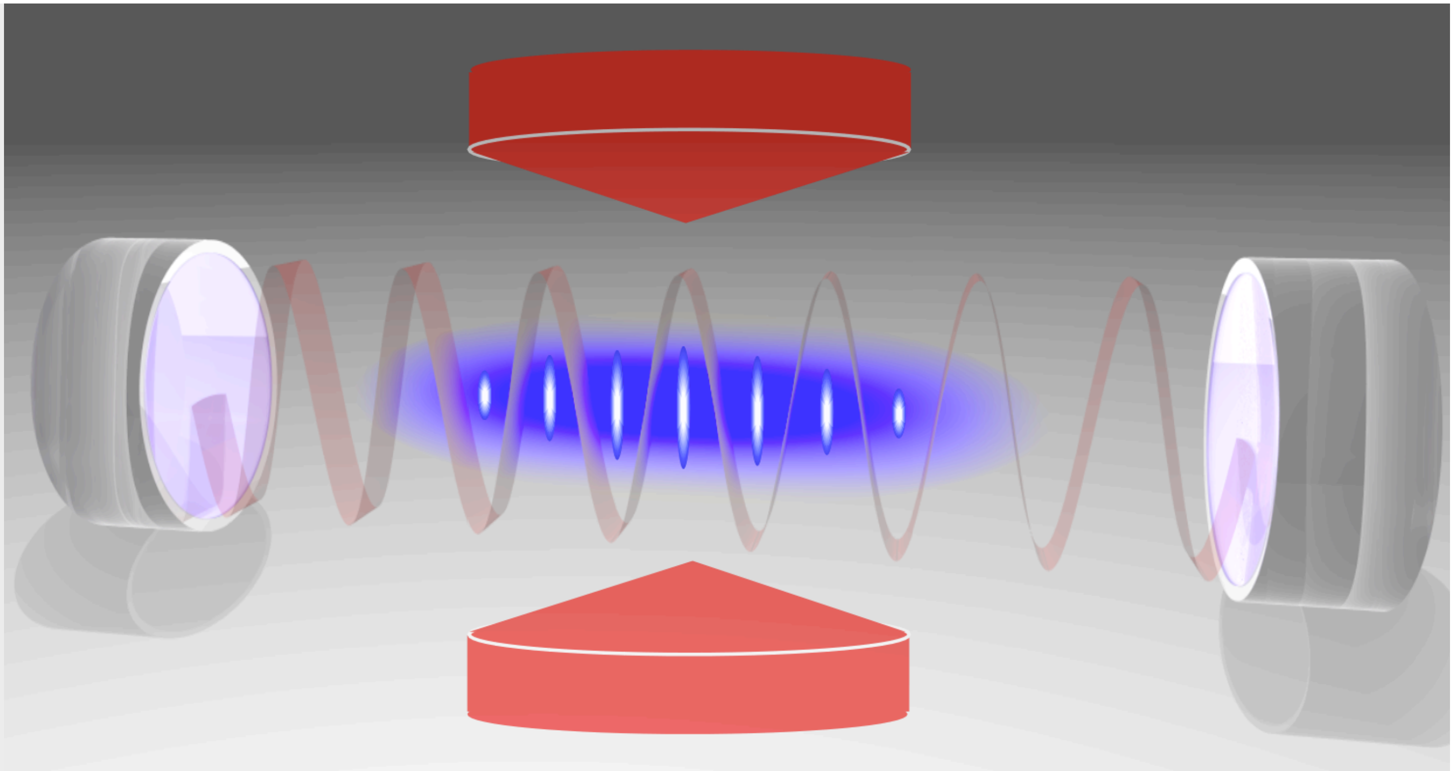
Universität Hamburg

INSTITUT FÜR LASERPHYSIK

Zentrum für Optische Quantentechnologien

Andreas Hemmerich
Bad Honnef 2016

Poster !



BEC in a high finesse optical cavity

- recoil-resolved cavity sideband cooling
- in situ monitor for Bloch oscillations
- controlling matter wave superradiance
- open Dicke model
- Hubbard model with infinite range interaction

Theory Support

Hamburg University

Ludwig Mathey
Reza Bakhtiari
Michael Thorwart

Ludwig

Reza

Michael

Hamburg Cavity Team

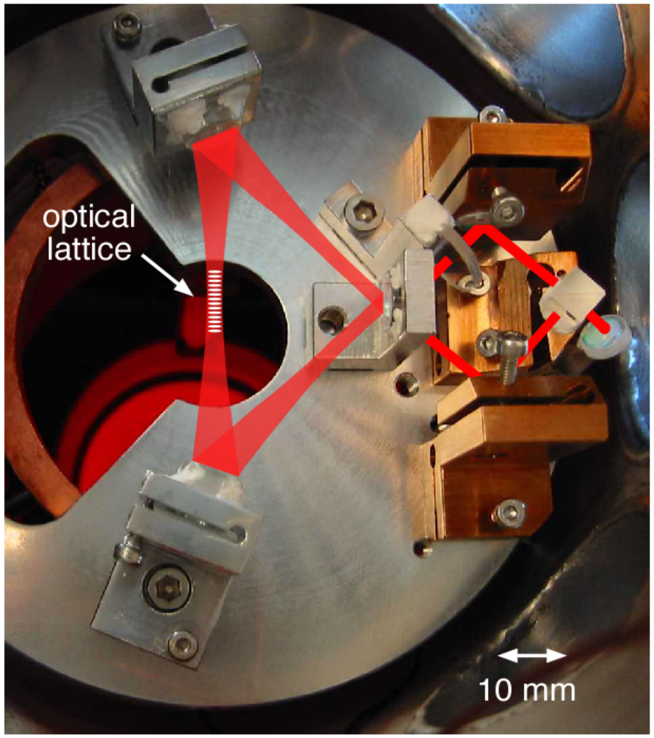
Hans Kessler
PhD Sep 2015

Christoph Georges
PhD student

José Vargas Roco
PhD student

Jens Klinder
PhD Dec 2015

Poster !



finesse : 180000
linewidth : 17 kHz
5×10^6 thermal atoms at
50 µK temperature

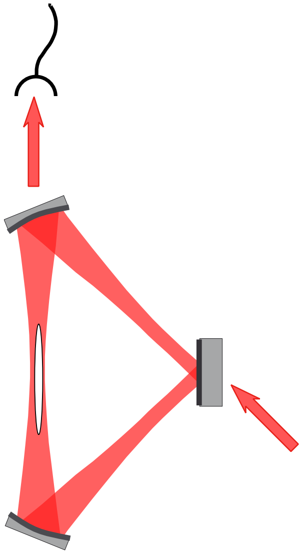
2003 (together with Zimmermann group, Tübingen)

- optical lattice in high finesse optical cavity
- dispersive strong collective coupling
- dispersive bistability, optomechanical backaction, self-organization

B. Nagorny, Th. Elsässer, A. Hemmerich, Phys. Rev. Lett. 91, 153033 (2003).

D. Kruse, C. von Cube, C. Zimmermann, and Ph.W. Courteille, PRL 91, 183601 (2003)

First BEC in cavity

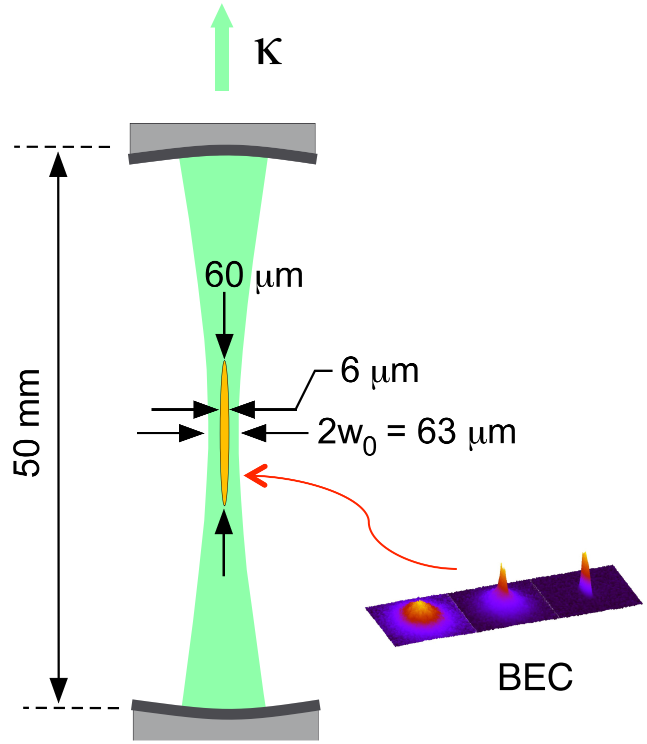


Unidirectionally coupled ring cavity

Self-organization transition, Collective atomic recoil lasing (CARL)

S. Slama, S. Bux, G. Krenz, C. Zimmermann, and Ph. W. Courteille, PRL 98, 053603 (2007)

Hamburg BEC cavity



finesse: $F \approx 340.000$

linewidth: $\kappa / 2\pi \approx$ 4.5 kHz

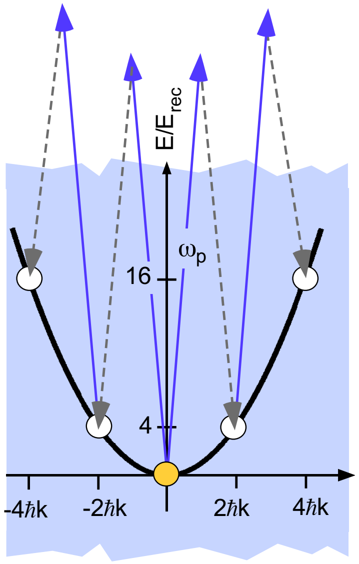
Purcell factor: $\eta \equiv \dfrac{24}{\pi w_0^2 k^2} F \approx 44$

^{87}Rb-BEC: $N_a \approx 1.2 \cdot 10^5$

light shift per photon: $\Delta_0 = 2\pi \times 0.36\ Hz$

shift of cavity resonance: $N_a \Delta_0 \approx -4\,\kappa$

Two regimes of cavity dissipation

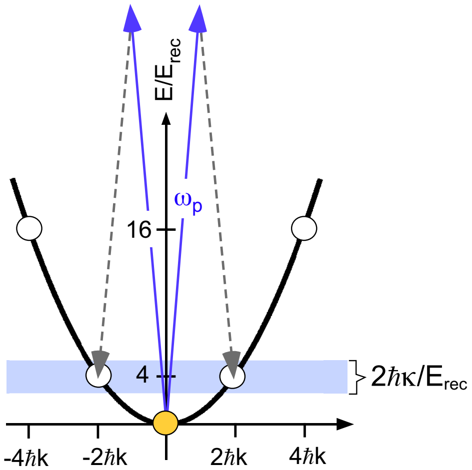


large cavity damping

Berkeley, Stanford, Tübingen, Zürich, ...

$$4\omega_{\mathrm{rec}} \ll \kappa$$

- → cavity field follows atomic dynamics
- → few-mode description only for negligible depletion of BEC (weak driving)



weak damping, resolved recoil

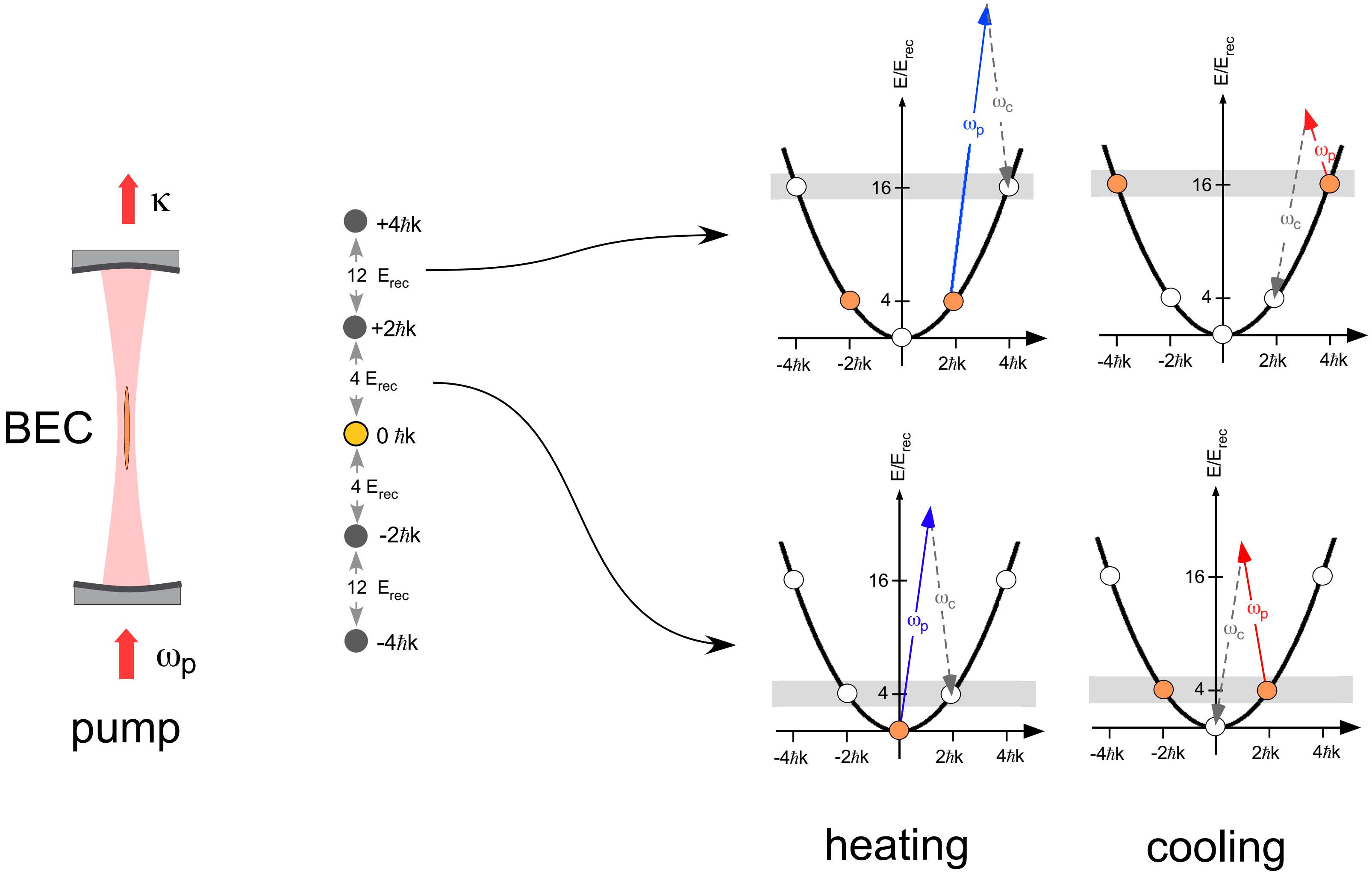
Hamburg

$$4\omega_{\mathrm{rec}} > \kappa$$

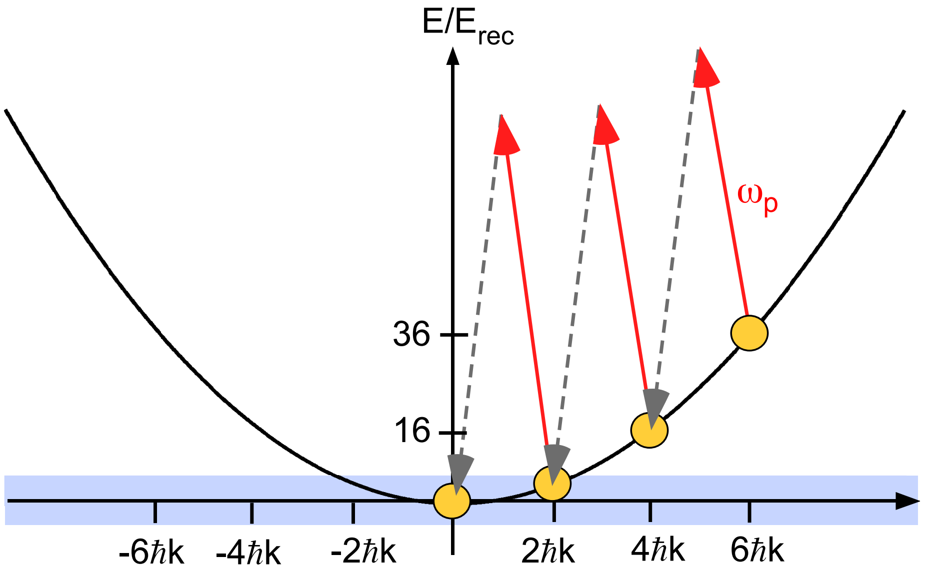
- → cavity field and atomic dynamics on comparable time scales
- → few-mode description well justified

Elementary scattering processes

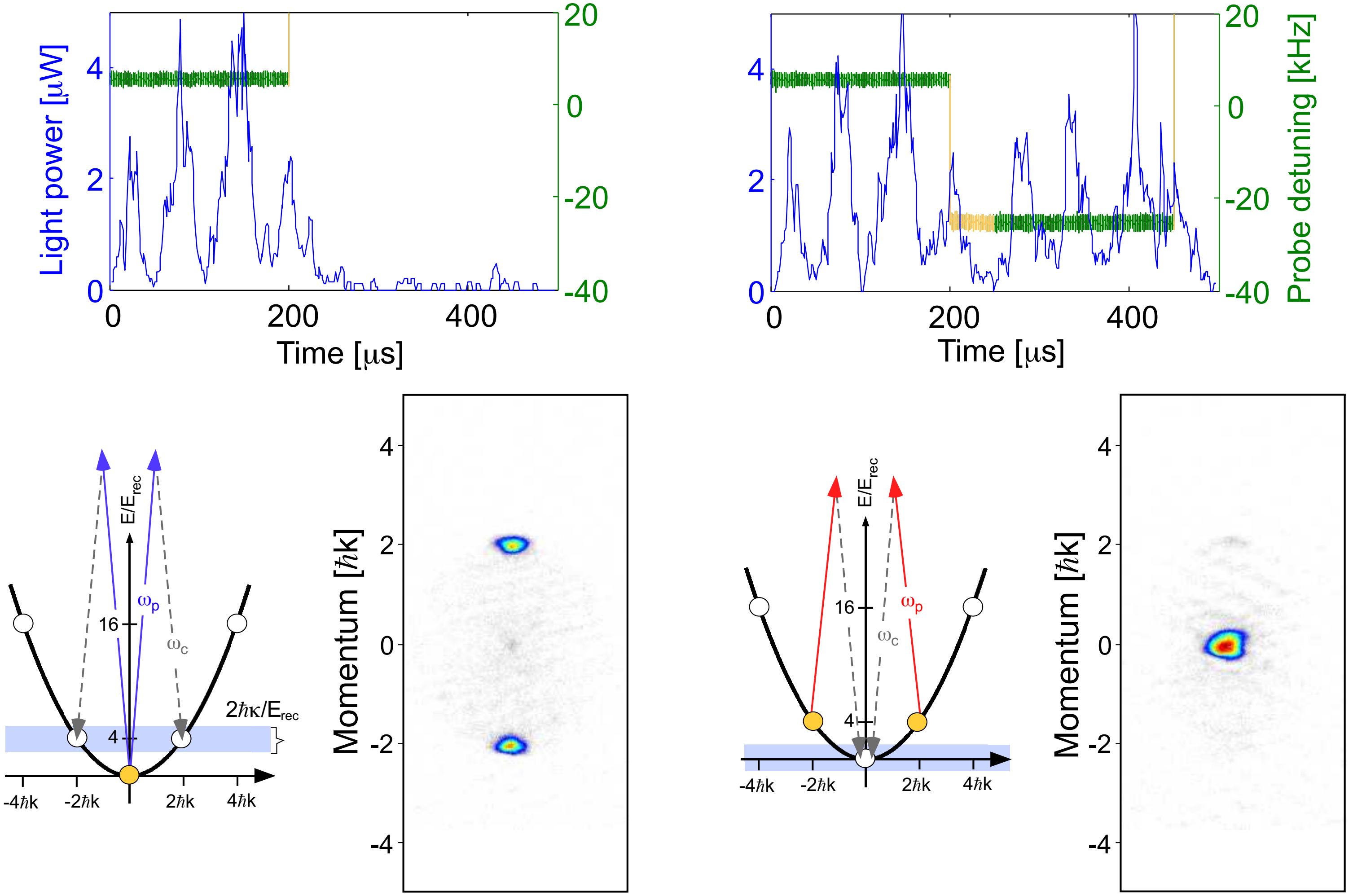
Axial coupling:



Cavity sideband cooling. . .

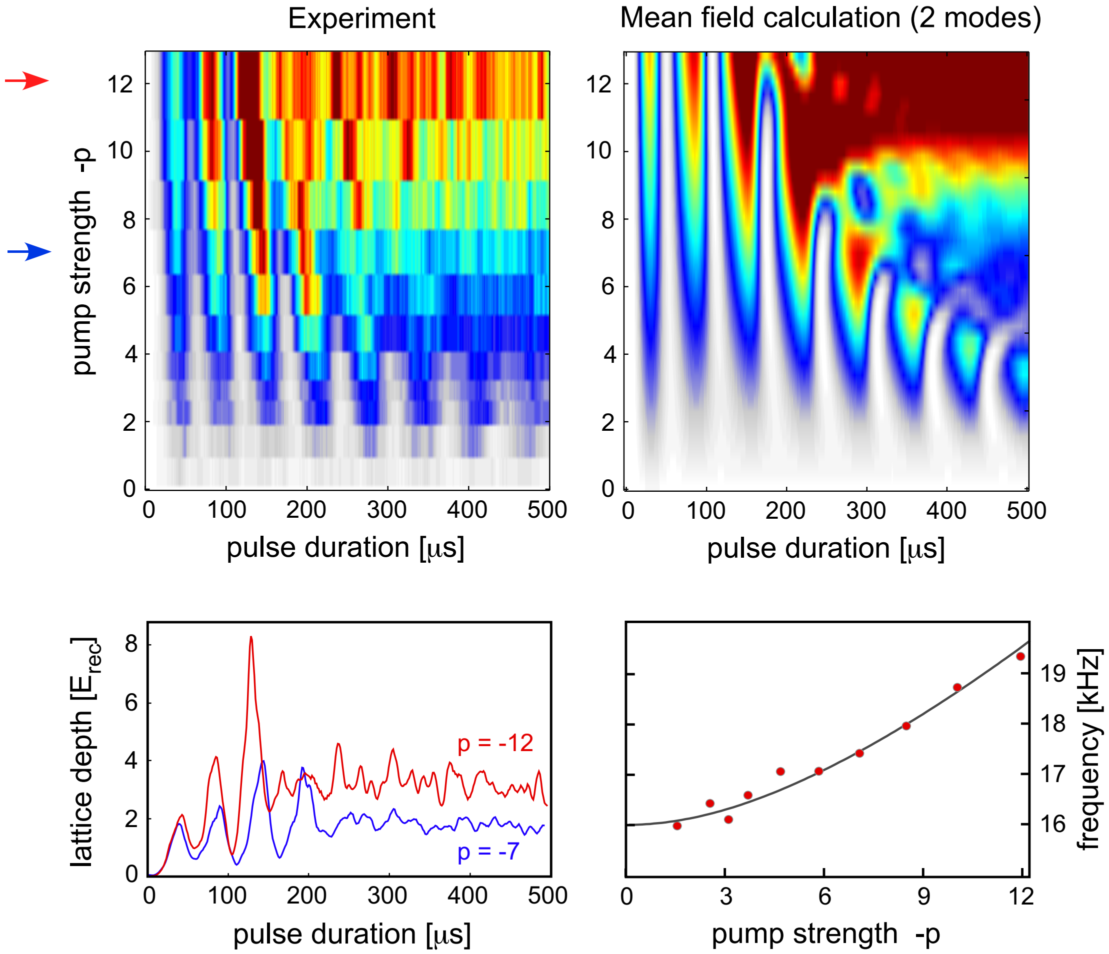


Heating and cooling pulses



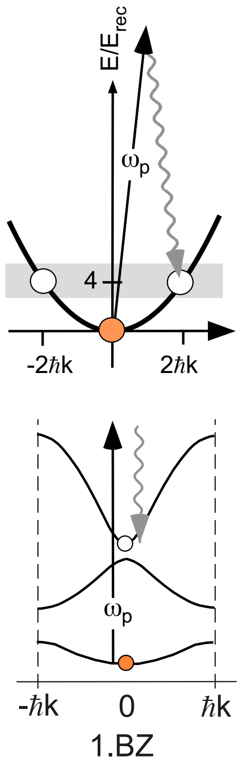
M. Wolke et al., Science 337, 85 (2012)

Heating pulse: time evolution of intra-cavity field



Experiment

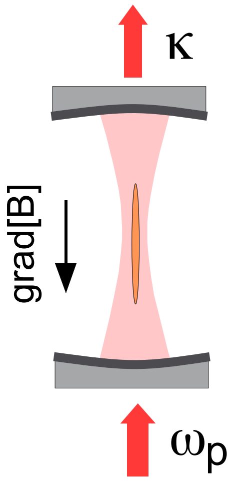
Mean field calculation (2 modes)

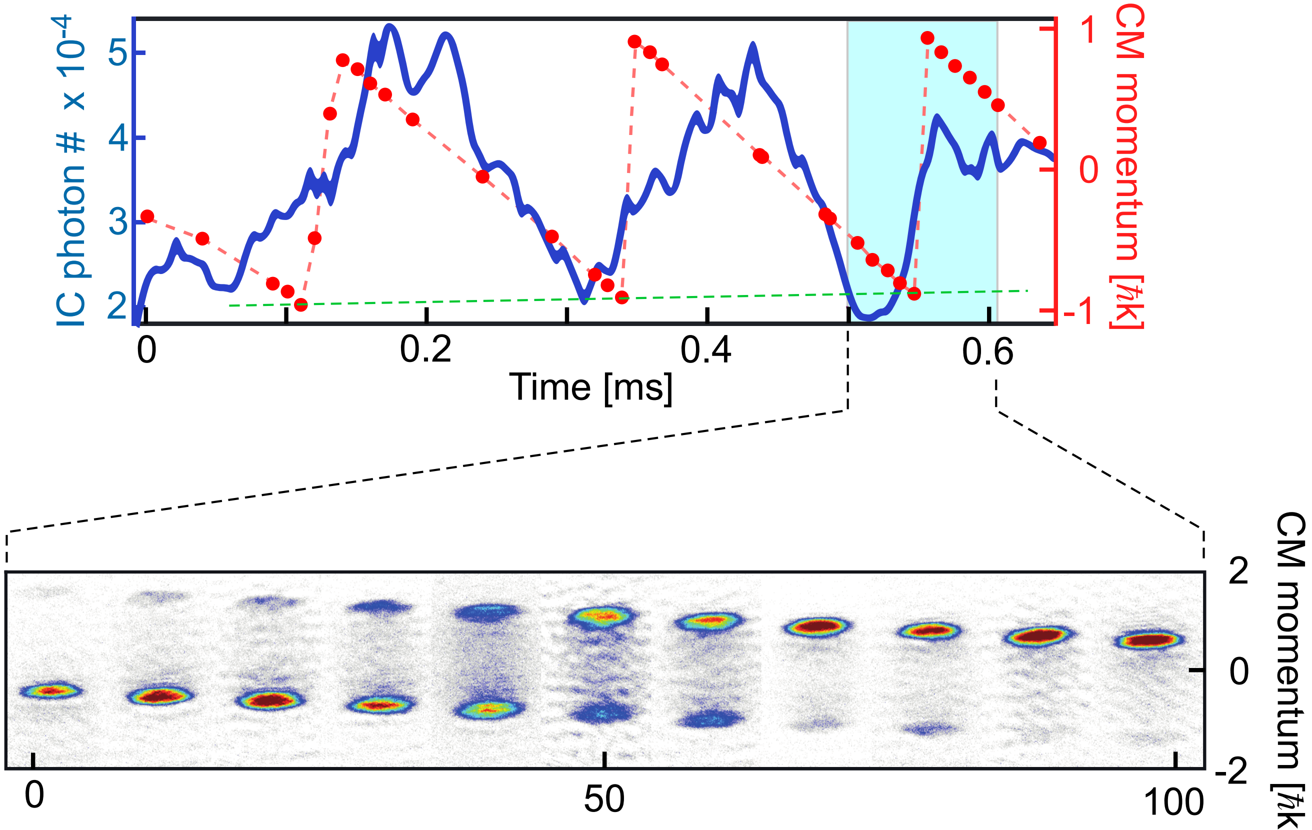


H. Keßler, et al., NJP 16, 053008 (2014)

$$p = \frac{N_p \Delta_0}{4\omega_{rec}} \qquad \delta_{eff} \approx 4.4\,\kappa \qquad q = \frac{N_a \Delta_0}{4\kappa} = -2.8$$

In-situ monitoring of Bloch oscillations

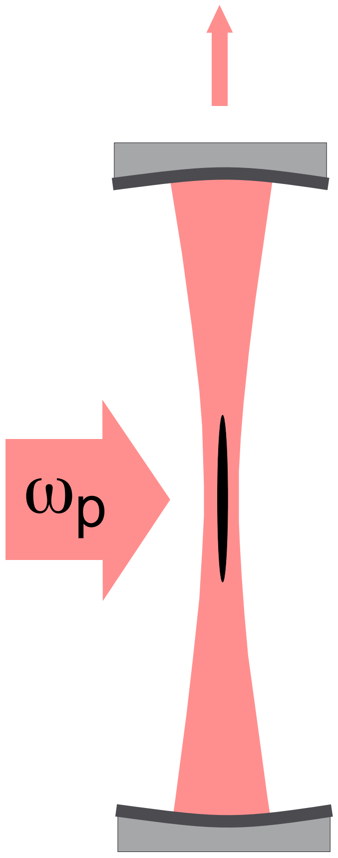




Poster !

Radial travelling wave coupling

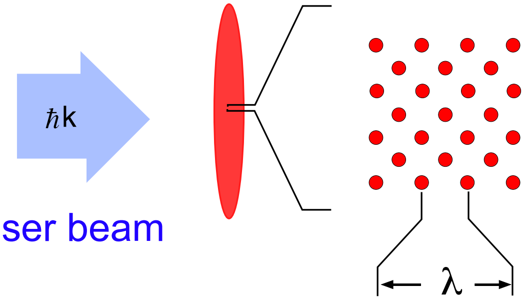
→ cavity controlled matter wave superradiance



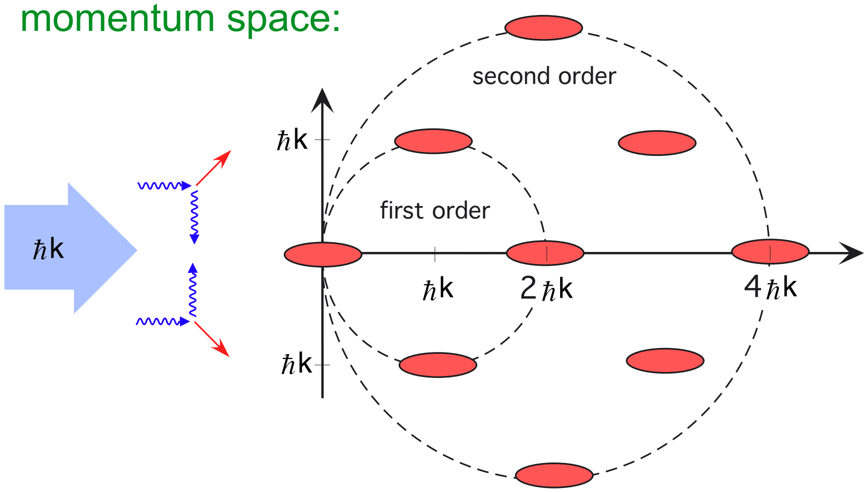
Matter wave superradiance without cavity

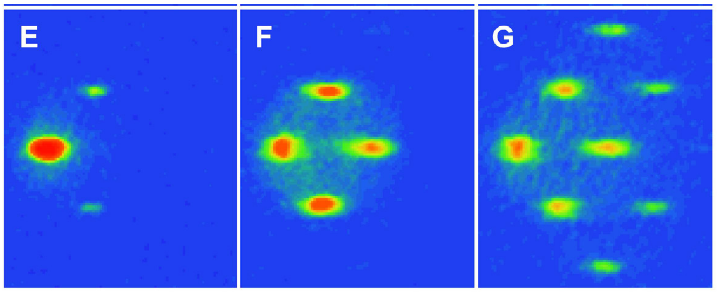
superradiance: atoms form transient moving optical lattice

position space:



momentum space:



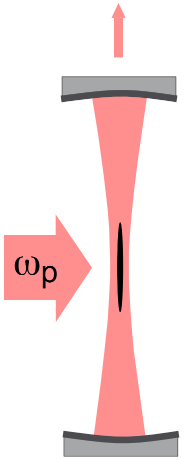


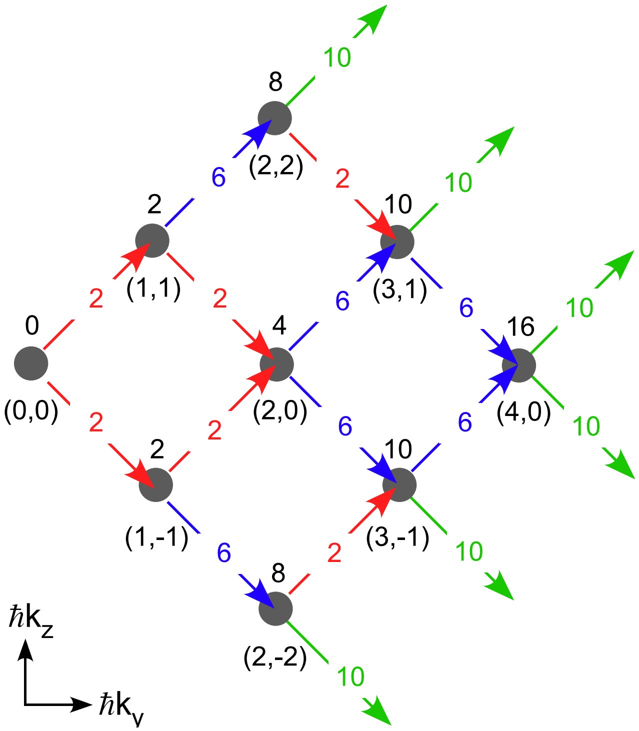
Ketterle Group, Science 285, 571 (1999)

Matter wave superradiance in recoil resolving cavity

→ controlling superradiant scattering

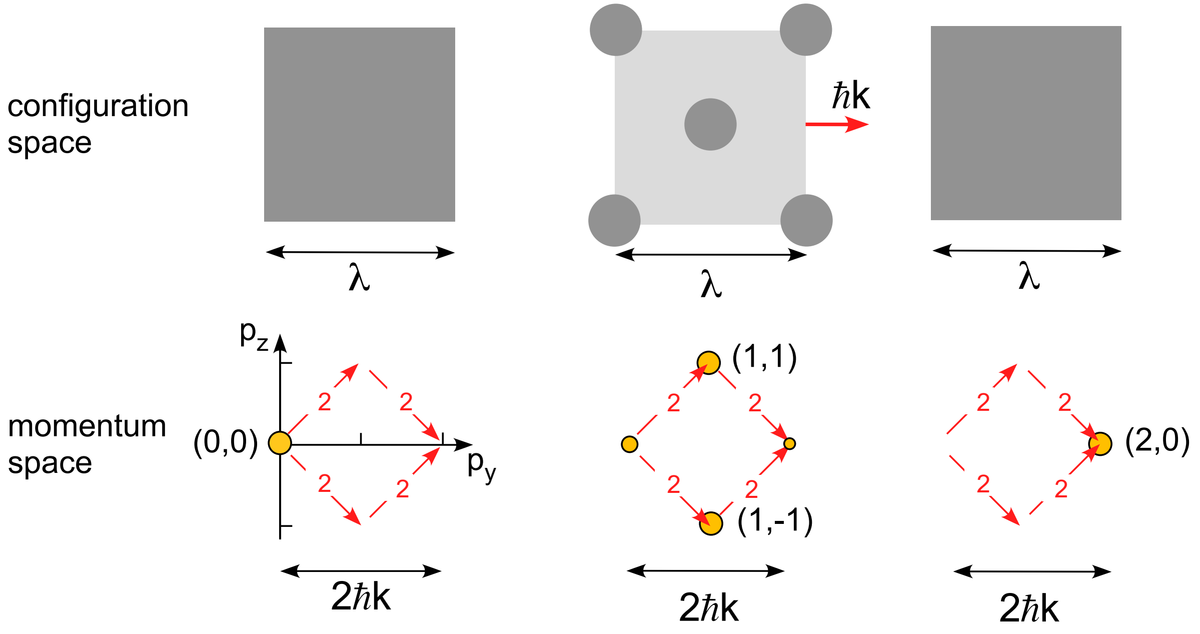
narrow cavity bandwidth permits selection of specific scattering process





Momentum transfer is superradiant

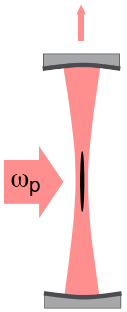
$2E_{rec}$ process

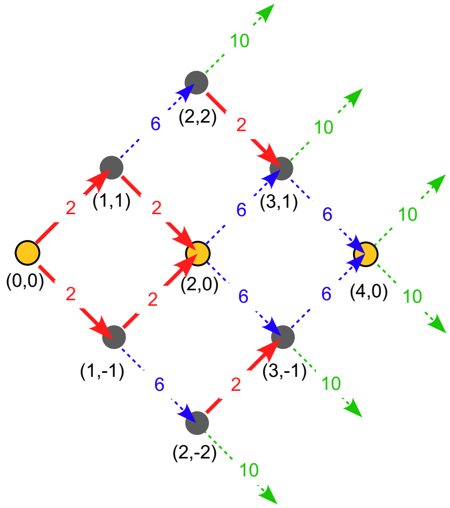


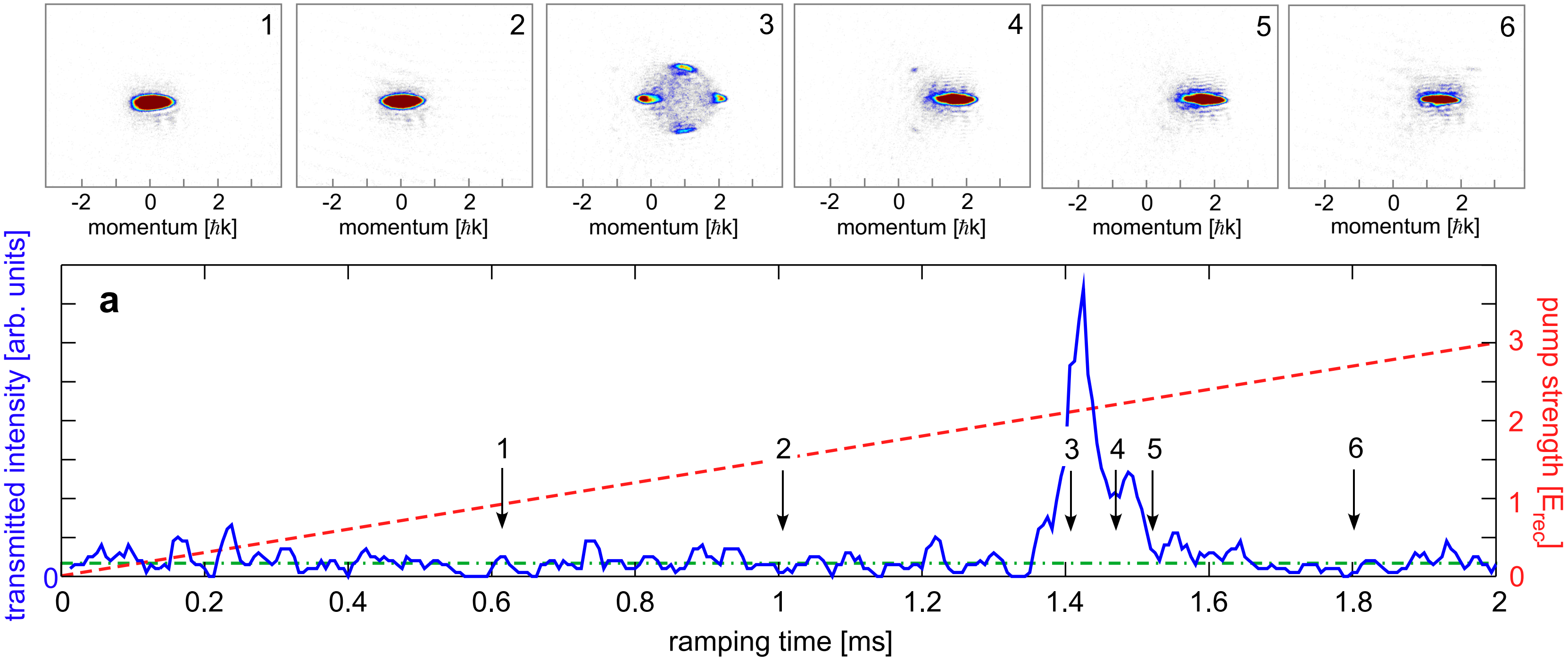
- constant atomic density
- destructive interference for scattering into cavity
- exponentially instable

- transient moving density grating
- constructive interference for scattering into cavity
  → superradiant pulse emitted into cavity

$2E_{rec}$ process

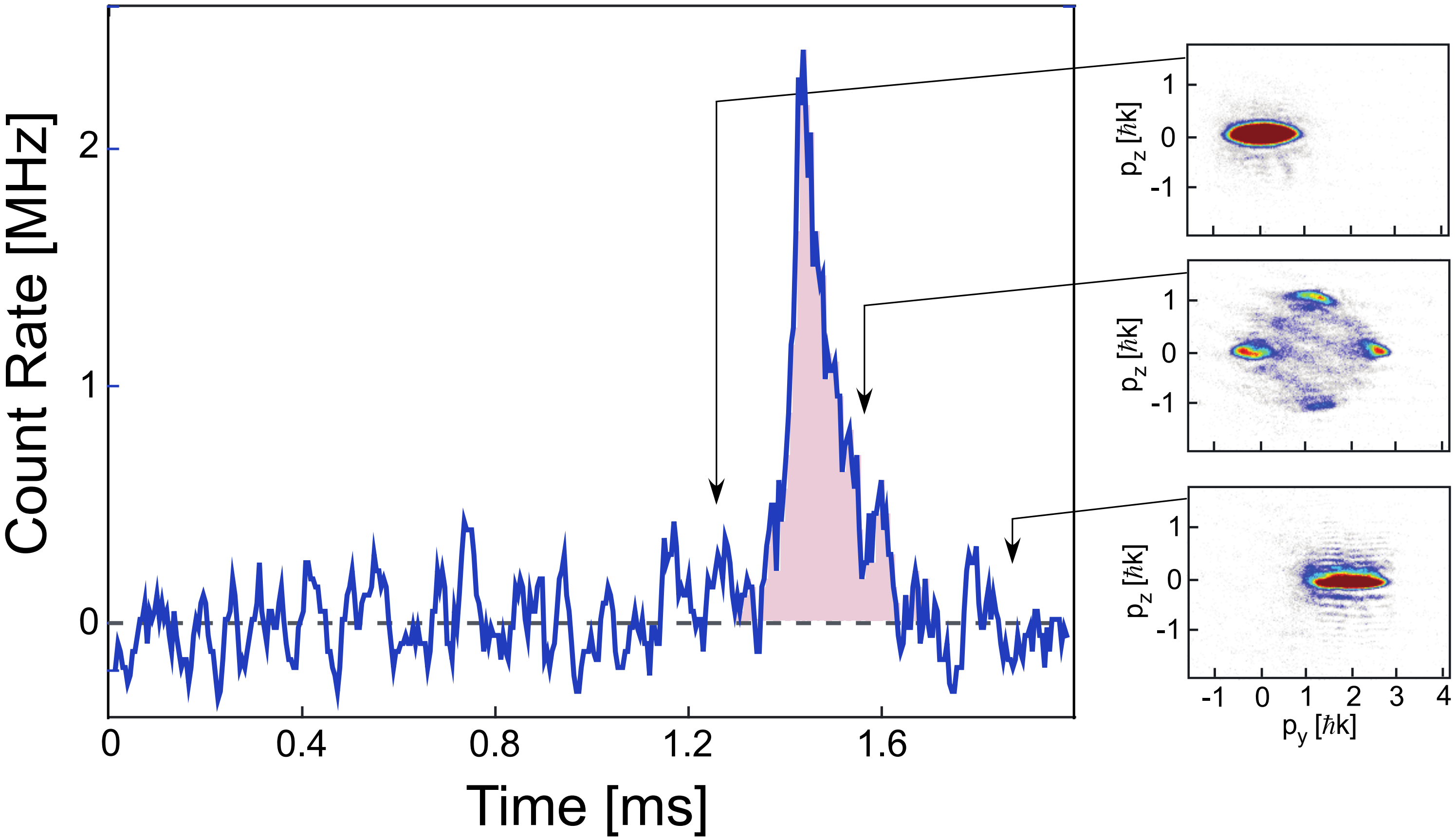




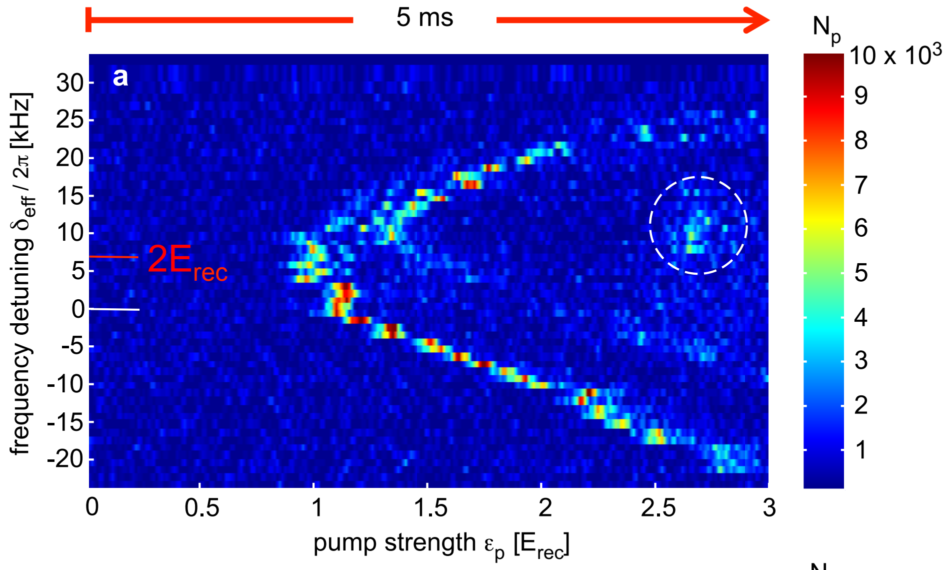


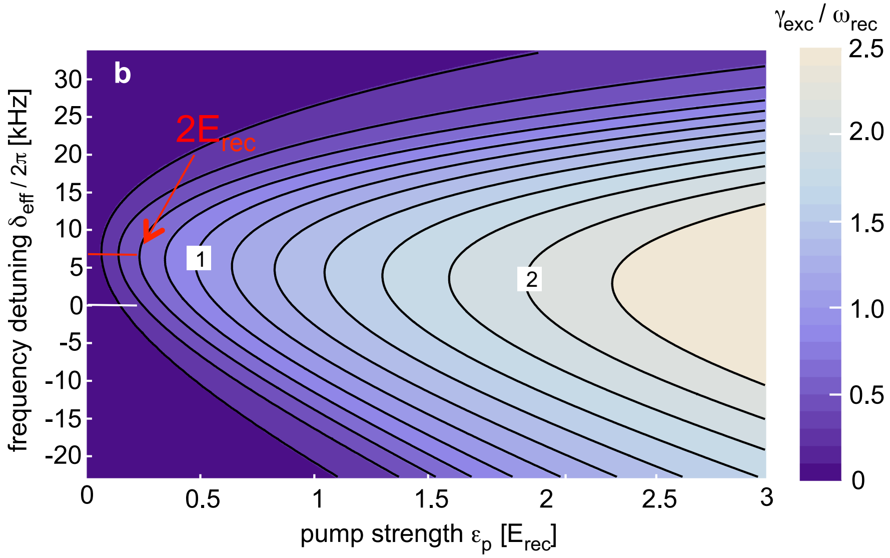
H. Keßler et al., PRL, 113, 070404 (2014)

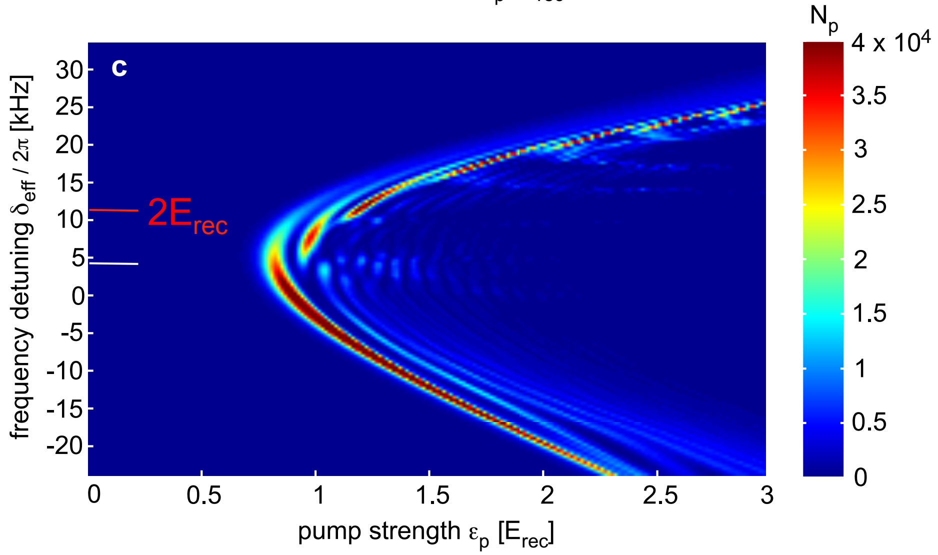
$2E_{rec}$ process

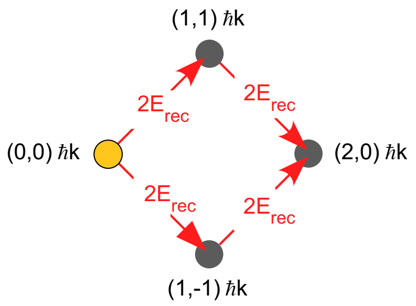


Instability boundary





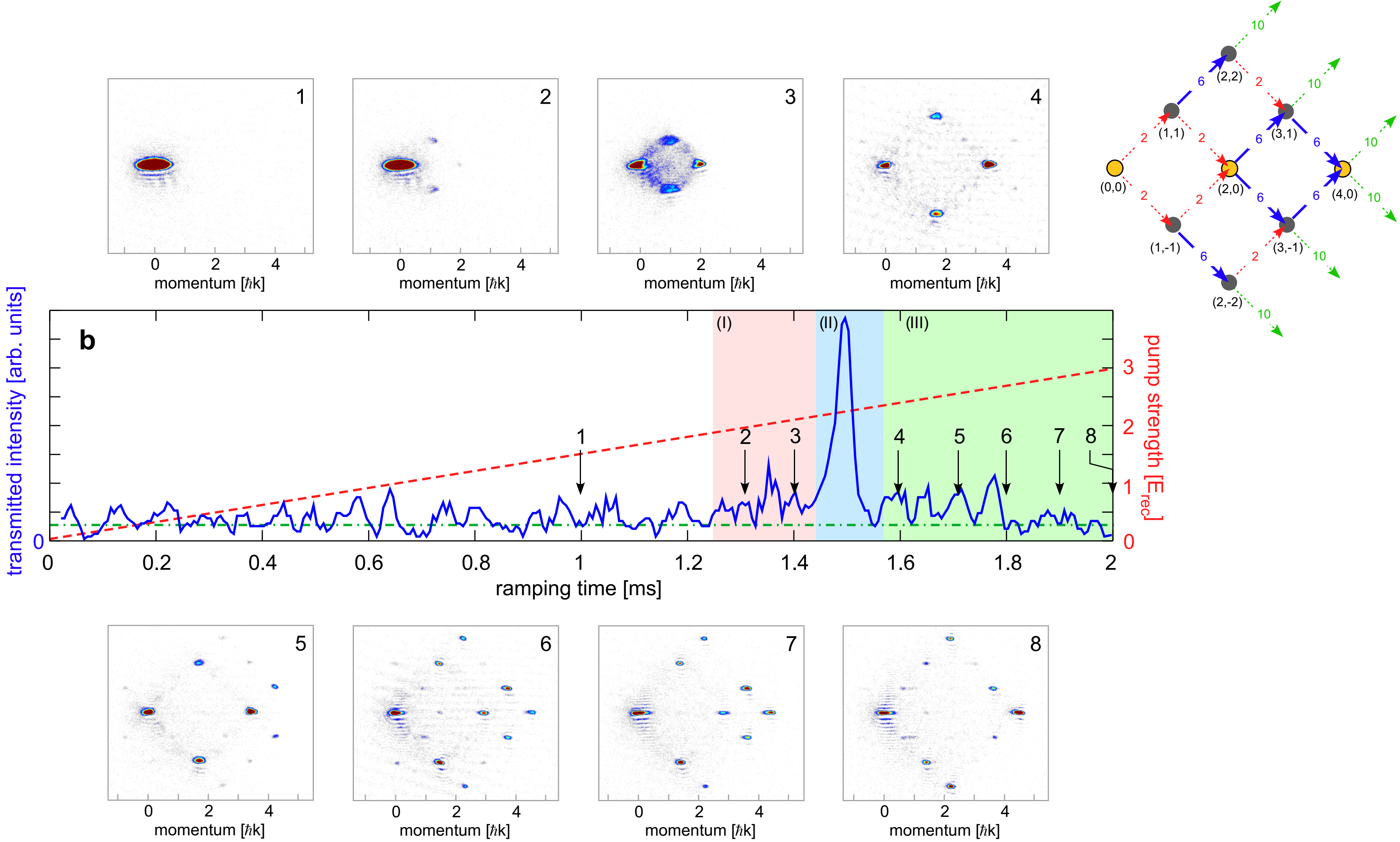




$2E_{rec}$ process

H. Keßler et al., PRL, 113, 070404 (2014)

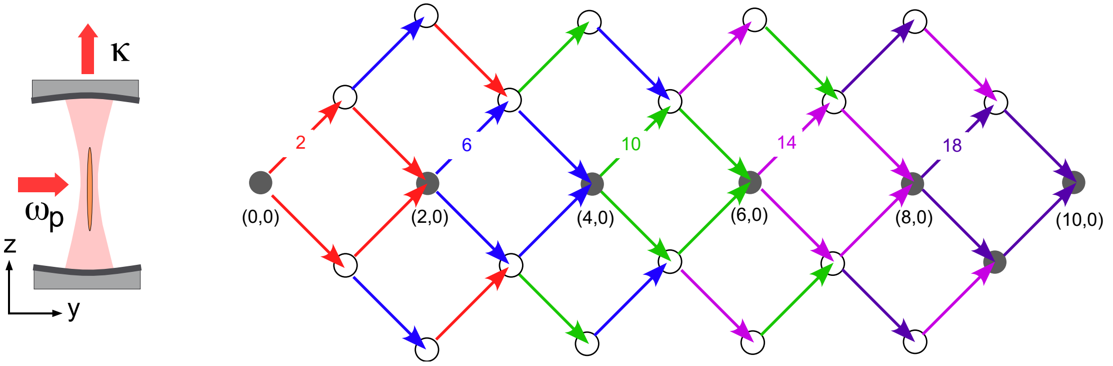
$6E_{rec}$ process

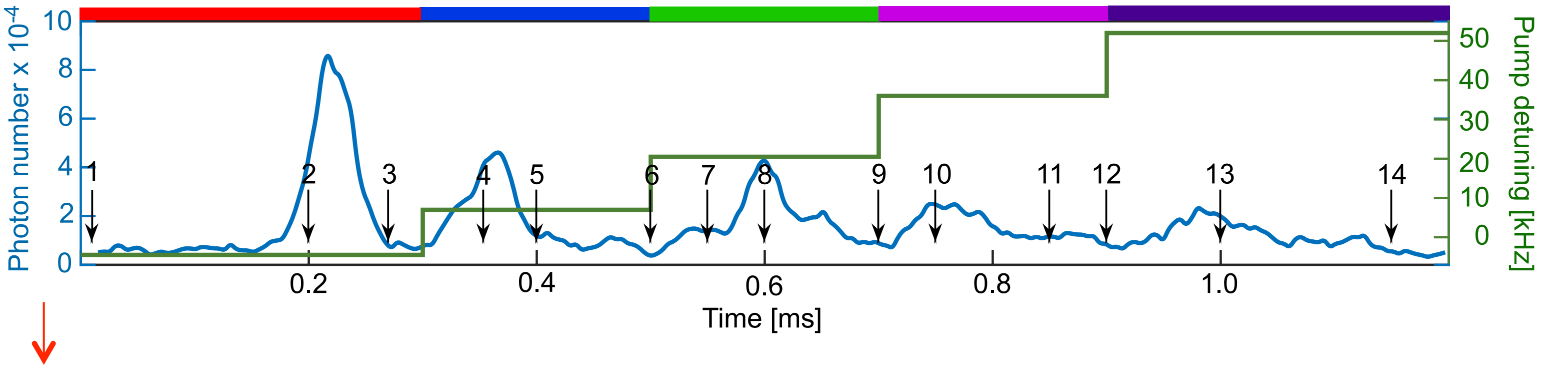


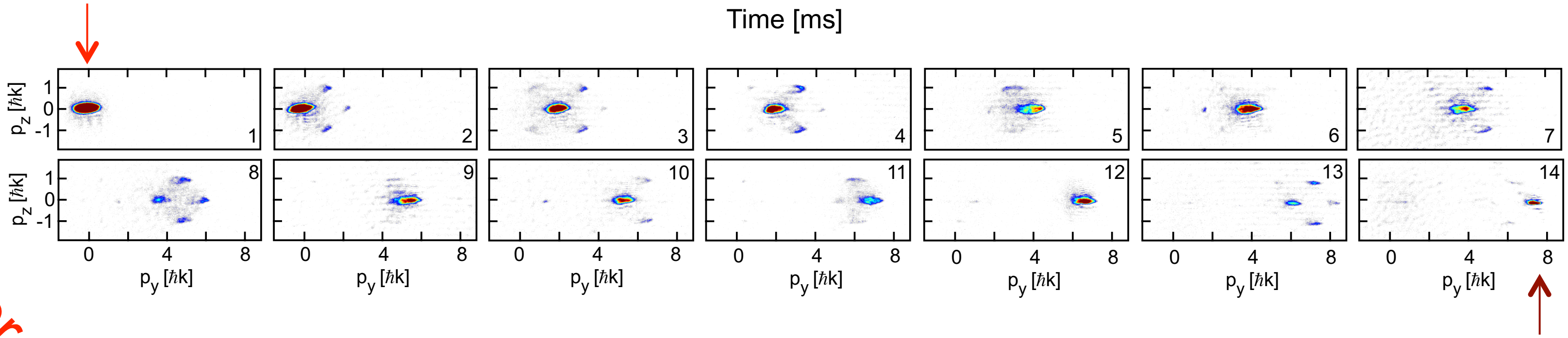
H. Keßler et al., PRL, 113, 070404 (2014)

Poster !

Superradiant atom accelerator

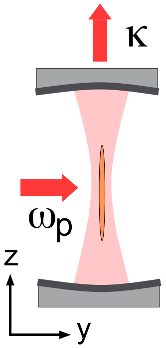


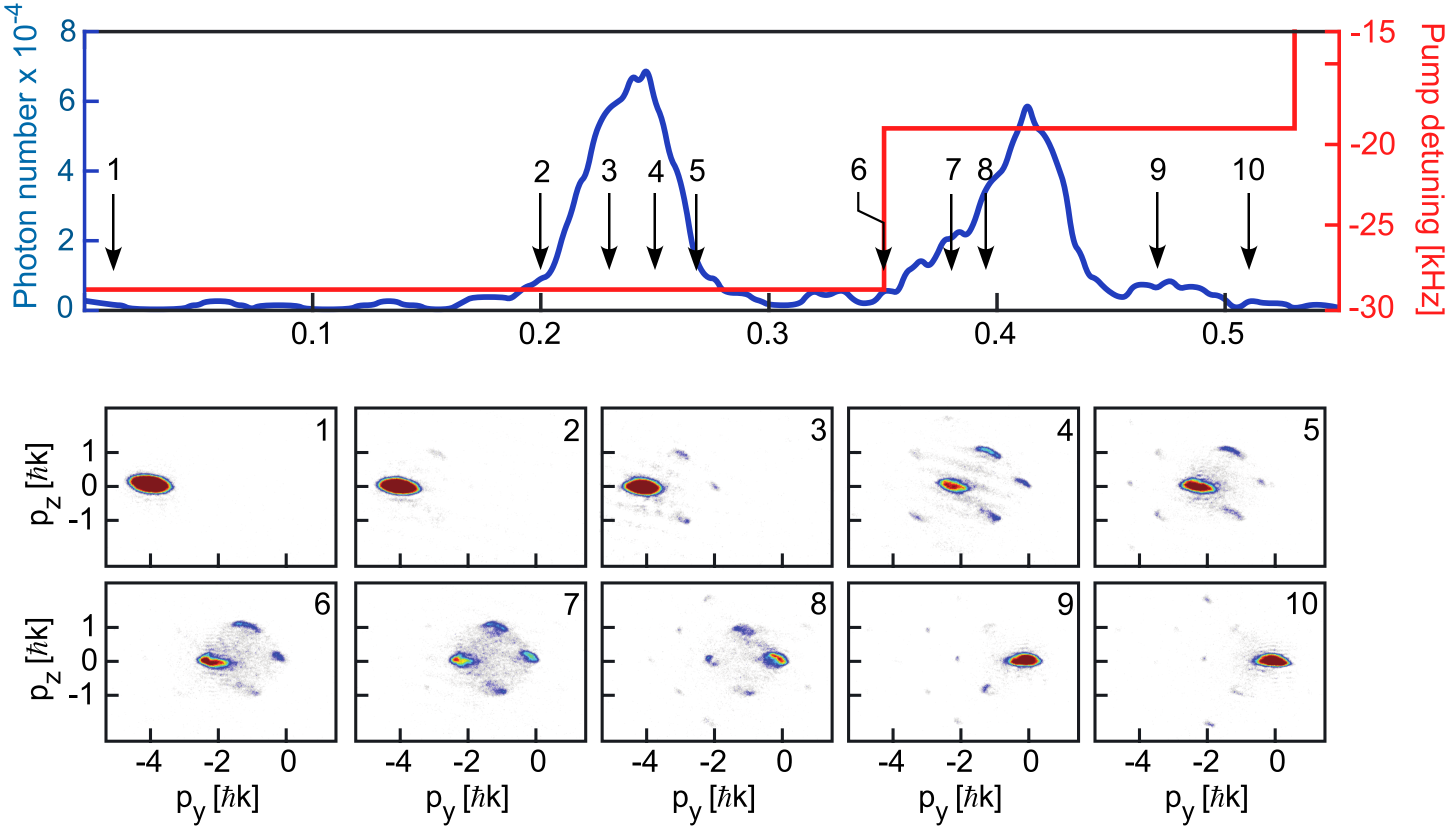




Poster !

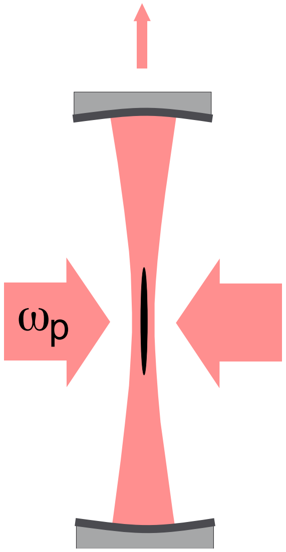
Superradiant atom decelerator





Poster !

Radial standing wave coupling



Self-organization transition, Dicke model and beyond ...

P. Domokos and H. Ritsch, PRL 89, 253003 (2002)

Adam T. Black, Hilton W. Chan, and Vladan Vuletic, PRL 91, 203001 (2003)

Dimer, Estienne, Parkins, and Carmichael PRA 75 (2007)

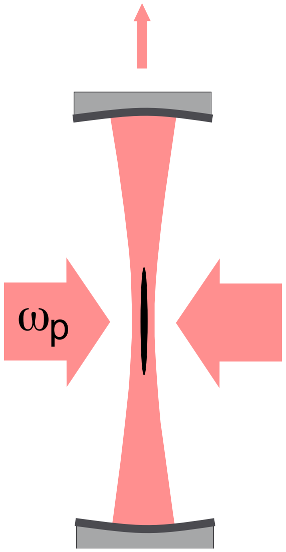
D. Nagy, G. Kónya, G. Szirmai, and P. Domokos, PRL 104, 130401 (2010)

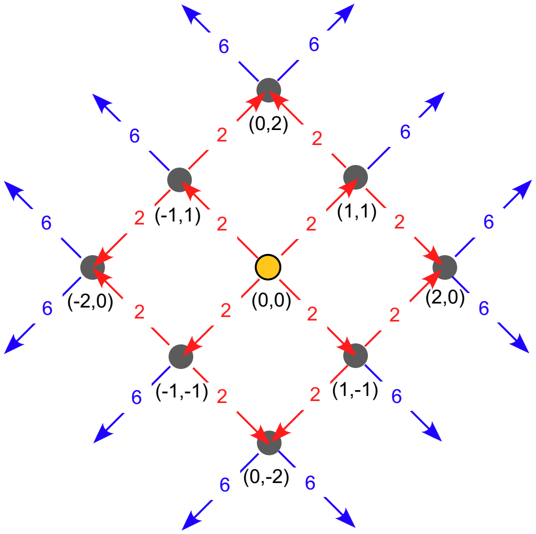
J. Keeling, M. J. Bhaseen, and B. D. Simons, PRL 105, 043001 (2010)

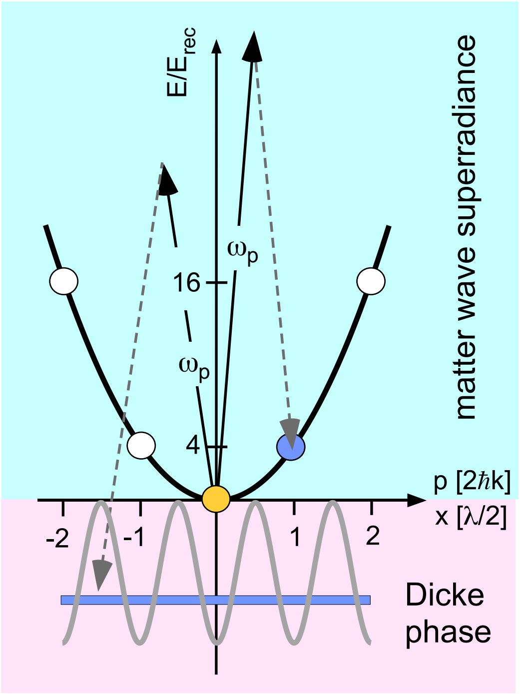
M. J. Bhaseen, J. Mayoh, B. D. Simons,1 and J. Keeling, PRA 85, 013817 (2012)

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

Radial standing wave coupling







$\omega_p > \omega_c$

$\omega_p < \omega_c$

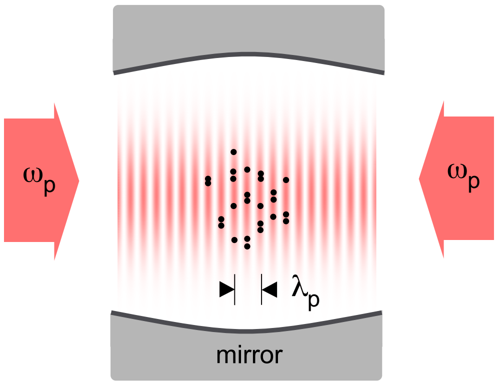
$\omega_p > \omega_c$ ➞ matter wave superradiance

$\omega_p < \omega_c$ ➞ Dicke phase transition

Dicke phase transition ($\omega_p < \omega_c$)

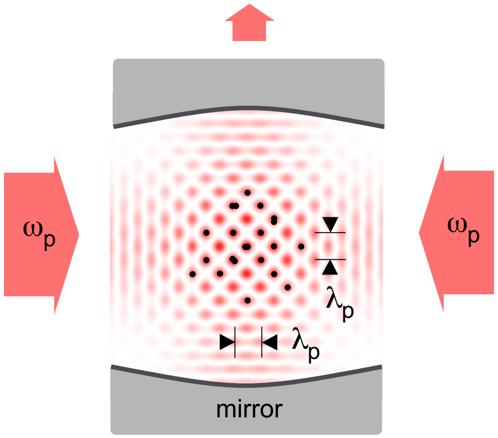
Th: Ritsch group
Exp: Esslinger group, Nature (2010)

Homogeneous phase (HP)



critical value of
pump strength

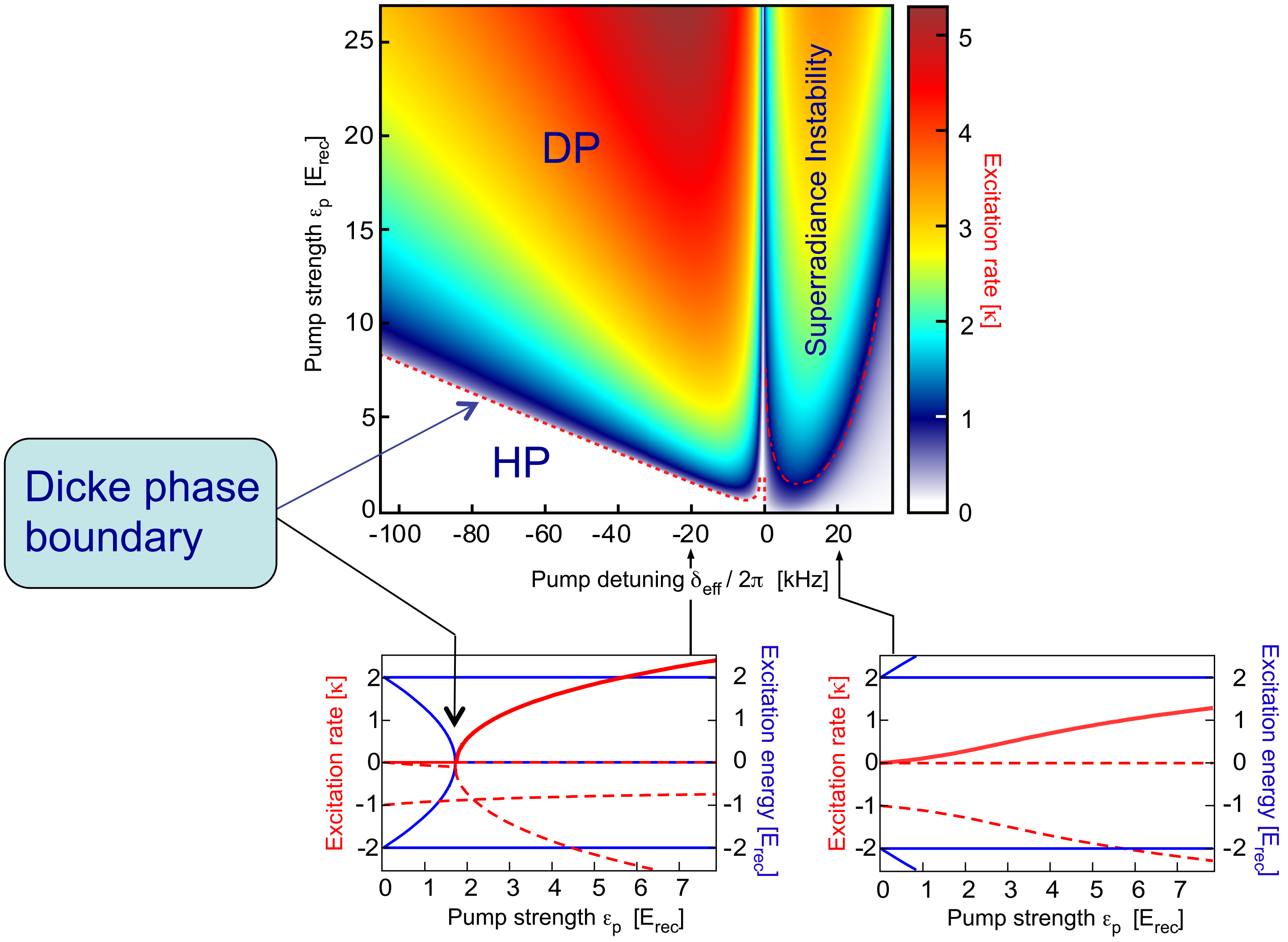
Dicke phase (DP)



- homogeneous atomic density along cavity axis
- destructive interference prevents scattering into cavity

- stationary intra-cavity optical lattice
- constructive interference for scattering into cavity (superradiance)

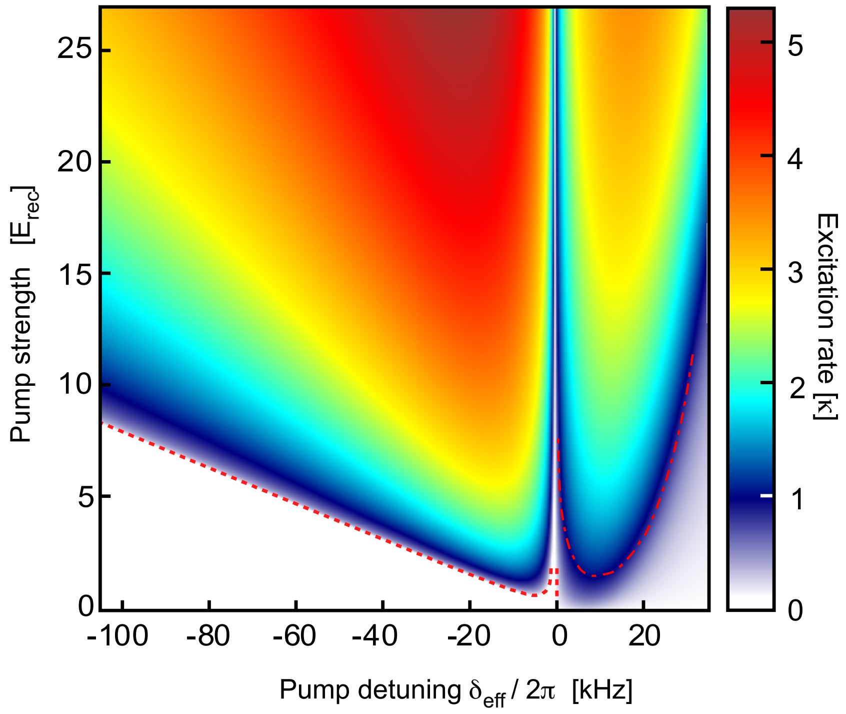
Stability analysis for homogeneous phase (HP)



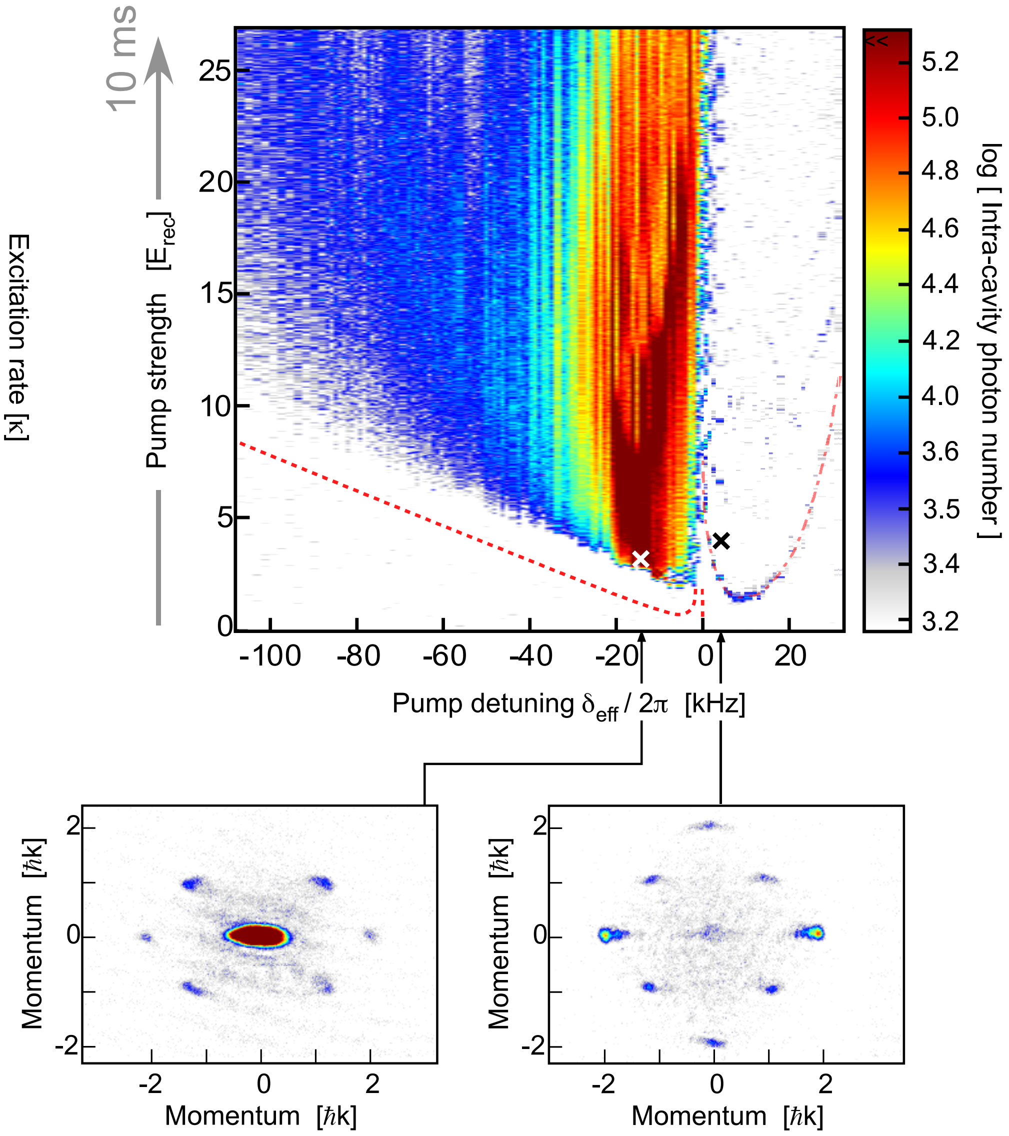
Dicke phase boundary

J. Klinder et al., PNAS, 112, 3290 (2015)

Observation of phase diagram

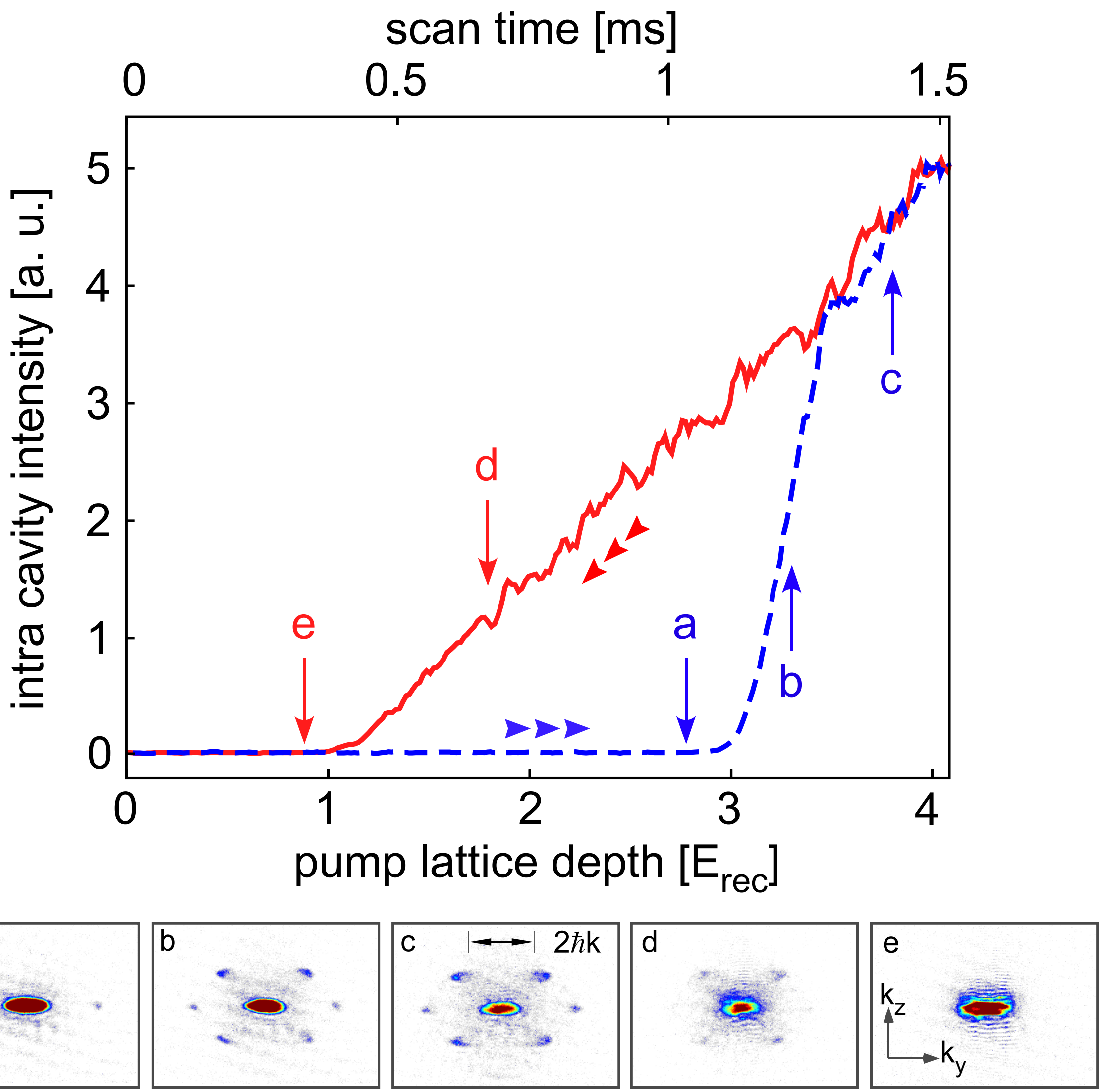


experiment



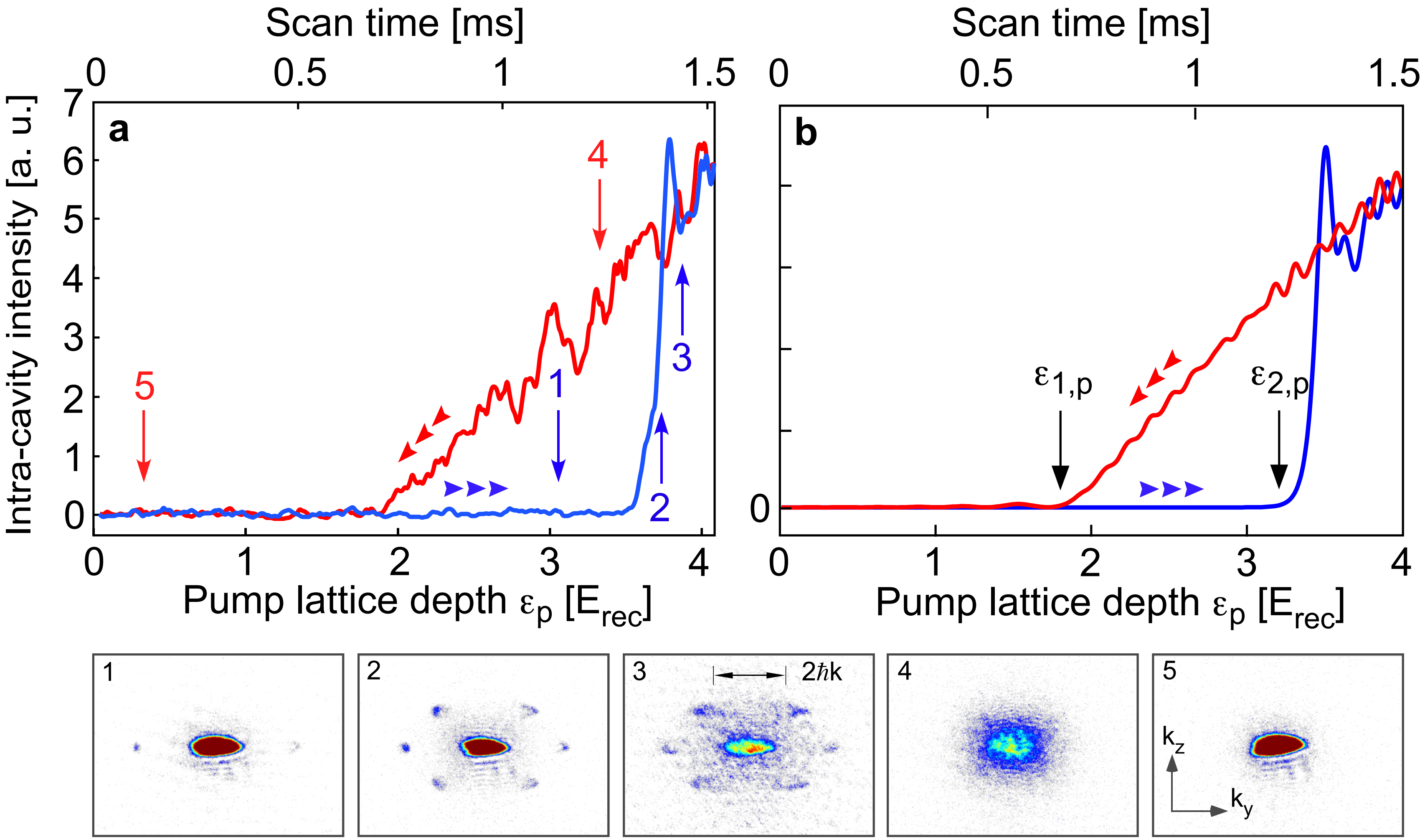
J. Klinder et al., PNAS, 112, 3290 (2015)

Crossing the phase boundary



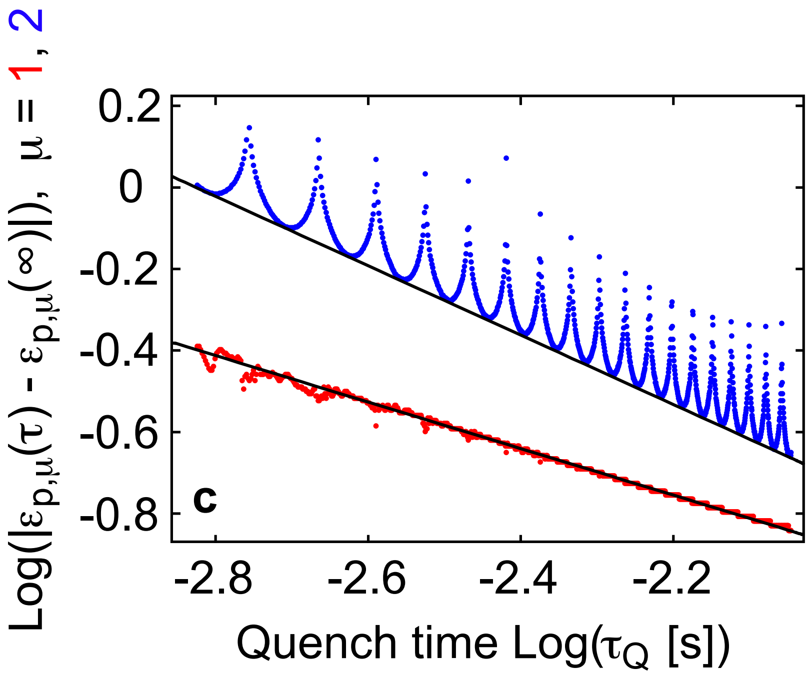
J. Klinder et al., PNAS, 112, 3290 (2015)

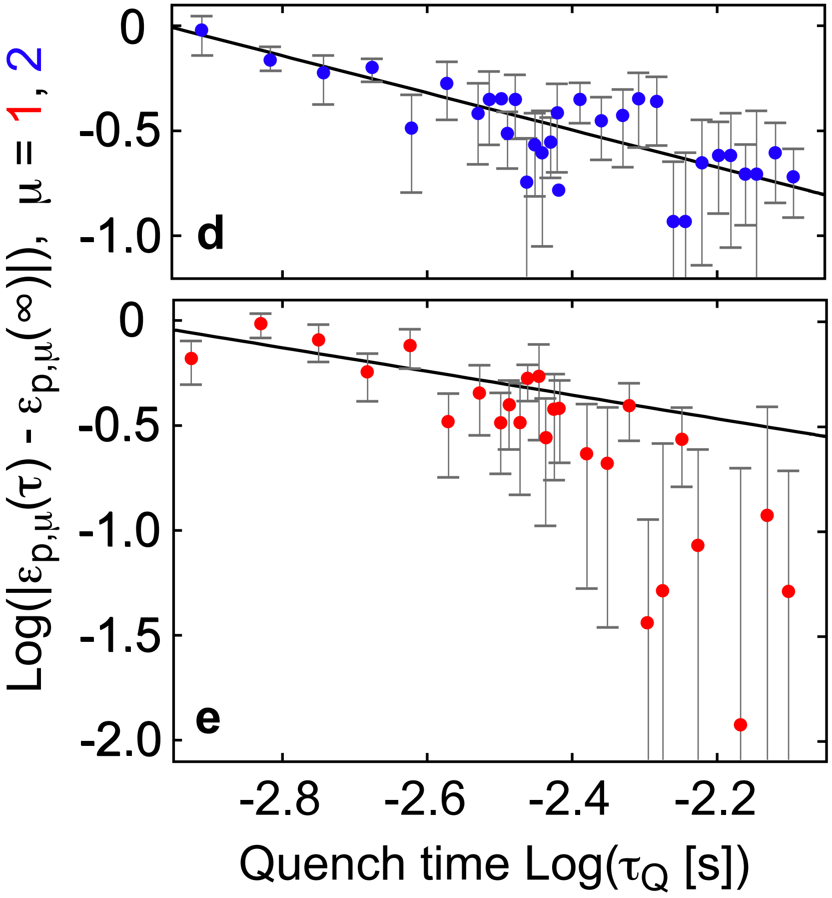
Comparison to mean field calculation



J. Klinder et al., PNAS, 112, 3290 (2015)

Dependance of dynamical transition thresholds on the quench time





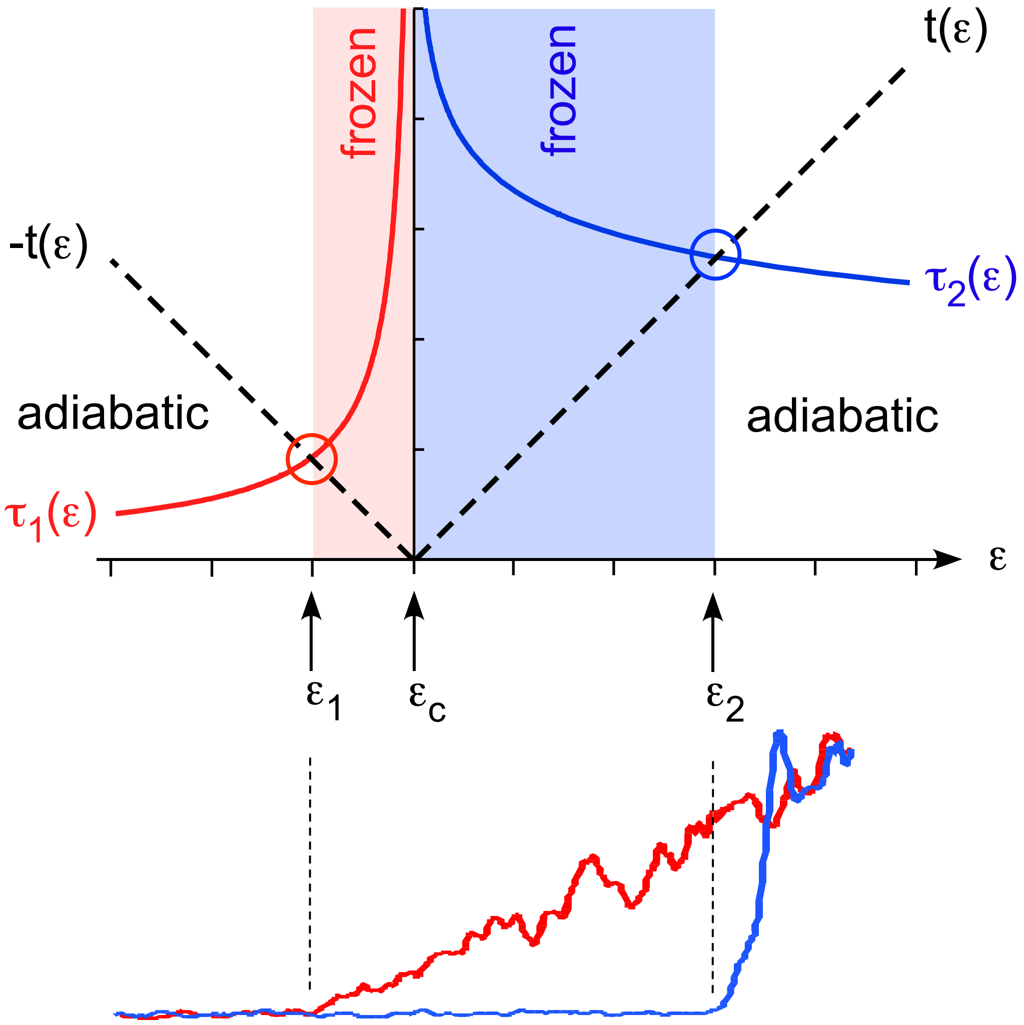
$$\varepsilon_{p,\mu} - \varepsilon_c \sim \tau_Q^{n_\mu}$$

$$n_1 = -0.57, n_2 = -0.85$$

J. Klinder et al., PNAS, 112, 3290 (2015)

Kibble Zurek scenario

del Campo & Zurek,
Int. J. Mod. Phys. A 29, 1430018 (2014).



$$\tau_\mu(\varepsilon) = \frac{\tau_0}{|\varepsilon - \varepsilon_c|^{z_\mu \nu_\mu}}$$

$$t(\varepsilon) = t_c + \frac{\varepsilon - \varepsilon_c}{\Delta\varepsilon}\,\tau_Q$$

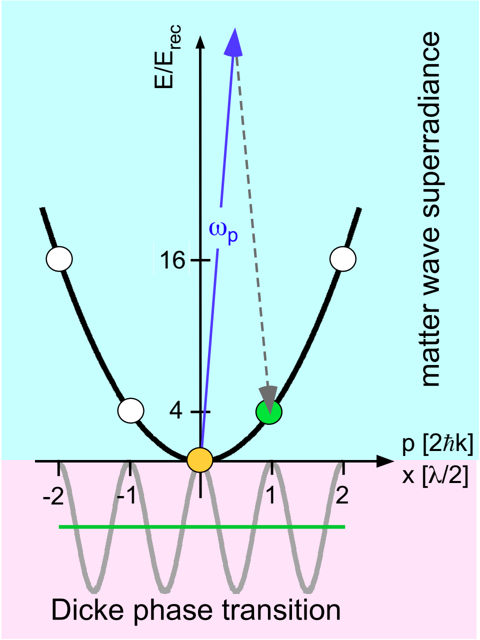
$$|t(\varepsilon_\mu)| = \tau_\mu(\varepsilon_\mu)$$

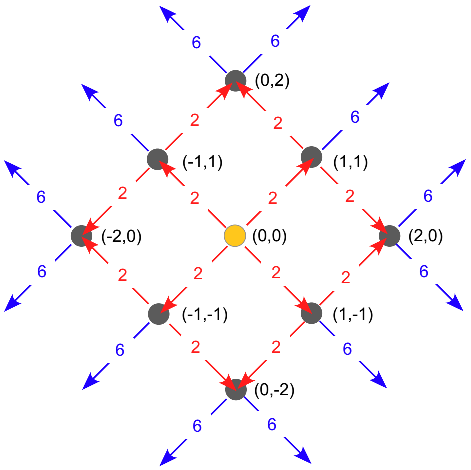
⬇

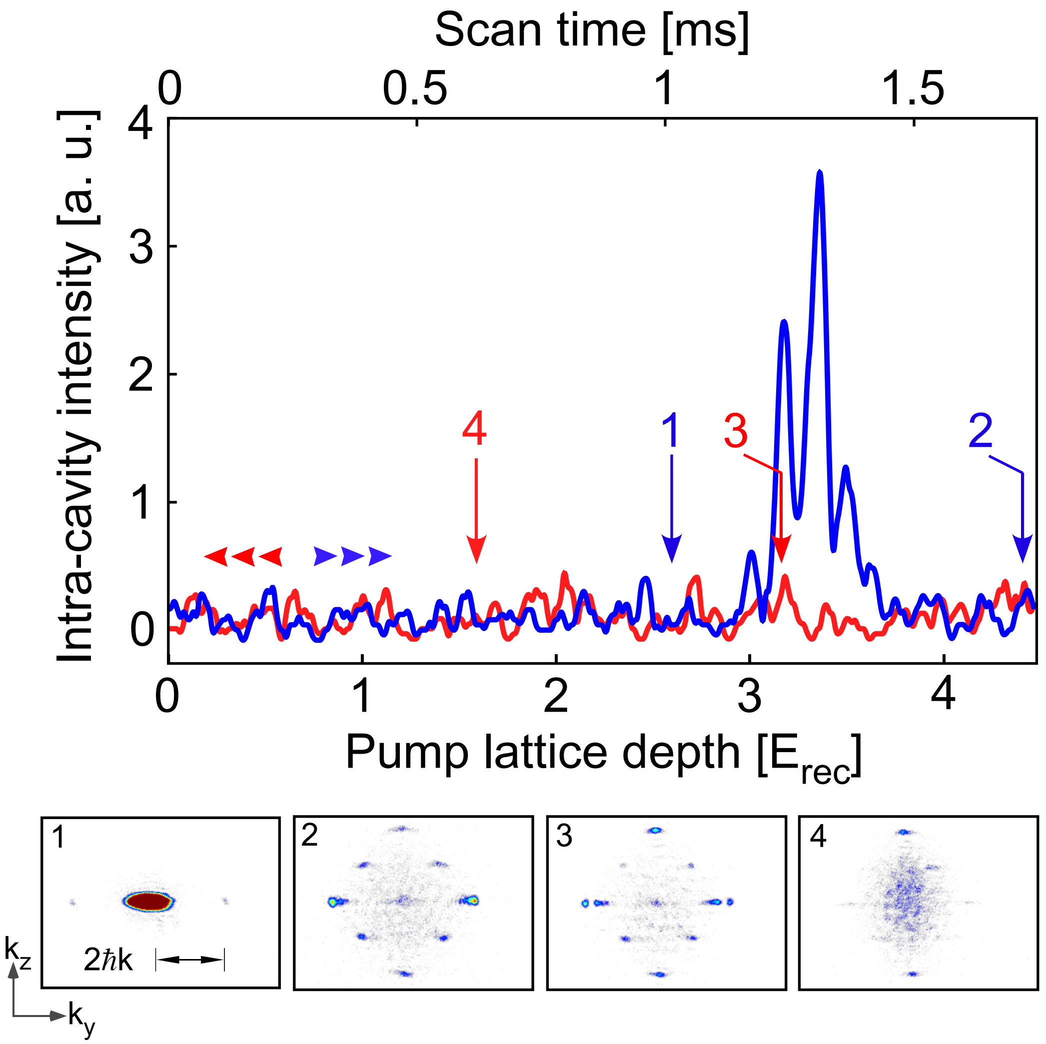
$$z_\mu \nu_\mu = -\left(1 + \frac{1}{n_\mu}\right), \quad \mu = 1,2$$

$$z_1\nu_1 = 0.75, \quad z_2\nu_2 = 0.18$$

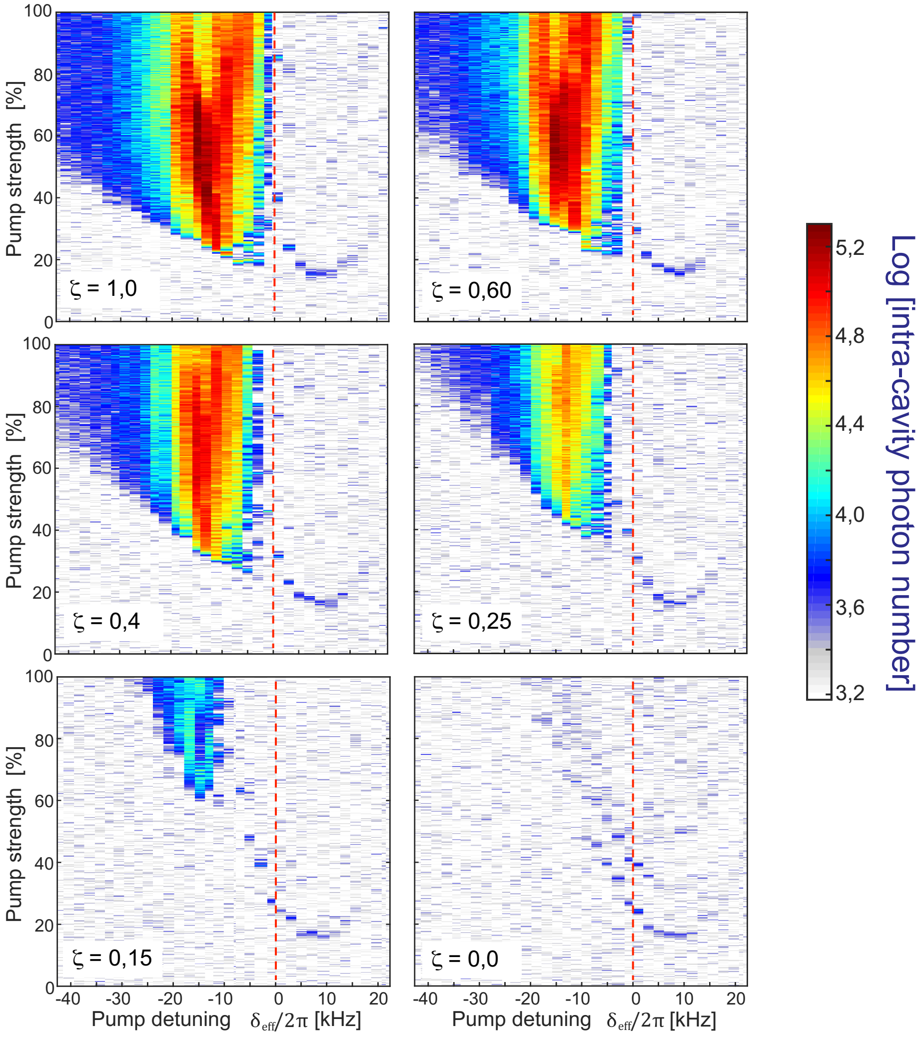
Positive detuning: Matter wave superradiance



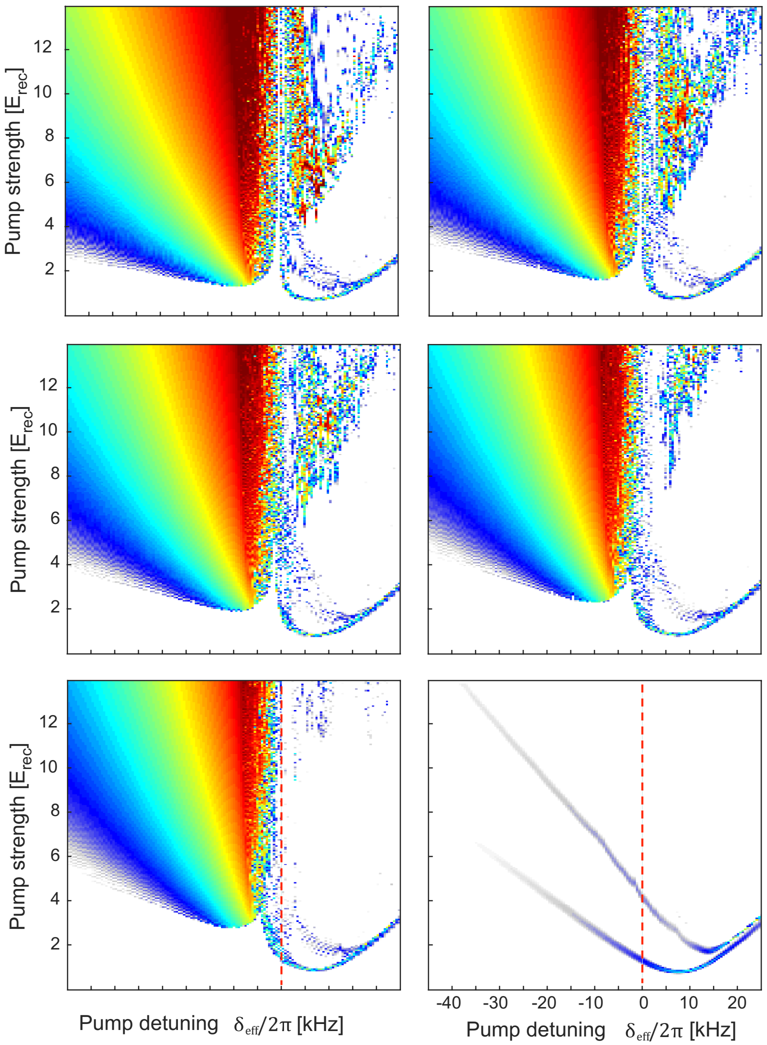




Crossover from bi-directional to uni-directional pumping

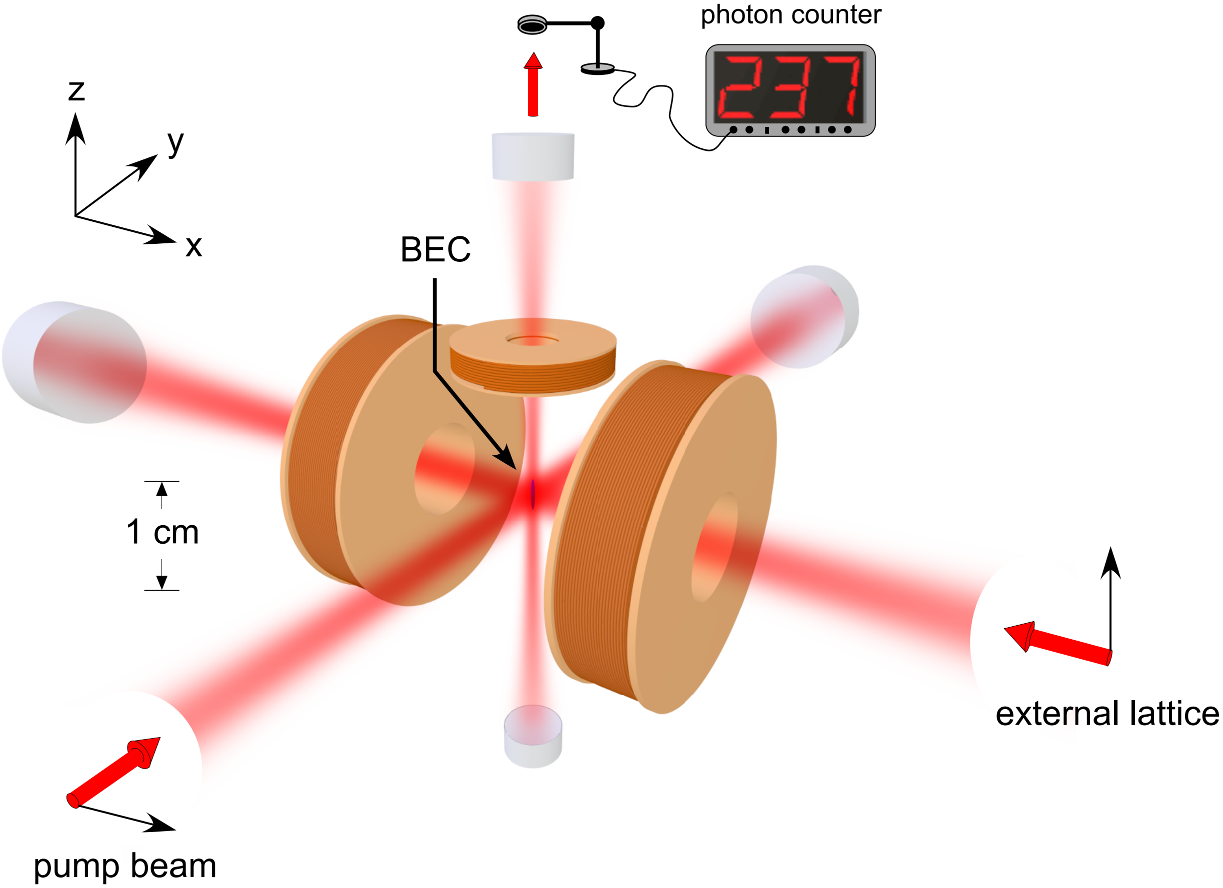


Experiment



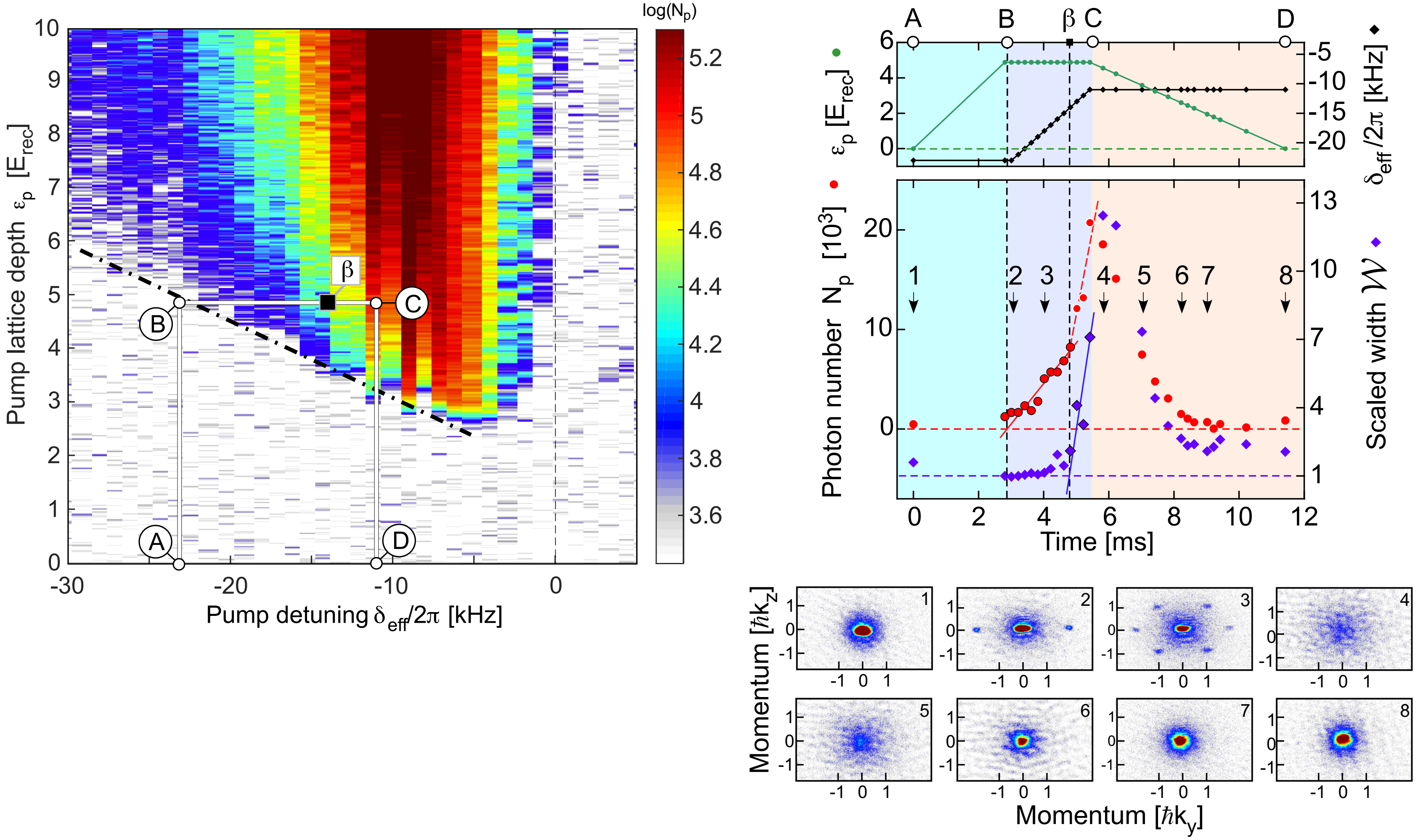
Mean field calculation

Combining Dicke model and bosonic Hubbard model



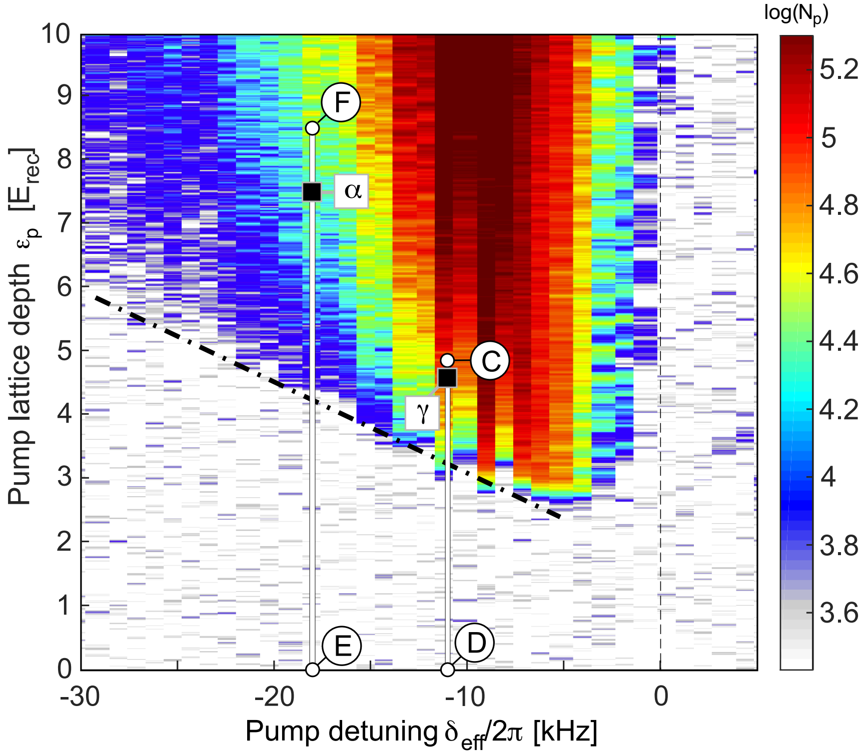
J. Klinder et al., PRL, 115, 230403 (2015)

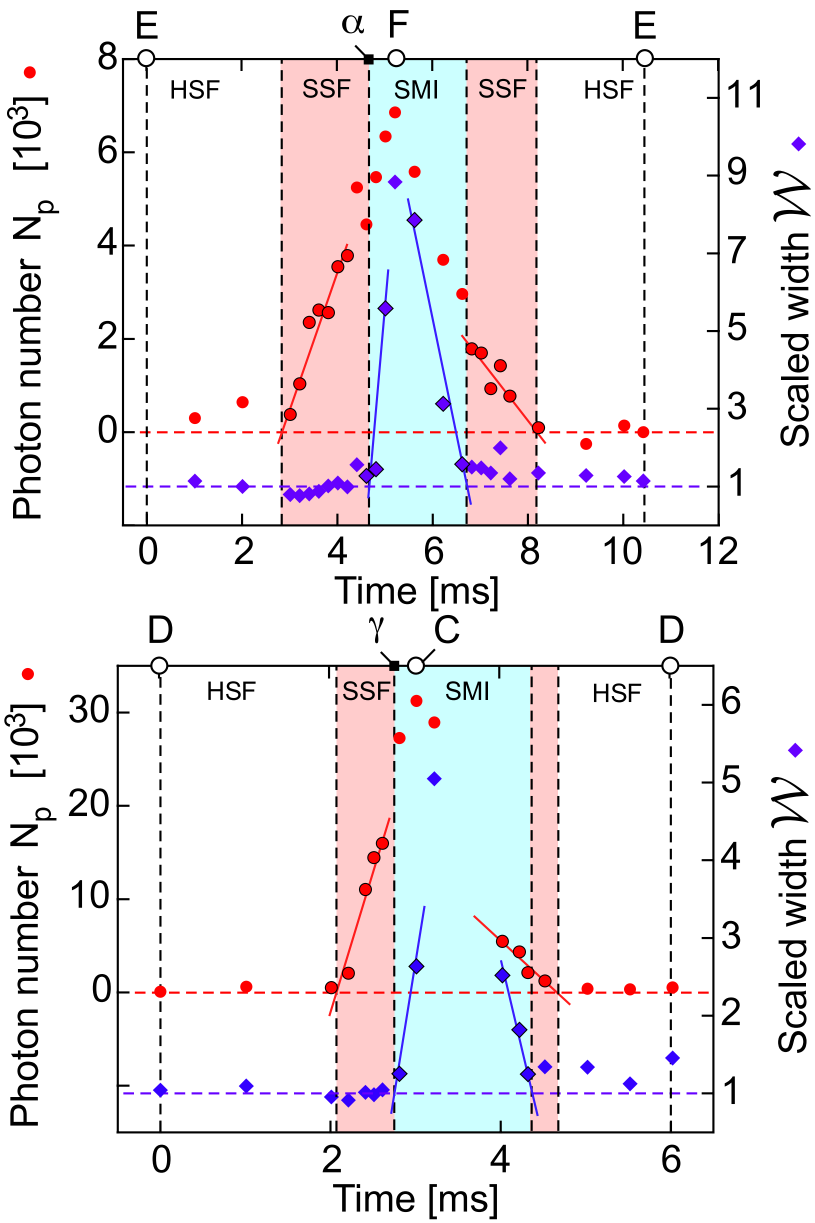
Mapping out phase diagram



- note the kink in the intra-cavity photon number as point β is passed
- note rapid loss of coherence as point β is passed

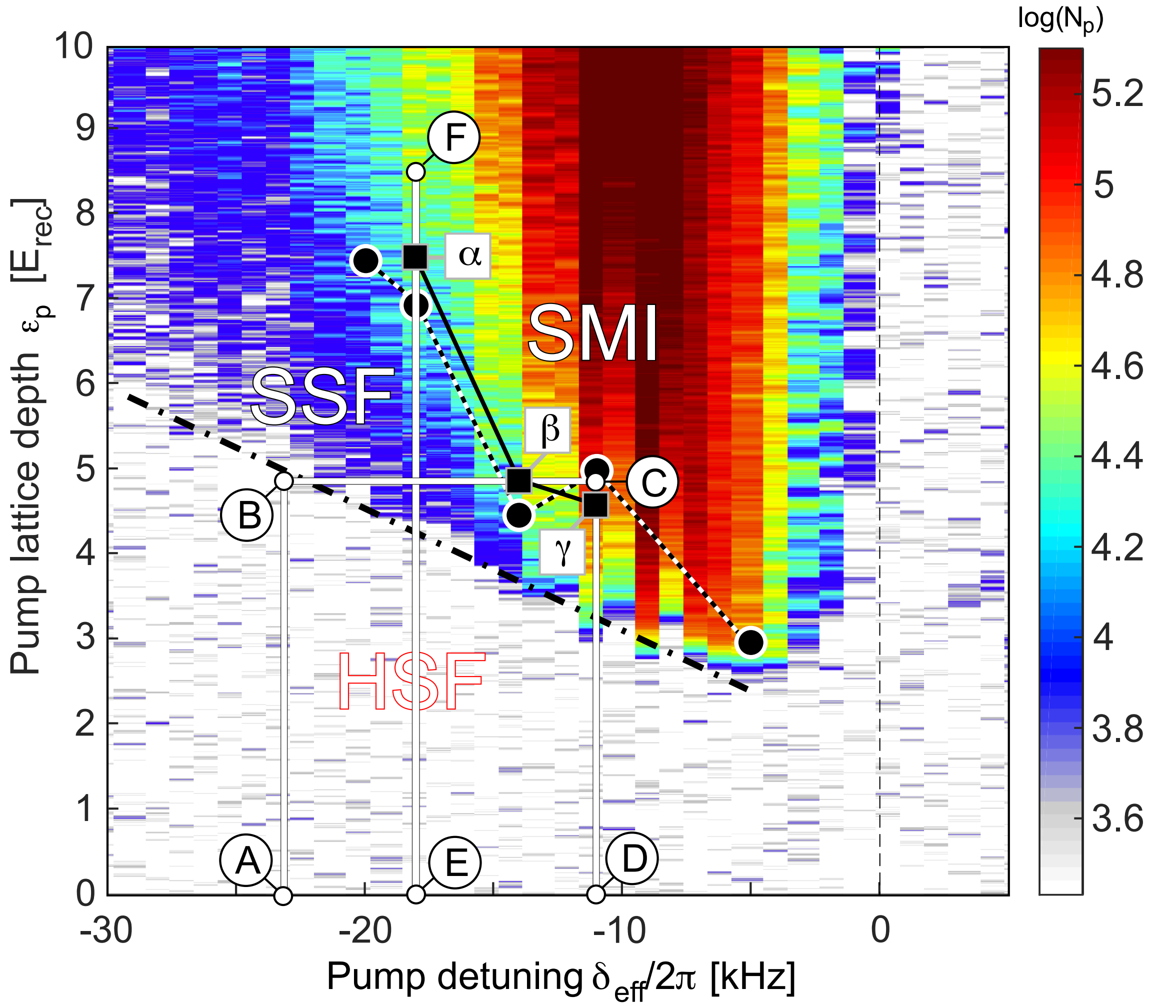
Mapping out phase diagram





J. Klinder et al., PRL, 115, 230403 (2015)

Mapping out phase diagram



J. Klinder et al., PRL, 115, 230403 (2015)

The Cavity Team

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