光-マグノン-マイクロ波-超伝導量子ビットのリンク
あるいは量子ピタゴラスイッチ

東大先端研

宇佐見康二

Quantum optics with collective excitations in solid

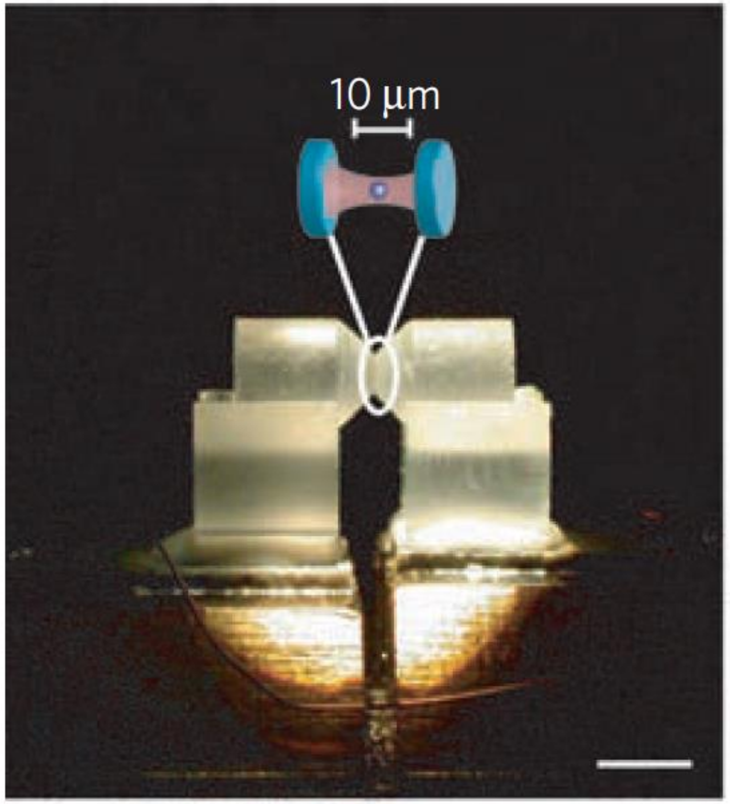
Koji Usami

RCAST, the University of Tokyo

Wonderful world of quantum optics

Cavity QED

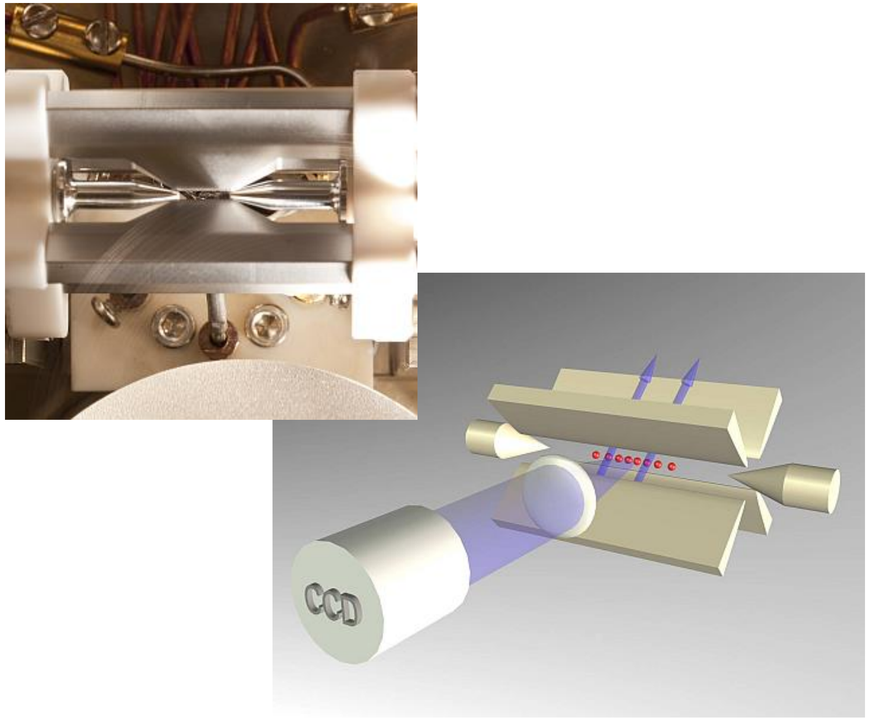
- Atom
- Photon



H.J. Kimble,
Nature **453,** 1023 (2008).

Ion Trap

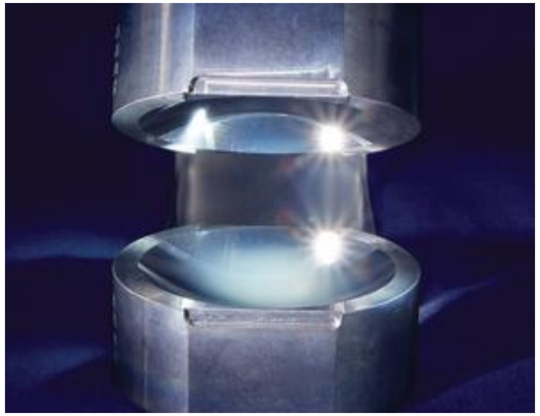
- Ion
- Phonon

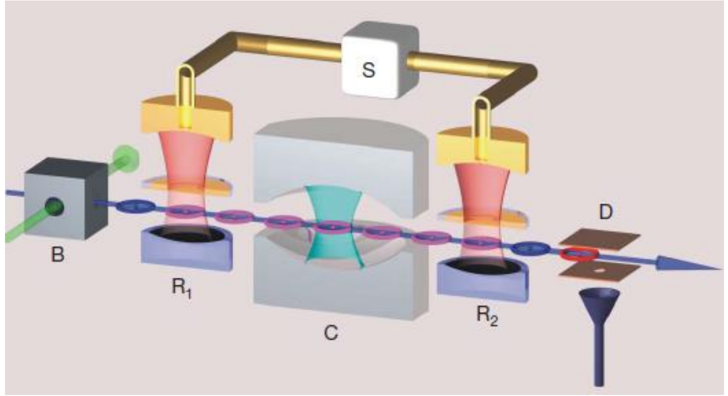


F. Schmidt-Kaler, *et al.,*
Nature **422,** 408 (2003).

Cavity QED with Rydberg atom

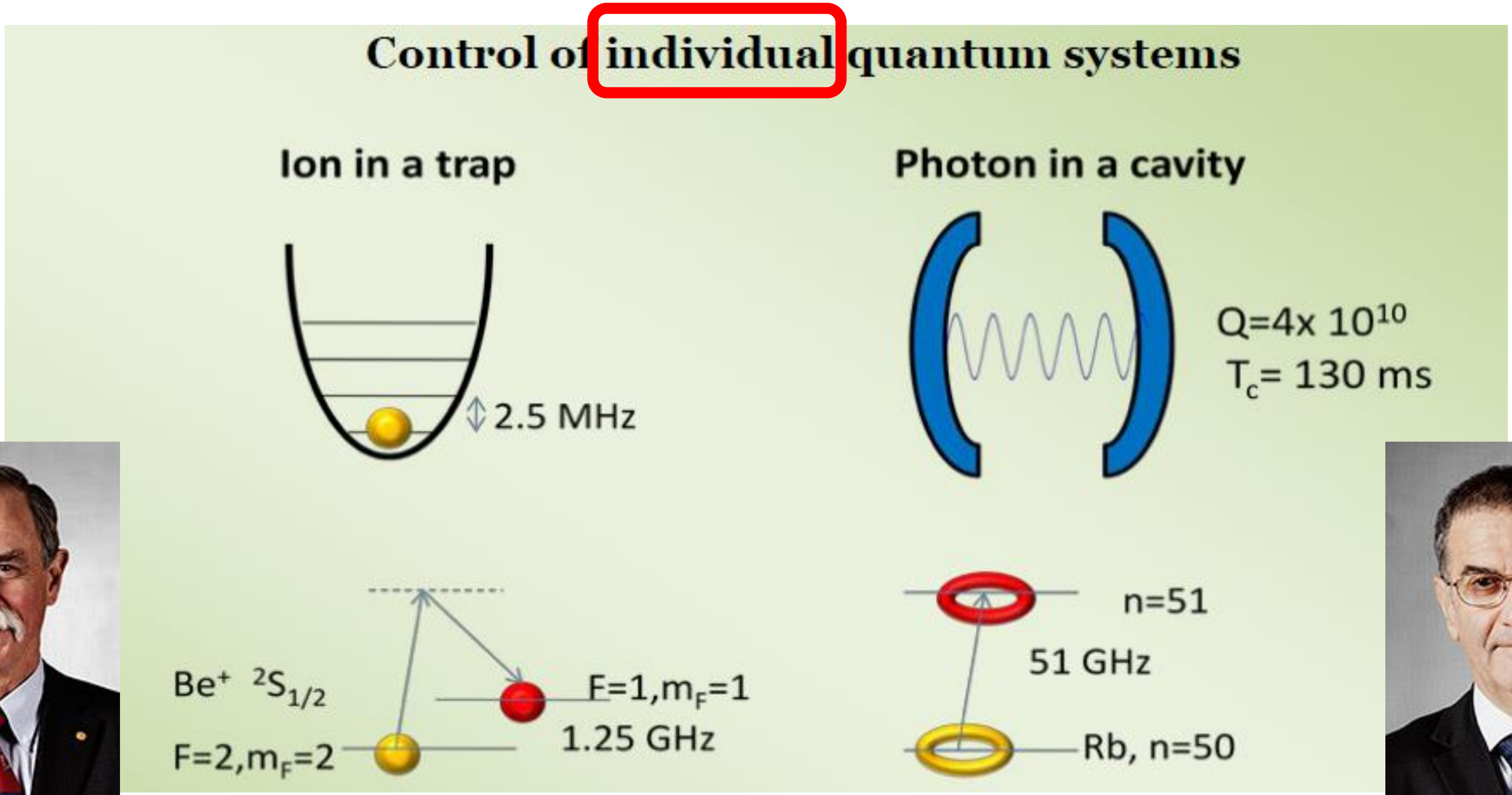
- Rydberg atom
- Microwave photon

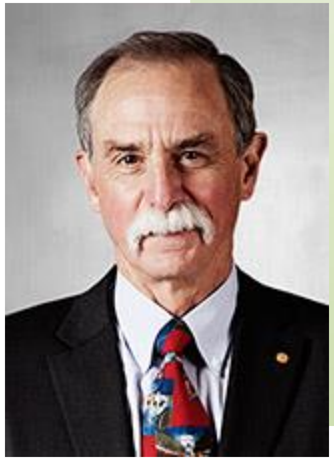




S. Gleyzes, *et al.,*
Nature **446**, 297 (2007)

Nobel Prize in Physics 2012

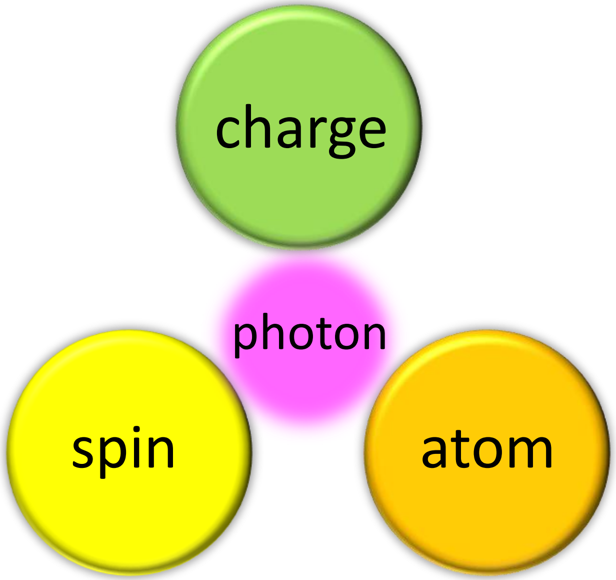




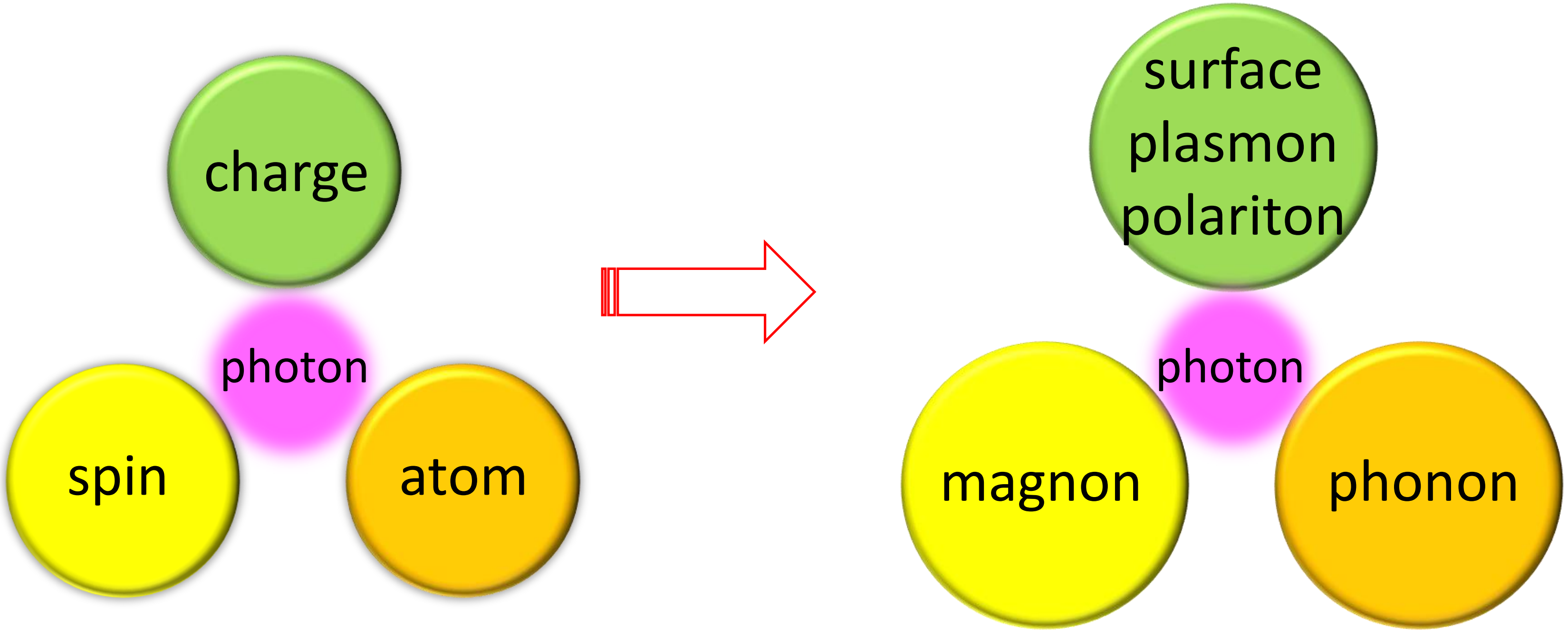
David J. Wineland

Serge Haroche

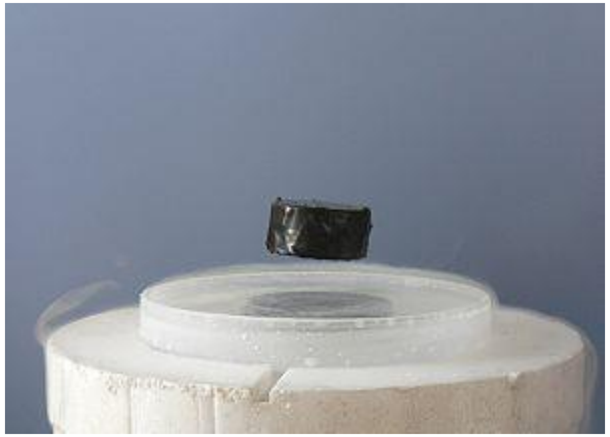
Individual quantum systems



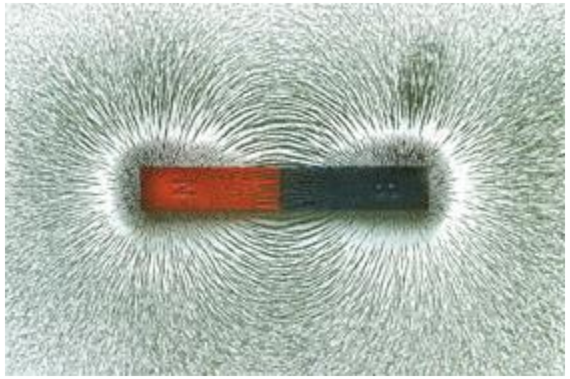
Collective excitations



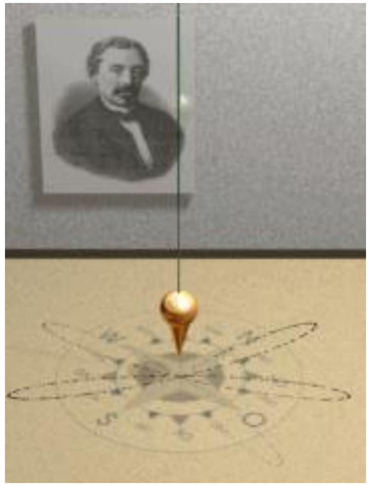
Macroscopic quantum systems



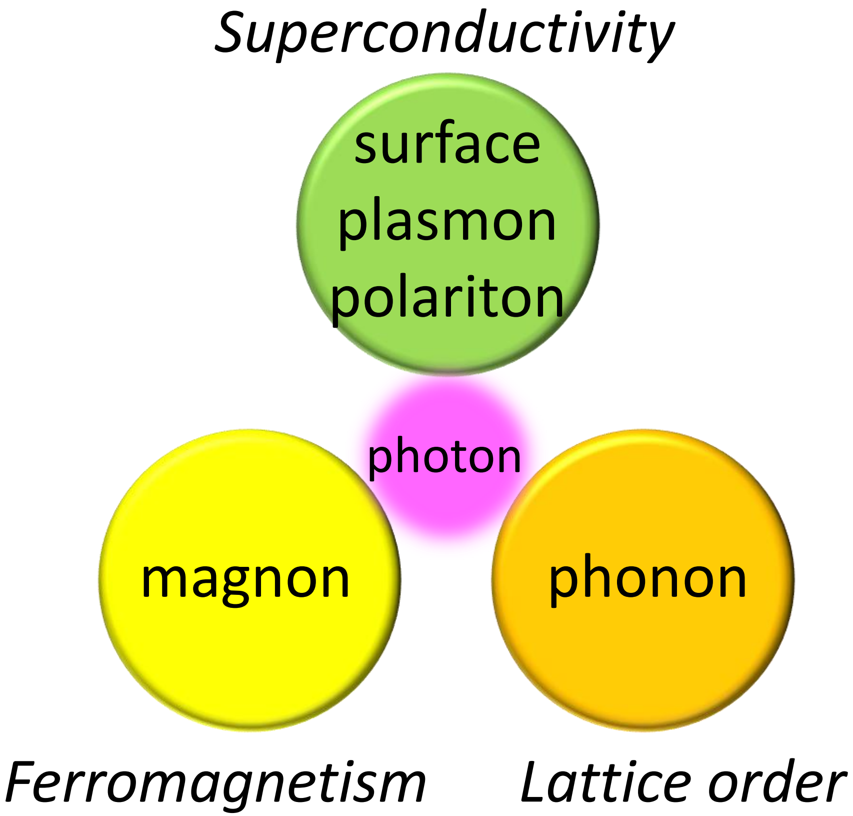
http://ja.wikipedia.org/



http://kids.gakken.co.jp

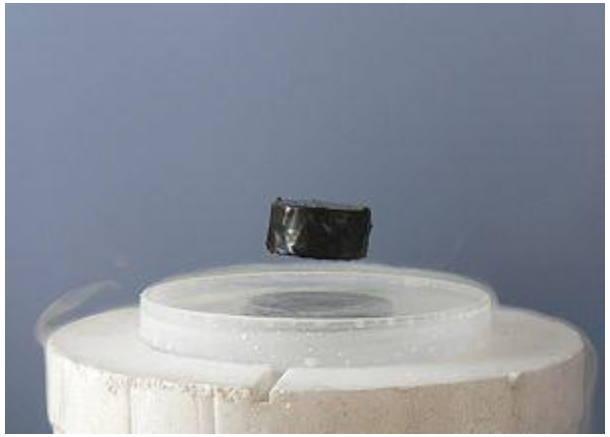


http://en.wikipedia.org/



Collective excitations

Spontaneous breaking of symmetry : Nambu-Goldstone **bosons**



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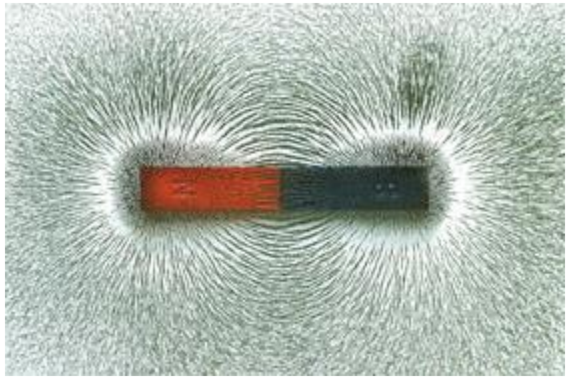
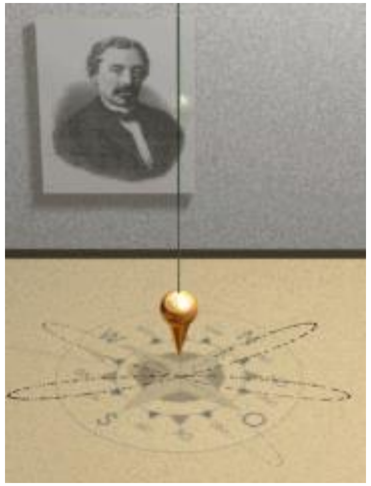


http://kids.gakken.co.jp



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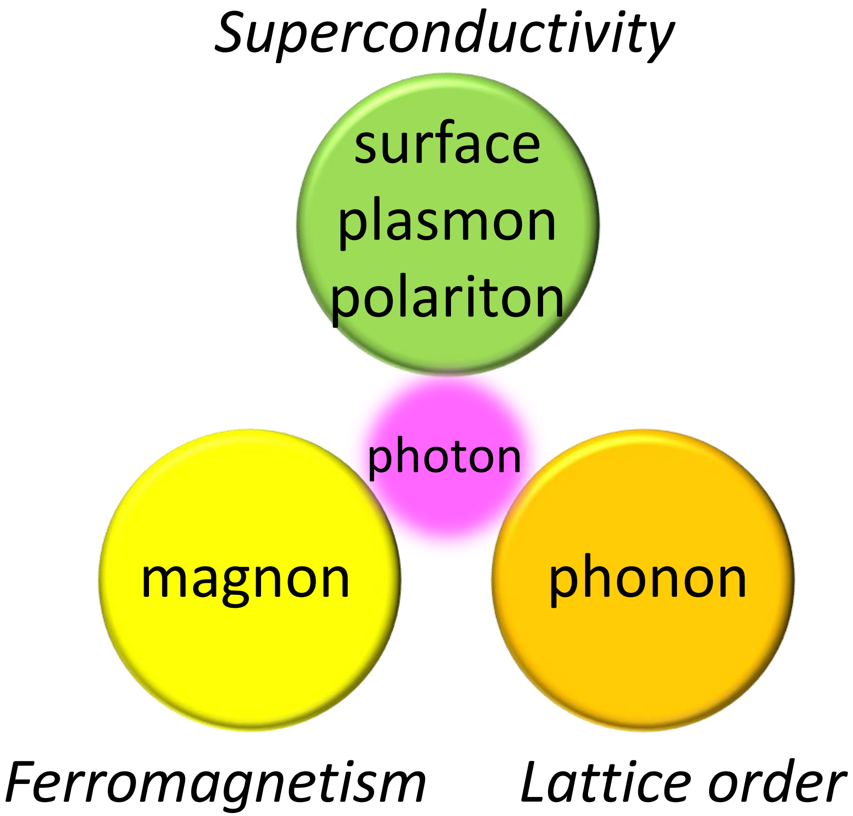
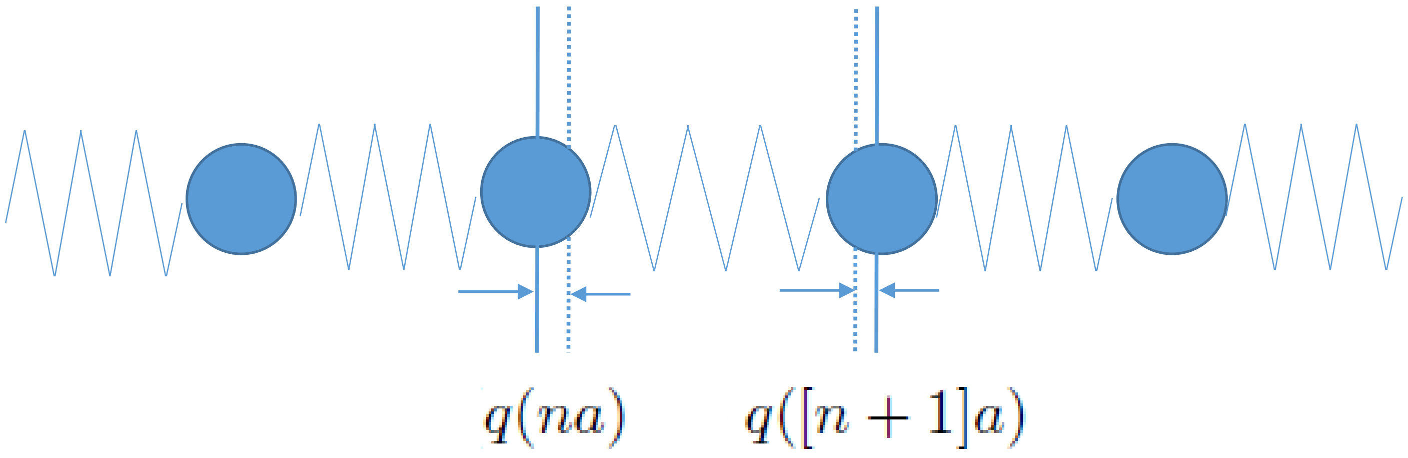


Phonons and nano-mechanics

Atomic chain



Potential:

$$V = \frac{1}{2}\kappa \sum_{n=1}^{N_a} \left(q(na) - q([n+1]a)\right)^2$$

Equation of motion:

$$\boxed{\begin{aligned} m\ddot{q}(na) &= -\frac{\partial V}{\partial q(na)} \\ &= -\kappa\left(2q(na) - q([n-1]a) - q([n+1]a)\right) \end{aligned}}$$

Coupled equations…

Continuum limit (a → 0)

Coupled equation of motion:

$$
\begin{aligned}
m\ddot{q}(na) &= -\frac{\partial V}{\partial q(na)} \\
&= -\kappa\left(\underline{2q(na) - q([n-1]a) - q([n+1]a)}\right)
\end{aligned}
$$

$$
\begin{aligned}
& (q(x_n) - q(x_n - a)) - (q(x_n + a) - q(x_n)) \\
=\; & -\left(\frac{\partial q(x_n + a)}{\partial x} - \frac{\partial q(x_n)}{\partial x}\right) a \\
=\; & -\left(\frac{\partial^2 q(x_n + a)}{\partial x^2}\right) a^2
\end{aligned}
$$

(1+1)-D boson field equation:

$$
m\ddot{q}(x) = \kappa\left(\frac{\partial^2 q(x)}{\partial x^2}\right) a^2 \quad \Longrightarrow \quad \boxed{\left(\frac{1}{v_s^2}\frac{\partial^2}{\partial t^2} - \frac{\partial^2}{\partial x^2}\right) q(x,t) = 0}
$$

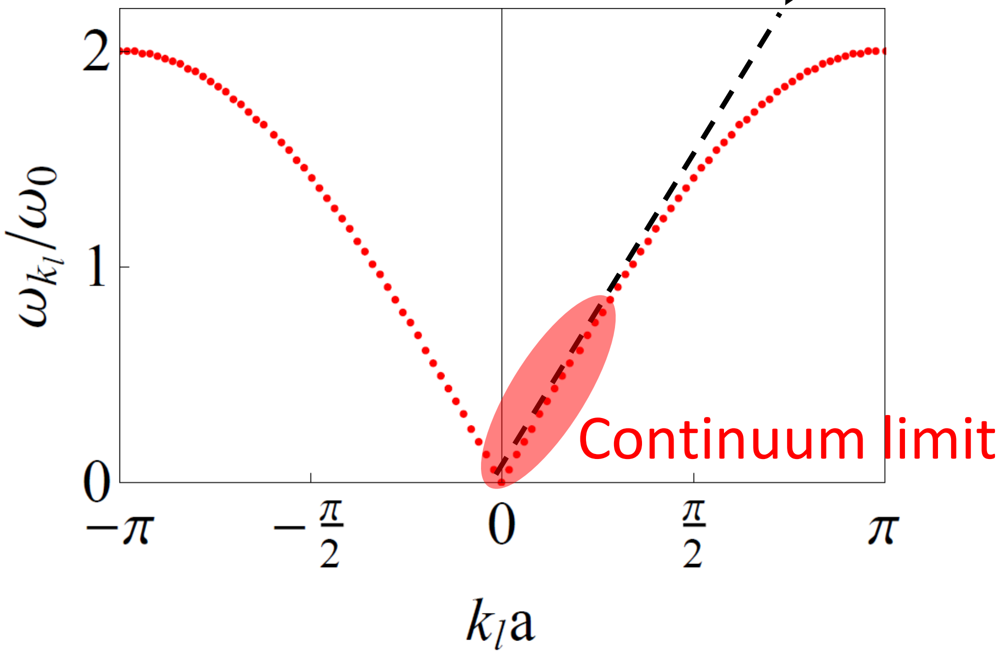
Continuum limit (a → 0)

(1+1)-D boson field equation:

$$m\ddot{q}(x) = \kappa\left(\frac{\partial^2 q(x)}{\partial x^2}\right)a^2 \Rightarrow \boxed{\left(\frac{1}{v_s^2}\frac{\partial^2}{\partial t^2} - \frac{\partial^2}{\partial x^2}\right)q(x,t) = 0}$$

Dispersion relation in continuum limit:

$$\boxed{\omega_k = v_s k}$$



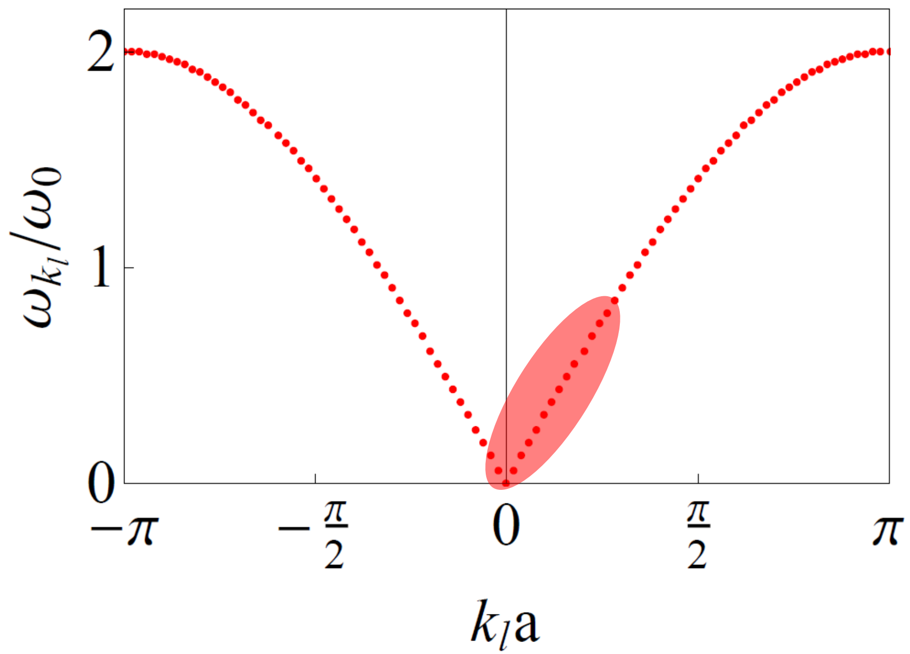
Sound velocity:

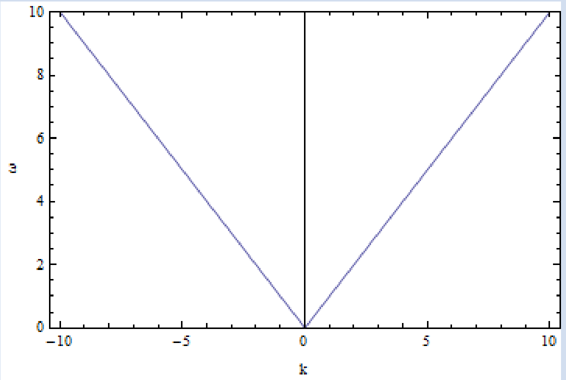
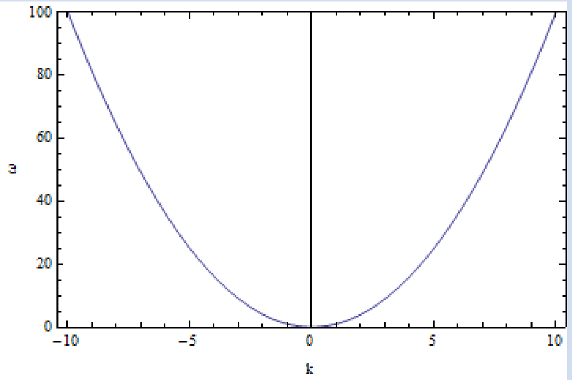
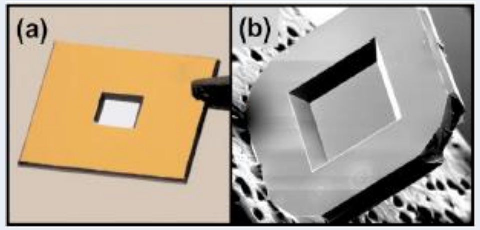
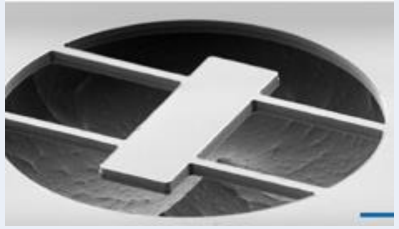
$$v_s = \sqrt{\frac{\kappa a^2}{m}} = \sqrt{\frac{\kappa a}{\left(\frac{m}{a}\right)}} = \sqrt{\frac{c_{11}}{\rho}}$$

Elastic constant

Mass density

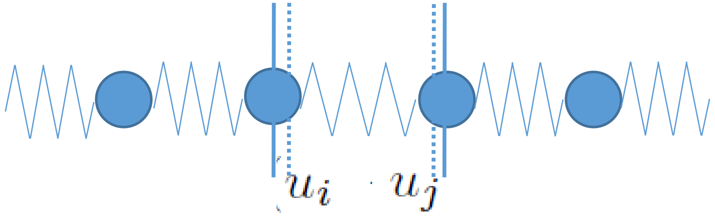
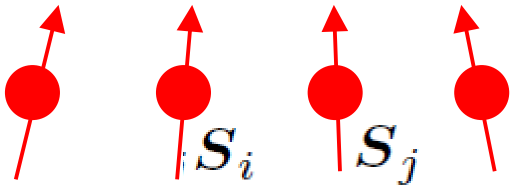
Boundary conditions make the discrete modes



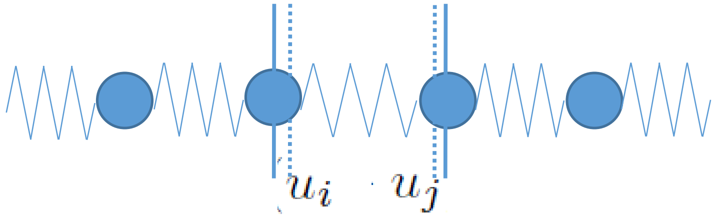
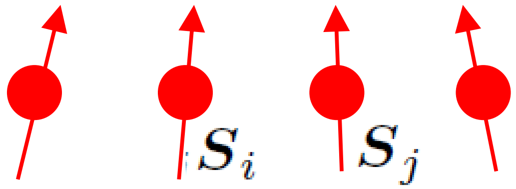
Type A	Type B
$\omega \propto k$ (linear dispersion)	$\omega \propto k^2$ (quadratic dispersion)
	
Doubly-clamped cantilevers 	Free-free cantilevers 

Ferromagnets and magnons

Interacting particles

	Atomistic viewpoint (microscopic)
Mechanics (Phonons)	 Covalent/molecular/ionic bonding
Magnets (Magnon)	 Exchange interaction

Interacting particles

	Atomistic viewpoint (microscopic)
Mechanics (Phonons)	$$\mathcal{U}_{\mathrm{el}} = \frac{1}{2}\sum_{i,j} K_{ij}\left(u_i - u_j\right)^2$$  Covalent/molecular/ionic bonding
Magnets (Magnon)	$$\mathcal{U}_{\mathrm{ex}} = -\sum_{i,j} J_{ij}\boldsymbol{S}_i \cdot \boldsymbol{S}_j$$  Exchange interaction

Continuum limit (k→0 limit)

	Atomistic viewpoint (microscopic)	**Continuum field viewpoint (macroscopic)**
Mechanics (Phonons)	$\mathcal{U}_{\mathrm{el}} = \frac{1}{2}\sum_{i,j} K_{ij}\left(u_i - u_j\right)^2$	$\mathcal{U}_{\mathrm{el}} = C_{\alpha\mu\beta\nu}\frac{\partial u_\alpha}{\partial x_\mu}\frac{\partial u_\beta}{\partial x_\nu}$
Magnets (Magnon)	$\mathcal{U}_{\mathrm{ex}} = -\sum_{i,j} J_{ij}\boldsymbol{S}_i \cdot \boldsymbol{S}_j$	$\mathcal{U}_{\mathrm{ex}} = C_{\mu\nu}\frac{\partial M_\alpha}{\partial x_\mu}\frac{\partial M_\alpha}{\partial x_\nu}$

Continuum limit (k→0 limit)

	Atomistic viewpoint (microscopic)	**Continuum feild viewpoint (macroscopic)**
Mechanics (Phonons)	$\mathcal{U}_{\mathrm{el}} = \frac{1}{2}\sum_{i,j} K_{ij}\left(u_i - u_j\right)^2$	$\mathcal{U}_{\mathrm{el}} = \boxed{C_{\alpha\mu\beta\nu}}\frac{\partial u_\alpha}{\partial x_\mu}\frac{\partial u_\beta}{\partial x_\nu}$
Magnets (Magnon)	$\mathcal{U}_{\mathrm{ex}} = -\sum_{i,j} J_{ij}\boldsymbol{S}_i \cdot \boldsymbol{S}_j$	$\mathcal{U}_{\mathrm{ex}} = \boxed{C_{\mu\nu}}\frac{\partial M_\alpha}{\partial x_\mu}\frac{\partial M_\alpha}{\partial x_\nu}$

Elastic rigidity (elastic constant)

Magnetic rigidity

that is, Harmonic potential

	Atomistic viewpoint (microscopic)	**Continuum feild viewpoint (macroscopic)**
Mechanics (Phonons)	$\mathcal{U}_{\mathrm{el}} = \frac{1}{2}\sum_{i,j} K_{ij}\left(u_i - u_j\right)^2$	$\mathcal{U}_{\mathrm{el}} = C_{\alpha\mu\beta\nu}\frac{\partial u_\alpha}{\partial x_\mu}\frac{\partial u_\beta}{\partial x_\nu}$
Magnets (Magnon)	$\mathcal{U}_{\mathrm{ex}} = -\sum_{i,j} J_{ij}\boldsymbol{S}_i \cdot \boldsymbol{S}_j$	$\mathcal{U}_{\mathrm{ex}} = C_{\mu\nu}\frac{\partial M_\alpha}{\partial x_\mu}\frac{\partial M_\alpha}{\partial x_\nu}$

Rigidity

1D lumped system
(spring)

$$\boxed{\mathcal{H}(X) = \frac{1}{2}kx^2}$$

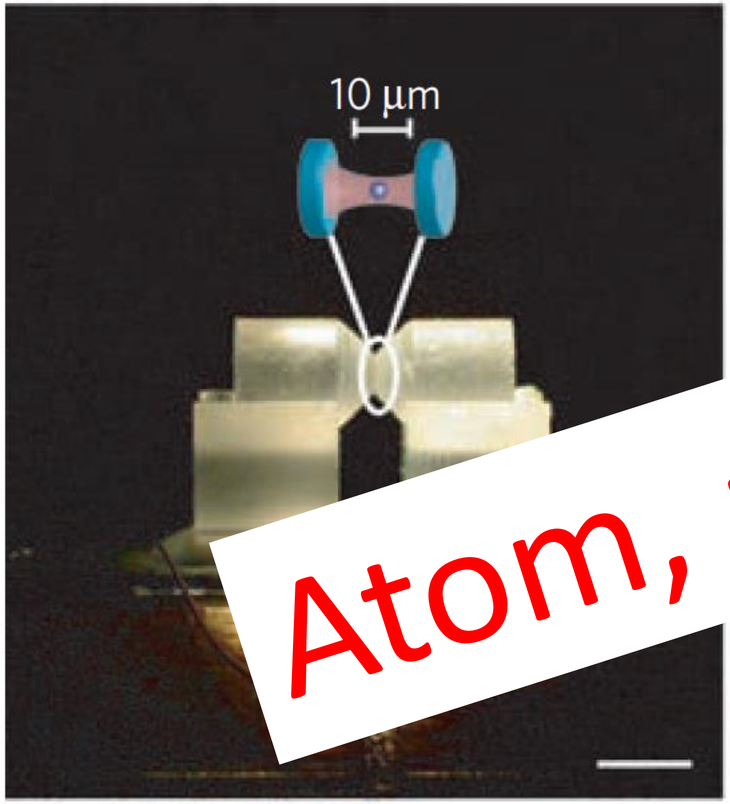
$$\mathcal{H}(X) = \cancel{\mathcal{H}(X_0)} + \cancel{\frac{\partial \mathcal{H}(X_0)}{\partial x}}x + \frac{1}{2}\underbrace{\frac{\partial^2 \mathcal{H}(X_0)}{\partial x^2}}_{k}x^2$$

neglect equilibrium

Wonderful world of quantum optics

Cavity QED

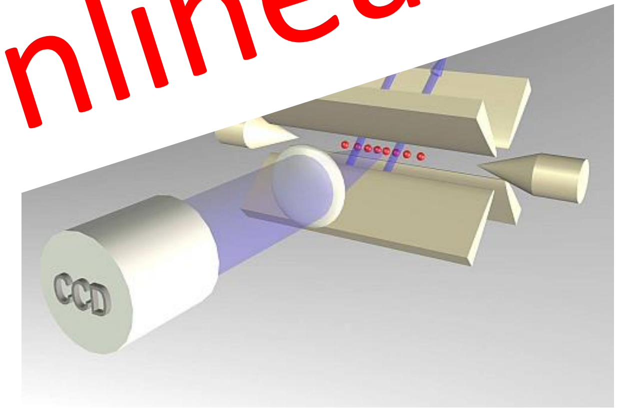
- Atom
- Photon



H.J. Kimble,
Nature **453,** 1023 (2008).

Ion Trap

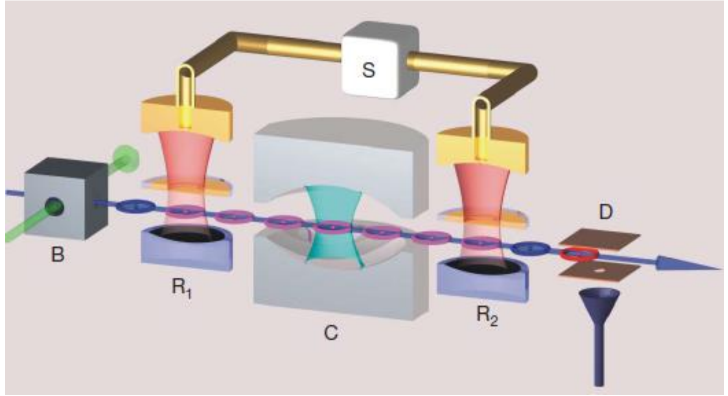
- Ion
- Phonon



F. Schmidt-Kaler, *et al.,*
Nature **422,** 408 (2003).

Cavity QED with Rydberg atom

- Rydberg atom
- Microwave photon

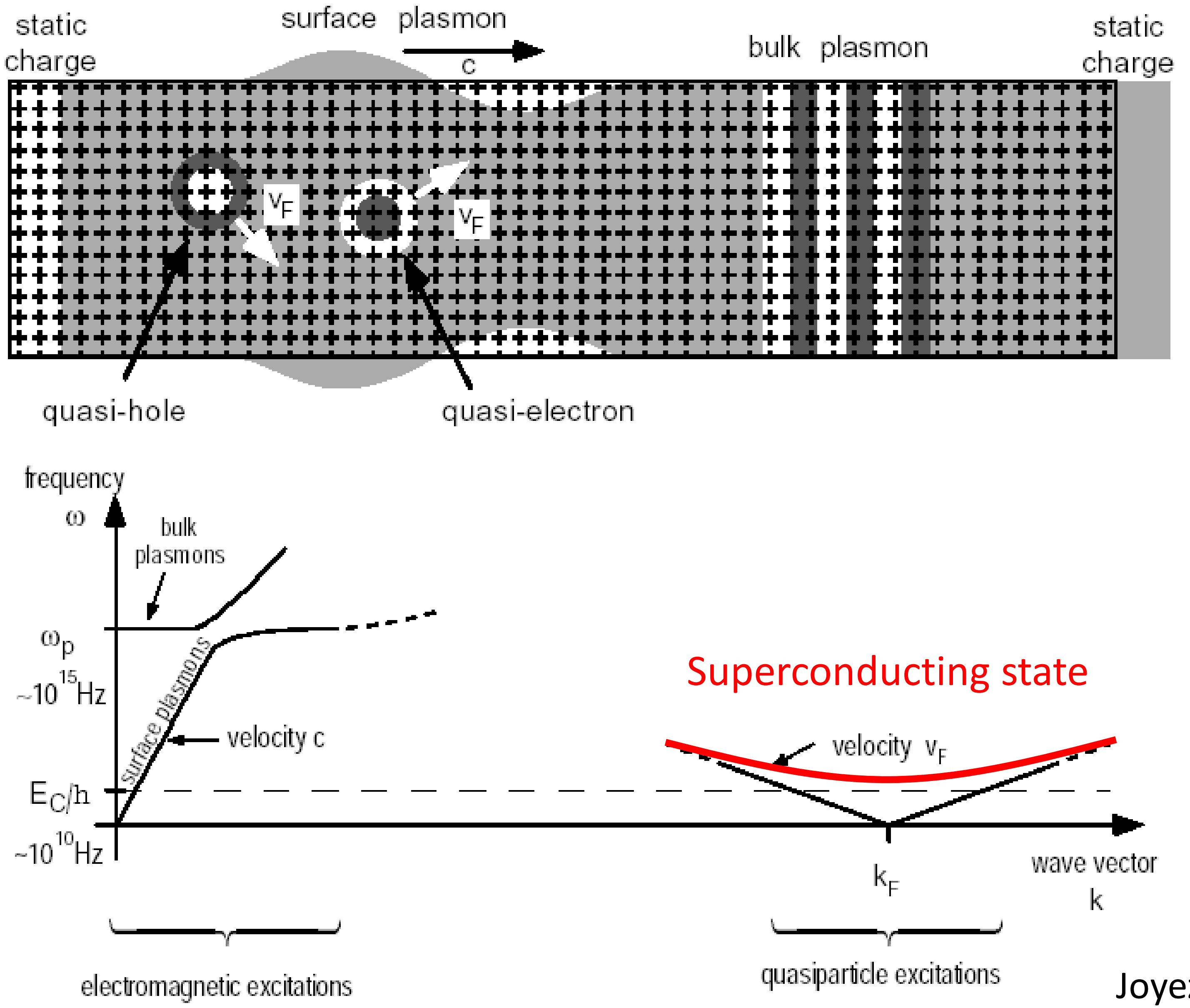


S. Gleyzes, *et al.,*
Nature **446**, 297 (2007)

Atom, a nonlinear element!

Superconductivity and Josephson atoms

Elementary excitation in metals



Joyez, Thesis (1995) CEA Saclay

Superconducting LC circuit

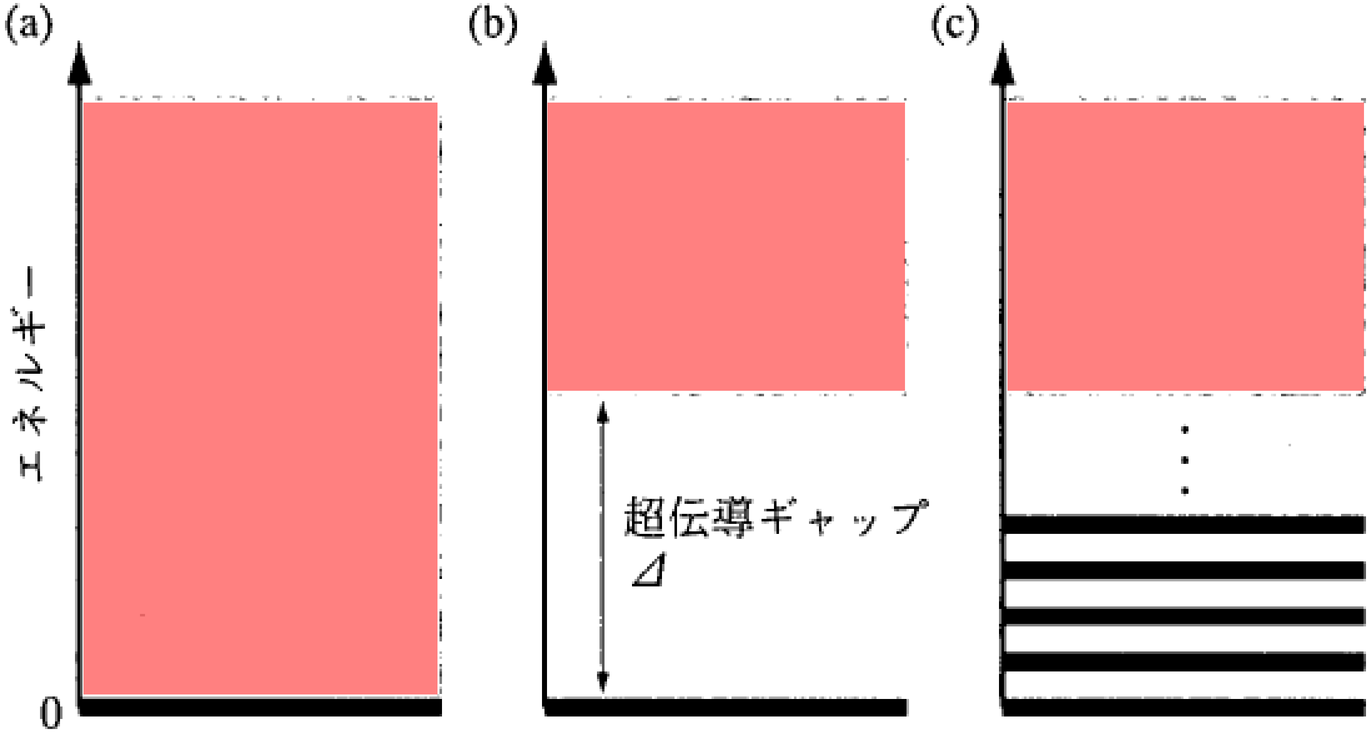
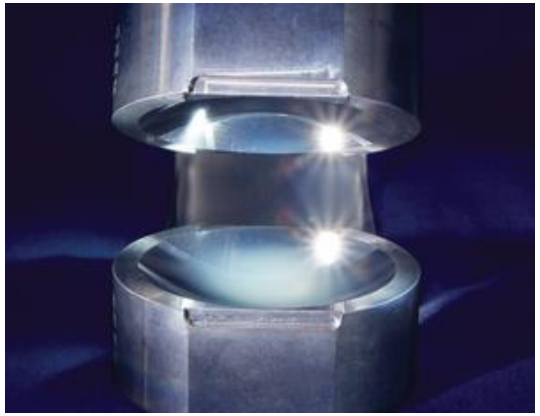


図1　模式的なエネルギー準位図．最下部の黒線が基底エネルギー準位，薄赤色部分は連続的な準位分布を示す．(a) フェルミ電子系，(b) 超伝導状態，(c) 超伝導共振器．

- Rydberg atom
- Microwave photon

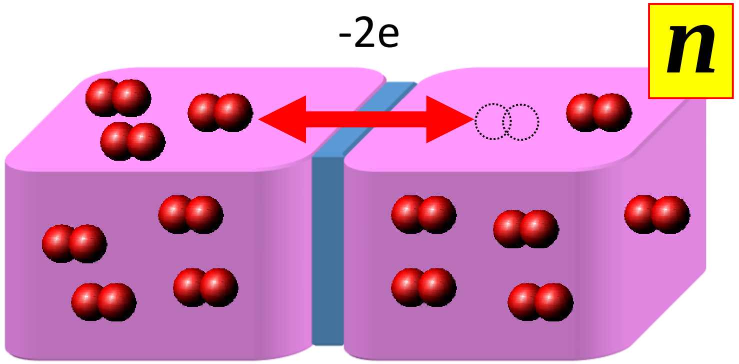


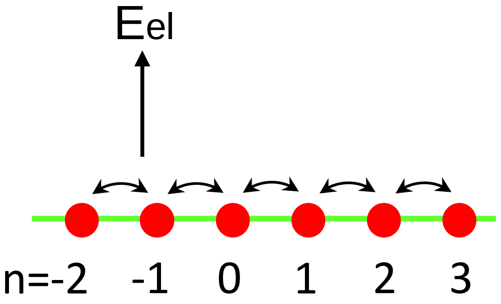
中村泰信、日本物理學會誌 57(11), 797-803, 2002-11-05

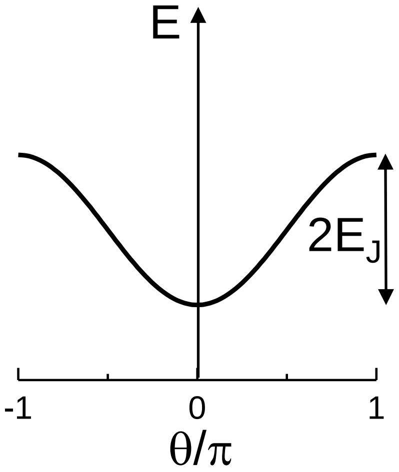
Josephson effect (lossless nonlinearity)

$\boxed{\text{number } \boldsymbol{n} \Leftrightarrow \text{phase difference } \boldsymbol{\theta}}$ $\quad [n,\theta] = -i$

B. D. Josephson 1962







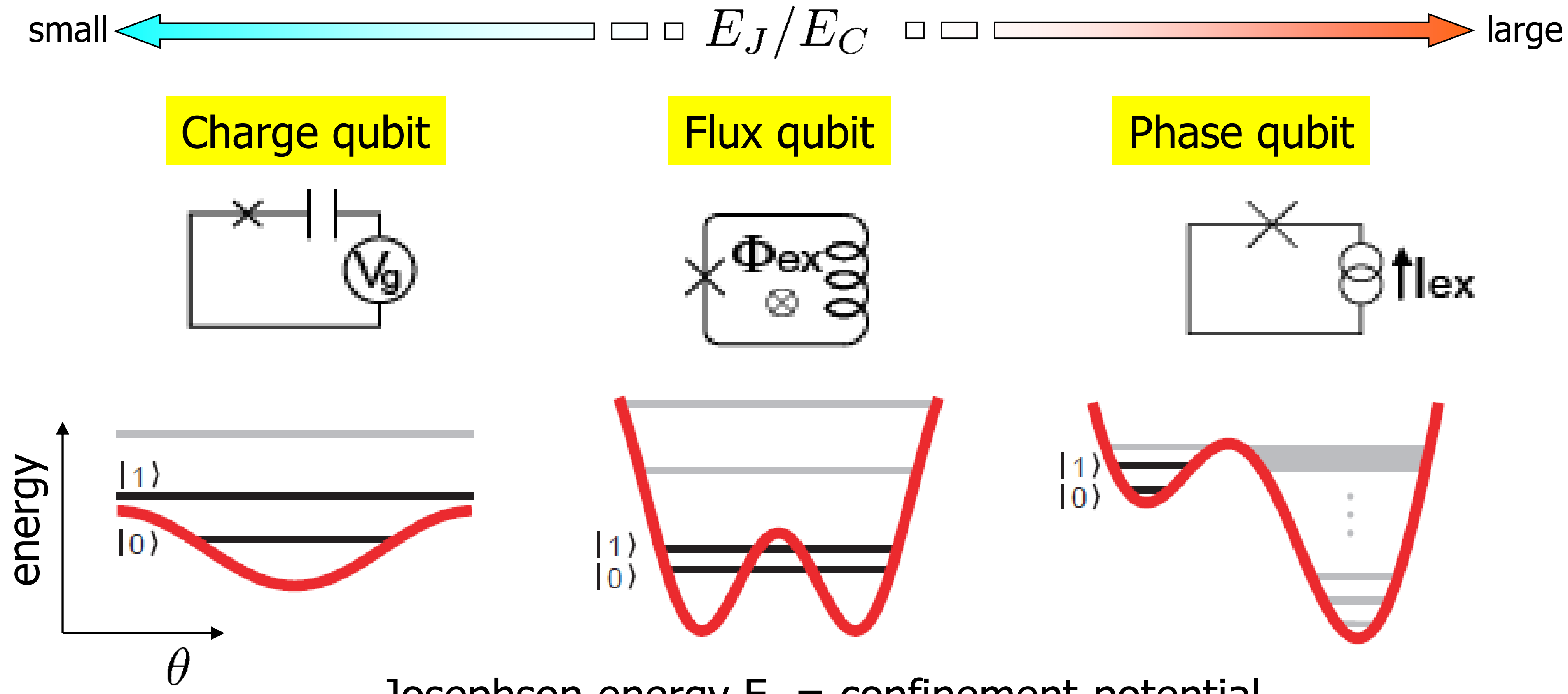
$$H = -\frac{E_J}{2}\sum_n \{|n\rangle\langle n+1| + |n+1\rangle\langle n|\} = -\int_0^{2\pi} d\theta E_J \cos\theta |\theta\rangle\langle\theta|$$

Tight-binding model in 1d lattice $\Rightarrow$ Bloch band

$$|\theta\rangle = \sum_n e^{in\theta}|n\rangle$$

Superconducting qubits

– artificial atoms in electrical circuit

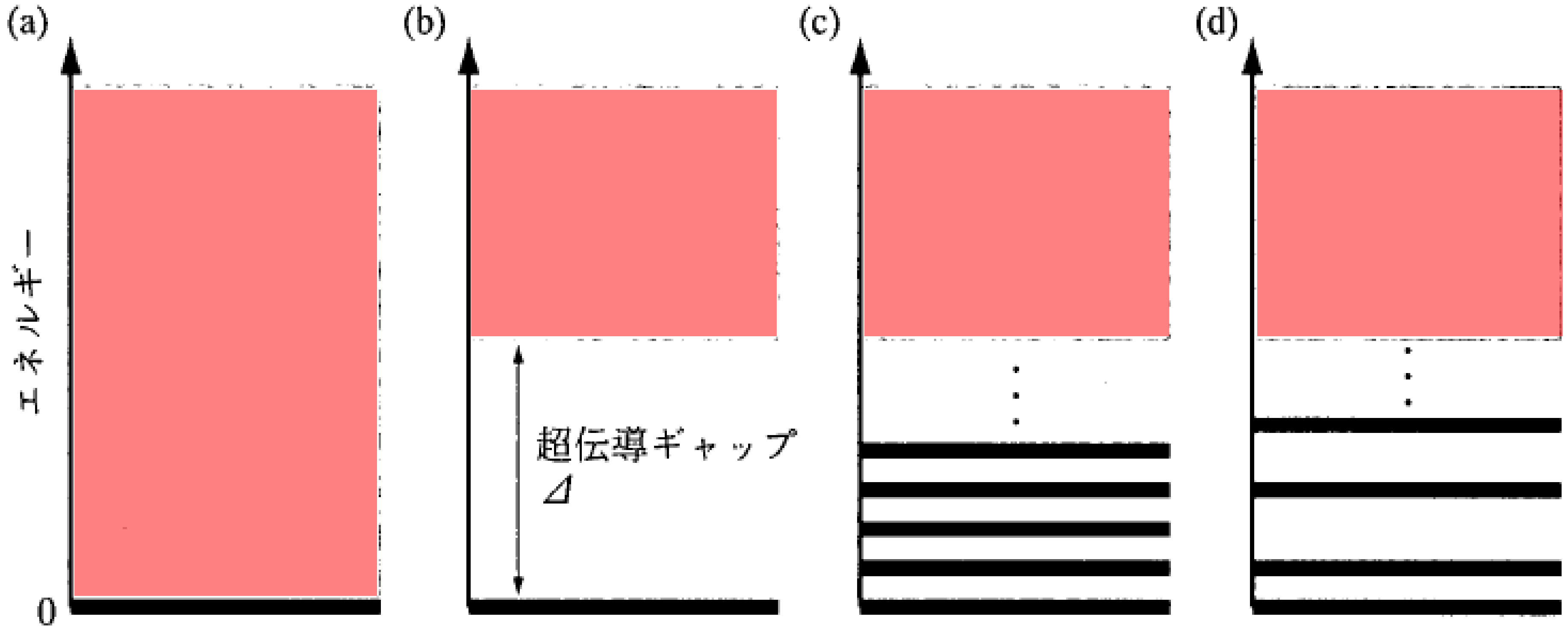


Josephson energy E_J = confinement potential
charging energy E_C = kinetic energy

typical qubit energy $E_{01} \sim 10\,\mathrm{GHz} \sim 0.5\,\mathrm{K}$

typical experimental temperature $T \sim 0.01\,\mathrm{K}$

Superconducting qubits
– artificial atoms in electrical circuit



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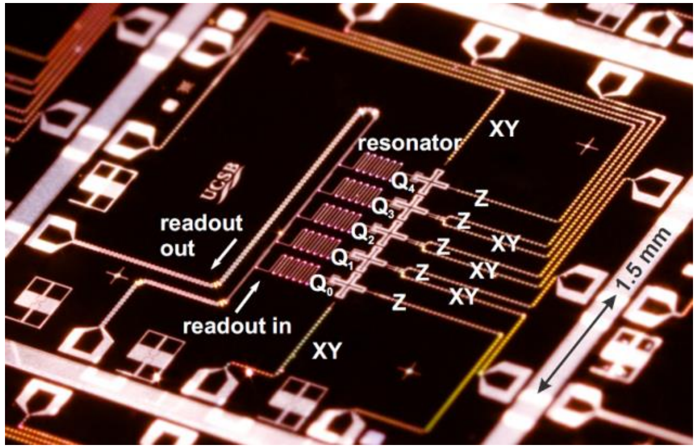
中村泰信、日本物理學會誌 57(11), 797-803, 2002-11-05

Advances of superconducting qubits

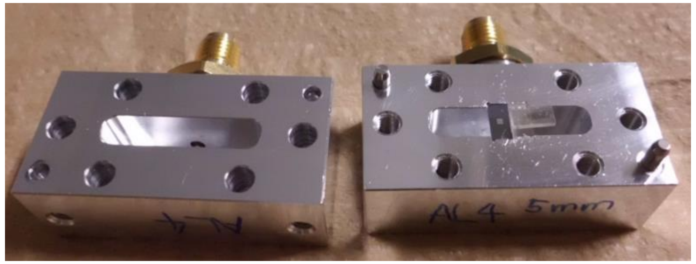
- Artificial quantum system in electrical circuits
- Strong coupling with microwave
- Design flexibility, integrability
- Improved coherence time

● 2D qubits

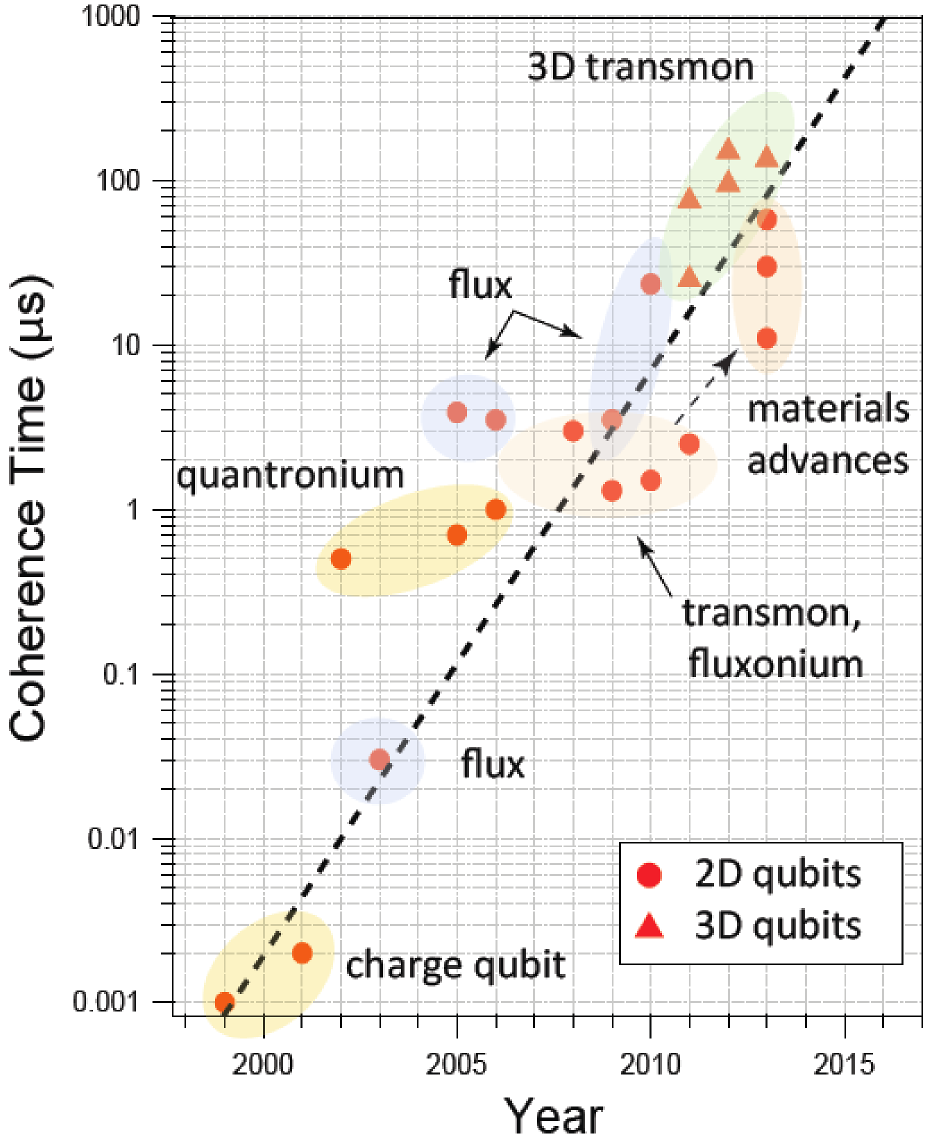


R. Barends et al. Nature (2014) UCSB

▲ 3D qubits



Courtesy of S. Kono



Courtesy of W. Oliver and P. Welander (MIT-LL)

Quantum transducers

Linking superconducting qubits

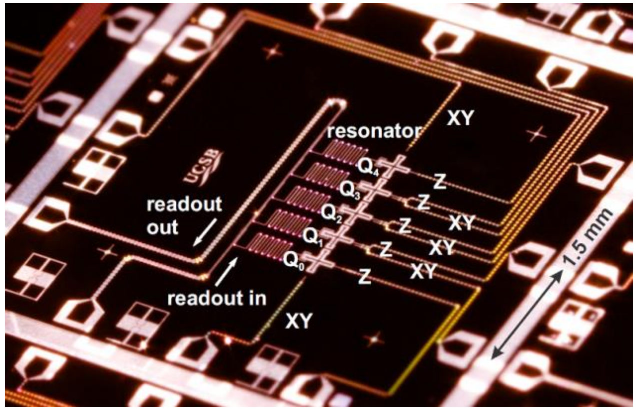
Superconducting Qubit

Dilution fridge (10mK)

X

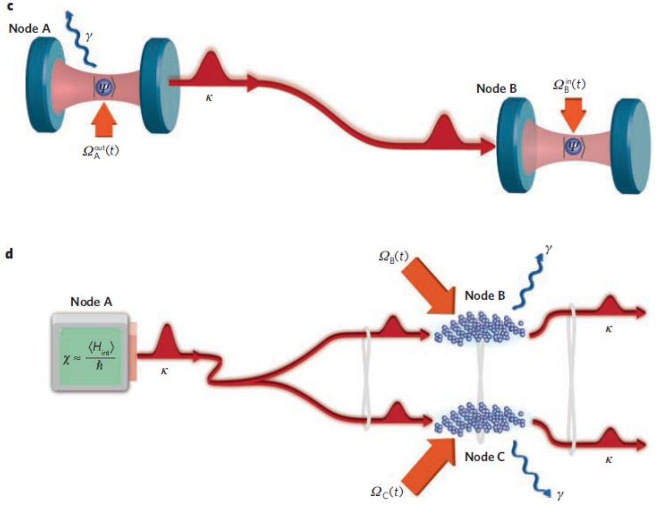
Optical photons (~200THz)

Quantum circuits



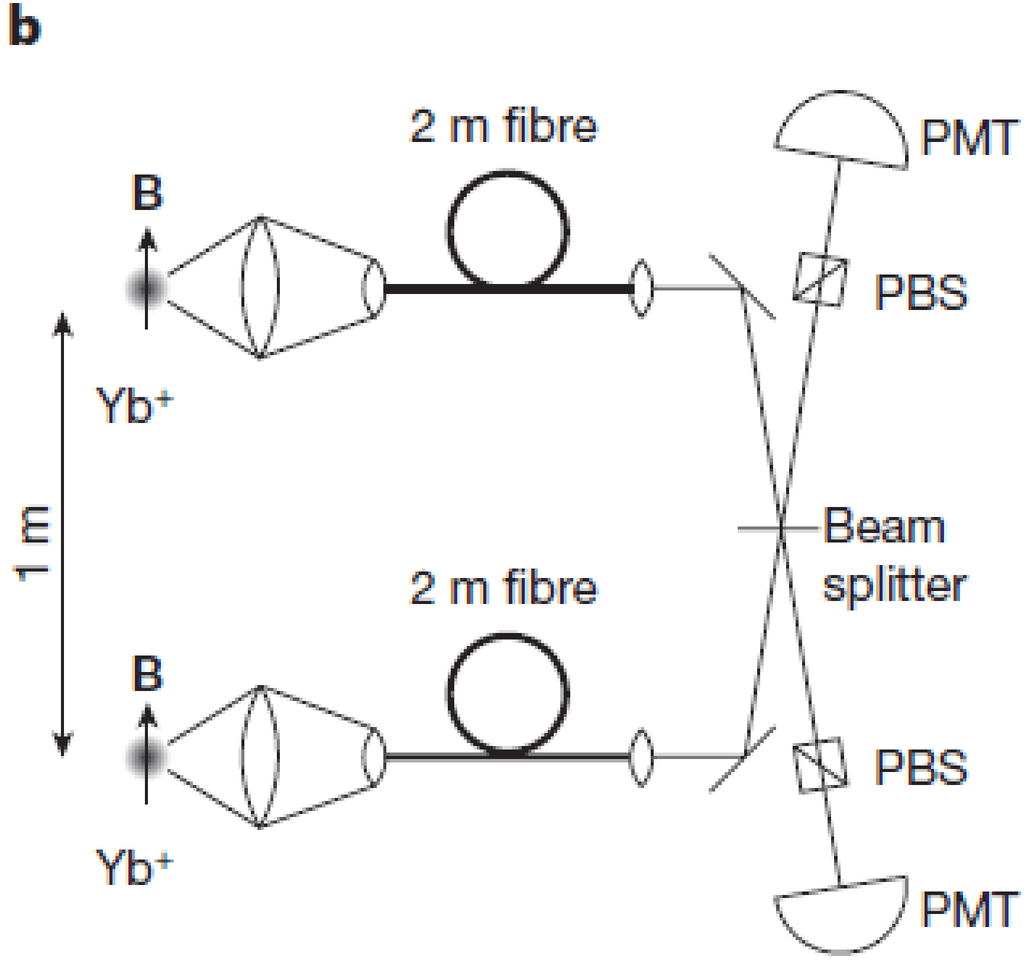
R. Barends et al. Nature (2014).

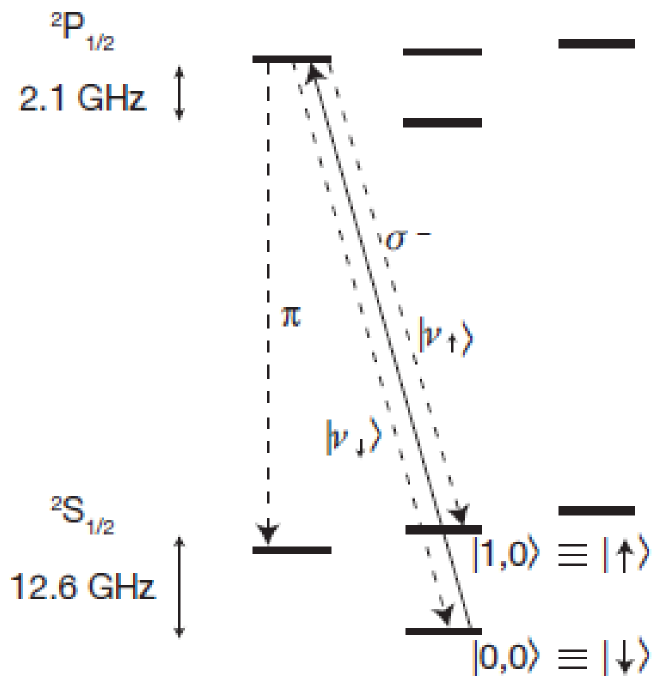
Quantum optics



H.J. Kimble, Nature **453,** 1023 (2008).

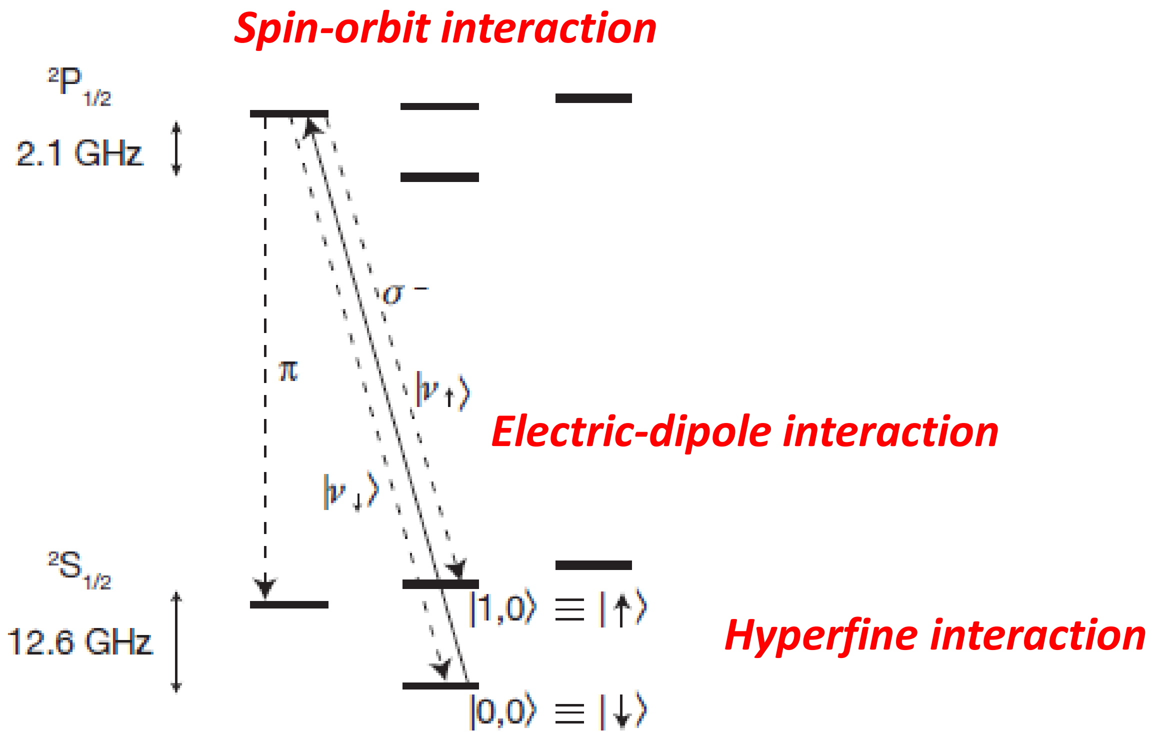
Linking single-atom qubits





D.L.Moehring, *et al.,* Nature **449,** 68 (2007).

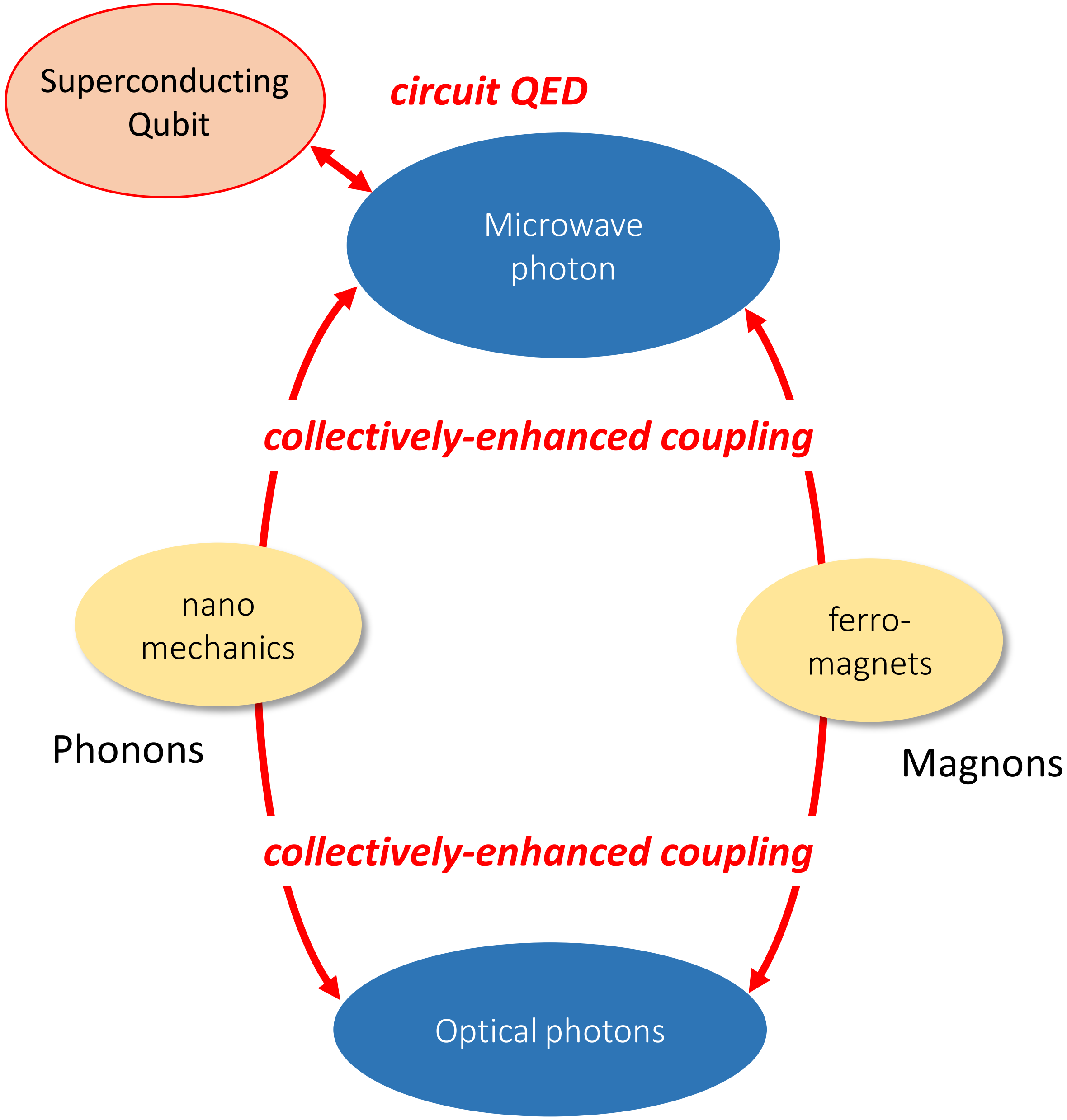
Quantum transducer for linking single-atom qubits



- Nuclear spin (n)
  - ***Hyperfine interaction***
- Electron spin (s)
  - ***Spin-orbit coupling***
- Orbital (l)
  - ***Electric-dipole interaction***
- light

D.L.Moehring, *et al.,* Nature **449,** 68 (2007).

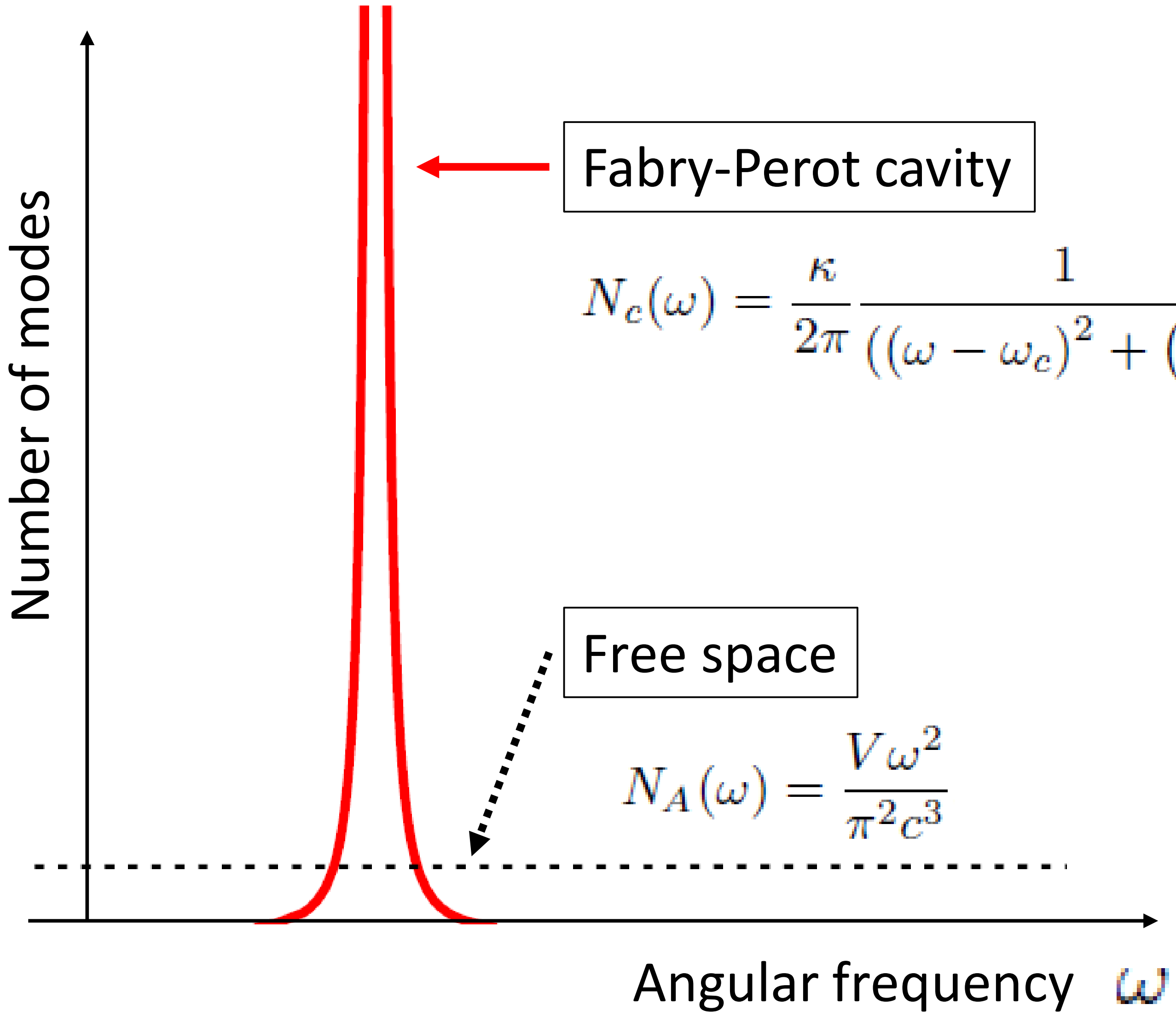
Quantum transducer architecture



- Superconducting qubit
  circuit QED
- Microwave
  collectively-enhanced coupling
- Magnon/phonon
  collectively-enhanced coupling
- light

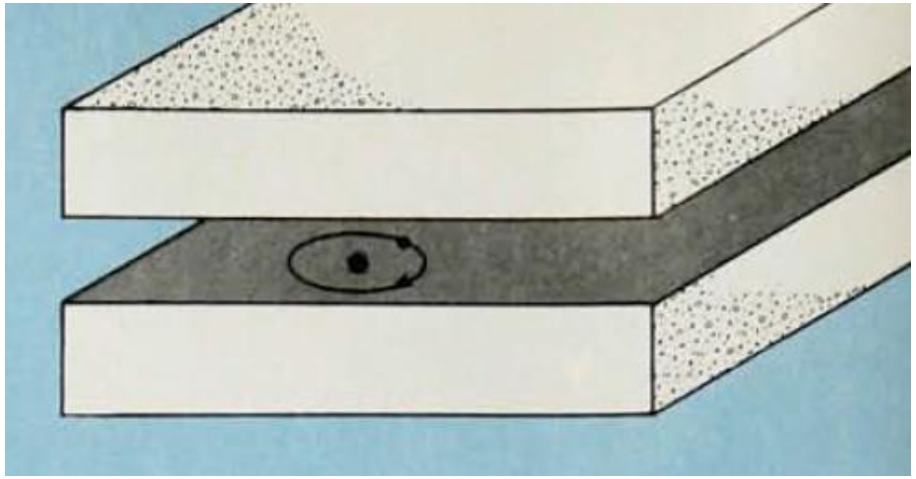
Circuit QED

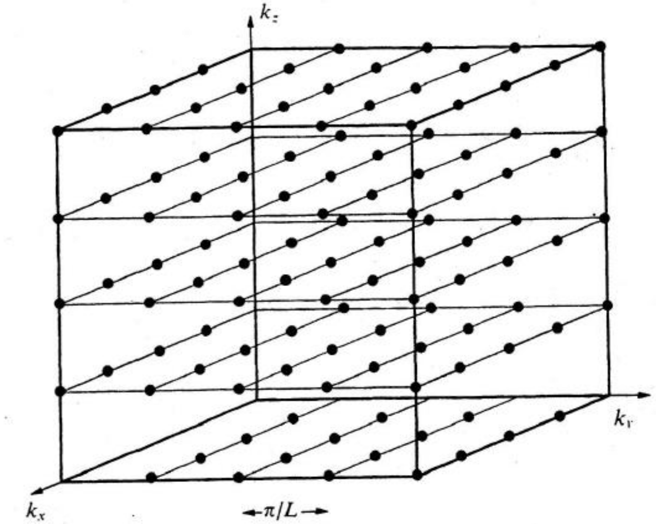
Purcell enhancement



$$N_c(\omega) = \frac{\kappa}{2\pi} \frac{1}{\left((\omega - \omega_c)^2 + \left(\frac{\kappa}{2}\right)^2\right)}$$

$$N_A(\omega) = \frac{V\omega^2}{\pi^2 c^3}$$

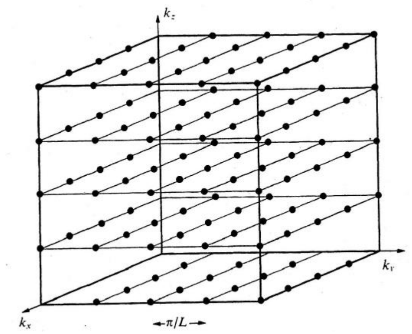




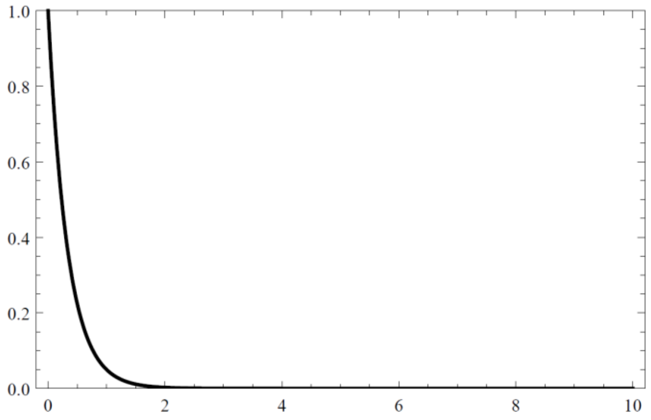
Jaynes-Cummings Hamiltonian

Einstein Hamiltonian

$$H_I = -i\hbar \sum_j \boxed{\lambda_j} \left(\hat{\sigma}_+ \hat{a}_j e^{i(\omega_A - \omega_j)t} - \hat{\sigma}_- \hat{a}_j^\dagger e^{-i(\omega_A - \omega_j)t} \right)$$

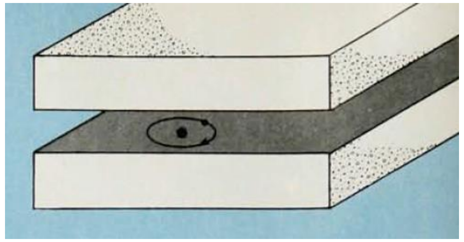


Fermi's golden rule

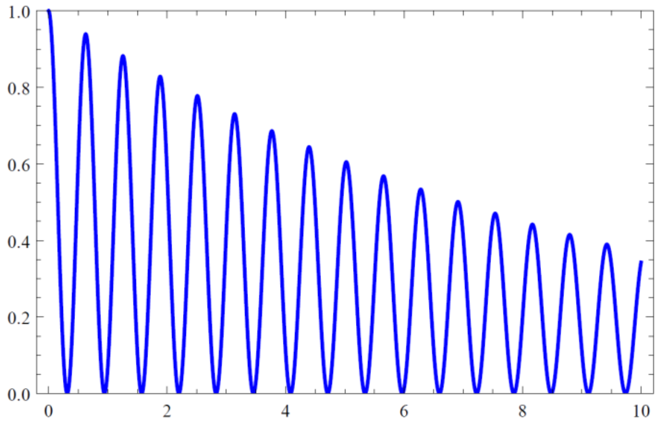


Jaynes-Cummings Hamiltonian

$$H_{JC} = -\, i\hbar \boxed{g} \left(\hat{\sigma}_+ \hat{a} - \hat{\sigma}_- \hat{a}^\dagger \right)$$



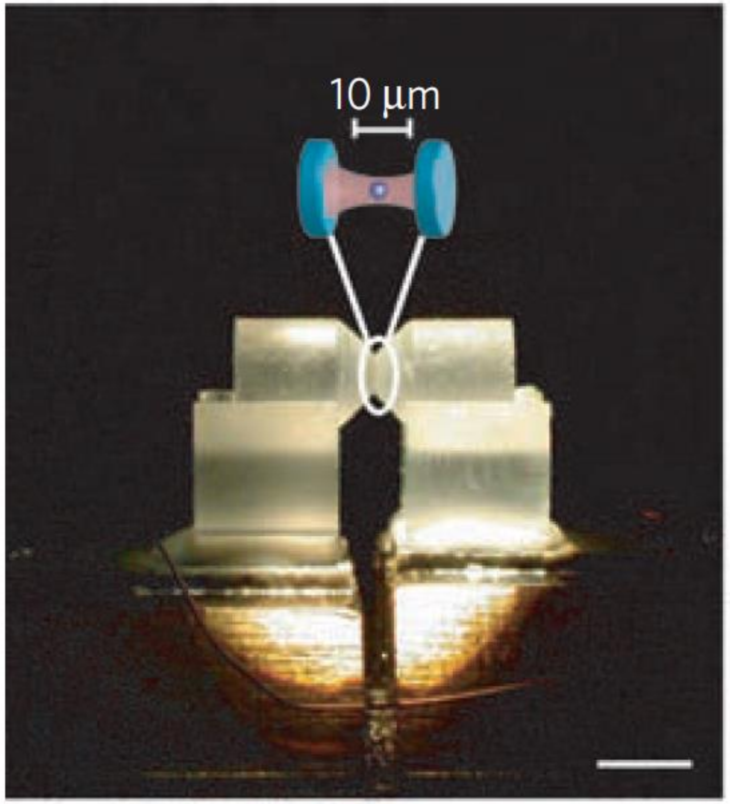
Rabi oscillation



QED systems

Cavity QED

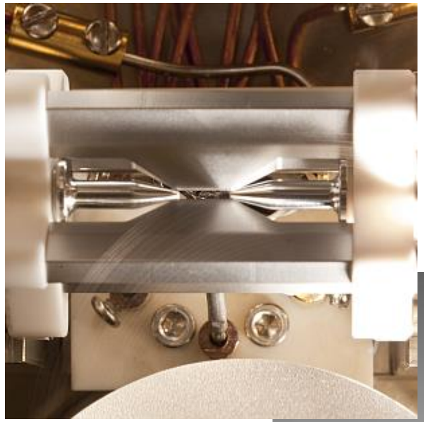
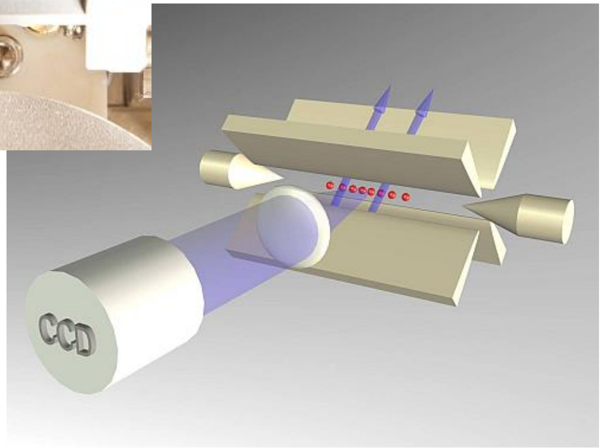
- Atom
- Photon



H.J. Kimble,
Nature **453,** 1023 (2008).

Ion Trap

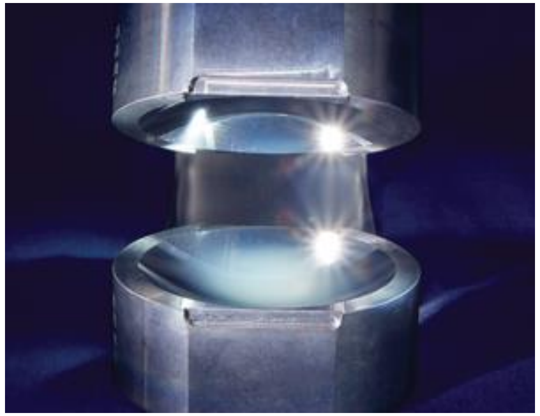
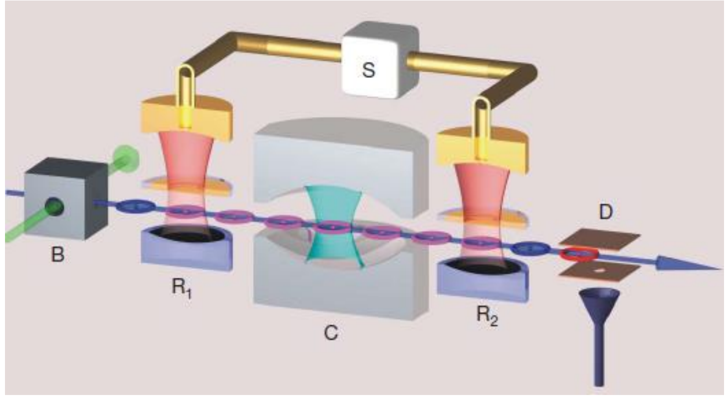
- Ion
- Phonon

F. Schmidt-Kaler, *et al.,*
Nature **422,** 408 (2003).

Cavity QED with Rydberg atom

- Rydberg atom
- Microwave photon

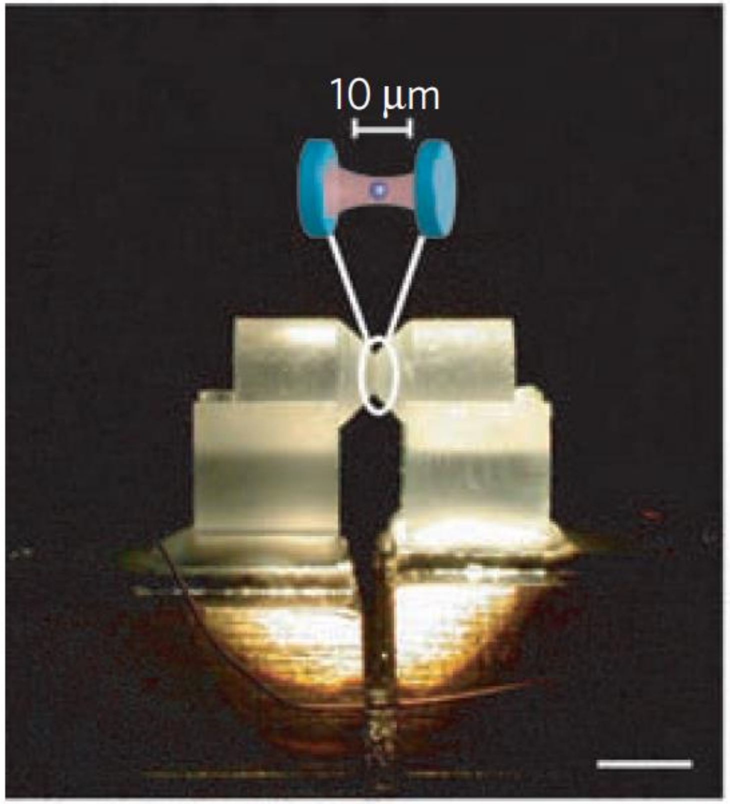



S. Gleyzes, *et al.,*
Nature **446**, 297 (2007)

Variants of cavity QED systems

Cavity QED

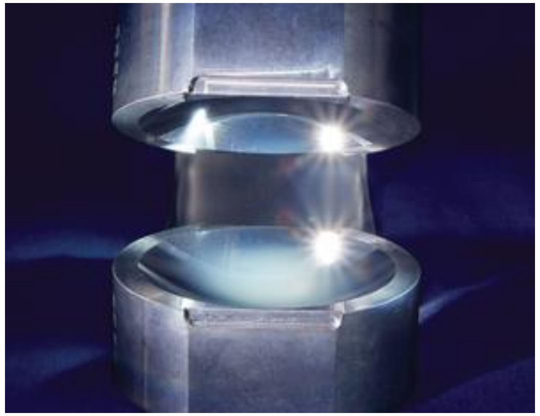
- Atom
- Photon

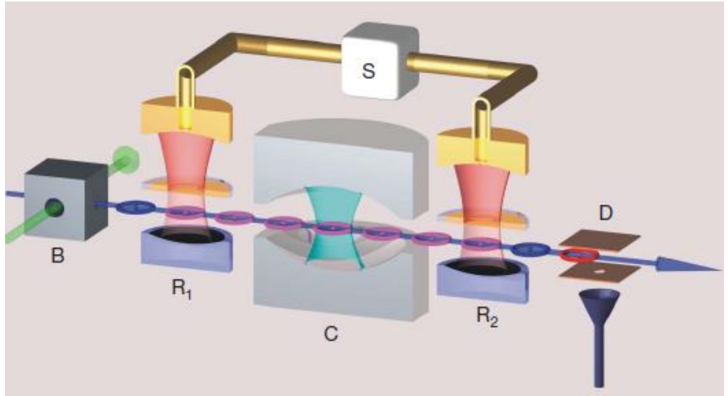


H.J. Kimble,
Nature **453,** 1023 (2008).

Cavity QED with Rydberg atom

- Rydberg atom
- Microwave photon

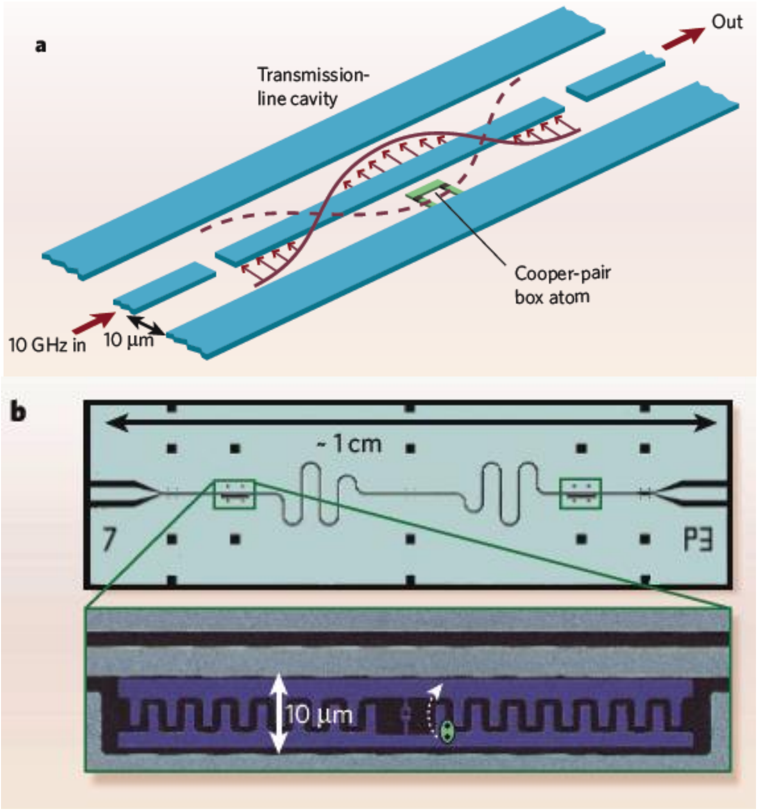




S. Gleyzes, *et al.*,
Nature **446**, 297 (2007)

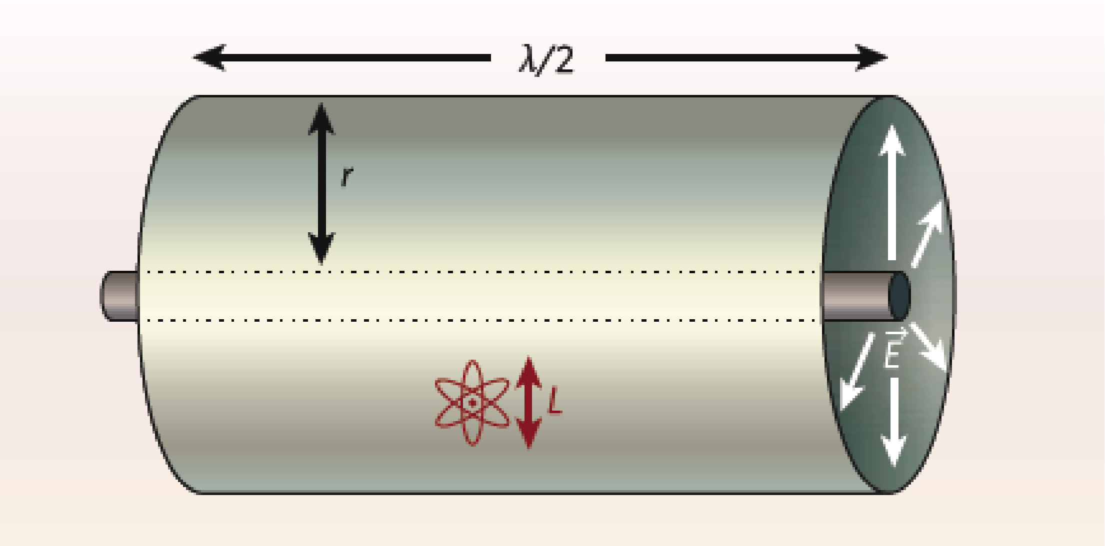
Superconducting Circuit

- Artificial atom
- Microwave photon



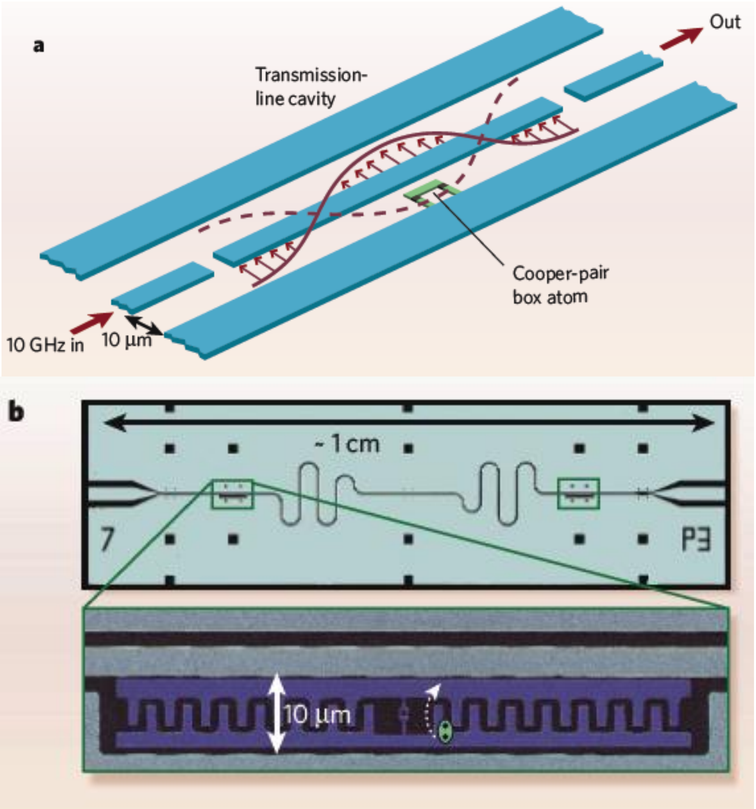
R. J. Schoelkopf and S. M. Girvin,
Nature **451,** 664 (2008).

Circuit QED



Superconducting Circuit

- Artificial atom
- Microwave photon



Fundamental limit of the coupling strength:

$$g_e = \frac{ea_0}{\hbar}\sqrt{\frac{\hbar\omega}{2\epsilon_0 V}} = ea_0\sqrt{\frac{\omega}{2\hbar\epsilon_0 V}} \Rightarrow g_c = \sqrt{\alpha}\omega$$

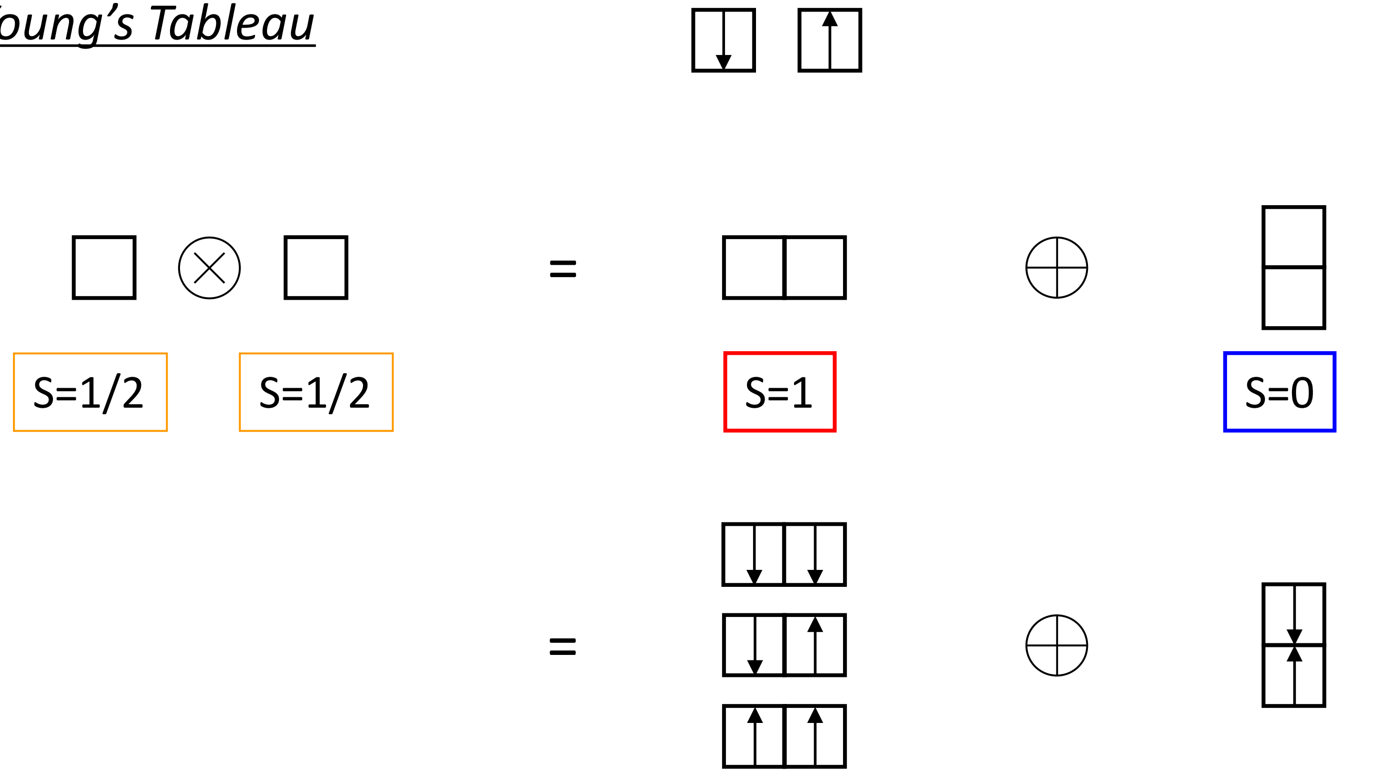
for cavity volume of $V \sim \lambda a_0^2$

R. J. Schoelkopf and S. M. Girvin, Nature **451,** 664 (2008).

Collectively-enhanced coupling

Angular Momentum addition

<u>Young's Tableau</u>



3 state

Triplet

(totally symmetric)

1 state

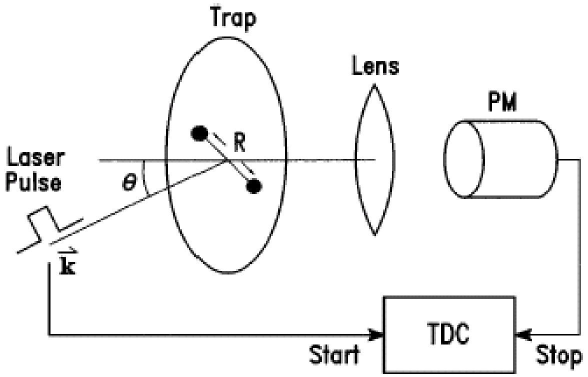
Singlet

(totally anti-symmetirc)

VOLUME 76, NUMBER 12 PHYSICAL REVIEW LETTERS 18 MARCH 1996

Observation of Superradiant and Subradiant Spontaneous Emission of Two Trapped Ions

R. G. DeVoe and R. G. Brewer
IBM Research Division, Almaden Research Center, 650 Harry Road, San Jose, California 95120-6099
(Received 19 October 1995)



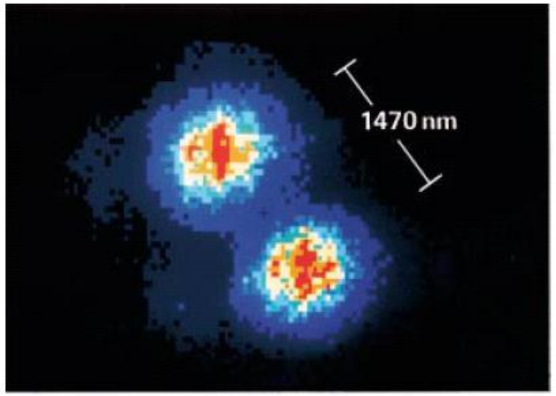
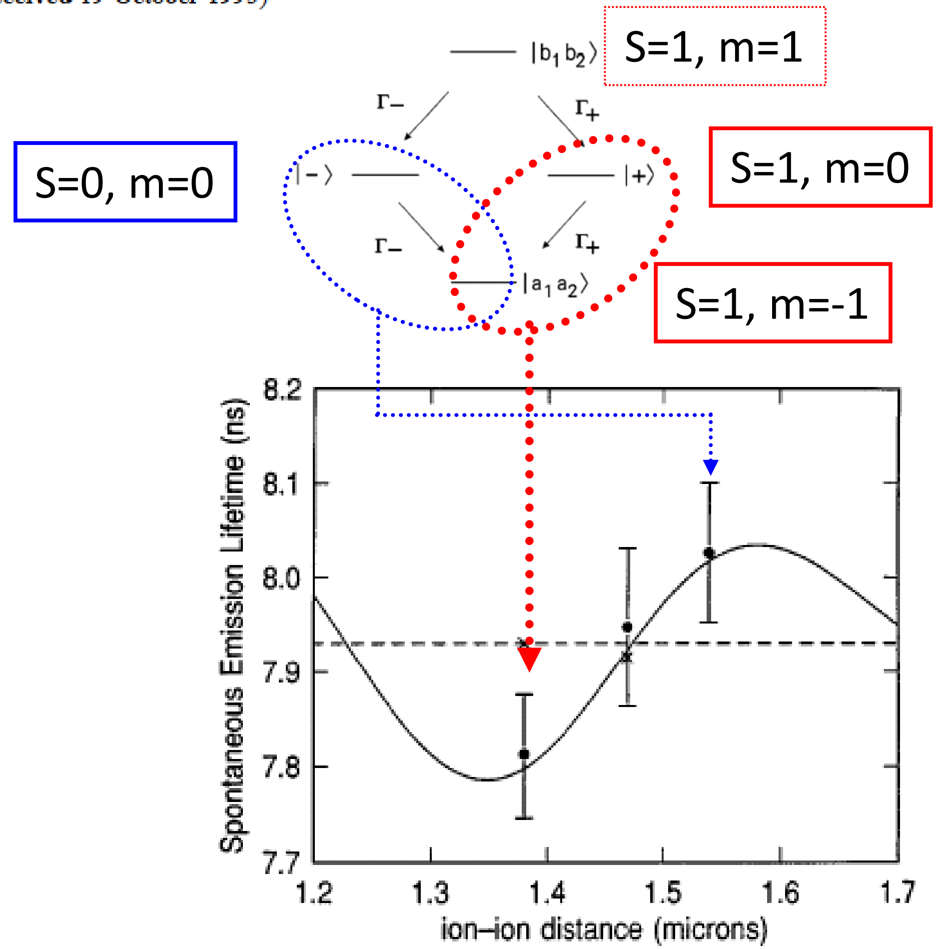
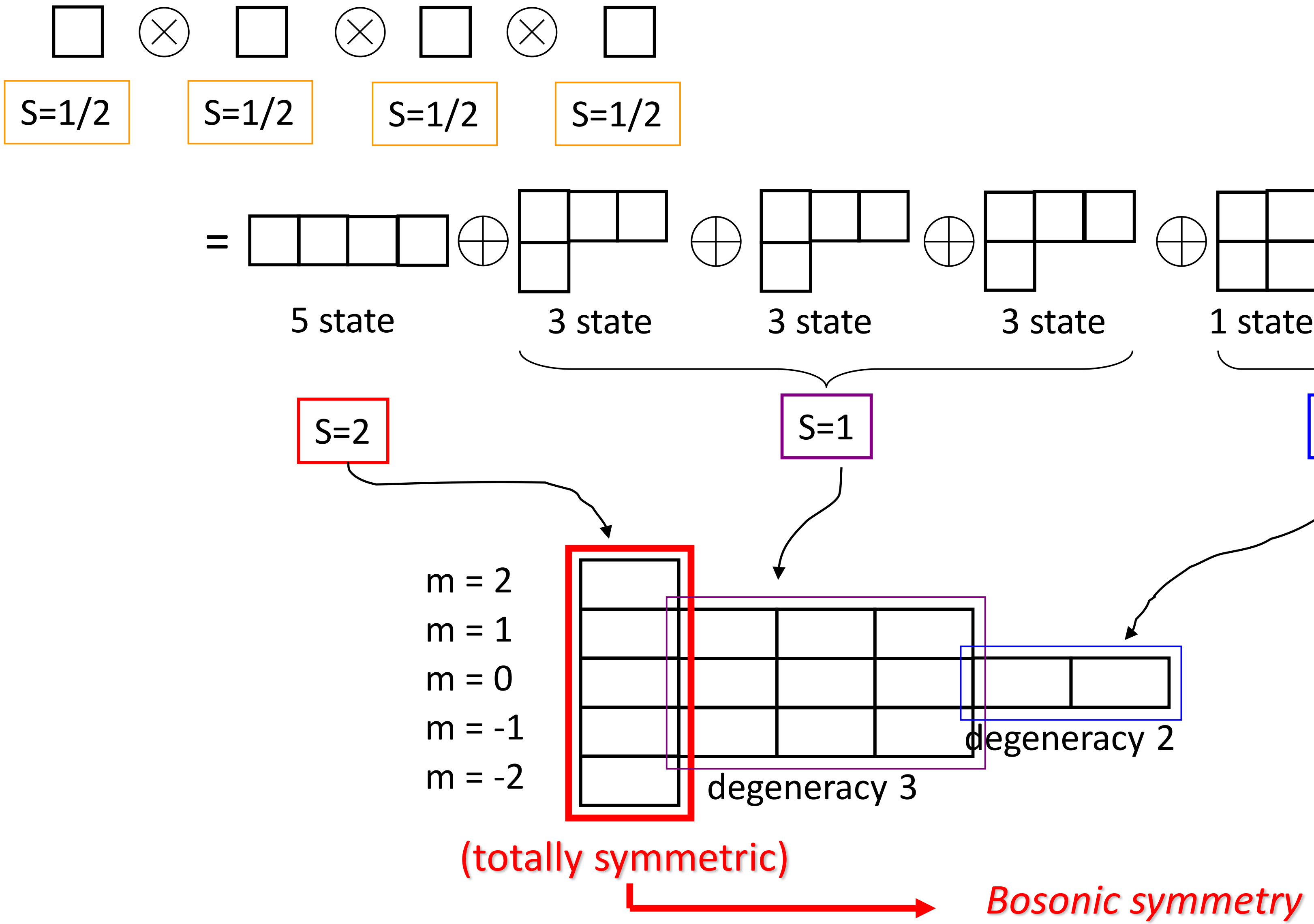


FIG. 4. (color) Diffraction-limited image of a two-ion crystal with $R = 1470$ nm. This determines the orientation of the interatomic vector $\vec{R}$ enabling a no-free-parameter fit.



Permutation Symmetry

- in case of 4 spin-1/2 particles -



Second Quantization of Spin

$$|\uparrow\rangle|\uparrow\rangle|\uparrow\rangle|\uparrow\rangle$$

$$|\uparrow\rangle|\uparrow\rangle|\uparrow\rangle|\downarrow\rangle \quad |\uparrow\rangle|\uparrow\rangle|\downarrow\rangle|\uparrow\rangle \quad |\uparrow\rangle|\downarrow\rangle|\uparrow\rangle|\uparrow\rangle \quad |\downarrow\rangle|\uparrow\rangle|\uparrow\rangle|\uparrow\rangle$$

$$|\uparrow\rangle|\uparrow\rangle|\downarrow\rangle|\downarrow\rangle \quad |\uparrow\rangle|\downarrow\rangle|\uparrow\rangle|\downarrow\rangle \quad |\uparrow\rangle|\downarrow\rangle|\downarrow\rangle|\uparrow\rangle \quad |\downarrow\rangle|\uparrow\rangle|\uparrow\rangle|\downarrow\rangle \quad |\downarrow\rangle|\uparrow\rangle|\downarrow\rangle|\uparrow\rangle \quad |\downarrow\rangle|\downarrow\rangle|\uparrow\rangle|\uparrow\rangle$$

$$|\uparrow\rangle|\downarrow\rangle|\downarrow\rangle|\downarrow\rangle \quad |\downarrow\rangle|\uparrow\rangle|\downarrow\rangle|\downarrow\rangle \quad |\downarrow\rangle|\downarrow\rangle|\uparrow\rangle|\downarrow\rangle \quad |\downarrow\rangle|\downarrow\rangle|\downarrow\rangle|\uparrow\rangle$$

$$|\downarrow\rangle|\downarrow\rangle|\downarrow\rangle|\downarrow\rangle$$

$$|S=2, m=2\rangle = |\uparrow\rangle|\uparrow\rangle|\uparrow\rangle|\uparrow\rangle \leftarrow \boxed{|4\rangle_\uparrow |0\rangle_\downarrow}$$ (CSS)

$$|S=2, m=1\rangle = \frac{1}{2}\left(|\uparrow\rangle|\uparrow\rangle|\uparrow\rangle|\downarrow\rangle + |\uparrow\rangle|\uparrow\rangle|\downarrow\rangle|\uparrow\rangle + |\uparrow\rangle|\downarrow\rangle|\uparrow\rangle|\uparrow\rangle + |\downarrow\rangle|\uparrow\rangle|\uparrow\rangle|\uparrow\rangle\right) \leftarrow \boxed{|3\rangle_\uparrow |1\rangle_\downarrow}$$ (Dicke, W)

$$|S=2, m=0\rangle = \frac{1}{\sqrt{6}}\left(|\uparrow\rangle|\uparrow\rangle|\downarrow\rangle|\downarrow\rangle + |\uparrow\rangle|\downarrow\rangle|\uparrow\rangle|\downarrow\rangle + |\uparrow\rangle|\downarrow\rangle|\downarrow\rangle|\uparrow\rangle + |\downarrow\rangle|\uparrow\rangle|\uparrow\rangle|\downarrow\rangle + |\downarrow\rangle|\uparrow\rangle|\downarrow\rangle|\uparrow\rangle + |\downarrow\rangle|\downarrow\rangle|\uparrow\rangle|\uparrow\rangle\right)$$

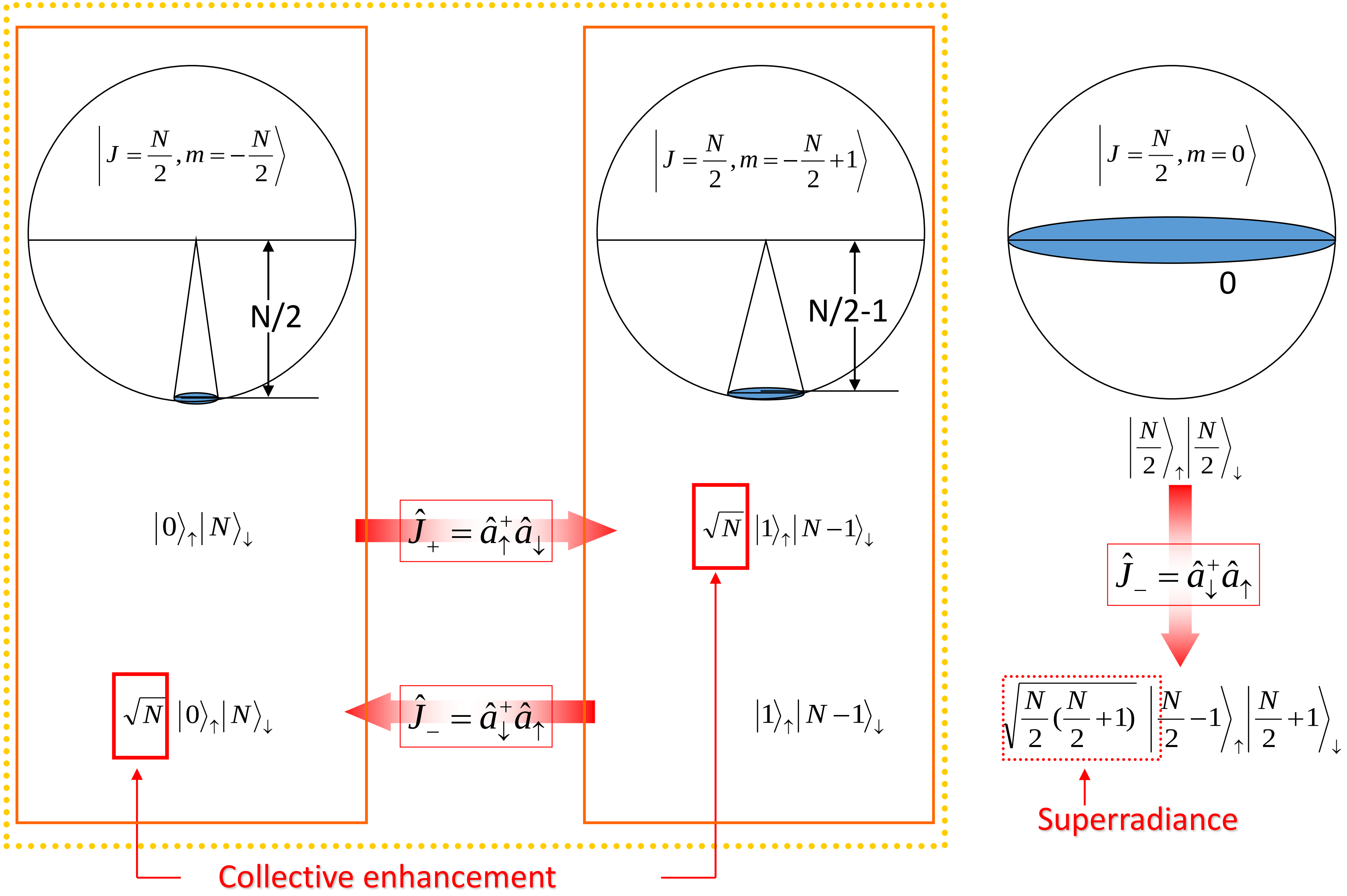
$$\boxed{|2\rangle_\uparrow |2\rangle_\downarrow}$$ (Super-radiant)

$$|S=2, m=-1\rangle = \frac{1}{2}\left(|\uparrow\rangle|\downarrow\rangle|\downarrow\rangle|\downarrow\rangle + |\downarrow\rangle|\uparrow\rangle|\downarrow\rangle|\downarrow\rangle + |\downarrow\rangle|\downarrow\rangle|\uparrow\rangle|\downarrow\rangle + |\downarrow\rangle|\downarrow\rangle|\downarrow\rangle|\uparrow\rangle\right)$$

$$\boxed{|1\rangle_\uparrow |3\rangle_\downarrow}$$ (Dicke, W)

$$|S=2, m=-2\rangle = |\downarrow\rangle|\downarrow\rangle|\downarrow\rangle|\downarrow\rangle \leftarrow \boxed{|0\rangle_\uparrow |4\rangle_\downarrow}$$ (CSS)

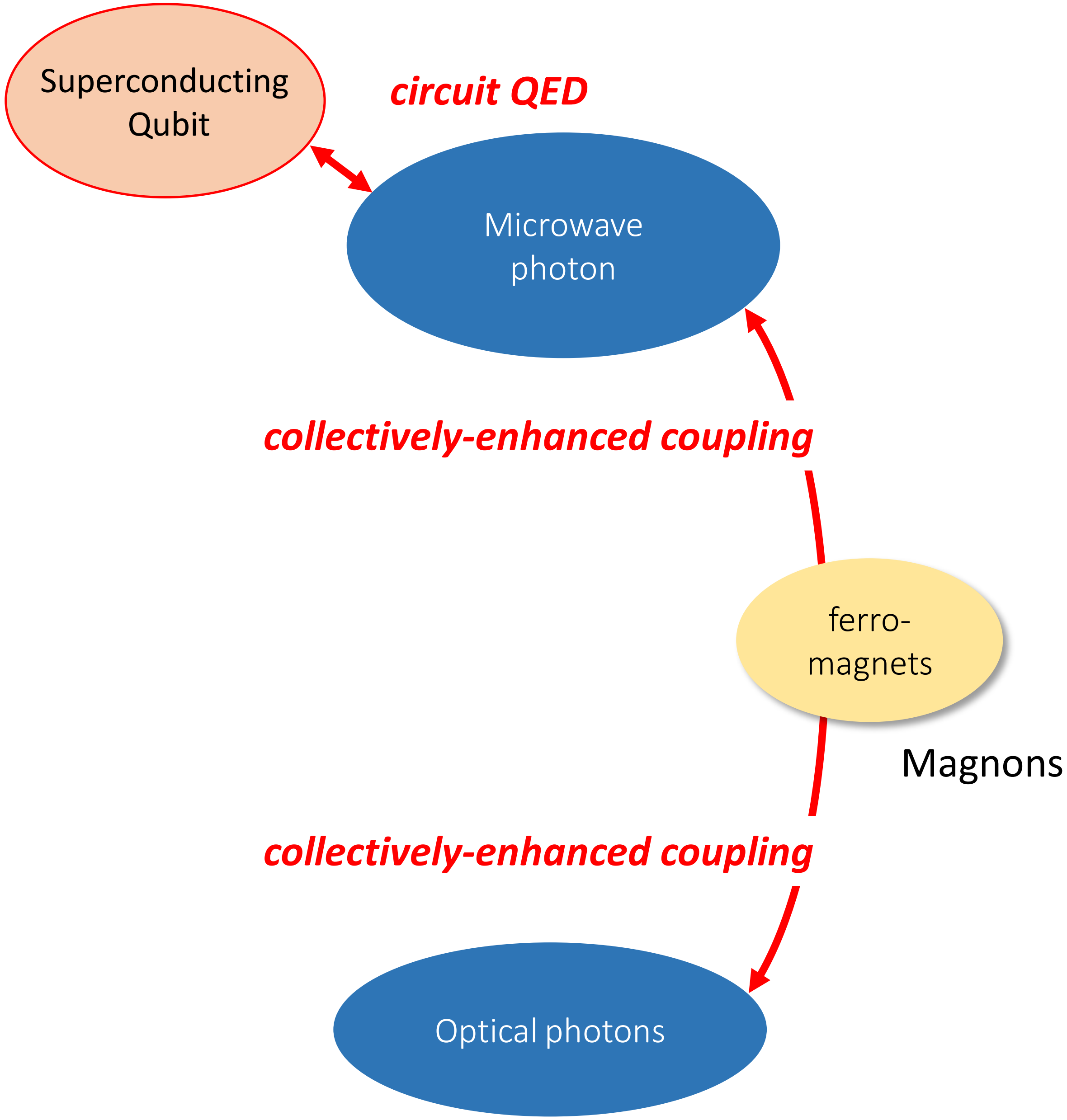
Collective enhancement



Cavity QED and collective enhancement

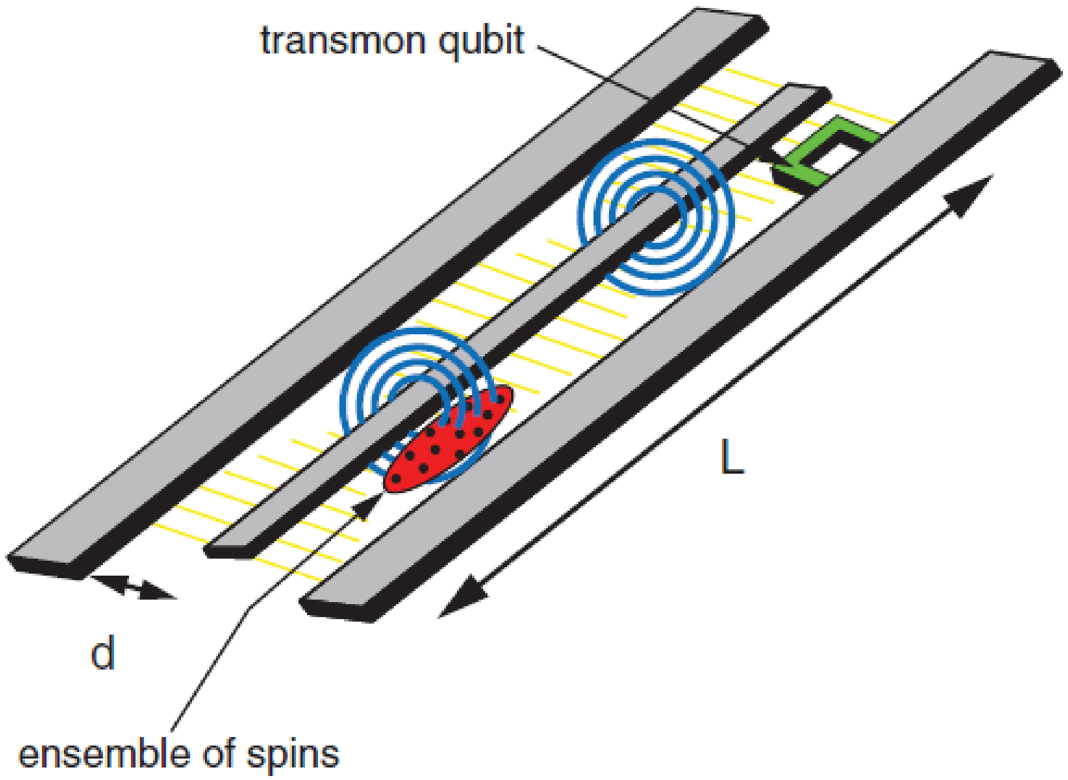
	Cavity QED	Collective enhancement
Coherent coupling rate	Rydberg atom $g_e = \boxed{d}\sqrt{\frac{\omega}{2\hbar\epsilon_0 \boxed{V}}}$ Micro cavity	$g_E = g_e\sqrt{\boxed{N}}$
Single-atom decay rate	$\gamma_A = \frac{2\pi}{3}\frac{V\omega^2}{\pi^2 c^3}g_e^2$	$\gamma_A = \frac{2\pi}{3}\frac{V\omega^2}{\pi^2 c^3}g_e^2$
Cavity decay rate	κ_c	$\kappa_L = \frac{c}{L}$
Cooperativity (SNR)	$C_s = \frac{4g_e^2}{\gamma_A \kappa_c}$	$C_c = \frac{4g_E^2}{\gamma_A \kappa_L} = \frac{4N g_e^2}{\gamma_A \kappa_L}$

Magnon transducer architecture



- Superconducting qubit
  circuit QED
- Microwave
  collectively-enhanced coupling
- Magnon
  collectively-enhanced coupling
- light

Paramagnetic spin ensemble quantum transducers



- **Circuit QED**

$$g_e = e a_0 \sqrt{\frac{\omega}{2\hbar\epsilon_0 V}}$$

- **Collective enhancement**

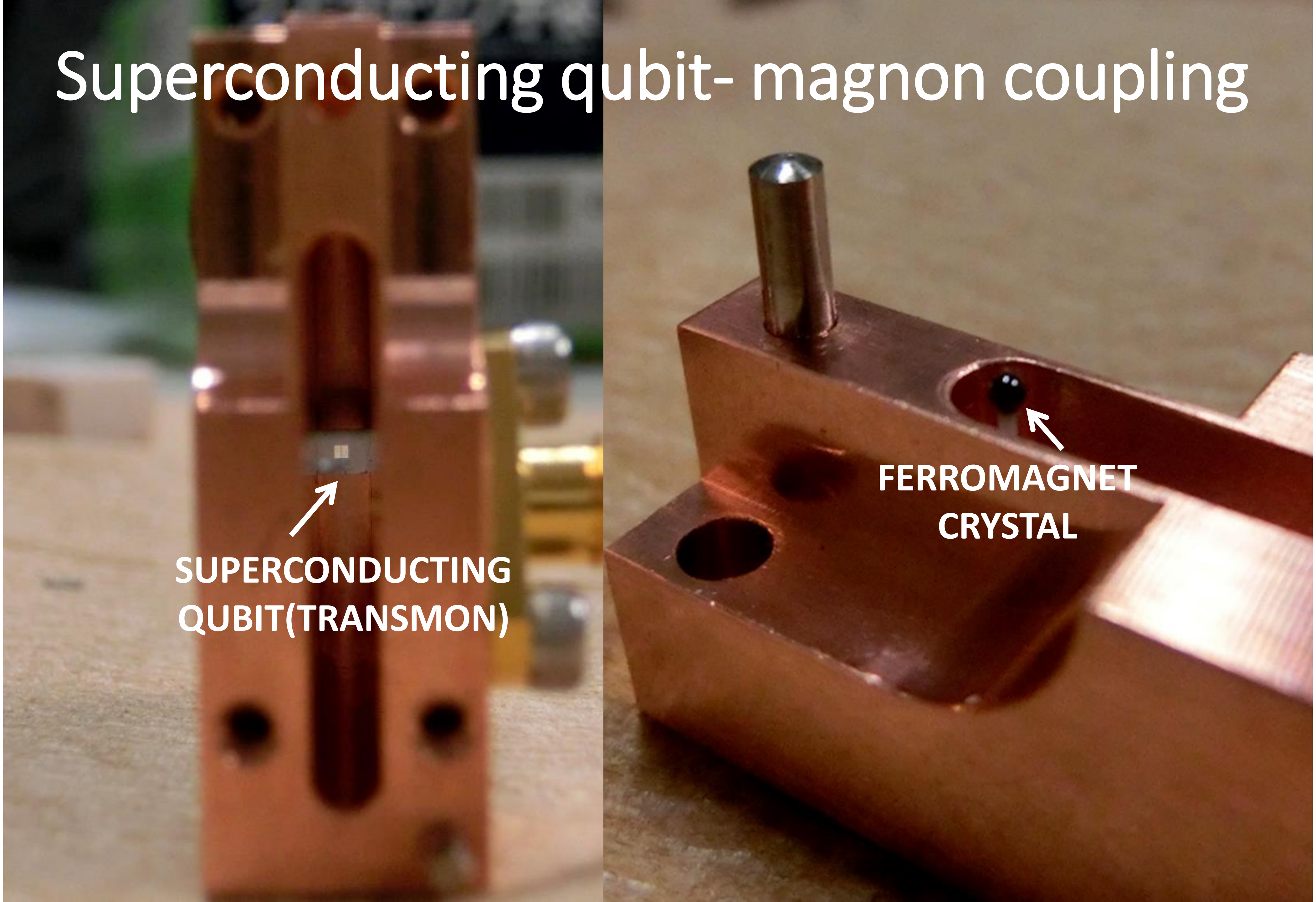
$$g_m = g_0\sqrt{N}$$

where single-spin coupling strength:

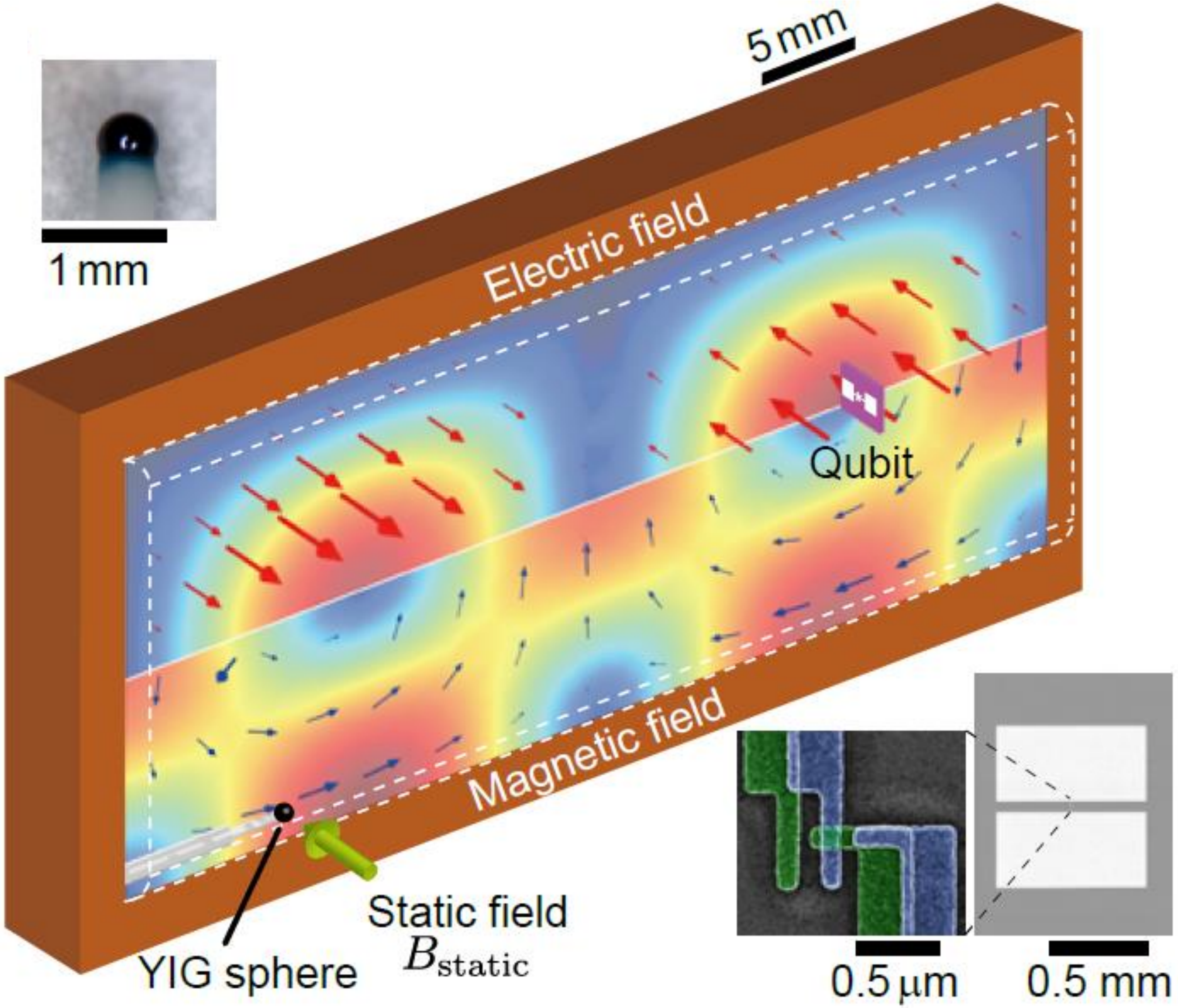
$$g_0 = \frac{2\mu_B}{\hbar}\sqrt{\frac{\mu_0\hbar\omega}{2V}} = \frac{2\mu_B}{c}\sqrt{\frac{\omega}{2\hbar\epsilon_0 V}} = \alpha g_e$$

A. Imamoglu, Phys. Rev. Lett. 102, 083602 (2009).

Experiments


Superconducting qubit- magnon coupling
SUPERCONDUCTING
QUBIT(TRANSMON)
FERROMAGNET
CRYSTAL

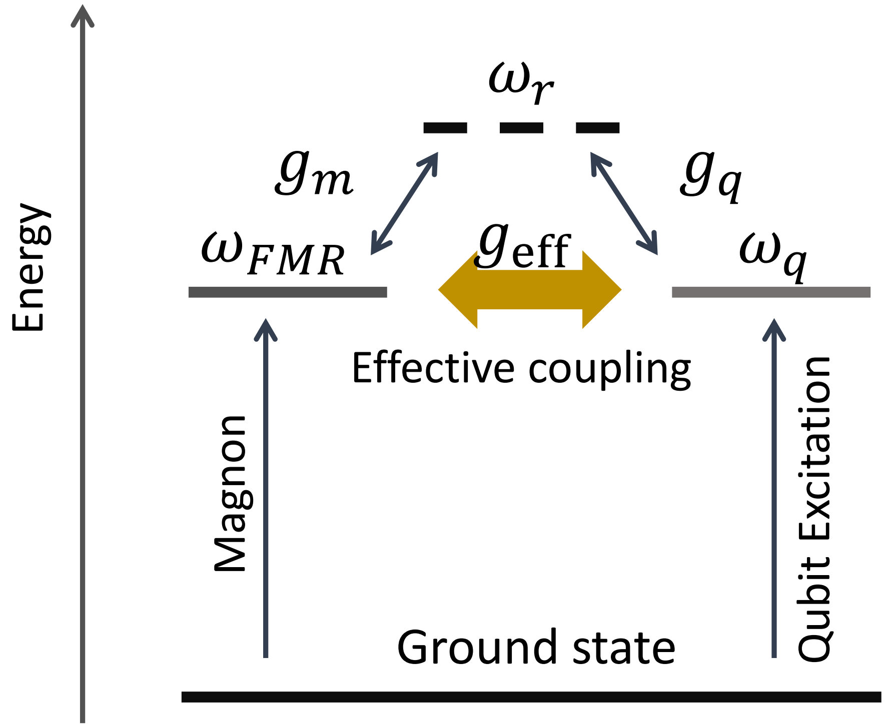
Coupling superconducting qubit with magnon



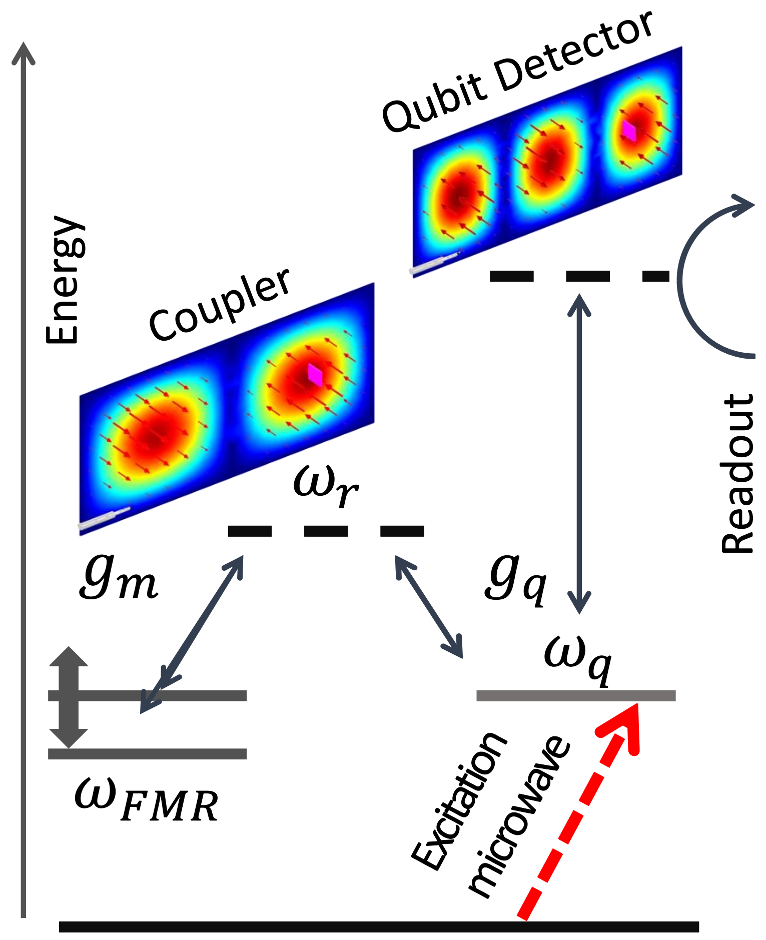
Magnon – cavity - qubit hybrid system

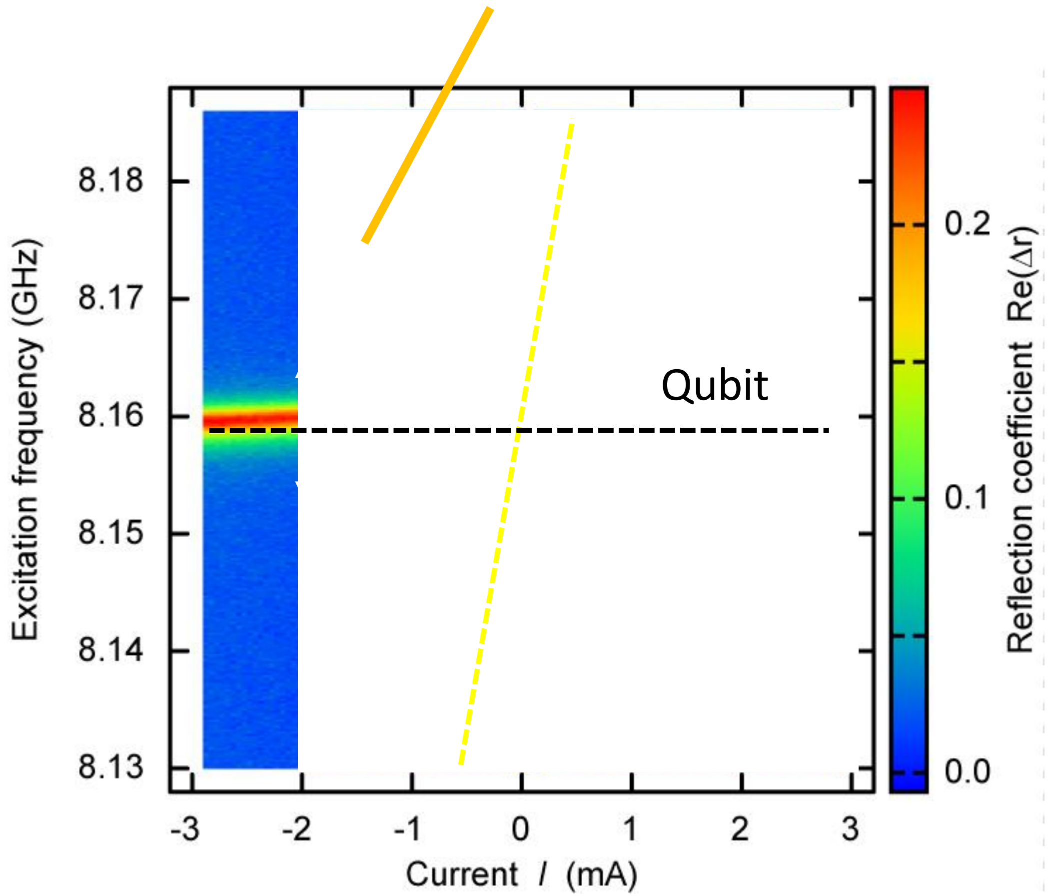
- Magnon-qubit coupling mediated by cavity

$$\hat{\mathcal{H}}/\hbar \sim \frac{g_m\, g_q}{\omega_r - \omega_{\mathrm{qubit}}} \left(\hat{a}_m^\dagger \hat{\sigma}^- + \hat{a}_m \hat{\sigma}^+\right)$$



Magnon Vacuum Rabi Splitting





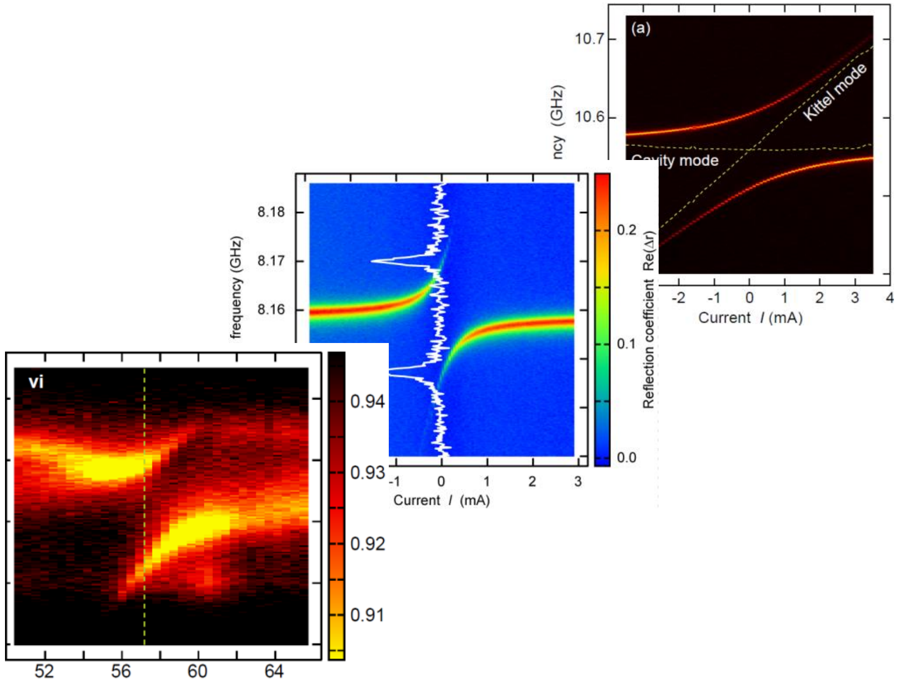
= Magnetic field
(applied locally to YIG sphere)

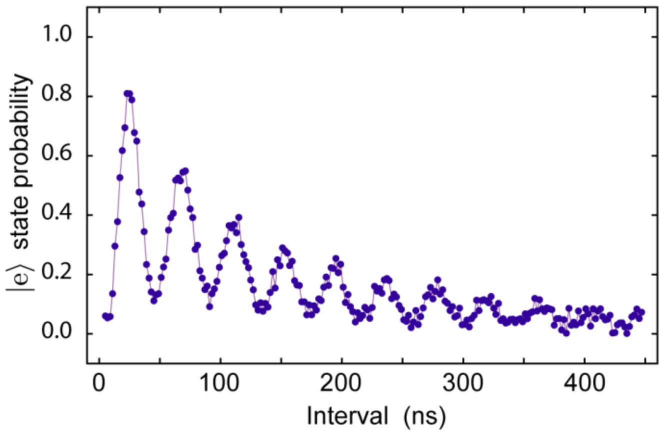
SUMMARY 1

- Strong magnon-photon coupling

- Strong magnon-qubit coupling

- Tunable coupling by parametric driving





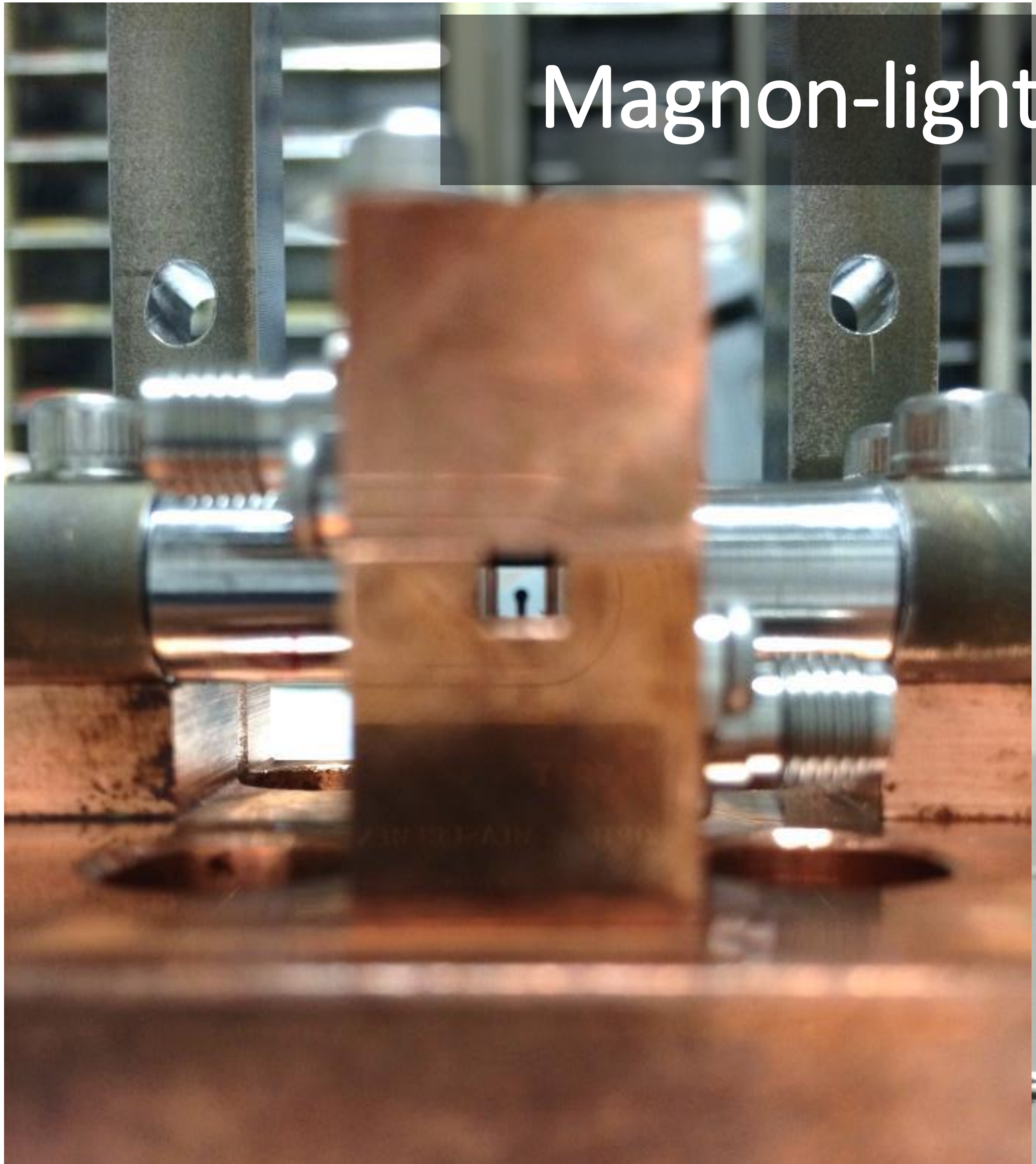
- Time-domain control & reaout magnons

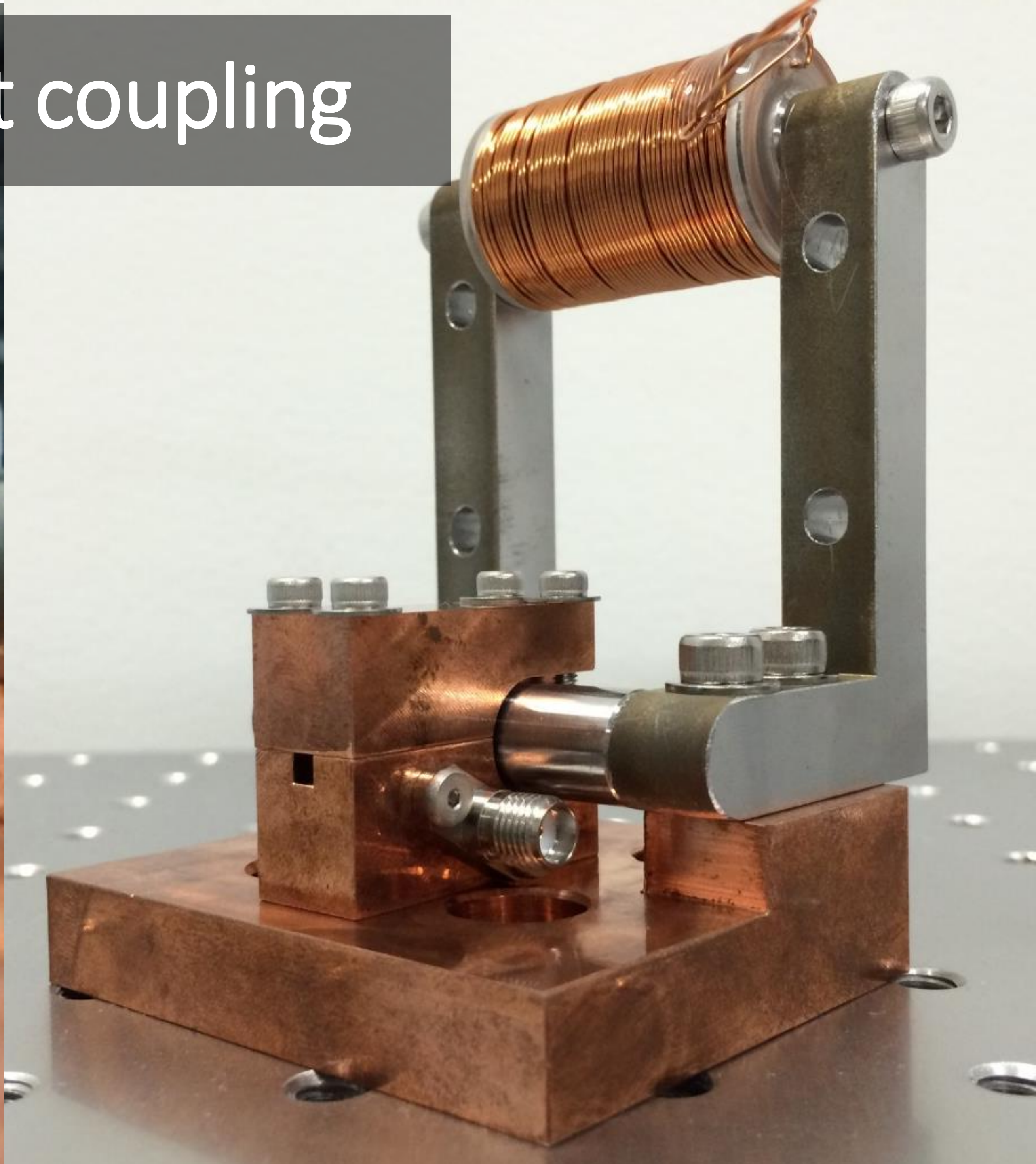
- Non-classical magnon control

- Magnon-state tomography

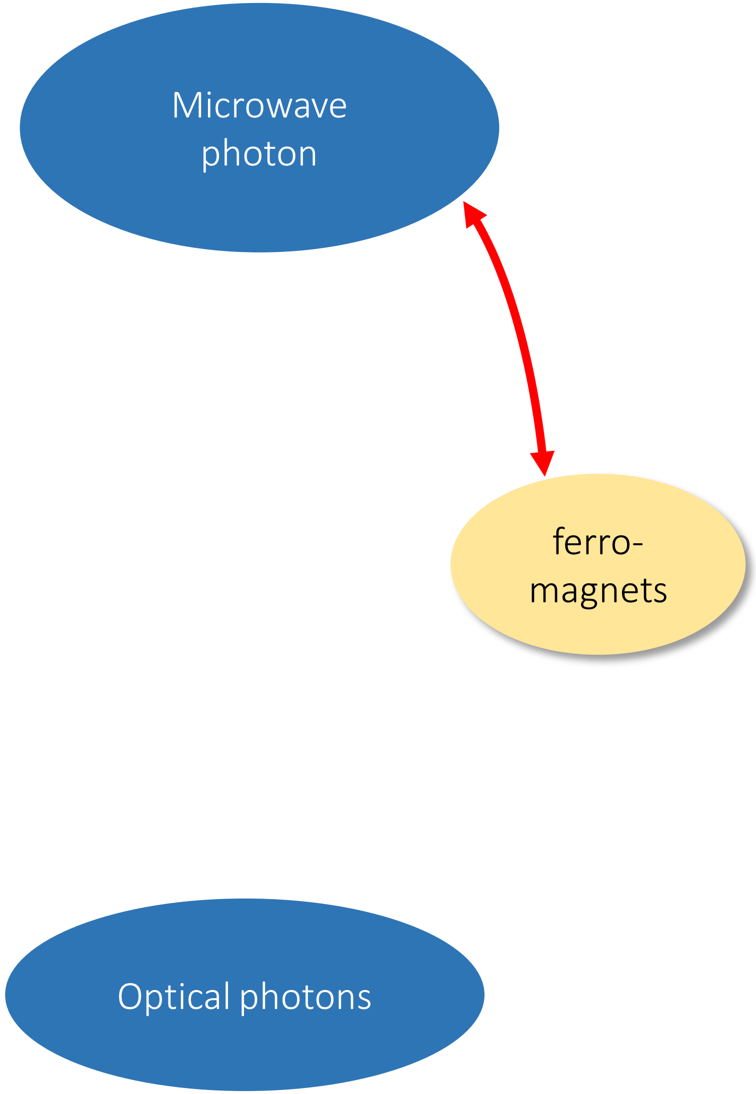
- Coupling to light

Magnon-light coupling





Collective enhancements



- **(Resonant) collective enhancement**

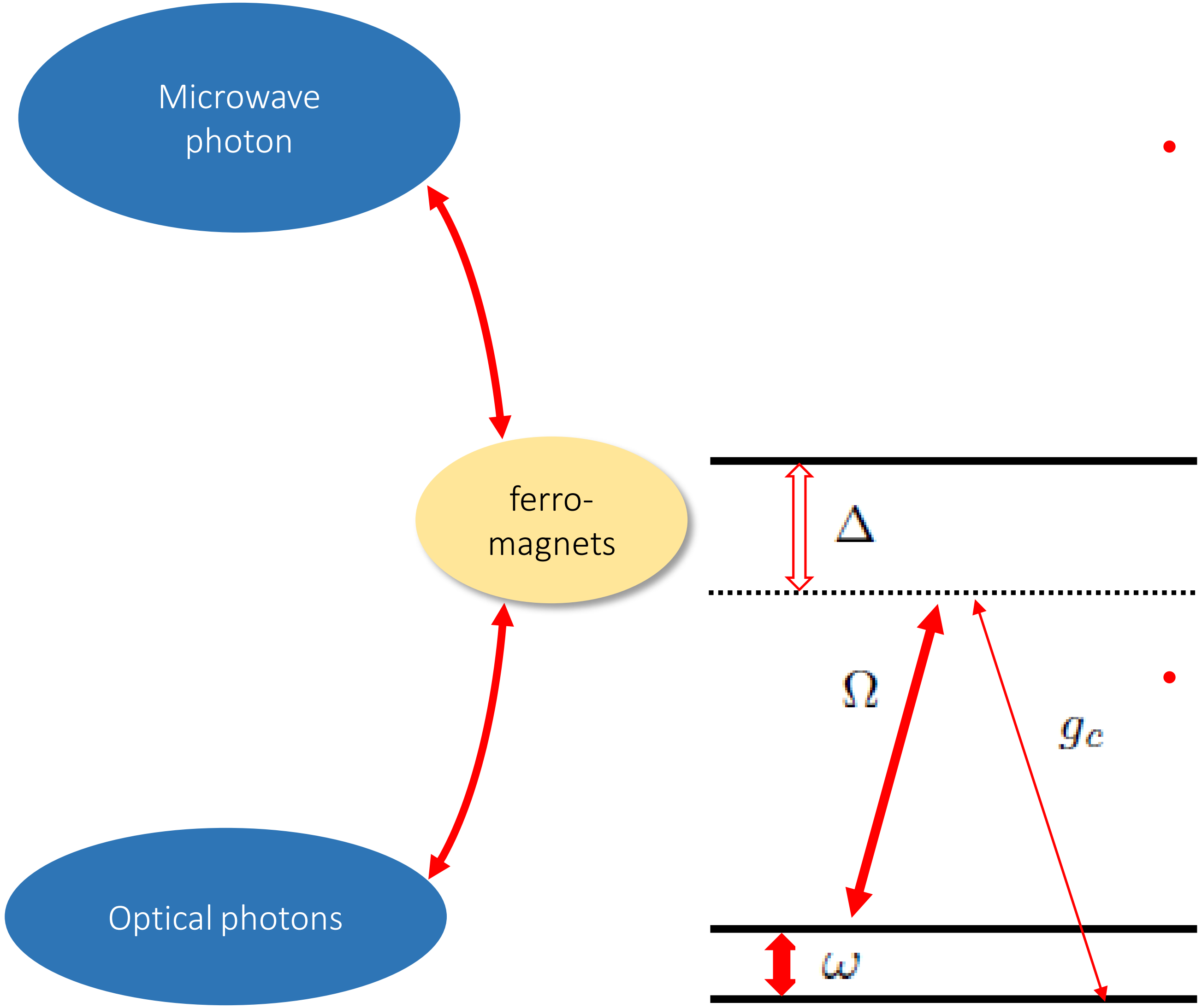
$$g_m = g_0\sqrt{N}$$

where single-spin coupling strength:

$$g_0 = \frac{2\mu_\mathrm{B}}{\hbar}\sqrt{\frac{\mu_0\hbar\omega}{2V}} = \frac{2\mu_B}{c}\sqrt{\frac{\omega}{2\hbar\epsilon_0 V}} = \alpha g_e$$

A. Imamoglu, Phys. Rev. Lett. **102,** 083602 (2009).

Collective enhancements



- <u>**(Resonant) collective enhancement**</u>

$$g_m = g_0\sqrt{N}$$

where single-spin coupling strength:

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- <u>**Raman collective enhancement (DLCZ)**</u>

$$\zeta = N\frac{|\Omega g_c|^2}{\Delta^2\kappa}$$

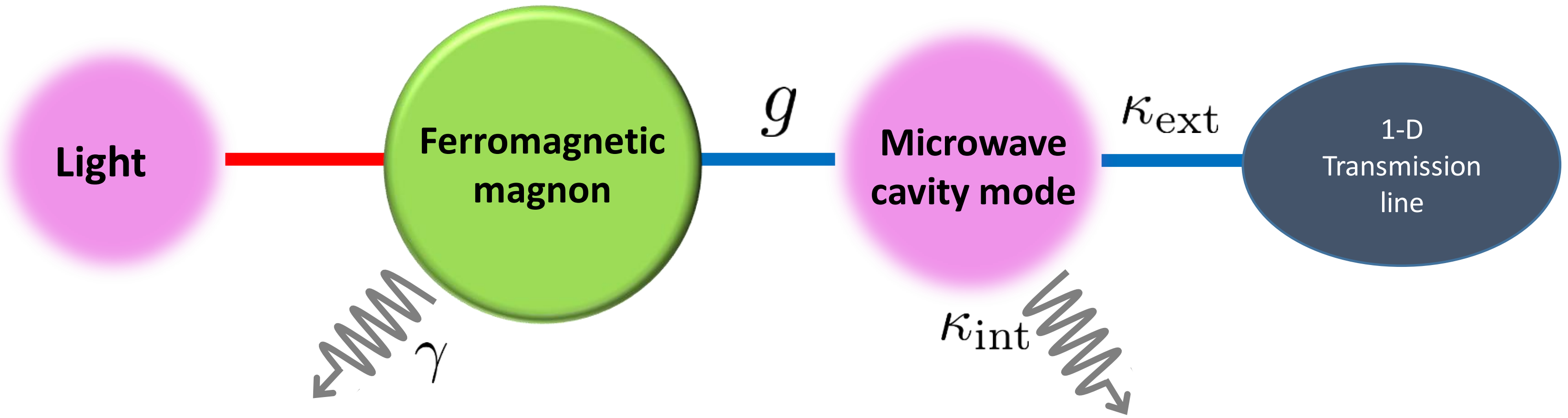
A. Imamoglu, Phys. Rev. Lett. **102,** 083602 (2009); L.-M. Duan et al., Nature **414,** 413 (2001).

Light-magnon coupling scheme

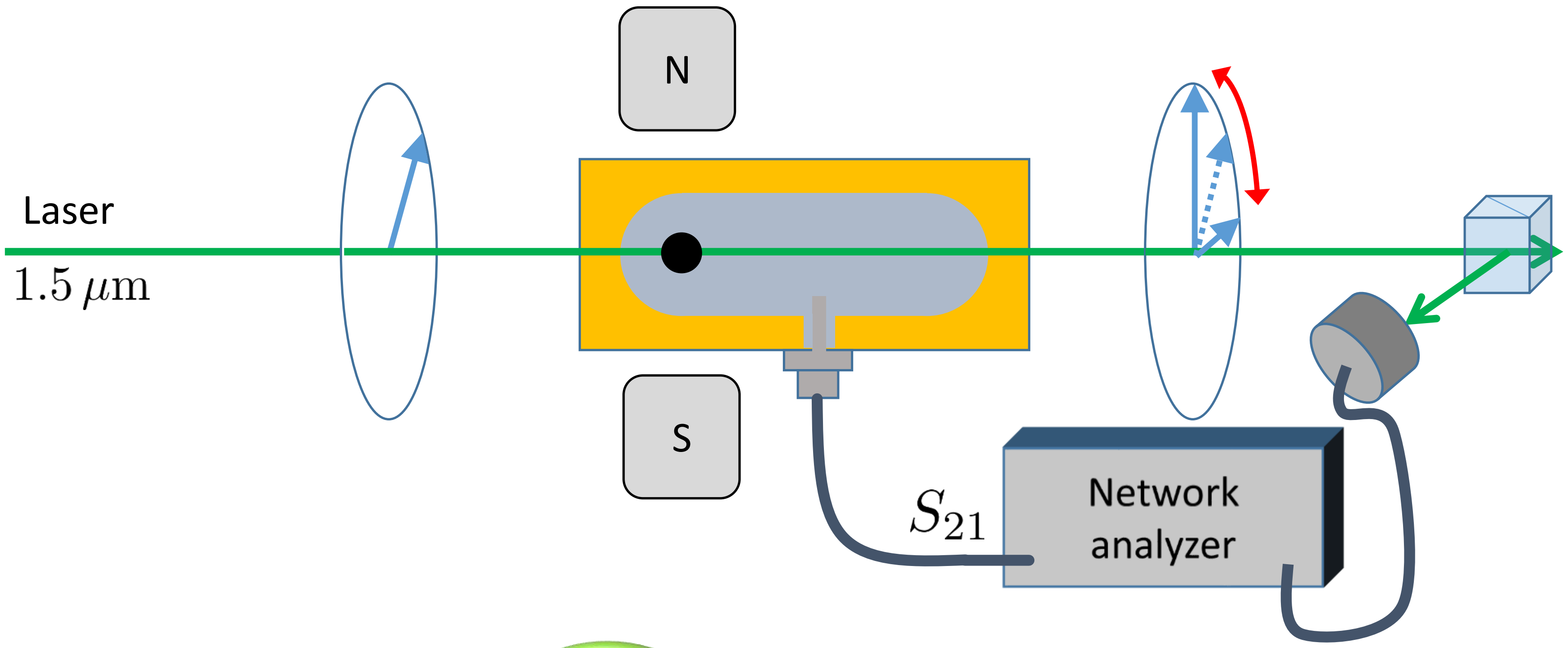
Faraday interaction: $\hat{H}_{\mathrm{I}} = \int_0^T \hbar G \boxed{\hat{j}_x(t')} \boxed{\hat{s}_x(t')} A c dt'$

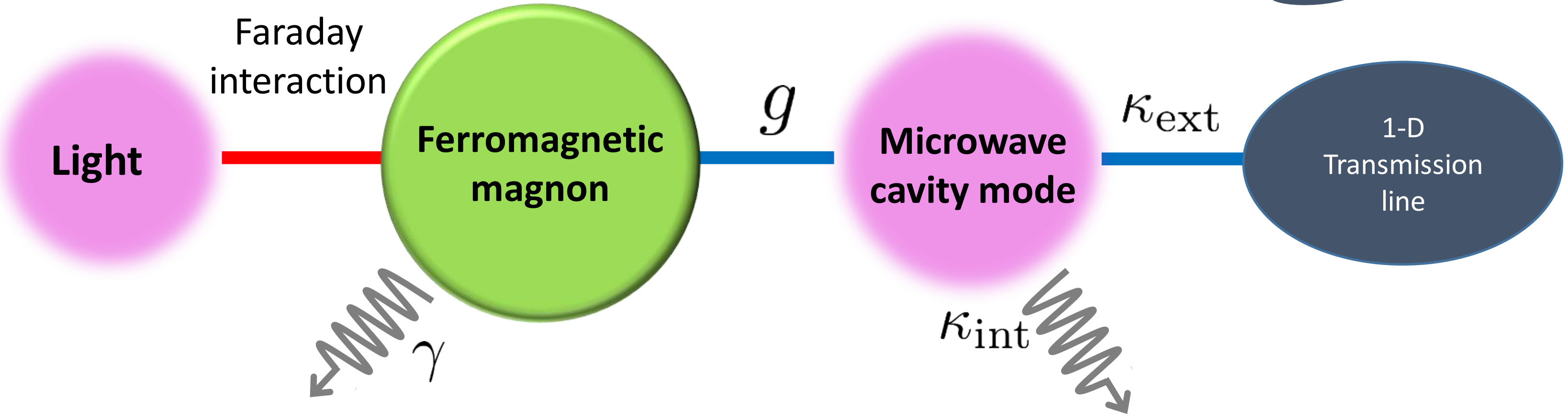
Collective spin operator   Stokes operator

Evolution of Stokes operator: $\frac{\partial}{\partial t}\hat{s}_\alpha(t) = \frac{1}{i\hbar}[\hat{s}_\alpha(t), \hat{H}_I]$ (Faraday rotation)

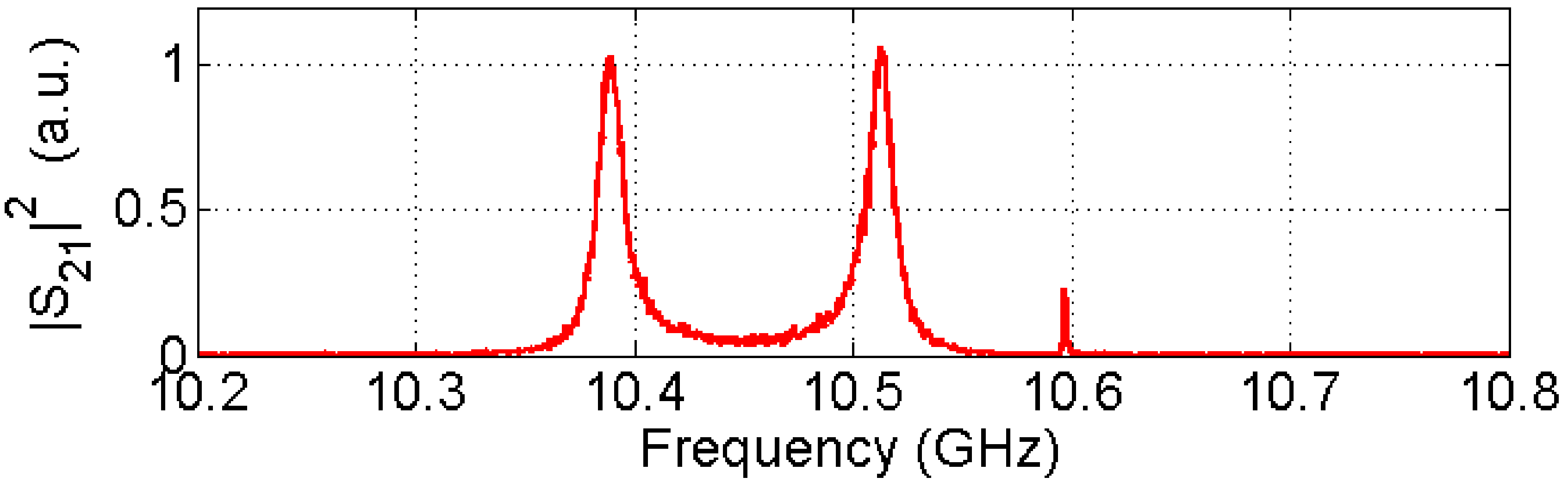


Light-magnon coupling scheme

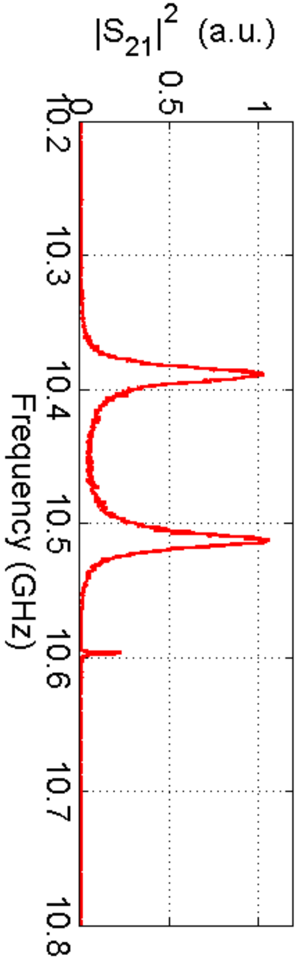


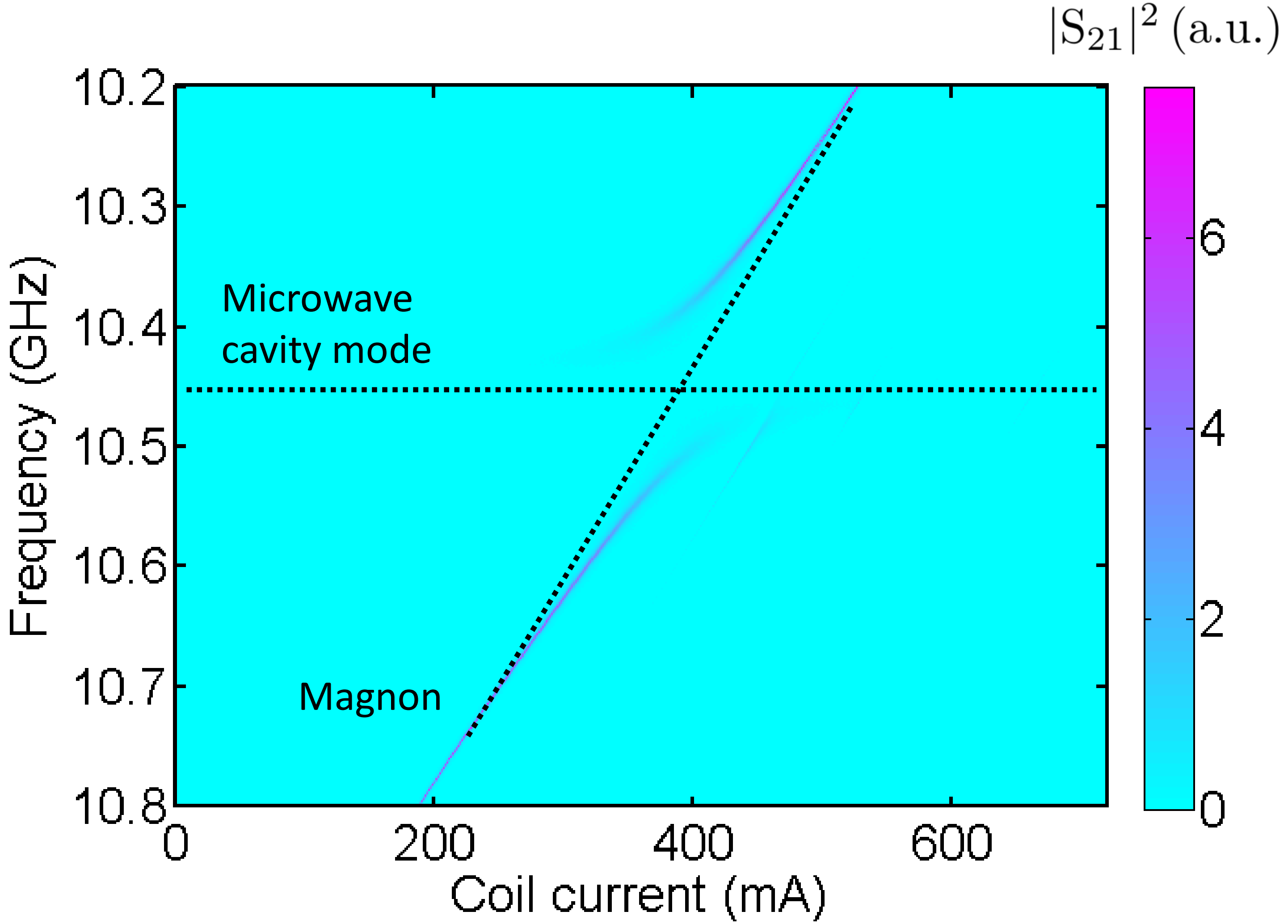


Sideband appear at normal mode frequencies

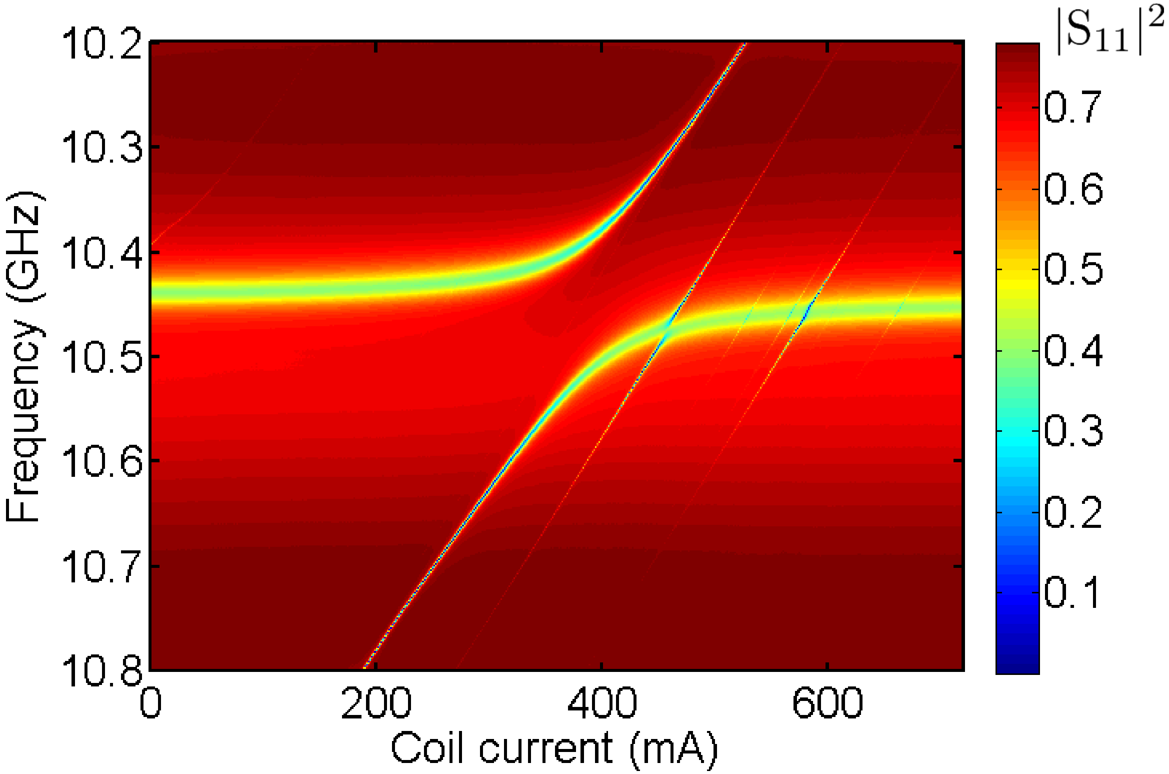


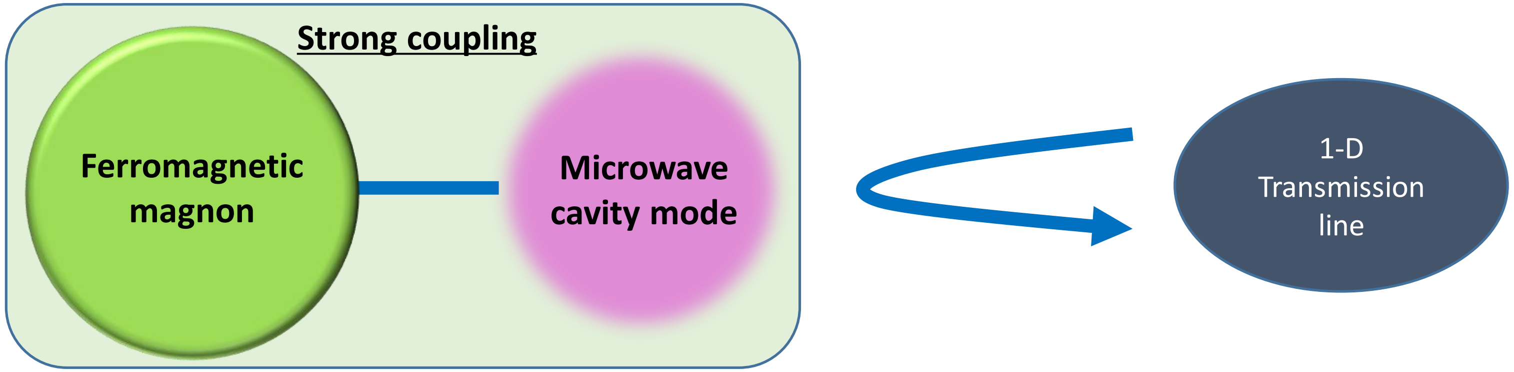
Magnon-cavity coupling probed by light



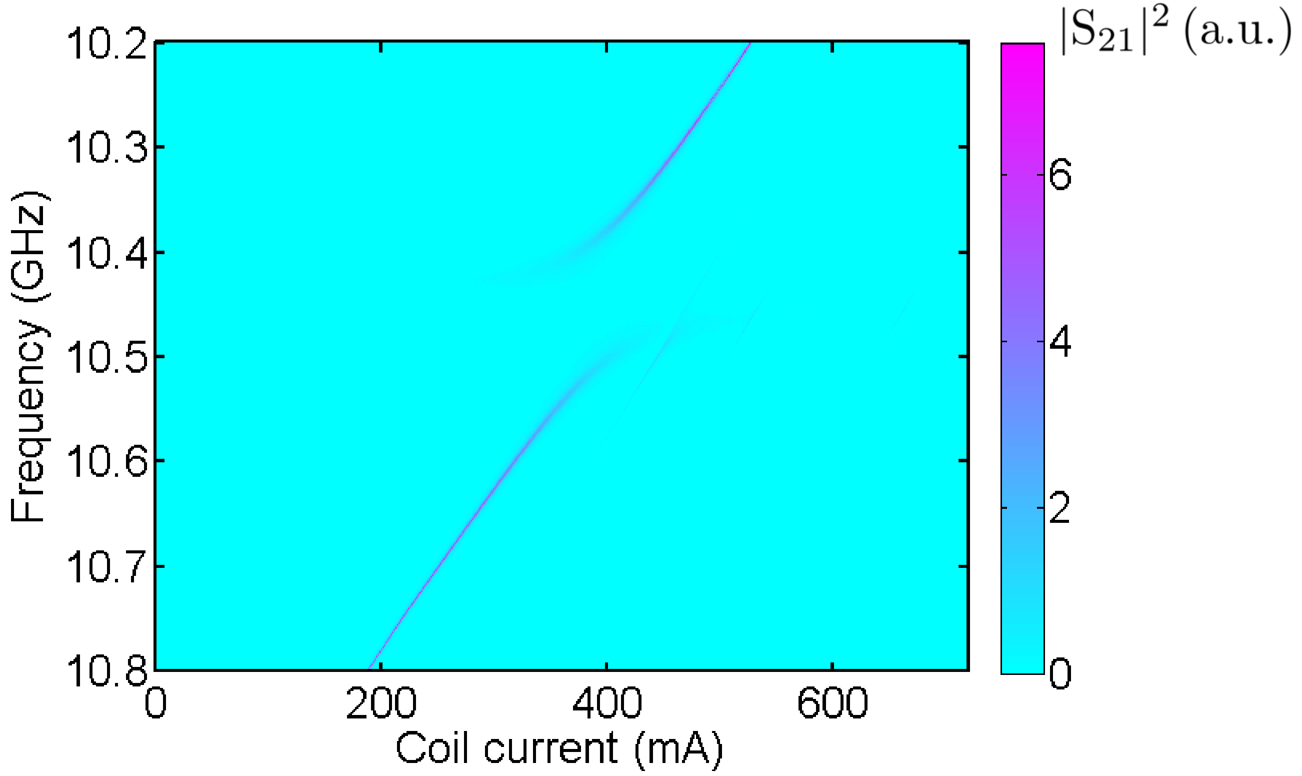


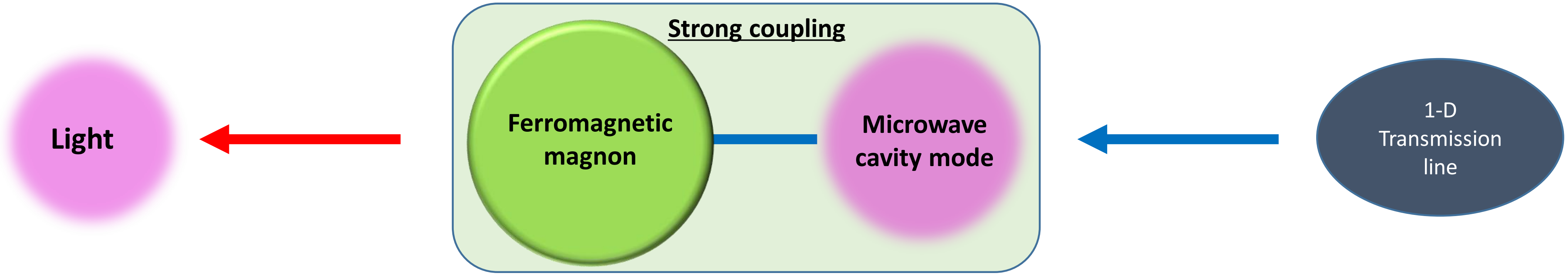
Microwave-light transducer





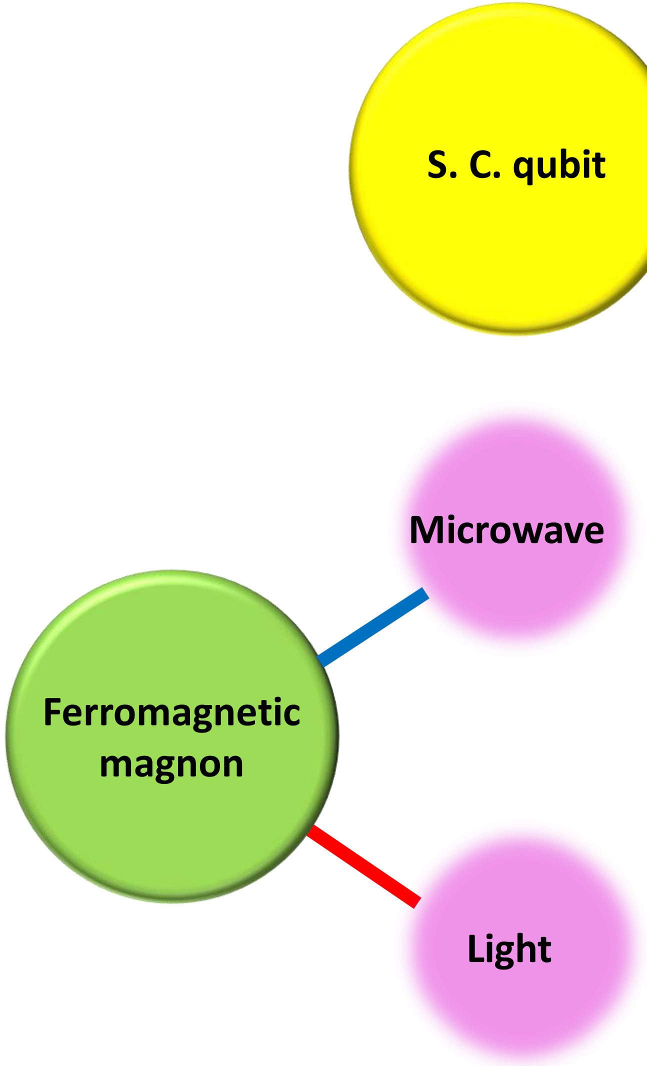
Microwave-light transducer

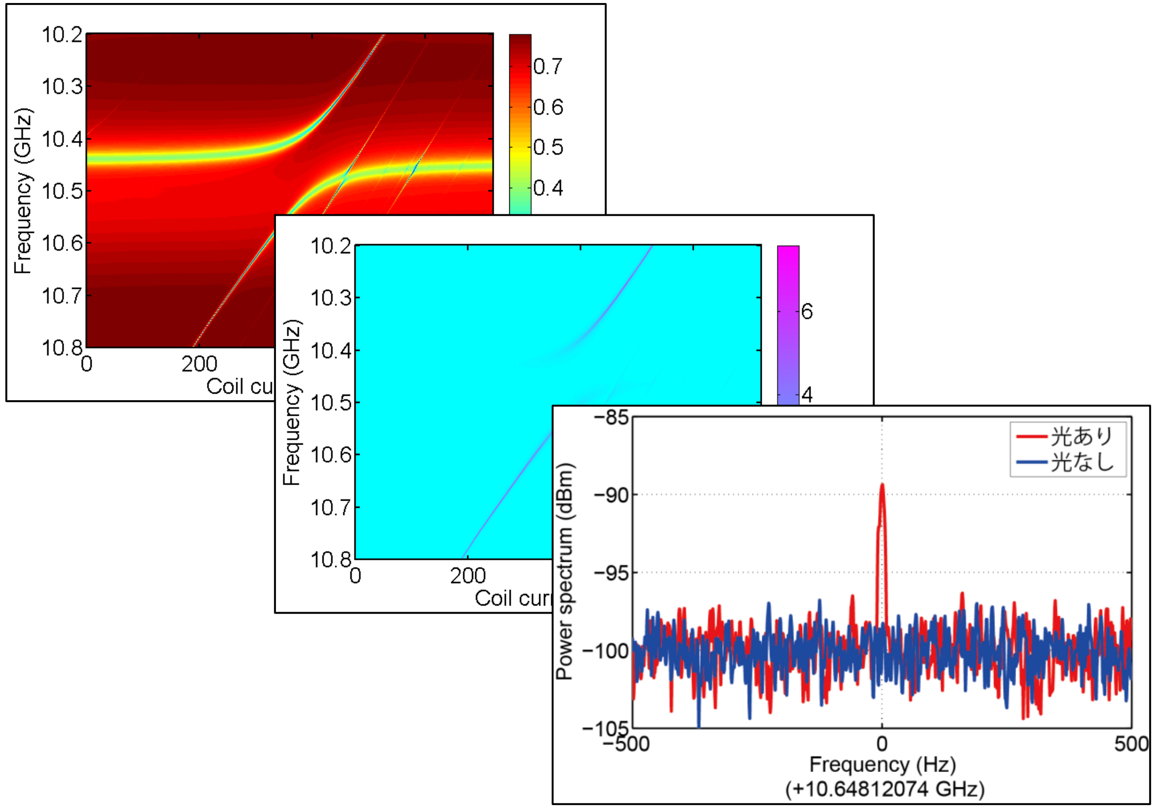




SUMMARY 2

- Realization of strong coupling magnon and M.W.
- Observation of the coupling system using light
- Realization of coherent m.w. generation using light





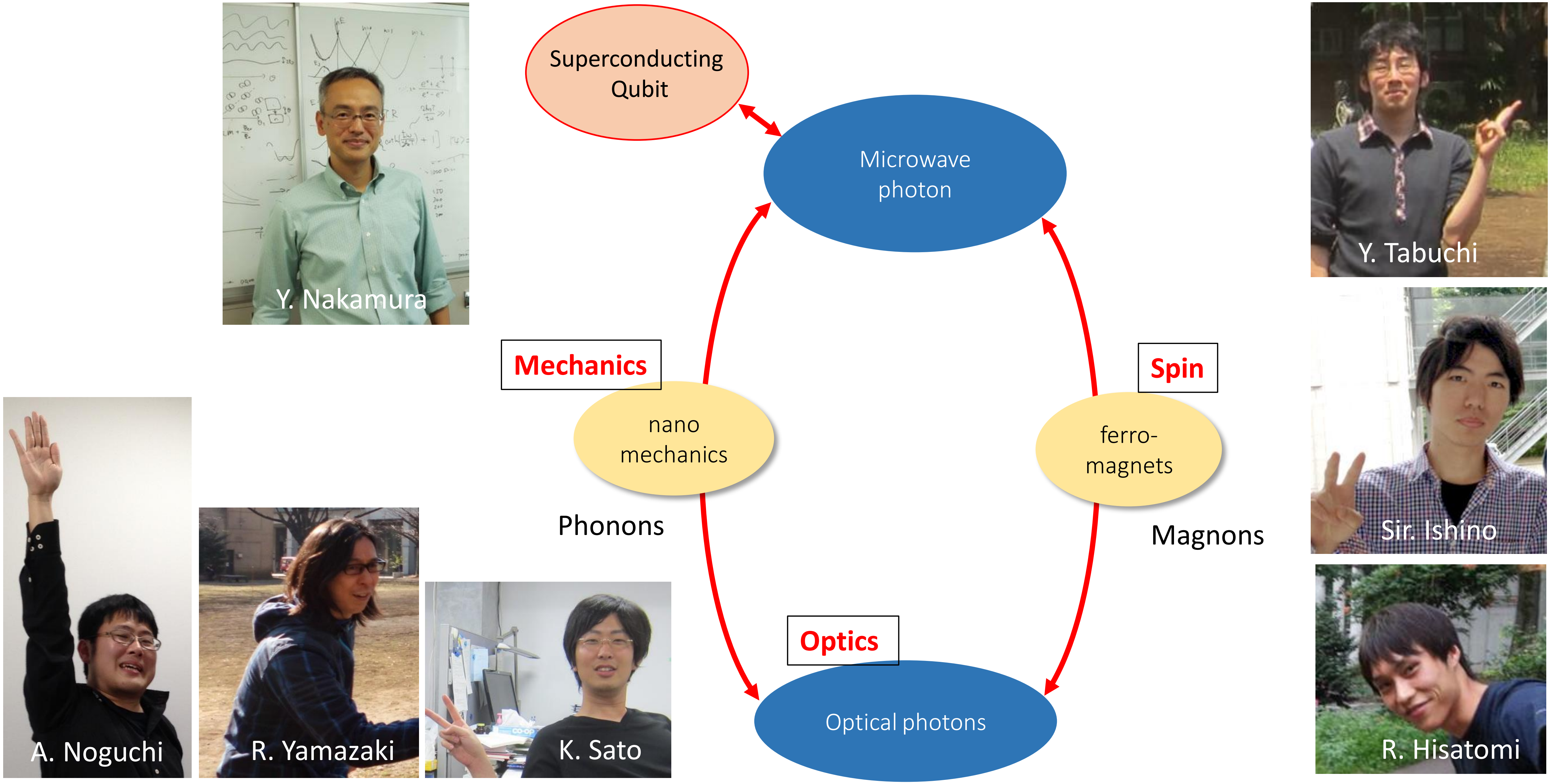
Why microwave?

- Small dissipation (superconductivity)
- Strong nonlinearity (Josephson effect)
- Strong confinement (ultra-small mode volume)

Why collective excitations?

- Large dimensions
- Easy mode-matching
- Collectively-enhanced coupling

Overview of Research activities



Overview of Research activities

Optomechanics-NMR

Waseda
Iwase lab

Kyoto
Takeda lab

Cavity cooling of magnon

UEC
Hakuta lab

Tokyo
Nomura lab

Thank you!