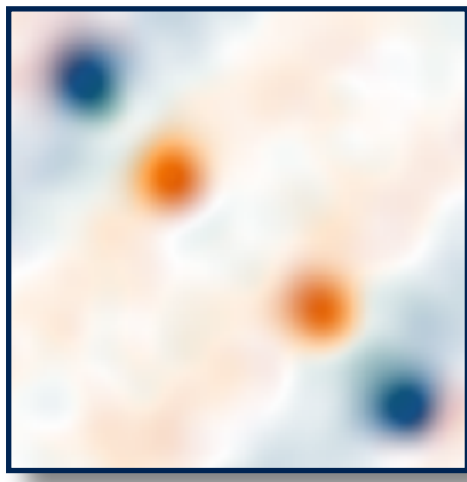
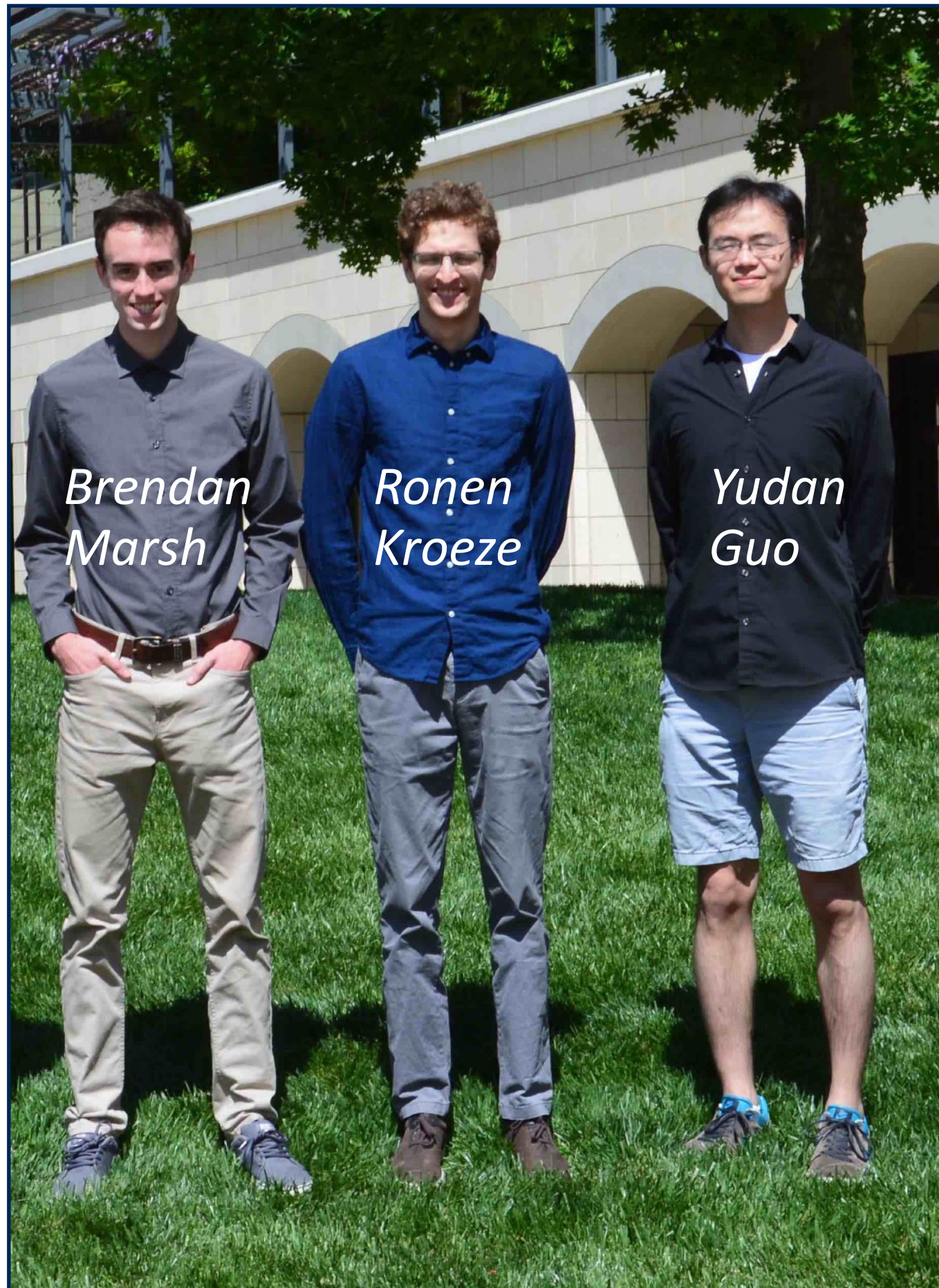




Multimode cavity QED for many-body physics: Engineering photon-mediated interactions among atoms and spins



Brendan
Marsh

Ronen
Kroeze

Yudan
Guo



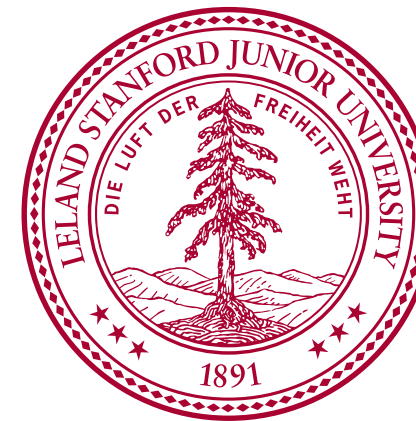
Prof. Jonathan Keeling (St. Andrews)

Prof. Sarang Gopalakrishnan (CUNY)

Prof. Surya Ganguli (Stanford)



Benjamin Lev
Departments of Physics and Applied Physics

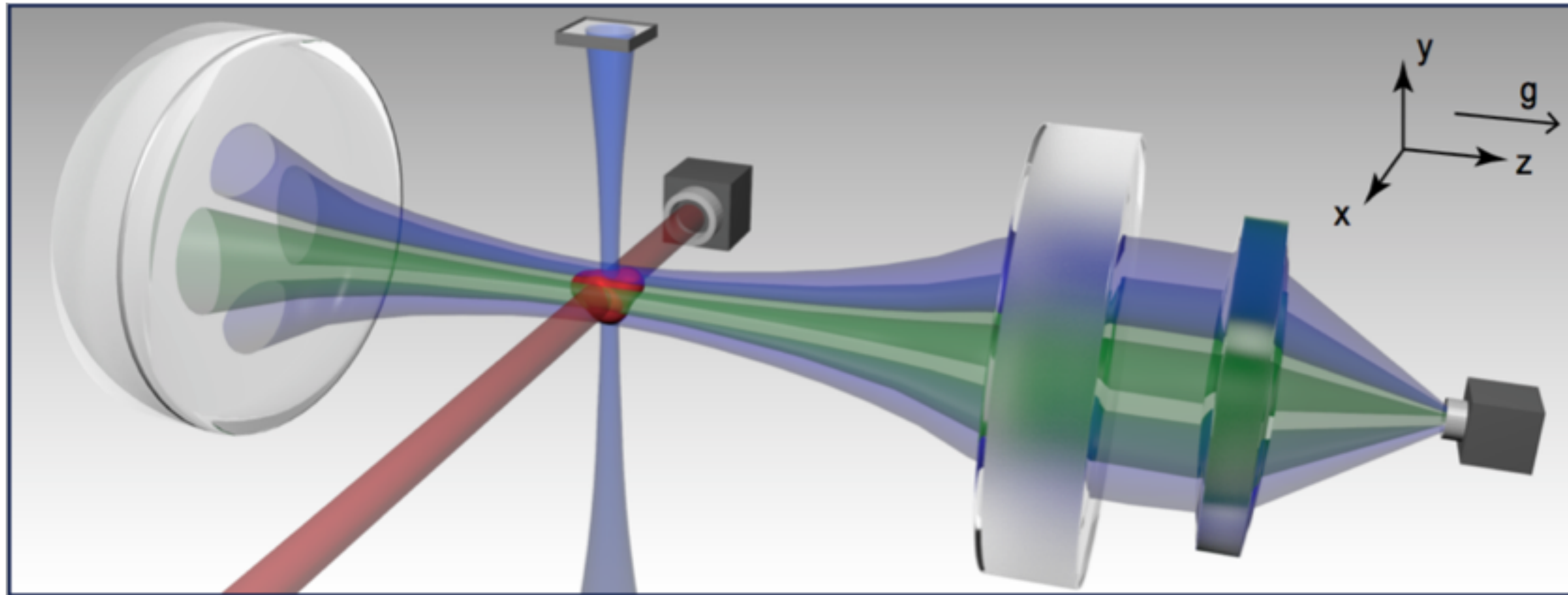


STANFORD
UNIVERSITY

LevLab.stanford.edu

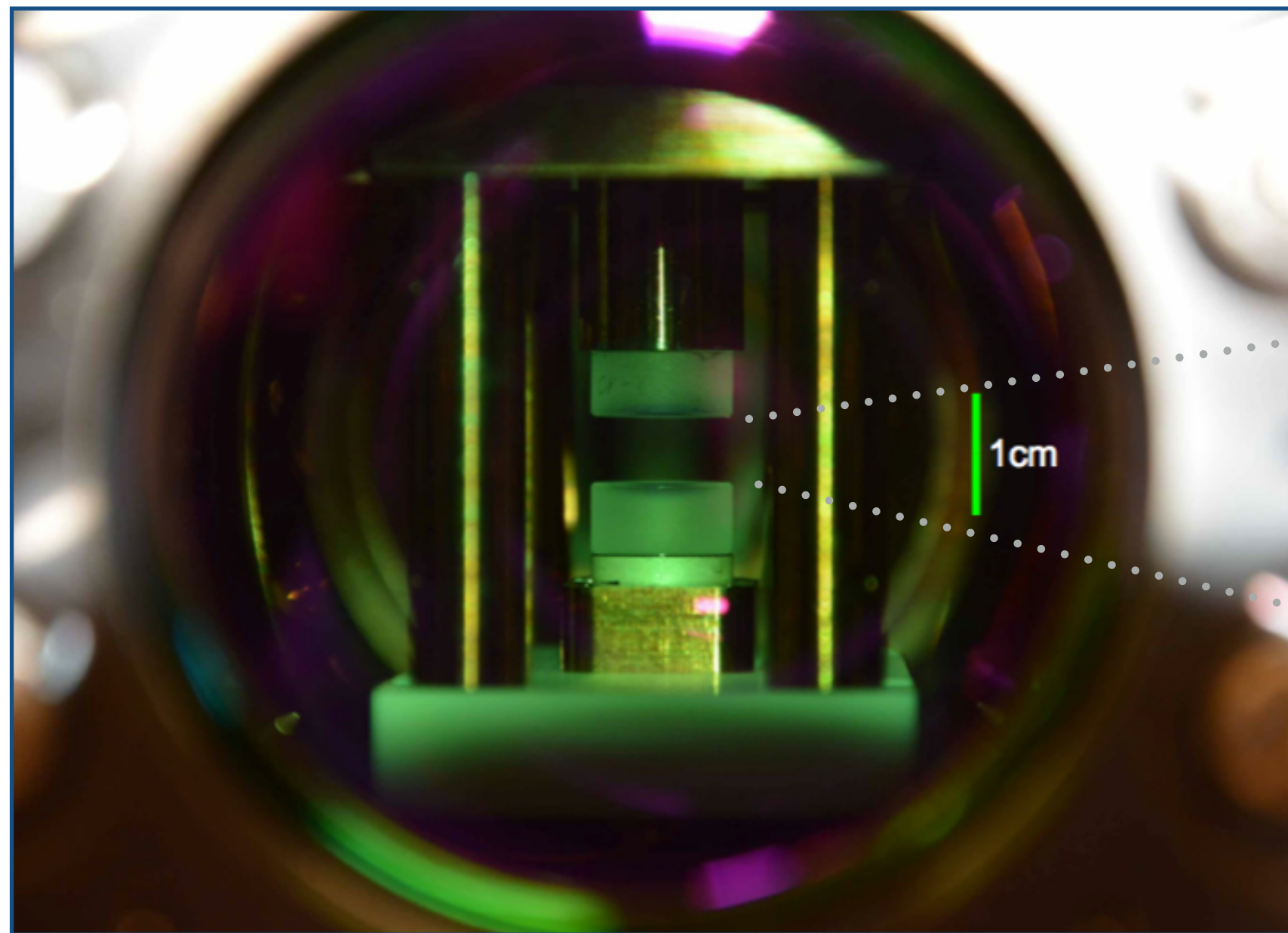
Multimode cavity QED w/BEC & spins

An intrinsically open (driven-dissipative) quantum system

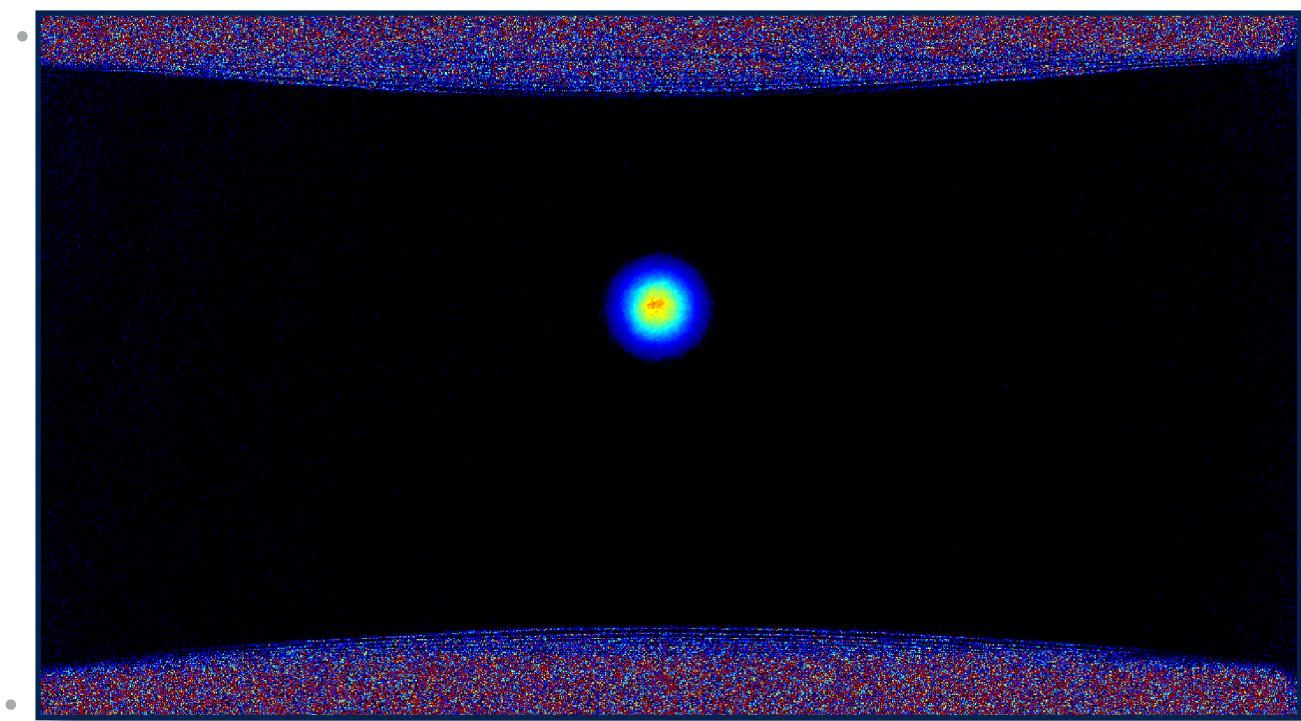


Adjustable-length cavity-BEC apparatus

Confocal cavity (10^3 modes) with BEC

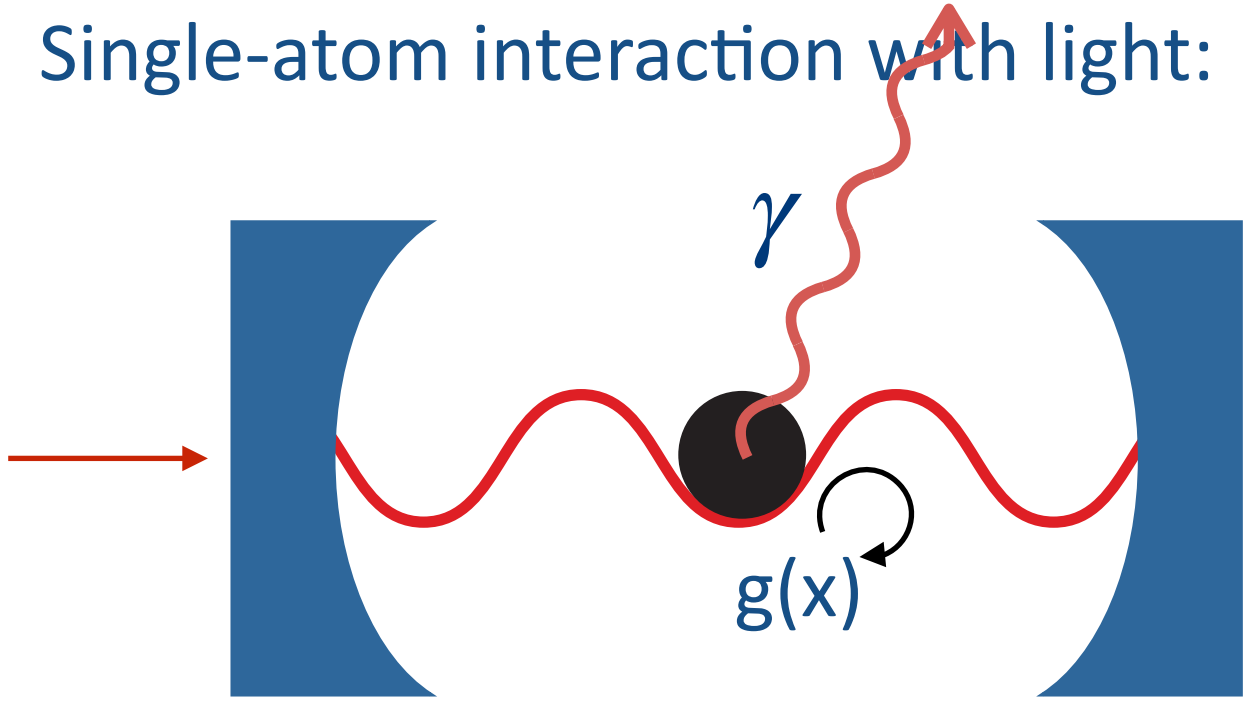


^{87}Rb BEC with 10^5 atoms



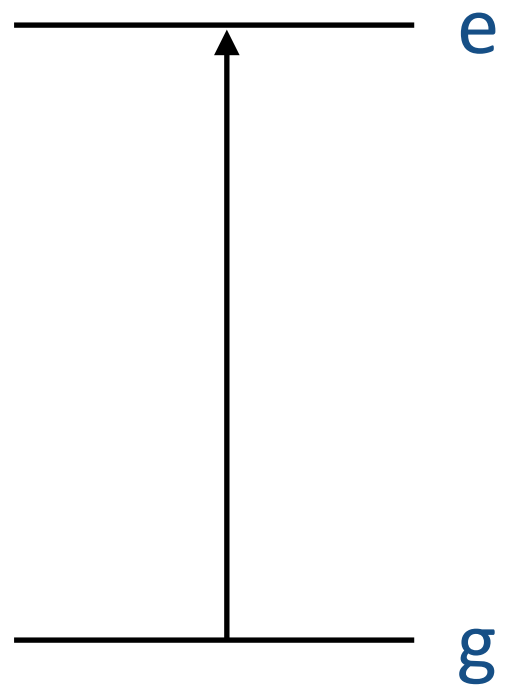
Photon-mediated atom-atom interaction

Single-atom interaction with light:



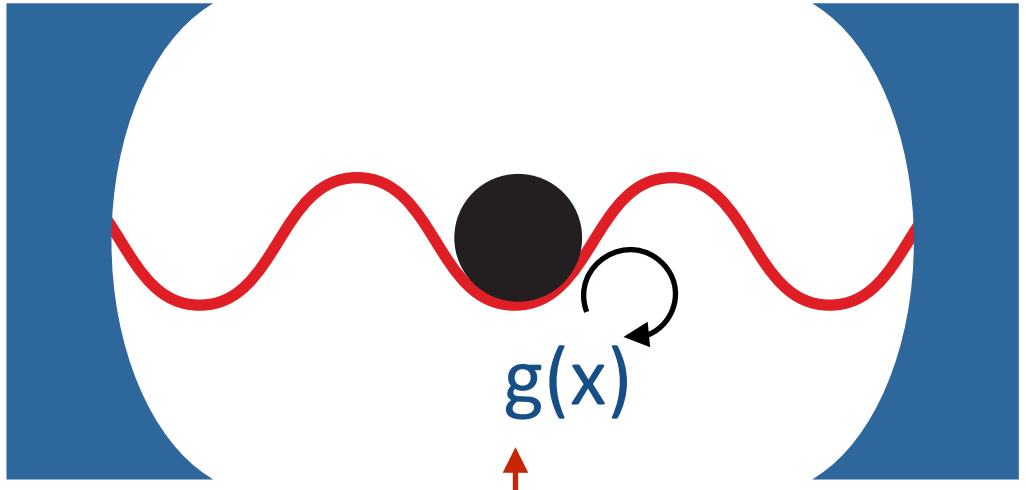
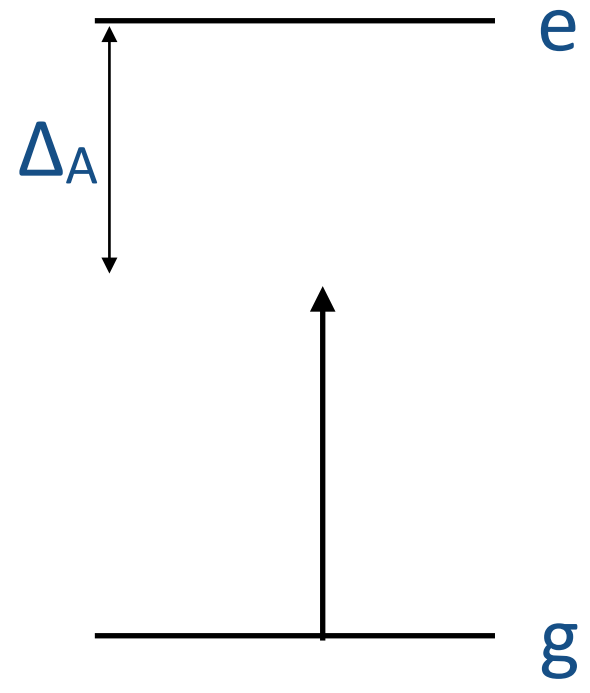
On resonance:

$$H_{int} \propto g(x)$$



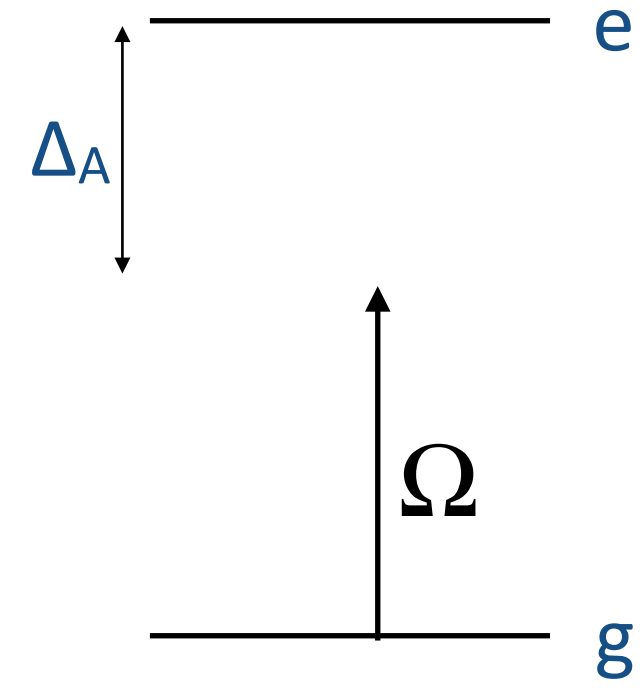
Off resonance:

$$H_{int} \propto \frac{g(x)^2}{\Delta_A}$$

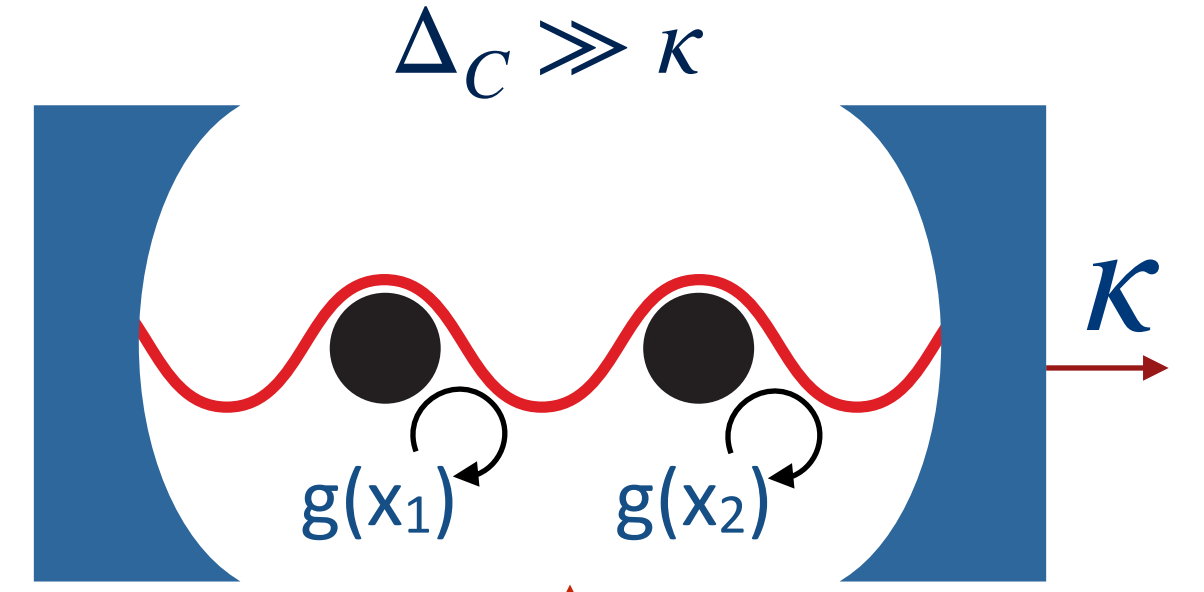


$$I_{pump} \propto \Omega^2$$

$$H_{int} \propto \frac{g(x)\Omega}{\Delta_A}$$



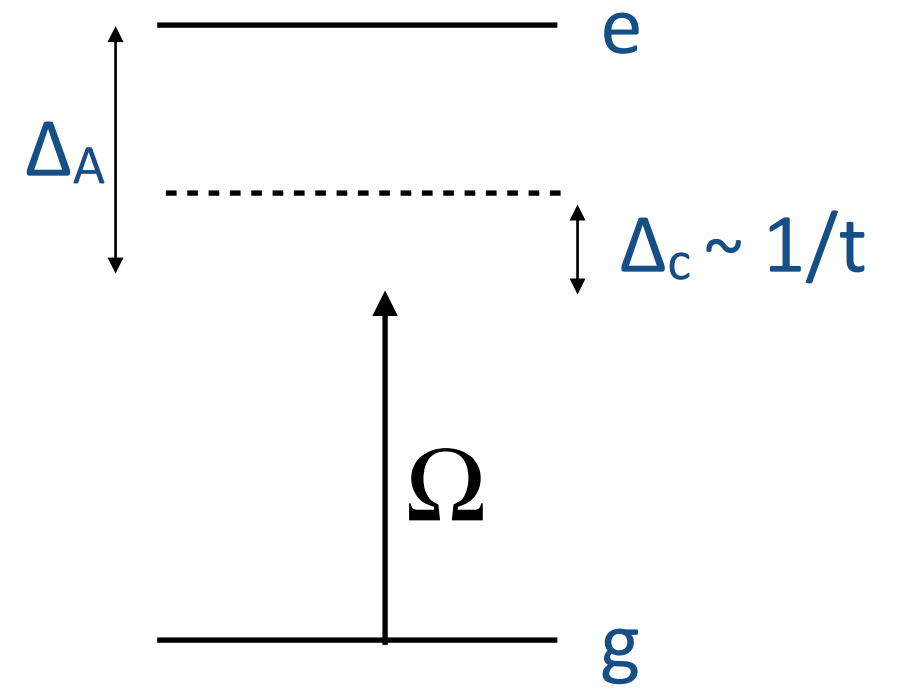
Atom-atom interaction:



$$\Delta_C \gg \kappa$$

$$I_{pump} \propto \Omega^2$$

$$H_{int} = \frac{g(x_1)g(x_2)\Omega^2}{\Delta_A^2\Delta_C}$$

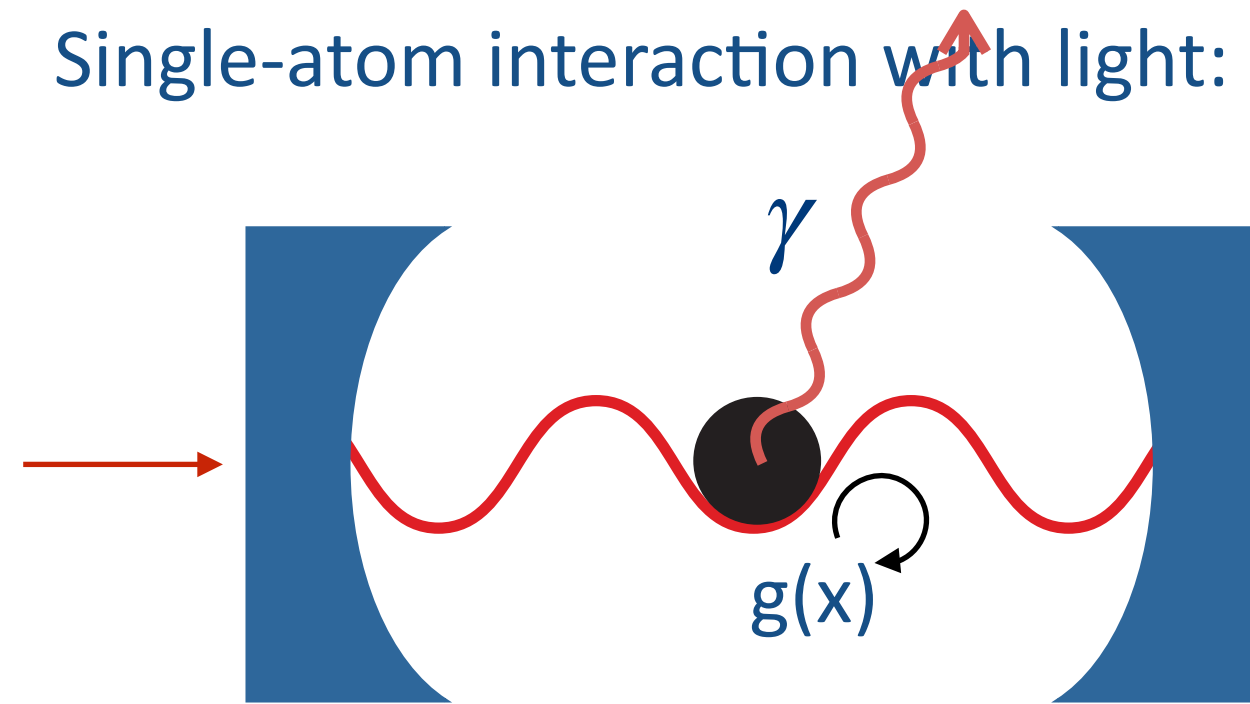


Photon-mediated atom-atom interaction

$$H_{int} = \frac{g_0^2 \Omega^2}{\Delta_A^2 \Delta_C} \Xi_{lm}(x_1, y_1, z_1) \Xi_{lm}(x_2, y_2, z_2)$$

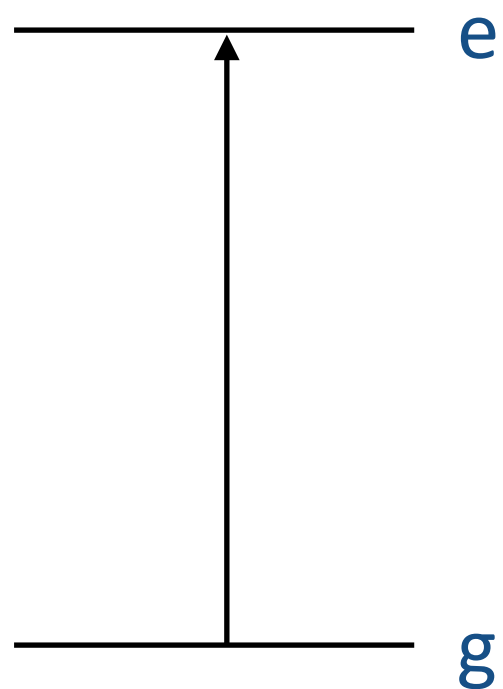
Mode function $\Xi_{lm}(y_1, z_1)$

Single-atom interaction with light:



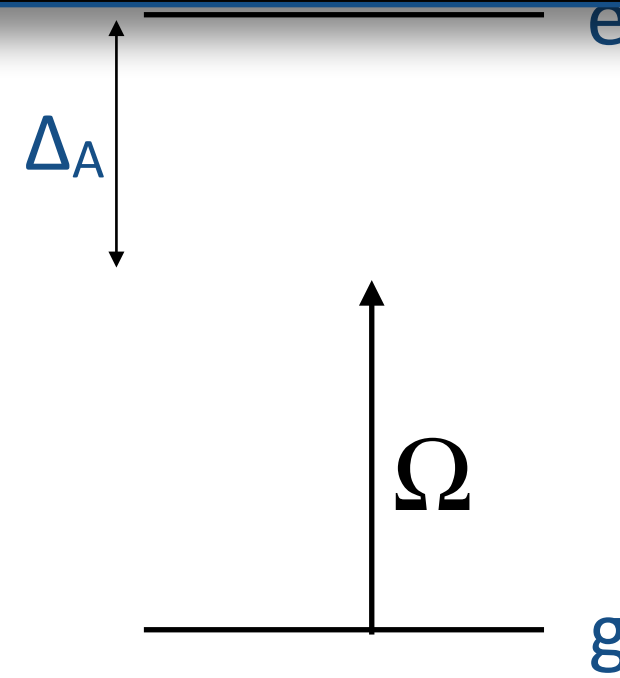
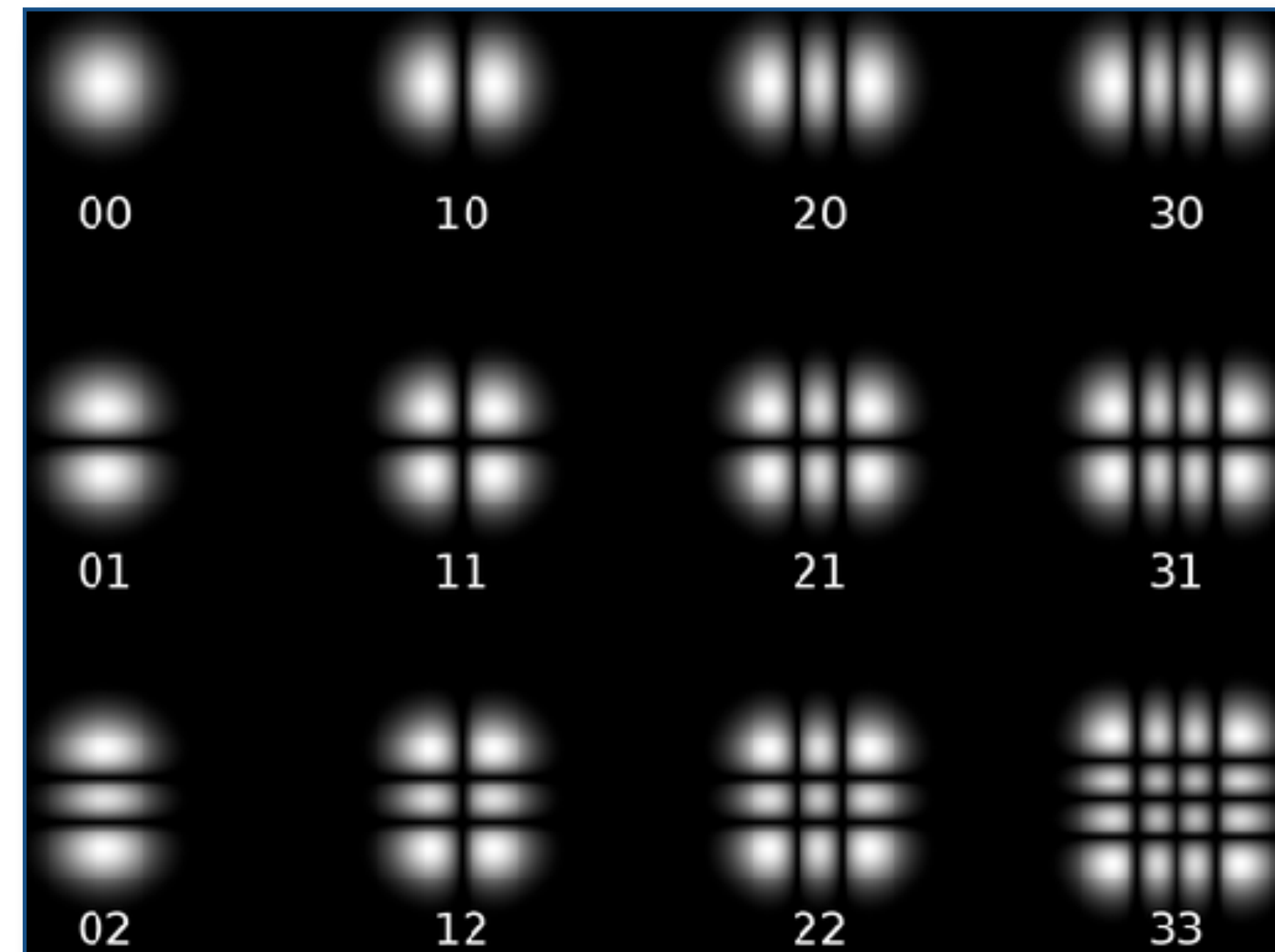
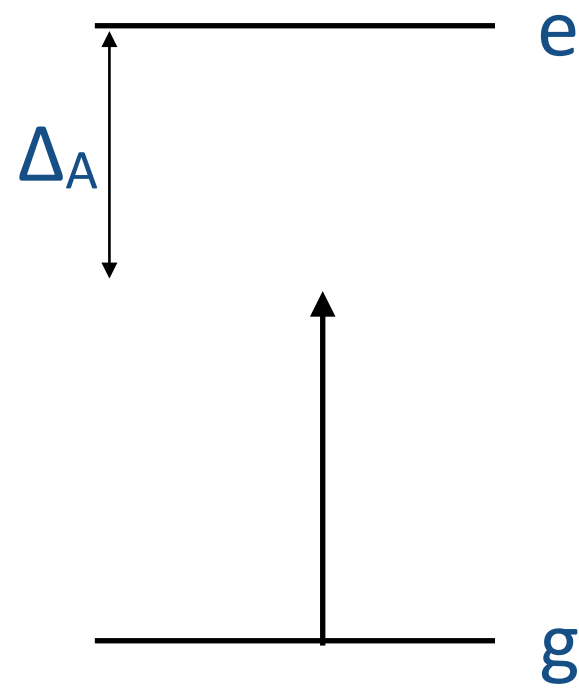
On resonance:

$$H_{int} \propto g(x)$$

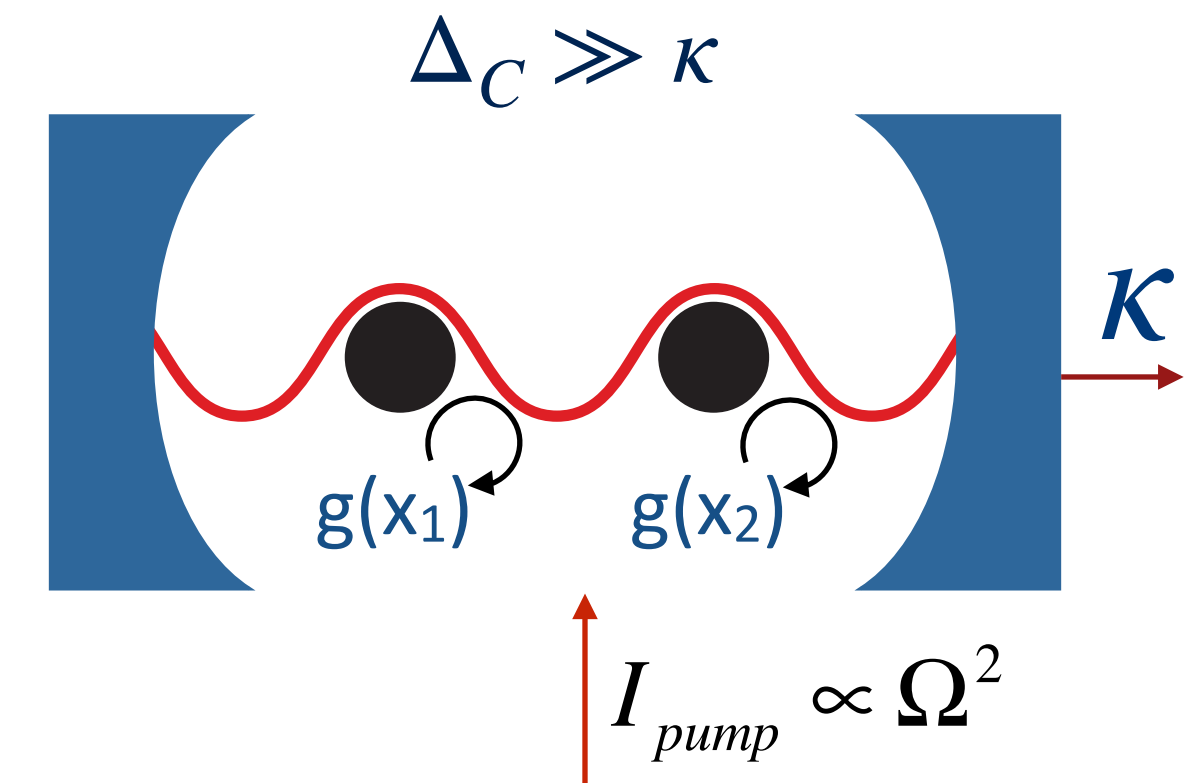


Off resonance:

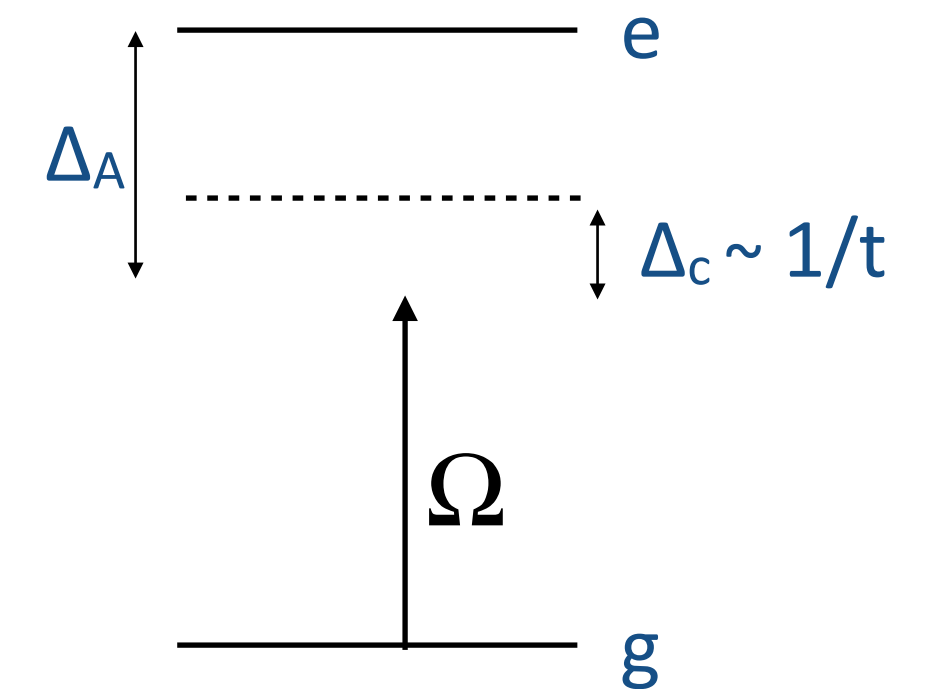
$$H_{int} \propto \frac{g(x)^2}{\Delta_A}$$



Atom-atom interaction:



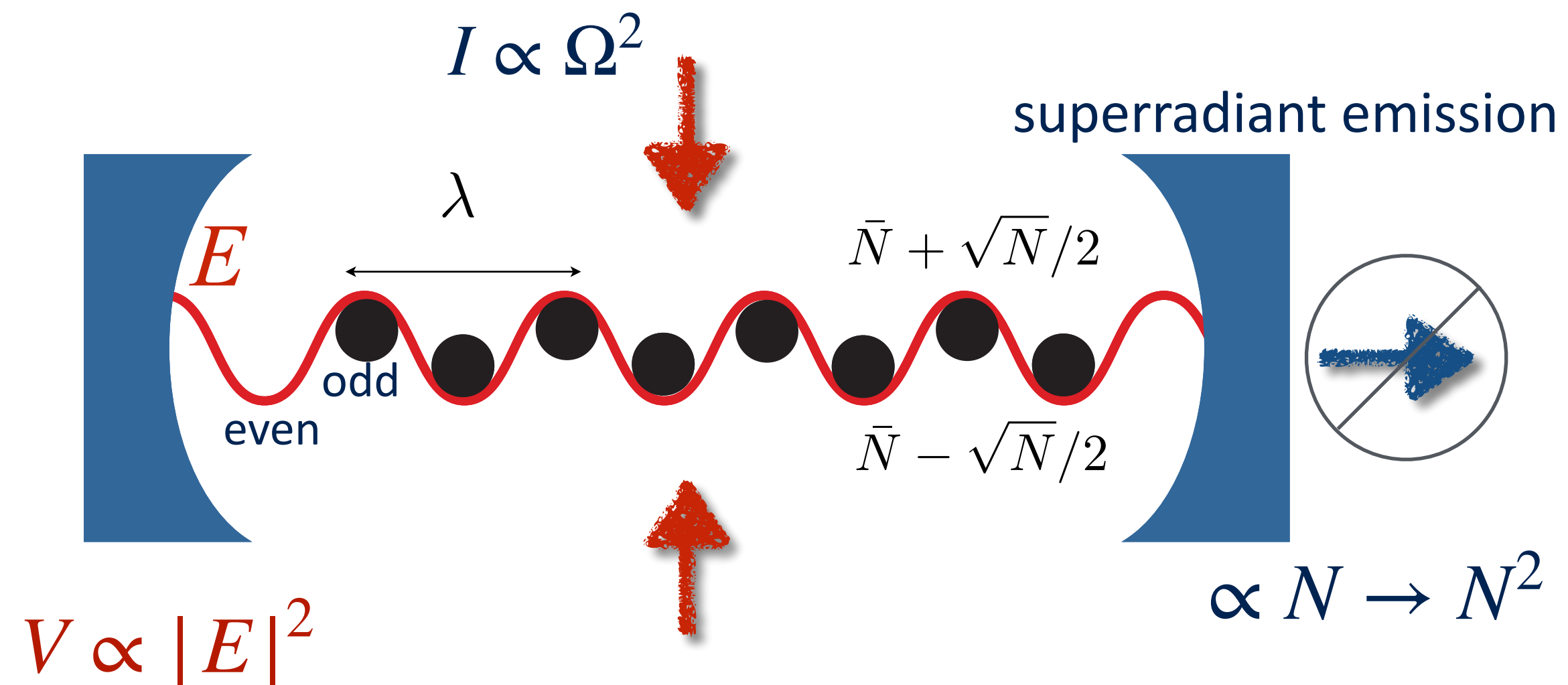
$$H_{int} = \frac{g(x_1)g(x_2)\Omega^2}{\Delta_A^2 \Delta_C}$$



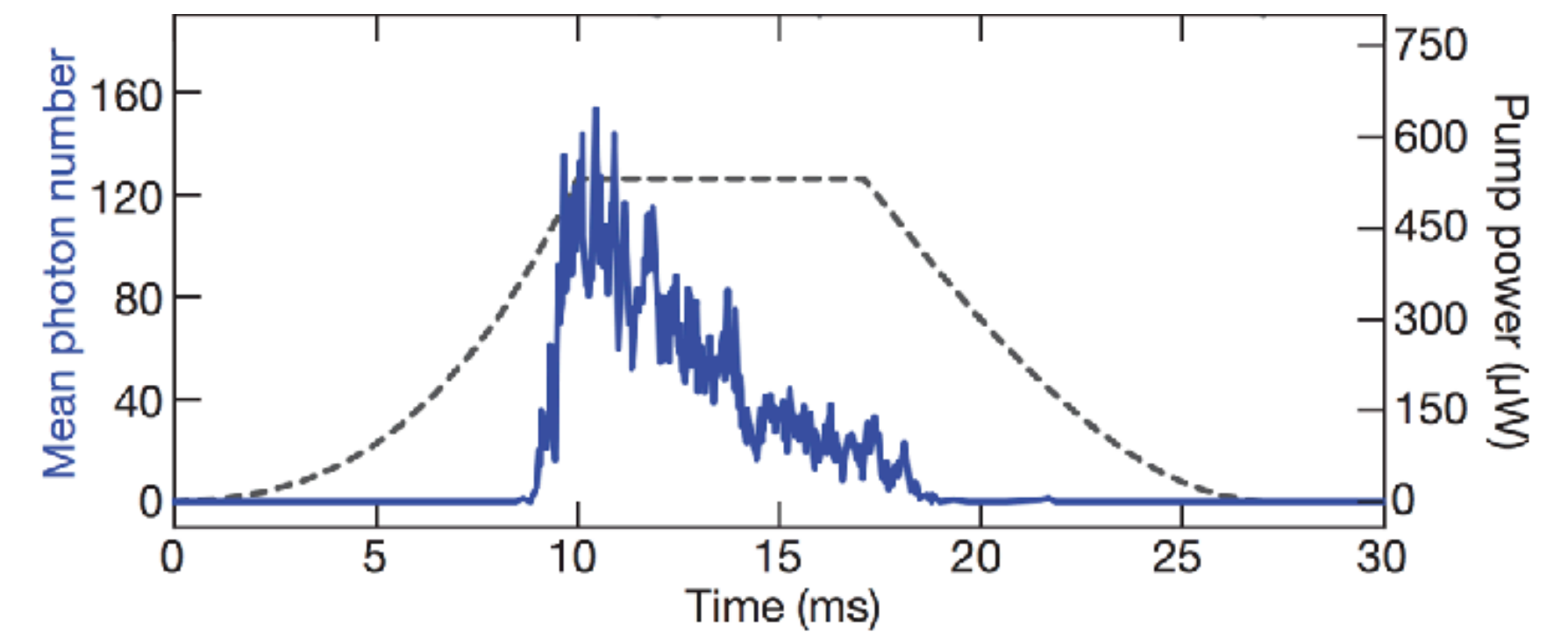
Self-organization in single-mode cavity

V. Vuletić; H. Ritsch & P. Domokos; H. Carmichael & S. Parkins; & T. Esslinger et al.

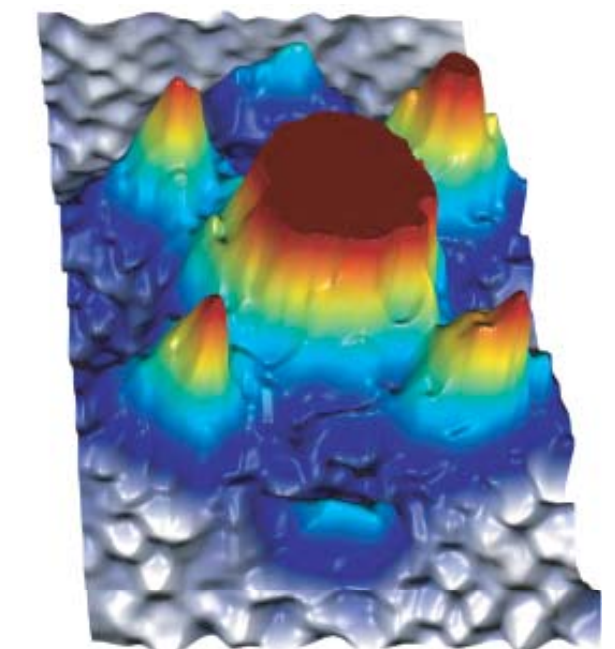
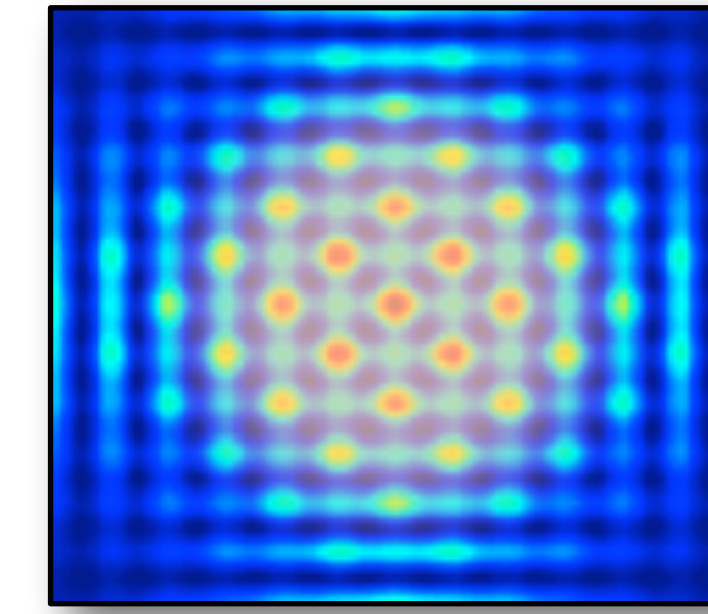
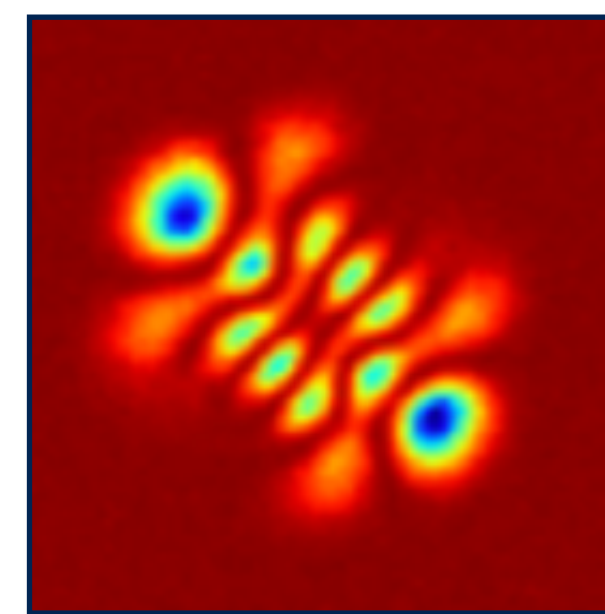
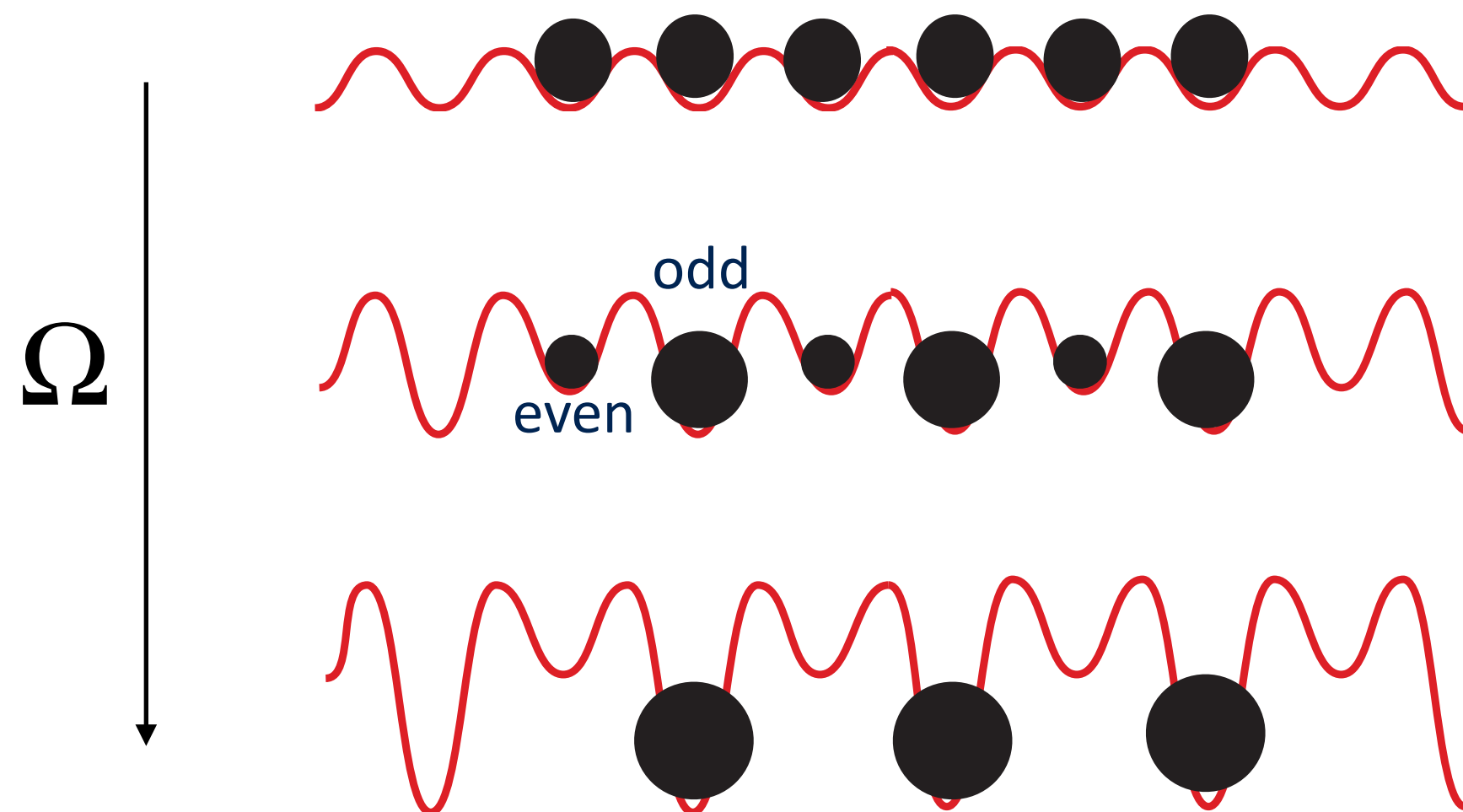
With BEC or spins, transition is a nonequilibrium superradiant (Hepp-Lieb) Dicke transition



$$NC > 1 \quad C \equiv g_0^2/\kappa\gamma$$



Supermode density-wave polariton condensate



T. Esslinger et al., Nature '10

A. Kollár, A. Papageorge, V. Vaidya, Y. Guo, J. Keeling, & B. Lev, Nature Comm. '17

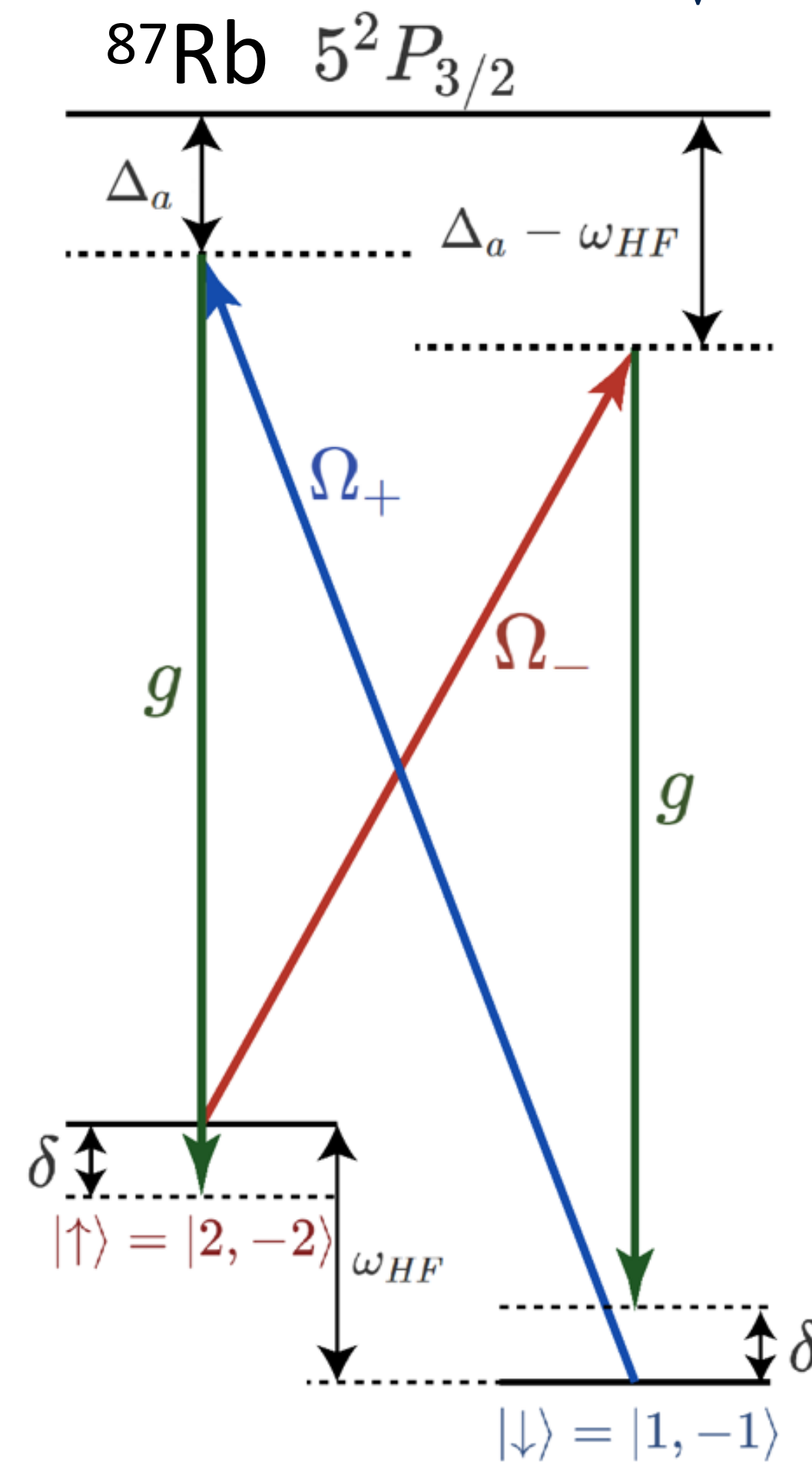
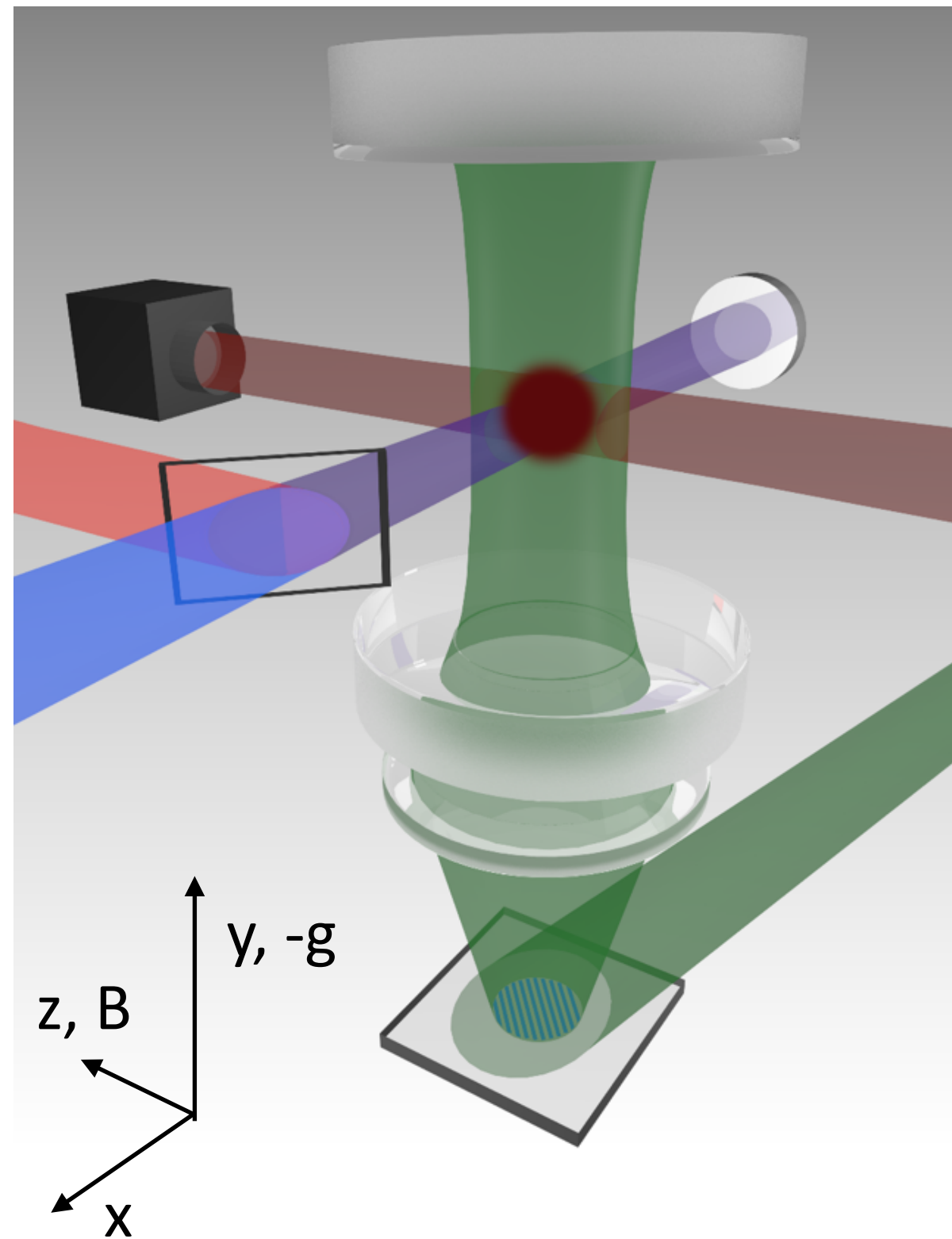
Spin-spin interactions in cavity QED

Double Raman pumps realize *superradiant* (Hepp-Lieb) Dicke nonequilibrium phase transition

$$H_{\text{Dicke}} = -\Delta_C \hat{a}^\dagger \hat{a} - \delta \hat{J}_z + \frac{\eta}{\sqrt{N}} (\hat{J}_+ + \hat{J}_-) (\hat{a} + \hat{a}^\dagger)$$

Superradiant threshold when:

$$\eta \equiv \frac{\sqrt{N} g \Omega}{\Delta_A} = \sqrt{\Delta_C \delta}$$



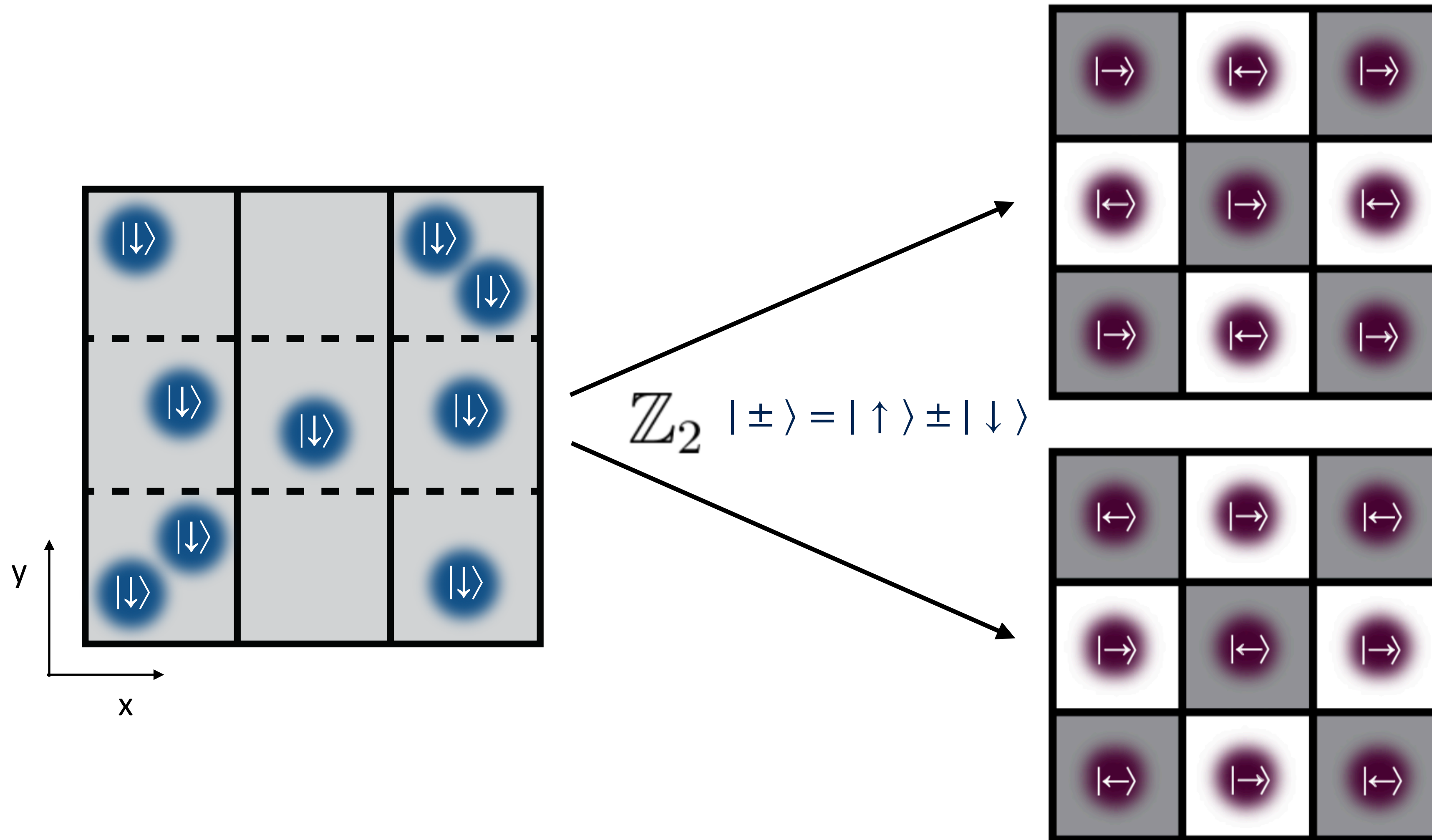
Dimer ... Carmichael PRA '07

S. Gopalakrishnan, B. Lev, & P. Goldbart PRL '11

S. Gopalakrishnan, B. Lev, & P. Goldbart Phil. Mag. (2012)

R. Kroeze, Y. Guo, V. Vaidya, J. Keeling & B. Lev, PRL '18

Spinor self-ordering phase



Spin-spin interactions in cavity QED

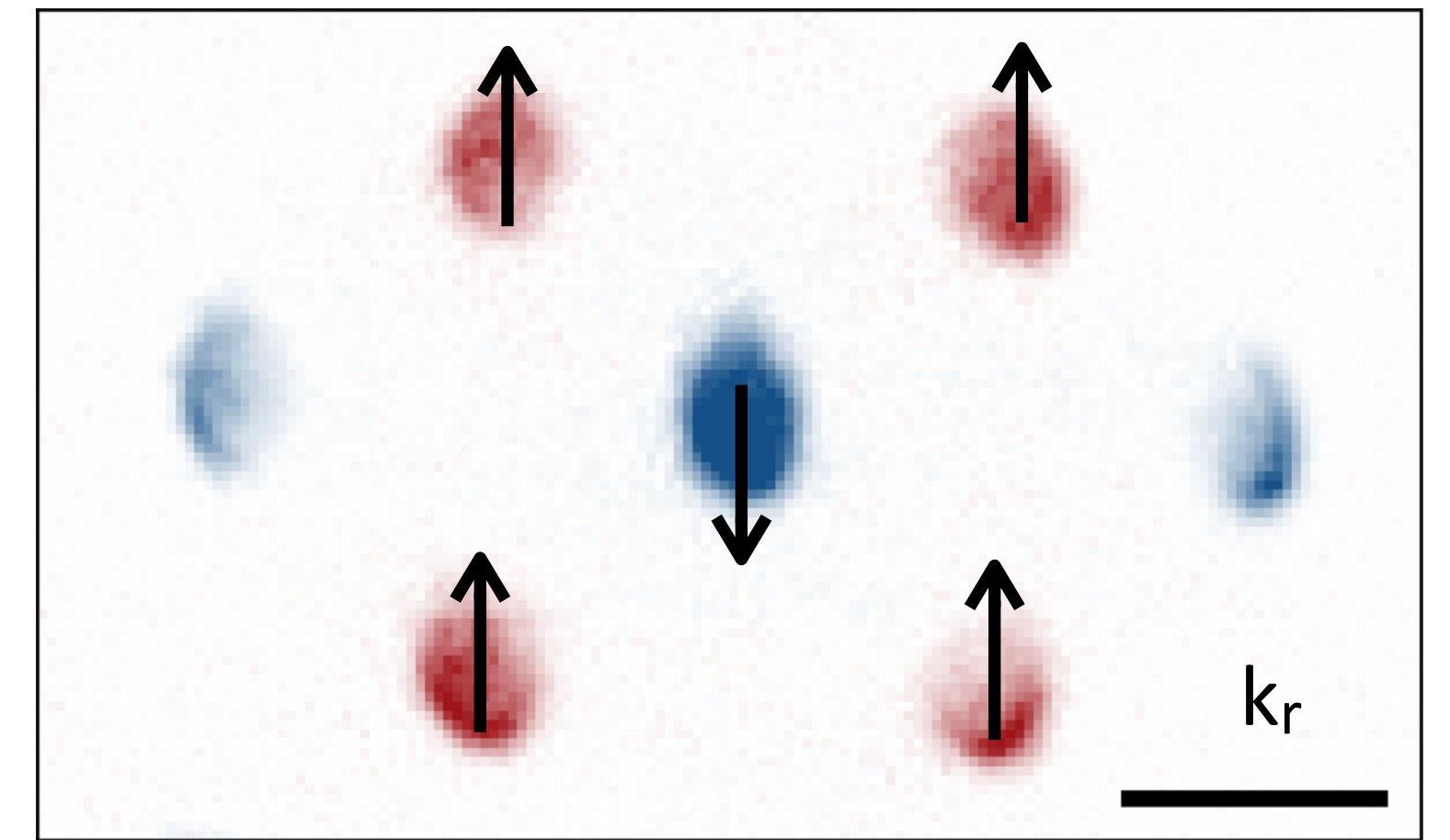
Double Raman pumps realize *superradiant* (Hepp-Lieb) Dicke nonequilibrium phase transition

$$H_{\text{Dicke}} = -\Delta_C \hat{a}^\dagger \hat{a} - \delta \hat{J}_z + \frac{\eta}{\sqrt{N}} (\hat{J}_+ + \hat{J}_-) (\hat{a} + \hat{a}^\dagger)$$

Superradiant threshold when:

$$\eta \equiv \frac{\sqrt{N} g \Omega}{\Delta_A} = \sqrt{\Delta_C \delta}$$

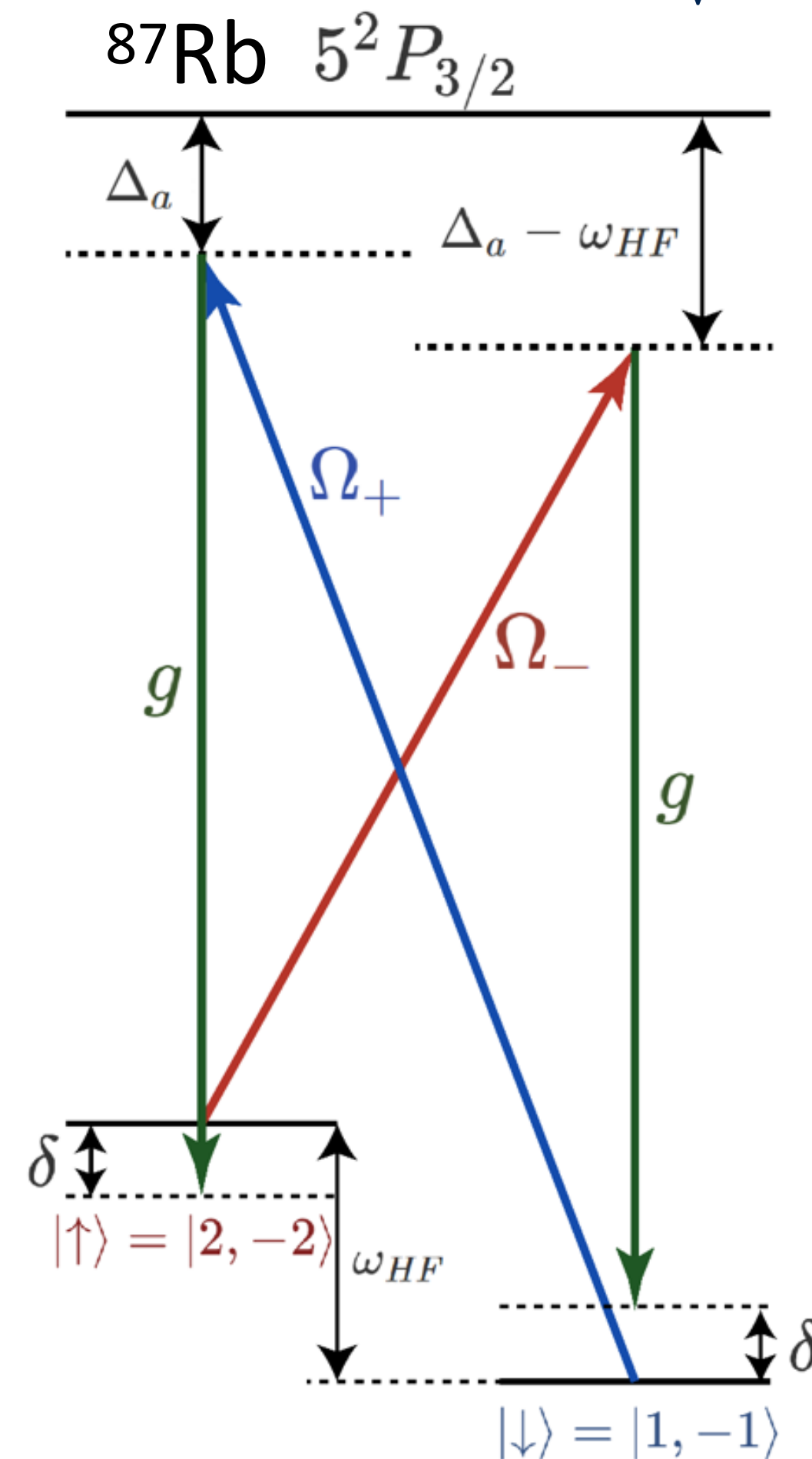
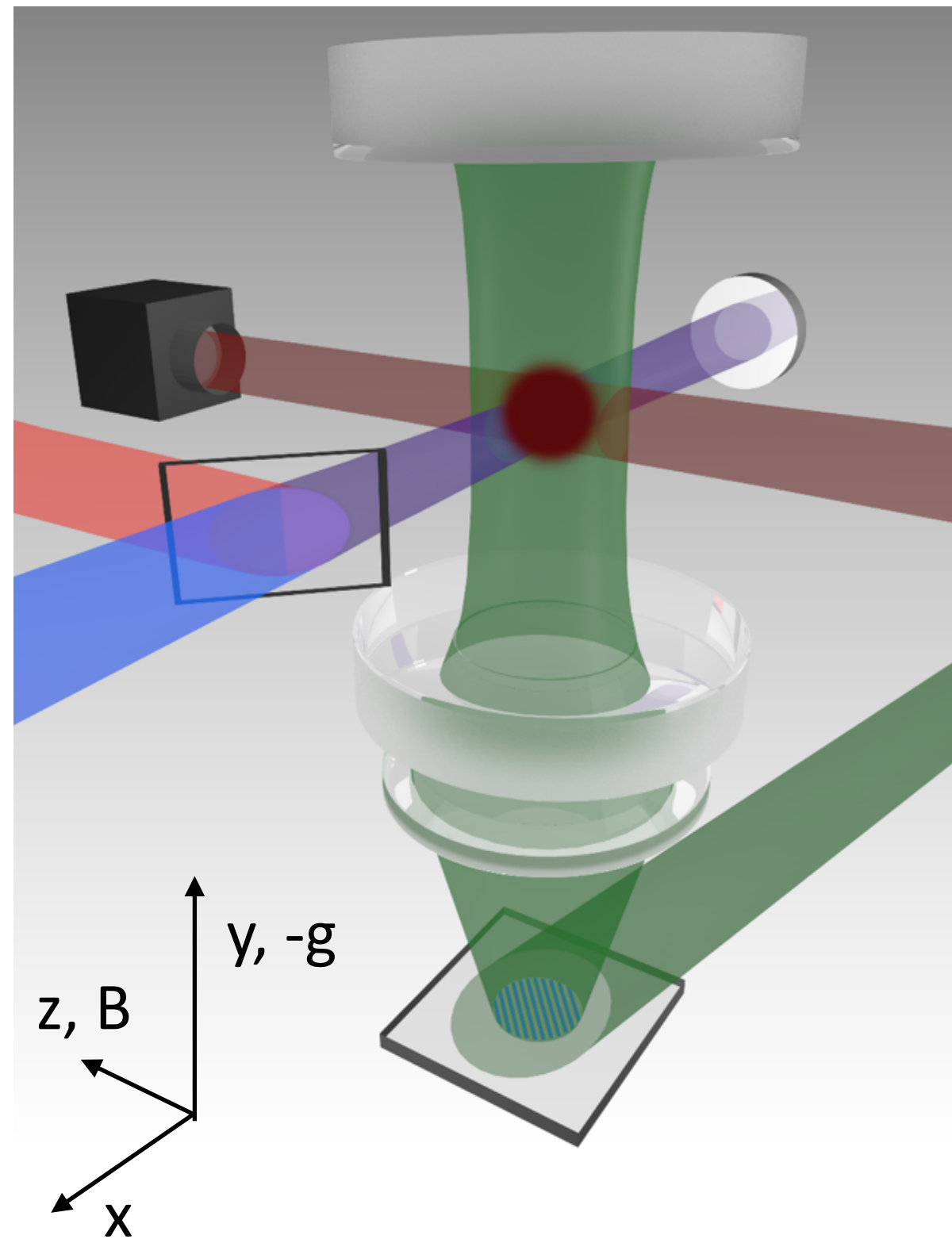
Spinor polariton condensate



In dispersive limit $\Delta_C \gg \kappa, \delta$:

Quantum Ising model

$$H = - \sum_{i < j} J_{ij}(\Omega^2) \sigma_z^i \sigma_z^j + \delta \sum_i \sigma_x^i$$



Dimer ... Carmichael PRA '07

S. Gopalakrishnan, B. Lev, & P. Goldbart PRL '11

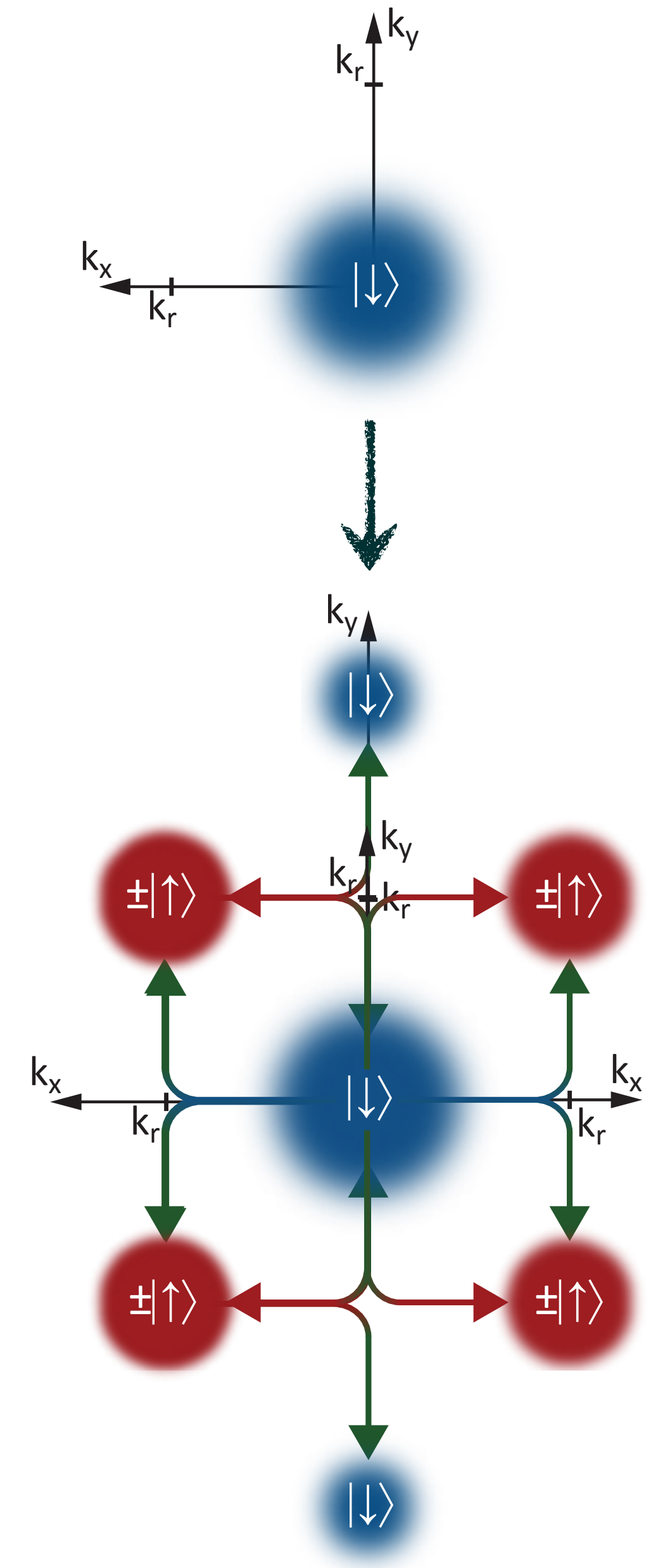
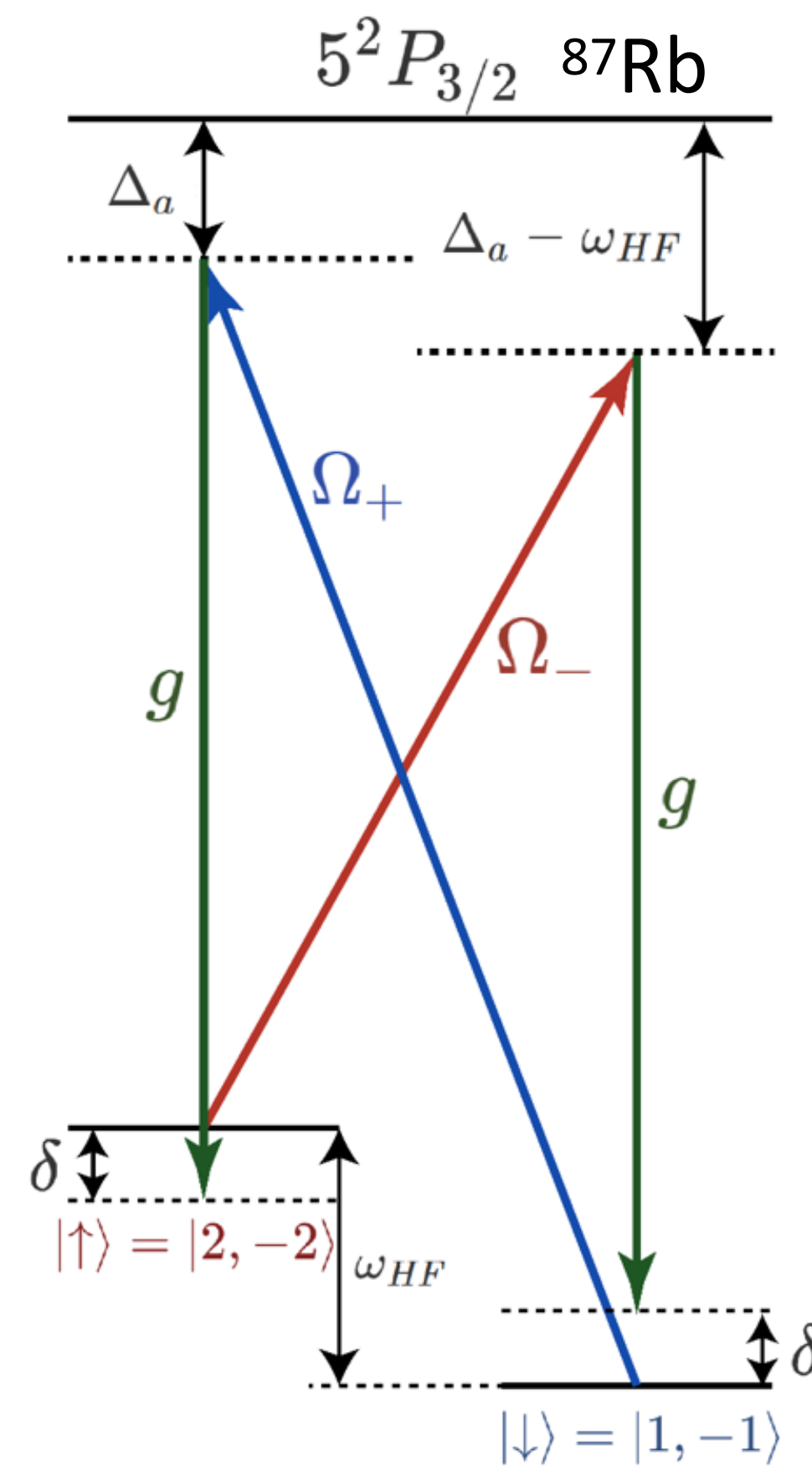
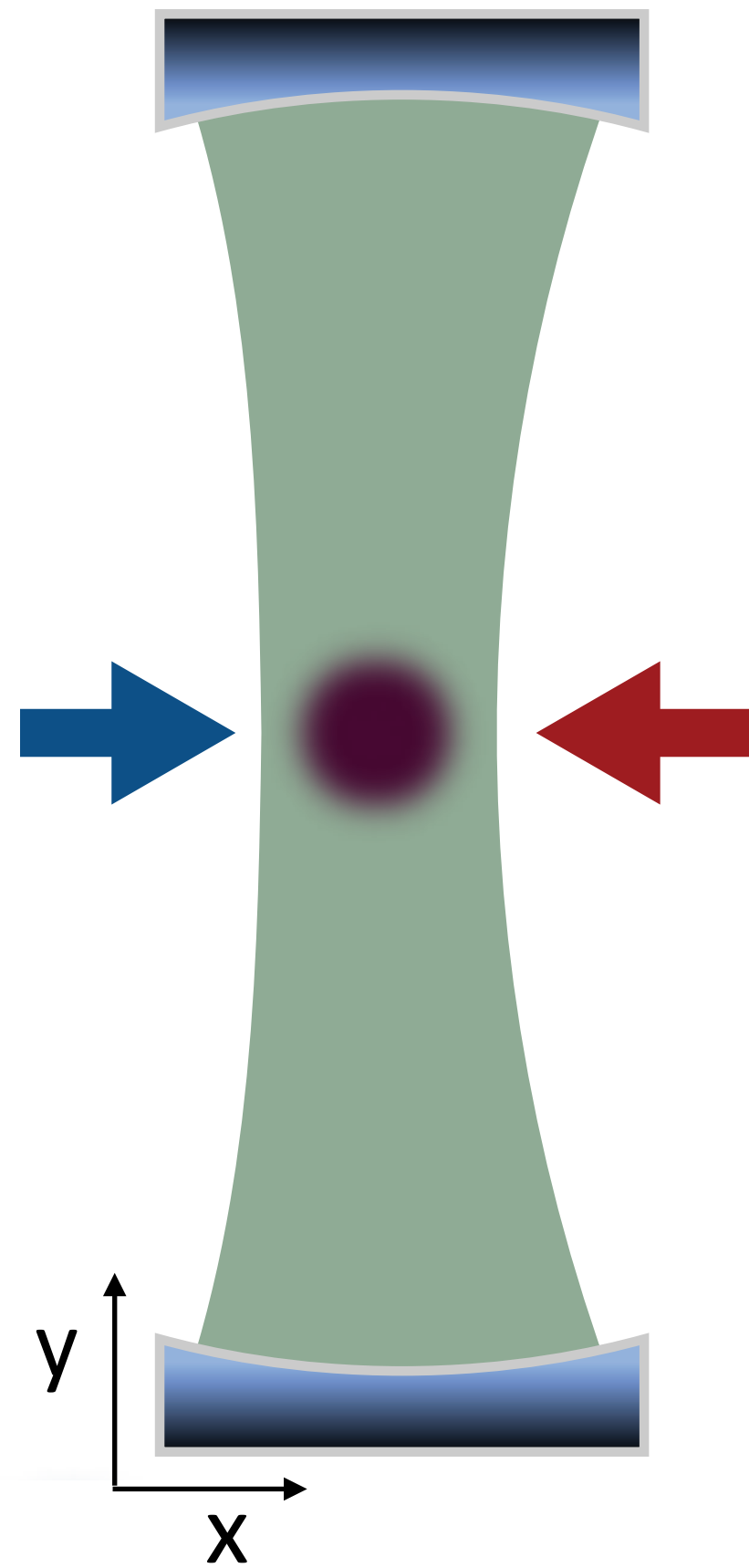
S. Gopalakrishnan, B. Lev, & P. Goldbart Phil. Mag. (2012)

R. Kroeze, Y. Guo, V. Vaidya, J. Keeling & B. Lev, PRL '18

Dynamical spin-orbit coupling

Cavity field forms legs of Raman coupling

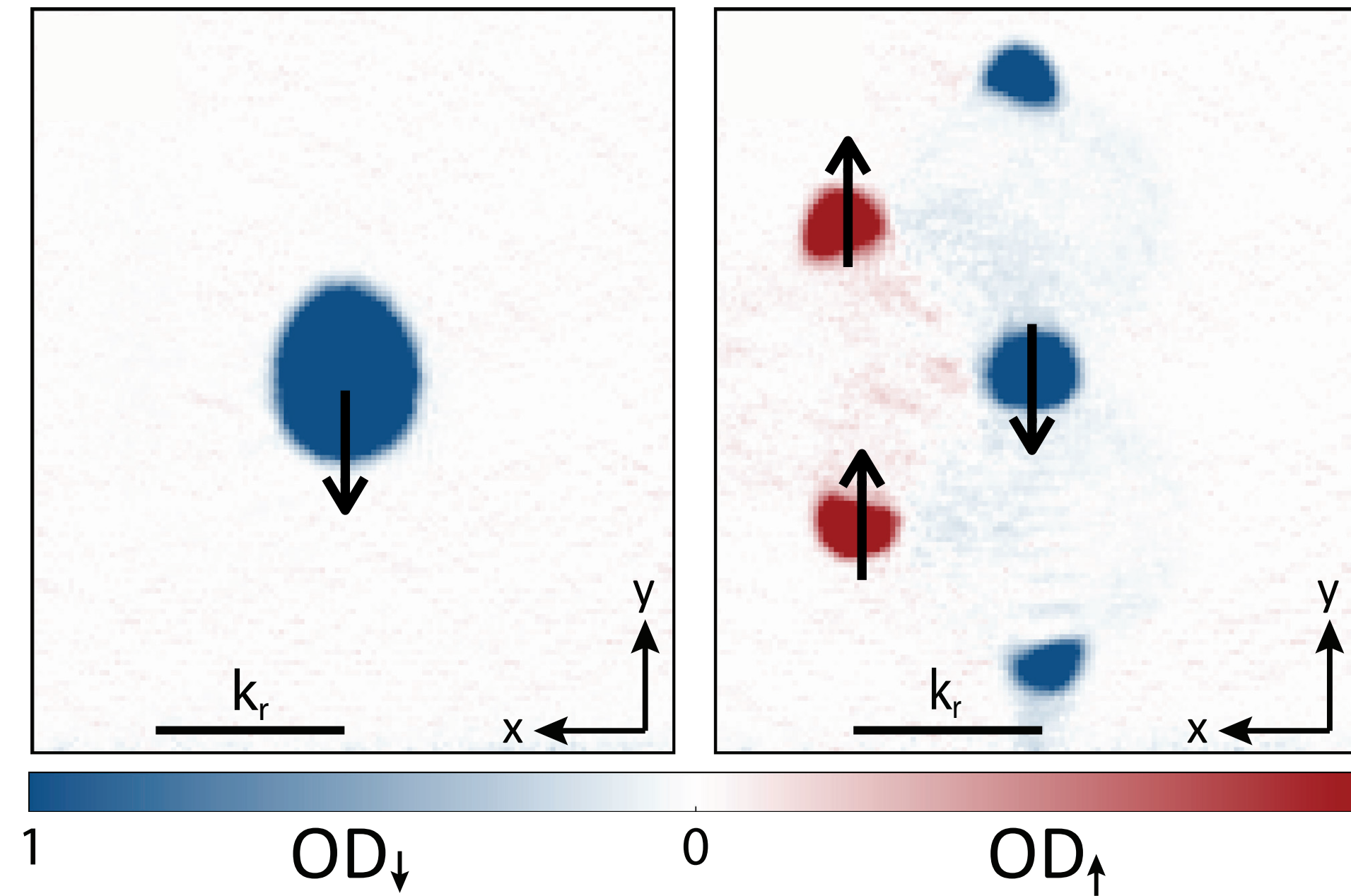
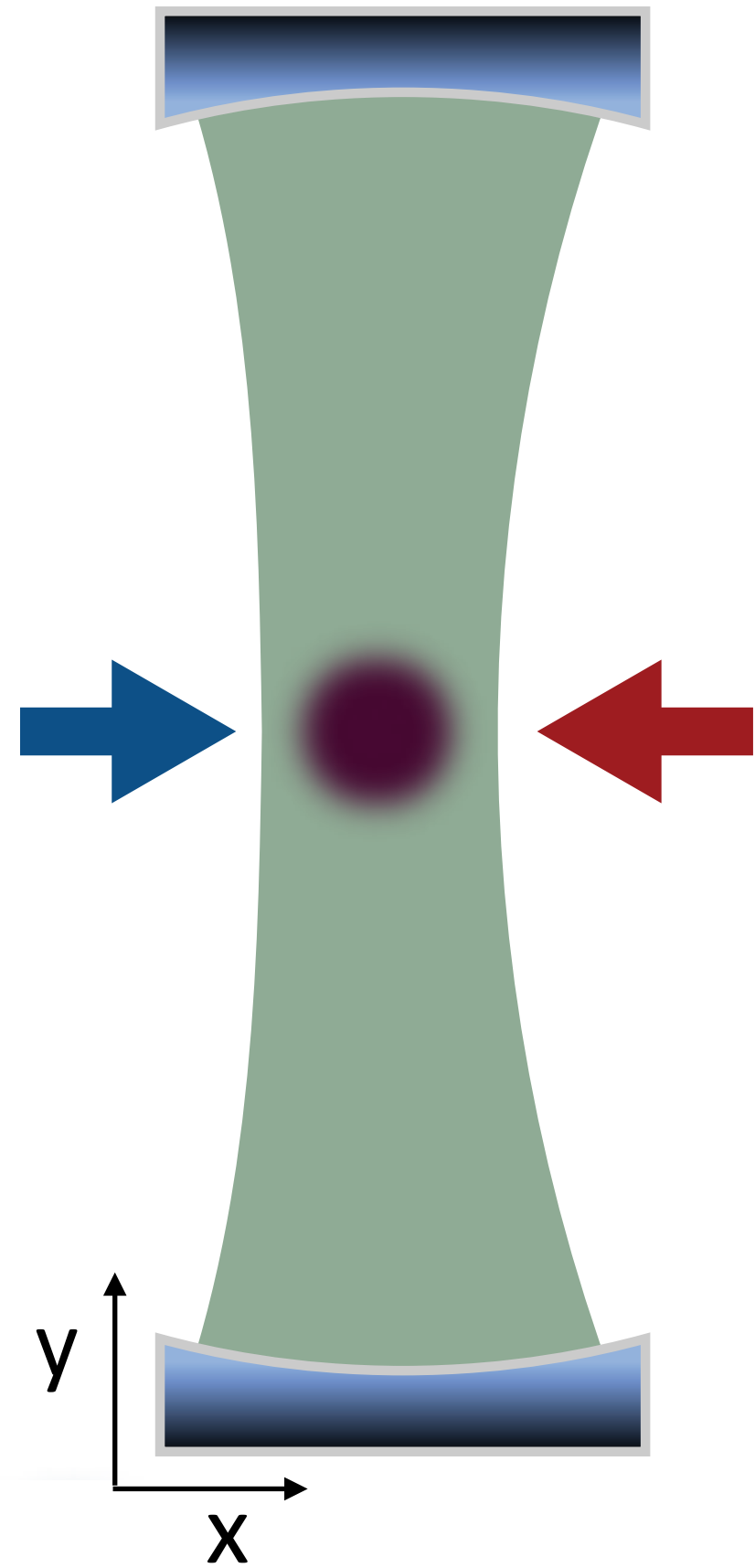
Use running-wave pumps



Dynamical spin-orbit coupling

Cavity field forms legs of Raman coupling

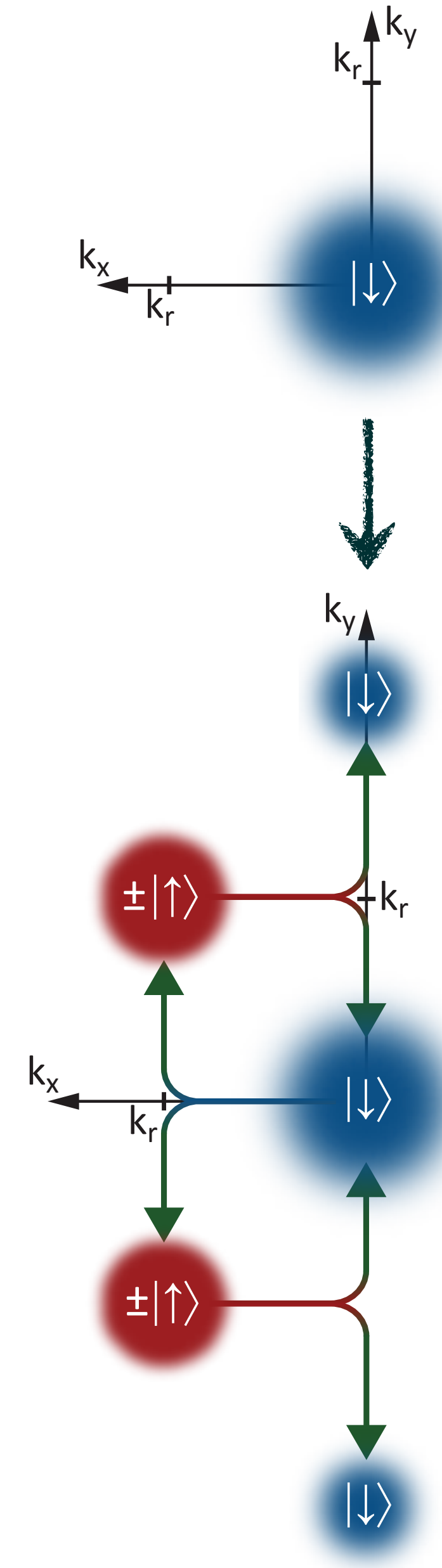
Use running-wave pumps



Resultant state is a spin helix:

$$|\psi\rangle = |\downarrow\rangle \pm e^{ikx} \cos(ky) |\uparrow\rangle$$

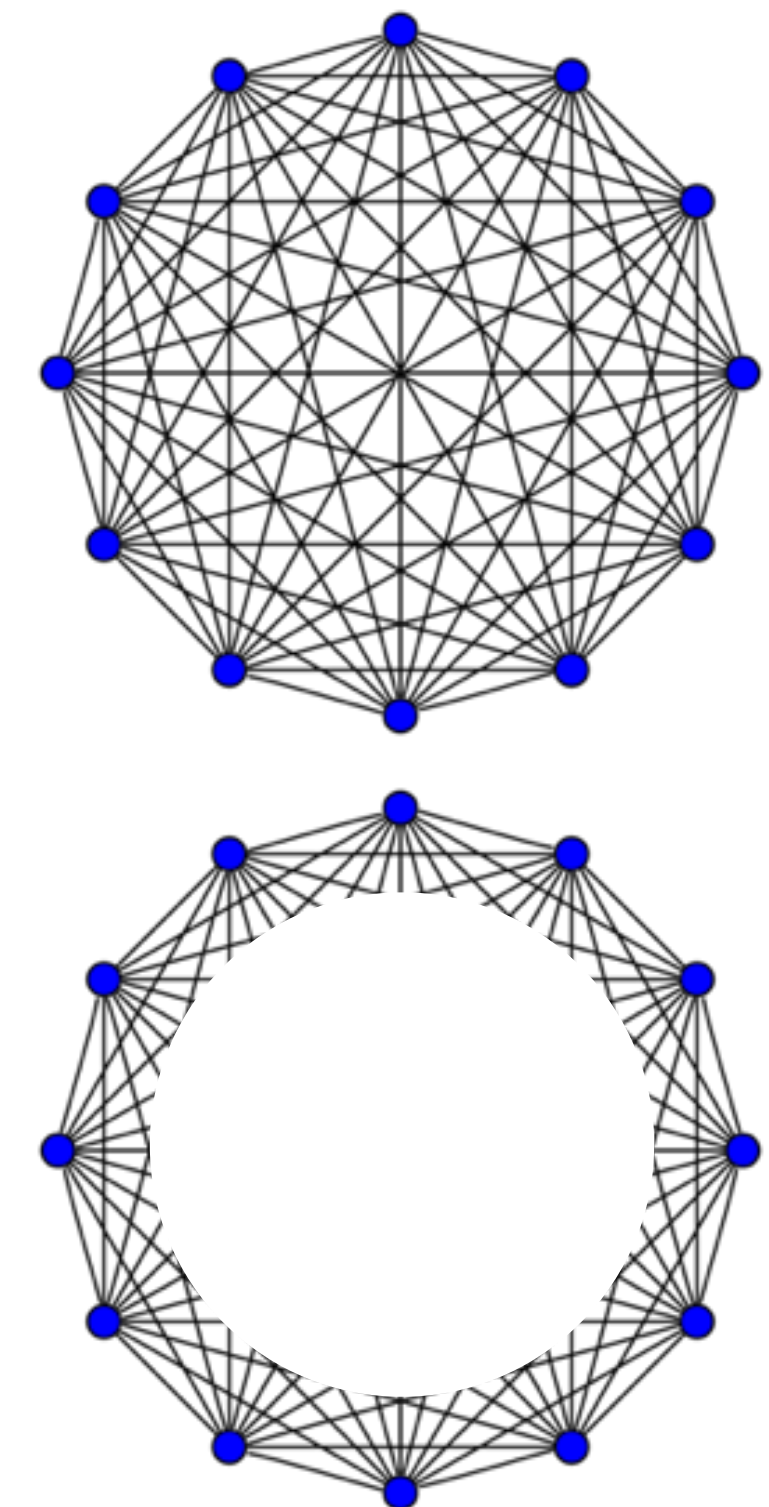
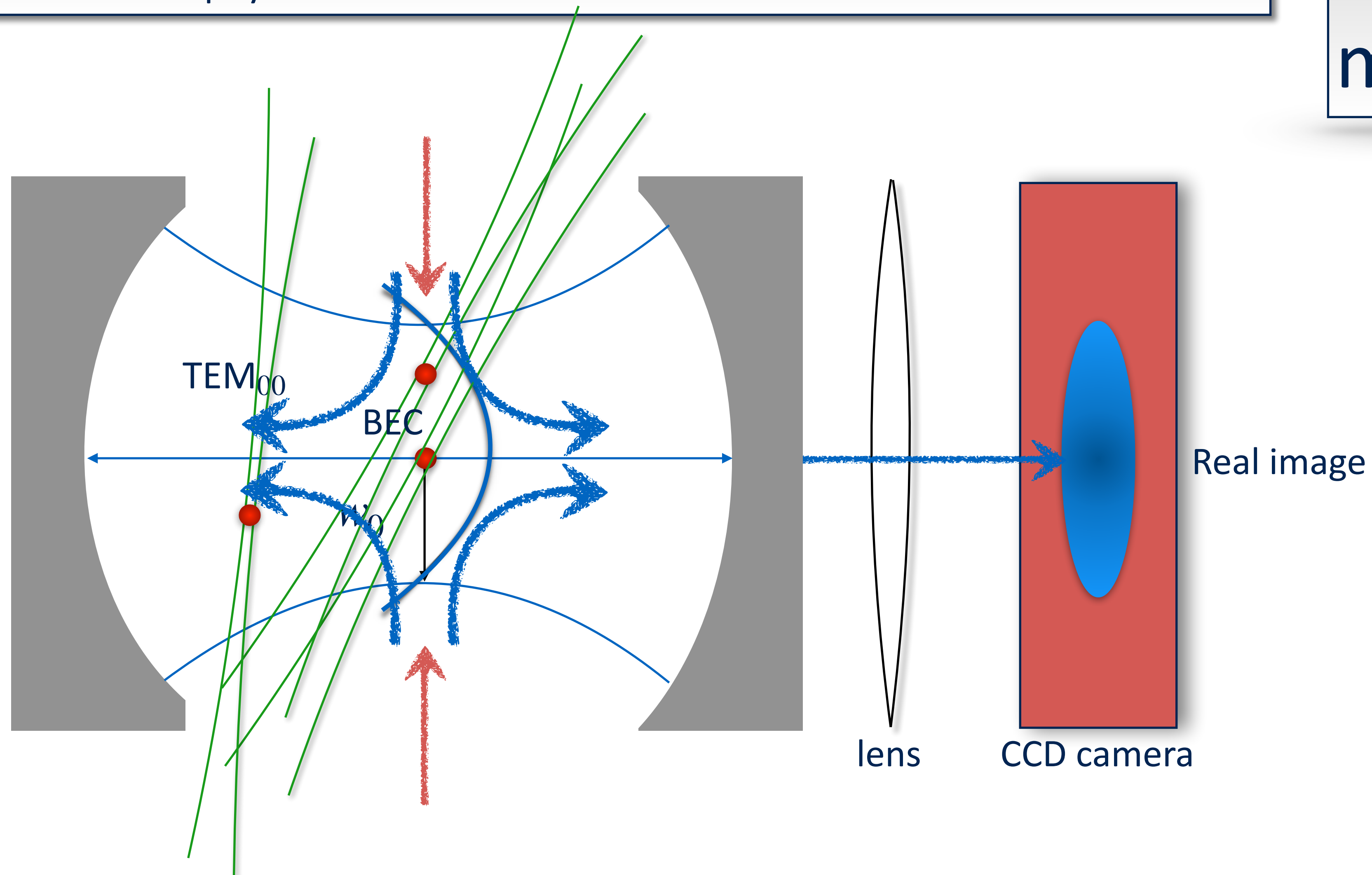
Could be used for creating dynamical gauge fields



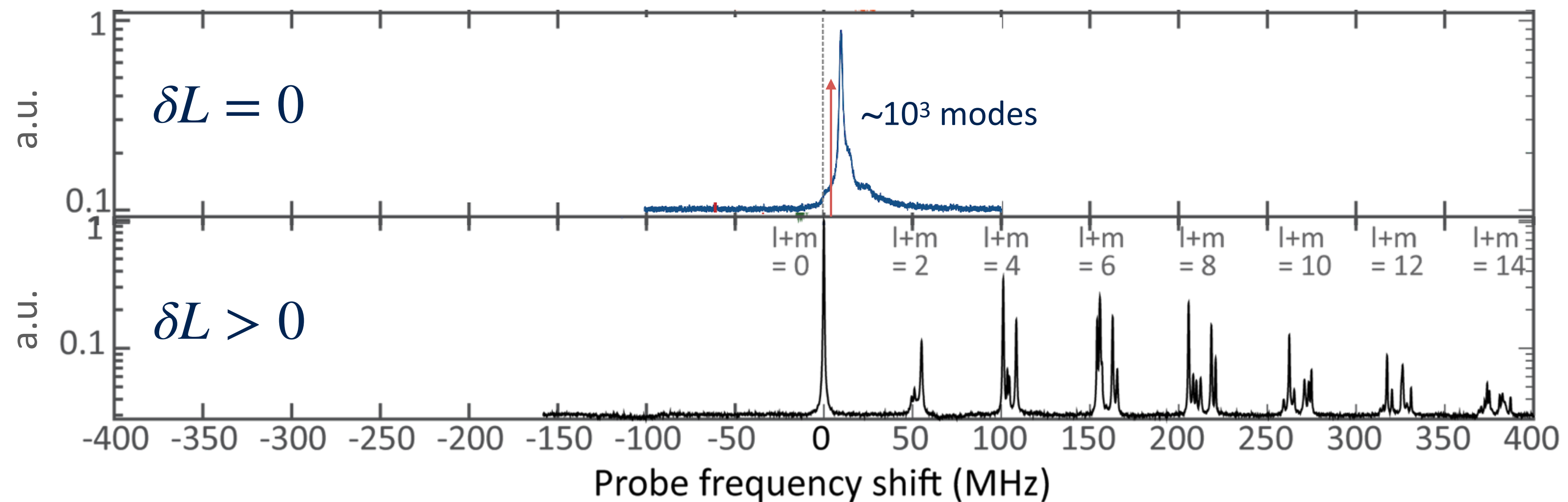
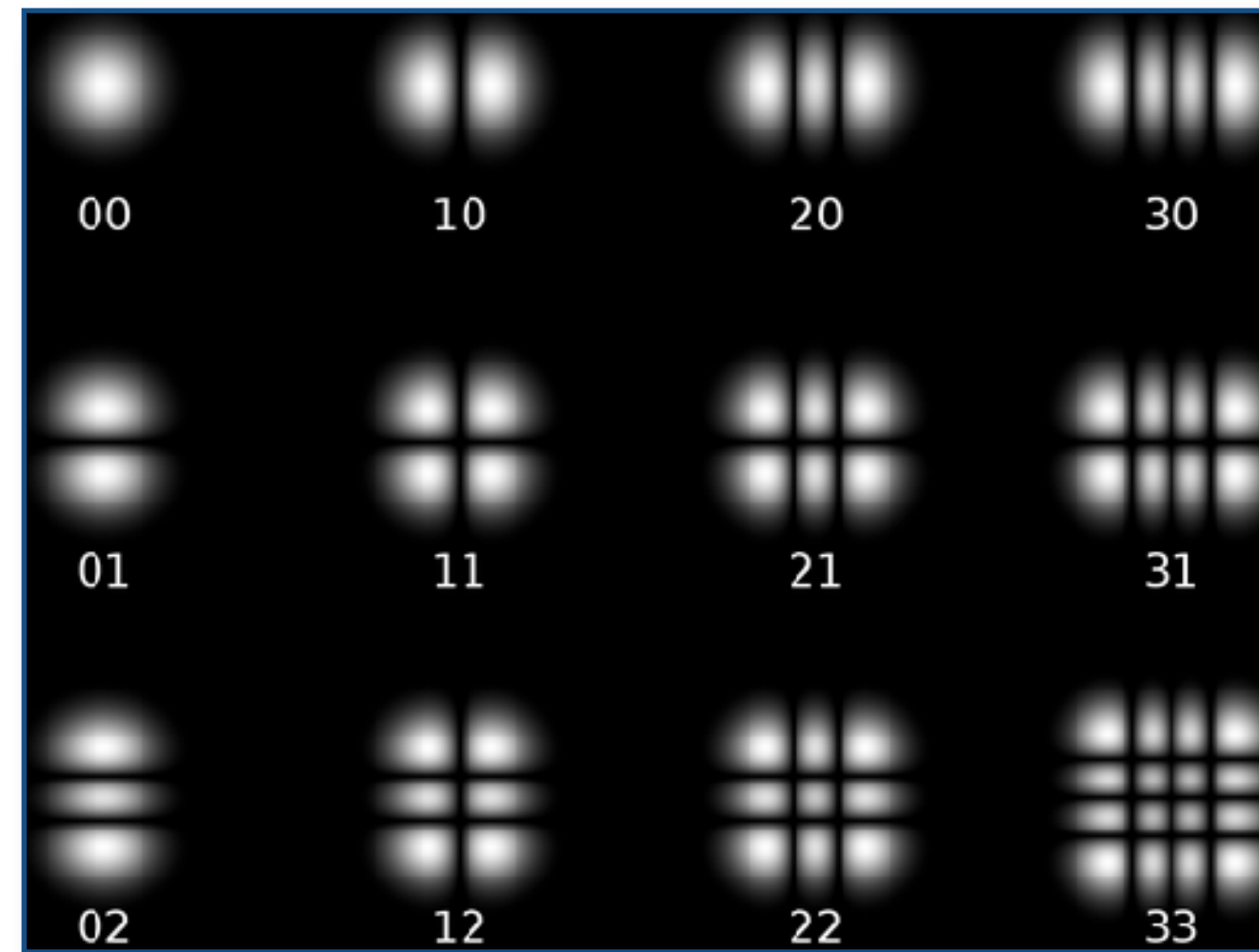
Engineering *spatial* control of interactions

- Single mode cavity: All atoms scatter into same, global photon wavepacket
- This results in a complete graph of all-to-all interactions
- Mean-field physics

Need
multimode cavities

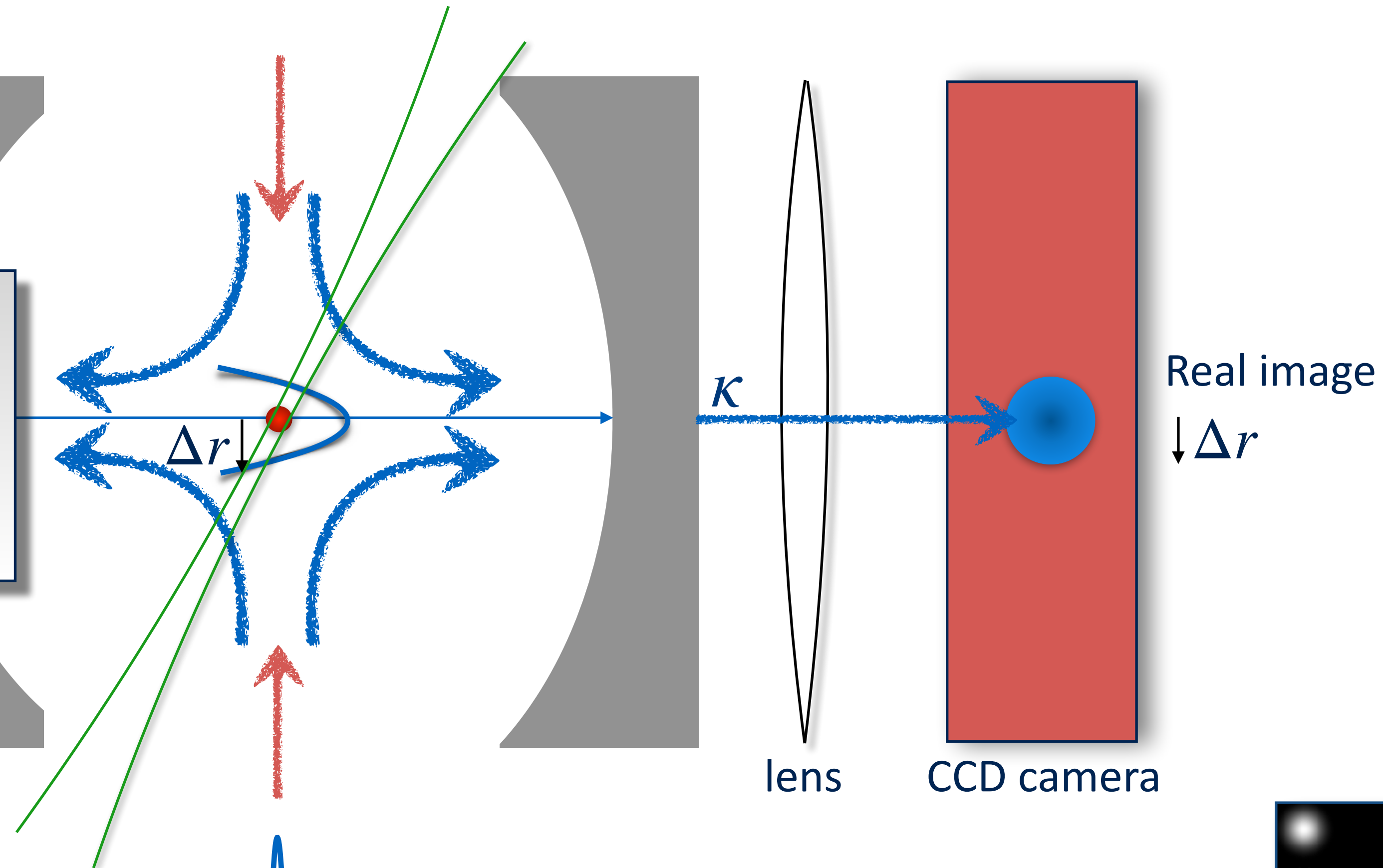


Multimode cavities provide frequency degenerate modes



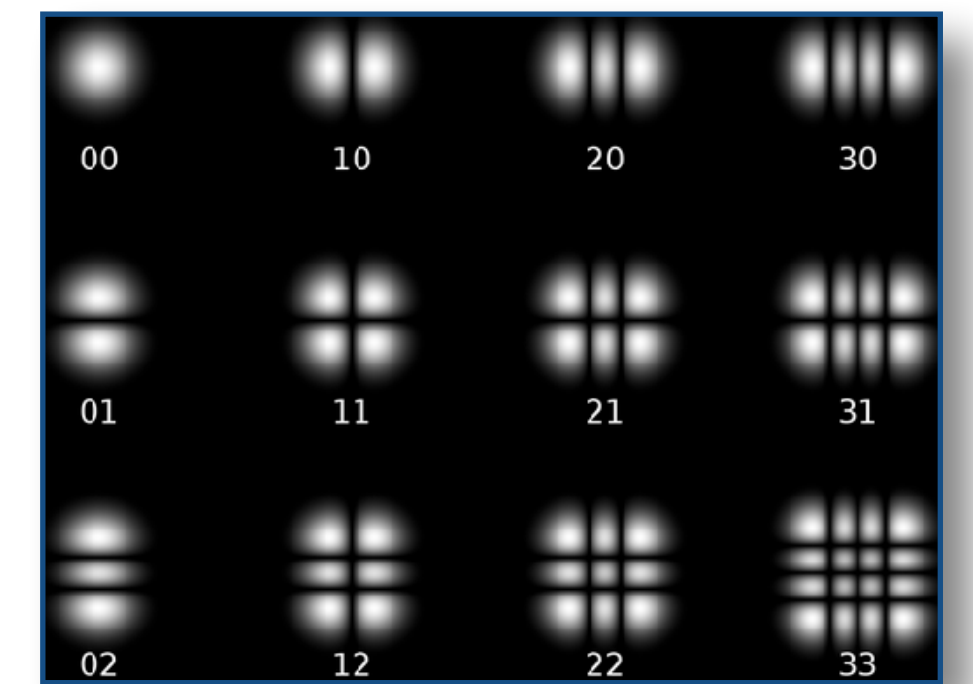
Local photon wavepacket in *multimode* cavity

- Single-atom cooperativity:
100x single-mode case
- Supermode enhancement:
 $C > 200!$



$$\sum_{lm} \text{[Oscillatory function]} = \text{[Envelope function]} \propto \frac{e^{-\Delta r/\xi}}{\sqrt{\Delta r/\xi}} \quad \xi \text{ set by number of modes}$$

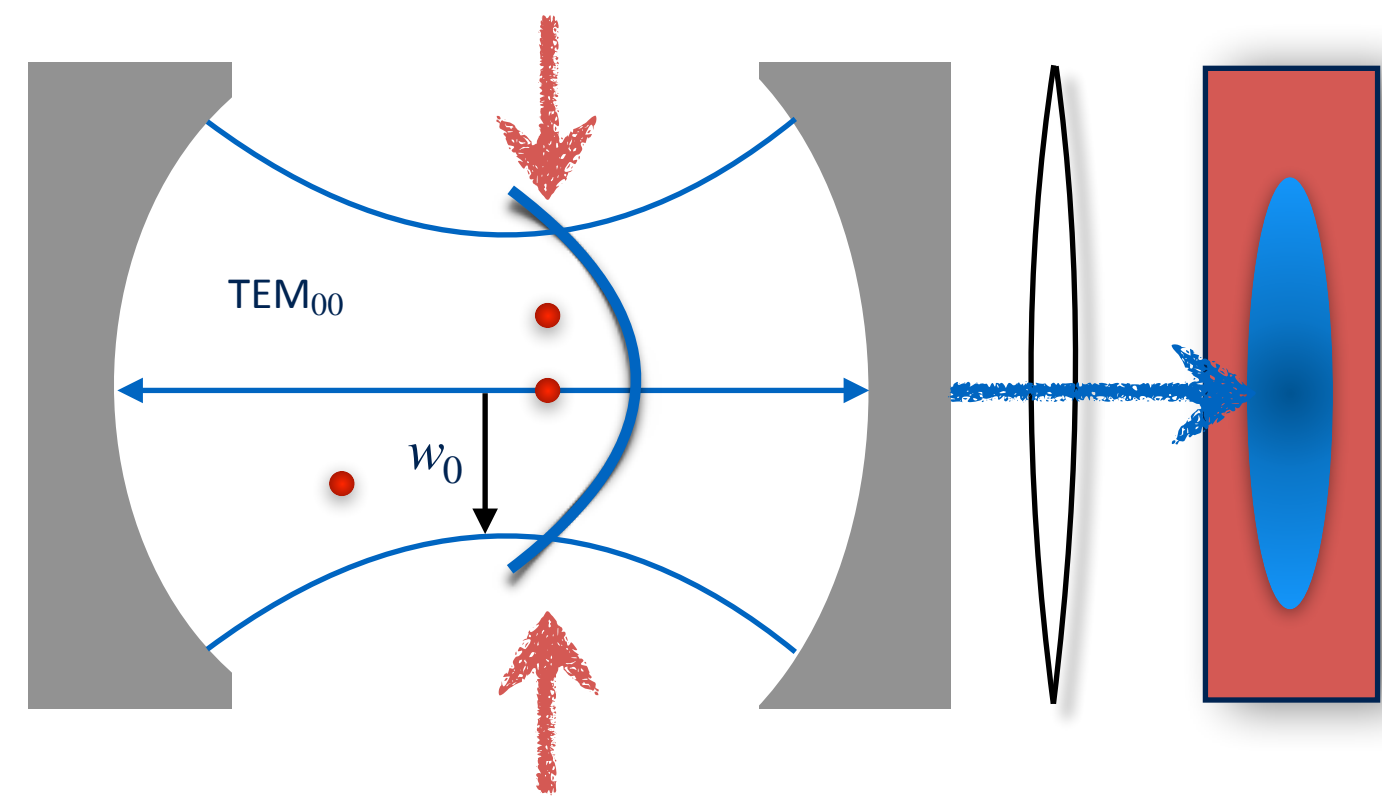
The diagram shows the summation of multiple modes (represented by the sum over lm) resulting in a localized wavepacket. The wavepacket is characterized by a sharp peak at Δr , with its envelope function proportional to $\frac{e^{-\Delta r/\xi}}{\sqrt{\Delta r/\xi}}$. The parameter ξ is determined by the number of modes.



TEM_{lm} Mode function

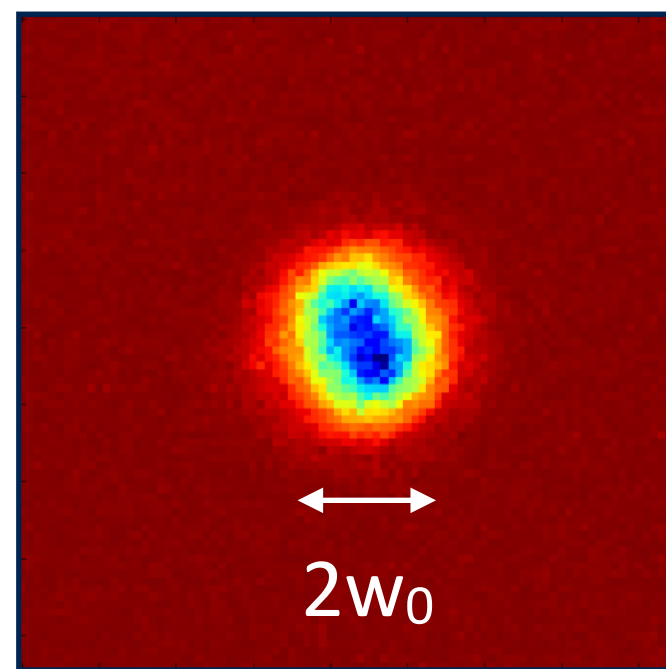
Observation of superradiant supermode

Single-mode cavity

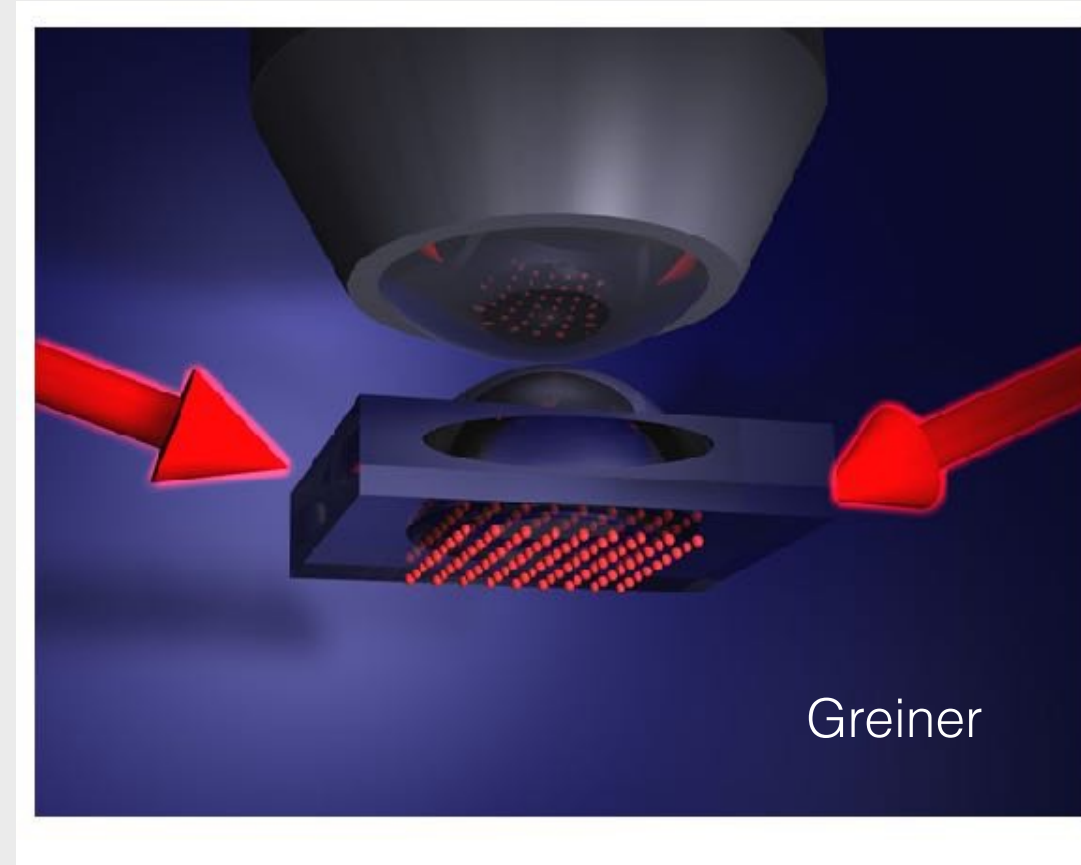


CCD image:

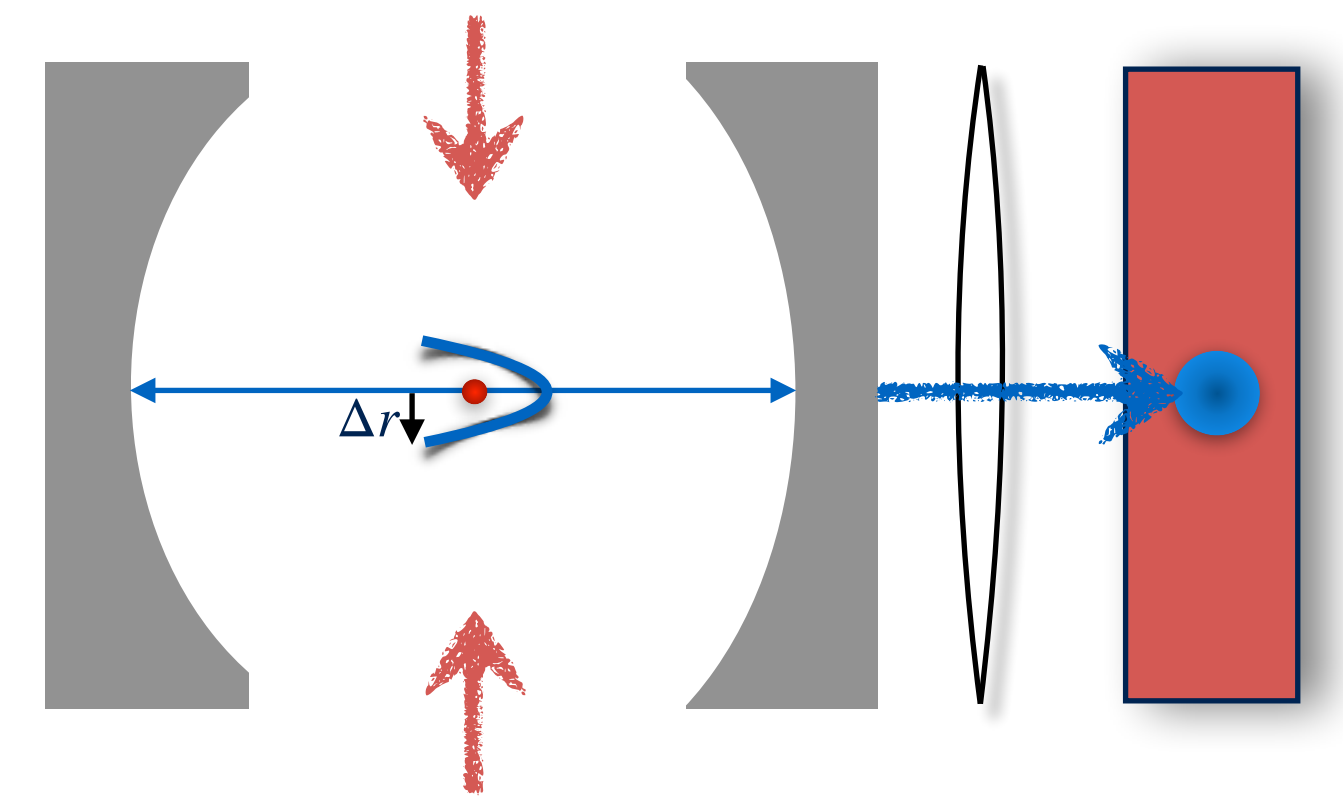
TEM_{00} mode



Active quantum gas microscope

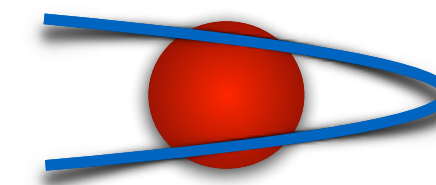


Multimode cavity

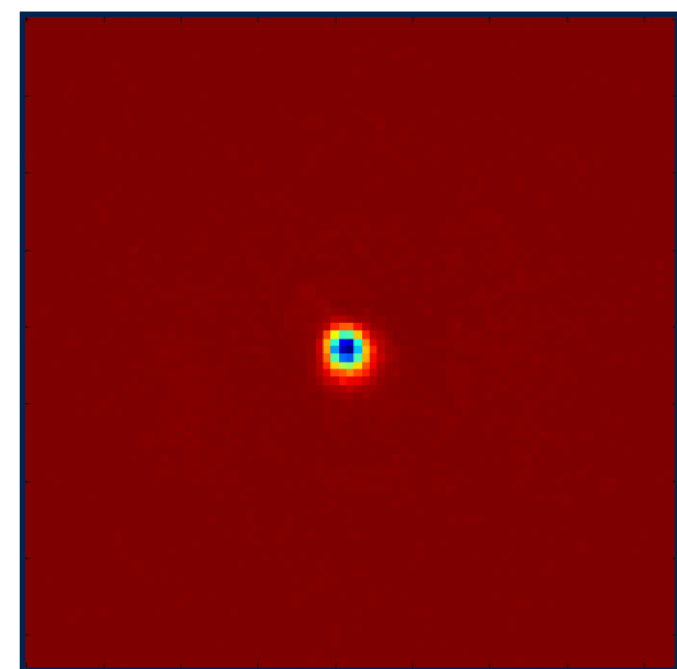


CCD image:

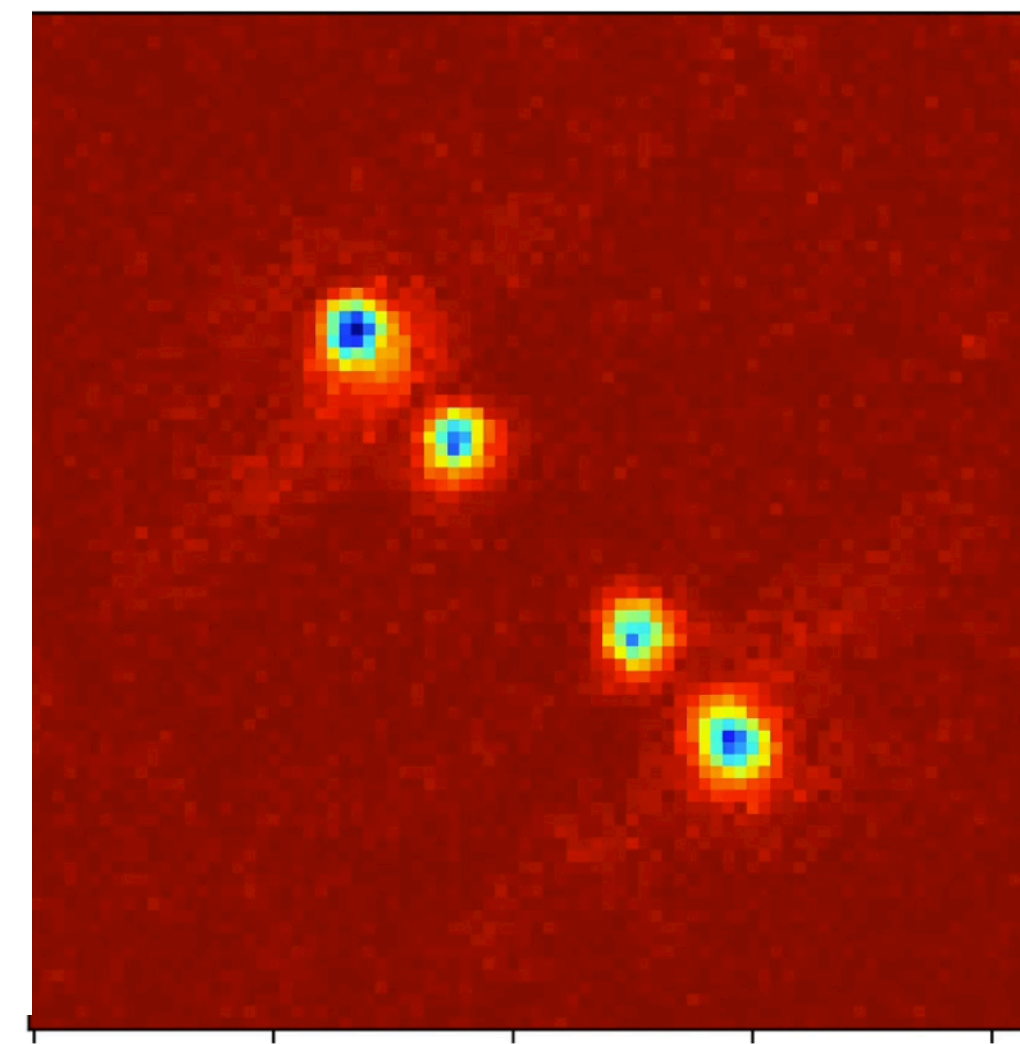
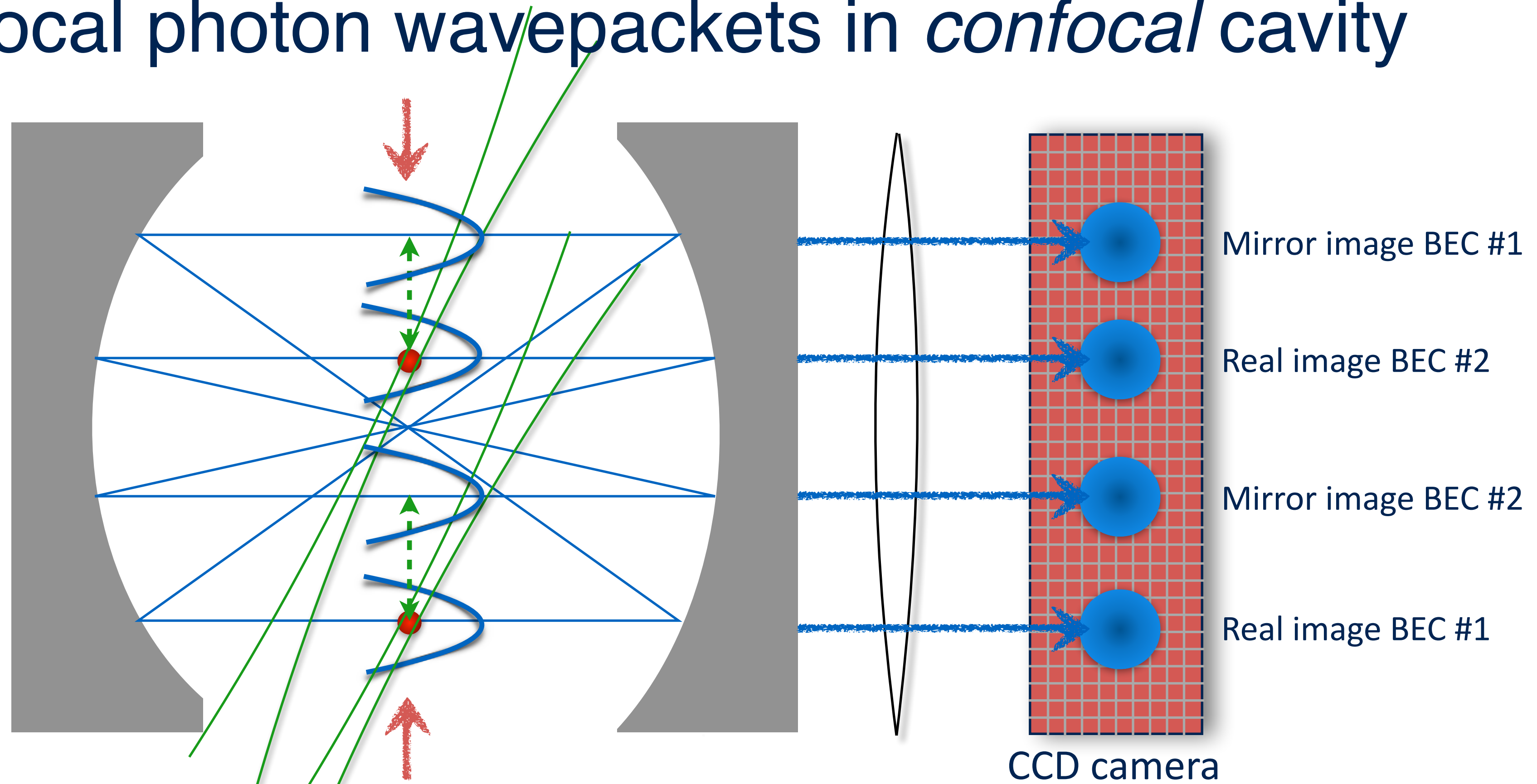
Spot limited by
BEC size...



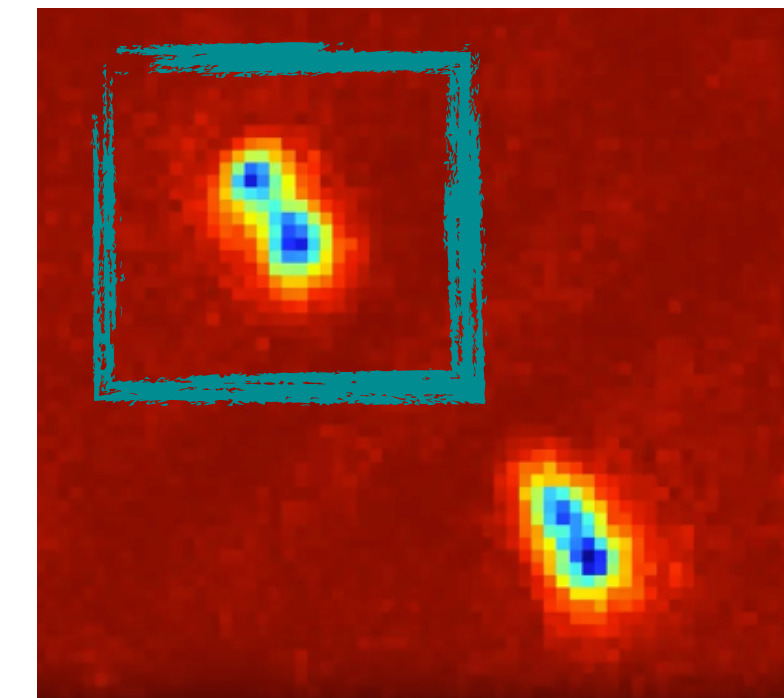
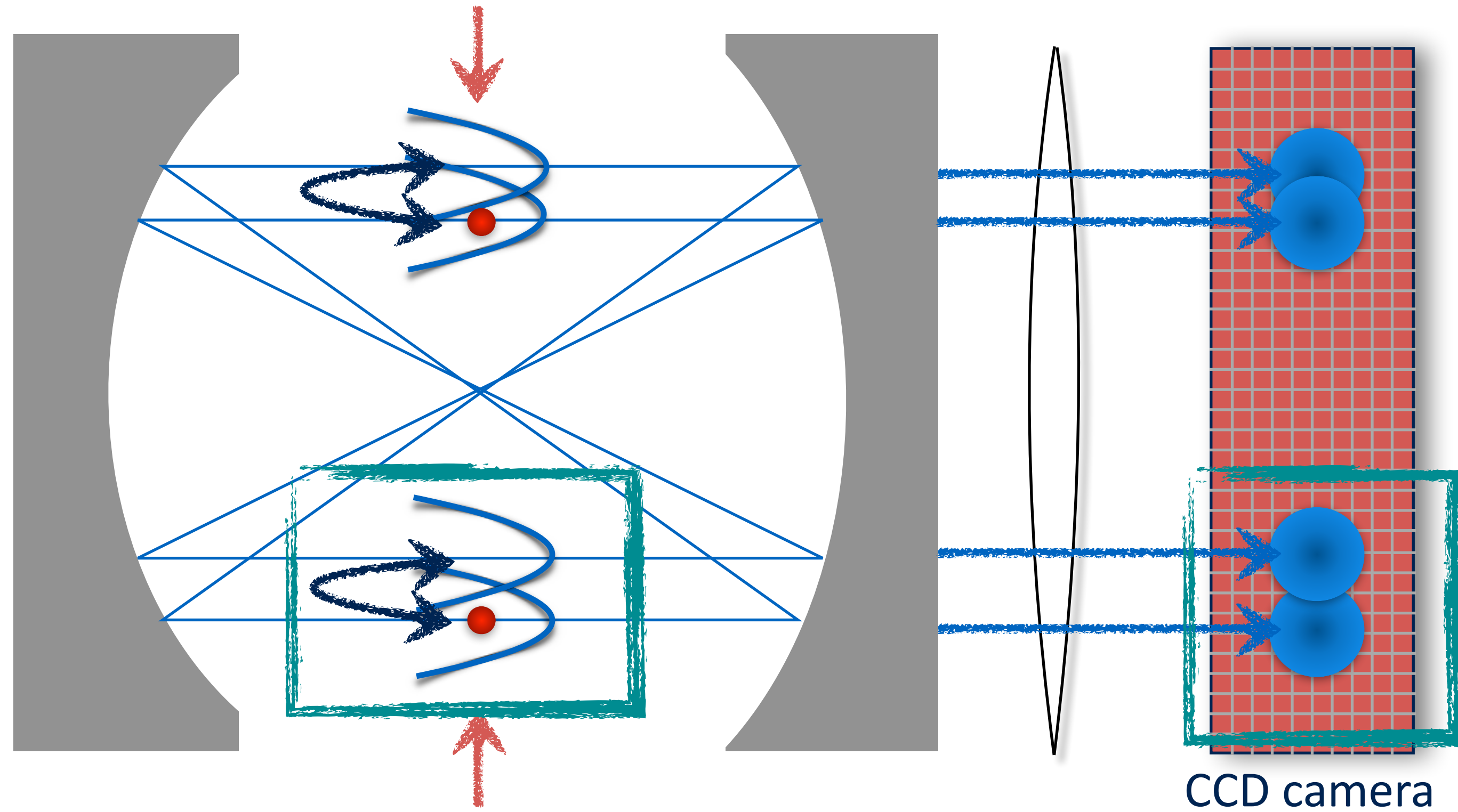
...not number
of modes

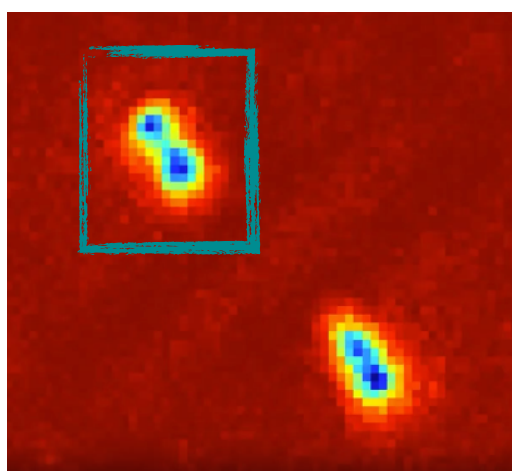


Local photon wavepackets in *confocal* cavity



Local photon-mediated interactions

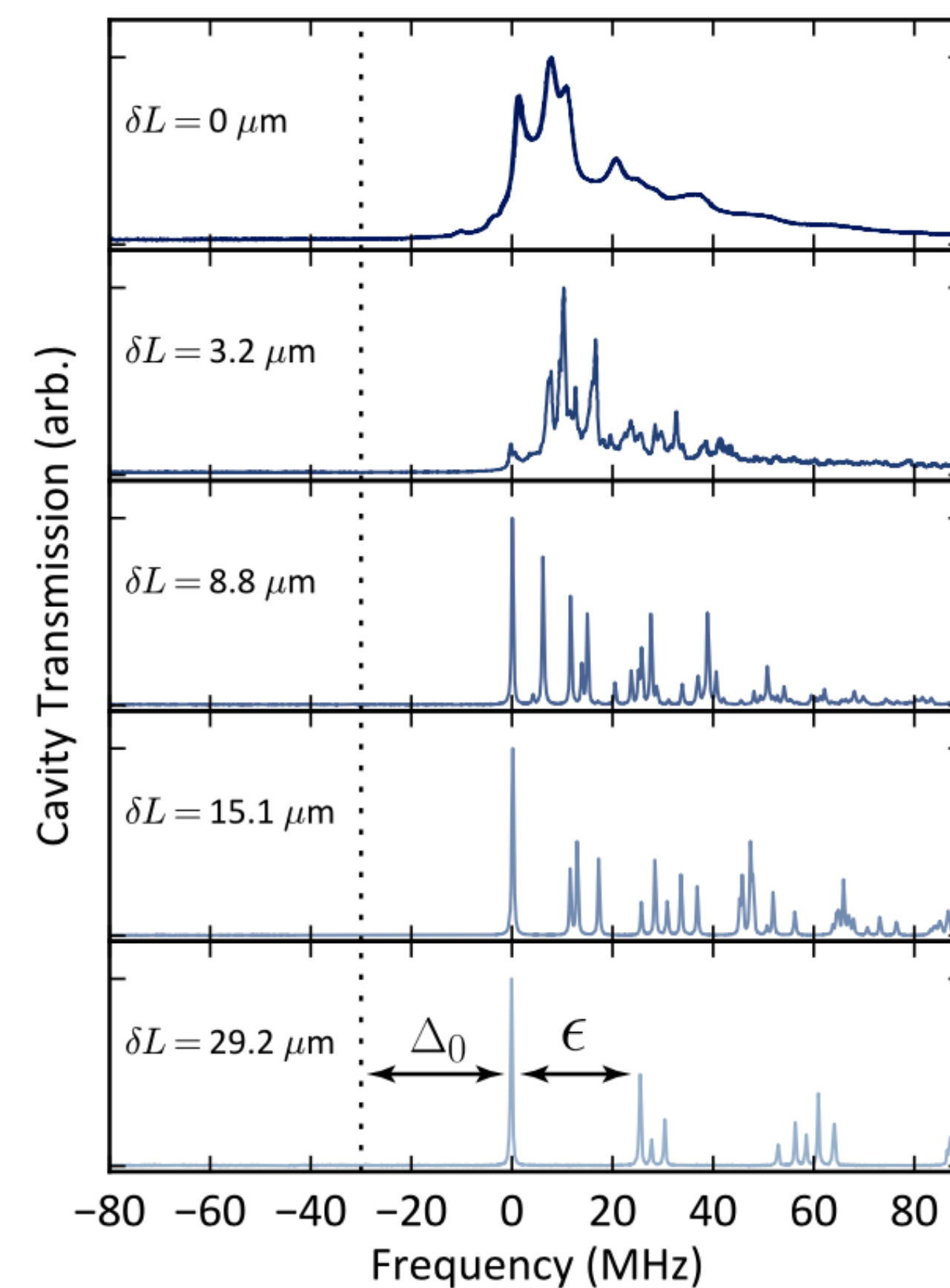
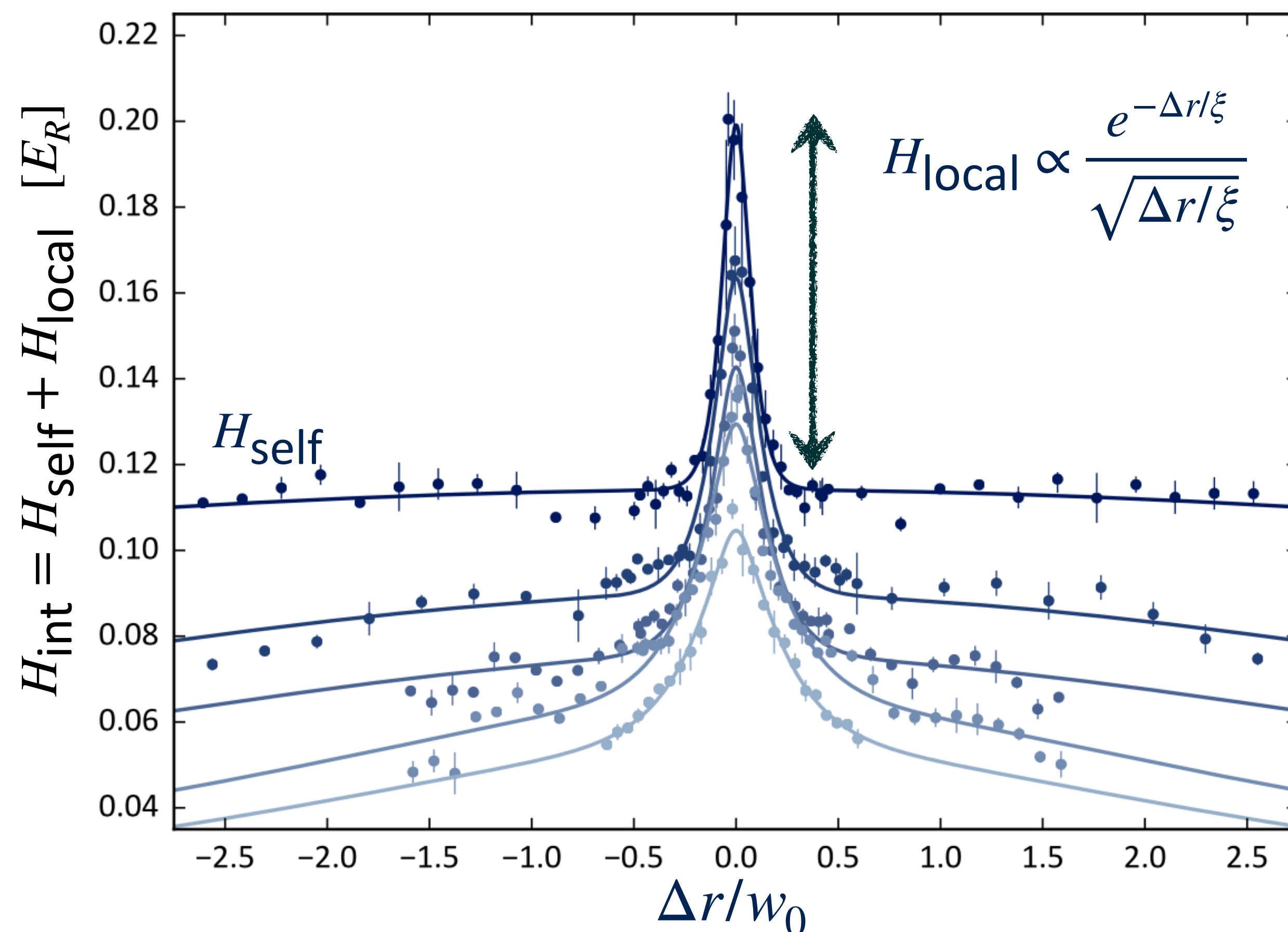




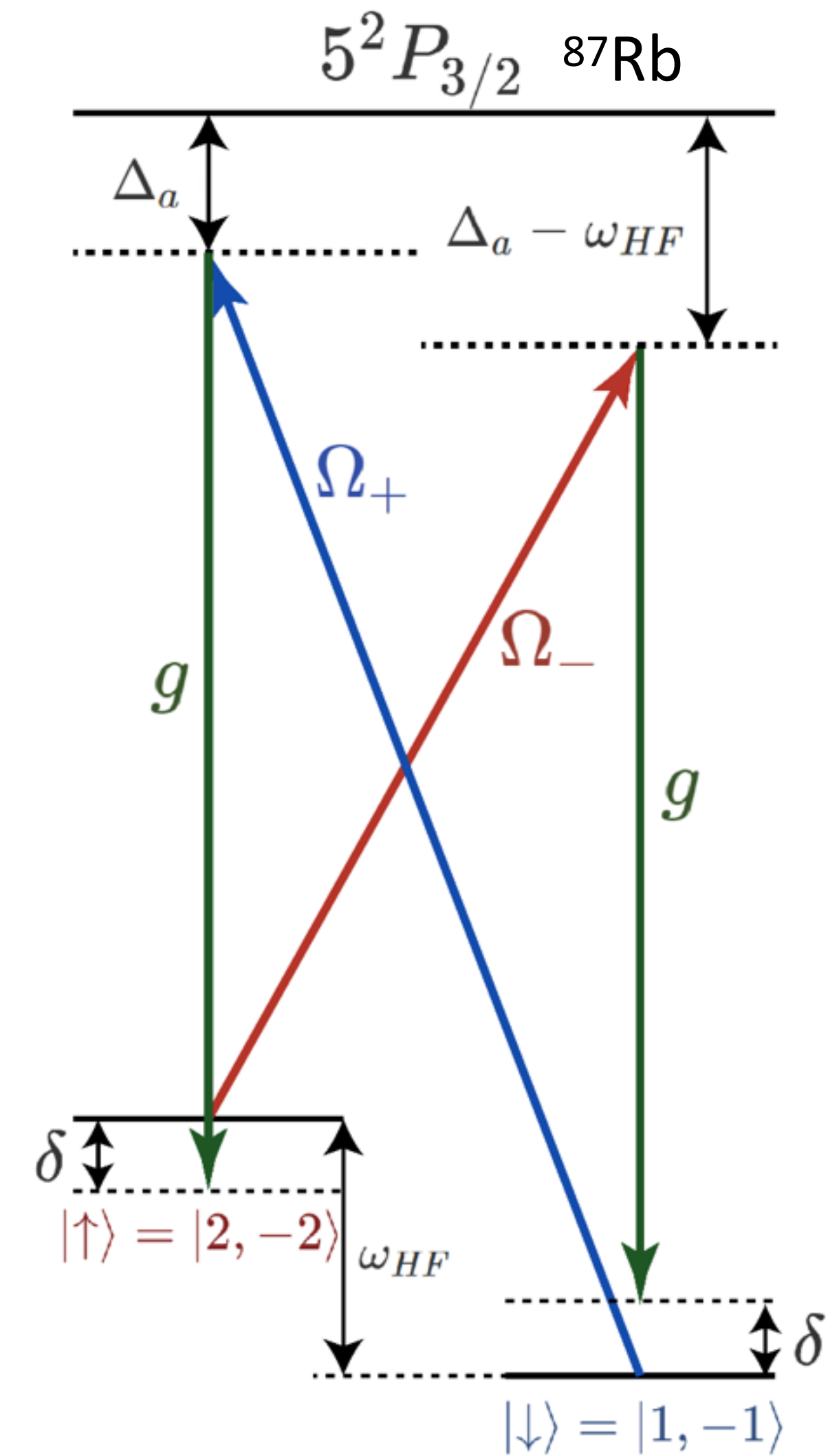
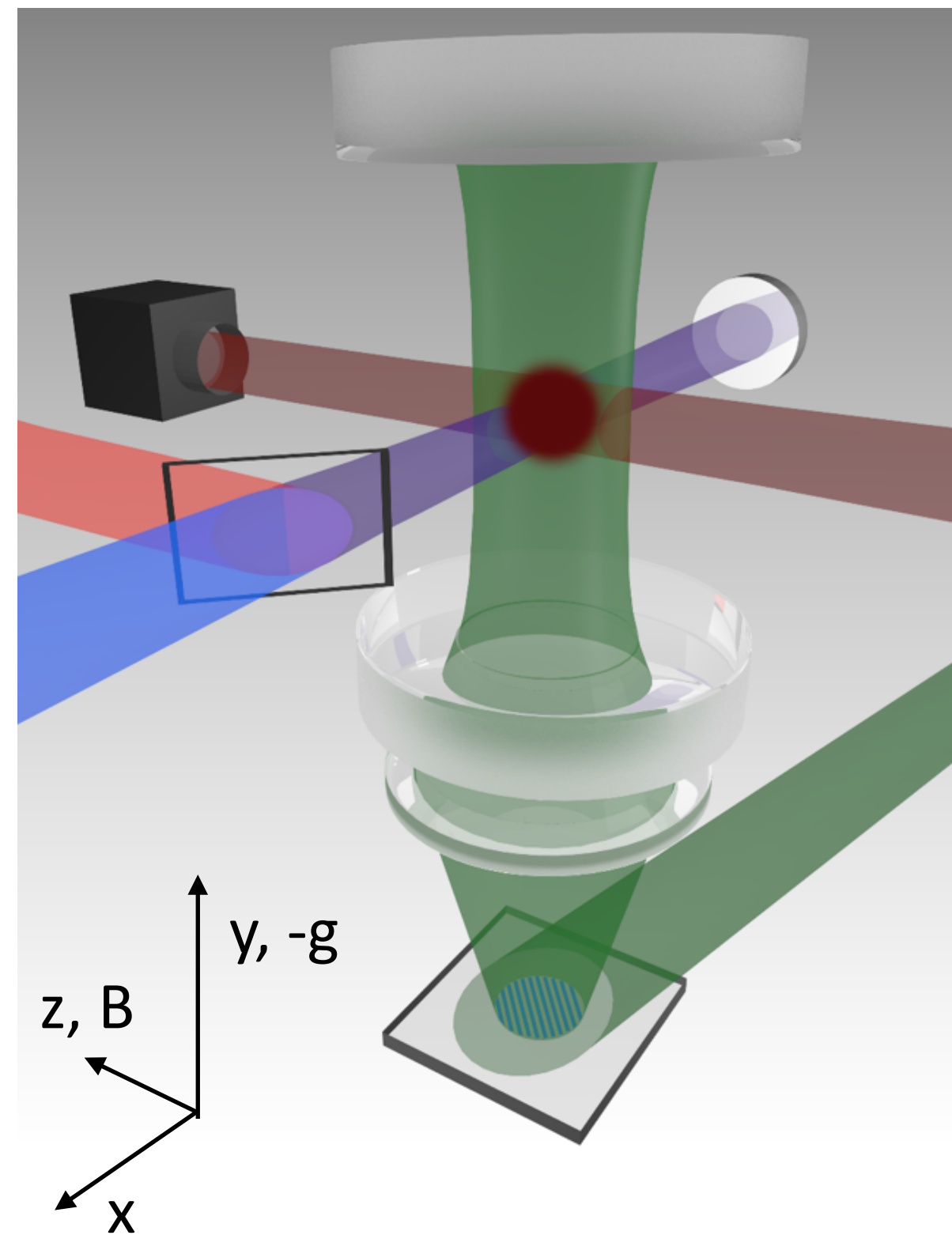
Tunable-range photon-mediated interaction

- Measure power at superradiant threshold
- Power *decreases* when photon wavepackets overlap due to interaction
- Plot inverse of this power to obtain interaction energy

Can tune ξ between $\sim 1 \mu\text{m}$ to $35 \mu\text{m}$

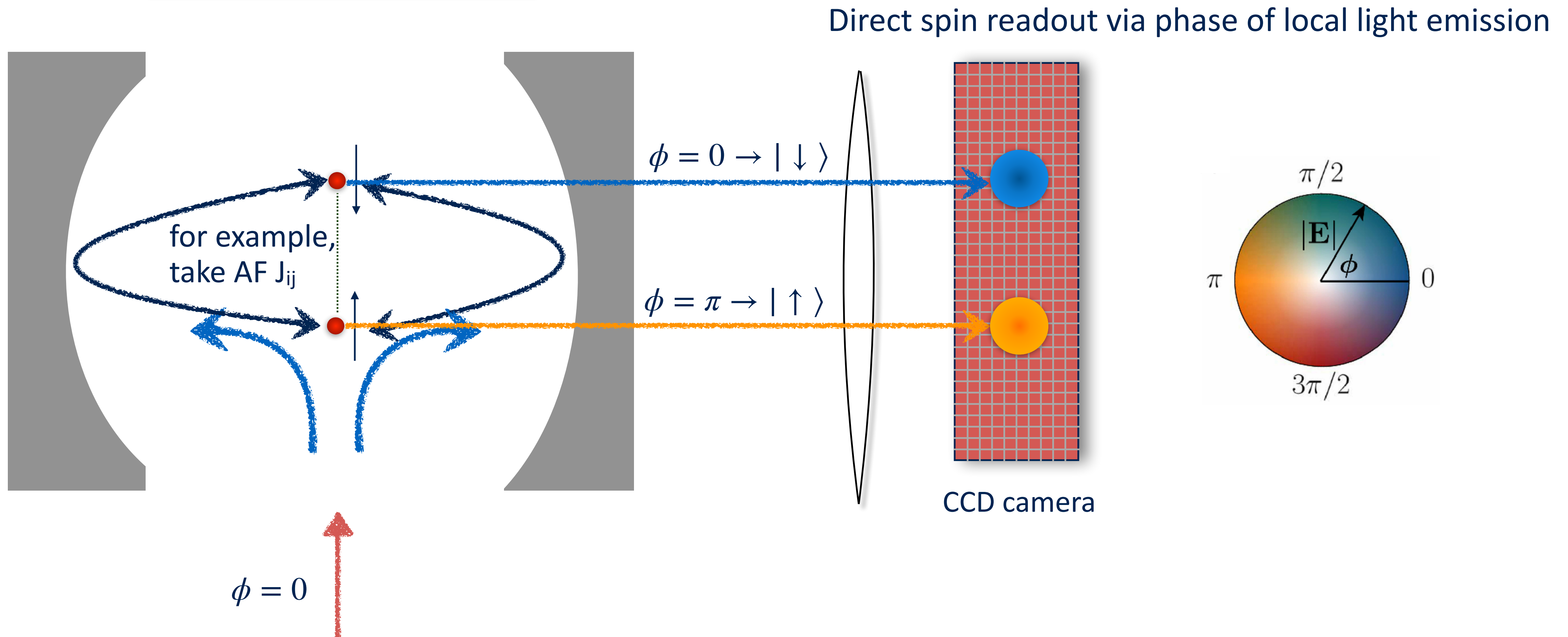


How does this work with spin-spin interactions?



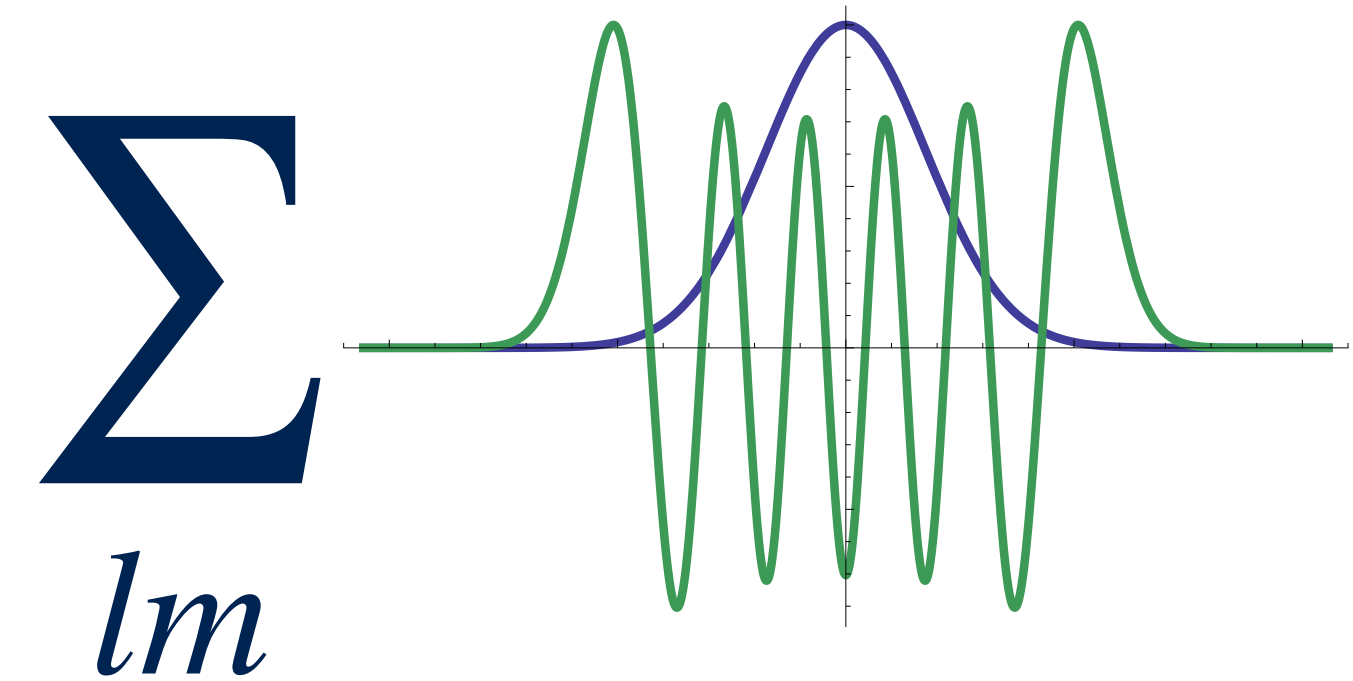
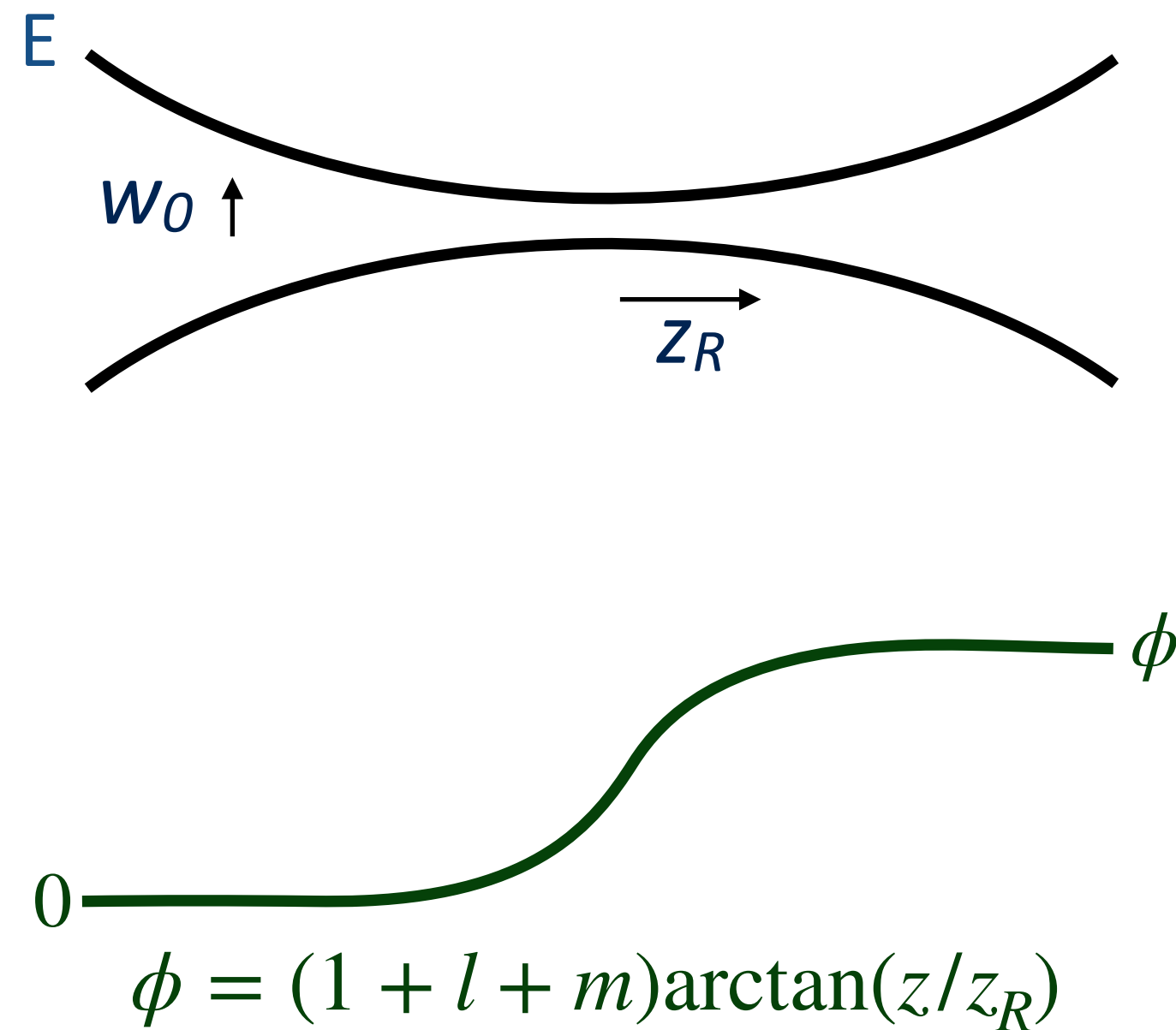
Geometrical picture for spin-spin interactions

- J_{ij} enhanced by the cavity
- J_{ij} is MHz vs Hz-scale for γ



From where do the sign-changing interactions come?

Gouy phases...

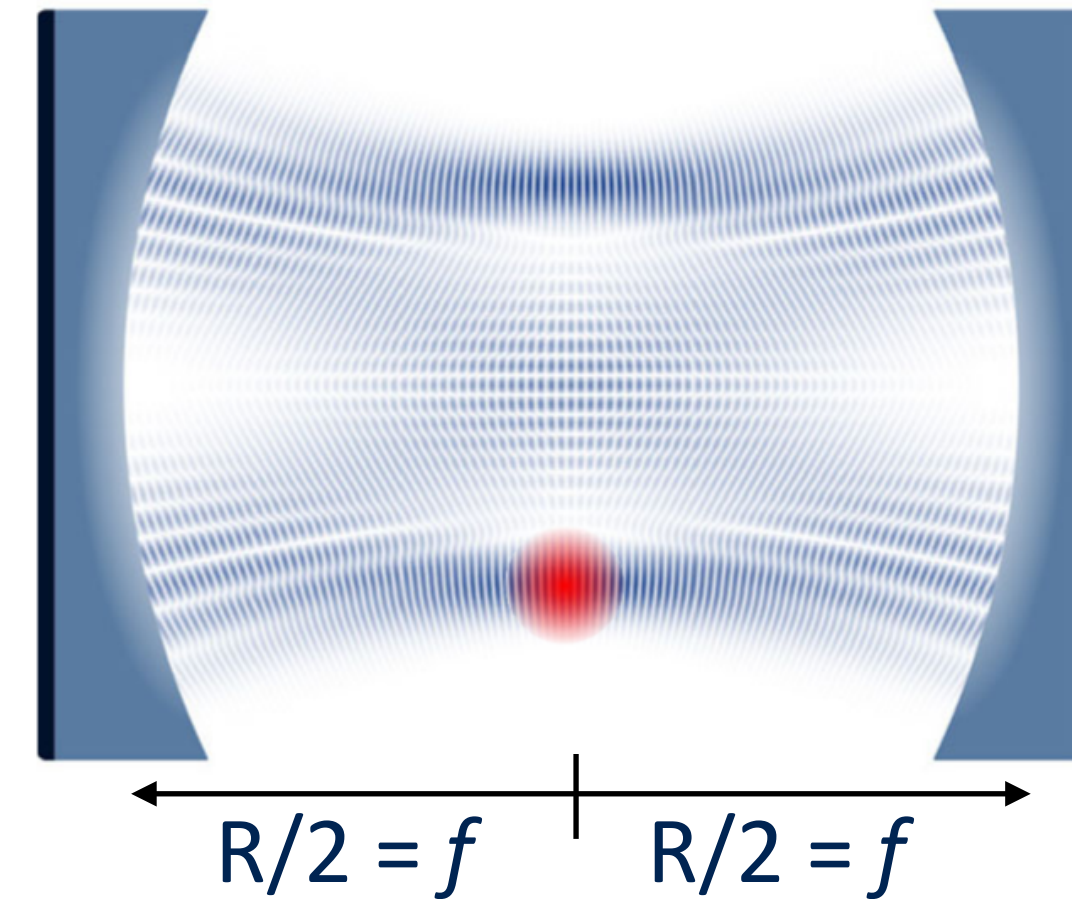
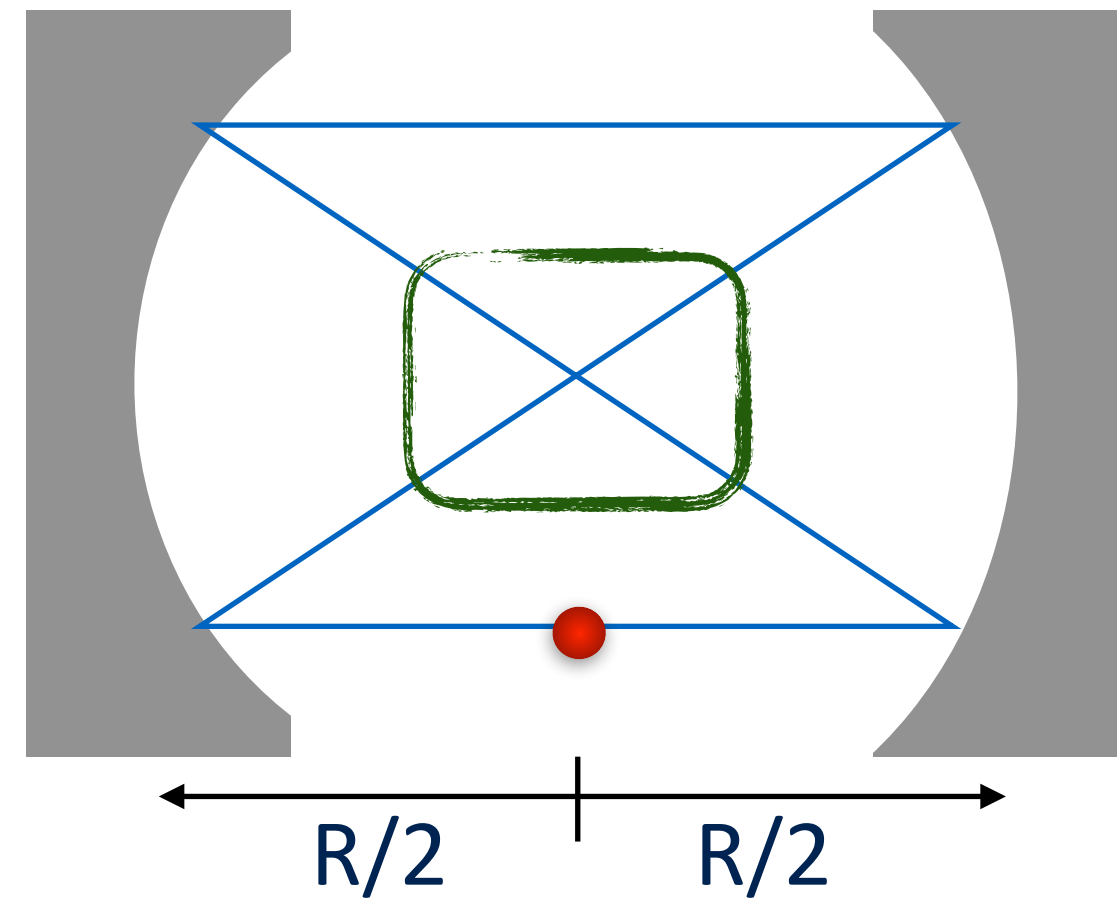


$$H_{\text{int}} \propto \sum_{lm} \Xi_{lm}(r_1) \Xi_{lm}(r_2)$$

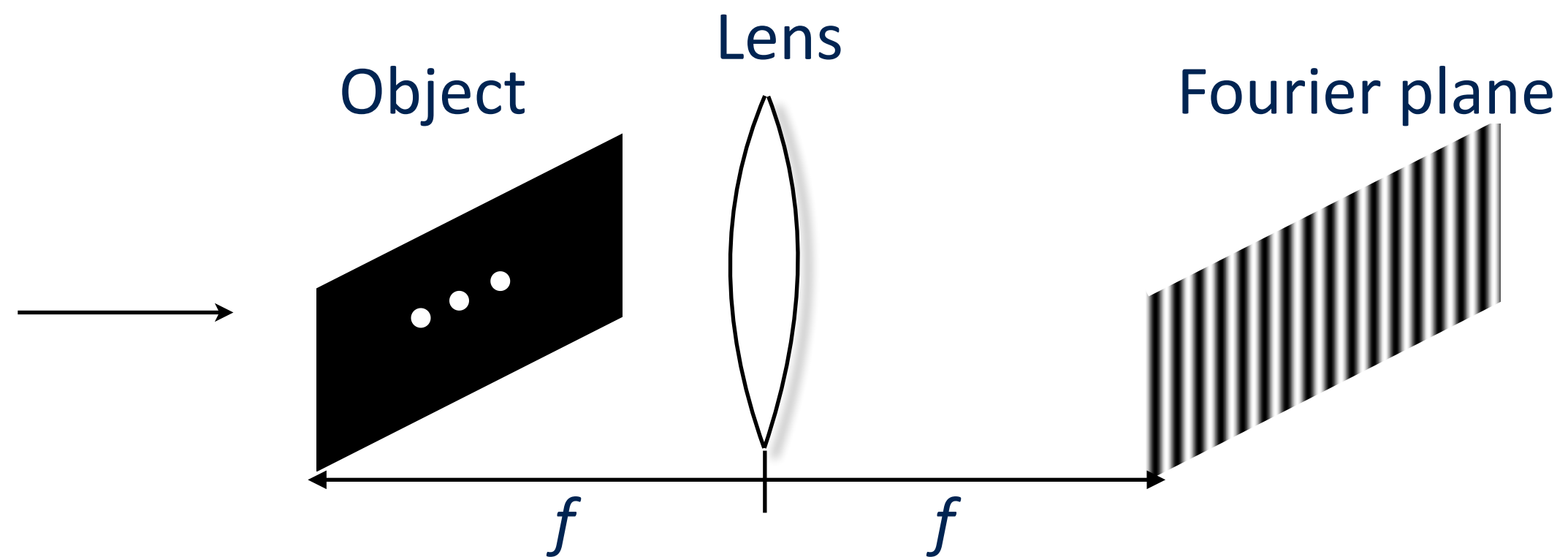
$$H_{\text{int}} = H_{\text{self}} + H_{\text{local}} + H_{\text{nonlocal}}$$

$$H_{\text{nonlocal}} \propto \cos\left(\frac{\mathbf{r}_1 \cdot \mathbf{r}_2}{w_0^2}\right)$$

Intuition: Non-local part of the photon wavepacket

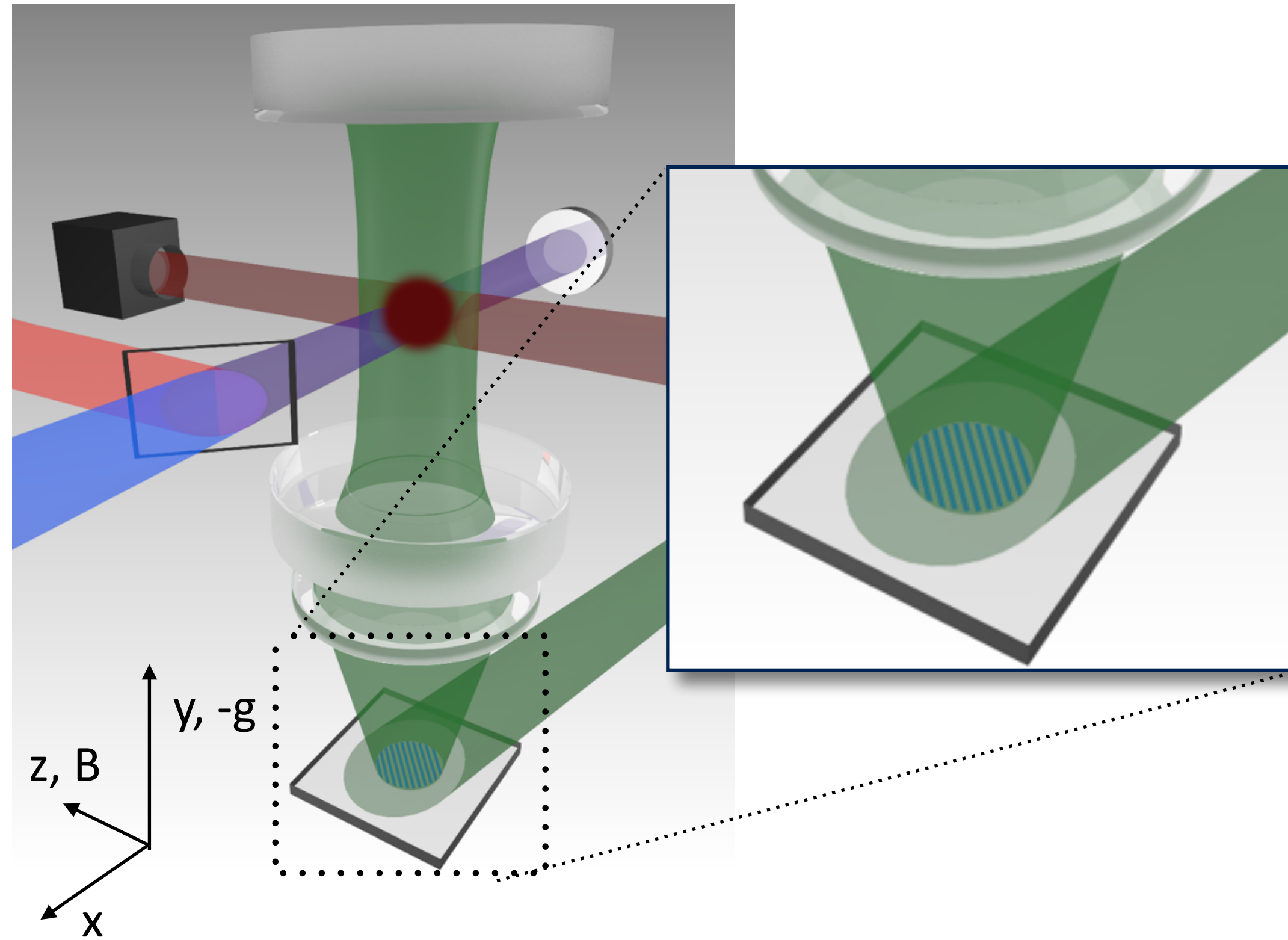


These fringes are the Fourier image of the wavepacket around the BEC



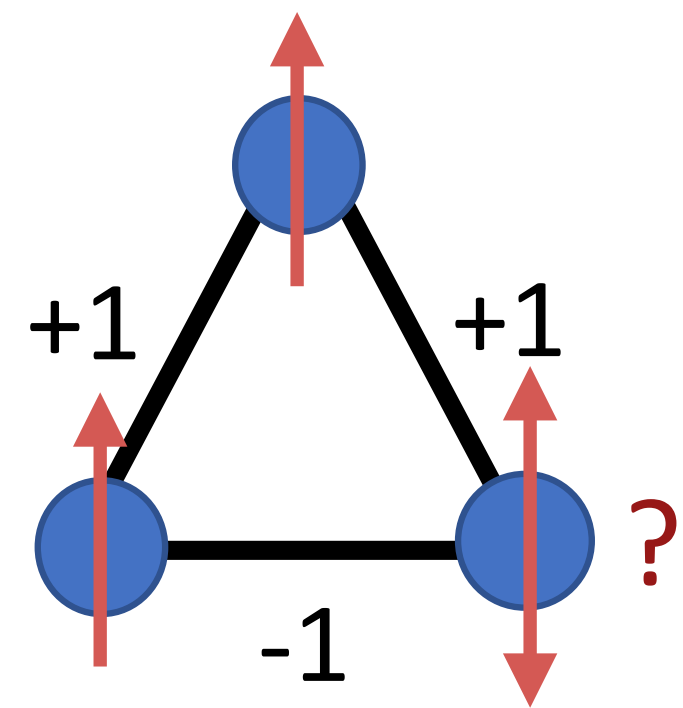
$$H_{\text{nonlocal}} \propto \cos\left(\frac{\mathbf{r}_1 \cdot \mathbf{r}_2}{w_0^2}\right)$$

Observation of sign-changing interactions



Spatial heterodyne of cavity emission

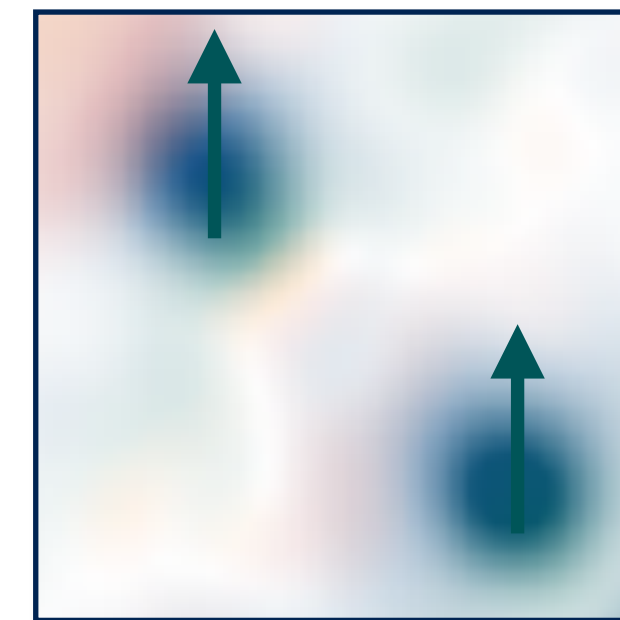
$$H_{int} = - \sum_{i < j} J_{ij} \sigma_z^i \sigma_z^j$$



Ingredient for geometrical frustration

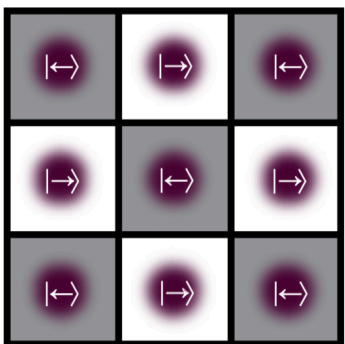
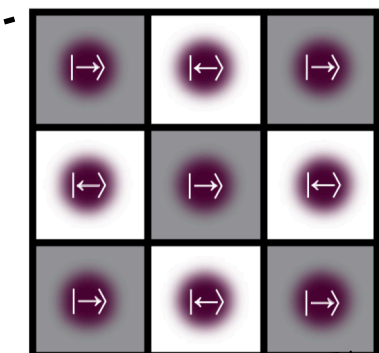
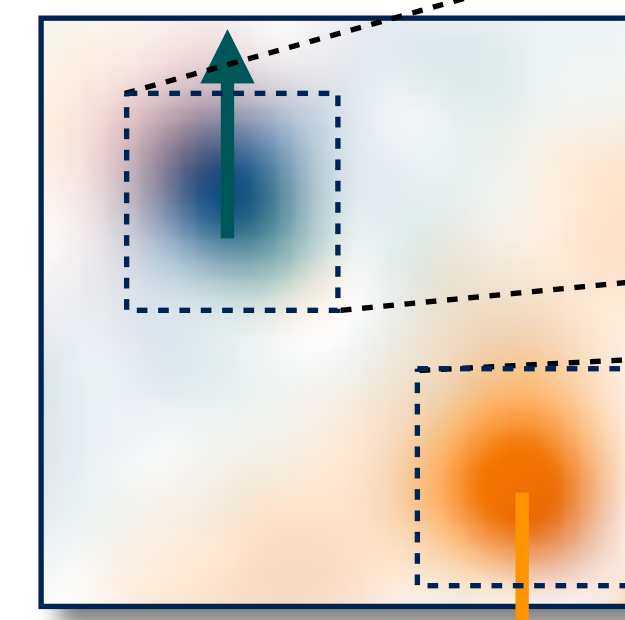
Ferromagnetic

$+J_{ij}$



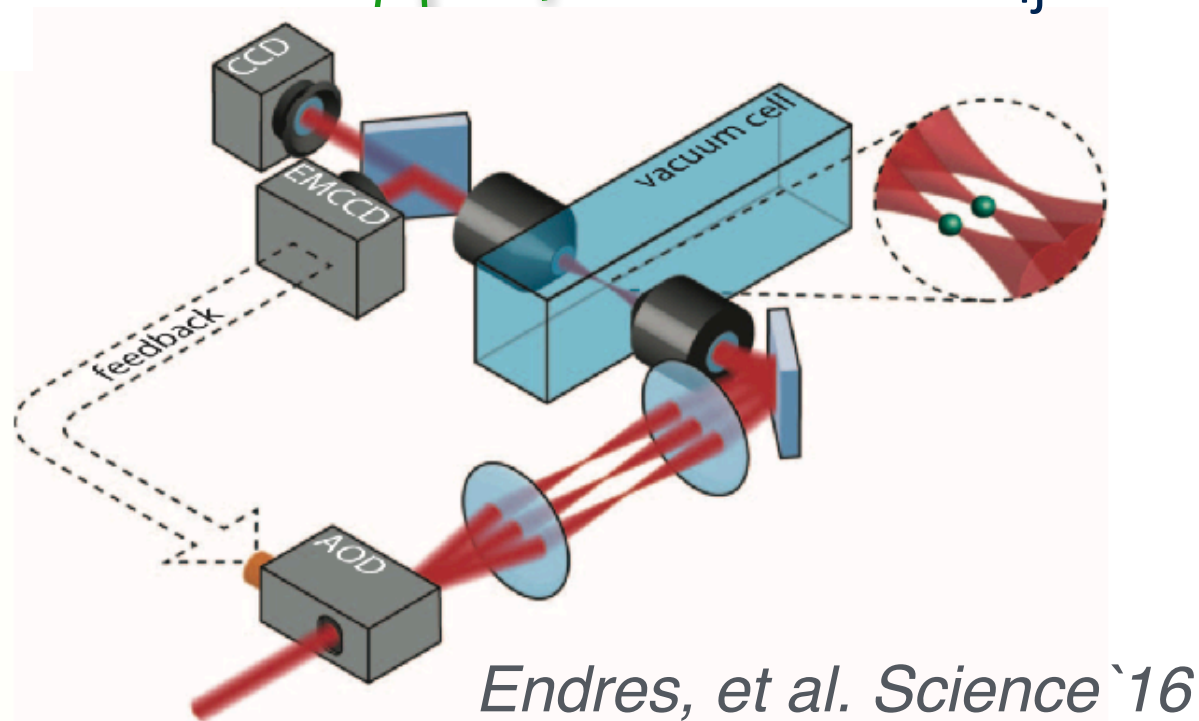
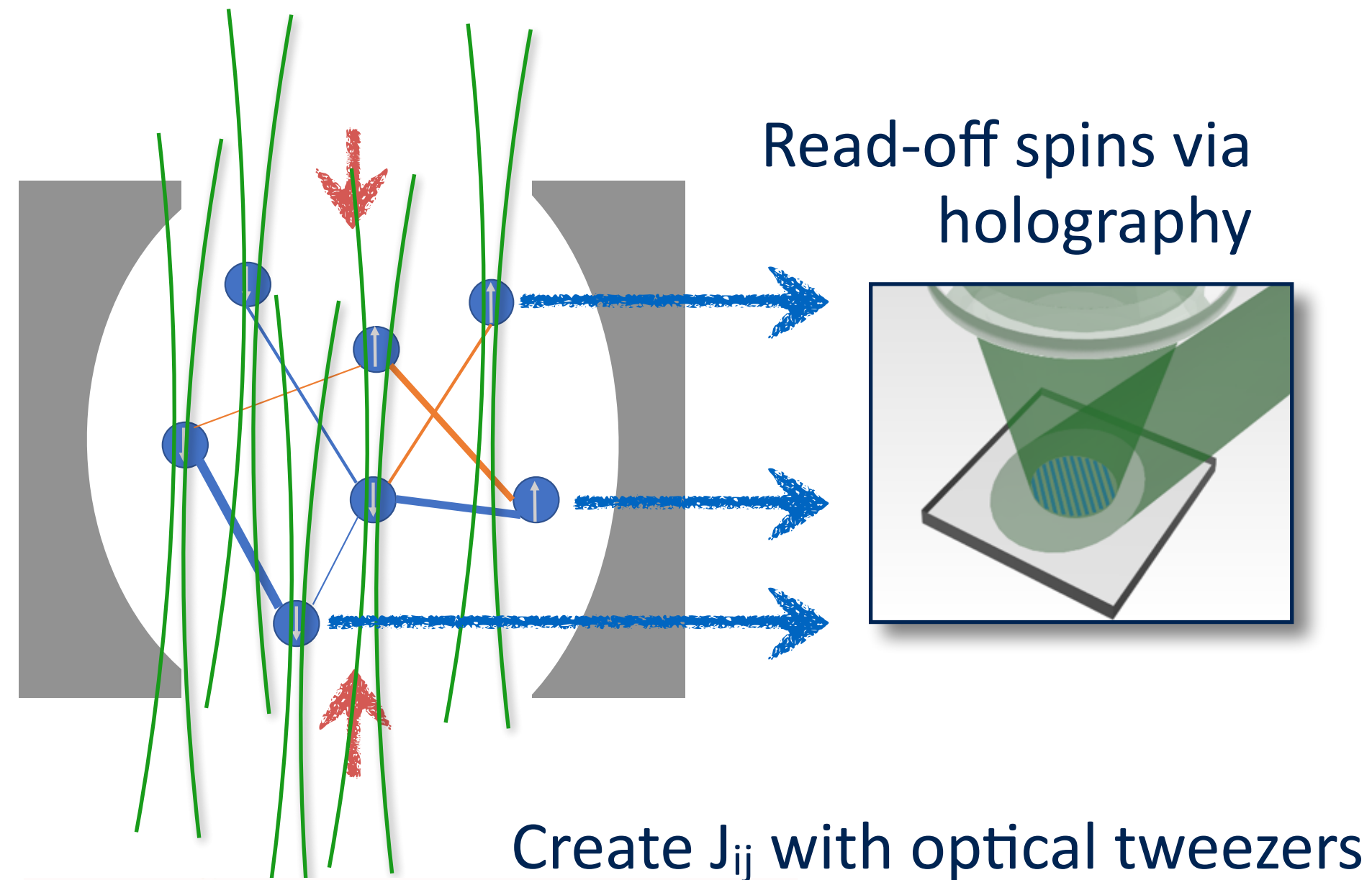
Anti-Ferromagnetic

$-J_{ij}$

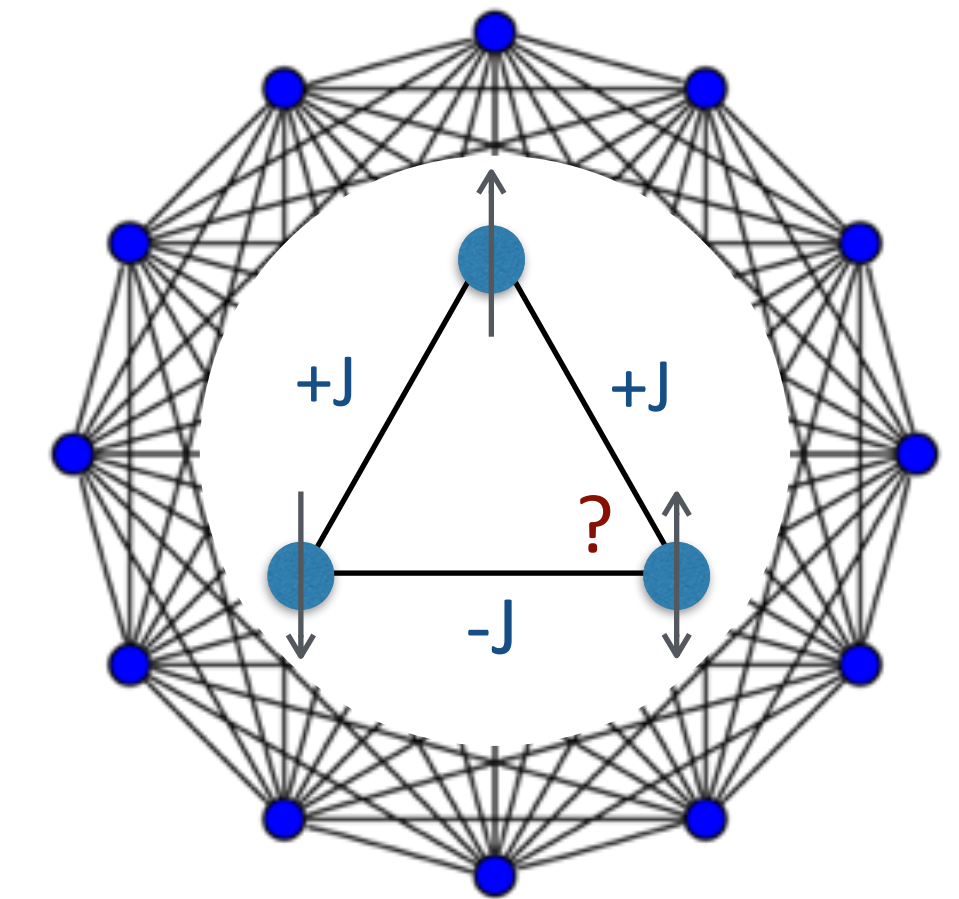
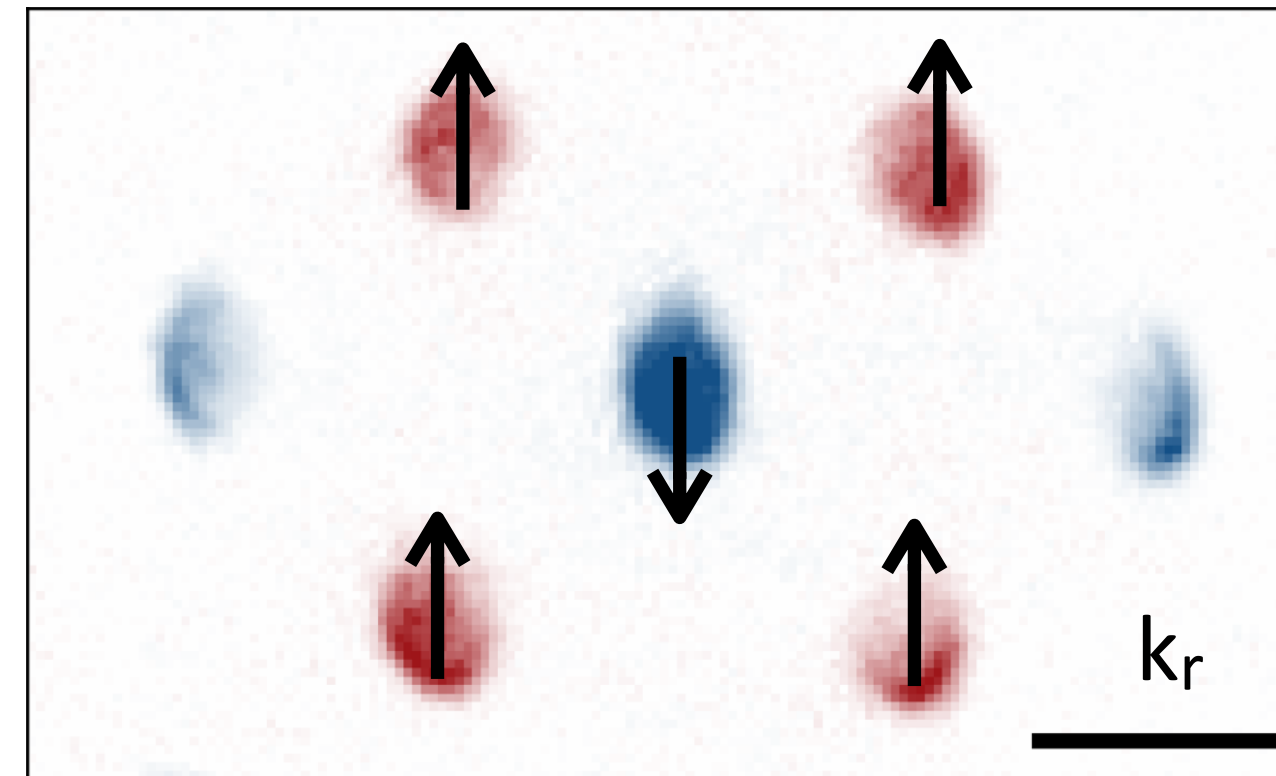


- Note: Data, not simulation
- Spin and checkerboard pattern locked

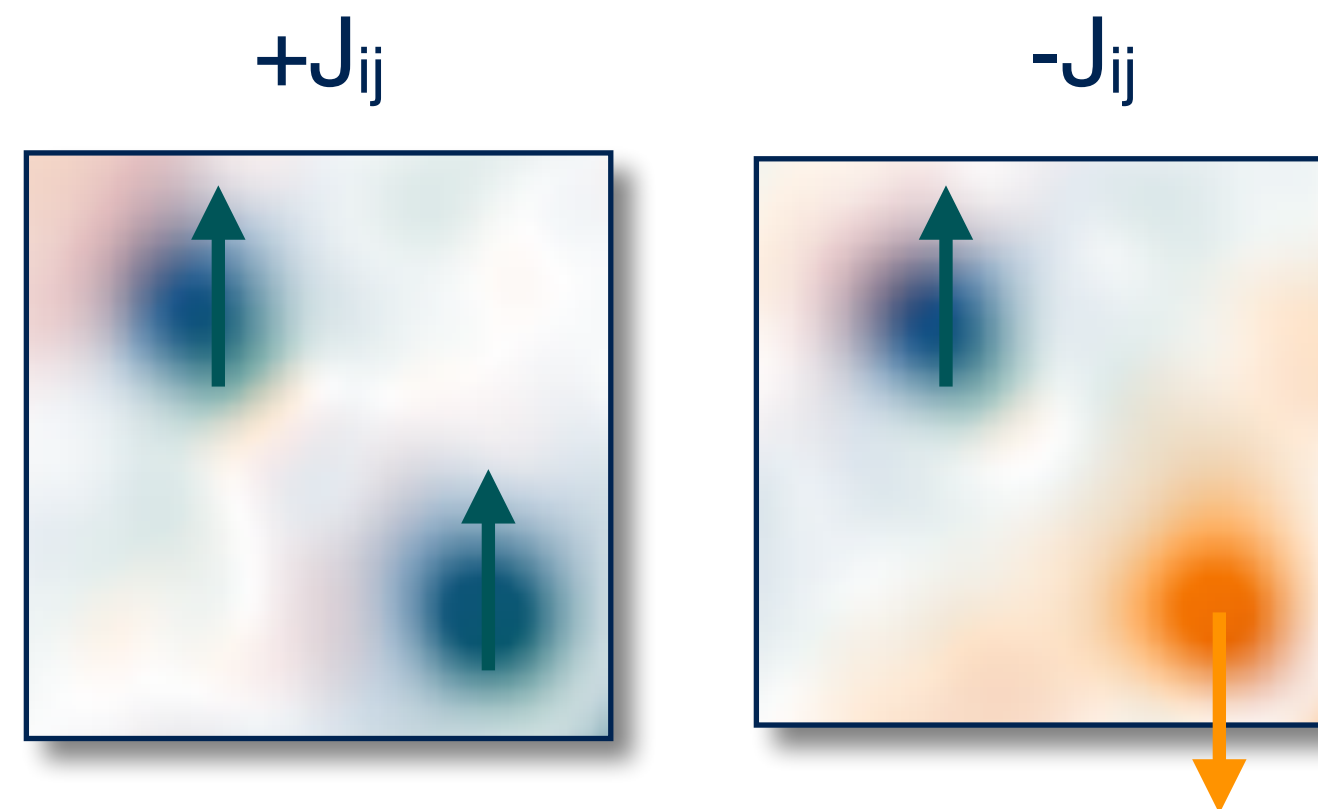
All ingredients demonstrated for quantum-optical spin glass



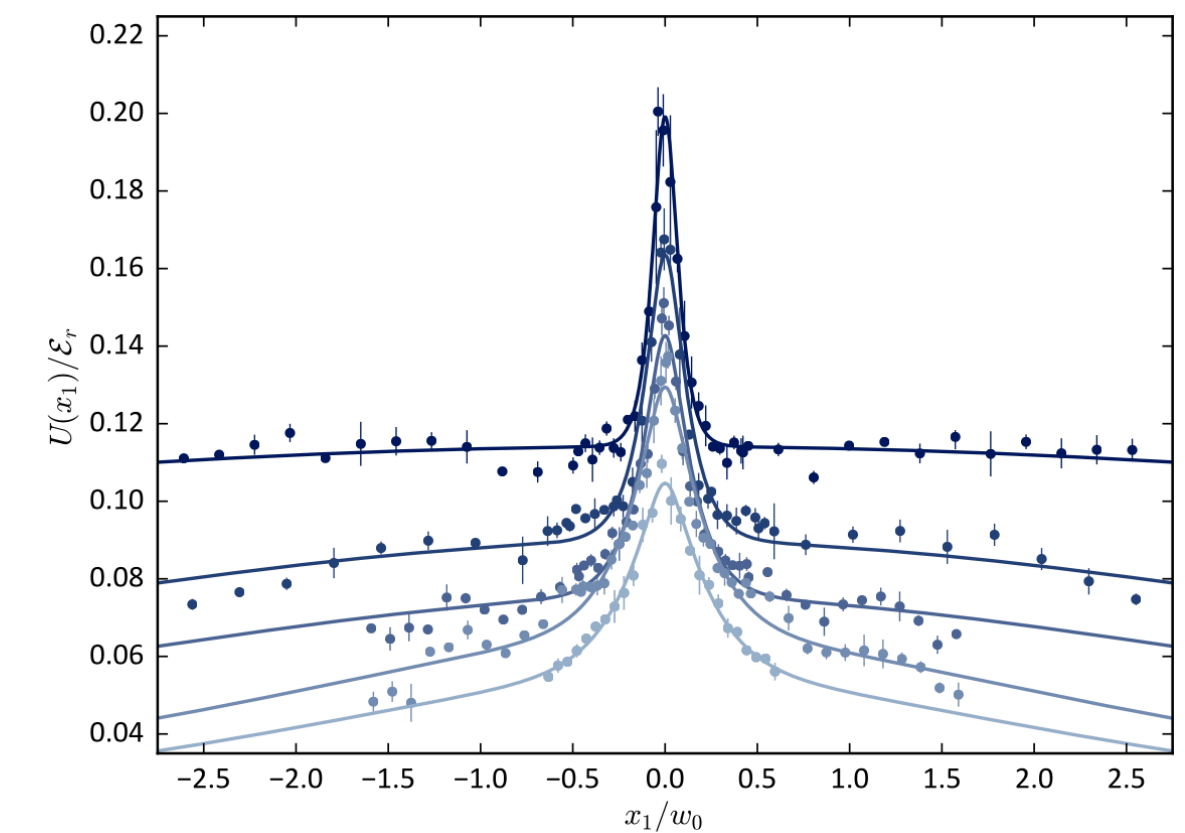
Spin interactions



Signed interactions

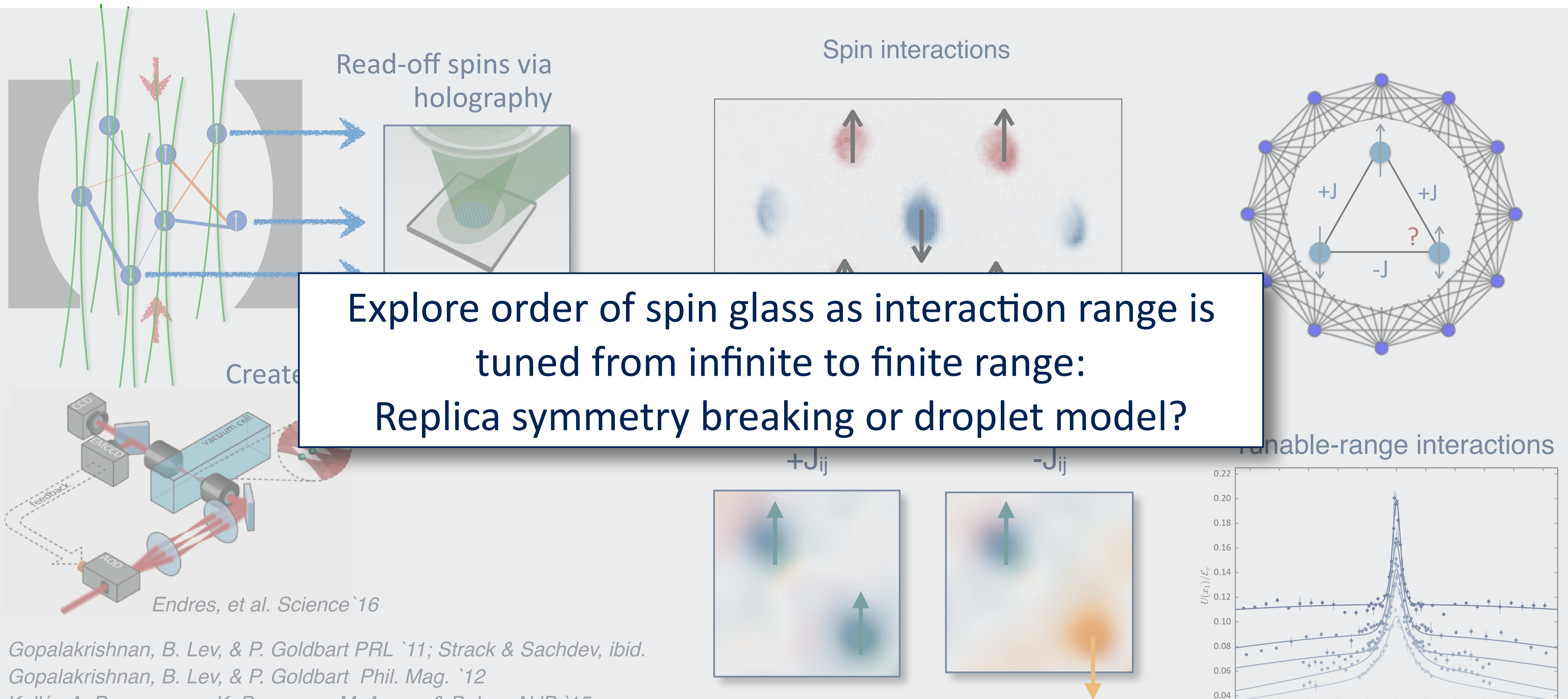


Tunable-range interactions



- S. Gopalakrishnan, B. Lev, & P. Goldbart PRL '11; Strack & Sachdev, ibid.*
S. Gopalakrishnan, B. Lev, & P. Goldbart Phil. Mag. '12
A. Kollár, A. Papageorge, K. Baumann, M. Armen & B. Lev, NJP '15
A. Kollár, A. Papageorge, V. Vaidya, Y. Guo, J. Keeling, & B. Lev, Nature Comm. '17
V. Vaidya, Y. Guo, R. Kroeze, K. Ballantine, A. Kollár, J. Keeling, & B. Lev, PRX '18
Y. Guo, R. Kroeze, V. Vaidya, J. Keeling & B. Lev PRL '19
Y. Guo, V. Vaidya, R. Kroeze, R. A. Lunney, B. Lev, & J. Keeling PRA '19

All ingredients demonstrated for quantum-optical spin glass

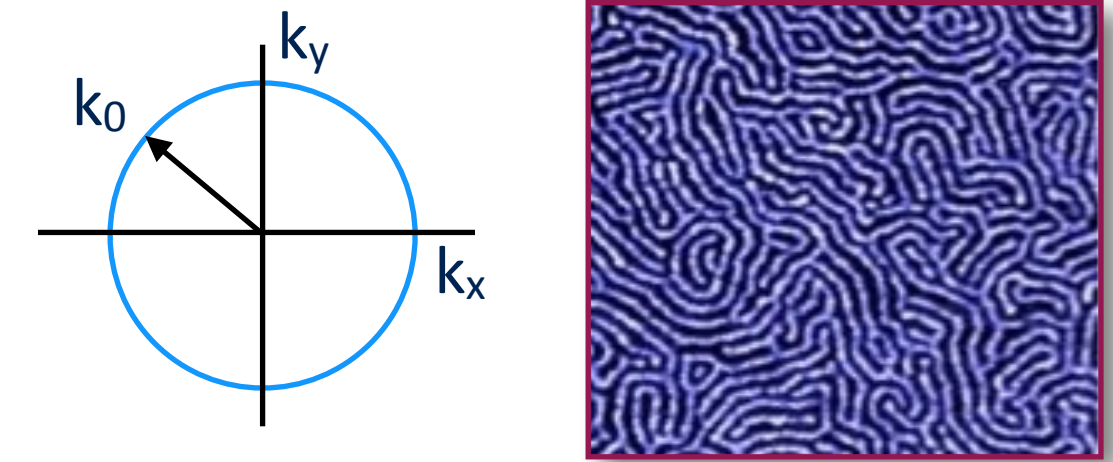


- S. Gopalakrishnan, B. Lev, & P. Goldbart PRL `11; Strack & Sachdev, ibid.*
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Y. Guo, R. Kroeze, V. Vaidya, J. Keeling & B. Lev PRL `19
Y. Guo, V. Vaidya, R. Kroeze, R. A. Lunney, B. Lev, & J. Keeling PRA `19

Future directions with multimode cavity QED

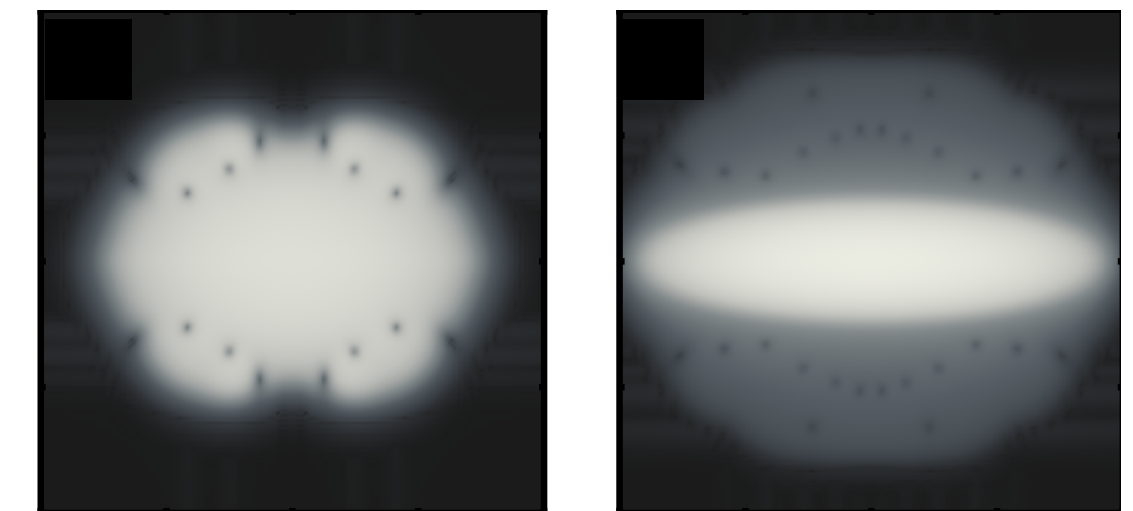
We can make a 2D fully emergent optical lattice —> unusual “Brazovskii” transition to a **quantum liquid crystal** state (also seen in high- T_c 's)...

S. Gopalakrishnan, B. Lev & P. Goldbart, Nature Physics '09, PRA '10



With multimode cavity and Raman pumping, we can make **dynamical gauge fields**, beginning with demonstrating a Meissner-like effect:

K. Ballentine, B. Lev, & J. Keeling, PRL '17; see also C. Kollath et al.



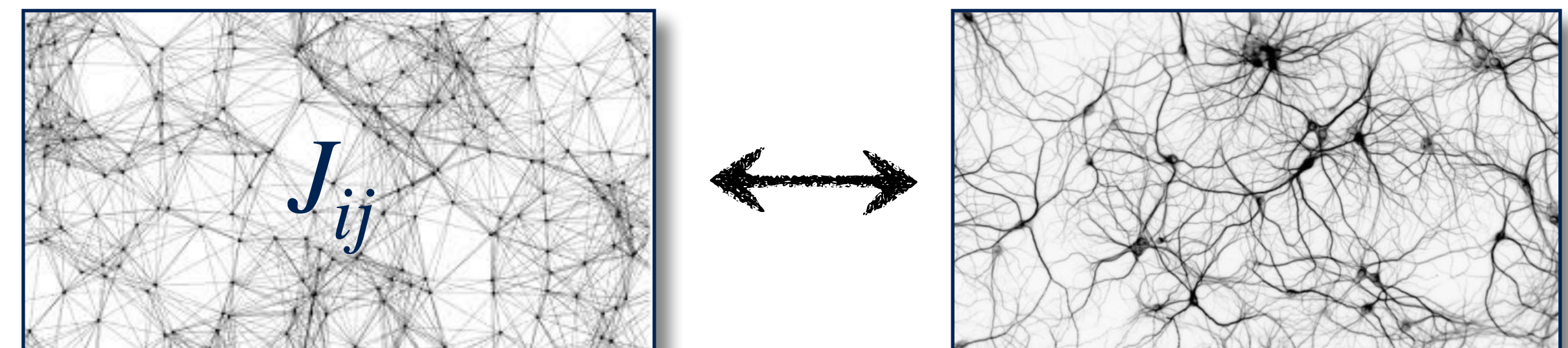
We are working toward making a **spin glass** which may enable **driven-dissipative neuromorphic computation**:

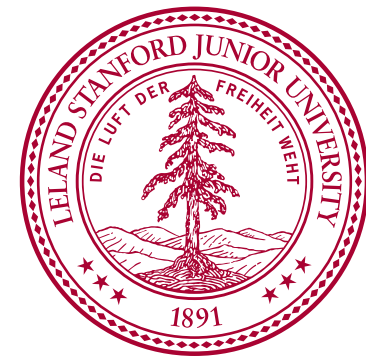
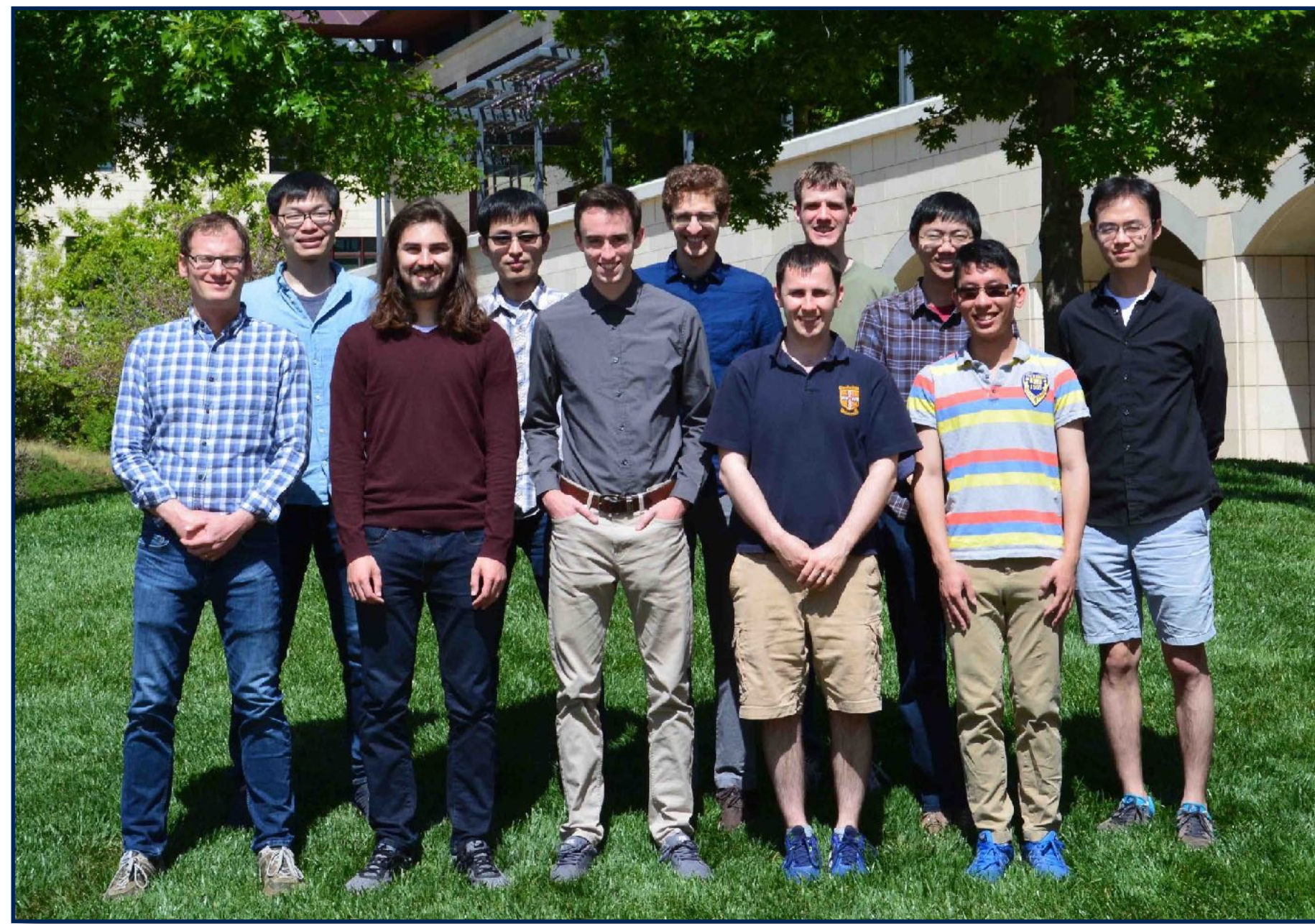
S. Gopalakrishnan, B. Lev, & P. Goldbart PRL '11; Strack & Sachdev, ibid.

S. Gopalakrishnan, B. Lev, & P. Goldbart Phil. Mag. '12

B. Marsh, Y. Guo, S. Ganguli, S. Gopalakrishnan, J. Keeling, & B. Lev in preparation

hard optimization problems





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UNIVERSITY

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Multimode, Many-Body Cavity QED

Yudan Guo

Ronen Kroeze

Brendan Marsh

Collaborators:

Jonathan Keeling (St. Andrews)

Sarang Gopalakrishnan (CUNY)

Surya Ganguli (Stanford)

Quantum integrability breaking with Dy

Wil Kao

Kuan-Yu Li

Kuan-Yu Lin

Collaborators:

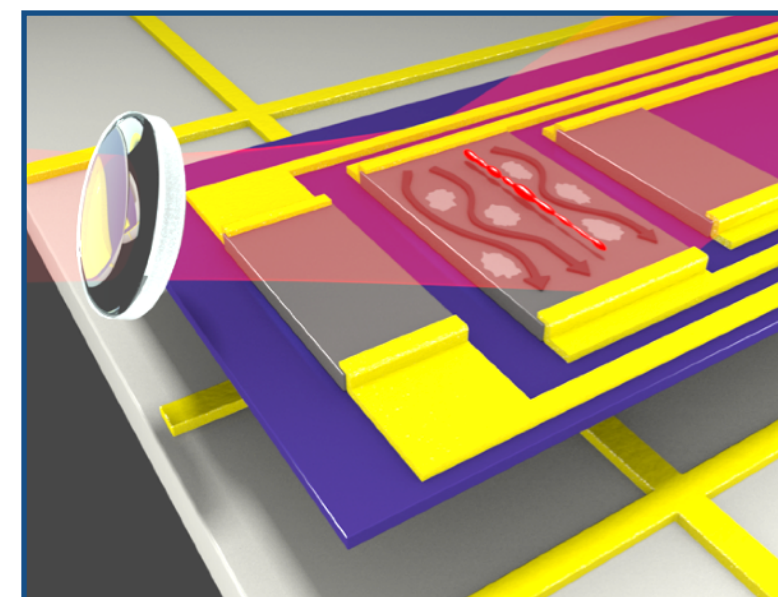
Sarang Gopalakrishnan (CUNY)

Marcos Rigol (Penn St)

Dipolar quantum Newton's cradle



Imaging electron nematics in pnictides with quantum gases



SQCRAMscope

Fan Yang

Stephen Taylor

Brandon Freudenstein

Steve Edkins (postdoc)

Collaborators:

Ian Fisher & Johanna Palmstrom (Stanford)