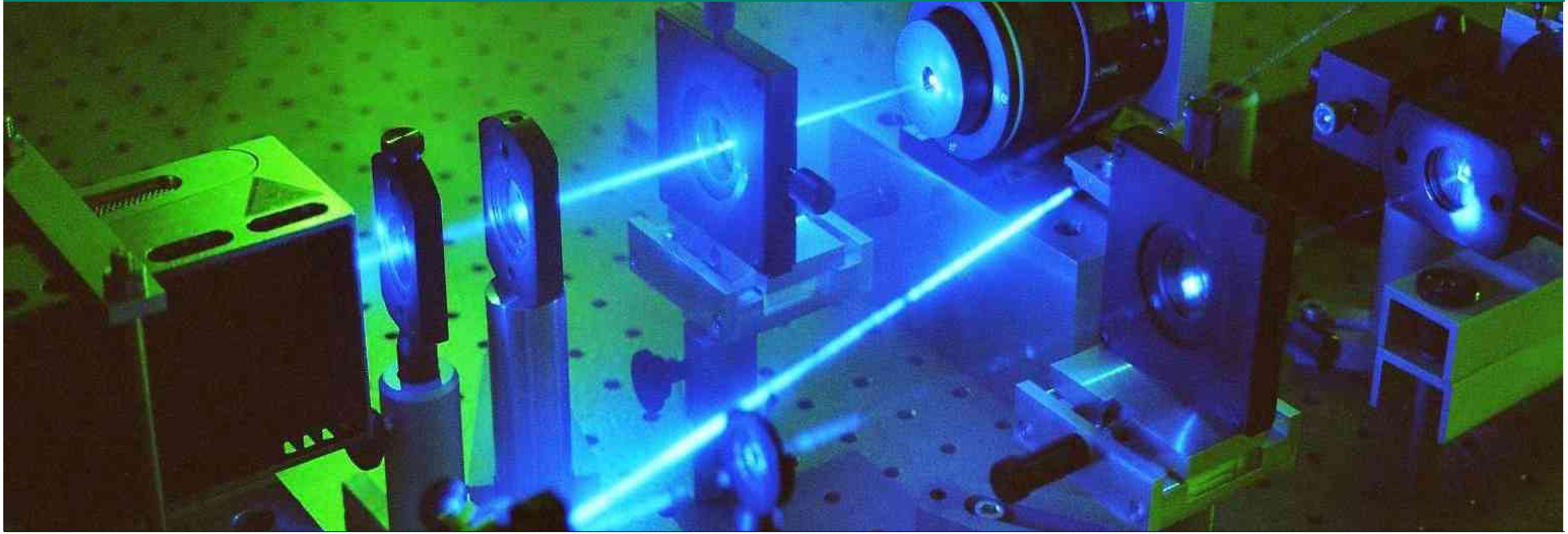
Quantum Key Distribution - what is it and why should you care?

Thomas Walther
Laser and Quantum Optics
TU Darmstadt



Physics in 1900

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Classical Mechanics

Translation, Rotation, Pendulum, Planetary Motion, Gravity,

Newton, Kepler, Copernikus, Galilei, …

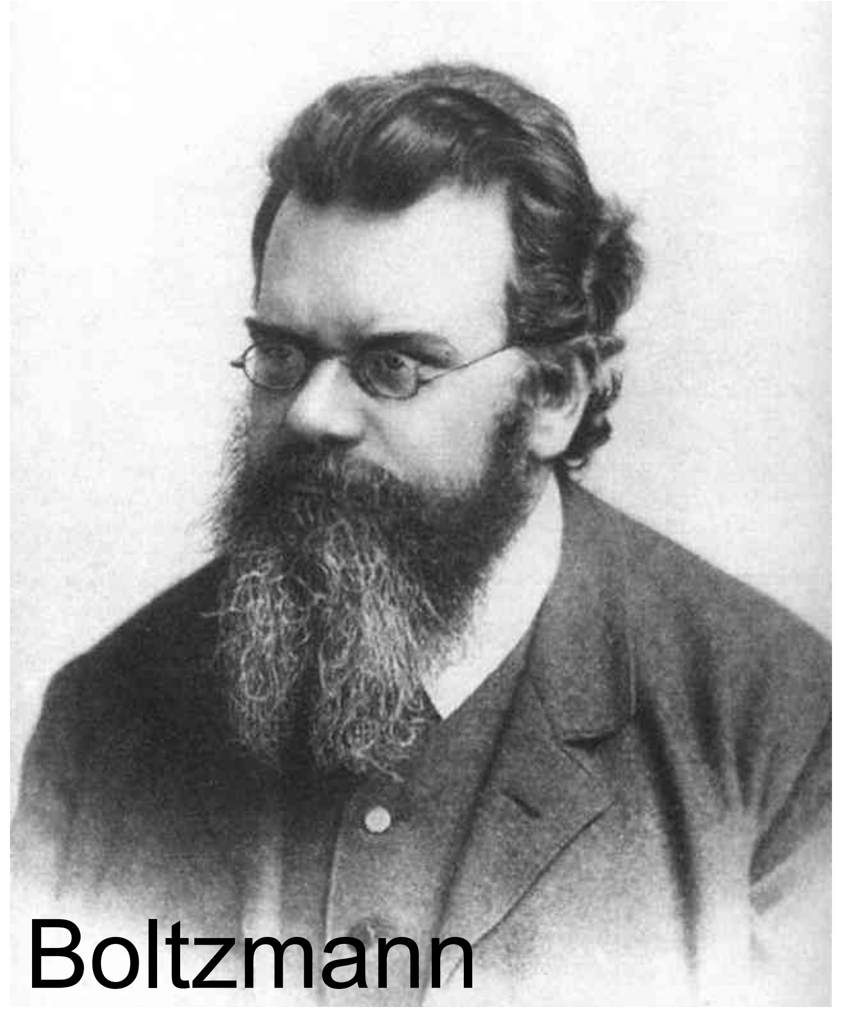
Kinetic Gas Theory

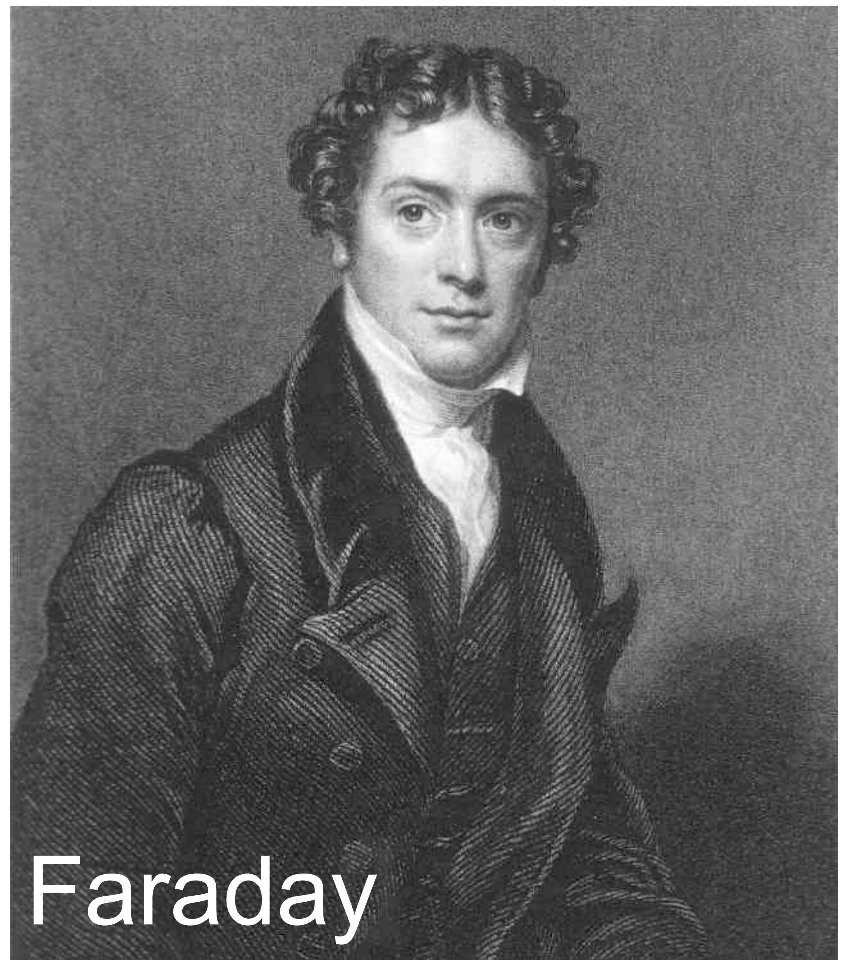
Explanation of Heat with Elements of Classical Mechanics

Electric and Magnetic Phenomena

Electric Fields, Magnetic Fields, Current, Charge, Induction

Faraday, Maxwell, Hertz, Gauss, Ampere, Volta u.a.





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Physics in 1900

- General opinion
  - Basic theories known
- Only few missing pieces
  - more experiments will fill voids

Blackbody Radiation

Historical Overview

CROSSING

Year	Theory	Experiment
1885		Balmer Series
1900	Quantization Hypothesis (Planck)	
1902		Experiments Photo effect (Lenard)
1905	Photo effect (Einstein)	
1909		Single Photon Experiments (Taylor)
1911		Cloud chamber
1913	Atomic modell (Bohr)	
1914		Franck-Hertz Experiment
1916	Atomic model (Sommerfeld)	
1921		Stern-Gerlach Experiment
1922		Compton effect
1924	Wave character of matter (deBroglie)	
1925	Spin, Formulations of QM by Schrödinger, Heisenberg, Dirac	
1926	Schrödinger Equation	Electron interference
1935	Entanglement, Einstein-Podolsky-Rosen-Paradox	Discovery of the Neutron

Historical Overview

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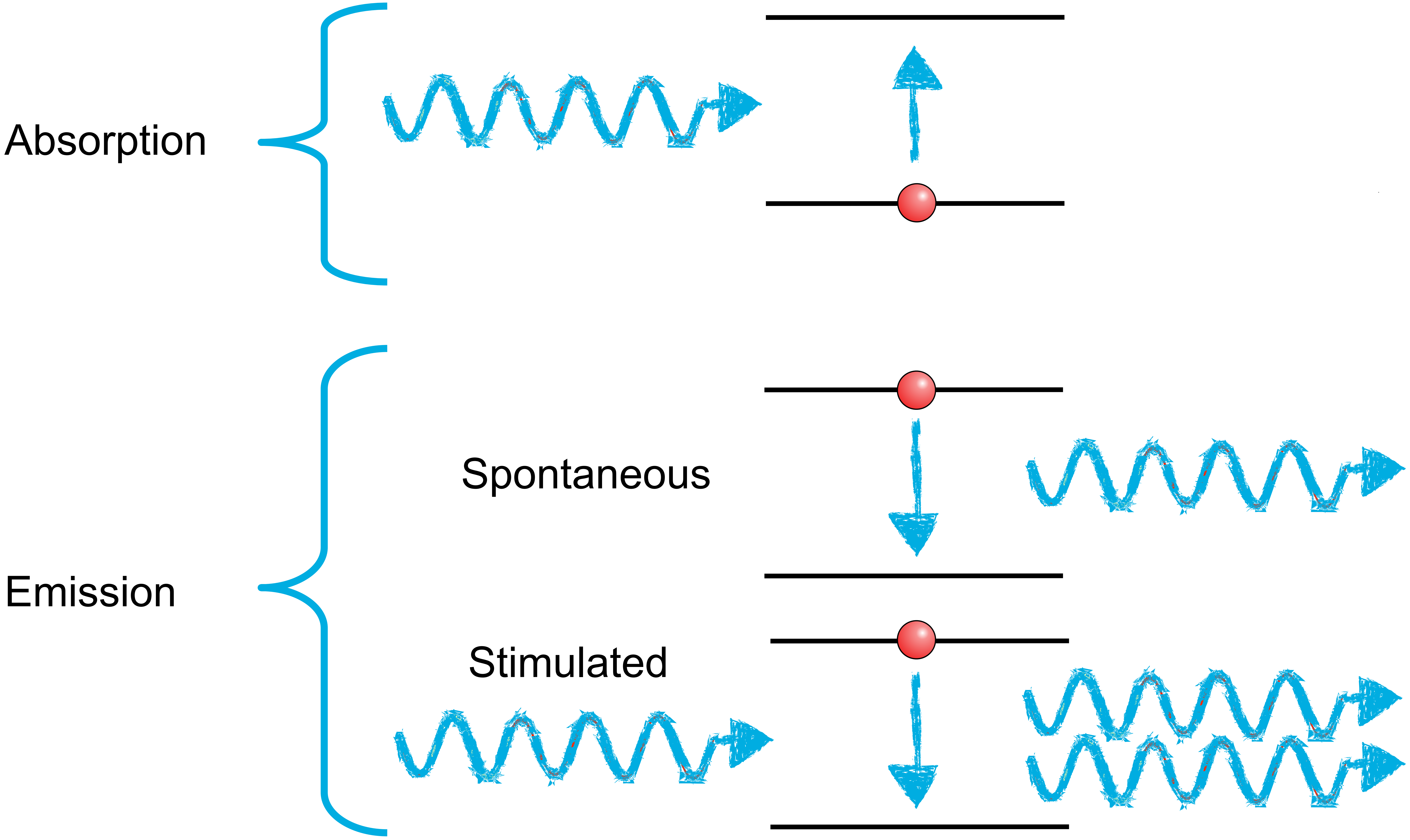
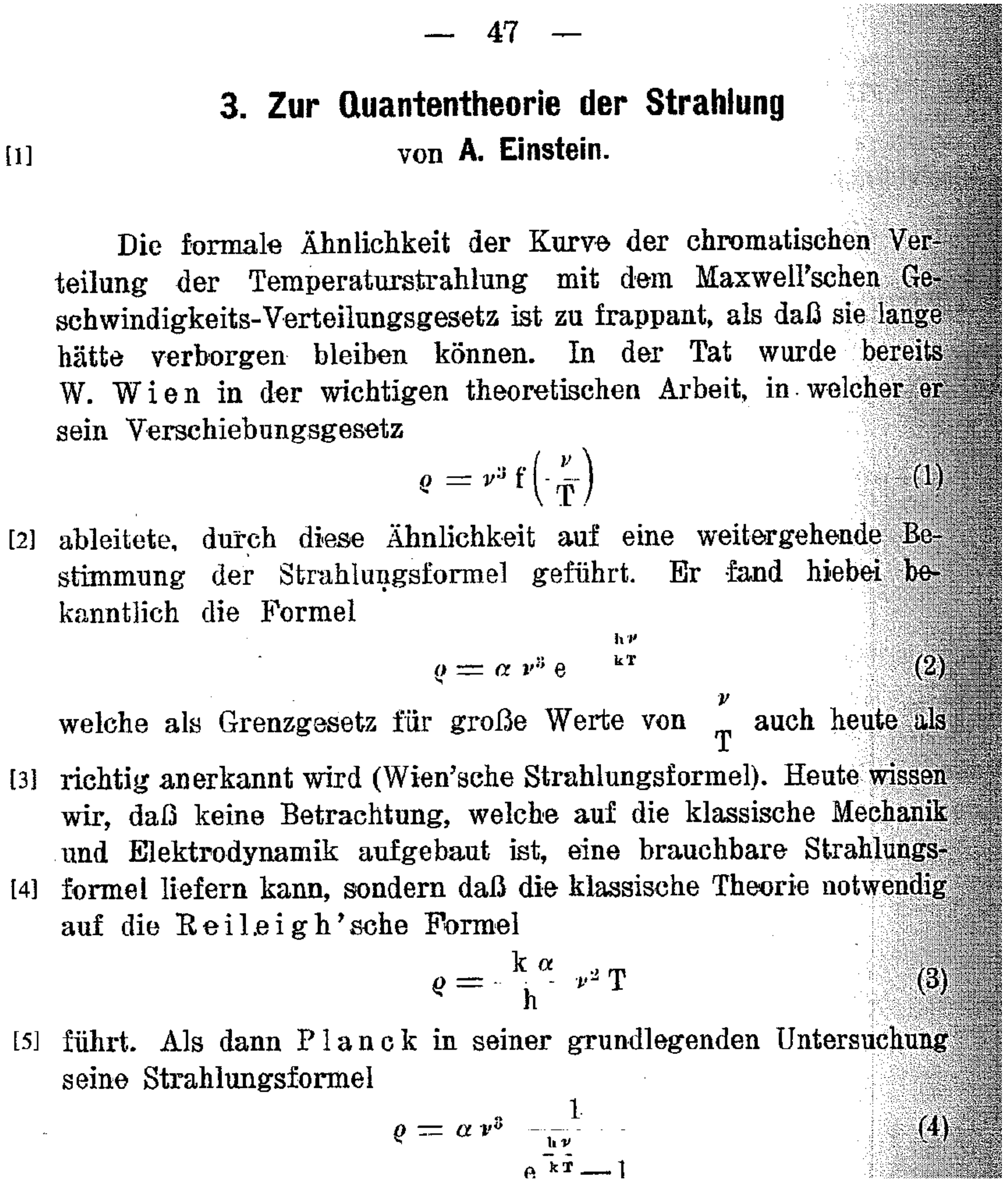
Quantum Physics: Interaction of Light with Atoms (Einstein 1917)





— 47 —

3. Zur Quantentheorie der Strahlung

von **A. Einstein.**

[1]

Die formale Ähnlichkeit der Kurve der chromatischen Verteilung der Temperaturstrahlung mit dem Maxwell'schen Geschwindigkeits-Verteilungsgesetz ist zu frappant, als daß sie lange hätte verborgen bleiben können. In der Tat wurde bereits W. Wien in der wichtigen theoretischen Arbeit, in welcher er sein Verschiebungsgesetz

$$\varrho = \nu^3 f\left(\frac{\nu}{T}\right) \quad (1)$$

[2] ableitete, durch diese Ähnlichkeit auf eine weitergehende Bestimmung der Strahlungsformel geführt. Er fand hiebei bekanntlich die Formel

$$\varrho = \alpha \nu^3 e^{-\frac{h\nu}{kT}} \quad (2)$$

welche als Grenzgesetz für große Werte von $\frac{\nu}{T}$ auch heute als

[3] richtig anerkannt wird (Wien'sche Strahlungsformel). Heute wissen wir, daß keine Betrachtung, welche auf die klassische Mechanik und Elektrodynamik aufgebaut ist, eine brauchbare Strahlungs-

[4] formel liefern kann, sondern daß die klassische Theorie notwendig auf die Reileigh'sche Formel

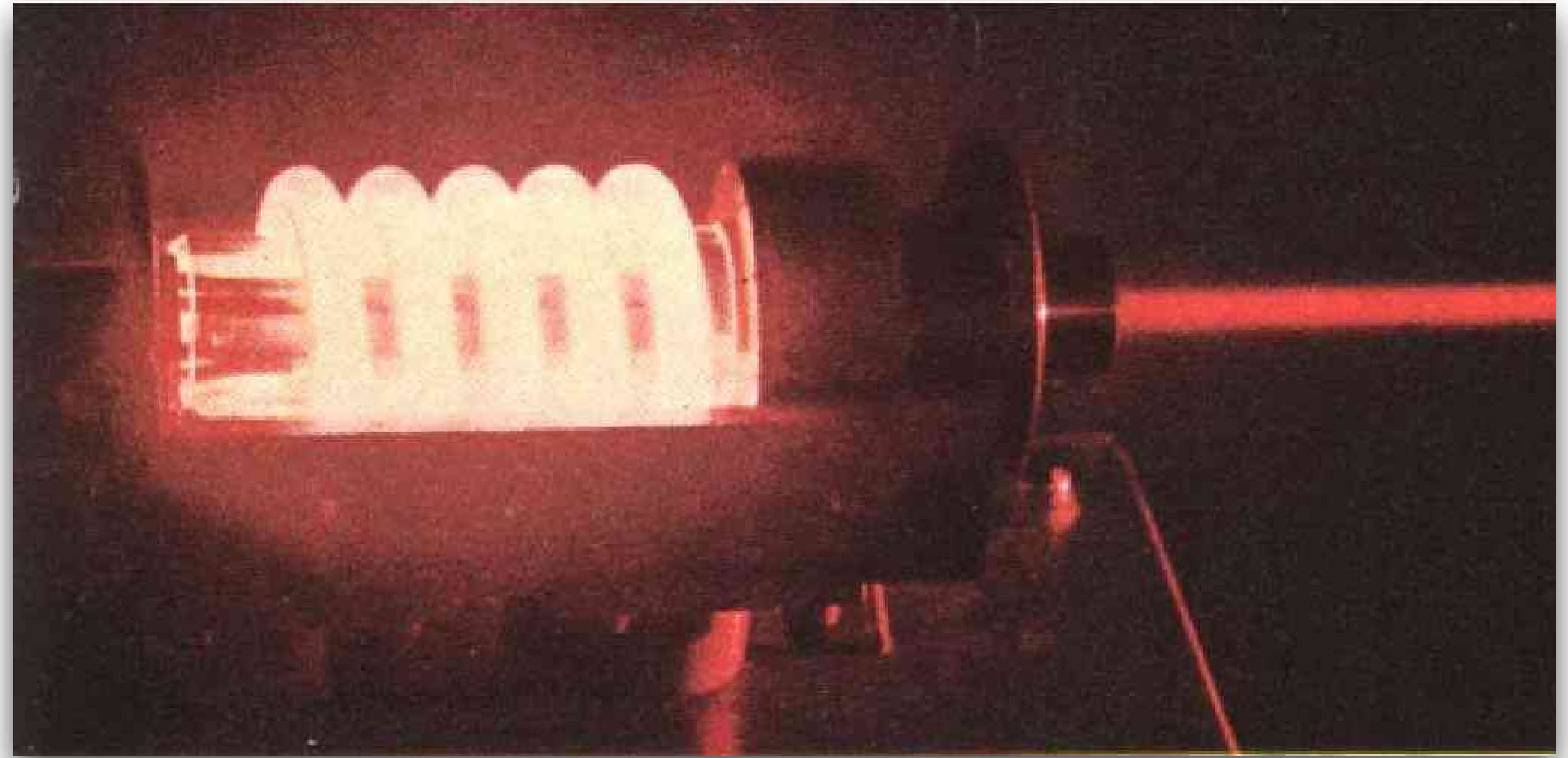
$$\varrho = \frac{k\alpha}{h} \nu^2 T \quad (3)$$

[5] führt. Als dann Planck in seiner grundlegenden Untersuchung seine Strahlungsformel

$$\varrho = \alpha \nu^3 \frac{1}{e^{\frac{h\nu}{kT}} - 1} \quad (4)$$

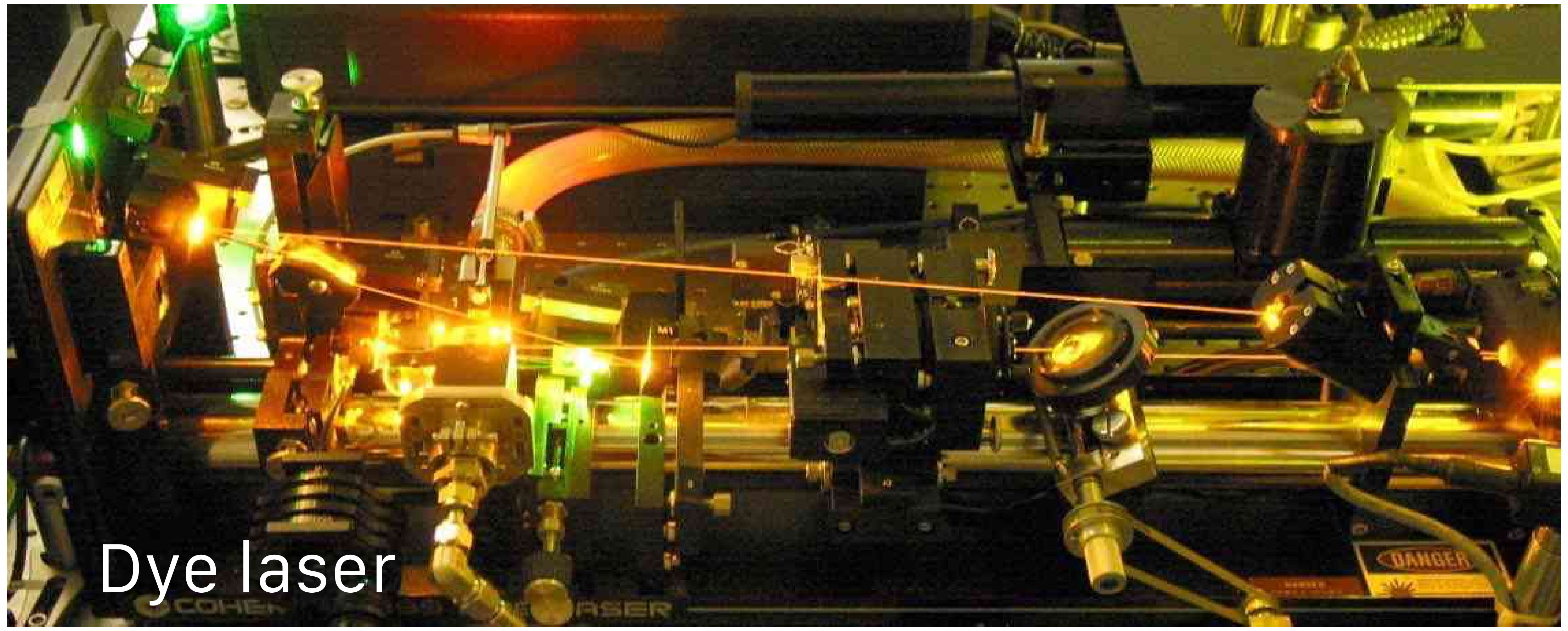
A. Einstein, Physikalische Zeitschrift **18**, 121-128 (1917)

16. May 1960 - the first laser

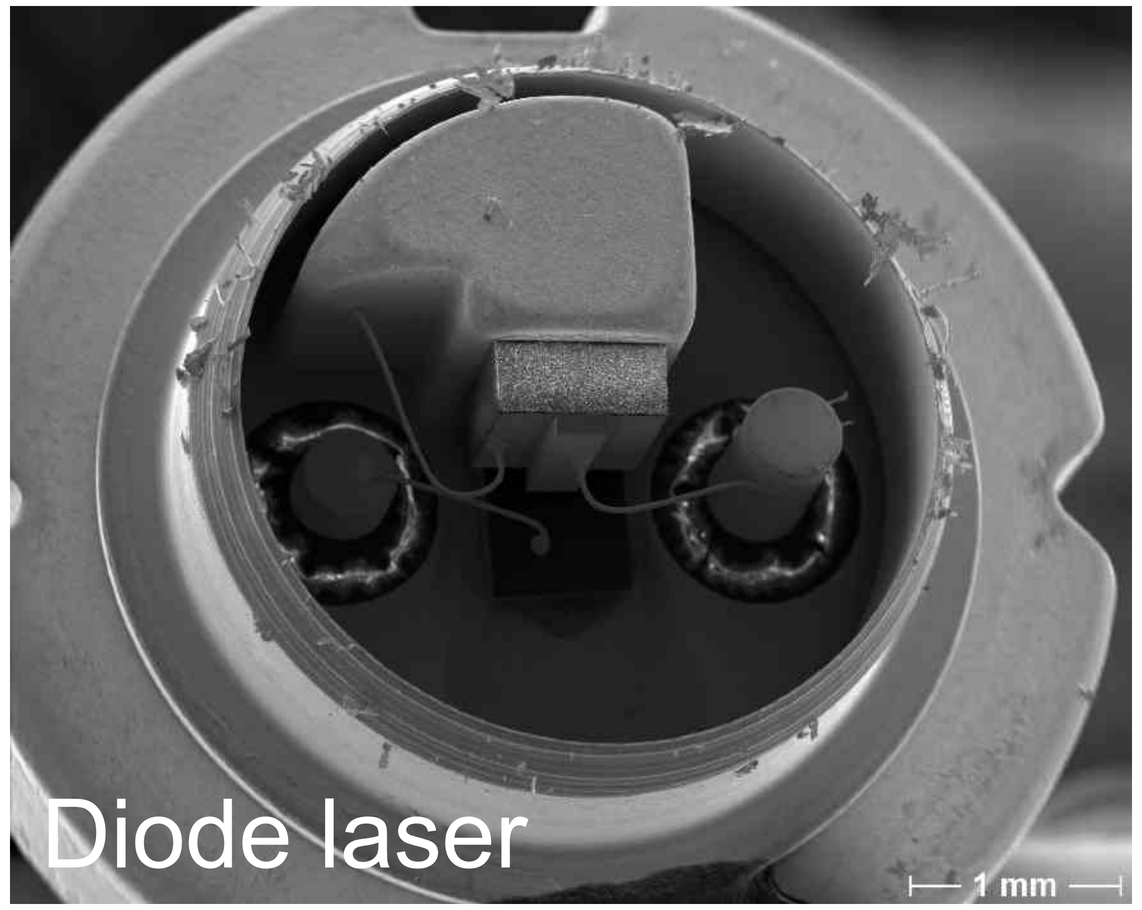


Theodore Maiman
Inventor of the Ruby Laser (1960)

Lasers Today

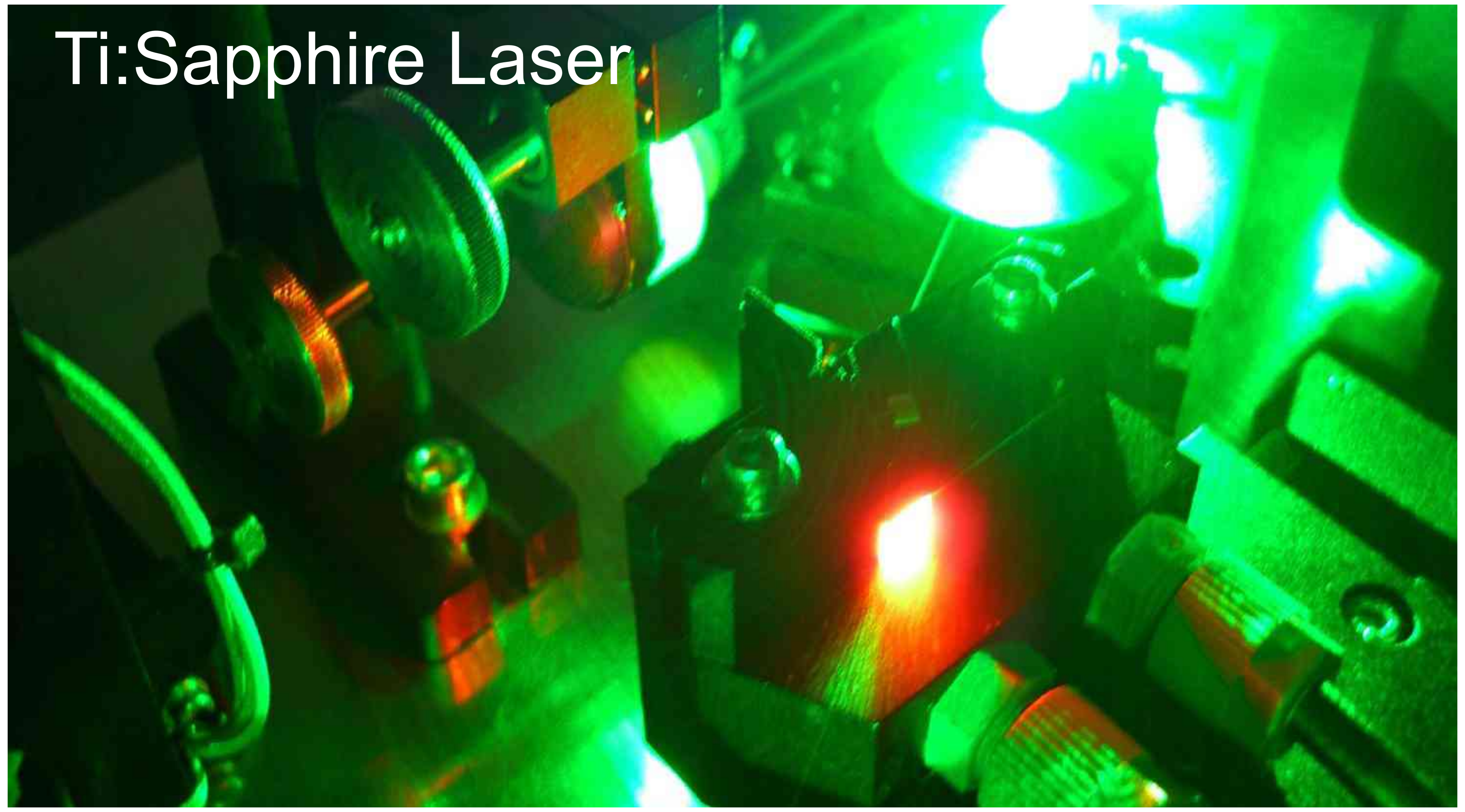


Dye laser

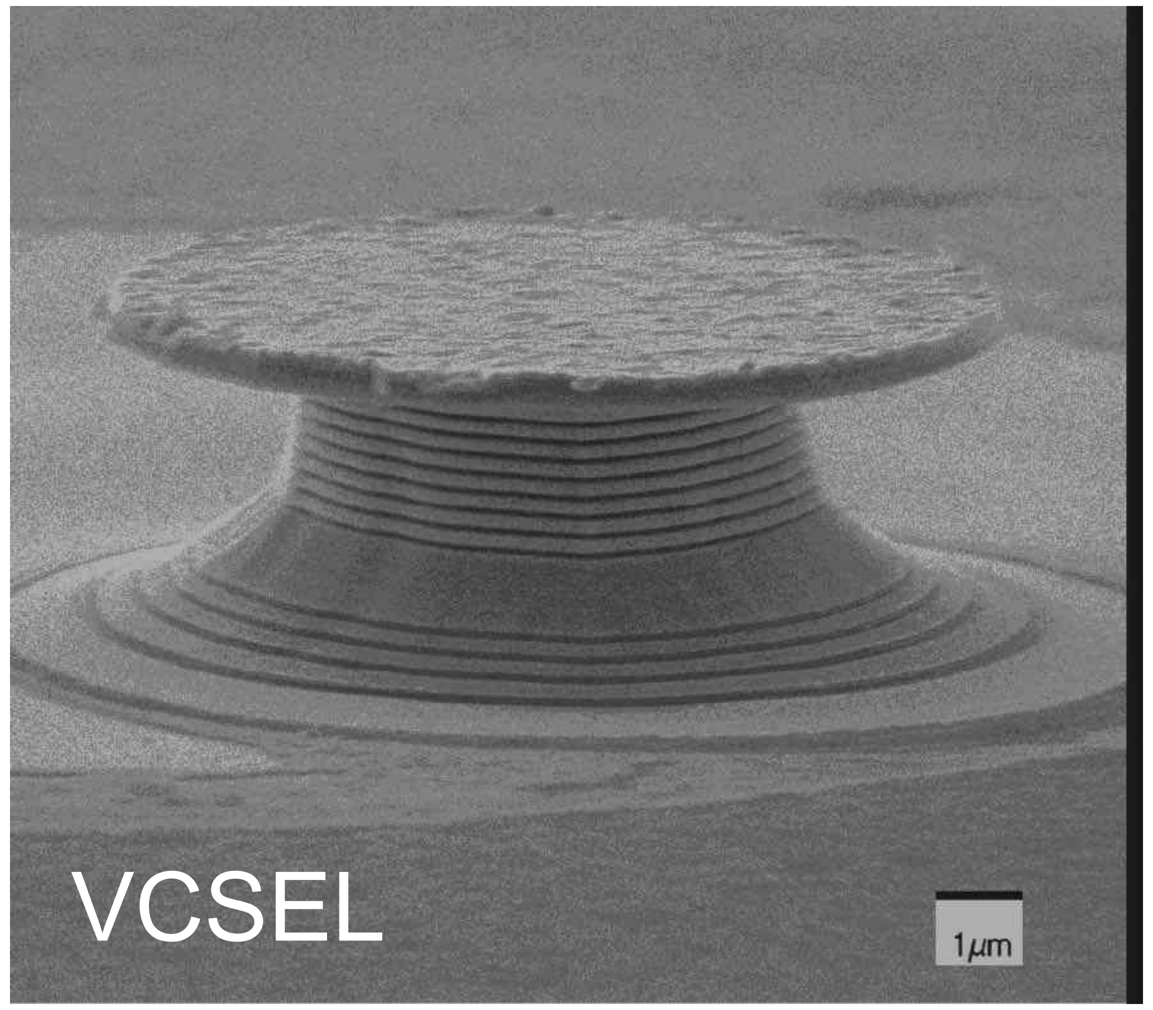


Diode laser

NIF, Livermore, California

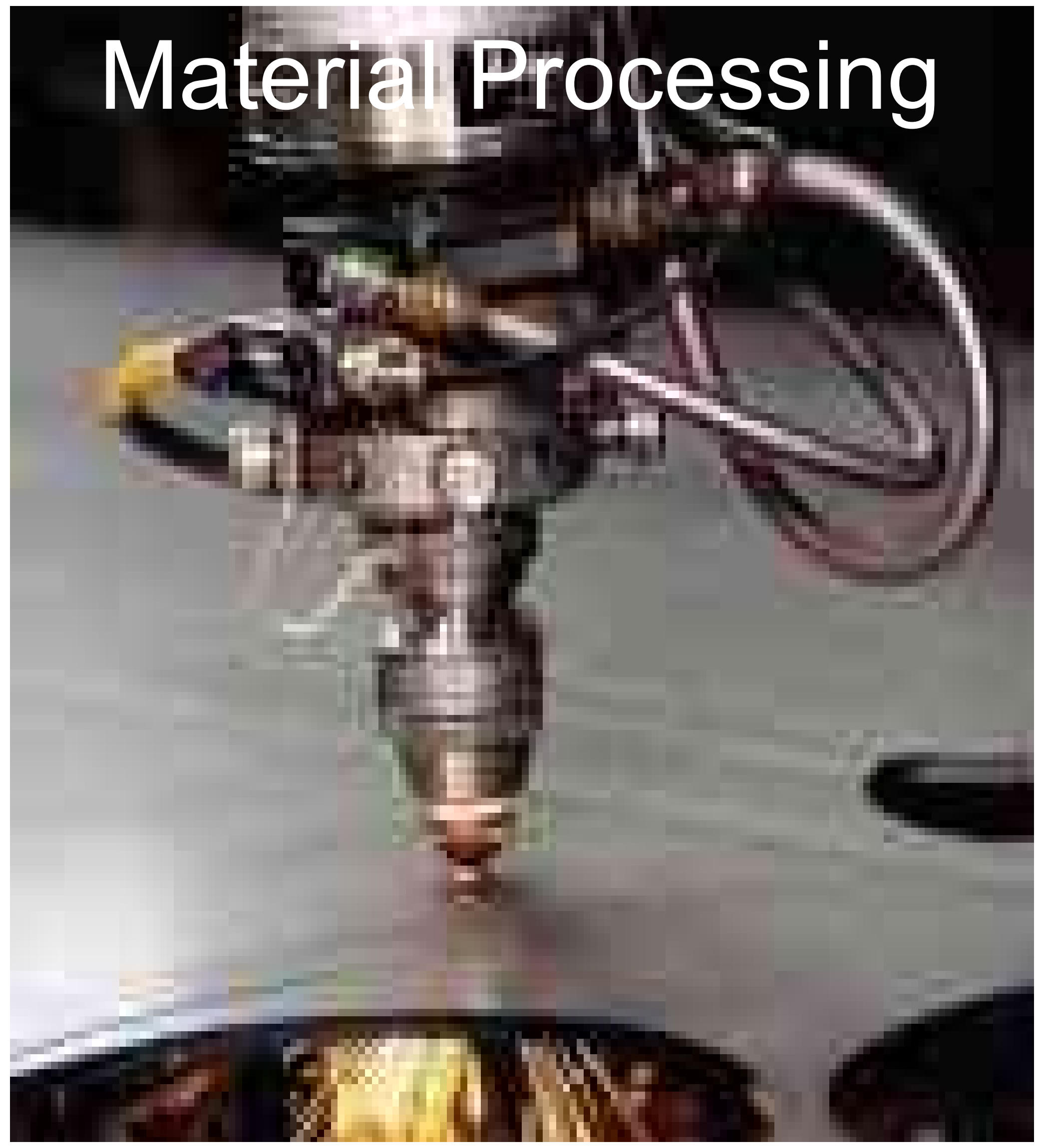


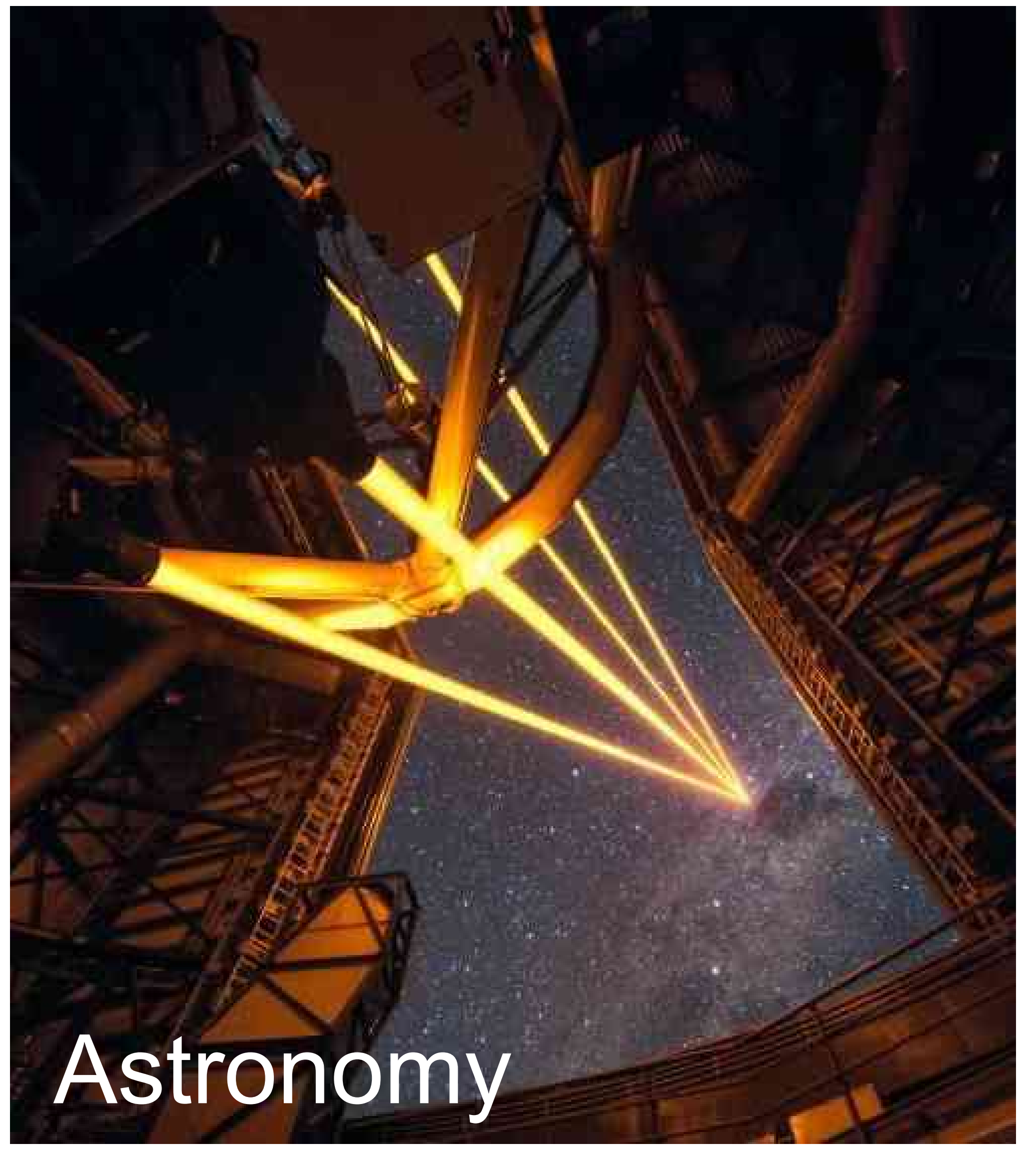
Ti:Sapphire Laser

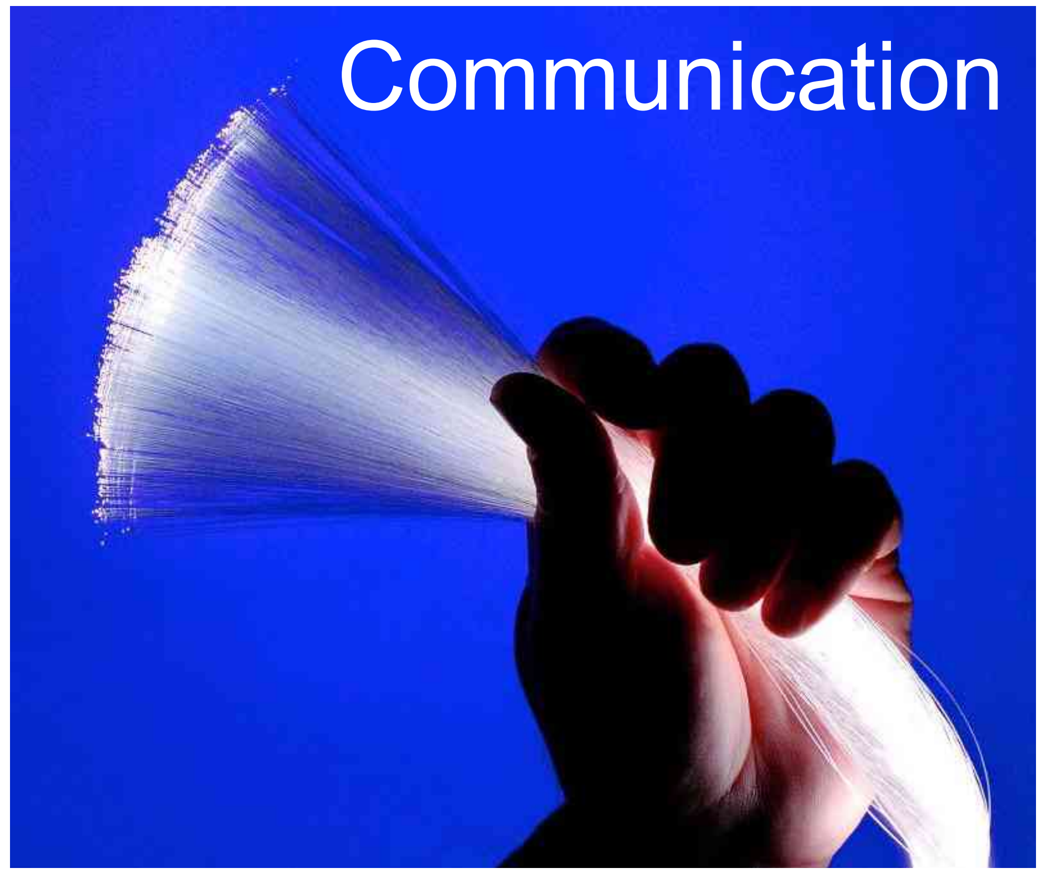


VCSEL

Ubiquity of the Laser







Sources: Wikimedia, NASA, Spiegel, Alsglobal

Other Technical Developments based on QM knowledge (Examples)

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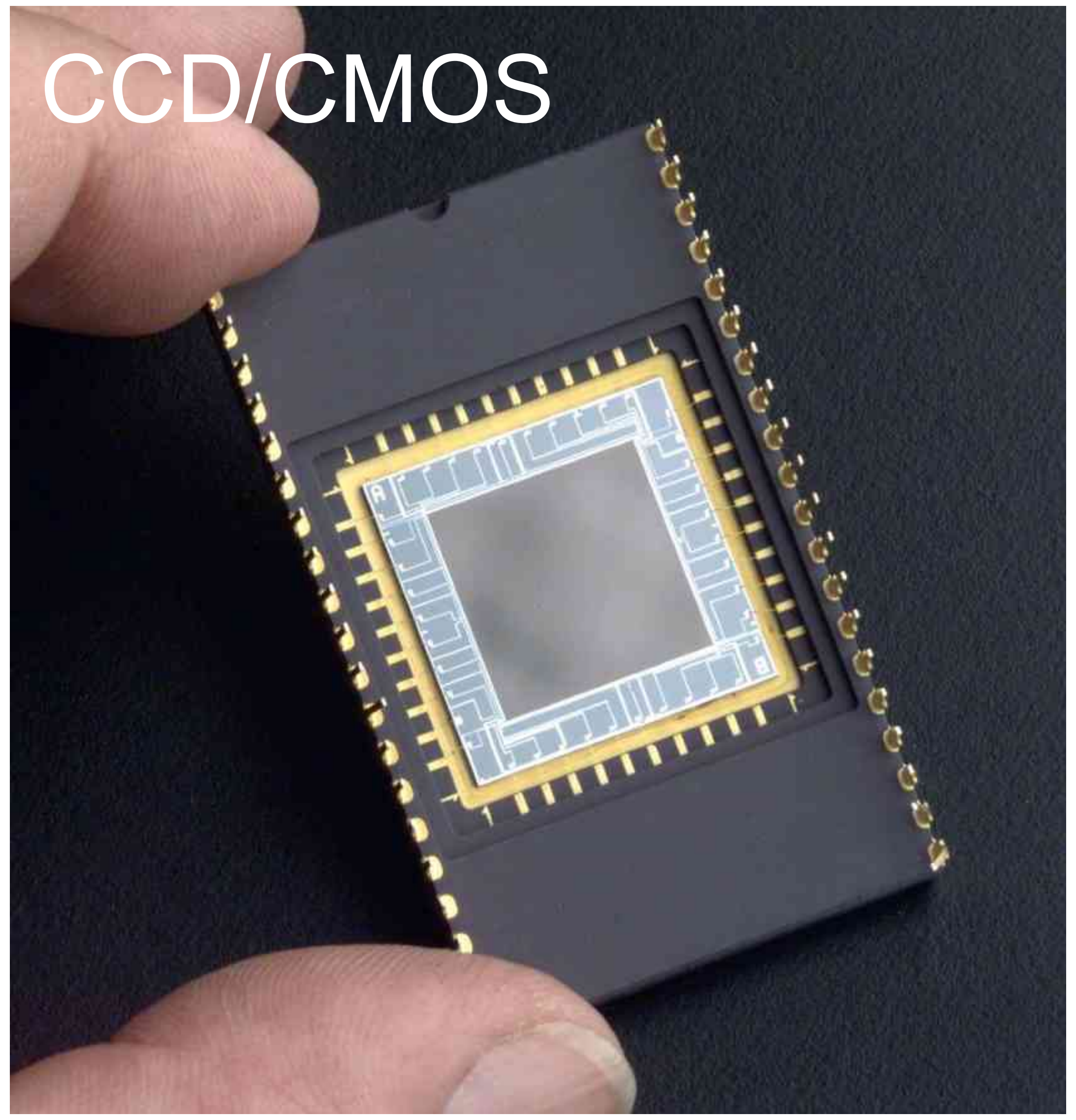
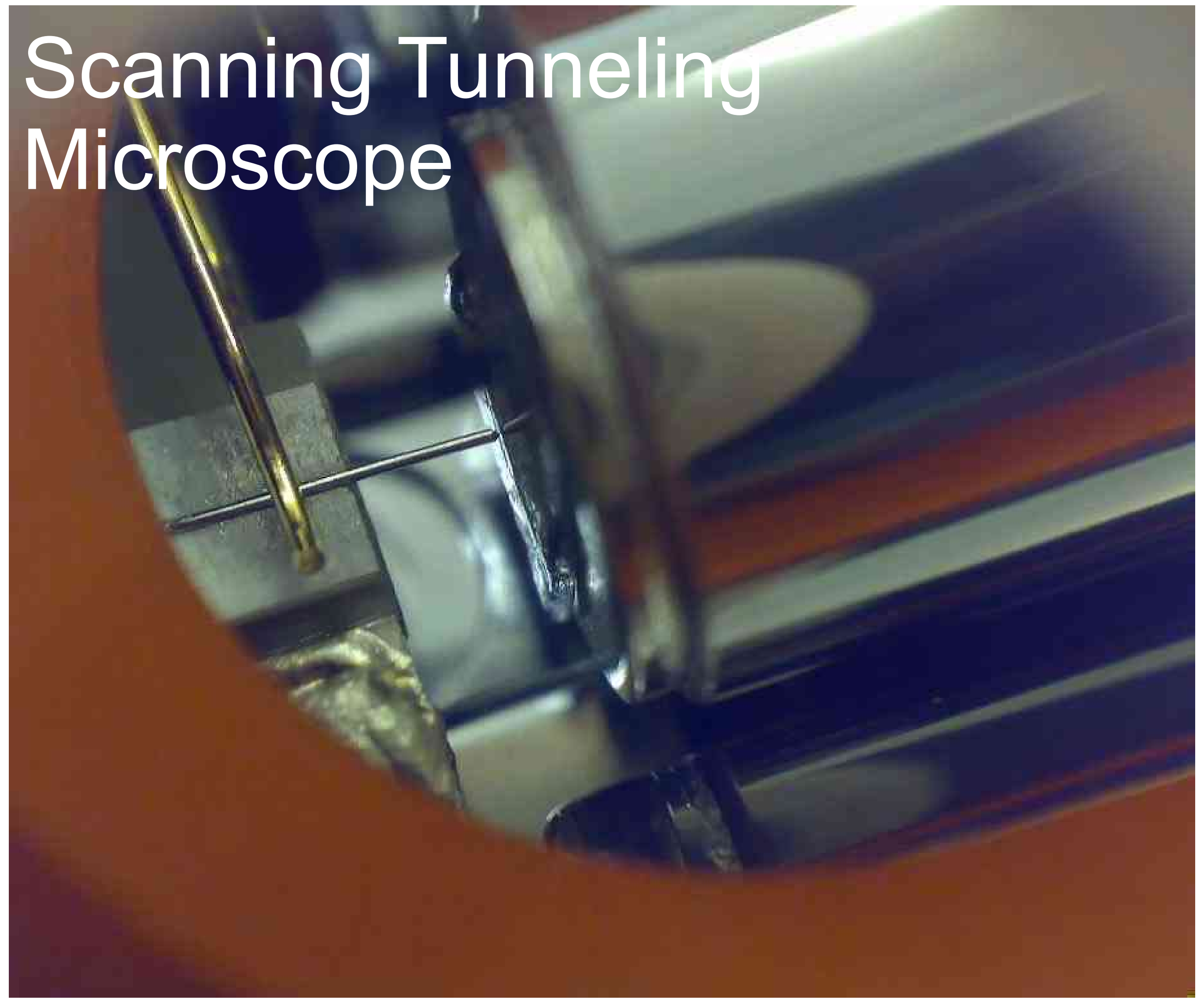
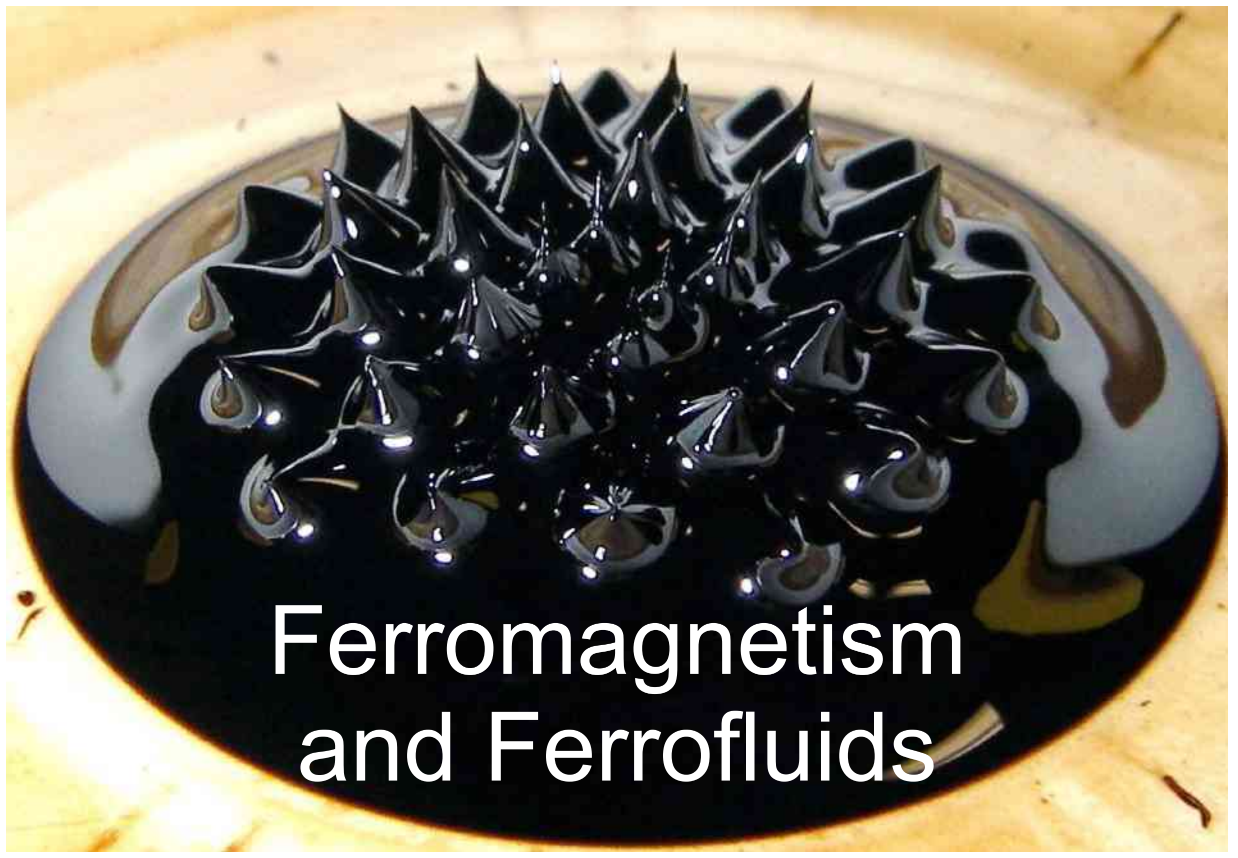
Transistor

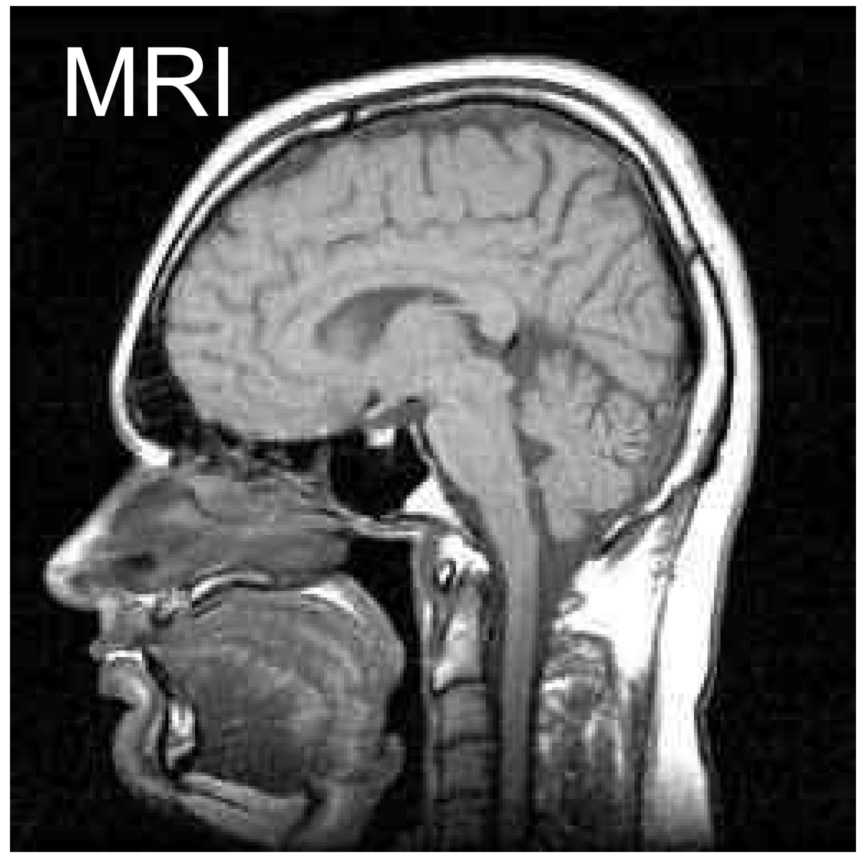
Semiconductors and Devices


CCD/CMOS


Scanning Tunneling Microscope


Superconductivity


Ferromagnetism and Ferrofluids


MRI


CD-ROM

Sources: Wikimedia, bgr.com

Basics of Quantum Mechanics

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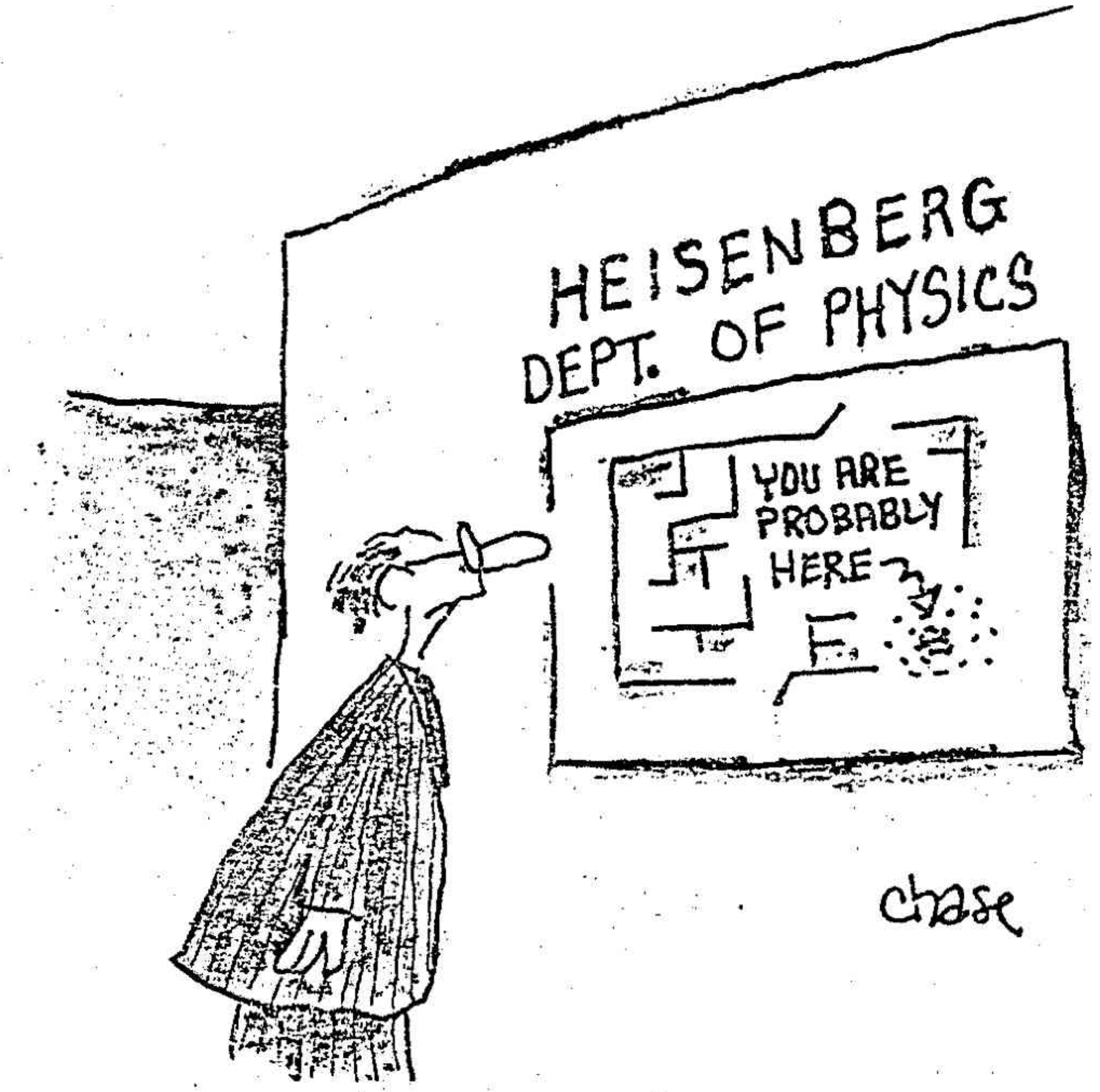
- Many parameters are quantized
  - photons, energy states, angular momentum, spin
- Measurement influences system
  - eigenstate of an measurement
- Probabilistic Interpretation (!)
  - Results of measurements cannot be predicted, only probabilities for outcomes
- Uncertainty relation
  - Non-commuting operators cannot be simultaneously measured with arbitrarily high accuracy
- Complementarity: Wave-Particle Duality
- Unknown Quantum States cannot be copied (No-Cloning Theorem)



How do we know it's correct?

Experiments

Wave-Particle Duality ⇒ Double Slit Experiment

Source: www.insidescience.org

Superposition ⇒ Schrödinger's Cat

Entanglement ⇒ Einstein-Podolsky-Rosen Paradox (Bell Inequalities)

Historical Overview - why did it take so long?

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Year	Theory	Experiment
1935	Reality, Locality, Entanglement	
1960		Invention of the Laser
1964	Bell's Inequality	
1972		First Bell-Experiment
1975		Cooling of Ions
1982	Simulation of Quantum Systems	
	No-Cloning Theorem	
1983		Laser Cooling of Atoms
1984	BB84-Protocol (Complementarity)	
1985	1st Quantum Algorithm	One-Atom Maser
1989	GHZ States	
1991	Ekert-Protocol (Entanglement)	
1993	Quantum-Teleportation (Entanglement)	Quantum Cryptography
1994	Shors Factorization Algorithm	
1995	Quantum Computer (Cirac, Zoller)	Bose-Einstein-Condensation
		Entangled Photons, Quantum Logic with Ions
1996	Grovers Quantum Algorithm	Entangled States (Ions and QED)

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UNIVERSITÄT PADERBORN Die Universität der Informationsgesellschaft

Historical Overview - why did it take so long?

1972		First Bell-Experiment
1975		Cooling of Ions
1982	Simulation of Quantum Systems	
	No-Cloning Theorem	
1983		Laser Cooling of Atoms
1984	BB84-Protocol (Complementarity)	
1985	1st Quantum Algorithm	One-Atom Maser
1989	GHZ States	
1991	Ekert-Protocol (Entanglement)	
1993	Quantum-Teleportation (Entanglement)	Quantum Cryptography
1994	Shors Factorization Algorithm	
1995	Quantum Computer (Cirac, Zoller)	Bose-Einstein-Condensation
		Entangled Photons, Quantum Logic with Ions
1996	Grovers Quantum Algorithm	Entangled States (Ions and QED)
	Error correcting quantum codes	
1997		Quantum Teleportation
2001		Quantum Computer (7-bit, Factorisation of 15)
2015		Definitive Test of Bell inequalities

... back to the future (actually today)

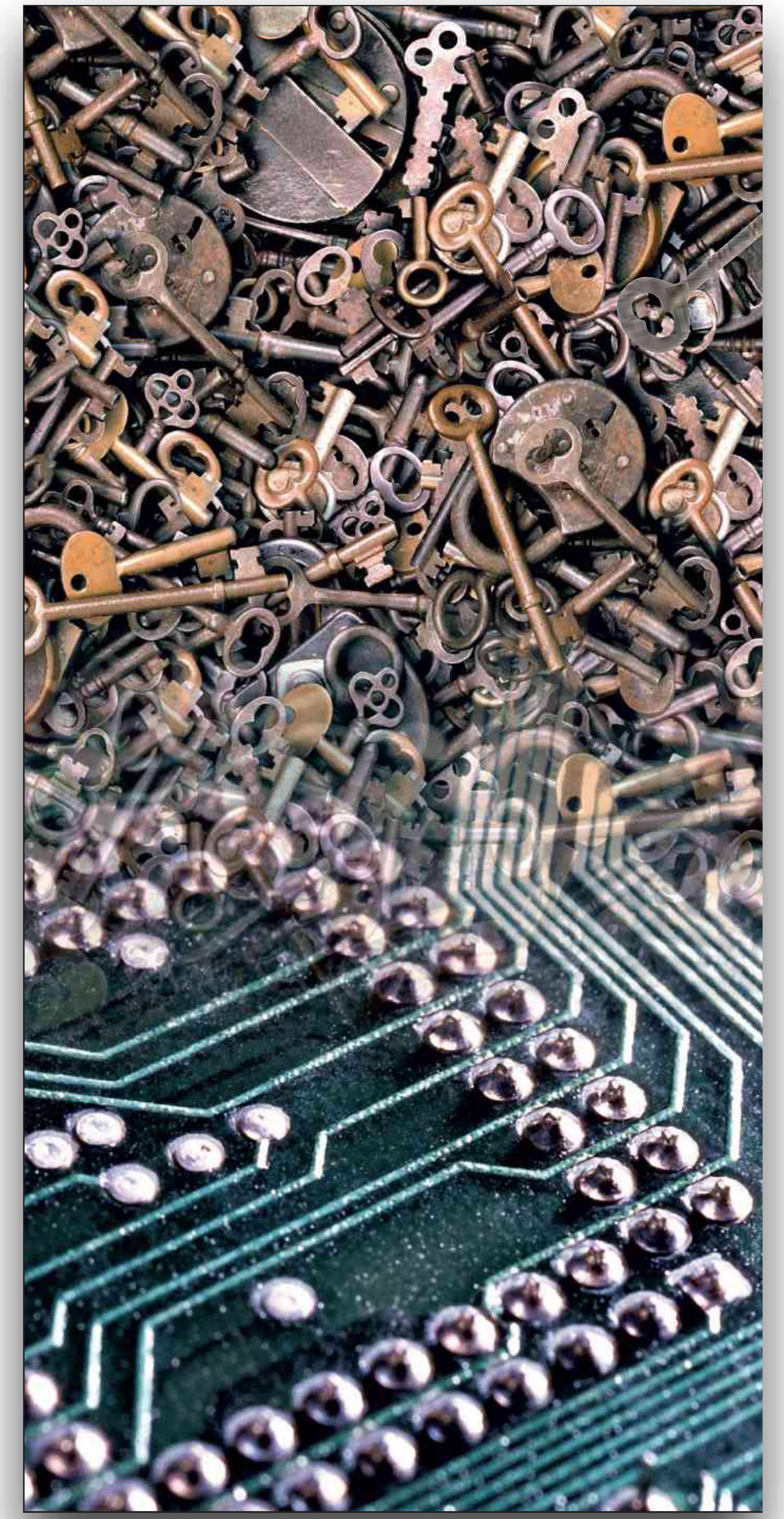
Quantum Information Processing

Quantum Communication

Quantum Teleportation

Quantum Computing

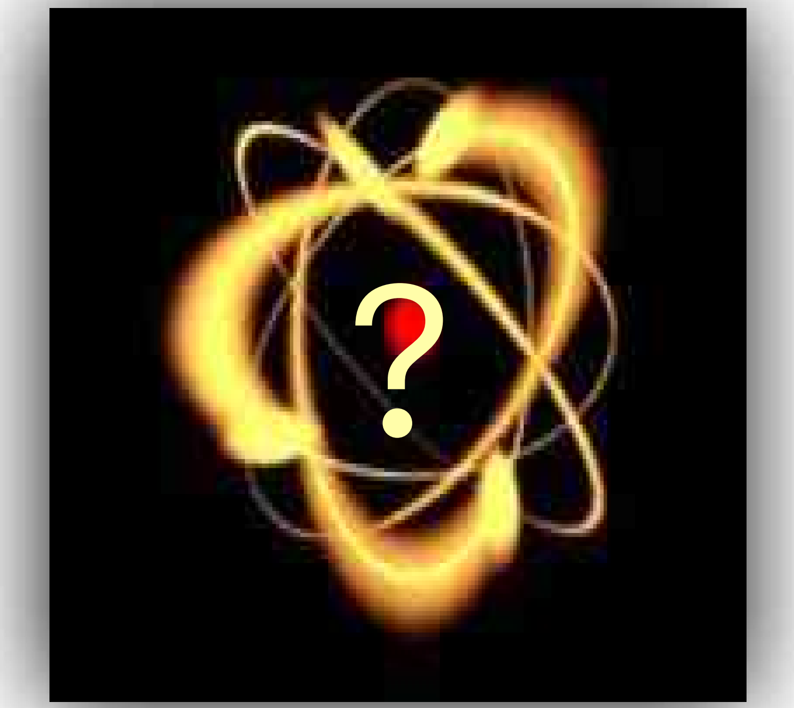
Quantum Key Distribution



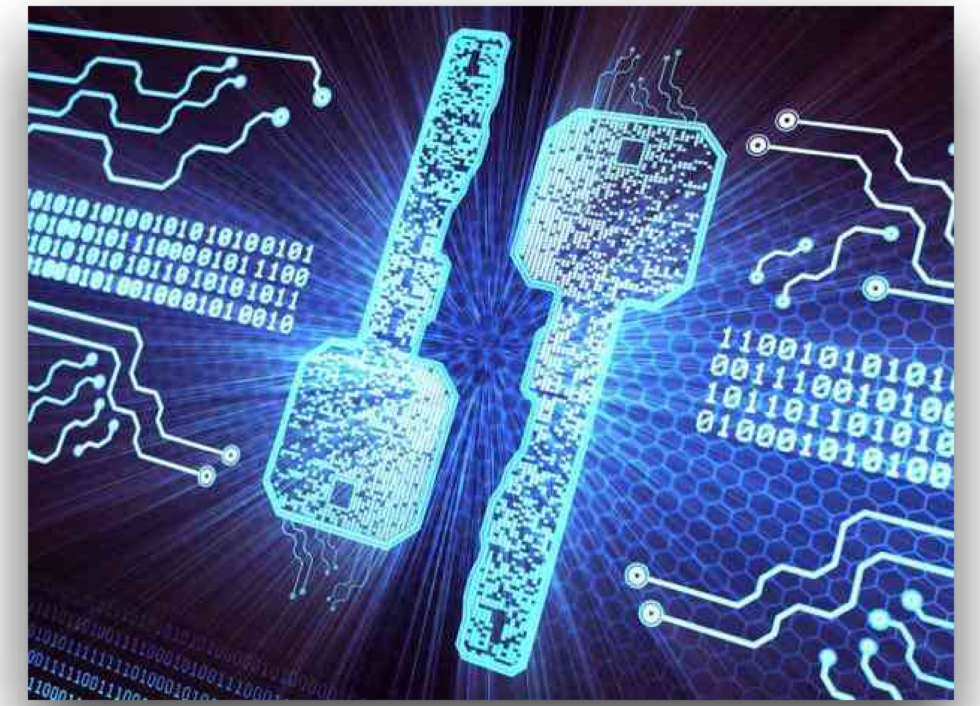
… back to the future (actually today)

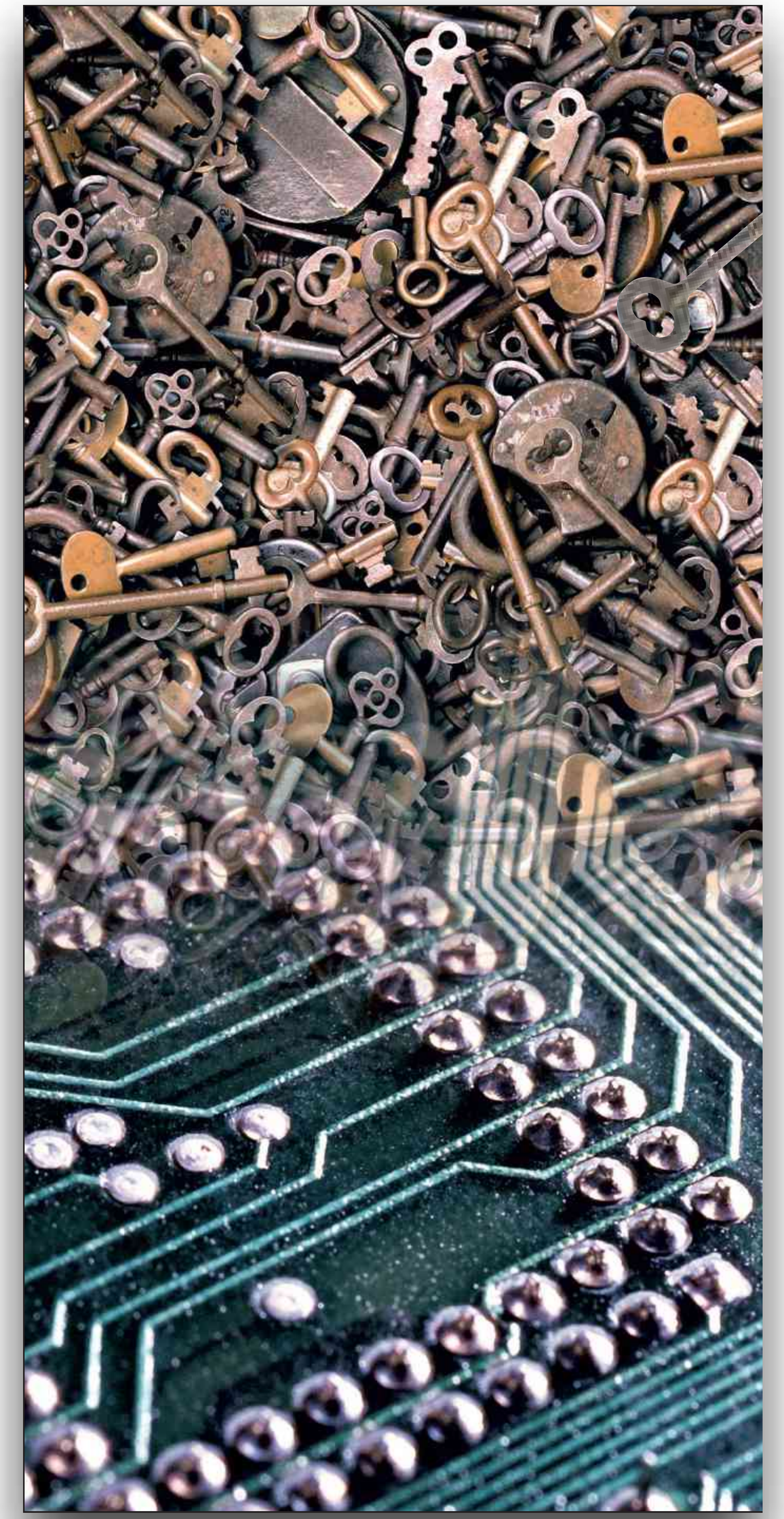
Quantum Information Processing

Quantum Computing



Quantum Key Distribution





Basic Ingredients: Superposition + Entanglement + Interference + No-Cloning

What, if we find a different theory?

Quantum Mechanics and its predictions must be a part of it.

Just like Newtonian mechanics is part of the theory of special relativity in the limit of small velocities.

Quantum Key Distribution

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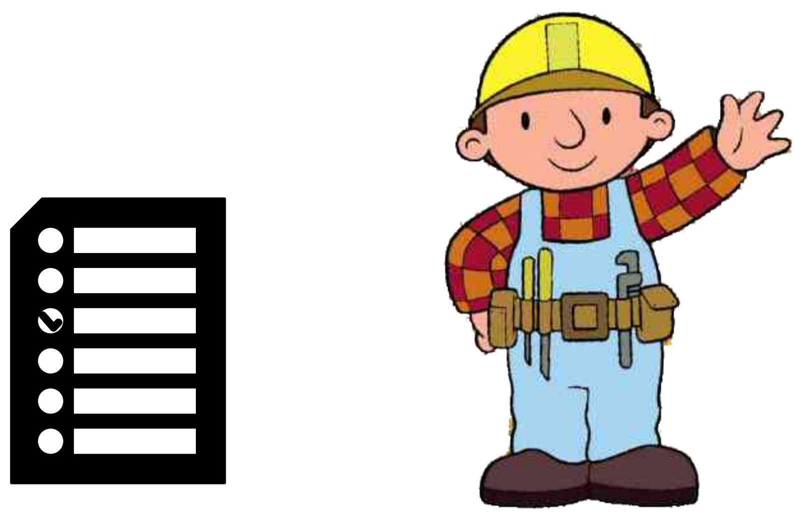
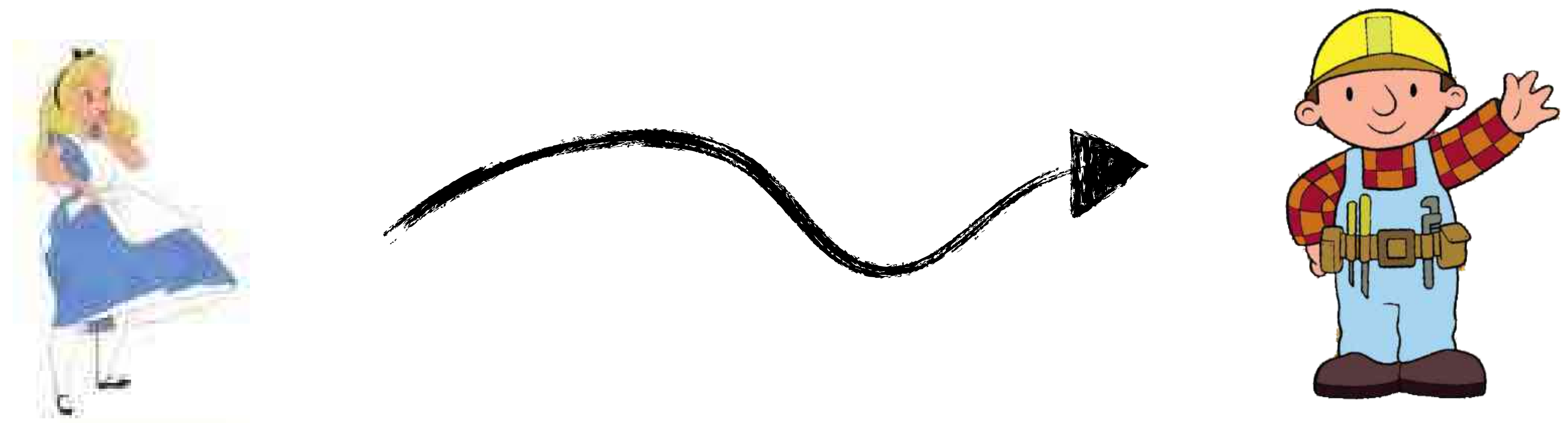
Alice 

Cryptography
- asymmetric key
- symmetric key

 Bob

Information theoretical Security:
Vernam One-Time-Pad
- random
- one time use
- length of message

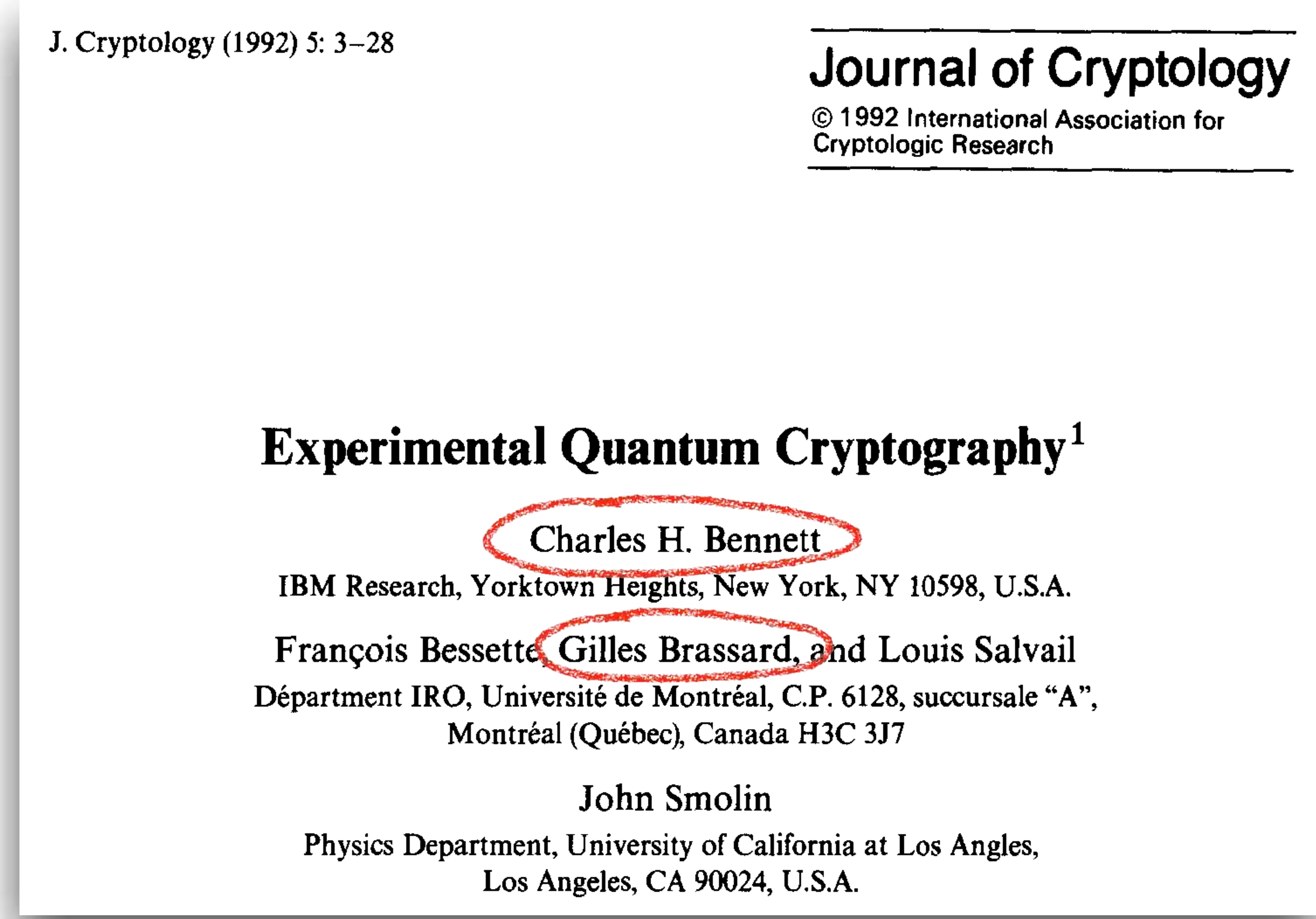
Alice  Bob

Quantum Channel

Security proofs exist for most protocols

N. Gisin, G. Ribordy, W. Tittel and H. Zbinden, Rev. Mod. Phys **74** (2002) 145

First Implementation of the BB84 protocol 1992



J. Cryptology (1992) 5: 3–28

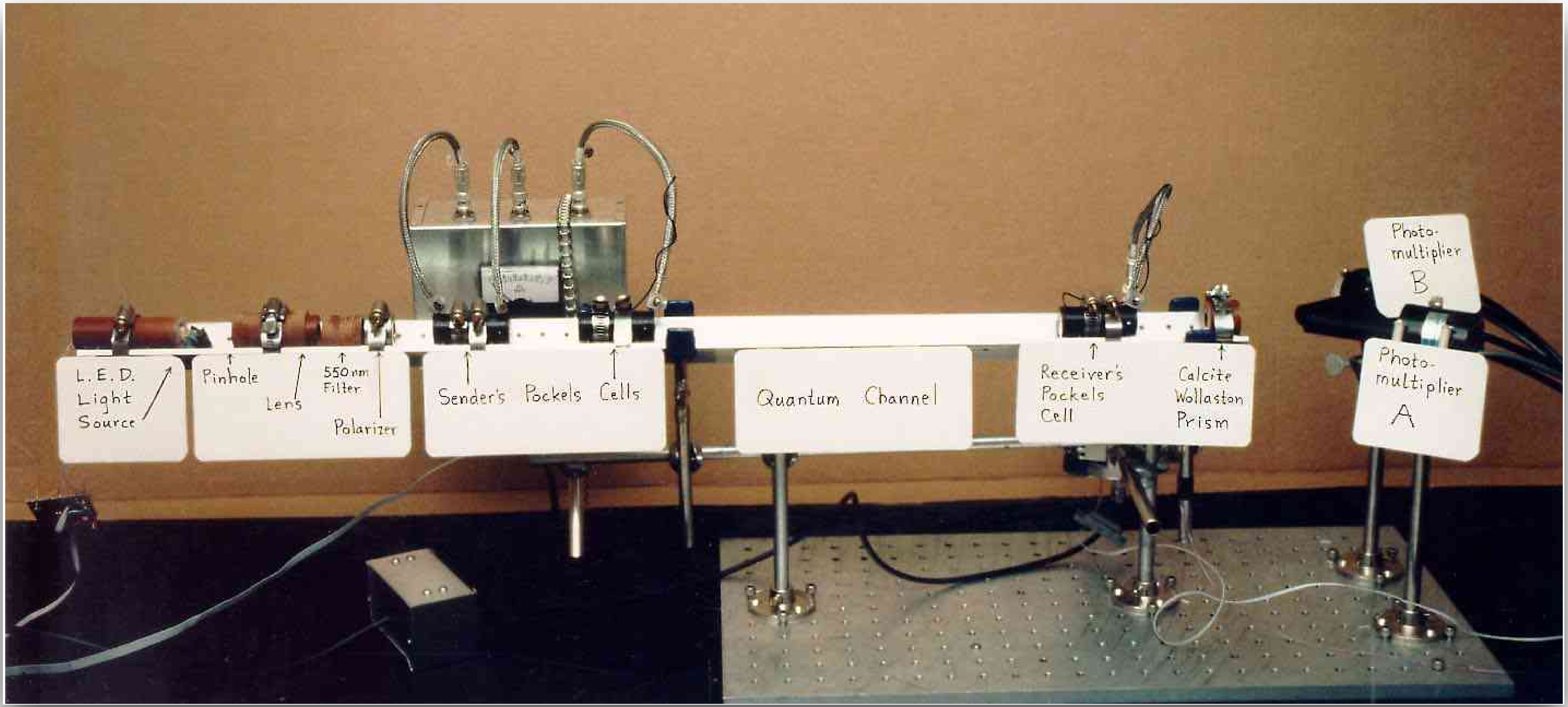
Journal of Cryptology
© 1992 International Association for Cryptologic Research

Experimental Quantum Cryptography[1]

Charles H. Bennett
IBM Research, Yorktown Heights, New York, NY 10598, U.S.A.

François Bessette, Gilles Brassard, and Louis Salvail
Département IRO, Université de Montréal, C.P. 6128, succursale "A", Montréal (Québec), Canada H3C 3J7

John Smolin
Physics Department, University of California at Los Angles, Los Angeles, CA 90024, U.S.A.



Past Development in a Nutshell

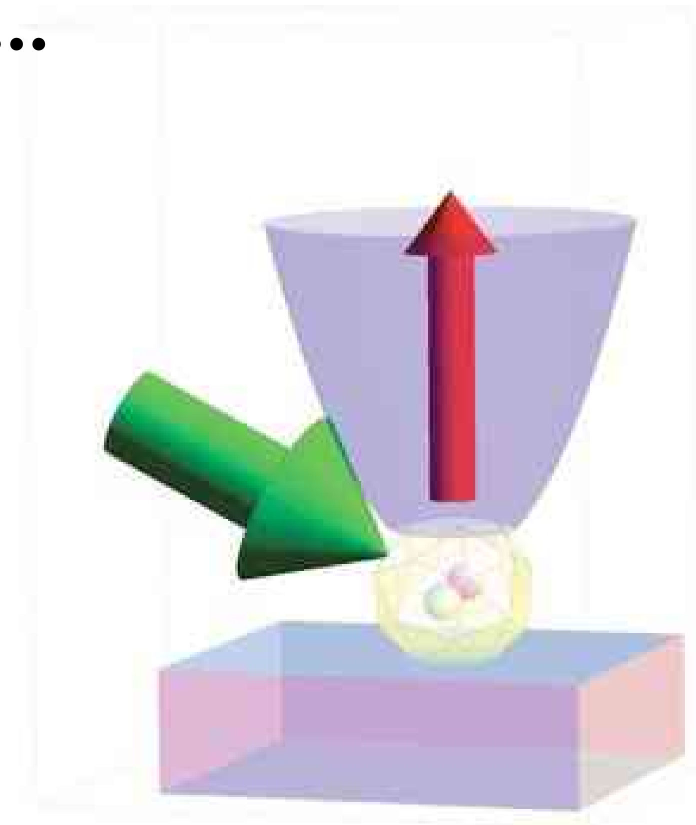
Protocols
- BB84
- Ekert91
- Phase-Timebin Entanglement
- COW
- Decoy
- …

Sources
- cw
- single-photon
- SPDC
- weak coherent pulses
- …

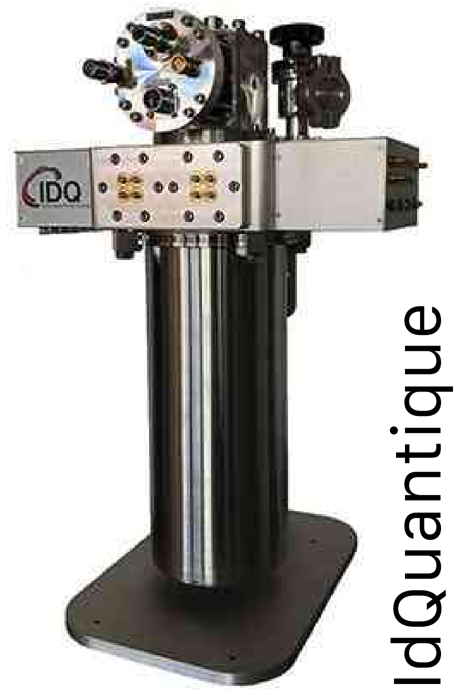
Transmission Medium
- Air
- Optical Fiber

Detectors
- PMT
- APD
- SC-Nanowire
- …

A. Ekert



nist.gov


Univ. Vienna



IdQuantique

Missing: Quantum Repeater ⇒ Trusted Nodes (for long distance)

Quantum Key Distribution

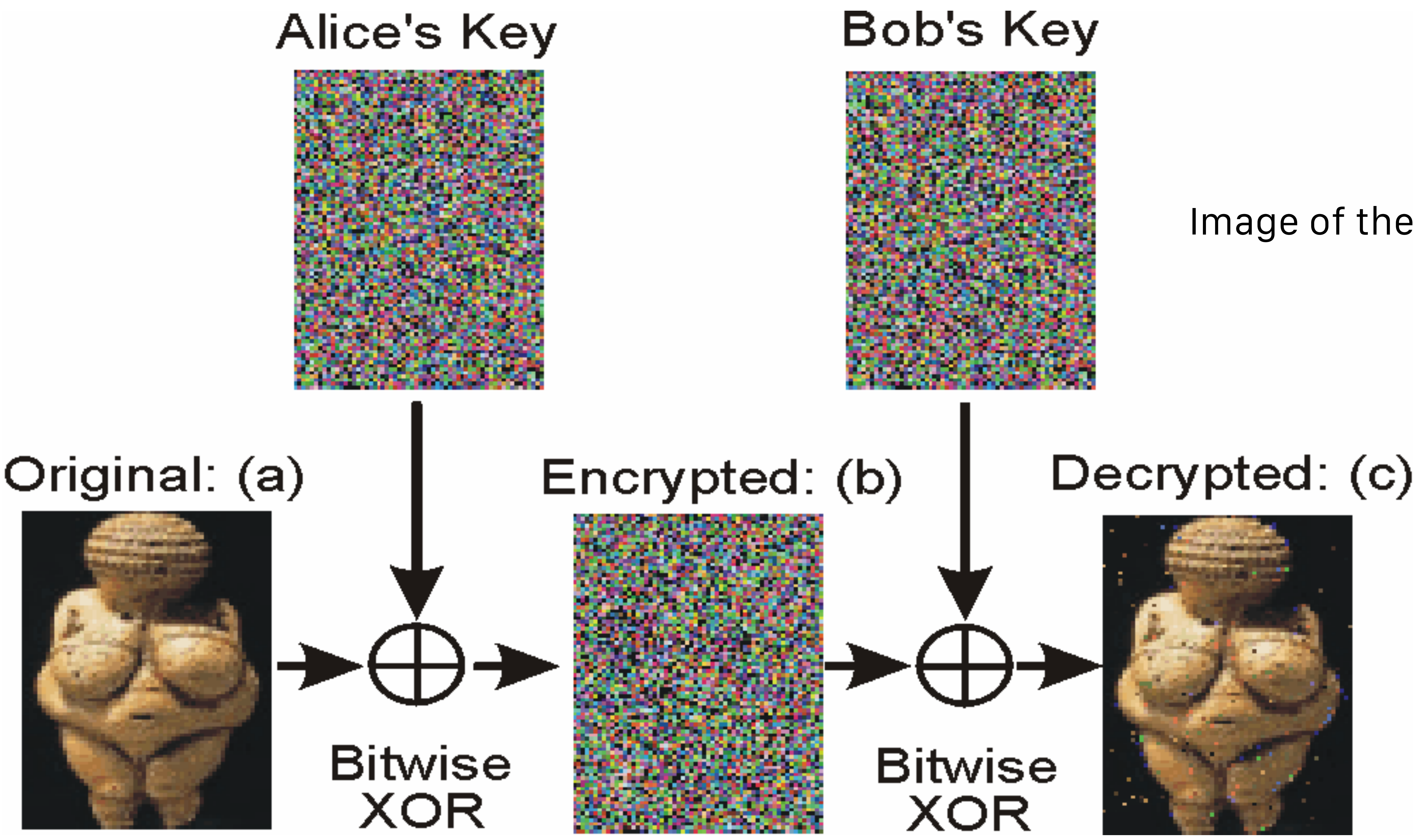


Image of the "Venus of Willendorf"

Anton Zeilinger, Univ. Vienna

Th. Jennewein et al, Phys. Rev. Lett. **84** (2000) 4729

Quantum Key Distribution: April 2004

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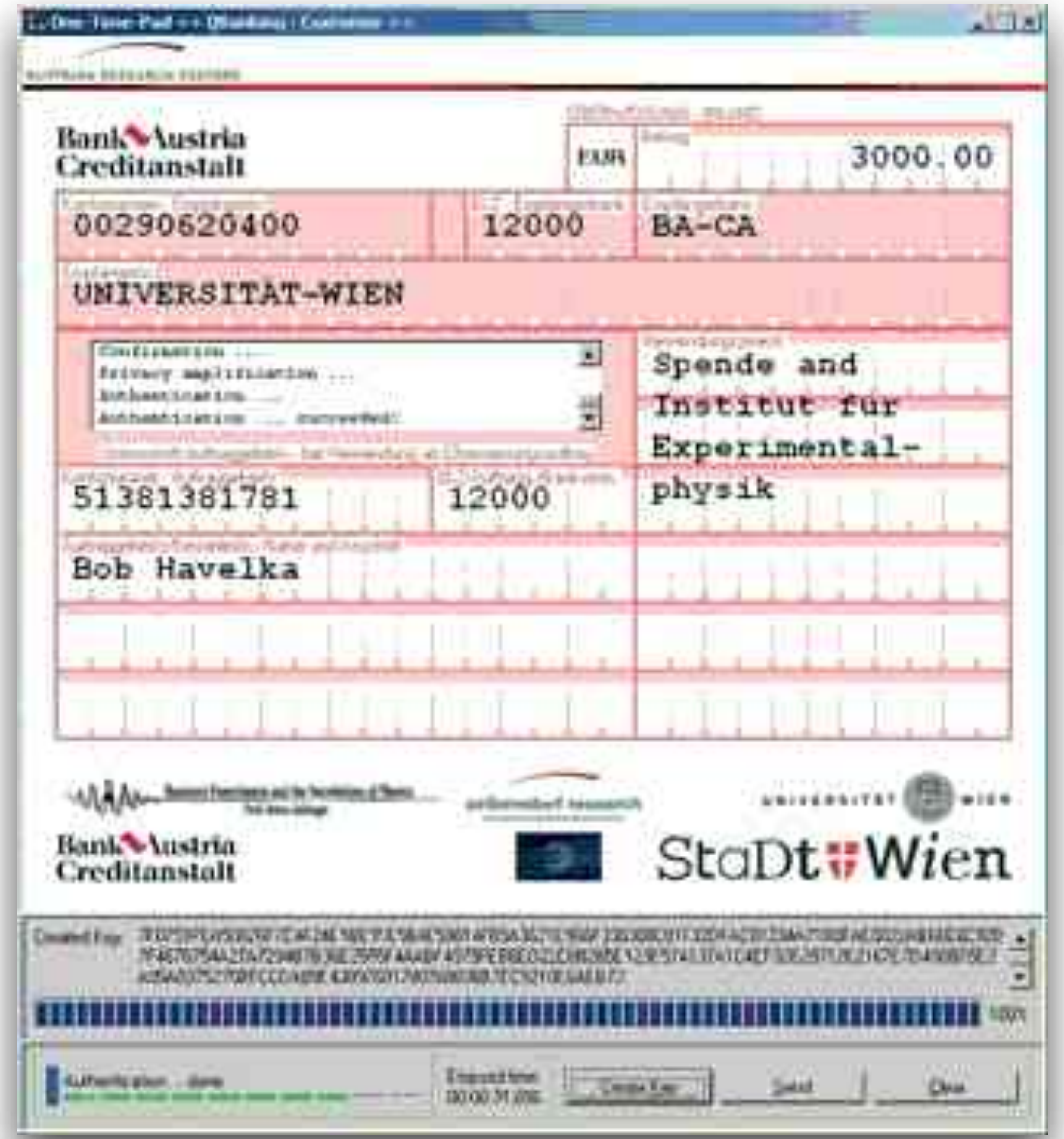

http://www.secoqc.net

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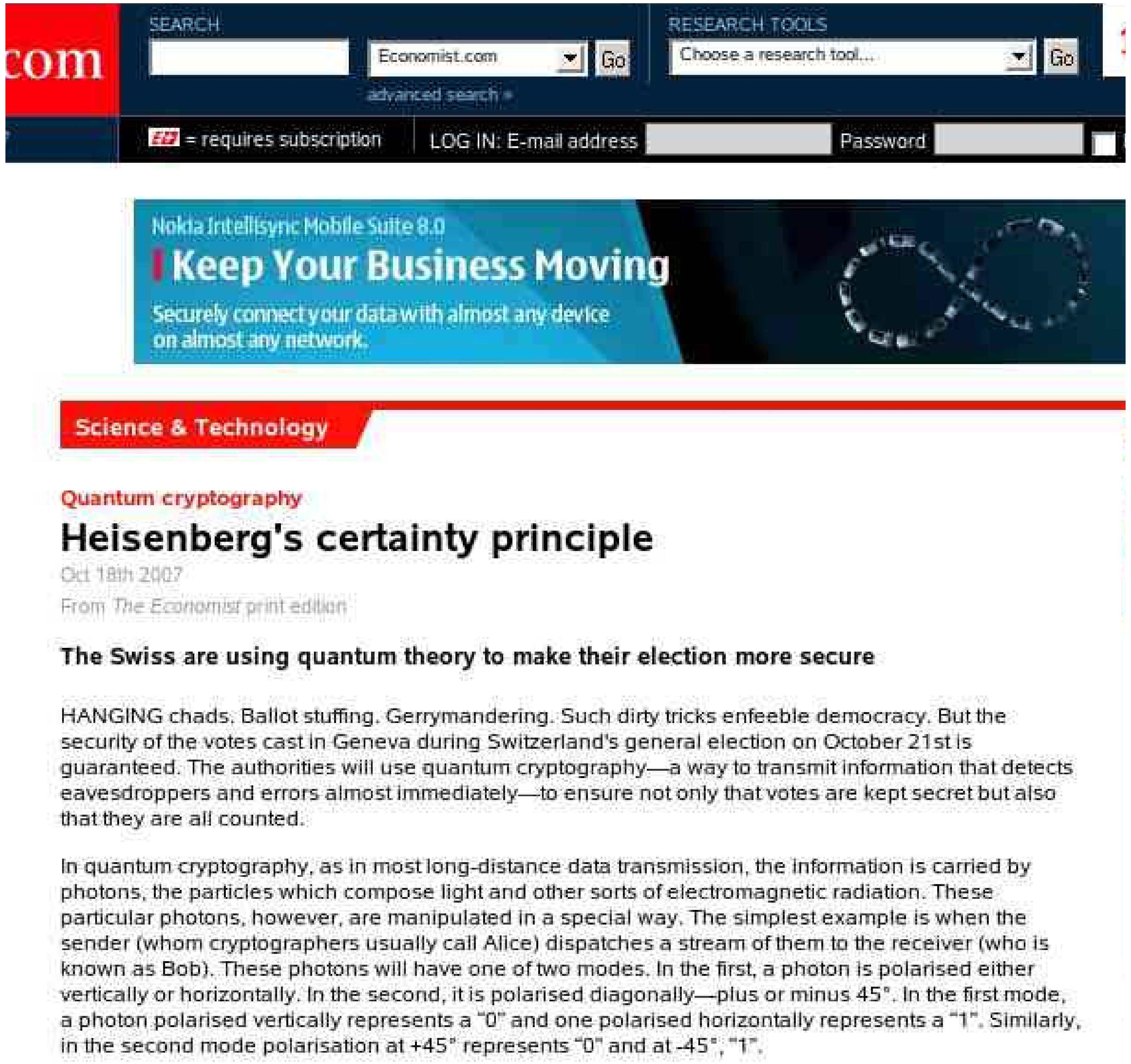
Quantum Key Distribution: Swiss Elections 2007



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Science & Technology

Quantum cryptography

Heisenberg's certainty principle

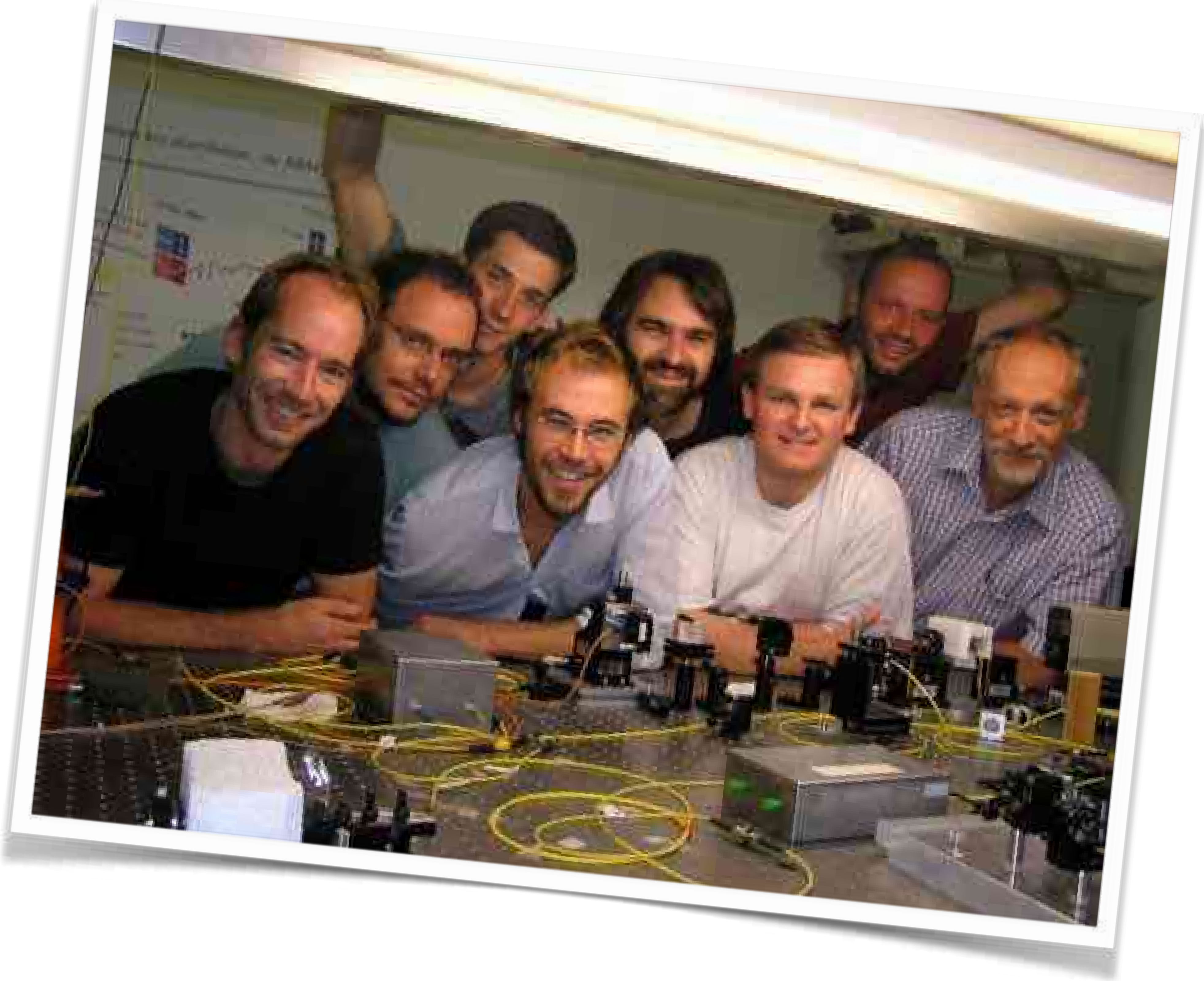
Oct 18th 2007

From *The Economist* print edition

The Swiss are using quantum theory to make their election more secure

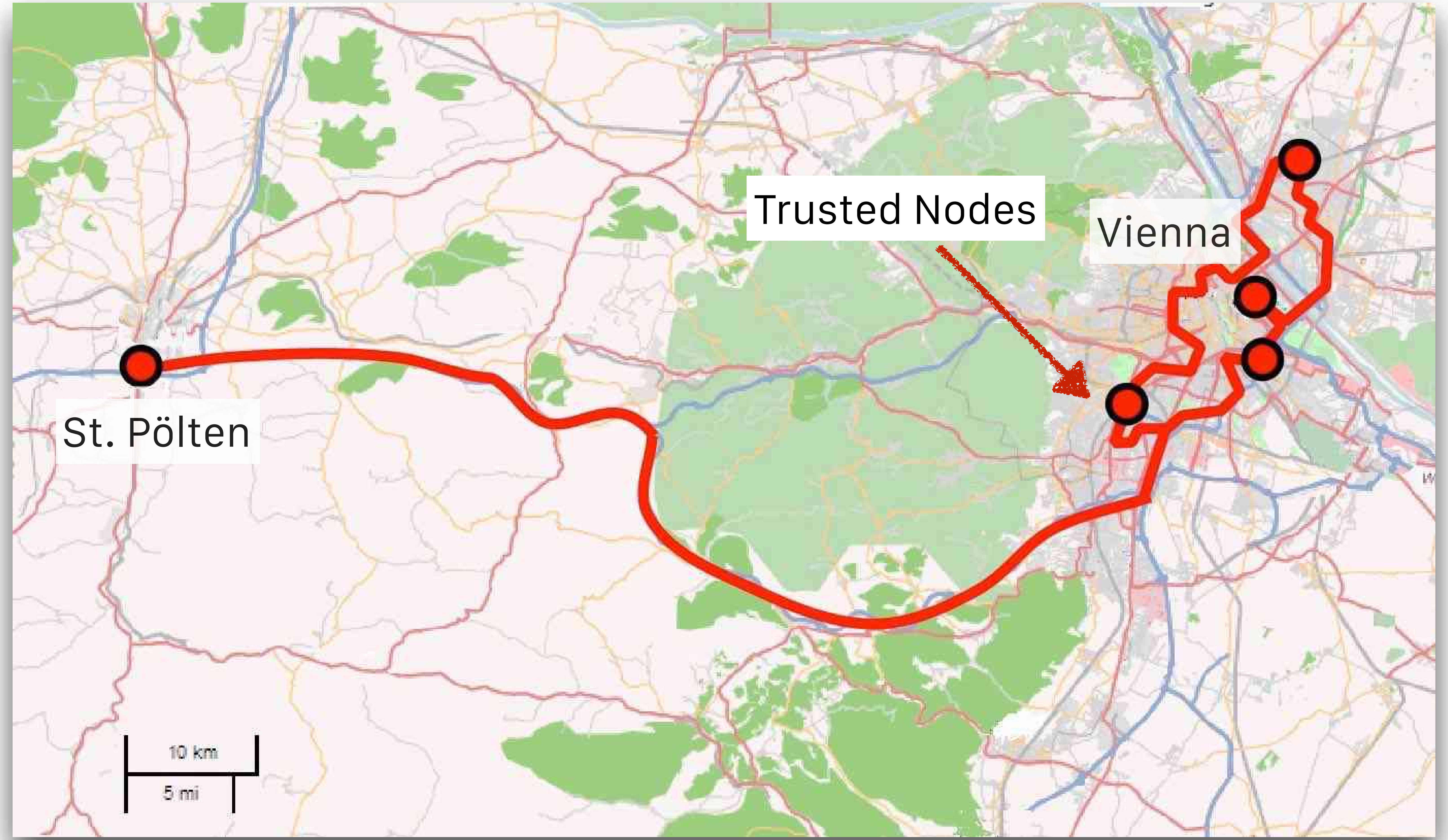
HANGING chads. Ballot stuffing. Gerrymandering. Such dirty tricks enfeeble democracy. But the security of the votes cast in Geneva during Switzerland's general election on October 21st is guaranteed. The authorities will use quantum cryptography—a way to transmit information that detects eavesdroppers and errors almost immediately—to ensure not only that votes are kept secret but also that they are all counted.

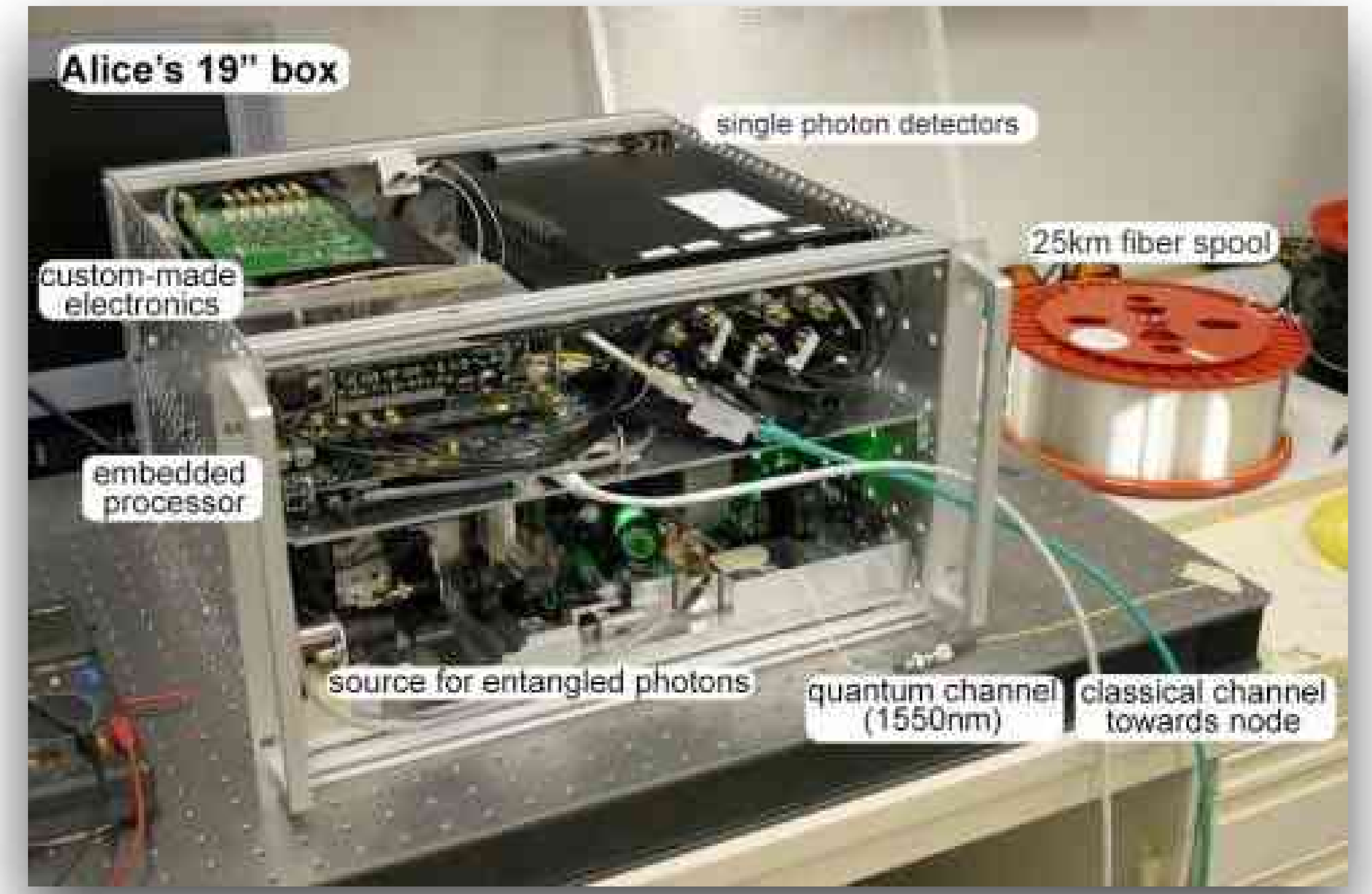
In quantum cryptography, as in most long-distance data transmission, the information is carried by photons, the particles which compose light and other sorts of electromagnetic radiation. These particular photons, however, are manipulated in a special way. The simplest example is when the sender (whom cryptographers usually call Alice) dispatches a stream of them to the receiver (who is known as Bob). These photons will have one of two modes. In the first, a photon is polarised either vertically or horizontally. In the second, it is polarised diagonally—plus or minus 45°. In the first mode, a photon polarised vertically represents a "0" and one polarised horizontally represents a "1". Similarly, in the second mode polarisation at +45° represents "0" and at -45°, "1".

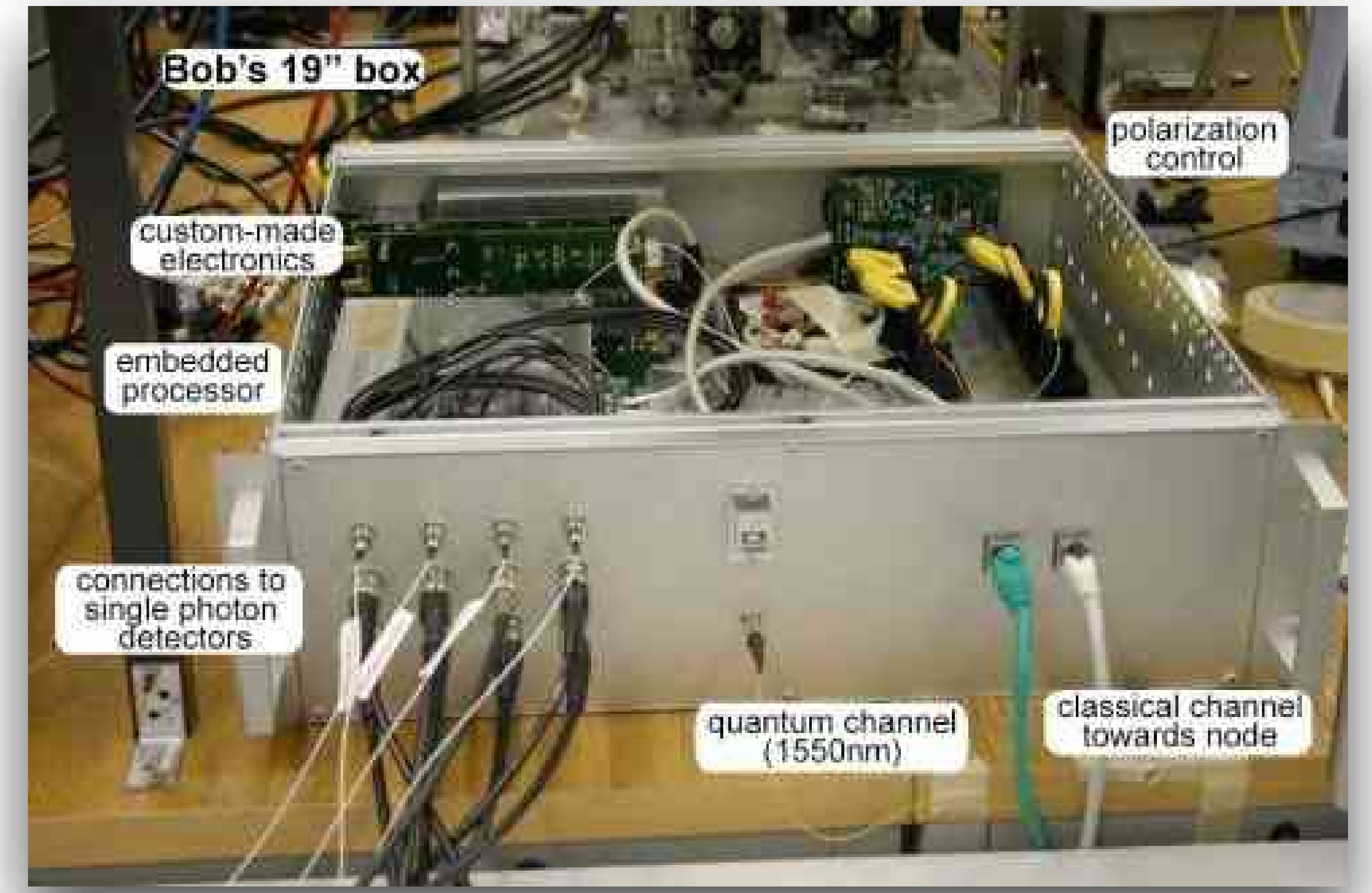


The Economist, Oct. 18th 2007

Quantum Networks: SECOQC - 2008







similar networks by DARPA, China, Geneva, Tokyo, Los Alamos, …

Quantum Key Distribution and the Race for Distance

CROSSING

nature photonics — LETTERS

PUBLISHED ONLINE

200 km: ~900 bits/s
307 km: 3.18 bits/s

Provably secure and practical quantum key distribution over 307 km of optical fibre

Boris Korzh[1]*, Charles Ci Wen Lim[1]*, Raphael Houlmann[1], Nicolas Gisin[1], Ming Jun Li[2], Daniel Nolan[2], Bruno Sanguinetti[1], Rob Thew[1] and Hugo Zbinden[1]

Entanglement-based quantum communication over 144 km

~100 bits/s

R. URSIN[1]*, F. TIEFENBACHER[1,2], T. SCHMITT-MANDERBACH[3,4], H. WEIER[4], T. SCHEIDL[1,2], M. LINDENTHAL[2], B. BLAUENSTEINER[1], T. JENNEWEIN[2], J. PERDIGUES[5], P. TROJEK[3,4], B. ÖMER[6], M. FÜRST[4], M. MEYENBURG[6], J. RARITY[7], Z. SODNIK[5], C. BARBIERI[8], H. WEINFURTER[3,4] AND A. ZEILINGER[1,2]*

Nature Physics **3** (2007) 481

PHYSICAL REVIEW LETTERS 121,

Editors' Suggestion | Featured in Physics

405 km: 6.6 bits/s

Secure Quantum Key Distribution over 421 km of Optical Fiber

Alberto Boaron,[1,*] Gianluca Boso,[1] Davide Rusca,[1] Cédric Vulliez,[1] Claire Autebert,[1] Misael Caloz,[1] Matthieu Perrenoud,[1] Gaëtan Gras,[1,2] Félix Bussières,[1] Ming-Jun Li,[3] Daniel Nolan,[3] Anthony Martin,[1] and Hugo Zbinden[1]
[1]*Group of Applied Physics, University of Geneva, Chemin de Pinchat 22, 1211 Geneva 4, Switzerland*
[2]*ID Quantique SA, Chemin de la Marbrerie 3, 1227 Carouge, Switzerland*
[3]*Corning Incorporated, Corning, New York 14831, USA*

(Received 10 July 2018; published 5 November 2018)

PHYSICAL REVIEW LETTERS 120,

Editors' Suggestion | Featured in Physics

1000 km: 3300 bits/s
600 km: 9000 bits/s

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]

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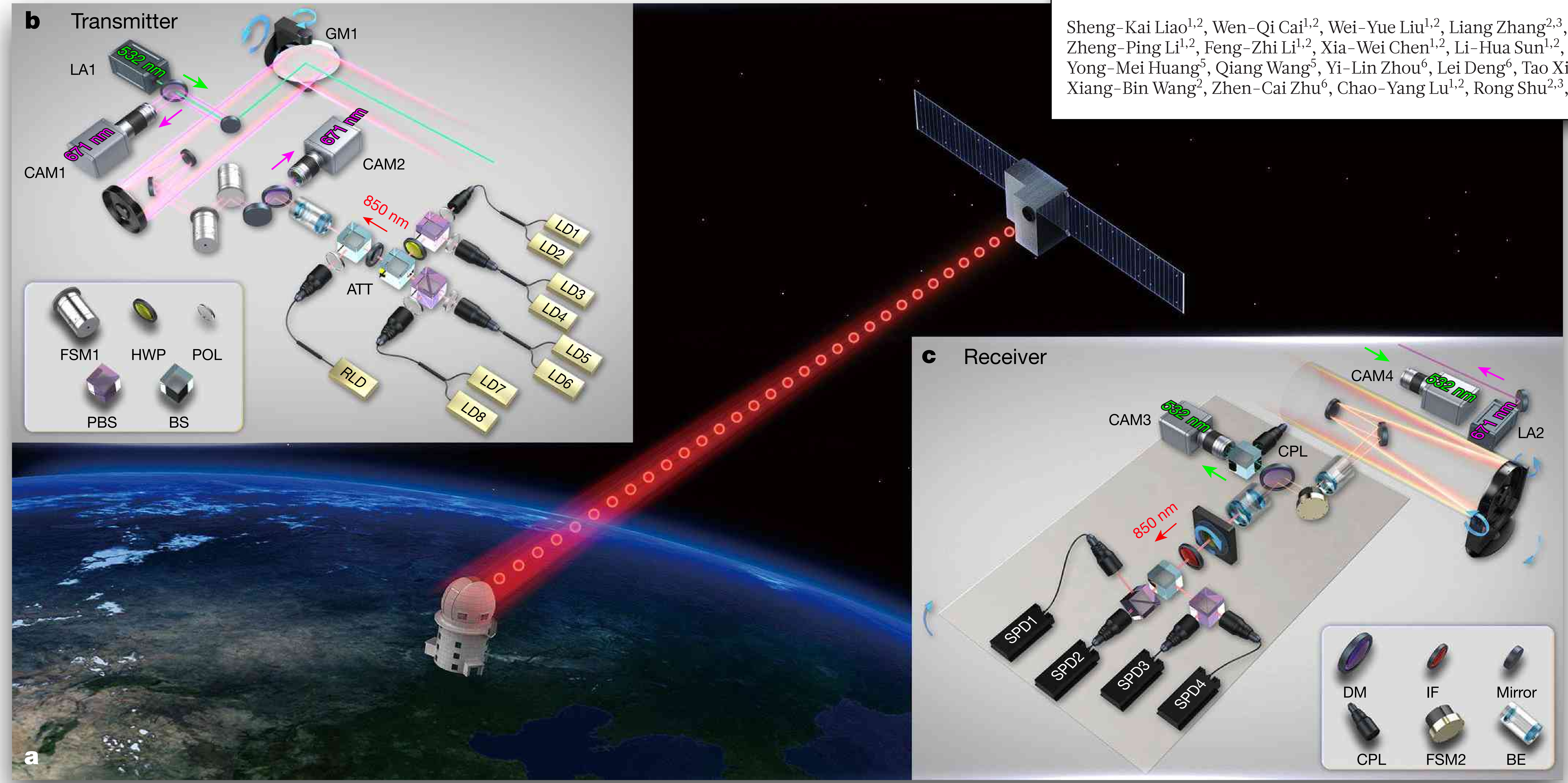
Satellite based Quantum Key Distribution

CROSSING

S-K. Liao et al., Nature **549** (2017), 42

Satellite-to-ground quantum key distribution

Sheng-Kai Liao[1,2], Wen-Qi Cai[1,2], Wei-Yue Liu[1,2], Liang Zhang[2,3], Yang Li[1,2], Ji-Gang Ren[1,2], Juan Yin[1,2], Qi Shen[1,2], Yuan Cao[1,2], Zheng-Ping Li[1,2], Feng-Zhi Li[1,2], Xia-Wei Chen[1,2], Li-Hua Sun[1,2], Jian-Jun Jia[3], Jin-Cai Wu[3], Xiao-Jun Jiang[4], Jian-Feng Wang[4], Yong-Mei Huang[5], Qiang Wang[5], Yi-Lin Zhou[6], Lei Deng[6], Tao Xi[7], Lu Ma[8], Tai Hu[9], Qiang Zhang[1,2], Yu-Ao Chen[1,2], Nai-Le Liu[1,2], Xiang-Bin Wang[2], Zhen-Cai Zhu[6], Chao-Yang Lu[1,2], Rong Shu[2,3], Cheng-Zhi Peng[1,2], Jian-Yu Wang[2,3] & Jian-Wei Pan[1,2]



~1000 bits/s

Deutsche Forschungsgemeinschaft

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Die Universität der Informationsgesellschaft

Interkontinental - 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]

Interkontinental - Qua

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

Editors' Suggestion | Featured in Physics

Satellite-Relayed Intercontinental Quantum Network

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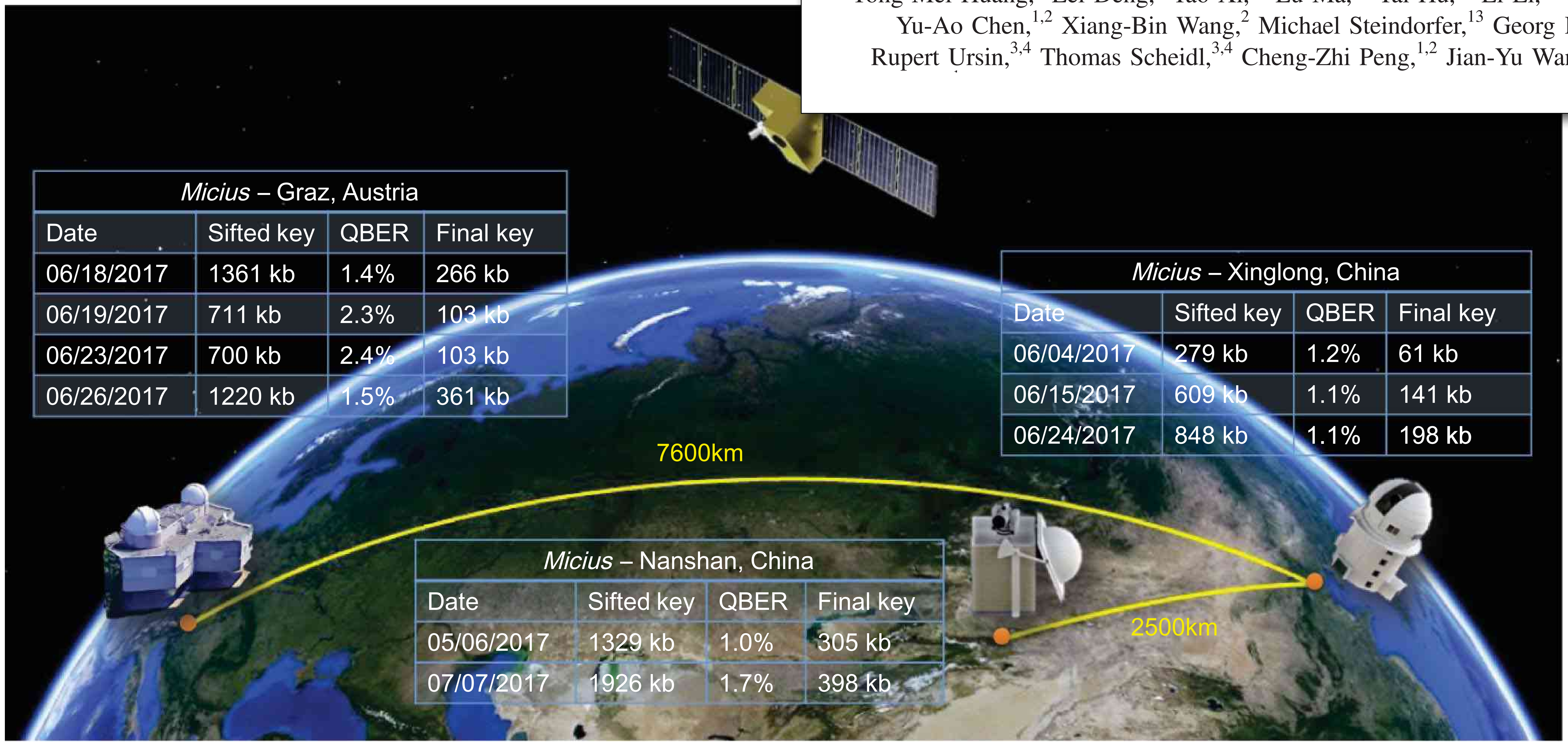
1000 km: 3300 bits/s
600 km: 9000 bits/s



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

FIG. 1. Illustration of the three cooperating ground stations (Graz, Nanshan, and Xinglong). Listed are all paths used for key generation and the corresponding final key length.

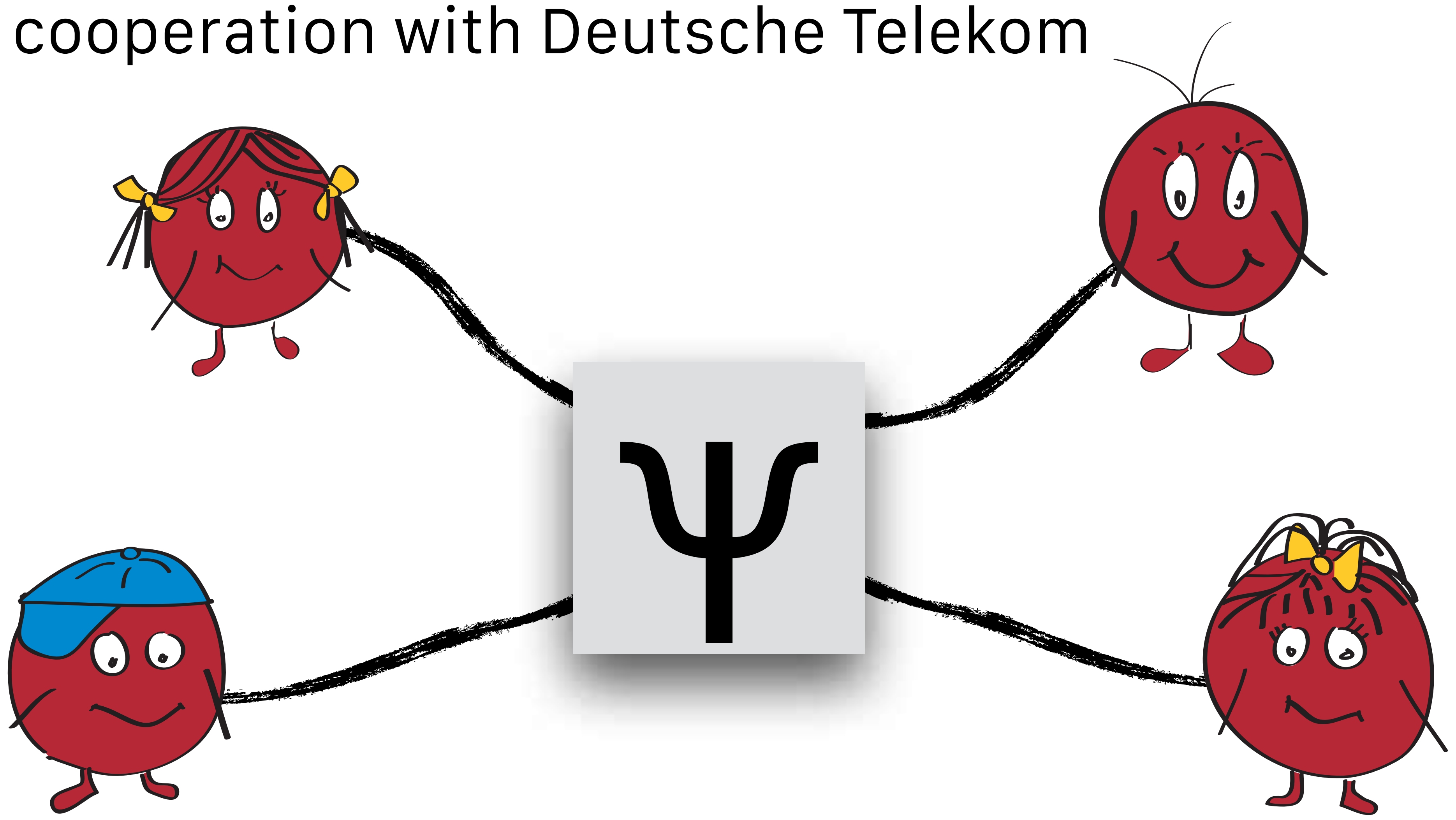
Key Length 100 kB

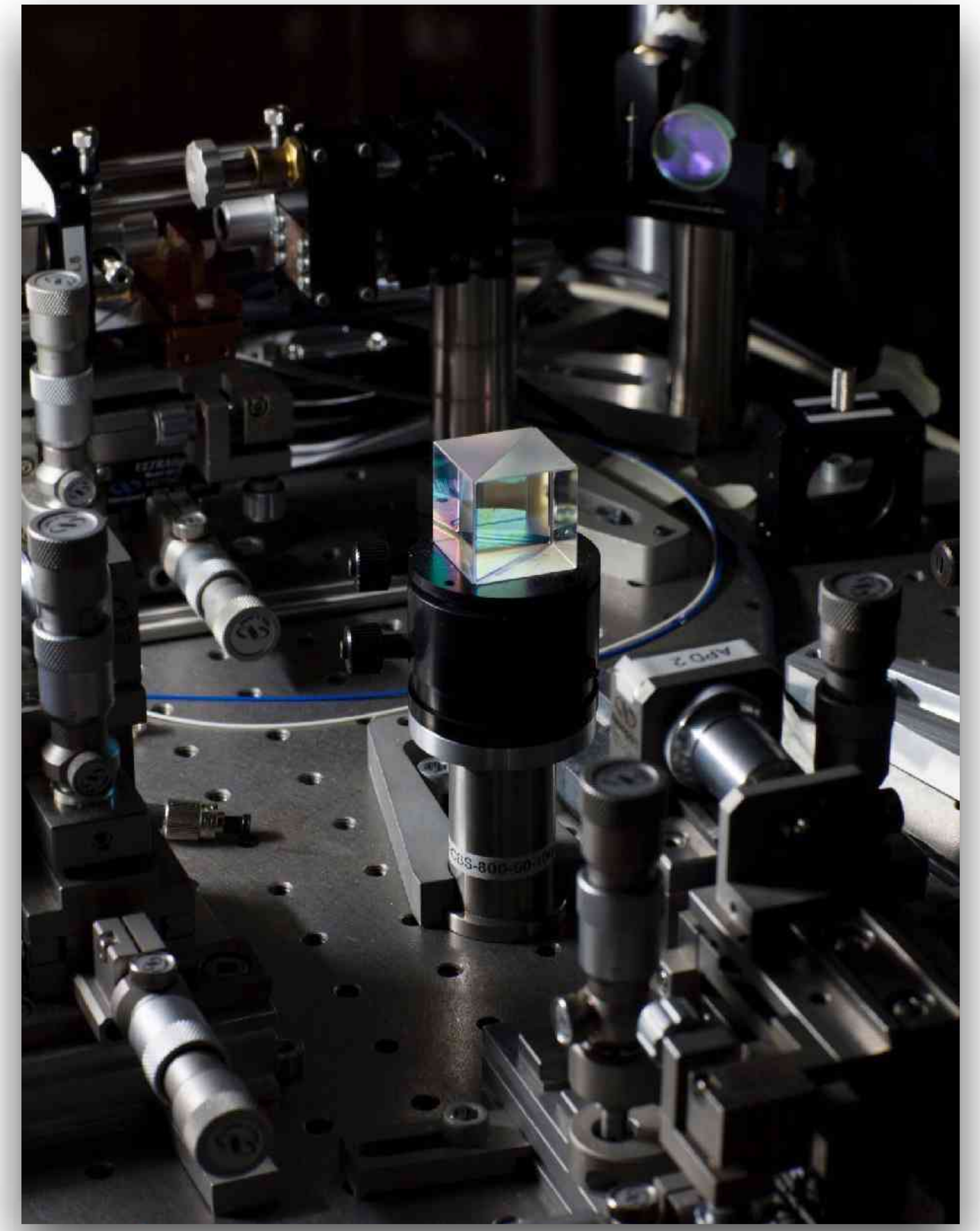
75 min-Video Conference (2 GByte)

change of AES-128 key every second
70 kB of quantum key used

Quantum Key Distribution in a Network

QKD in cooperation with Deutsche Telekom

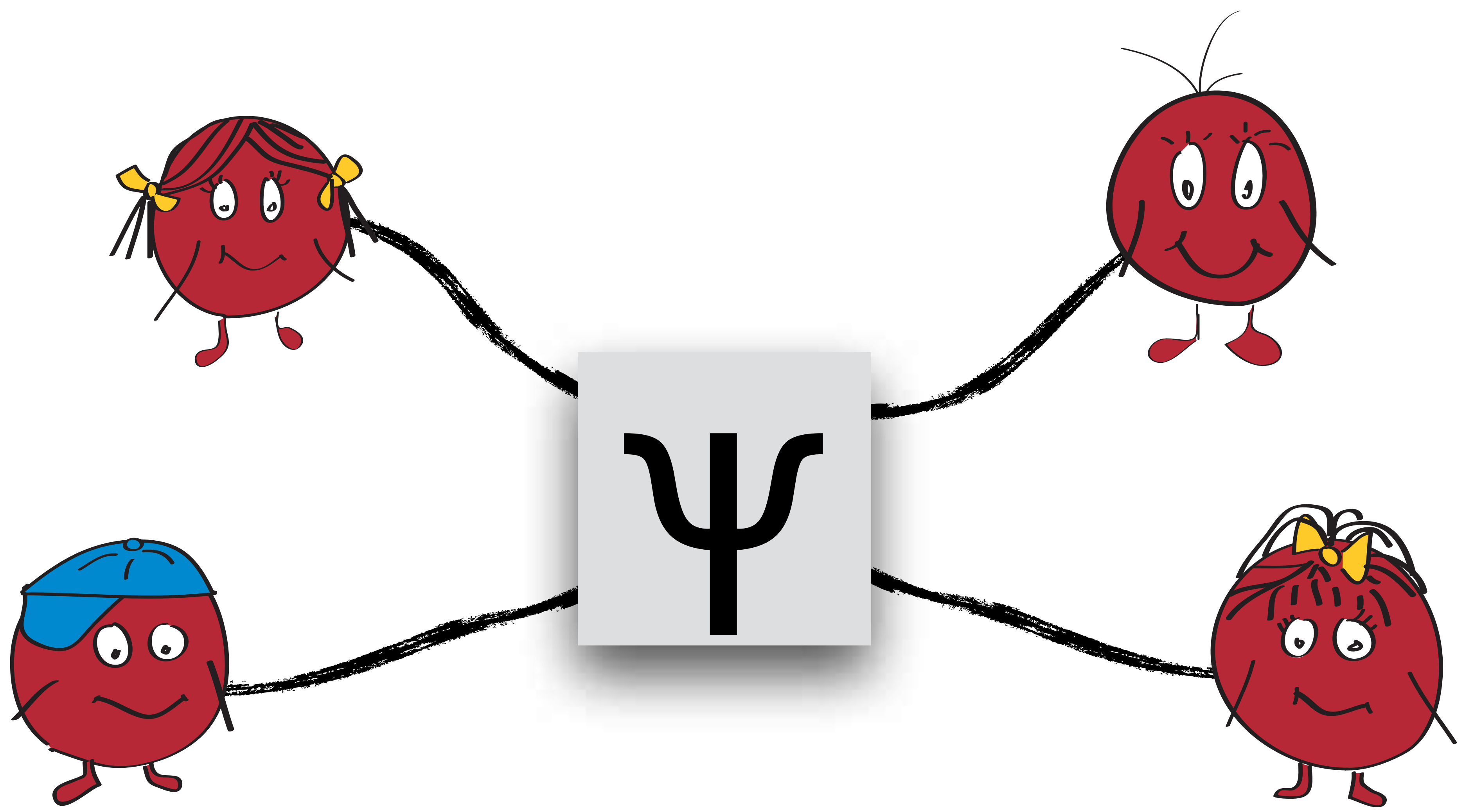




in cooperation with

Quantum Hub

Phase-Timebin-Entanglement-Protocol



any 2 parties can exchange key

investigation of

- scalability
- security
- performance
- side channels

in cooperation with

QKD in cooperation with Deutsche Telekom

Basic Idea

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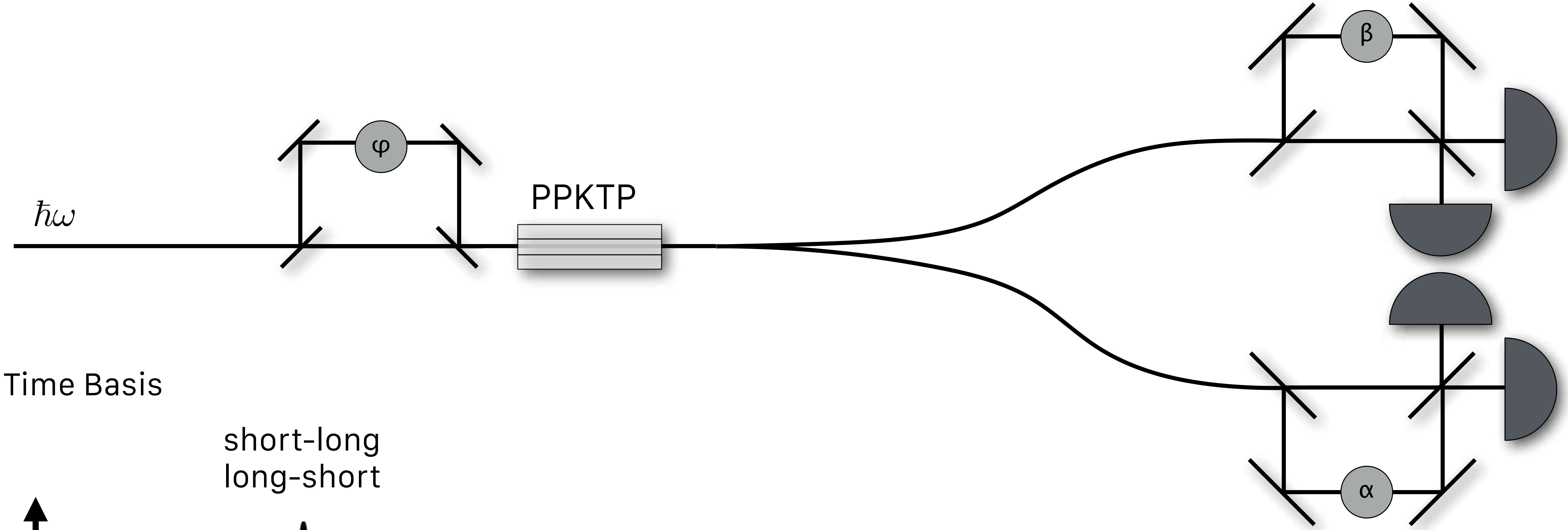
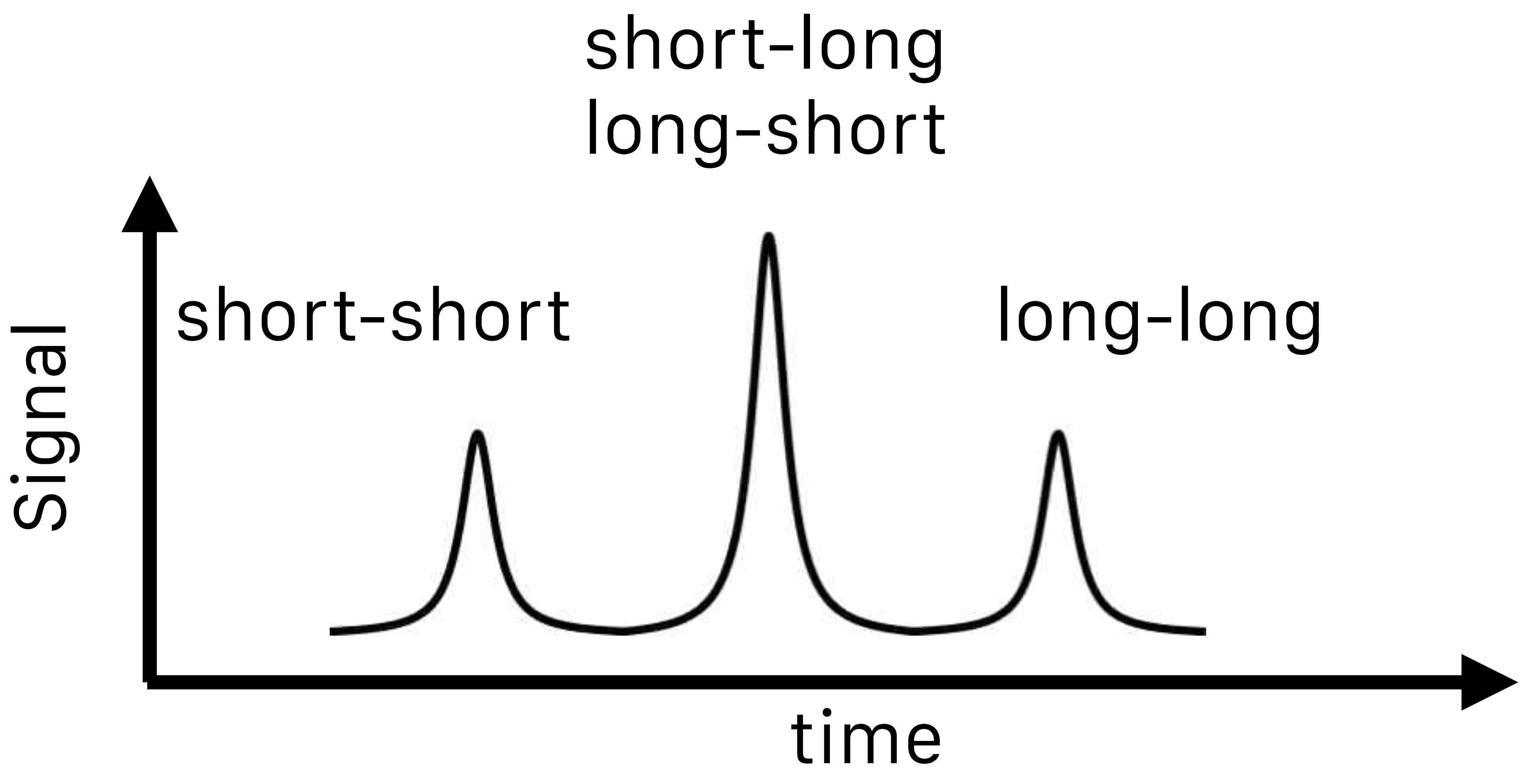


Time Basis



Phase Basis

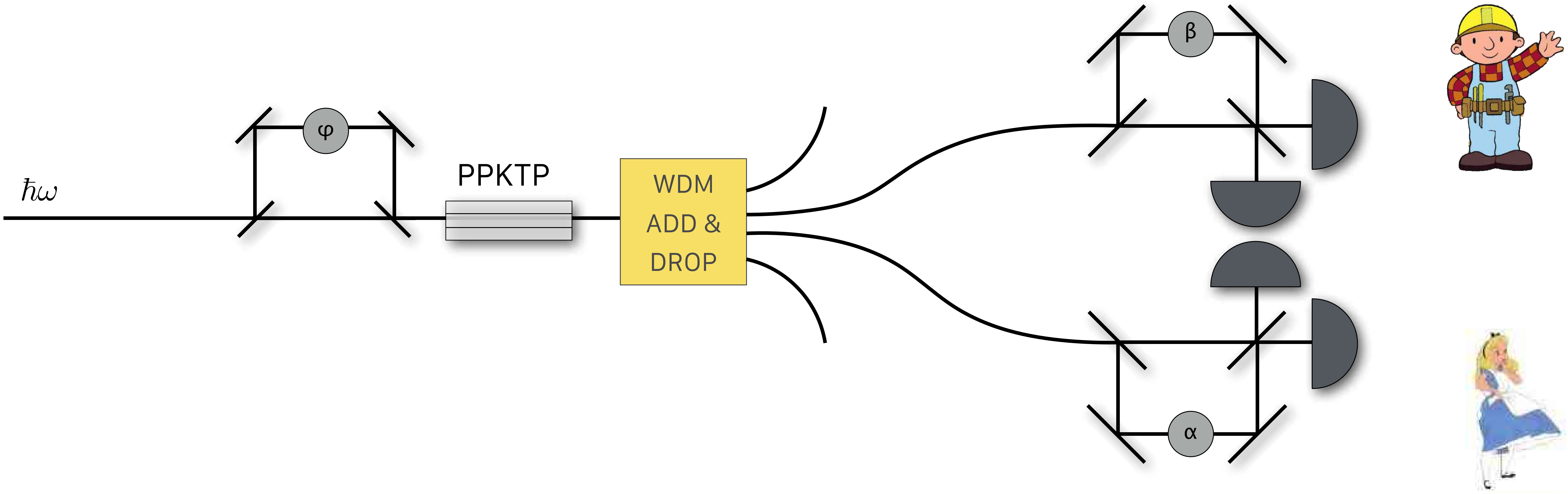
$$P(0_A 1_B \text{ oder } 1_A 0_B) \propto 1 - \cos(\alpha + \beta - \varphi)$$

Challenges:

temperature control to mK

timing resolution

Quantum Hub

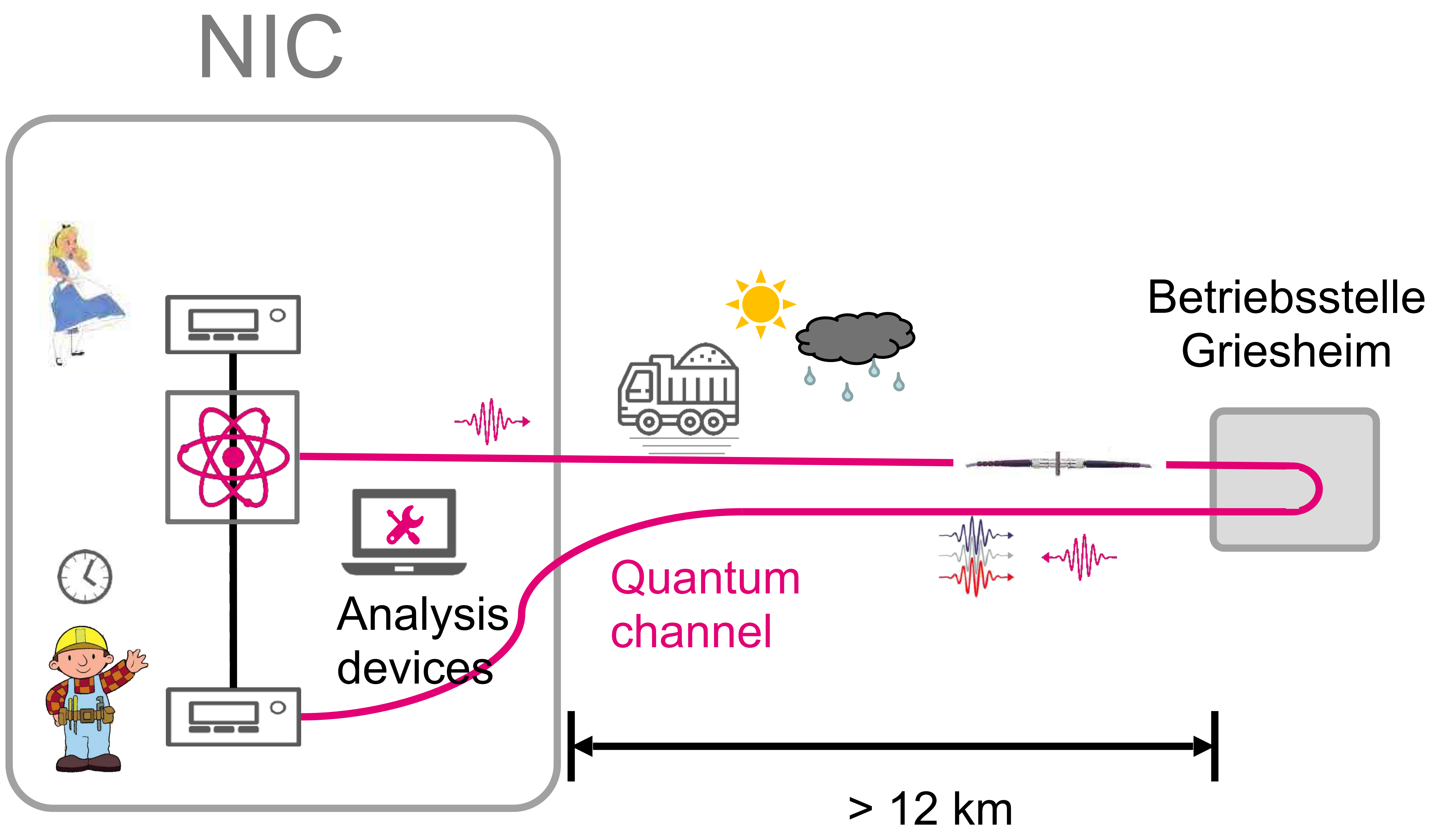


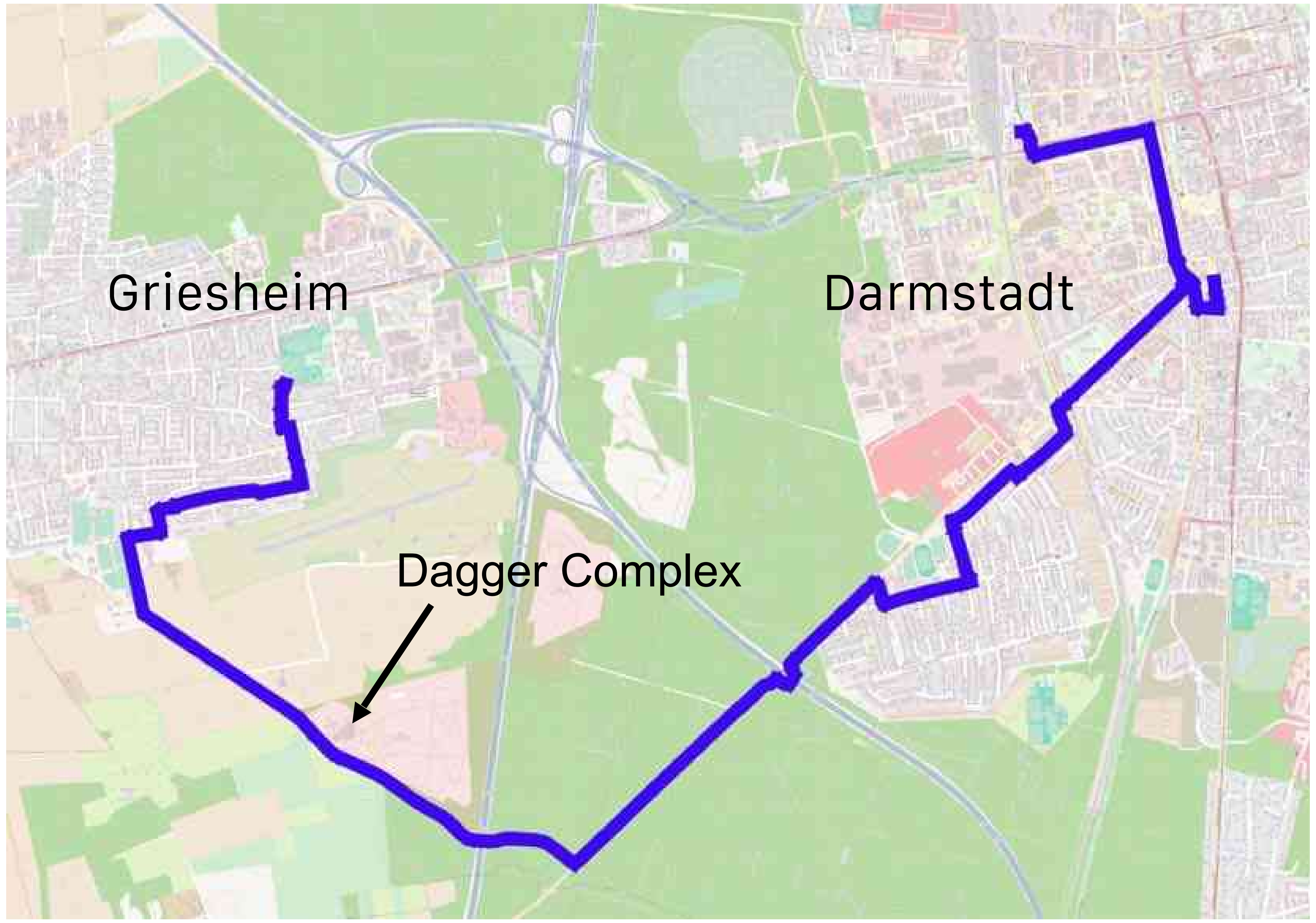
related approach using polarisation entanglement:

S. Wengerowsky, S.K. Joshi, F. Steinlechner, H. Hübel and R. Ursin, Nature **564** (2018) 225

E.Y Zhu, C. Corbari, A. Gladyshev, P.G. Kazansky, H-K. Lo and L. Qian, JOSA B **36** (2019) B1

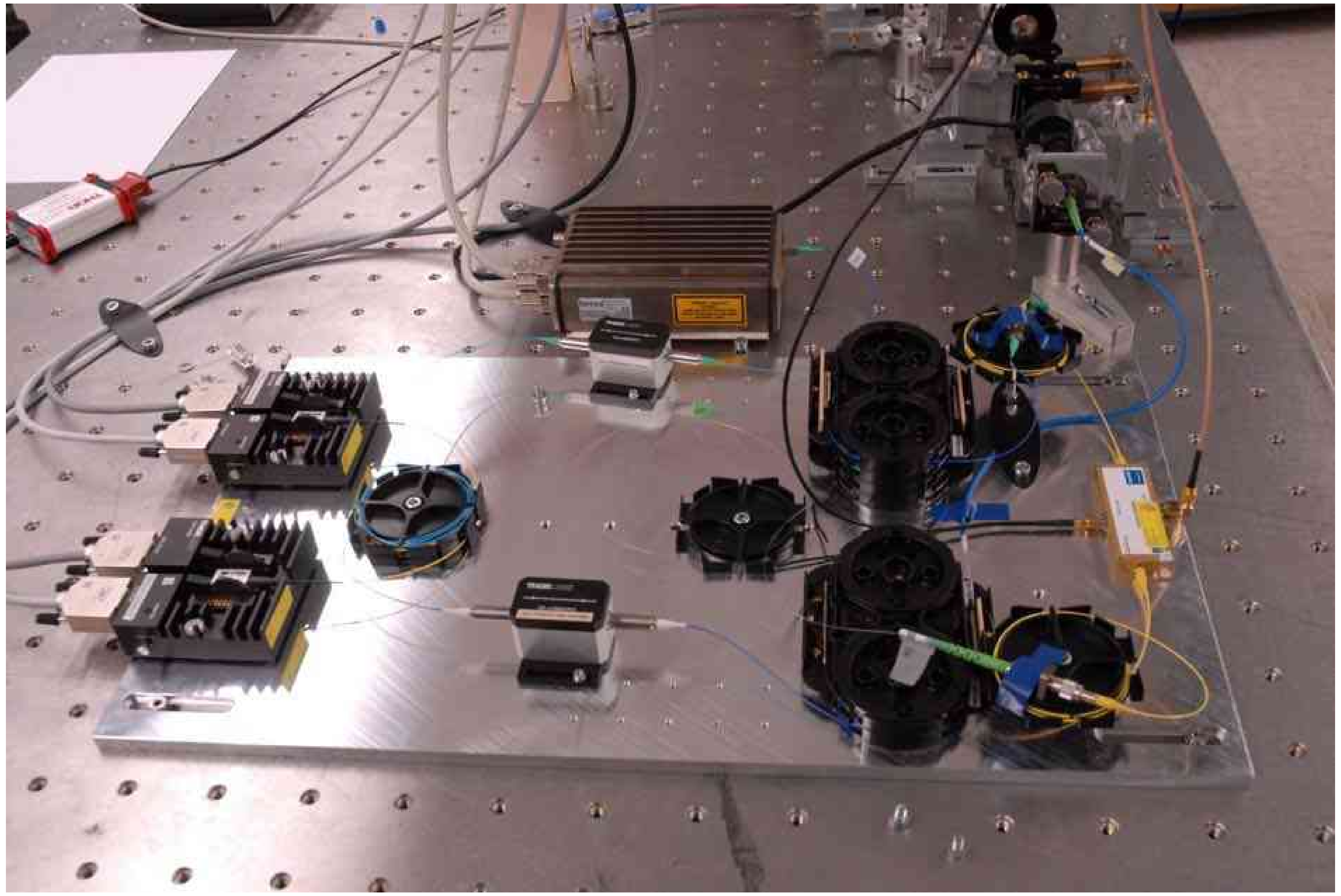
Collaboration with Deutsche Telekom



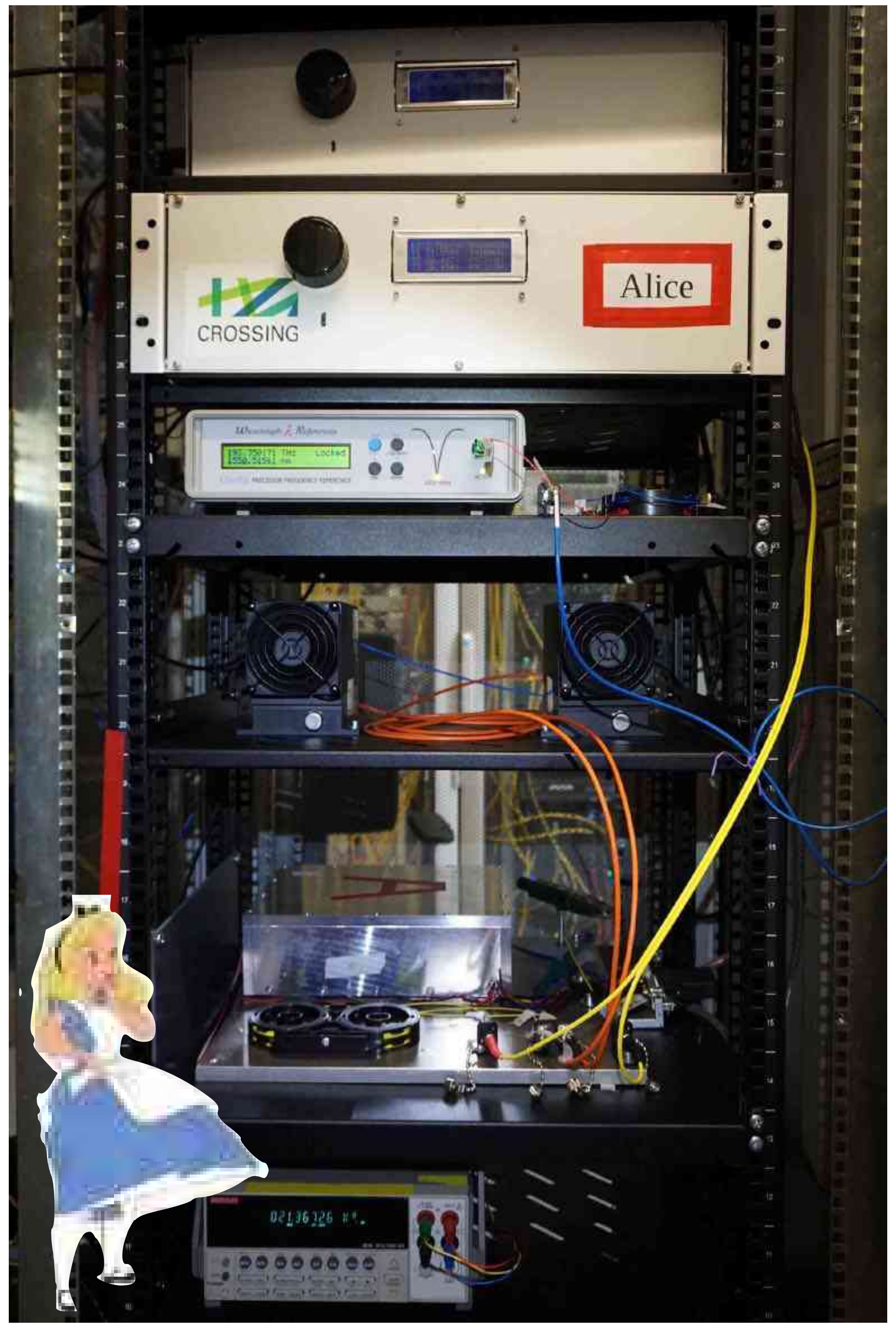


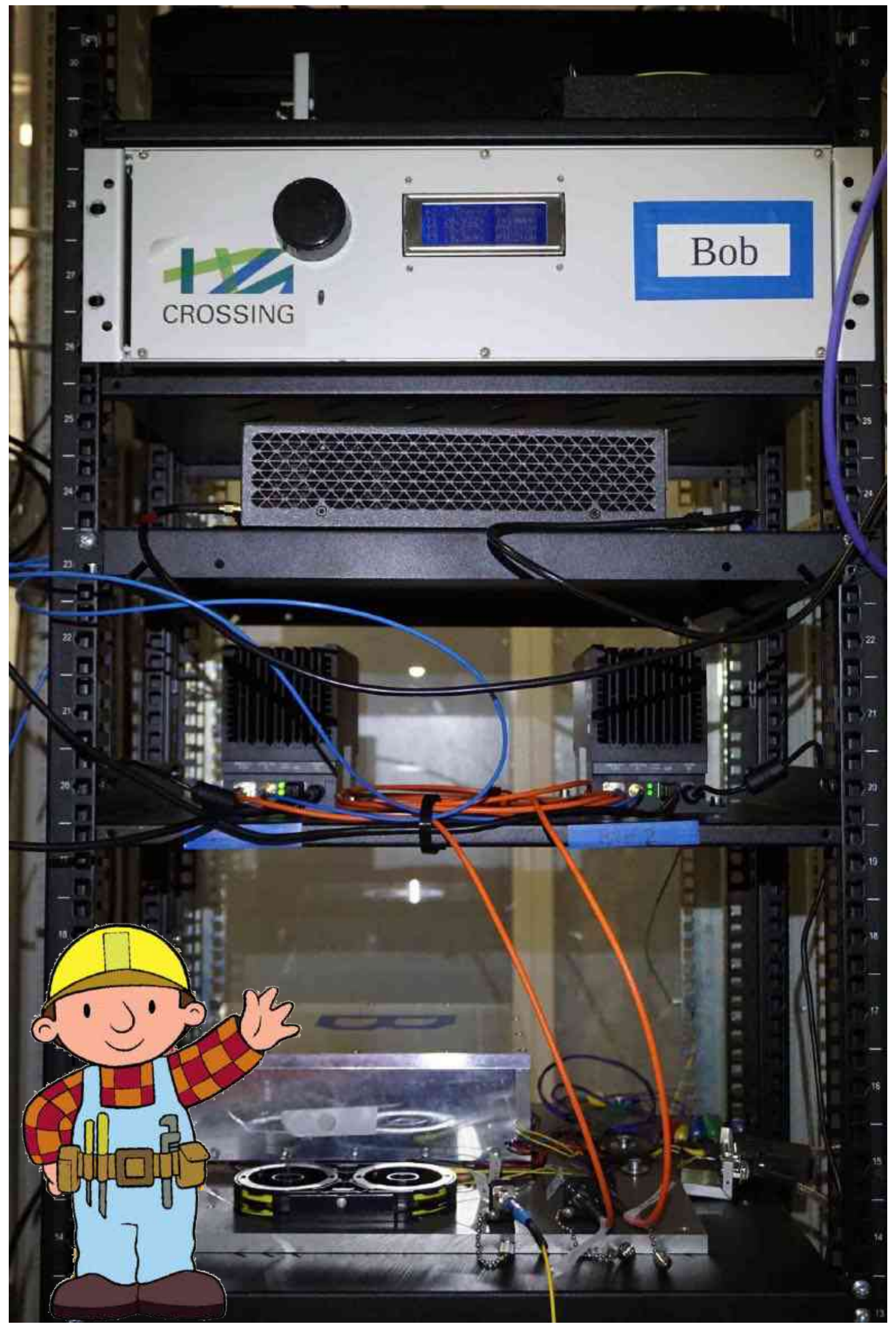
in cooperation with

Our QKD System @ Deutsche Telekom



Source (2nd generation)





Preliminary Tests

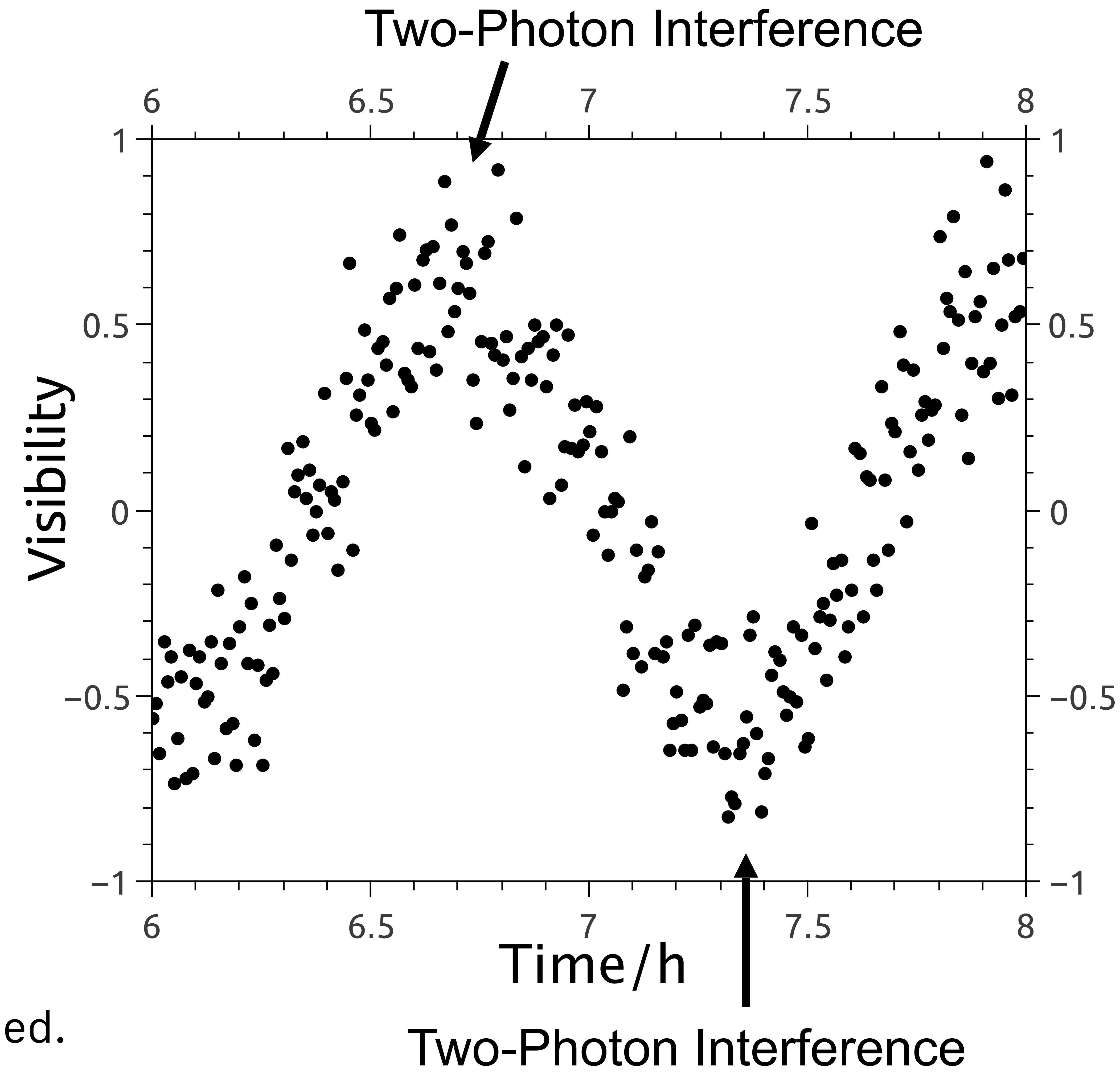
Setup of Equipment at Telekom Lab (since about 6 months

Goals

- Test of Components for Quantum Hub
- Realistic Telecom Environment
    - Acoustic Noise and Temperature Instability
    - 26 km of Fiber incl. Splices and Connectors

1st Preliminary Tests

- Temperature control working
- Time basis working
- Phase basis can be sufficiently well controlled



Temperature is slowly sweeped.

Next Steps

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Improvements & stability

Influence of environment

Next hardware generation

Key management and post-processing

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Quantum Key Distribution

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Quantum Key Distribution

- secure technology
- implementation is key
- device independent security possible
- large distance / intercontinental key distribution is possible via trusted nodes
- quantum repeater needed
- network aspects (more than just Alice and Bob) relatively unexplored

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Tobias Wieczorek

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