Top

Left side

TEST

Right side

bottom

An introduction to light-matter interaction, from cavity QED to waveguide QED 3

Les Houches,
April 2019

Luis A. Orozco
www.jqi.umd.edu

University of Maryland 1856

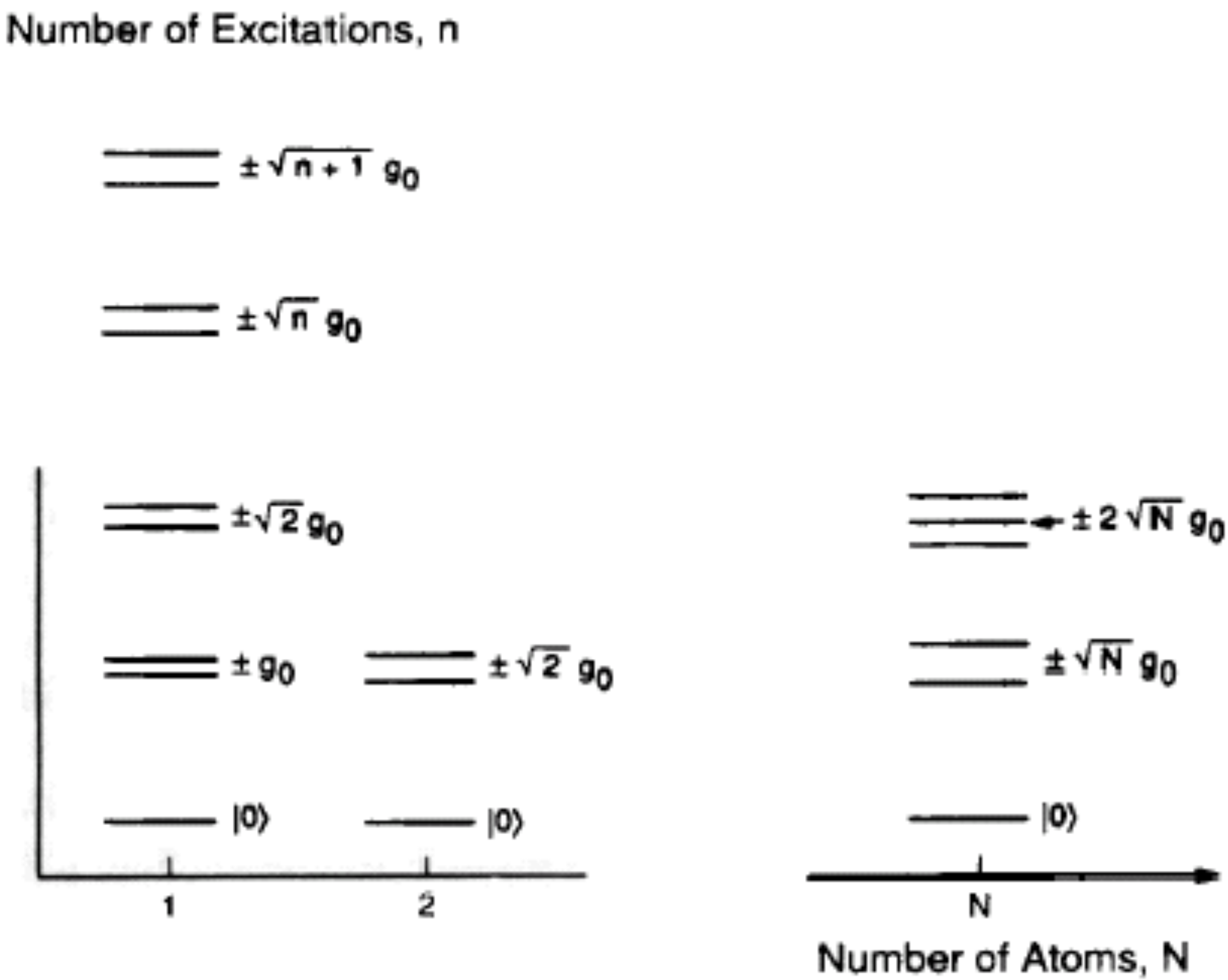
jqi | PHYSICS FRONTIER CENTER
JOINT QUANTUM INSTITUTE

NIST

The presentation will be available at:

http://www.physics.umd.edu/rgroups/amo/orozco/results/2019/Results19.htm

Some Quantum Optics Experiments in CQED



Number of Excitations, n
$\pm\sqrt{n+1}\, g_0$
$\pm\sqrt{n}\, g_0$
$\pm\sqrt{2}\, g_0$
$\pm g_0$
$\pm\sqrt{2}\, g_0$
$|0\rangle$
$|0\rangle$
1
2
$\pm 2\sqrt{N}\, g_0$
$\pm\sqrt{N}\, g_0$
$|0\rangle$
N
Number of Atoms, N

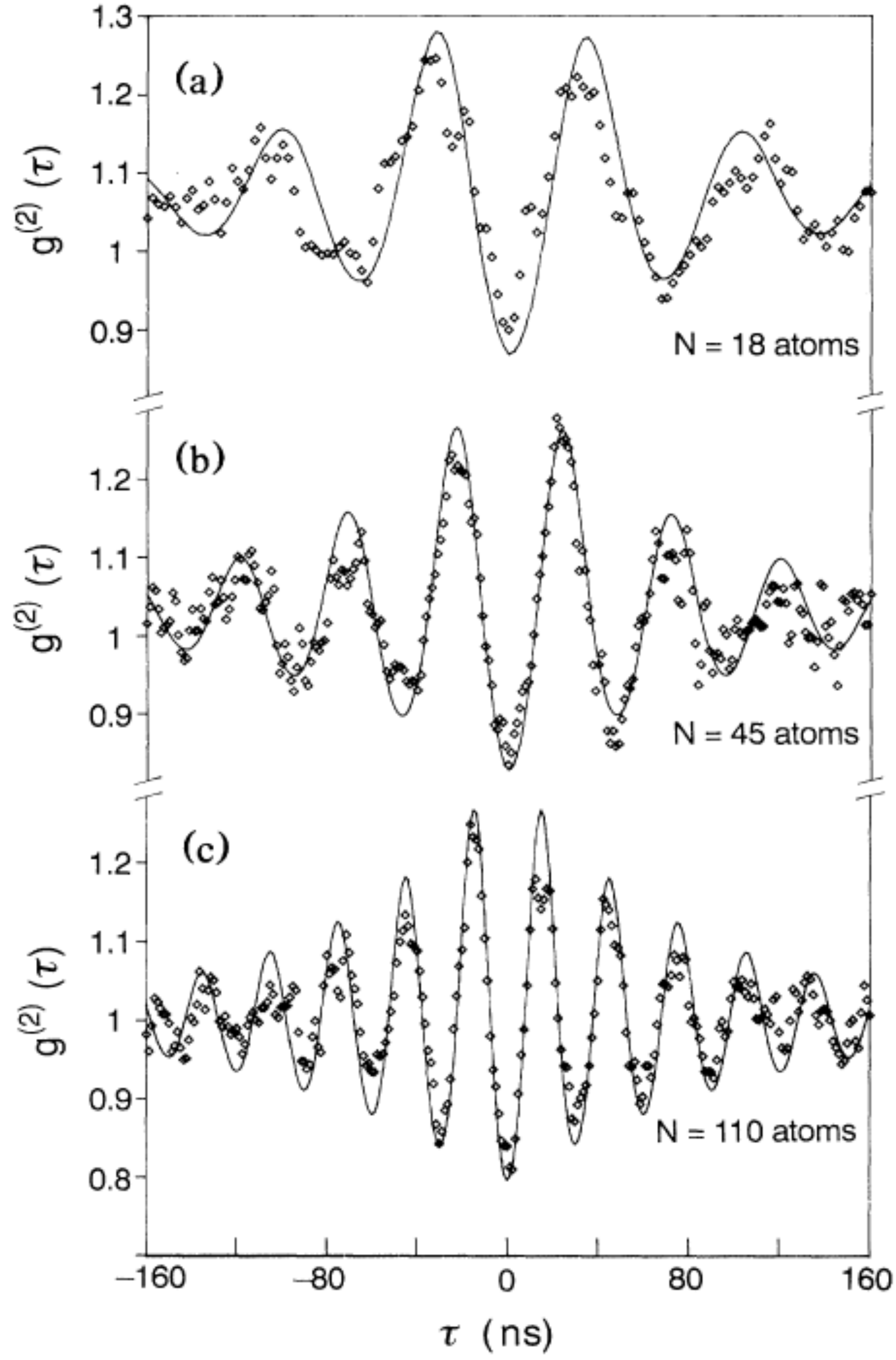
Optical Bistability and Photon Statistics in Cavity Quantum Electrodynamics

G. Rempe, R. J. Thompson, R. J. Brecha,[a] W. D. Lee,[b] and H. J. Kimble

Norman Bridge Laboratory of Physics 12-33, California Institute of Technology, Pasadena, California 91125

(Received 28 June 1991)

The quantum statistical behavior of a small collection of N two-state atoms strongly coupled to the field of a high-finesse optical cavity is investigated. Input-output characteristics are recorded over the range $3 \lesssim N \lesssim 65$, with bistability observed for $N \gtrsim 15$ intracavity atoms and for a saturation photon number $n_0 \simeq 0.8$. For weak excitation the transmitted field exhibits photon antibunching as a nonclassical manifestation of state reduction and quantum interference with the magnitude of the nonclassical effects largely independent of N.



(a)
N = 18 atoms
(b)
N = 45 atoms
(c)
N = 110 atoms
g(2) (τ)
τ (ns)
1.3
1.2
1.1
1
0.9
0.8
–160
–80
0
80
160

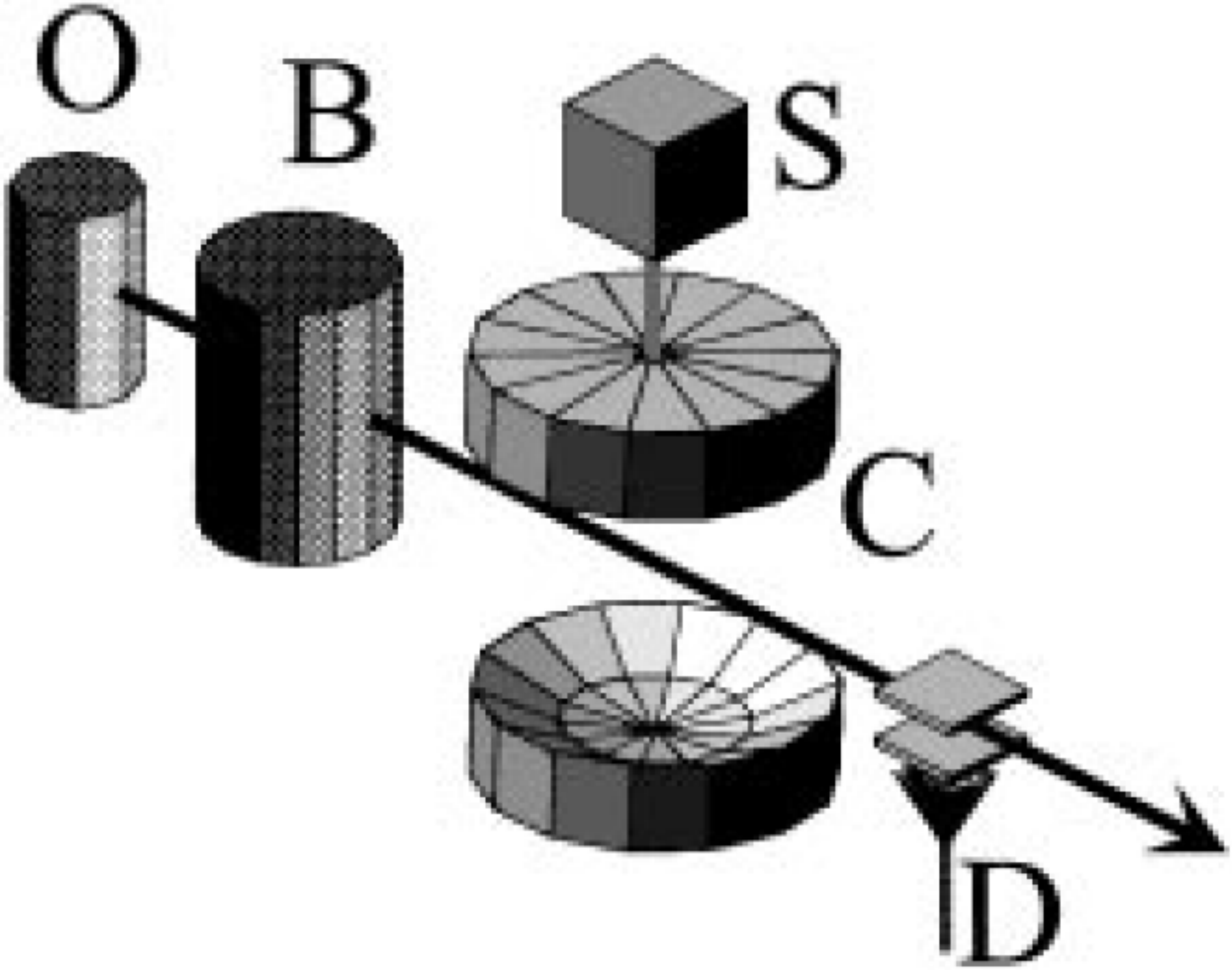
Quantum Rabi Oscillation: A Direct Test of Field Quantization in a Cavity

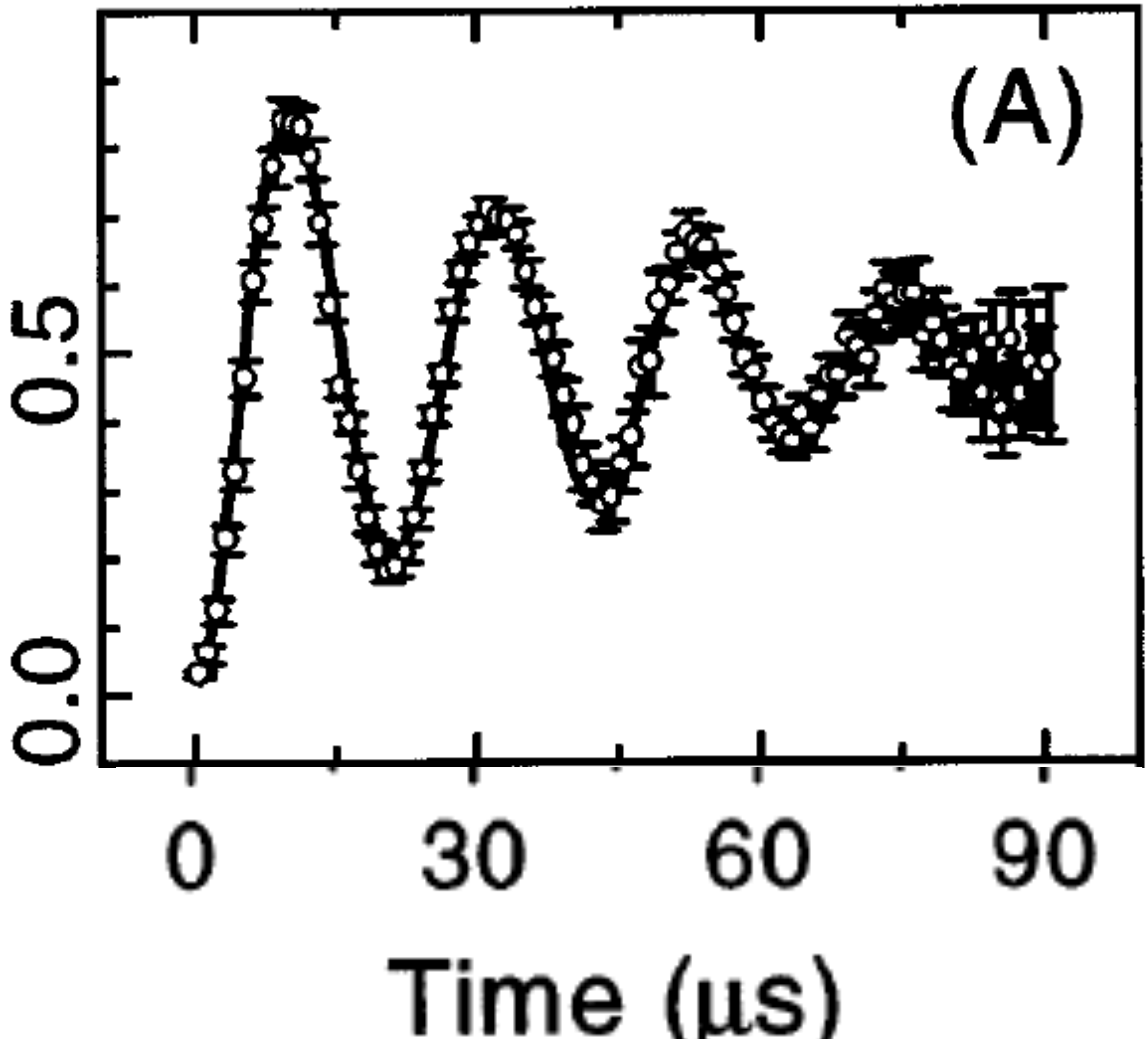
M. Brune, F. Schmidt-Kaler, A. Maali, J. Dreyer, E. Hagley, J.M. Raimond, and S. Haroche

Laboratoire Kastler Brossel, Département de Physique de l'Ecole Normale Supérieure, 24 rue Lhomond, F-75231 Paris Cedex 05, France*

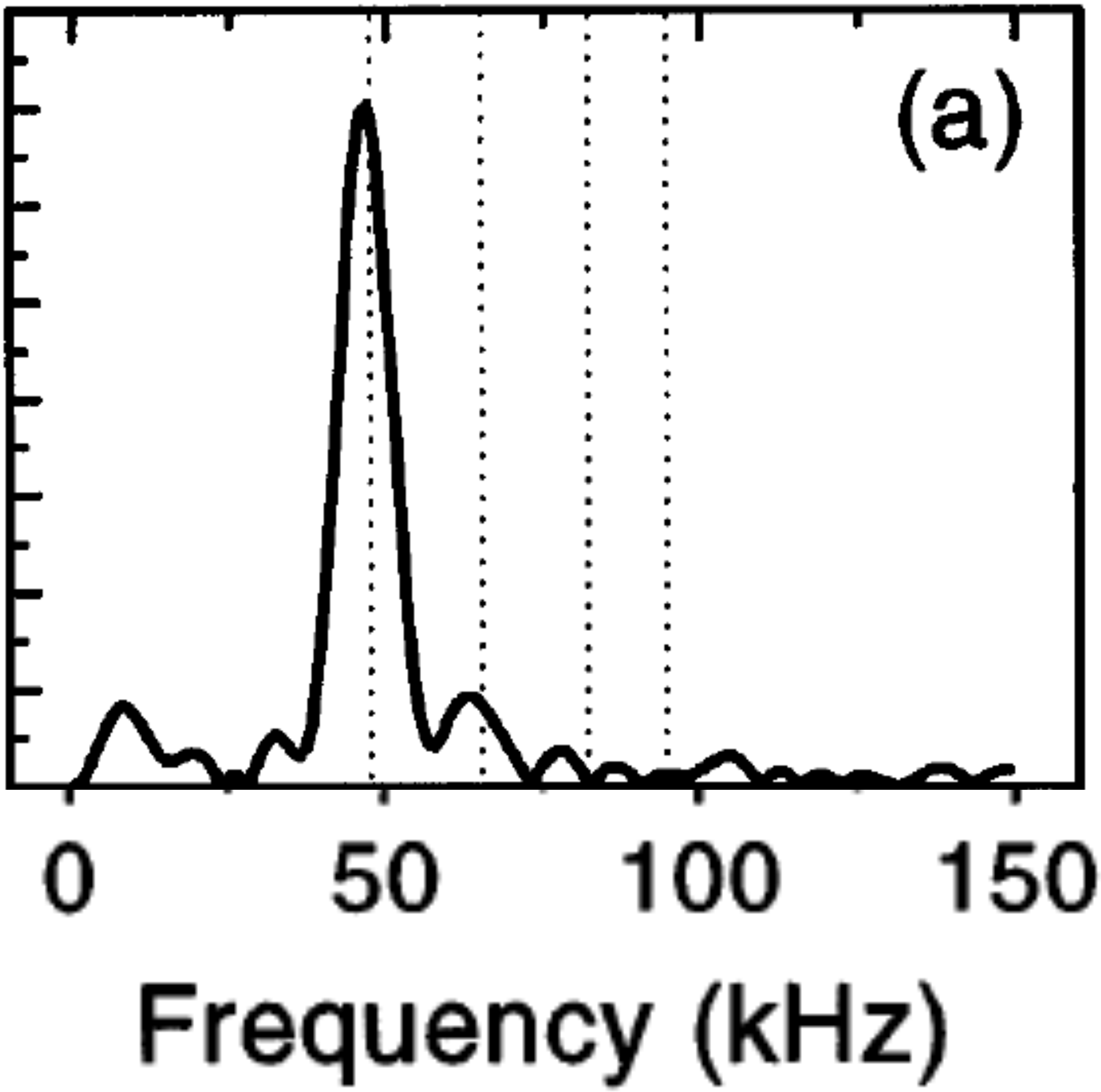
(Received 9 November 1995)

We have observed the Rabi oscillation of circular Rydberg atoms in the vacuum and in small coherent fields stored in a high Q cavity. The signal exhibits discrete Fourier components at frequencies proportional to the square root of successive integers. This provides direct evidence of field quantization in the cavity. The weights of the Fourier components yield the photon number distribution in the field. This investigation of the excited levels of the atom-cavity system reveals nonlinear quantum features at extremely low field strengths.

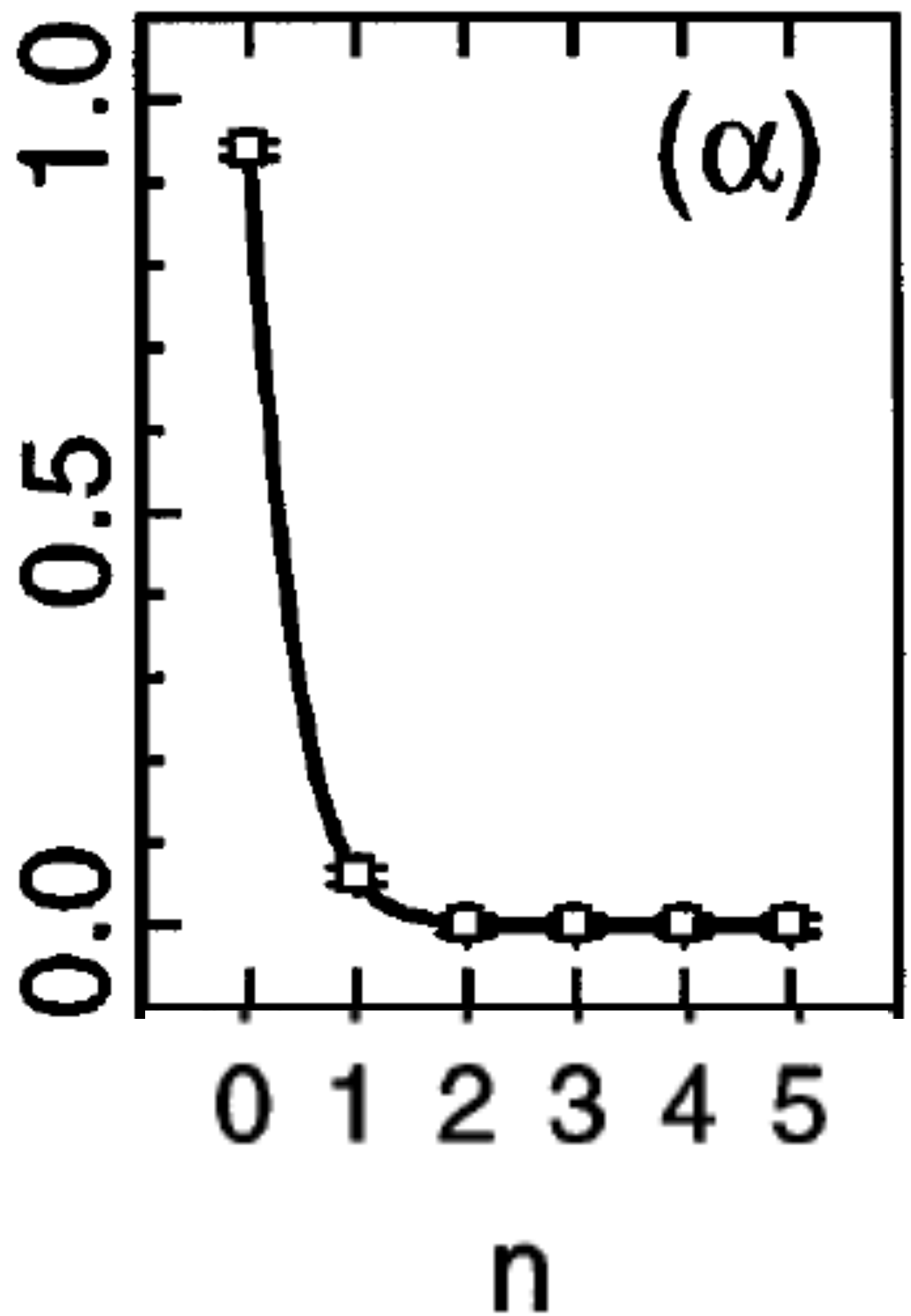

O
B
S
C
D



(A)
0.0
0.5
0
30
60
90
Time (µs)



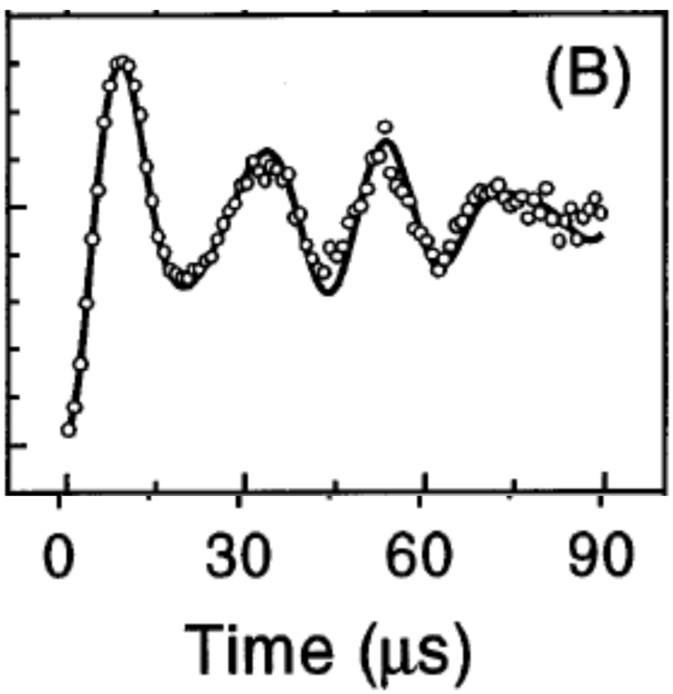
(a)
0
50
100
150
Frequency (kHz)



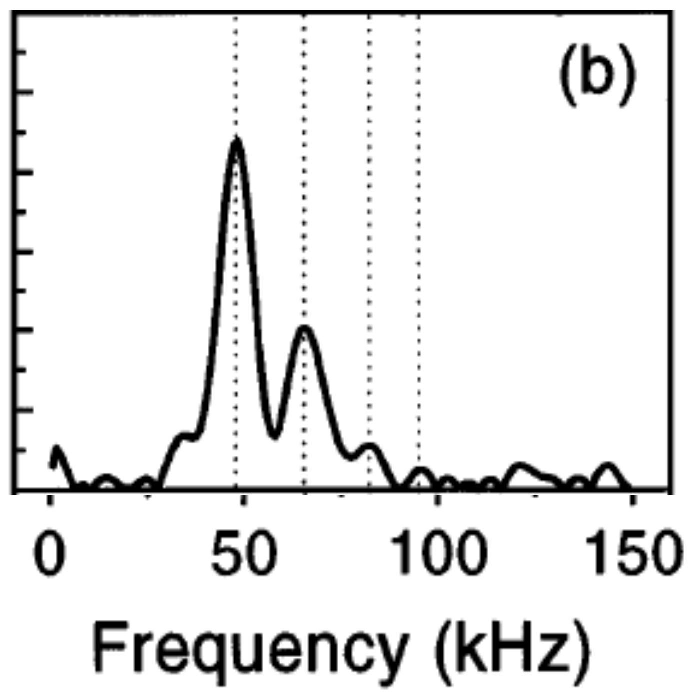
(α)
1.0
0.5
0.0
0 1 2 3 4 5
n

For two photons

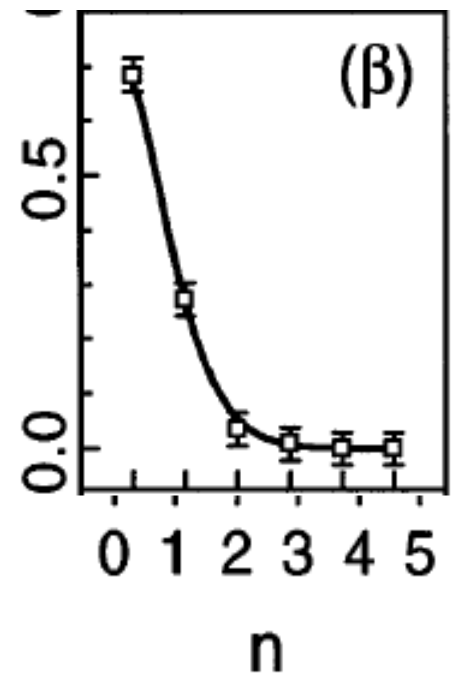
Oscillations



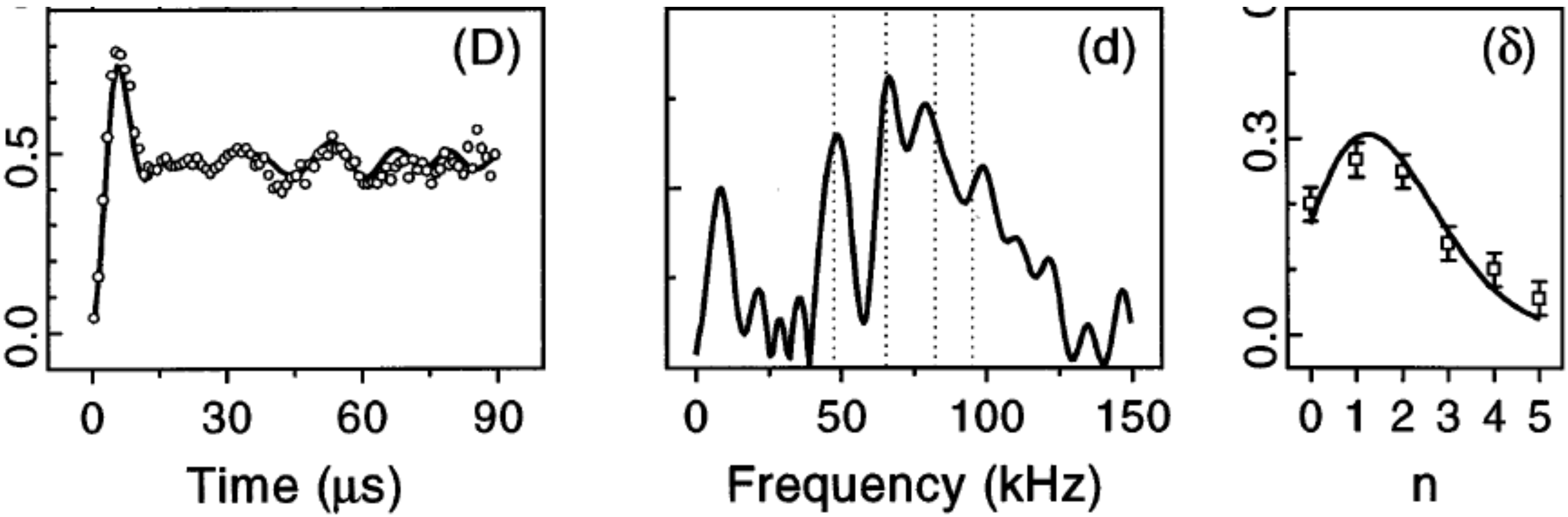
Fourier Transform



P(n)



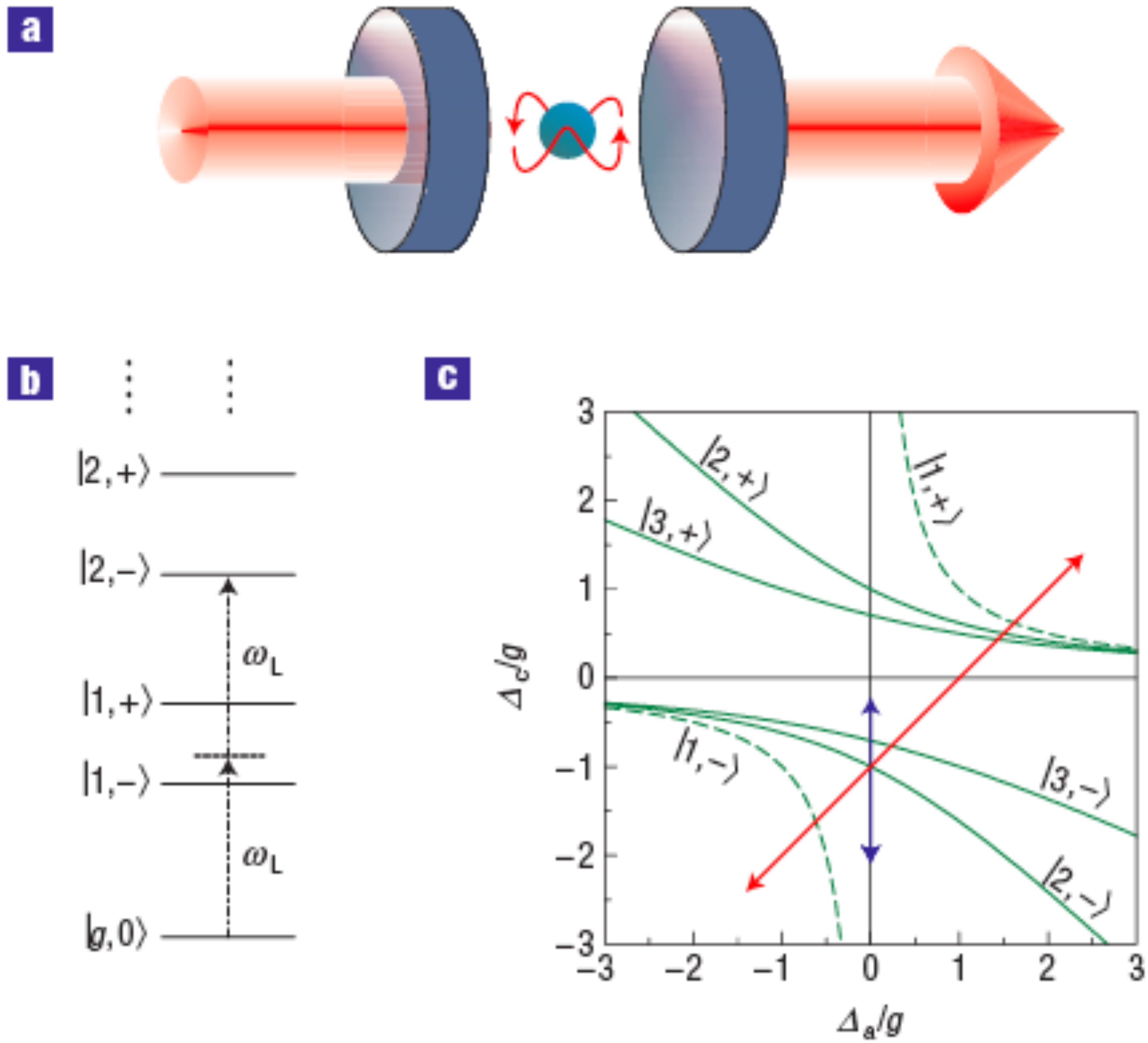
For four photons



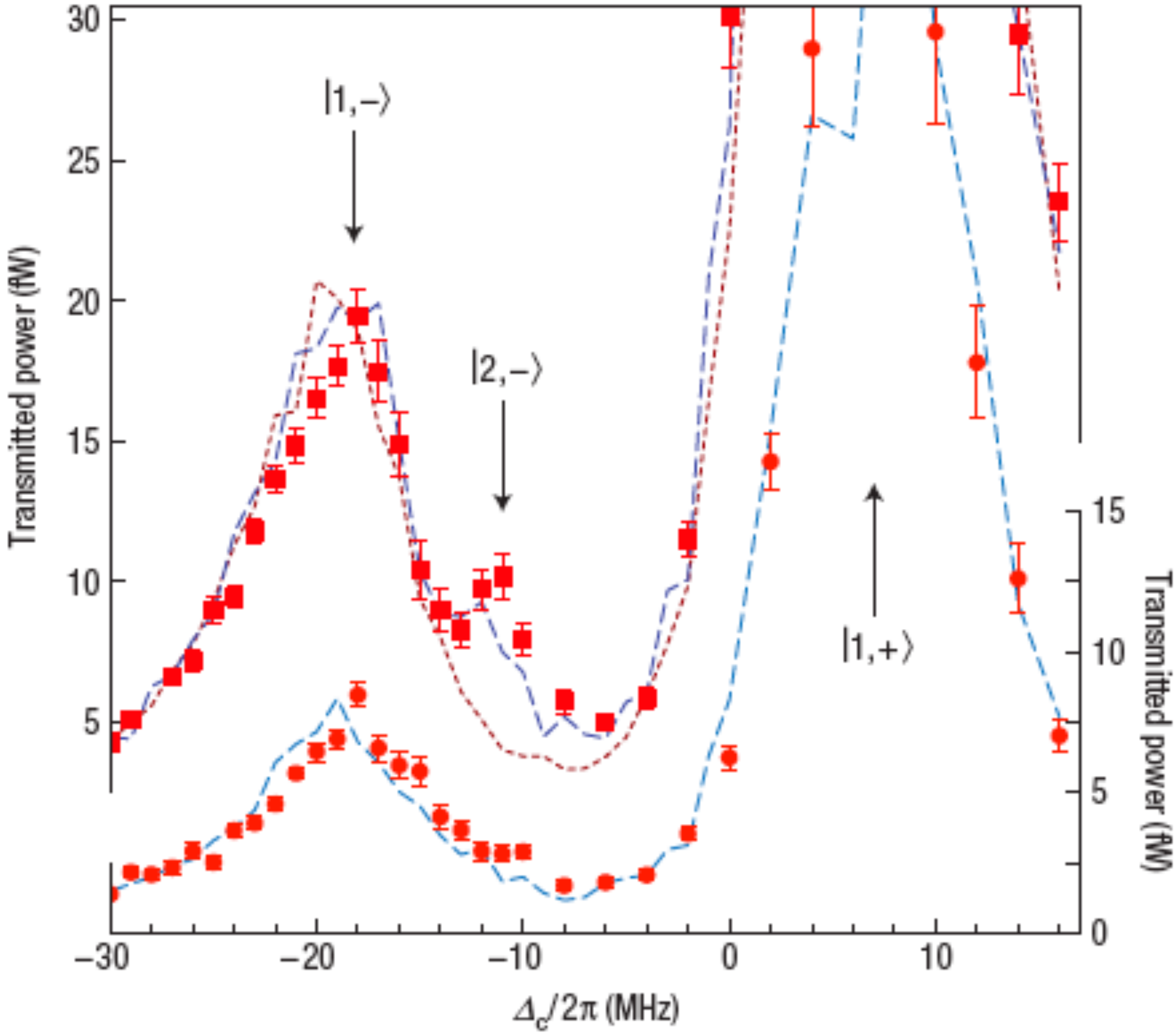
Nonlinear spectroscopy of photons bound to one atom

I. SCHUSTER, A. KUBANEK, A. FUHRMANEK, T. PUPPE, P. W. H. PINKSE, K. MURR AND G. REMPE*
Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Straße 1, D-85748 Garching, Germany
*e-mail: gerhard.rempe@mpq.mpg.de

Published online: 13 April 2008; doi:10.1038/nphys940



a
b
c
|2,+⟩
|2,−⟩
|1,+⟩
|1,−⟩
|g,0⟩
ω_L
ω_L
|2,+⟩
|1,+⟩
|3,+⟩
|1,−⟩
|3,−⟩
|2,−⟩
Δ_c/g
Δ_a/g
3
2
1
0
−1
−2
−3
−3
−2
−1
0
1
2
3



|1,−⟩
|2,−⟩
|1,+⟩
Transmitted power (fW)
Transmitted power (fW)
Δc/2π (MHz)
30
25
20
15
10
5
15
10
5
0
−30
−20
−10
0
10

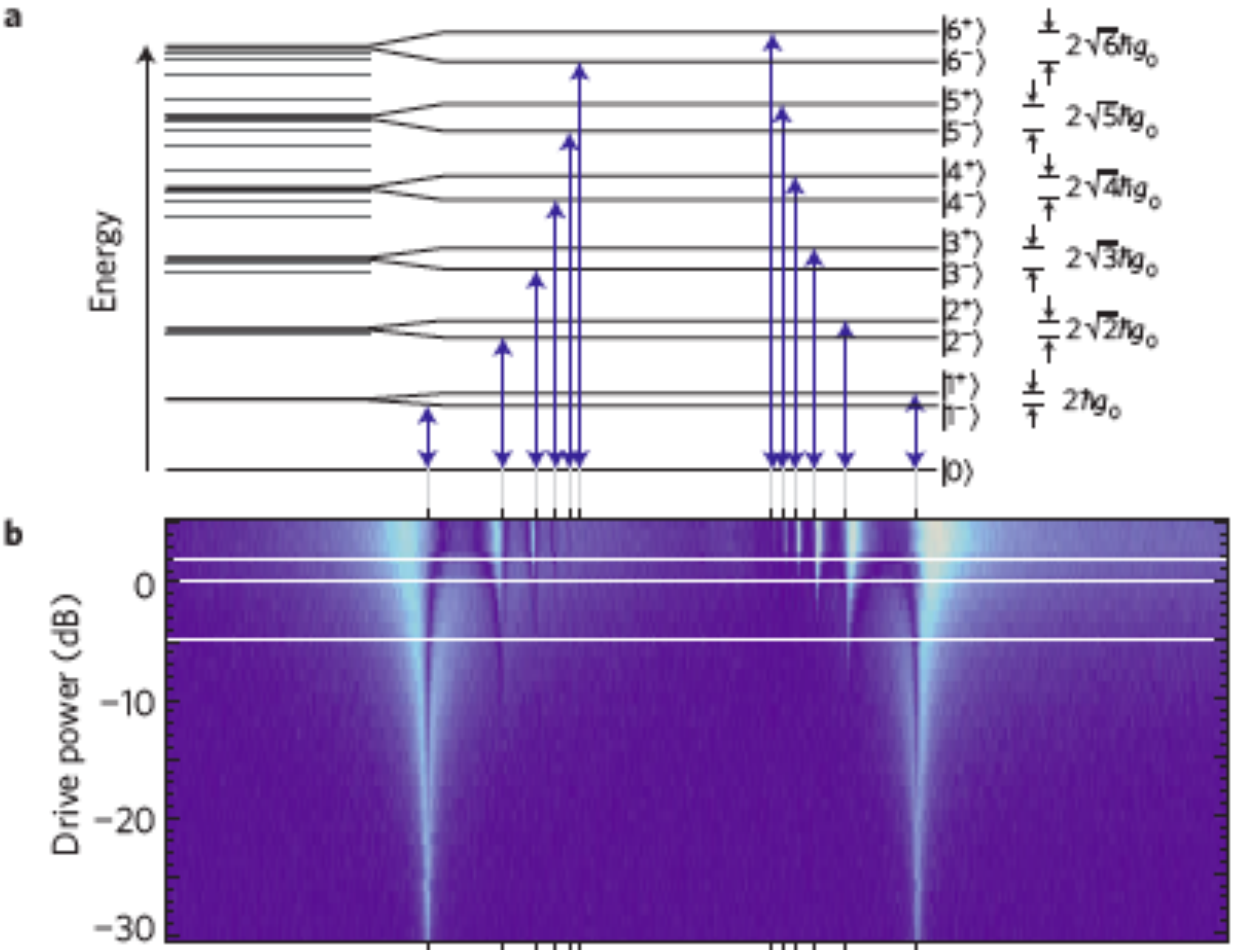
nature physics

LETTERS

PUBLISHED ONLINE: 14 DECEMBER 2008; CORRECTED ONLINE: 15 DECEMBER 2008 | DOI: 10.1038/NPHYS1154

Nonlinear response of the vacuum Rabi resonance

Lev S. Bishop[1], J. M. Chow[1], Jens Koch[1], A. A. Houck[1], M. H. Devoret[1], E. Thuneberg[2], S. M. Girvin[1] and R. J. Schoelkopf[1]*


a
b
Energy
|6⁺⟩
|6⁻⟩
|5⁺⟩
|5⁻⟩
|4⁺⟩
|4⁻⟩
|3⁺⟩
|3⁻⟩
|2⁺⟩
|2⁻⟩
|1⁺⟩
|1⁻⟩
|0⟩
$2\sqrt{6}\hbar g_0$
$2\sqrt{5}\hbar g_0$
$2\sqrt{4}\hbar g_0$
$2\sqrt{3}\hbar g_0$
$2\sqrt{2}\hbar g_0$
$2\hbar g_0$
Drive power (dB)
0
−10
−20
−30

Photon Antibunching and Squeezing for a Single Atom in a Resonant Cavity

H. J. Carmichael

Department of Physics, University of Arkansas, Fayetteville, Arkansas 72701

(Received 12 August 1985)

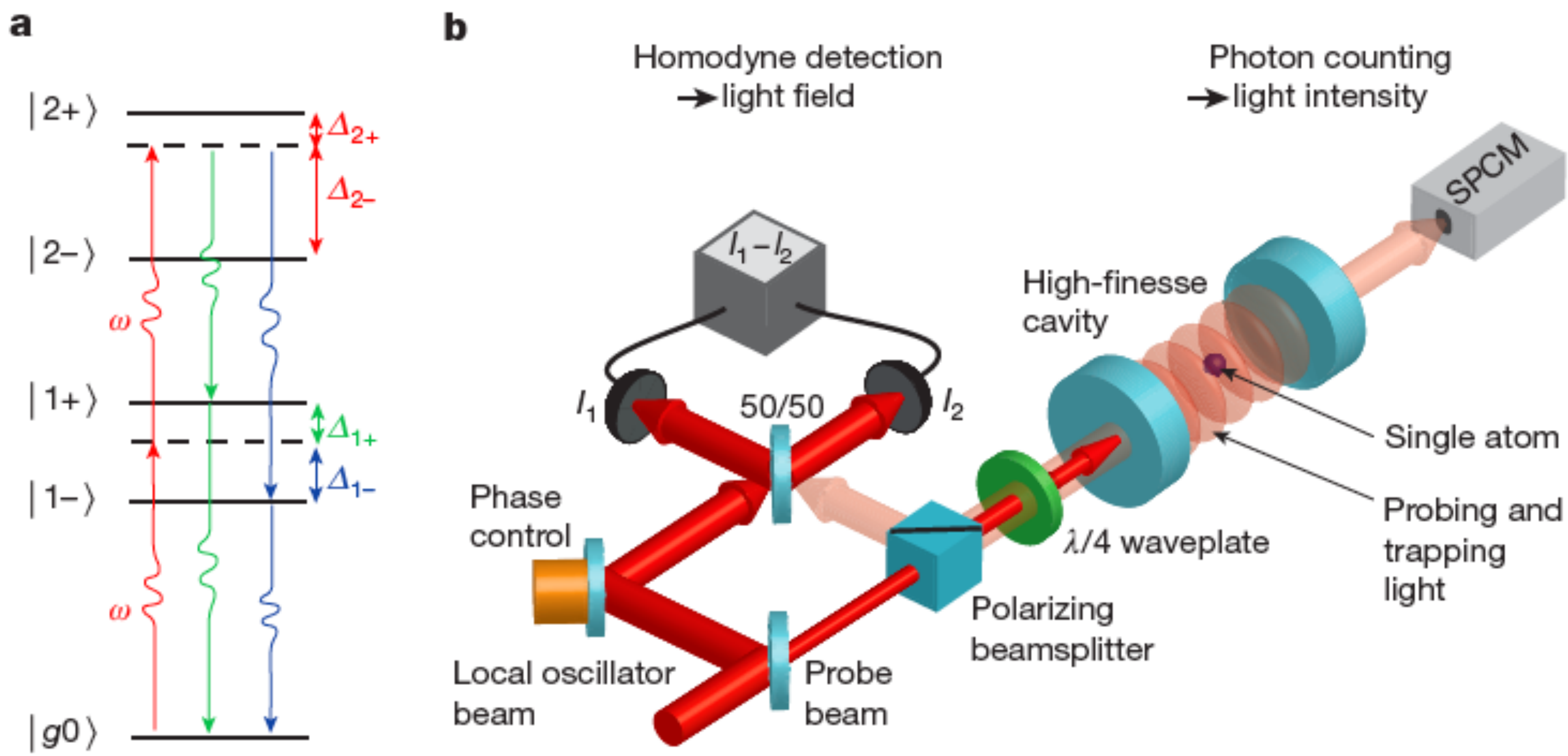
The transmitted light from an optical cavity containing a single two-level atom may show photon antibunching and squeezing. The two effects are closely related and simply understood in terms of the theory of single-atom resonance fluorescence. It follows that corresponding nonclassical effects in optical bistability do not originate in atomic collectivity.

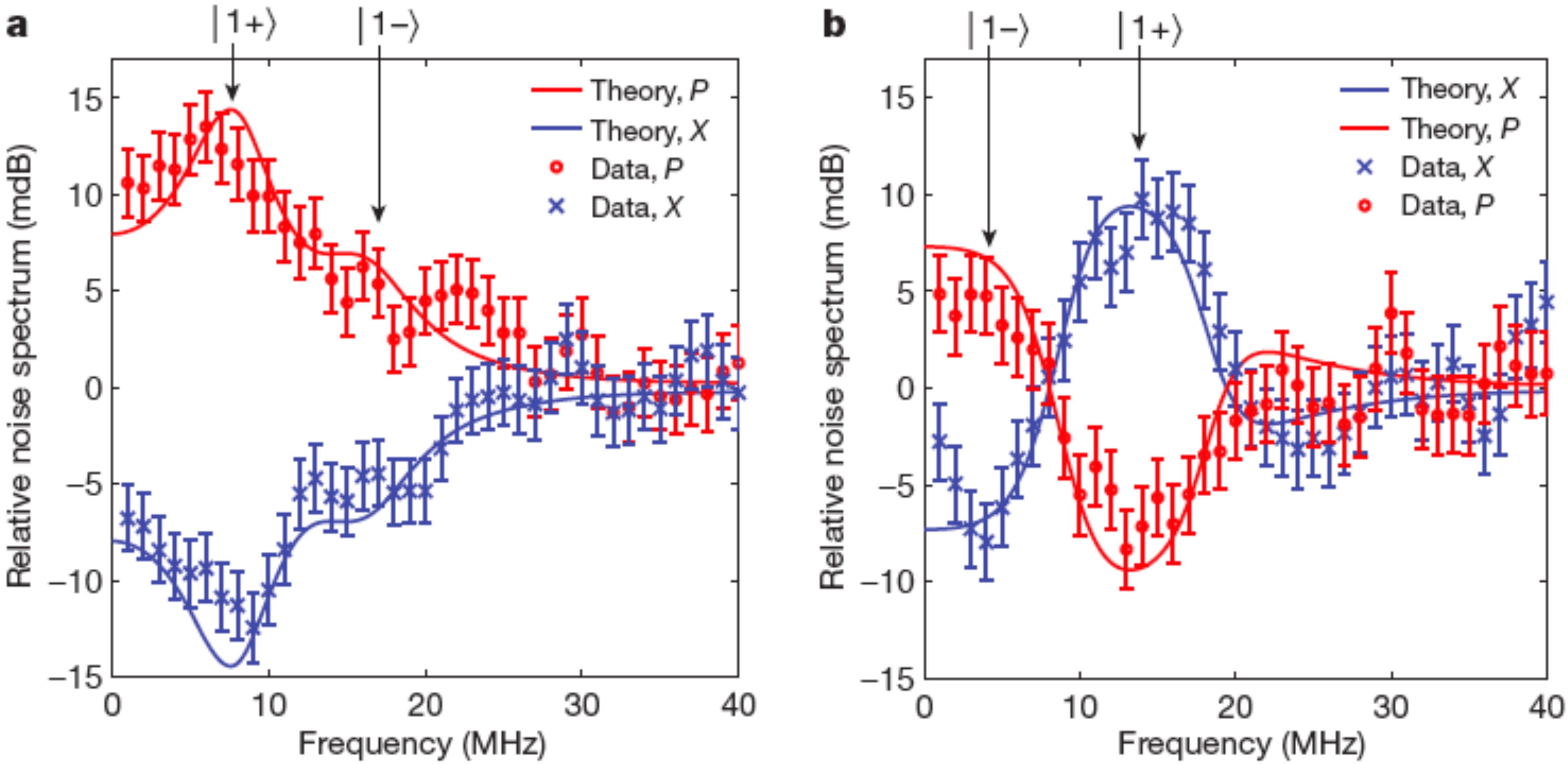
LETTER

doi:10.1038/nature10170

Observation of squeezed light from one atom excited with two photons

A. Ourjoumtsev[1,2], A. Kubanek[1], M. Koch[1], C. Sames[1], P. W. H. Pinkse[1]†, G. Rempe[1] & K. Murr[1]

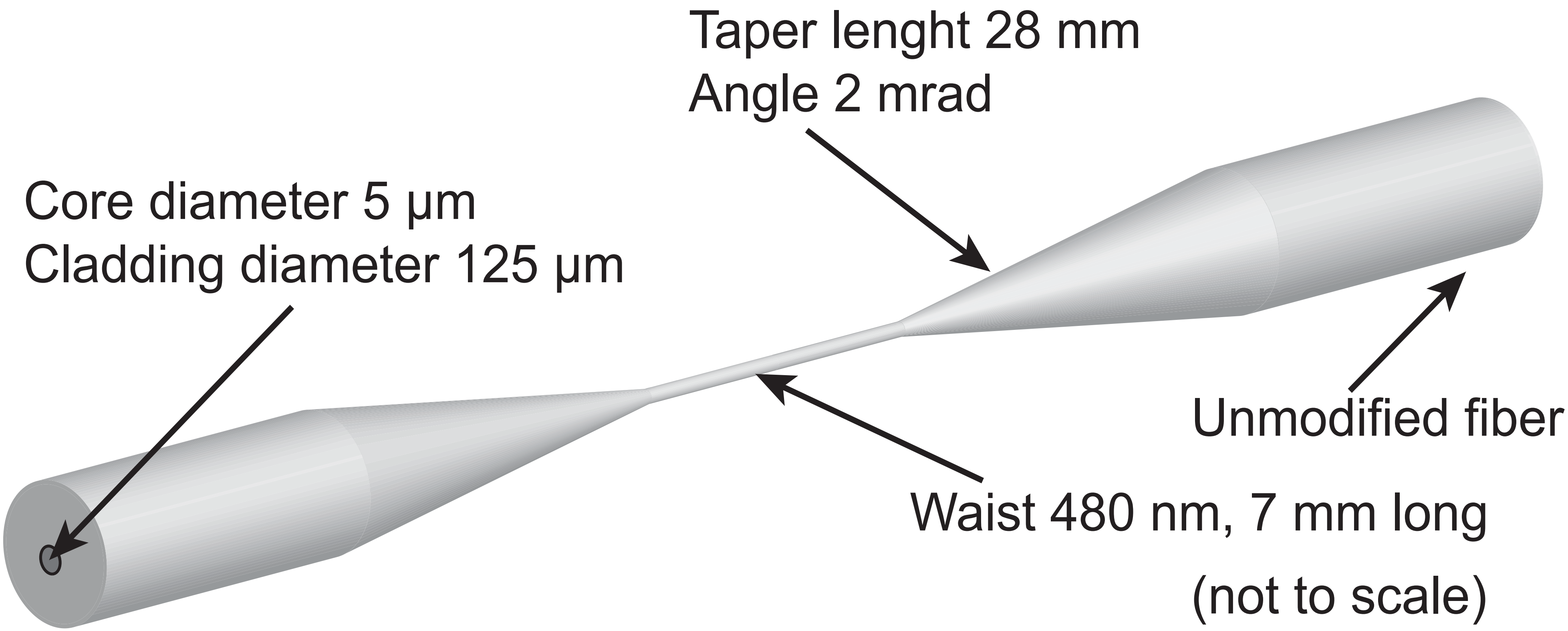

a
|2+⟩
Δ2+
Δ2−
|2−⟩
ω
|1+⟩
Δ1+
Δ1−
|1−⟩
ω
|g0⟩
b
Homodyne detection
→ light field
Photon counting
→ light intensity
SPCM
I1 − I2
High-finesse cavity
I1
50/50
I2
Single atom
Phase control
λ/4 waveplate
Probing and trapping light
Polarizing beamsplitter
Local oscillator beam
Probe beam



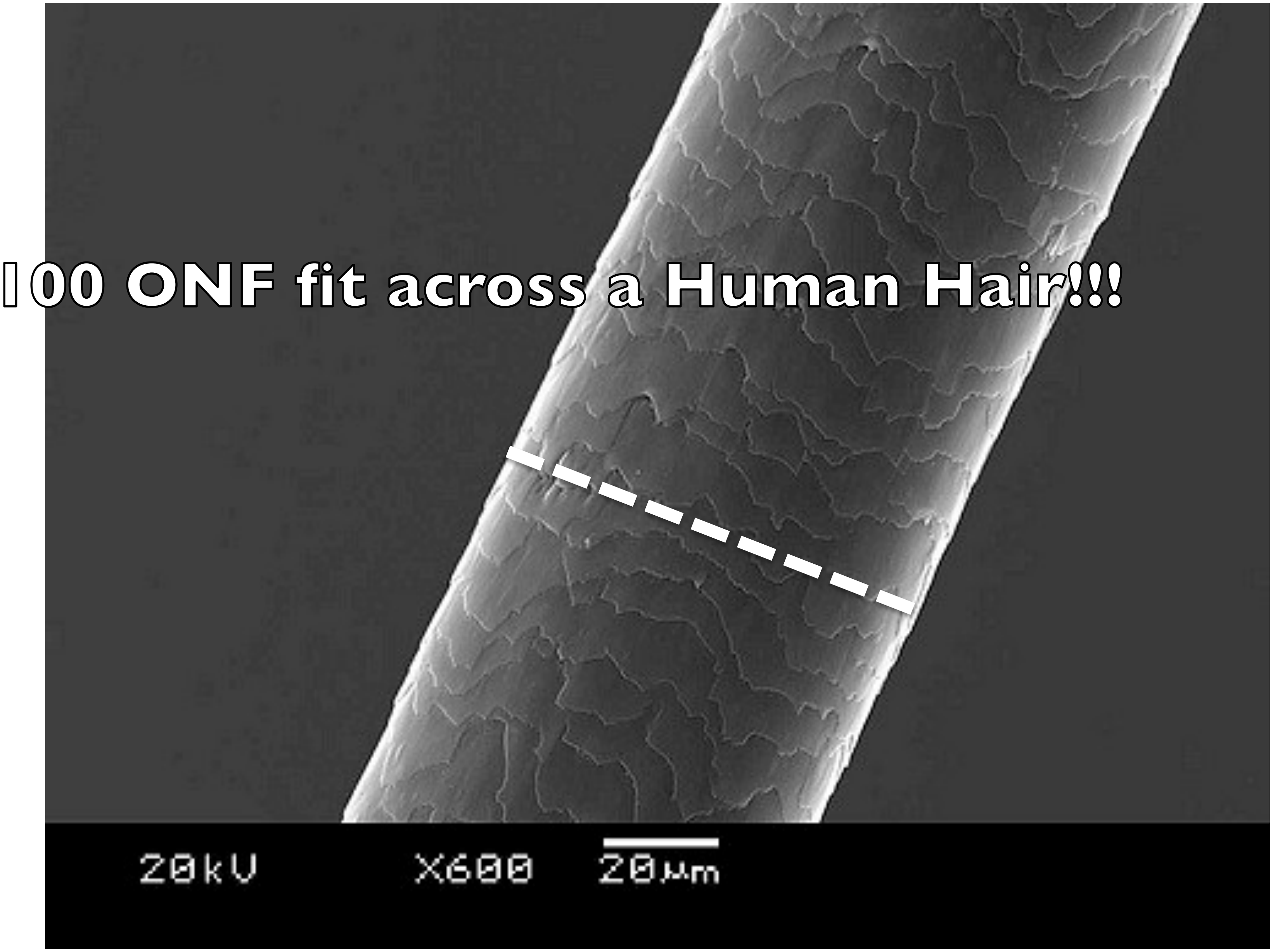
a
|1+⟩
|1−⟩
Theory, P
Theory, X
Data, P
Data, X
Relative noise spectrum (mdB)
Frequency (MHz)
15
10
5
0
−5
−10
−15
0
10
20
30
40
b
|1−⟩
|1+⟩
Theory, X
Theory, P
Data, X
Data, P
Relative noise spectrum (mdB)
Frequency (MHz)

From Cavity QED to Waveguide QED

Optical Nanofibers

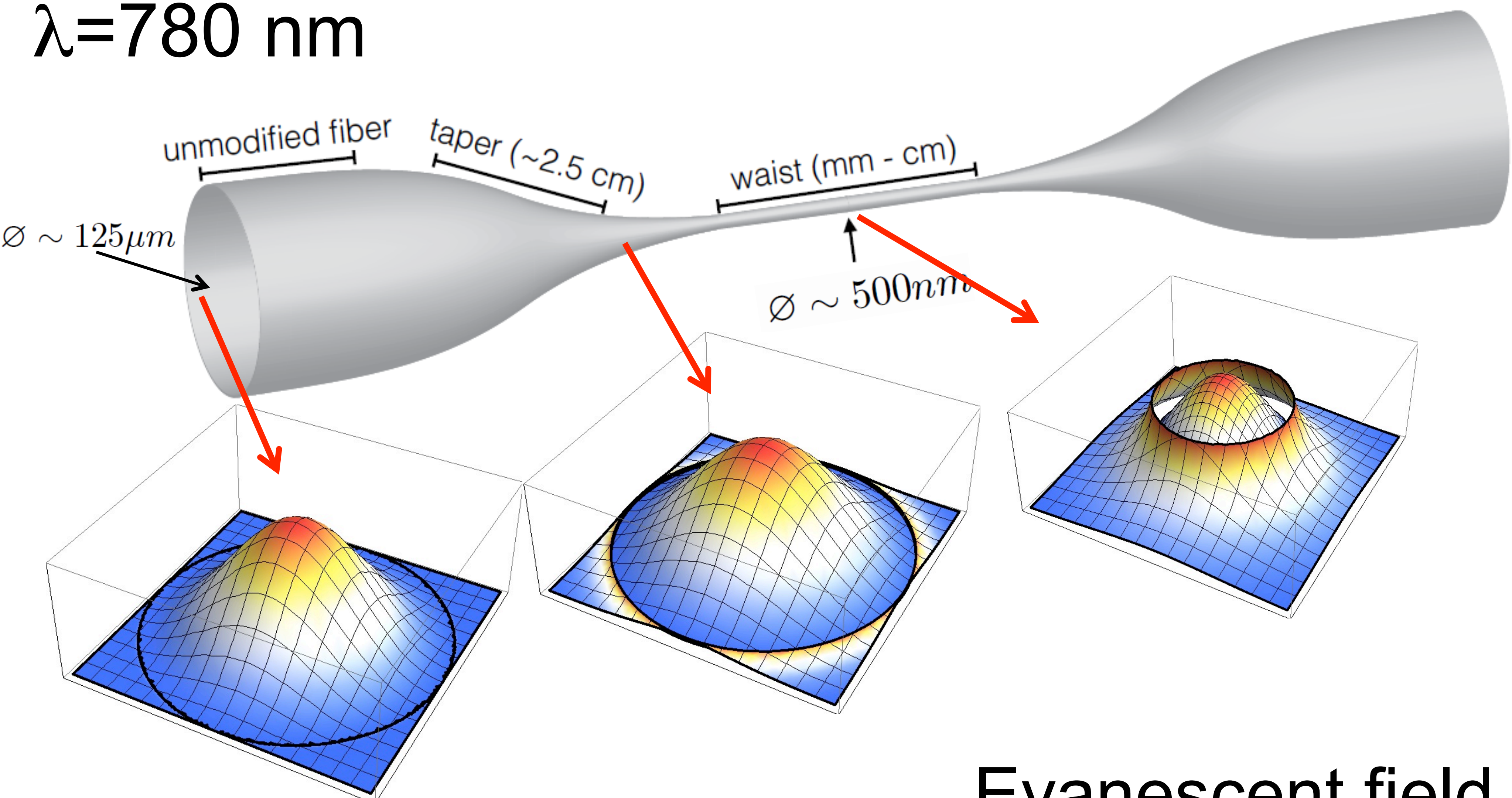


The scale



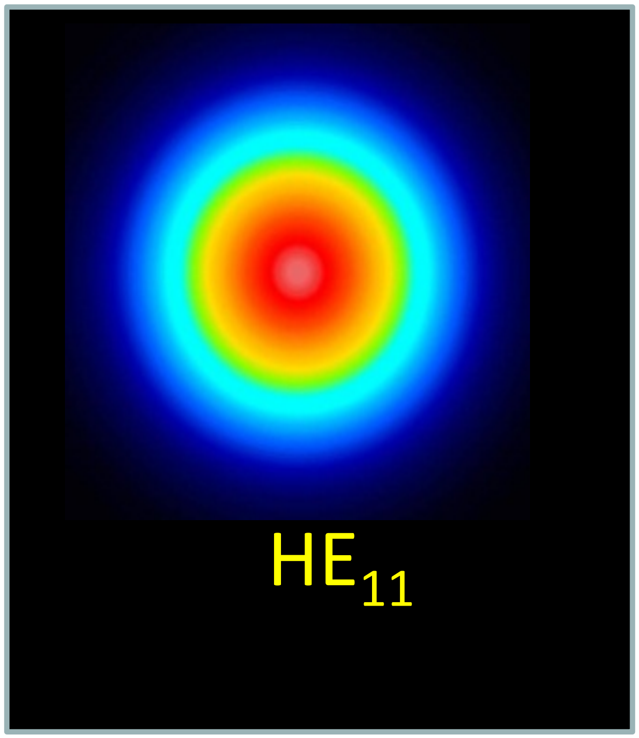
Optical Nanofibers

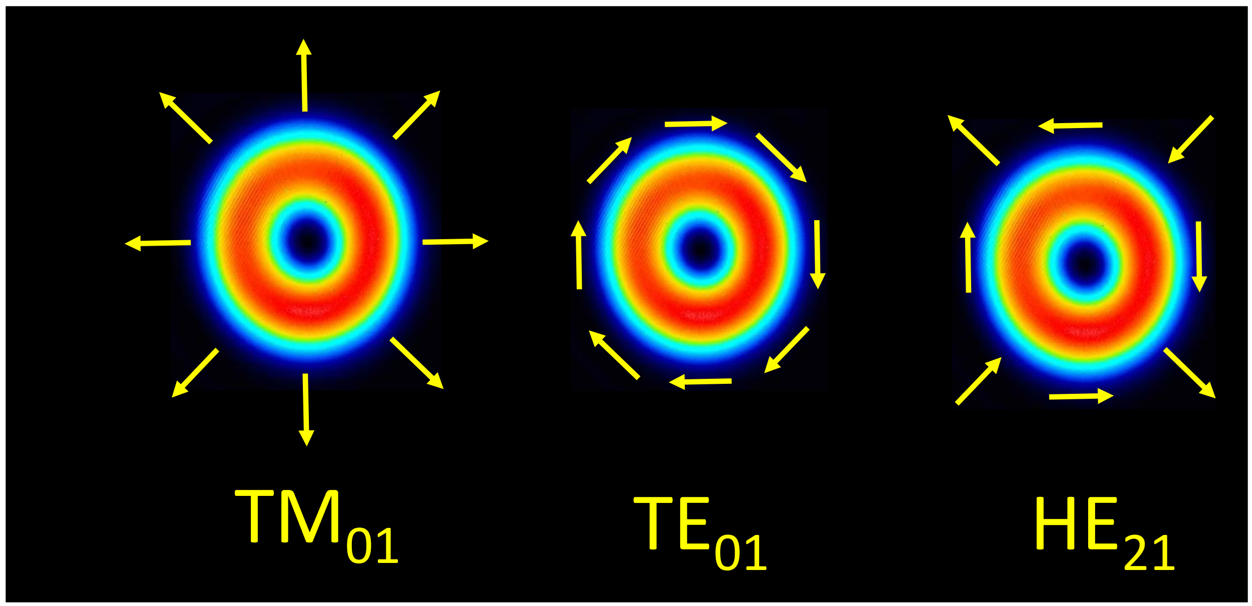
λ=780 nm



Evanescent field

Lowest order fiber modes
Intensities and polarizations

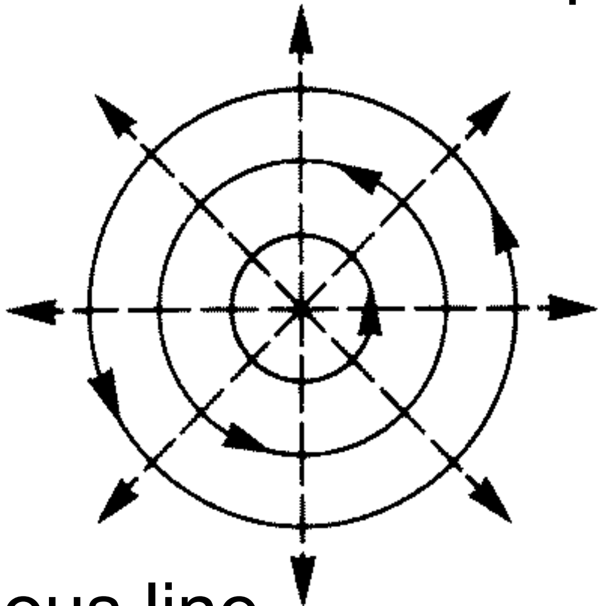




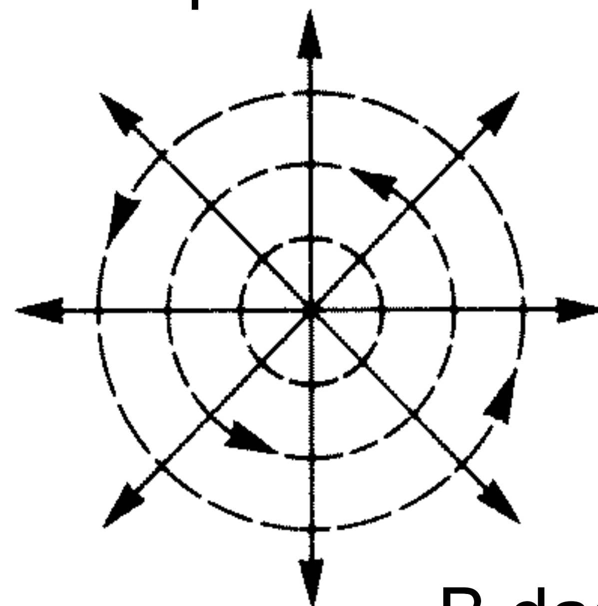
Transversal component of the polarization

E continuous line

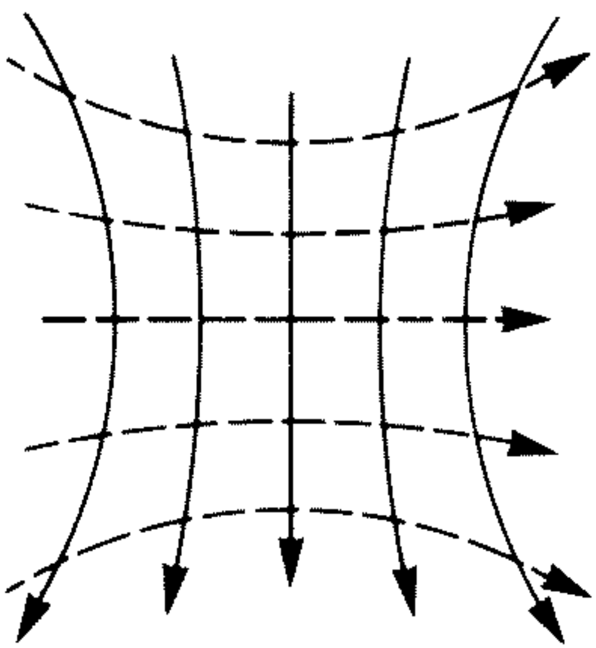
B dashed line



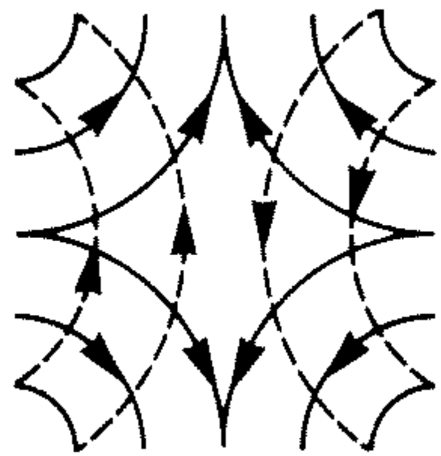
TE_{01}



TM_{01}

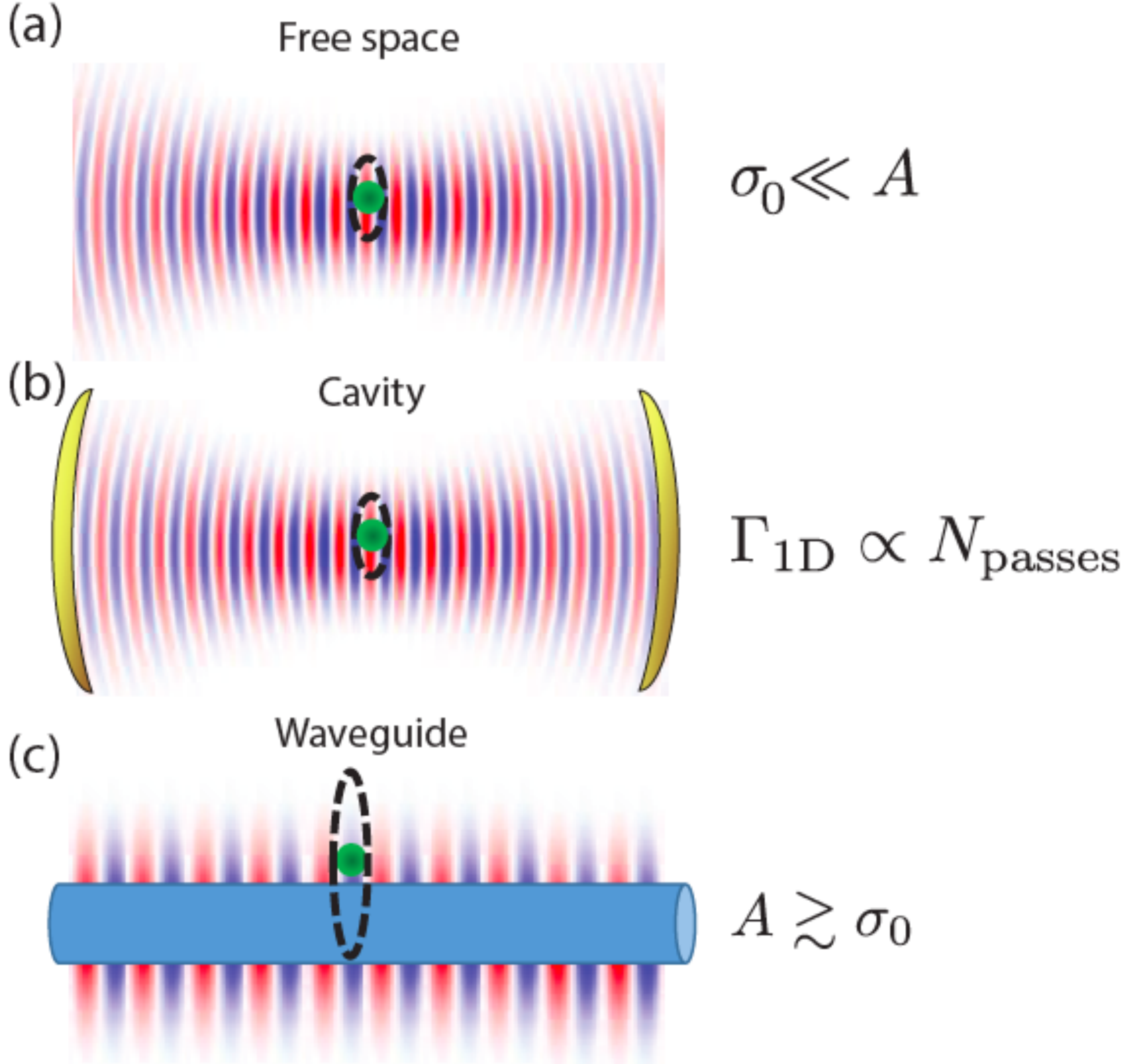


HE_{11}



HE_{21}

Introduction to optical nanofibers, as waveguide



PhD Thesis Jonathan Hood

Decay into the nanofiber mode

Density of modes in 1D

$$\gamma_{1D} \approx \frac{2\pi}{\hbar} \rho\left(k\right) \left\langle H_{int} \right\rangle^2$$

Decay into the nanofiber mode

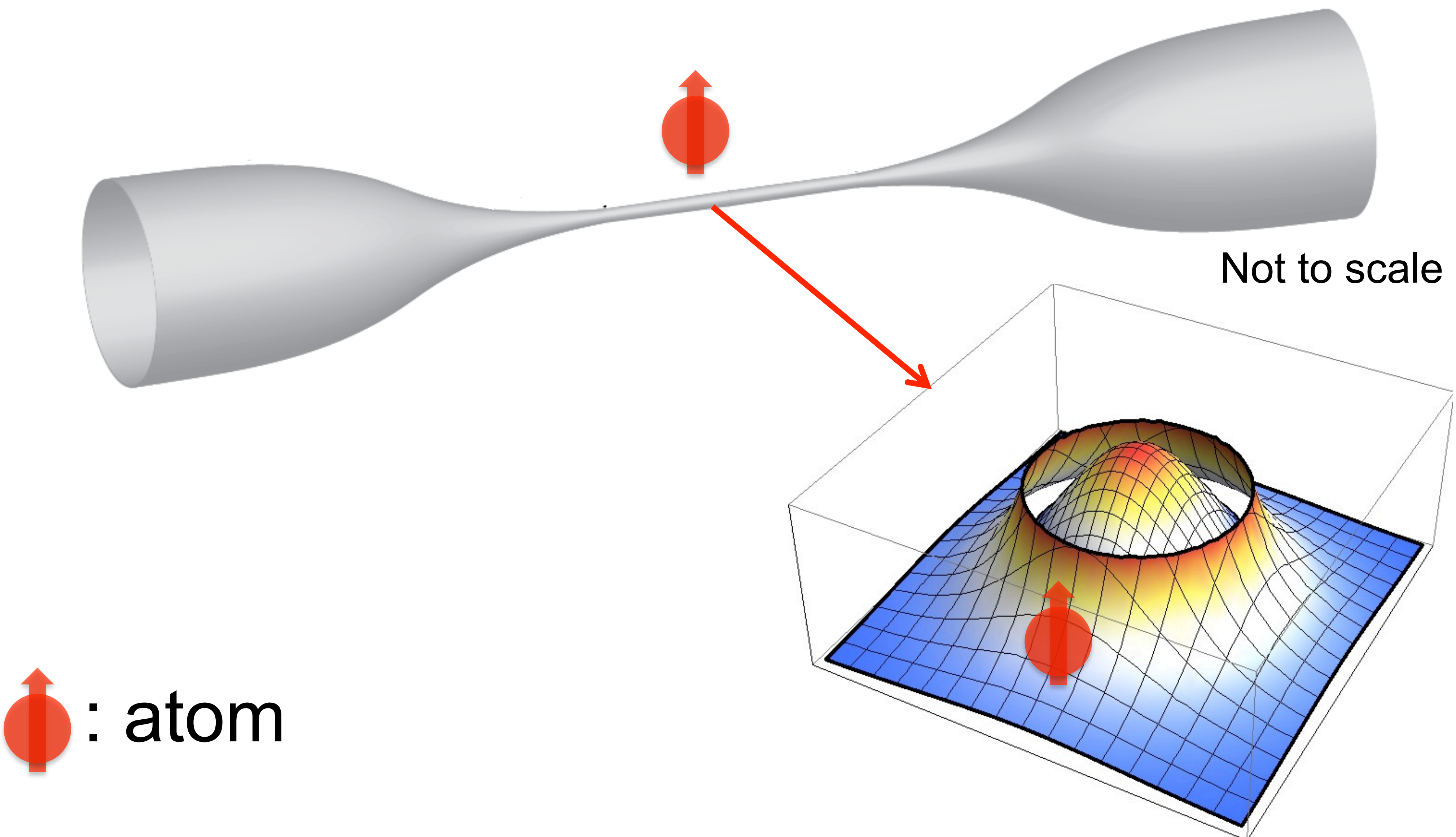
Density of modes

$$\gamma_{1D} \approx \frac{2\pi}{\hbar} \rho(k) \langle H_{int} \rangle^2$$

Proportional to the electric field of the guided mode

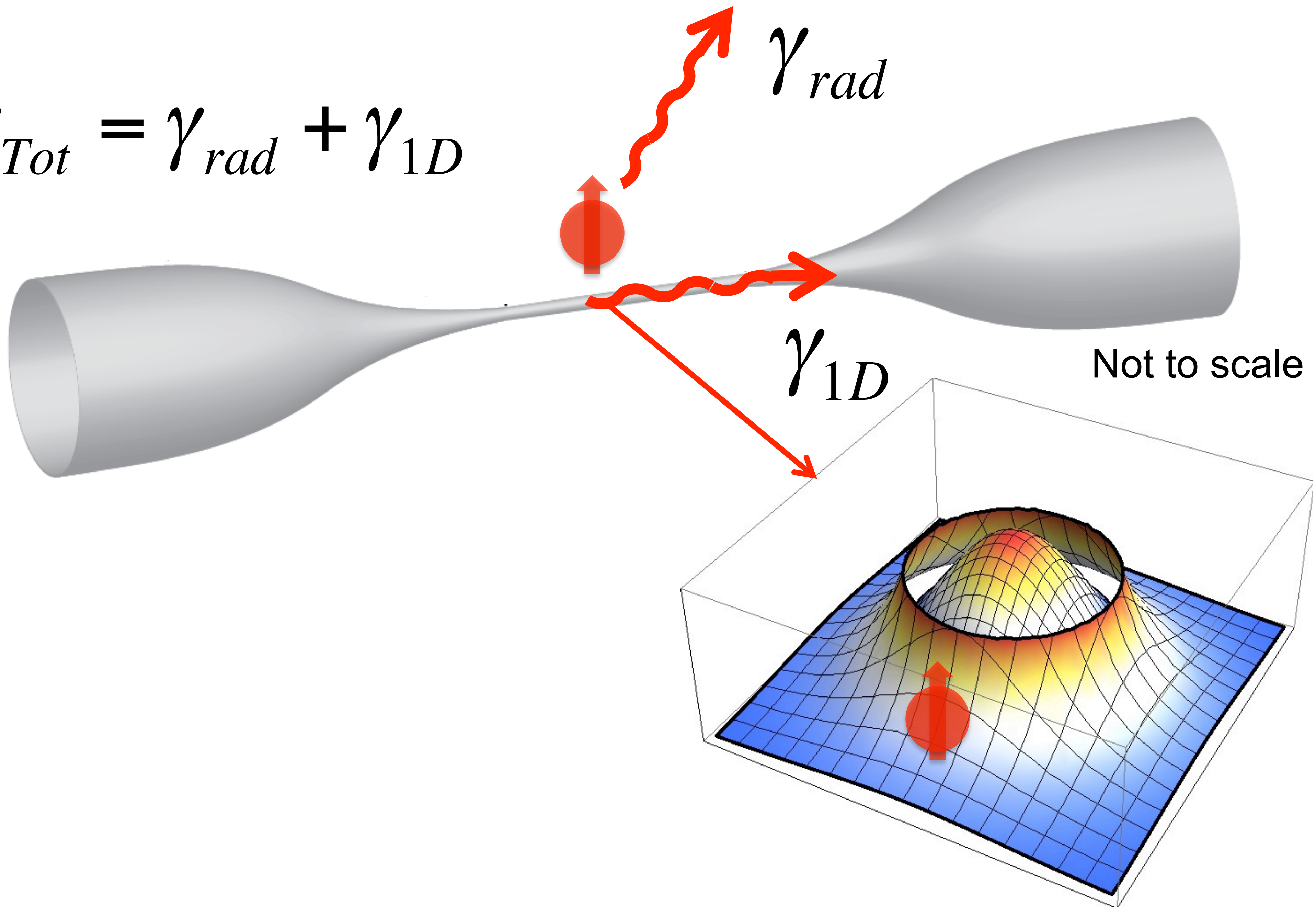
$$|E|^2 = \mathcal{E}^2 \left[K_0^2(qr) + w K_1^2(qr) + f K_2^2(qr) \right]$$

Evanescent Coupling

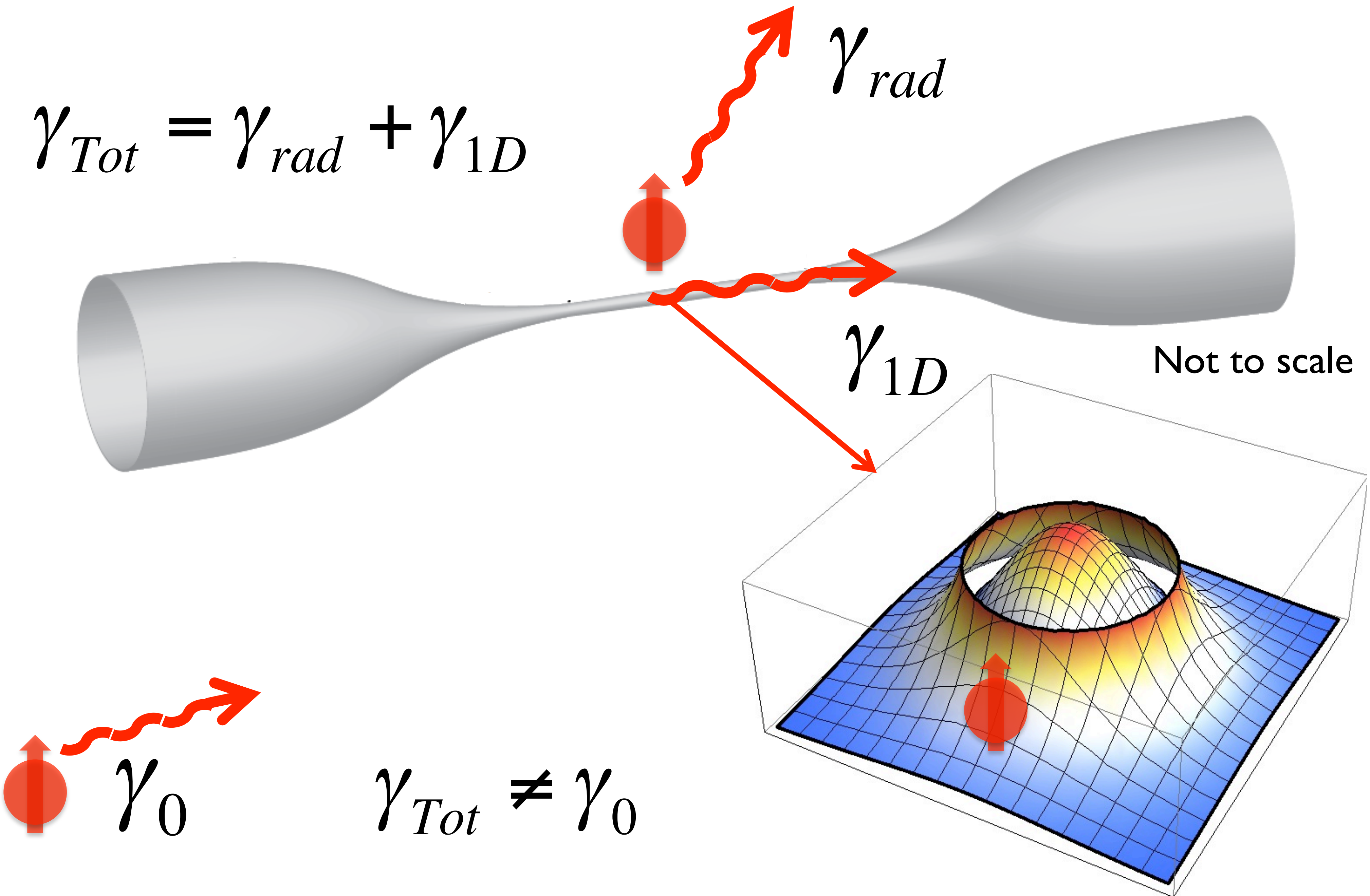


Evanescent Coupling

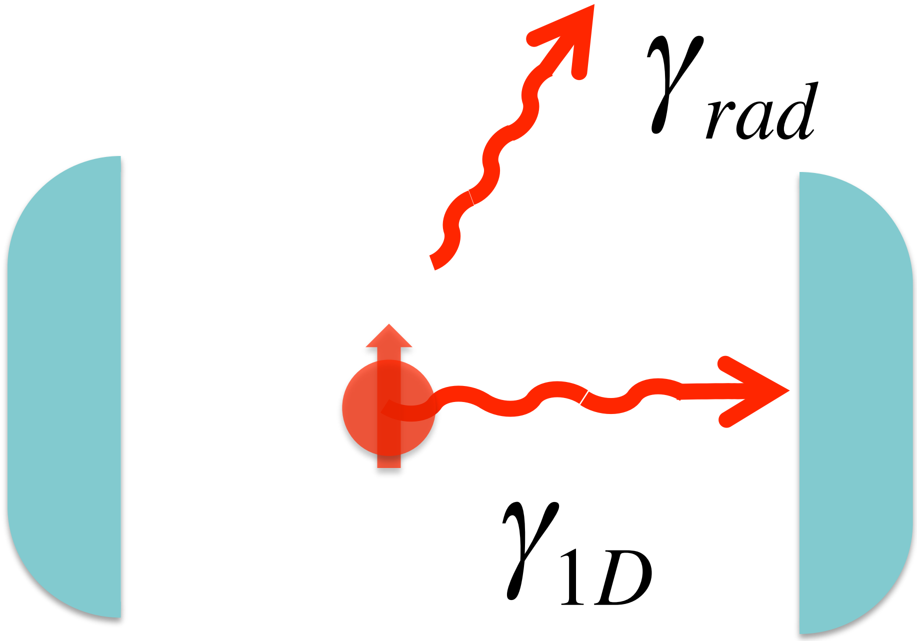
$$\gamma_{Tot} = \gamma_{rad} + \gamma_{1D}$$

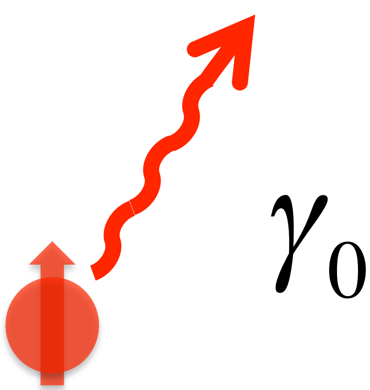


Evanescent Coupling



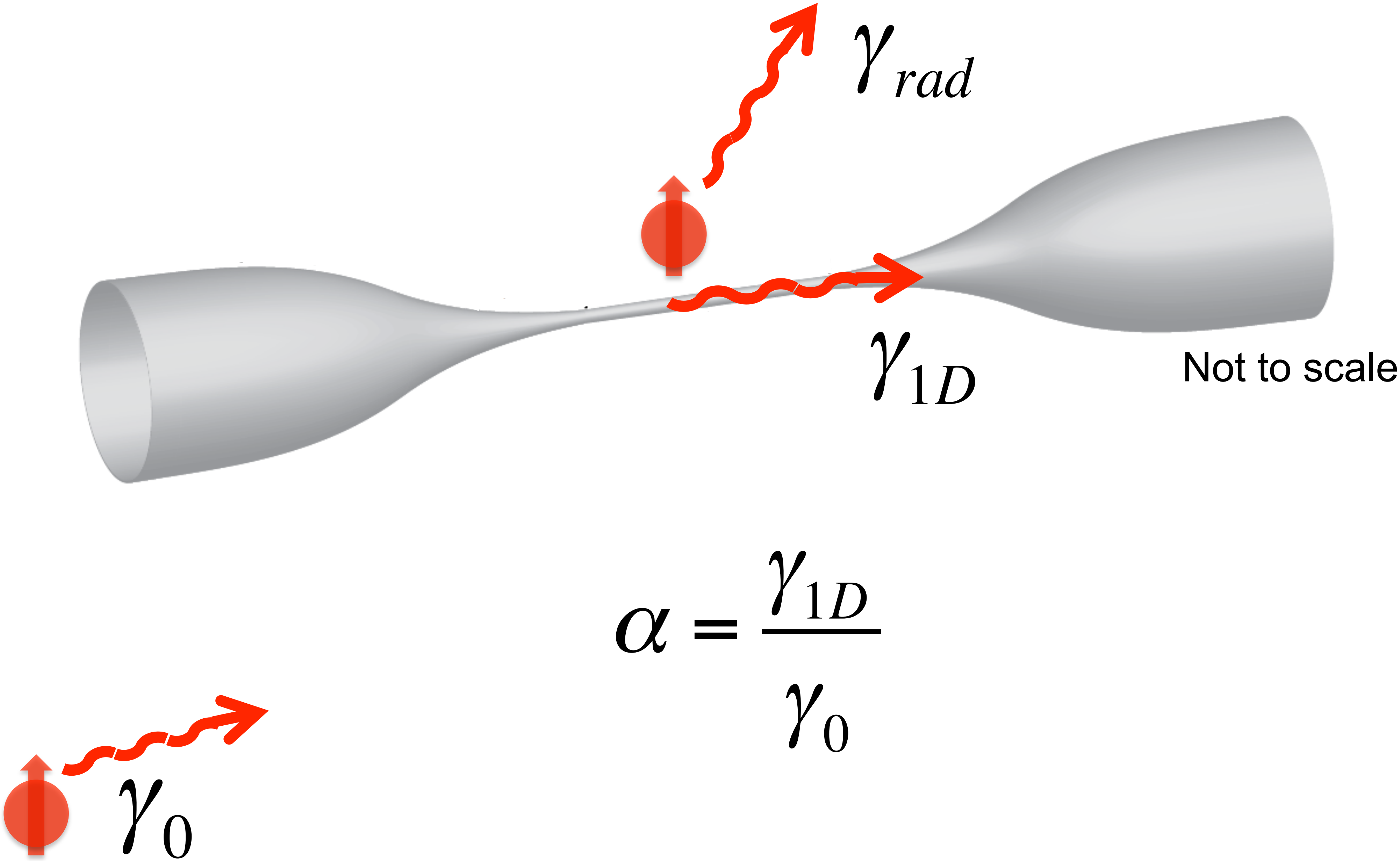
Coupling Enhancement





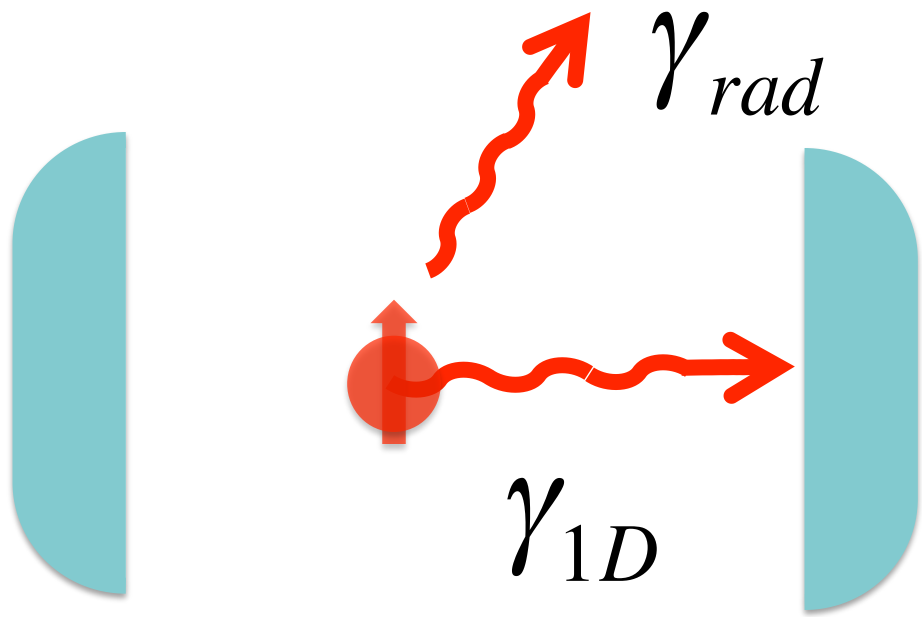
$$\alpha = \frac{\gamma_{1D}}{\gamma_0}$$

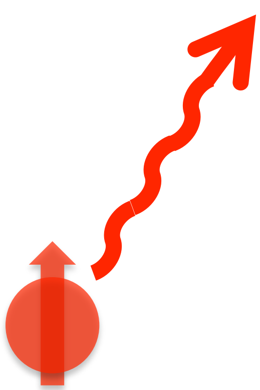
Coupling Enhancement



$$\alpha = \frac{\gamma_{1D}}{\gamma_0}$$

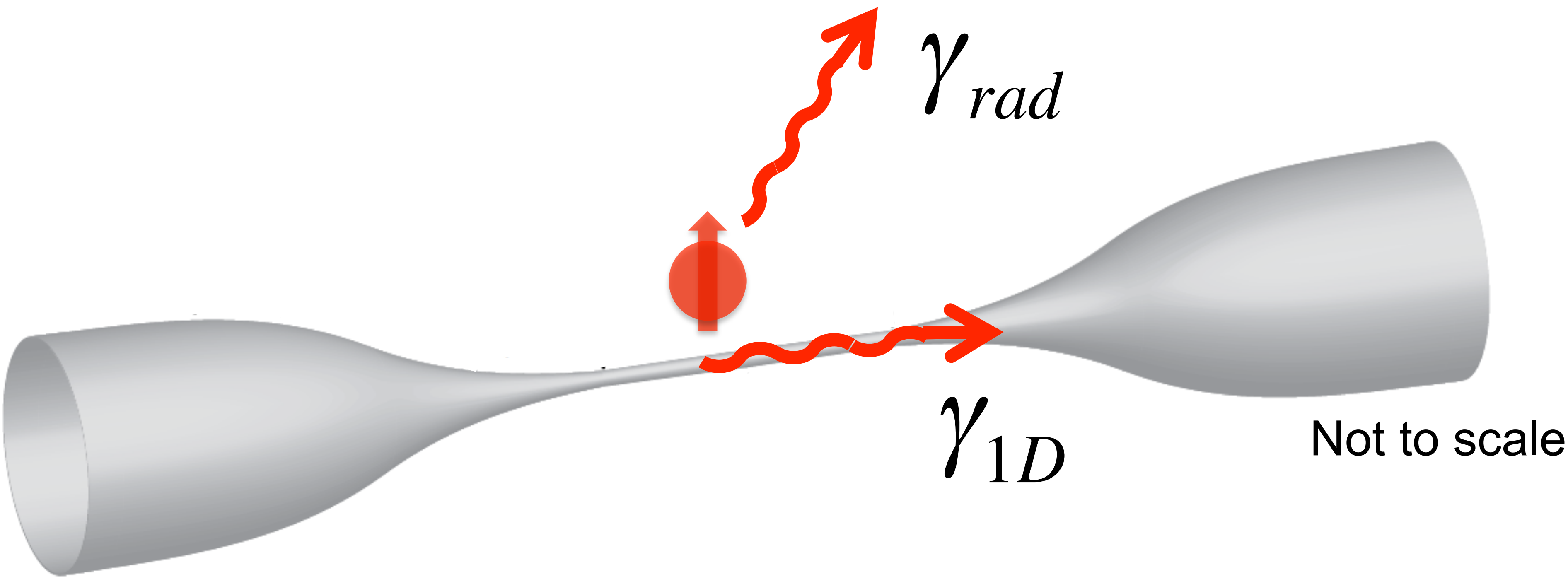
Coupling Efficiency





$$\beta = \frac{\gamma_{1D}}{\gamma_{Tot}} \quad ; \quad \gamma_{Tot} = \gamma_{1D} + \gamma_{rad}$$

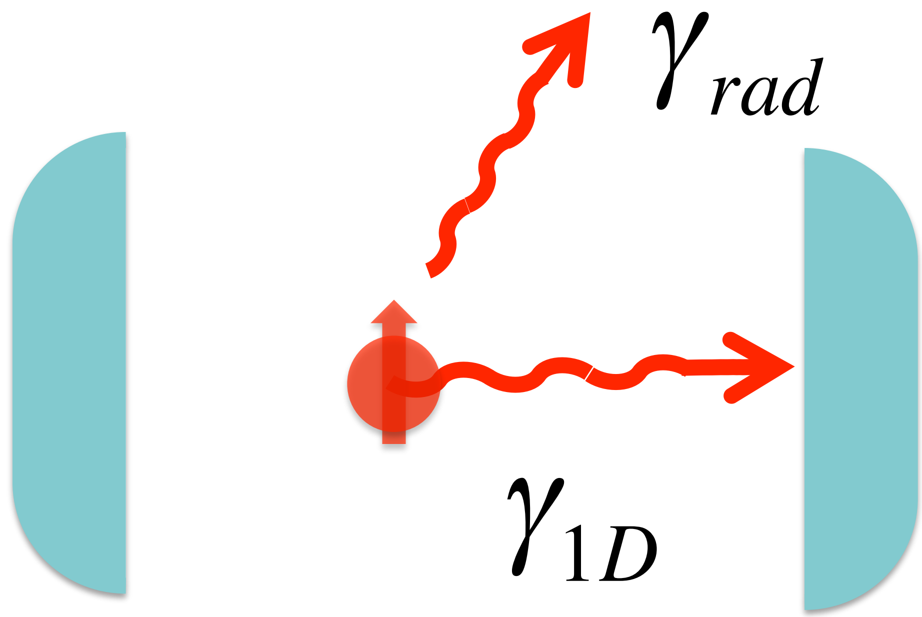
Coupling Efficiency

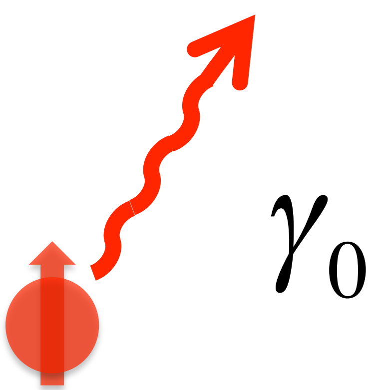


$$\beta = \frac{\gamma_{1D}}{\gamma_{Tot}}$$

$$\gamma_{Tot} = \gamma_{rad} + \gamma_{1D}$$

Purcell Factor

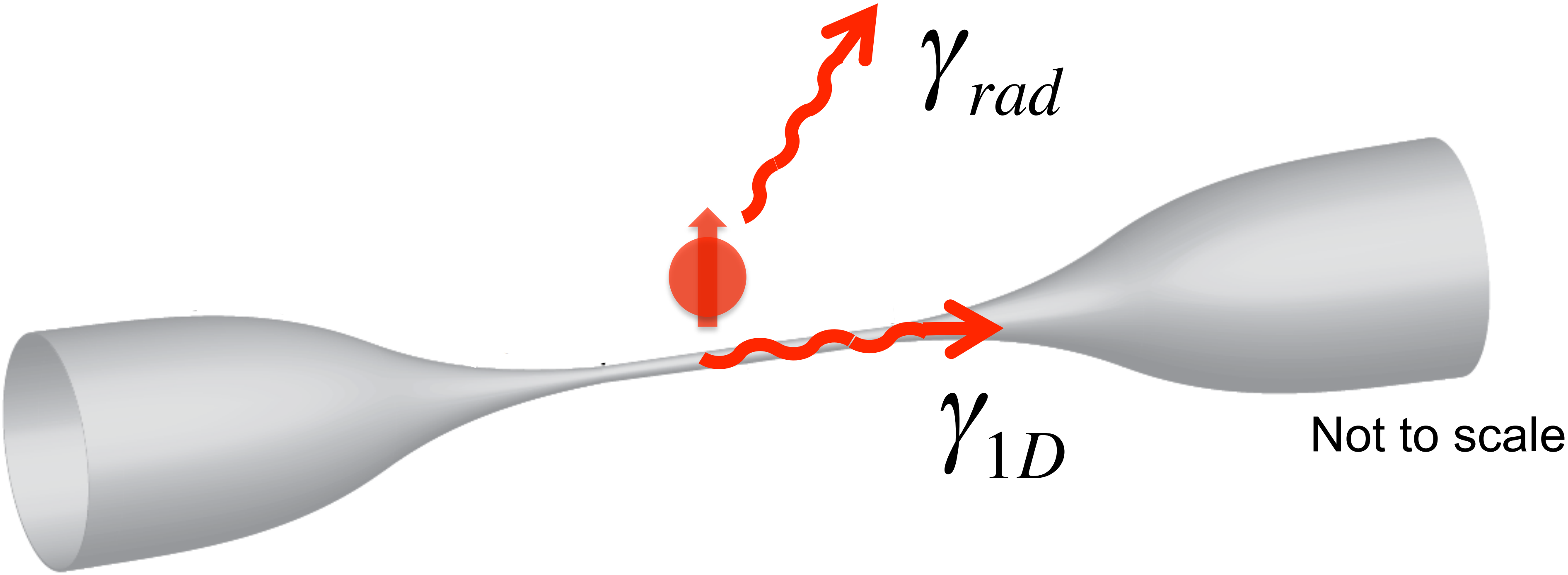




$$F_P = \frac{\gamma_{tot}}{\gamma_0} = \frac{\alpha}{\beta}$$

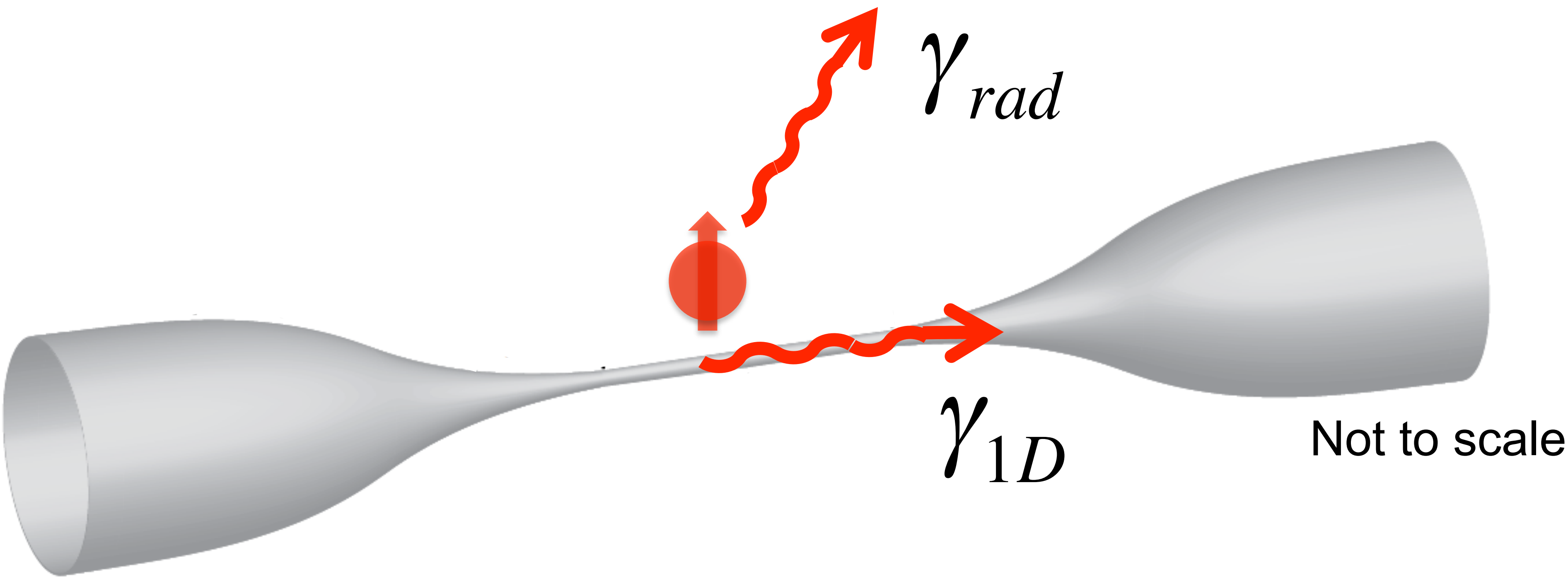
$$\gamma_{Tot} = \gamma_{1D} + \gamma_{rad}$$

Purcell Factor



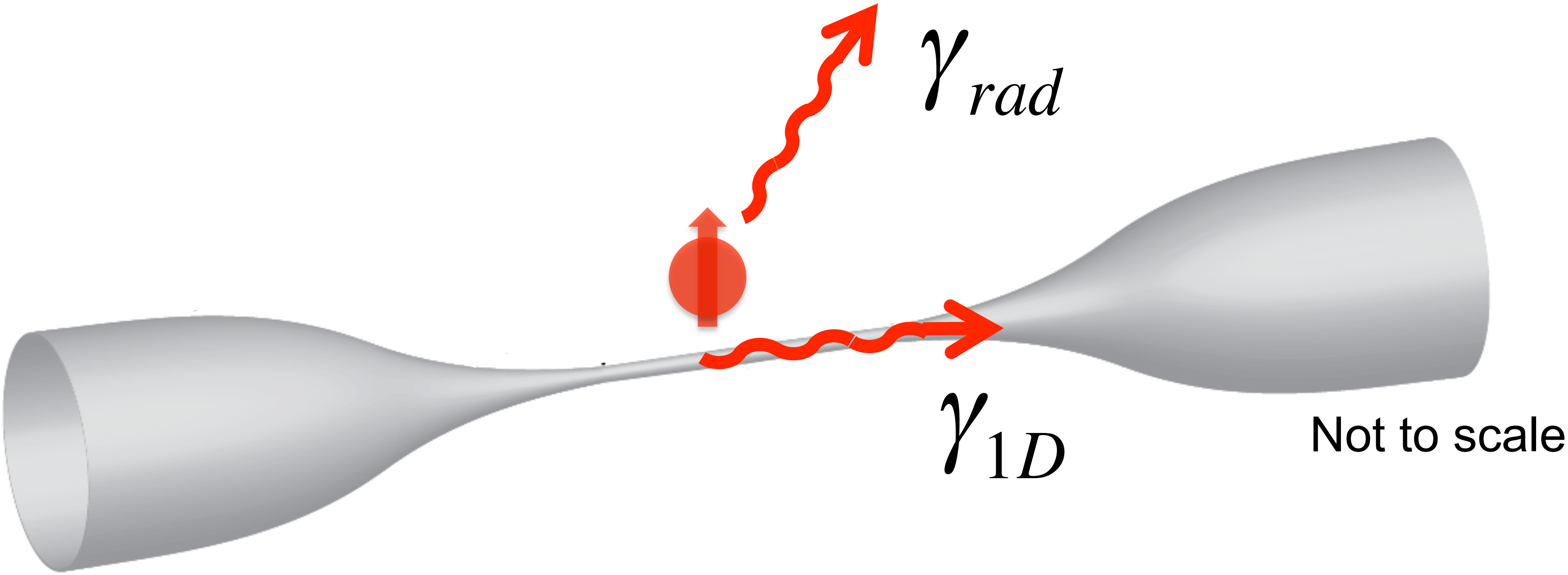
$$F_P = \frac{\gamma_{tot}}{\gamma_0} = \frac{\alpha}{\beta}$$

Cooperativity



$$C_1 = \frac{\beta}{(1-\beta)} = \frac{\gamma_{1D}}{\gamma_{rad}}$$

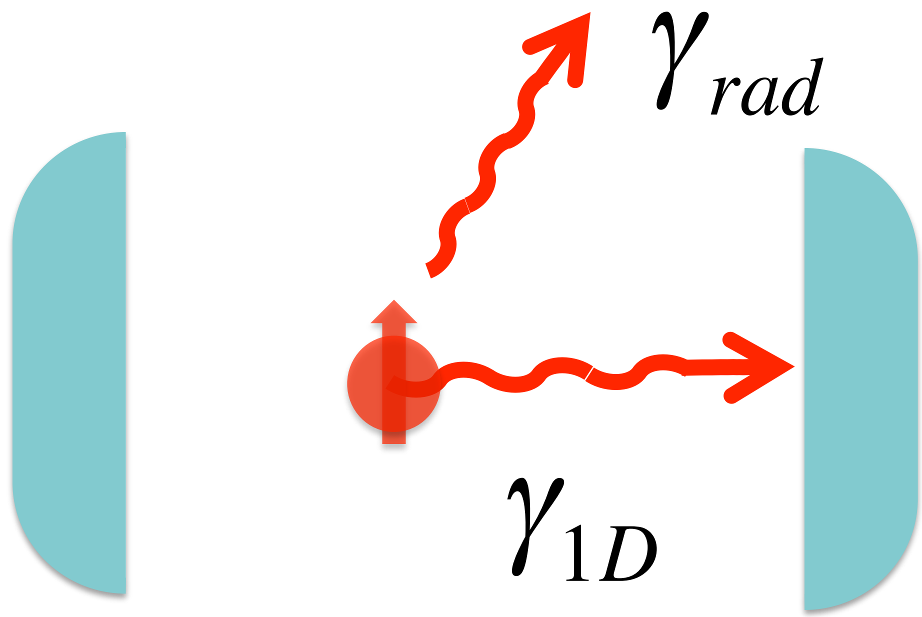
Cooperativity

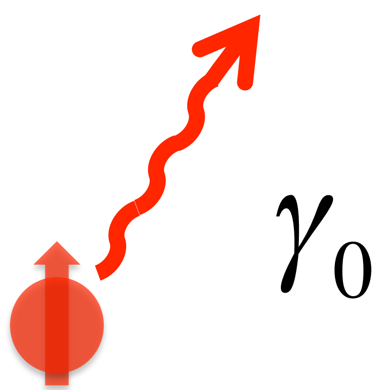


$$C_1 = \frac{\beta}{(1-\beta)} = \frac{\gamma_{1D}}{\gamma_{rad}}$$

C_1 is the ratio of what goes into the selected mode to what goes into all the rest

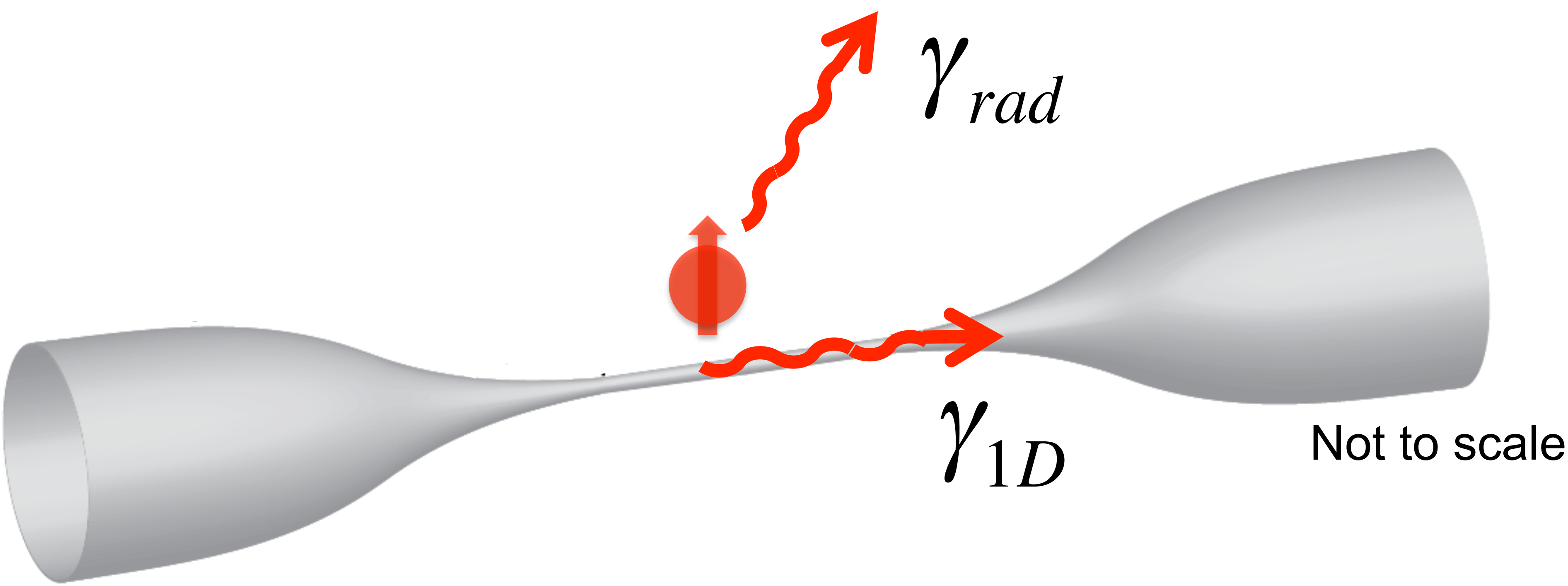
Cooperativity





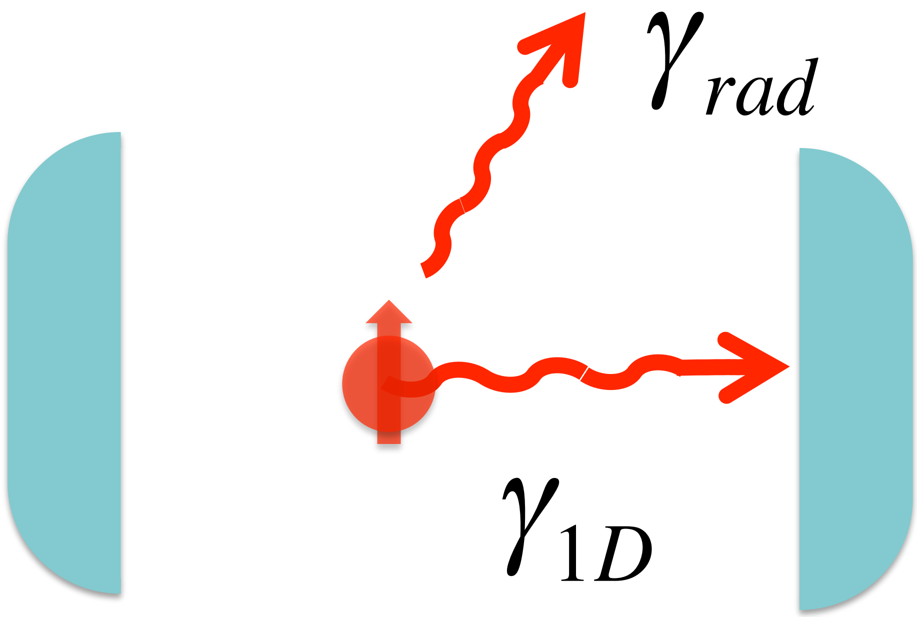
$$C_1 = \frac{\beta}{(1-\beta)} = \frac{\gamma_{1D}}{\gamma_{rad}}$$

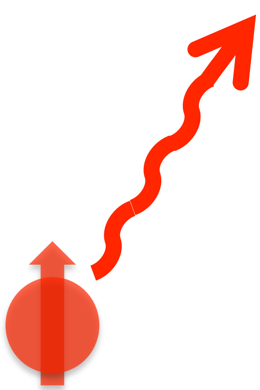
Cooperativity



$$C_1 = \frac{\beta}{(1-\beta)} = \frac{\gamma_{1D}}{\gamma_{rad}}$$

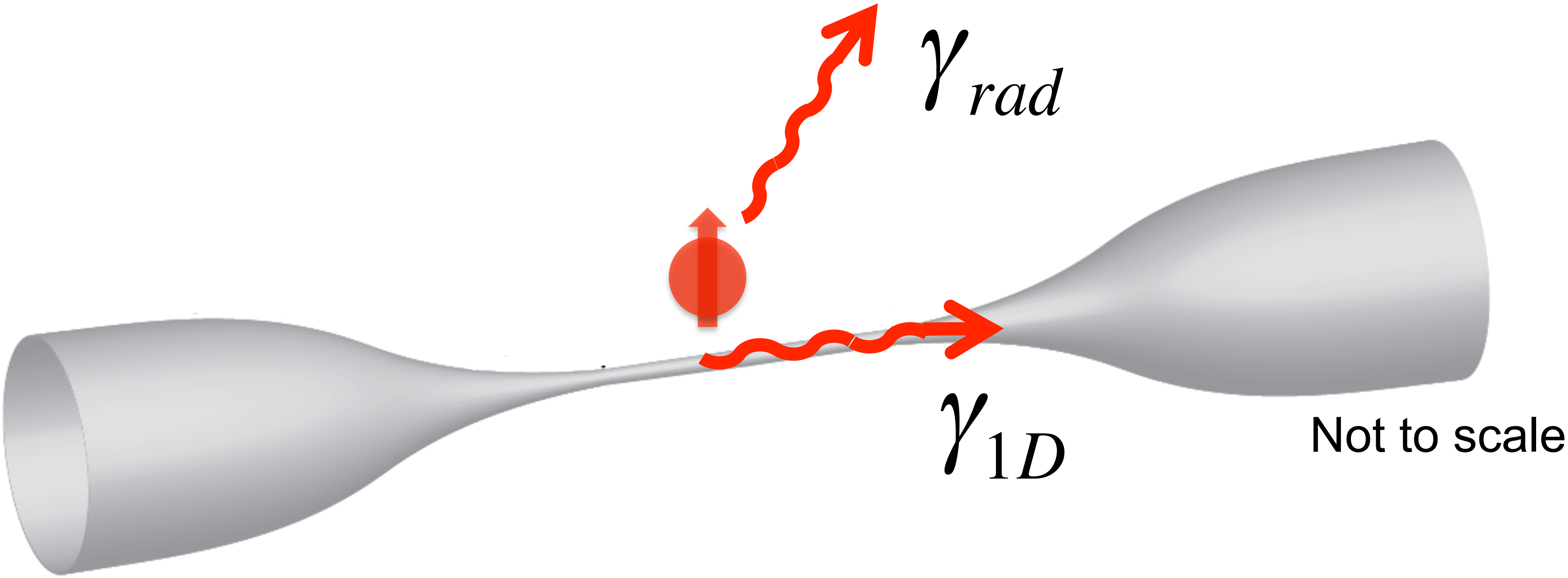
Cooperativity





$$C_1 = \frac{\sigma_0}{Area_{\mathrm{mode}}} \frac{1}{T}$$

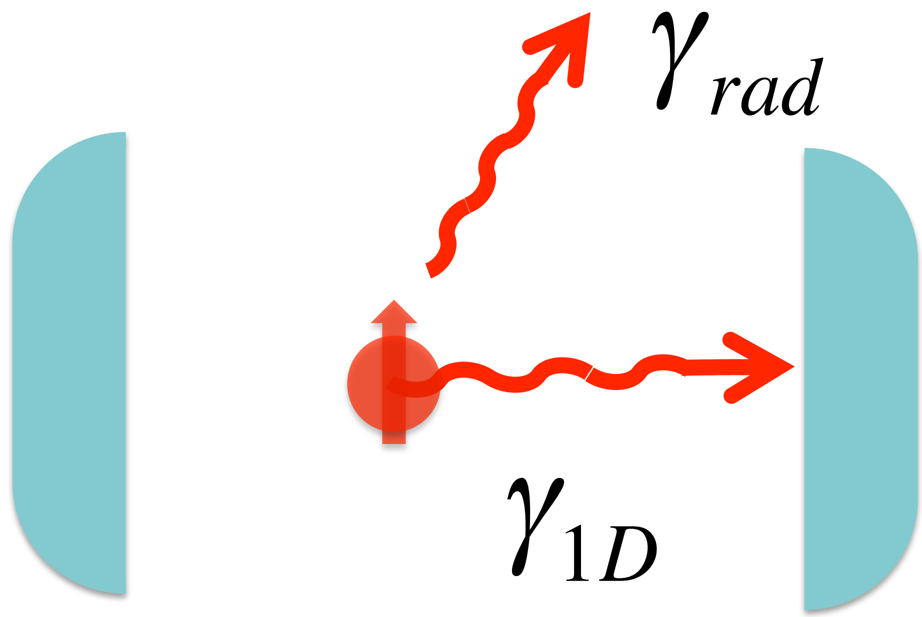
Cooperativity



no mirrors
T=1

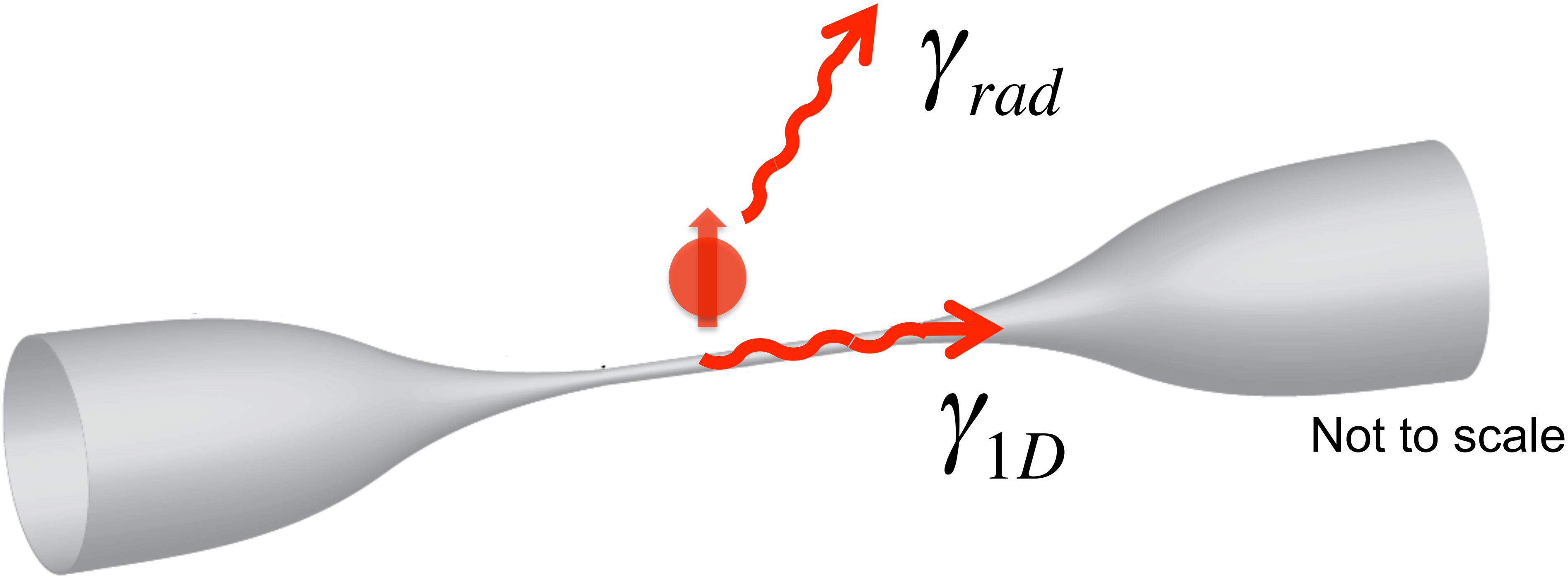
$$C_1 = \frac{\sigma_0}{Area_{\mathrm{mode}}}$$

Cooperativity



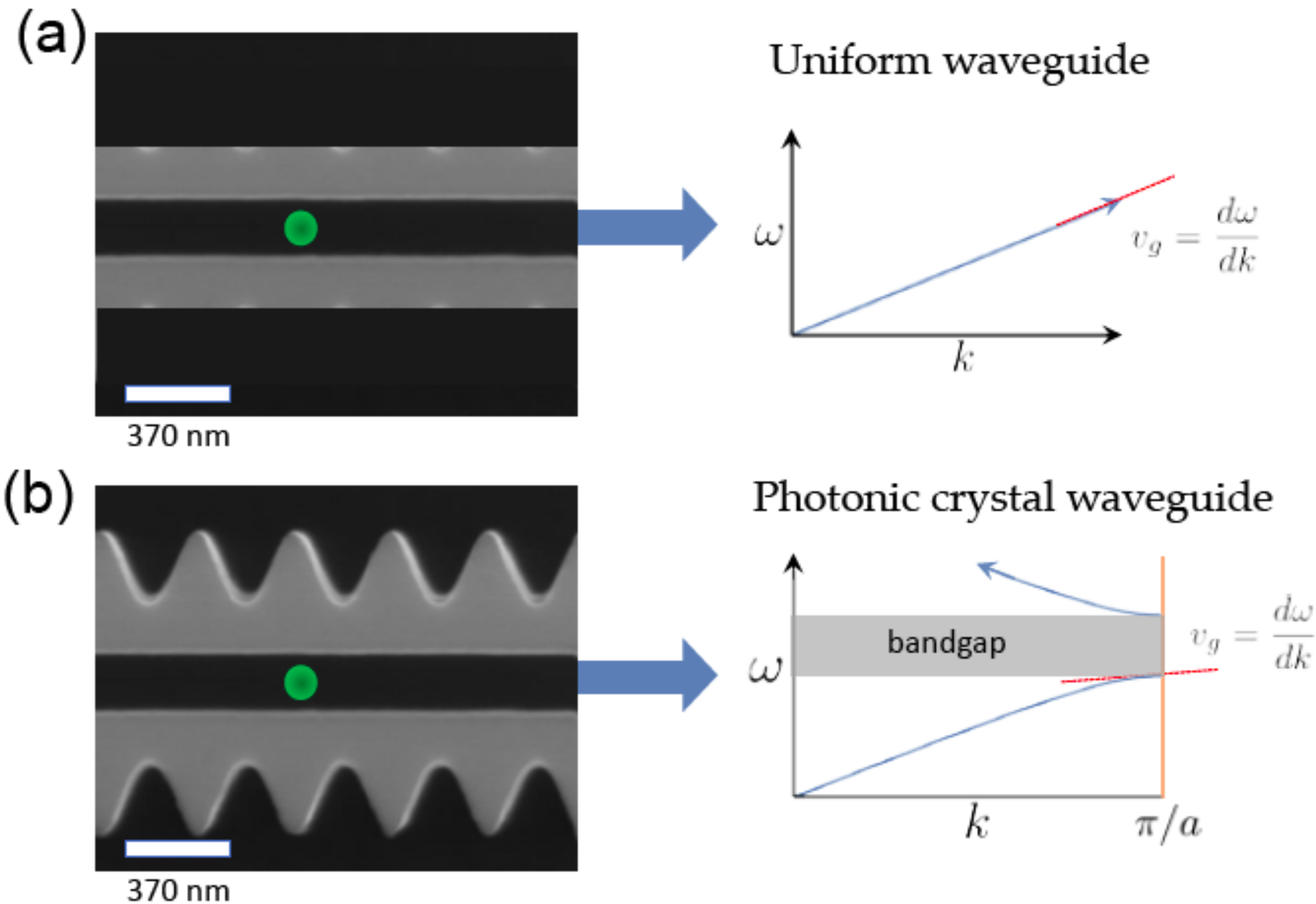
$$C_1 = \frac{g^2}{\kappa\gamma_{rad}} = \left(\frac{\sigma_0}{A_{\mathrm{mode}}}\right)\left(\frac{c}{v_g}\right) = \frac{\gamma_{1D}}{\gamma_{rad}}$$

Cooperativity



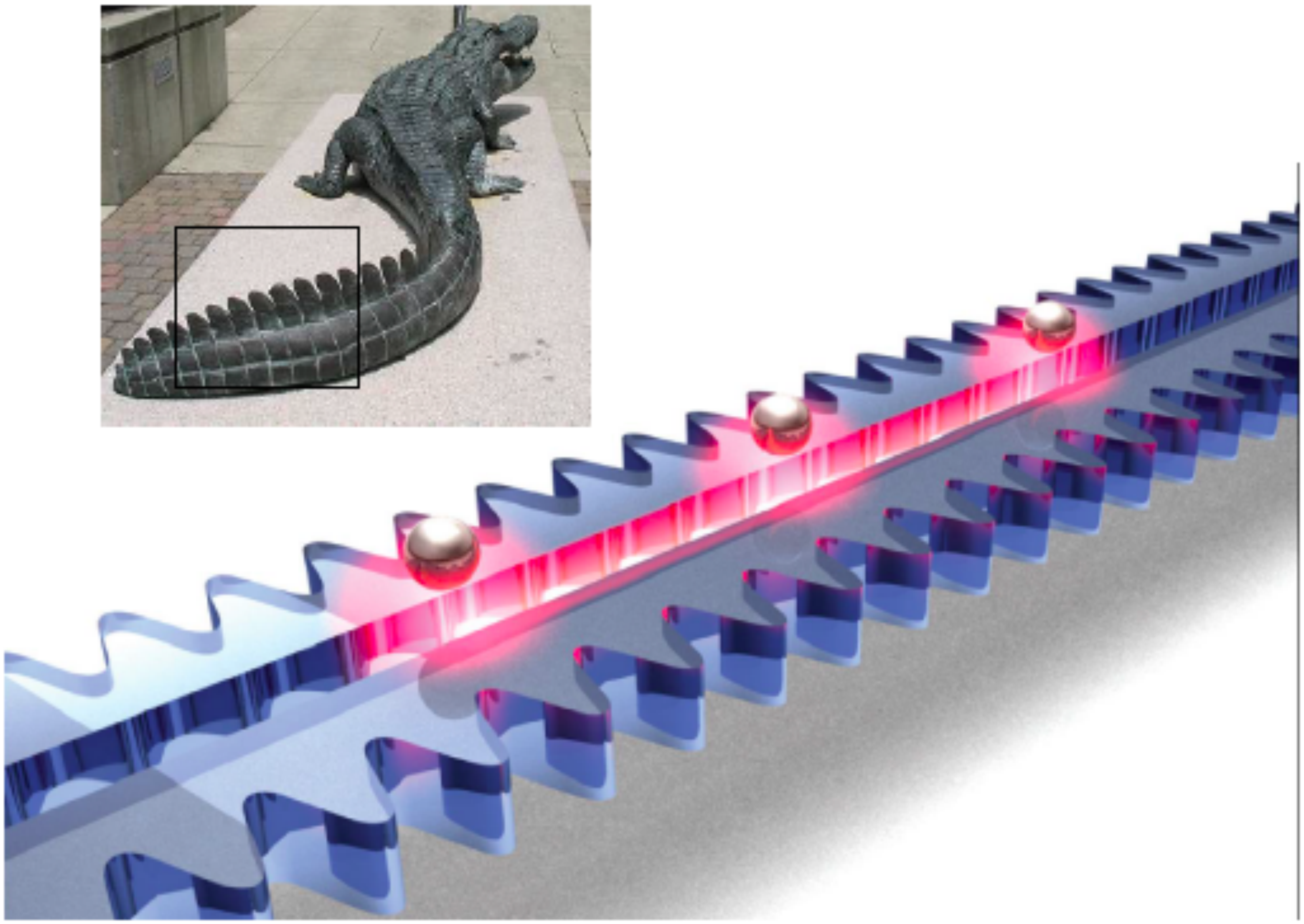
$$C_1 = \frac{\sigma_0}{Area_{\mathrm{mode}}} n_{eff} = \frac{\gamma_{1D}}{\gamma_{rad}}$$

4.What happens on a photonic structure?

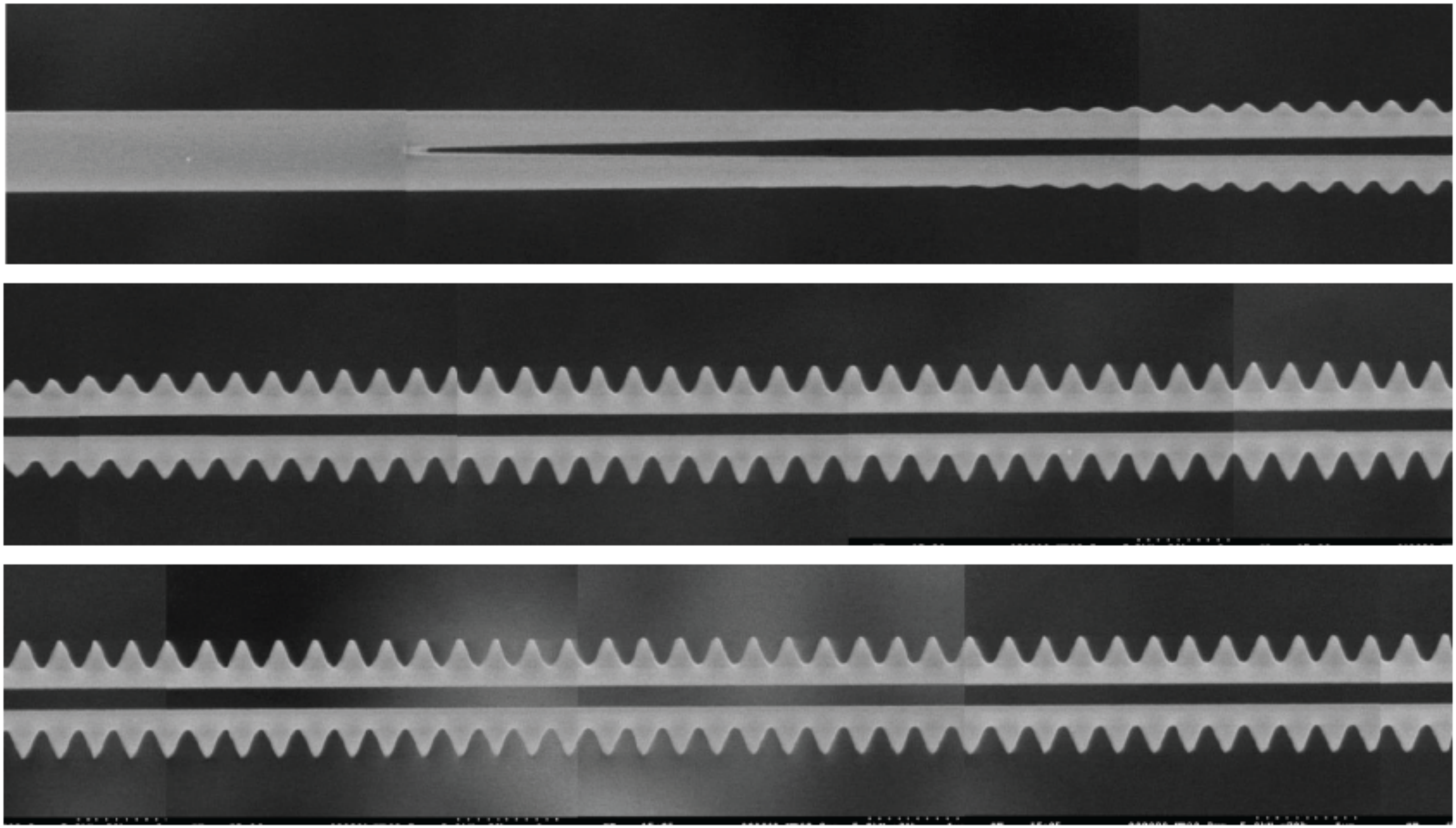


PhD Thesis Jonathan Hood

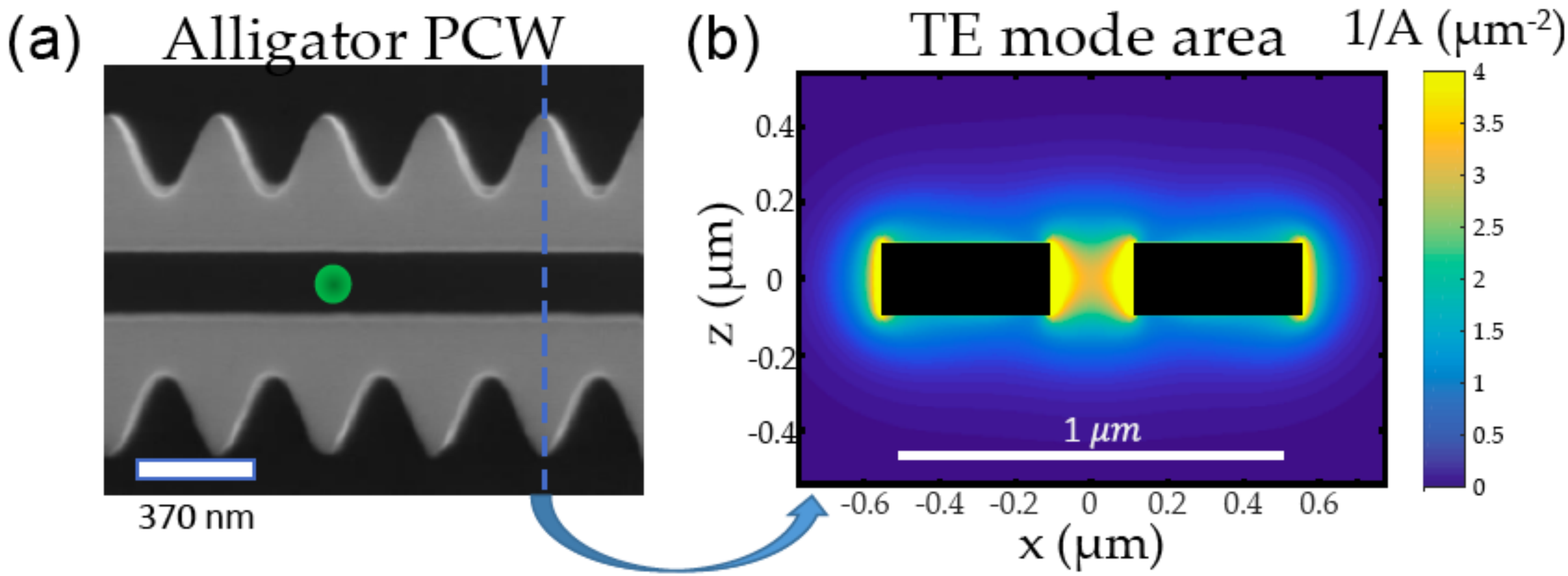
The alligator photonic crystal waveguide (Cal Tech)



PhD Thesis Jonathan Hood



Mode area: $$A_k = \frac{\int_{\text{area}} d^2\mathbf{r}\,\epsilon(\mathbf{r})|\mathbf{E}_k(\mathbf{r})|^2}{\max\left[\,\epsilon(\mathbf{r})|\mathbf{E}_k(\mathbf{r})|^2\,\right]}.$$



Scanning electron microscope

Cross section of the intensity

PhD Thesis Jonathan Hood

Because there is a bandgap, the cooperativity grows with it. It can also create a “cavity mode” that does not move attached to the atom

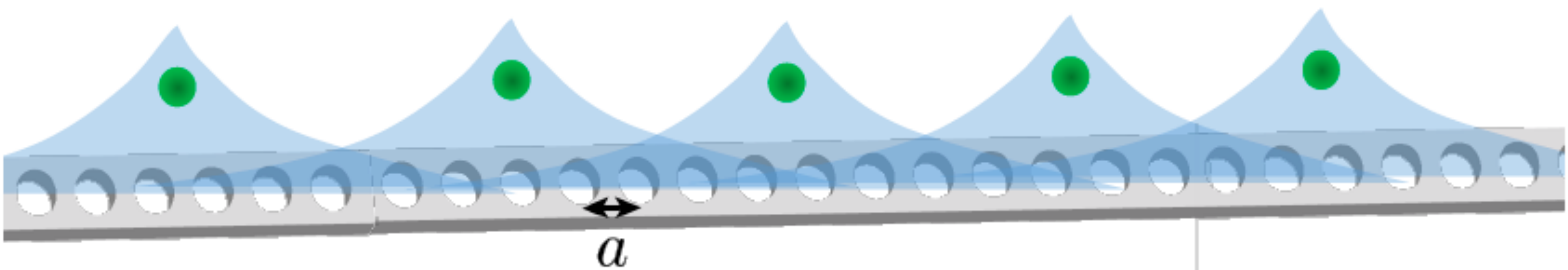


Figure 1.12: Atoms coupled to the bandgap of a photonic crystal waveguide. The atoms and photon cloud form atom-photon bound states.

PhD Thesis Jonathan Hood

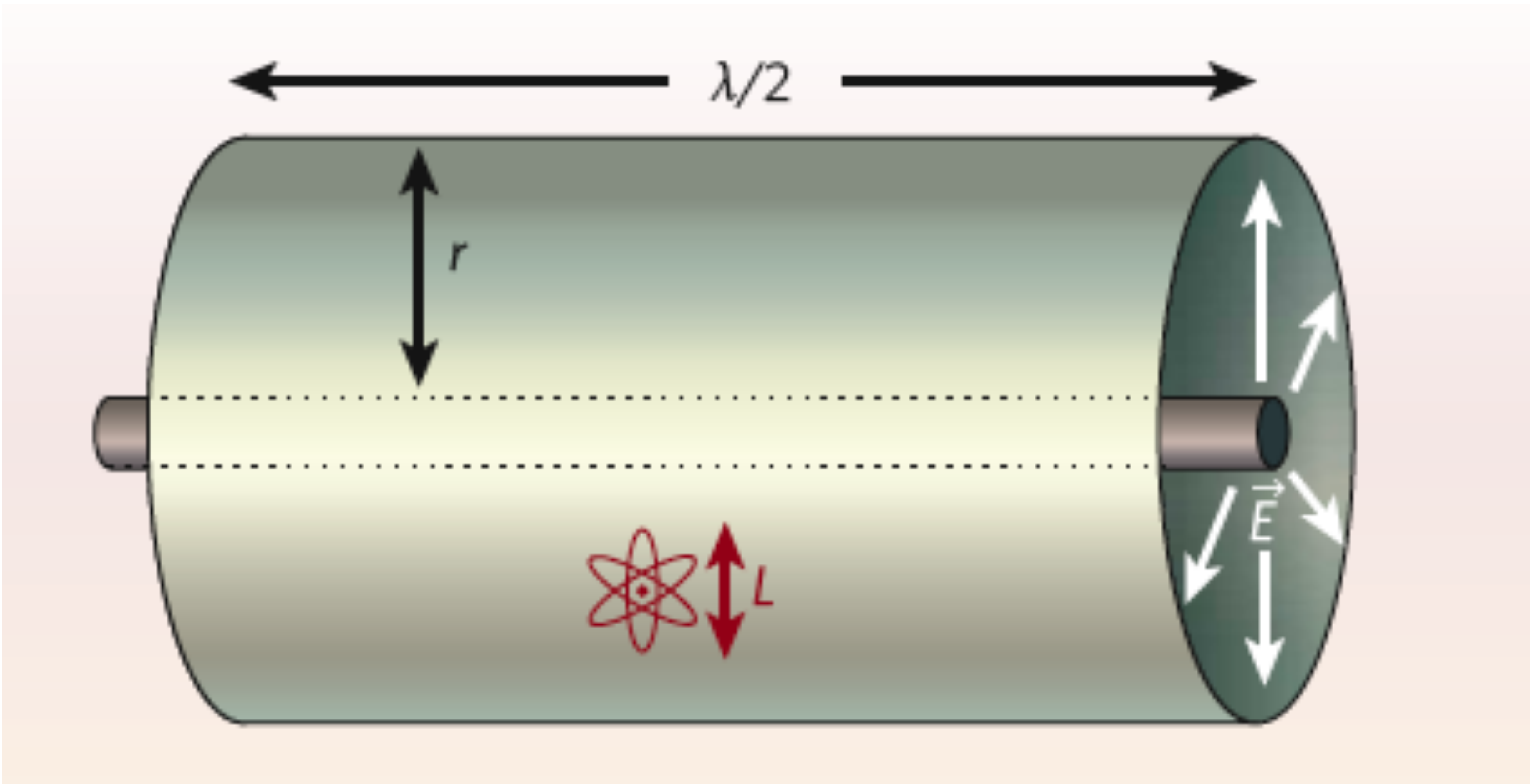
5. Limit of coupling atom and electromagnetic field, the case of circuit QED

nature Vol 451|7 February 2008

Wiring up quantum systems

R. J. Schoelkopf and S. M. Girvin

The emerging field of circuit quantum electrodynamics could pave the way for the design of practical quantum computers.



The dipole d with characteristic length L is in a coaxial cavity of lengh $\lambda/2$ and radius r

The coaxial mode volume is much more confined than λ³

$$g = \frac{dE_\upsilon}{\hbar}; \quad d = eL$$

$$V_{eff} = \pi r^2 \lambda / 2;$$

$$E_\upsilon = \frac{1}{r}\sqrt{\frac{\hbar\omega^2}{2\pi^2\varepsilon_0 c}}$$

$$\frac{g}{\omega} = \left(\frac{L}{r}\right)\sqrt{\frac{e^2}{2\pi^2\varepsilon_0\hbar c}} = \left(\frac{L}{r}\right)\sqrt{\frac{2\alpha}{\pi}}$$

Now the coupling constant can be a percentage of the frequency!

$$\frac{g}{\omega} = \left(\frac{L}{r}\right)\sqrt{\frac{2\alpha}{\pi}} = 0.068\left(\frac{L}{r}\right)$$

Be careful as the Jaynes Cummings model may no longer be adequate

Some bibliography:

1. Hyatt M. Gibbs, *Optical Bistability: Controlling Light with Light* (Academic Press, Orlando, 1985).

2. L. A. Lugiato, *Optical Bistability*, in Progress in Optics, edited by E. Wolf (North-Holland, Amsterdam, 1984), Vol. XXI, pp. 69-216.

3. *Cavity Quantum Electrodynamics*, edited by Paul R. Berman, Advances in Atomic Molecular and Optical Physics Supplement 2, Academic Press, Boston 1994.

4. S. Haroche and J. M. Raimond, *Exploring the Quantum: Atoms, Cavities, and Photons* (Oxford Univ. Press, 2006).

5. S. L. Mielke, G. T. Foster, J. Gripp, and L. A. Orozco, "Time Response of a coupled atoms-cavity system," Opt. Lett. **22**, 325 (1997).

6. Gripp, S. L. Mielke, L. A. Orozco, "Evolution of the Vacuum Rabi Peaks in a detuned Atoms-Cavity System," Phys. Rev. A **56**, 3262 (1997).

7. P. Solano, J. A. Grover, J. E. Hoffman, S. Ravets, F. K. Fatemi, L. A. Orozco, and S. L. Rolston “Optical Nanofibers: A New Platform for Quantum Optics.” Advances in Atomic Molecular and Optical Physics, Vol. 46, 355-403, Edited by E. Arimondo, C. C. Lin, and S. F. Yelin, Academic Press, Burlington 2017. arXiv:1703.10533

8.- R. J. Schoelkopf and S. M. Girvin, “Wiring up quantum systems.” Nature, **451**, (2008)

Thanks