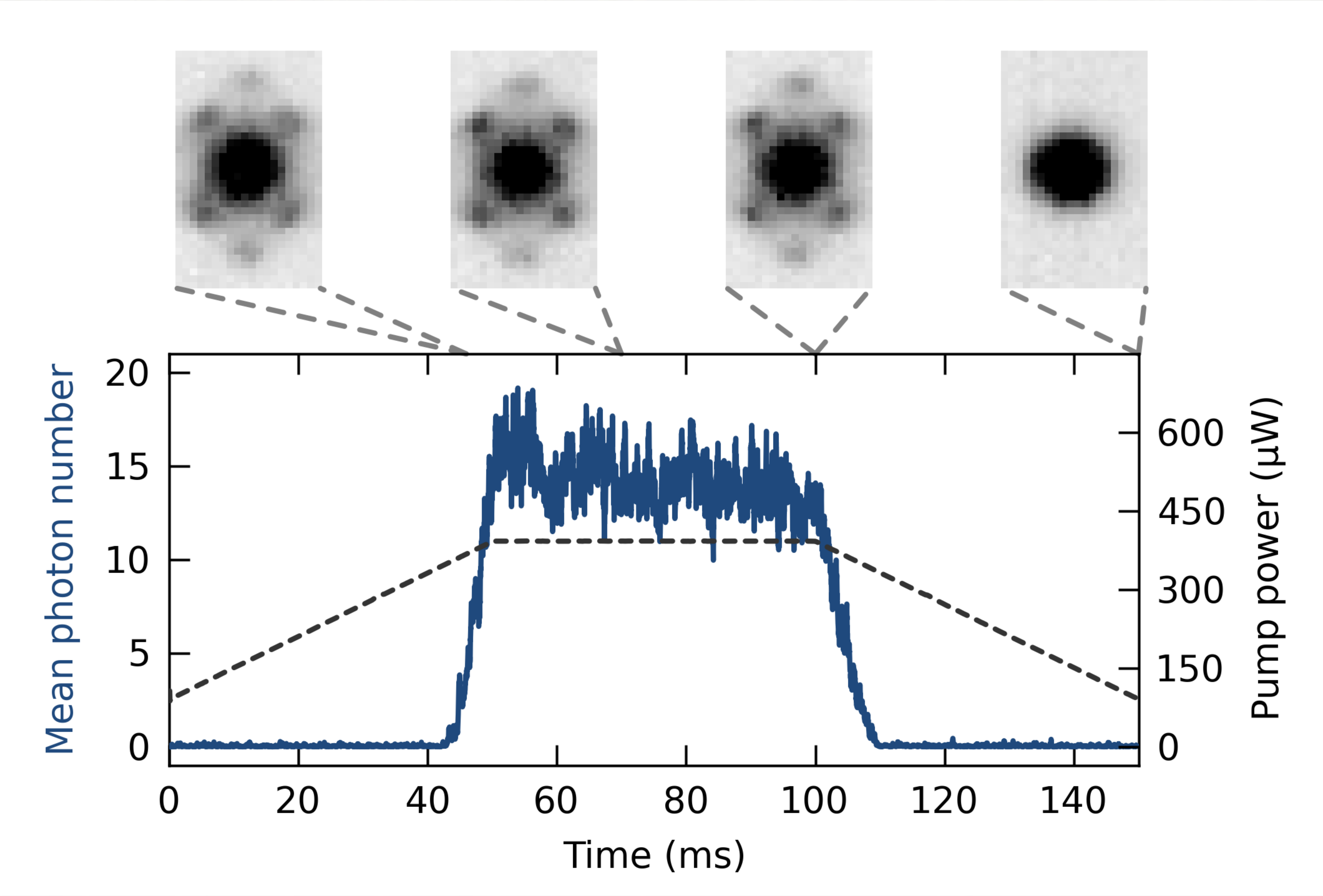
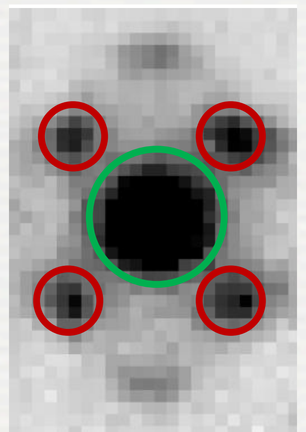
Stability and coherence



- (non-trivial) crystalline order
- but off diagonal long range orger not detroyed

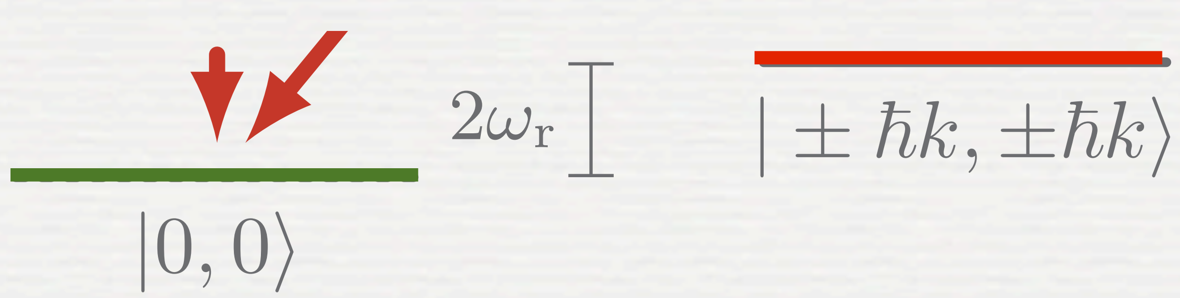
can be regarded as a supersolid

Beyond mean field: two mode expansion

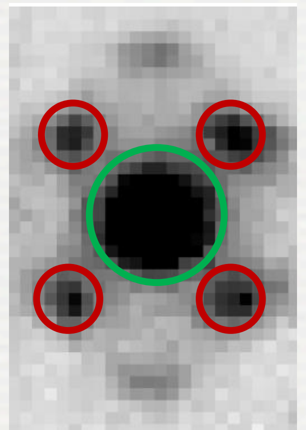


$$|p_x, p_z\rangle = |0,0\rangle$$

$$|\pm\hbar k, \pm\hbar k\rangle = \sum_{\mu,\nu=\pm1} |\mu\hbar k, \nu\hbar k\rangle/2$$



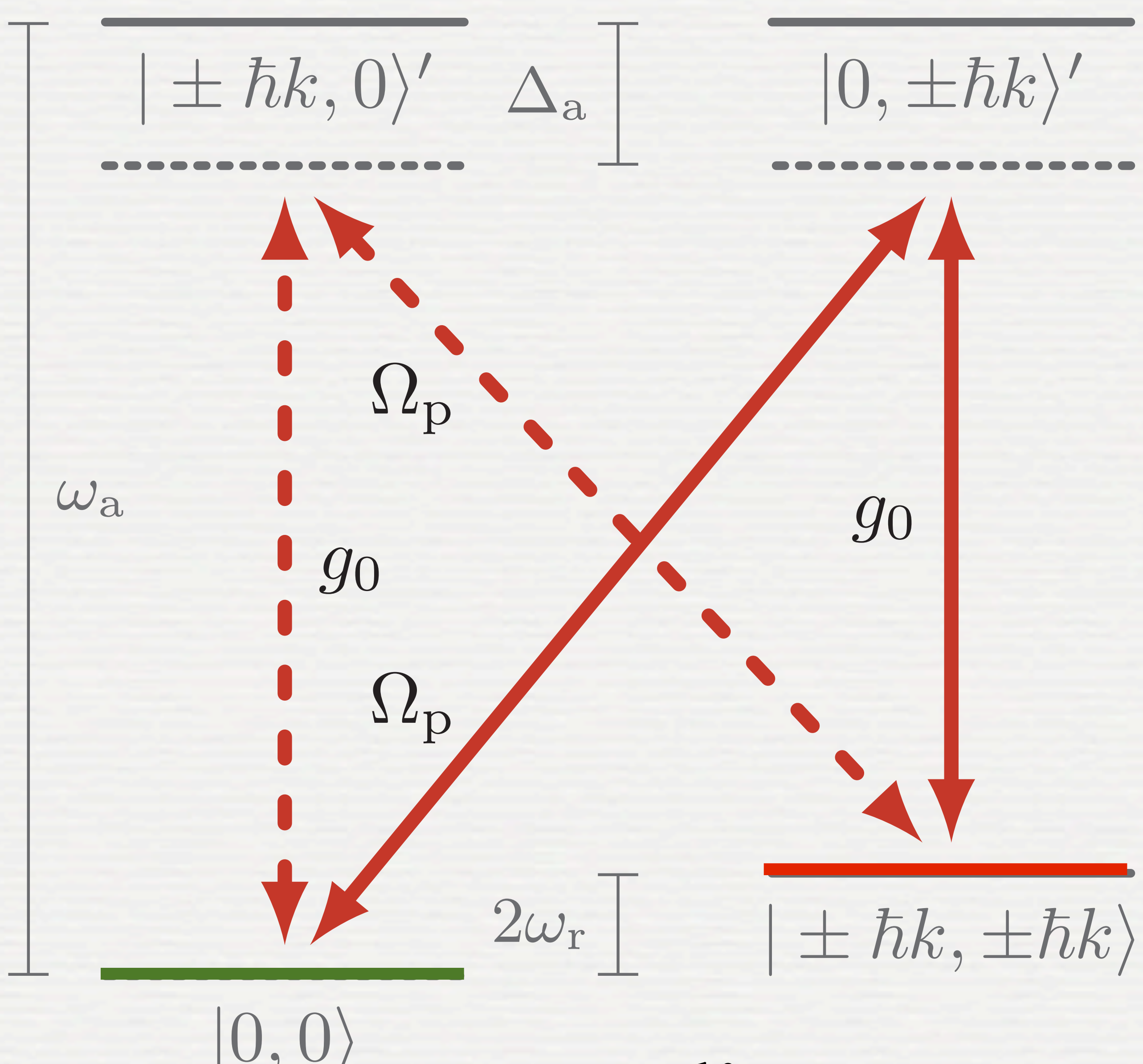
Beyond mean field: two mode expansion



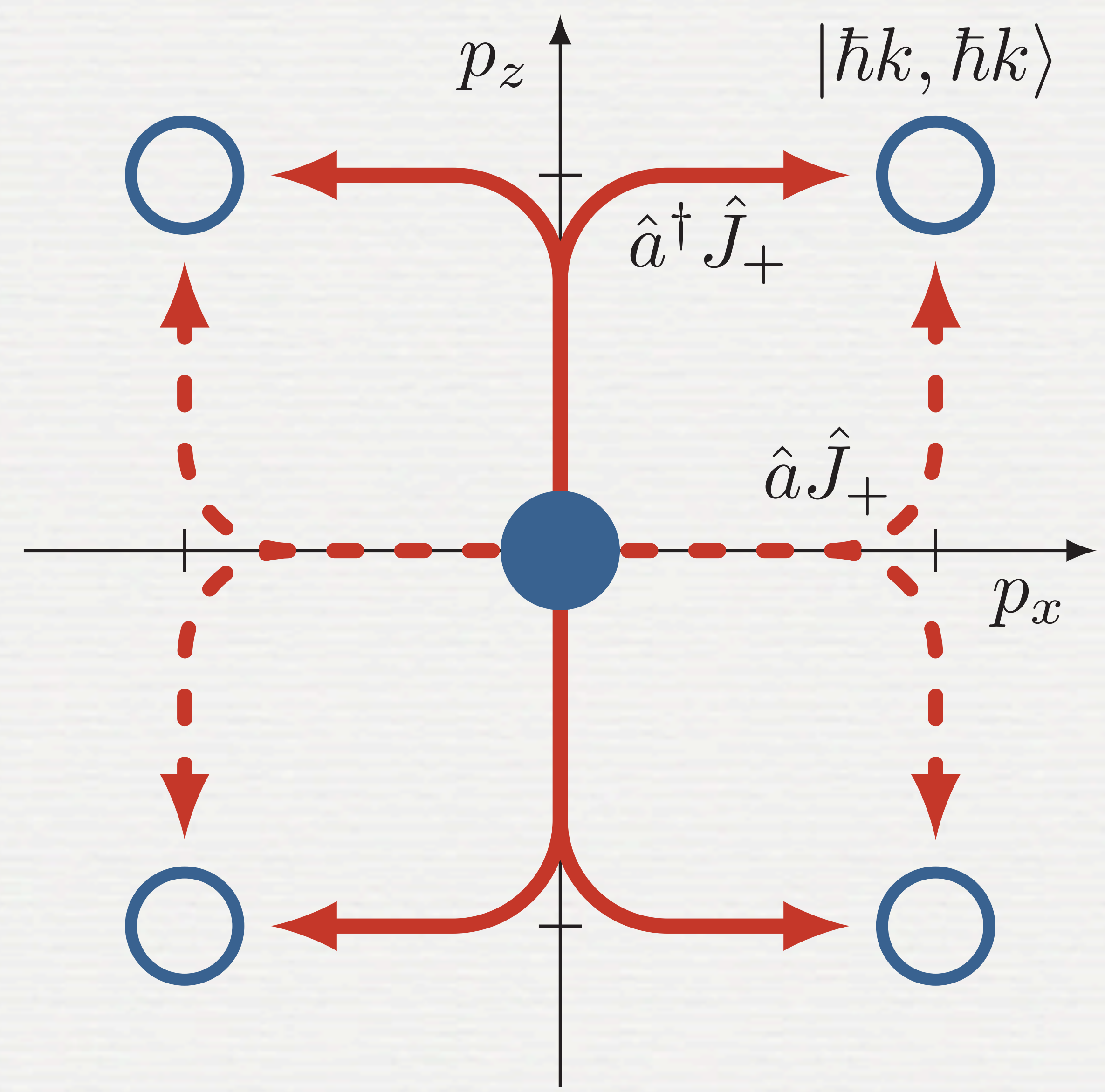
$|p_x, p_z\rangle = |0, 0\rangle$

coupled to $|\pm\hbar k, \pm\hbar k\rangle = \sum_{\mu,\nu=\pm 1} |\mu\hbar k, \nu\hbar k\rangle/2$

via two balanced pump-cavity two-photon transitions

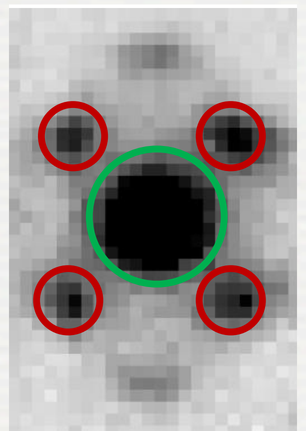


energy diagram



momentum diagram

Beyond mean field: two mode expansion



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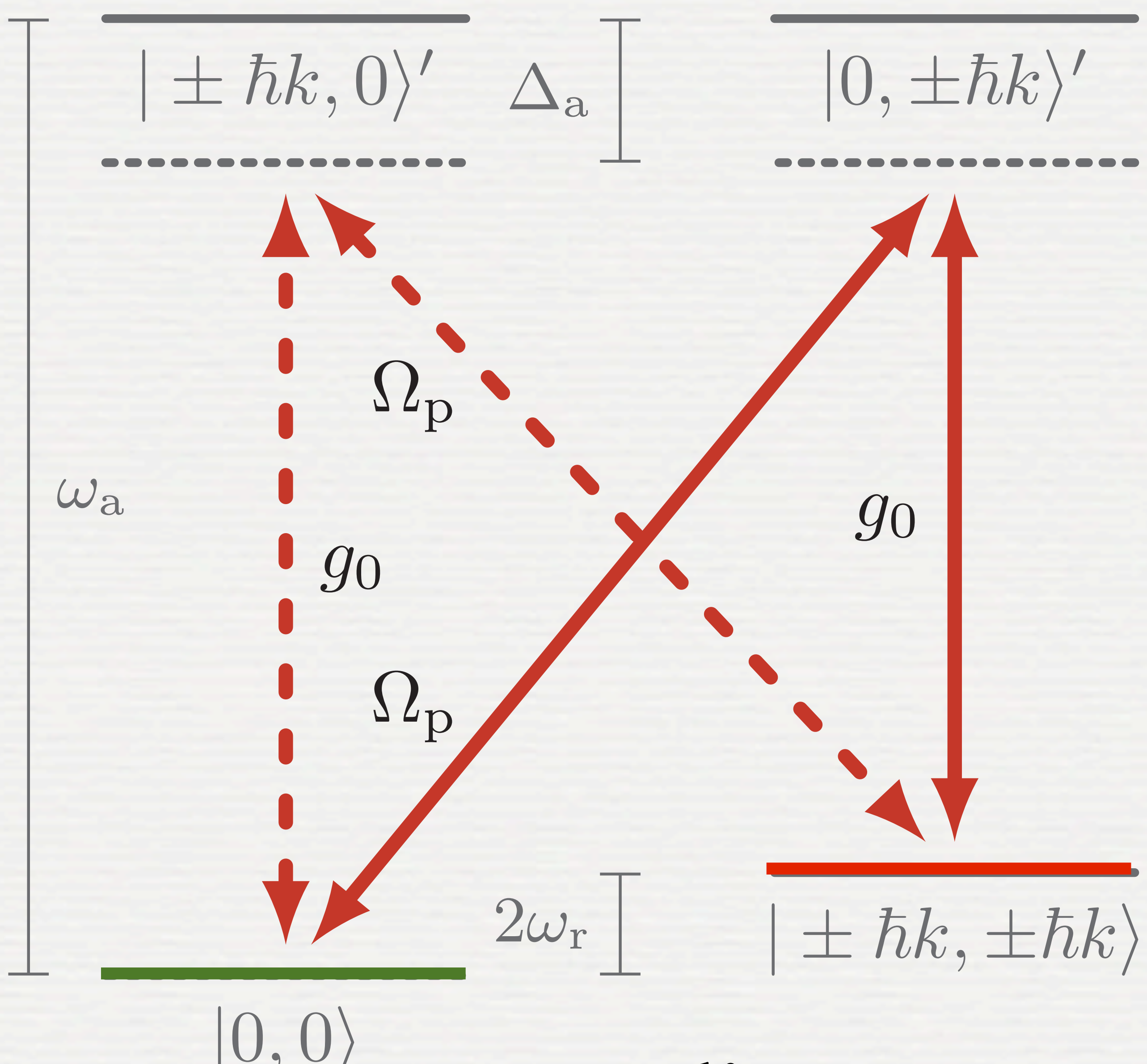
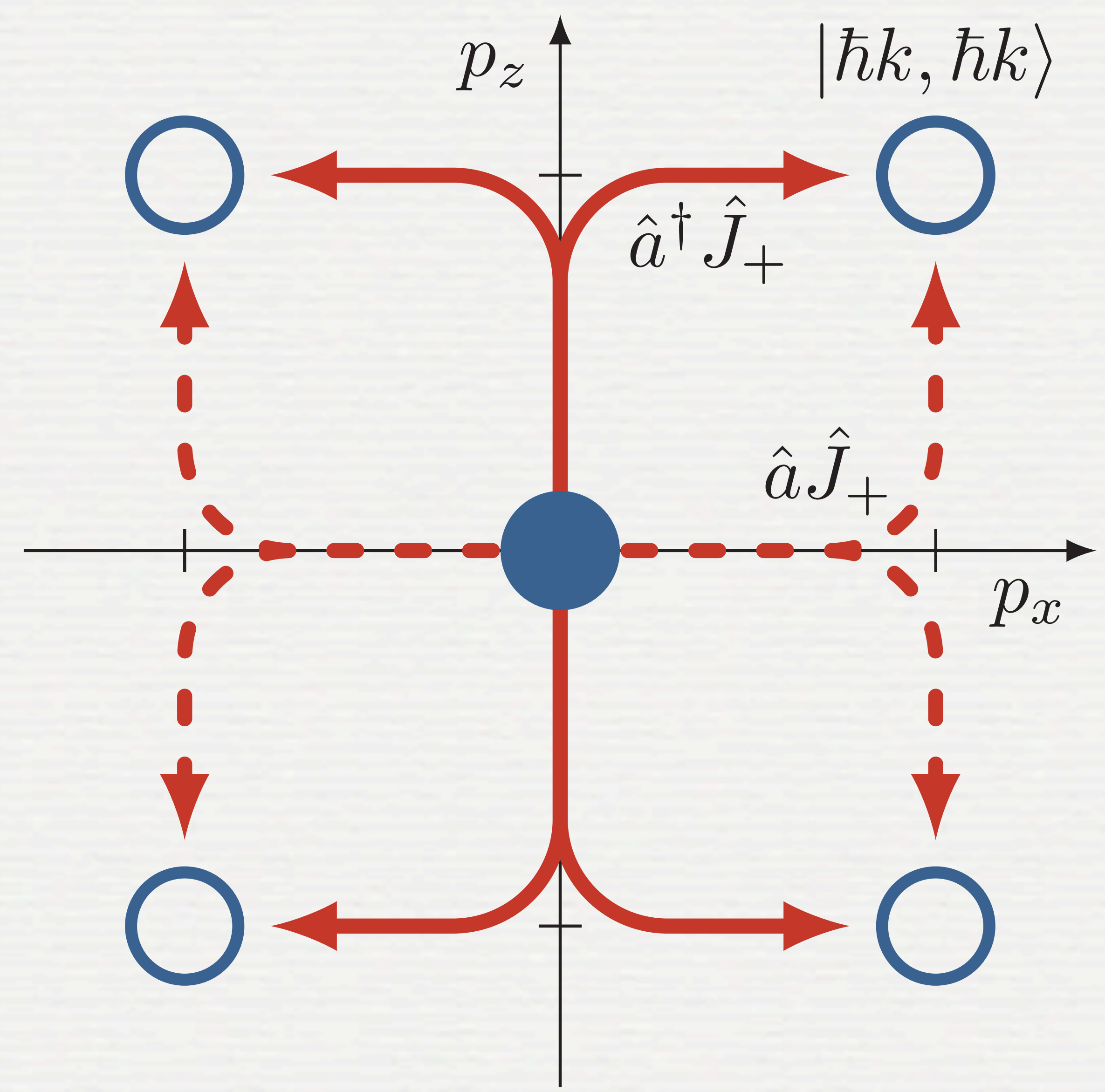
coupled to $|\pm\hbar k, \pm\hbar k\rangle = \sum_{\mu,\nu=\pm1} |\mu\hbar k, \nu\hbar k\rangle/2$

via two balanced pump-cavity two-photon transitions



energy diagram



momentum diagram

$$\hat{H}/\hbar = \omega_0 \hat{J}_z + \omega \hat{a}^\dagger \hat{a} + \frac{\lambda}{\sqrt{N}}(\hat{a}^\dagger + \hat{a})(\hat{J}_+ + \hat{J}_-) + U_0 \mathcal{M} \hat{c}_1^\dagger \hat{c}_1 \hat{a}^\dagger \hat{a}.$$

Two-mode expansion of the second quantized many-body hamiltonian from $\hat{H}_{(1)}$

$$\hat{\Psi} = \hat{c}_0|0,0\rangle + \hat{c}_1|\pm\hbar k, \pm\hbar k\rangle$$

$$\hat{c}_0^\dagger \hat{c}_0 + \hat{c}_1^\dagger \hat{c}_1 = N$$

$$\hat{J}_z = \tfrac{1}{2}(\hat{c}_1^\dagger \hat{c}_1 - \hat{c}_0^\dagger \hat{c}_0)$$

$$\hat{J}_+ = \hat{c}_1^\dagger \hat{c}_0 = \hat{J}_-^\dagger$$

$$\omega_0 = 2\omega_r = \hbar k^2/m$$

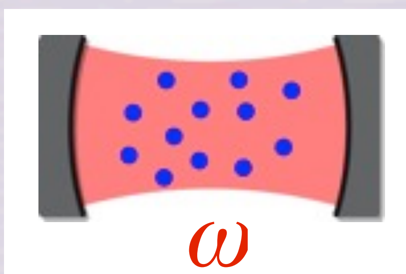
$$\omega = -\tilde{\Delta}_c$$
$$(\tilde{\omega}_c = \omega_c + U_0 N/2)$$

$$\lambda = \eta\sqrt{N/4}$$

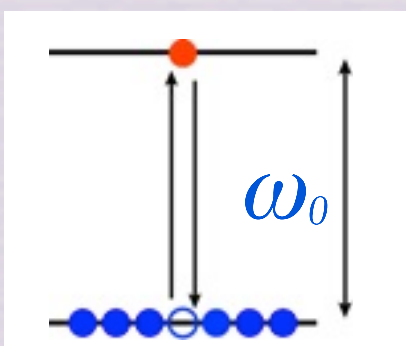
Dicke quantum phase transition

- Modèle de Dicke:

N atomes, 1 mode du champ



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



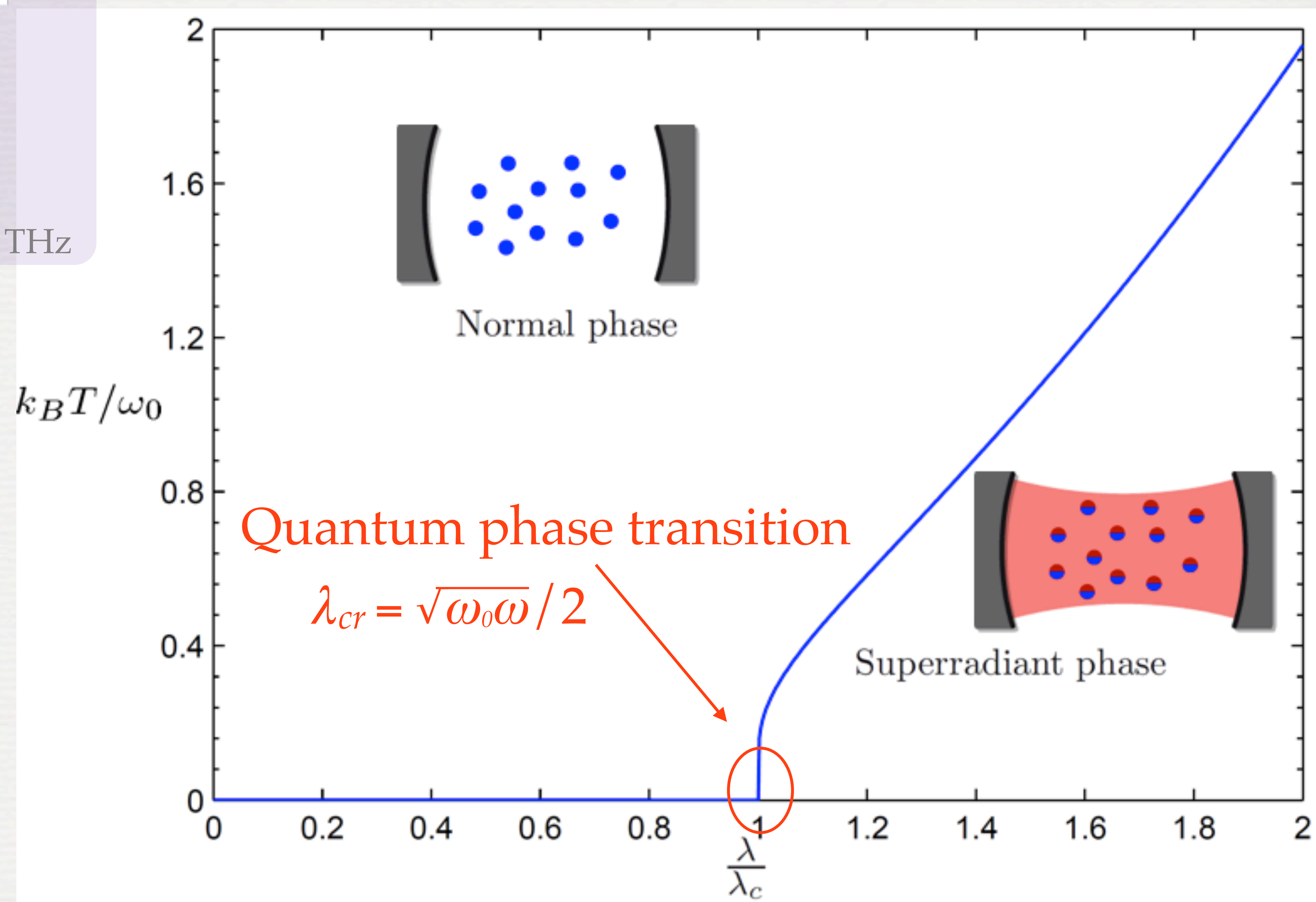
transition normal - superradiant:

$$\lambda > \quad \lambda_{cr} = \sqrt{\omega_0 \omega}\,/\,2$$

$\omega_0 \sim$ 100 THz

proposed 2-photon realization: Carmichael (2007)

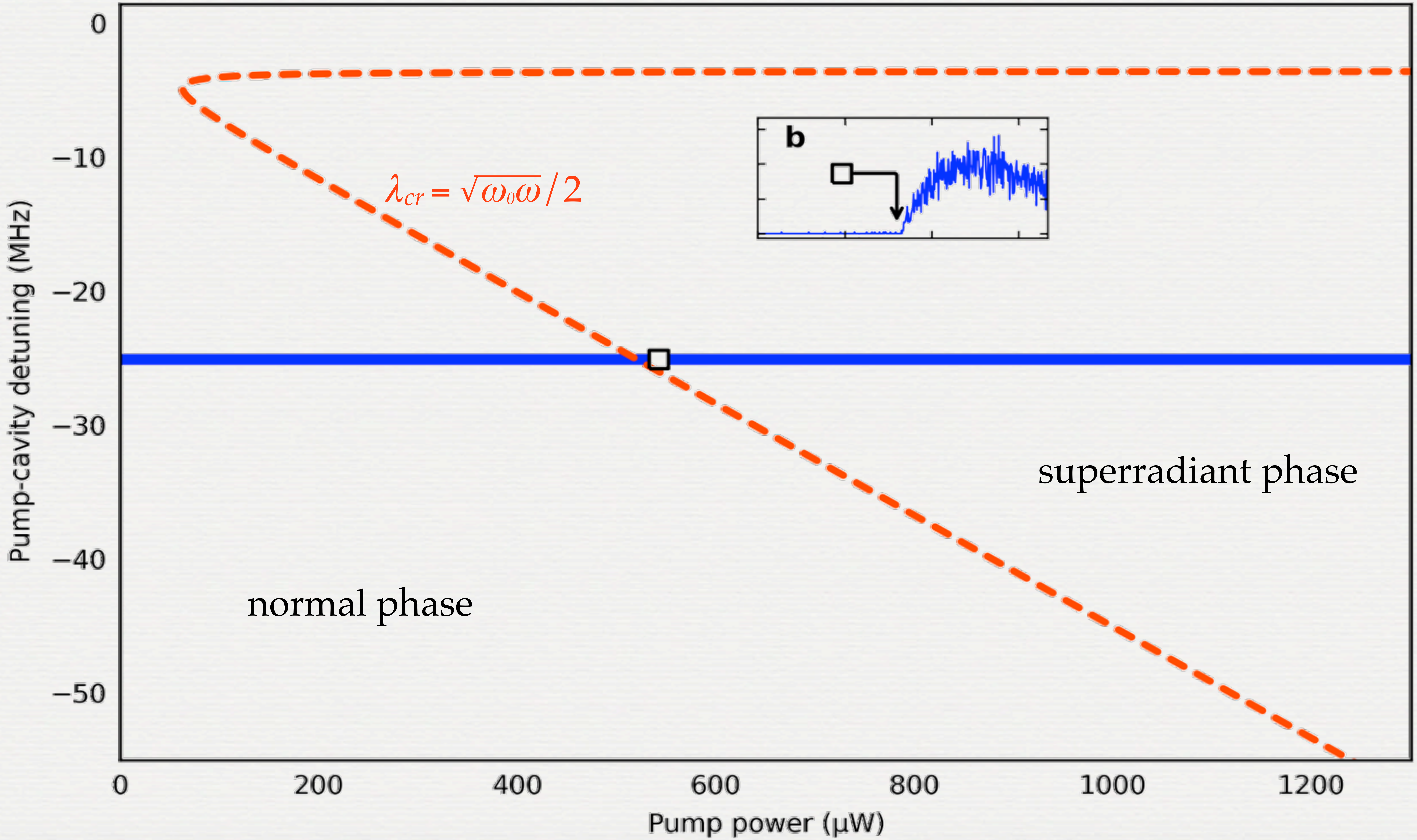
Hepp and Lieb,
Wang and Hioe, 1973



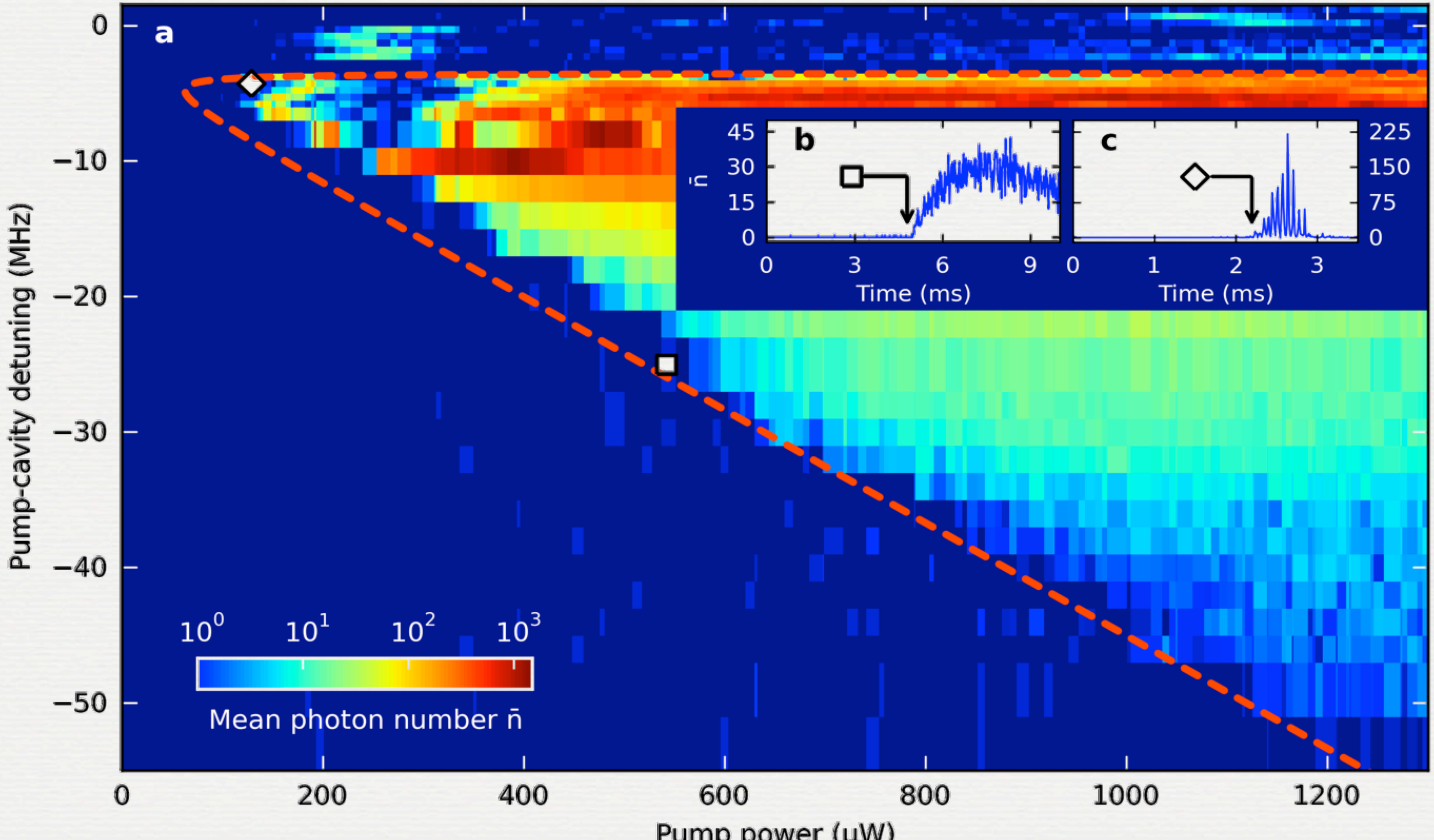
Self-organization is a
two-photon realization
of Dicke phase transition

mapping to : see also Domokos, 2010

Dicke quantum phase transition



Dicke quantum phase transition



Further studies and Perspectives

PRL **107**, 140402 (2011)   PHYSICAL REVIEW LETTERS   week ending 30 SEPTEMBER 2011

✓ **Exploring Symmetry Breaking at the Dicke Quantum Phase Transition**

K. Baumann, R. Mottl, F. Brennecke,* and T. Esslinger

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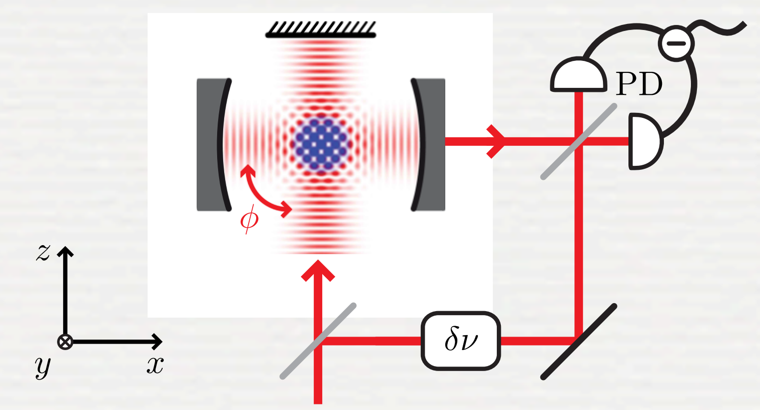
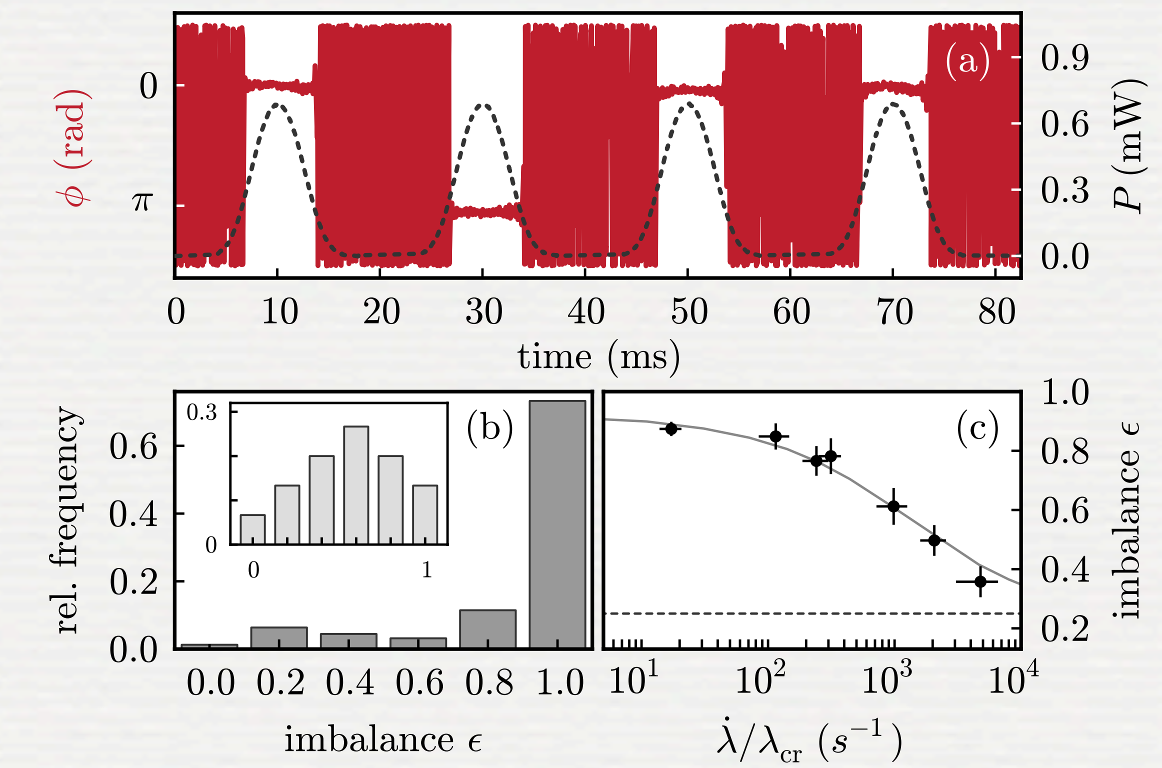
(Received 29 April 2011; revised manuscript received 18 July 2011; published 30 September 2011)

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.

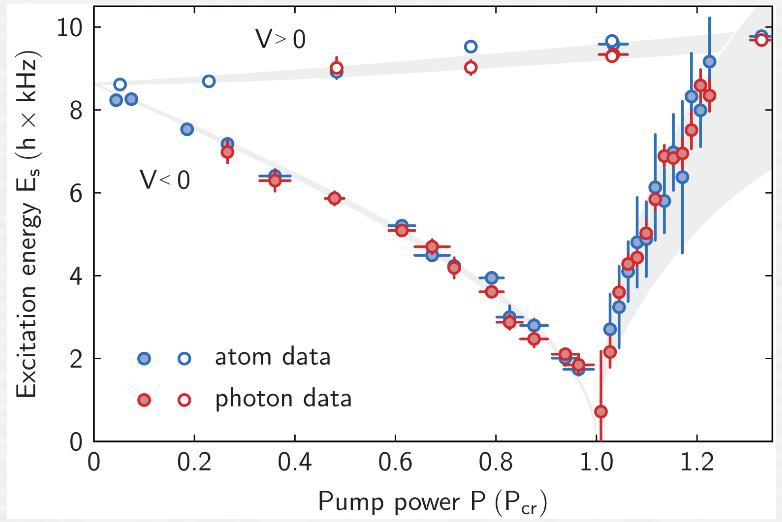


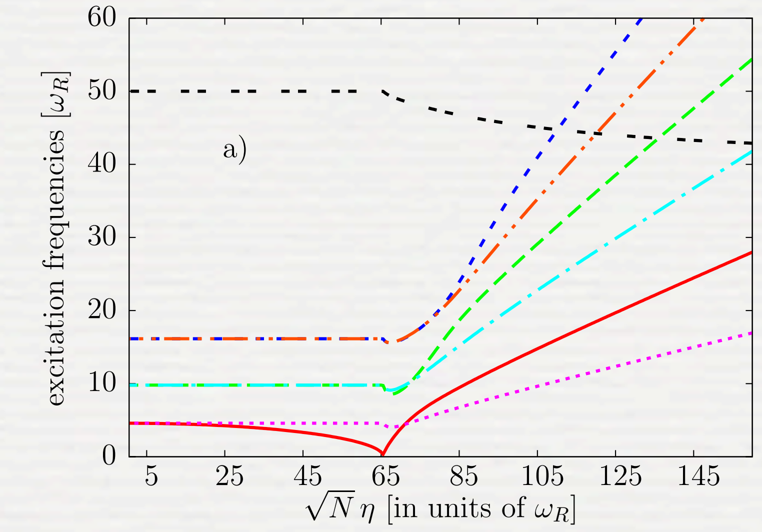


✓ **Roton-Type Mode Softening in a Quantum Gas with Cavity-Mediated Long-Range Interactions**

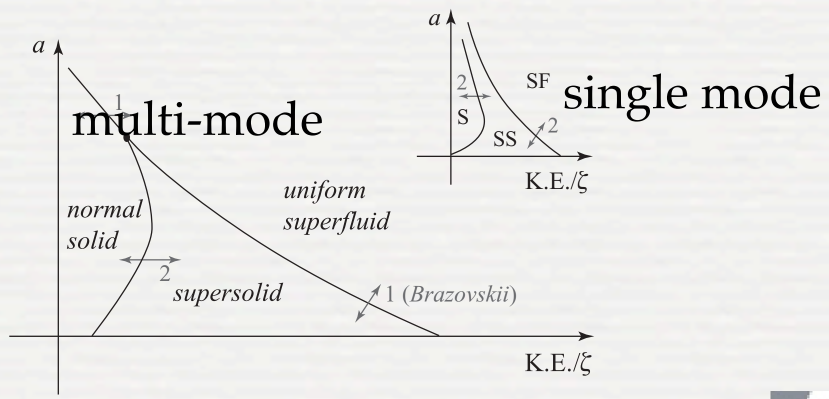
R. Mottl, F. Brennecke, K. Baumann, R. Landig, T. Donner, T. Esslinger*

Long-range interactions in quantum gases are predicted to give rise to an excitation spectrum of roton character, similar to that observed in superfluid helium. We investigated the excitation spectrum of a Bose-Einstein condensate with cavity-mediated long-range interactions, which couple all particles to each other. Increasing the strength of the interaction leads to a softening of an excitation mode at a finite momentum, preceding a superfluid-to-supersolid phase transition. We used a variant of Bragg spectroscopy to study the mode softening across the phase transition. The measured spectrum was in very good agreement with ab initio calculations and, at the phase transition, a diverging susceptibility was observed. The work paves the way toward quantum simulation of long-range interacting many-body systems.



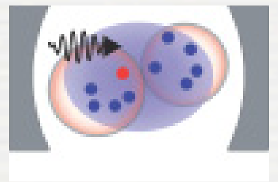


Domokos 2008



- Towards multiple cavity modes   Goldbart 2010
- Other approach for longe range interactions: Rydberg atoms

Cavity QED with a Rydberg blocked atomic ensemble, ***C. Guerlin*** *et al.*, PRA 82, 053832 (2010)



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