IV São Paulo School on light and cold atoms

Quantum networks with cold atoms

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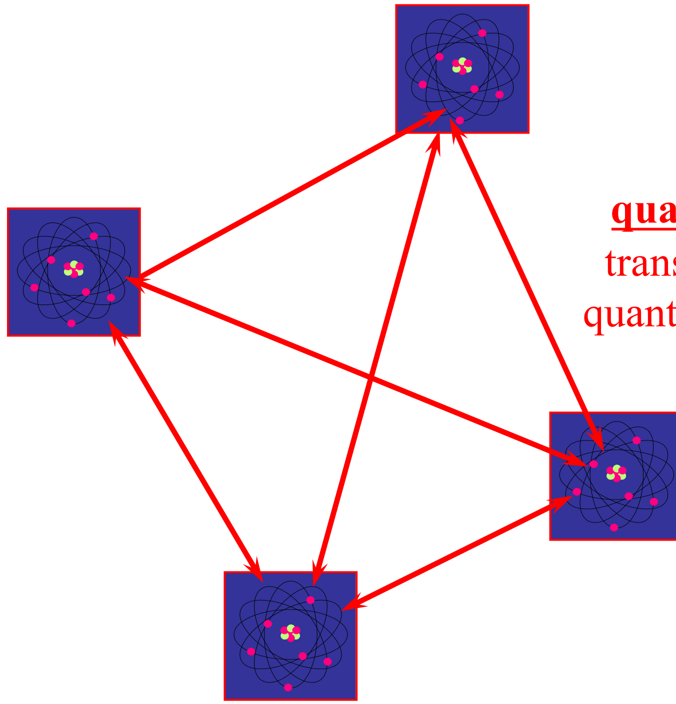
Quantum Networks

quantum sites
generate, process, and store
quantum information



quantum channels
transport / distribute
quantum entanglement

General goal: To implement various quantum information protocols using distributed physical resources

"*The quantum internet*", H.J. Kimble, Nature **453**, 1023 (2008)

Motivation

Quantum Information

new technologies

- quantum computation
  - ⇒ new way to compute
  - ⇒ potential for great impact
- quantum communication
  - ⇒ ultra-security
- quantum sensing
  - ⇒ ultra-sensitivity

new frontier of physics

- quantum correlated systems at larger scales (N>>2)
- foundations of quantum mechanics
- new level of control of physical systems

Quantum networks

* well-controlled systems
* well-stablished experimental techniques
* good agreement theory × experiment

* new problems
* new approach

Atomic Physics + **Quantum Optics** + **Quantum Information**

Ideal for quantum engineering
and tests of fundamental concepts

Progress in Quantum Electronics 99 (2025) 100551

Contents lists available at ScienceDirect

Progress in Quantum Electronics

journal homepage: www.elsevier.com/locate/pqe

Invited review

The road to quantum internet: Progress in quantum network testbeds and major demonstrations

Jianqing Liu [a],*, Thinh Le [a], Tingxiang Ji [a], Ruozhou Yu [a], Demitry Farfurnik [b,c], Greg Byrd [b], Daniel Stancil [b]

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[b] Department of Electrical and Computer Engineering, North Carolina State University, Raleigh, 27606, USA
[c] Department of Physics, North Carolina State University, Raleigh, 27606, USA

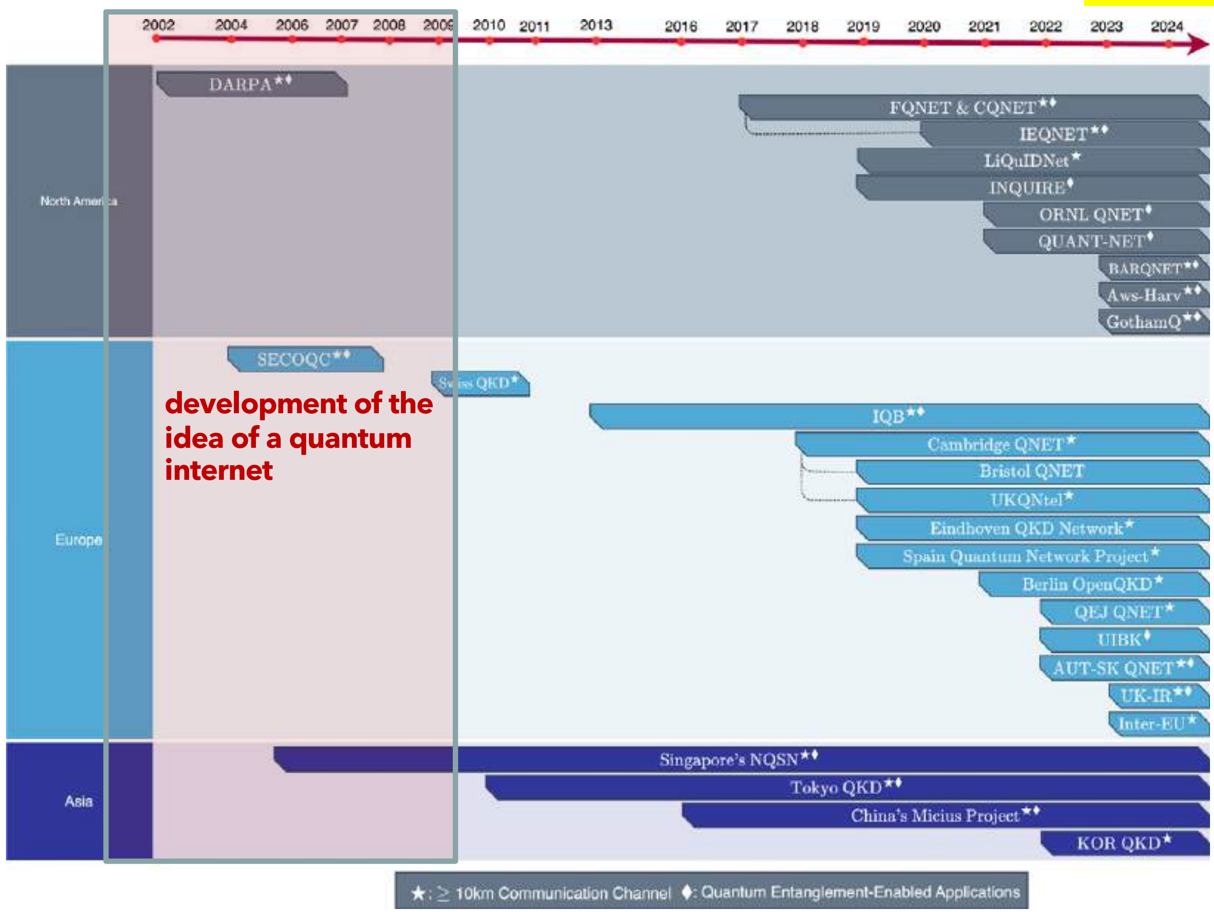
focus of this minicourse

case study

Brazil

Quantum Rio Network

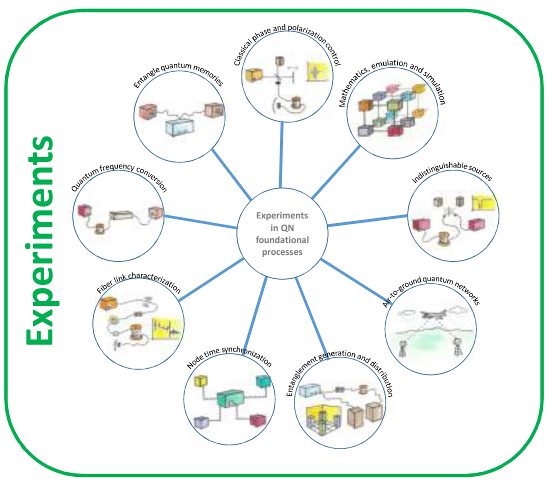
Recife Quantum Network



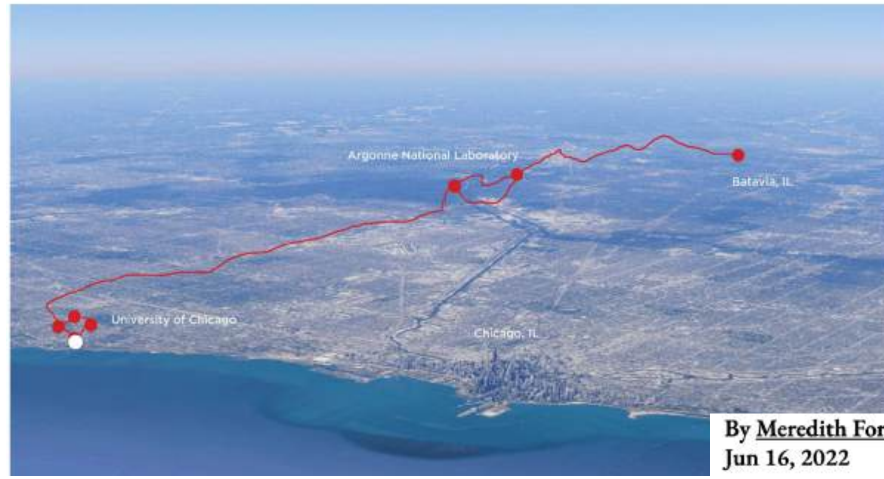
USA: quantum entanglement networks

DC-QNet

DC-QNet Map



Chicago expands and activates quantum network, taking steps toward a secure quantum internet

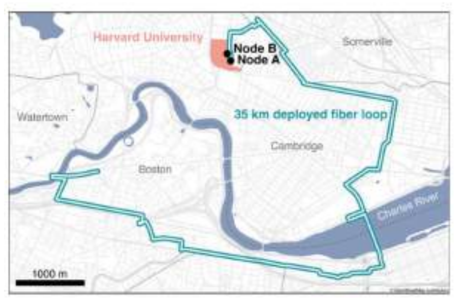


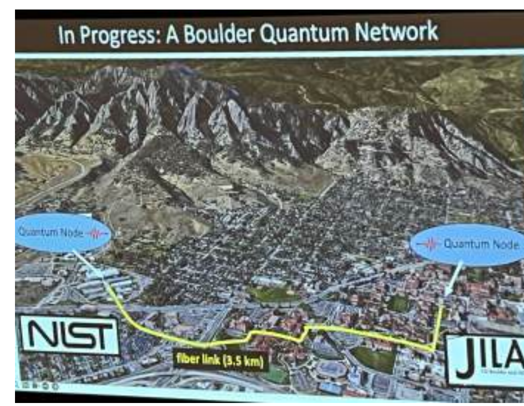
By Meredith Fore
Jun 16, 2022

MAY 15, 2024 Editors' notes

Physicists demonstrate first metro-area quantum computer network in Boston

by Harvard University





China

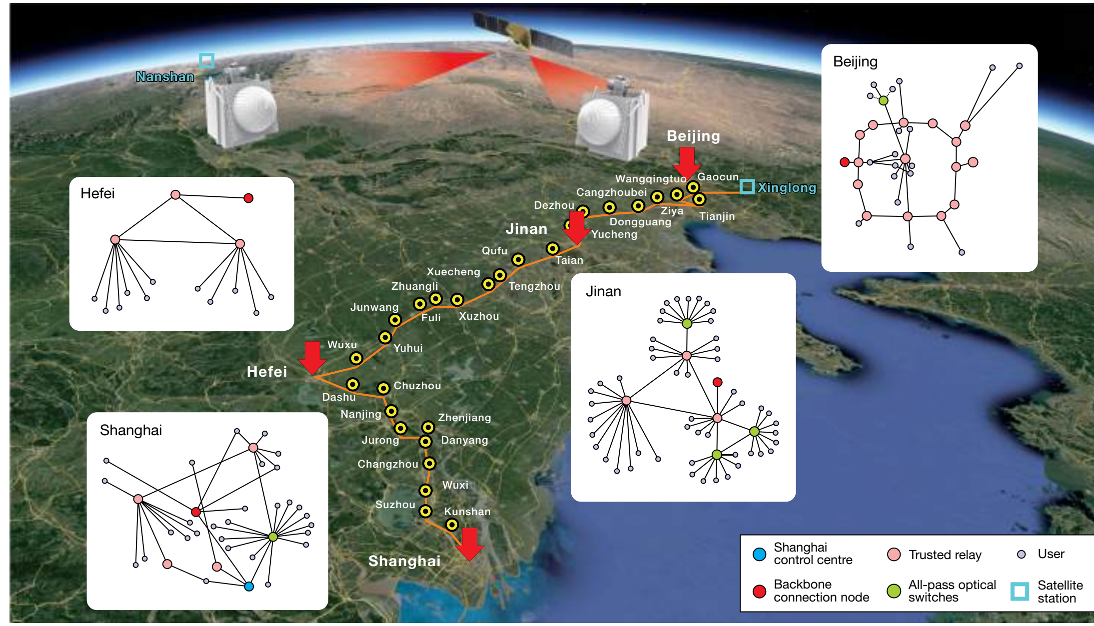
214 | Nature | Vol 589 | 14 January 2021

Article

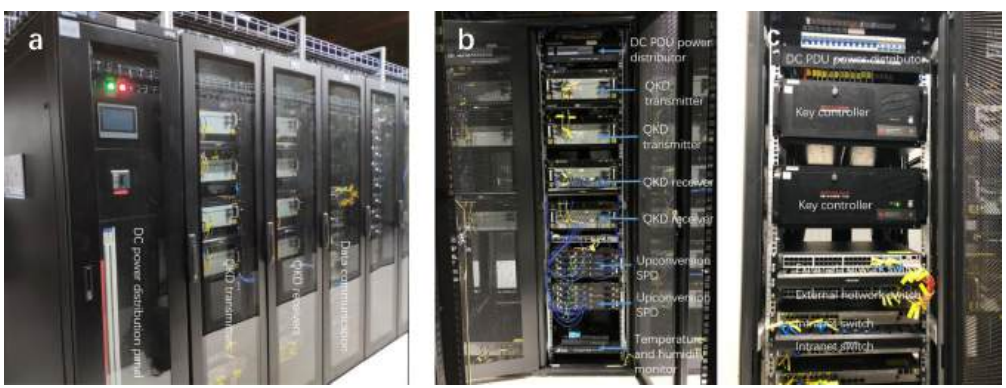
An integrated space-to-ground quantum communication network over 4,600 kilometres

https://doi.org/10.1038/s41586-020-03093-8
Received: 1 March 2019
Accepted: 2 November 2020
Published online: 6 January 2021
Check for updates

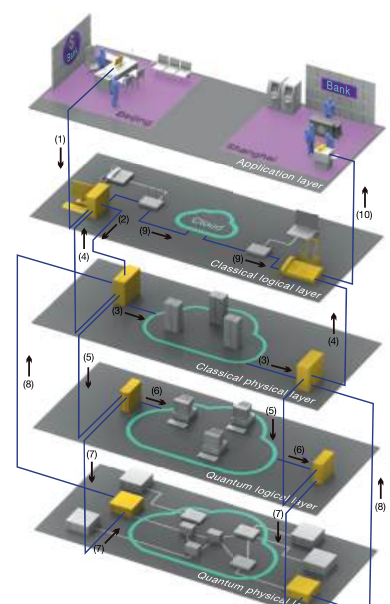
Yu-Ao Chen[1,2]✉, Qiang Zhang[1,2], Teng-Yun Chen[1,2], Wen-Qi Cai[1,2], Sheng-Kai Liao[1,2], Jun Zhang[1,2], Kai Chen[1,2], Juan Yin[1,2], Ji-Gang Ren[1,2], Zhu Chen[1,2], Sheng-Long Han[1,2], Qing Yu[3], Ken Liang[3], Fei Zhou[4], Xiao Yuan[1,2], Mei-Sheng Zhao[1,2], Tian-Yin Wang[1,2], Xiao Jiang[1,2], Liang Zhang[2,5], Wei-Yue Liu[1,2], Yang Li[1,2], Qi Shen[1,2], Yuan Cao[1,2], Chao-Yang Lu[1,2], Rong Shu[2,5], Jian-Yu Wang[2,5], Li Li[1,2], Nai-Le Liu[1,2], Feihu Xu[1,2], Xiang-Bin Wang[4], Cheng-Zhi Peng[1,2]✉ & Jian-Wei Pan[1,2]✉



more than 2000 km and 700 QKD fiber links



Extended Data Fig. 1 | Hardware at the relay nodes of the backbone network. **a**, Overview of the typical hardware. **b**, QKD devices. **c**, Control and classical communication devices. SPD, single-photon detector; PDU, power distribution unit.



QKD ⇒ Quantum Key Distribution

China

Micius Satellite

June, 2017: distribution of quantum entanglement among systems separated by 1200 km

Article Nature | Vol 582 | 25 June 2020 | **501**

Entanglement-based secure quantum cryptography over 1,120 kilometres

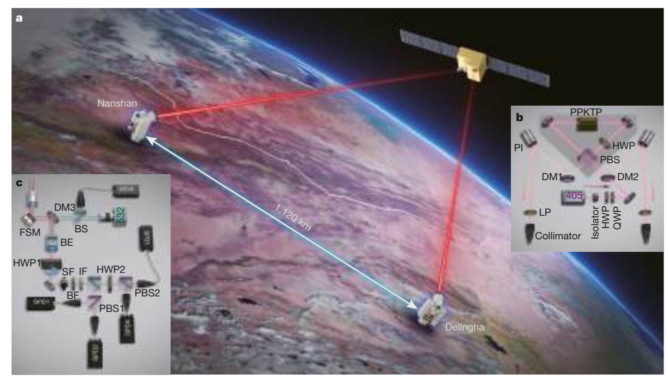
https://doi.org/10.1038/s41586-020-2401-y

Received: 15 July 2019

Accepted: 13 May 2020

Published online: 15 June 2020

Juan Yin[1,2,3], Yu-Huai Li[1,2,3], Sheng-Kai Liao[1,2,3], Meng Yang[1,2,3], Yuan Cao[1,2,3], Liang Zhang[2,3,4], Ji-Gang Ren[1,2,3], Wen-Qi Cai[1,2,3], Wei-Yue Liu[1,2,3], Shuang-Lin Li[1,2,3], Rong Shu[2,3,4], Yong-Mei Huang[5], Lei Deng[6], Li Li[1,2,3], Qiang Zhang[1,2,3], Nai-Le Liu[1,2,3], Yu-Ao Chen[1,2,3], Chao-Yang Lu[1,2,3], Xiang-Bin Wang[2], Feihu Xu[1,2,3], Jian-Yu Wang[2,3,4], Cheng-Zhi Peng[1,2,3]✉, Artur K. Ekert[7,8] & Jian-Wei Pan[1,2,3]✉



Satellite network up to 2030

China

Nature | Vol 640 | 3 April 2025 | 47

Article

Microsatellite-based real-time quantum key distribution

https://doi.org/10.1038/s41586-025-08739-z

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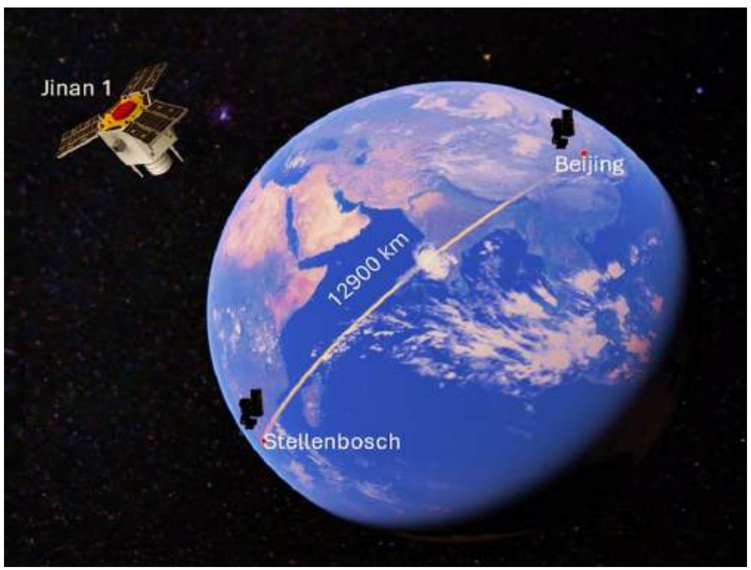
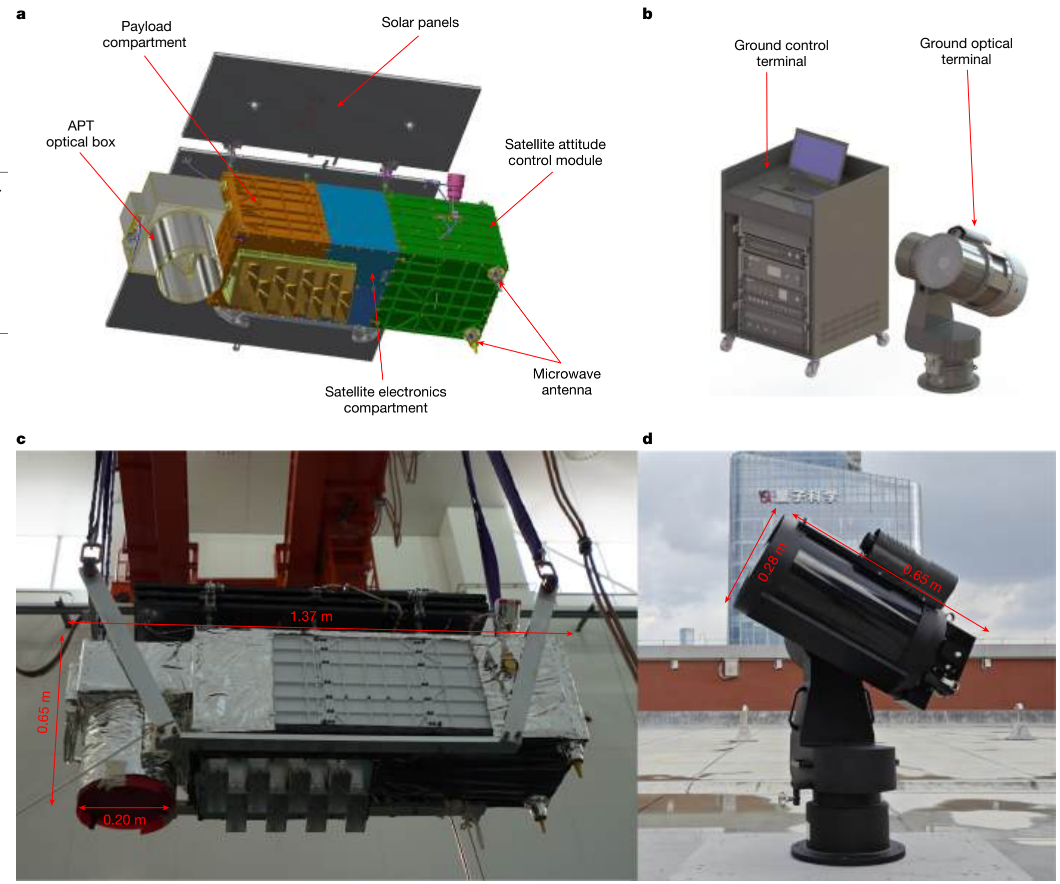
Check for updates

Yang Li[1,2,3,14], Wen-Qi Cai[1,2,3,14], Ji-Gang Ren[1,2,3,14], Chao-Ze Wang[1,2,3], Meng Yang[1,2,3], Liang Zhang[3,4], Hui-Ying Wu[5], Liang Chang[5], Jin-Cai Wu[3,4], Biao Jin[6], Hua-Jian Xue[1,2,3], Xue-Jiao Li[1,2,3], Hui Liu[6], Guang-Wen Yu[1,2,3], Xue-Ying Tao[1,2,3], Ting Chen[5], Chong-Fei Liu[3,4], Wen-Bin Luo[1,2,3], Jie Zhou[6], Hai-Lin Yong[6], Yu-Huai Li[1,2,3], Feng-Zhi Li[1,2,3], Cong Jiang[7], Hao-Ze Chen[8], Chao Wu[8], Xin-Hai Tong[9], Si-Jiang Xie[9], Fei Zhou[7], Wei-Yue Liu[1,2,3], Yaseera Ismail[10,11], Francesco Petruccione[10,12,13], Nai-Le Liu[1,2,3], Li Li[1,2,3], Feihu Xu[1,2,3], Yuan Cao[1,2,3], Juan Yin[1,2,3], Rong Shu[3,4], Xiang-Bin Wang[7], Qiang Zhang[1,2,3,7], Jian-Yu Wang[3,4], Sheng-Kai Liao[1,2,3]✉, Cheng-Zhi Peng[1,2,3]✉ & Jian-Wei Pan[1,2,3]✉





micro satellite
23 kg

ground station
100 kg

Europe

European Commission

Shaping Europe's digital future

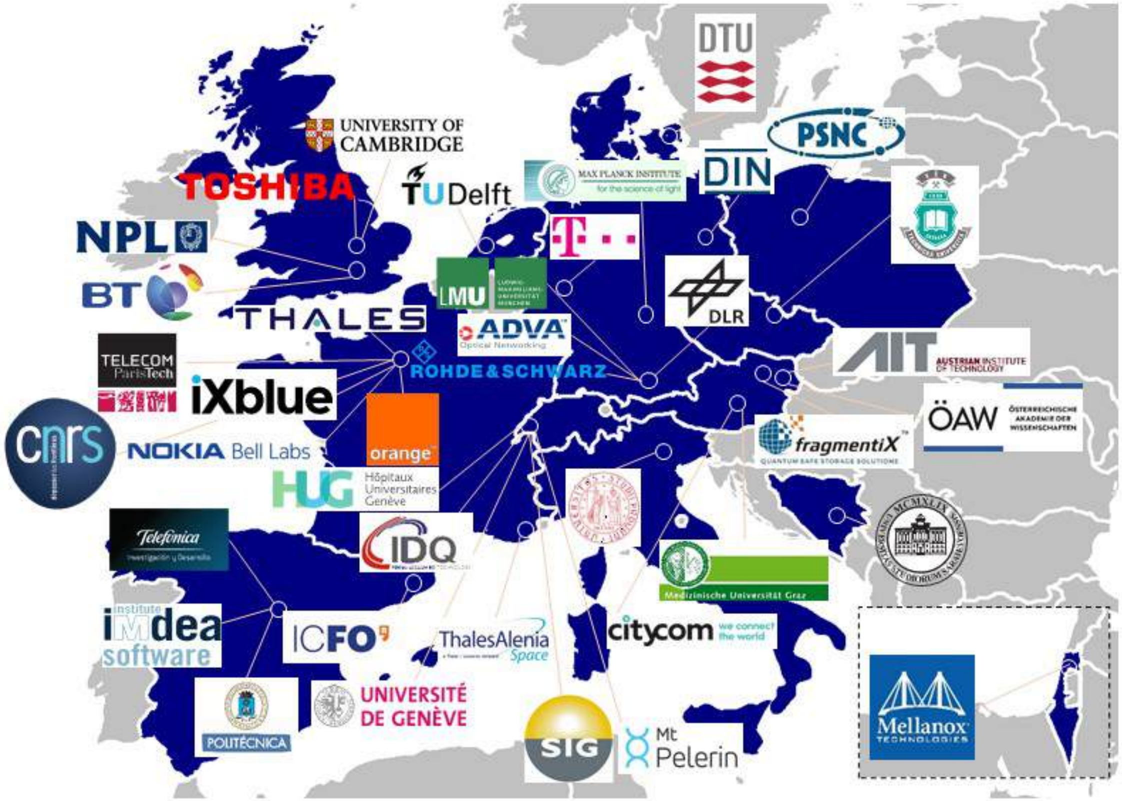
The European Quantum Communication Infrastructure (EuroQCI) Initiative

OPEN QKD

Contribute to quantum cryptography standardization and security certification efforts

Lay the foundations for a Pan-European Quantum Network

Kick-start a competitive European QKD industry

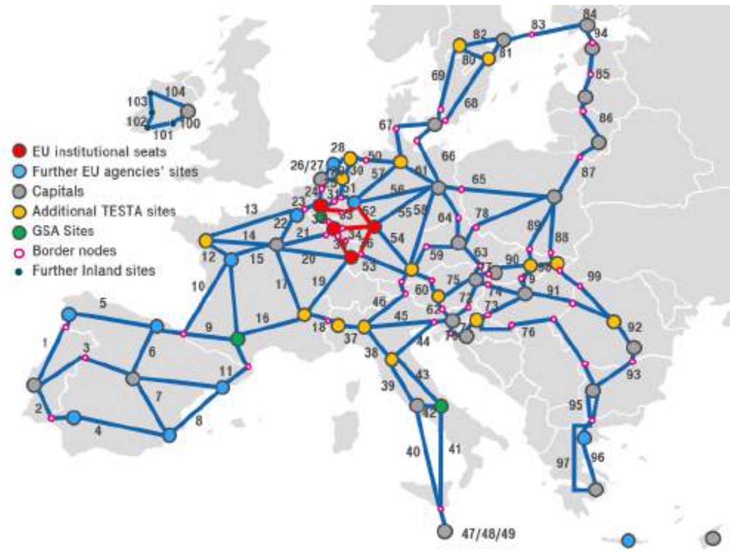


+ satellite project

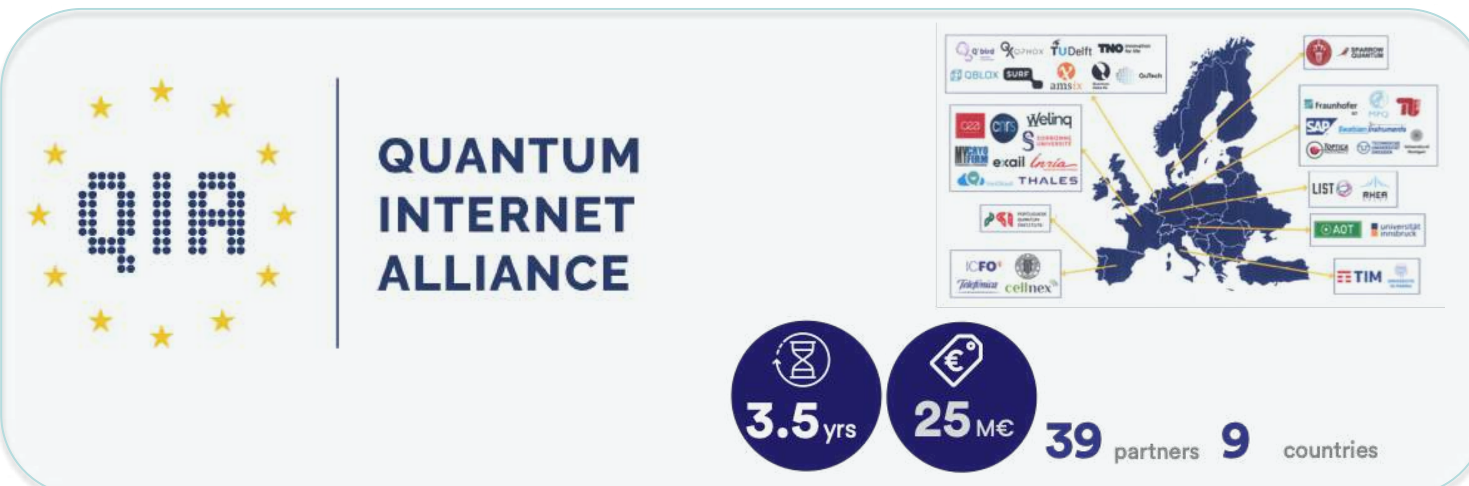
Europe

EuroQCI: The Terrestrial Segment

Terrestrial Segment: a federation of national terrestrial QCI networks



- Cross-border connection of EU capitals using fibre networks for ultra-secure exchange of cryptographic keys, authentication, time & frequency distribution, …
- Terrestrial topology for EuroQCI fibre backbone connecting European metropolitan areas in all 27 MS + relay nodes (100 km max fibre length)
- Total length of about 44.000 km



Quantum networks with cold atoms

⇒ light-matter interfaces

⇒ quantum memories

⇒ quantum entanglement networks

⇒ quantum communication + processing

⇒ Not focused on quantum cryptography

↳ Infrastructure for a multi-purpose quantum internet

Program

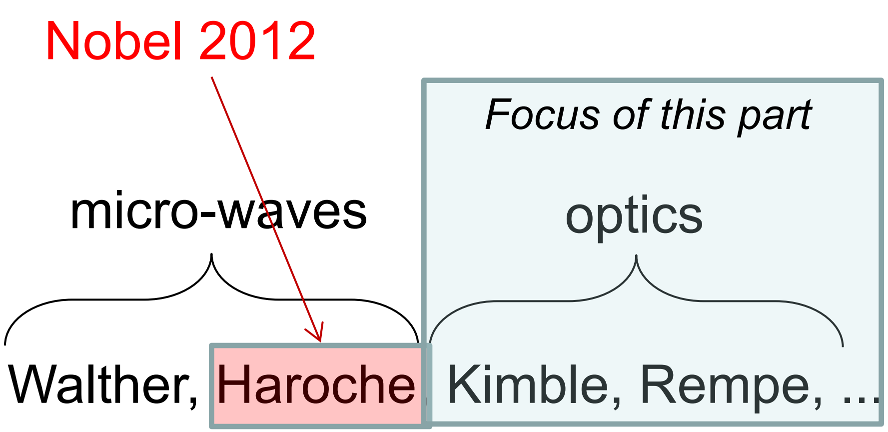
Part I: networks based on
cavity Quantum Electrodynamics

Part II: networks based on
atomic collective states

Part III: Recife Quantum Network

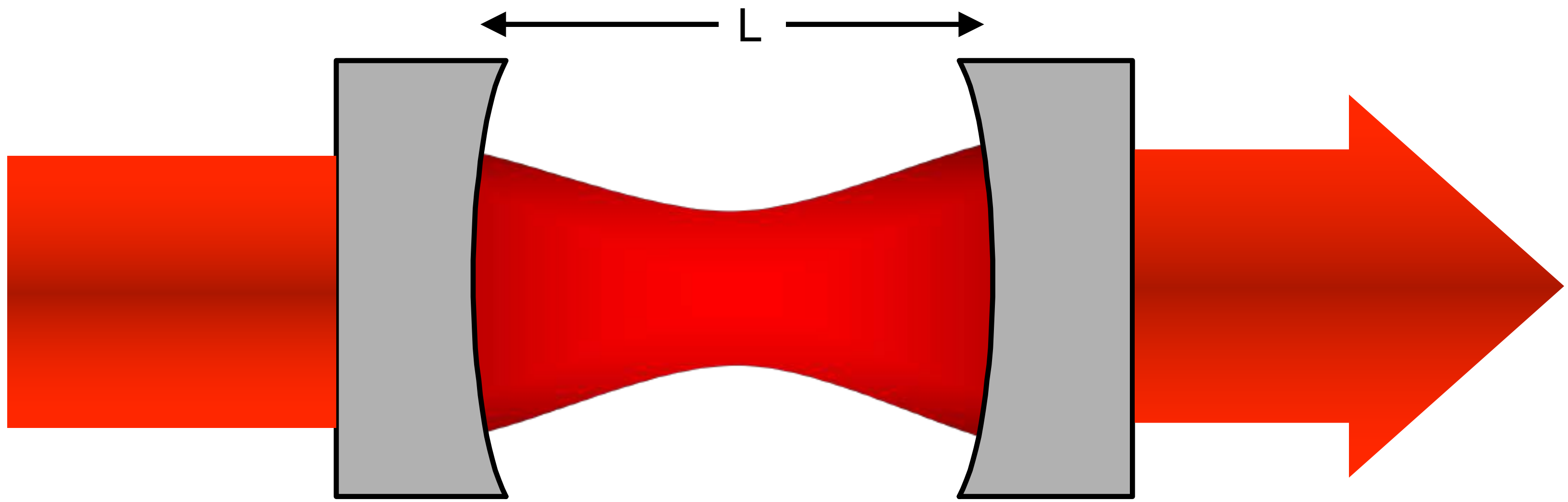
Part I

networks based on *cavity Quantum Electrodynamics*

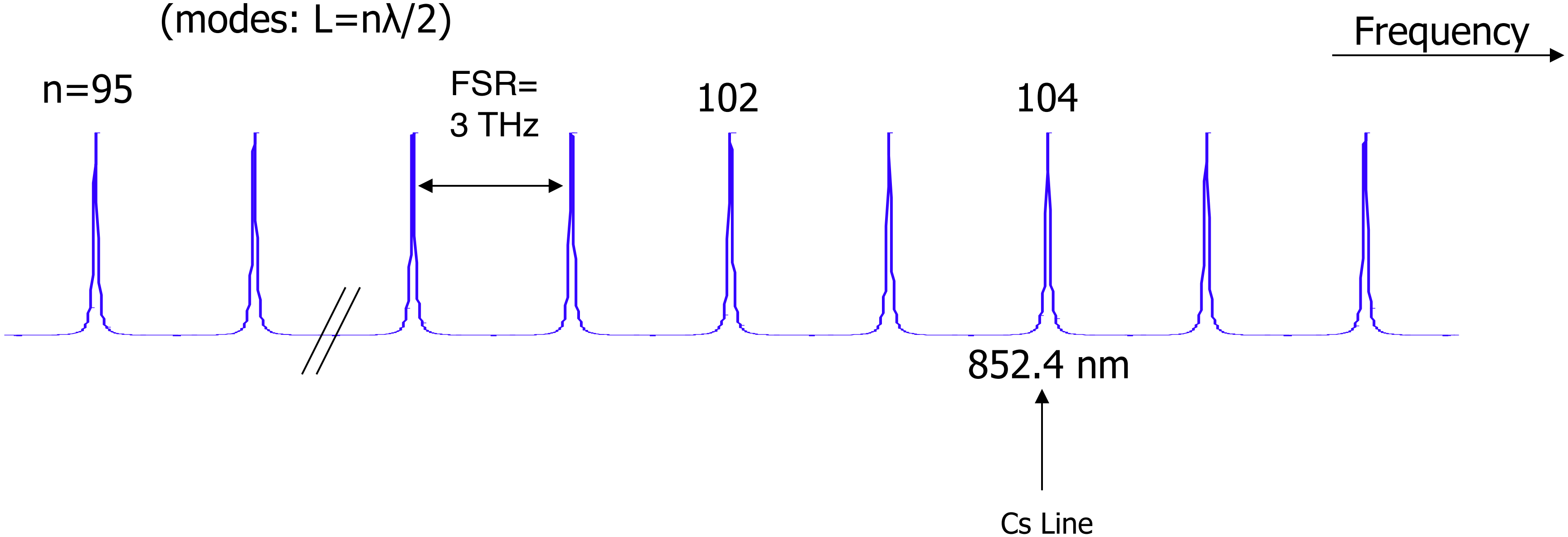


atom-cavity coupling

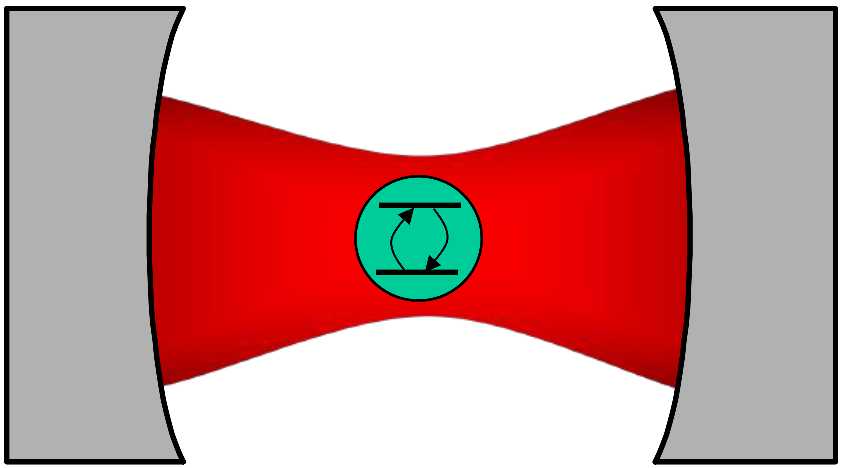
Cavity



Transmission Spectrum of an Optical Cavity (Length L=43 μm)
(modes: $L = n\lambda/2$)



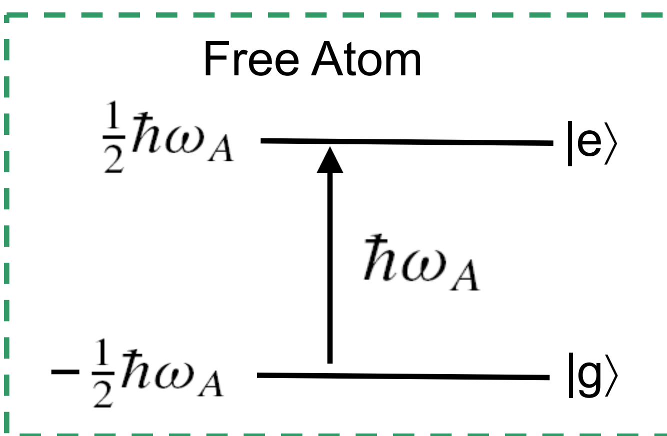
Cavity + atom

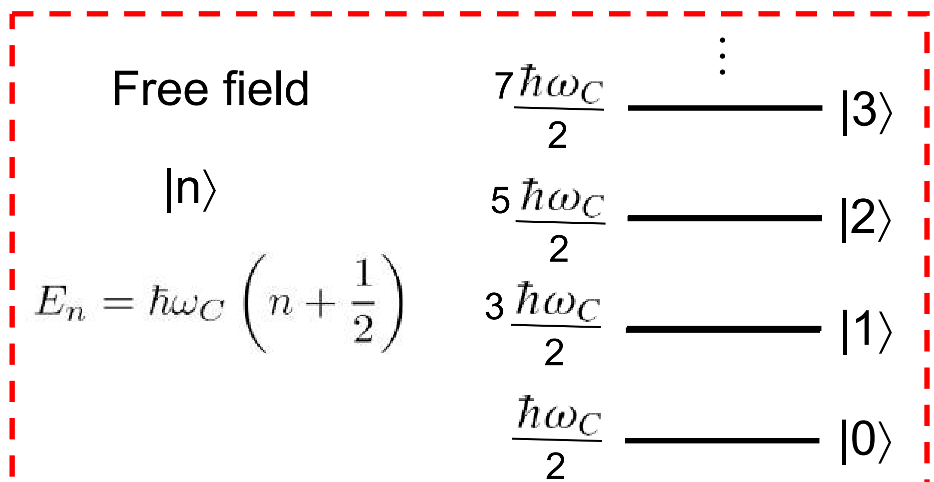


$\omega_A \equiv$ atomic resonance frequency

$\omega_C \equiv$ Cavity resonance frequency

Total energy = Free-atom energy + Free-field energy + Interaction energy





Total energy = Free-atom energy + Free-field energy + Interaction energy

Atom-field interaction

$$\hbar g = \mu E$$

Vacuum electric field:

$$\frac{\hbar\omega}{2} = \int \varepsilon_0 E^2 dV \quad \Rightarrow \quad E = \sqrt{\frac{\hbar\omega}{2\varepsilon_0 V}}$$

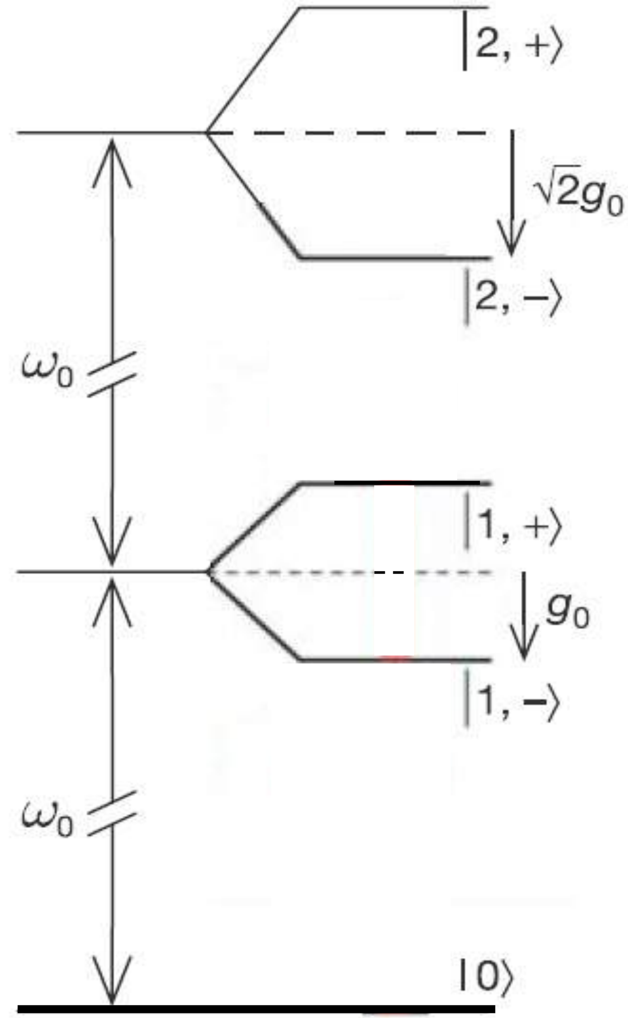
$\Downarrow$

$$g(\mathbf{r}) = \left(\frac{\mu^2 \omega_C}{2\hbar\epsilon_0 V_M}\right)^{\frac{1}{2}} U(\mathbf{r}) \equiv g_0 U(\mathbf{r})$$

$2g_0 \equiv$ Rabi frequency of 1 photon

<u>Resonant case</u>

$$\omega_A = \omega_C = \omega_0$$



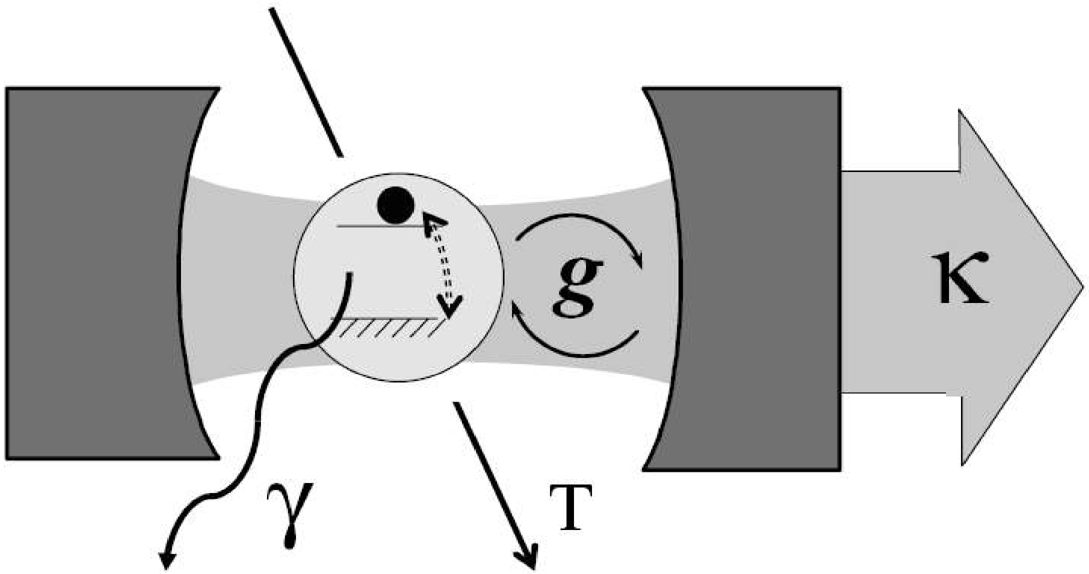
Strong Coupling

realistic model

⇩

Open Quantum System

dissipation rates (decoherence)



$\kappa \equiv$ decay rate of the cavity field

$\gamma \equiv$ radiative decay rate of excited atomic state
(for modes $\neq$ cavity)

T $\equiv$ atom flight time through the cavity

Strong coupling regime

⇩

$$g_0 >> (\gamma, \kappa, T^{-1})$$

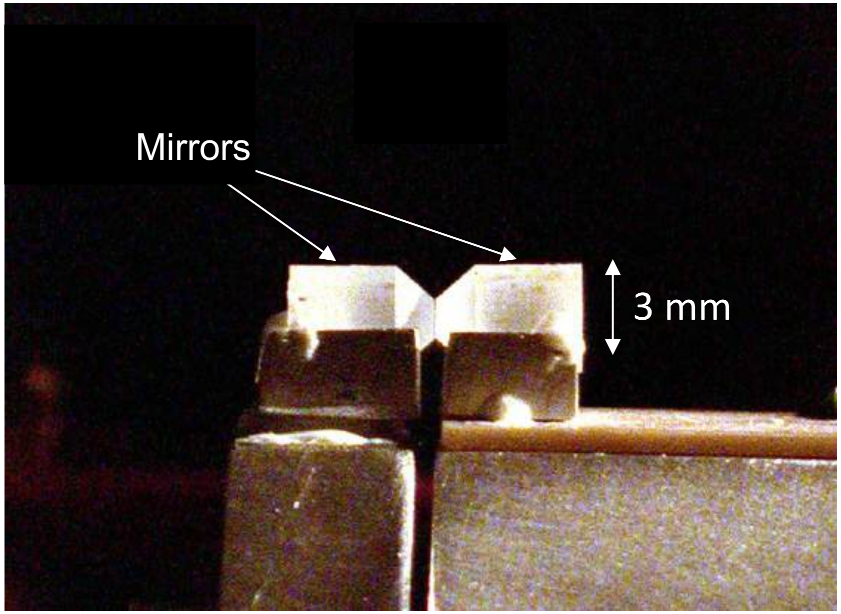
⇩

strong interaction
1 atom ⇔ 1 photon

⇩

"extreme" quantum dynamics

Cavities in the lab (old Caltech system)



$$g_0 = \left(\frac{\mu^2 \omega_C}{2\hbar \epsilon_0 V_M} \right)^{\frac{1}{2}} \propto V_M^{-1/2}$$

$L \cong 43\ \mu\text{m} \equiv$ Cavity length

$\omega_0 \cong 15\ \mu\text{m} \equiv$ mode waist

$$g_0 = 2\pi \times 32\ \text{MHz}$$

decay rates

$$\gamma = 2\pi \times 2.6\ \text{MHz}$$ (caesium atom)

$$\kappa = 2\pi \times 3.3\ \text{MHz}$$

High finesse cavity $\mathcal{F} = 4.2 \times 10^5$

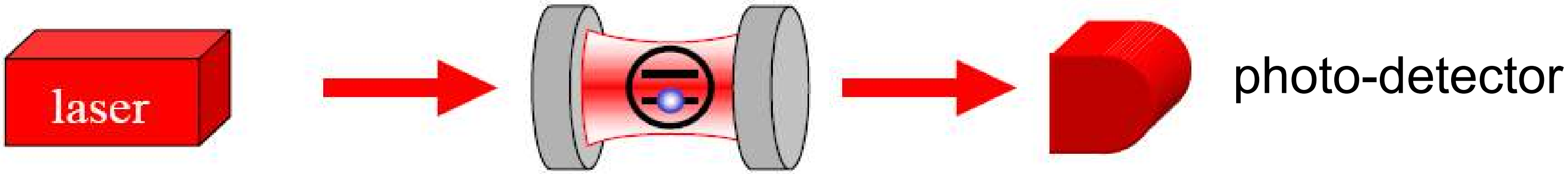
(reflectivity of mirrors R=0.9999984)

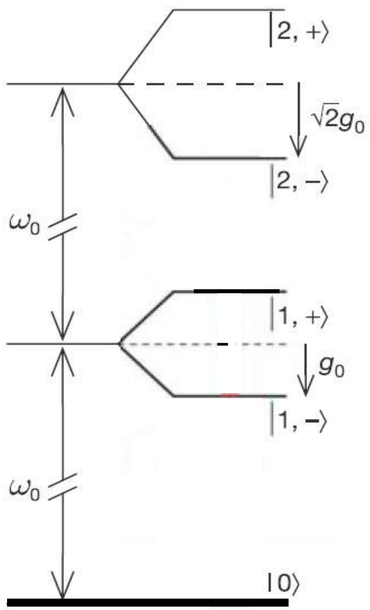
First experiments → T = 0.4 μs → T^{-1} = 2.5 MHz

current experiments → T > 1 s → T^{-1} < 1 Hz

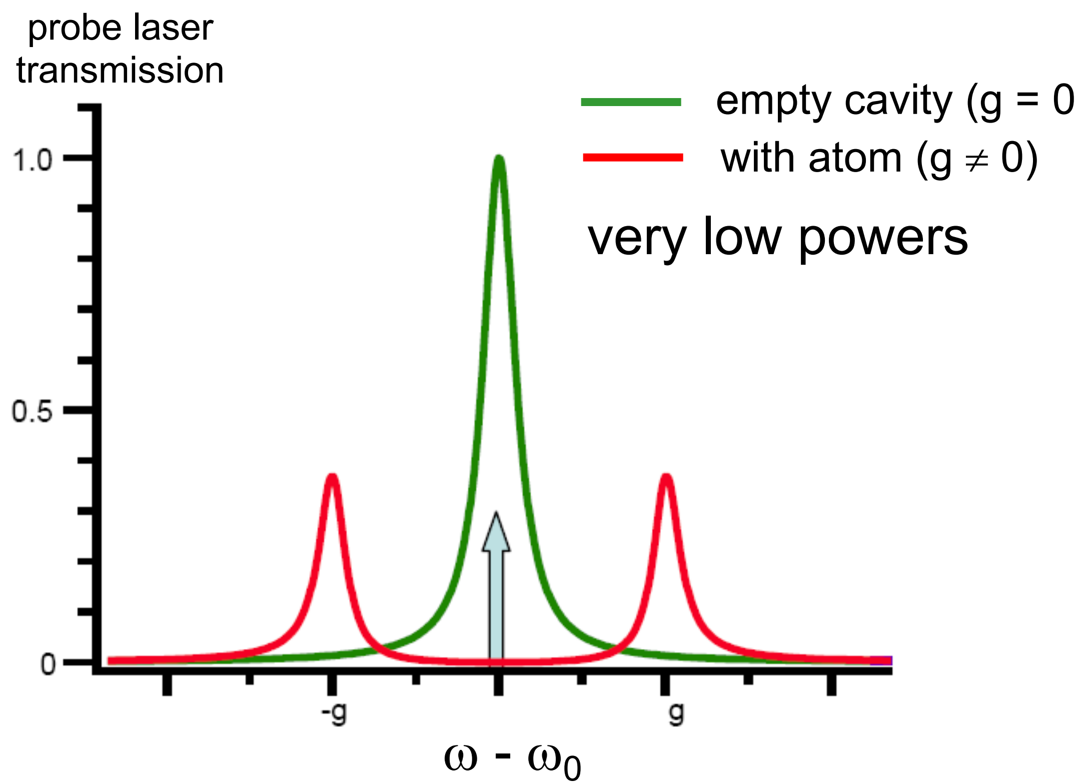
McKeever *et al*., Phys. Rev. Lett. **90**, 133602 (2003)

Strong Coupling: experimental signature





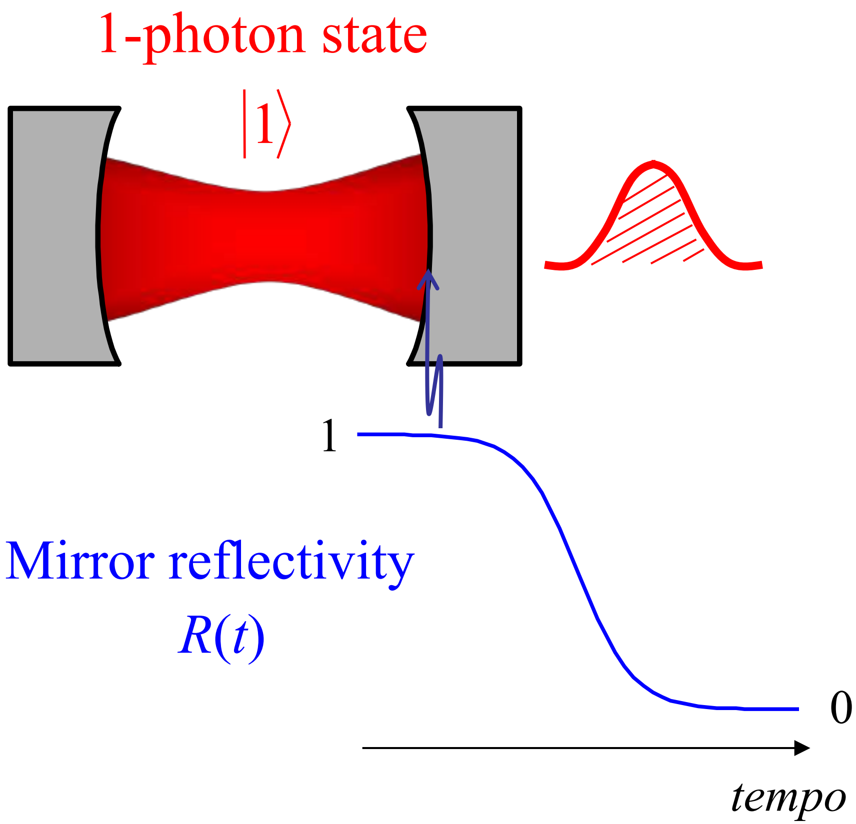
vacuum-Rabi splitting

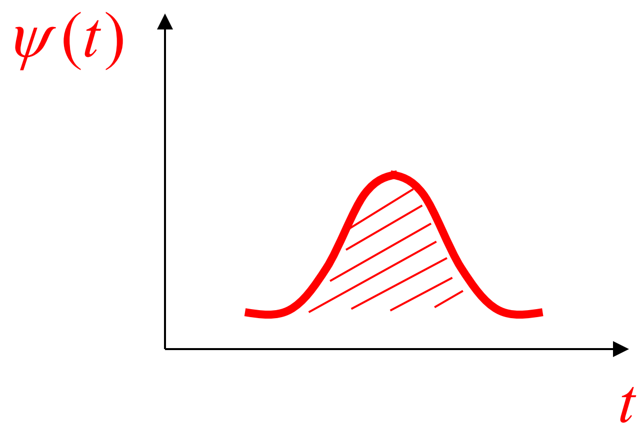


G. S. Agarwal, Phys. Rev. Lett. **53**, 1732 (1984)

idea of a quantum network

Application example:
Emission of 1 photon from an "empty" cavity

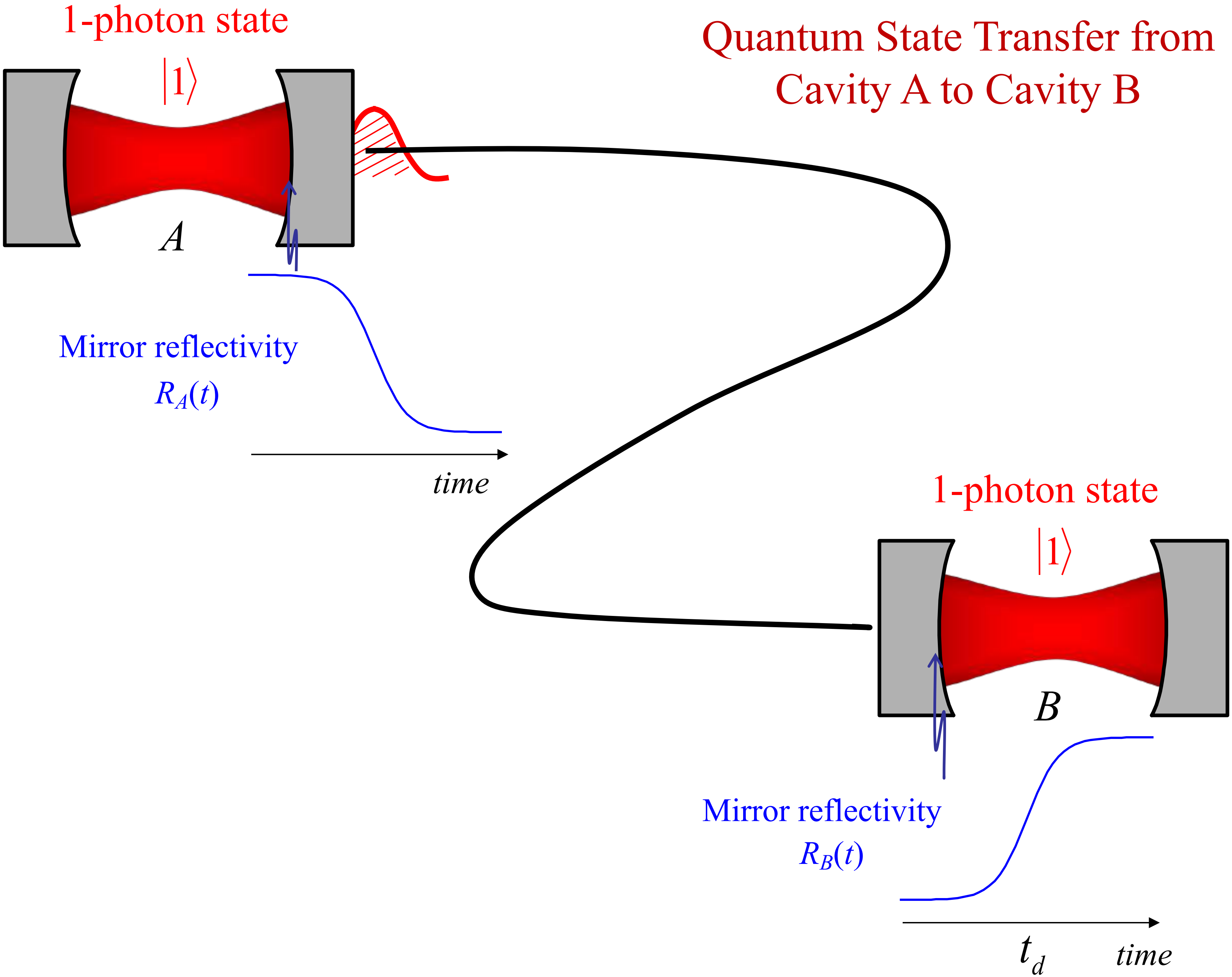




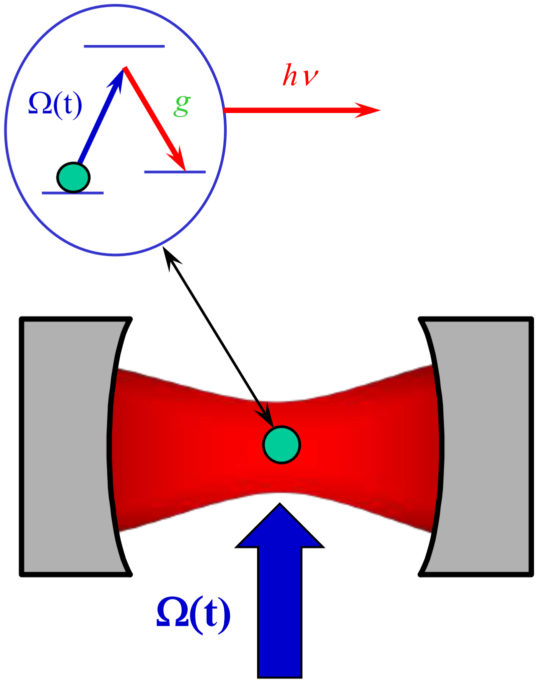
Highlights of this "photon generation" process:

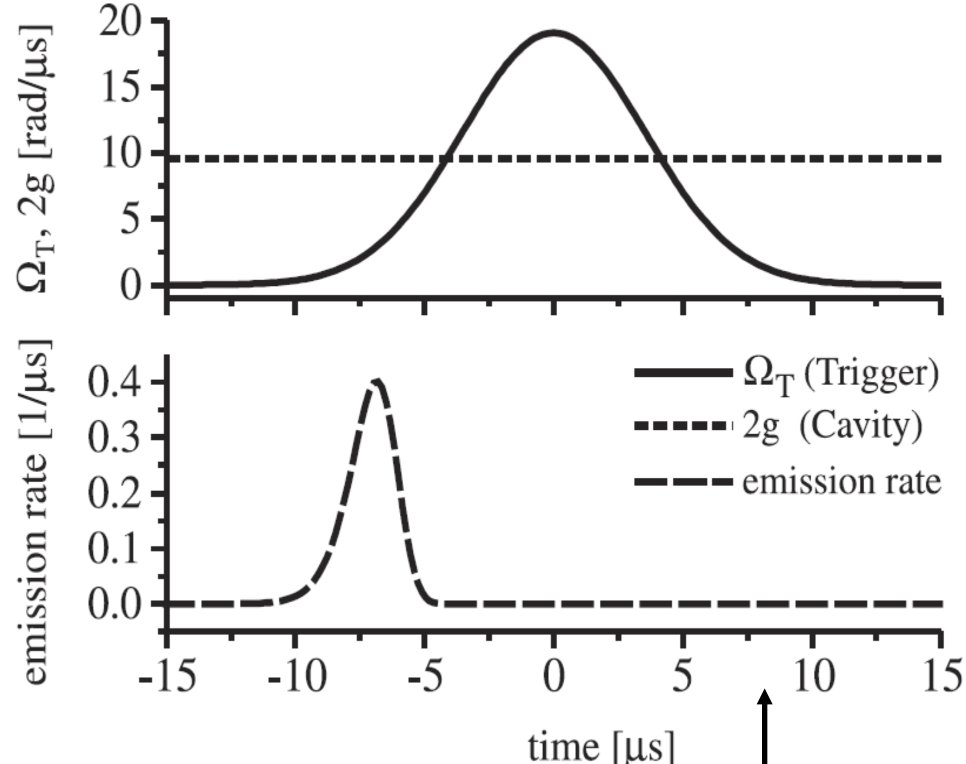
- Stationary photons are mapped 1 to 1 on traveling photons
- The process is a deterministic mapping from "inside" to "outside"
- The temporal shape of the photonic wavepacket is controlled via R(t)

Quantum State Transfer from Cavity A to Cavity B



Quantum state transfer between Atom, Cavity Field, and Propagating Field





$$|D\rangle = \cos\theta |a\rangle|0\rangle - \sin\theta |b\rangle|1\rangle,$$

$$\text{where } \cos\theta = \frac{1}{\sqrt{1+\frac{\Omega^2(t)}{g^2}}}$$

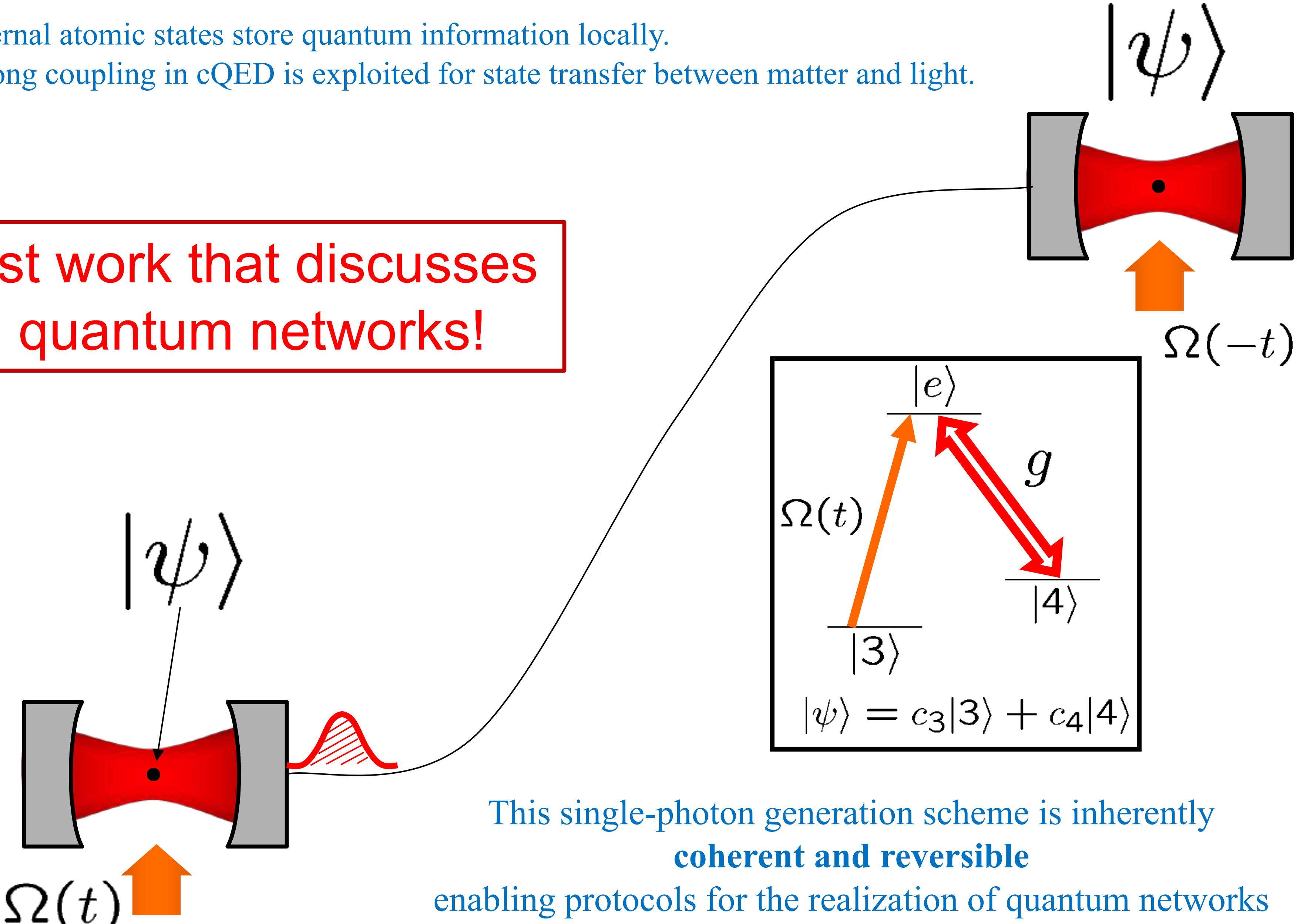
A. S. Parkins, P. Marte, P. Zoller, & H. J. Kimble, Phys. Rev. Lett. **71**, 3095 (1993)
J. I. Cirac, P. Zoller, H. J. Kimble, & H. Mabuchi, Phys. Rev. Lett. **78**, 3221 (1997)
A. Kuhn, M. Hennrich, T. Bondo, & G. Rempe, Appl. Phys. B **69**, 373 (1999)

cQED-based Quantum Networks

J. I. Cirac, P. Zoller, H. J. Kimble, & H. Mabuchi, Phys. Rev. Lett. 78, 3221 (1997)

- Internal atomic states store quantum information locally.
- Strong coupling in cQED is exploited for state transfer between matter and light.

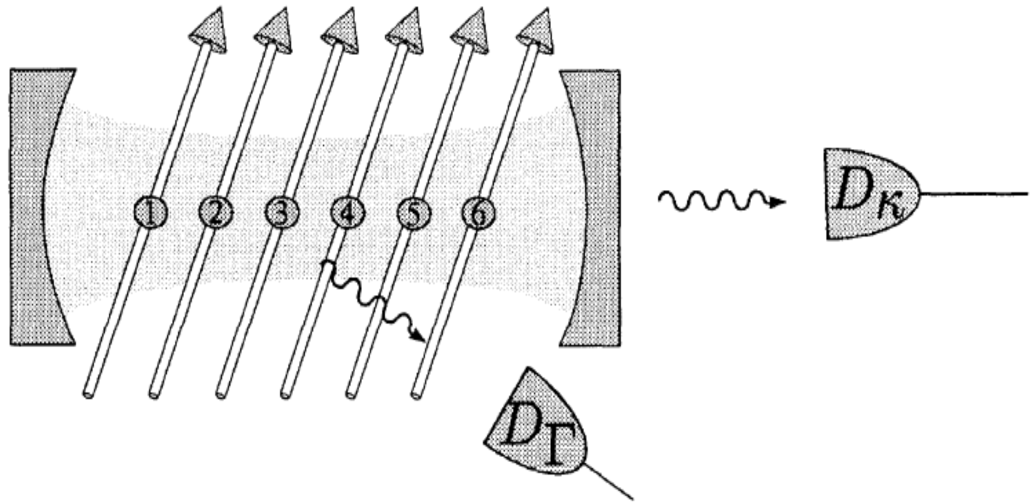
1st work that discusses quantum networks!

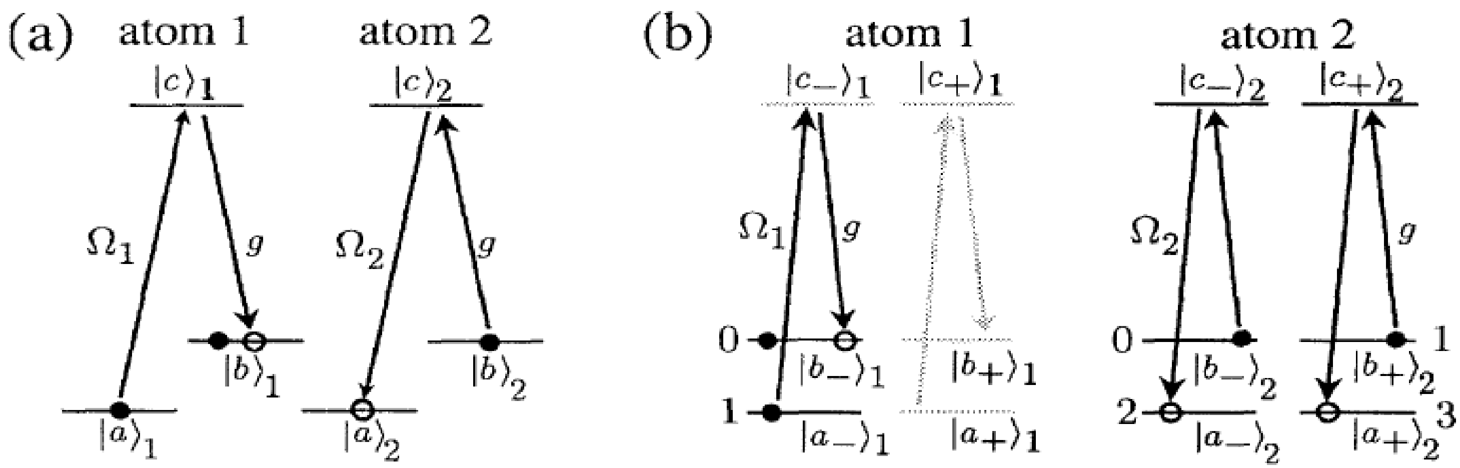


This single-photon generation scheme is inherently **coherent and reversible** enabling protocols for the realization of quantum networks

Decoherence, Continuous Observation, and Quantum Computing: A Cavity QED Model

T. Pellizzari, S. A. Gardiner, J. I. Cirac,* and P. Zoller
Institut für Theoretische Physik, Universität Innsbruck, 6020 Innsbruck, Austria
(Received 27 June 1995)

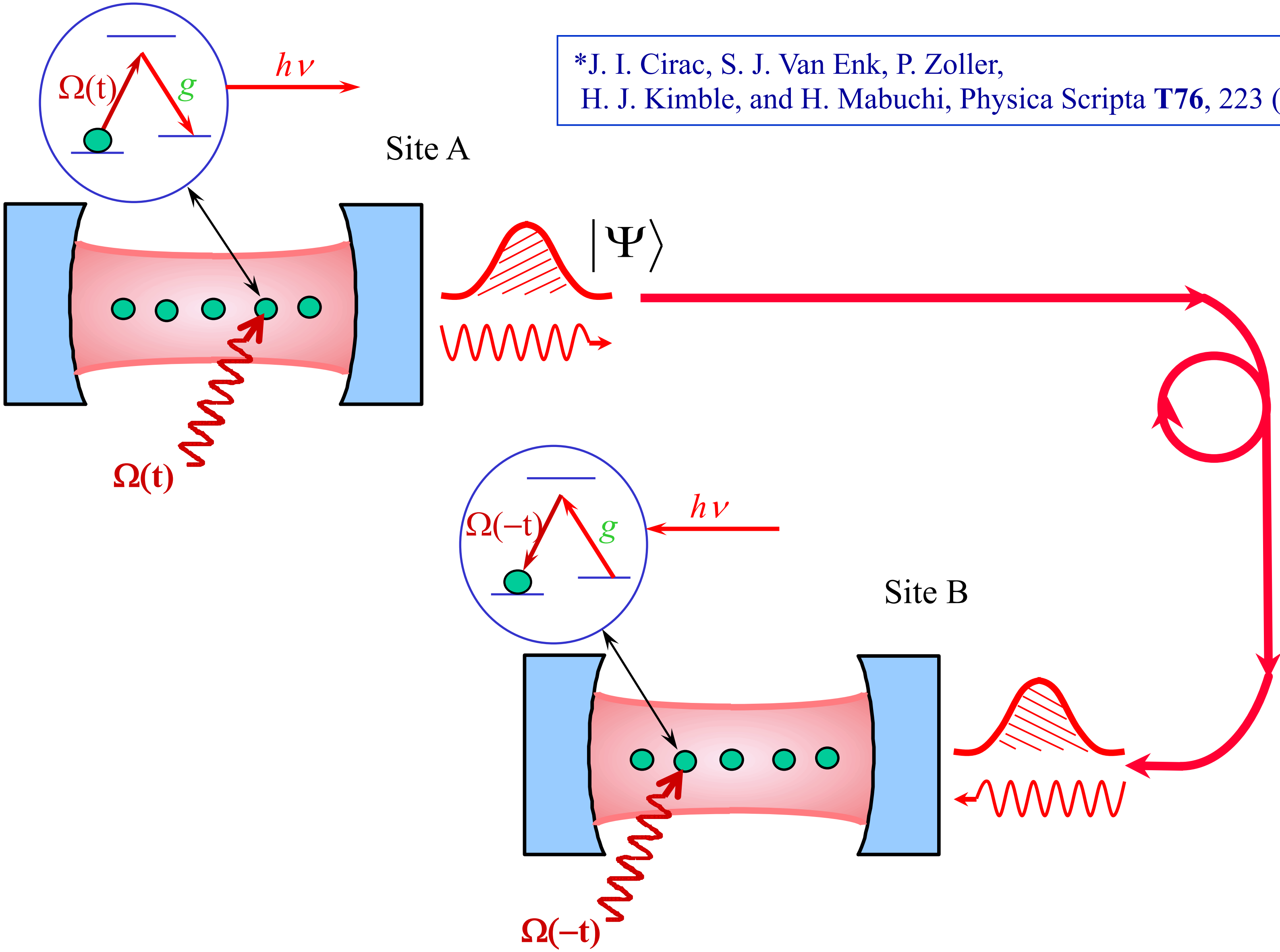




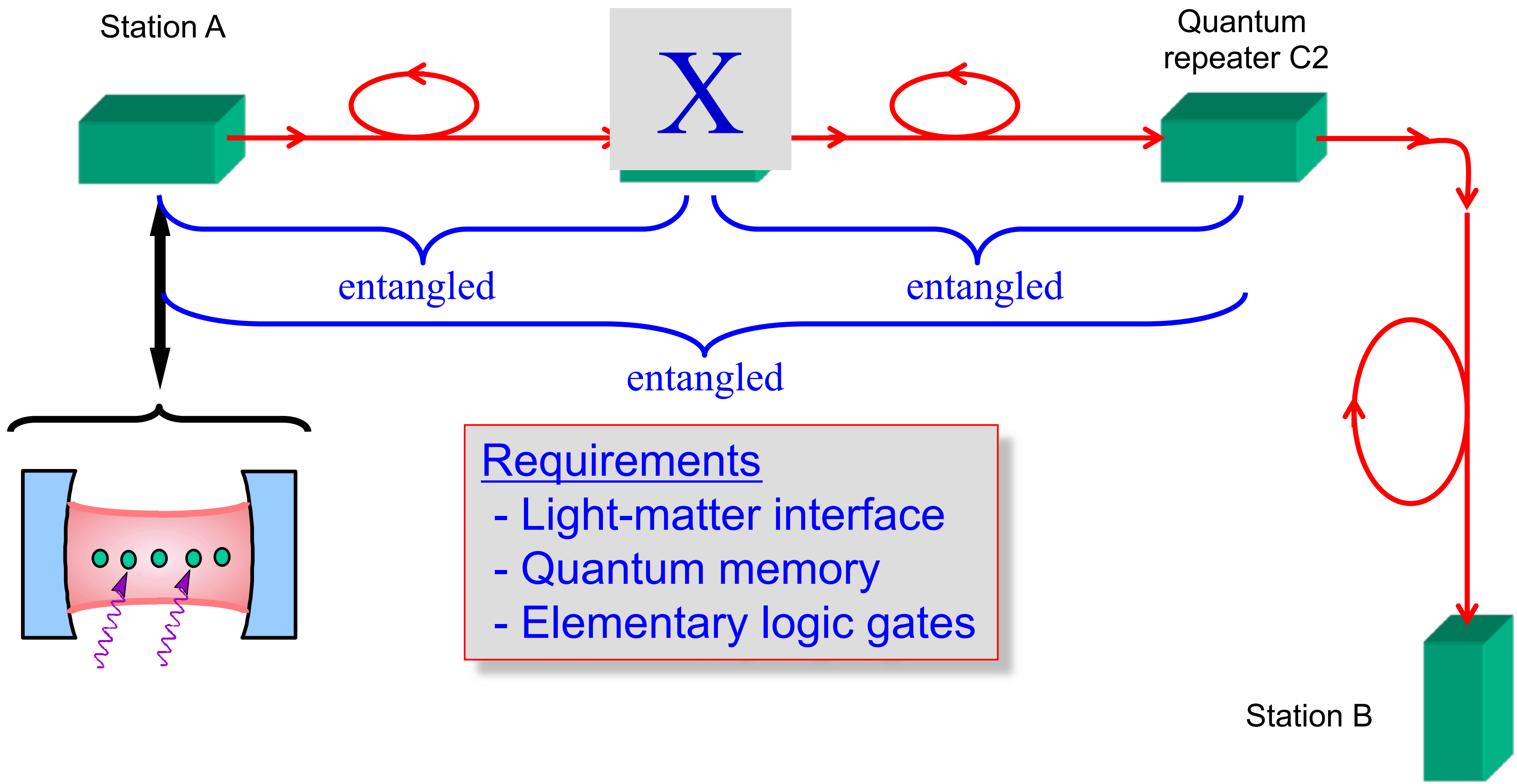
Quantum State Exchange*

Combining stationary and traveling qubits to realize quantum networks for distributed quantum communication and computing

*J. I. Cirac, S. J. Van Enk, P. Zoller, H. J. Kimble, and H. Mabuchi, Physica Scripta **T76**, 223 (1998)



Scalable Quantum Networks enable Quantum Repeater Architectures*
H.-J. Briegel, W. Dür, J. I. Cirac, & P. Zoller, Phys. Rev. Lett. 81, 5932 (1998).



Requirements
- Light-matter interface
- Quantum memory
- Elementary logic gates

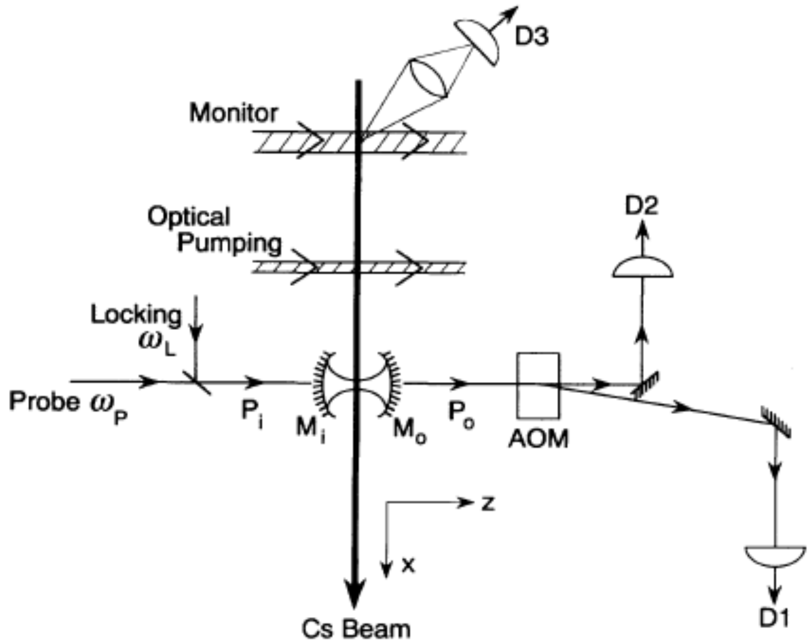
* H.-J. Briegel, S. J. van Enk, J. I. Cirac, P. Zoller,
em*The Physics of Quantum Information*, D. Bouwmeester et al., eds. (Springer, Berlin, 2000).

experimental pathway to strong coupling

Observation of Normal-Mode Splitting for an Atom in an Optical Cavity

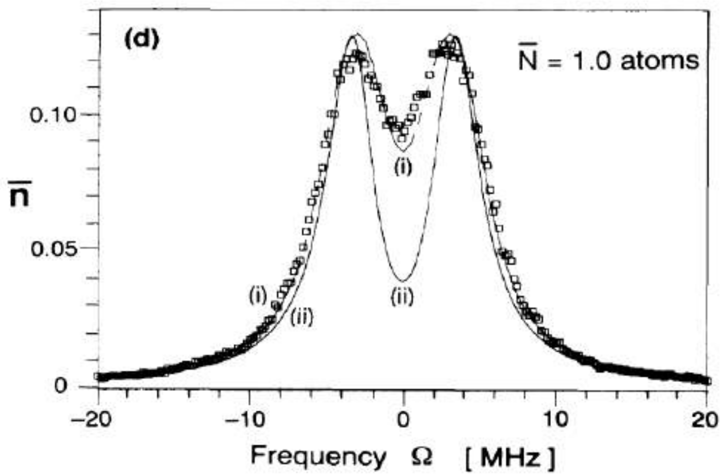
R. J. Thompson, G. Rempe, and H. J. Kimble

Experimental apparatus



Cavity transmission spectrum in the weak field limit

$$T(\omega_p) = T_0 \left| \frac{\kappa[\gamma_\perp + i(\omega_0 - \omega_p)]}{(\omega_p - \lambda_+)(\omega_p - \lambda_-)} \right|^2$$

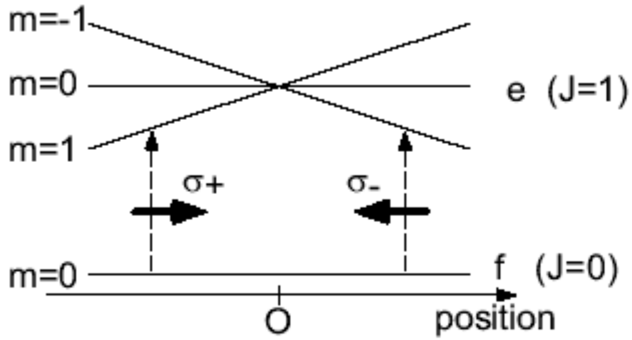


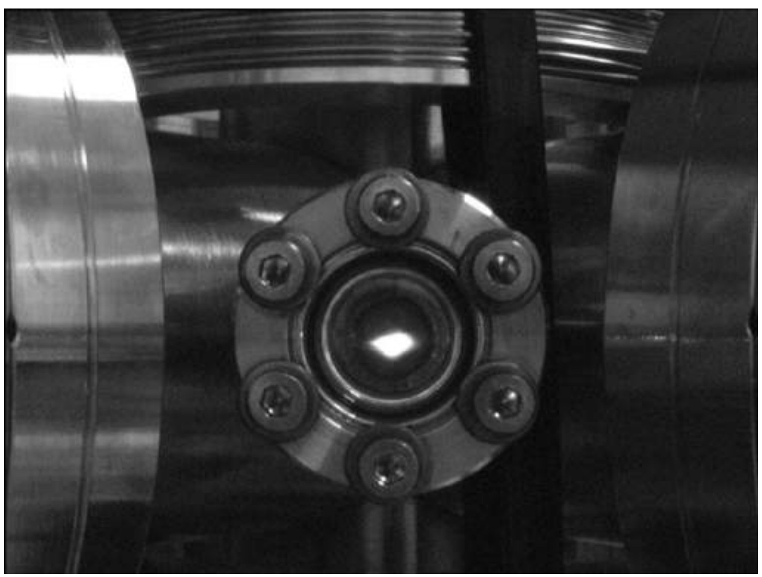
Limitations:
Short time of flight (T~0.4 μs)
fluctuations in the number of atoms (average ~ 1)

⇩

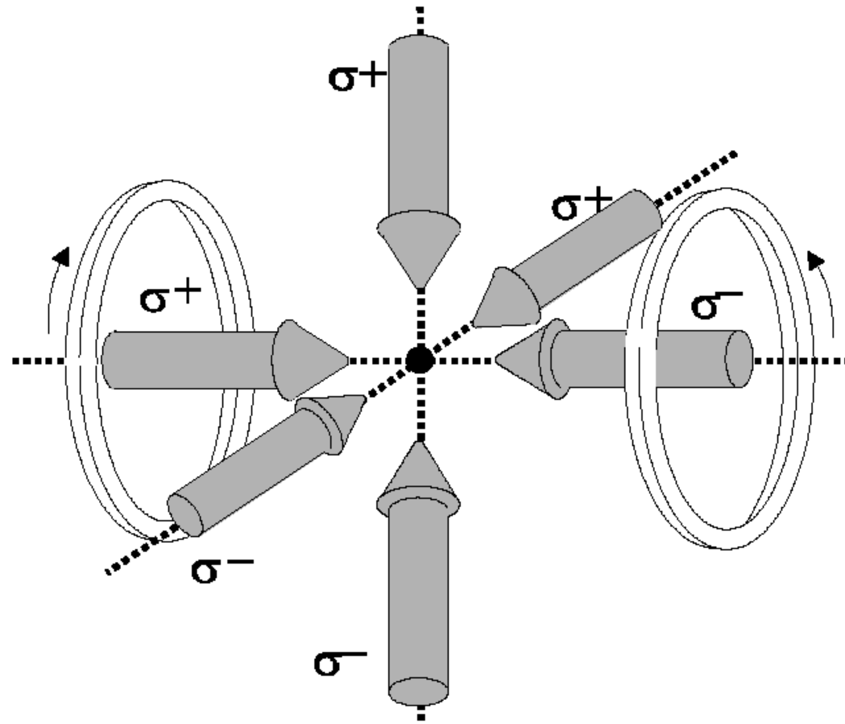
J. J. Childs, K. An, M. S. Otteson, R. R. Dasari, & M. S. Feld, Phys. Rev. Lett. **77**, 2901 (1996)

Magneto-Optical Trap(MOT)



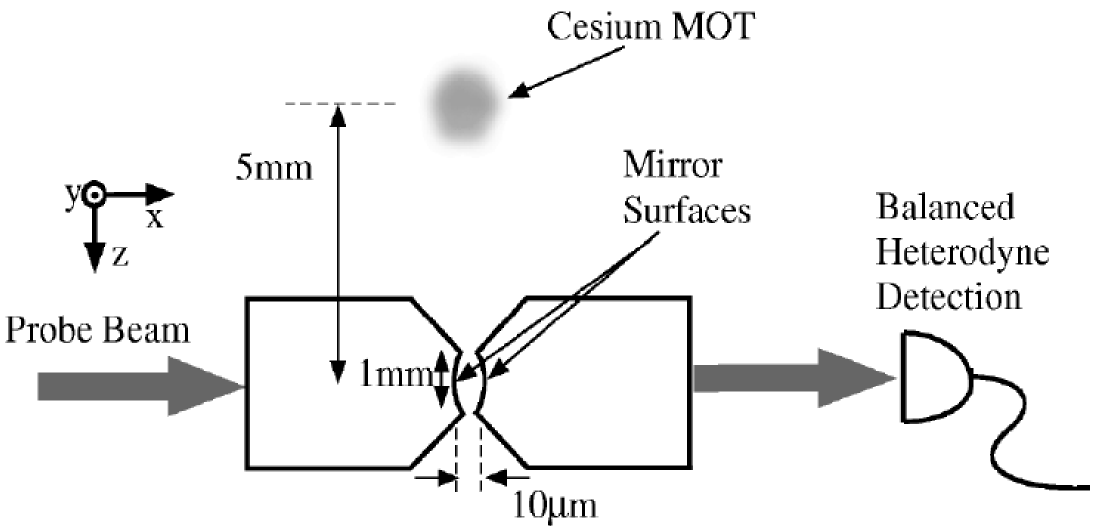


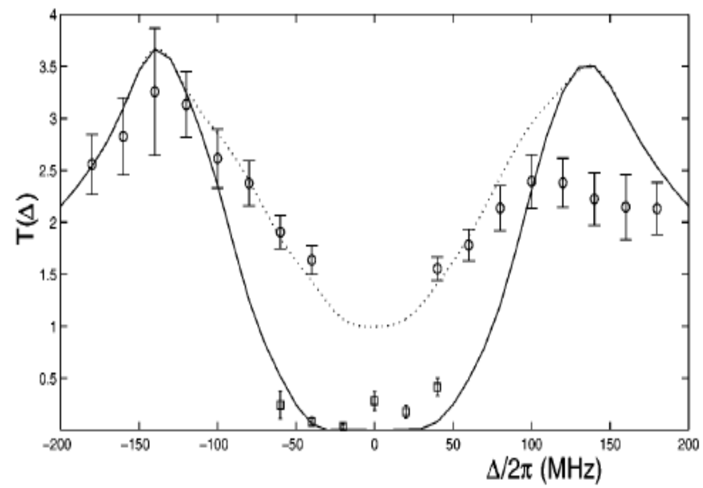
2×10^{9} ^{87}Rb , Temperature < 100 μK

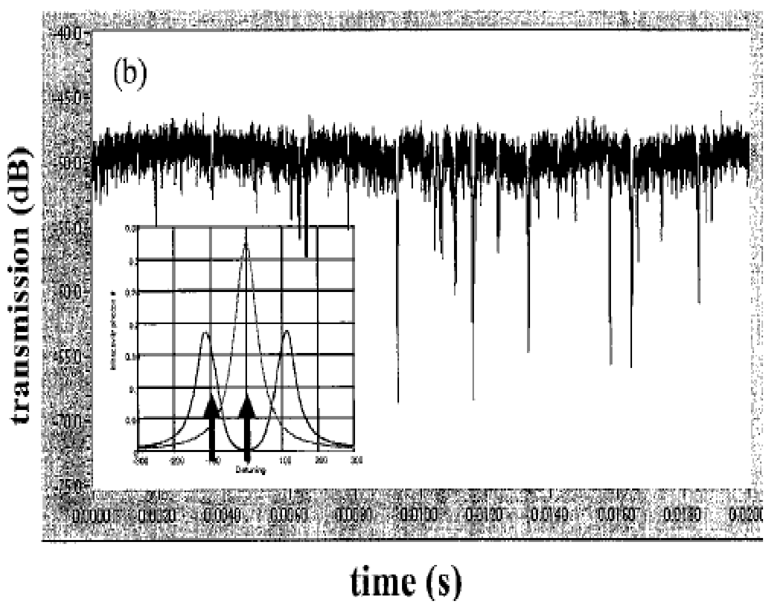


Real-Time Cavity QED with Single Atoms

C. J. Hood, M. S. Chapman, * T. W. Lynn, and H. J. Kimble





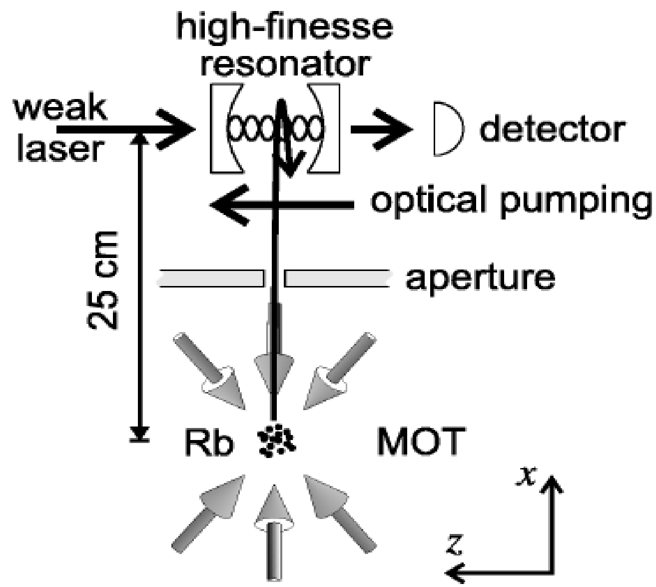


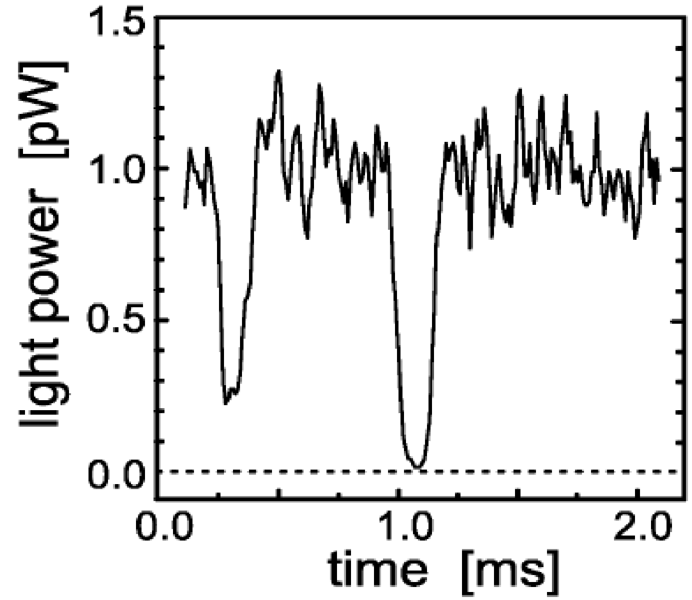
better time of flight T ~ 100 μs

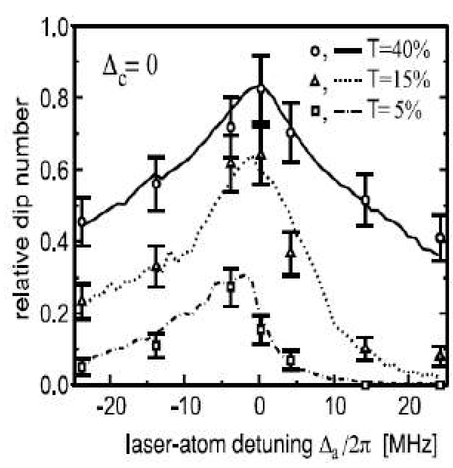
still average in the number of atoms

Dynamics of Single-Atom Motion Observed in a High-Finesse Cavity

P. Münstermann, T. Fischer, P. Maunz, P. W. H. Pinkse, and G. Rempe







Time of flight T > 100 μs

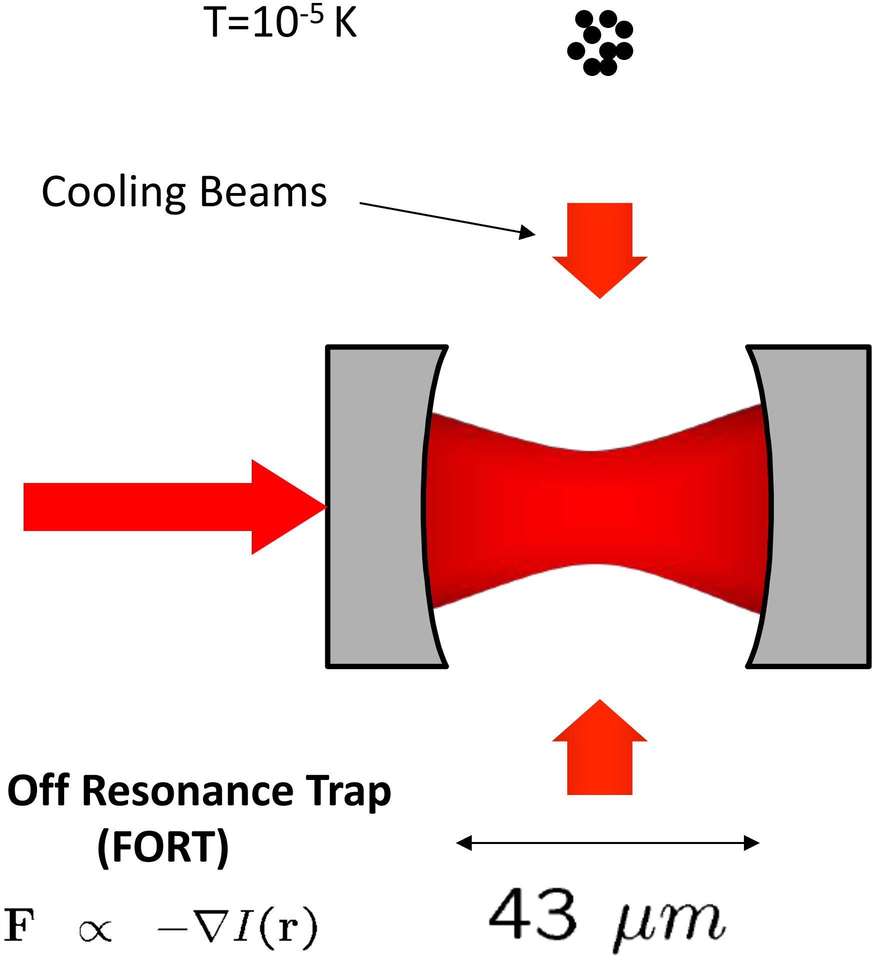
VOLUME 83, NUMBER 24 PHYSICAL REVIEW LETTERS 13 DECEMBER 1999

Trapping of Single Atoms in Cavity QED

J. Ye,* D. W. Vernooy, and H. J. Kimble

Cloud
~ 10^5 cesium atoms
T=10^{-5} K

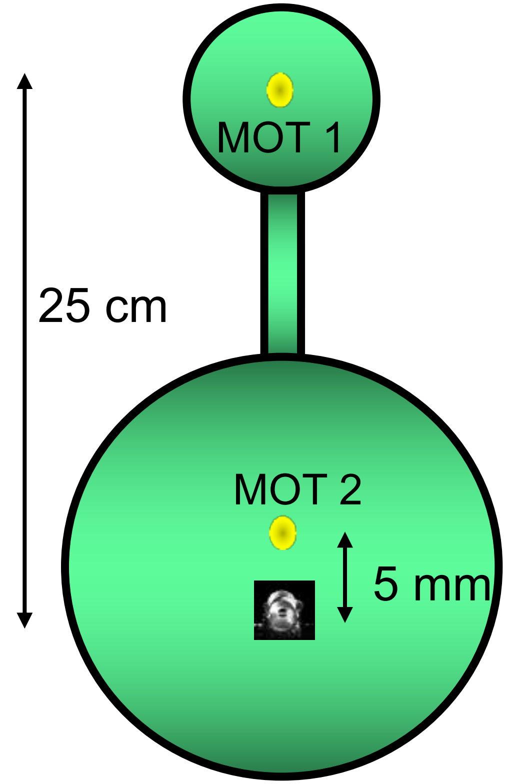
Cooling Beams



Far Off Resonance Trap (FORT)

$$\mathbf{F} \propto -\nabla I(\mathbf{r})$$

Upstairs chamber:
collection MOT, 10^{-8} torr



UHV downstairs chamber: 10^{-10} torr
~ 10^2 seconds for collision lifetime

Life time: T~28ms

VOLUME 90, NUMBER 13 PHYSICAL REVIEW LETTERS week ending 4 APRIL 2003

State-Insensitive Cooling and Trapping of Single Atoms in an Optical Cavity

J. McKeever, J. R. Buck, A. D. Boozer, A. Kuzmich, H.-C. Nägerl, D. M. Stamper-Kurn, and H. J. Kimble

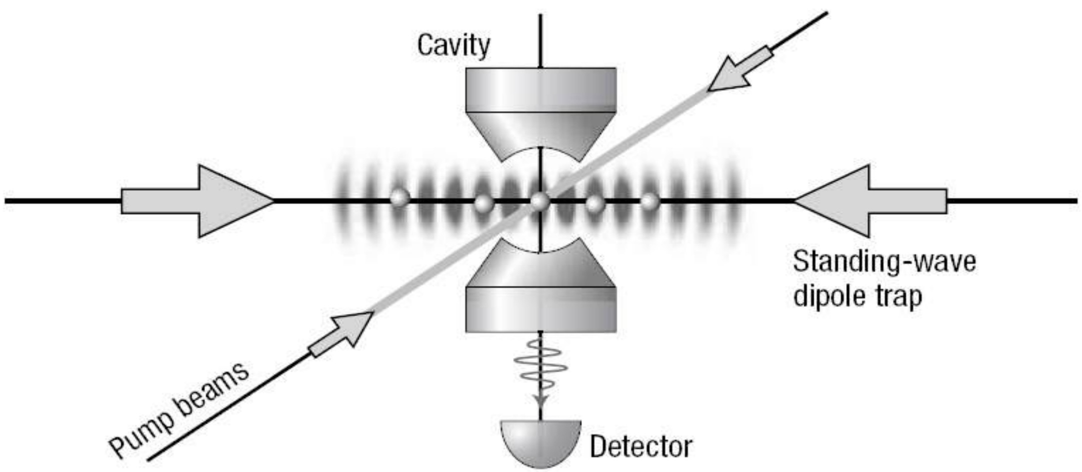
Life time: T~3s

ARTICLES

Vacuum-stimulated cooling of single atoms in three dimensions

STEFAN NUßMANN, KARIM MURR, MARKUS HIJLKEMA, BERNHARD WEBER, AXEL KUHN AND GERHARD REMPE*

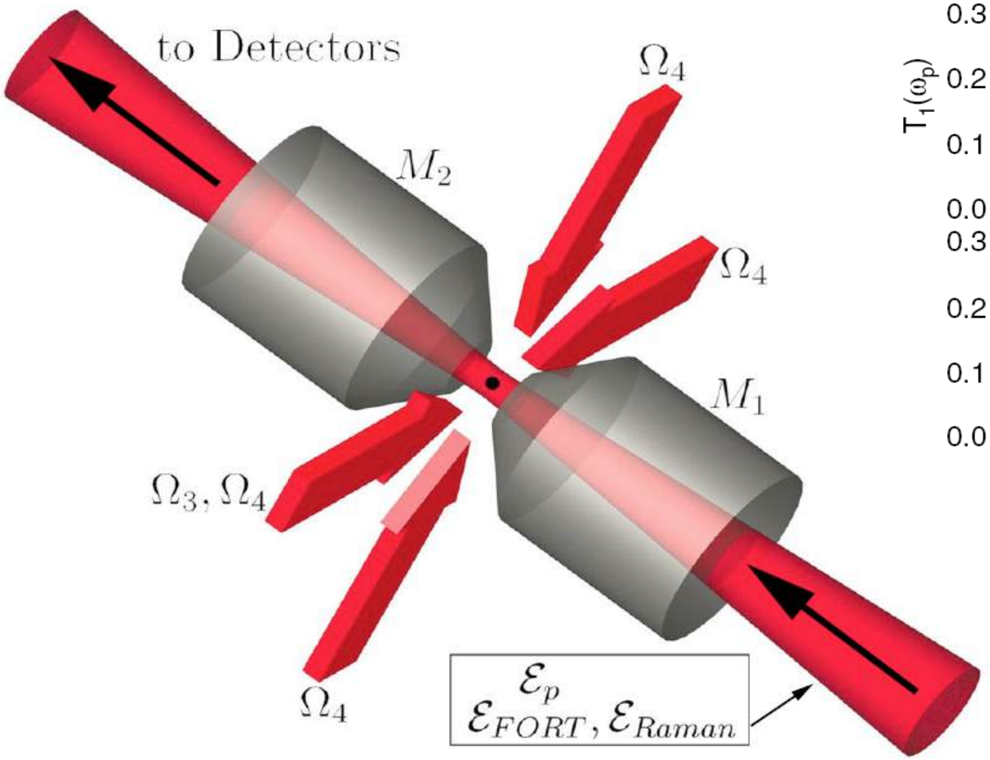
122 nature physics | VOL 1 | NOVEMBER 2005 | www.nature.com/naturephysics

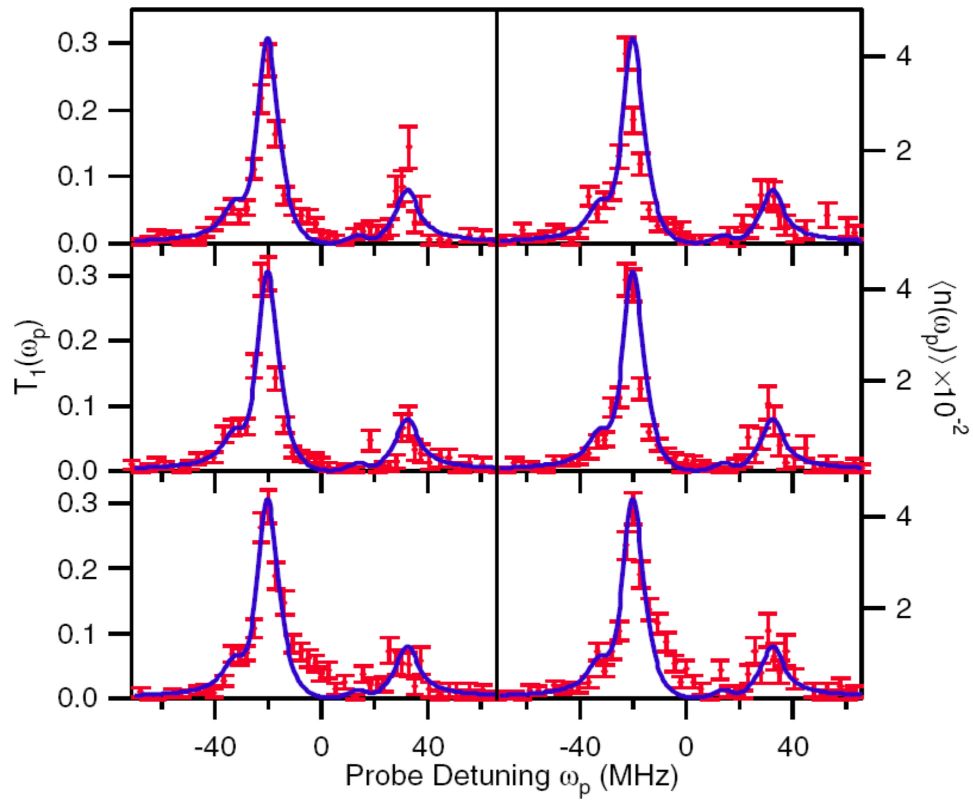


Life time: T~17s

Observation of the Vacuum Rabi Spectrum for One Trapped Atom

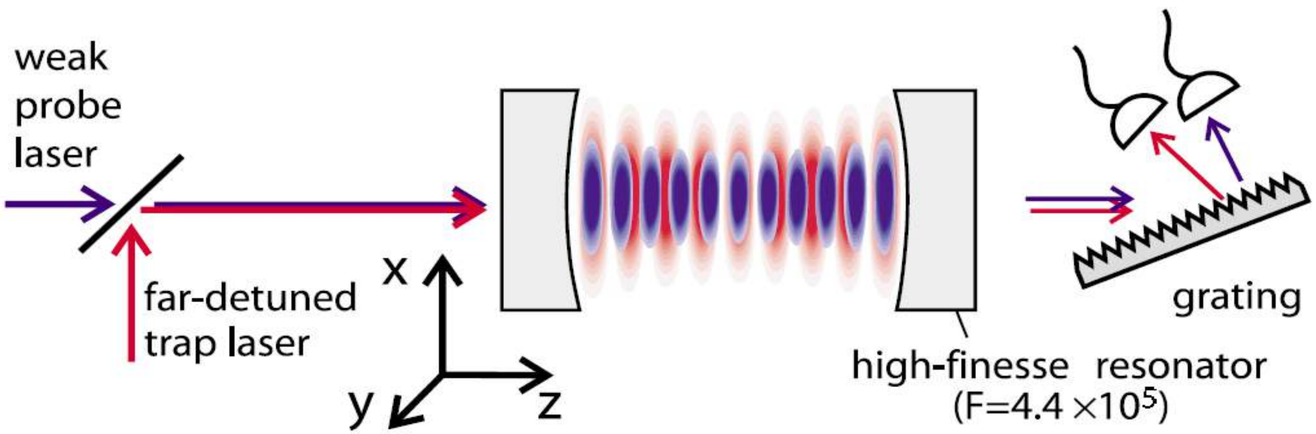
A. Boca, R. Miller, K. M. Birnbaum, A. D. Boozer, J. McKeever, and H. J. Kimble

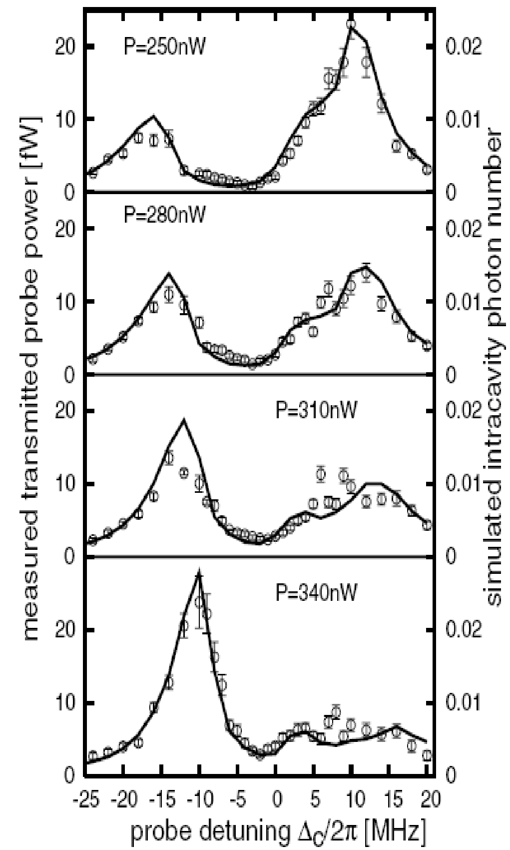




Normal-Mode Spectroscopy of a Single-Bound-Atom–Cavity System

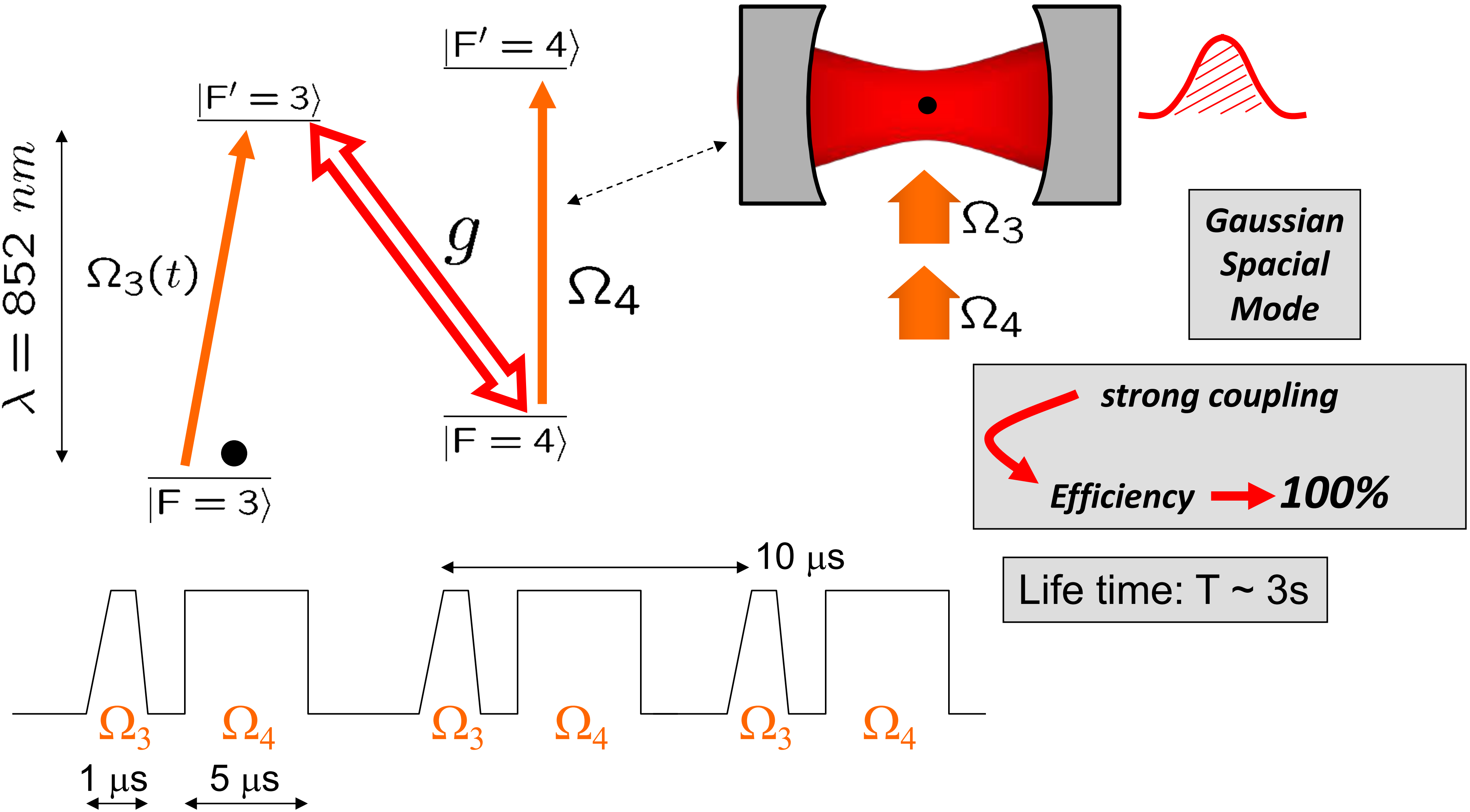
P. Maunz, T. Puppe, I. Schuster, N. Syassen, P. W. H. Pinkse, and G. Rempe





Deterministic generation of single photons

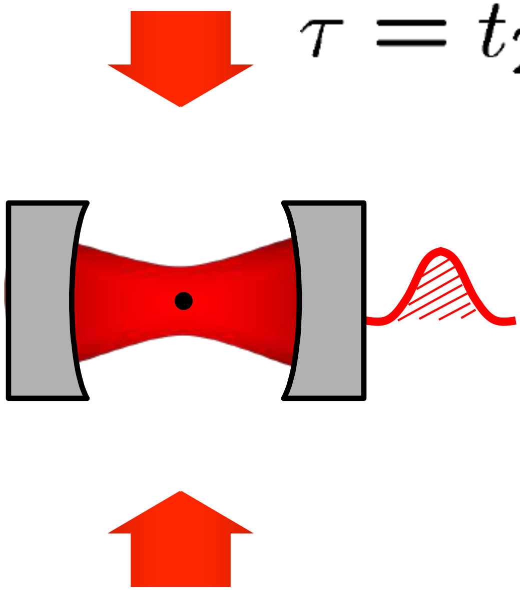
J. McKeever, A. Boca, D. Boozer, R. Miller, J. Buck, A. Kuzmich, HJK, Science 303, 1992 (2004)



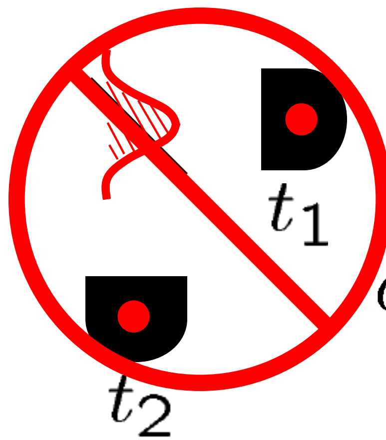
ADIABATIC TRANSFER via DARK EIGENSTATES

A. S. Parkins, P. Marte, and P. Zoller, and H. J. Kimble, Phys. Rev. Lett. 71, 3095 (1993)

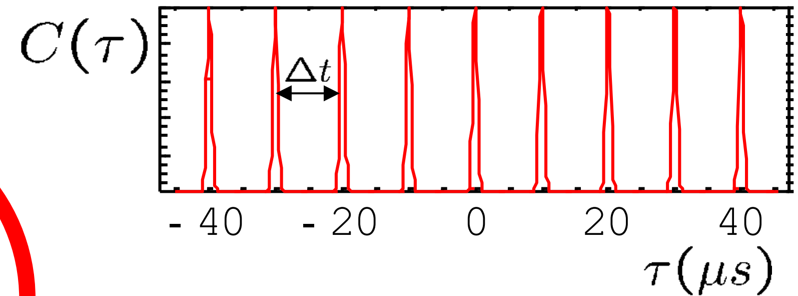
Correlation functions: How do we know that they are single photons?



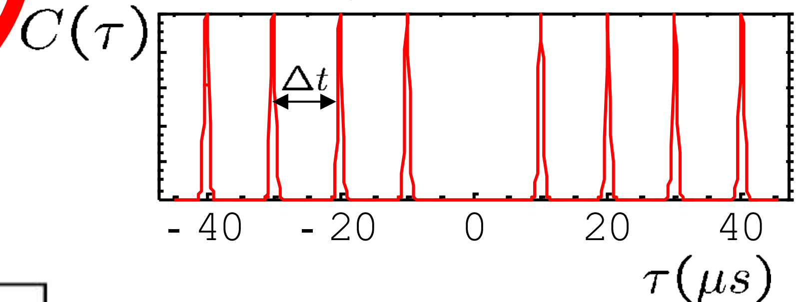
$$\tau = t_2 - t_1 = \Delta t$$



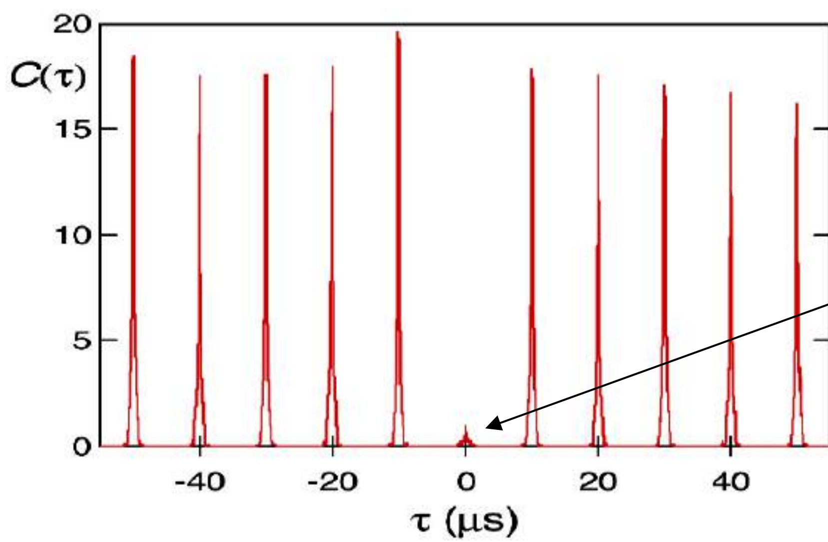
Weak laser pulses
(Classical Coherent State)



1-photon source



Experimental Results



Suppression of two-photon events:

R=20.8 ±1.8

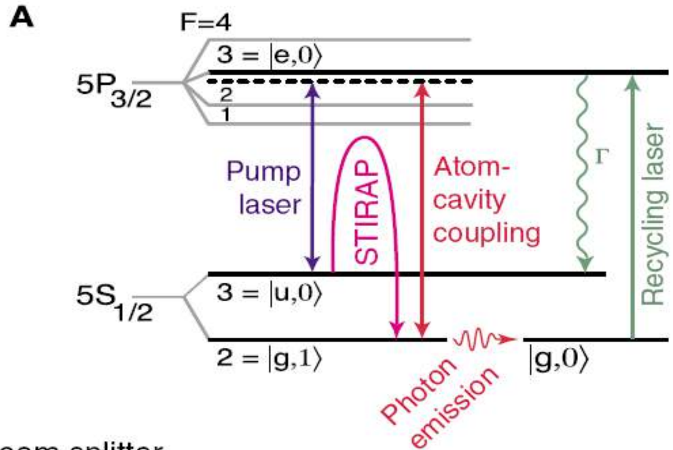
relative to coherent states

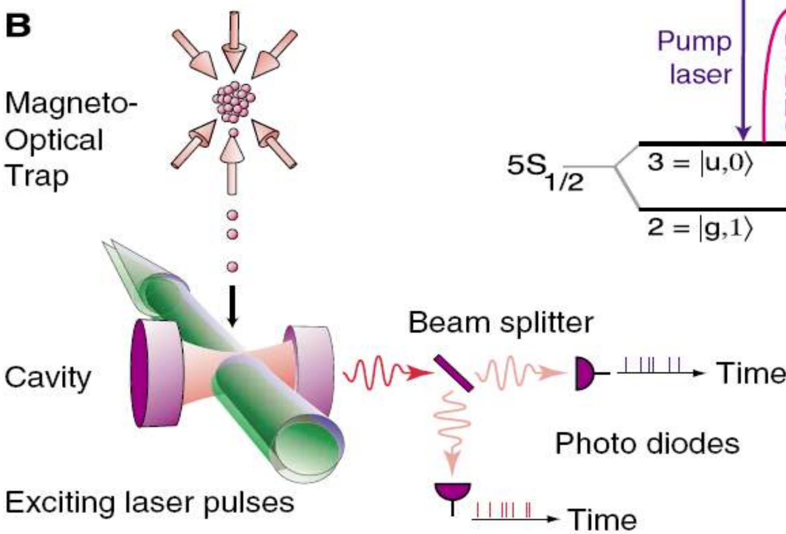
But, worse than expected due to the small probability of having 2 atoms in the cavity

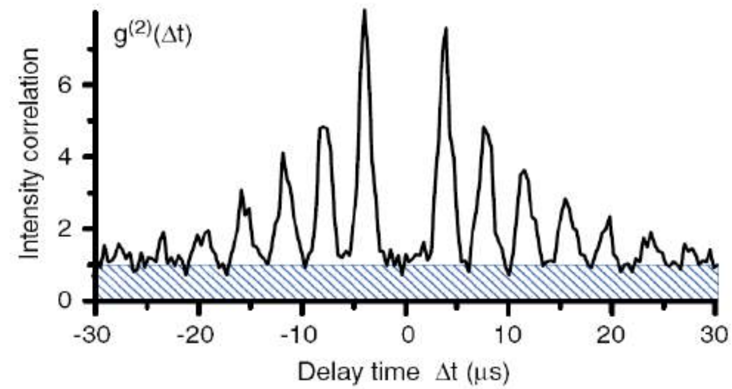
VOLUME 89, NUMBER 6 PHYSICAL REVIEW LETTERS 5 AUGUST 2002

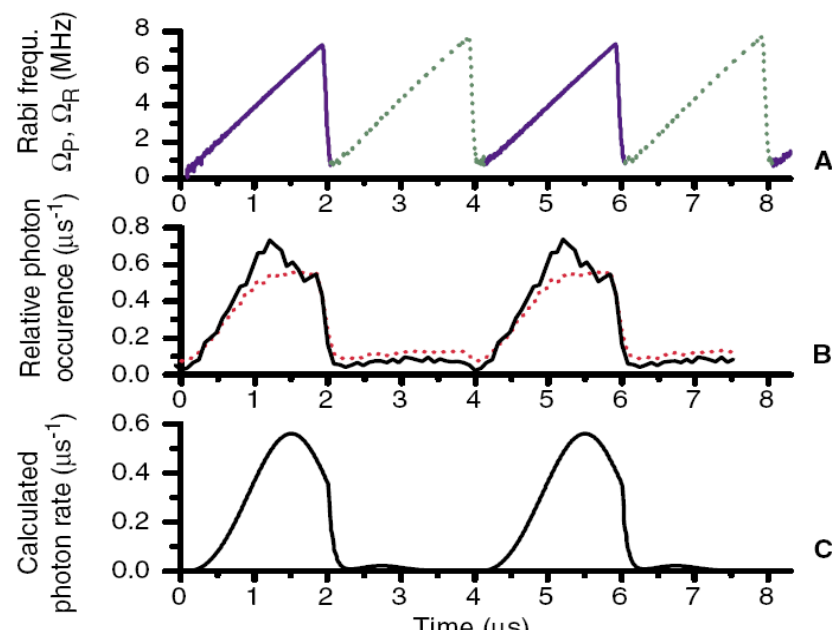
Deterministic Single-Photon Source for Distributed Quantum Networking

Axel Kuhn, Markus Hennrich, and Gerhard Rempe









time of flight: T ~ 18s

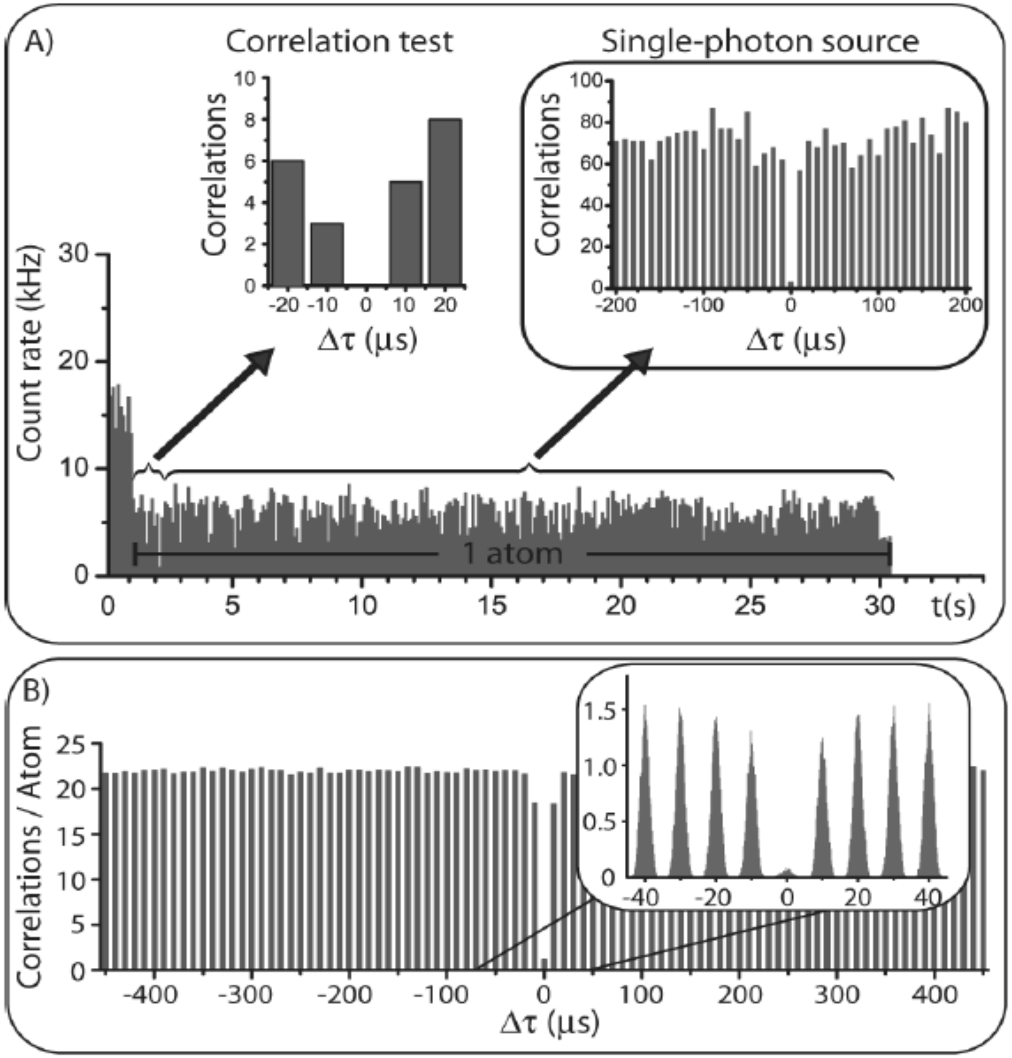
A single-photon server with just one atom

MARKUS HIJLKEMA[1], BERNHARD WEBER[1], HOLGER P. SPECHT[1], SIMON C. WEBSTER[1], AXEL KUHN[2] AND GERHARD REMPE[1]*

[1] Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Str. 1, D-85748 Garching, Germany
[2] Department of Physics, University of Oxford, Clarendon Laboratory, Parks Road, Oxford OX1 3PU,
*e-mail: gerhard.rempe@mpq.mpg.de

Nature Phys. 3, 253 (2007)

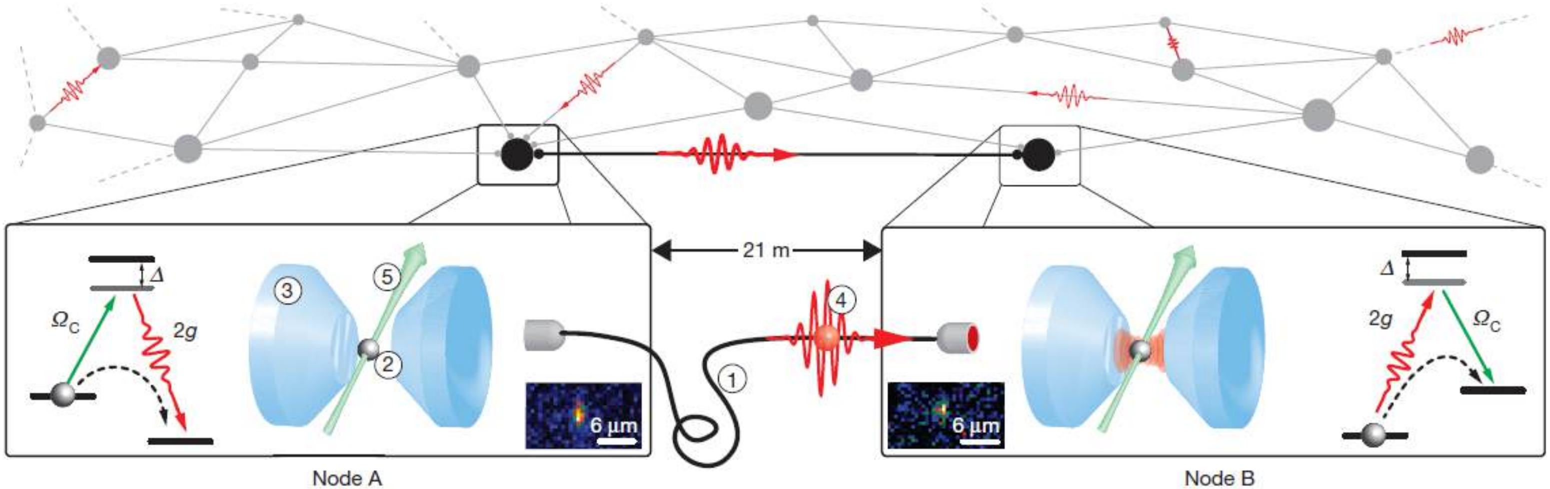
Train of
300,000 single photons
throughout 30 s

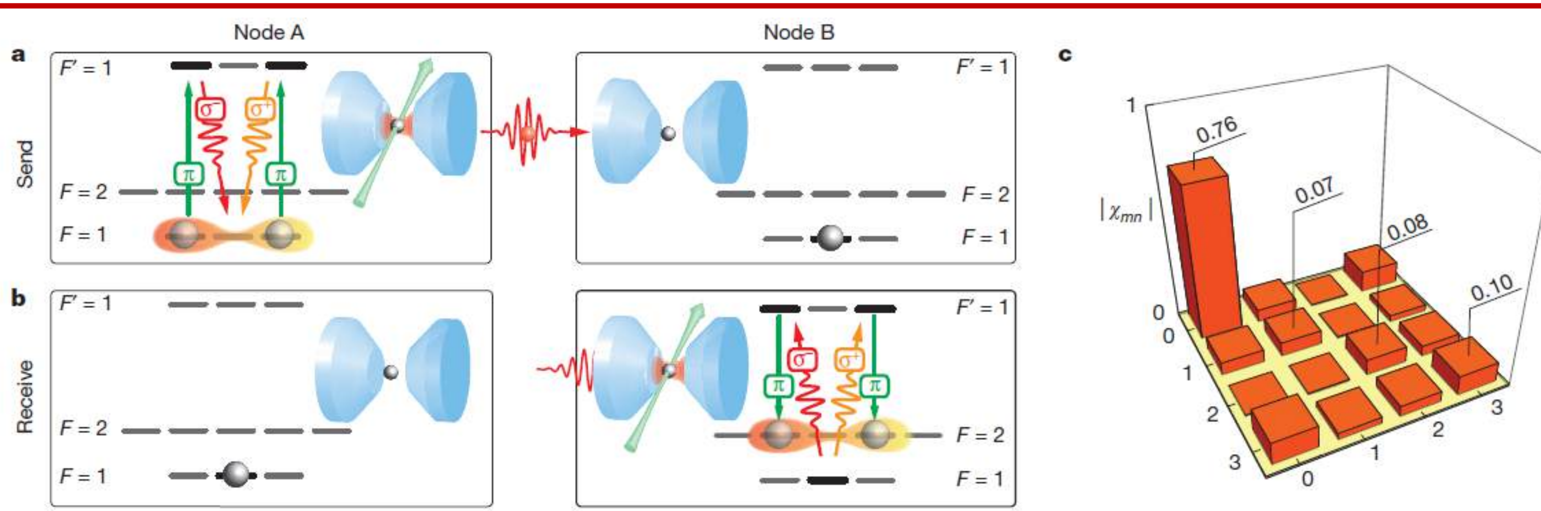


moving forward to a quantum network

An elementary quantum network of single atoms in optical cavities

Stephan Ritter[1], Christian Nölleke[1], Carolin Hahn[1], Andreas Reiserer[1], Andreas Neuzner[1], Manuel Uphoff[1], Martin Mücke[1], Eden Figueroa[1], Joerg Bochmann[1]† & Gerhard Rempe[1]



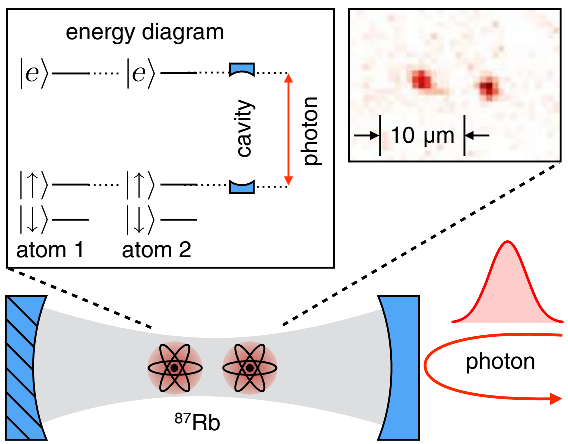


CNOT logic gate

PHYSICAL REVIEW X **8,** 011018 (2018)

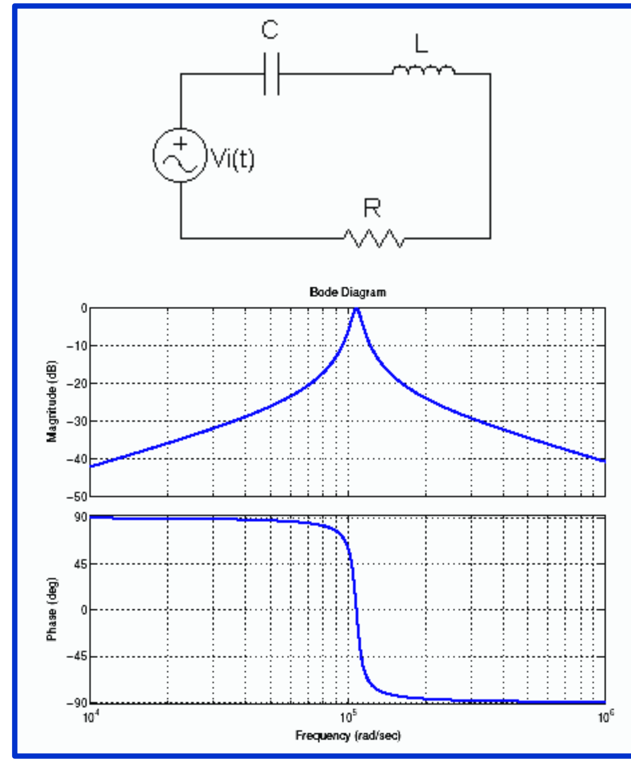
Photon-Mediated Quantum Gate between Two Neutral Atoms in an Optical Cavity

Stephan Welte,* Bastian Hacker, Severin Daiss, Stephan Ritter,† and Gerhard Rempe
Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Strasse 1, 85748 Garching, Germany



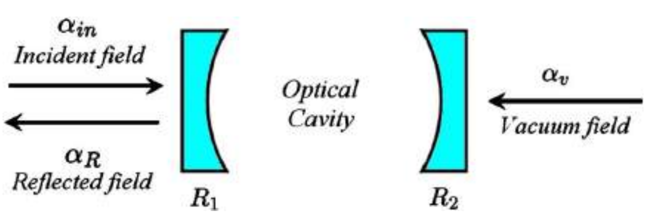
$|\uparrow\uparrow\rangle \rightarrow |\uparrow\uparrow\rangle$ $|\uparrow\downarrow\rangle \rightarrow |\uparrow\downarrow\rangle$

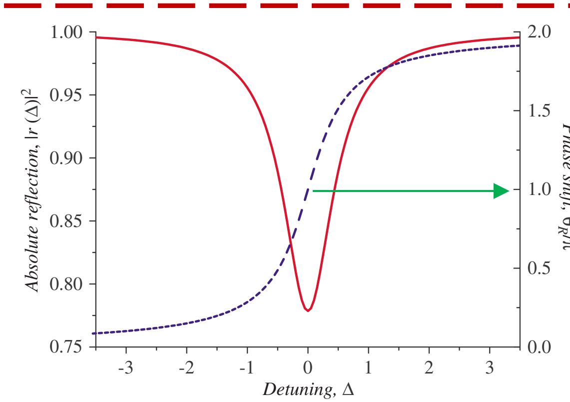
$|\downarrow\uparrow\rangle \rightarrow |\downarrow\uparrow\rangle$ $|\downarrow\downarrow\rangle \rightarrow -|\downarrow\downarrow\rangle$



The conversion of phase to amplitude fluctuations of a light beam by an optical cavity

Alessandro S. Villar[a)]
Institut für Experimentalphysik, Universität Innsbruck, Technikerstrasse 25/4, 6020 Innsbruck, Austria and Institute for Quantum Optics and Quantum Information, Austrian Academy of Sciences, 6020 Innsbruck, Austria





CNOT logic gate

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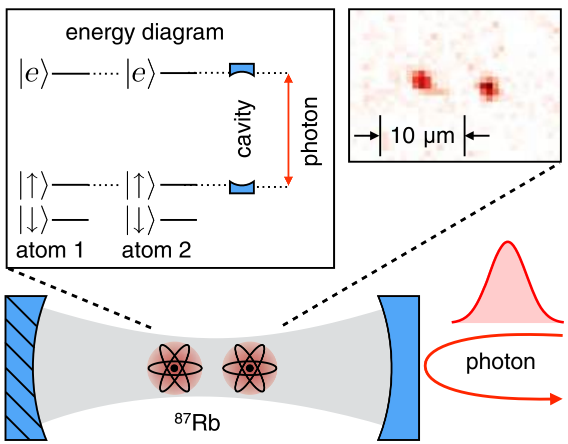


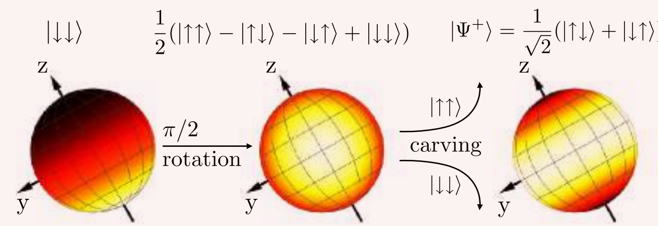
$|\uparrow\uparrow\rangle \rightarrow |\uparrow\uparrow\rangle$ $\quad |\uparrow\downarrow\rangle \rightarrow |\uparrow\downarrow\rangle$

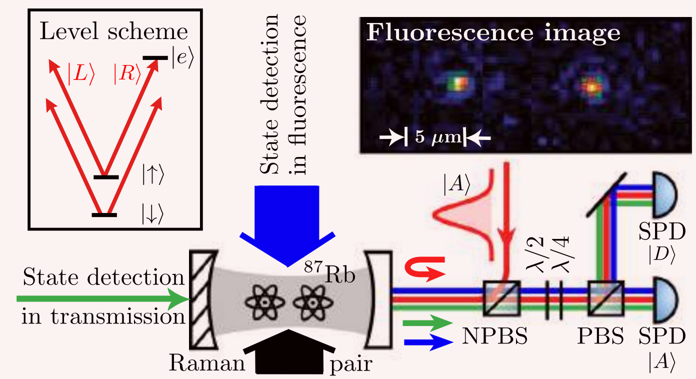
$|\downarrow\uparrow\rangle \rightarrow |\downarrow\uparrow\rangle$ $\quad |\downarrow\downarrow\rangle \rightarrow -|\downarrow\downarrow\rangle$

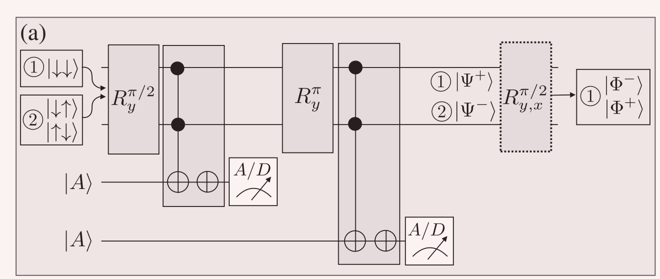
PRL **118,** 210503 (2017) PHYSICAL REVIEW LETTERS week ending 26 MAY 2017

Cavity Carving of Atomic Bell States

Stephan Welte,* Bastian Hacker, Severin Daiss, Stephan Ritter, and Gerhard Rempe
Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Strasse 1, 85748 Garching, Germany







CNOT logic gate

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Stephan Welte,* Bastian Hacker, Severin Daiss, Stephan Ritter,† and Gerhard Rempe
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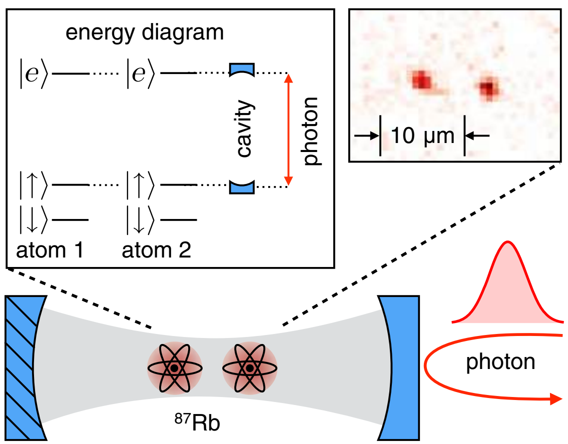
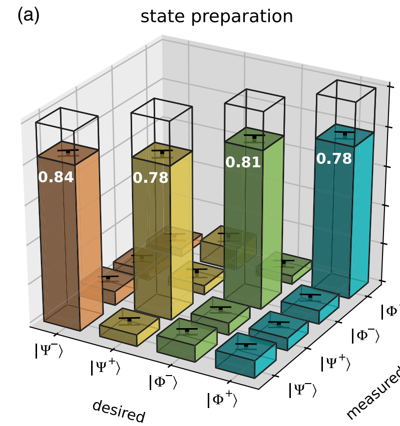
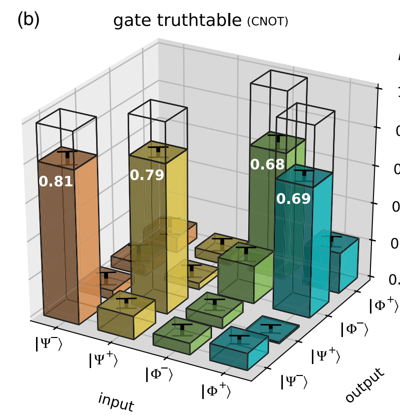
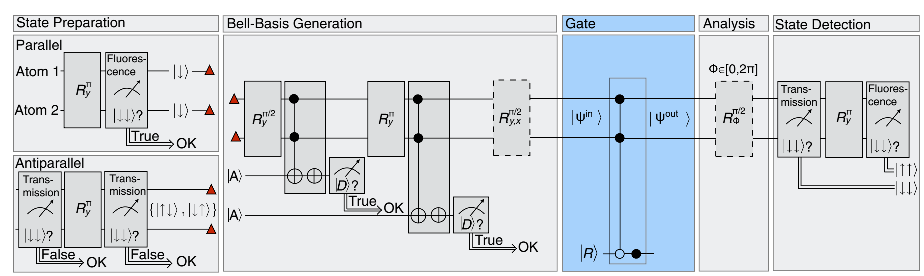


$$|\uparrow\uparrow\rangle \rightarrow |\uparrow\uparrow\rangle \qquad |\uparrow\downarrow\rangle \rightarrow |\uparrow\downarrow\rangle$$
$$|\downarrow\uparrow\rangle \rightarrow |\downarrow\uparrow\rangle \qquad |\downarrow\downarrow\rangle \rightarrow -|\downarrow\downarrow\rangle$$

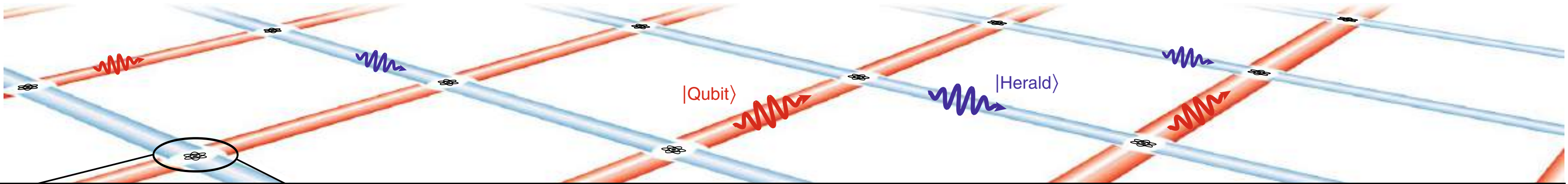
$$|\Psi^-\rangle = \frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle) \rightarrow \frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle) = |\Psi^-\rangle,$$
$$|\Psi^+\rangle = \frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle) \rightarrow \frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle) = |\Psi^+\rangle,$$
$$|\Phi^-\rangle = \frac{1}{\sqrt{2}}(|\uparrow\uparrow\rangle - |\downarrow\downarrow\rangle) \rightarrow \frac{1}{\sqrt{2}}(|\uparrow\uparrow\rangle + |\downarrow\downarrow\rangle) = |\Phi^+\rangle,$$
$$|\Phi^+\rangle = \frac{1}{\sqrt{2}}(|\uparrow\uparrow\rangle + |\downarrow\downarrow\rangle) \rightarrow \frac{1}{\sqrt{2}}(|\uparrow\uparrow\rangle - |\downarrow\downarrow\rangle) = |\Phi^-\rangle.$$

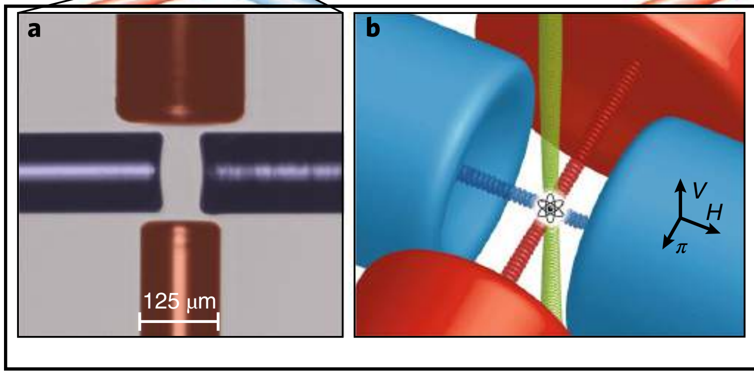






cross cavities





nature physics

LETTERS

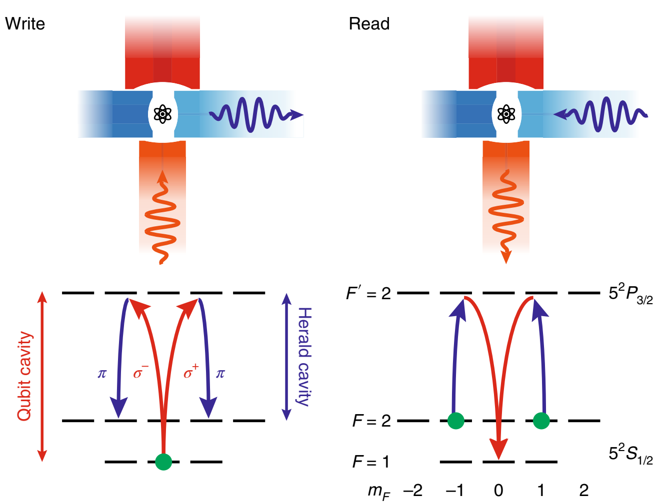
https://doi.org/10.1038/s41567-020-0855-3

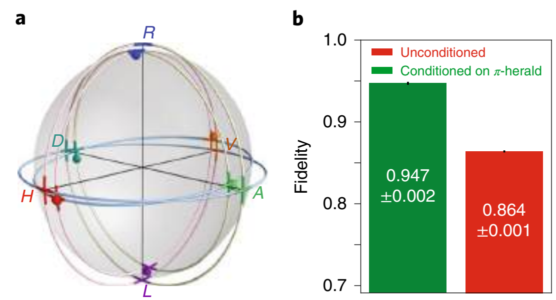
NATURE PHYSICS | VOL 16 | JUNE 2020

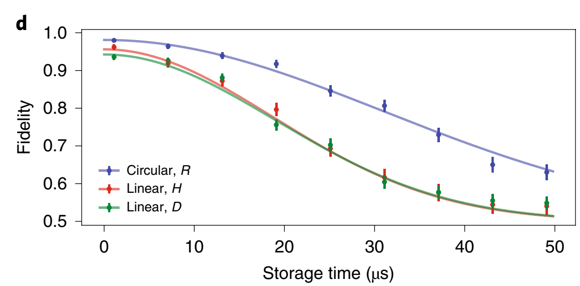
Check for updates

A quantum network node with crossed optical fibre cavities

Manuel Brekenfeld[1]✉, Dominik Niemietz[1], Joseph Dale Christesen[1,2] and Gerhard Rempe[1]





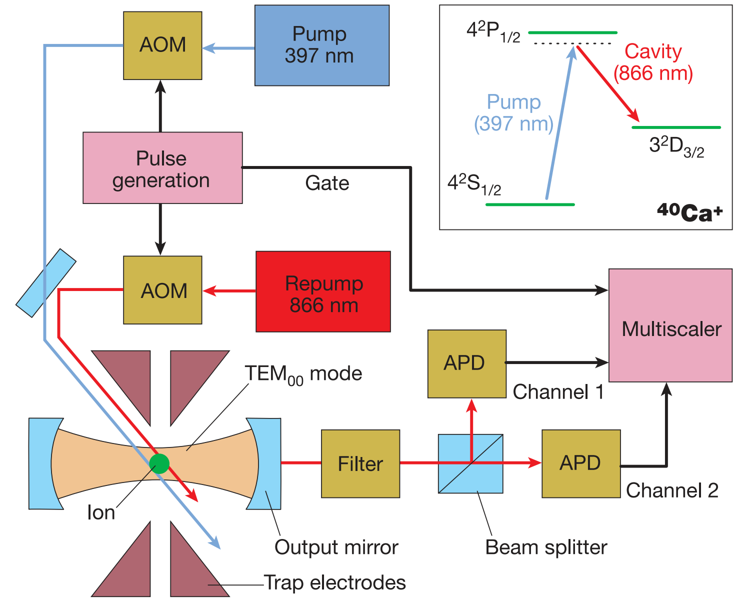


other cavity QED systems

cQED in ion traps

New perspectives with an ion-based system

Better controlled atomic system: more advanced atomic clocks and quantum computers



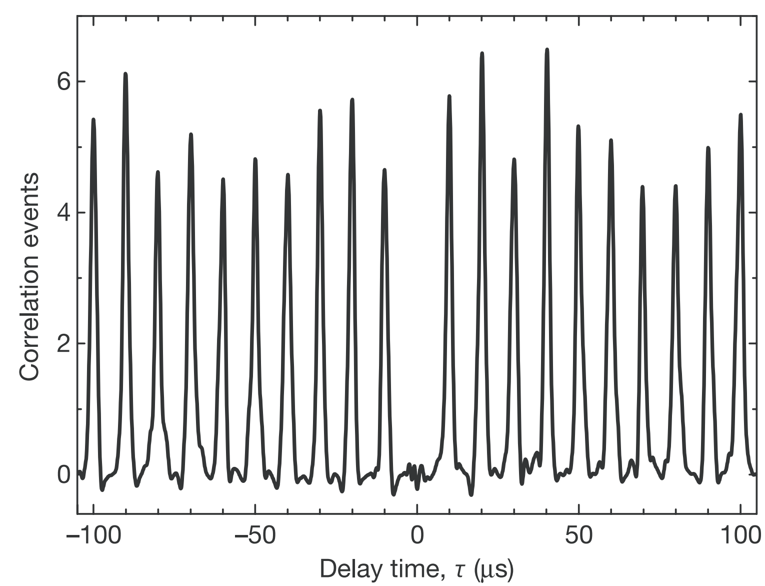
letters to nature

Continuous generation of single photons with controlled waveform in an ion-trap cavity system

Matthias Keller[1], Birgit Lange[1], Kazuhiro Hayasaka[2], Wolfgang Lange[1] & Herbert Walther[1,3]

[1]*Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Strasse 1, 85748 Garching, Germany*
[2]*National Institute of Information and Communications Technology, 588-2 Iwaoka, Nishi-ku, Kobe 651-2492, Japan*
[3]*Sektion Physik der Universität München, Am Coulombwall 1, 85748 Garching, Germany*

NATURE | VOL 431 | 28 OCTOBER 2004 | **1075**



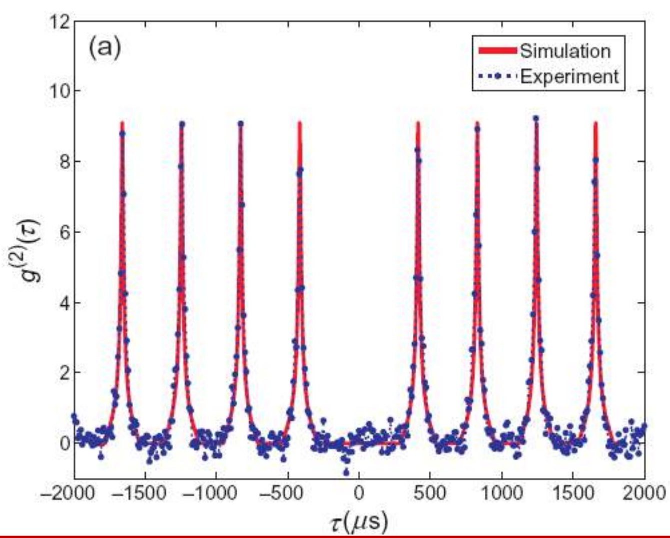
New Journal of Physics 11 (2009) 103004

New Journal of Physics
The open-access journal for physics

Deterministic single-photon source from a single ion

H G Barros[1,2,3], A Stute[1,2], T E Northup[1], C Russo[1,2], P O Schmidt[1] and R Blatt[1,2]

[1] Institut für Experimentalphysik, Universität Innsbruck, 6020 Innsbruck, Austria
[2] Institut für Quantenoptik und Quanteninformation (IQOQI), 6020 Innsbruck, Austria

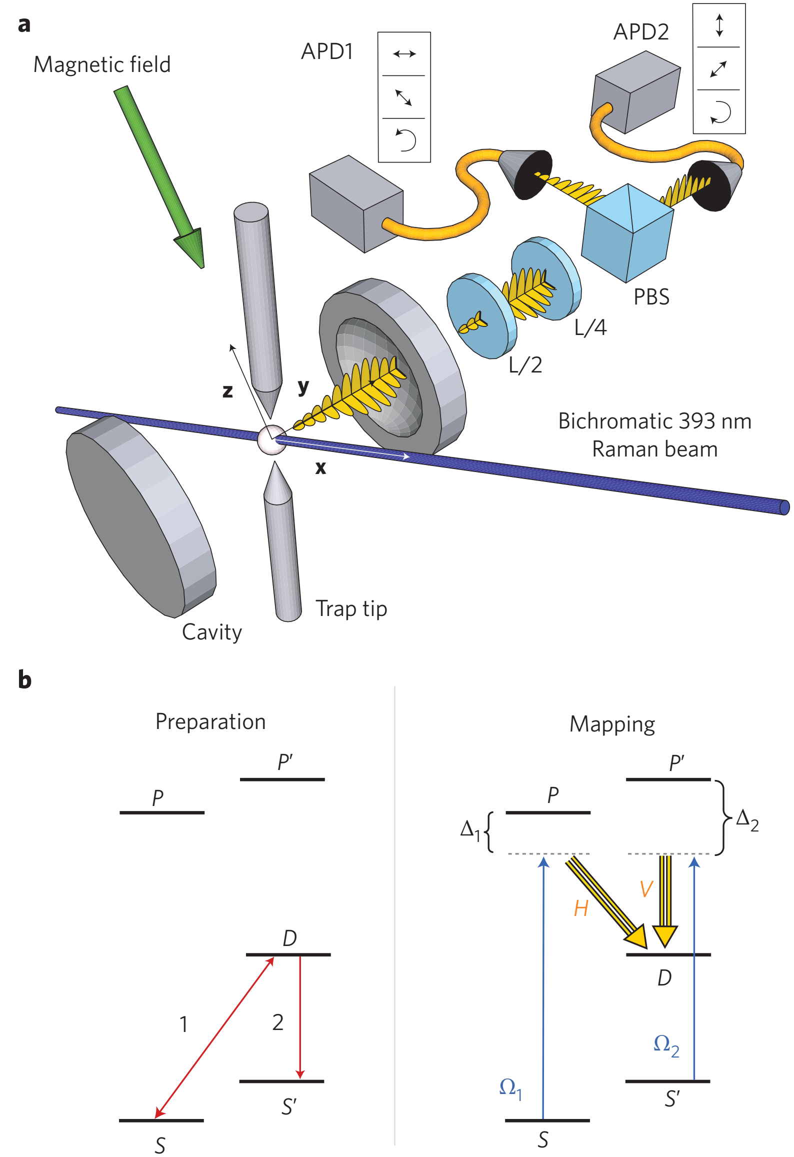


nature photonics
LETTERS
PUBLISHED ONLINE: 3 FEBRUARY 2013 | DOI: 10.1038/NPHOTON.2012.358

Quantum-state transfer from an ion to a photon

A. Stute[1†], B. Casabone[1†], B. Brandstätter[1], K. Friebe[1], T. E. Northup[1]* and R. Blatt[1,2]

[1]Institut für Experimentalphysik, Universität Innsbruck, Technikerstraße 25, 6020 Innsbruck, Austria, [2]Institut für Quantenoptik und Quanteninformation der Österreichischen Akademie der Wissenschaften, Technikerstraße 21a, 6020 Innsbruck, Austria; †These authors contributed equally to this work.
*e-mail: tracy.northup@uibk.ac.at



$$\left(\cos\alpha|S\rangle + e^{i\varphi}\sin\alpha|S'\rangle\right)\otimes|0\rangle \longrightarrow |D\rangle\otimes\left(\cos\alpha|H\rangle + e^{i\varphi}\sin\alpha|V\rangle\right)$$

cQED with nano-emitters

VOLUME 89, NUMBER 23 PHYSICAL REVIEW LETTERS 2 DECEMBER 2002

Efficient Source of Single Photons: A Single Quantum Dot in a Micropost Microcavity

Matthew Pelton,* Charles Santori, Jelena Vučković, Bingyang Zhang,† Glenn S. Solomon,‡
Jocelyn Plant, and Yoshihisa Yamamoto†
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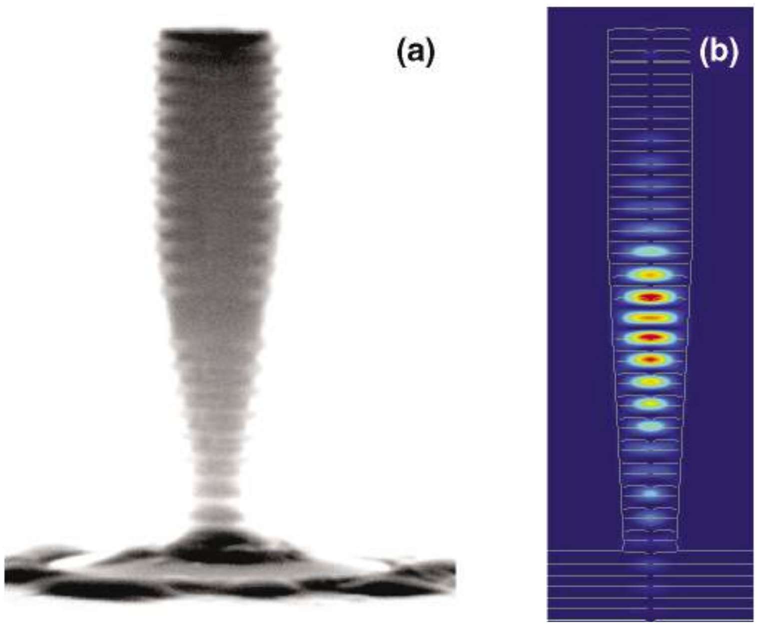

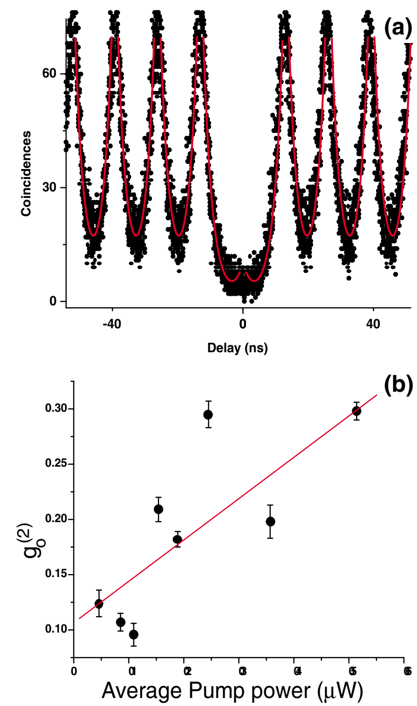

38% coupling to the cavity

Vacuum Rabi splitting with a single quantum dot in a photonic crystal nanocavity

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NATURE | VOL 432 | 11 NOVEMBER 2004 | **200**

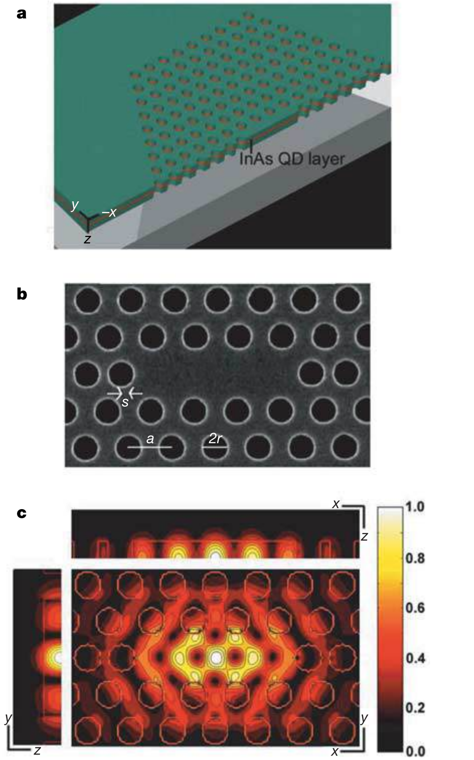


Figure 1 Photonic crystal nanocavity. **a**, Diagram. Half of a hexagon-shaped array of holes forming a nanocavity; scale is ~5 μm across at the cut. **b**, Scanning electron micrograph of a fabricated nanocavity, showing the hole spacing *a*, hole diameter 2*r*, and shift *s* of the two holes at the ends of the 'spacer' formed by omitting three holes. **c**, Computed optical field magnitude superimposed on the nanocavity structure. The scale bar shows the normalized amplitude of the electric field, |*E*|/max(|*E*|). Also shown are a horizontal slice (above main panel) and a vertical slice (left of main panel) through the centre of the spacer.

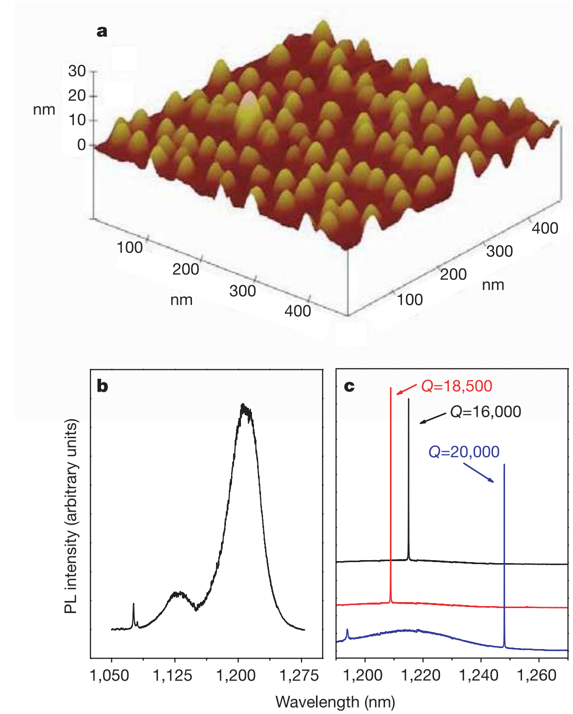


Figure 2 Quantum dots and cavity modes. **a**, Atomic force microscope profile of a layer of InAs QDs similar to the layer used but without layers above. The typical dot size is ~25 nm diameter and 3–4 nm height, and the dot density is 300–400 μm^{-2}. **b**, QD ensemble photoluminescence for high excitation power, showing both the lowest (1,175–1,250 nm) and first excited (1,100–1,150 nm) transitions. **c**, PL from the three nanocavities with the highest values of *Q* (uncorrected for ~0.04-nm instrument width). Averaging time: 0.1 s for left two peaks; 0.5 s for right.

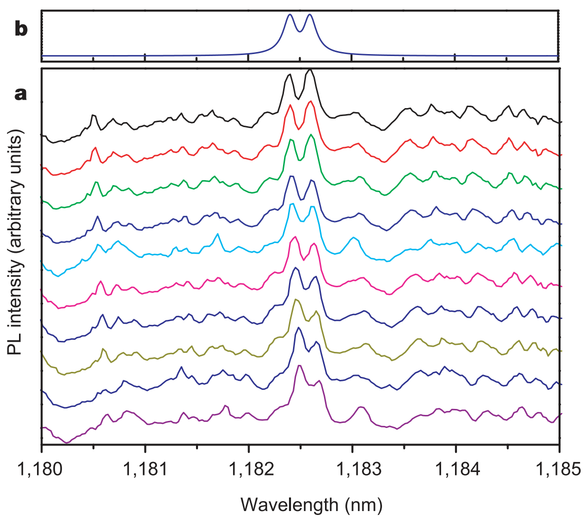
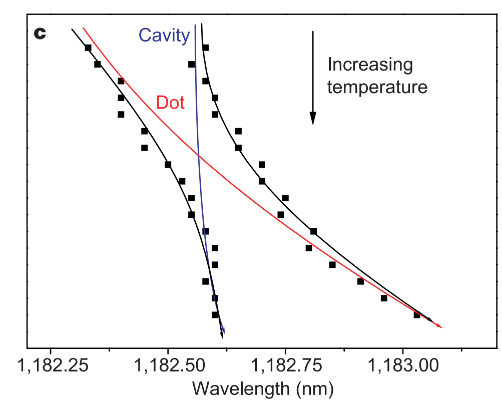


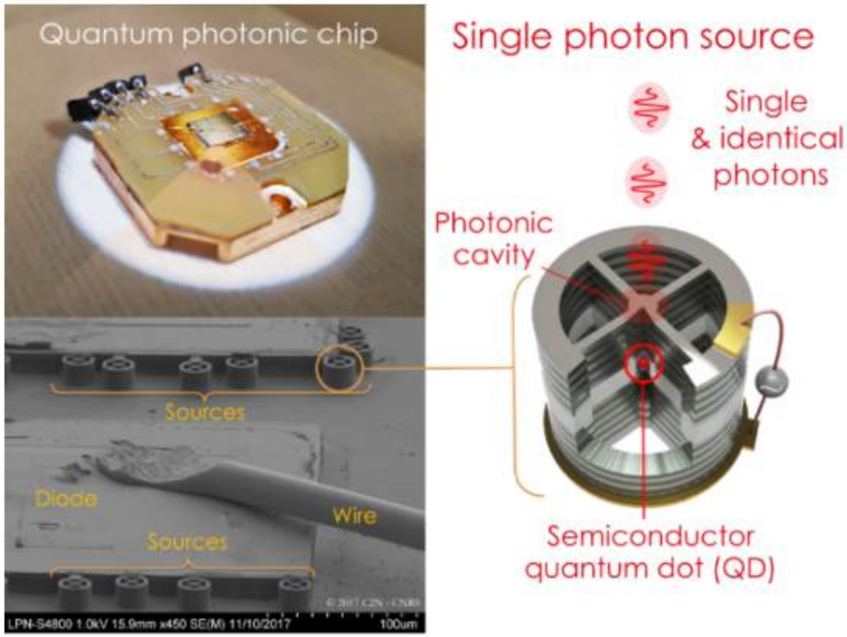
Figure 4 Dot–nanocavity vacuum Rabi splitting. **a**, Near-zero-detuning PL spectra (different run from Fig. 3b), showing double-peaked emission. Temperature is scanned in 0.5 K steps, from 15 K at the top to 19.5 K at the bottom; 0.78 μW and 60 s average. **b**, Plot of analytic expression for zero-detuning emission using $g = 20.6$ GHz $= 0.096$ nm, $\kappa = 42.3$ GHz $= 0.197$ nm, $\gamma = 21.5$ GHz $= 0.1$ nm.



Commercial Single Photon Sources

France

QUANDELA

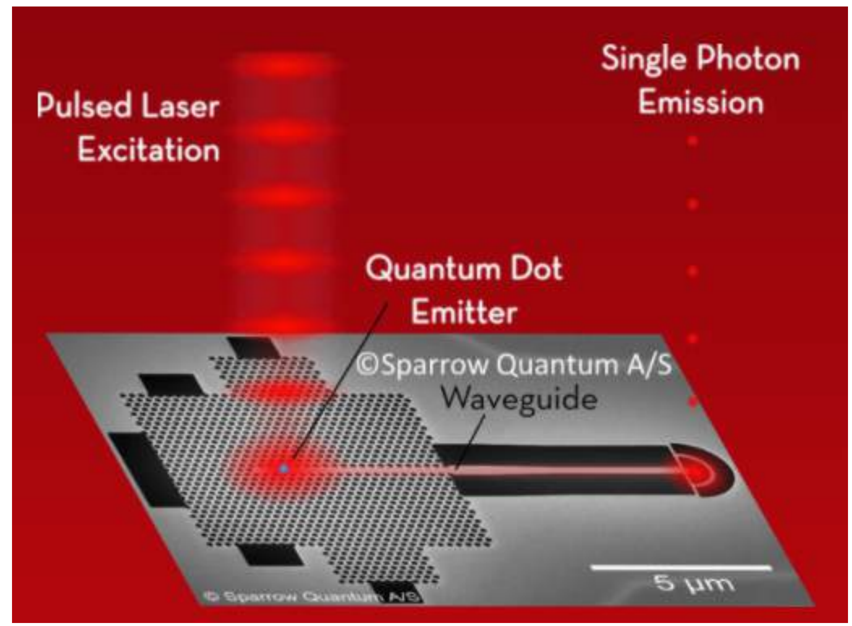


Quandela develops a unique Quantum Computing platform based on Photonic Qubits generated by efficient quantum light sources.

Denmark

Sparrow Quantum

SINGLE-PHOTON SOURCE



Motivation*

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articles

A scheme for efficient quantum computation with linear optics

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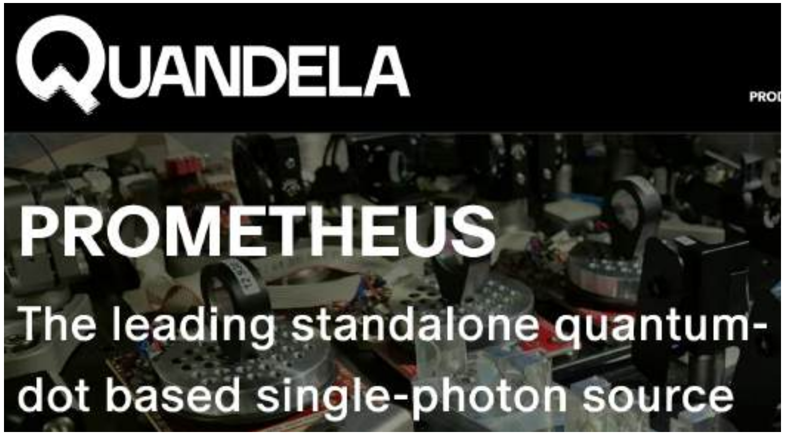
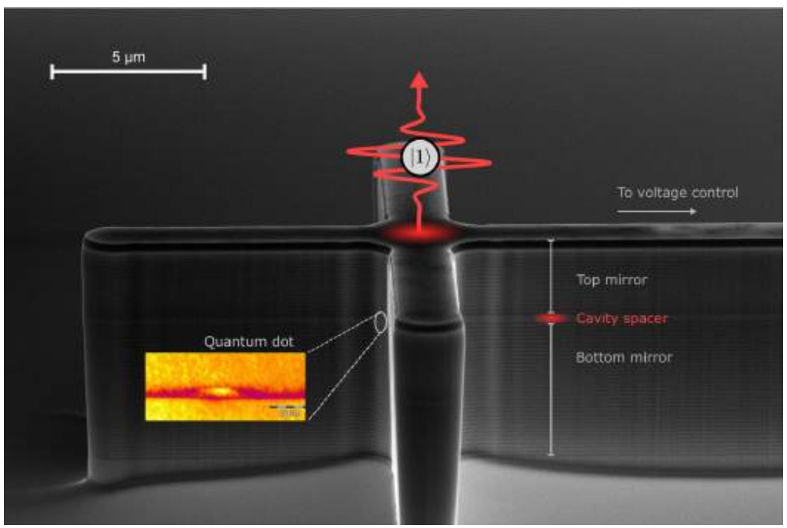
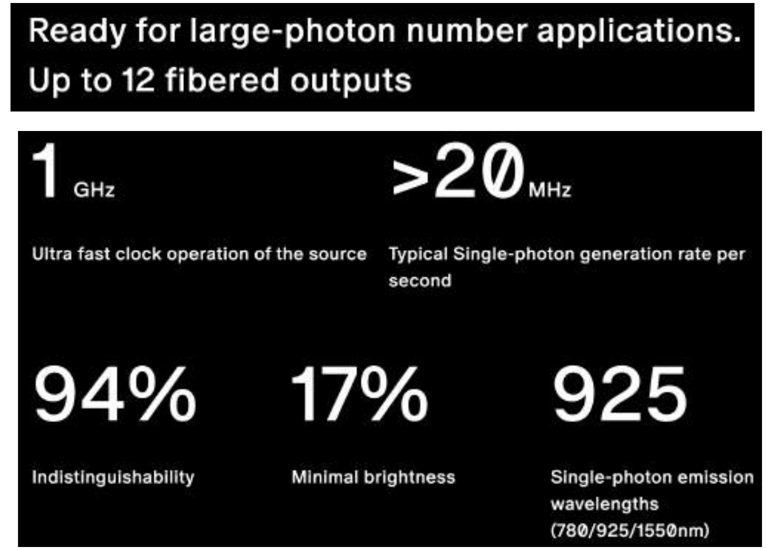
Quantum computers promise to increase greatly the efficiency of solving problems such as factoring large integers, combinatorial optimization and quantum physics simulation. One of the greatest challenges now is to implement the basic quantum-computational elements in a physical system and to demonstrate that they can be reliably and scalably controlled. One of the earliest proposals for quantum computation is based on implementing a quantum bit with two optical modes containing one photon. The proposal is appealing because of the ease with which photon interference can be observed. Until now, it suffered from the requirement for non-linear couplings between optical modes containing few photons. Here we show that efficient quantum computation is possible using only beam splitters, phase shifters, single photon sources and photo-detectors. Our methods exploit feedback from photo-detectors and are robust against errors from photon loss and detector inefficiency. The basic elements are accessible to experimental investigation with current technology.

* Original proposal is hard to scale up due to rapid increase in required physical resources, but proposals along these lines have evolved since then.







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Metrological characterization of a commercial single-photon source with high photon flux emission

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cQED with superconducting junctions

Quantum Josephson Junctions

VOLUME 55, NUMBER 15 PHYSICAL REVIEW LETTERS 7 OCTOBER 1985

Energy-Level Quantization in the Zero-Voltage State of a Current-Biased Josephson Junction

John M. Martinis, Michel H. Devoret,[(a)] and John Clarke

2025 Nobel Prize

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(Received 14 June 1985)

We report the first observation of quantized energy levels for a macroscopic variable, namely the phase difference across a current-biased Josephson junction in its zero-voltage state. The position of these energy levels is in quantitative agreement with a quantum mechanical calculation based on parameters of the junction that are measured in the classical regime.

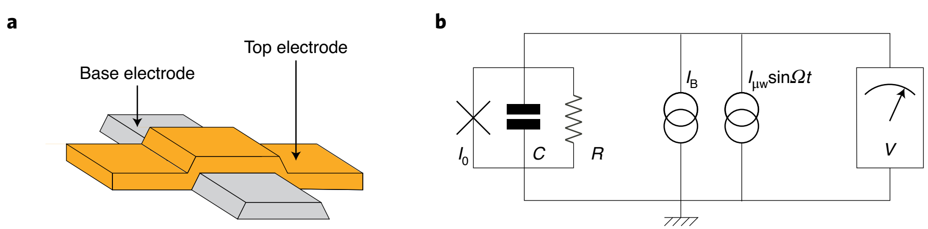

Fig. 1 | The Josephson junction and its measurement circuit. a, Schematic of a cross-strip Josephson superconducting tunnel junction. Our devices consist of a Nb base electrode and a top PbIn alloy electrode separated by a ~1-nm thick Nb-oxide layer formed by plasma-oxidation of the base electrode. **b**, Circuit schematic of a Josephson element (cross) shunted by a capacitance C and resistance R, and connected to both static bias (I_B) and microwave ($I_{\mu w}$) current sources. The voltage V across the junction is measured by a low-noise audio-frequency amplifier chain represented symbolically. Panel **b** adapted with permission from ref. [2], APS.

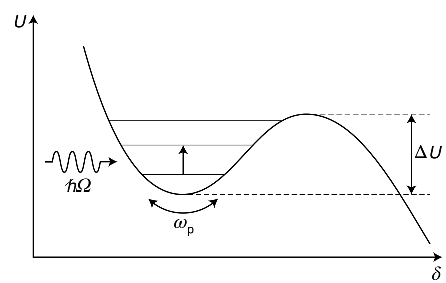

Fig. 2 | Cubic potential in which the macroscopic phase difference δ of the junction evolves quantum mechanically. Microwave irradiation at frequency $\Omega/2\pi$ induces transitions between the energy levels that quantum mechanics predicts to exist in the well. These transitions are detected by enhancement of the tunnelling rate, measured in the configuration of Fig. 1b. The transition frequencies are comparable with the plasma frequency $\omega_p/2\pi$. Figure adapted with permission from ref. [5], APS.

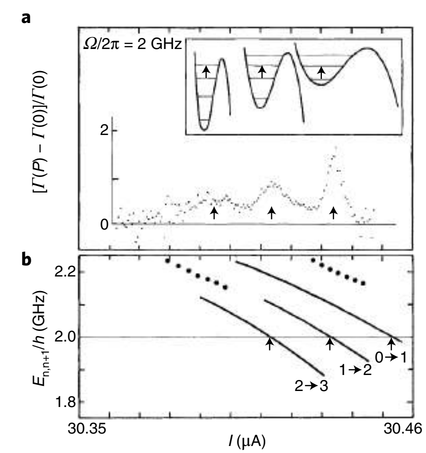

Fig. 3 | Resonances induced by microwaves at 2.0 GHz. a, $[\Gamma(P) - \Gamma(0)]/\Gamma(0)$ versus I for an $80 \times 10\ \mu m^2$ junction at 28 mK ($k_BT/\hbar\Omega = 0.29$). Arrows indicate positions of resonances. Inset: corresponding transitions between energy levels. **b**, Calculated energy level spacings $E_{n,n+1}$ versus I for $I_0 = 30.572 \pm 0.017$ μA and $C = 47.0 \pm 3.0$ pF. Dotted lines indicate uncertainties in the 0→1 curve due to uncertainties in I_0 and C. Arrows indicate values of bias current at which resonances are predicted. Figure reproduced with permission from ref. [5], APS.

Comment | Published: 02 March 2020

Quantum Josephson junction circuits and the dawn of artificial atoms

John M. Martinis, Michel H. Devoret & John Clarke

Nature Physics 16, 234–237 (2020) | Cite this article

Jaynes-Cummings Model

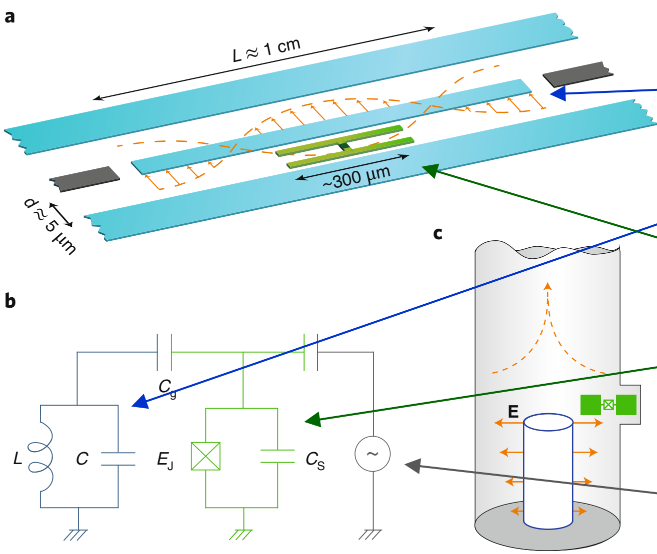

Fig. 1 | Realizations of circuit QED. a, Schematic representation of a superconducting transmon qubit (green) coupled to a 1D transmission-line resonator. The transmon is formed by two superconducting islands connected by a Josephson junction. With lateral dimensions (~300 μm) much smaller than that of the resonator (~1 cm), multiple transmons can be fabricated in the same resonator (not shown). The input and output ports of the resonator are shown in grey. The orange lines and arrows illustrate the electric field distribution for the resonator's second mode. **b**, Lumped-element version where an LC circuit (blue) plays the role of the oscillator. The voltage source (grey) is used to control the quantum state of the transmon (green). **c**, Three-dimensional coaxial

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https://doi.org/10.1038/s41567-020-0806-z
Check for updates

Quantum information processing and quantum optics with circuit quantum electrodynamics

Alexandre Blais[1,2,3], Steven M. Girvin[4,5] and William D. Oliver[6,7,8]

free cavity

$$\hat{H}_{\mathrm{LC}} = \hbar\omega_{\mathrm{r}}\hat{a}^\dagger\hat{a}$$

Free transmon

$$\hat{H}_{\mathrm{T}} = \hbar\omega_{\mathrm{q}}\hat{b}^\dagger\hat{b} + \hbar K\hat{b}^\dagger\hat{b}^\dagger\hat{b}\hat{b}$$

Anharmonicity: will be neglected for a situation of near-resonance

lateral excitation

$$\hat{H}_{\mathrm{drive}} = \epsilon(t)(\hat{b}^\dagger + \hat{b})$$

interaction

$$\hat{H}_{\mathrm{coupling}} = \hbar g(\hat{a}^\dagger + \hat{a})(\hat{b}^\dagger + \hat{b})$$

Total Hamiltonian

$$\hat{H}_{\mathrm{JC}} = \hbar\omega_{\mathrm{r}}\hat{a}^\dagger\hat{a} + \frac{\hbar\omega_{\mathrm{q}}}{2}\hat{\sigma}_z + \hbar g\left(\hat{a}^\dagger\hat{\sigma}_- + \hat{a}\hat{\sigma}_+\right)$$

vacuum-Rabi splitting

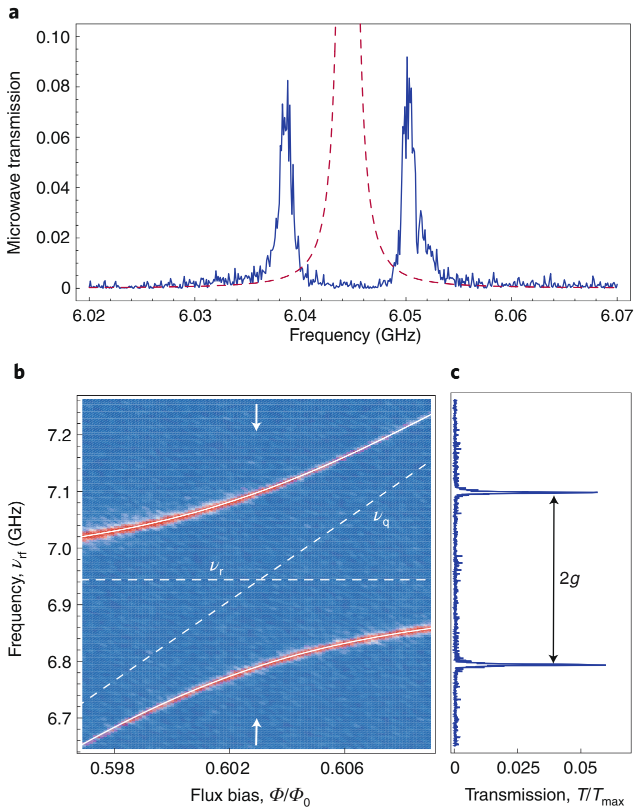

Fig. 2 | Vacuum Rabi splitting. a, Transmission power spectrum of transmission-line resonator as a function of the input drive frequency displaying clear vacuum Rabi splitting. The solid blue line is measured at the qubit-resonator resonance $\Delta = 0$ while the dashed red line shows the spectrum measured at strong detuning $|\Delta| = |\omega_q - \omega_r| \gg g$ where only the resonator is probed. **b**, The resonator transmission spectra versus drive frequency ν_{rf} and external flux bias Φ/Φ_0, where Φ_0 is the flux quantum. The flux bias is used to tune the qubit frequency and allows mapping of the full qubit-resonator anti-crossing. Blue corresponds to low transmission and red to high transmission. The solid white line correspond to the dressed qubit-resonator energies, while the dashed white lines indicate the bare resonator frequency $\nu_r = \omega_r/2\pi$ and qubit transition frequency $\nu_q = \omega_q/2\pi$ with its flux dependence. **c**, Resonator transmission at the flux bias indicated by the arrows in **b** and corresponding to qubit-resonator resonance. The vacuum Rabi splitting is clearly observed. Panels adapted with permission from: **a**, ref. [8], Springer Nature Ltd; **b**,**c**, ref. [123], Springer Nature Ltd.

letters to nature

Strong coupling of a single photon to a superconducting qubit using circuit quantum electrodynamics

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Vol 454 | 17 July 2008 | **doi:10.1038/nature07112** nature

LETTERS

Climbing the Jaynes–Cummings ladder and observing its $\sqrt{n}$ nonlinearity in a cavity QED system

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315

$$\frac{g}{2\pi} = 154\ \text{MHz} \gg \frac{\gamma}{2\pi} = 2.6\ \text{MHz}$$

Computer Architectures

PHYSICAL REVIEW A **69**, 062320 (2004)

Cavity quantum electrodynamics for superconducting electrical circuits: An architecture for quantum computation

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PHYSICAL REVIEW A **75**, 032329 (2007)

Quantum-information processing with circuit quantum electrodynamics

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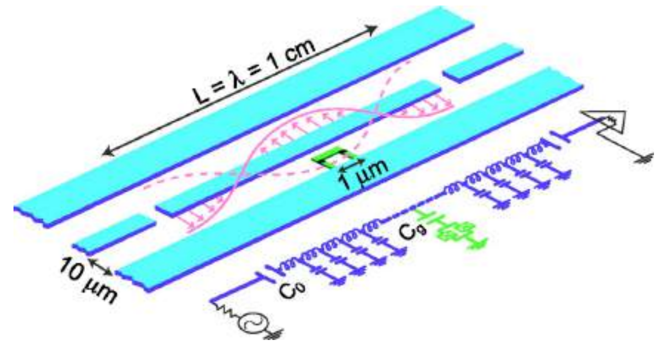

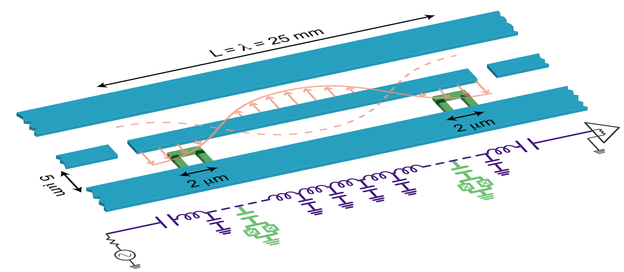

Parameter	Symbol	3D optical	3D microwave	1D circuit
Resonance or transition frequency	$\omega_r/2\pi$, $\Omega/2\pi$	350 THz	51 GHz	10 GHz
Vacuum Rabi frequency	g/π, g/ω_r	220 MHz, 3×10^{-7}	47 kHz, 1×10^{-7}	100 MHz, 5×10^{-3}
Transition dipole	d/ea_0	~1	1×10^{3}	2×10^{4}
Cavity lifetime	$1/\kappa, Q$	10 ns, 3×10^{7}	1 ms, 3×10^{8}	160 ns, 10^{4}
Atom lifetime	$1/\gamma$	61 ns	30 ms	2 μs
Atom transit time	$t_{transit}$	$\geqslant50$ μs	100 μs	∞
Critical atom number	$N_0=2\gamma\kappa/g^2$	6×10^{-3}	3×10^{-6}	$\leqslant6\times10^{-5}$
Critical photon number	$m_0=\gamma^2/2g^2$	3×10^{-4}	3×10^{-8}	$\leqslant1\times10^{-6}$
Number of vacuum Rabi flops	$n_{Rabi}=2g/(\kappa+\gamma)$	~10	~5	$\sim10^{2}$

Arbitrarily complex architectures

PHYSICAL REVIEW APPLIED 8, 034021 (2017)

Scalable Quantum Circuit and Control for a Superconducting Surface Code

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Engineering cryogenic setups for 100-qubit scale superconducting circuit systems

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