Quantum Optics: when do we need it?
Part 2: for light-matter interaction

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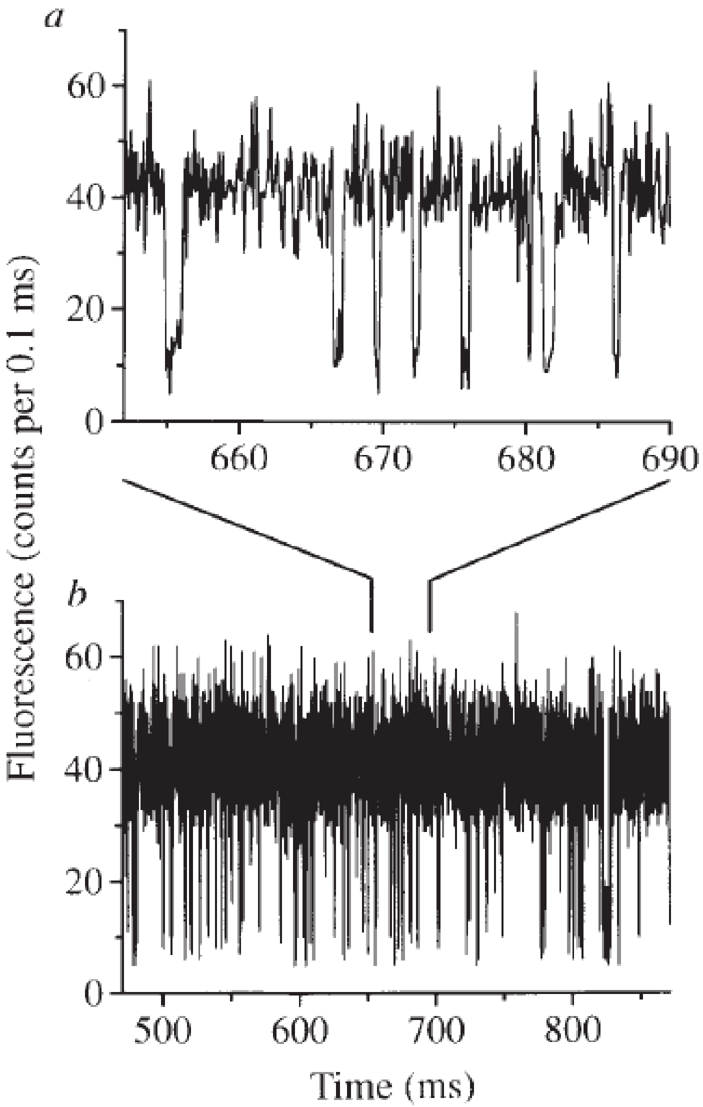
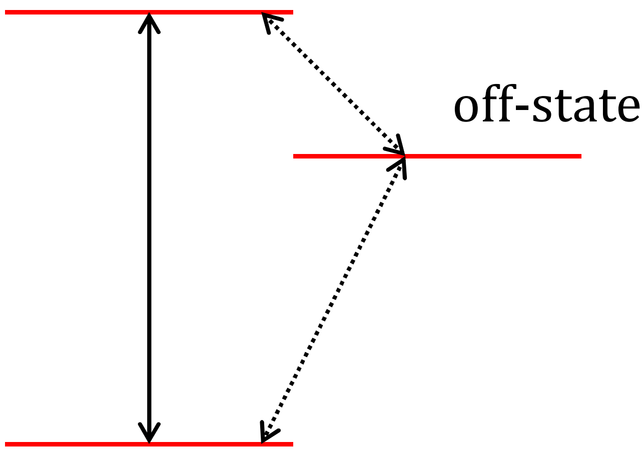
Intermittent fluorescence due to quantum jumps

Quantization of the atomic system is enough; no field quantization





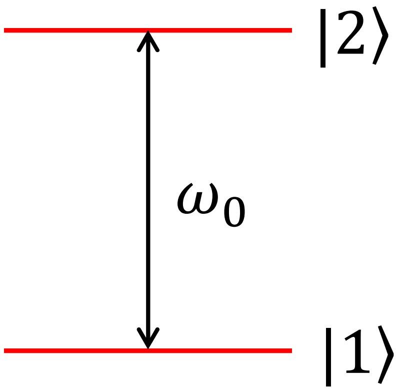
Th. Basché et al., Nature 373, 132 (1995)

Interaction Hamiltonian

$$\mathcal{H} = \mathcal{H}_{field} + \mathcal{H}_{atom} + \mathcal{H}_{interaction}$$

$$\mathcal{H}_{field} = \hbar\omega_L\left(\hat{a}^{\dagger}\hat{a} + \frac{1}{2}\right)$$

$$\mathcal{H}_{atom} = \hbar\omega_0(|2\rangle\langle 2| - |1\rangle\langle 1|)$$



Interaction via electric dipole:

$$\begin{aligned}\mathcal{H}_{interaction} &= -\hat{\mu}(t).\hat{E}(t)\\ &= \hbar\Omega_R\left(e^{-i\omega_0 t}|2\rangle\langle 1| + e^{i\omega_0 t}|1\rangle\langle 2|\right)\left(e^{-i\omega_L t} + e^{i\omega_L t}\right)/2\\ &\approx \hbar\Omega_R/2\left(e^{i(\omega_L-\omega_0)t}|2\rangle\langle 1| + e^{-i(\omega_L-\omega_0)t}|1\rangle\langle 2|\right)\end{aligned}$$

(rotating-wave approximation)

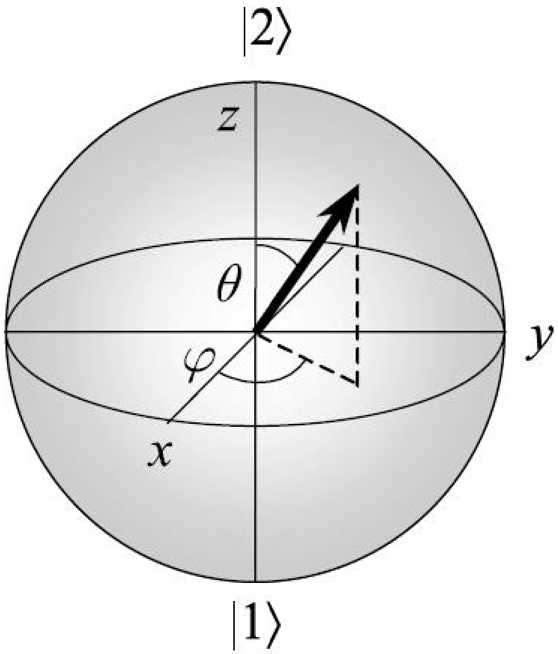
Rabi frequency: $\Omega_R \equiv \mu_{12}.E_0/\hbar$

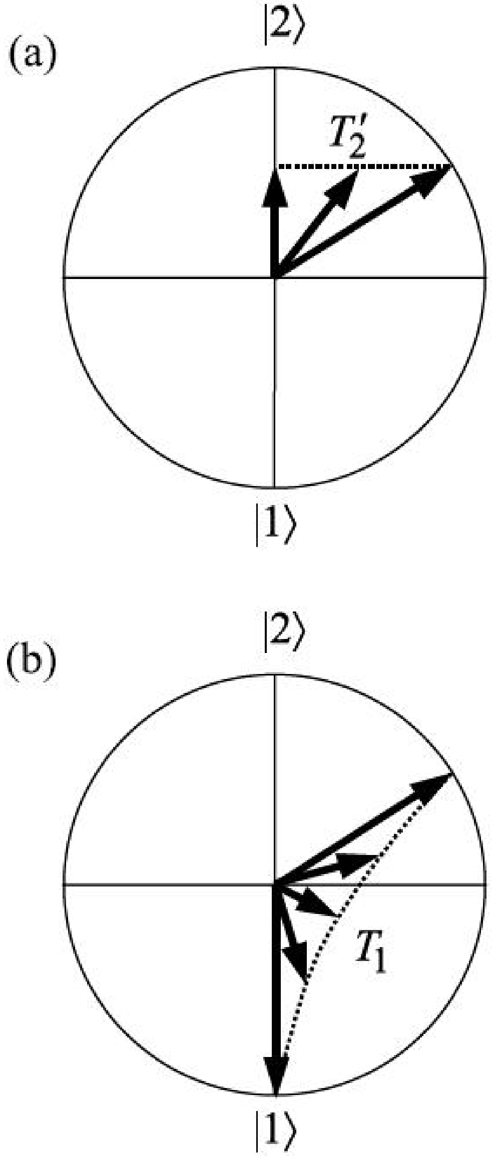
Bloch sphere & atomic decay processes

$$|\psi\rangle = c_1|1\rangle + c_2|2\rangle$$

$$S_z = \langle |c_2|^2 - |c_1|^2 \rangle$$

$$S_x + iS_y = \langle 2c_1 . c_2^* \rangle$$





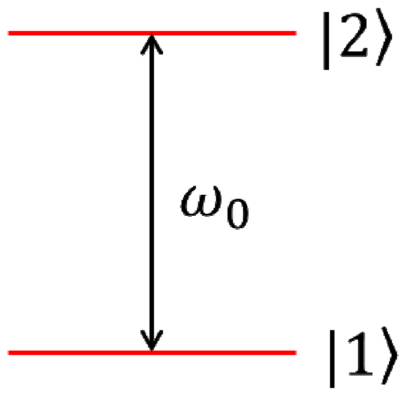
Pure dephasing

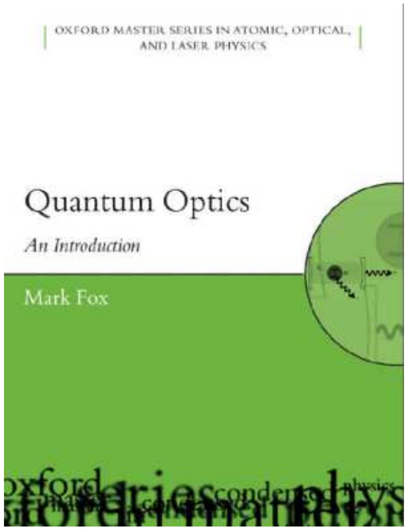
Population decay

Figs. 9.9 & 9.10 from 'Quantum optics' by M. Fox

Rabi oscillations in strongly driven system

Rabi oscillations do not require optical field quantization





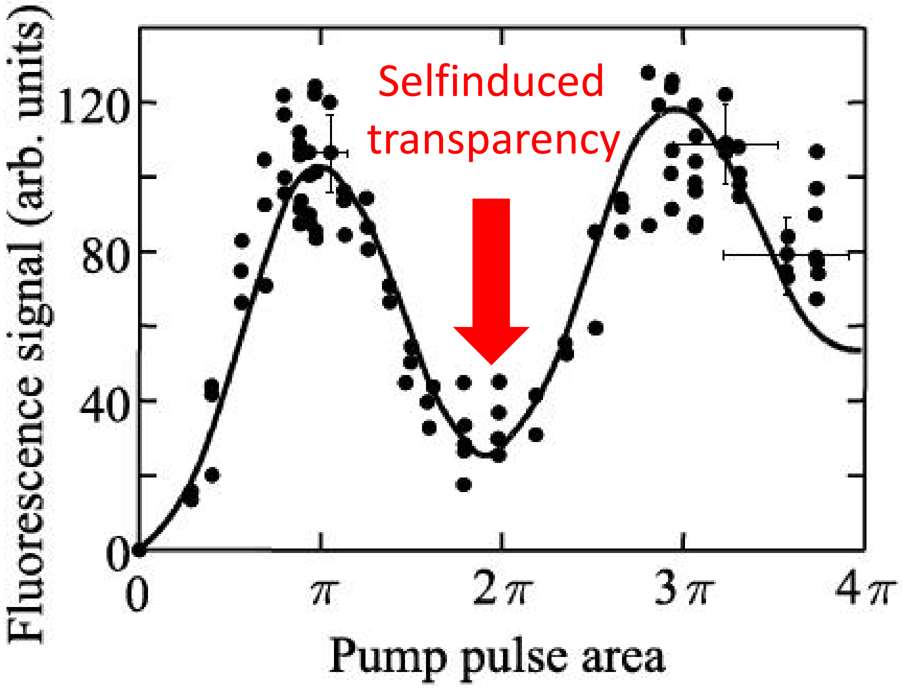
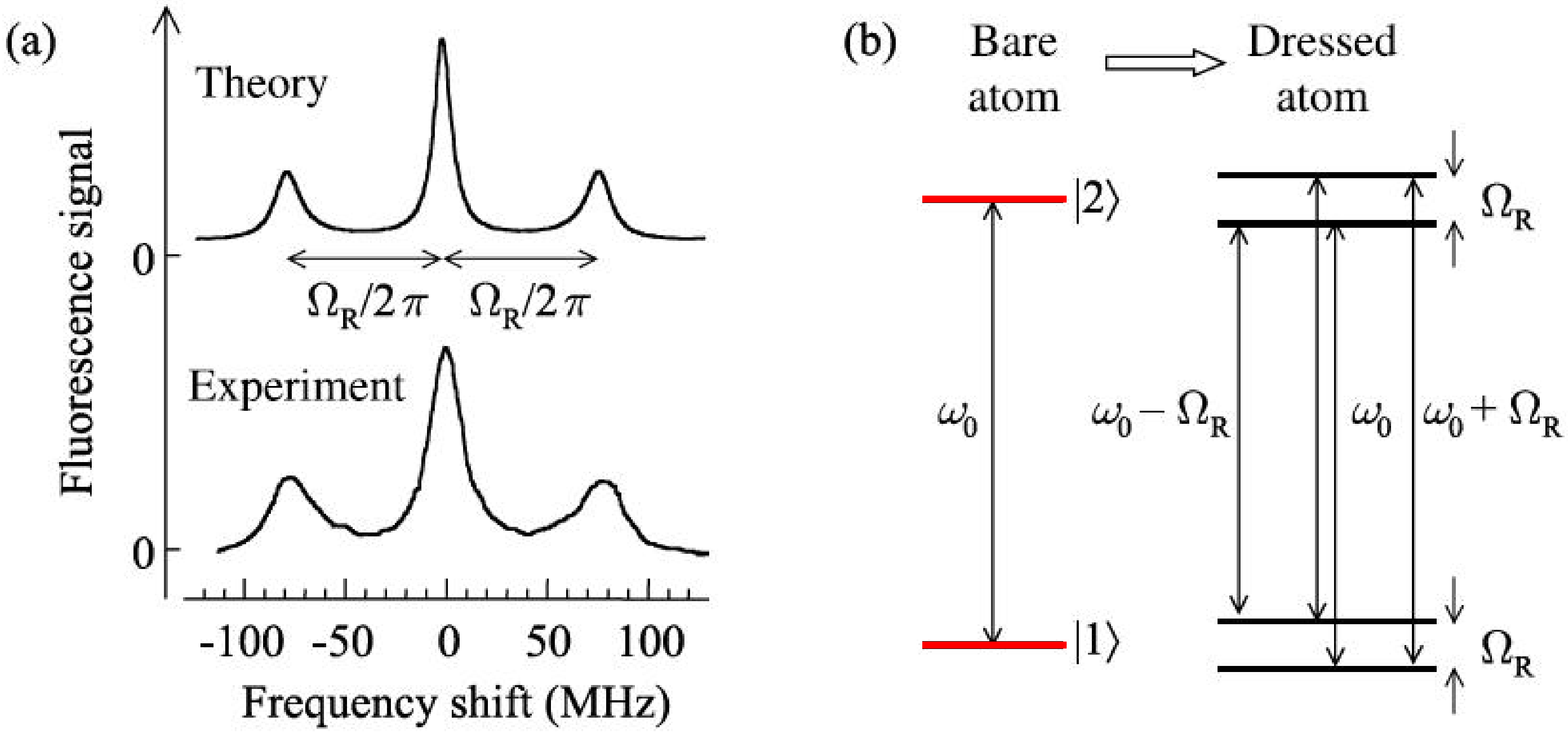


Fig. 9.6 from 'Quantum optics' by M. Fox

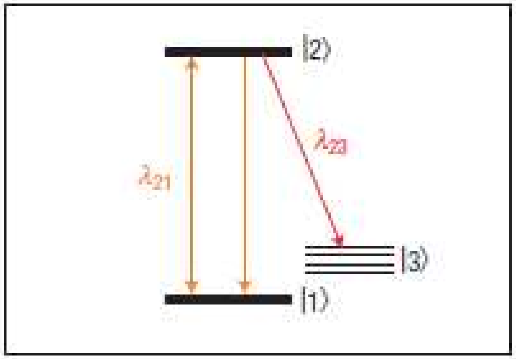
Mollow triplet observed in resonant fluorescence

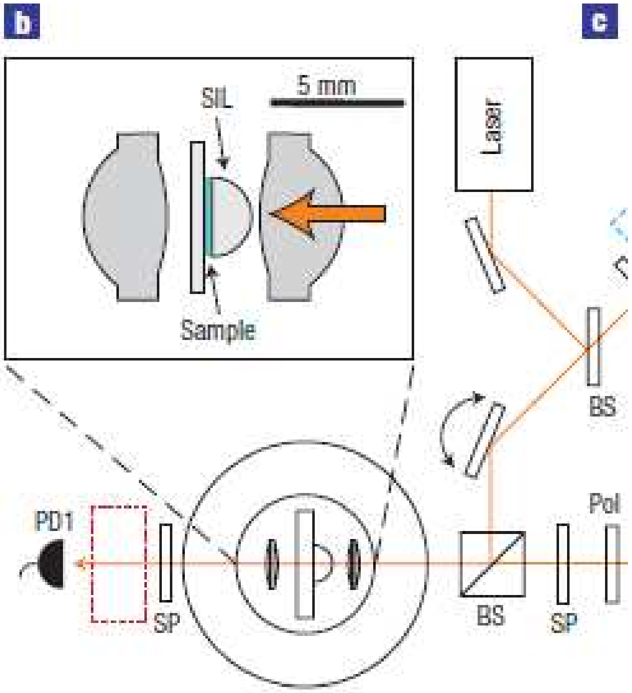


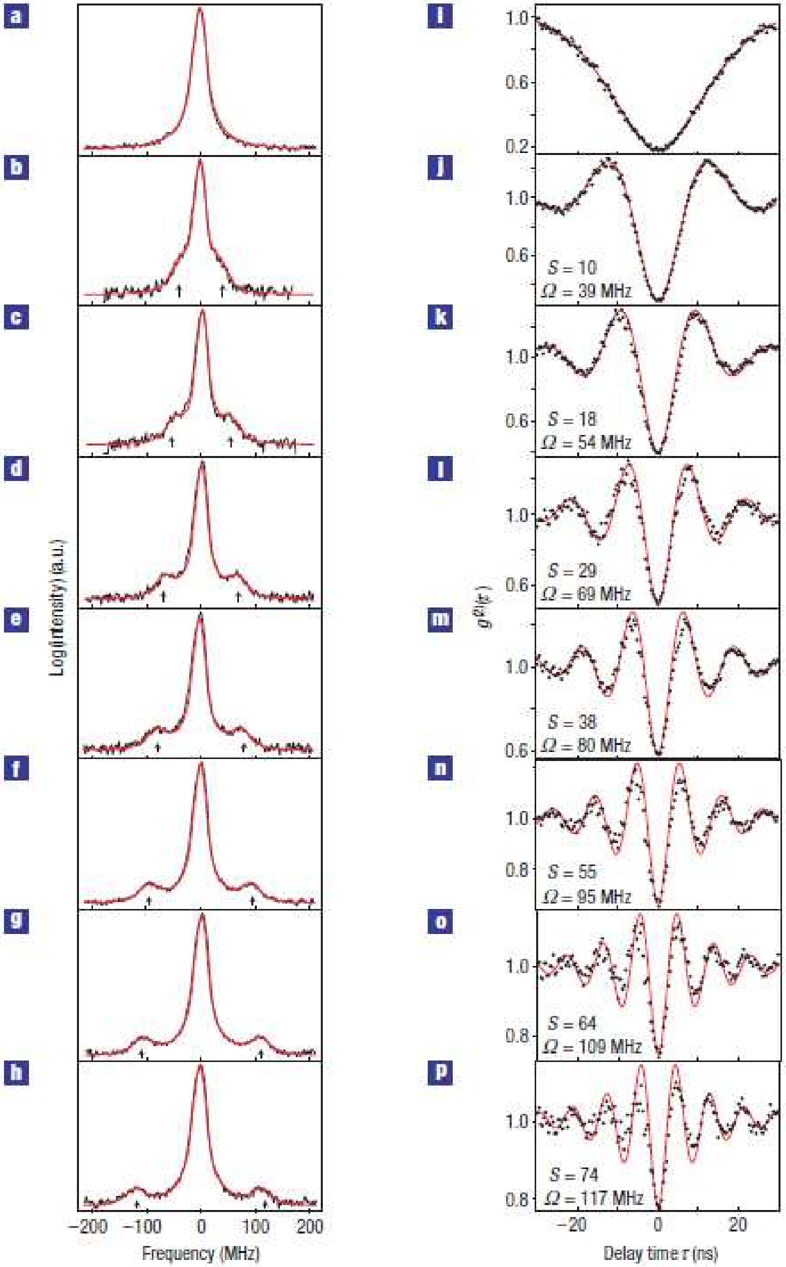
Dressed states: $\boxed{|\psi\rangle = (|1, n+1\rangle \pm |2, n\rangle)/\sqrt{2}}$

Fig. 9.7 from 'Quantum optics' by M. Fox

Resonant fluorescence & time correlation



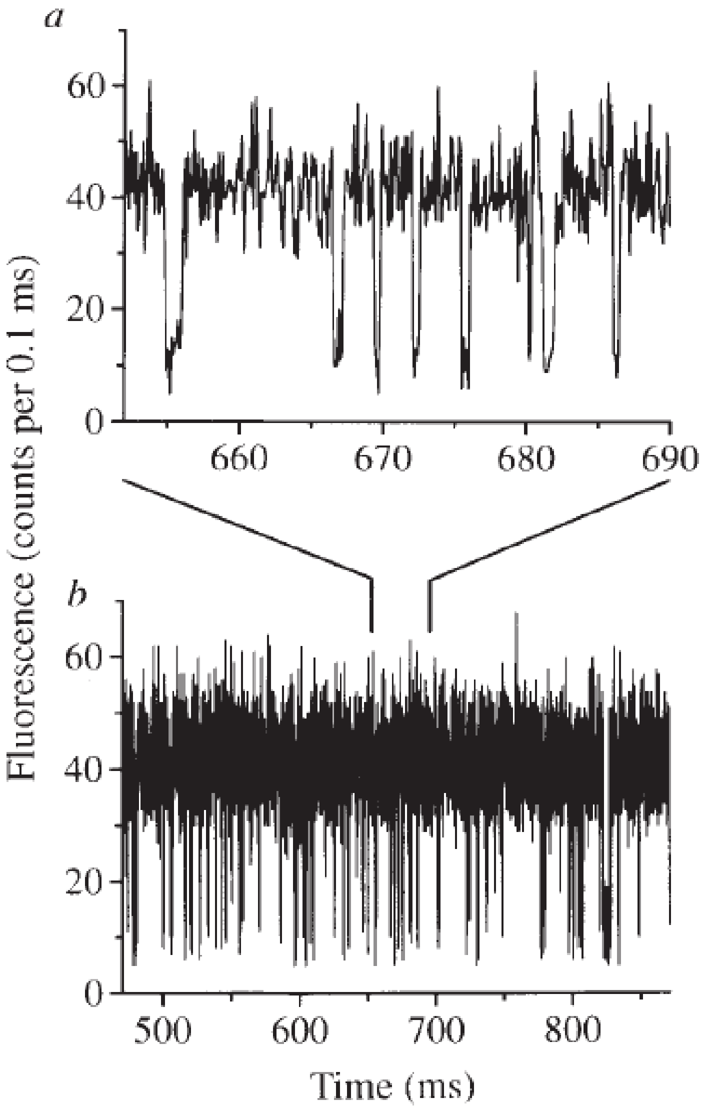


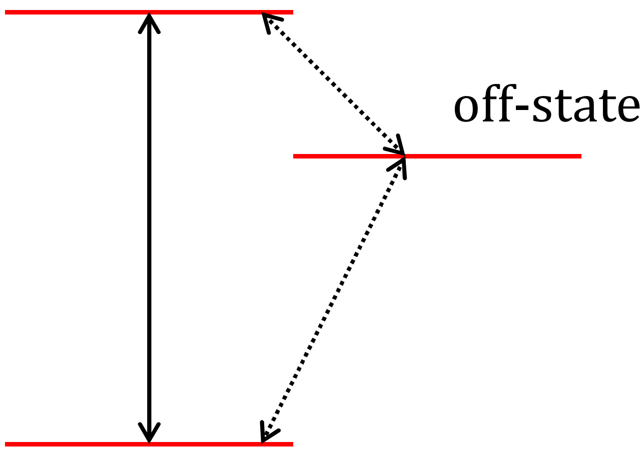


Wrigge et. Al, Nature physics 4, 80 (2008)

Intermittent fluorescence due to quantum jumps

Quantization of the atomic system is enough; no field quantization





Th. Basché et al., Nature 373, 132 (1995)

Nobel prize in Chemistry 2014

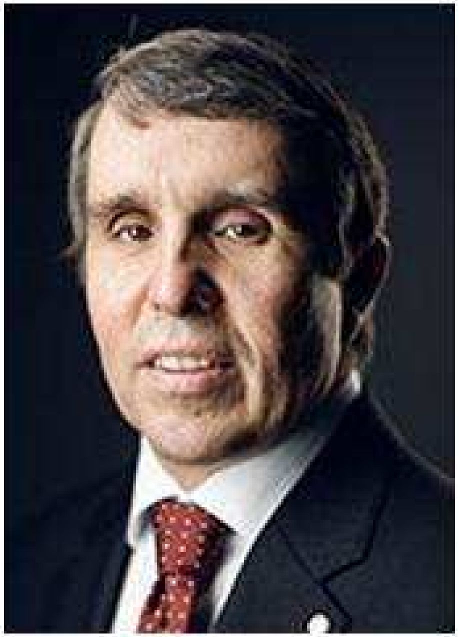


Photo: A. Mahmoud

Eric Betzig

Prize share: 1/3

Photo: A. Mahmoud

Stefan W. Hell

Prize share: 1/3

Photo: A. Mahmoud

William E. Moerner

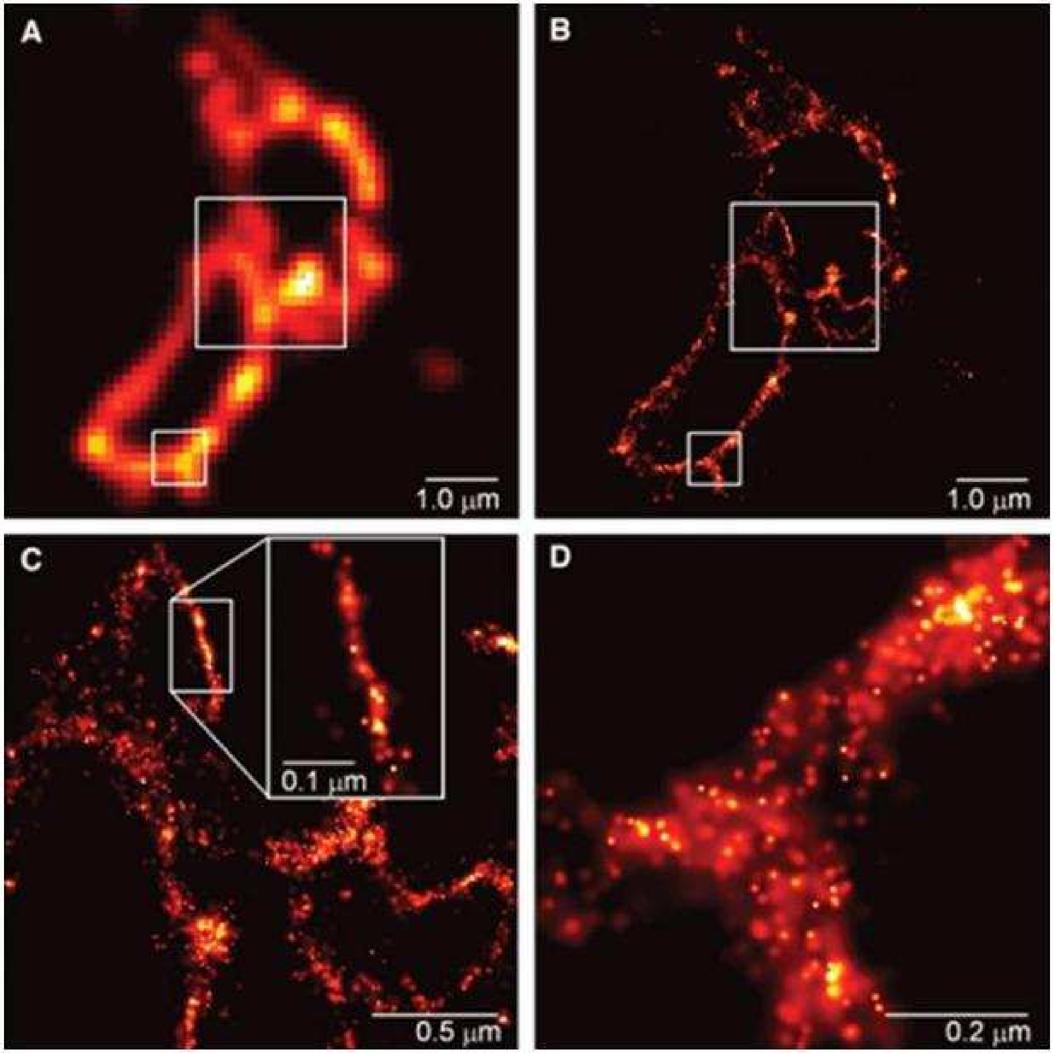
Prize share: 1/3

The Nobel Prize in Chemistry 2014 was awarded jointly to Eric Betzig, Stefan W. Hell and William E. Moerner *"for the development of super-resolved fluorescence microscopy"*.

Eric Betzig: Super-resolved fluorescence microscopy

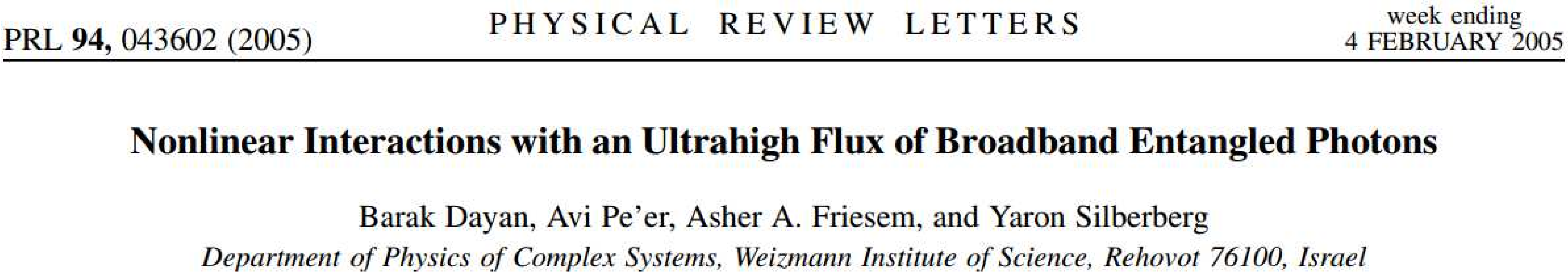
A. Diffraction limit

B-D.
Single-molecule
imaging



PALM = Photo-activated localization microscopy
STORM = Stochastic optical reconstruction microscopy

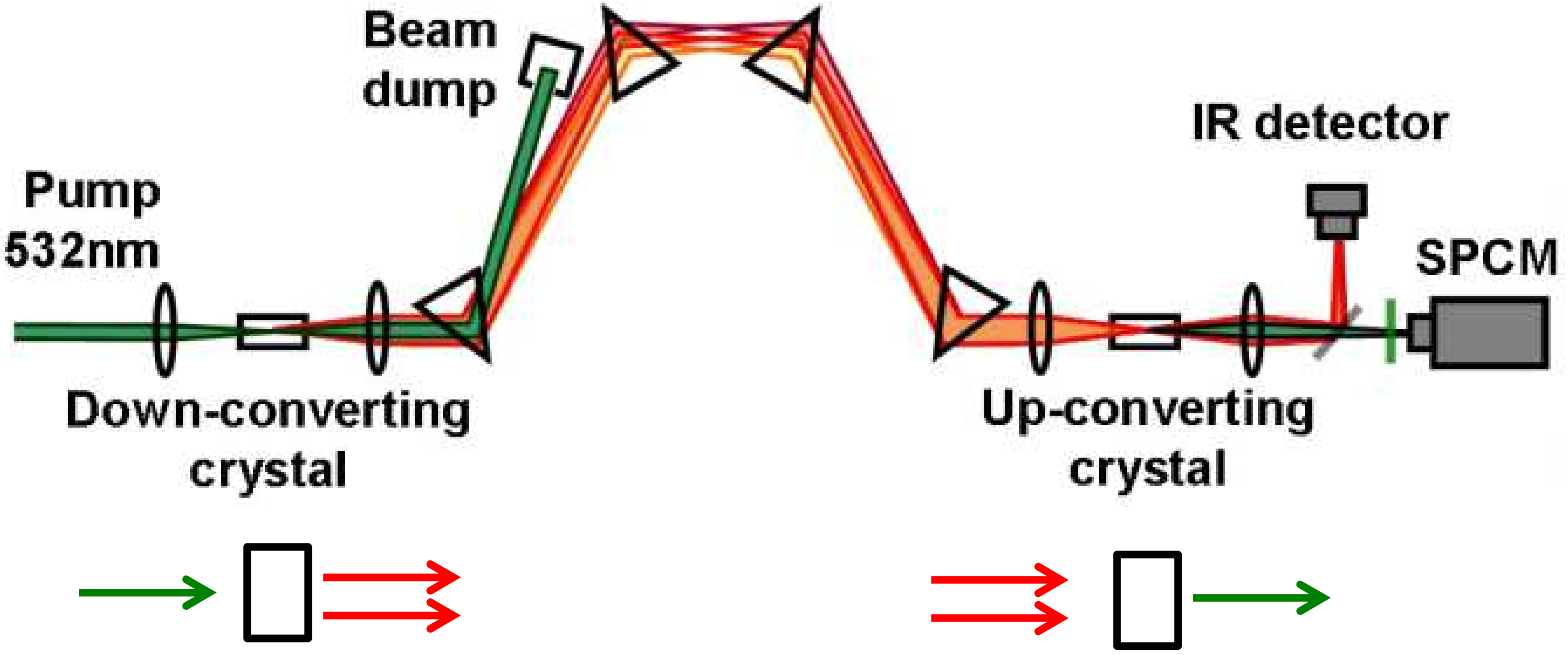
Nonlinear interaction can require field quantization



PRL **94,** 043602 (2005) PHYSICAL REVIEW LETTERS week ending 4 FEBRUARY 2005

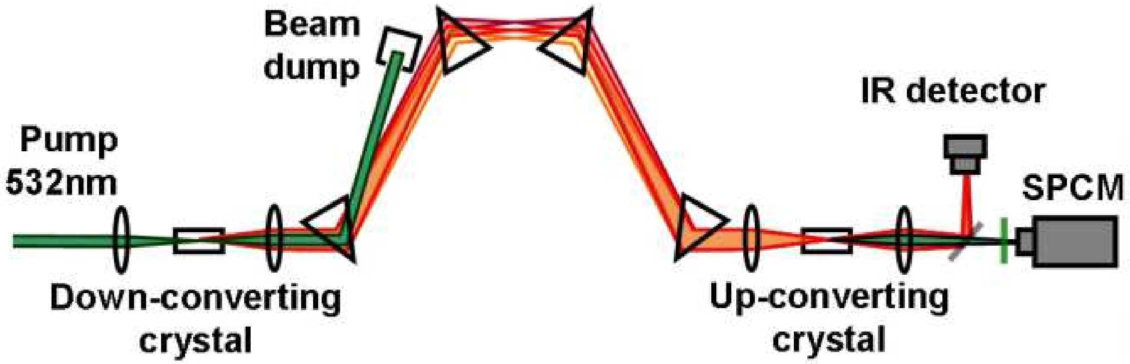
Nonlinear Interactions with an Ultrahigh Flux of Broadband Entangled Photons

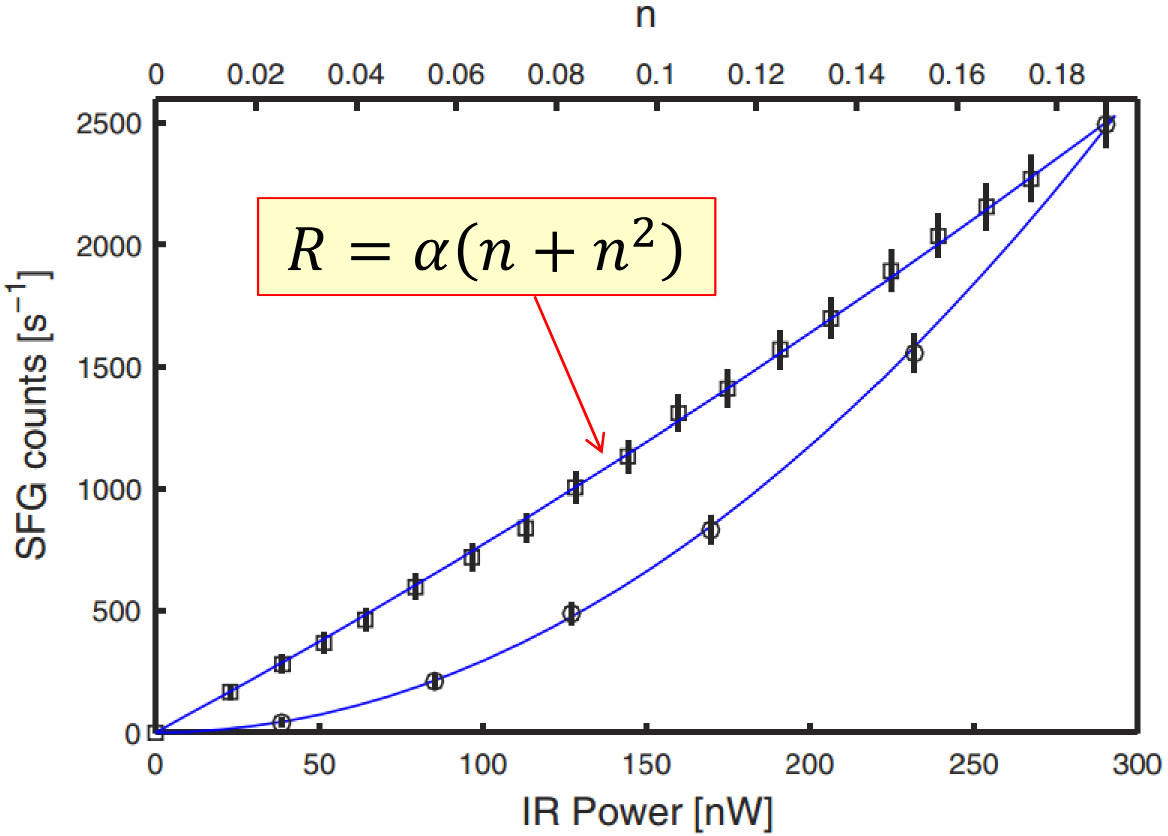
Barak Dayan, Avi Pe'er, Asher A. Friesem, and Yaron Silberberg
Department of Physics of Complex Systems, Weizmann Institute of Science, Rehovot 76100, Israel



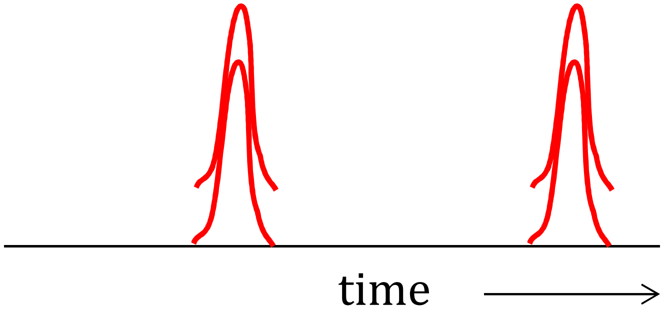
Experiment: place neutral density filter in pump or pair beam

Second-harmonic generation with entangled photons



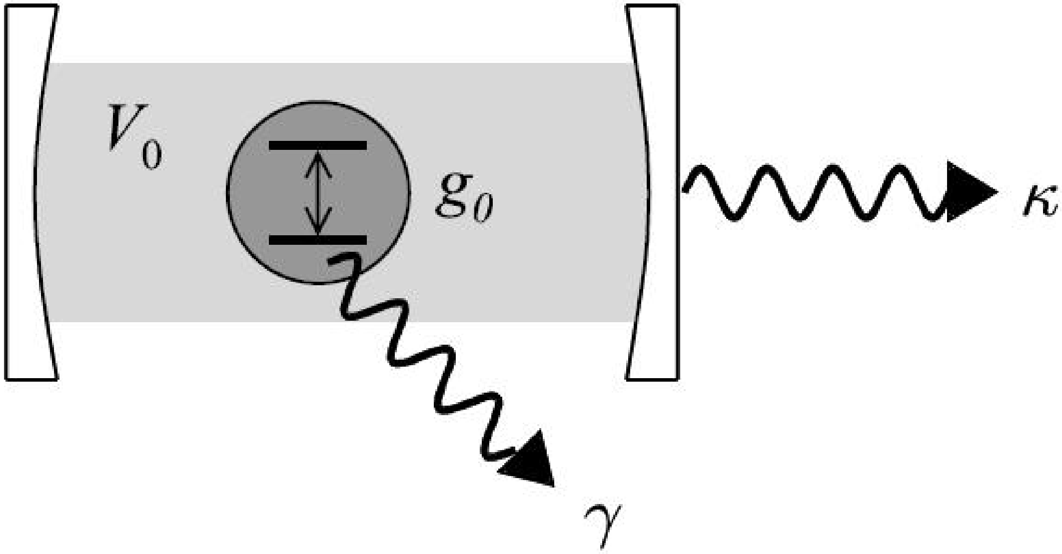


$$R = \alpha(n + n^2)$$



Interaction with discrete optical modes

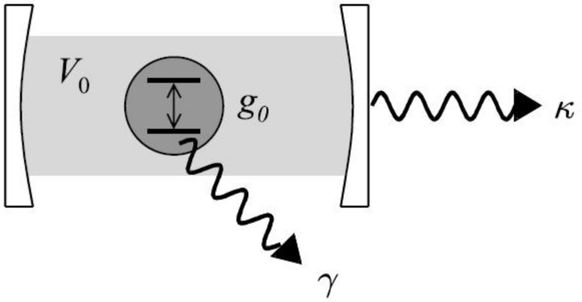
Claim: Field quantization is only needed to describe interaction with discrete modes of the optical field (= field in a cavity)



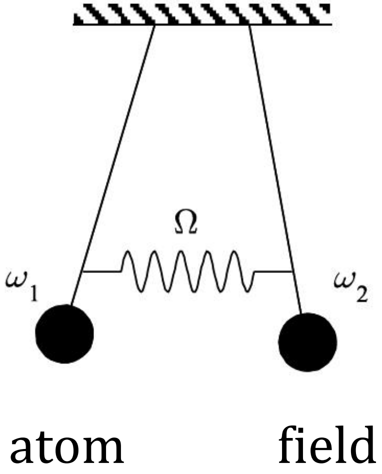
Three rates:
- Decay atomic coherence γ
- Decay optical field κ
- Interaction (vacuum Rabi) $g = \Omega_0$

Fig. 10.4 from 'Quantum optics' by M. Fox

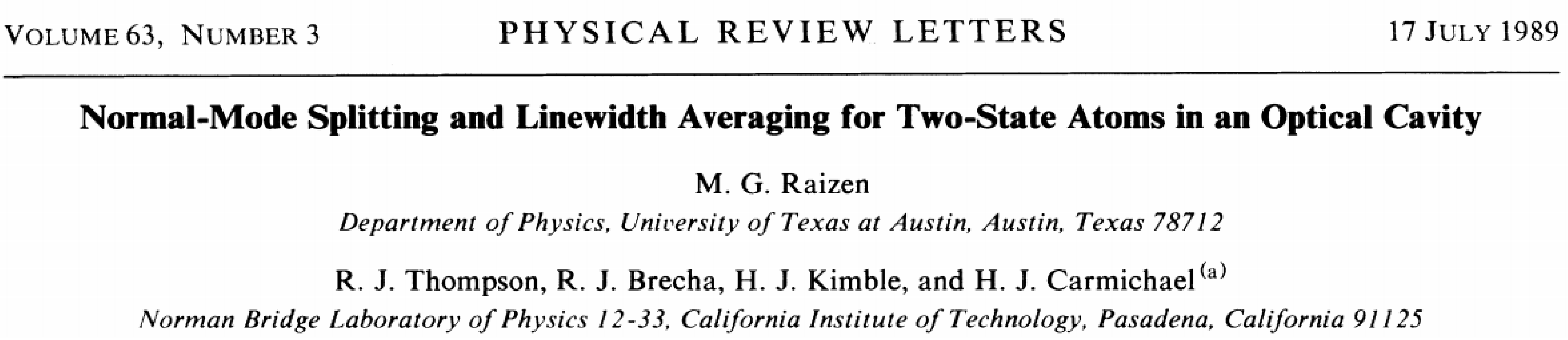
Three regimes of coupling



- Weak coupling: $g \ll \{\gamma, \kappa\}$
- Intermediate coupling: $\gamma < g < \kappa$ Cooperativity: $C = g^2/\kappa\gamma$
- Strong coupling: $g > \{\gamma, \kappa\}$
  (Dressed states)



Transmission spectra of optical cavity with N>>1 Na atoms

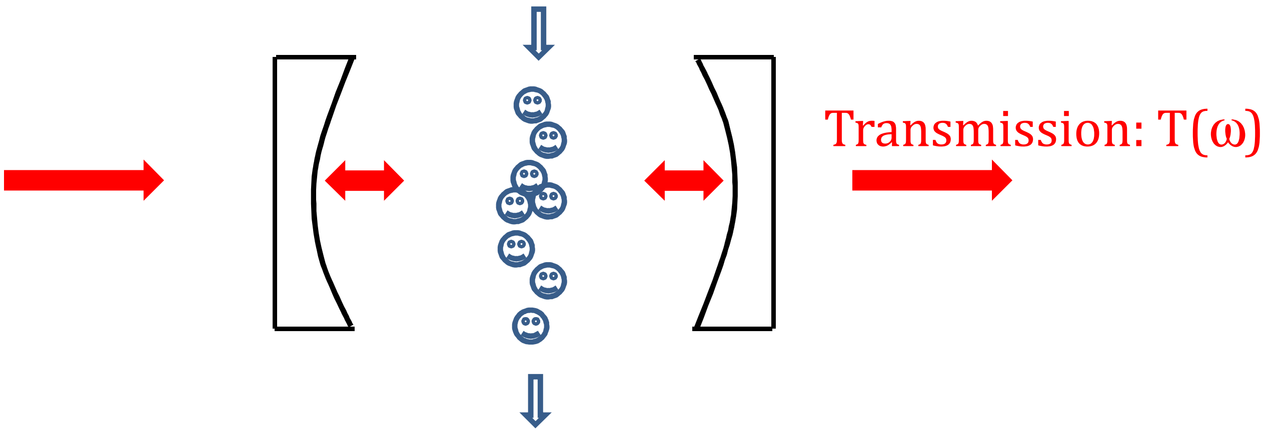


VOLUME 63, NUMBER 3 PHYSICAL REVIEW LETTERS 17 JULY 1989

Normal-Mode Splitting and Linewidth Averaging for Two-State Atoms in an Optical Cavity

M. G. Raizen
Department of Physics, University of Texas at Austin, Austin, Texas 78712

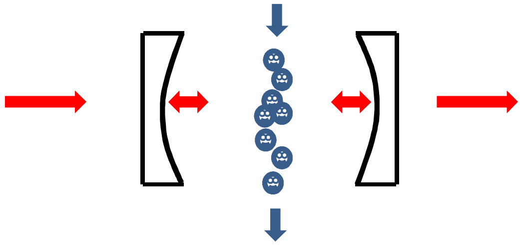
R. J. Thompson, R. J. Brecha, H. J. Kimble, and H. J. Carmichael[(a)]
Norman Bridge Laboratory of Physics 12-33, California Institute of Technology, Pasadena, California 91125



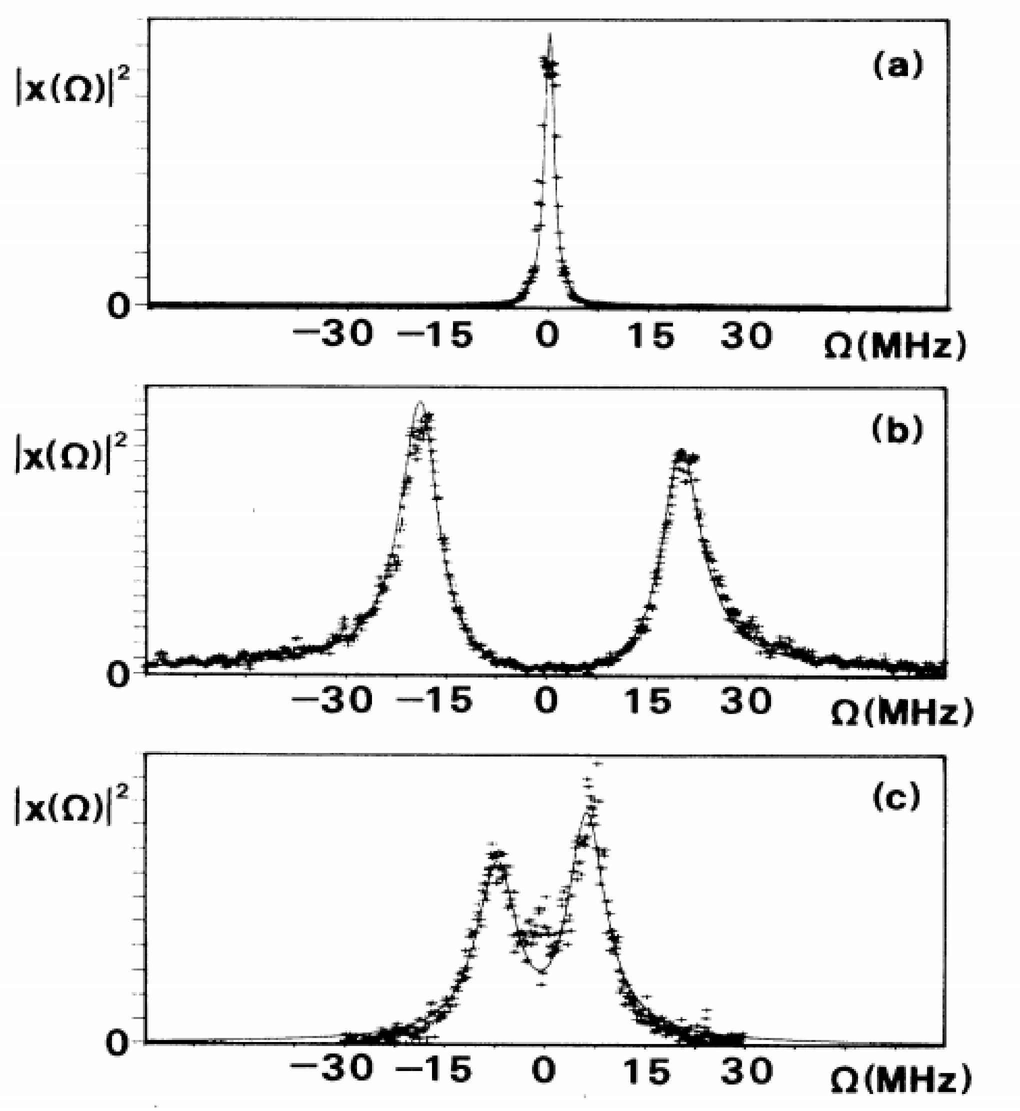
Transmission: T(ω)

Na atoms falling through optical cavity
on average 20 < N < 600 atoms in cavity

Transmission spectra of optical cavity with N>>1 Na atoms



Normal mode splitting $\propto \sqrt{N} \propto \sqrt{C}$



- Empty cavity

  Cooperativity C=0

- C = 36

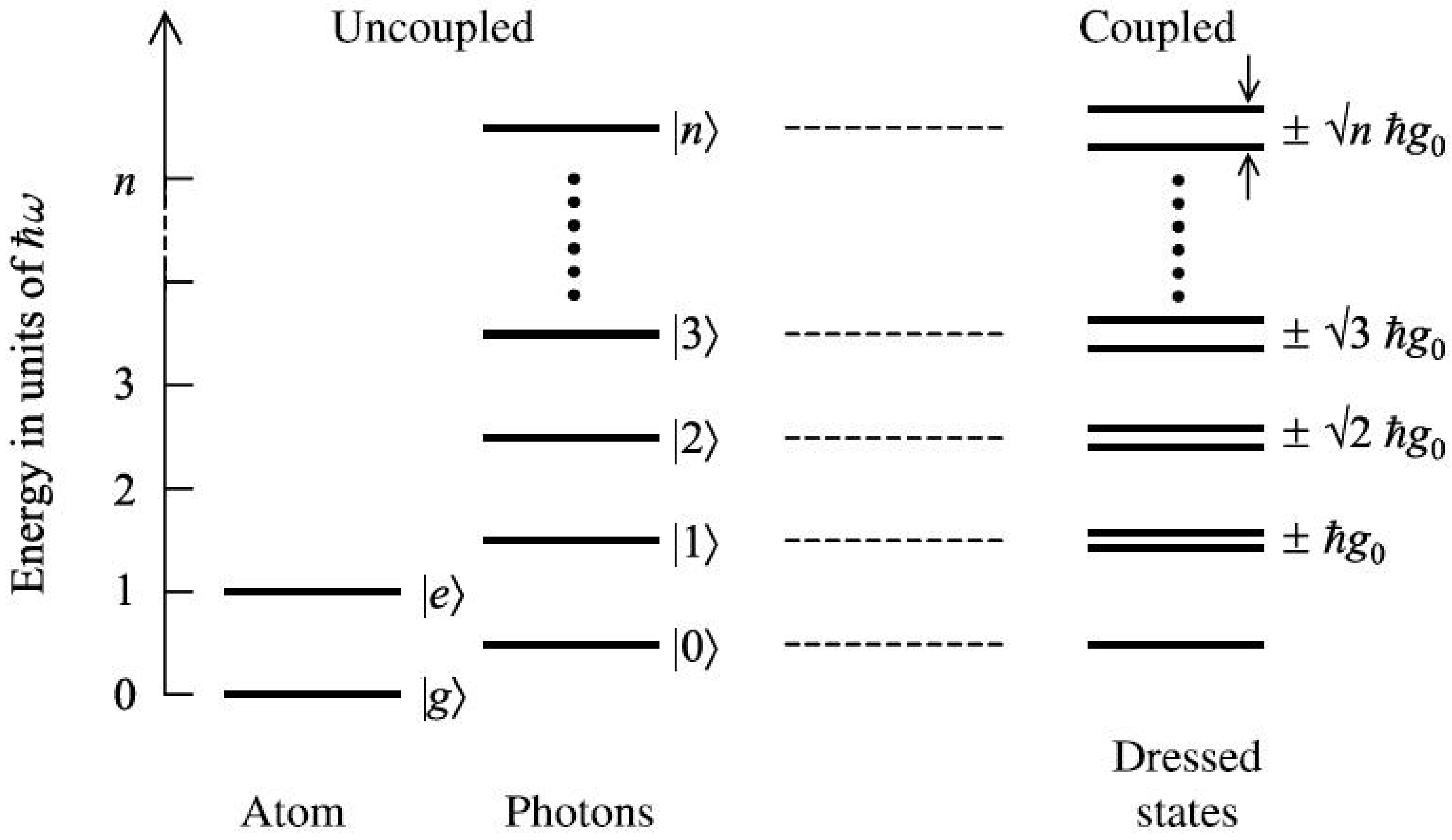
- C=4.7

Jaynes-Cummings ladder of dressed states

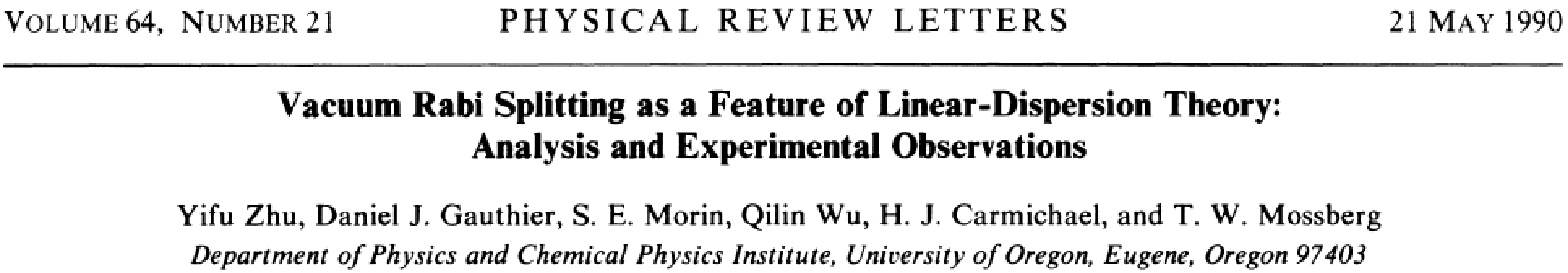
$$\boxed{\mathcal{H}_{interaction} = \hbar g_0 \left(\hat{a}|2\rangle\langle 1| + \hat{a}^\dagger |1\rangle\langle 2|\right)}$$ (single atom)

$$\boxed{g = g_0\sqrt{n+1}\sqrt{N}}$$

n = number of photons
N = number of atoms



Classical explanation for vacuum Rabi splitting



VOLUME 64, NUMBER 21 PHYSICAL REVIEW LETTERS 21 MAY 1990

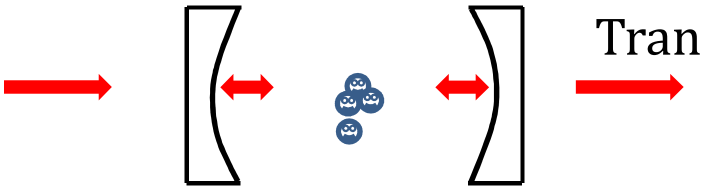
Vacuum Rabi Splitting as a Feature of Linear-Dispersion Theory: Analysis and Experimental Observations

Yifu Zhu, Daniel J. Gauthier, S. E. Morin, Qilin Wu, H. J. Carmichael, and T. W. Mossberg
Department of Physics and Chemical Physics Institute, University of Oregon, Eugene, Oregon 97403

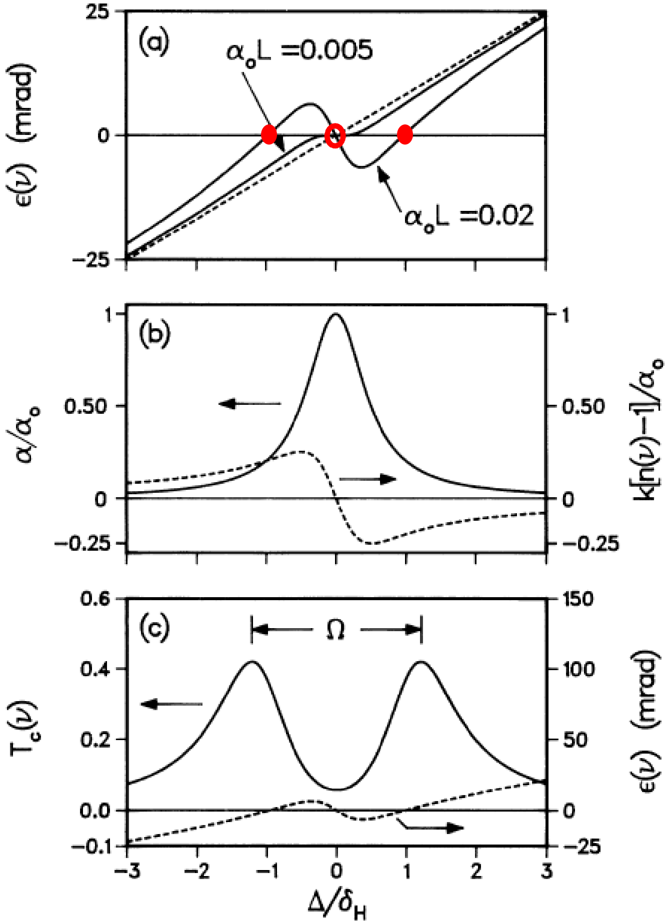
Optical phase delay ε(ω) upon cavity roundtrip

Medium: absorption + dispersion

$$\boxed{\alpha(\omega) = \alpha_0/[1 + i(\omega - \omega_0)/\gamma]}$$



Transmission: T(ω)



Nobel prize in Physics 2012

Photo: U. Montan

Serge Haroche

Prize share: 1/2

Photo: U. Montan

David J. Wineland

Prize share: 1/2

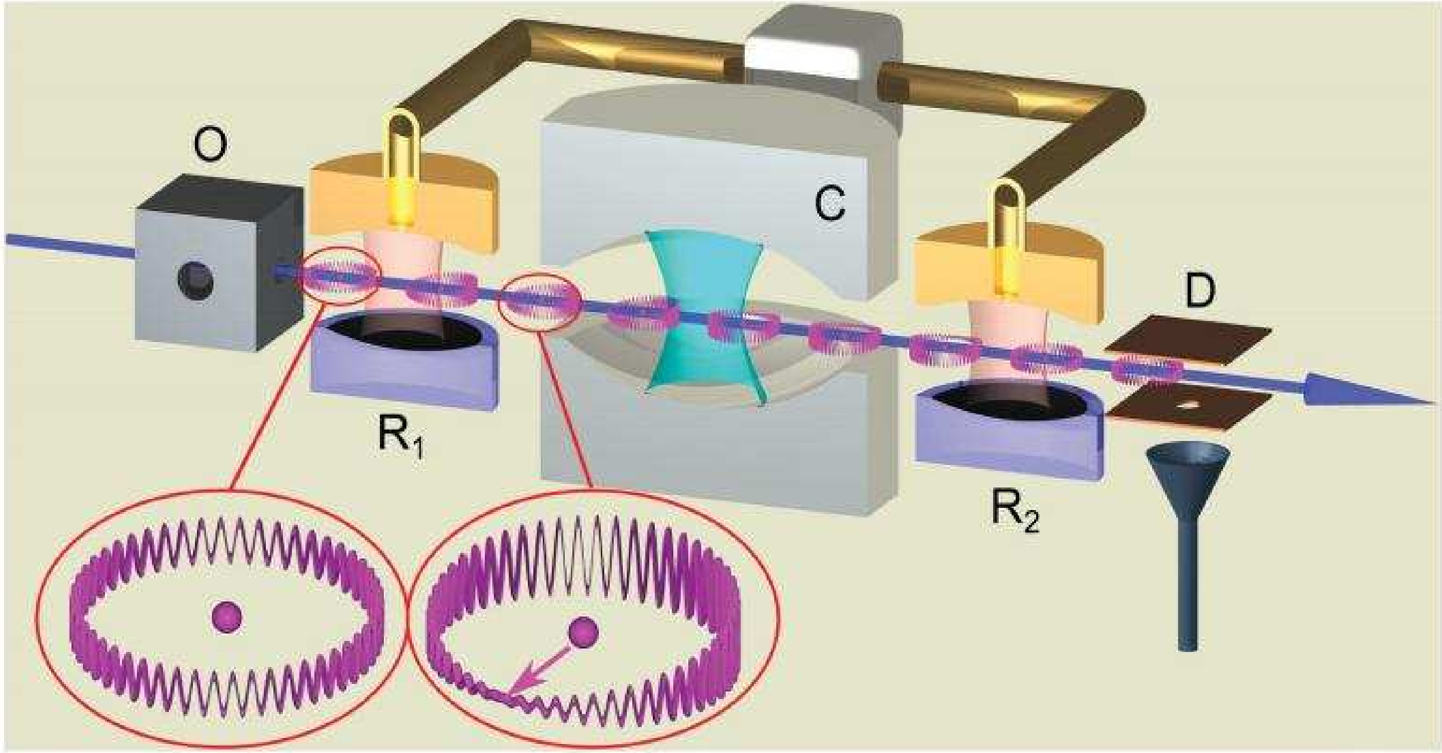
The Nobel Prize in Physics 2012 was awarded jointly to Serge Haroche and David J. Wineland *"for ground-breaking experimental methods that enable measuring and manipulation of individual quantum systems"*

REVIEWS OF MODERN PHYSICS, VOLUME 85, JULY–SEPTEMBER 2013

Nobel Lecture: Controlling photons in a box and exploring the quantum to classical boundary[*]

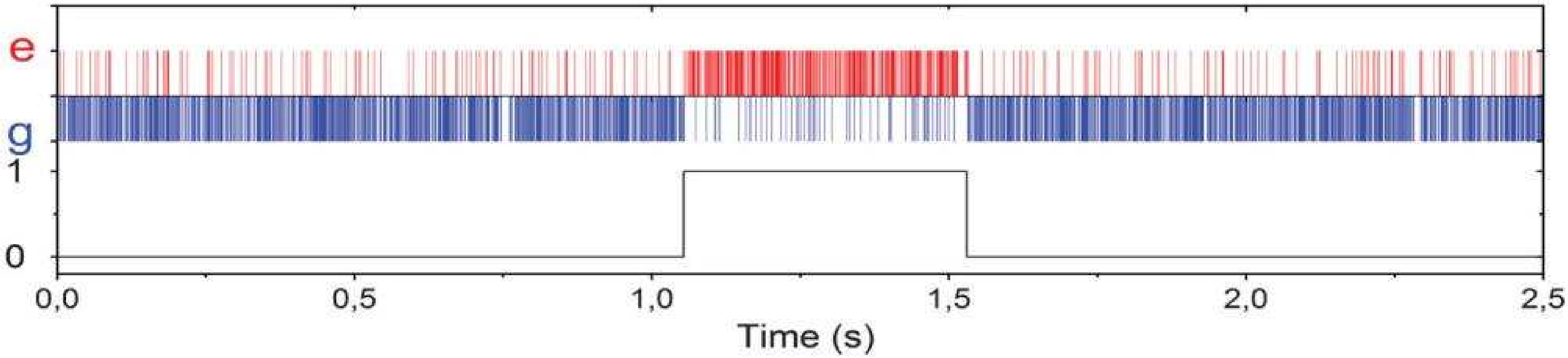
Serge Haroche

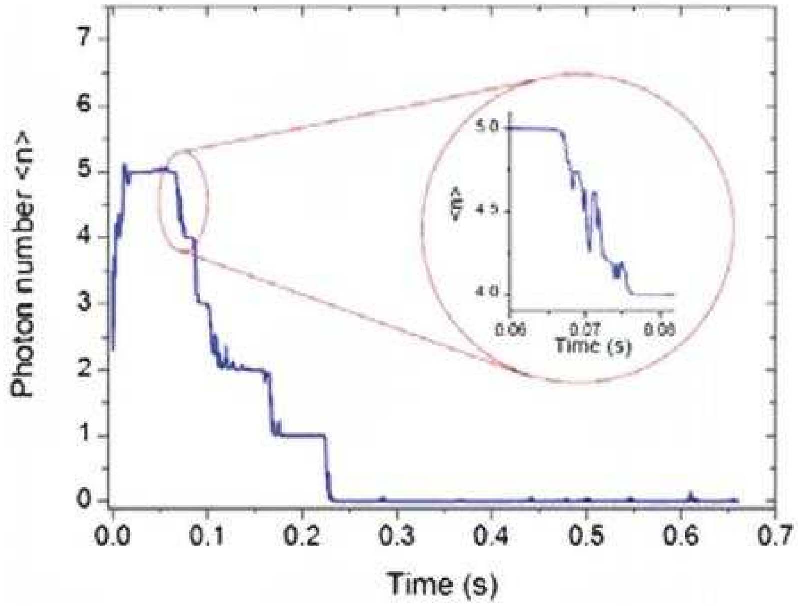
Laboratoire Kastler Brossel de l'Ecole Normale Supérieure, 24 Rue Lhomond, 75231, Paris, and Collège de France, 11 Place Marcelin Berthelot, 75005, Paris, France

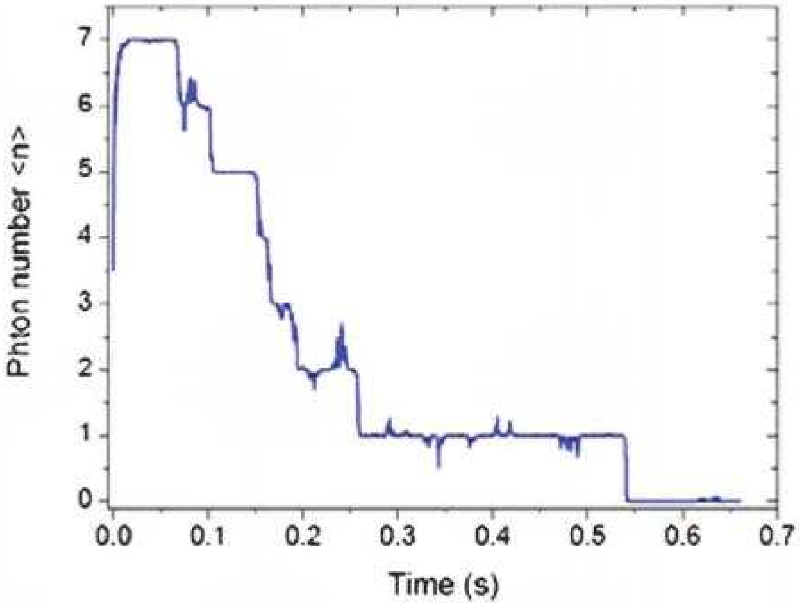


Haroche: observation of quantum jumps in the field!

Example of measurement of quantum jumps in the optical field:

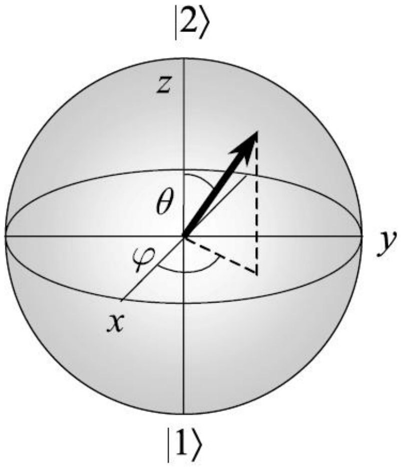






Conclusion: When do we need quantum optics?

- Optics in free space: classical field suffices (practically always)
  - Quantum description of medium:
    - Bloch sphere, Rabi oscillations & Mollow triplet
  - Special: non-linear optics with quantum-entangled photon pairs



- Optics in cavity: classical description gets you a long way
  - Dressed states in strong-coupling regime
  - Classical description: optical dispersion!
  - Special: heroic cavity QED experiments