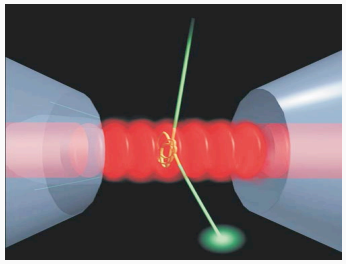
Cavity QED: Quantum Control with Single Atoms and Single Photons

Scott Parkins

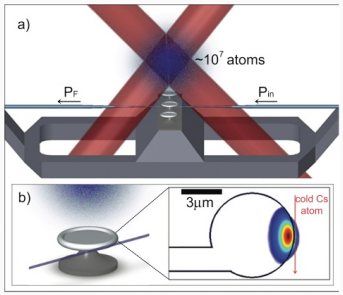
17 April 2008

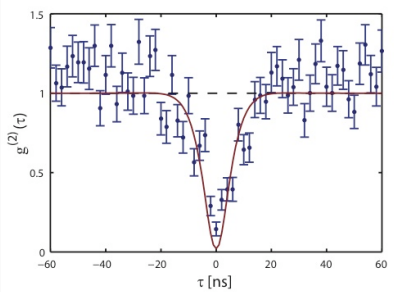
Outline

- Quantum networks
- Cavity QED
  - Strong coupling cavity QED
  - Network operations enabled by cavity QED



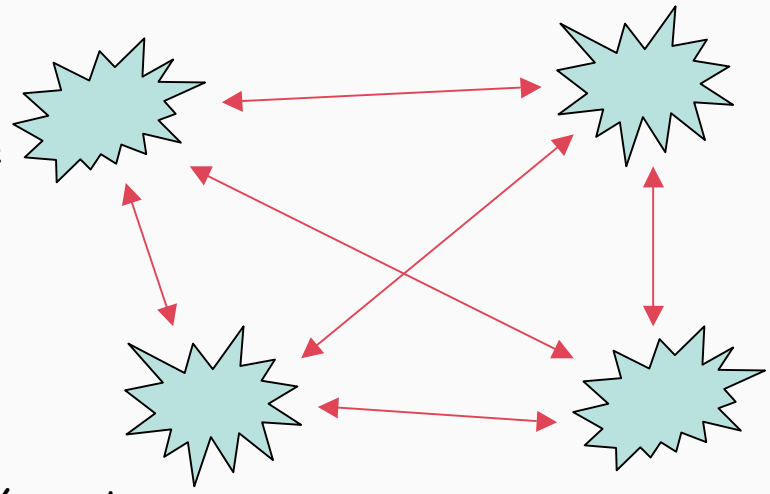
- Microtoroidal resonators and cold atoms
  - Cavity QED with microtoroids
  - Observation of strong coupling
  - The "bad cavity" regime
  - A photon turnstile dynamically regulated by one atom
  - Future possibilities





Quantum Networks

Quantum node: generation, processing, & storage of quantum information (states)



Quantum channel: transfer & distribution of quantum entanglement

Matter, e.g., atoms (quantum information stored in internal, electronic states)

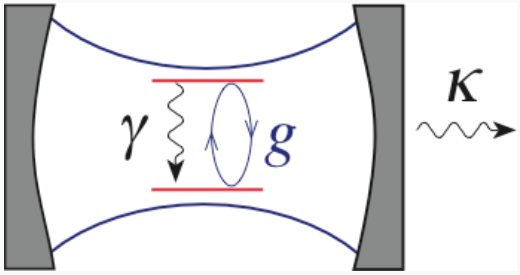
Light, e.g., single photons (quantum information stored in photon number or polarisation states)

Matter-light interface

Require deterministic, reversible quantum state transfer between material system and light field

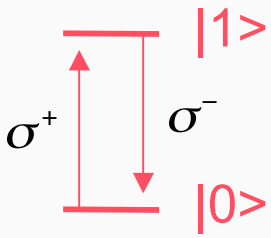
C. Monroe, "Quantum information processing with atoms and photons," Nature **424**, 839 (2003)

Cavity Quantum Electrodynamics (Cavity QED)



Atom-cavity interaction Hamiltonian

$$H = \omega_{\text{cav}} a^{+} a + \omega_{\text{atom}} \sigma^{+} \sigma^{-} + g\left(a^{+}\sigma^{-} + \sigma^{+} a\right)$$



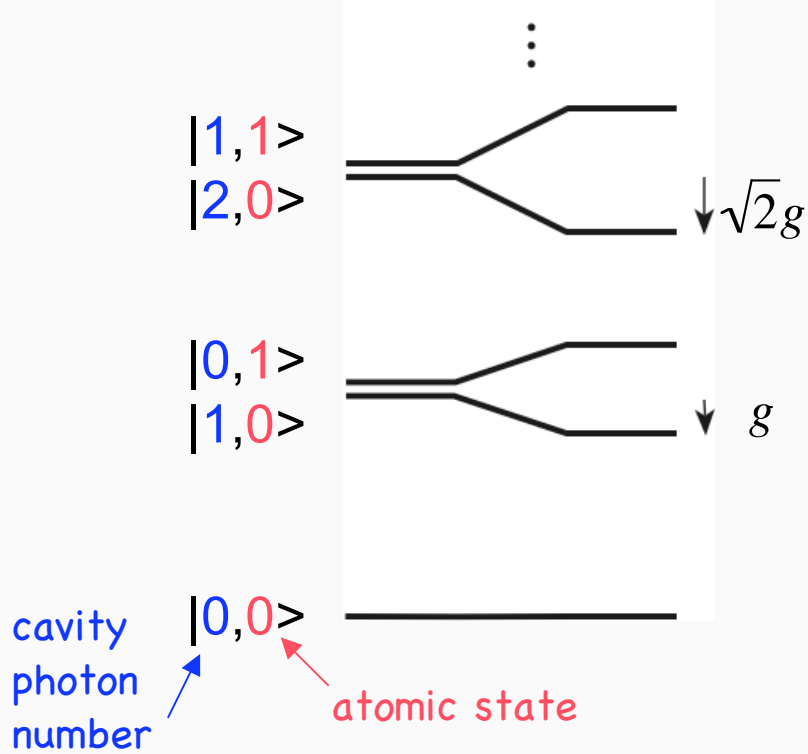
2-level atom

$$g \sim \mu_{01} E$$

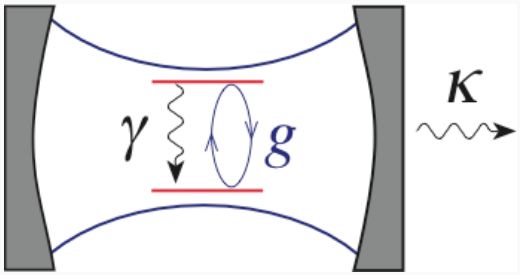
μ_{01} - atomic transition dipole moment

E - electric field per photon

$$E \sim \sqrt{\hbar \omega_{\text{cav}} / V_{\text{mode}}}$$



Strong Coupling Cavity QED



γ - atomic spontaneous emission rate

κ- cavity field decay rate

Strong dipole transition in optical cavity of small mode volume, high finesse

$$g >> \kappa, \gamma$$

Coherent dynamics dominant over dissipative processes

- Nonlinear optics with single photons
- Strong single-atom effects on cavity response
- Controllable manipulation of quantum states

Network Operations Enabled by Cavity QED

(i) Quantum State Transfer: Atom $\leftrightarrow$ Field

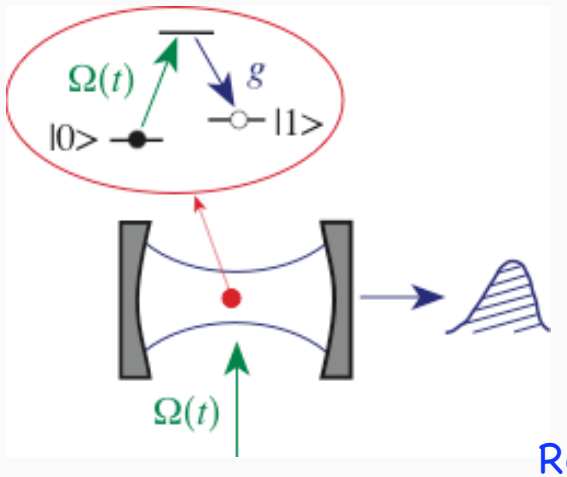
(ii) Quantum State Transfer: Node $\leftrightarrow$ Node

(iii) Conditional Quantum Dynamics

(i) Quantum State Transfer: Atom ↔ Field

SP, P. Marte, P. Zoller, & H.J. Kimble, "Synthesis of arbitrary quantum states via adiabatic transfer of Zeeman coherence," Phys. Rev. Lett. **71**, 3095 (1993)

Theory



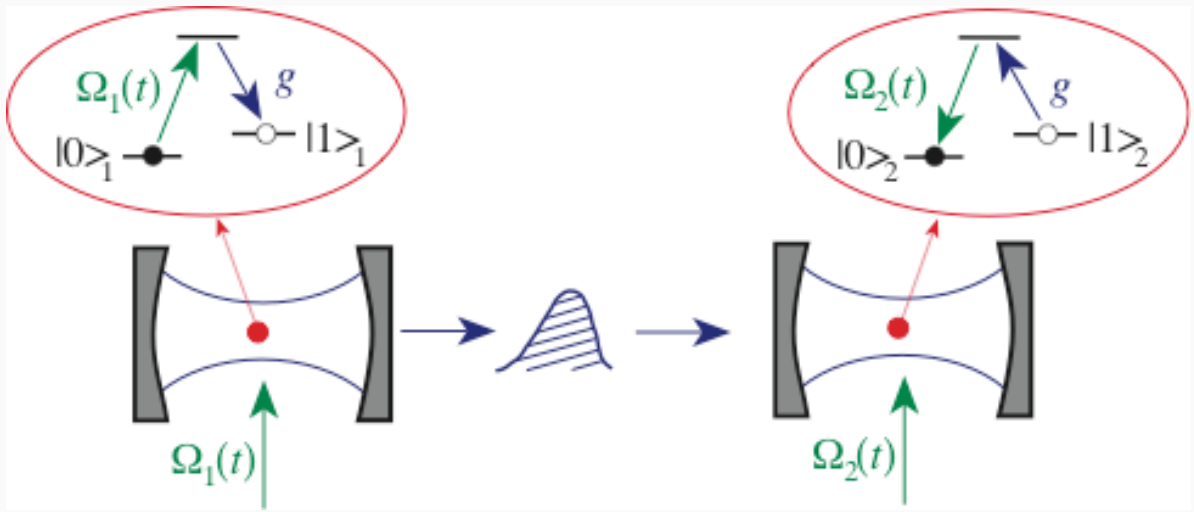
$$\left(\alpha|0\rangle + \beta|1\rangle\right)_{\text{atom}} \otimes |0\rangle_{\text{field}}$$
$$\rightarrow |0\rangle_{\text{atom}} \otimes \left(\alpha|0\rangle + \beta|1\rangle\right)_{\text{field}}$$

Recent experiments

- T. Wilk, S.C. Webster, A. Kuhn, & G. Rempe, "Single-atom single-photon quantum interface," Science **317**, 488 (2007)
- A.D. Boozer, A. Boca, R. Miller, T.E. Northup, & H.J. Kimble, "Reversible state transfer between light and a single trapped atom," Phys. Rev. Lett. **98**, 193601 (2007)

(ii) Quantum State Transfer: Node ↔ Node

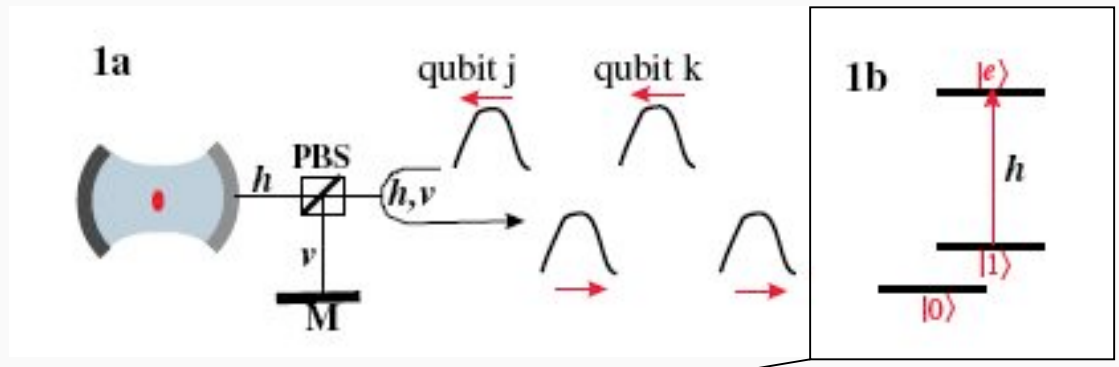
J.I. Cirac, P. Zoller, H.J. Kimble, & H. Mabuchi, "Quantum state transfer and entanglement distribution among distant nodes in a quantum network," Phys. Rev. Lett. **78**, 3221 (1997)

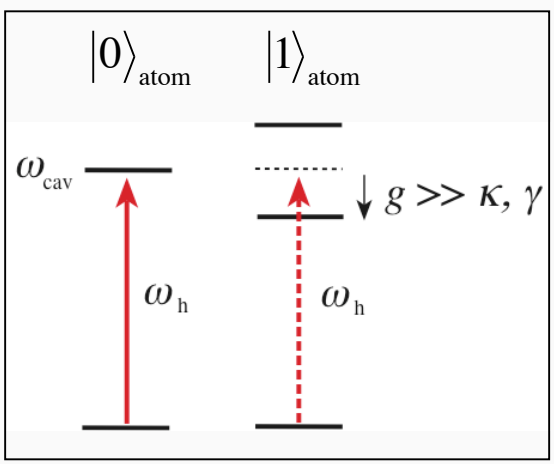


$$\left(\alpha|0\rangle + \beta|1\rangle\right)_{\text{atom 1}} \otimes |0\rangle_{\text{atom 2}} \rightarrow |0\rangle_{\text{atom 1}} \otimes \left(\alpha|0\rangle + \beta|1\rangle\right)_{\text{atom 2}}$$

(iii) Conditional Quantum Dynamics

L.-M. Duan & H.J. Kimble, "Scalable photonic quantum computation through cavity-assisted interactions," Phys. Rev. Lett. **92**, 127902 (2004)





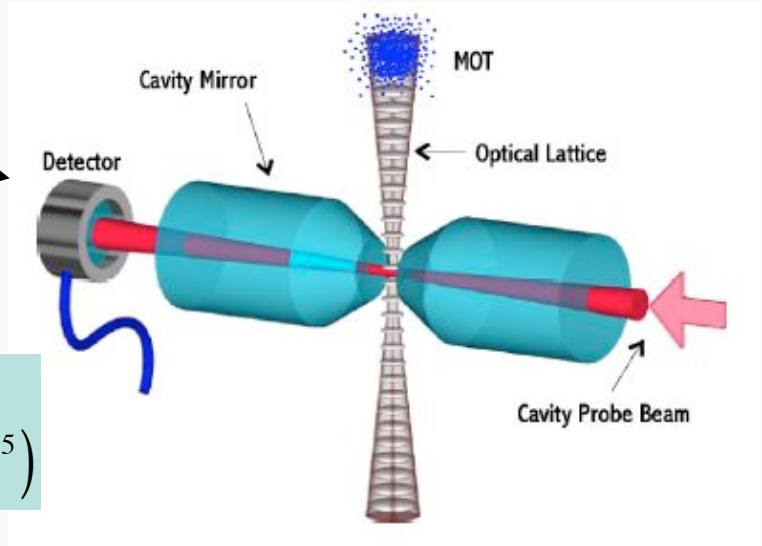
Atomic-state-dependent phase shift of h-polarisation

$$\left(\alpha|\mathrm{v}\rangle+\beta|\mathrm{h}\rangle\right)_{\mathrm{photon}}\otimes\begin{Bmatrix}|0\rangle_{\mathrm{atom}}\\|1\rangle_{\mathrm{atom}}\end{Bmatrix}\rightarrow\begin{Bmatrix}\left(\alpha|\mathrm{v}\rangle-\beta|\mathrm{h}\rangle\right)_{\mathrm{photon}}\otimes|0\rangle_{\mathrm{atom}}\\\left(\alpha|\mathrm{v}\rangle+\beta|\mathrm{h}\rangle\right)_{\mathrm{photon}}\otimes|1\rangle_{\mathrm{atom}}\end{Bmatrix}$$

Experimental Cavity QED With Cold Atoms

Cavity QED with cold neutral atoms (Fabry-Perot resonators)

- H.J. Kimble (Caltech)
- G. Rempe (MPQ, Garching)
- M. Chapman (Georgia Tech)
- D. Stamper-Kurn (Berkeley)
- D. Meschede (Bonn)
- L. Orozco (Maryland)
- …



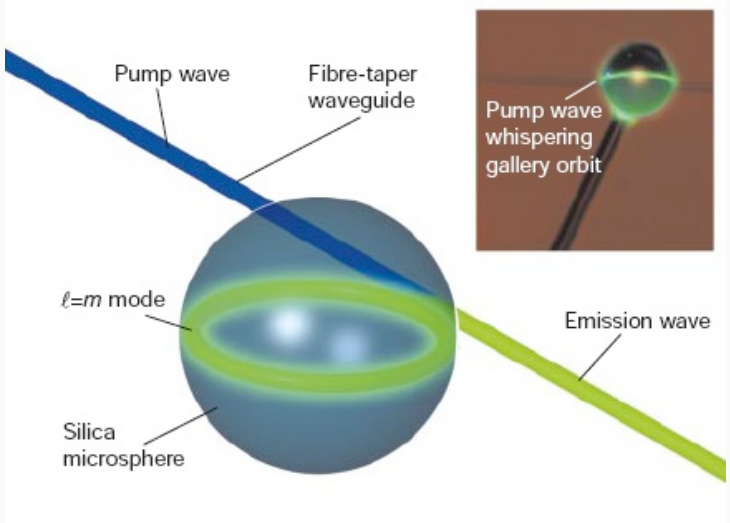
Typically $\begin{cases} g/2\pi \sim \text{few} \times 10\ \text{MHz} \\ \kappa/2\pi \sim \text{few MHz} \ \left(Q \sim 10^5\right) \end{cases}$

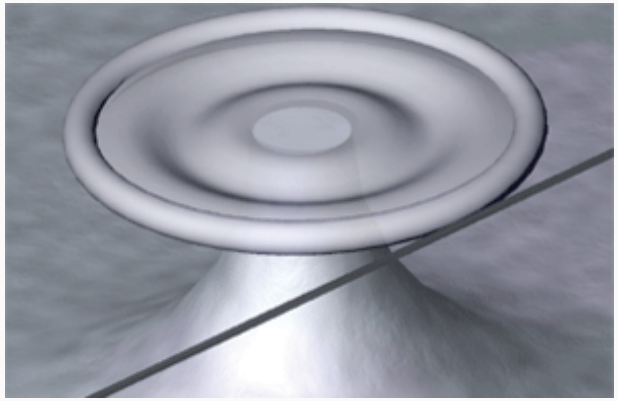
Cavity QED with trapped ions

- R. Blatt (Innsbruck)
- W. Lange (Sussex)
- C. Monroe (Maryland)
- M. Chapman (Georgia Tech)
- …

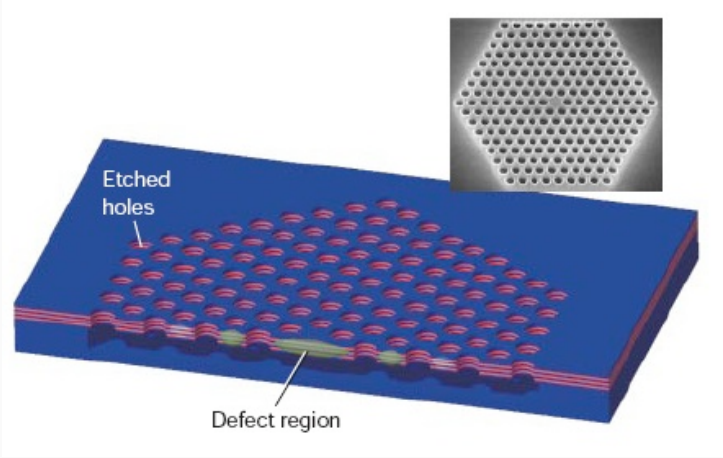
New Architectures: Optical Microcavities

K.J. Vahala, "Optical microcavities," Nature **424**, 839 (2003)



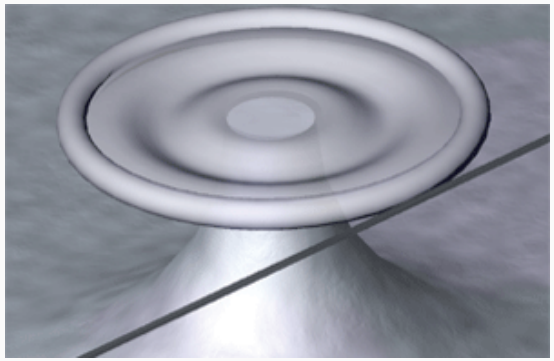


- Lithographically fabricated
- Integrable with atom chips, scalable networks



Microtoroidal Resonators

Outline:

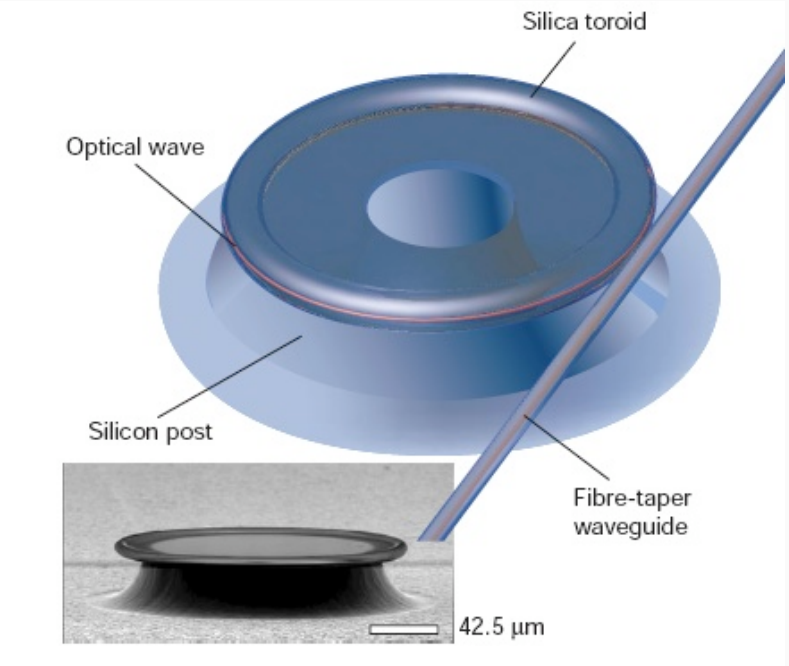


- Microtoroidal resonators and fiber tapers
  - critical coupling
- Microtoroidal resonators and cold atoms
  - physical setup, basic parameters
  - strong coupling cavity QED
- Experimental observation of strong coupling

- The "bad cavity" regime
- A photon turnstile dynamically regulated by one atom
- Further possibilities
  - single photon transistor

Microtoroidal Resonators + Fiber Tapers

S.M. Spillane, T.J. Kippenberg, O.J. Painter, & K.J. Vahala, "Ideality in a fiber-taper-coupled microresonator system for application to cavity quantum electrodynamics," Phys. Rev. Lett. **91**, 043902 (2003)



- Coupling through evanescent fields
- 99.97% fiber-taper to microtoroid coupling efficiency!
- Readily integrated into quantum networks
- Ultrahigh Q-factors and small mode volumes

Projected Cavity QED Parameters

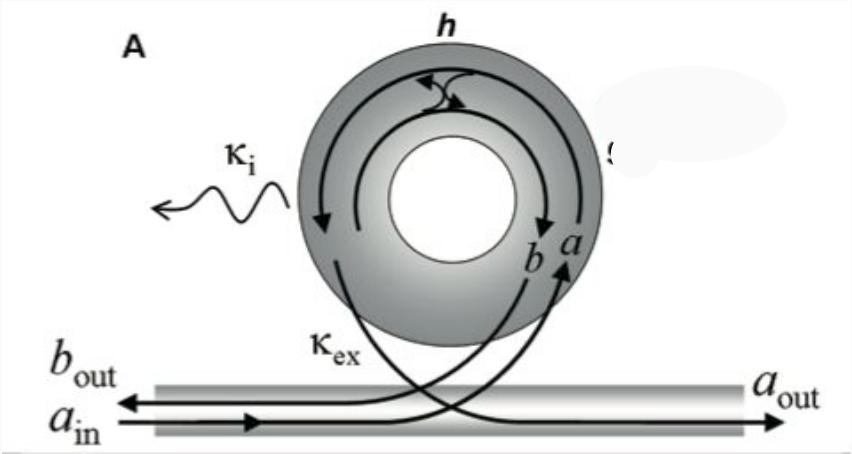
S.M. Spillane, T.J. Kippenberg, K.J. Vahala, W. Goh, E. Wilcut, & H.J. Kimble, "Ultrahigh-Q toroidal microresonators for cavity quantum electrodynamics," Phys. Rev. A **71**, 013817 (2005)

Microtoroid of major diameter 10-20 microns:

$$\begin{cases} g/2\pi \sim \text{few} \times 100\ \text{MHz} \\ \kappa_{\text{i}}/2\pi < 1\ \text{MHz} \quad \left(Q \sim 10^{8-9}\right) \end{cases}$$

near surface of toroid

Microtoroidal Resonator - Critical Coupling



Output fields

$$a_{\text{out}} = a_{\text{in}} + \sqrt{2\kappa_{\text{ex}}}\, a$$

$$b_{\text{out}} = b_{\text{in}} + \sqrt{2\kappa_{\text{ex}}}\, b$$

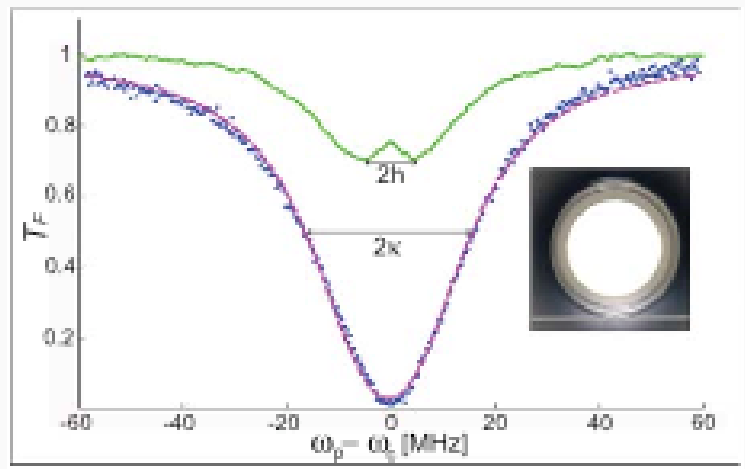
$$T_{\text{F}} = \frac{\langle a_{\text{out}}^{+} a_{\text{out}} \rangle}{\langle a_{\text{in}}^{+} a_{\text{in}} \rangle}$$

Critical coupling condition

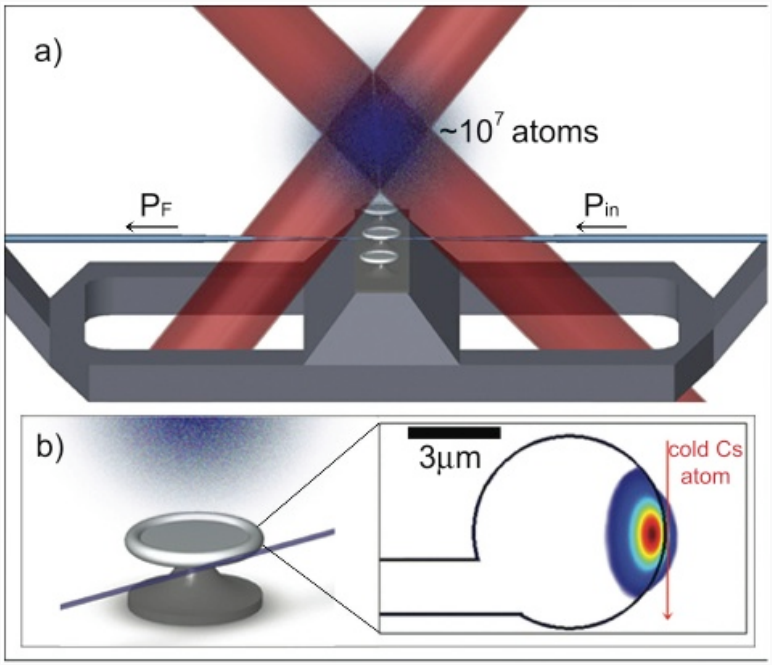
$$\kappa_{\text{ex}} = \kappa_{\text{ex}}^{\text{cr}} = \sqrt{\kappa_{\text{i}}^{2} + h^{2}}$$

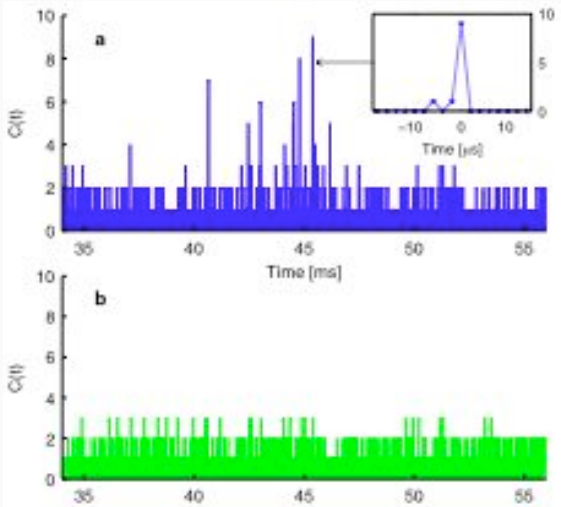
$$\Rightarrow \quad T_{\text{F}}(\Delta_{\text{C}} = 0) = 0$$

(destructive interference in forward direction)



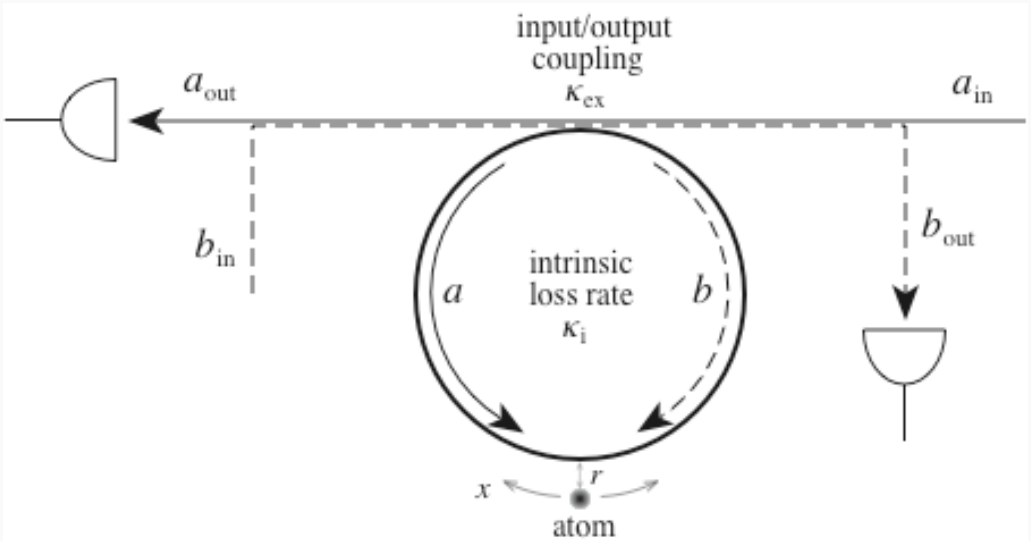
Microtoroidal Resonators + Cold Atoms





- Atoms couple to evanescent field of whispering gallery modes, "disrupt" critical coupling condition

Microtoroid Cavity QED - Basic Parameters



- Mode-mode coupling h
- Atom-field coupling

$$g_{tw}(r,x) = g_0^{tw}(r)e^{ikx}$$
$$g_0^{tw}(r) \sim e^{-kr}$$

$$H = \Delta_A \sigma^+\sigma^- + \Delta_C\left(a^+a + b^+b\right)$$
$$+ h\left(a^+b + b^+a\right) + \left(E_p^* a + E_p a^+\right)$$
$$+ \left(g_{tw}^* a^+\sigma^- + g_{tw}\sigma^+ a\right) + \left(g_{tw} b^+\sigma^- + g_{tw}^*\sigma^+ b\right)$$

Probe field driving, frequency ω_p

$$\left(\Delta_A = \omega_A - \omega_p, \quad \Delta_C = \omega_C - \omega_p\right)$$

Normal Mode Picture

Define normal mode operators: $A = \frac{1}{\sqrt{2}}(a+b), \quad B = \frac{1}{\sqrt{2}}(a-b)$

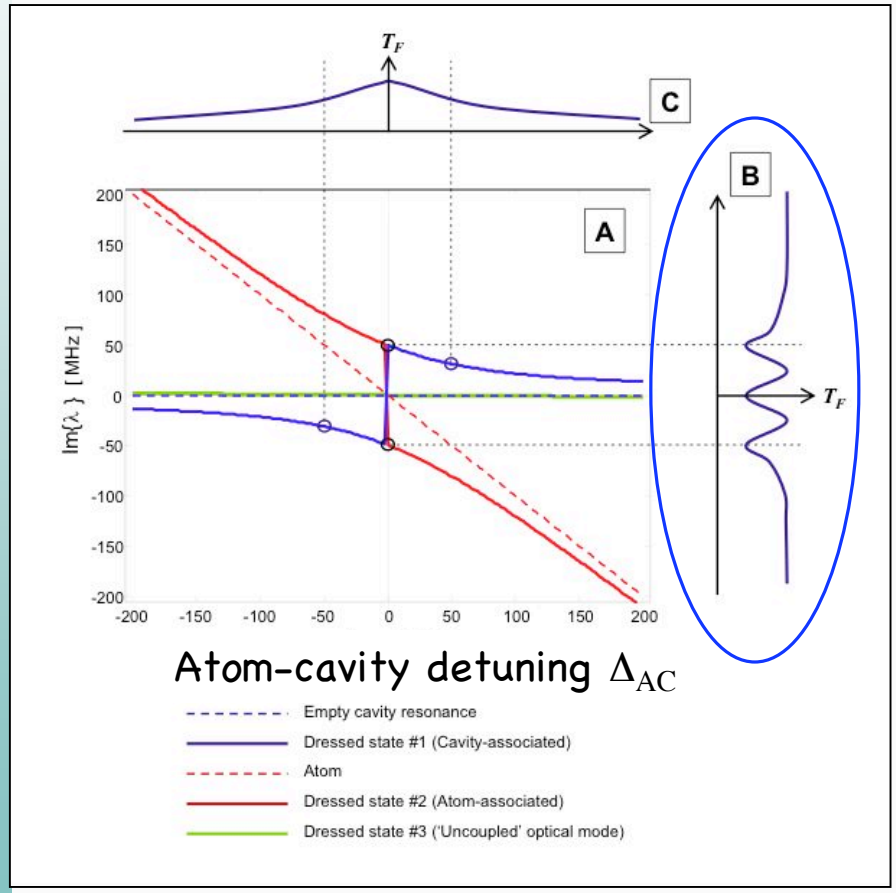
$$H = \Delta_A \sigma^+\sigma^- + (\Delta_C + h)A^+A + (\Delta_C - h)B^+B$$
$$+ \frac{1}{\sqrt{2}}\left[E_p^*(A+B) + E_p\left(A^+ + B^+\right)\right]$$
$$+ g_A\left(A^+\sigma^- + \sigma^+A\right) - \mathrm{i}g_B\left(B^+\sigma^- - \sigma^+B\right)$$

$g_A = g_0 \cos(kx)$ $\quad$ $g_0 = \sqrt{2}g_0^{\mathrm{tw}}$ $\quad$ $g_B = g_0 \sin(kx)$

Normal modes ↔ standing waves around circumference of toroid

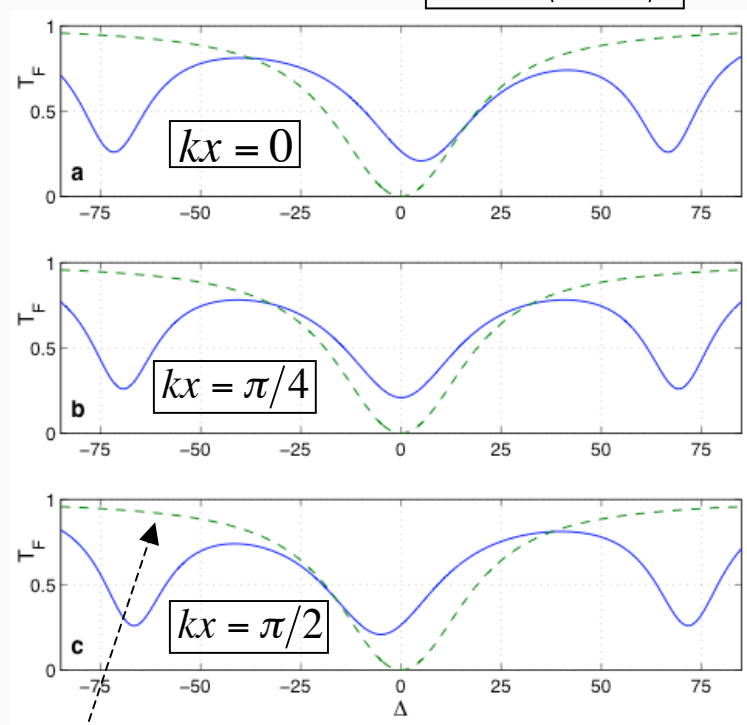
Microtoroid Cavity QED

Level structure (vacuum Rabi splitting)



Forward transmission

$$T_F = \frac{\langle a_{out}^{+} a_{out} \rangle}{\langle a_{in}^{+} a_{in} \rangle}$$

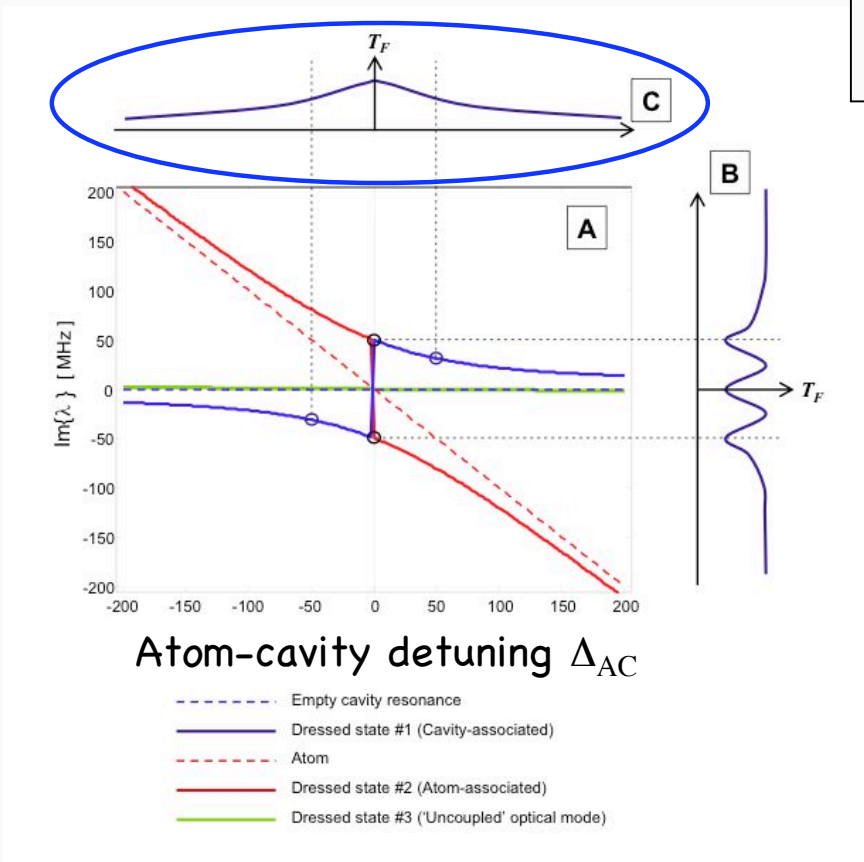


Probe field detuning

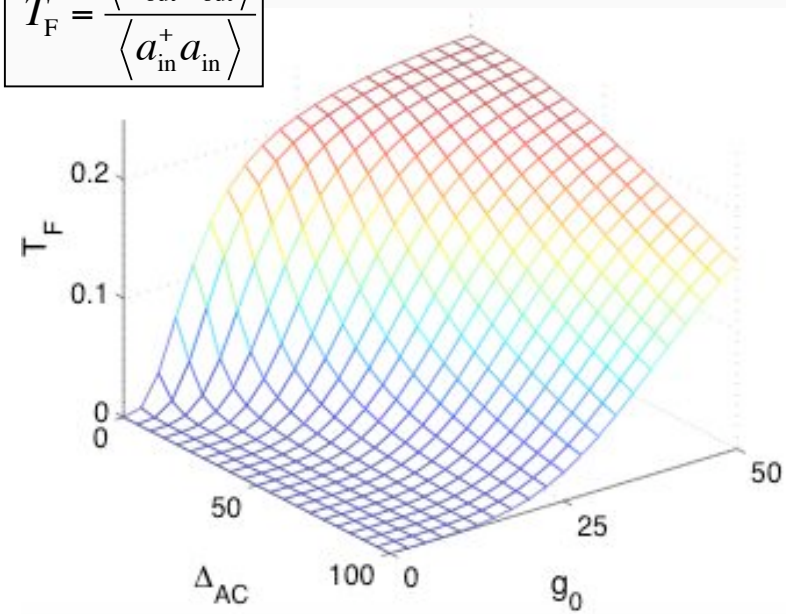
$(\Delta_{AC} = 0)$

no atom

Microtoroid Cavity QED

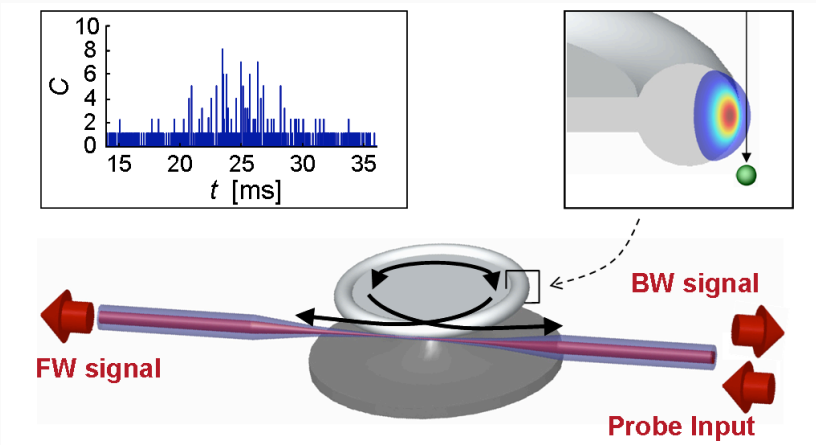


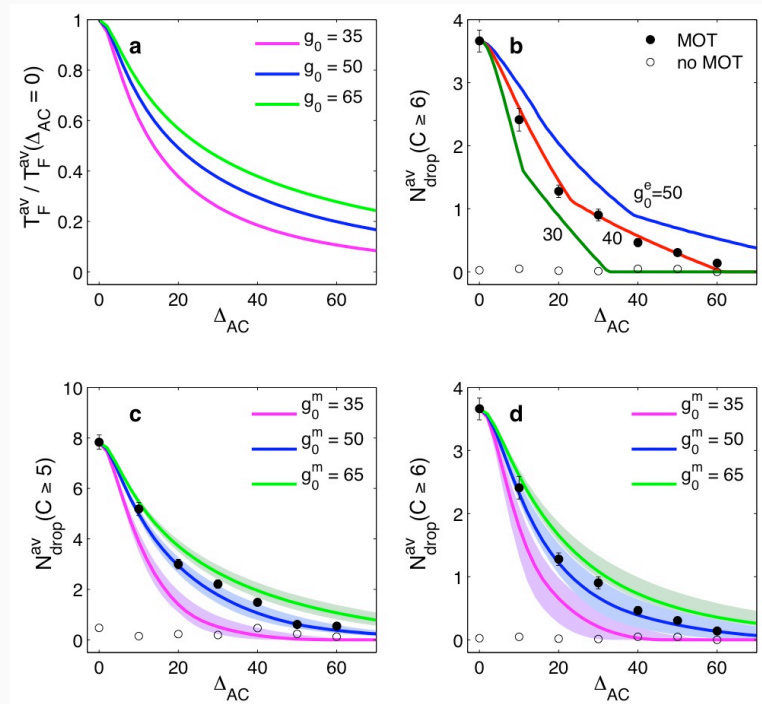
$$T_F = \frac{\langle a_{out}^{+} a_{out} \rangle}{\langle a_{in}^{+} a_{in} \rangle}$$



Can use dependence of T_F on Δ_{AC} to determine g_0

Observation of Strong Coupling





$$g_0^{\max} \approx 2\pi \cdot 50\ \text{MHz} > \begin{cases} \kappa_{\text{tot}} \approx 2\pi \cdot 18\ \text{MHz} \\ \gamma_{\perp} = 2\pi \cdot 2.6\ \text{MHz} \end{cases}$$

T. Aoki, B. Dayan, E. Wilcut, W.P. Bowen, SP, T.J. Kippenberg, K.J. Vahala & H.J. Kimble, Nature **443**, 671 (2006)

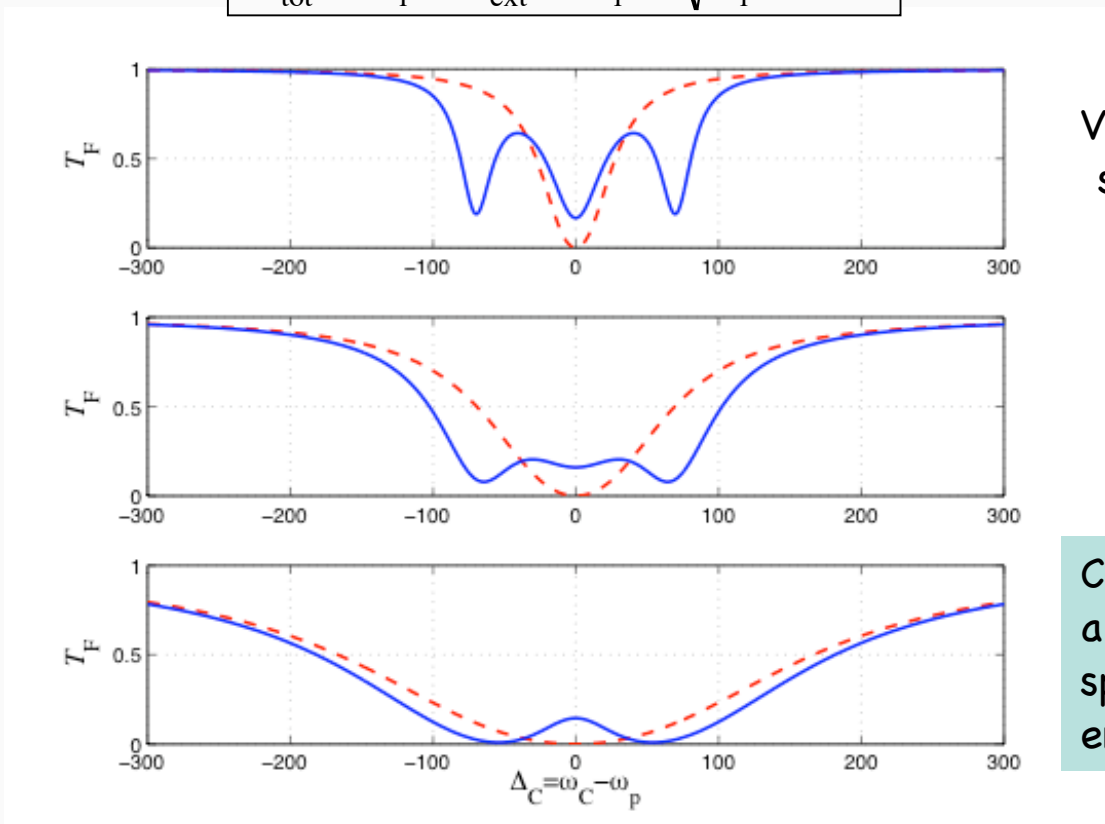
Effect of Increasing Cavity Loss

$$\kappa_{\text{tot}} = \kappa_{\text{i}} + \kappa_{\text{ext}}^{\text{cr}} = \kappa_{\text{i}} + \sqrt{\kappa_{\text{i}}^2 + h^2}$$

$\kappa_{\text{tot}} < g_0$

$\kappa_{\text{tot}} \approx g_0$

$\kappa_{\text{tot}} >> g_0$



Vacuum Rabi splitting

Cavity-enhanced atomic spontaneous emission

"Bad Cavity" Regime

$$\kappa_{\text{tot}} \approx 2\pi \cdot 165\ \text{MHz} >> \begin{cases} g_0^{\max} \approx 2\pi \cdot 70\ \text{MHz} \\ \gamma_\perp = 2\pi \cdot 2.6\ \text{MHz} \end{cases}$$

(Caltech '07)

- Theory: Adiabatic elimination of cavity modes
- Effective master equation for atomic density matrix:

$$\dot{\rho}_{\text{A}} = -\text{i}\left[H_{\text{A}}, \rho_{\text{A}}\right] + \frac{\Gamma}{2}\left(2\sigma^- \rho_{\text{A}} \sigma^+ - \sigma^+\sigma^- \rho_{\text{A}} - \rho_{\text{A}} \sigma^+\sigma^-\right)$$

$$H_{\text{A}} = \Delta'_{\text{A}} \sigma^+\sigma^- + \left(\Omega_0 \sigma^+ + \Omega_0^* \sigma^-\right)$$

- Cavity-enhanced atomic spontaneous emission rate

$$\Gamma \sim \gamma + \frac{2g_0^2}{\kappa_{\text{tot}}} = \gamma(1 + 2C), \quad C = \frac{g_0^2}{\kappa_{\text{tot}}\gamma}$$

single-atom "cooperativity" parameter

Output Fields: Bad Cavity Regime

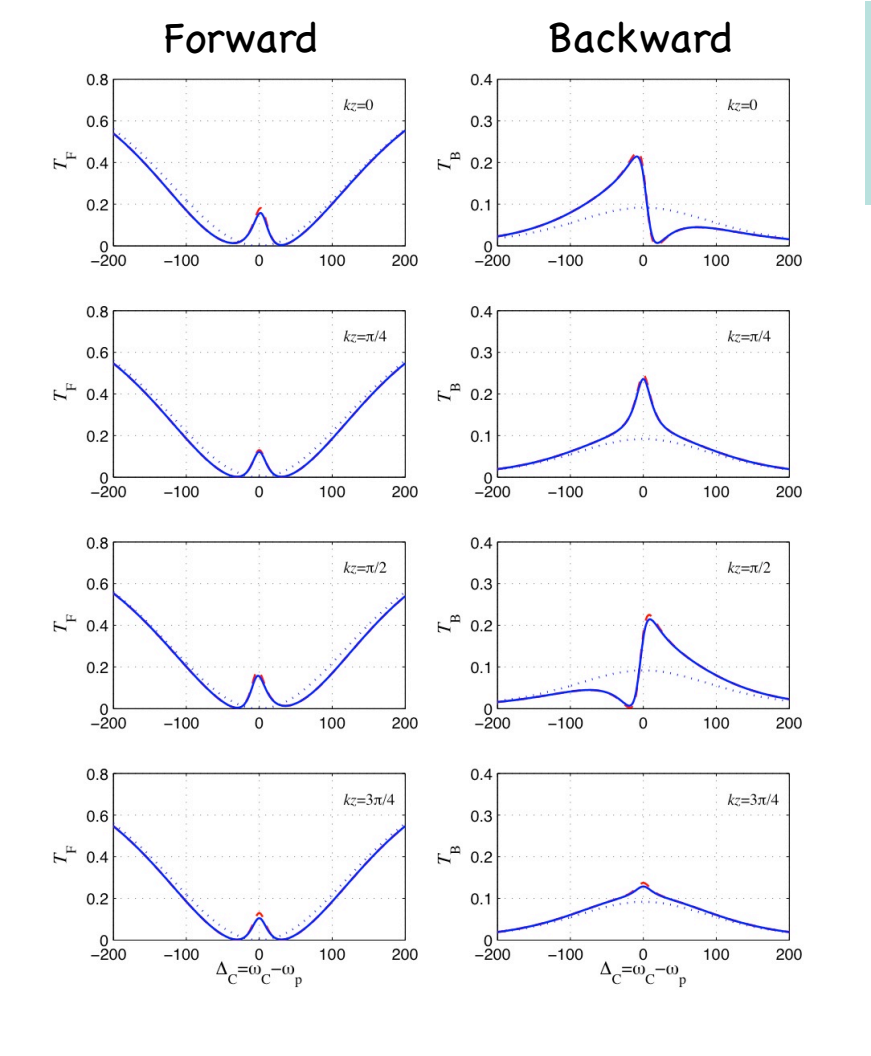
$$a_{\text{out}} = a_{\text{in}} + \sqrt{2\kappa_{\text{ex}}}\, a \quad \rightarrow \quad \alpha_0 + \alpha_- \sigma_-$$

$$b_{\text{out}} = b_{\text{in}} + \sqrt{2\kappa_{\text{ex}}}\, b \quad \rightarrow \quad \beta_0 + \beta_- \sigma_-$$

$\begin{Bmatrix} \alpha_0 \\ \beta_0 \end{Bmatrix}$ = coherent amplitudes <u>without</u> atom

Forward/Backward Spectra

Central atomic resonance, width ≈ Γ



$$\begin{cases} g_0^{\mathrm{tw}}/2\pi = 50\ \mathrm{MHz} \\ (\kappa_{\mathrm{i}},\kappa_{\mathrm{ext}})/2\pi = (75,90)\ \mathrm{MHz} \\ h/2\pi = 50\ \mathrm{MHz} \end{cases}$$

Different azimuthal positions x

A Photon "Turnstile"

Bad cavity regime

$$a_{\text{out}} \rightarrow \alpha_0 + \alpha_- \sigma^-$$
$$b_{\text{out}} \rightarrow \beta_0 + \beta_- \sigma^-$$

- Critical coupling: $\alpha_0(\Delta_C \approx 0) \approx 0, \ \beta_0(\Delta_C \approx 0) \neq 0$
- `1st' photon transmitted into a_{out} can only originate from atom
- Emission projects atom into ground state
- `2nd' photon cannot be transmitted until atomic state regresses to steady-state, time scale $1/\Gamma$

  $\Rightarrow$ excess photons `rerouted' to b_{out}

Microtoroid-atom system only transmits photons in the forward direction one-at-a-time

Note: Other photon turnstile devices

e.g.,

- J. Kim, O. Benson, H. Kan, & Y. Yamamoto, "A single-photon turnstile device," Nature **397**, 500 (1999) (semiconductor)
- K.M. Birnbaum, A. Boca, R. Miller, A.D. Boozer, T.E. Northup, & H.J. Kimble, "Photon blockade in an optical cavity with one trapped atom," Nature **436**, 87 (2005)

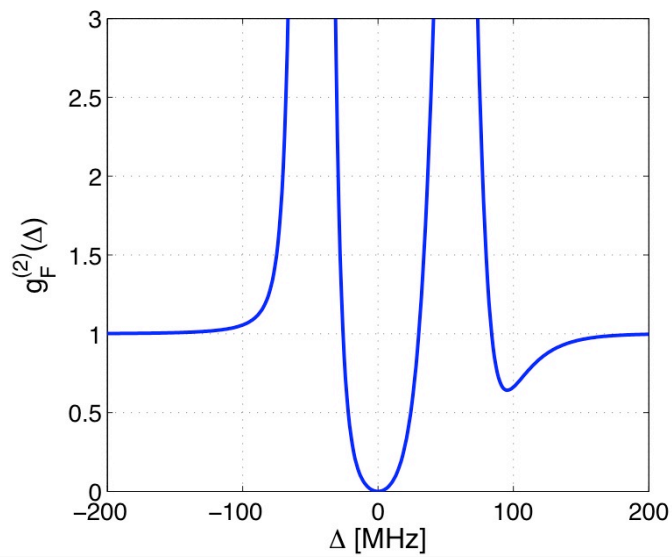
Blockade a structural effect due to anharmonicity of energy spectrum for multiple excitations

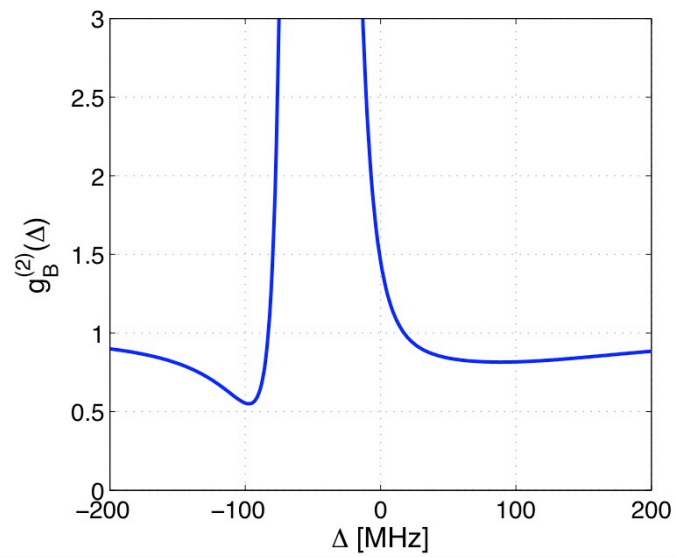
Microtoroid-atom system: blockade regulated dynamically by conditional state of one atom
→ efficient mechanism, insensitive to many experimental imperfections

Intensity Correlation Functions

$$g_{\mathrm{F}}^{(2)} = \frac{\left\langle \left(a_{\mathrm{out}}^{+}\right)^{2} a_{\mathrm{out}}^{2} \right\rangle}{\left\langle a_{\mathrm{out}}^{+} a_{\mathrm{out}} \right\rangle^{2}}, \quad g_{\mathrm{B}}^{(2)} = \frac{\left\langle \left(b_{\mathrm{out}}^{+}\right)^{2} b_{\mathrm{out}}^{2} \right\rangle}{\left\langle b_{\mathrm{out}}^{+} b_{\mathrm{out}} \right\rangle^{2}}$$

(probabilities of "simultaneous" photon detections)



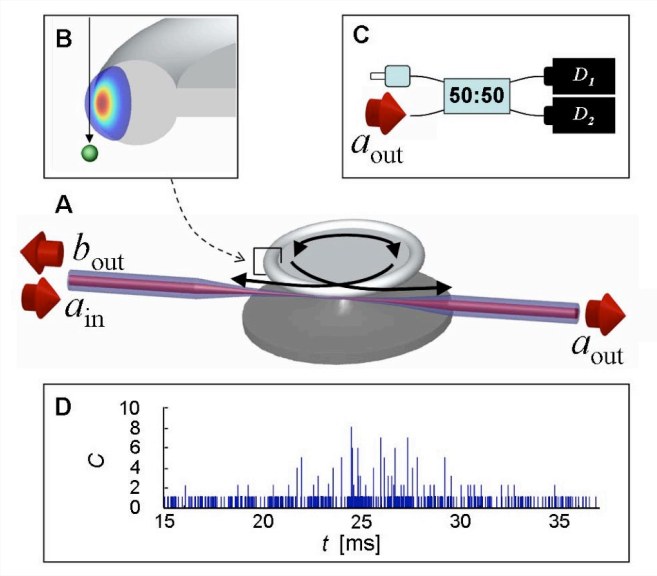


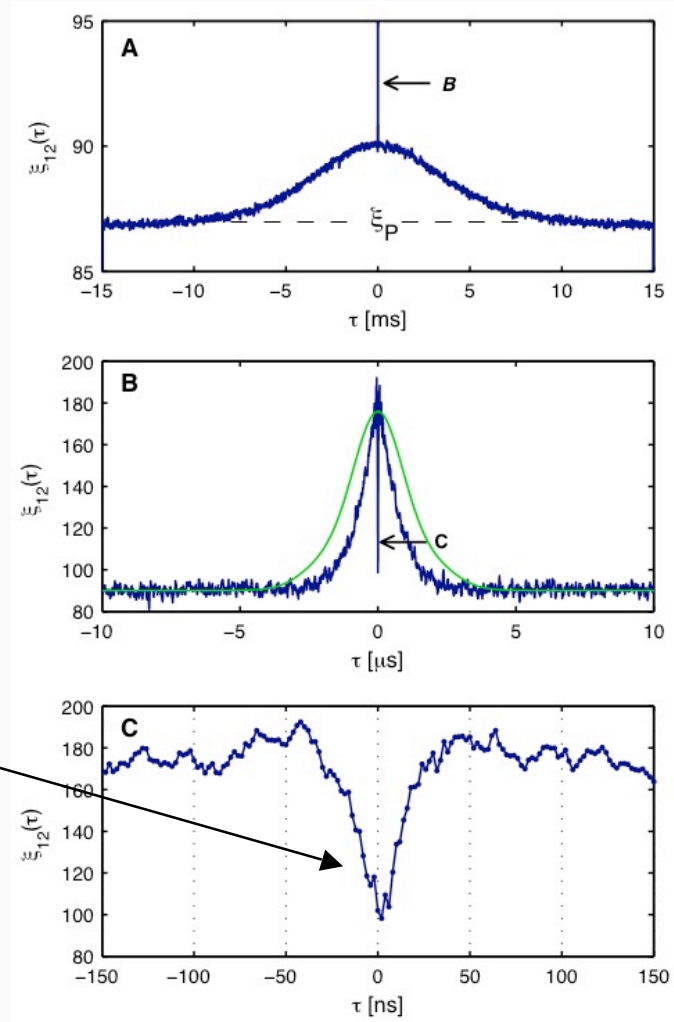
antibunching at $\Delta \approx 0$

bunching at $\Delta \approx 0$

$$\left\langle \left(a_{\mathrm{out}}^{+}\right)^{2} a_{\mathrm{out}}^{2} \right\rangle \sim \left\langle \sigma^{+2} \sigma^{-2} \right\rangle = 0$$

Experiment (Caltech '07)



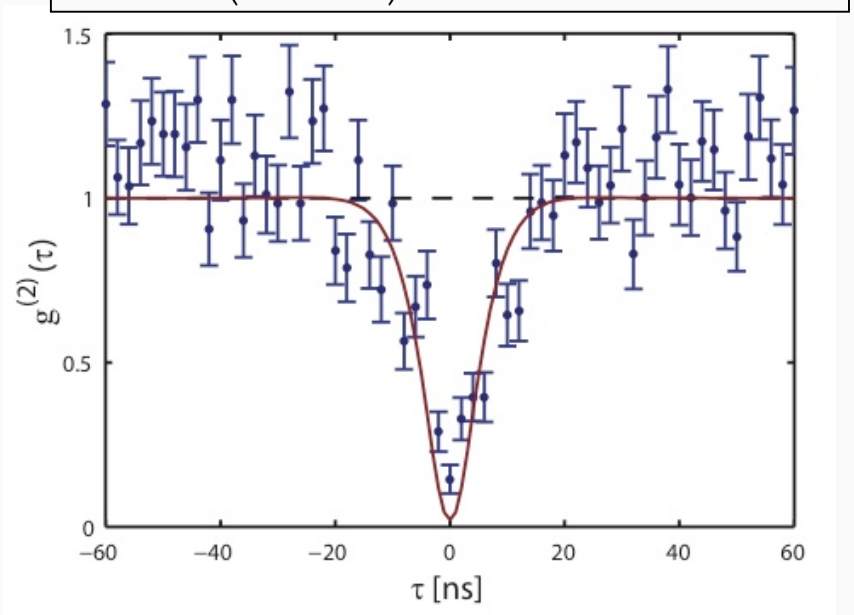


- Cross correlation $\xi_{12}(\tau)$
- $\xi_{12}(\tau) > \xi_{12}(0)$ a prima facie observation of <u>nonclassical light</u>

Observation of Antibunching/Turnstile Effect

- Analysis of single and joint detections at $D_{1,2}$ <u>conditioned on single atom transit</u>

$$g_{\mathrm{F}}^{(2)}(\tau) \approx \left(1 - \mathrm{e}^{-\Gamma t/2}\right)^2, \quad 1/\Gamma \approx 2.8\ \mathrm{ns}\ \left(C \sim 5\right)$$



"Blockade" effect <u>robust</u>, e.g., requires only

$$\frac{2g(\vec{r})^2}{\kappa_{\mathrm{tot}}\gamma} > 1$$

Dayan, Parkins, Aoki, Kimble, Ostby & Vahala, "A Photon Turnstile Dynamically Regulated by One Atom," Science **319**, 1062 (2008)

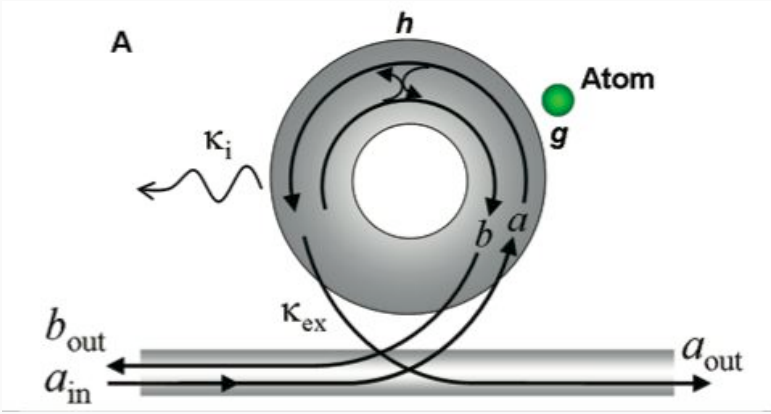
In the Future …

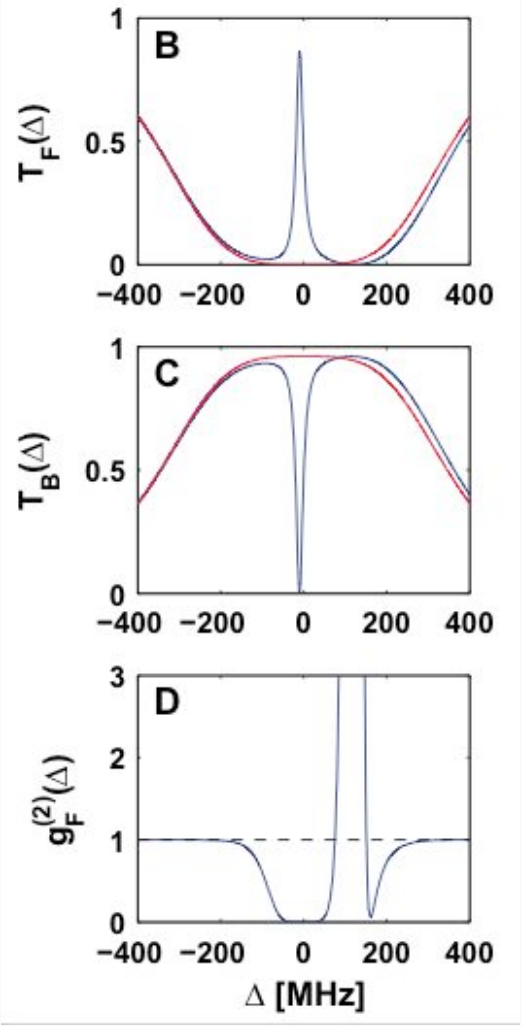
- Minimise intrinsic losses

  $\kappa_i << \kappa_{ex}$

- Large mode-mode coupling h

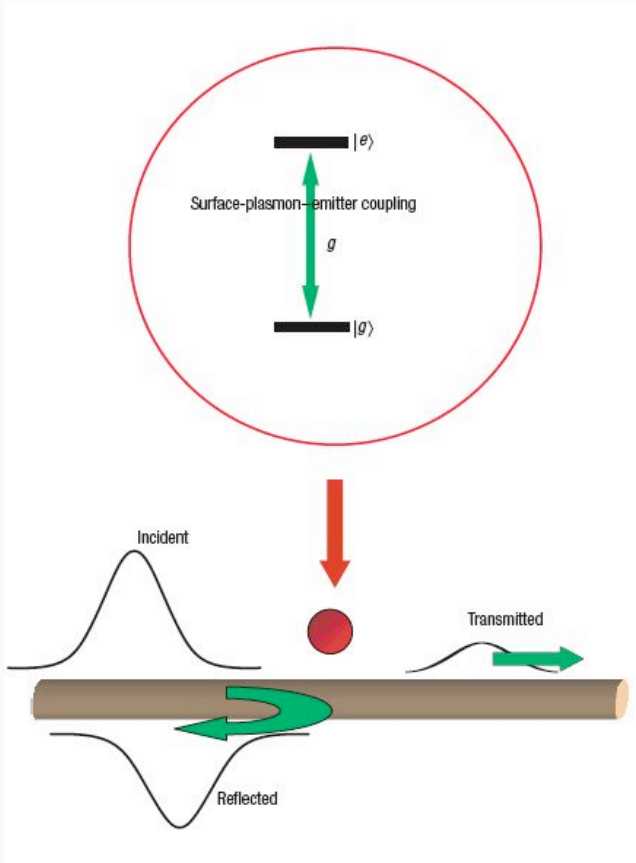
$\Rightarrow$ Near-ideal input/output

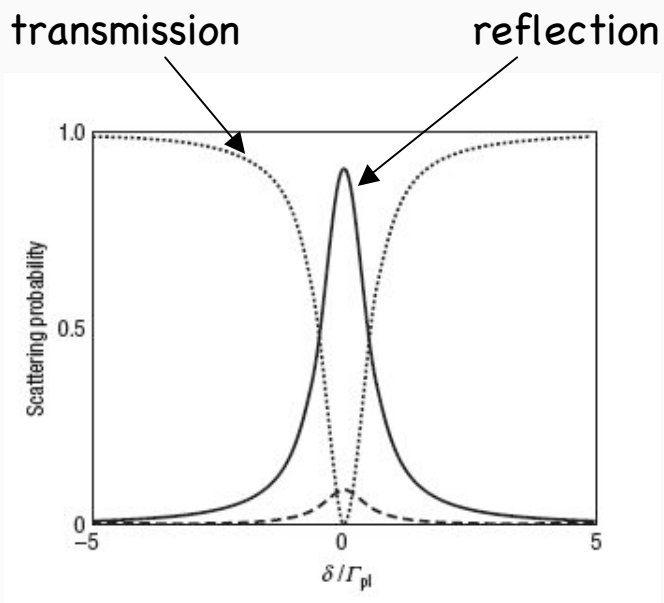




Single Photon "Transistor"

D.E.Chang, A.S. Sorensen, E.A. Demler, & M.D. Lukin, "A single-photon transistor using nanoscale surface plasmons," Nature Physics **3**, 807 (2007)





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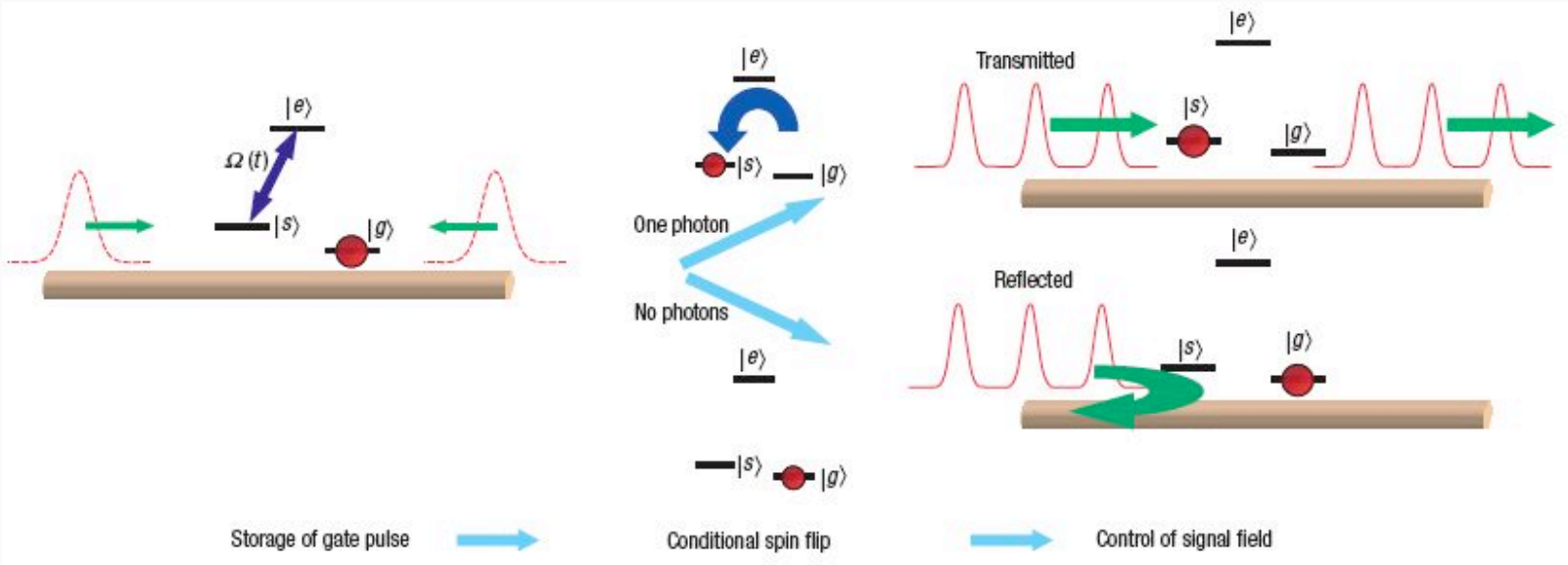


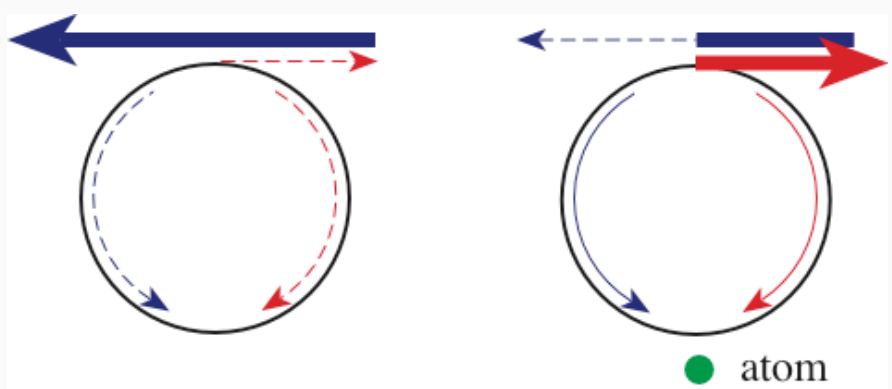
Microtoroid + Atom: Over-Coupled Regime

Bad cavity regime

$$a_{\text{out}} \rightarrow \alpha_0 + \alpha_- \sigma^-$$
$$b_{\text{out}} \rightarrow \beta_0 + \beta_- \sigma^-$$

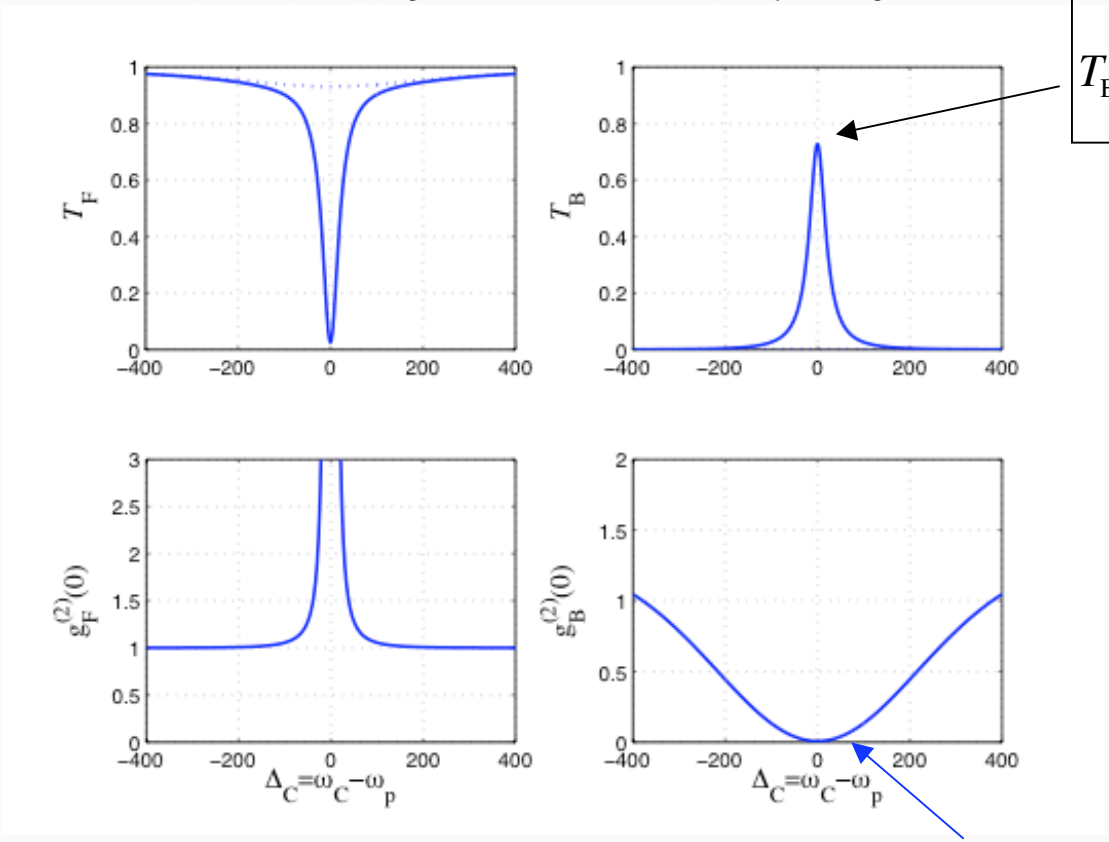
- Strong over-coupling: $\kappa_{\text{ex}} >> h,\ \kappa_{\text{i}} \quad (\kappa_{\text{tot}} \approx \kappa_{\text{ex}})$
- No atom ($\alpha_- = \beta_- = 0$): strong transmission, small reflection ($\beta_0 \approx 0$)
- With atom: destructive interference between α_0 and $\alpha_- \sigma^-$

  $\Rightarrow$ strong reflection, small transmission



Spectra and Correlations: Over-Coupled Regime

Transmission Reflection



$$T_B(\Delta_C = 0) \approx \left(\frac{\kappa_{ex}}{\kappa_{tot}}\right)^2 \left(\frac{2C}{1+2C}\right)^2$$

$$\kappa_{tot} \approx \kappa_{ex}$$

$$C \sim \frac{g_0^2}{\kappa_{tot}\gamma} >> 1$$

Single atom cooperativity

antibunching in reflected field

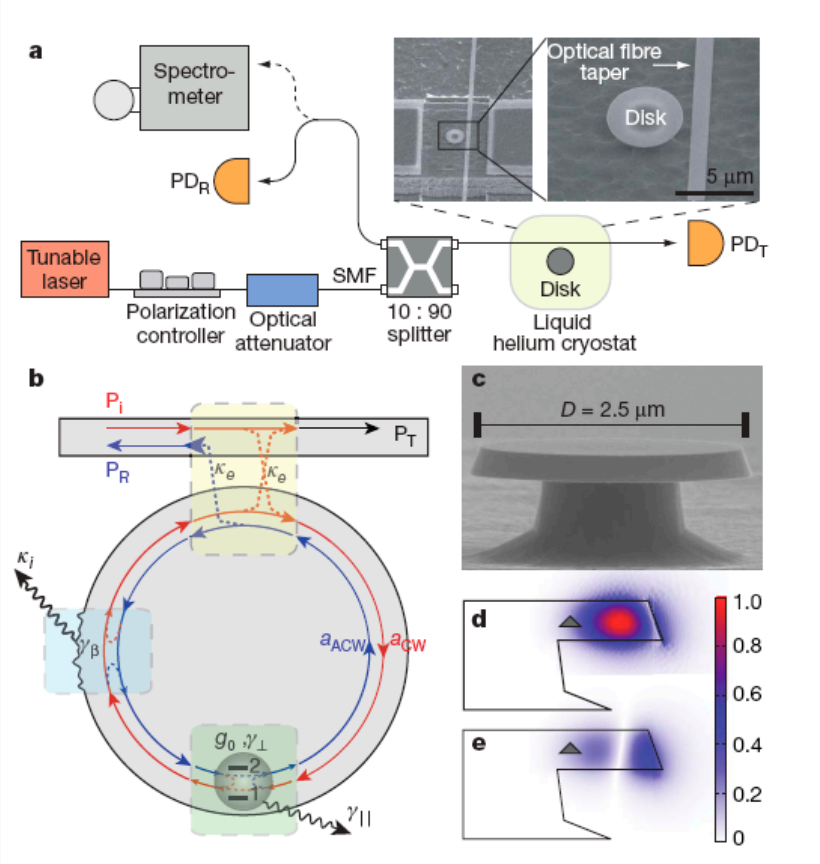
… and beyond

- Controlled interactions of photons
- Trapping of atoms close to toroid
- Multi-toroid/atom systems

  → Scalable quantum processing on atom chips

Microdisk-Quantum Dot Systems

K. Srinivasan & O. Painter, "Linear and nonlinear optical spectroscopy of a strongly coupled microdisk-quantum dot system," Nature **450**, 862 (2007)



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