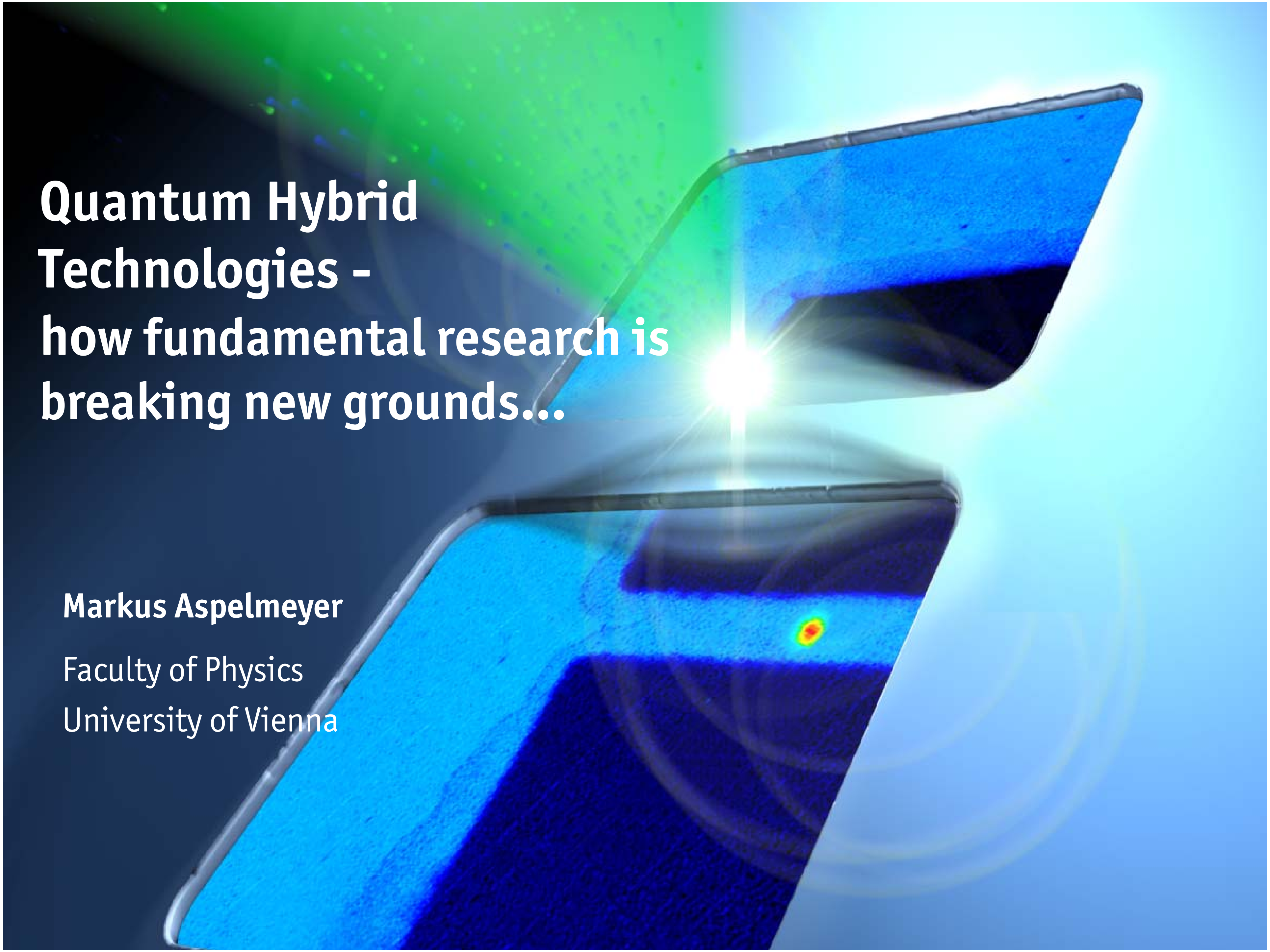
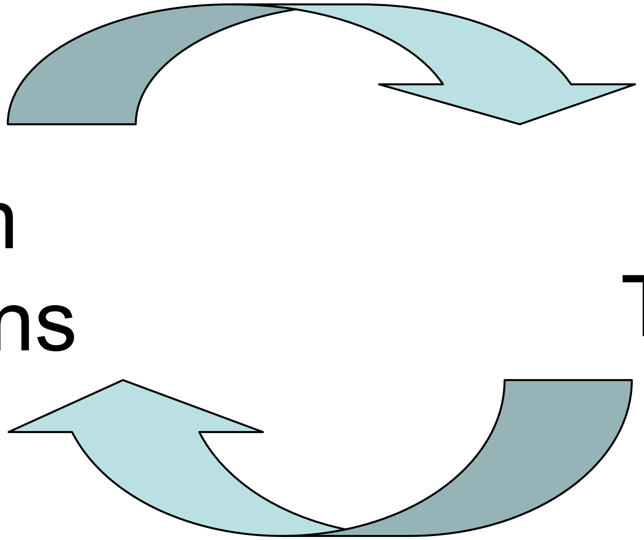


Quantum Hybrid Technologies - how fundamental research is breaking new grounds...

Markus Aspelmeyer

Faculty of Physics
University of Vienna

Fundamental vs Applied Research: Give and Take...



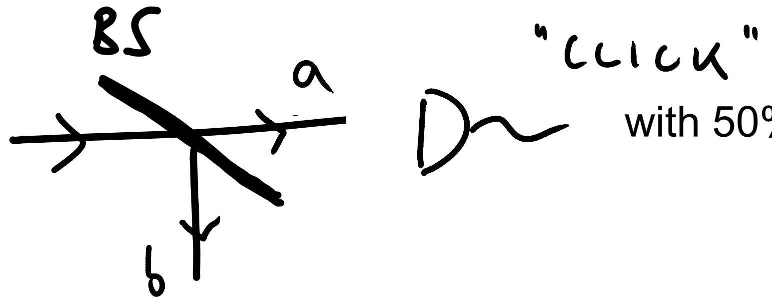
Quantum Information

Quantum Foundations

Quantum Technology

Quantum Opto-Mechanics

Conceptual challenges of quantum theory: Randomness



Single-photon source

with 50% probability

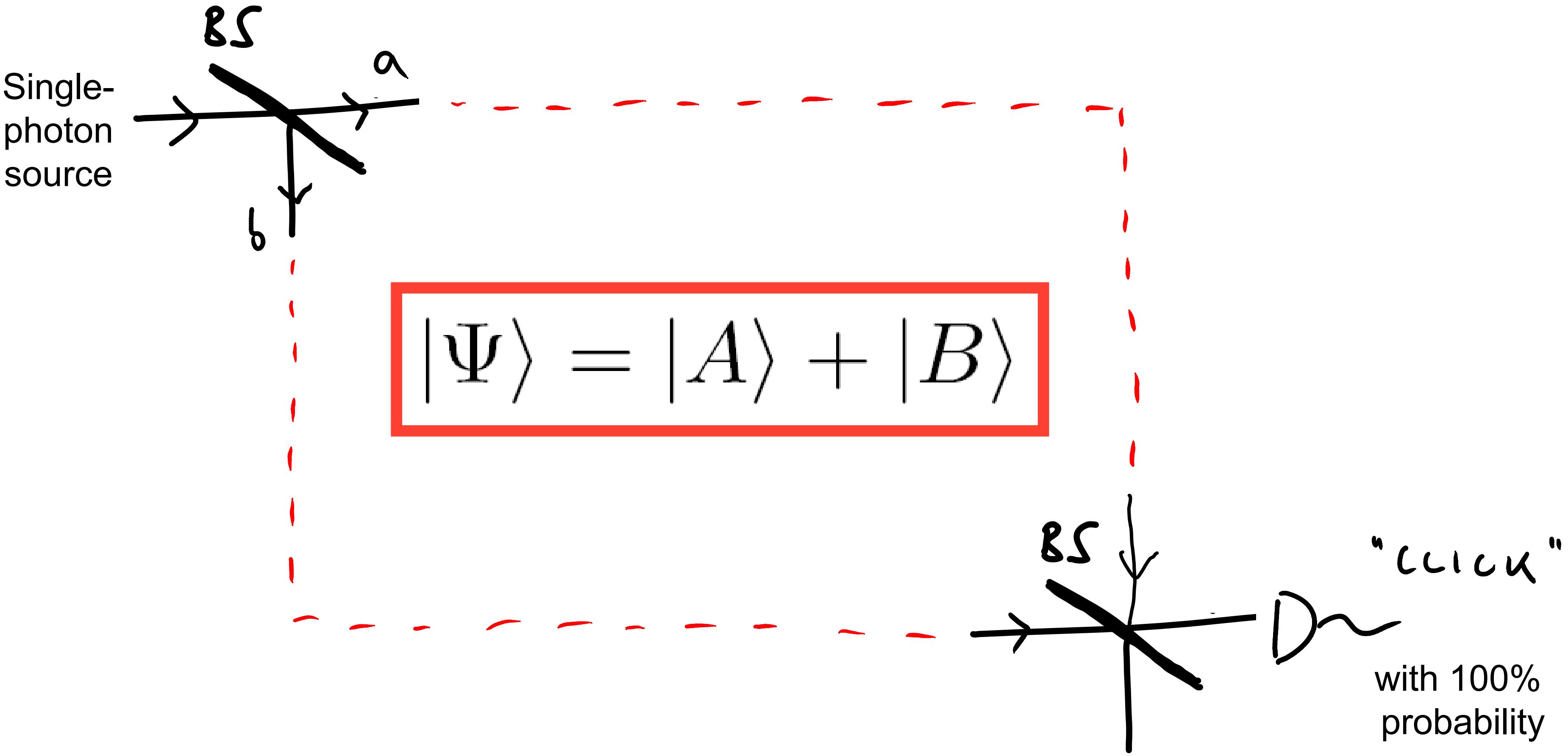
→ **Objective randomness!**

$$\boxed{|\Psi\rangle = |A\rangle + |B\rangle}$$

"The Weakness of the Theory lies ... in the Fact, that Time and Direction of the Elementary Process are left to „Chance".”

A. Einstein, 1917 Z. Physik

Conceptual challenges of quantum theory: Which way?



Single-photon source

$$\boxed{|\Psi\rangle = |A\rangle + |B\rangle}$$

with 100% probability

WHICH WAY? A or B?

Quantum-Superposition:
how can we talk about *physical reality* in a consistent way?

MAY 15, 1935 PHYSICAL REVIEW VOLUME 47

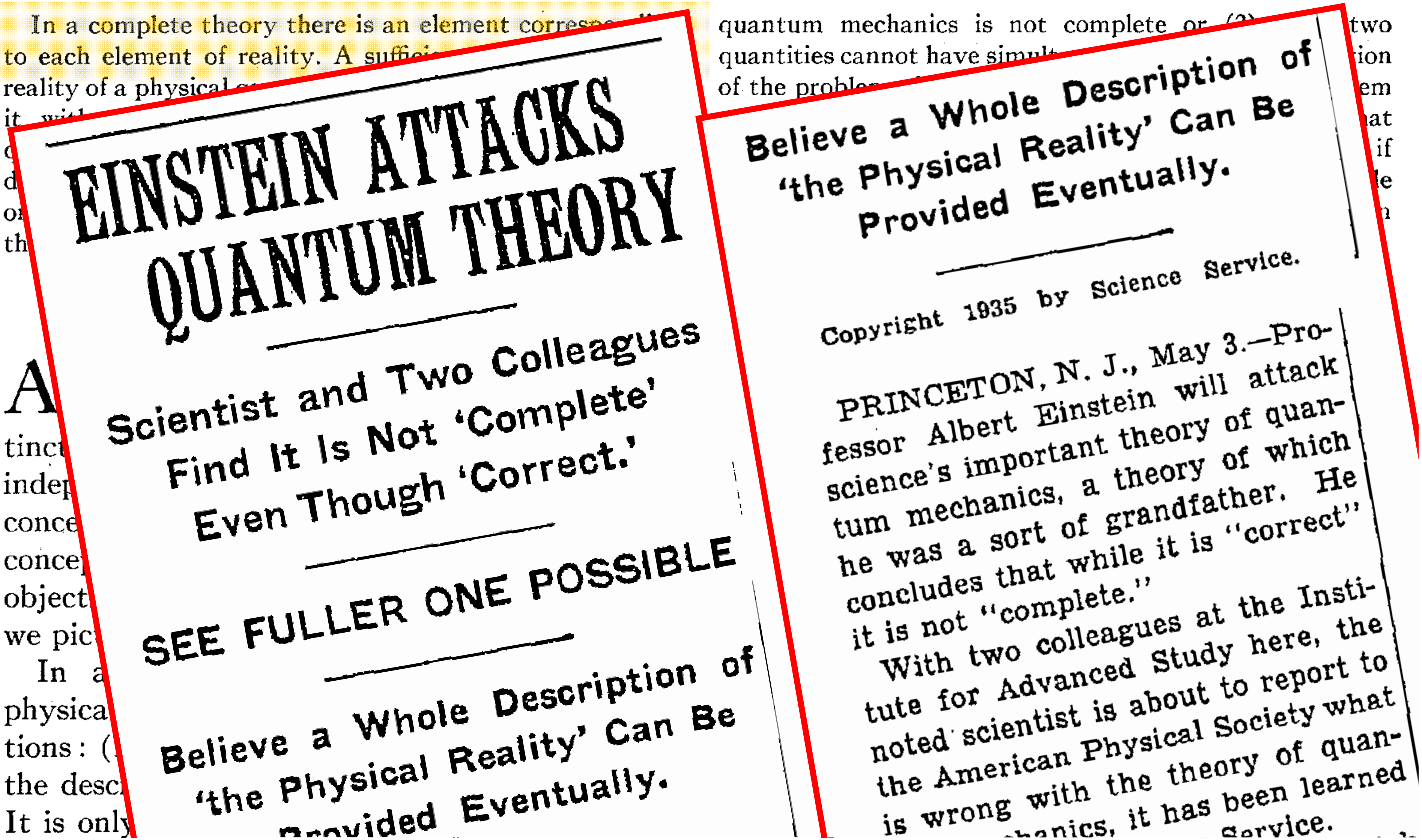
Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?

A. EINSTEIN, B. PODOLSKY AND N. ROSEN, *Institute for Advanced Study, Princeton, New Jersey*

(Received March 25, 1935)

In a complete theory there is an element corresp
to each element of reality. A suffici
reality of a physical qu
it with

quantum mechanics is not complete or (2) two
quantities cannot have simult ion
of the probl em



EINSTEIN ATTACKS QUANTUM THEORY

Scientist and Two Colleagues Find It Is Not 'Complete' Even Though 'Correct.'

SEE FULLER ONE POSSIBLE

Believe a Whole Description of 'the Physical Reality' Can Be Provided Eventually.

Believe a Whole Description of 'the Physical Reality' Can Be Provided Eventually.

Copyright 1935 by Science Service.

PRINCETON, N. J., May 3.—Professor Albert Einstein will attack science's important theory of quantum mechanics, a theory of which he was a sort of grandfather. He concludes that while it is "correct" it is not "complete."

With two colleagues at the Institute for Advanced Study here, the noted scientist is about to report to the American Physical Society what is wrong with the theory of quan-
chanics, it has been learned
Service.

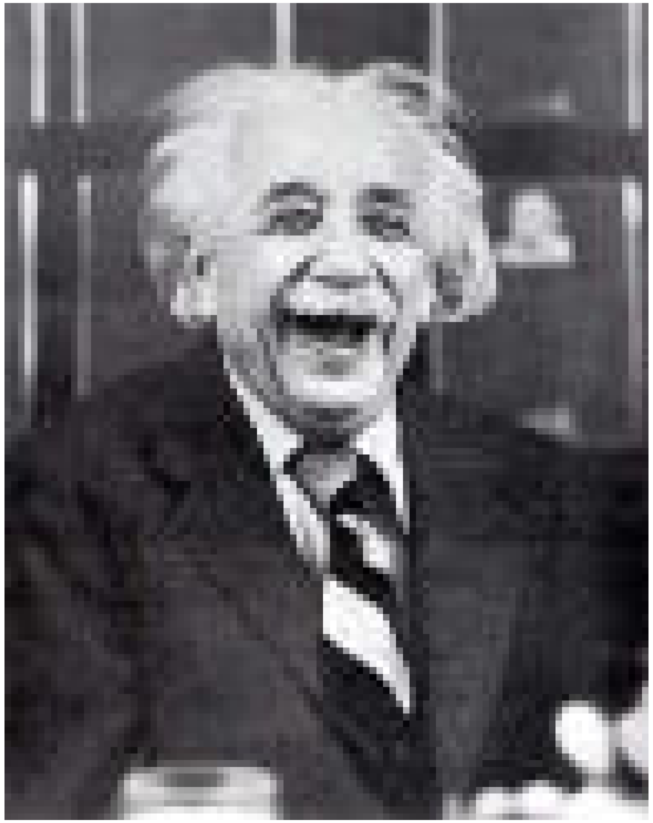
Verschränkung / Entanglement

$$|\Psi\rangle_{12} = \frac{1}{\sqrt{2}}(|0\rangle_1|0\rangle_2 + |1\rangle_1|1\rangle_2)$$

- **non-separable** quantum states
- state describes **only joint correlations**
- no information on individual subsystems

Erwin Schrödinger

Naturwissenschaften **23**, 807 (1935)



Entanglement in particular shows that a quantum mechanical description of physical reality is incomplete!

John Bell (1964)

That is correct. However, it **cannot be completed (in a reasonable way)**!

Bell‘s Theorem / GHZ Theorem

J. S. Bell, Physics 1, 1 (1964)
Greenberger, Horne, Zeilinger (1989)

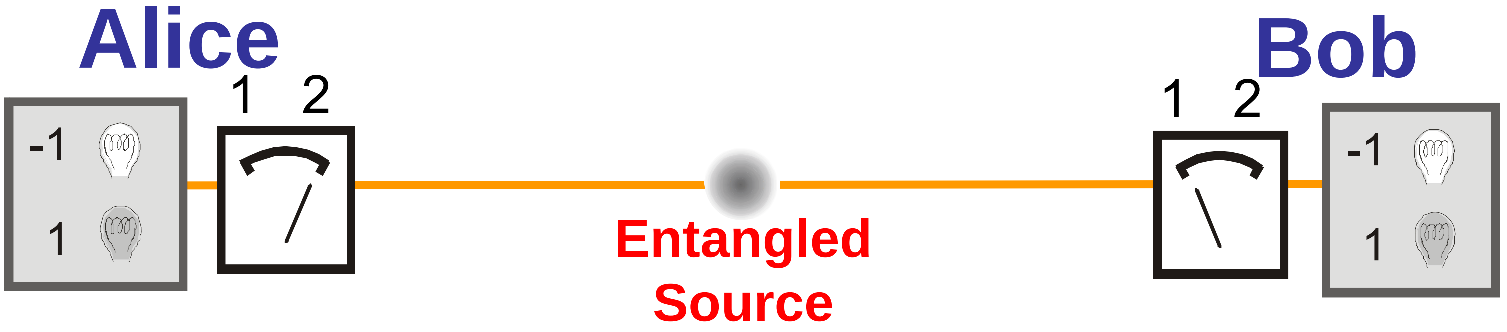
A) Predictions of quantum theory are correct

B) **Realism:** The outcome of *any* measurement depends on properties carried by the system prior to and independent of the measurement

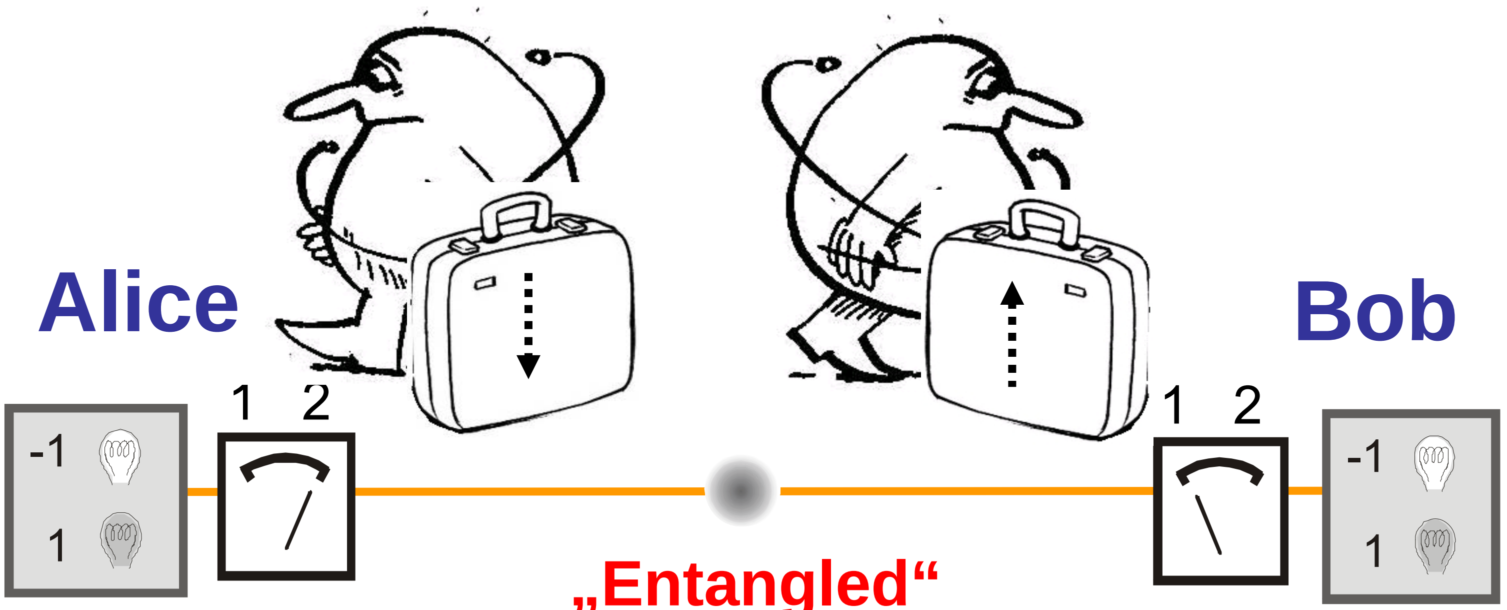
C) **Locality:** The outcome of any meaurement is independent of actions in space-like separated regions.

Bell’s theorem: granted A), either B) or C) or both fail

→ ***experimentally testable using entangled particles***



Bell‘s Theorem



Alice

Bob

„Entangled“ Source

$A_1=\pm1$,
$A_2=\pm1$

$B_1=\pm1$,
$B_2=\pm1$

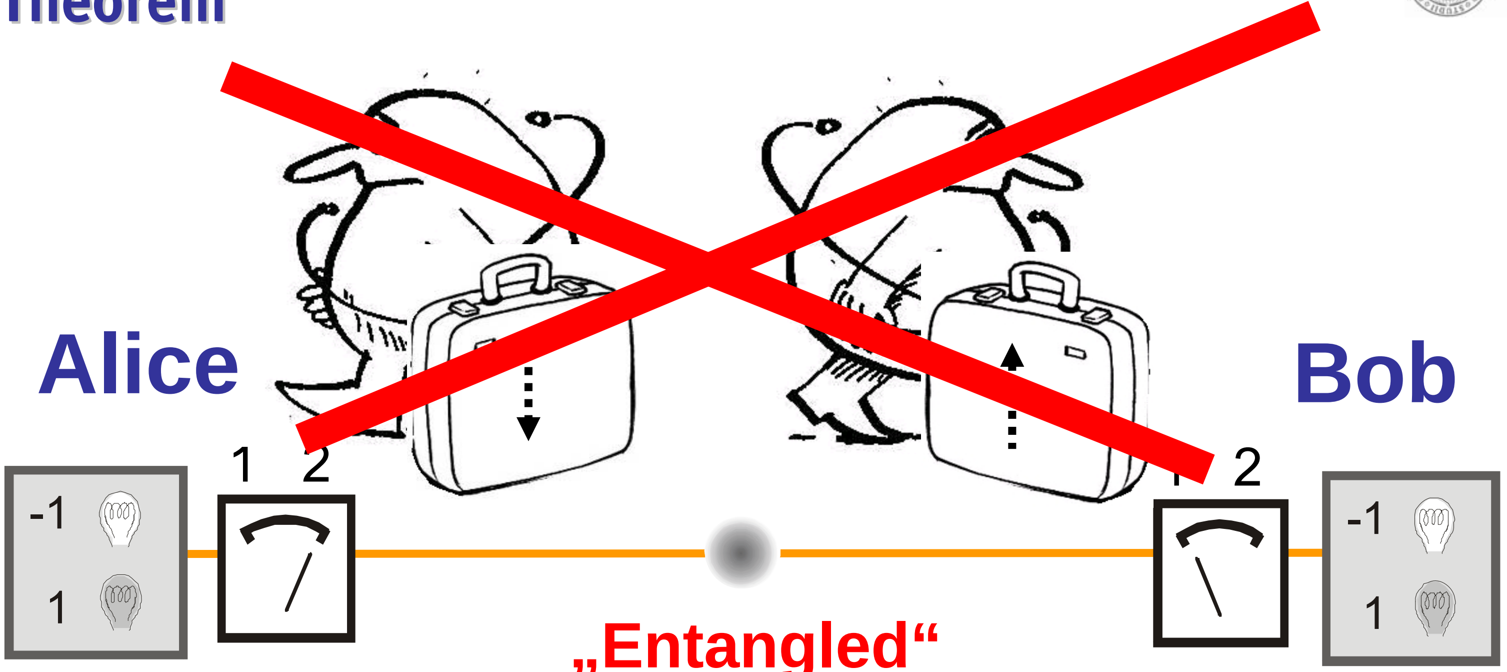
Correlation function: $E_{21}=p(A_2B_1=1)-p(A_2B_1=-1)$

Local Realism: $E_{11}+E_{12}+E_{21}-E_{22}\leq 2$

Quantum Mechanics: $\boxed{2\sqrt{2}}$

Bell 1964, CHSH 1969, Bell 1971, CH 1974, GHZ 1989

Bell‘s Theorem



Alice

Bob

„Entangled“ Source

$A_1=\pm1$,
$A_2=\pm1$

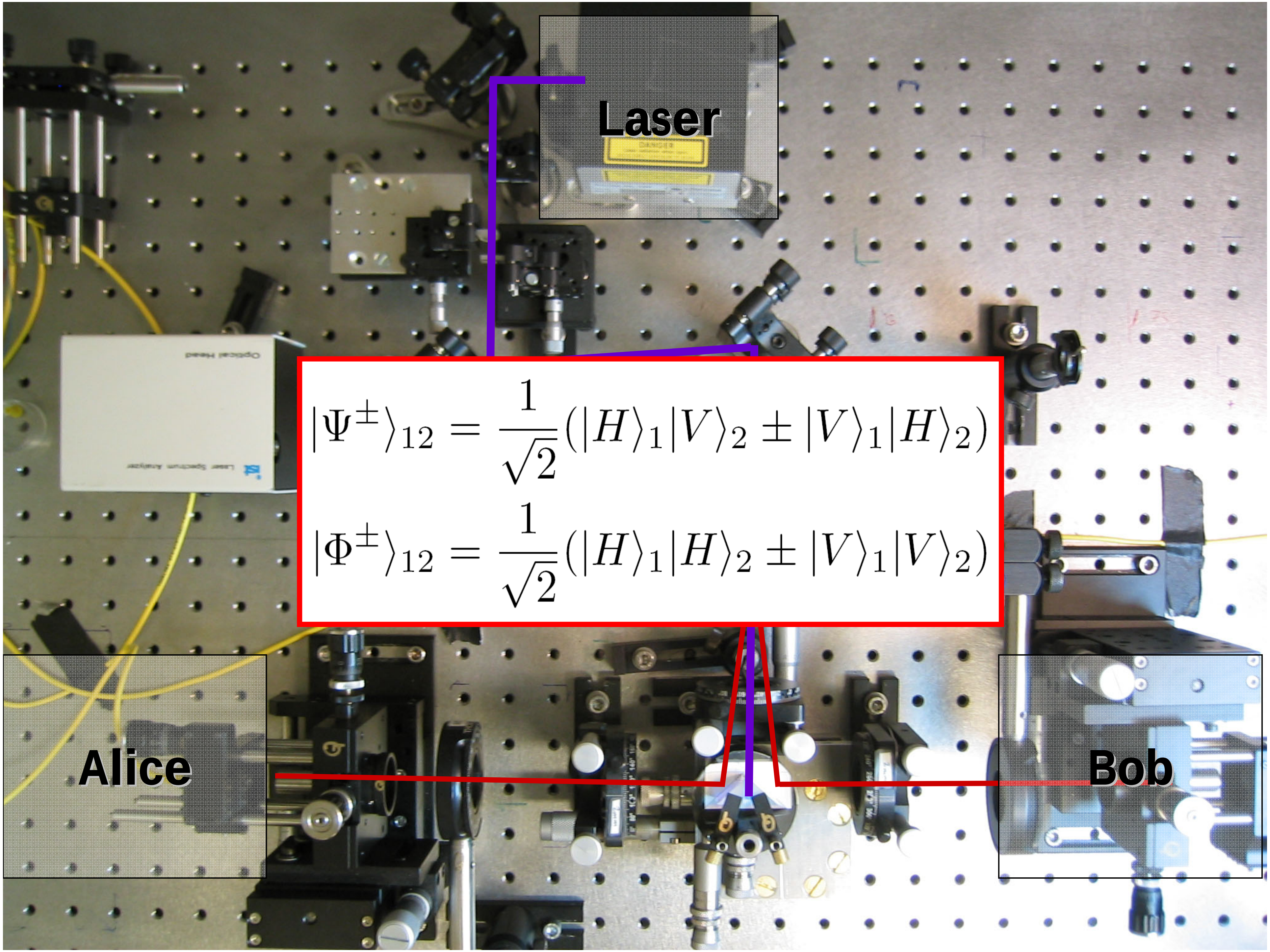
$B_1=\pm1$,
$B_2=\pm1$

Correlation function: $E_{21}=p(A_2B_1=1)-p(A_2B_1=-1)$

Local Realism: $E_{11}+E_{12}+E_{21}-E_{22}\leq 2$

Quantum Mechanics: $\boxed{2\sqrt{2}}$

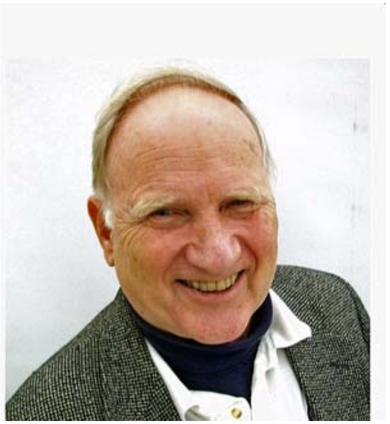
Bell 1964, CHSH 1969, Bell 1971, CH 1974, GHZ 1989



$$|\Psi^{\pm}\rangle_{12} = \frac{1}{\sqrt{2}}(|H\rangle_1|V\rangle_2 \pm |V\rangle_1|H\rangle_2)$$

$$|\Phi^{\pm}\rangle_{12} = \frac{1}{\sqrt{2}}(|H\rangle_1|H\rangle_2 \pm |V\rangle_1|V\rangle_2)$$

Bell Experiments

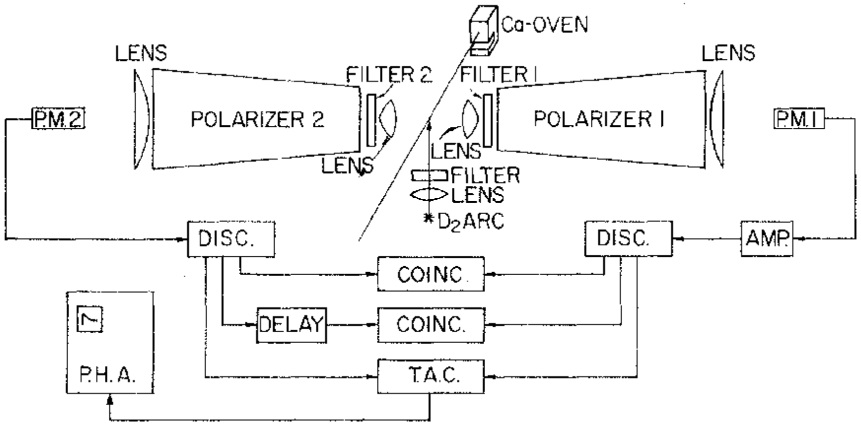


Experimental Test of Local Hidden-Variable Theories*

Stuart J. Freedman and John F. Clauser
Department of Physics and Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720

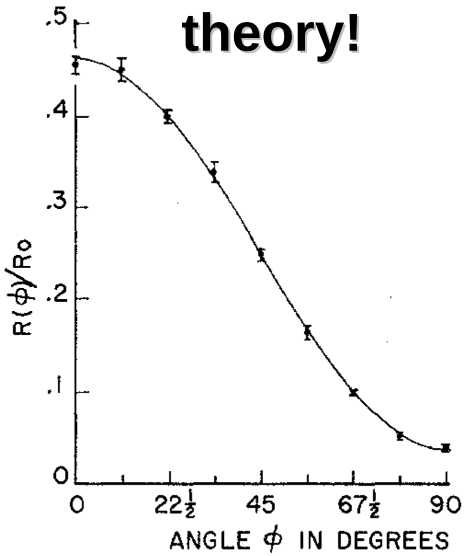
(Received 4 February 1972)

We have measured the linear polarization correlation of the photons emitted in an atomic cascade of calcium. It has been shown by a generalization of Bell's inequality that the existence of local hidden variables imposes restrictions on this correlation in conflict with the predictions of quantum mechanics. Our data, in agreement with quantum mechanics, violate these restrictions to high statistical accuracy, thus providing strong evidence against local hidden-variable theories.



PRL **28**, 938 (1972)

No deviation from quantum theory!

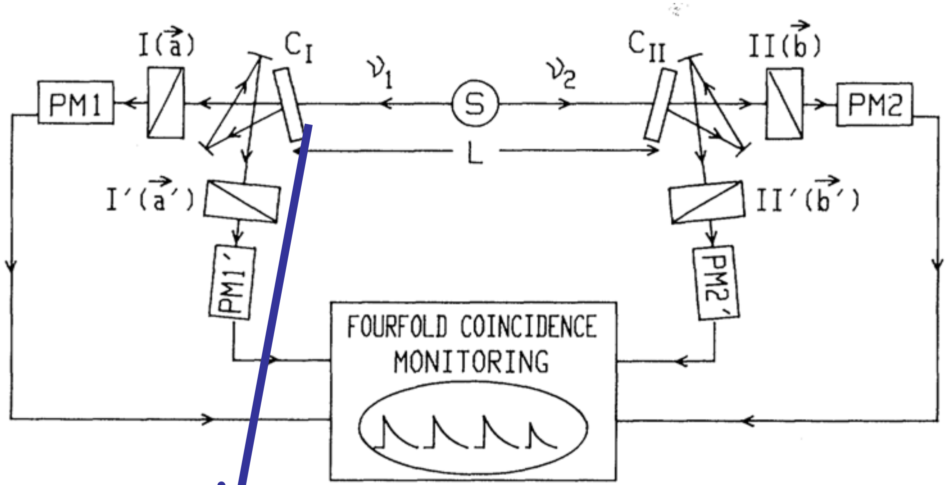


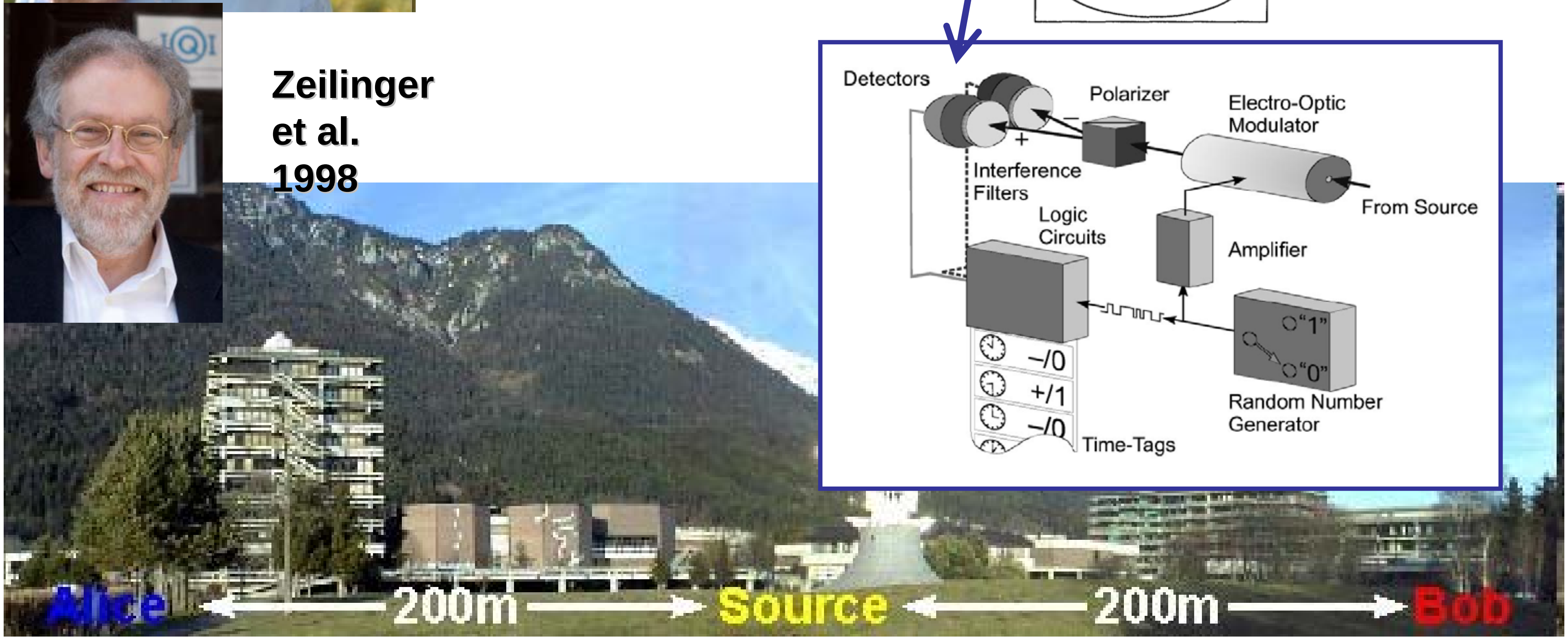
Experimental loopholes? (locality! Static settings)

Bell Experiments under locality condition

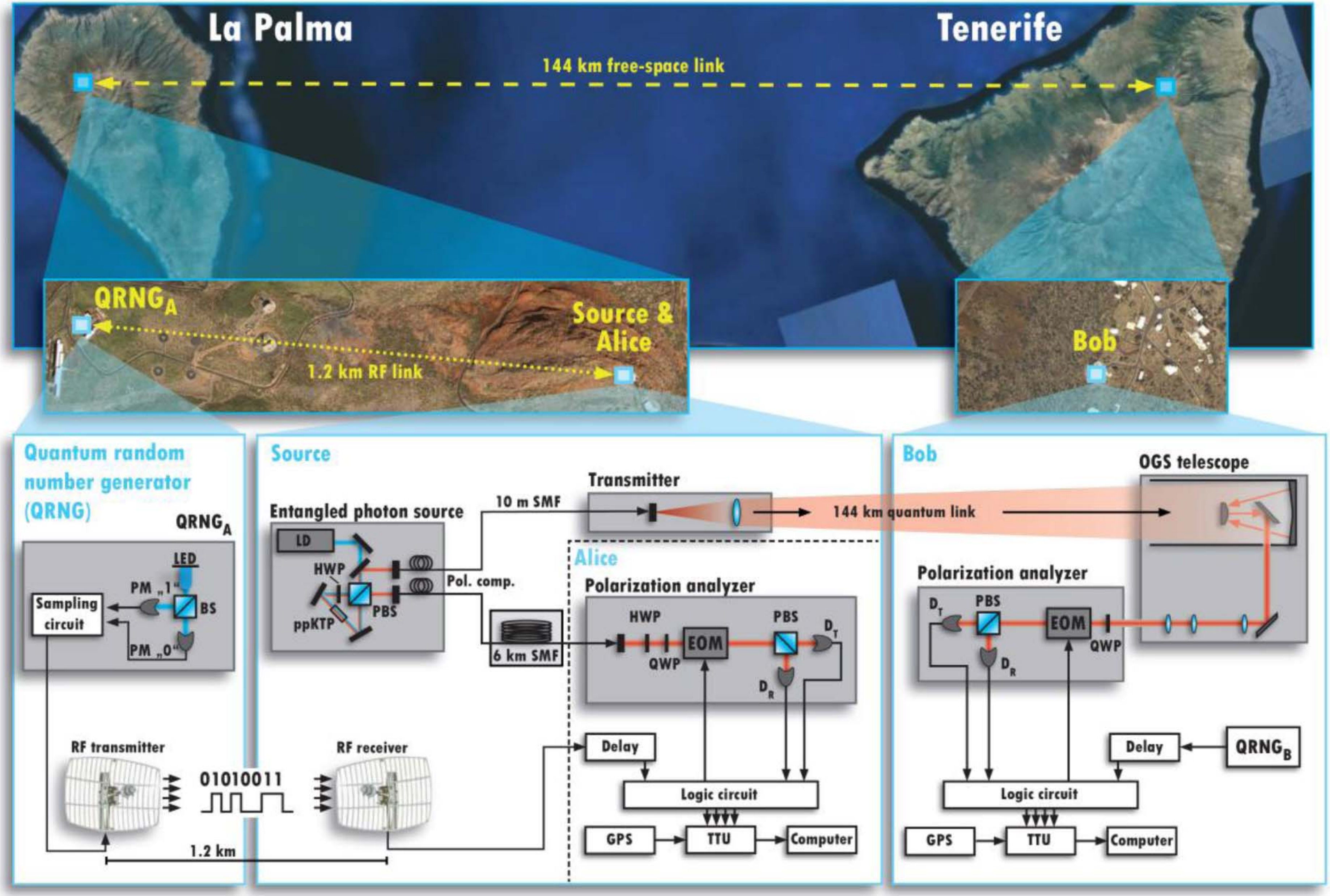
Random setting of measurement direction:
„spooky action“ or non-realism?

Aspect
et al.
1984





Zeilinger
et al.
1998



Entanglement over 144 km, Ursin, Weinfurter, Zeilinger et al., Nature Physics (2007)

Bell test over 144 km, Scheidl, Zeilinger et al. (2008)

What is left?

Local realistic theories are **inconsistent**

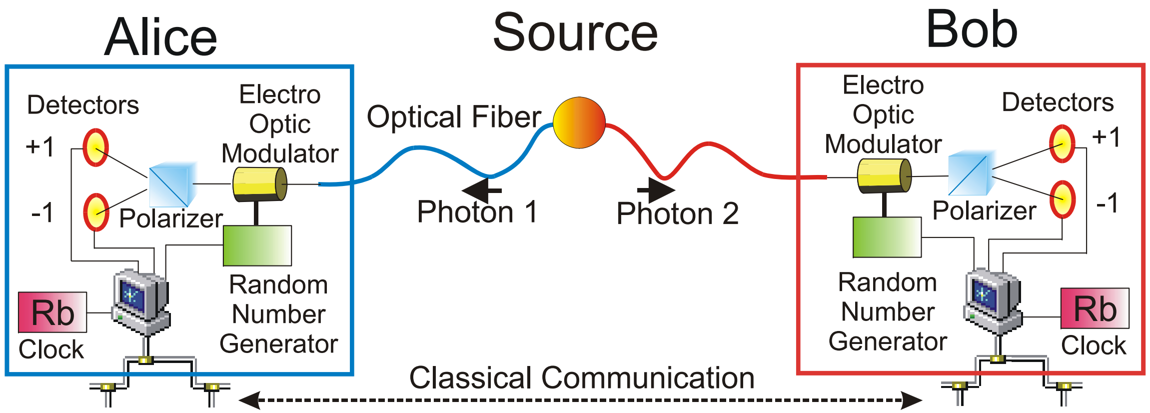
with predictions of quantum theory

with experimental observation

Which assumption is wrong?

- **Locality**?
- **Realism**?
- Locality **and** realism?
- …other pre-assumptions? (Aristotelean logic?)

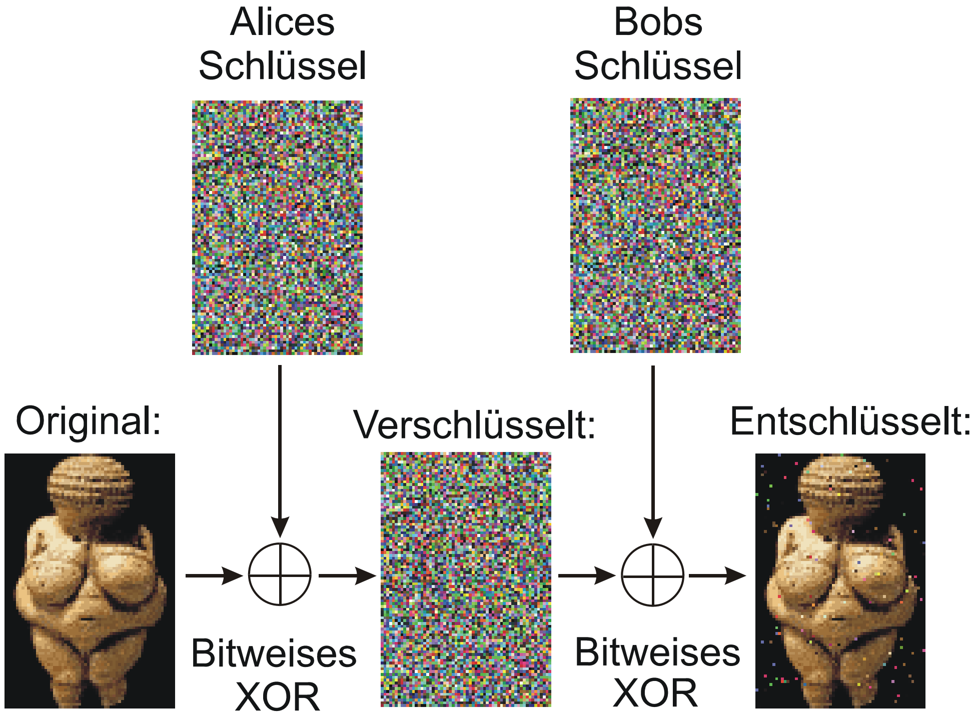
Quantum Cryptography



Alice
Source
Bob
Detectors
+1
-1
Polarizer
Electro Optic Modulator
Random Number Generator
Rb Clock
Optical Fiber
Photon 1
Photon 2
Classical Communication

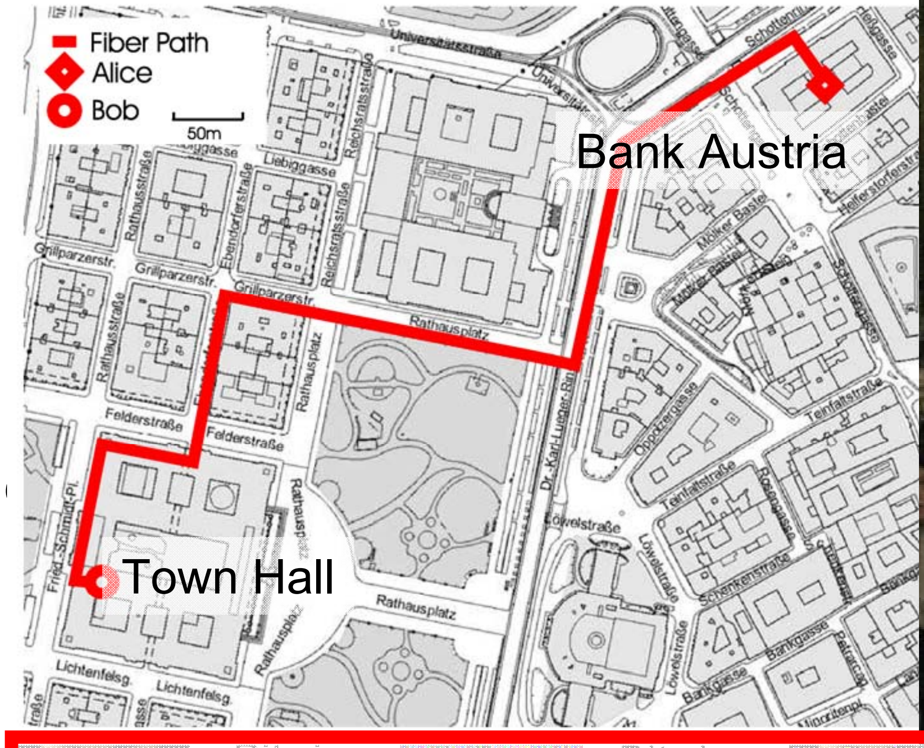
Entanglement creates shared random sequence (=key)

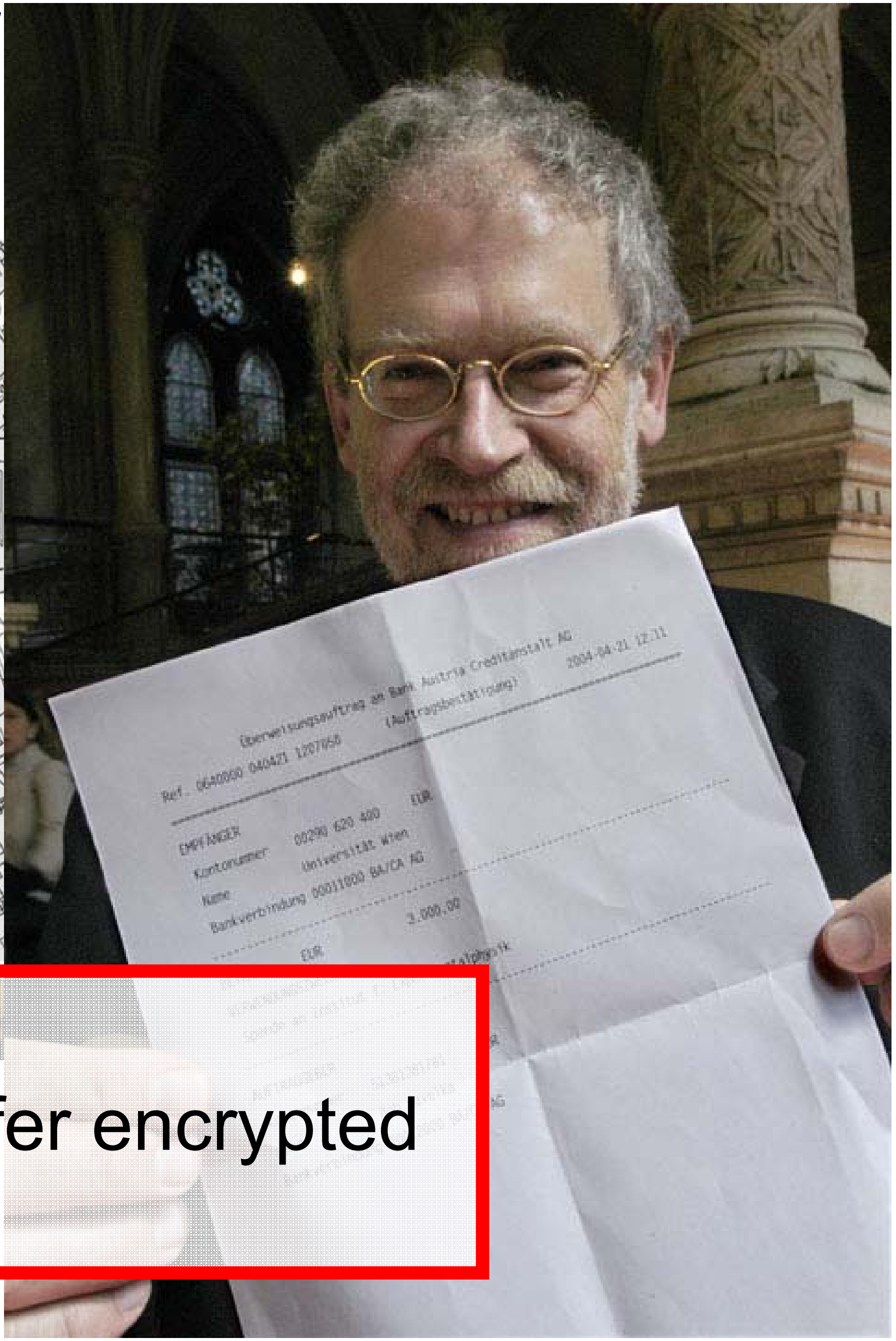
Security guaranteed e.g. by Bell inequality



Alices Schlüssel
Bobs Schlüssel
Original:
Verschlüsselt:
Entschlüsselt:
Bitweises XOR
Bitweises XOR

Quantum Cryptography





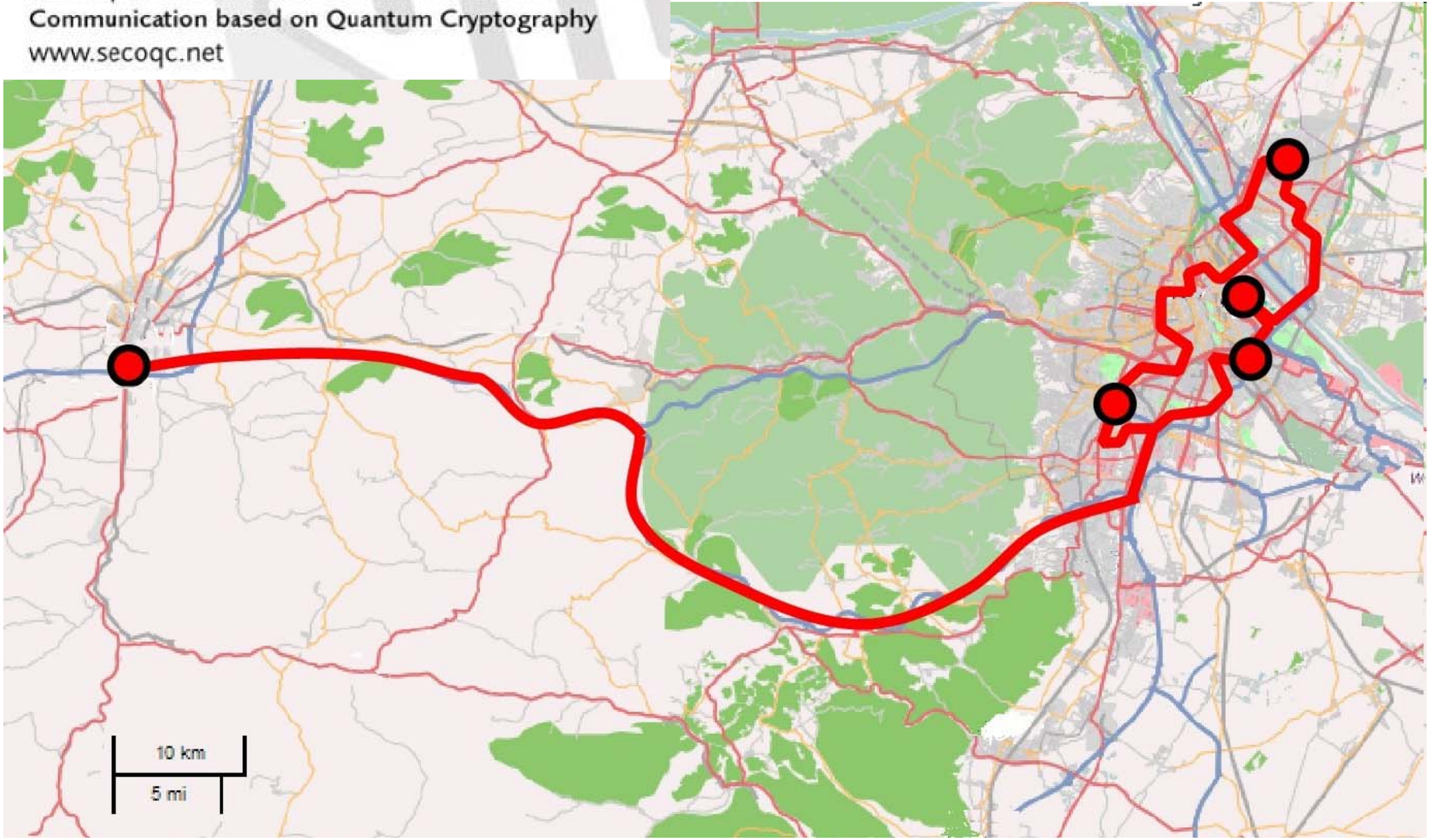
Vienna, 21. April 2004:
Worldwide first bank transfer encrypted via quantum cryptography

SECOQC

Development of a Global Network for Secure
Communication based on Quantum Cryptography
www.secoqc.net

42 European partners from University and Industry

Quantum Cryprography in Vienna‘s glass fibre network



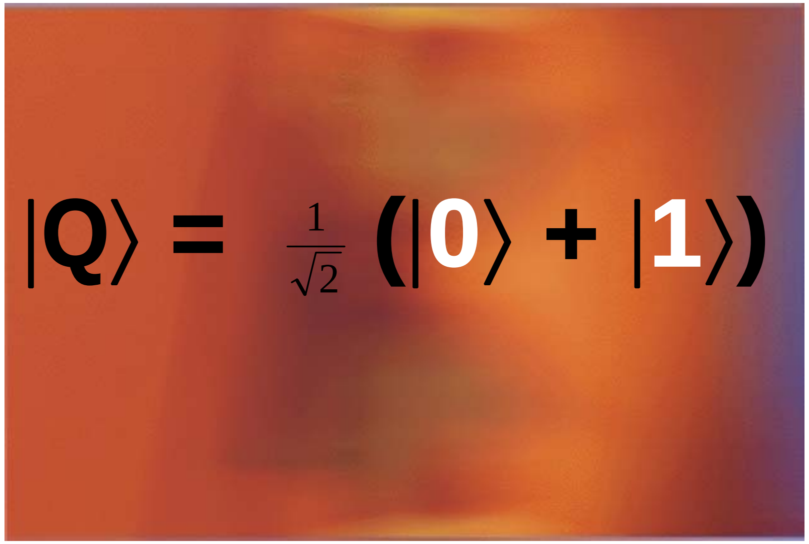
Quantum Information

Bit

„0“ or „1“

|computer> = 00000000
|computer> = 00000001
|computer> = 00000010

Qubit



$$|Q\rangle = \frac{1}{\sqrt{2}}\left(|0\rangle + |1\rangle\right)$$

„0“ and „1“

|Q-computer> = 00000000 + 00000001 + 00000010 + …

…

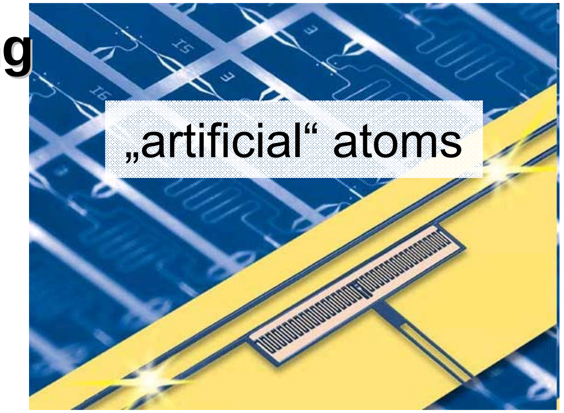
QUANTUM-HYBRID-TECHNOLOGIES:

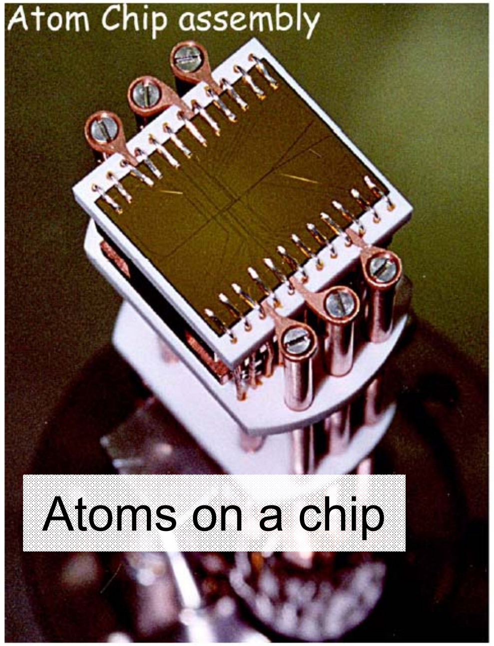
Quantum information processing

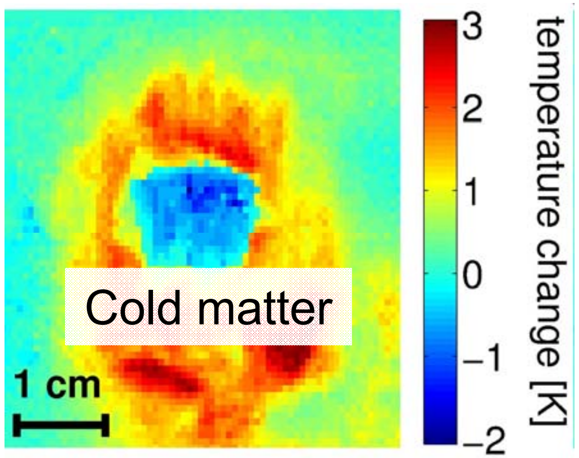
Quantum metrology

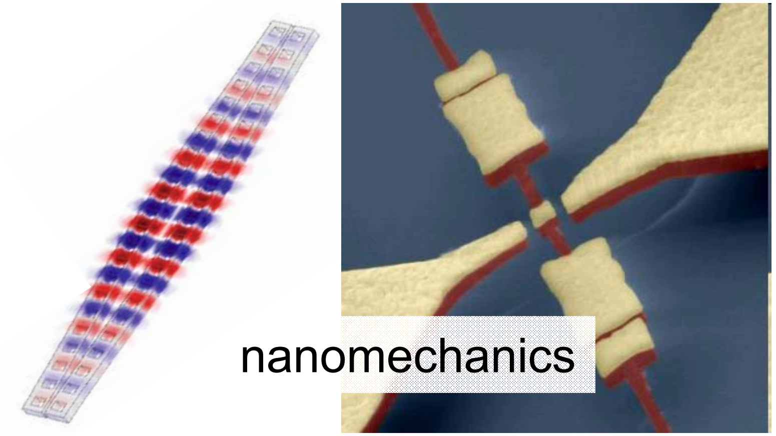
Quantum simulation

…









The zoology of quantum systems

- Photons
- Atoms/Ions
- neutrons, electrons
- Atomic gases, ultracold atoms
- Quantum dots
- Superconducting electronic circuits
- Spins in solid states
- Micro- and nanomechanical resonators
- …

Solid state!

Quantum entanglement: a key resource

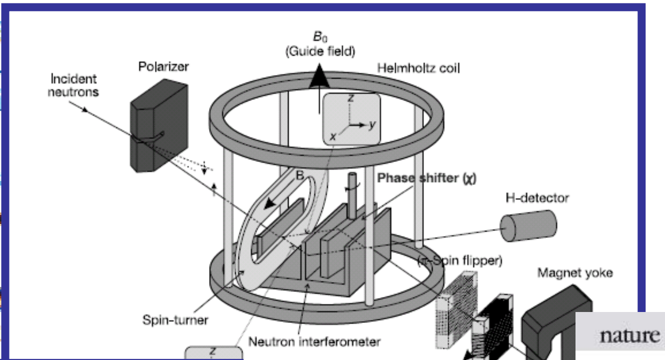
EPORTS

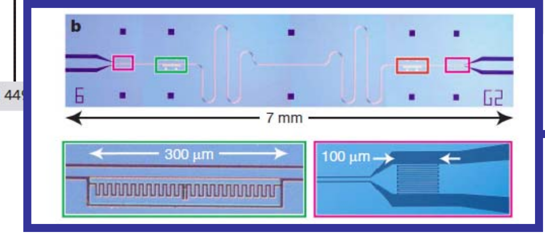
Violation of a Bell-like inequality in single-neutron interferometry

Yuji Hasegawa[1], **Rudolf Loidl**[1,2], **Gerald Badurek**[1], **Matthias Baron**[1,2] **& Helmut Rauch**[1]

[1] *Atominstitut der Österreichischen Universitäten, Stadionallee 2, A-1020 Wien, Austria*
[2] *Institute Laue Langevi*

Non-local correlati
been extensively
Podolsky and Ros
Many proposals an
theories and the
reported[3–7]; usually
recently an expe





LETTE

Coupling superconducting qubits via a cavity bus

J. Majer[1]*, J. M. Chow[1]*, J. M. Gambetta[1], Jens Koch[1], B. R. Johnson[1], J. A. Schreier[1], L. Frunzio[1], D. I. Schu
A. A. Houck[1], A. Wallraff[1]†, A. Blais[1]†, M. H. Devoret[1], S. M. Girvin[1] & R. J. Schoelkopf[1]

Superconducting circuits are promising candidates for constructing quantum bits (qubits) in a quantum computer; single-qubit operations are now routine[1,2], and several examples[3–9] of two-qubit interactions and gates have been demonstrated. These experi-

charge and phase qubits, and inductive coupling for flu
Therefore, these coupling mechanisms have been restricted
interactions and couple only nearest-neighbour qubits. In th
we present a coupling that is realized with a cavity that is a distributed

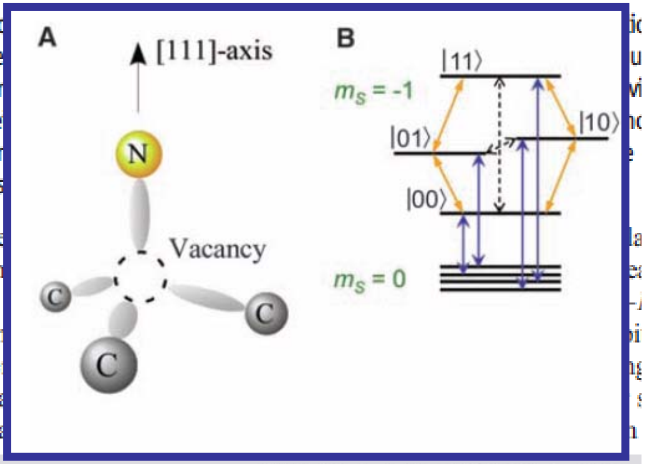
---

Multipartite Entanglement Among Single Spins in Diamond

P. Neumann,[1]* N. Mizuochi,[2]* F. Rempp,[1] P. Hemmer,[3] H. Watanabe,[4] S. Yamasak
V. Jacques,[1] T. Gaebel,[1] F. Jelezko,[1] J. Wrachtrup[1]†

Robust entanglement at roo
quantum technology. We de
in a small quantum register
spins are controlled via the
center. Quantum correlation
room temperature, which is

Schrödinger coined the
to mean a peculiar n
action in which the
more physical objects can
when separated. Since the
retrieval of entanglement a
have become of fundament



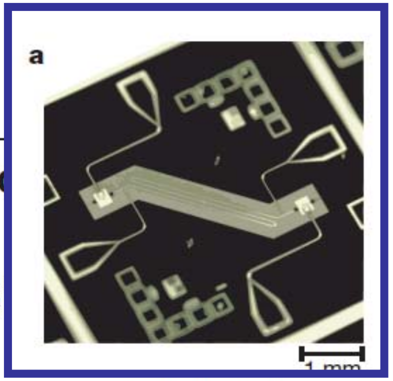
---

nature
Vol 461|24 September 2009|**doi:10.1038/nature08363**

LETTERS

Violation of Bell's inequality in Jo phase qubits

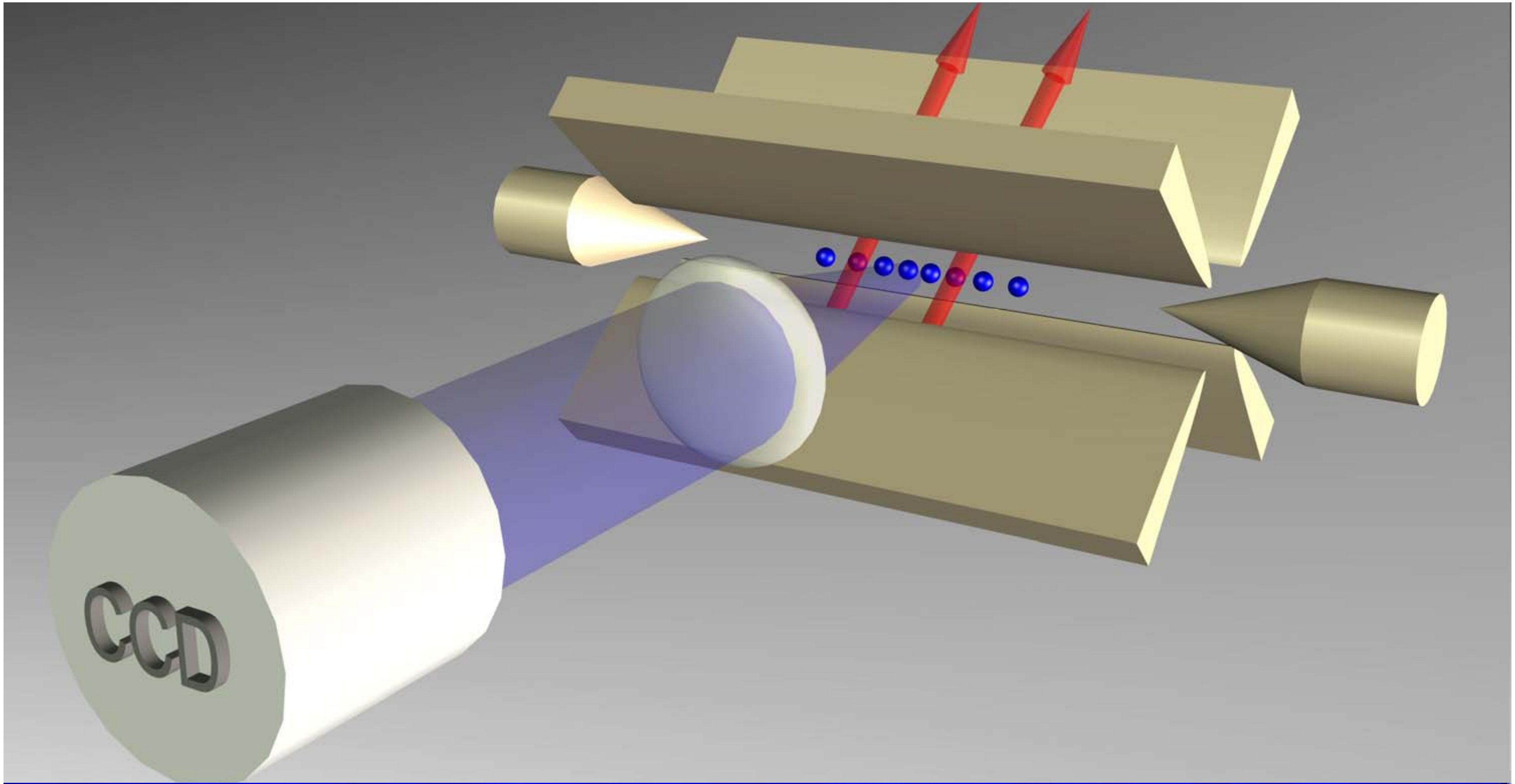
Markus Ansmann[1], H. Wang[1], Radoslaw C. Bialczak[1], Max Hofheinz[1],
D. Sank[1], M. Weides[1], J. Wenner[1], A. N. Cleland[1] & John M. Martinis[1]

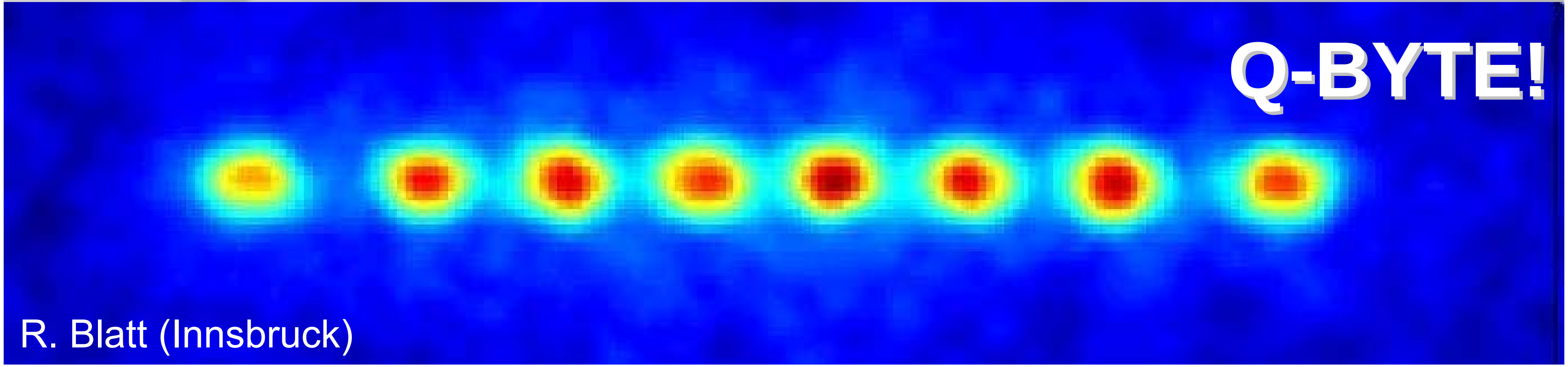


The measurement process plays an awkward role in quantum mechanics, because measurement forces a system to 'choose' between possible outcomes in a fundamentally unpredictable manner. Therefore, hidden classical processes have been considered as possibly predetermining measurement outcomes while preserving their statistical distributions[1]. However, a quantitative

$$S = E(a, b) + E(a', b) - E(a, b') + E(a', b') \qquad (2)$$

Classical (predetermined) outcomes result in a Bell signal $|S| \le 2$, whereas quantum mechanics permits a larger signal $|S| \le 2\sqrt{2} = 2.828$, for the appropriate measurement axes. Completely random outcomes result in $S = 0$. An experiment returns a Bell violation if $|S| > 2$, and





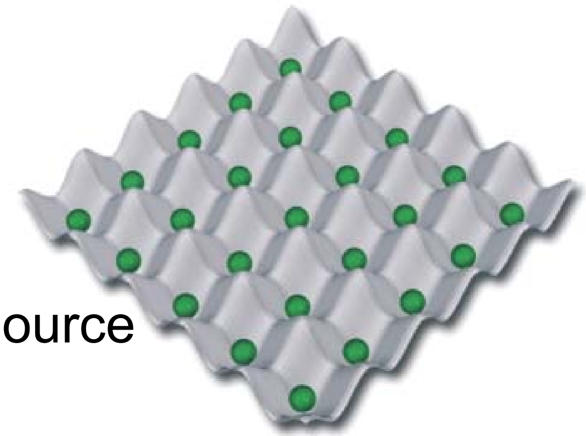
Q-BYTE!

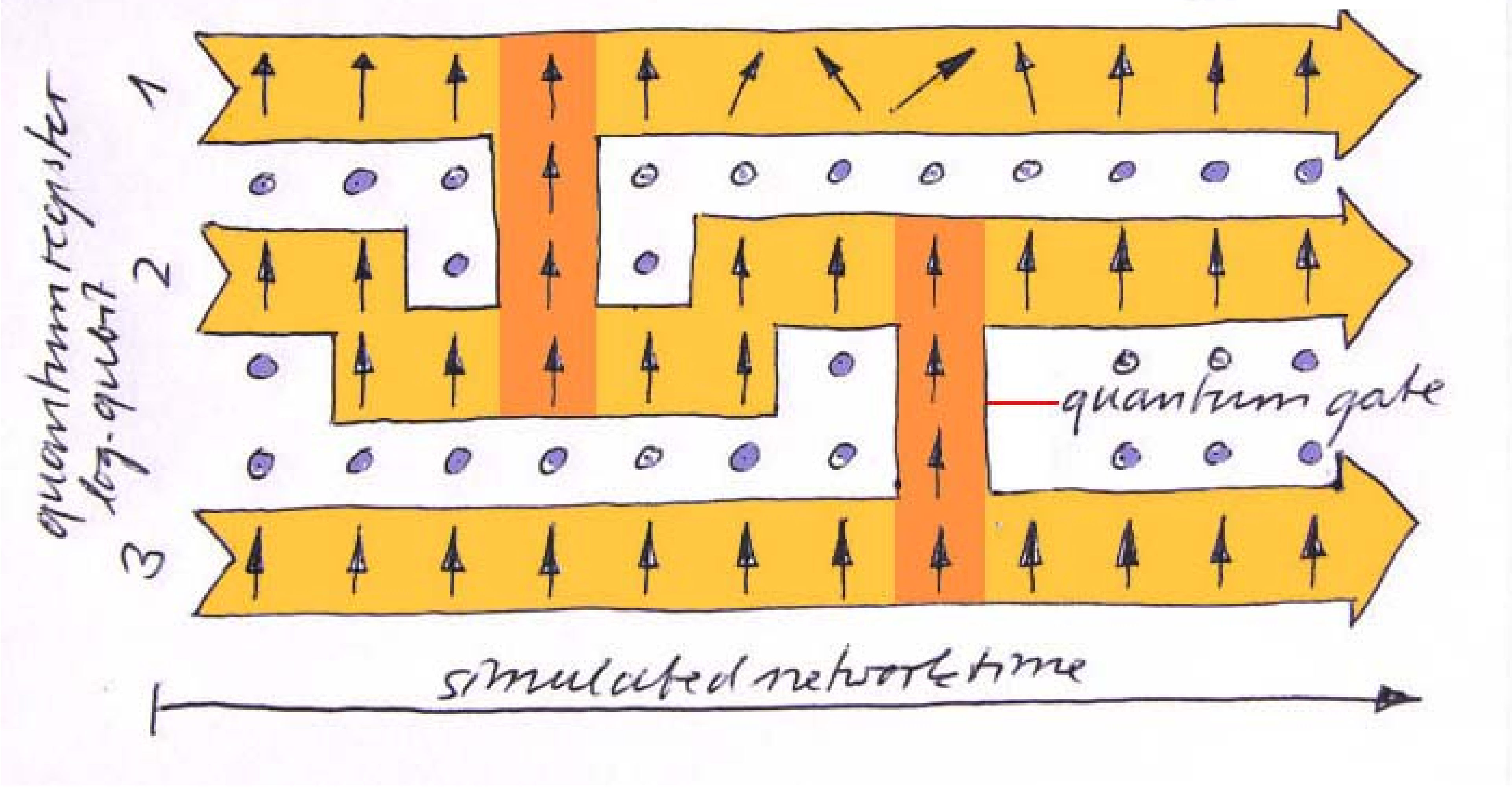
R. Blatt (Innsbruck)

„One-Way" Quantum Computer

(Raussendorff & Briegel 1998;
exp: Walther, Zeilinger 2005)

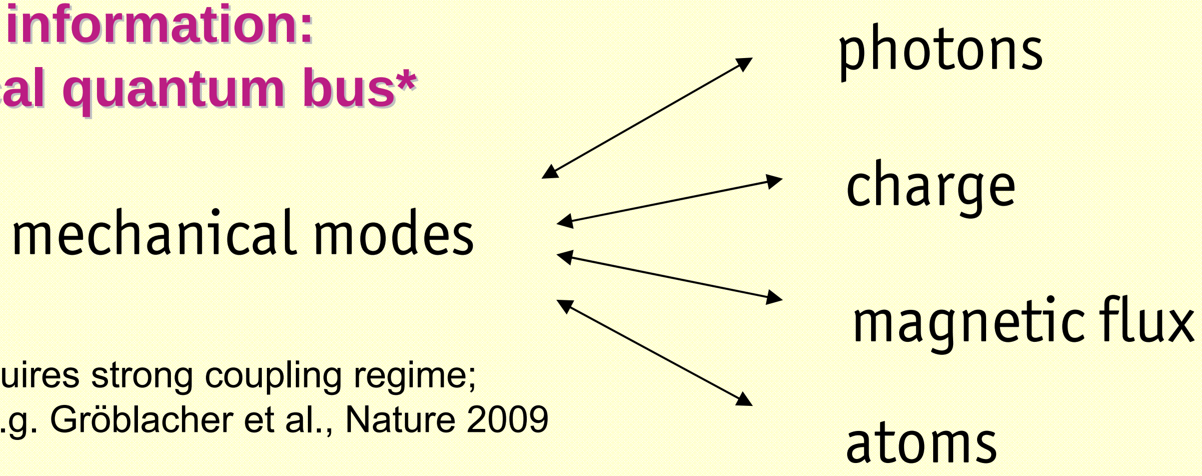
Multi-particle Entanglement as a universal resource





Mechanical Quantum Hybrids for QIPC

Quantum information:
mechanical quantum bus*



mechanical modes

photons

charge

magnetic flux

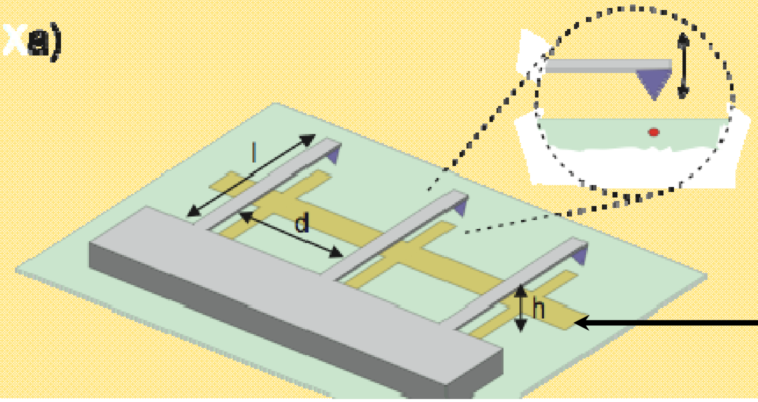
atoms

* Requires strong coupling regime;
see e.g. Gröblacher et al., Nature 2009

Long-range spin-spin interactions mediated by electrically coupled nano-resonator arrays

quant-ph 0908.0316 (2009)

Peter Rabl[1], Frank Koppens[2], Jack G. E. Harris[3], Peter Zoller[4], and Mikhail D. Lukin[1,2]

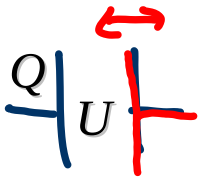


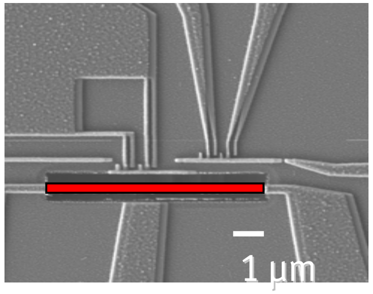
- cantilever with magnetic tip
- NV centers as qubits (+ microwave)

- capacitive coupling of cantilevers:
  phonon bus

Mechanics coupled to quantum systems

charge





force

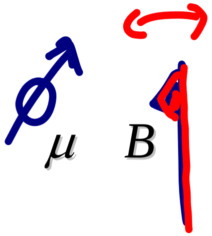
$$F = \frac{Q \cdot U}{d}$$

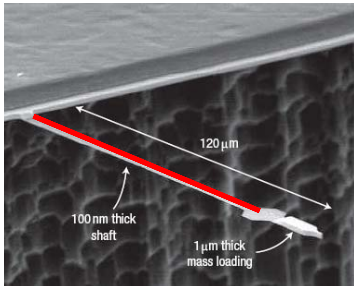
examples

single electron (SSET)

single electron (Cooper-Pair Box) < 50 aN

spin



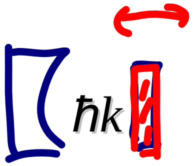


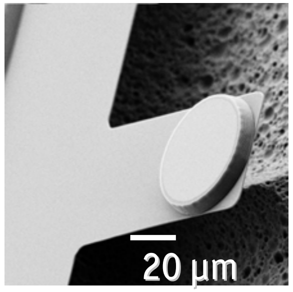
$$F = \mu \cdot \underline{\nabla} \, \underline{B}$$

single atom / electron spin $< 10^2$ aN

single nuclear spin < 0.05 aN

photon momentum

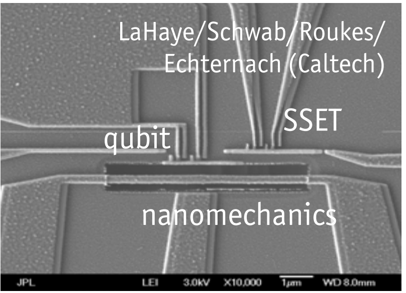




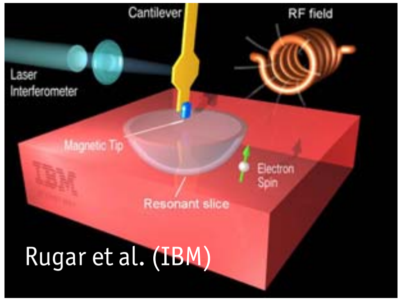
$$F = \frac{2\hbar k}{t_{cav}}$$

single photon (optical cavity) $\sim 10^3$ aN

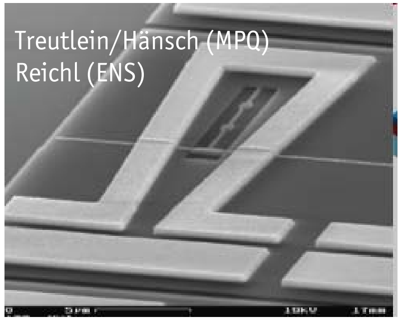
single photon (MW cavity) $\sim 10^{-3}$ aN



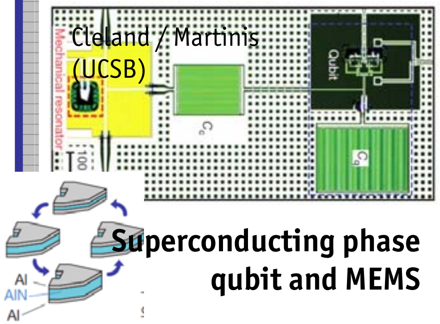
qubit coupled to NEMS



single electron spin - MOMS

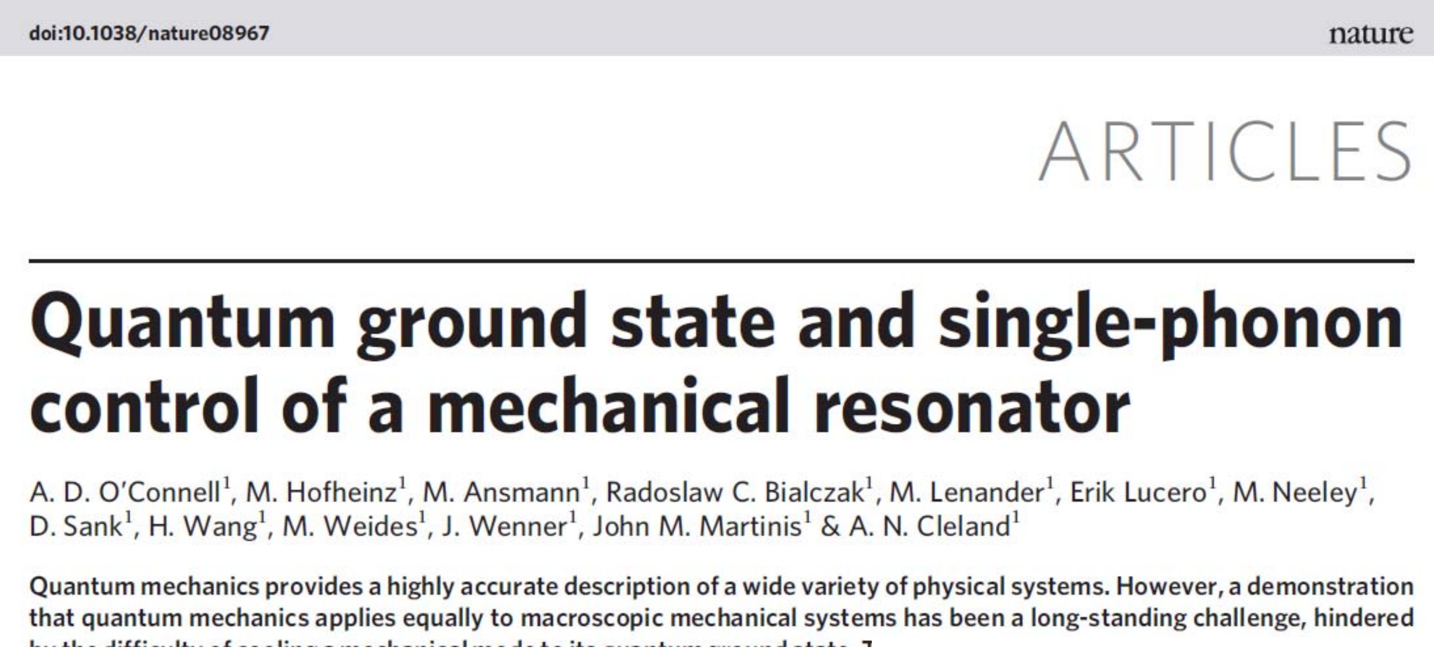


BEC coupled to MEMS



Superconducting phase qubit and MEMS

Mechanical Systems IN the quantum regime



doi:10.1038/nature08967 nature

ARTICLES

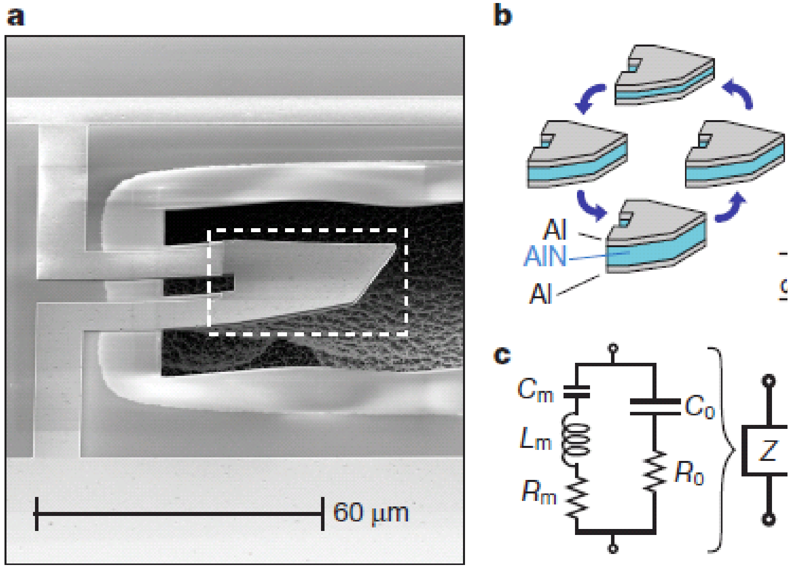
Quantum ground state and single-phonon control of a mechanical resonator

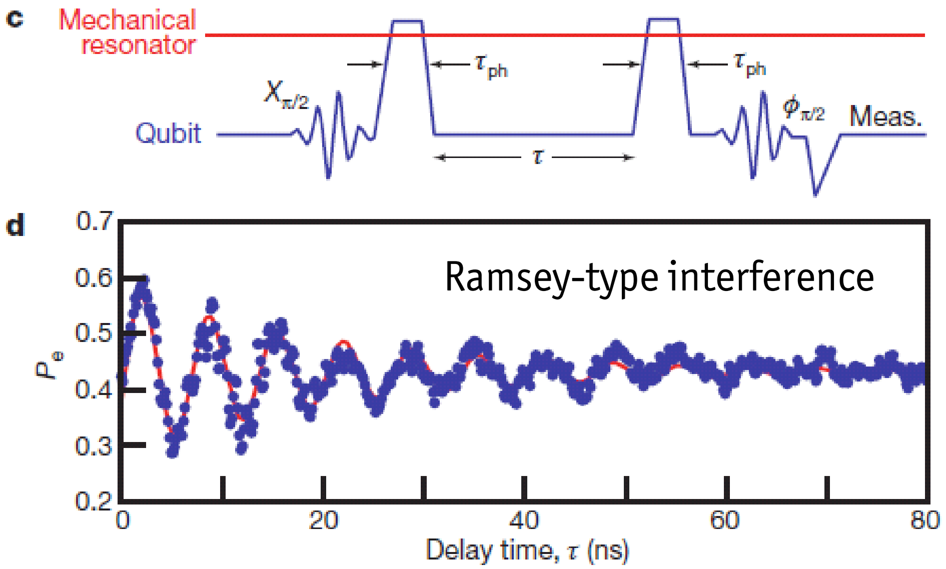
A. D. O'Connell[1], M. Hofheinz[1], M. Ansmann[1], Radoslaw C. Bialczak[1], M. Lenander[1], Erik Lucero[1], M. Neeley[1], D. Sank[1], H. Wang[1], M. Weides[1], J. Wenner[1], John M. Martinis[1] & A. N. Cleland[1]

Quantum mechanics provides a highly accurate description of a wide variety of physical systems. However, a demonstration that quantum mechanics applies equally to macroscopic mechanical systems has been a long-standing challenge, hindered

6 GHz piezo vibration
→ n ~ 0.07 @ 20 mK

Cleland/Martinis groups (UCSB); April 2010





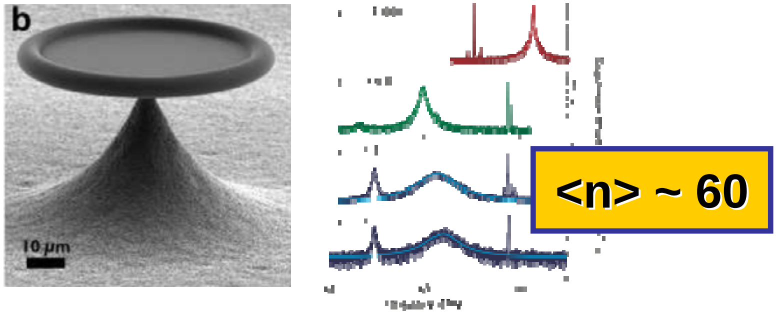
Ramsey-type interference

Mechanical systems CLOSE TO the quantum regime

Micromechanics close to the quantum ground state

→ Laser cooling by optical photons

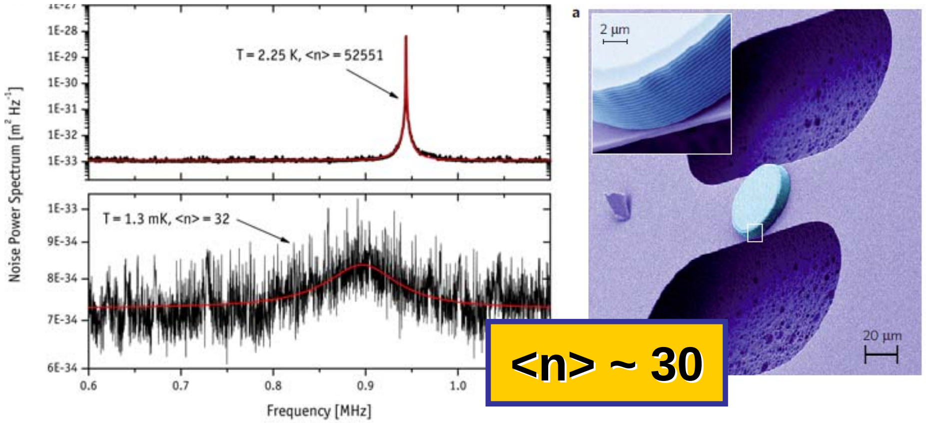
Schliesser et al., ***Nature Physics*** **5**, 509 (2009)



<n> ~ 60

Munich (Kippenberg group):
- Microtoroidal mechanics
- Sensing close to the uncertainty limit

Gröblacher et al., ***Nature Physics*** **5**, 485 (2009)



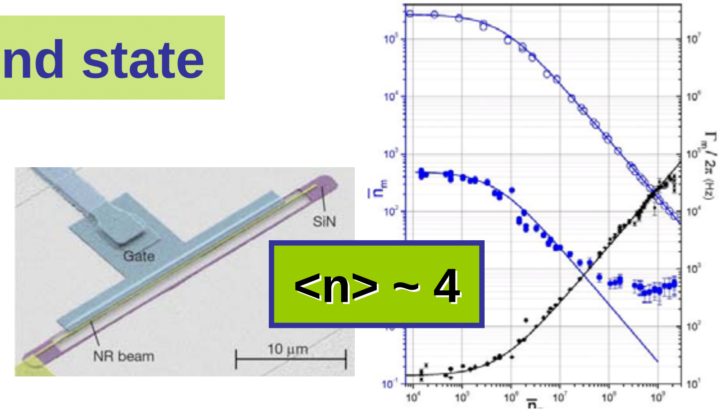
<n> ~ 30

Vienna (Aspelmeyer group):
- Ultracold micromechanics with Bragg mirror pads
- Laser cooling in a cryogenic cavity

Nanomechanics close to the quantum ground state

→ Laser cooling by microwave photons

Caltech (Schwab group):
- Nanomechanical resonator inside a superconducting microwave cavity
- precooling in dilution cryostat



<n> ~ 4

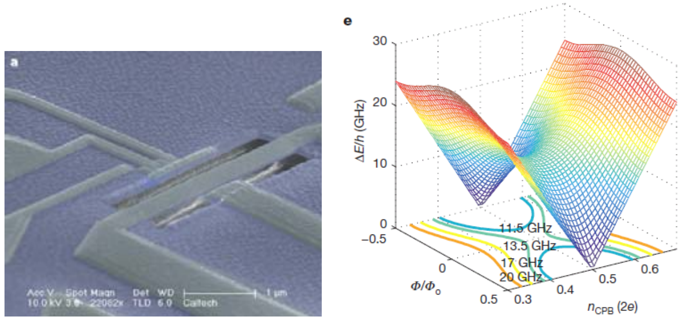
Rocheleau et al., ***Nature*** **463**, 72 (2010)

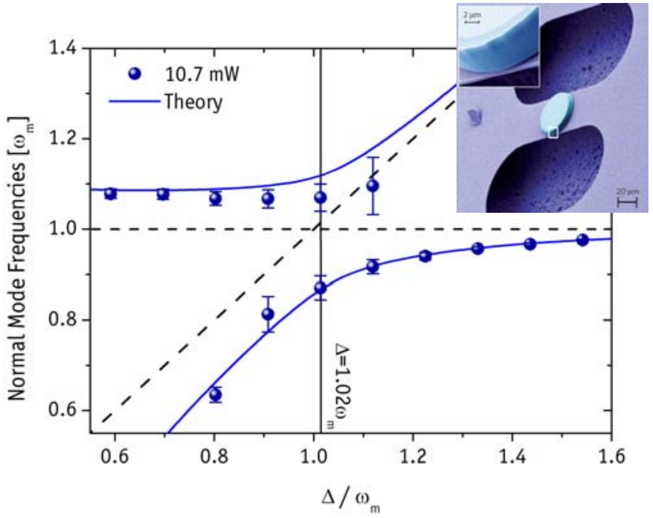
Mechanical coupling to quantum systems

LaHaye et al., ***Nature* 459**, 960 (2009)

Nanomechanical measurements of a superconducting qubit

M. D. LaHaye[1], J. Suh[1], P. M. Echternach[3], K. C. Schwab[2] & M. L. Roukes[1]





Strong mechanical coupling

Gröblacher et al., ***Nature* 460**, 724 (2009)

Observation of strong coupling between a micromechanical resonator and an optical cavity field

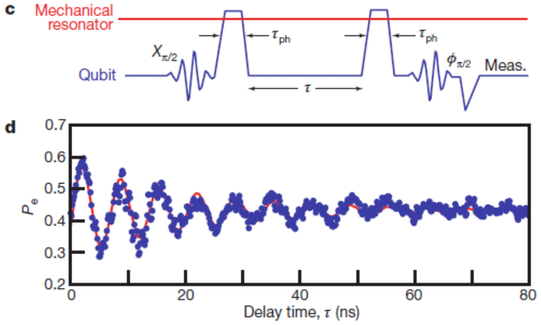
Simon Gröblacher[1,2], Klemens Hammerer[3,4], Michael R. Vanner[1,2] & Markus Aspelmeyer[1]

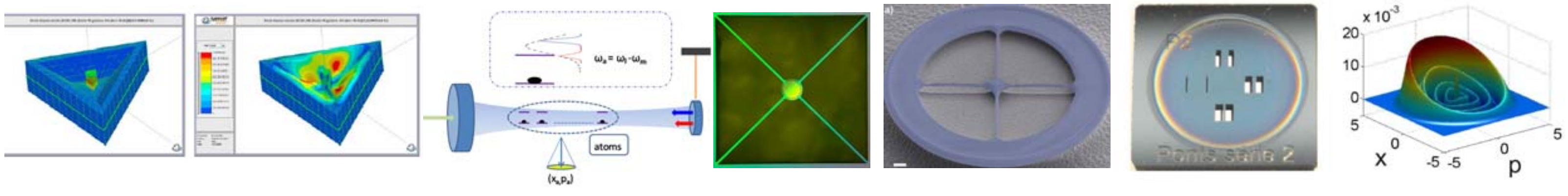
Strong mechanical coupling to quantum systems

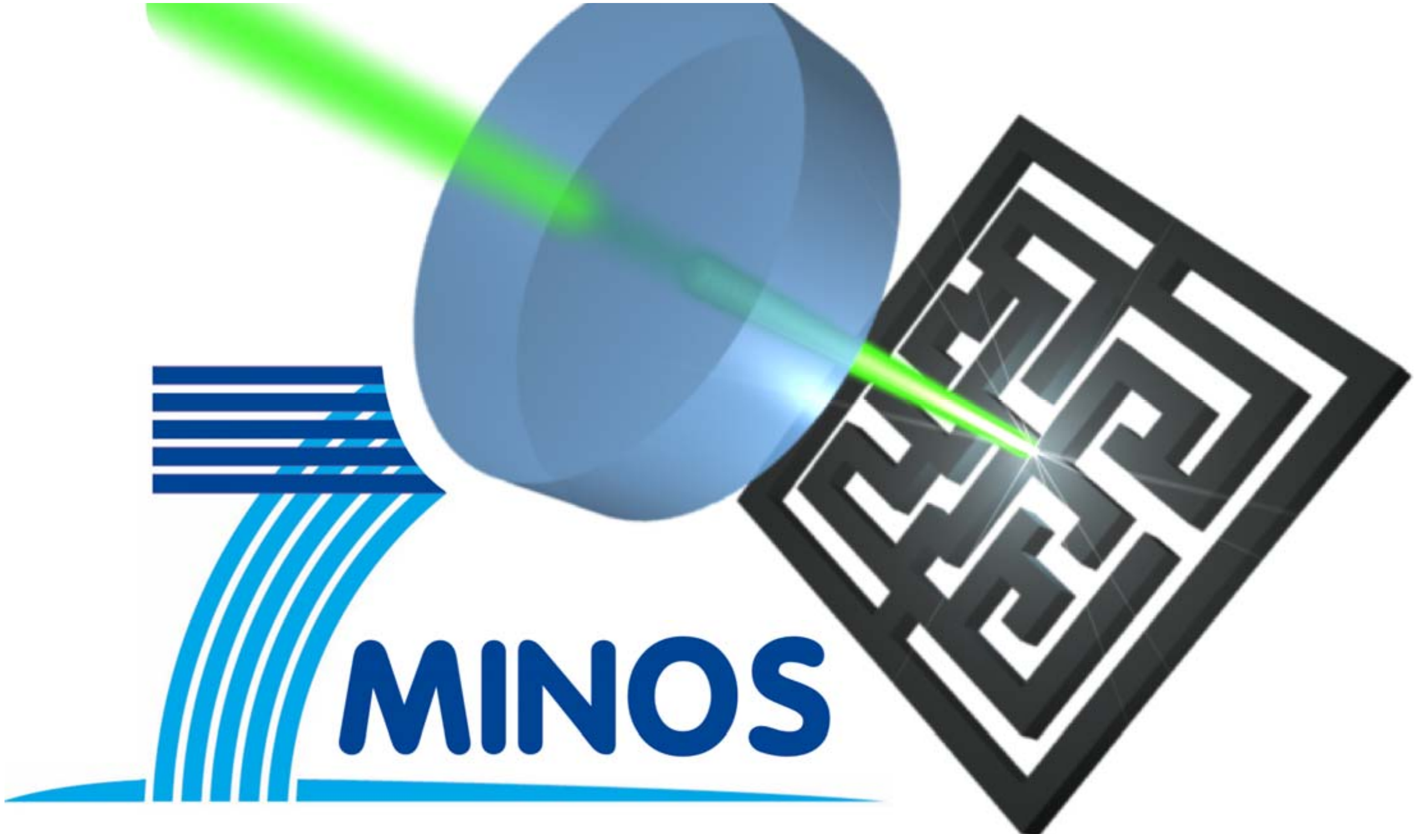
O'Connell et al., ***Nature***, advance online publication

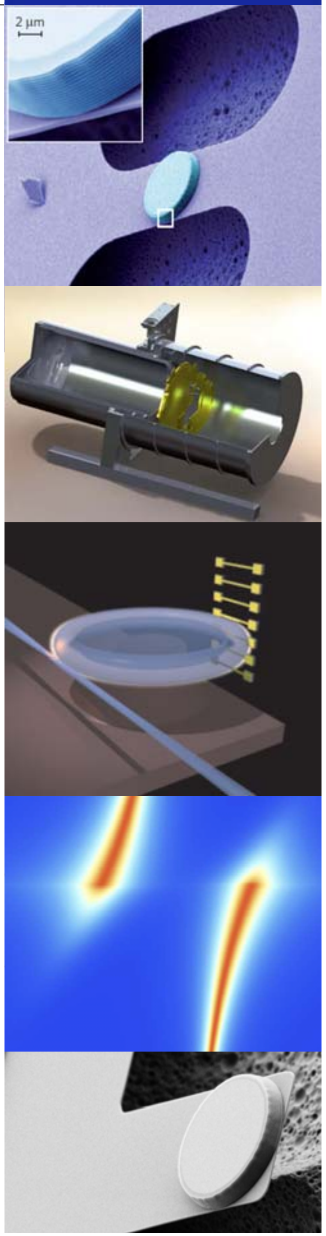
Quantum ground state and single-phonon control of a mechanical resonator

A. D. O'Connell[1], M. Hofheinz[1], M. Ansmann[1], Radoslaw C. Bialczak[1], M. Lenander[1], Erik Lucero[1], M. Neeley[1], D. Sank[1], H. Wang[1], M. Weides[1], J. Wenner[1], John M. Martinis[1] & A. N. Cleland[1]









Micro- and Nano-Optomechanical Systems for ICT and QIPC (MINOS)

an FP7 STREP Project of the FET-Open Initiative

10/2008 – 10/2011, 6 EU partners, 2.3M€
Worldwide first concerted effort, USA & Australia ramping up now

From quantum technology to quantum foundations

articles

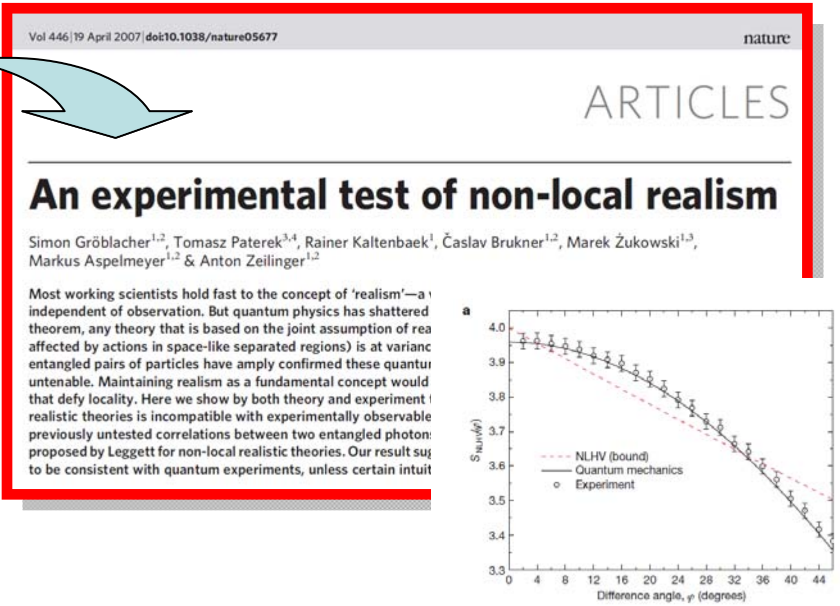
Experimental one-way quantum computing

P. Walther[1], K. J. Resch[1], T. Rudolph[2], E. Schenck[1*], H. Weinfurter[3,4], V. Vedral[1,5,6], M. Aspelmeyer[1] & A. Zeilinger[1,7]

[1] *Institute of Experimental Physics, University of Vienna, Boltzmanngasse 5, 1090 Vienna, Austria*
[2] *QOLS, Blackett Laboratory, Imperial College London, London SW7 2BW, UK*
[3] *Department of Physics, Ludwig Maximilians University, D-80799 Munich, Germany*
[4] *Max Planck Institute for Quantum Optics, D-85741 Garching, Germany*
[5] *The Erwin Schrödinger Institute for Mathematical Physics, Boltzmanngasse 9, 1090 Vienna, Austria*
[6] *The School of Physics and Astronomy, University of Leeds, Leeds LS2 9JT, UK*
[7] *IQOQI, Institute for Quantum Optics and Quantum Information, Austrian Academy of Sciences, Boltzmanngasse 3, 1090 Vienna, Austria*

* Permanent address: Ecole normale supérieure, 45, rue d'Ulm, 75005 Paris, France

Standard quantum computation is based on sequences of unitary quantum logic gates that process qubits. The one-way quantum computer proposed by Raussendorf and Briegel is entirely different. It has changed our understanding of the requirements for quantum computation and more generally how we think about quantum physics. This new model requires qubits to be initialized in a highly entangled cluster state. From this point, the quantum computation proceeds by a sequence of single-qubit measurements



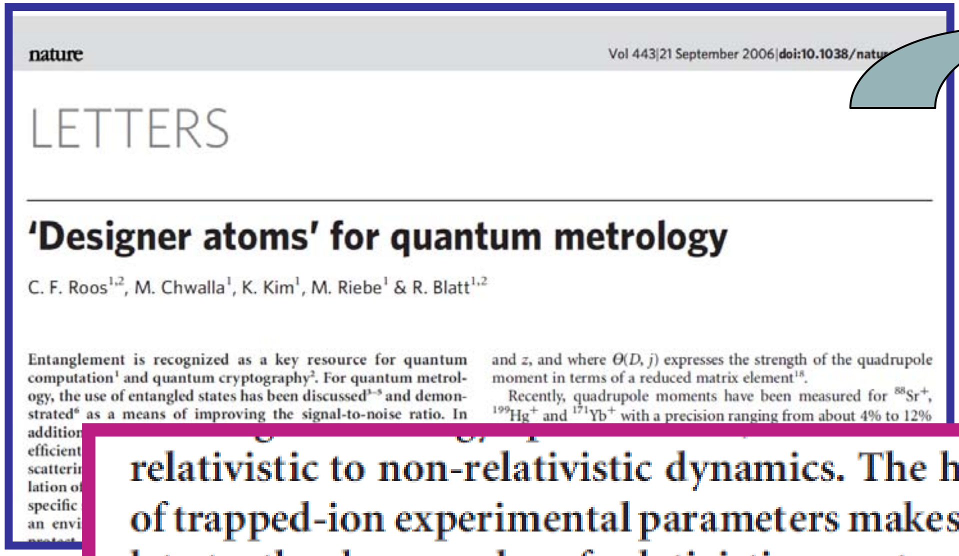
Vol 446 | 19 April 2007 | **doi:10.1038/nature05677** nature

ARTICLES

An experimental test of non-local realism

Simon Gröblacher[1,2], Tomasz Paterek[3,4], Rainer Kaltenbaek[1], Časlav Brukner[1,2], Marek Żukowski[1,3], Markus Aspelmeyer[1,2] & Anton Zeilinger[1,2]

**Most working scientists hold fast to the concept of 'realism'—a
independent of observation. But quantum physics has shattered
theorem, any theory that is based on the joint assumption of rea
affected by actions in space-like separated regions) is at varianc
entangled pairs of particles have amply confirmed these quantu
untenable. Maintaining realism as a fundamental concept would
that defy locality. Here we show by both theory and experiment
realistic theories is incompatible with experimentally observable
previously untested correlations between two entangled photon
proposed by Leggett for non-local realistic theories. Our result su
to be consistent with quantum experiments, unless certain intuit**



nature Vol 443 | 21 September 2006 | **doi:10.1038/natu**

LETTERS

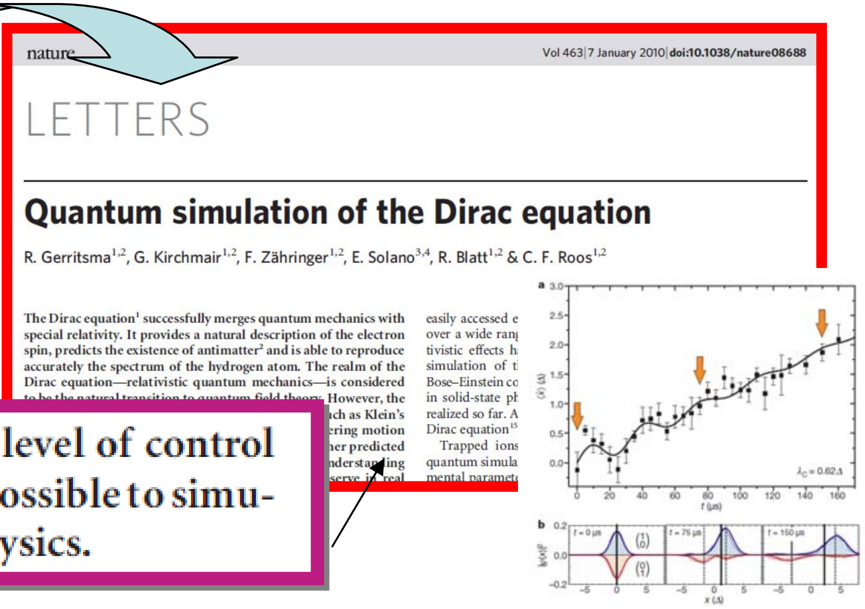
'Designer atoms' for quantum metrology

C. F. Roos[1,2], M. Chwalla[1], K. Kim[1], M. Riebe[1] & R. Blatt[1,2]

Entanglement is recognized as a key resource for quantum computation[1] and quantum cryptography[2]. For quantum metrology, the use of entangled states has been discussed[3–5] and demonstrated[6] as a means of improving the signal-to-noise ratio. In
addition
efficient
scatterin
lation of
specific
an envi

and z, and where $\Theta(D, j)$ expresses the strength of the quadrupole moment in terms of a reduced matrix element[18].

Recently, quadrupole moments have been measured for $^{88}\mathrm{Sr}^+$, $^{199}\mathrm{Hg}^+$ and $^{171}\mathrm{Yb}^+$ with a precision ranging from about 4% to 12%



nature Vol 463 | 7 January 2010 | **doi:10.1038/nature08688**

LETTERS

Quantum simulation of the Dirac equation

R. Gerritsma[1,2], G. Kirchmair[1,2], F. Zähringer[1,2], E. Solano[3,4], R. Blatt[1,2] & C. F. Roos[1,2]

The Dirac equation[1] successfully merges quantum mechanics with special relativity. It provides a natural description of the electron spin, predicts the existence of antimatter[2] and is able to reproduce accurately the spectrum of the hydrogen atom. The realm of the Dirac equation—relativistic quantum mechanics—is considered to be the natural transition to quantum field theory. However, the
ch as Klein's
ering motion
her predicted
nderstanding
serve in real

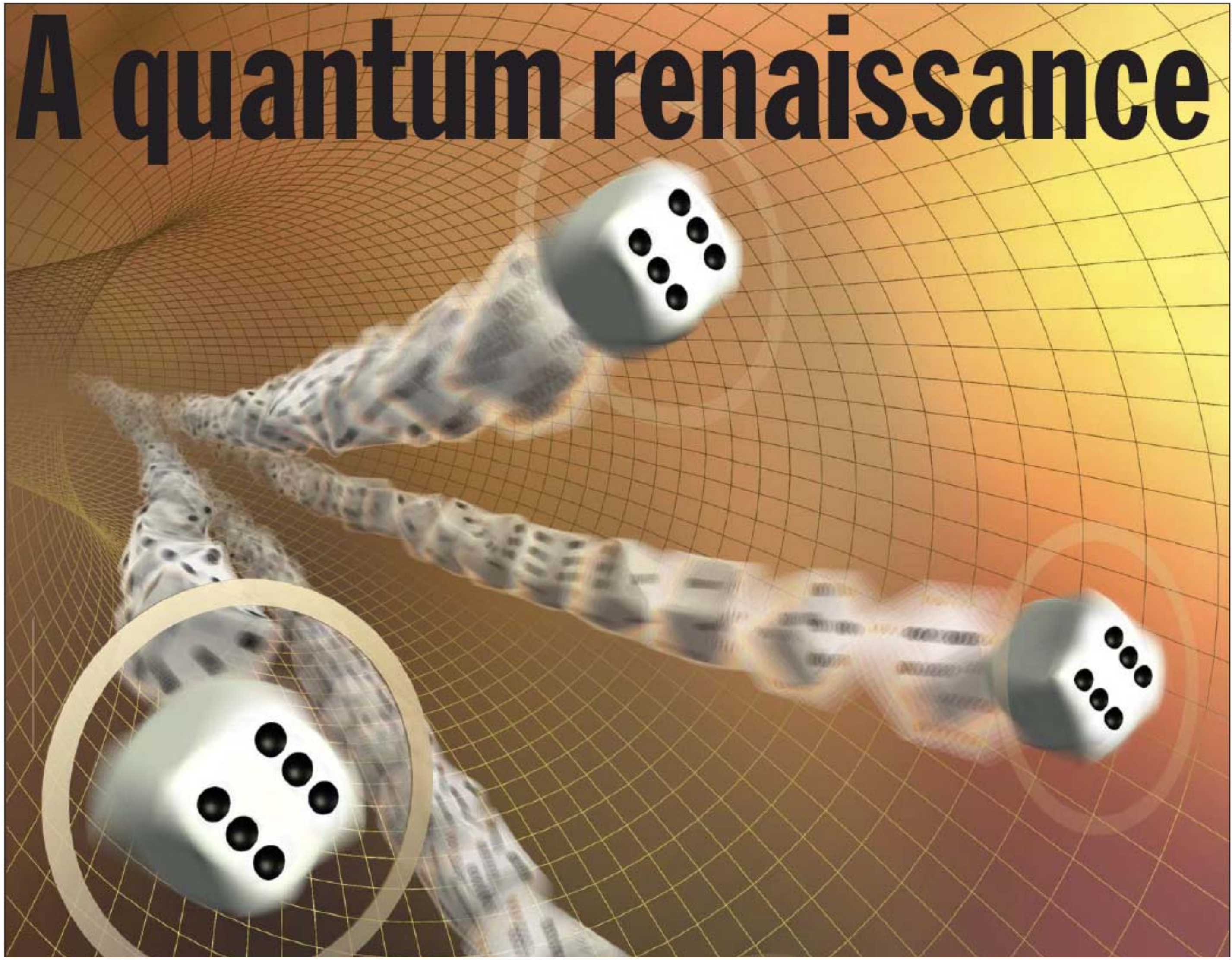
easily accessed e
over a wide rang
tivistic effects h
simulation of t
Bose–Einstein co
in solid-state ph
realized so far. A
Dirac equation[15]
Trapped ions
quantum simula
mental paramete

relativistic to non-relativistic dynamics. The high level of control of trapped-ion experimental parameters makes it possible to simulate textbook examples of relativistic quantum physics.

Aspelmeyer & Zeilinger

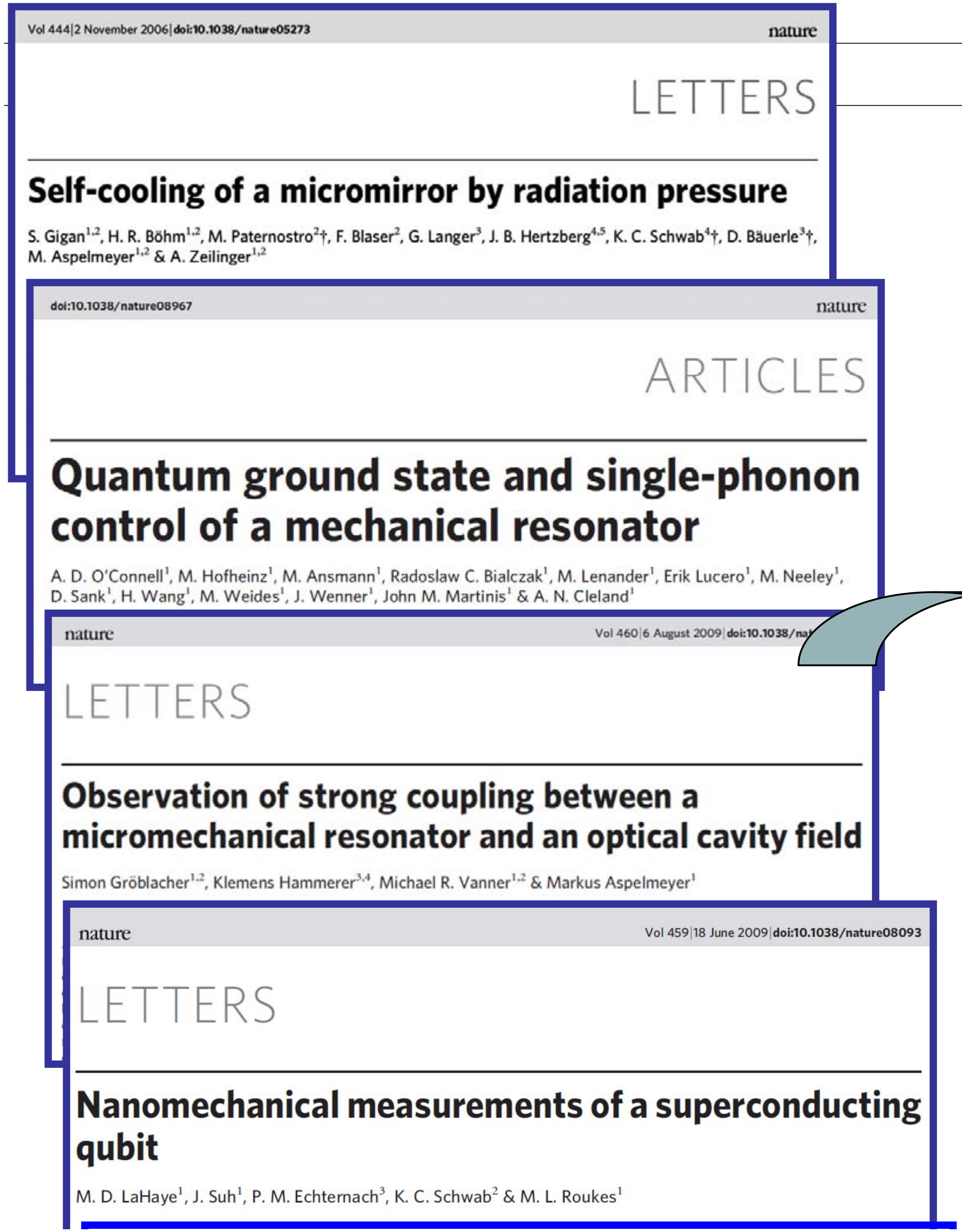
Physics World, July 2008

A quantum renaissance


ARKITEK

Physicists can now routinely exploit the counterintuitive properties of quantum mechanics to transmit, encrypt and even process information. But as **Markus Aspelmeyer** and **Anton Zeilinger** describe, the technological advances of quantum information science are now enabling researchers to readdress fundamental puzzles raised by quantum theory

From quantum technology to quantum foundations



Vol 444|2 November 2006|doi:10.1038/nature05273 nature

LETTERS

Self-cooling of a micromirror by radiation pressure

S. Gigan[1,2], H. R. Böhm[1,2], M. Paternostro[2]†, F. Blaser[2], G. Langer[3], J. B. Hertzberg[4,5], K. C. Schwab[4]†, D. Bäuerle[3]†, M. Aspelmeyer[1,2] & A. Zeilinger[1,2]

---

doi:10.1038/nature08967 nature

ARTICLES

Quantum ground state and single-phonon control of a mechanical resonator

A. D. O'Connell[1], M. Hofheinz[1], M. Ansmann[1], Radoslaw C. Bialczak[1], M. Lenander[1], Erik Lucero[1], M. Neeley[1], D. Sank[1], H. Wang[1], M. Weides[1], J. Wenner[1], John M. Martinis[1] & A. N. Cleland[1]

---

nature Vol 460|6 August 2009|doi:10.1038/na

LETTERS

Observation of strong coupling between a micromechanical resonator and an optical cavity field

Simon Gröblacher[1,2], Klemens Hammerer[3,4], Michael R. Vanner[1,2] & Markus Aspelmeyer[1]

---

nature Vol 459|18 June 2009|doi:10.1038/nature08093

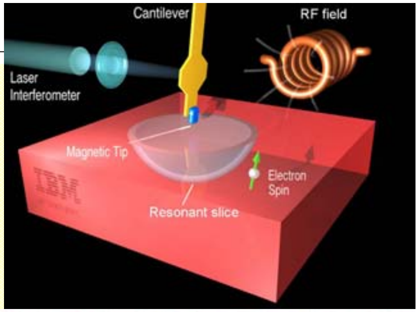
LETTERS

Nanomechanical measurements of a superconducting qubit

M. D. LaHaye[1], J. Suh[1], P. M. Echternach[3], K. C. Schwab[2] & M. L. Roukes[1]

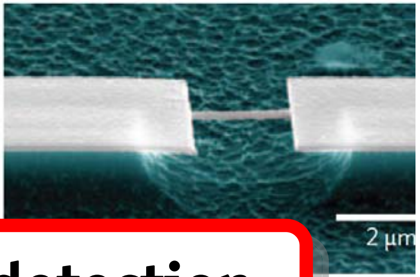
Mechanical quantum systems provide access to a **complete new parameter regime for experimental physics** (size, mass, sensitivity)

Mechanical (Quantum) Hybrids – for sensing

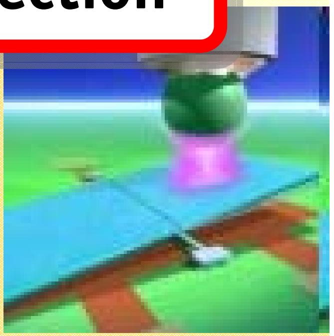


Today (existing technology)**:**

- **single electron-spin** detection via magnetic resonance
- **attometer-scale** displacement sensing (10^{-18} m)
- **zeptonewton-scale** force sensing (10^{-21} N)
- **yoctogram-scale** mass sensitivity (10^{-24} g)



Towards quantum limits of force- and displacement detection



Exploiting a new regime of (mechanical) sensing

→ **3D imaging of individual macromolecules** (Rugar, IBM)

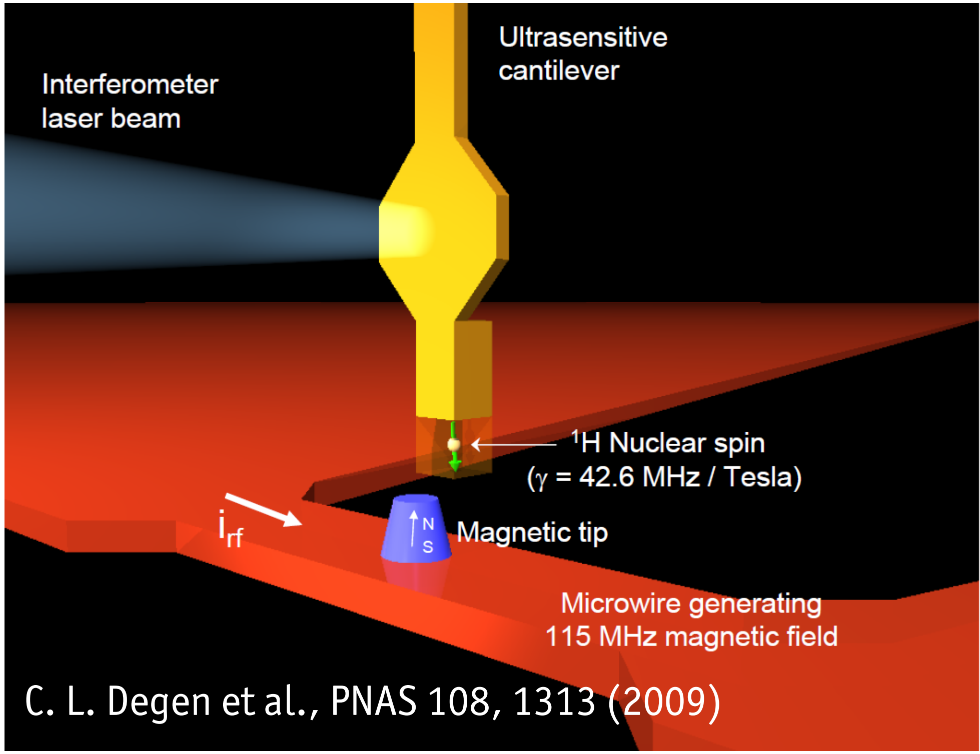
→ **Novel magnetometers based on spins in diamond** (Lukin, Harvard)

→ **Mechanical detection of Casimir forces** (Capasso, Harvard)

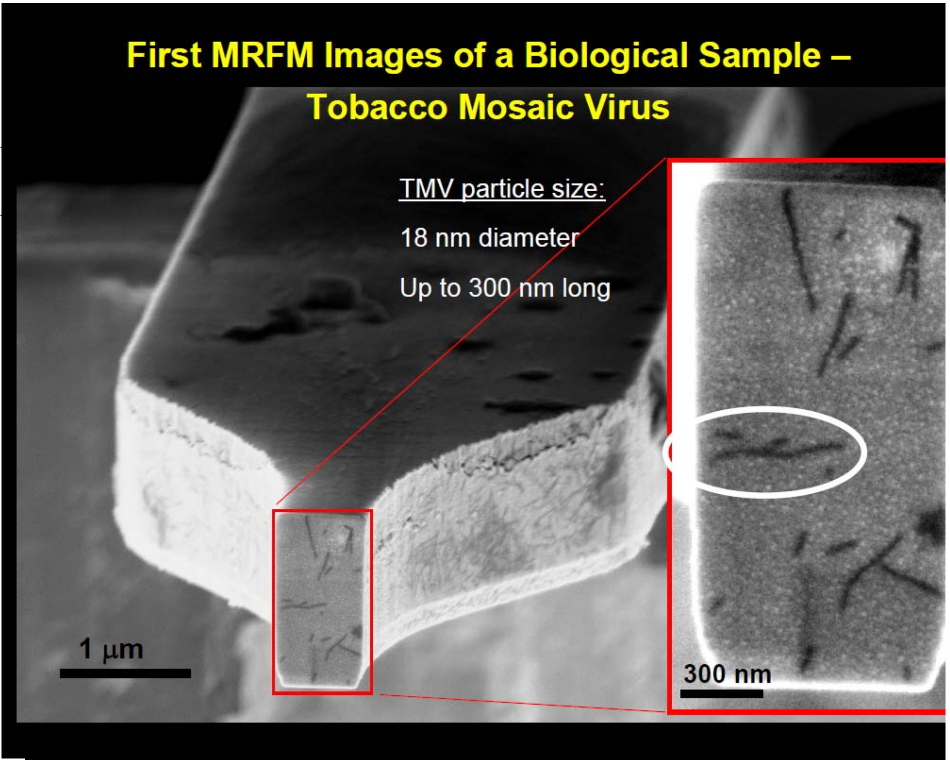
→ **Measuring Gravitation at small length scales** (Kapitulnik, Stanford)

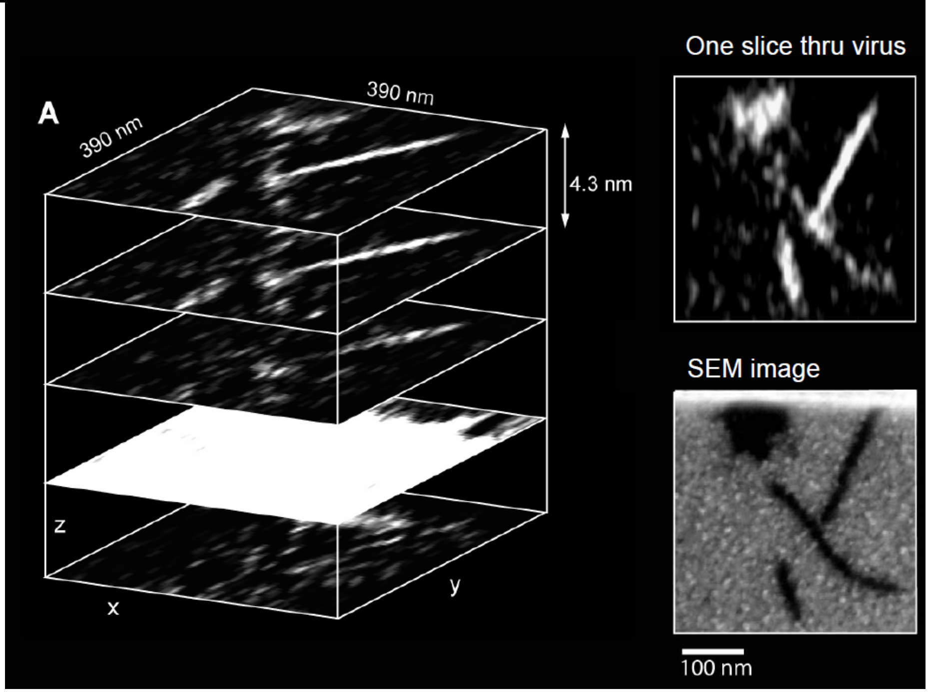
→**Improving the sensitivity of gravitational wave detectors** (LIGO, GEO)

…



C. L. Degen et al., PNAS 108, 1313 (2009)



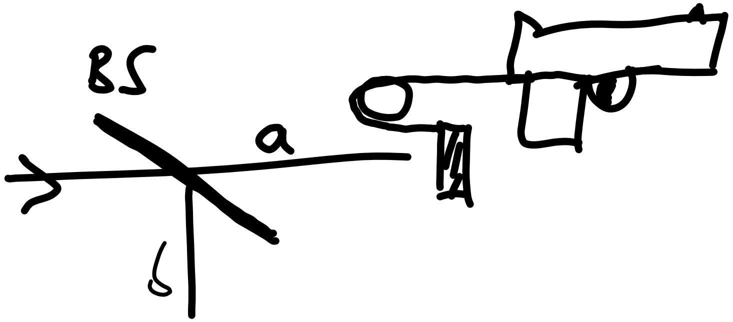


Example: 3D reconstruction of a Tobacco Mosaic Virus by magnetic resonance force microscopy (Rugar group, IBM)

→ **100 million times improvement in volume sensitivity** compared to best conventional MRI

Schrödinger's Cat: The Measurement Problem

E. Schrödinger, Naturwissenschaften 23, 52 ff. (1935)

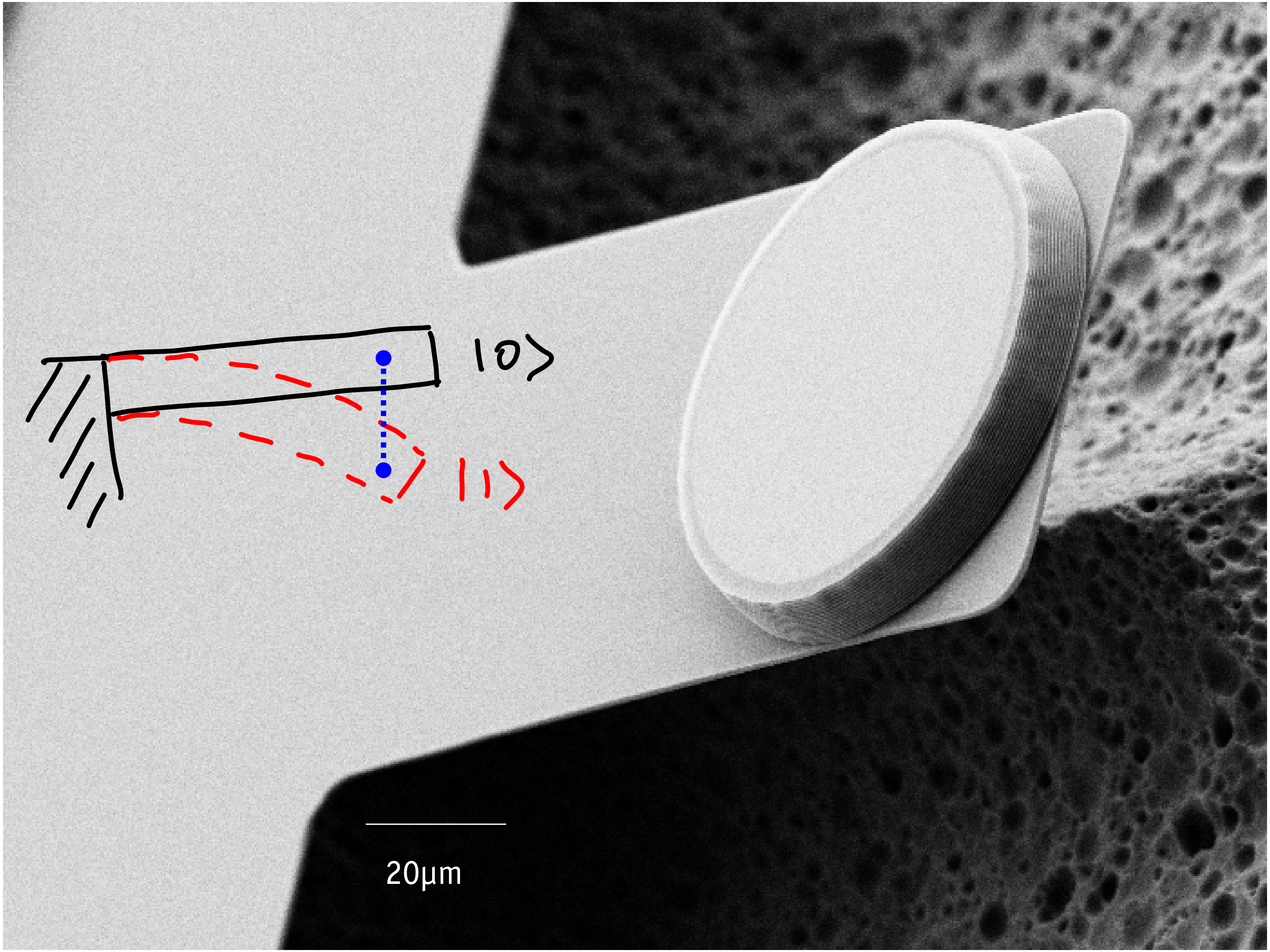


single-photon source

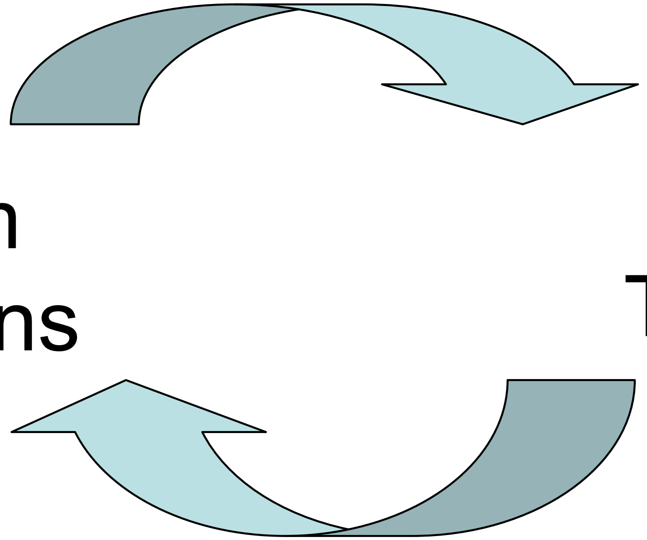
$|0\rangle_a + |1\rangle_a \rightarrow |0\rangle_a |$  $\rangle_{cat} + |1\rangle_a |$  $\rangle_{cat}$

Schrödinger's Cat = Entanglement involving **macroscopically distinct states**

⟶ should be possible for **arbitrarily large systems**


|0⟩
|1⟩
20µm

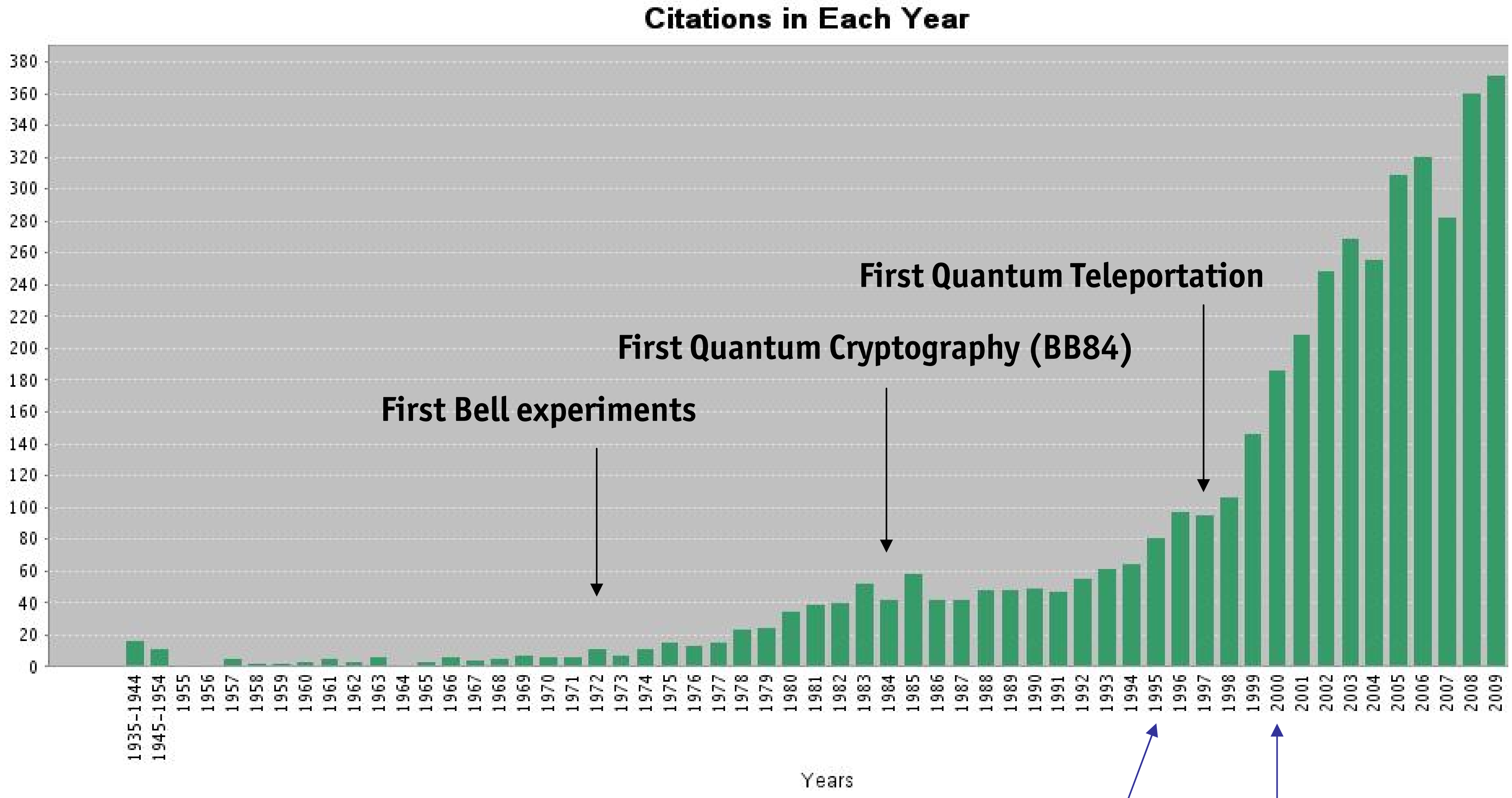
Fundamental vs Applied Research: Give and Take...



Quantum Foundations

Quantum Technology

Fundamental vs Applied Research: Give and Take...



First Quantum Teleportation

First Quantum Cryptography (BB84)

First Bell experiments

Pathfinder project for quantum information science (FP4)

IST QuComm
1st FET PI on Quantum Information (FP5)

Take-Home Message

- **Quantum Foundations** has radically changed our view of information processing → QIPC

- **Quantum Information Technologies** have opened up a new frontier for fundamental research (also: QIT for solid state, field theory, etc.)

- New experiments on the foundations of quantum physics will eventually lead to new (quantum) technologies