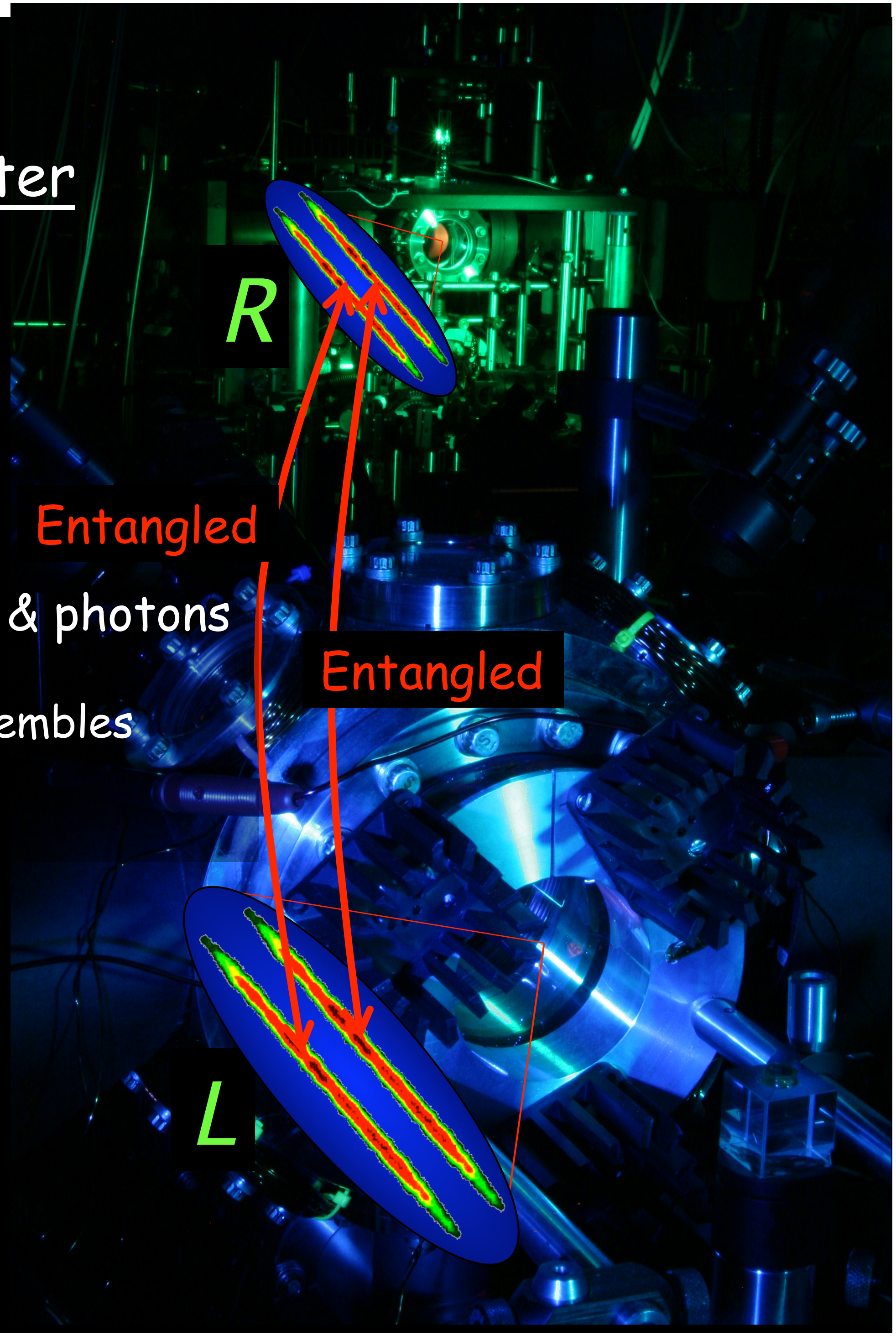
Quantum Networks – The interface of light and matter

H. Jeff Kimble
California Institute of Technology
25 April 2009

- Overview of quantum networks
  - From formal to physical
- Strong interactions of single atoms & photons
  - Cavity quantum electrodynamics
  - Collective excitations & atomic ensembles
  - Quadripartite entanglement – 1 photon shared among 4 modes

Recent review
"The Quantum Internet"
H. J. Kimble, Nature **453**, 1023 (2008)

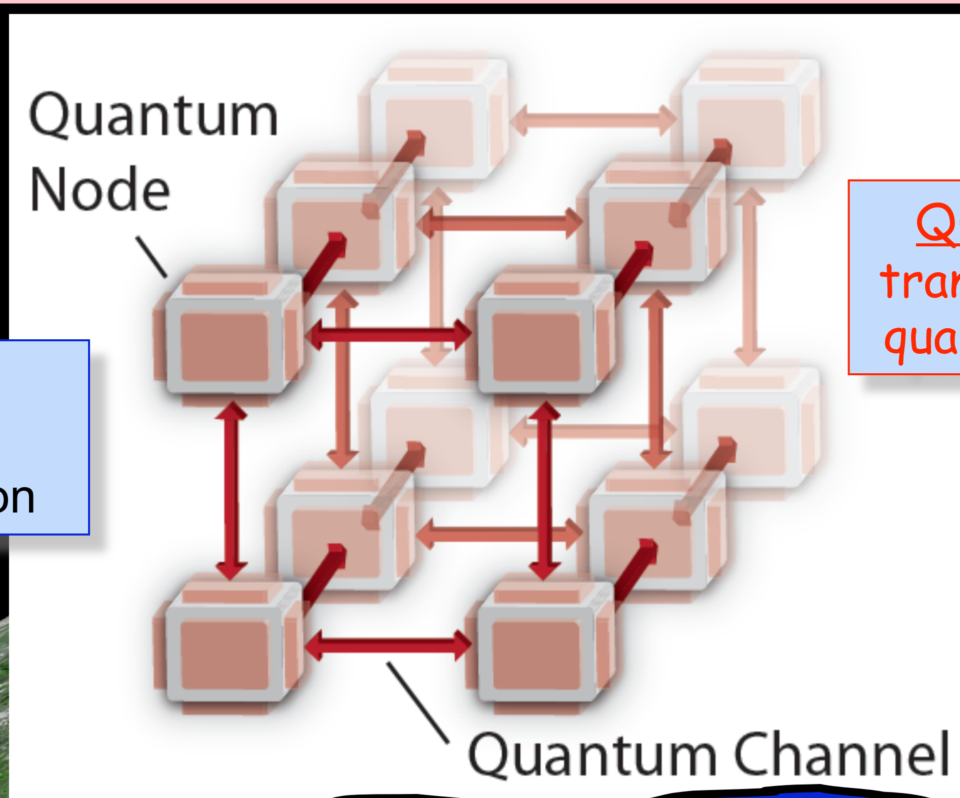


IARPA
BE THE FUTURE

Quantum Optics

Quantum Networks

➪ Fundamental Scientific Question and Diverse Technical Challenges



Quantum Node-
process / store
quantum information

Quantum Channel -
transport / distribute
quantum entanglement

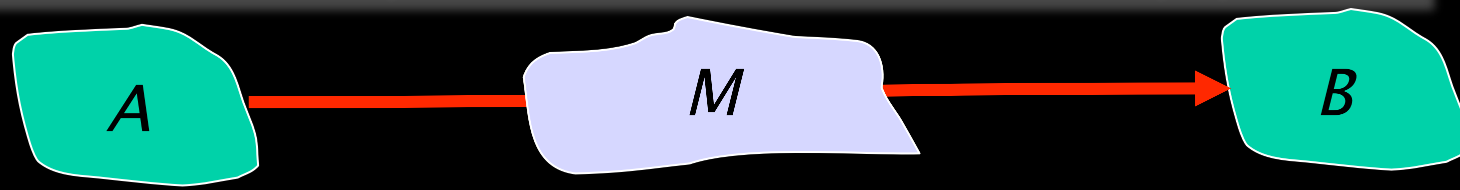
Theoretical issues

- Does it "work" – capabilities beyond *any* classical system
- Characterization of entangled states ➪ Computationally intractable!

Experimental implementation

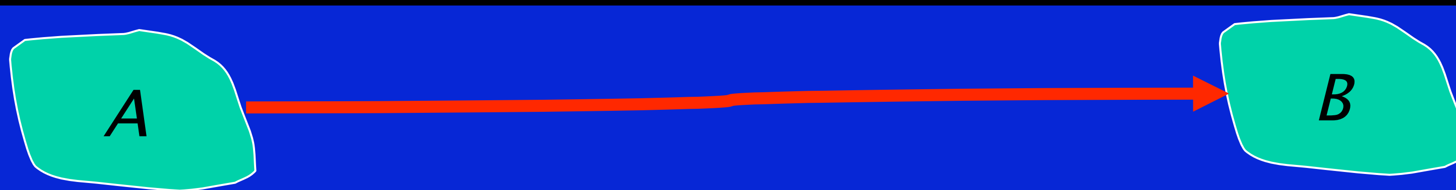
- Physical processes for reliable generation, processing, & transport of quantum states

A Broader Perspective –
What is the impact of information science on physics?



- Quantum enabled metrology – What can *A, B* learn about *M*?
  - Beyond the standard quantum limits to measurement precision
  - Nonclassical states of light and matter

Quantum interferometry, clock synchronization,… –
M – gravity waves, dispersive medium, …



- The physical limits to communication –

Transmission rate: $R \le \dfrac{c}{l_p}$, where Planck length $l_p = \sqrt{\hbar G/c^3} \sim 2\times 10^{-35}\,m$

One bit [or qubit] per Planck time $t_p \sim 5\times 10^{-44}\,s$

Achieved with objects on the verge of becoming black holes!

Lloyd, Giovannetti, Maccone, Phys. Rev. Lett. **93**, 100501 (2004)

Quantum Networks as Quantum Many Body Systems

NEWS & VIEWS

nature physics | VOL 2 | DECEMBER 2006 | www.nature.com/naturephysics

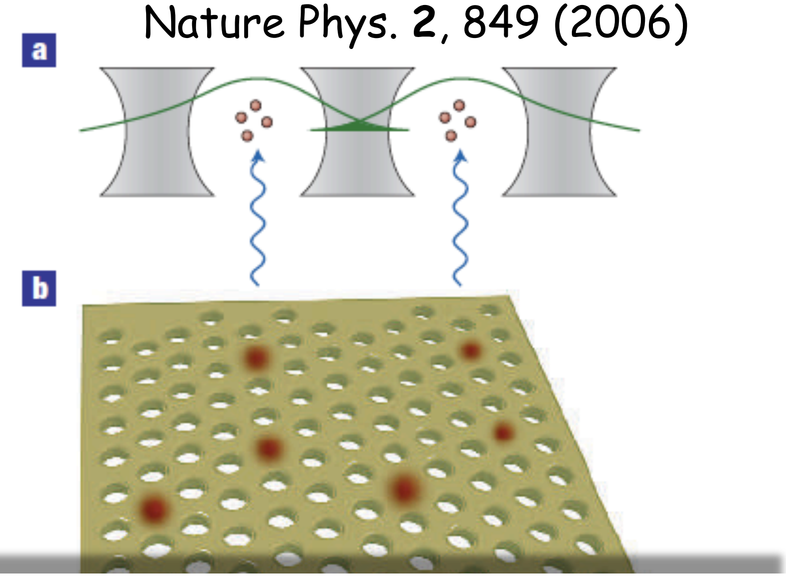
QUANTUM OPTICS

Light does matter

FABRIZIO ILLUMINATI

Strongly correlated systems are difficu
individual interacting elements. Engine
level atoms, and laser light could enab

"interaction"



Hartmann et al., Nature Phys. **2**, 849 (2006)

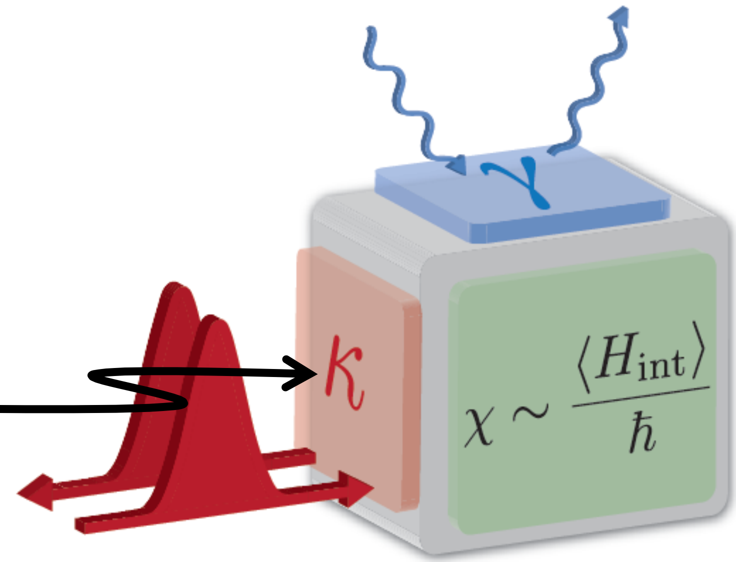
Entanglement percolation in quantum networks

nature physics | VOL 3 | APRIL 2007 | www.nature.com/naturephysics

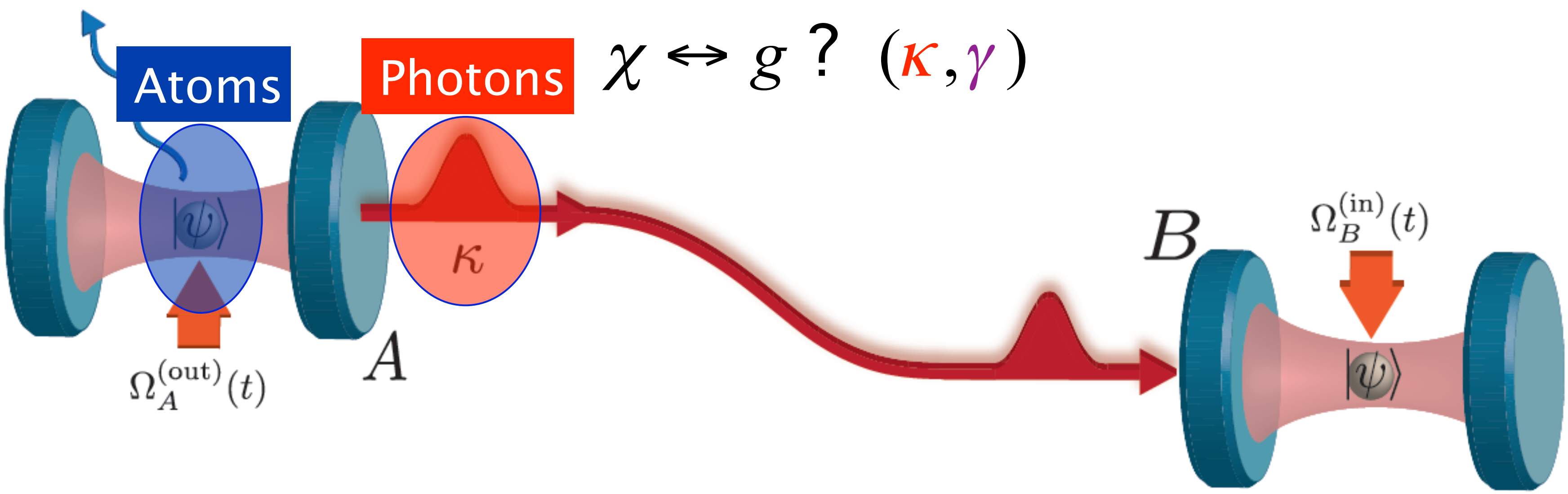
ANTONIO ACÍN[1,2*], J. IGNACIO CIRAC[3*†] AND MACIEJ LEWENSTEIN[1,2*]

A Quantum Interface between Matter and Light

What's inside here?



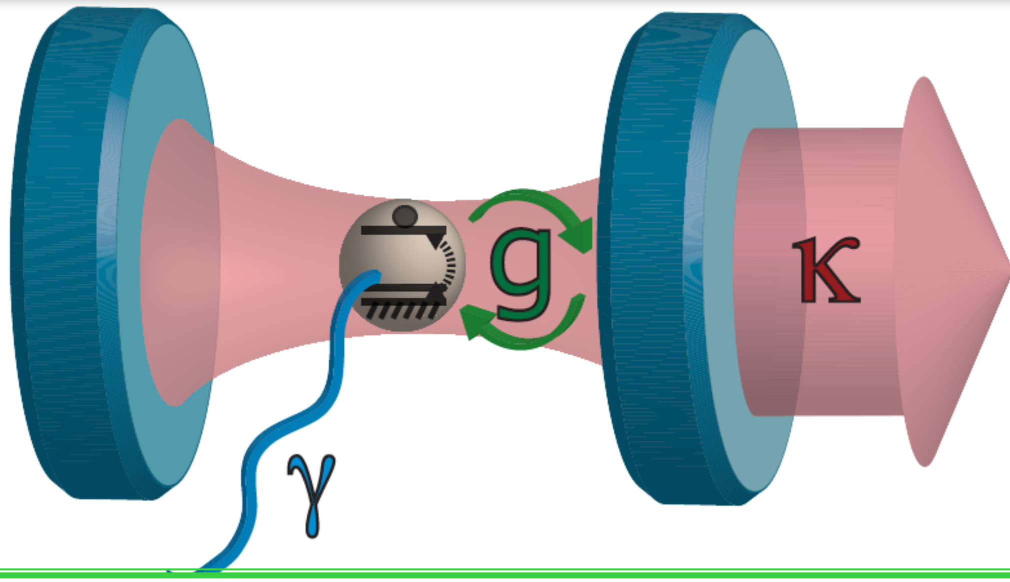
- Strongly coupled atom – photon via cavity QED



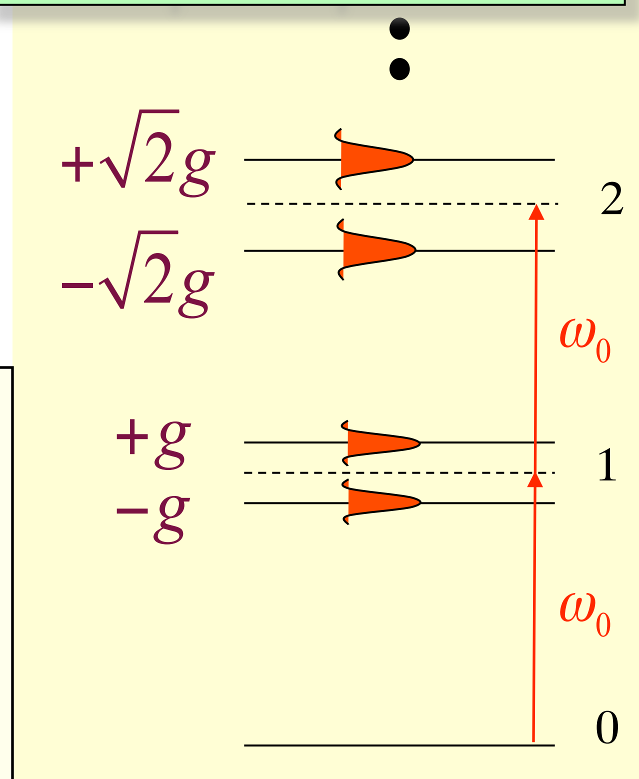
Quantum Networks Enabled by Cavity QED

J. I. Cirac, P. Zoller, H. J. Kimble, & H. Mabuchi, PRL **78**, 3221 (1997)

Strong Coupling in Cavity QED - Rates and Ratios



Dominance of coherent, reversible evolution over irreversible dissipative processes



Atom + Cavity field

Strong Coupling $g/(\gamma, \kappa) >> 1$

Critical photon number

$$n_0 = \frac{\gamma^2}{2g^2} < 1$$

Nonlinear optics with *one photon* per mode

$n_0 \sim 10^{-3} - 10^{-4}$ photons

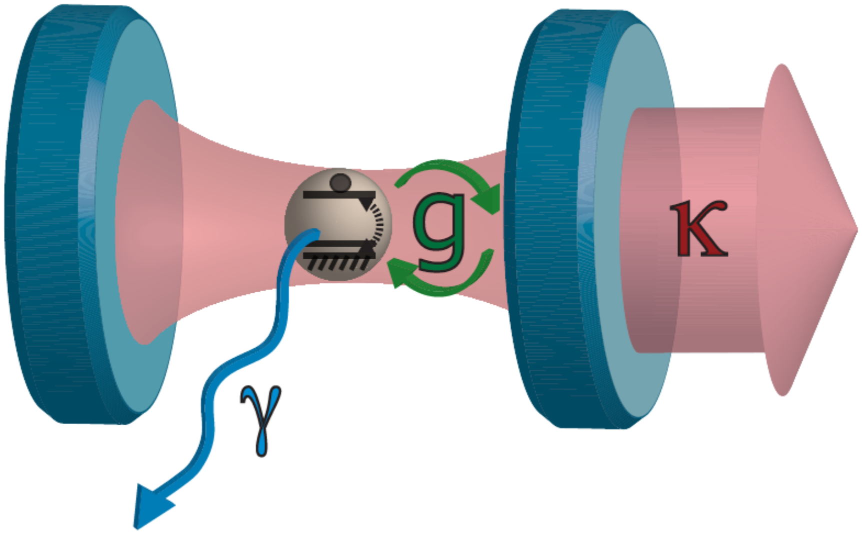
Critical atom number

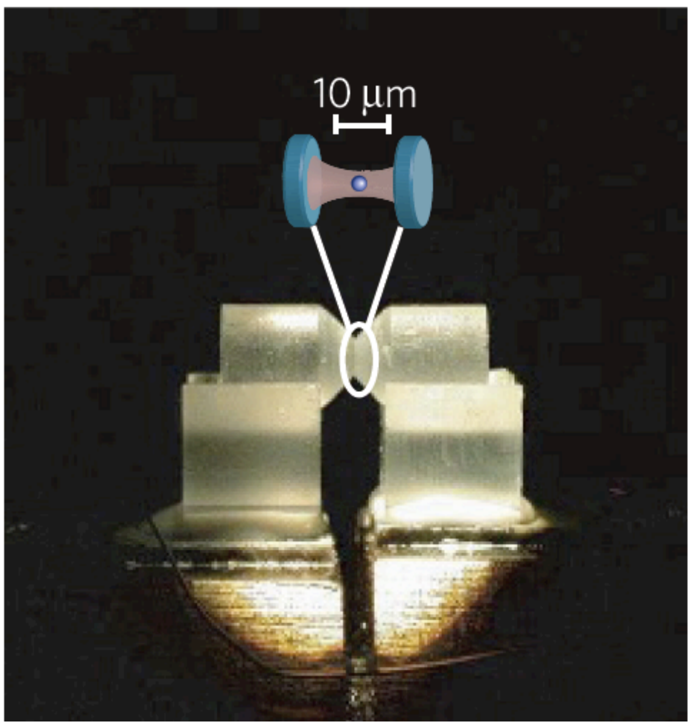
$$N_0 = \frac{2\gamma\kappa}{g^2} < 1$$

Single-atom **switching of optical cavity response**

$N_0 \sim 10^{-2} - 10^{-3}$ atoms

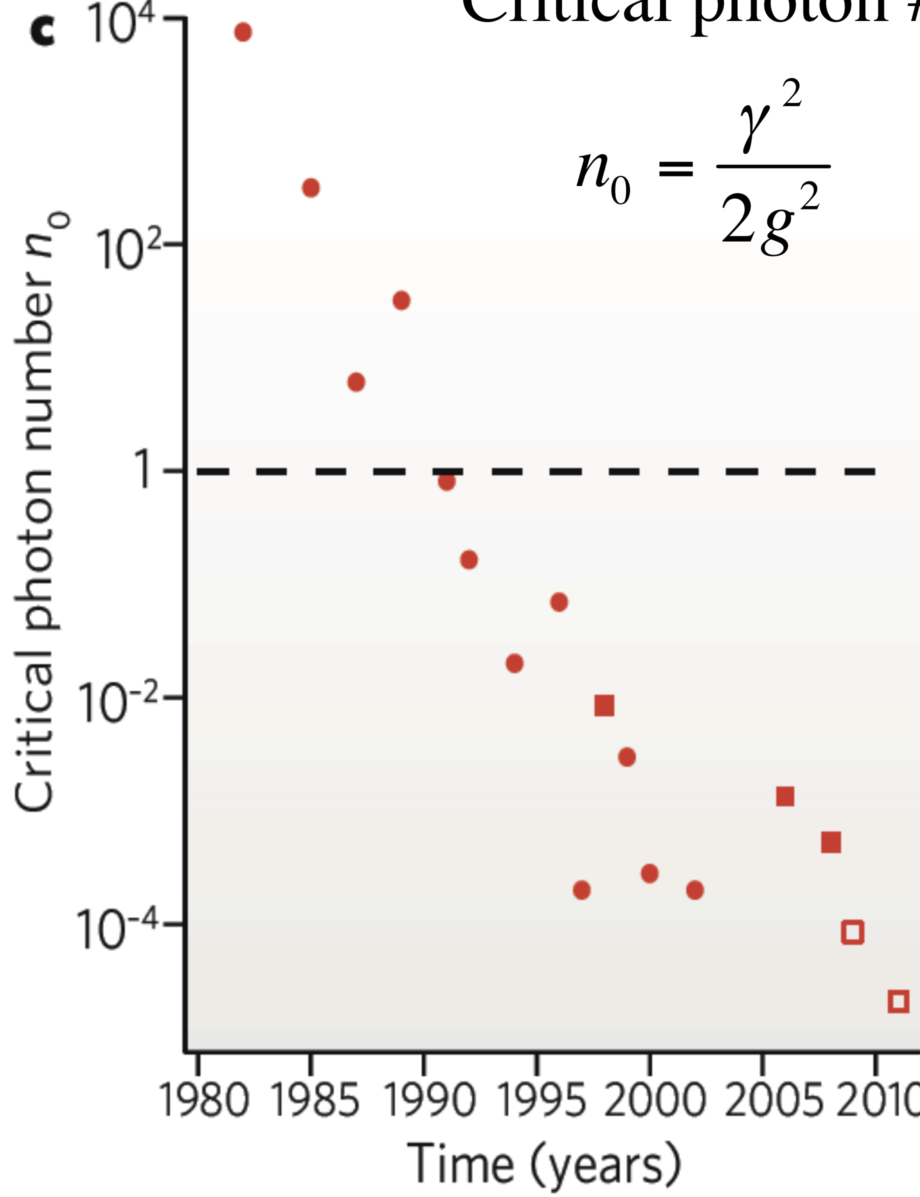
My Quest for Strong Coupling of Single Atoms and Photons





Critical photon #

$$n_0 = \frac{\gamma^2}{2g^2}$$

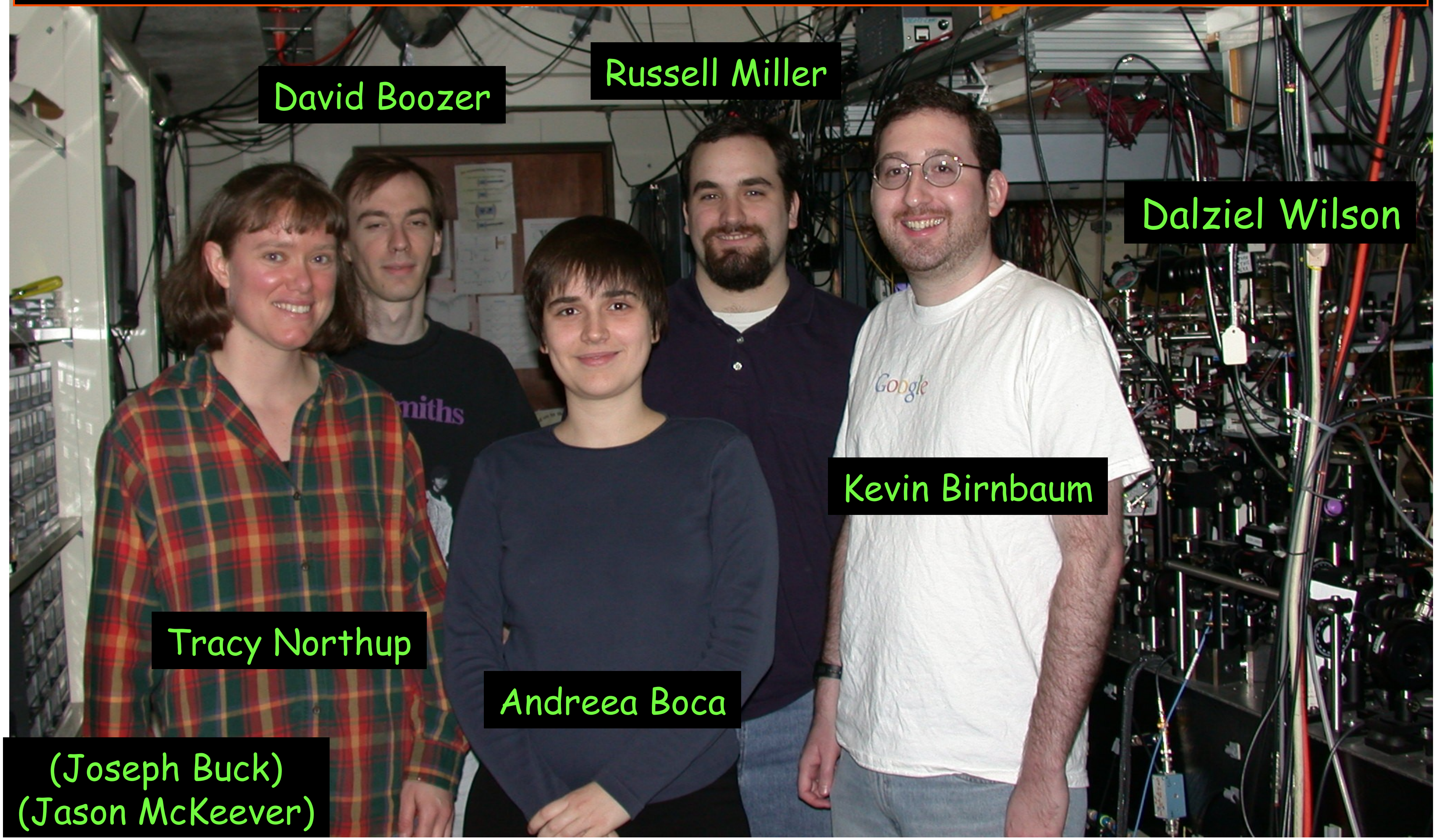


Caltech – The People

1 Cesium Atom Trapped in an Optical Cavity in a Regime of Strong Coupling

• J. Ye, D. W. Vernooy & HJK, PRL **83**, 4987 (1999)

• J. McKeever, J. R. Buck, A. D. Boozer, A. Kuzmich, H.-C. Nägerl, D. M. Stamper-Kurn & HJK, PRL **90**, 133602 (2003)

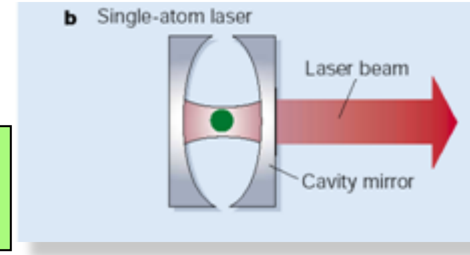


Step-by-Step towards Full Control in Cavity QED

A One-Atom Laser in a Regime of Strong Coupling

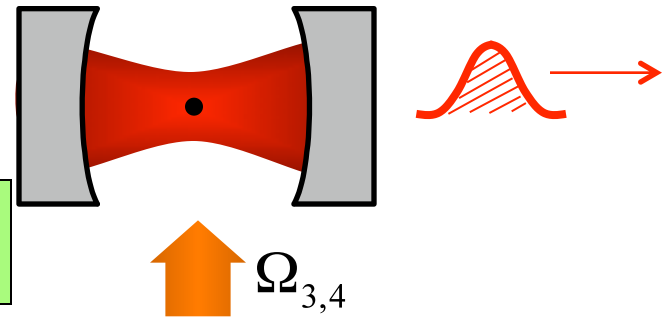
J. McKeever, A. Boca, D. Boozer, J. Buck, & HJK
Experiment - Nature **425**, 268 (2003)
Theory – PRA **70**, 023814 (2004)

Laser operation at the conceptual limit



Single Photon Generation *On Demand*

J. McKeever, A. Boca, D. Boozer, R. Miller, J. Buck, A. Kuzmich, & HJK, Science **303**, 1992 (2004)



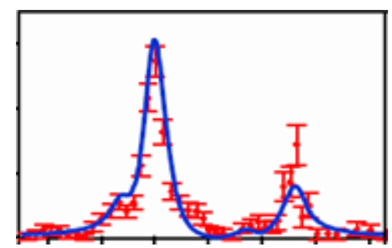
A critical resource for Quantum Information Science

Vacuum-Rabi Splitting for One and the Same Atom

A. Boca, R. Miller, K. Birnbaum, D. Boozer, J. McKeever & HJK, PRL **93**, 233603 (2004)

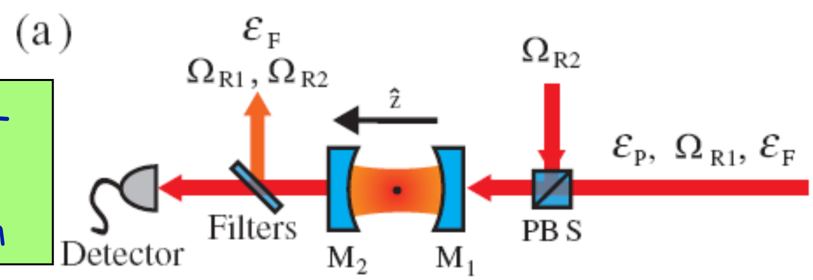
A Quantum « Protocol »

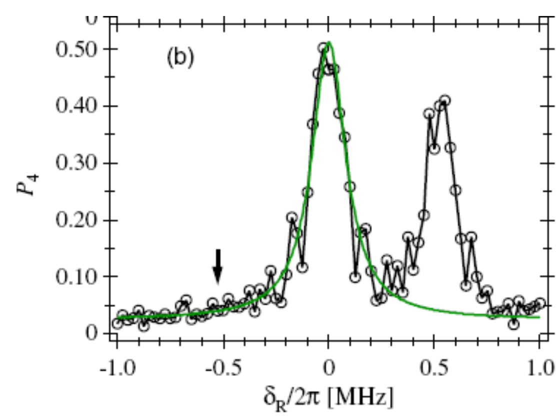
All previous measurements required N ~ 10^3-10^5 atoms



Cooling to the Ground State of Axial Motion

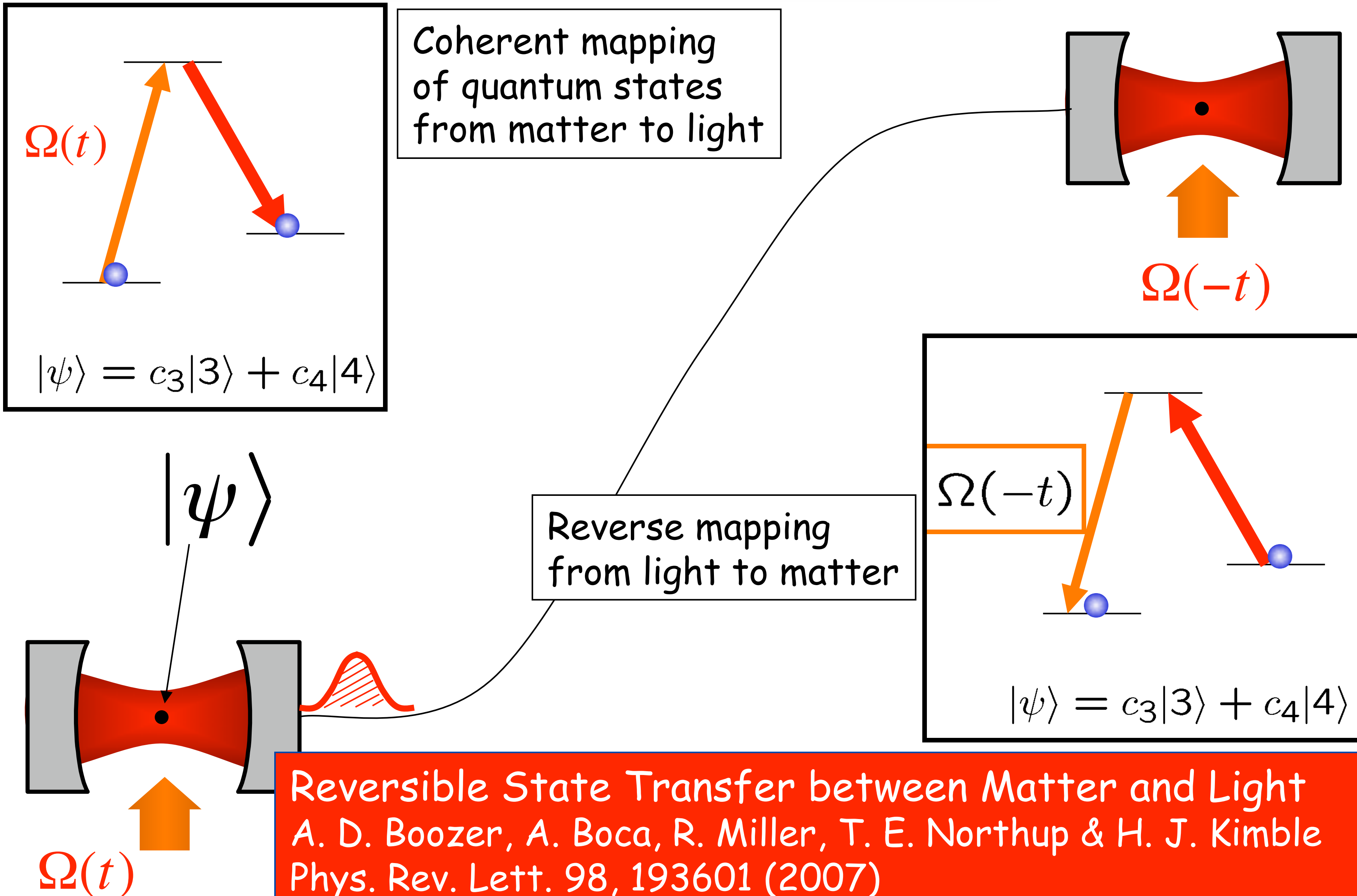
A. D. Boozer, A. Boca, R. Miller, T. E. Northup & HJK, PRL **97**, 083602 (2006)





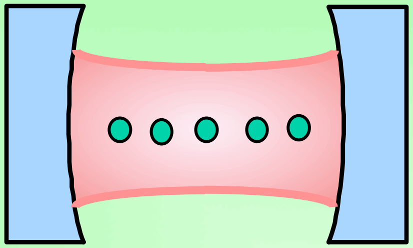
A new regime for cQED –
Quantization of internal & external degrees of freedom

Single Photon Generation "On Demand"
J. McKeever, A. Boca, D. Boozer, R. Miller, J. Buck,
A. Kuzmich & H. J. Kimble, Science 303, 1992 (2004)



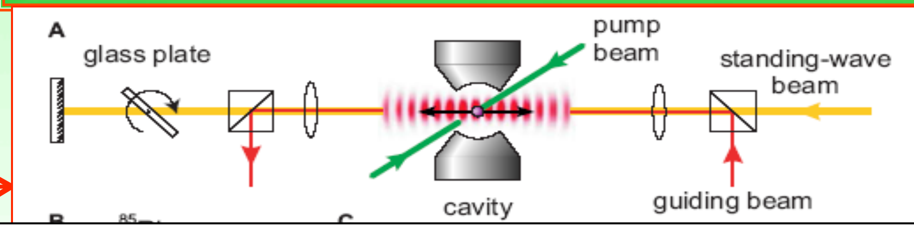
Reversible State Transfer between Matter and Light
A. D. Boozer, A. Boca, R. Miller, T. E. Northup & H. J. Kimble
Phys. Rev. Lett. 98, 193601 (2007)

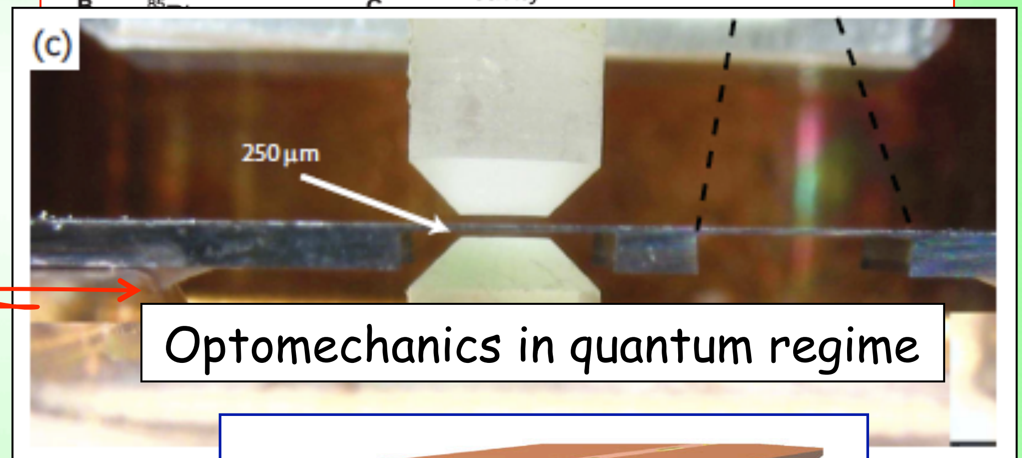
Cavity QED with Localized Atoms – A brief overview



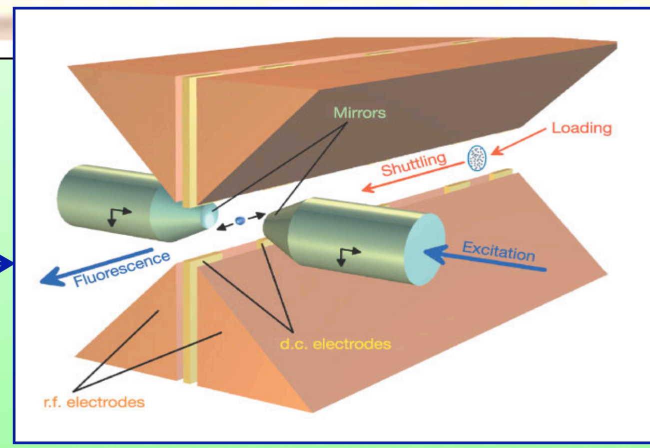
QUANTUM INFORMATION SCIENCE
- Quantum measurement
- Quantum logic, computation, communication
- Quantum-classical interface

- Cavity QED with cold (neutral) atoms
  - H. J. Kimble, Caltech
  - G. Rempe, MPQ Garching
  - T. Kuga, University of Tokyo
  - M. Chapman, Georgia Tech
  - V. Vuletić, MIT
  - L. Orozco, U Maryland
  - D. Meschede, University of Bonn
  - E. Hinds, Imperial
  - D. Stamper-Kurn, UC Berkeley
  - T. Esslinger, ETH
  - J. Reichel, ENS
  - J. Schmiedmayer, TU-Wien …



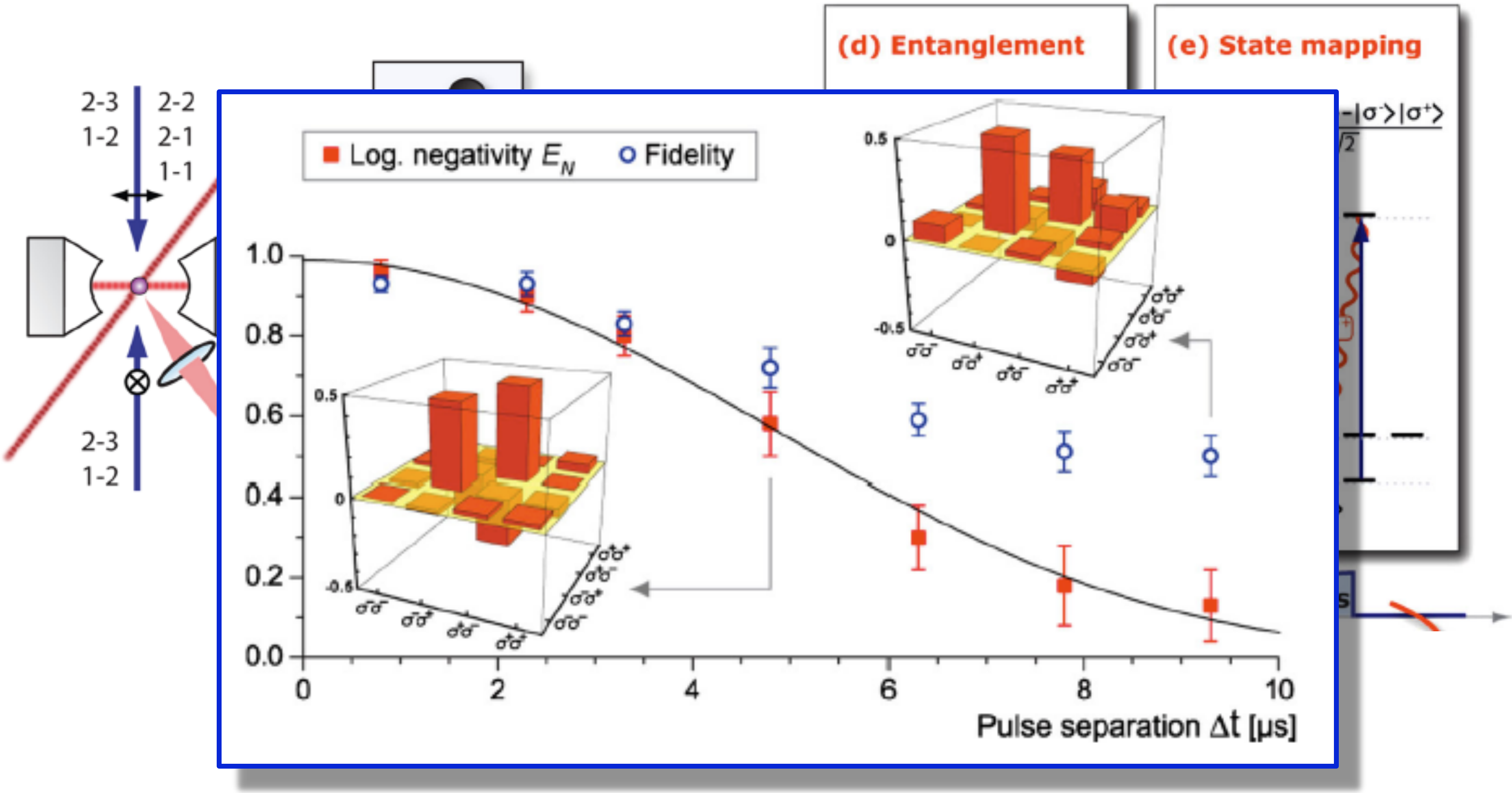


- Cavity QED with trapped ions
  - R. Blatt, University of Innsbruck
  - (H. Walther, MPQ Garching)
  - W. Lange, University of Sussex
  - C. Monroe, U Maryland
  - F. Schmidt-Kaler, Ulm
  - …



Photon-Photon Entanglement with a Single Trapped Atom

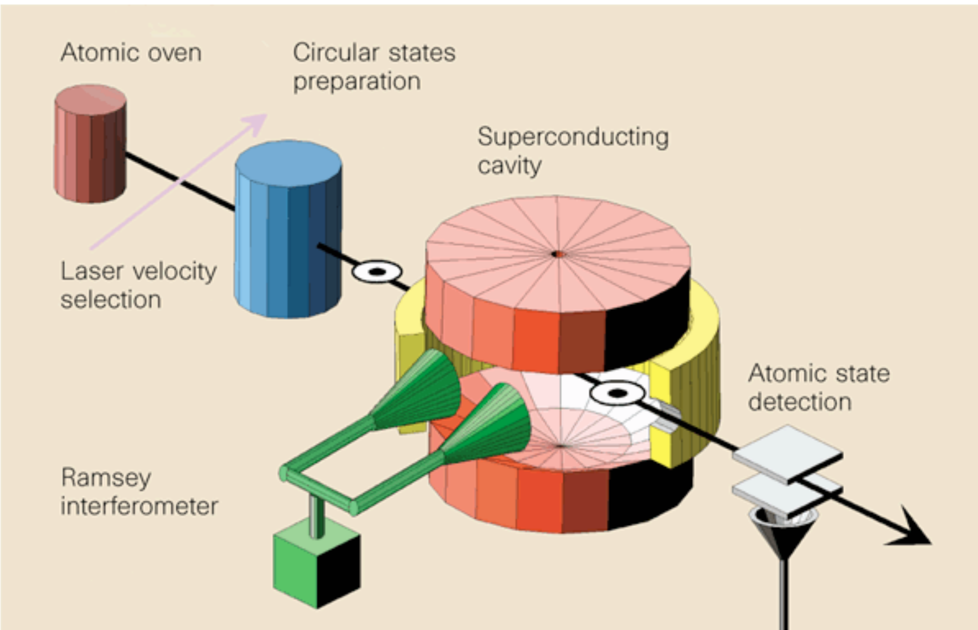
B. Weber, H. P. Specht, T. Müller, J. Bochmann, M. Mücke, D. L. Moehring,* and G. Rempe
Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Strasse 1, 85748 Garching, Germany
(Received 11 September 2008; published 20 January 2009)

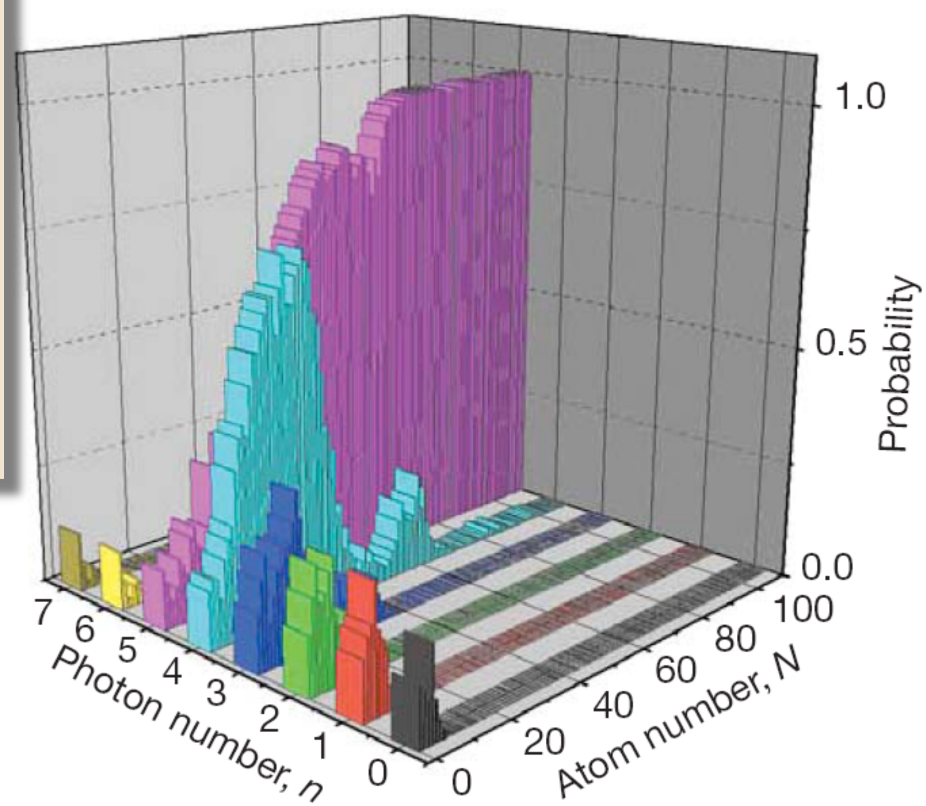


Progressive field-state collapse and quantum non-demolition photon counting

Christine Guerlin[1], Julien Bernu[1], Samuel Deléglise[1], Clément Sayrin[1], Sébastien Gleyzes[1], Stefan Kuhr[1]†, Michel Brune[1], Jean-Michel Raimond[1] & Serge Haroche[1,2]

Vol 448|23 August 2007|**doi:10.1038/nature06057**

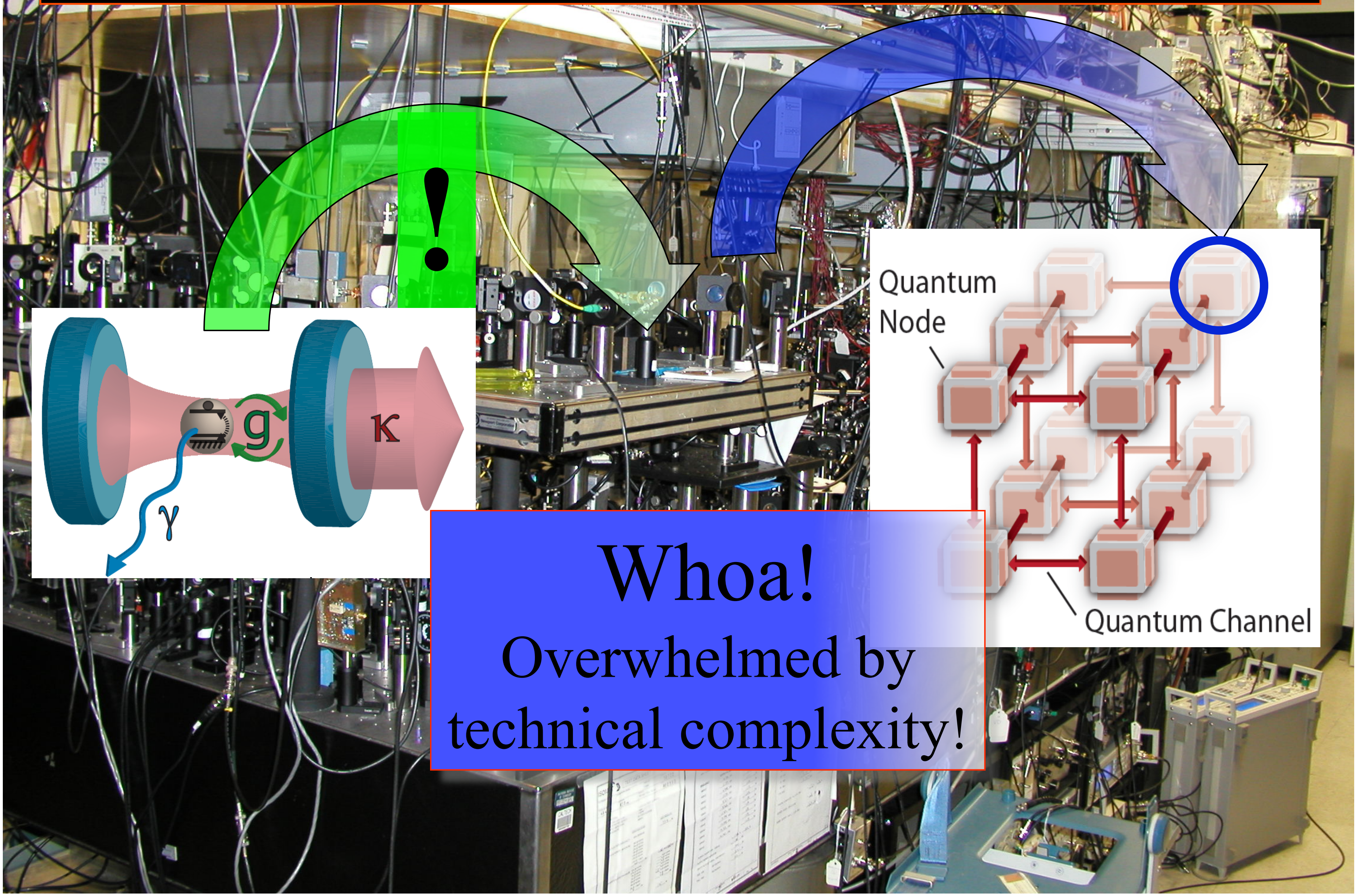




Cavity QED in the Microwave Regime
S. Haroche, ENS, Paris

Caltech – The Real Story

1 Cesium Atom Trapped in an Optical Cavity in a Regime of Strong Coupling



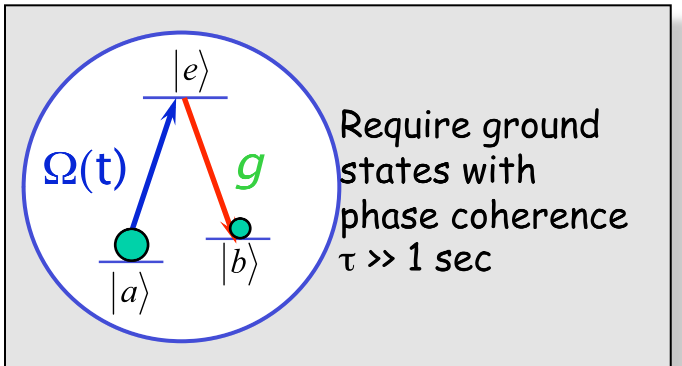
A Menagerie of Physical Systems for Cavity QED – A Sampling

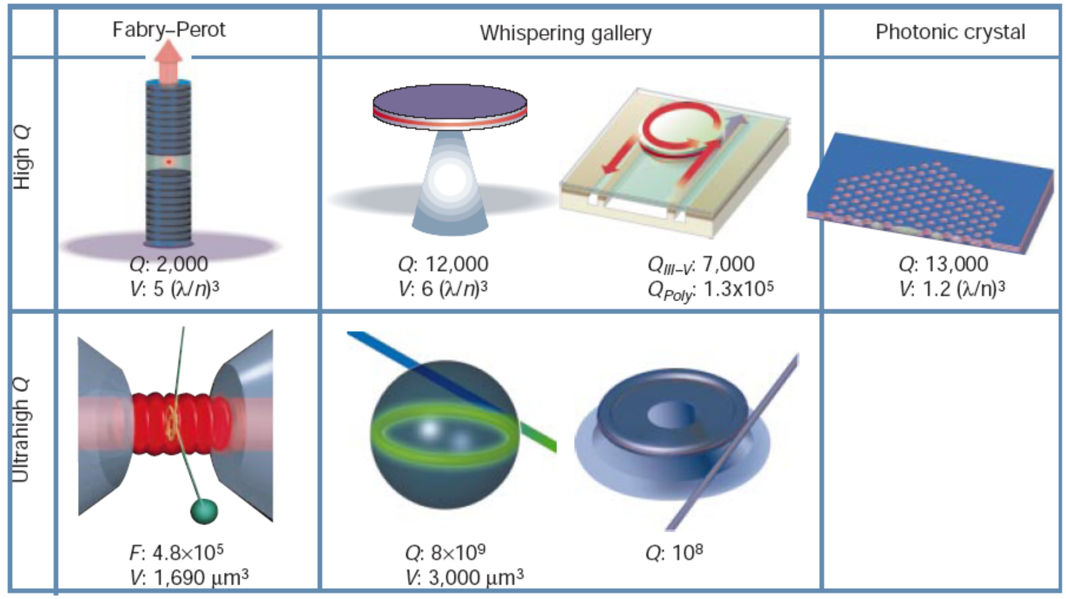
NATURE | VOL 424 | 14 AUGUST 2003 | www.nature.com/nature

insight review articles

Optical microcavities

Kerry J. Vahala



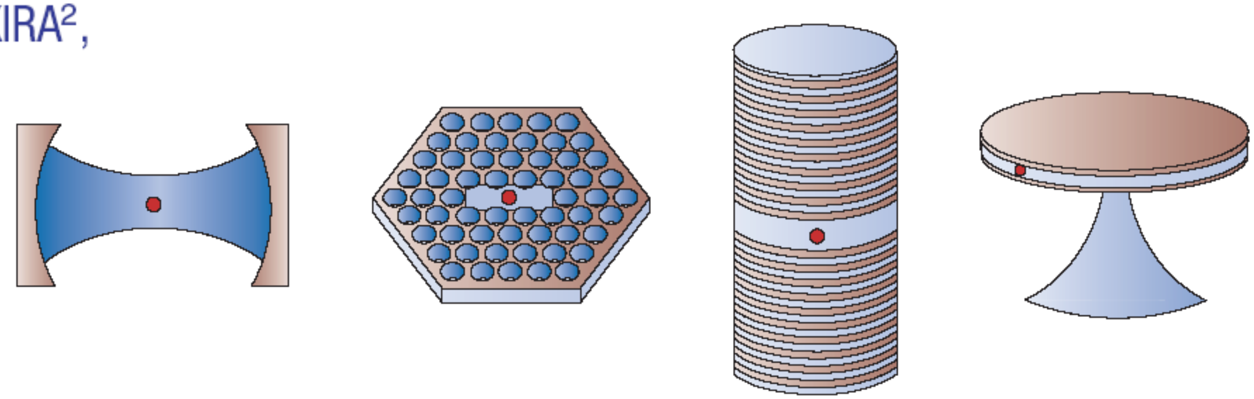


nature physics | VOL 2 | FEBRUARY 2006 | www.nature.com/naturephysics

REVIEW ARTICLE

Vacuum Rabi splitting in semiconductors

G. KHITROVA[1]*, H. M. GIBBS[1], M. KIRA[2], S. W. KOCH[2] AND A. SCHERER[3]



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.

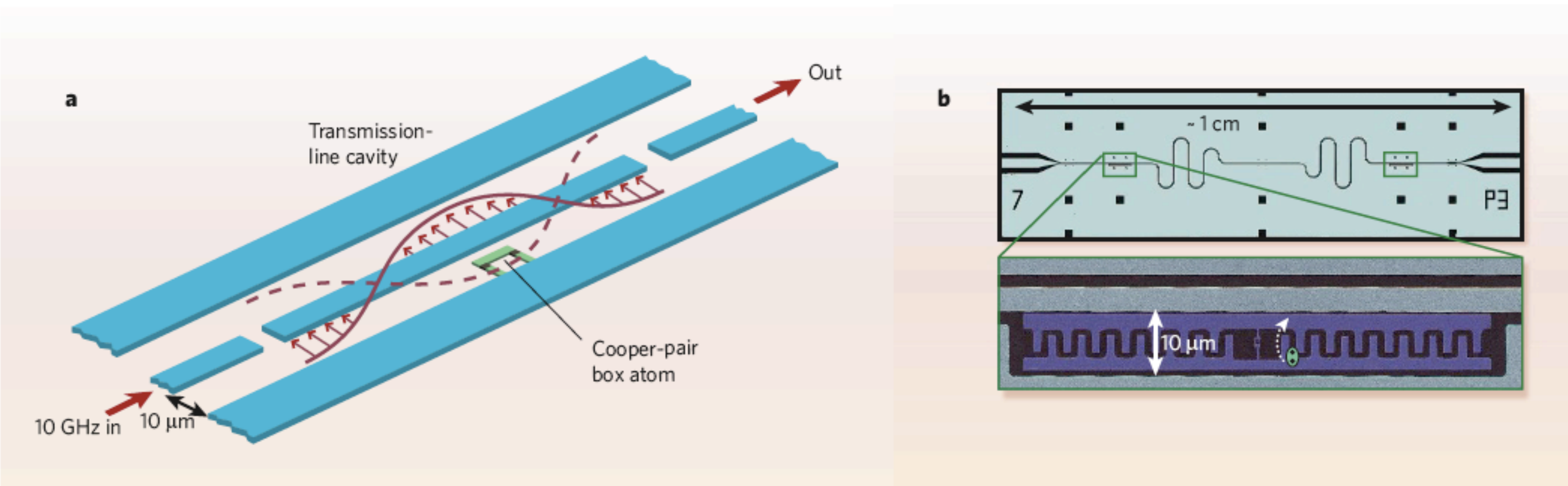


Figure 2 | Circuit QED devices. a, Schematic representation (adapted from ref. 22) of the circuit analogue of cavity quantum electrodynamics (QED), where a superconducting qubit (green) interacts with the electric fields (pink) in a transmission line (blue), consisting of a central conductor and two ground planes on either side. The cavity is defined by two gaps (the mirrors) separated by about a wavelength. The cavity and qubit are measured by sending microwave signals down the cable on one side of the cavity and collecting the transmitted microwaves on the output side. **b**, Micrograph of an actual circuit QED device that achieves the strong-coupling limit. It consists of a superconducting niobium transmission line on a sapphire substrate with two qubits (green boxes) on either side. The inset shows one of the superconducting Cooper-pair box charge qubits located at the ends of the cavity where the electric fields are maximal. The qubit has two aluminium 'islands' connected by a small Josephson junction. Changing the state of the qubit corresponds to moving a pair of electrons from the bottom to top (shown schematically).

A New Paradigm for Cavity QED - S. Spillane et al., PRA **71**, 013817 (2005)

Ultrahigh-Q toroidal microresonators for cavity quantum electrodynamics

S. M. Spillane, T. J. Kippenberg, and K. J. Vahala
Thomas J. Watson Laboratory of Applied Physics, California Institute of Technology, Pasadena, California 91125, USA

Projections –

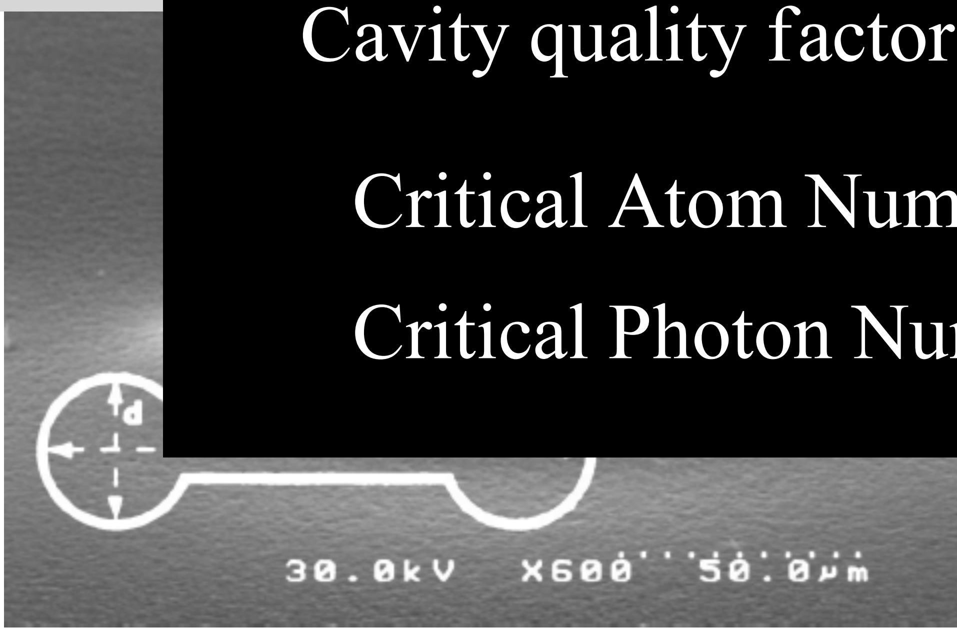
Coupling coefficient $g_0 / 2\pi \simeq 400 MHz$

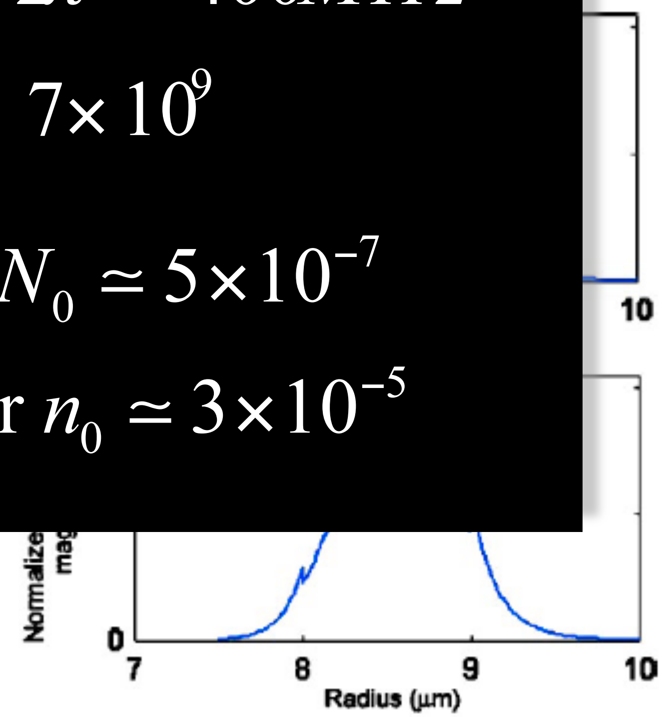
Cavity quality factor $Q \simeq 7 \times 10^9$

Critical Atom Number $N_0 \simeq 5 \times 10^{-7}$

Critical Photon Number $n_0 \simeq 3 \times 10^{-5}$

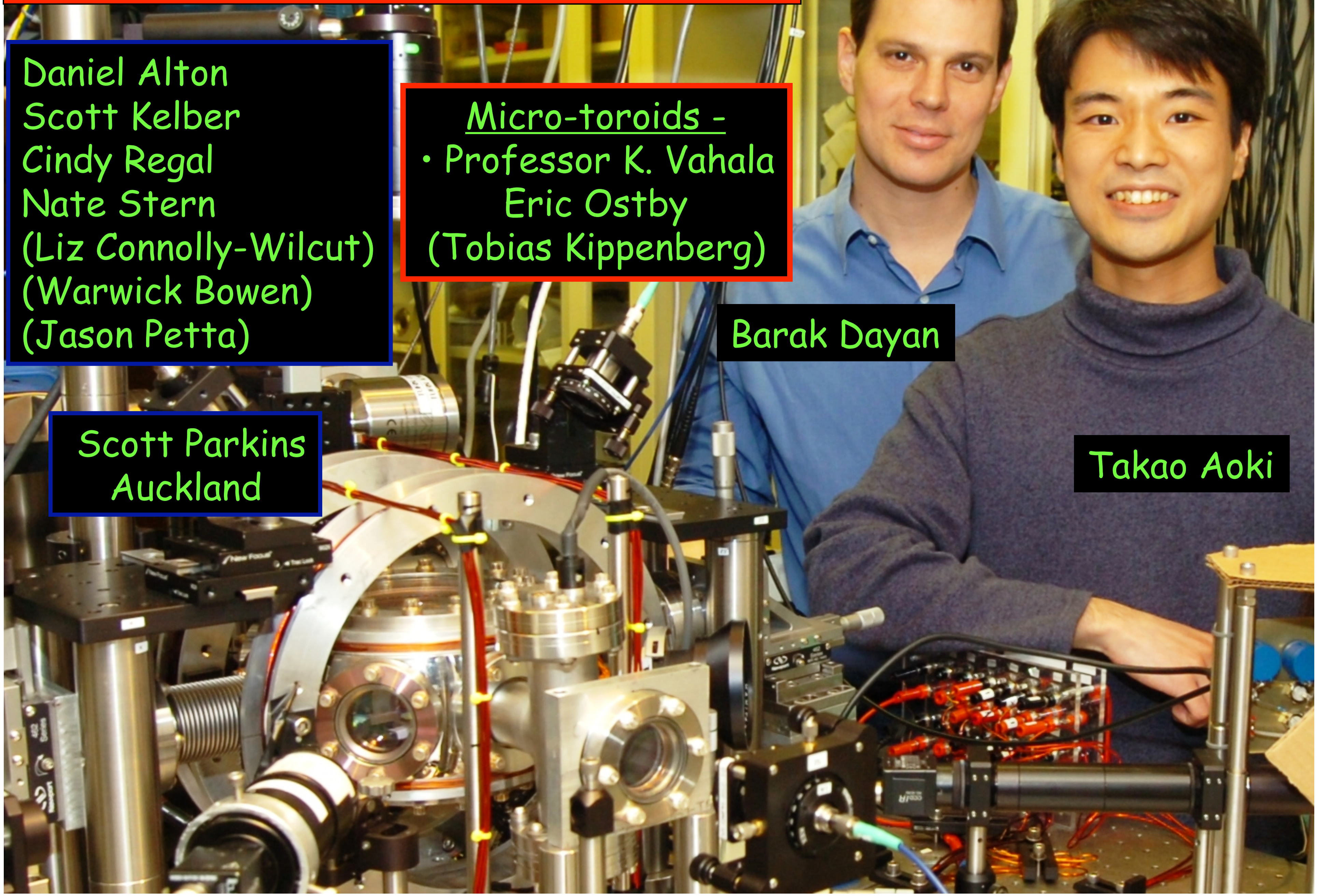
Milli
transit



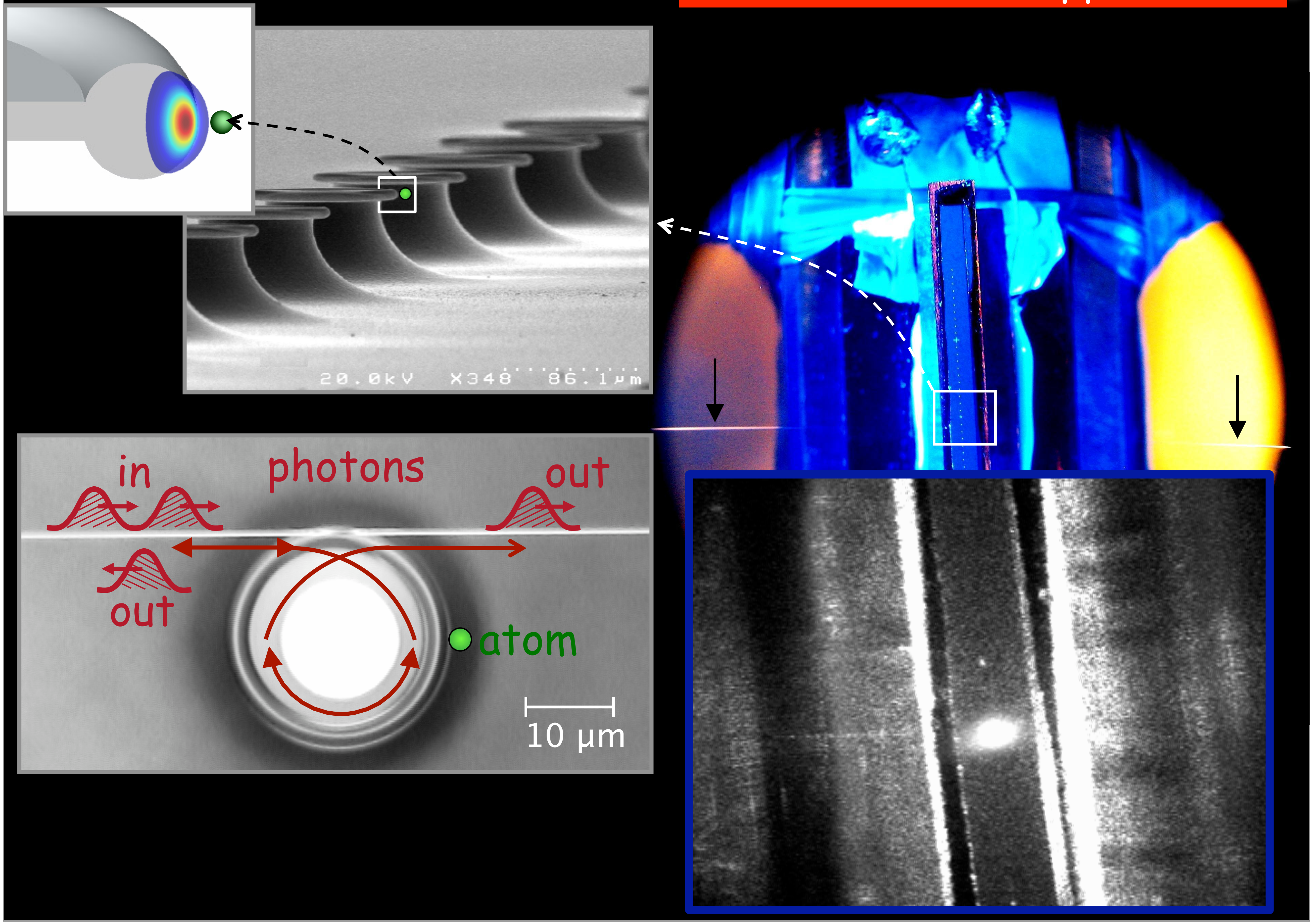


Ultra-high-Q toroid microcavity, K. Vahala, Nature **424**, 839 (2003)

Cavity QED with Micro-Toroidal Resonators
S. Spillane et al., PRA **71**, 013817 (2005)



Zoom into the Apparatus

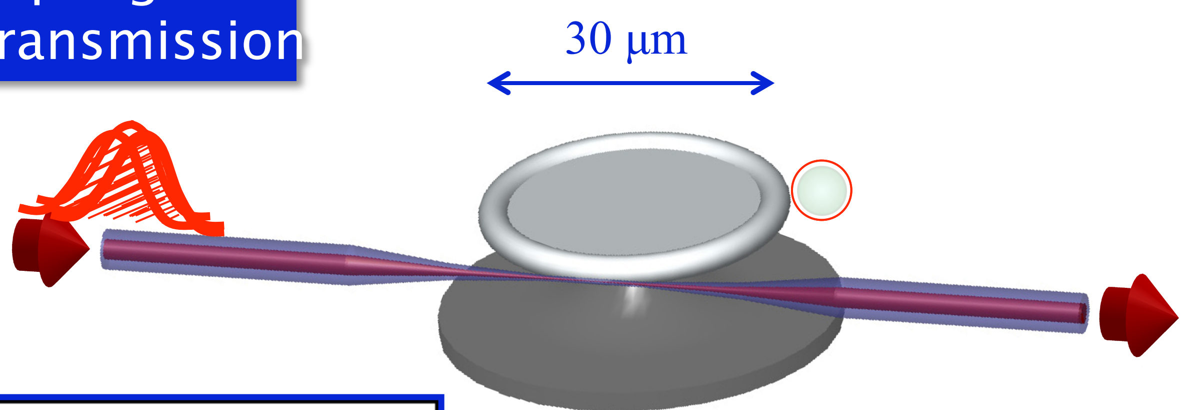


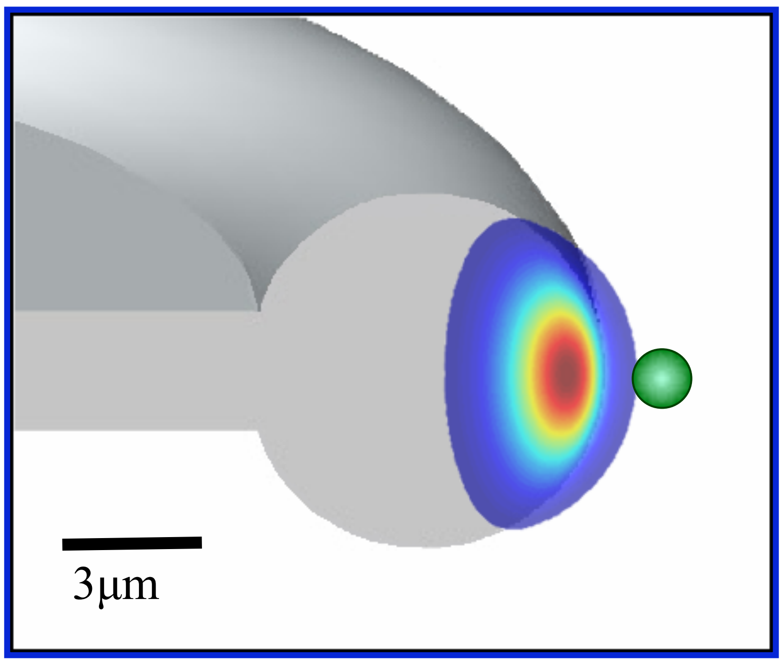
A Photon Turnstile* Dynamically Regulated by 1 Atom

B. Dayan, A. S. Parkins, T. Aoki, E. P. Ostby, K. J. Vahala, & H. J. Kimble

Science **319**, 1062 (2008)

critical coupling –
no atom, no transmission



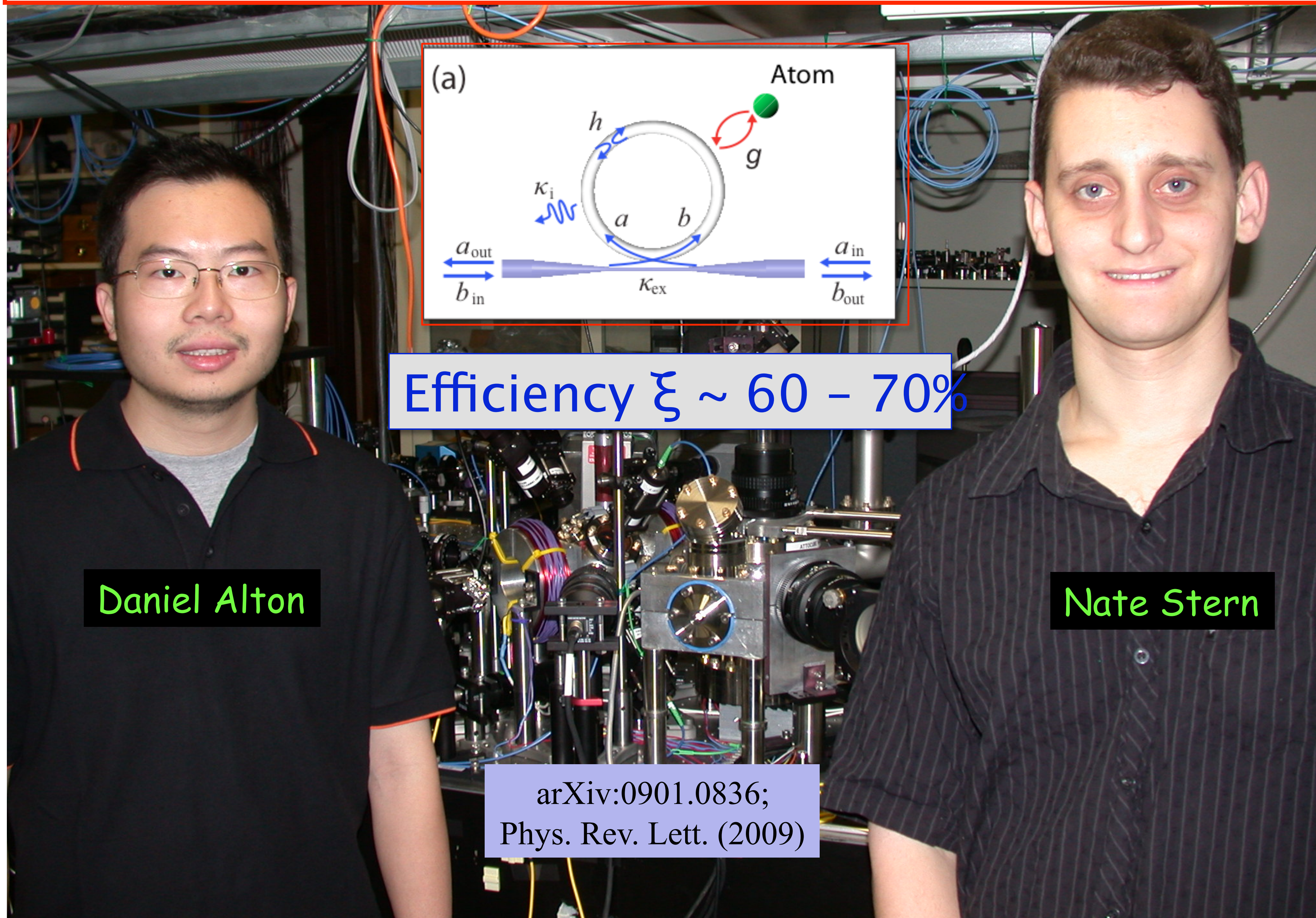


Photon transport regulated by single-atom dynamics

*J. Kim, O. Benson, H. Kan & Y. Yamamoto, Nature **397**, 500 (1999)

Efficient routing of single photons by one atom and a microtoroidal cavity

Takao Aoki,[†a] A. S. Parkins,[b] D. J. Alton,[†] C. A. Regal,[†] Barak Dayan,[†c] E. Ostby,[‡] K. J. Vahala,[‡] and H. J. Kimble[†]



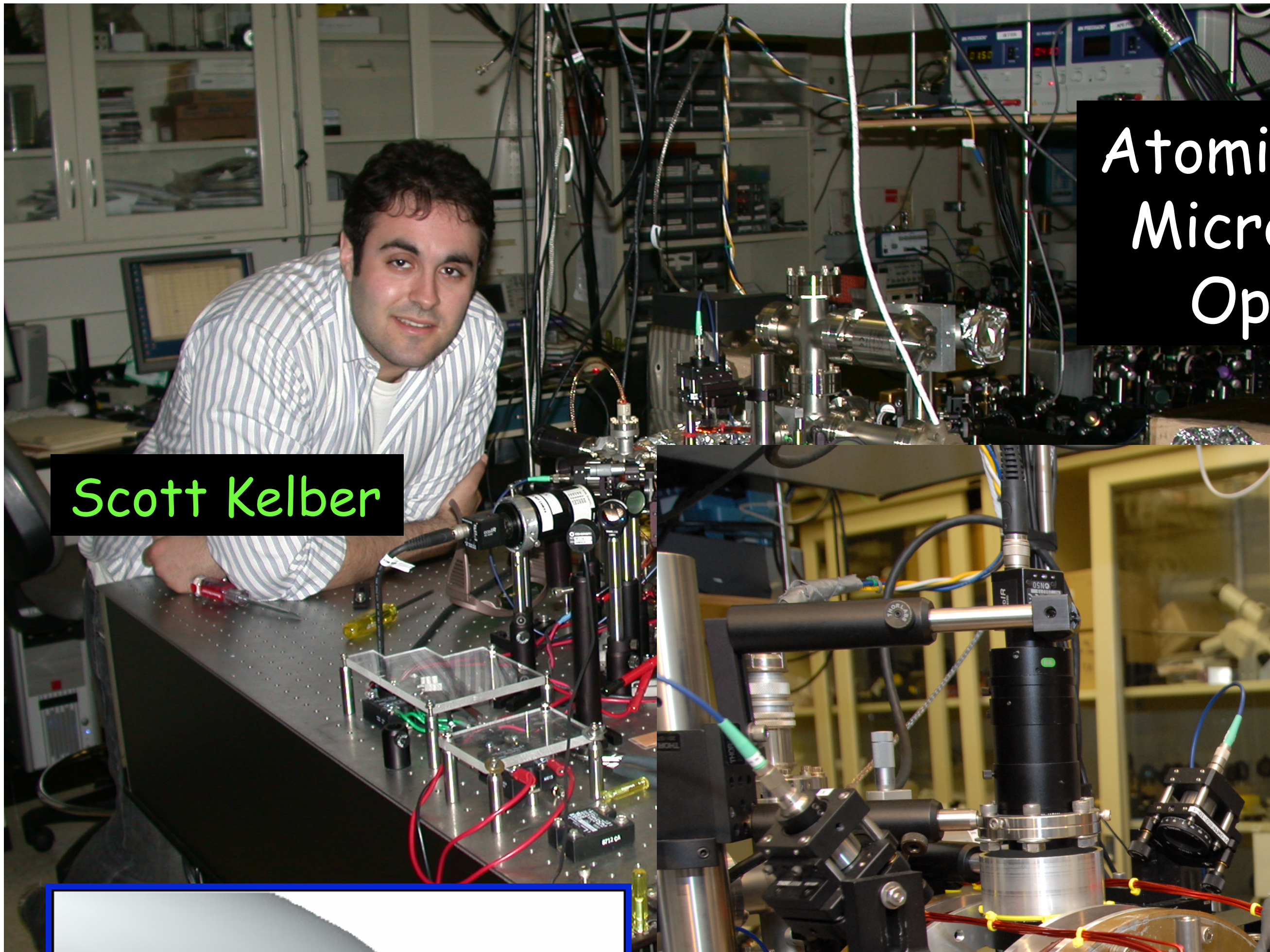
Efficiency ξ ~ 60 – 70%

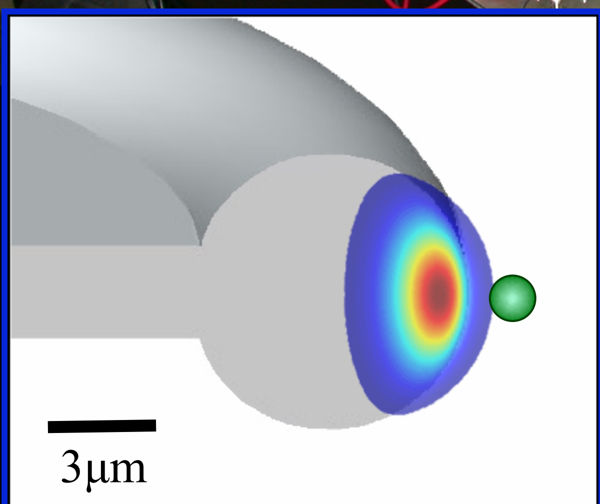
Daniel Alton

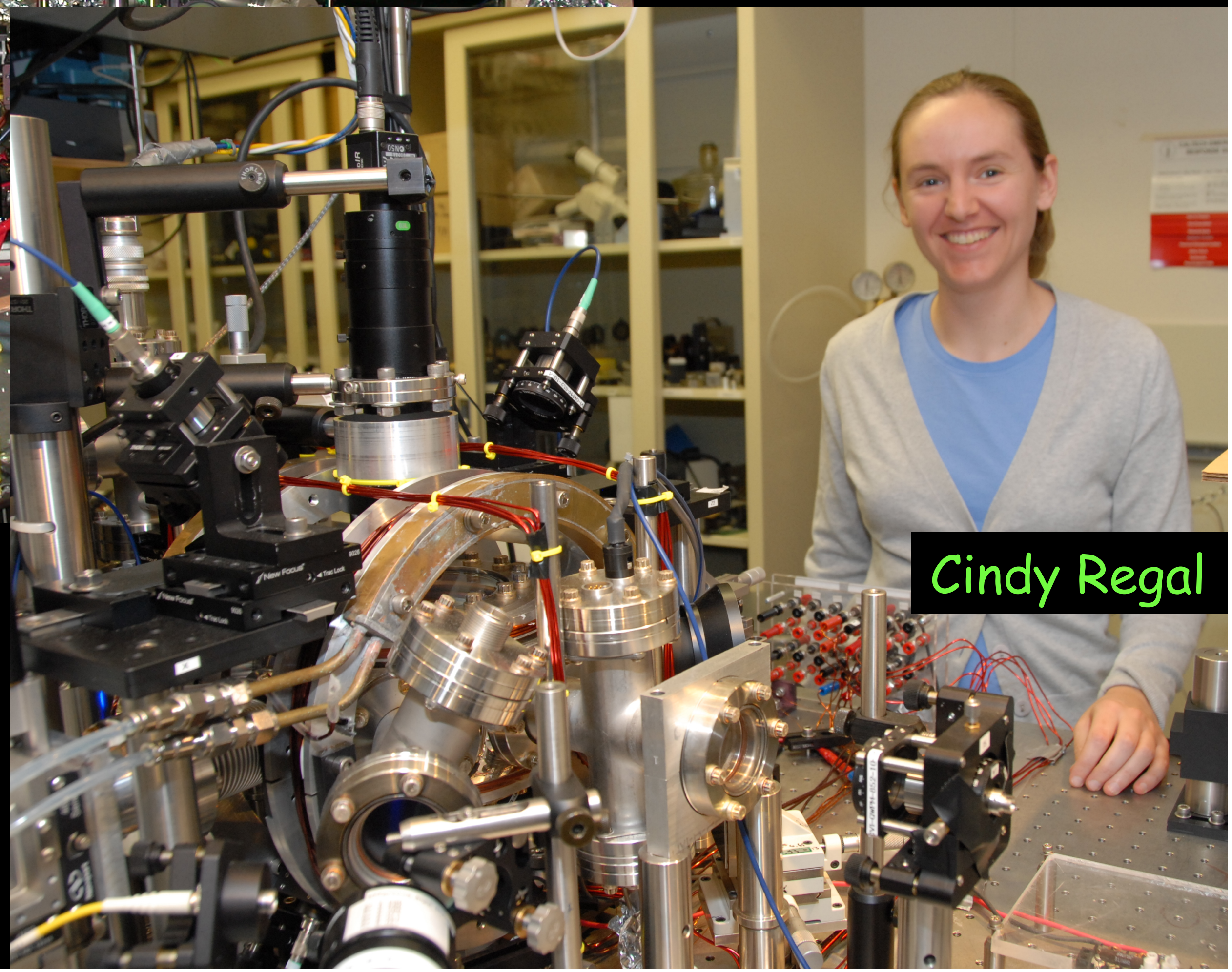
Nate Stern

arXiv:0901.0836;
Phys. Rev. Lett. (2009)

Atomic Localization Near Micro and Nano-Scopic Optical Resonators







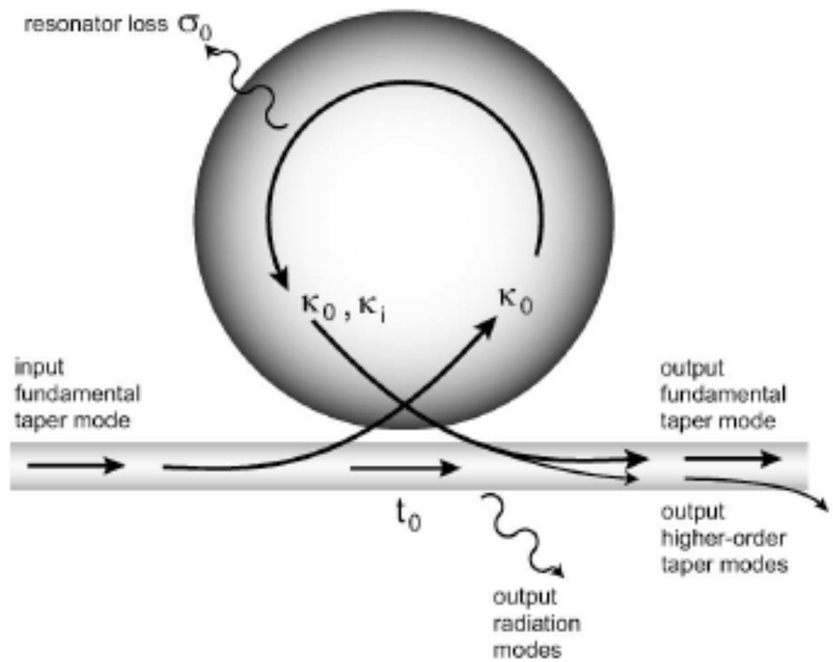
Coupling to Micro-Toroidal Resonators with Tapered Optical Fibers
S. M. Spillane, T. J. Kippenberg, O. J. Painter, & K. J. Vahala, PRL **91**, 043902 (2003)

D. W. Vernooy, V. S. Ilchenko, H. Mabuchi, E. W. Streed & HJK, Opt. Lett. **23**, 247 (1998)

$$Q_{measured} \approx 8\times 10^{9} \rightarrow Q_{projected} \geq 10^{10}$$

Ideality $\approx$ 99.97%

~ Mode matching efficiency



Coupling to Micro-Toroidal Resonators with Tapered Optical Fibers
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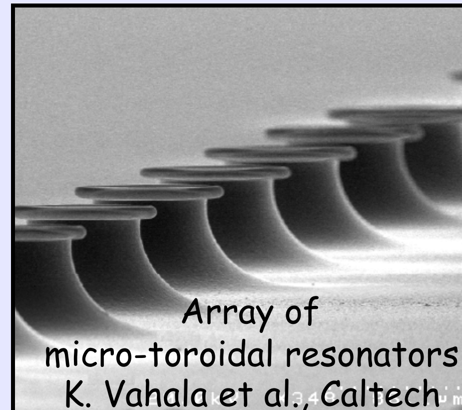
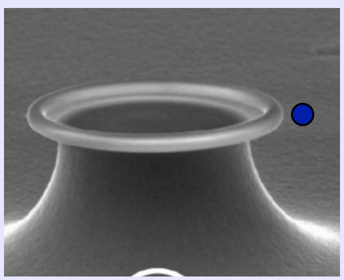
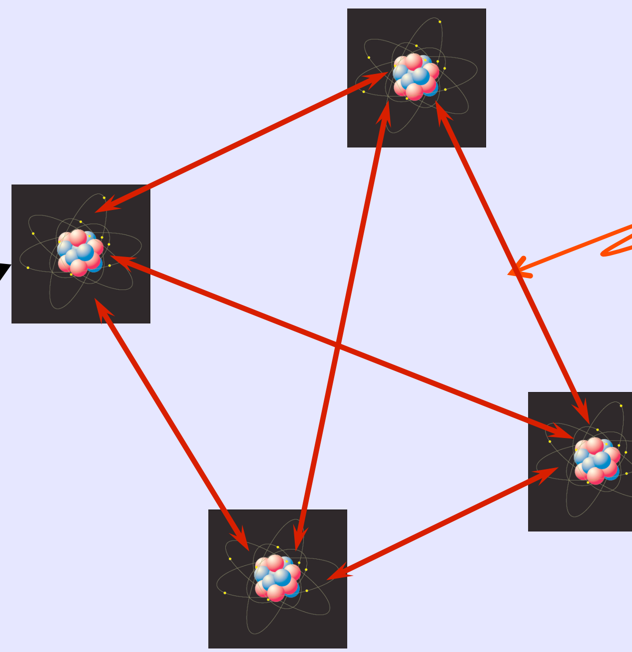
D. W. Vernooy, V. S. Ilchenko, H. Mabuchi, E. W. Streed & HJK, Opt. Lett. **23**, 247 (1998)

$$Q_{measured} \approx 8\times10^{9} \rightarrow Q_{projected} \geq 10^{10}$$

Provides a realistic pathway to quantum networks
with strong coupling and
high intrinsic efficiency for input/output operations







• Quantum channel – **transport and distribute**

• Quantum node – **generate, process, store quantum information**

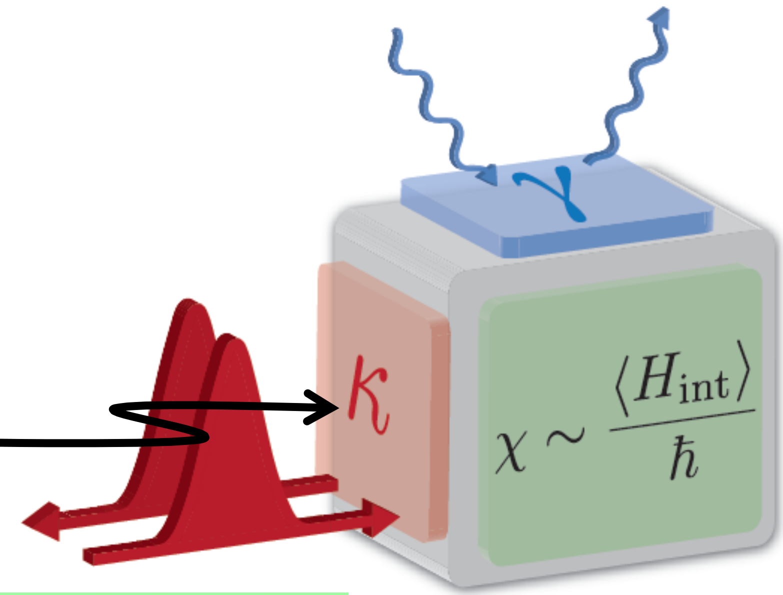
$$Q_{\text{intrinsic}} : 10^{10}$$

$$Q_{\text{I-O}} : 10^{7}$$

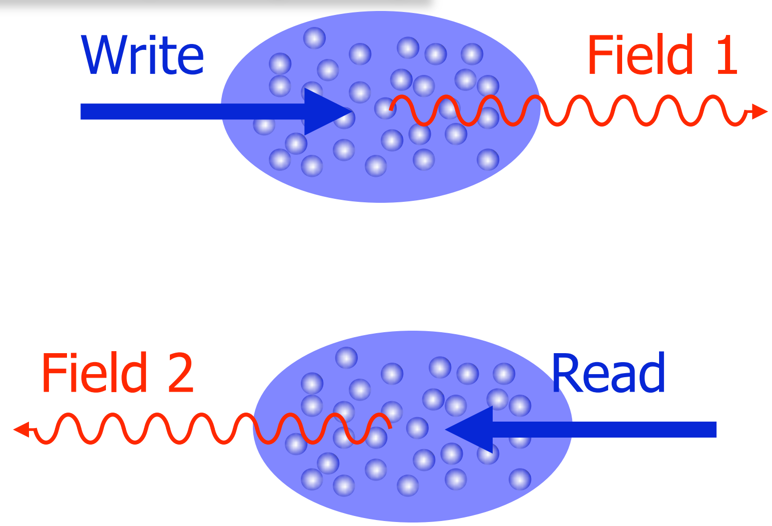
$$\Rightarrow \textit{Efficiency} : 99.9\%$$

A Quantum Interface between Matter and Light

What's inside here?



- Ensemble of ~ 10^5 atoms
- Utilize strong interaction of single photons and collective spin excitations
- Duan, Cirac, Lukin & Zoller – *DLCZ*, Nature **414**, 413 (2001)



Writing and reading single spin excitations

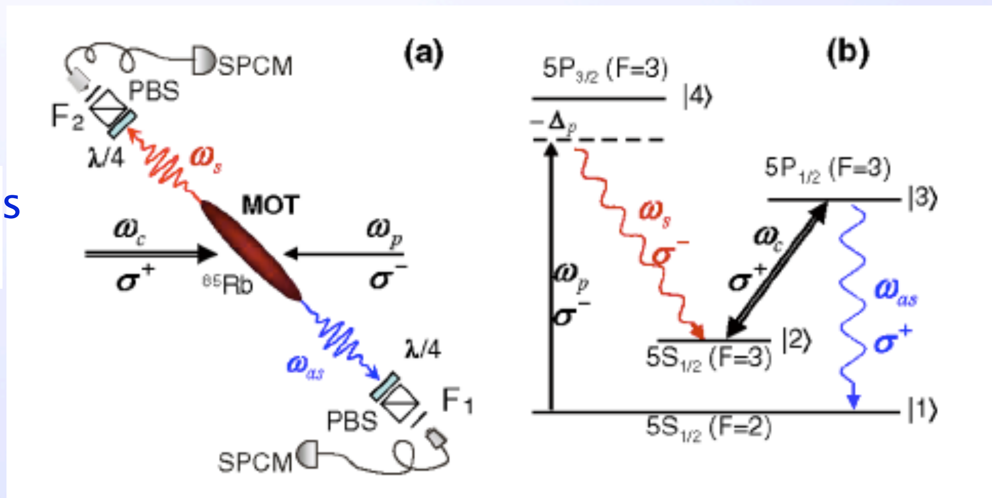
Overview of Experiments – Implementation of *DLCZ* Protocol (and variants)

- <u>Ensembles of cold atoms</u>
  - H. J. Kimble, Caltech (2003)
  - A. Kuzmich, Georgia Tech
  - S. E. Harris, Stanford
  - V. Vuletic, MIT
  - J.-W. Pan, Heidelberg
  - M. Kozuma, Tokyo …

QUANTUM INFORMATION SCIENCE
- Quantum memory
- Quantum networks
- Heralded single photons …

- <u>Room temperature atomic ensembles</u>
  - M. Lukin, Harvard (2003)
  - G.-C Guo, Hefei
  - A. Lvovsky, Calgary …

Temporal control of bi-photons
Harris group, Stanford



Single-photon bus connecting spin-wave quantum memories

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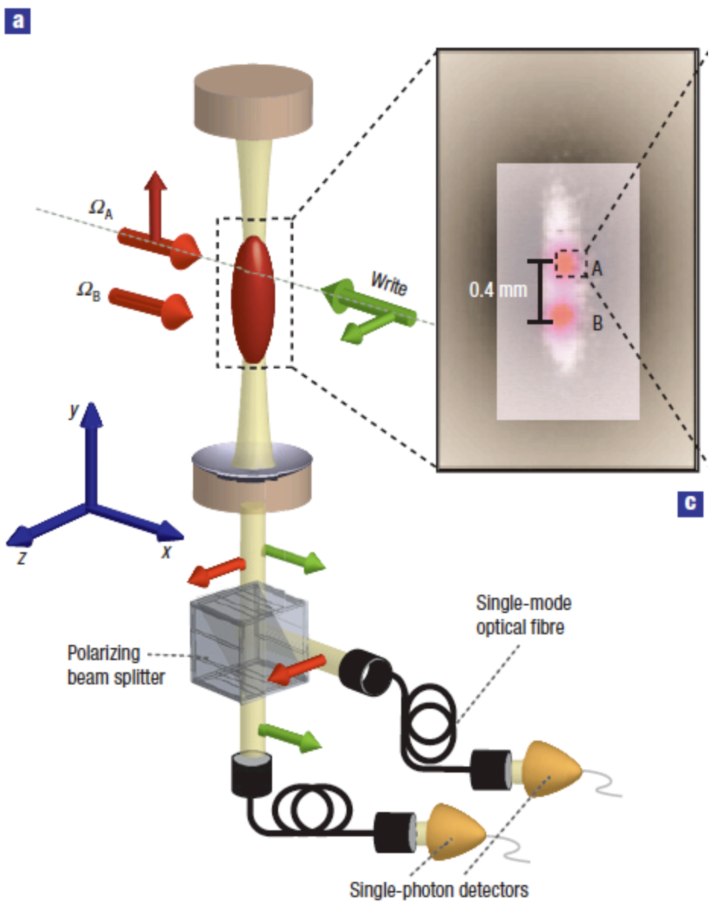
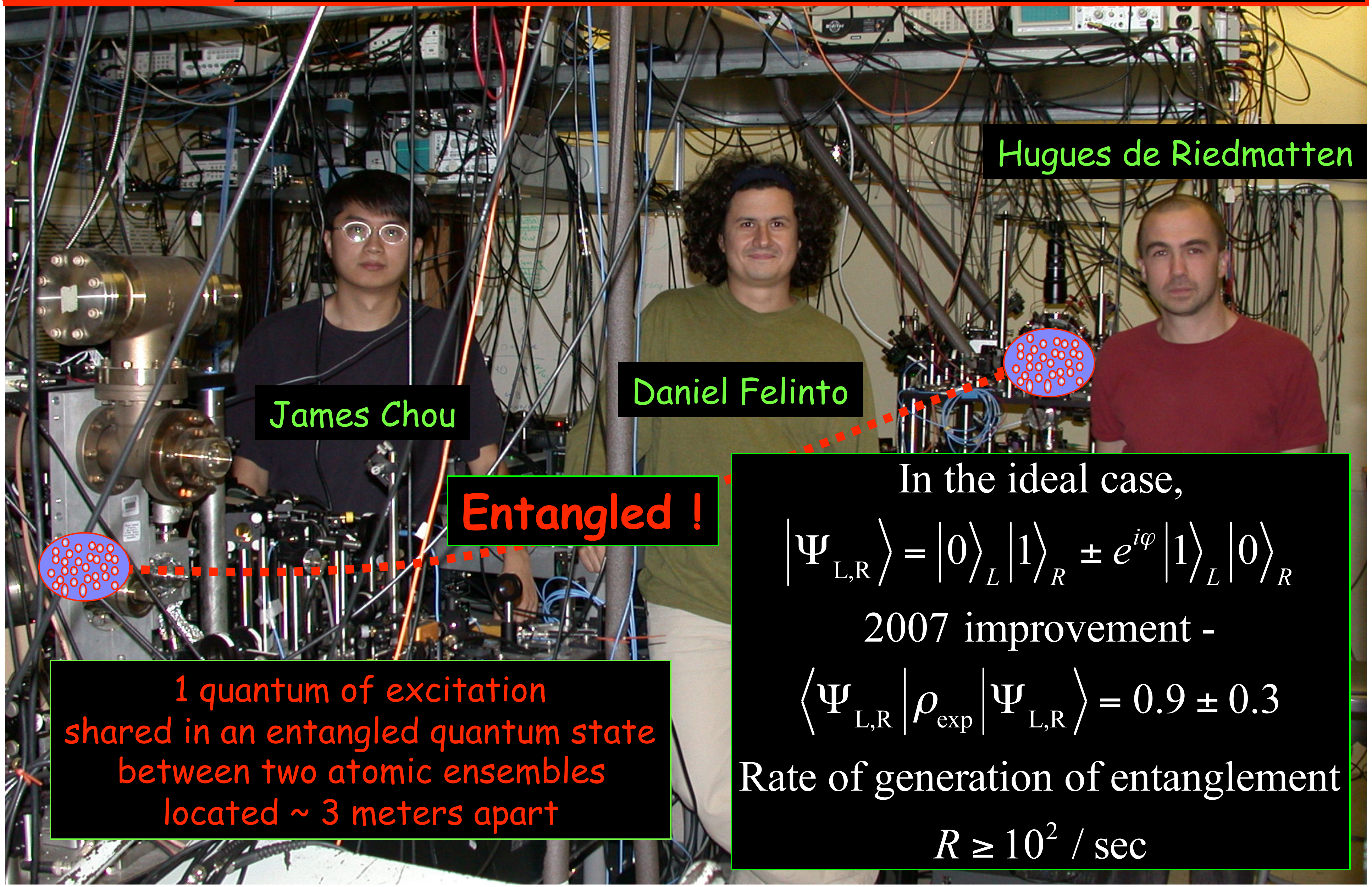


Concurrence C

$$C = 0.041 \pm 0.011 > 0$$

"Measurement-Induced Entanglement for Excitation Stored in Remote Atomic Ensembles," C. W. Chou, H. de Riedmatten, D. Felinto, S. V. Polyakov, S. J. van Enk, and H. J. Kimble, Nature **438**, 828 (2005)



1 quantum of excitation
shared in an entangled quantum state
between two atomic ensembles
located ~ 3 meters apart

In the ideal case,

$$\left|\Psi_{\mathrm{L,R}}\right\rangle = \left|0\right\rangle_L \left|1\right\rangle_R \pm e^{i\varphi} \left|1\right\rangle_L \left|0\right\rangle_R$$

2007 improvement -

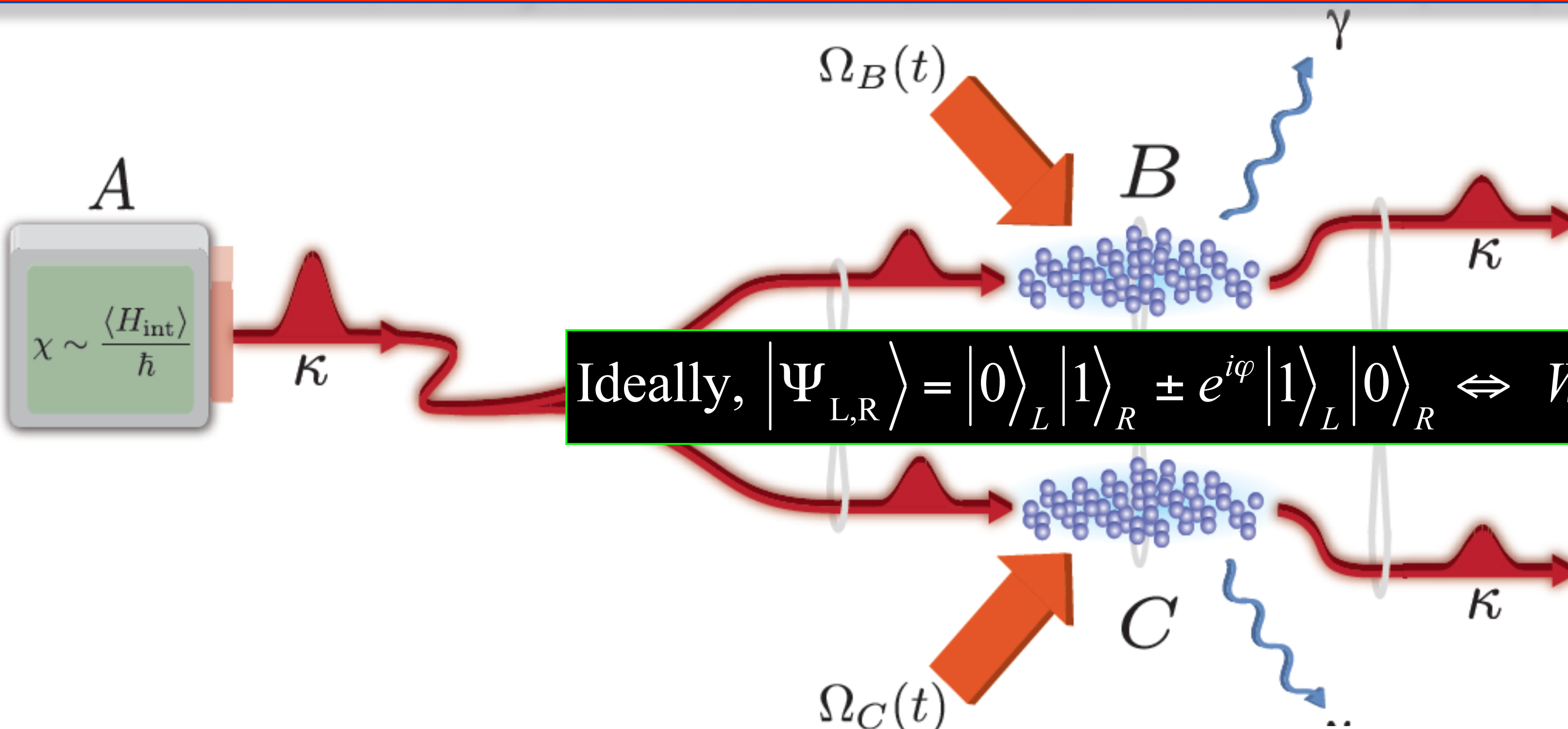
$$\left\langle \Psi_{\mathrm{L,R}} \right| \rho_{\mathrm{exp}} \left| \Psi_{\mathrm{L,R}} \right\rangle = 0.9 \pm 0.3$$

Rate of generation of entanglement

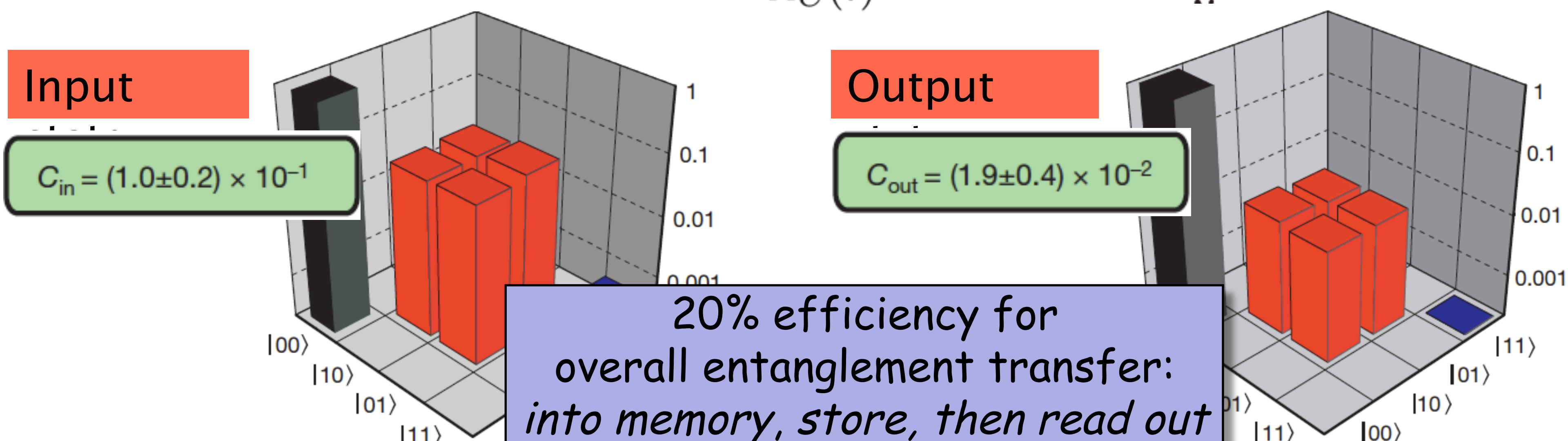
$$R \geq 10^2 \ / \ \mathrm{sec}$$

"Mapping photonic entanglement into and out of a quantum memory"

K. S. Choi, H. Deng, J. Laurat, and H. J. Kimble, Nature **452**, 67 (2008)



Ideally, $|\Psi_{L,R}\rangle = |0\rangle_L |1\rangle_R \pm e^{i\varphi} |1\rangle_L |0\rangle_R \Leftrightarrow W$ state



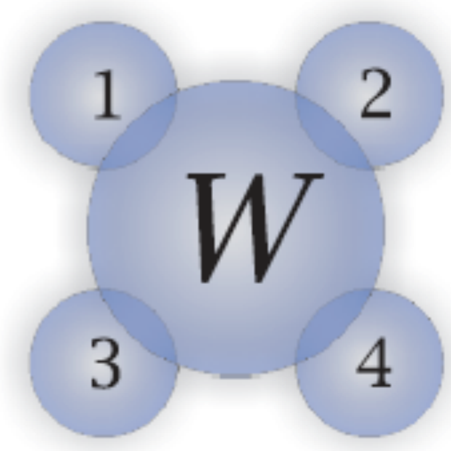
20% efficiency for
overall entanglement transfer:
into memory, store, then read out

Generation and Characterization of *N* – partite *W* states

$$|W\rangle = \frac{1}{\sqrt{N}} \sum_{i=1}^{N} |0, \cdots, 0_{i-1}, 1_i, 0_{i+1}, \cdots, 0\rangle$$

- For example, a quadripartite *W* state –

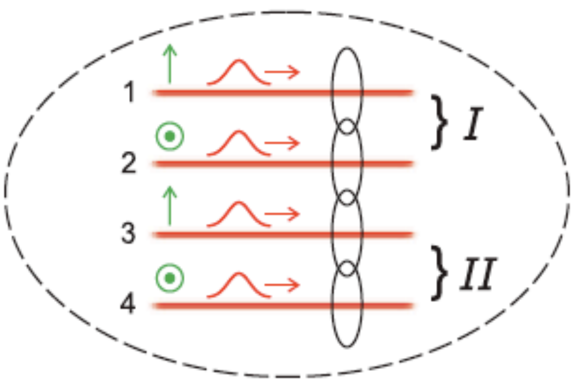
$$|W\rangle = \frac{1}{2}\left[\left(|1000\rangle + e^{i\phi_1}|0100\rangle\right) + e^{i\phi}\left(|0010\rangle + e^{i\phi_2}|0001\rangle\right)\right]$$

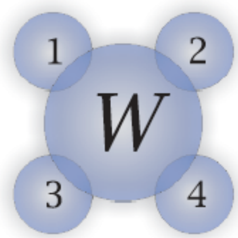


- An excluded *W* state –

"Multipartite entanglement for one photon shared among four optical modes"

Scott B. Papp, Kyung Soo Choi, H. Deng, P. Lougovski, S. J. van Enk & HJK, Science (2009)





Quadripartite entanglement – 4 modes sharing 1 photon

$$\Delta \Leftrightarrow V_{ijkl}$$

$$\Delta = 1 - \sum P^2$$

"Multipartite entanglement for one photon shared among four optical modes"

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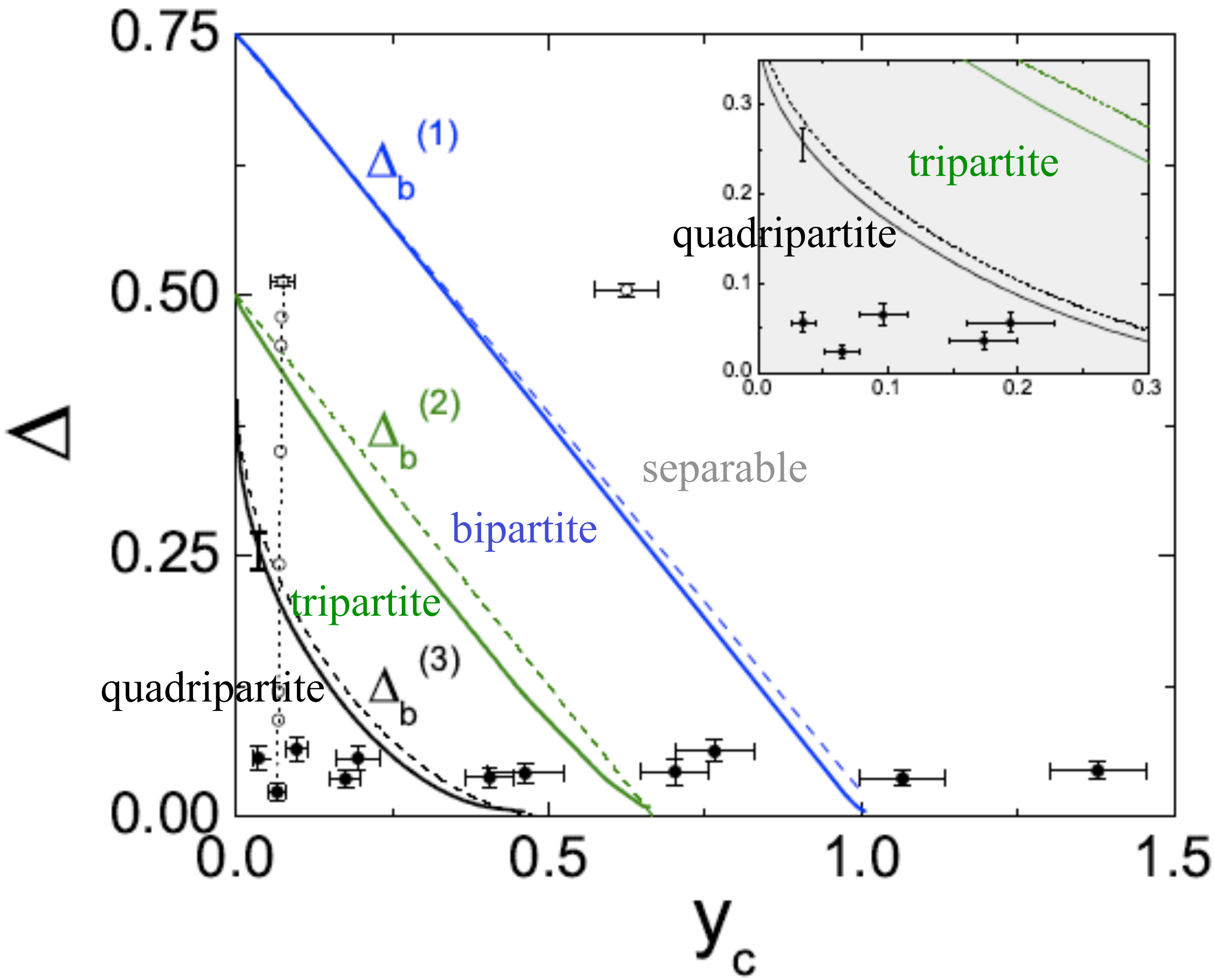
Quadripartite entanglement – 4 modes sharing 1 photon

Δ

from fringe visibilities V_{ijkl}

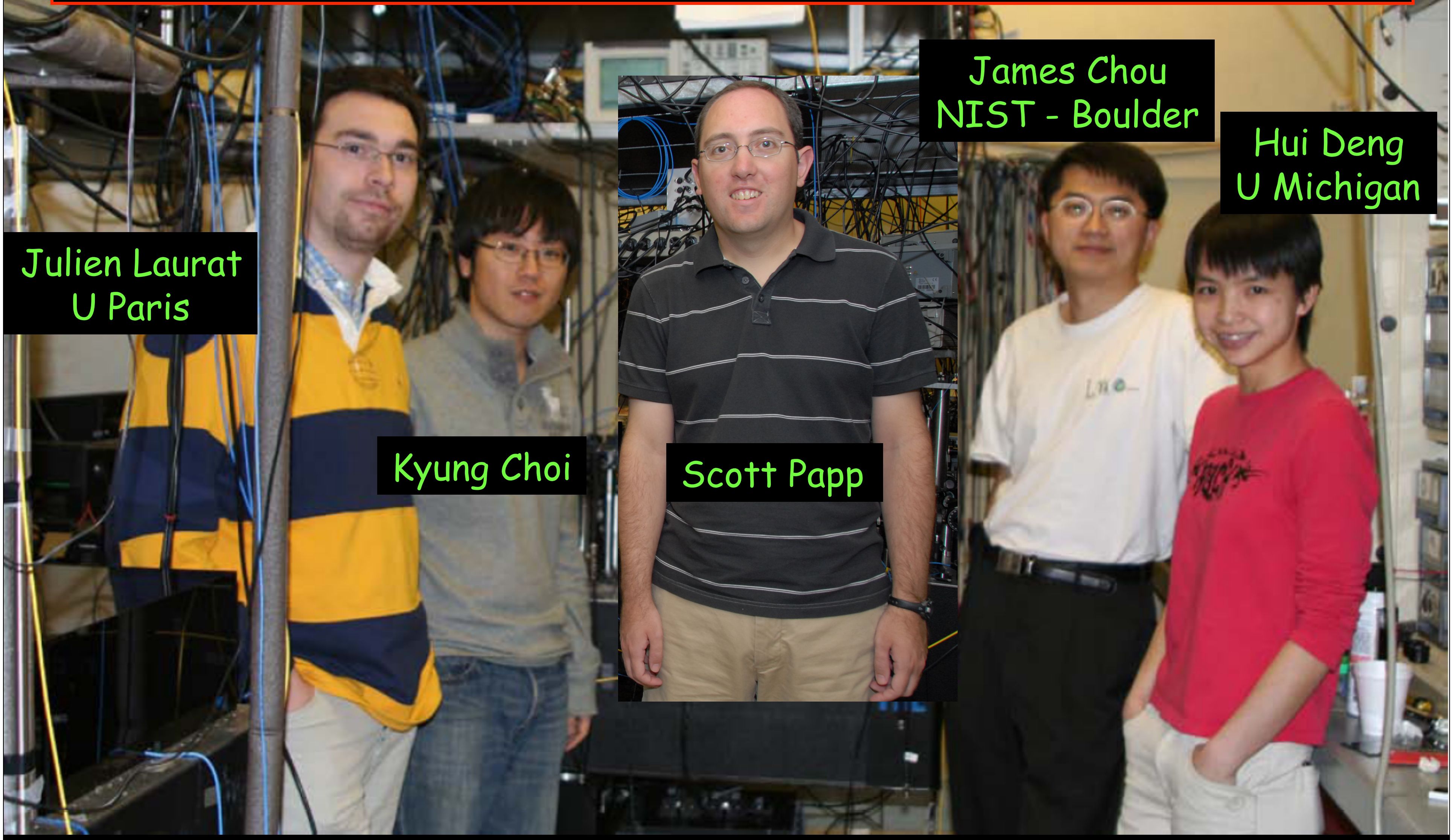
$$y_c = \frac{3}{2}\frac{p_{\geq 2}\,p_0}{p_1^2}$$

from photon statistics

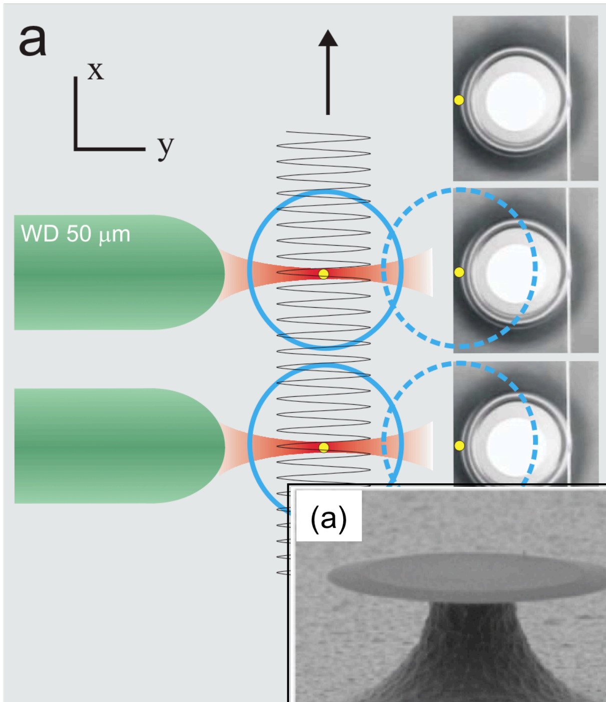


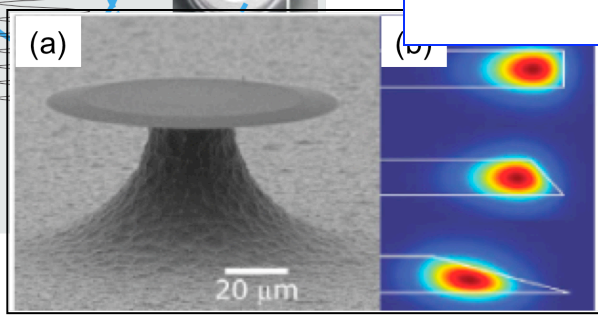
"Functional Quantum Nodes for Entanglement Distribution over Scalable Quantum Networks"

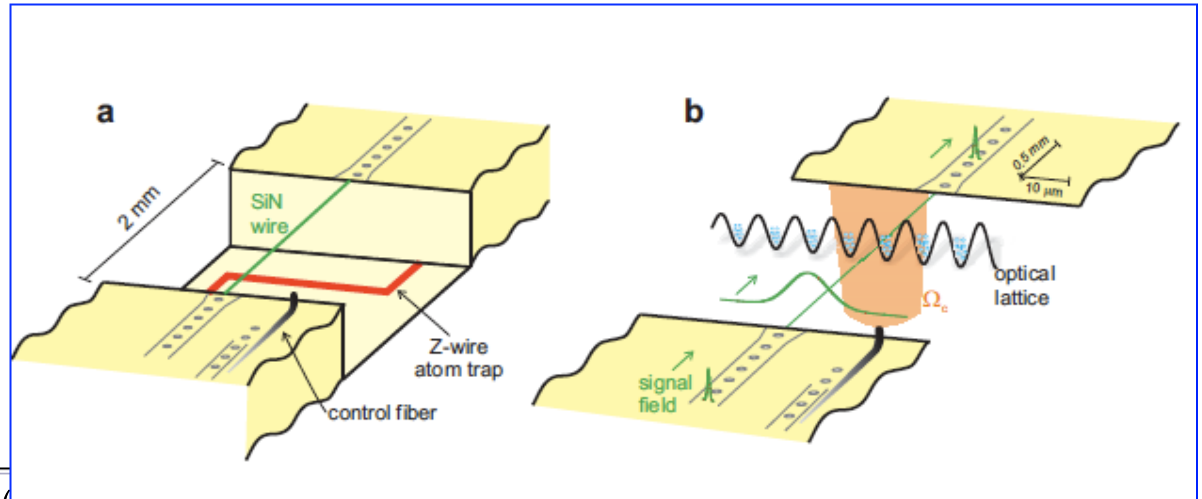
C.-W. Chou, J. Laurat, H. Deng, K. S. Choi, H. de Riedmatten, D. Felinto & H. J. Kimble, **Science 316**, 1316 (2007)

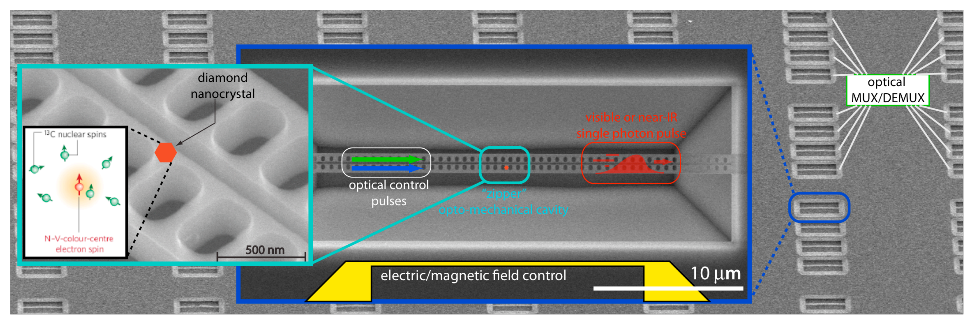


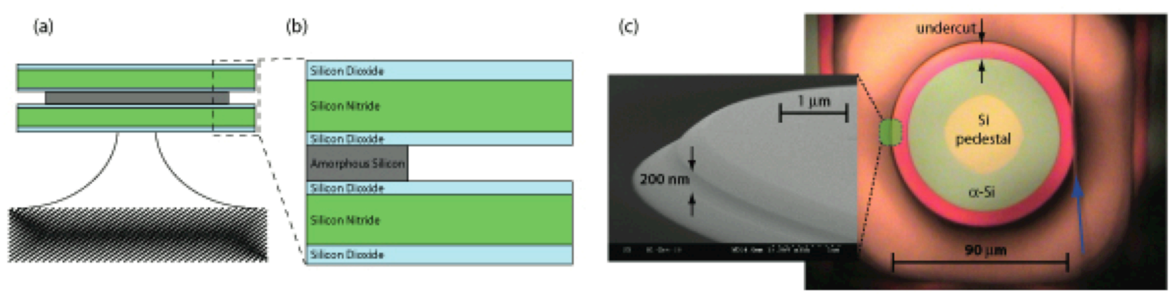
Quantum networks based upon atom-cavity systems –
Atoms as "stationary qubits" ⇔ Photons as "flying qubits"
Oskar Painter, Kerry Vahala (Caltech); David Awschalom (UCSB); Cindy Regal (JILA)











Photonic Circuits –
- Mirco- & nano-resonators
- Low-loss propagation

O. Painter & K. Vahala

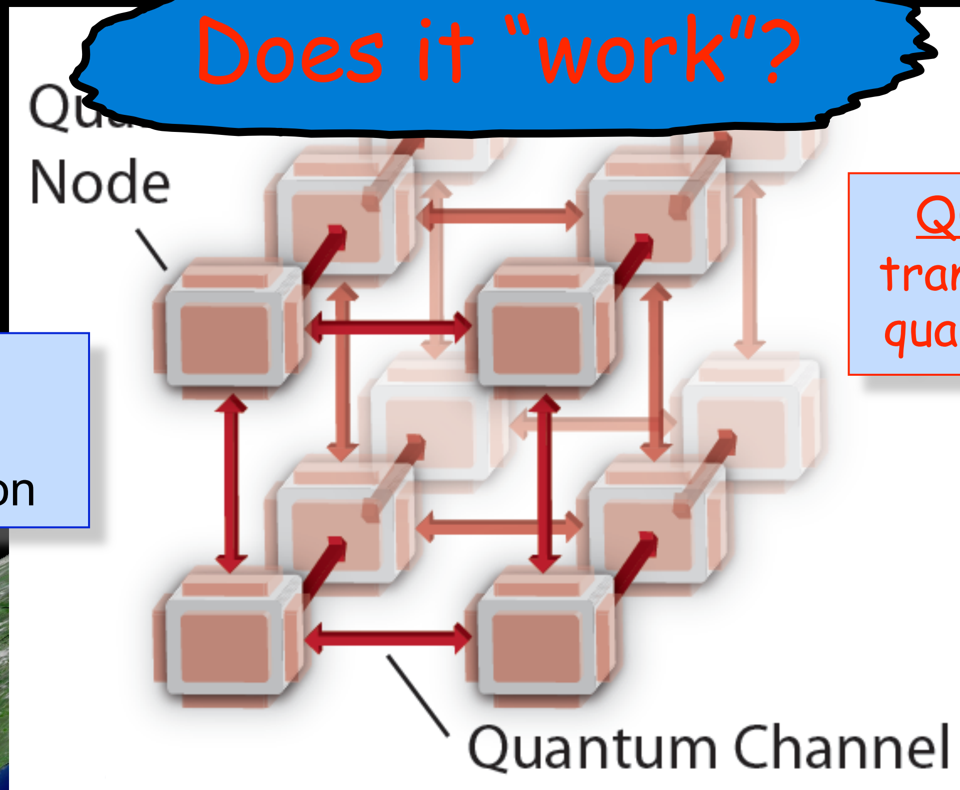
Color Centers –

D. Awschalom, O. Painter

Quantum Networks

➪ Fundamental Scientific Question and Diverse Technical Challenges

Does it "work"?



<u>Quantum Node-</u>
process / store
quantum information

<u>Quantum Channel -</u>
transport / distribute
quantum entanglement

Characterization and Verification
of Entanglement for Multipartite Systems –

1. Algorithmic 2. Brute force ρ 3. Physical ….