The Second Quantum Revolution

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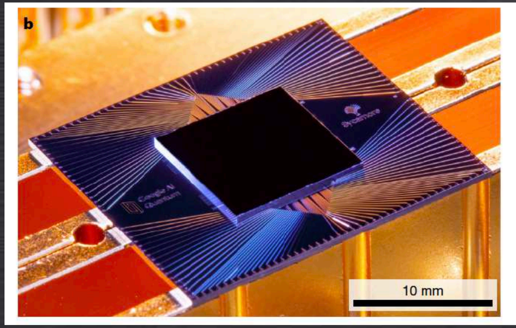
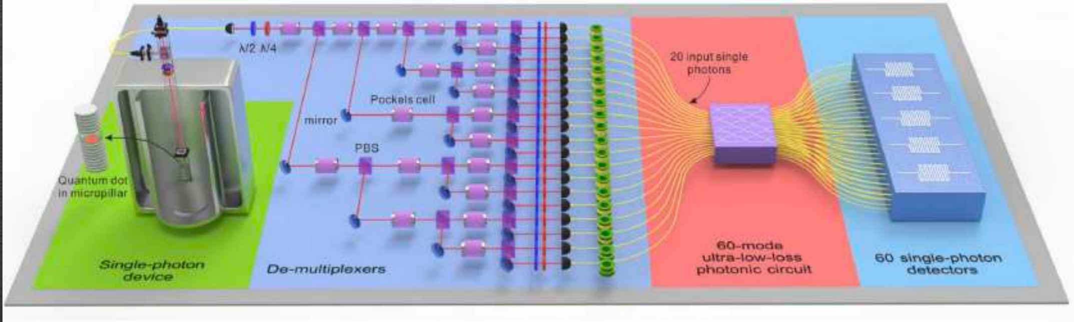
Sapienza Università di Roma





www.quantumlab.it

Quantum computer: Microsoft approach

Google claims 'quantum supremacy'; others say hold on a qubit

Published On: October 23, 2019 08:15 PM NPT By: Reuters

IBM

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Quantum Computing

On “Quantum Supremacy”

The New York Times

Opinion

Why Google's Quantum Supremacy Milestone Matters

The company says its quantum computer can complete a calculation much faster than a supercomputer. What does that mean?

By Scott Aaronson

Dr. Aaronson is the founding director of the Quantum Information Center at the University of Texas at Austin.

Oct. 30, 2019

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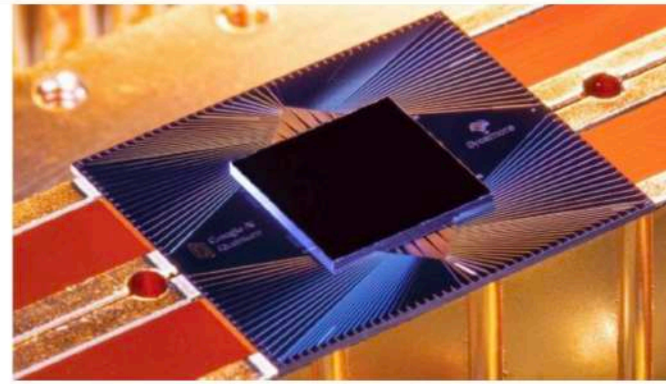
Il computer quantistico di Google: "Ecco le prove della nostra supremazia nel settore"



Oct. 23, 2019

Google and NASA Achieve Quantum Supremacy

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Science

Google scientists say they've achieved ‘quantum supremacy’ breakthrough over classical computers

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309 views | Dec 10, 2019, 07:30am

What Is Quantum Supremacy, And What Does It Mean For Entrepreneurs?

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It's official: Google has achieved quantum supremacy

PHYSICS 23 October 2019

Let's start from 1927…

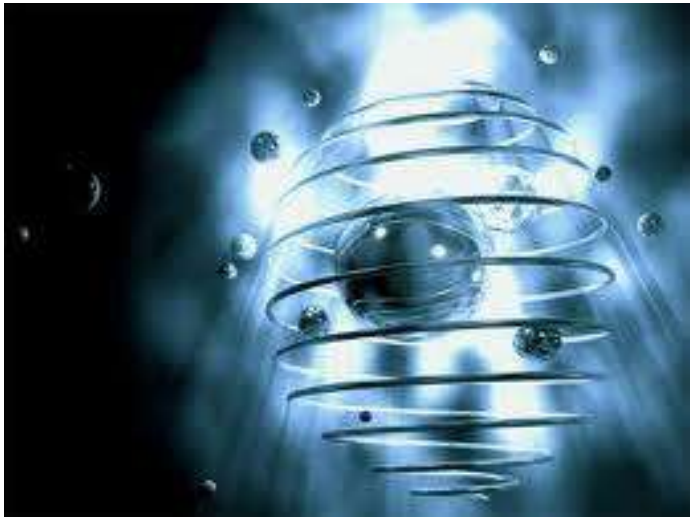
The “golden year” of Quantum Mechanics: Solvay conference (1927)

Quantum Physics: Planck, Einstein, Bohr, Dirac, Schroedinger, Heisenberg, Pauli,...

Quantum mechanics..

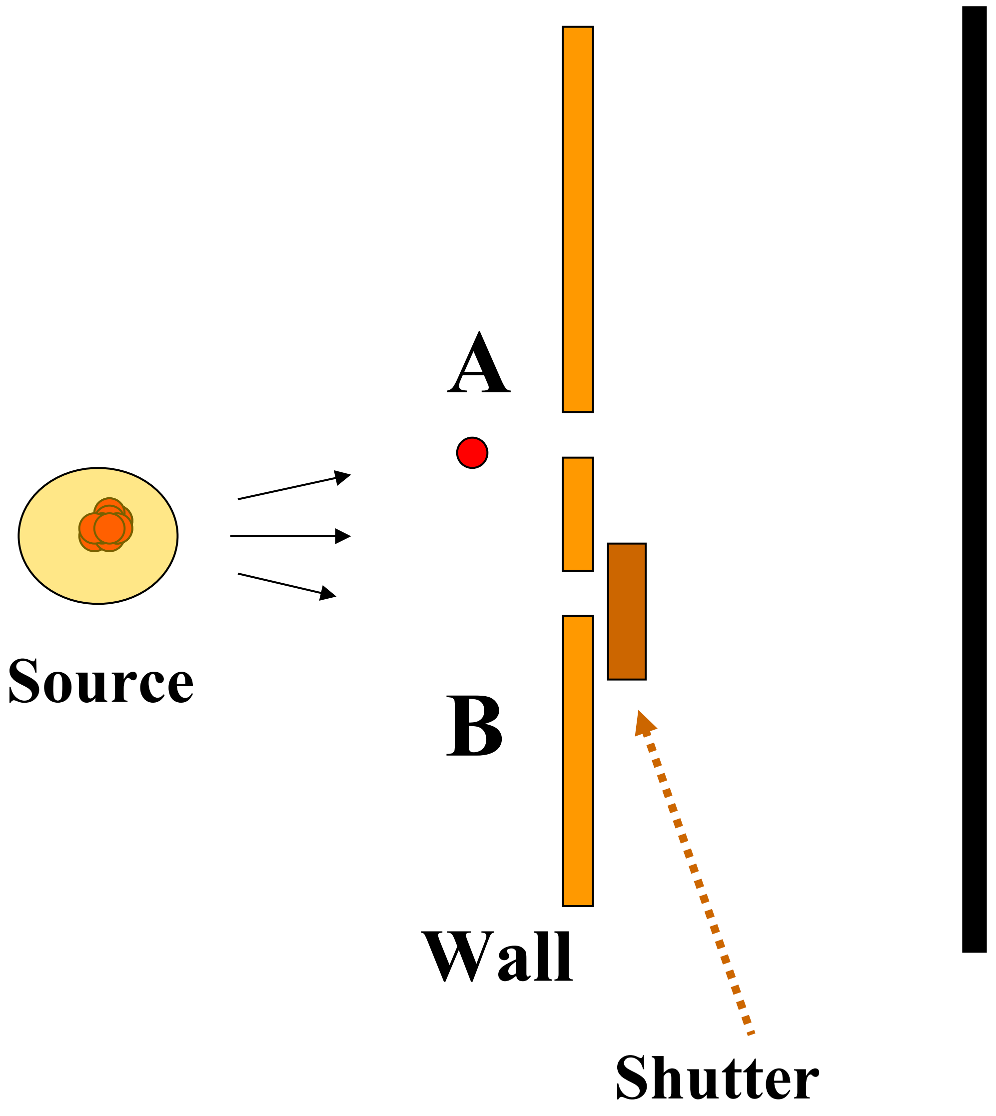
Energy, like matter, has a discontinuous nature being formed by elementary quantities.

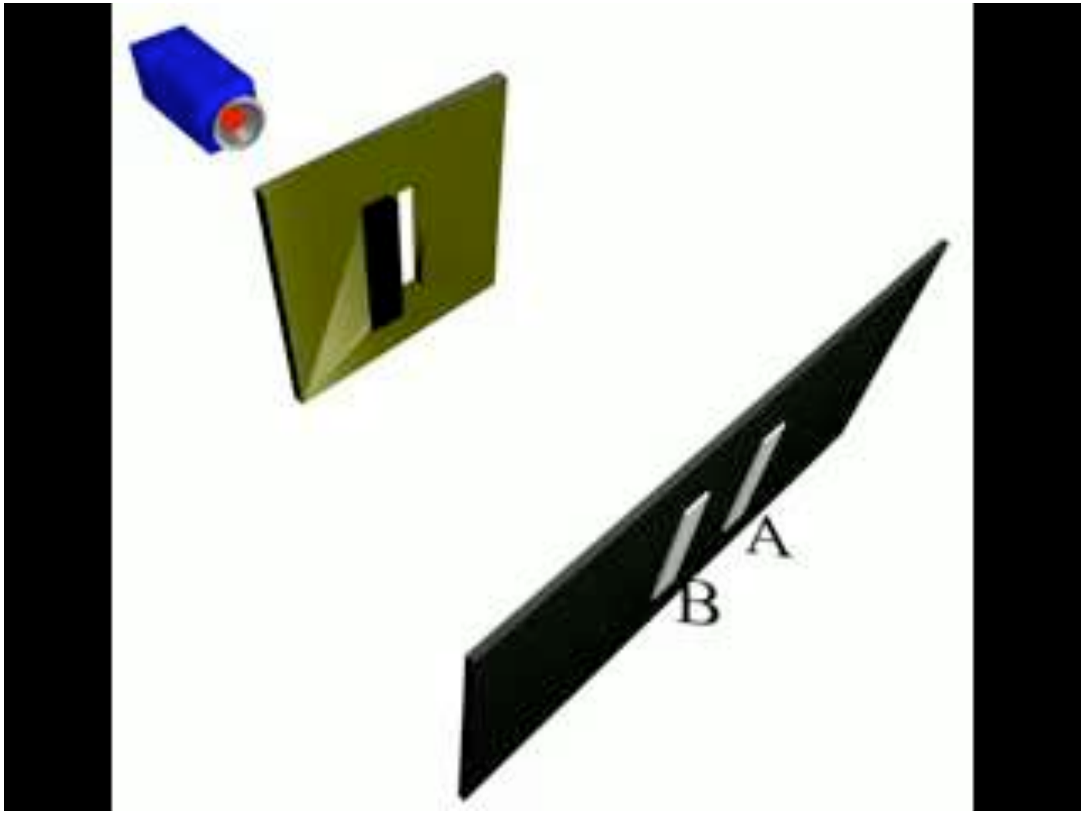
QUANTUM THEORY

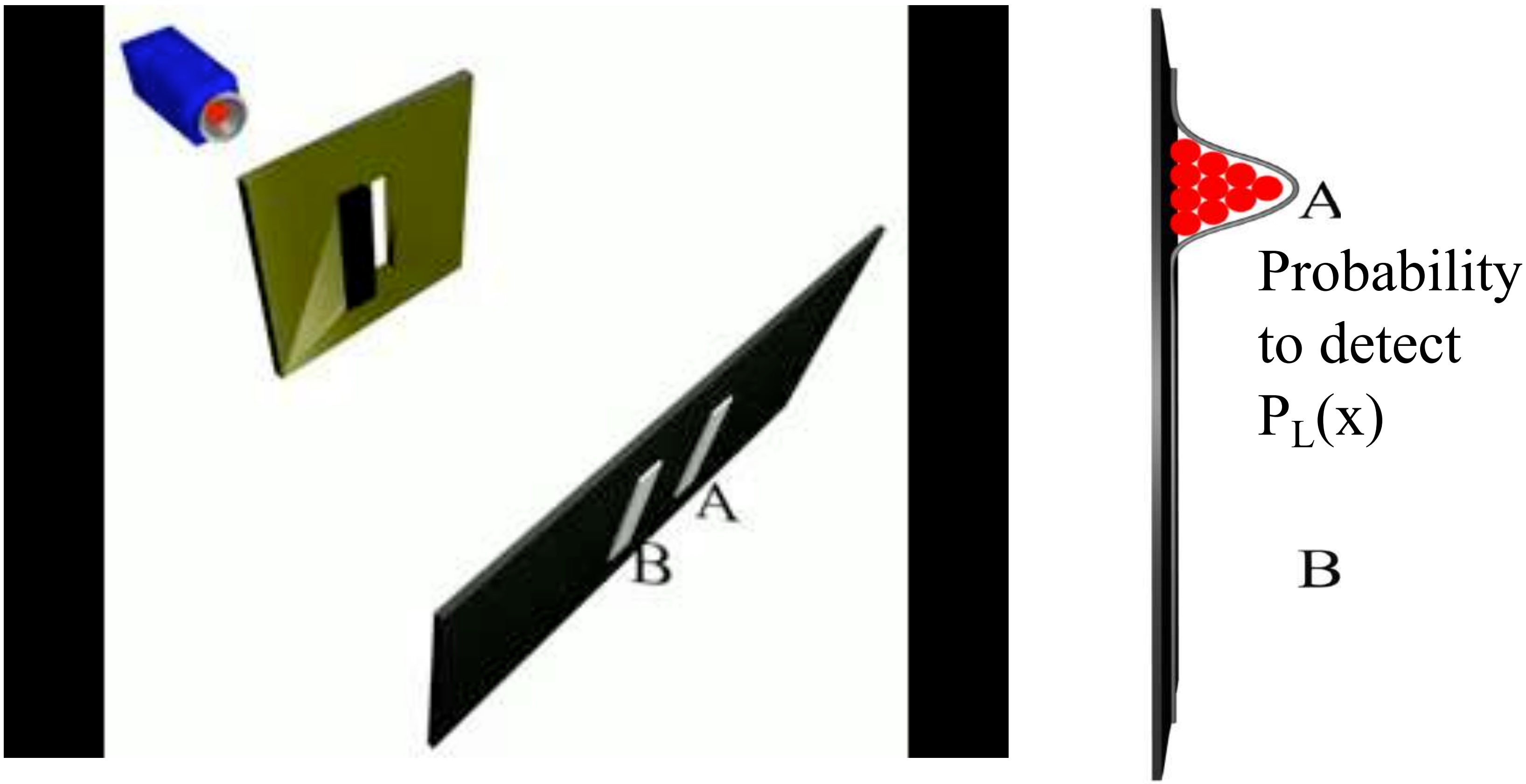


All processes of interaction between bodies (the "force fields") are "quantized" ["Elementary particles": photons, electrons ..]

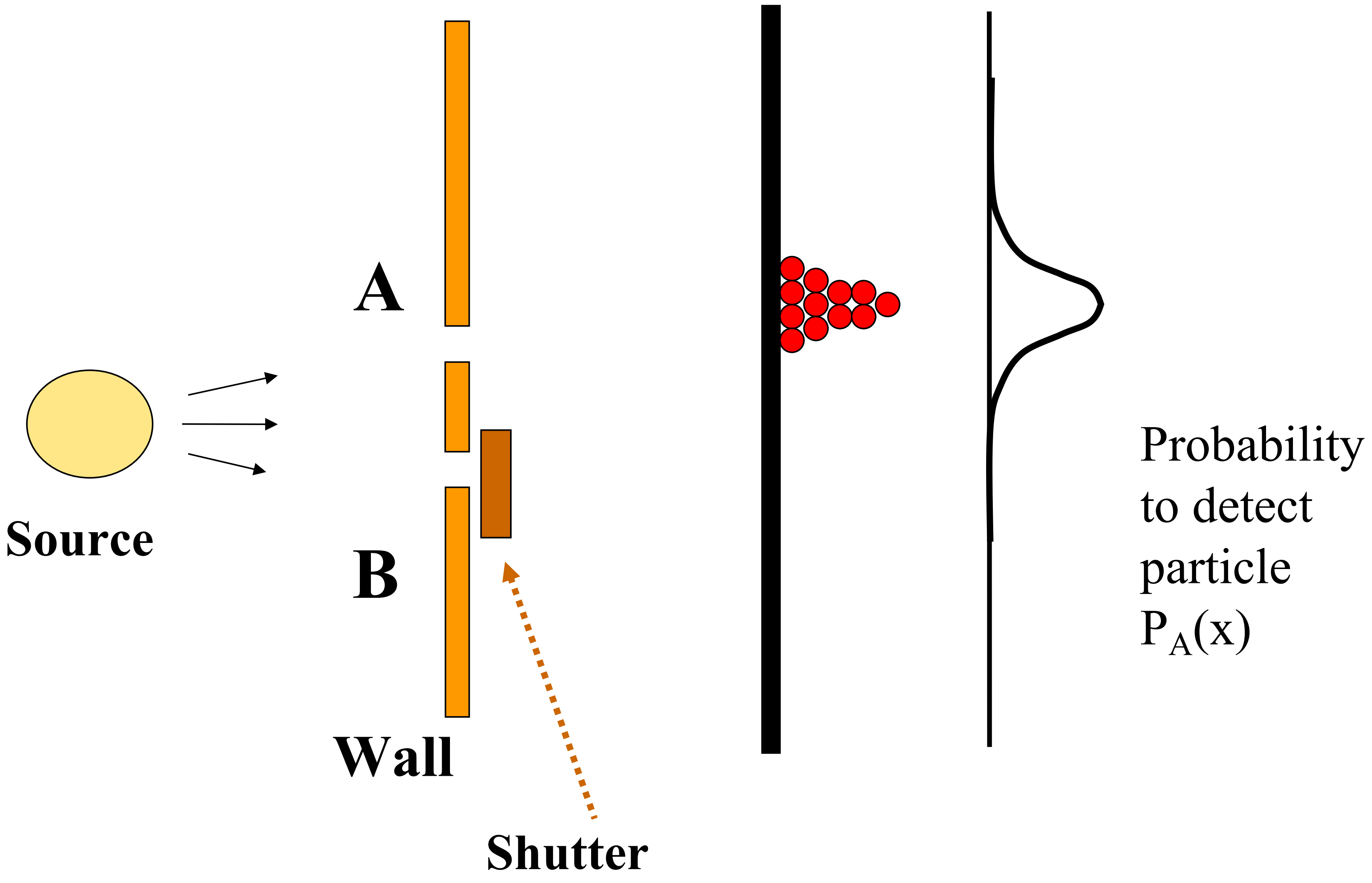
Single particle interference



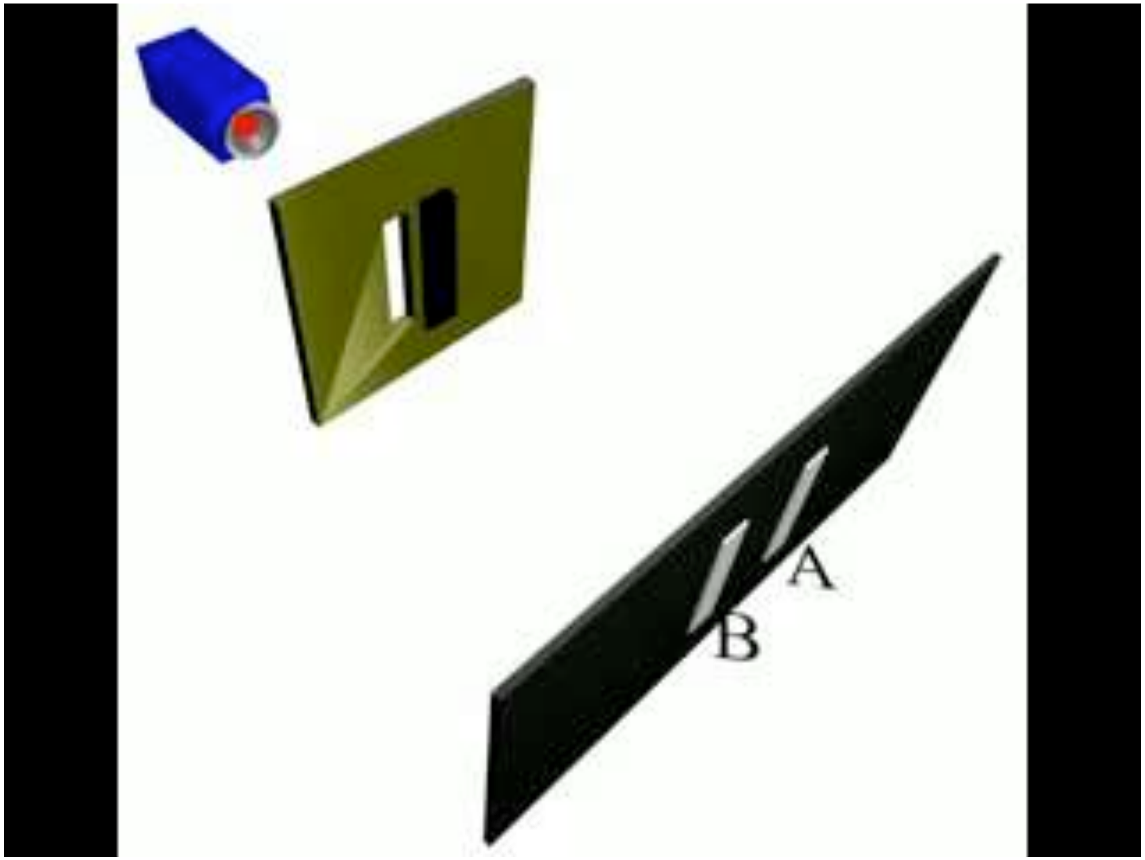

A
B


A
B
A
Probability
to detect
P_L(x)
B

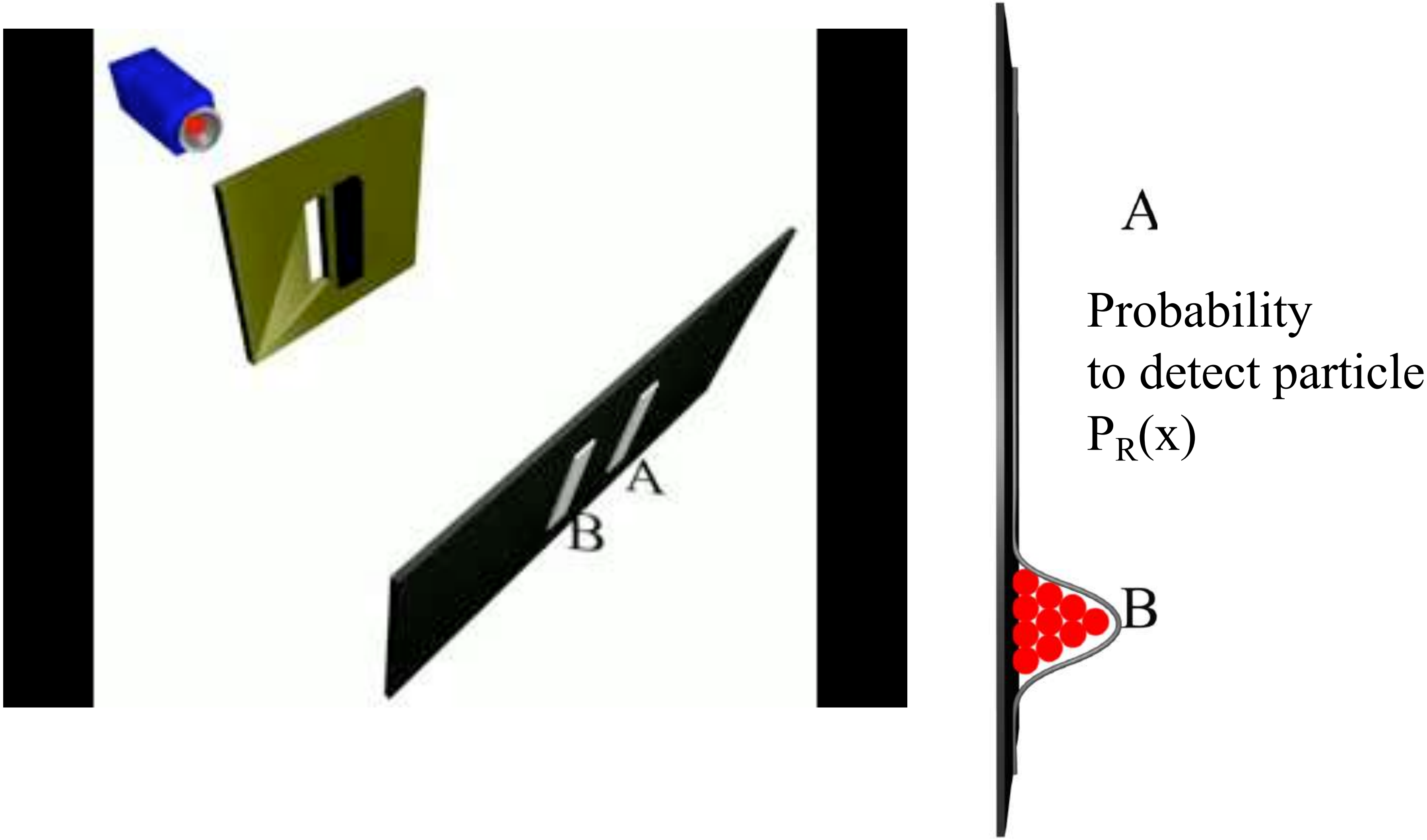
Single particle interference



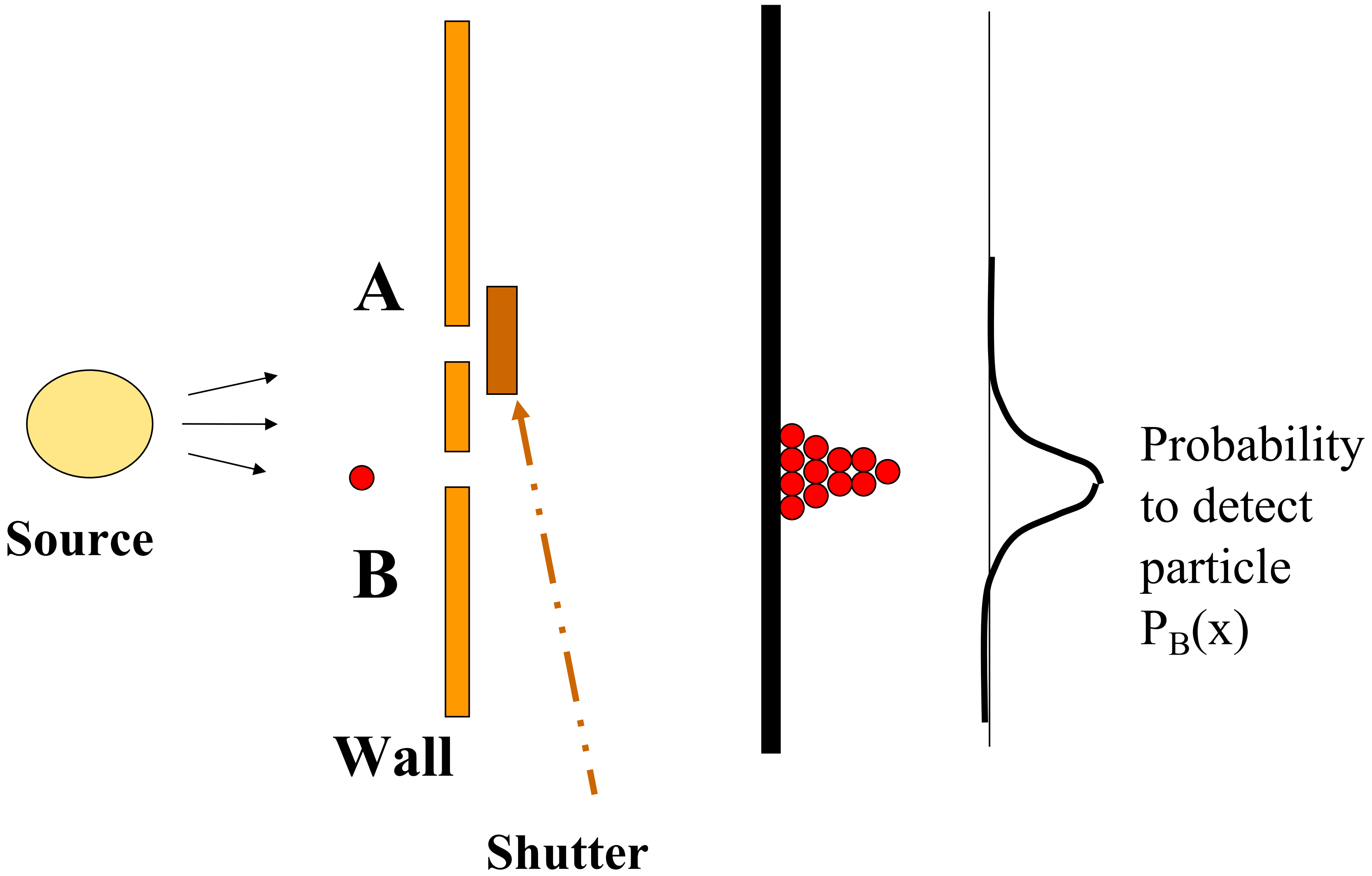
Single particle interference



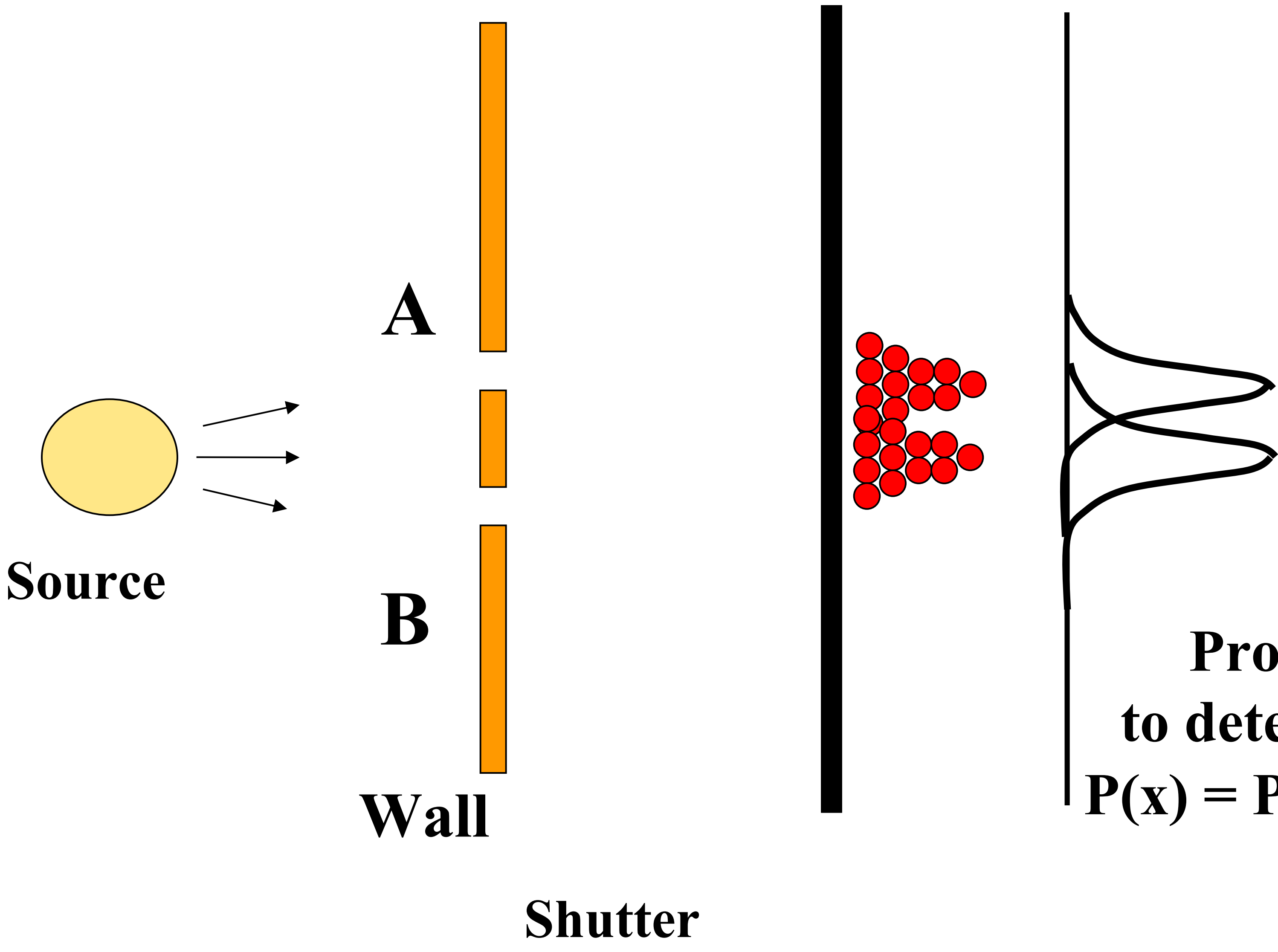
Single particle interference



Single particle interference



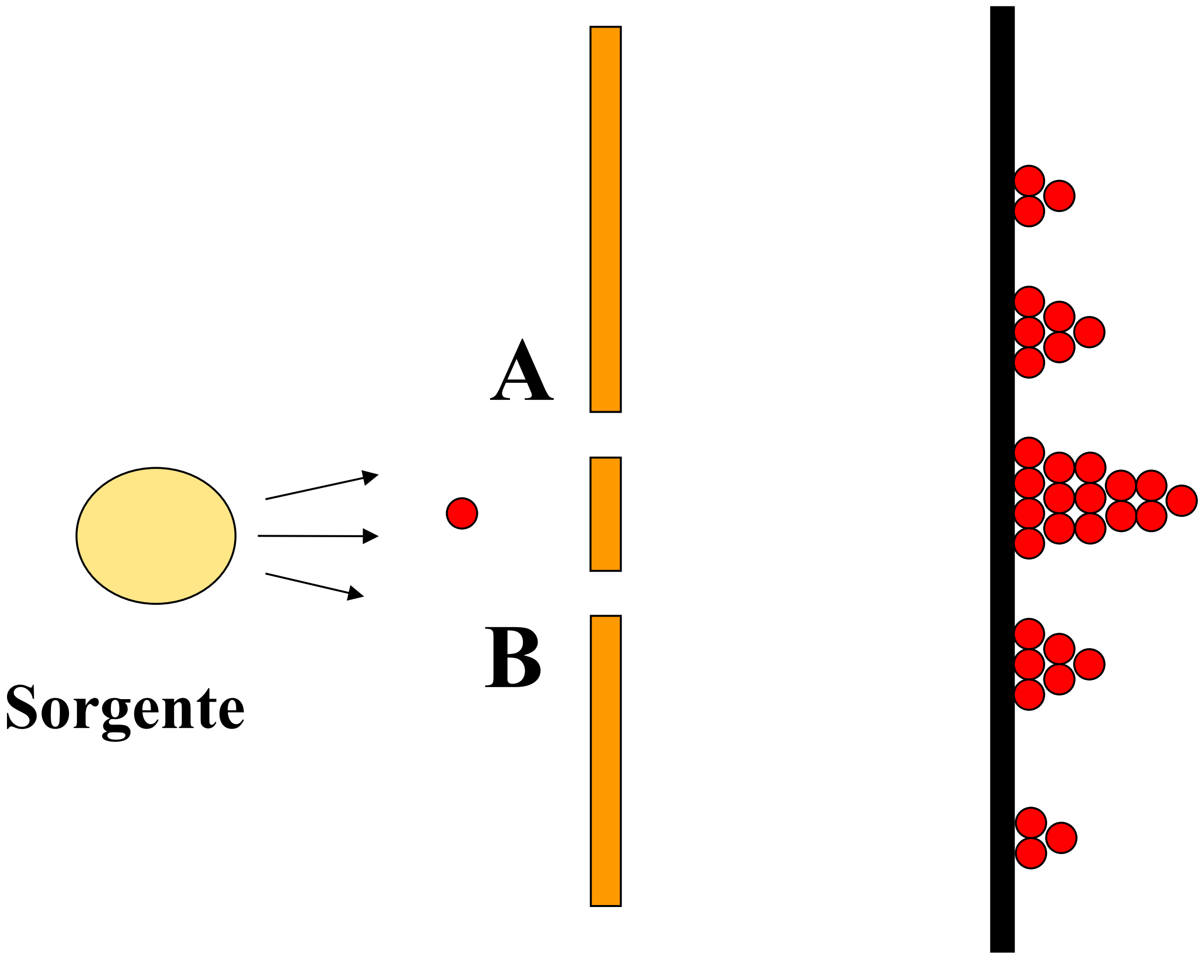
"Classical behavior"



Probability to detect particle

$$P(x) = P_A(x) + P_B(x)$$

Quantum interference



Which slit does the photon pass through?
It is as if it passed from both!

$$|\,fotone\ in\ A\rangle + |\,fotone\ in\ B\rangle$$

Coexistence of two complementary realities

Quantum interference

"…the heart of quantum mechanics. In reality it contains the only mystery ..."

R.P. Feynman (1965)

Quantum interference

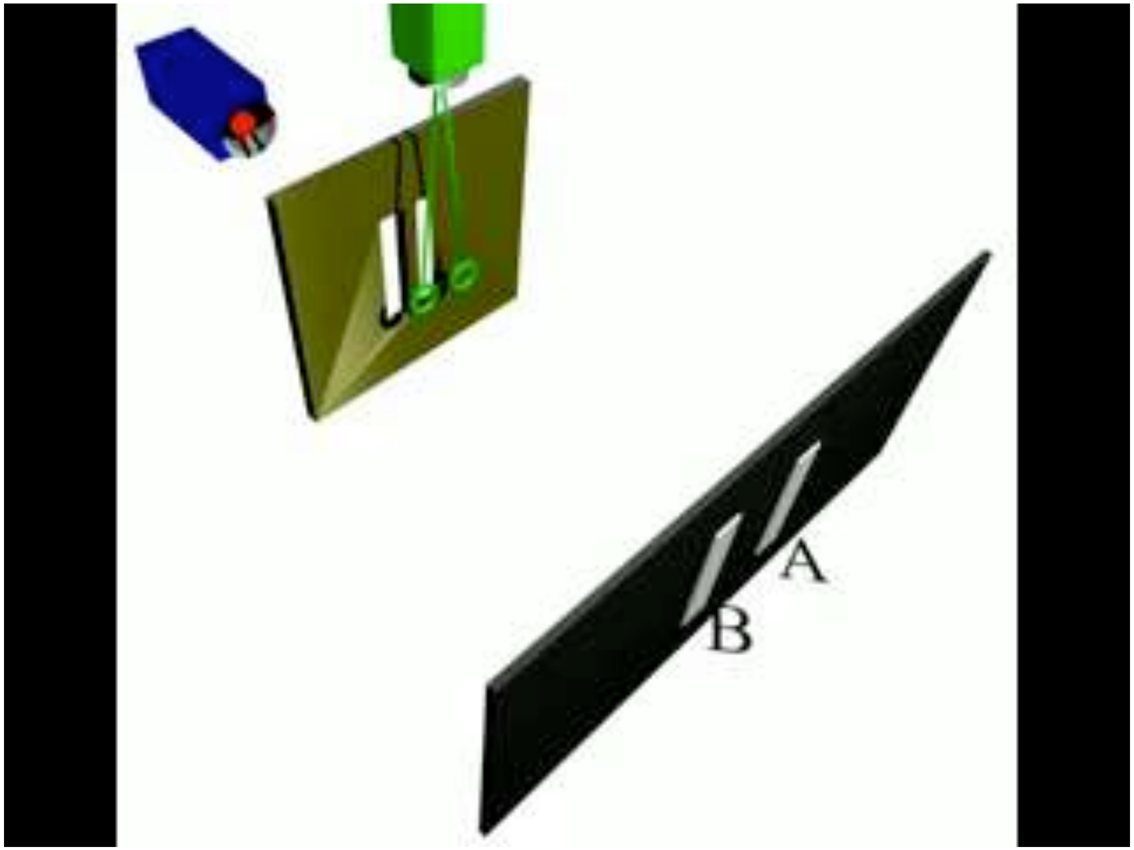
Classical physics: a particle can travel along path A or along path B

Quantum physics: “a particle can travel along path A and along path B "

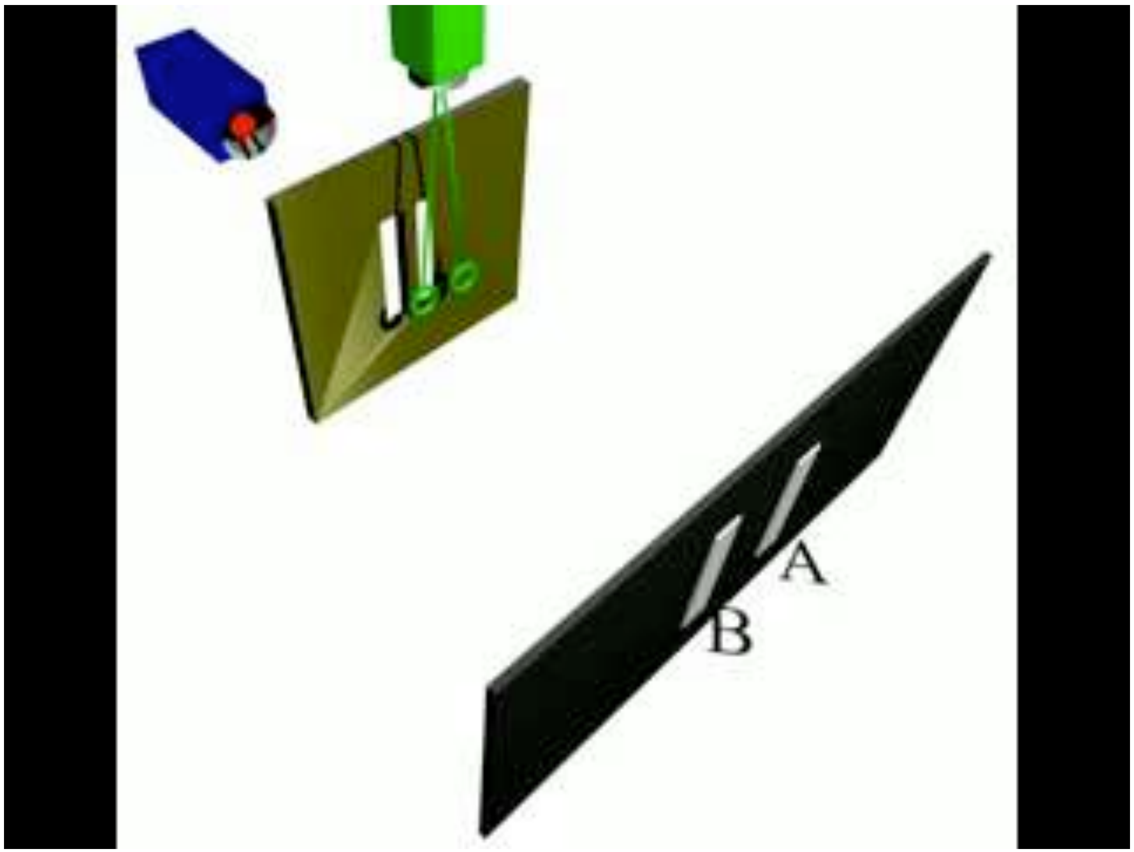
The particle is in an overlapping state of the two trajectories.

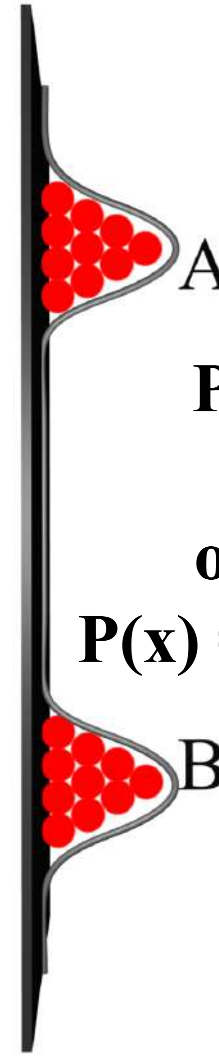
The wave function that characterizes the system is written as......

$$|fotone\ in\ A\rangle + |fotone\ in\ B\rangle$$


A
B

”Classical” behavior





Probability to detect one particle

$$P(x) = P_L(x) + P_R(x)$$

“It from bit”

J.A.Wheeler

Reality is also created by our questions, or by the information acquired.

The observation disturbs the phenomenon [“Heisenberg indeterminism”]

“It from bit”

J.A.Wheeler

“There is a moon in the sky if I don't look at it?”

A. Einstein

Einstein:
« *God doesn't play dice* »

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.

PRINCETON, N. J., May 3.—Professor Albert Einstein will attack

point out that where two physical quantities such as the position of a particle and its velocity interact, a knowledge of one quantity precludes knowledge about the other. This is the famous principle of uncertainty put forward by Professor Werner Heisenberg and incorporated in the quantum theory. This very fact, Professor Einstein feels, makes the quantum theory fail in the requirements necessary for a satisfactory physical theory.

Two Requirements Listed.

These two requirements are:

1. The theory should make possible a calculation of the facts of nature and predict results which can be accurately checked by experiment; the theory should be, in other words, correct.

2. Moreover, a satisfactory theory should, as a good image of the objective world, contain a counterpart for things found in the objective world; that is, it must be a complete theory.

Quantum theory, Professor Ein-

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THE NEW YORK TIMES, SATURDAY, MAY 4, 1935.

EINSTEIN ATTAC[KS] QUANTUM THE[ORY]

Scientist and Two Colle[agues] Find It Is Not 'Compl[ete'] Even Though 'Correct'

SEE FULLER ONE POSS[IBLE]

Believe a Whole Descript[ion of] 'the Physical Reality' Ca[n Be] Provided Eventually.

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 corresponding to each element of reality. A sufficient condition for the reality of a physical quantity is the possibility of predicting it with certainty, without disturbing the system. In quantum mechanics in the case of two physical quantities described by non-commuting operators, the knowledge of one precludes the knowledge of the other. Then either (1) the description of reality given by the wave function in quantum mechanics is not complete or (2) these two quantities cannot have simultaneous reality. Consideration of the problem of making predictions concerning a system on the basis of measurements made on another system that had previously interacted with it leads to the result that if (1) is false then (2) is also false. One is thus led to conclude that the description of reality as given by a wave function is not complete.

other words, correct.

2. Moreover, a satisfactory theory should, as a good image of the objective world, contain a counterpart for things found in the physical...

external world and to help us to obtain further knowledge of it. Before a theory can be considered to be satisfactory it must pass two very severe tests. First, the theory...

that quantum mechanics is not a complete theory."

Raises Point of Doubt.

« While we have shown that the wave function does not provide a complete description of the physical reality, we left open the question of whether or not such a description exists.

We believe, however, that such a theory is possible. »

N. Rosen.

In the quantum theory as now used, the latest Einstein paper will

Prizes in physics, including one to Einstein, have been awarded for various phases of the researches leading up to quantum mechanics.

quantum mechanics, in its present form, is not complete.

"In quantum mechanics the condition of any physical system, such

standpoint. But I am afraid that thus far the statistical theories have withstood criticism."

Einstein-Podolsky-Rosen paradox: Entanglement

Let's consider two particles (photons A and B)

$$|0\rangle_A |1\rangle_B$$

Einstein-Podolsky-Rosen paradox: Entanglement

Let's consider two particles (photons A and B)

$$|1\rangle_A |0\rangle_B$$

Einstein-Podolsky-Rosen paradox: Entanglement

Let's consider two particles (photons A and B)

$$|0\rangle_A |1\rangle_B \quad + \quad |1\rangle_A |0\rangle_B$$

Einstein-Podolsky-Rosen paradox: Entanglement

Let's consider two particles (photons A and B)

$$\left|\Psi\right\rangle_{AB} = \frac{\left|0\right\rangle_A \left|1\right\rangle_B - \left|1\right\rangle_A \left|0\right\rangle_B}{\sqrt{2}}$$

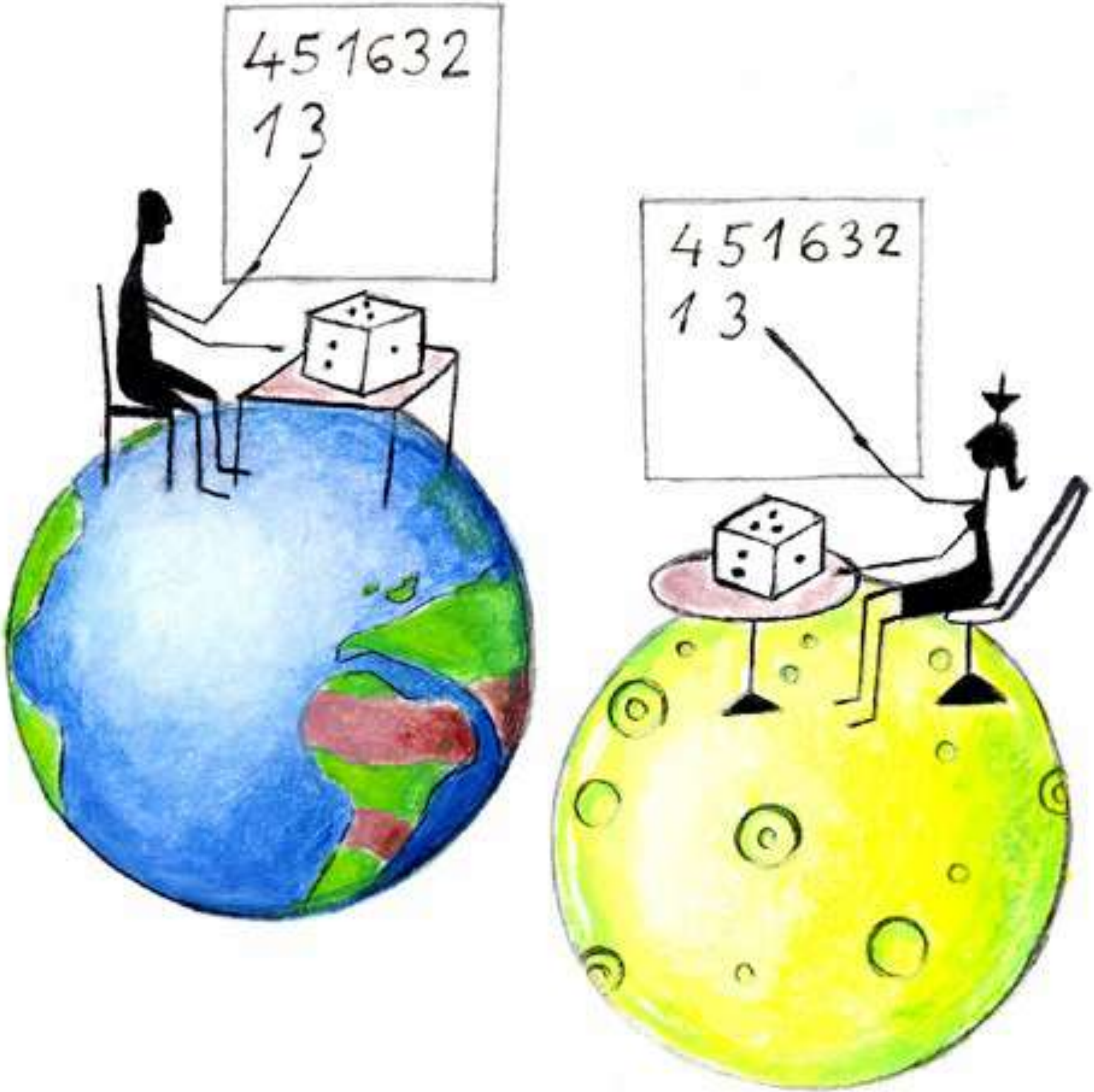
Two entangled particles

$$|\Psi\rangle_{AB} = \frac{|0\rangle_A|1\rangle_B - |1\rangle_A|0\rangle_B}{\sqrt{2}}$$

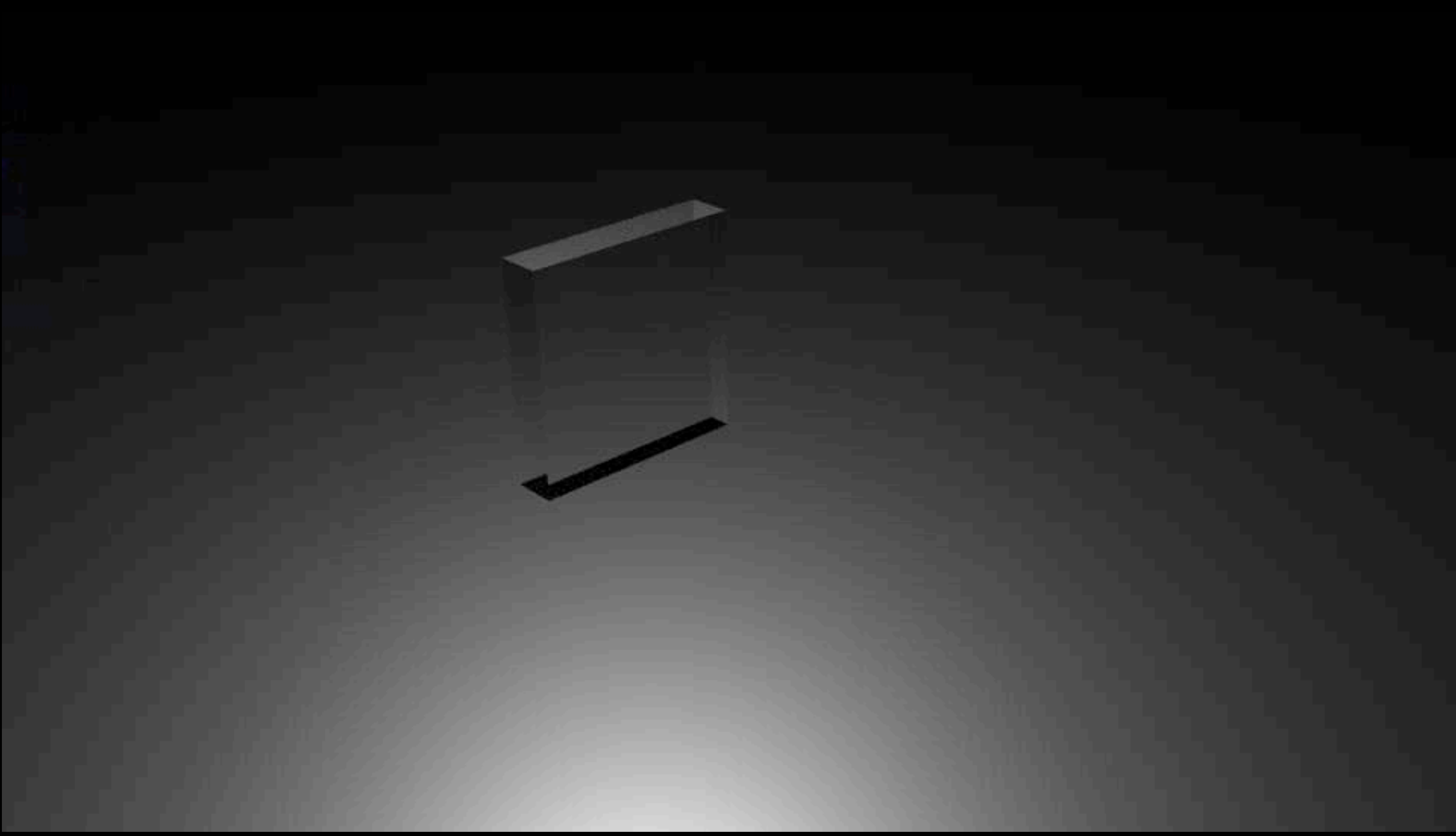
« I would not call **entanglement** one but rather the **characteristic trait of quantum mechanics**, the one that enforces its entire departure from classical lines of thought. »

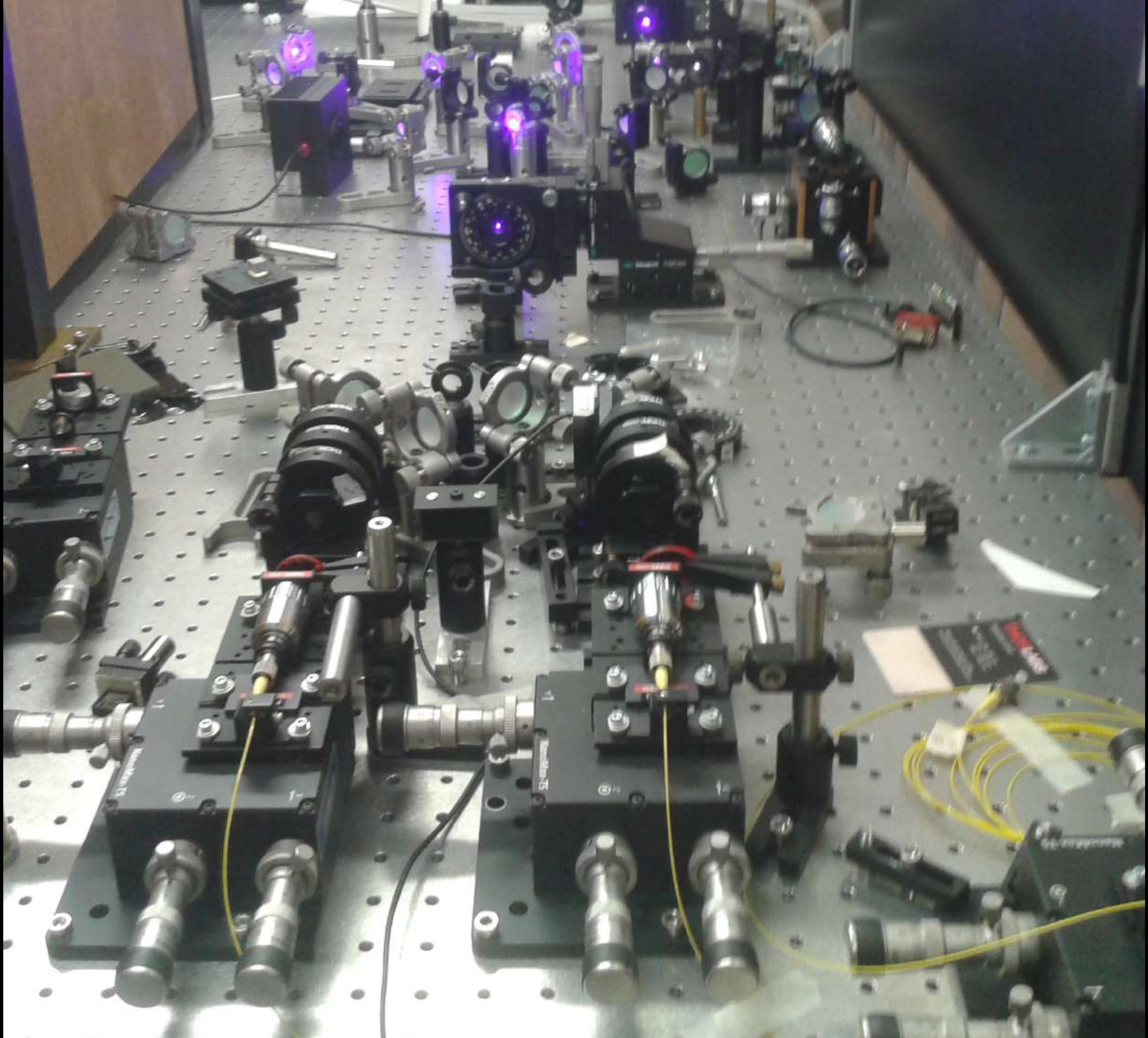
E. Schroedinger

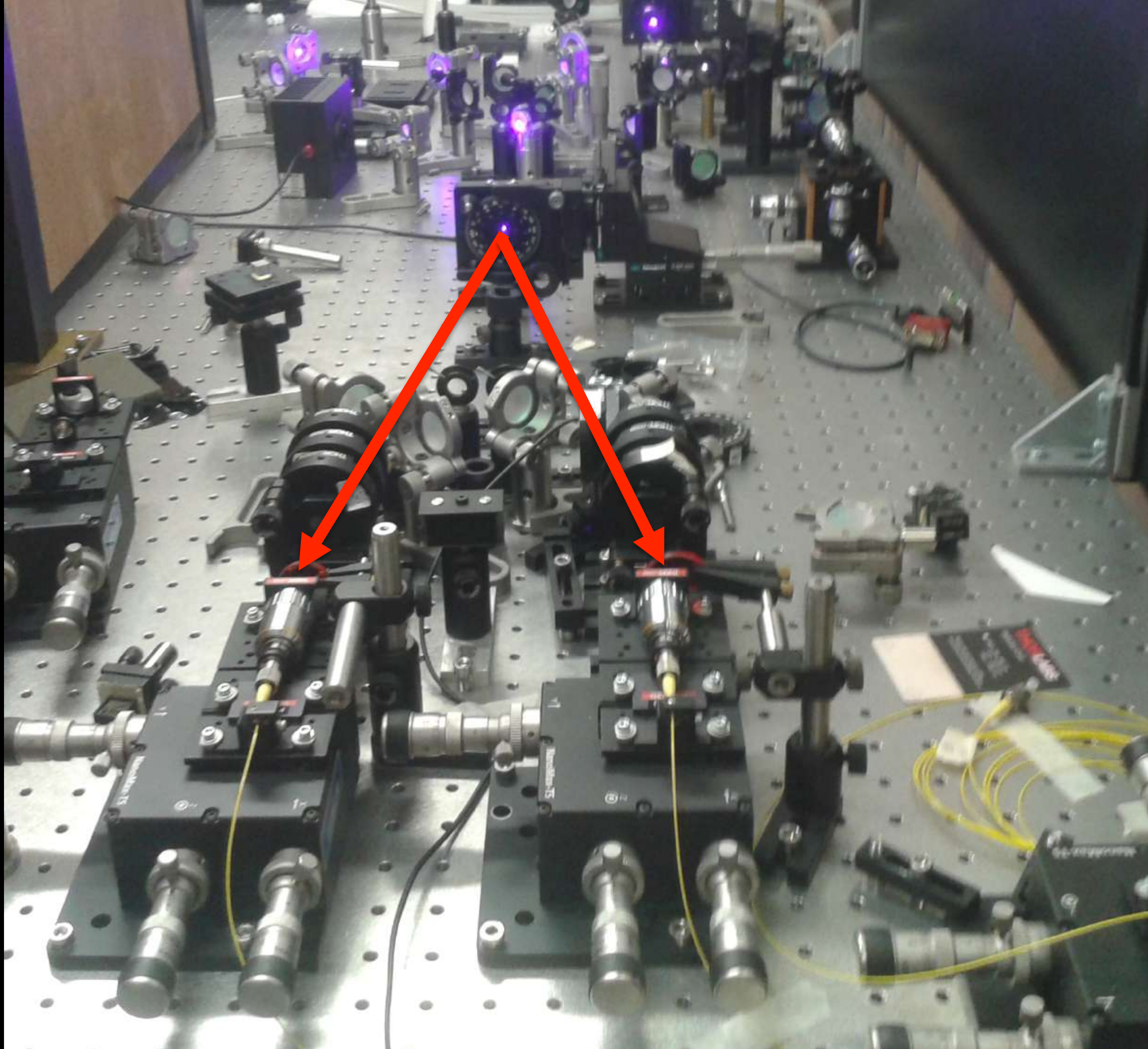
Quantum non-locality



Generation of entangled states

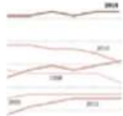






SCIENCE


Sorry, Einstein. Quantum Study Suggests 'Spooky Action' Is Real.


2015 Likely to Be Hottest Year Ever Recorded


Museum Specimens Find New Life Online


New Species of Galápagos Tortoise Is Identified

SCIENCE

710 COMMENTS

Sorry, Einstein. Quantum Study Suggests 'Spooky Action' Is Real.

By JOHN MARKOFF OCT. 21, 2015

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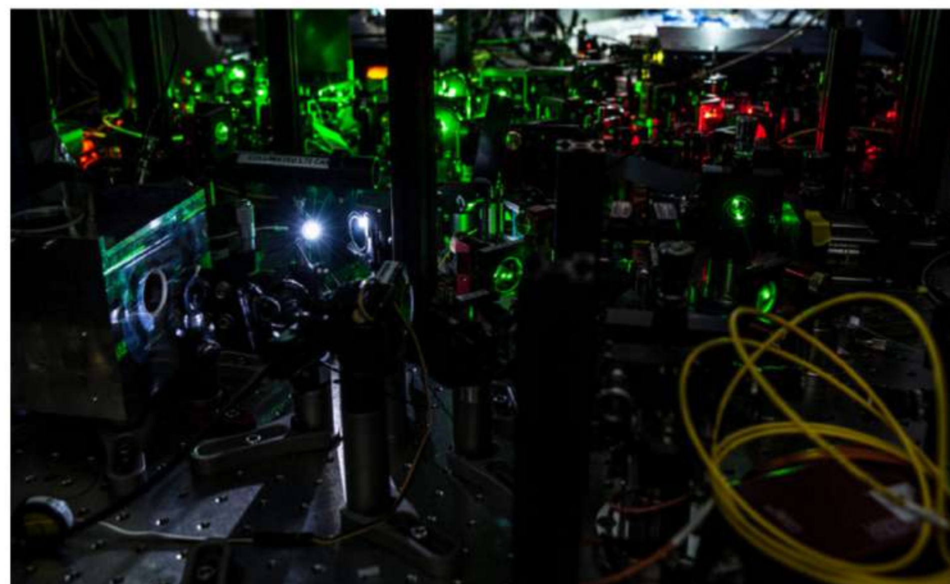
In a landmark study, scientists at Delft University of Technology in the Netherlands reported that they had conducted an experiment that they say proved one of the most fundamental claims of quantum theory — that objects separated by great distance can instantaneously affect each other's behavior.



Part of the laboratory setup for an experiment at Delft University of Technology, in which two diamonds were set 1.3 kilometers apart, entangled and then shared information.
Frank Auperle/Delft University of Technology

The finding is another blow to one of the bedrock principles of standard physics known as "locality," which states that an object is directly influenced only by its immediate surroundings. The Delft study, published Wednesday in the journal Nature, lends further credence to an idea that Einstein famously rejected. He said

European Research Program on Quantum Technologies

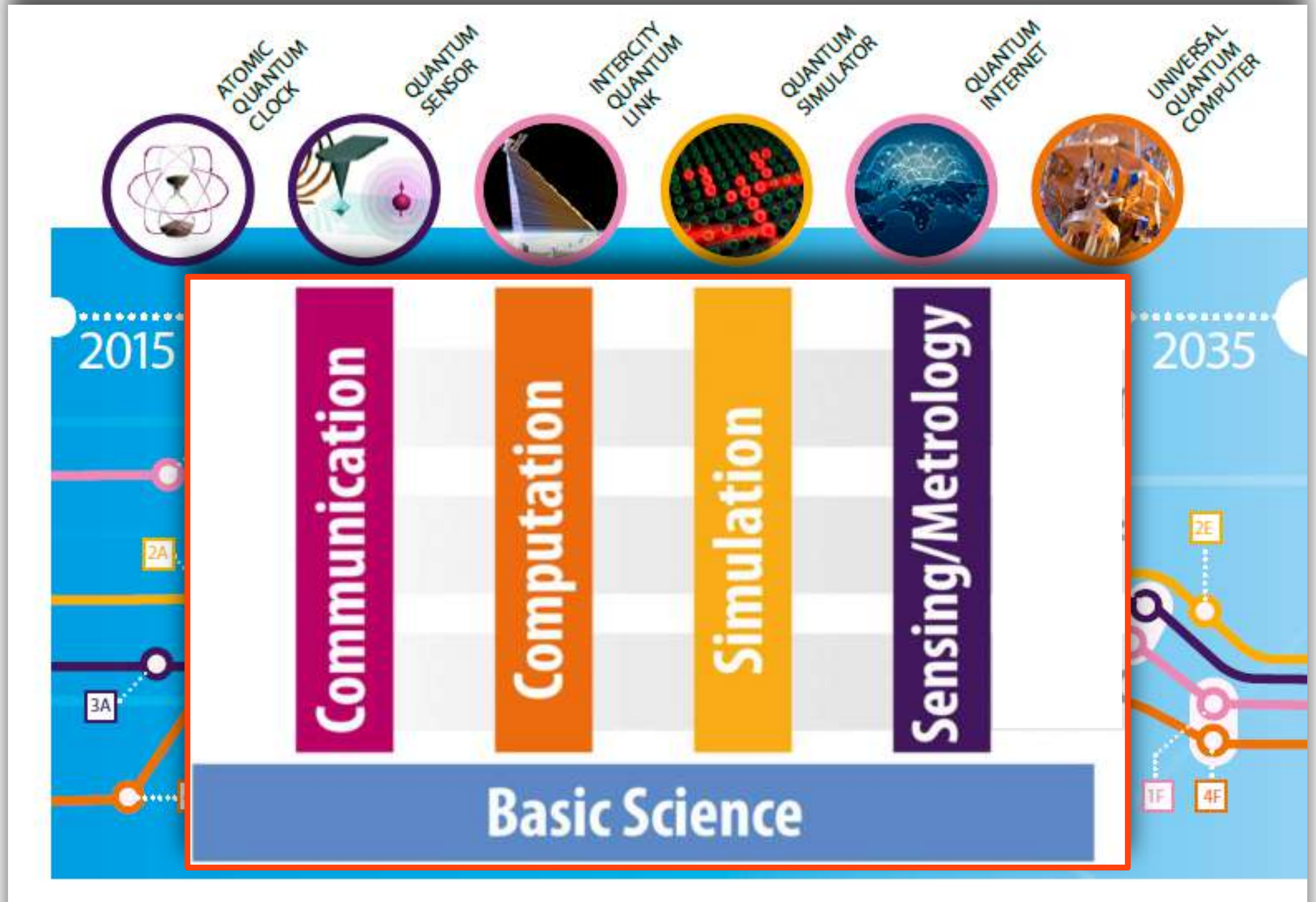
The second quantum revolution…

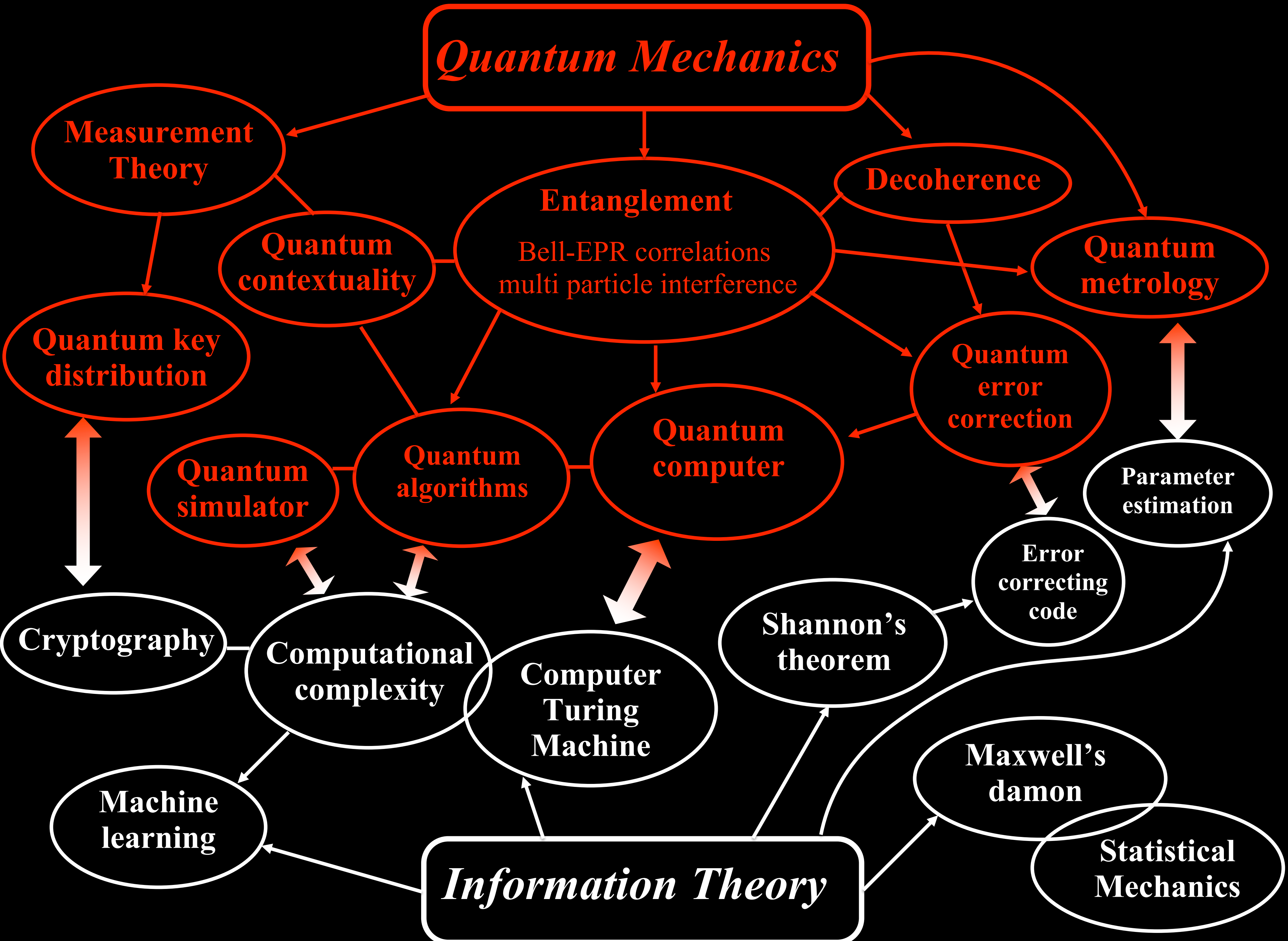
Quantum information

$$\alpha|0\rangle + \beta|1\rangle$$

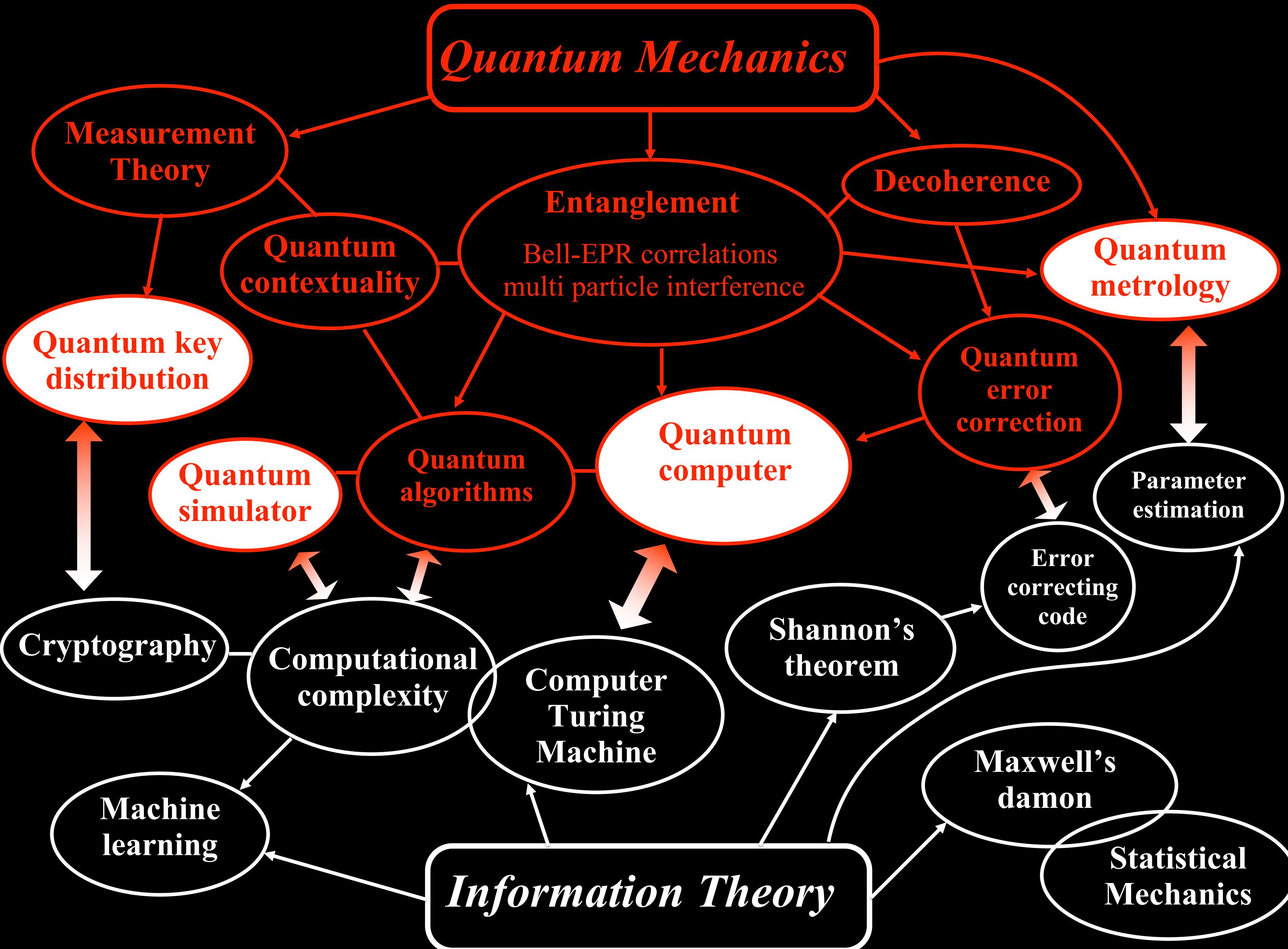
Quantum bit (qubit)

Quantum information





Quantum Mechanics
Measurement Theory
Entanglement
Bell-EPR correlations
multi particle interference
Decoherence
Quantum metrology
Quantum contextuality
Quantum key distribution
Quantum error correction
Quantum computer
Quantum algorithms
Quantum simulator
Parameter estimation
Error correcting code
Cryptography
Computational complexity
Computer Turing Machine
Shannon's theorem
Maxwell's damon
Statistical Mechanics
Machine learning
Information Theory


Quantum Mechanics
Measurement Theory
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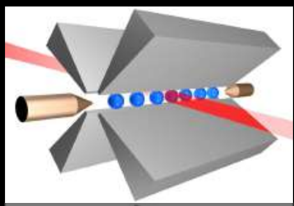
Decoherence
Quantum contextuality
Quantum metrology
Quantum key distribution
Quantum error correction
Quantum computer
Quantum algorithms
Quantum simulator
Parameter estimation
Error correcting code
Cryptography
Computational complexity
Computer Turing Machine
Shannon's theorem
Maxwell's damon
Statistical Mechanics
Machine learning
Information Theory

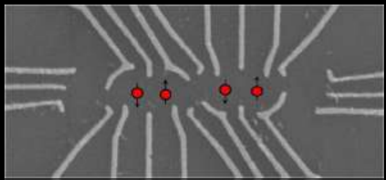
Implementation of Quantum Information

Trapped ions



Single photons

Spin qubit



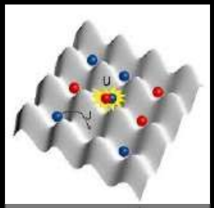
Quantum computation

Quantum simulation

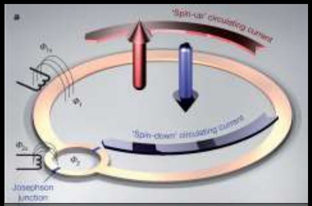
Quantum communication

Quantum metrology

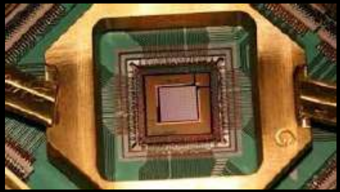
Foundations of Quantum Mechanics



Cold atoms in optical lattices

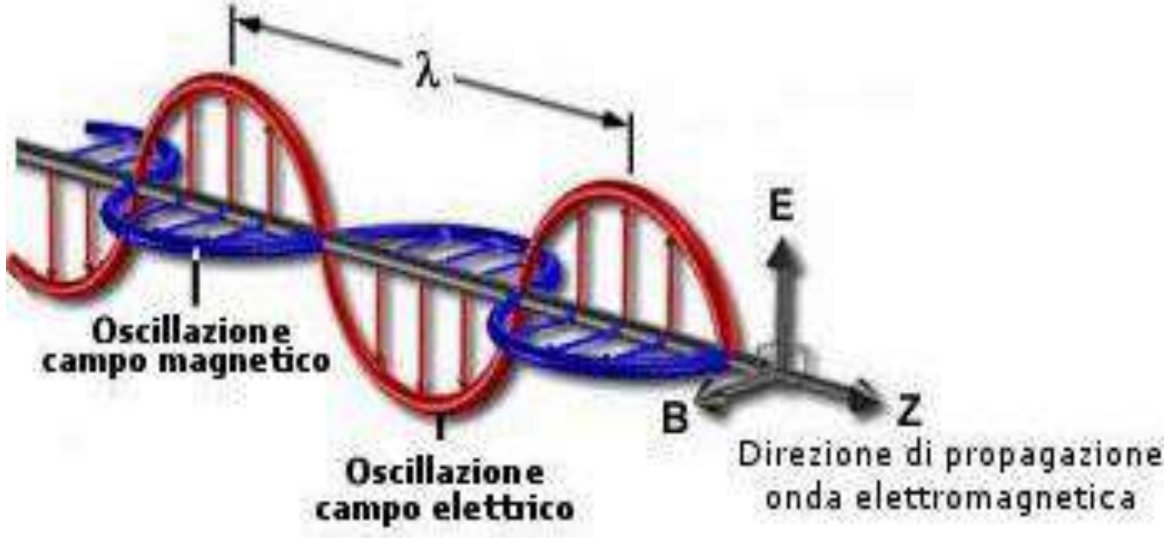


Superconducting qubits



Quantum annealers

Polarizzation of a single photon



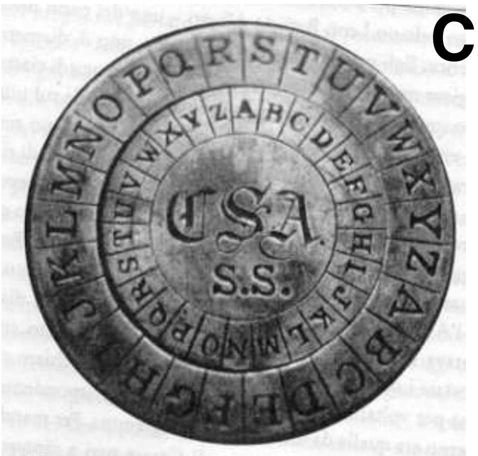
Polarization of a single photon

$$\alpha|H\rangle + \beta|V\rangle$$

H: horizontal

V: vertical

Classical cryptography



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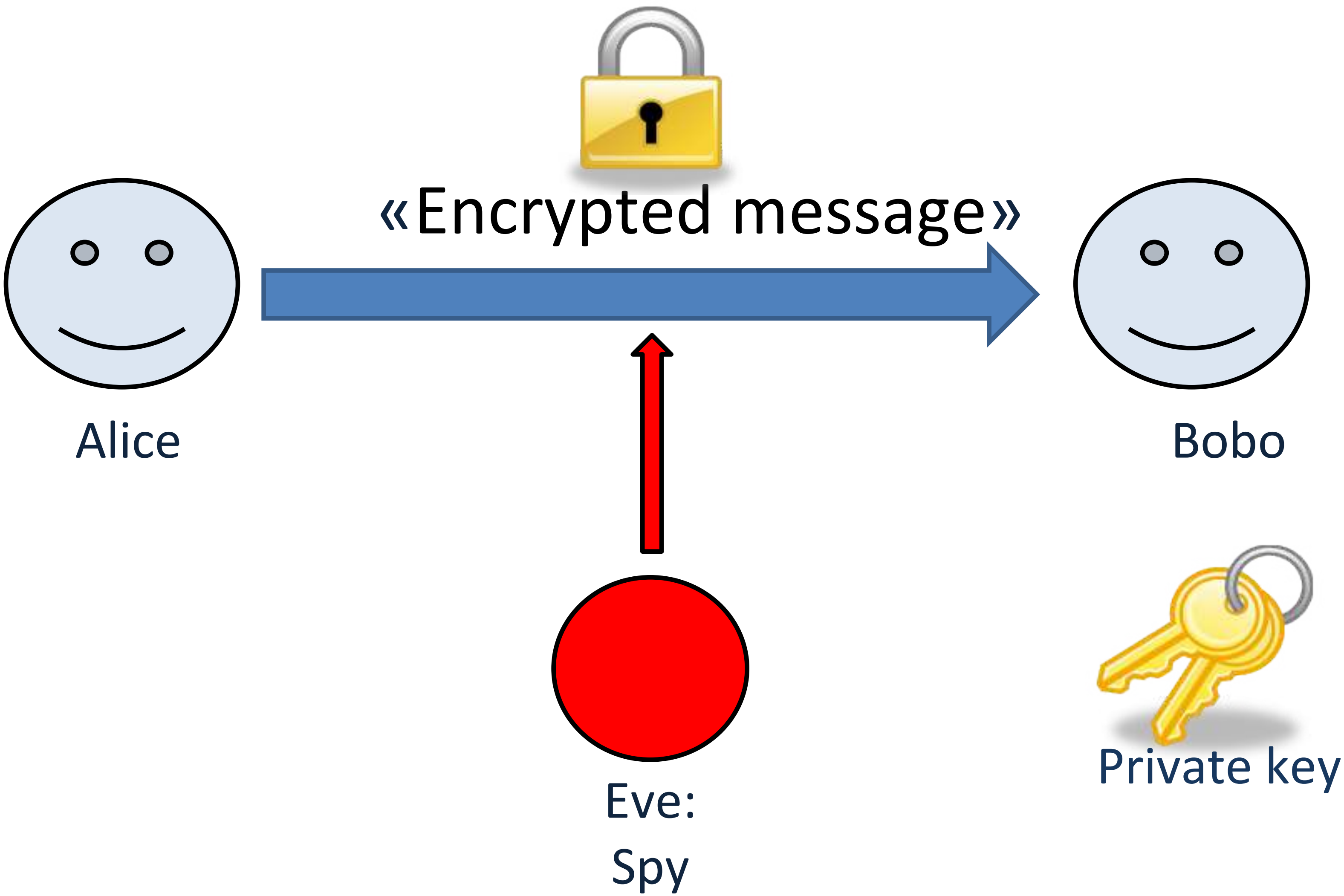
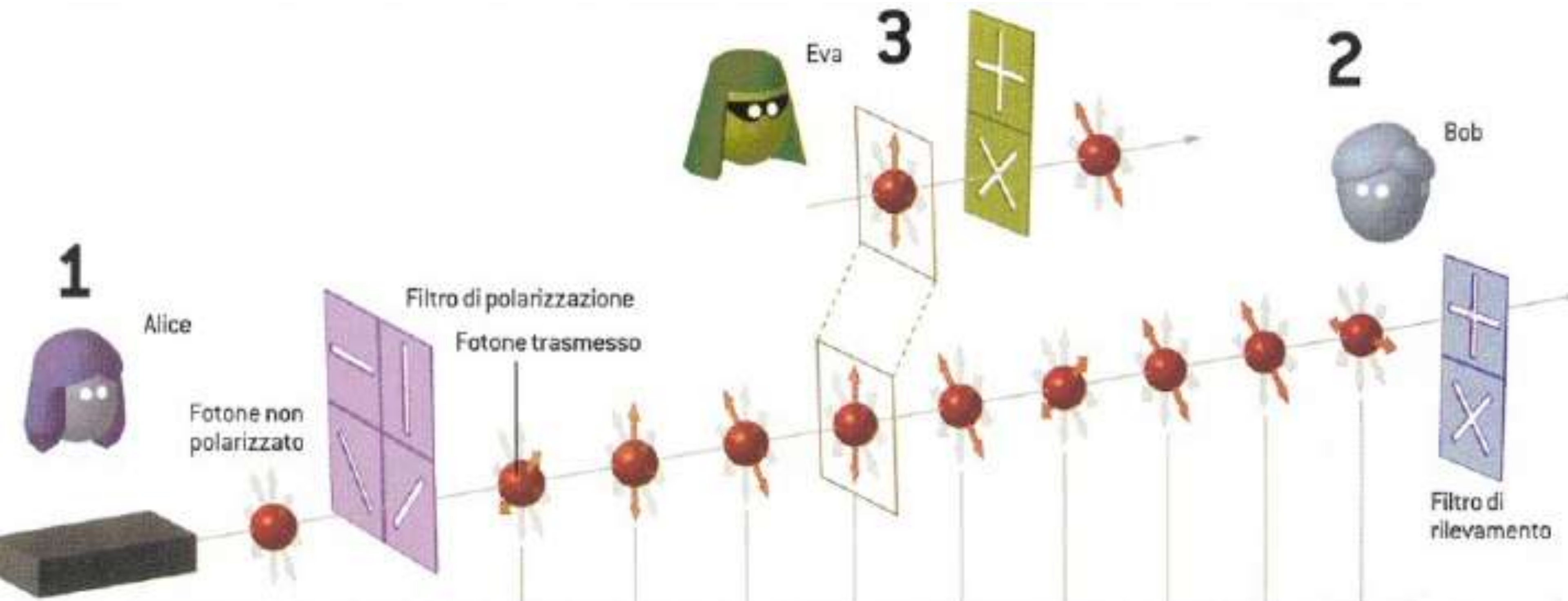
Classic Cryptography: Private Key

Private key protocol: key exchange via secure channel!



Quantum cryptography



Sequenza di bit di Alice:	0	0	1	0	1	0	1	1	1
Schema di filtraggio di Alice:	/	|	\	|	\	/	\	\	—
Schema di rilevamento di Bob:	+	+	+	+	×	+	+	×	+
Misurazione dei bit di Bob:	1	0	1	0	1	0	0	1	1
Sequenza ottenuta (chiave):	–	0	–	0	1	–	–	1	1

Micius: "Quantum Sputnik"

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MAGAZINE OF THE SOCIETY FOR SCIENCE & THE PUBLIC

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YEAR IN REVIEW QUANTUM PHYSICS, 2017 TOP 10

A quantum communications satellite proved its potential 2017

Intercontinental video call sets distance record for cryptography via entangled ph

BY EMILY CONOVER 8:28AM, DECEMBER 13, 2017

Magazine issue: Vol. 192, No. 11, December 23, 2017, p. 27

Science & Environment

China's quantum satellite in big leap

By Roland Pease
BBC Radio Science Unit

INSIDE SCIENCE Reliable news for an expanding universe

CREATURE CULTURE EARTH HUMAN PHYSICS SPACE SPORTS TECHNOLOGY

Is China the Leader in Quantum Communications?

Chinese scientists have built two major quantum infrastructure projects, and the race is on to take the next step.

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China's quantum satellite achieves 'spooky action' at record distance

By Gabriel Popkin | Jun. 15, 2017, 2:

The Economist Topics Current edition More

Keeping telecommunications secret

The first quantum-cryptographic satellite network will be Chinese

Quantum cryptography's early birds

Micius Quantum Communication Satellite

Micius was launched aboard Long March 2D rocket in August 2016. Image: courtesy of Xinhua/Jin Liwang.

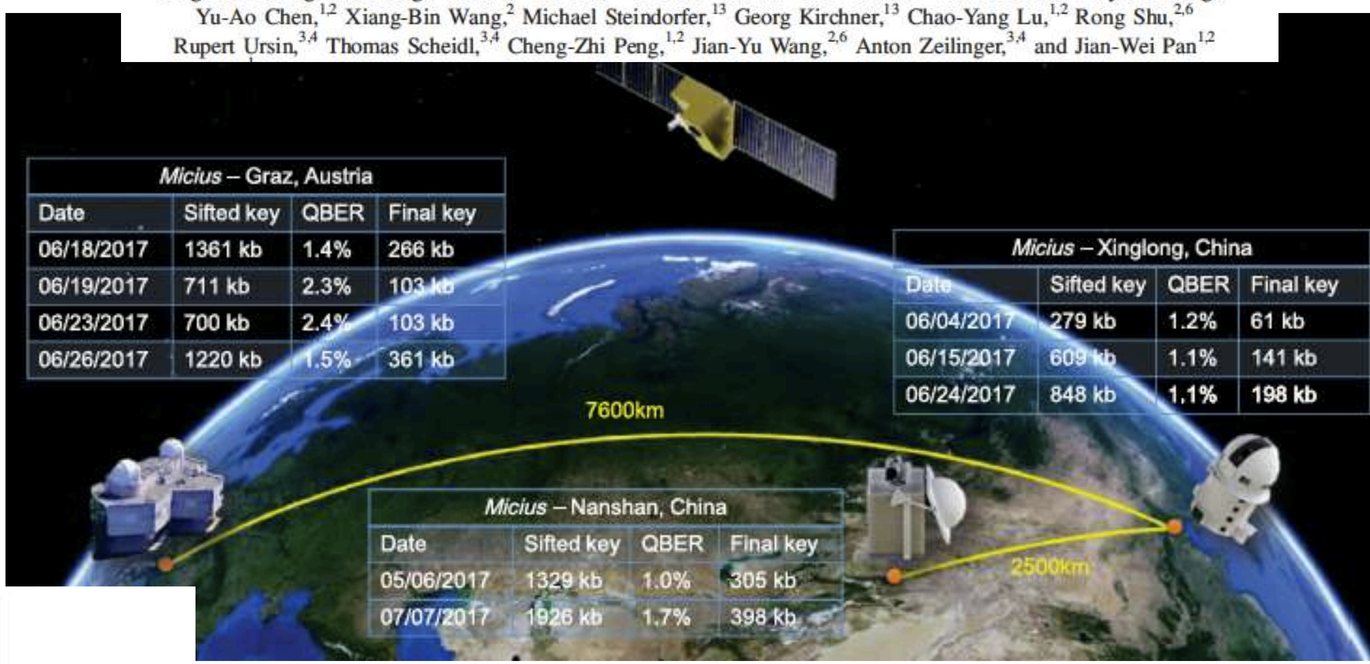
State-of-the-art in Satellite-based quantum key distribution

PHYSICAL REVIEW LETTERS **120**, 030501 (2018)

Editors' Suggestion Featured in Physics

Satellite-Relayed Intercontinental Quantum Network

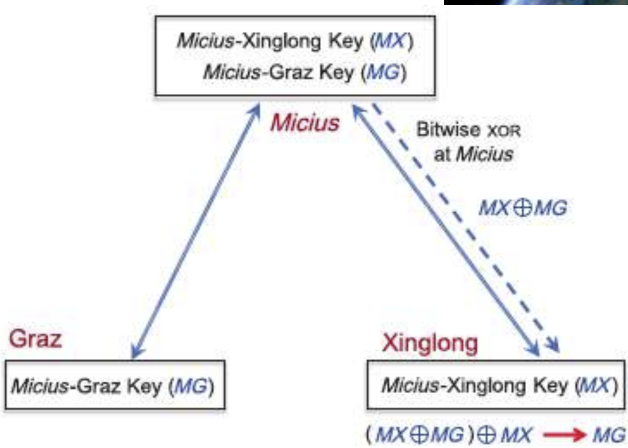
Sheng-Kai Liao,[1,2] Wen-Qi Cai,[1,2] Johannes Handsteiner,[3,4] Bo Liu,[4,5] Juan Yin,[1,2] Liang Zhang,[2,6] Dominik Rauch,[3,4] Matthias Fink,[4] Ji-Gang Ren,[1,2] Wei-Yue Liu,[1,2] Yang Li,[1,2] Qi Shen,[1,2] Yuan Cao,[1,2] Feng-Zhi Li,[1,2] Jian-Feng Wang,[7] Yong-Mei Huang,[8] Lei Deng,[9] Tao Xi,[10] Lu Ma,[11] Tai Hu,[12] Li Li,[1,2] Nai-Le Liu,[1,2] Franz Koidl,[13] Peiyuan Wang,[13] Yu-Ao Chen,[1,2] Xiang-Bin Wang,[2] Michael Steindorfer,[13] Georg Kirchner,[13] Chao-Yang Lu,[1,2] Rong Shu,[2,6] Rupert Ursin,[3,4] Thomas Scheidl,[3,4] Cheng-Zhi Peng,[1,2] Jian-Yu Wang,[2,6] Anton Zeilinger,[3,4] and Jian-Wei Pan[1,2]

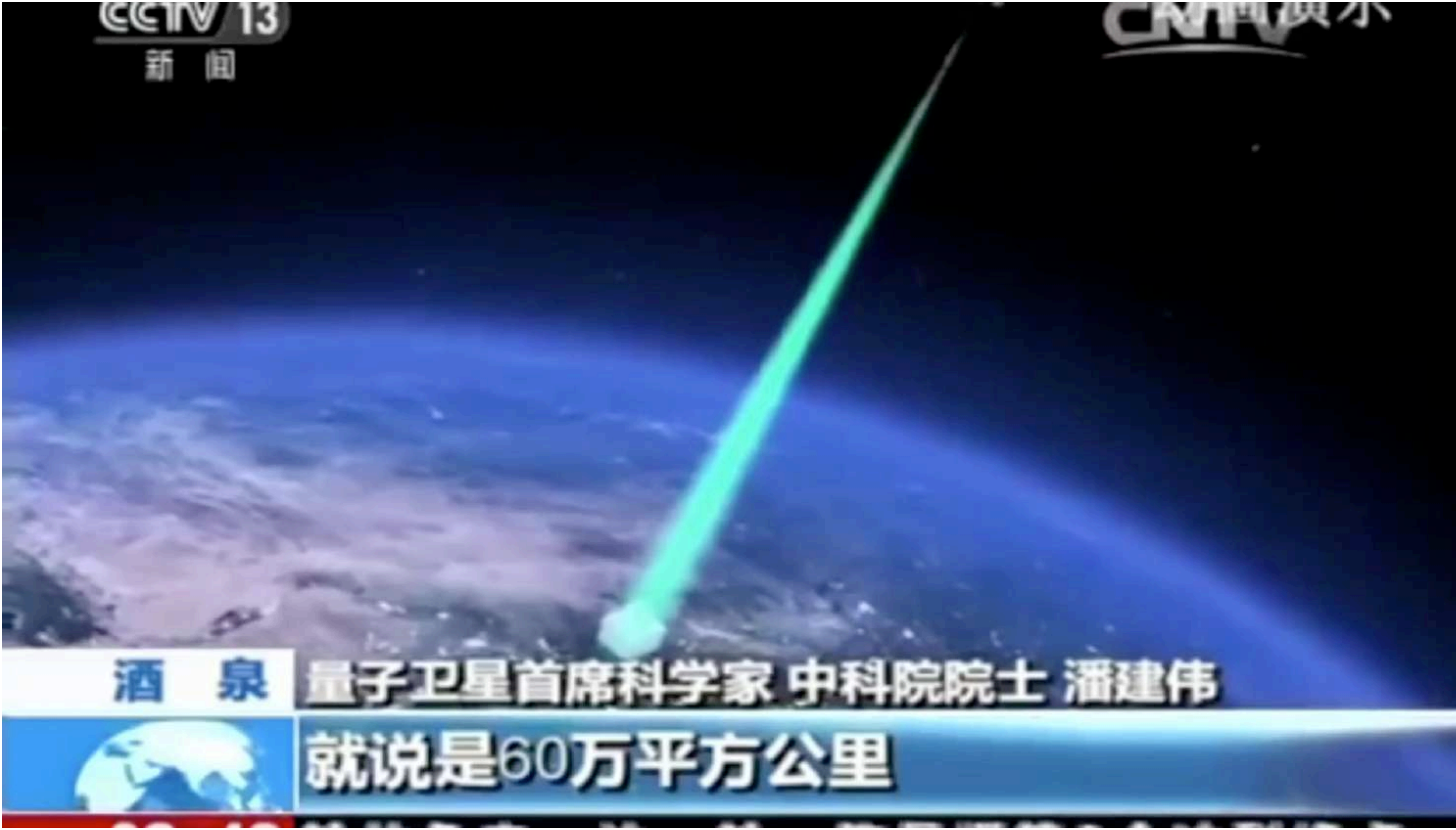


Micius – Graz, Austria			
Date	Sifted key	QBER	Final key
06/18/2017	1361 kb	1.4%	266 kb
06/19/2017	711 kb	2.3%	103 kb
06/23/2017	700 kb	2.4%	103 kb
06/26/2017	1220 kb	1.5%	361 kb

Micius – Xinglong, China			
Date	Sifted key	QBER	Final key
06/04/2017	279 kb	1.2%	61 kb
06/15/2017	609 kb	1.1%	141 kb
06/24/2017	848 kb	1.1%	198 kb

Micius – Nanshan, China			
Date	Sifted key	QBER	Final key
05/06/2017	1329 kb	1.0%	305 kb
07/07/2017	1926 kb	1.7%	398 kb

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就说是60万平方公里

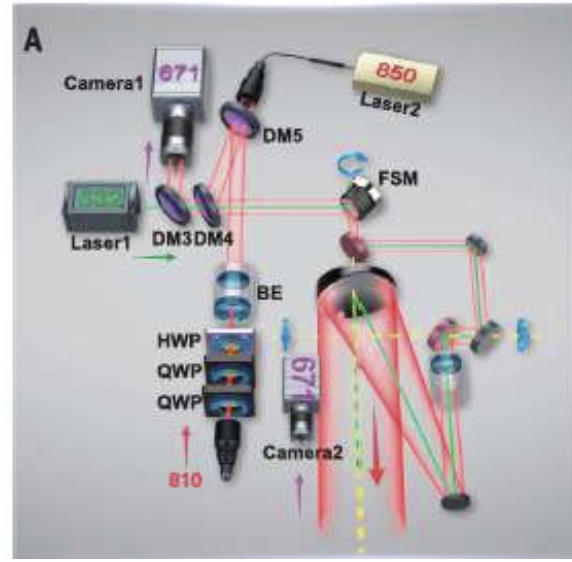
State-of-the-art in Satellite-based quantum key distribution

RESEARCH ARTICLE

QUANTUM OPTICS Yin *et al.*, *Science* **356**, 1140–1144 (2017) 16 June 2017

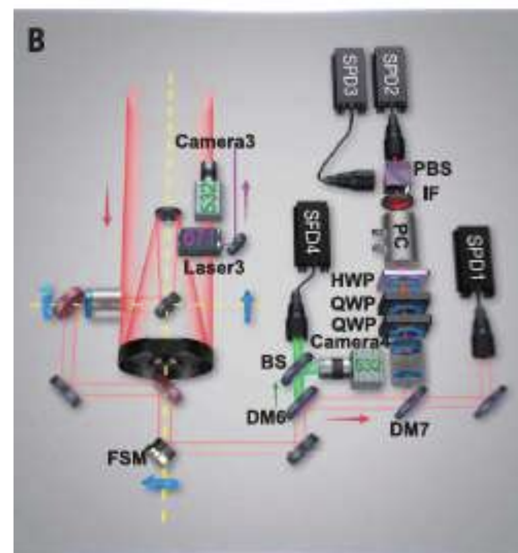
Satellite-based entanglement distribution over 1200 kilometers

Juan Yin,[1,2] Yuan Cao,[1,2] Yu-Huai Li,[1,2] Sheng-Kai Liao,[1,2] Liang Zhang,[2,3] Ji-Gang Ren,[1,2] Wen-Qi Cai,[1,2] Wei-Yue Liu,[1,2] Bo Li,[1,2] Hui Dai,[1,2] Guang-Bing Li,[1,2] Qi-Ming Lu,[1,2] Yun-Hong Gong,[1,2] Yu Xu,[1,2] Shuang-Lin Li,[1,2] Feng-Zhi Li,[1,2] Ya-Yun Yin,[1,2] Zi-Qing Jiang,[3] Ming Li,[3] Jian-Jun Jia,[3] Ge Ren,[4] Dong He,[4] Yi-Lin Zhou,[5] Xiao-Xiang Zhang,[6] Na Wang,[7] Xiang Chang,[8] Zhen-Cai Zhu,[5] Nai-Le Liu,[1,2] Yu-Ao Chen,[1,2] Chao-Yang Lu,[1,2] Rong Shu,[2,3] Cheng-Zhi Peng,[1,2*] Jian-Yu Wang,[2,3*] Jian-Wei Pan[1,2*]



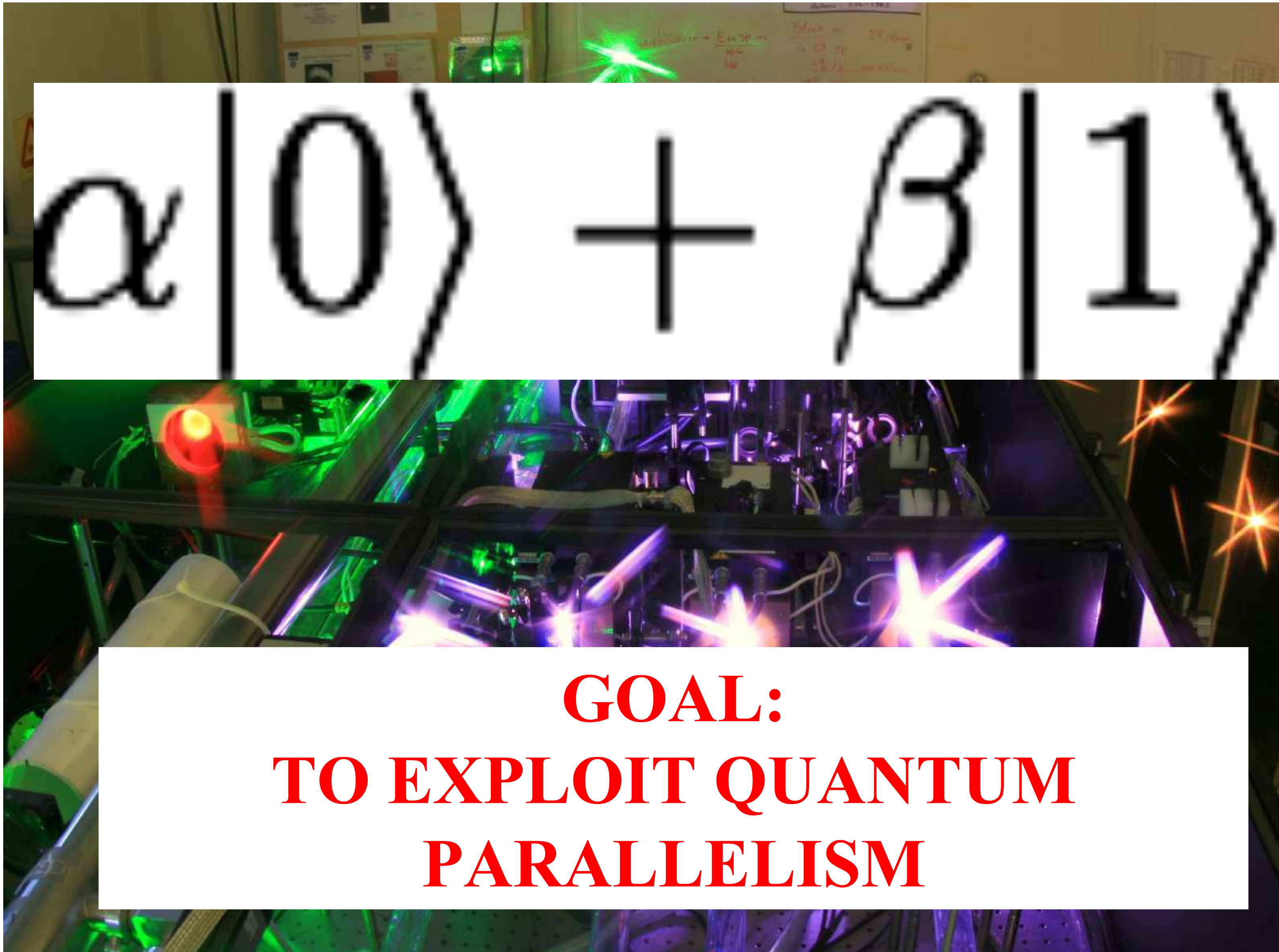
sender module

Distribution of entanglement (Bell's inequality)
air-to-ground via two-link satellite



receiver module

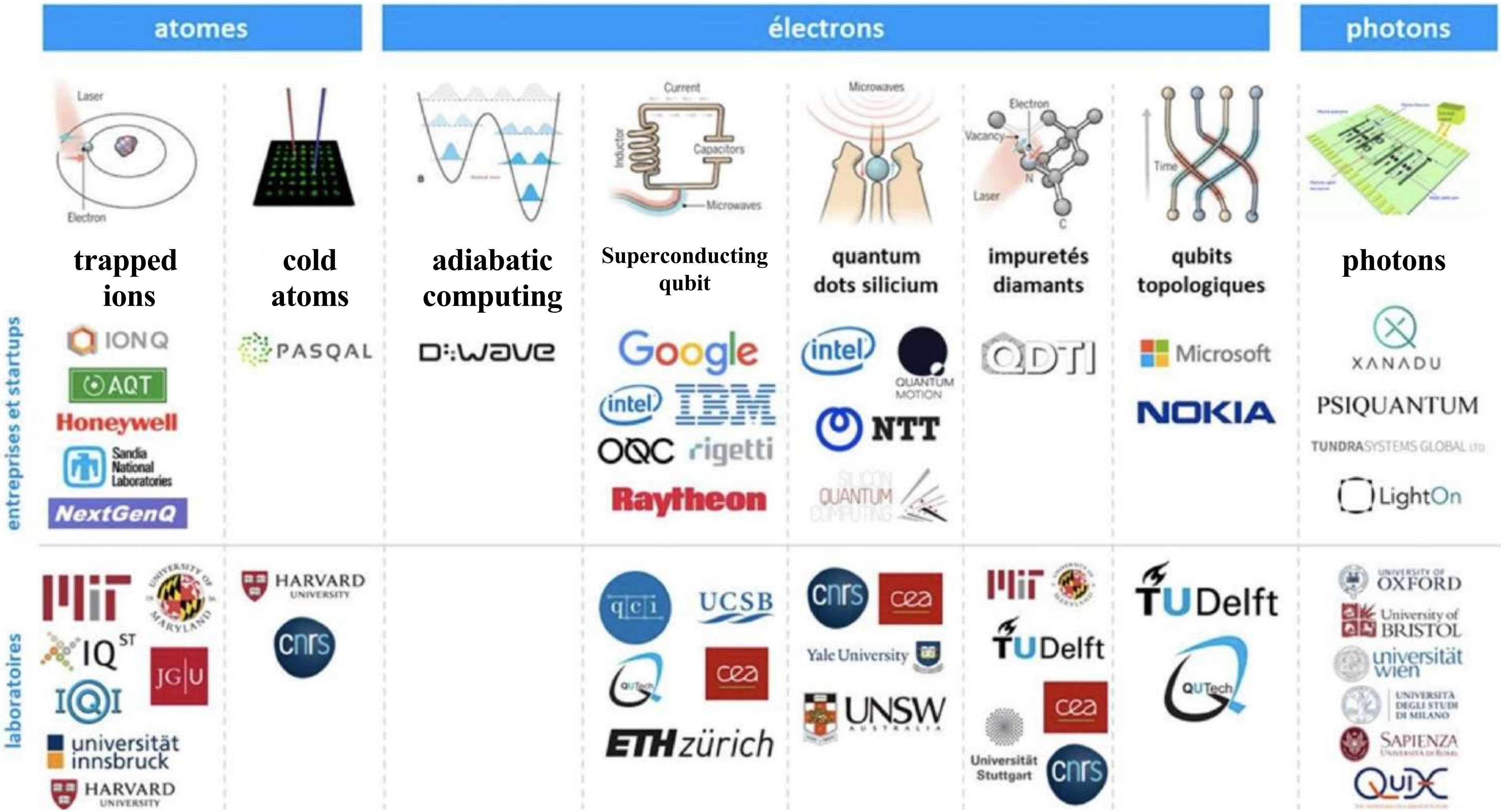
QUBIT (Quantum Bit)



$$\alpha|0\rangle + \beta|1\rangle$$

GOAL:
TO EXPLOIT QUANTUM PARALLELISM

Current platforms and worldwide effort



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Quantum parallelism

Classical	Quantum
1 bit	1 qubit → 2 orthogonal states
0	$\|0\rangle_A + \|1\rangle_A$
2 bit	2 qubit → 4 orthogonal states
01	$\|0\rangle_A\|0\rangle_B + \|0\rangle_A\|1\rangle_B + \|1\rangle_A\|0\rangle_B + \|1\rangle_A\|1\rangle_B$
3 bit	3 qubit → 8 orthogonal states
010	$\|0\rangle_A\|0\rangle_B\|0\rangle_C + \|0\rangle_A\|0\rangle_B\|1\rangle_B + \|0\rangle_A\|1\rangle_B\|0\rangle_C + \|0\rangle_A\|1\rangle_B\|1\rangle_C + \|1\rangle_A\|0\rangle_B\|0\rangle_C + \|1\rangle_A\|0\rangle_B\|1\rangle_C + \|1\rangle_A\|1\rangle_B\|0\rangle_C + \|1\rangle_A\|1\rangle_B\|1\rangle_C$

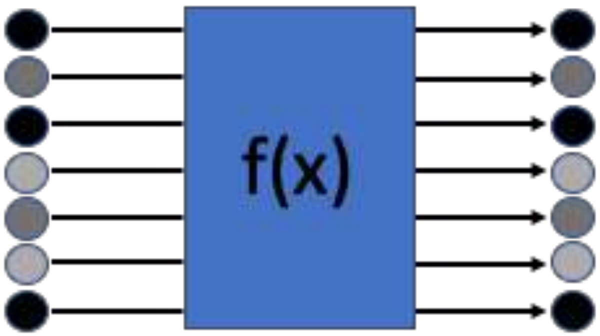
Inaccessibility of all the information of the wave functions

GOOD NEWS....

The quantum computation is parallel over 2^N inputs

<u>Esempio:</u> 3 qubits

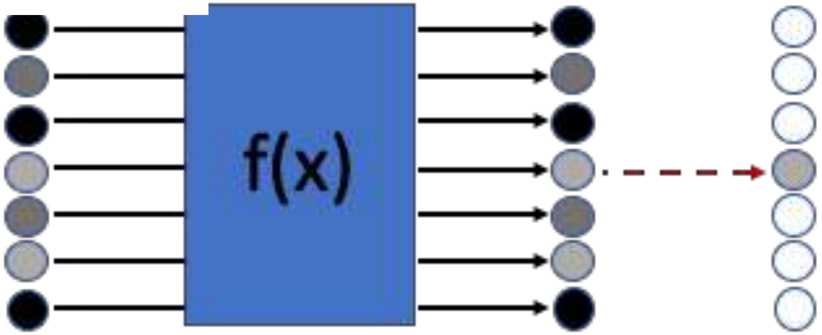
$|\Psi\rangle =$
$a_0|000\rangle + a_1|001\rangle + a_2|010\rangle + a_3|011\rangle +$
$a_4|100\rangle + a_5|101\rangle + a_6|110\rangle + a_7|111\rangle$



BAD NEWS....

The measurement process outputs one state with probability $|a_i|^2$

Es.: $|\Psi\rangle = |000\rangle$



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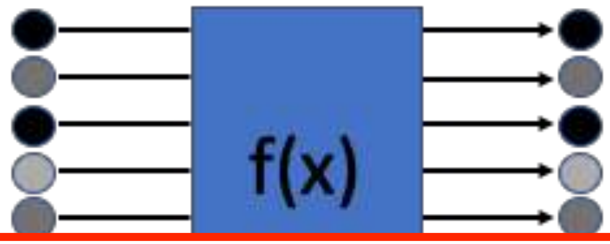
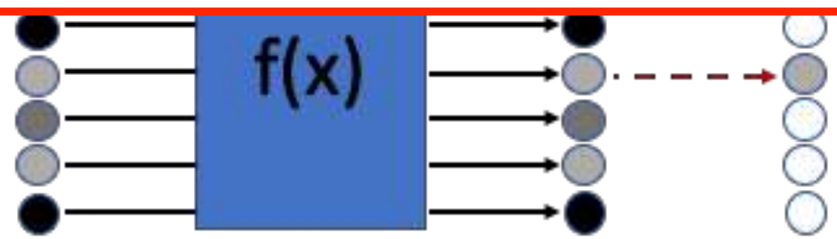


Goal: to exploit quantum parallelism and to extract the desired information from the system

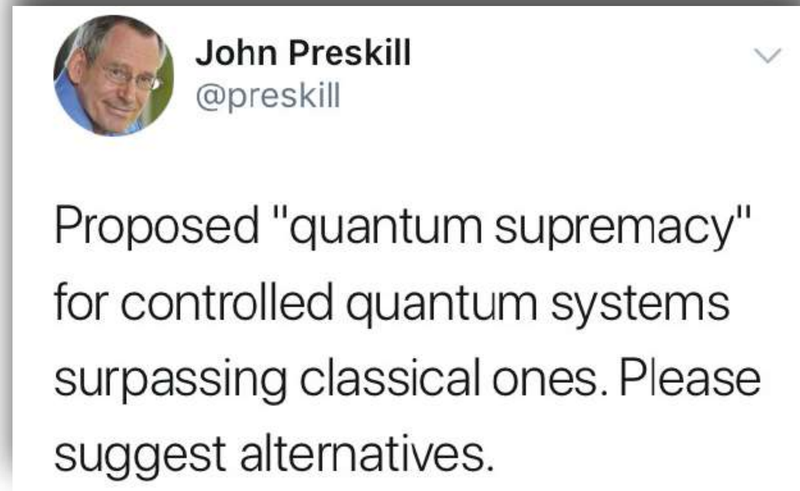
Quantum algorithms need to be processed appropriately

Es.: $|\Psi\rangle = |000\rangle$



How to achieve quantum supremacy?

(Quantum advantage)



How to achieve quantum supremacy?

(Quantum advantage)

John Preskill
@preskill

Proposed "quantum supremacy" for controlled quantum systems surpassing classical ones. Please suggest alternatives.

Nature Special Issue on "Quantum software"

REVIEW

doi:10.1038/nature23458

Quantum computational supremacy

Aram W. Harrow[1] & Ashley Montanaro[2]

The field of quantum algorithms aims to find ways to speed up the solution of computational problems by using a quantum computer. A key milestone in this field will be when a universal quantum computer performs a computational task that is beyond the capability of any classical computer, an event known as quantum supremacy. This would be easier to achieve experimentally than full-scale quantum computing, but involves new theoretical challenges. Here we present the leading proposals to achieve quantum supremacy, and discuss how we can reliably compare the power of a classical computer to the power of a quantum computer.

[1]Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA. [2]School of Mathematics, University of Bristol, Bristol BS8 1TW, UK.

New Scientist

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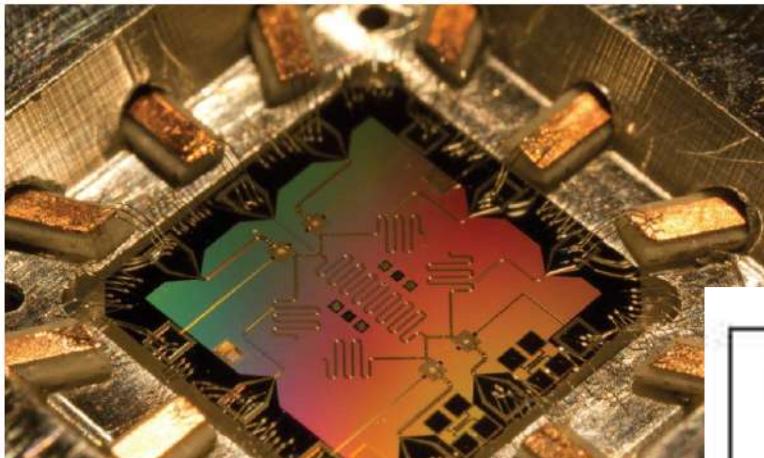
THIS WEEK 31 August 2016

Revealed: Google's plan for quantum computer supremacy

The field of quantum computing is undergoing a rapid shake-up, and engineers at Google have quietly set out a plan to dominate



Intelligent Machines

Google Reveals Blueprint for Quantum Supremacy

The ability of quantum machines to outperform classical computers is called quantum supremacy. Now Google says it has this goal firmly in its sights.

by Emerging Technology from the arXiv October 4, 2017

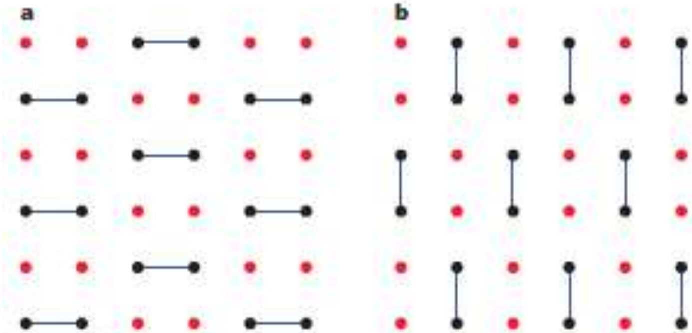
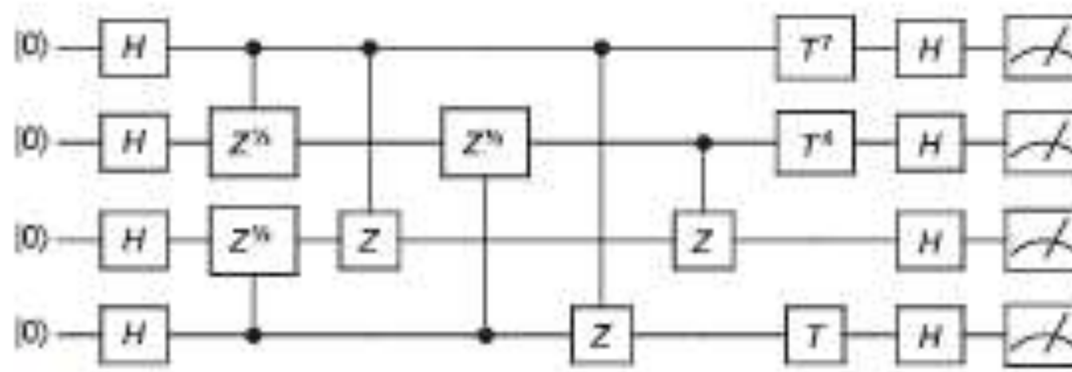


Figure 1 | A 2D lattice of superconducting qubits proposed as a way to demonstrate quantum supremacy. Panels **a** and **b** depict the condition of the lattice at two illustrative timesteps. At each timestep, two-qubit gates (blue) are applied across some pairs of neighbouring qubits, and random one-qubit gates (red) are applied on other qubits. This experiment was proposed[12] by the quantum-AI group at Google; see Box 2 for more details.

BOX 2

Random quantum circuits

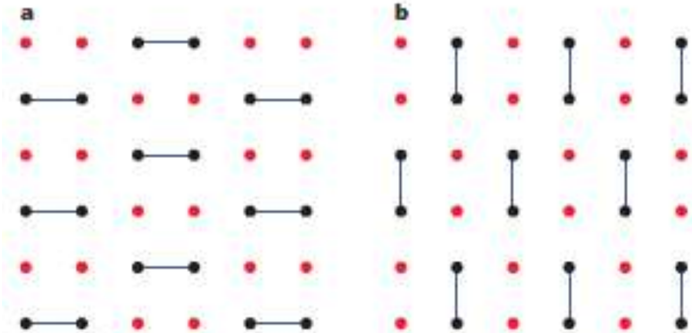


Box 2 Figure | Example of an IQP circuit. Between two columns of Hadamard gates (*H*) is a collection of diagonal gates (*T* and controlled-$\sqrt{Z}$). Although these diagonal gates may act on the same qubit many times

BOX 1

Boson sampling

Box 1 Figure | Diagram of a boson sampling e
(red waveforms) are injected on the left-hand s
beamsplitters (shown black) that is set up to ge
transformation. Photons are detected on the ri
to a probability distribution conjectured to be h
classically. Photonic modes are represented by
are represented by two lines coming together, c
directional couplers in an integrated photonic c



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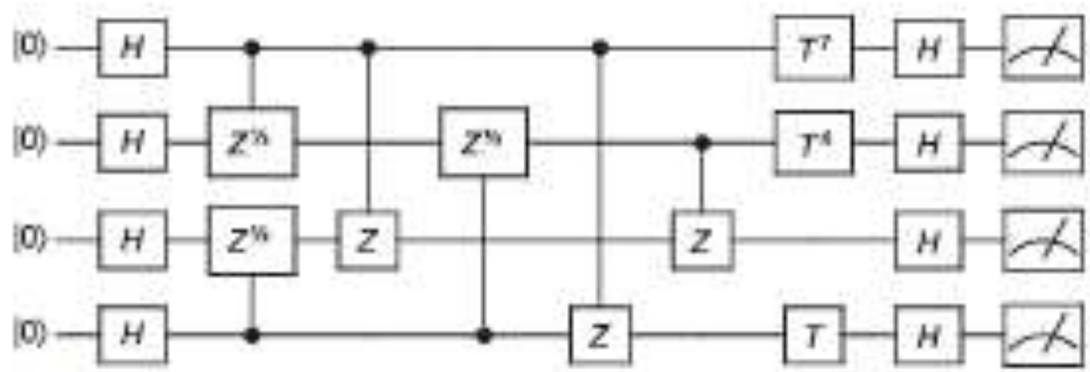

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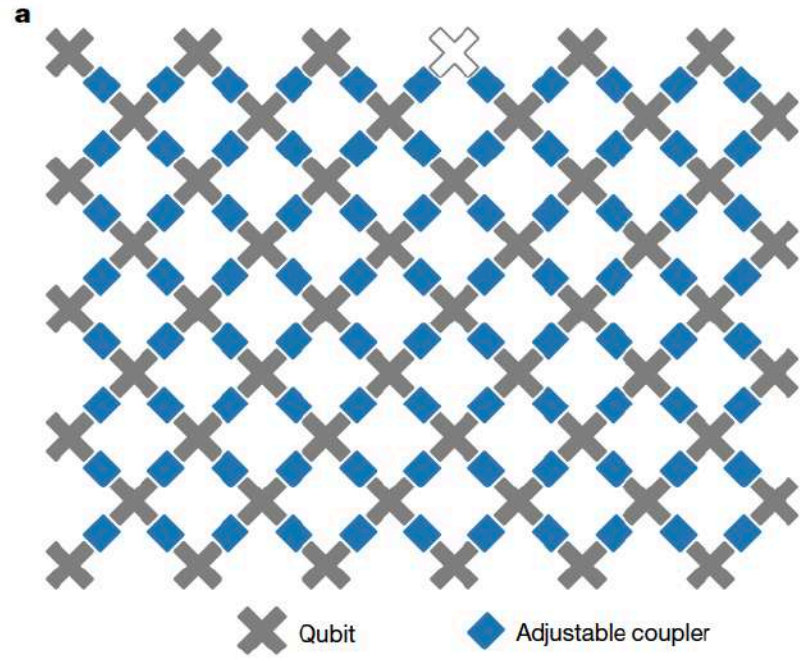
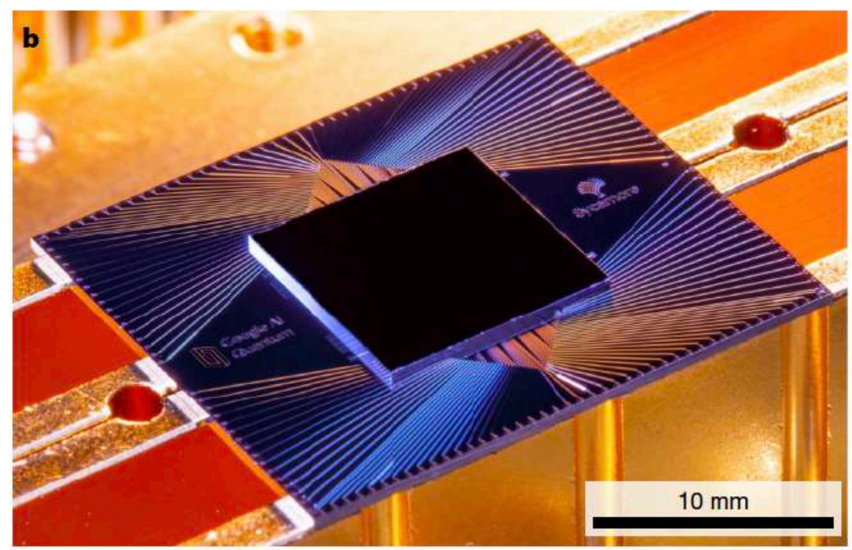
nature
International journal of science

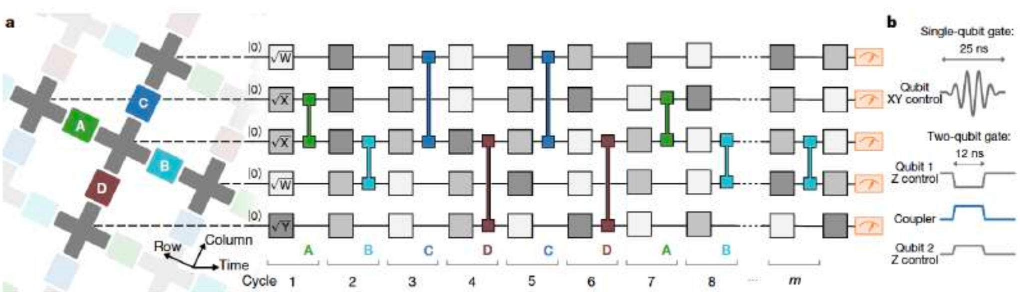
Article | Published: 23 October 2019

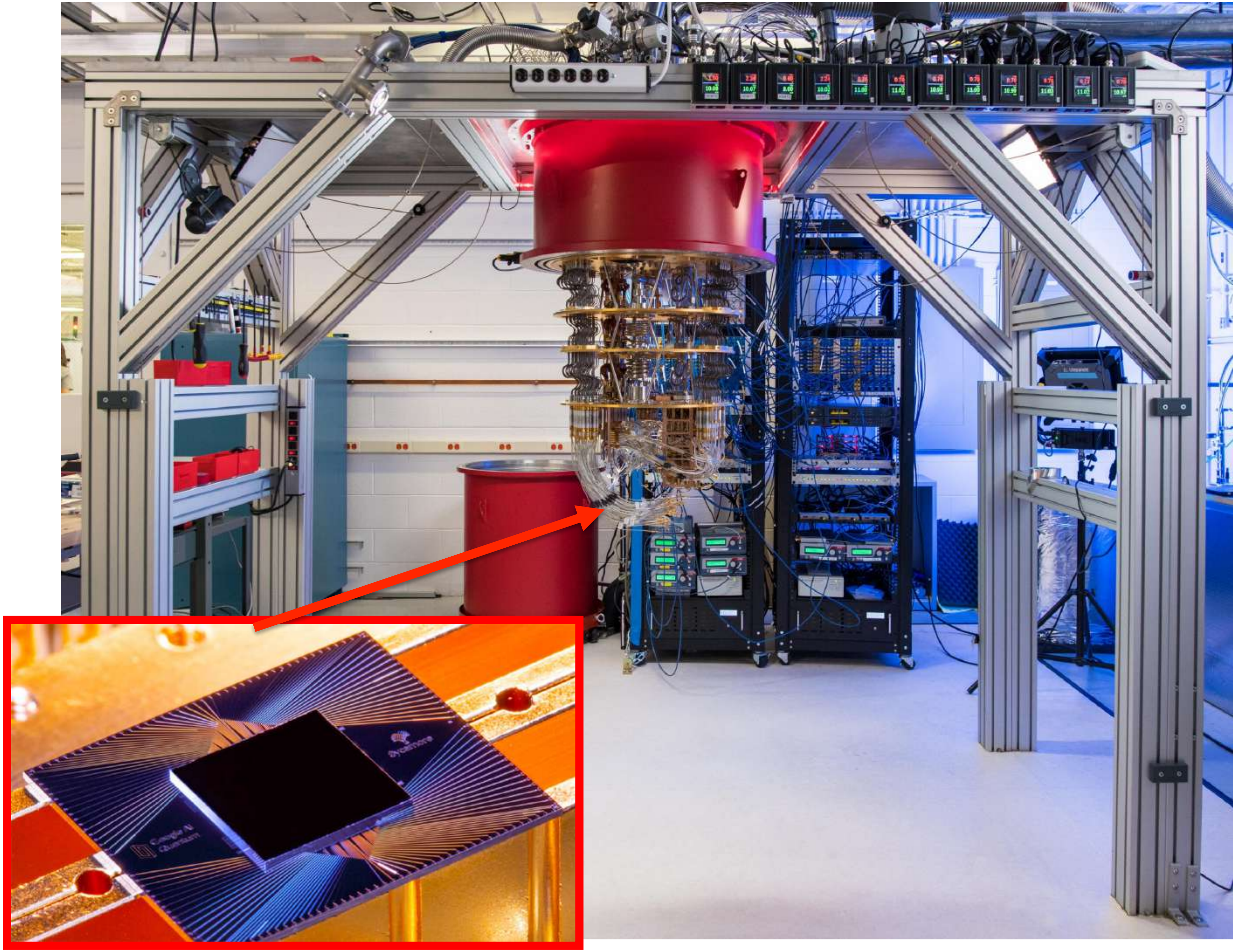
Quantum supremacy using a programmable superconducting processor

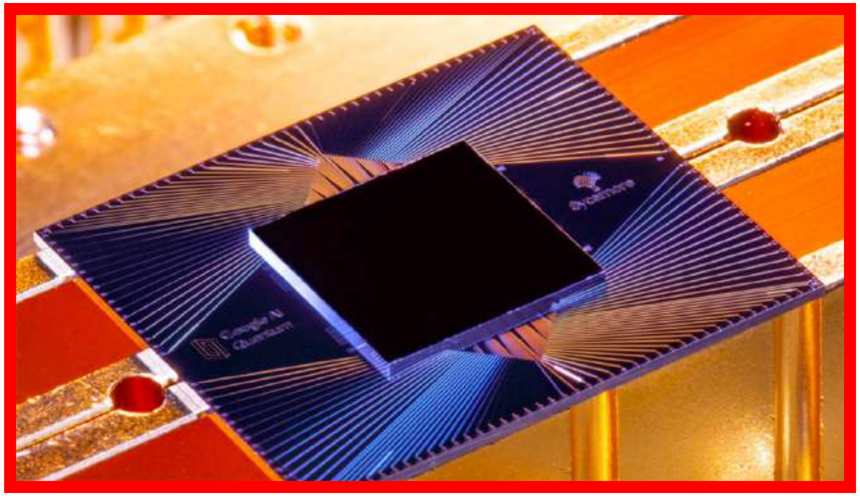
Frank Arute, Kunal Arya, […] John M. Martinis








Sycamore
Google AI Quantum

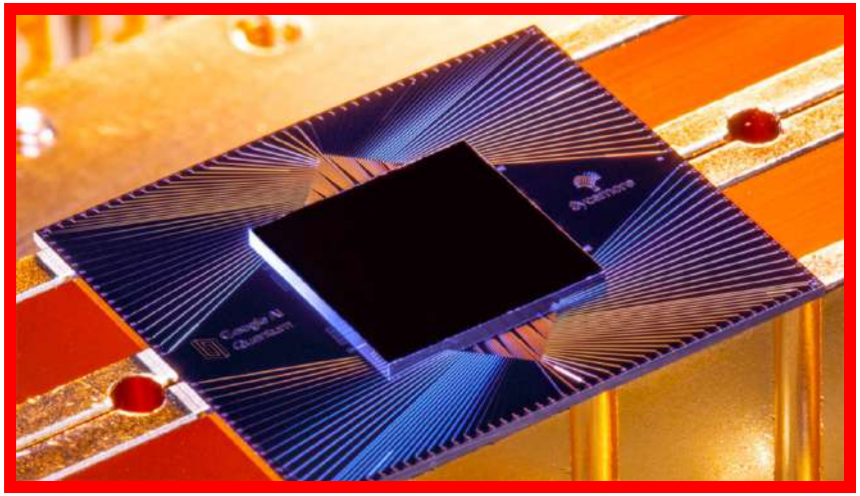


1 qubit —> dimension of Hilbert space =2

2 qubit —> dimension of Hilbert space =2^{2}=4

3 qubit —> dimension of Hilbert space =2^{2}=8

The size of Hilbert's space grows exponentially with the number of qubits



53 qubit:

dimension of Hilbert space

$$2^{53} = 1.8 \times 10^{16}$$

1 qubit —> dimension of Hilbert space =2

2 qubit —> dimension of Hilbert space $=2^2=4$

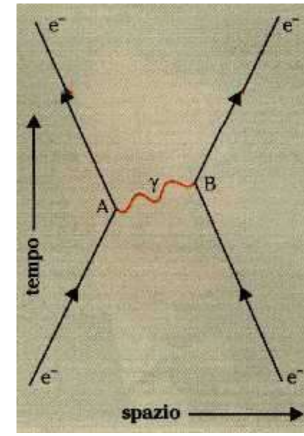
3 qubit —> dimension of Hilbert space $=2^2=8$

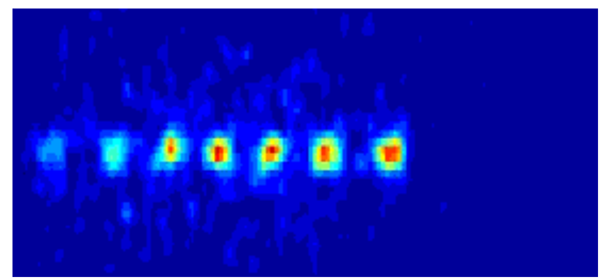
The size of Hilbert's space grows exponentially with the number of qubits

MACROSCOPIC WORLD

CLASSICAL PHYSICS

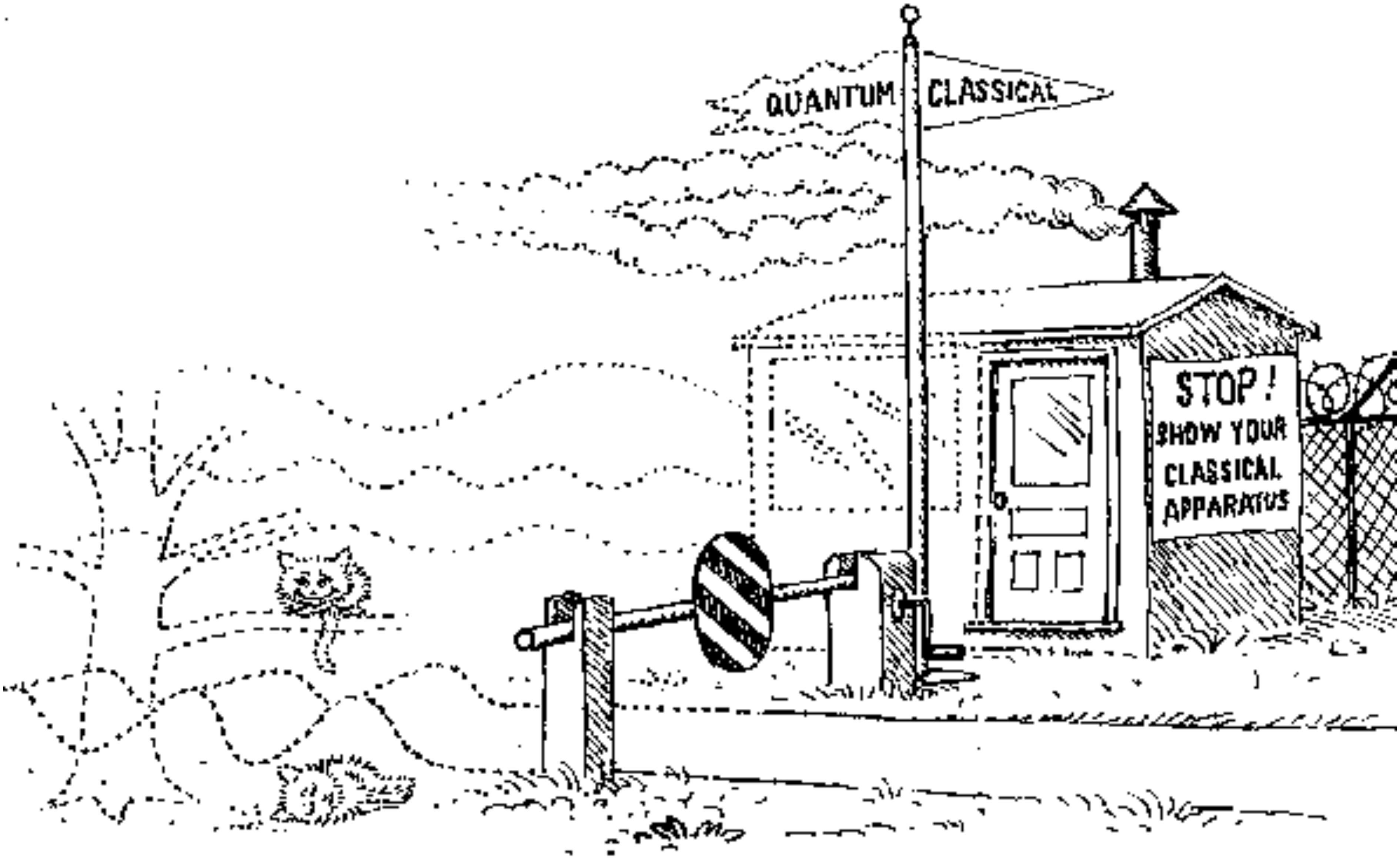
MICROSCOPIC WORLD





QUANTUM PHYSICS

The boundary between quantum and classical world

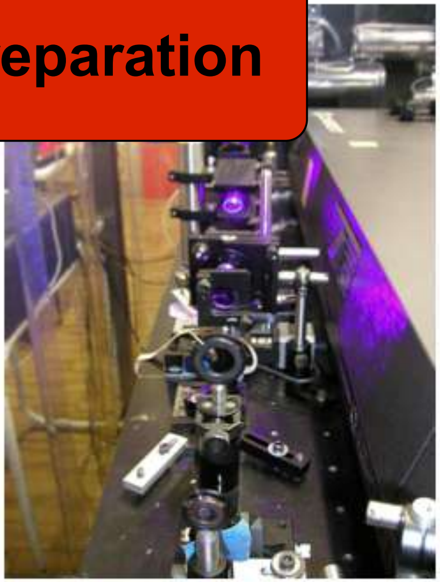


Zurek, Physics Today, October 1991, page 38

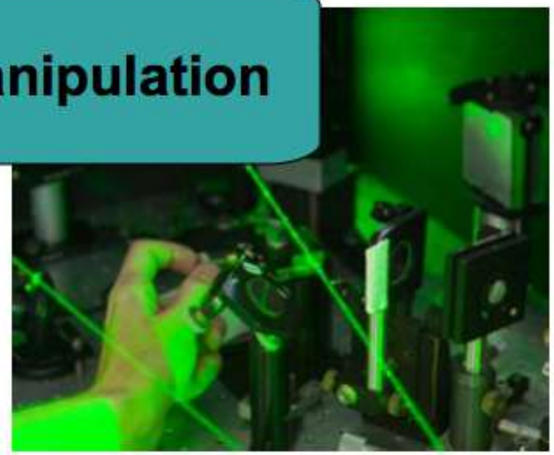
Schrodinger's Cat

Integrated quantum photonics

Preparation



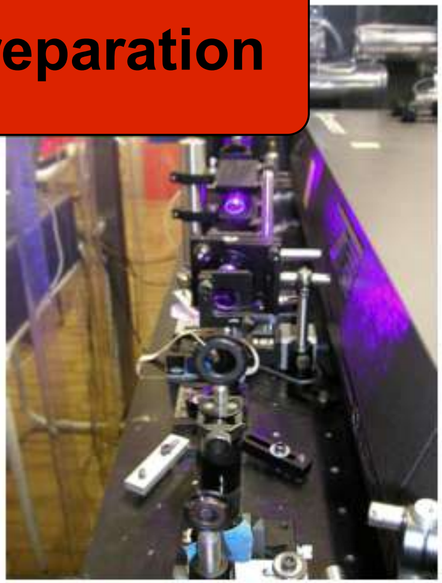
Manipulation



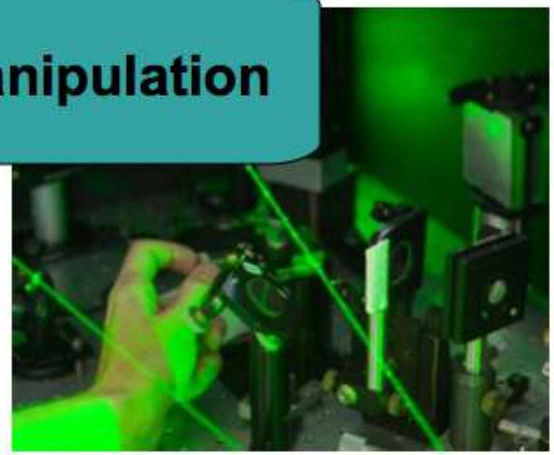
Detection

Integrated quantum photonics

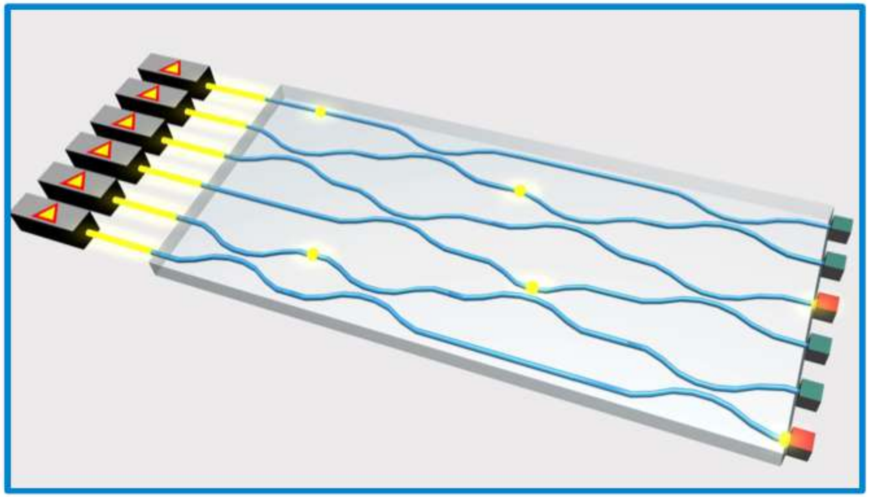
Preparation



Manipulation



Detection



- Single photon sources
- Manipulation
- Single photon detectors
ON THE SAME CHIP

Thank you!

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www.3dquest.eu

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Enjoy life, enjoy quantum!