Quantum technologies with atoms and ions: overview and perspectives

Carlo Sias

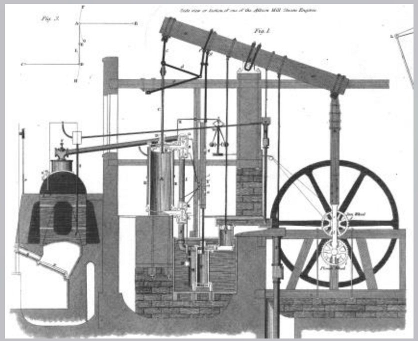
Istituto Nazionale di Ricerca Metrologica
European Laboratory for Nonlinear Spectroscopy

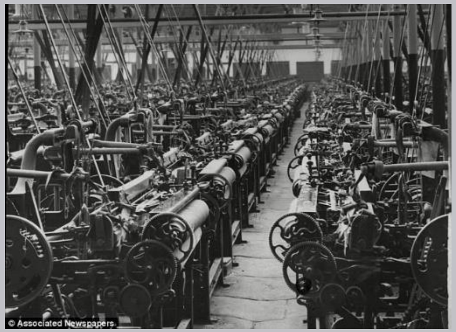
GSSI, L'Aquila, 28th February 2018

Motivations

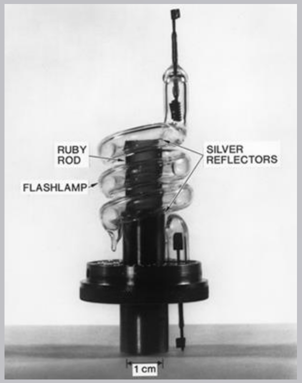
Understanding physics enables new technology

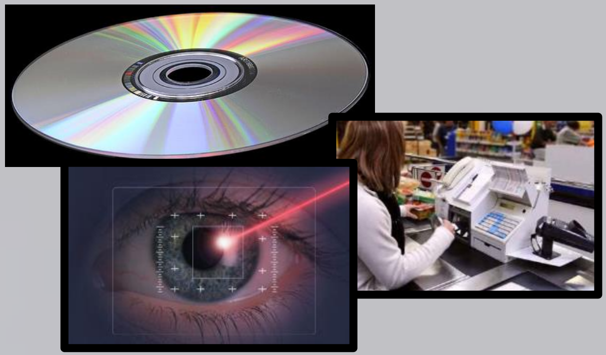
Thermodynamics





Optics, spectroscopy





Understanding physics enables new technology

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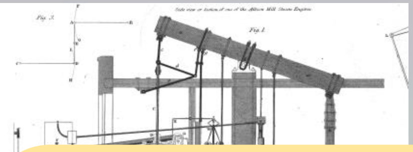
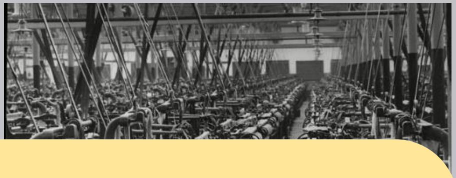
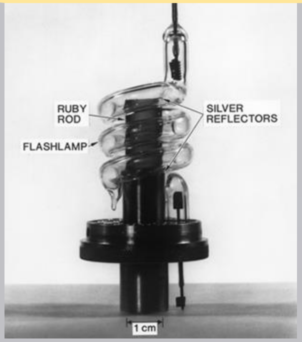
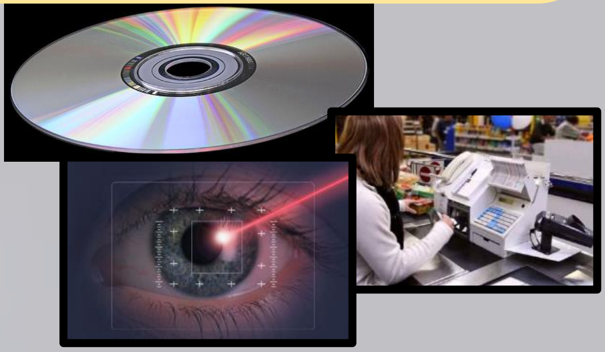




Can we build new technology based on quantum mechanics?





Outline of my talk

1. Introduction to basic concepts of quantum physics
2. Quantum Cryptography
3. Quantum computers
4. Quantum simulators
5. Precision measurements and sensing
6. Perspectives and conclusions

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1. **Introduction to basic concepts of quantum physics**
2. Quantum Cryptography
3. Quantum computers
4. Quantum simulators
5. Precision measurements and sensing
6. Perspectives and conclusions

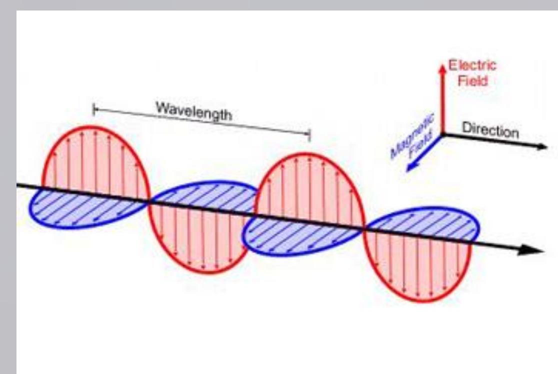
A few ingredients

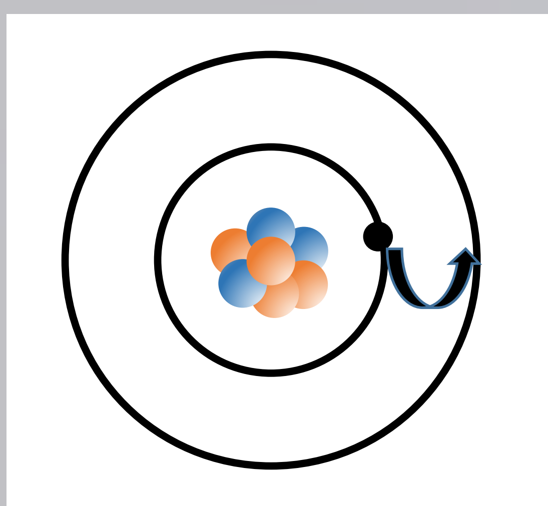
A two-level system

Basically a physical object living in a 2-dimensional Hilbert space. Its *state* (vector) is expressed with a *ket*

Polarization of photons

$|H\rangle, |V\rangle$





Electronic orbitals

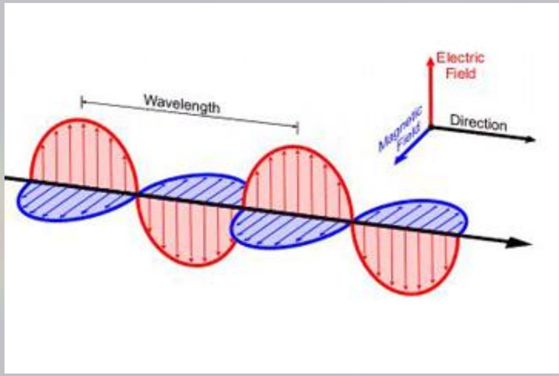
$|g\rangle, |e\rangle$

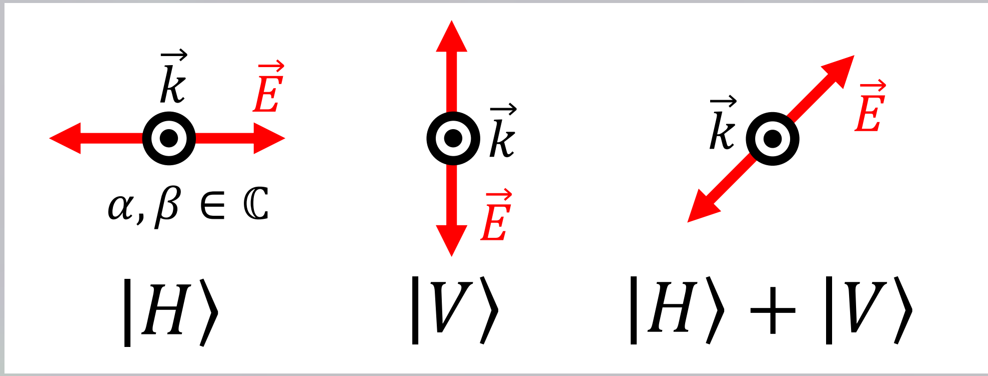
...MANY others

A few ingredients

Superposition principle

A superposition of two quantum states is a quantum state

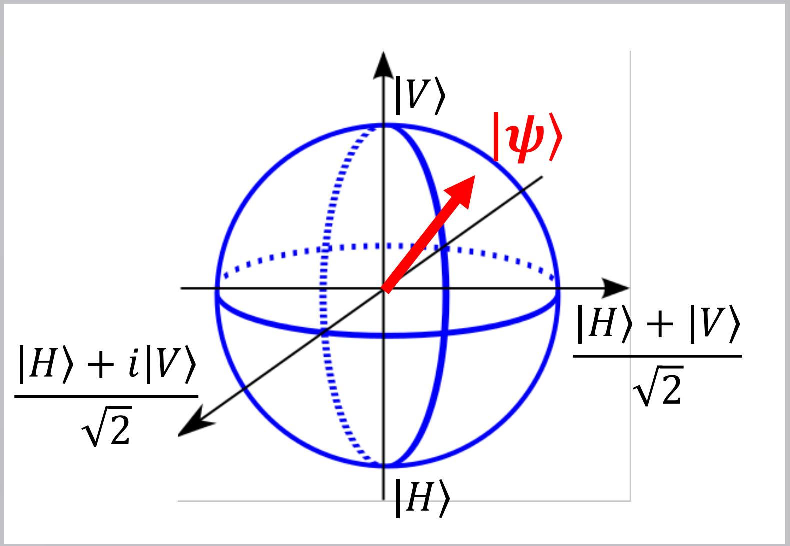




A generic superposition state lies in the Bloch sphere

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

$$\alpha, \beta \in \mathbb{C}, \quad |\alpha|^2 + |\beta|^2 = 1$$

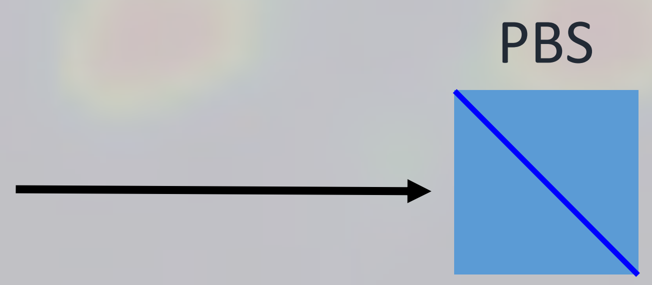


A few ingredients

Projective measurement

Measuring the quantum state CHANGES the quantum state

Experiment: let's send some light to a Polarizing Beamsplitter



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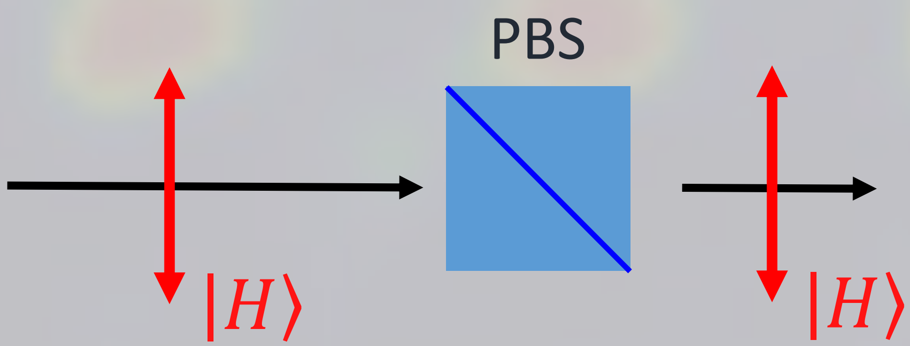

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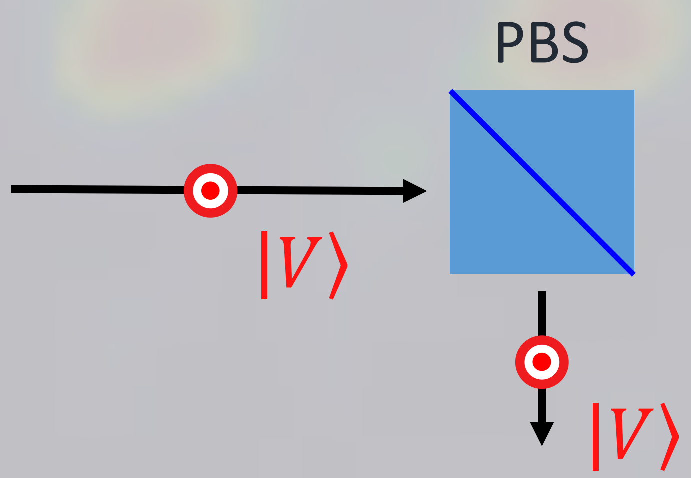

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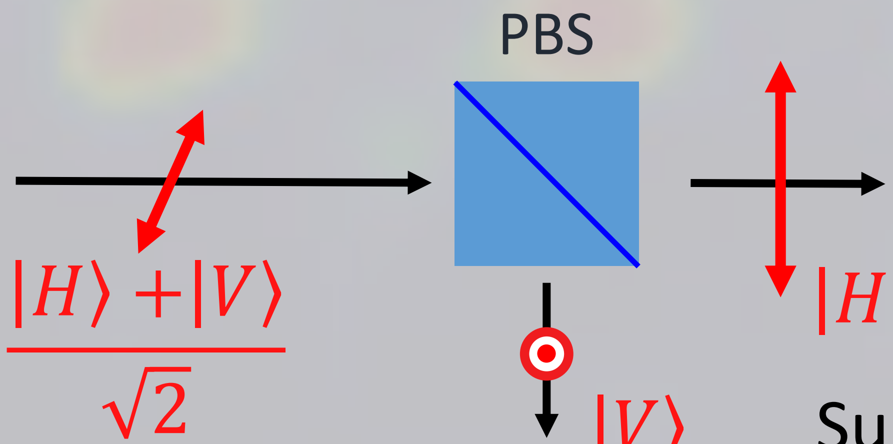

$$\frac{|H\rangle + |V\rangle}{\sqrt{2}}$$

$|V\rangle$

$|H\rangle$

Superposition!

A few ingredients

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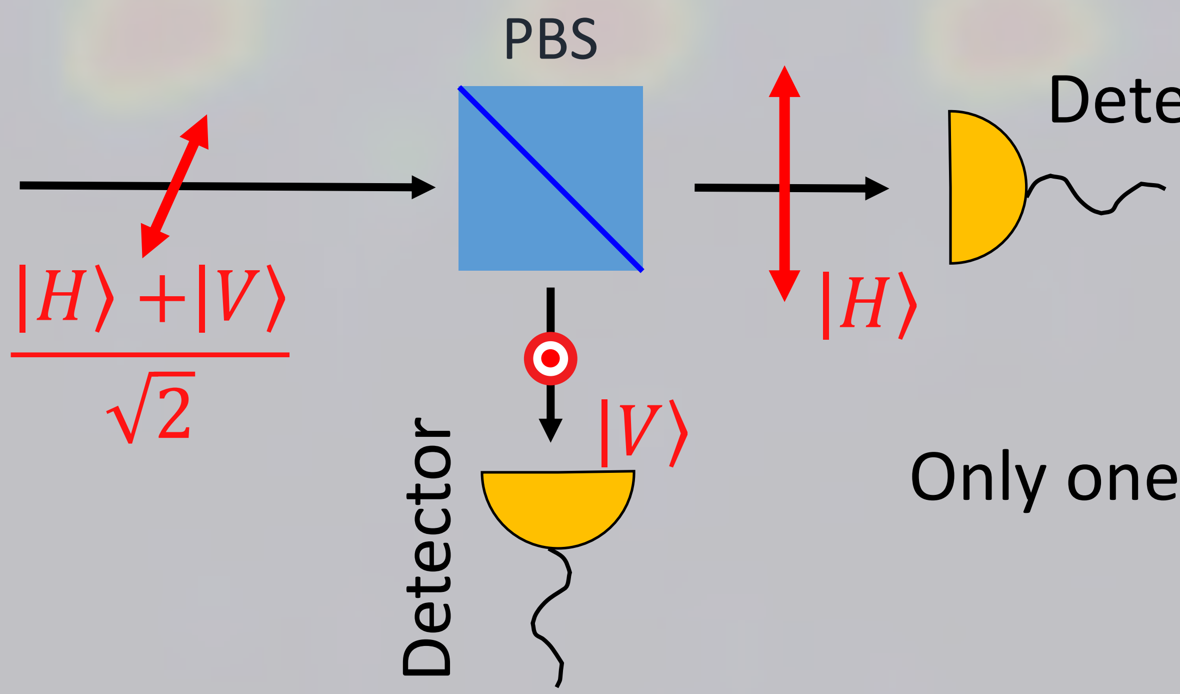

Only one clicks!

A few ingredients

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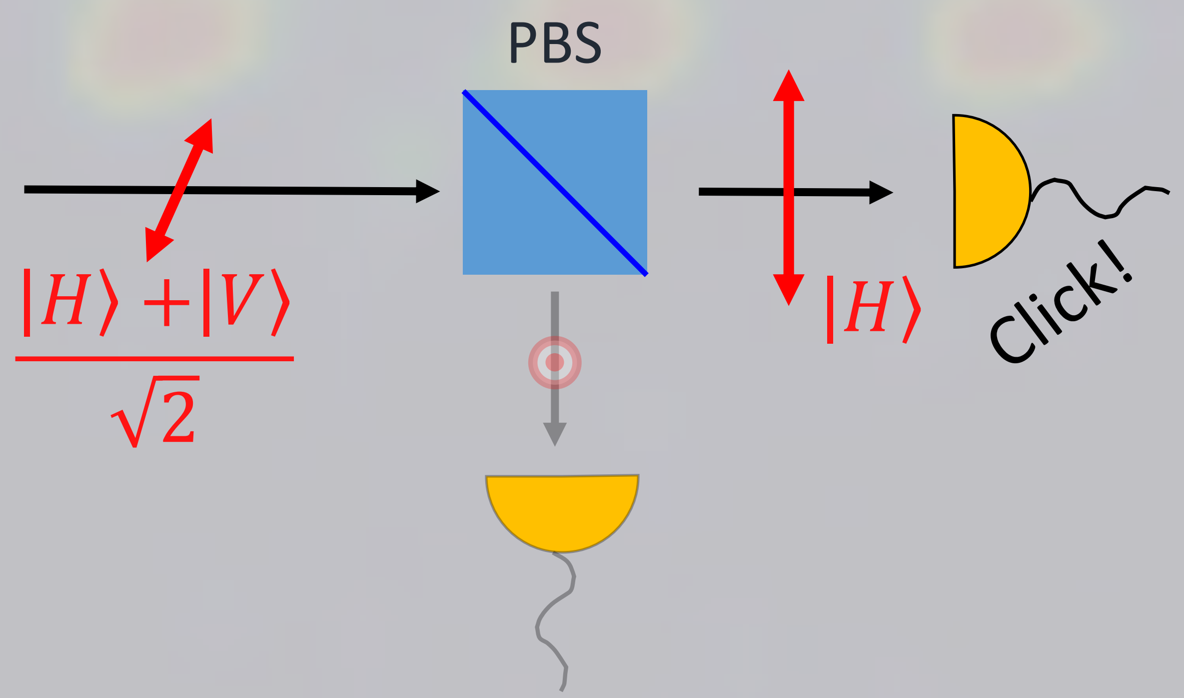

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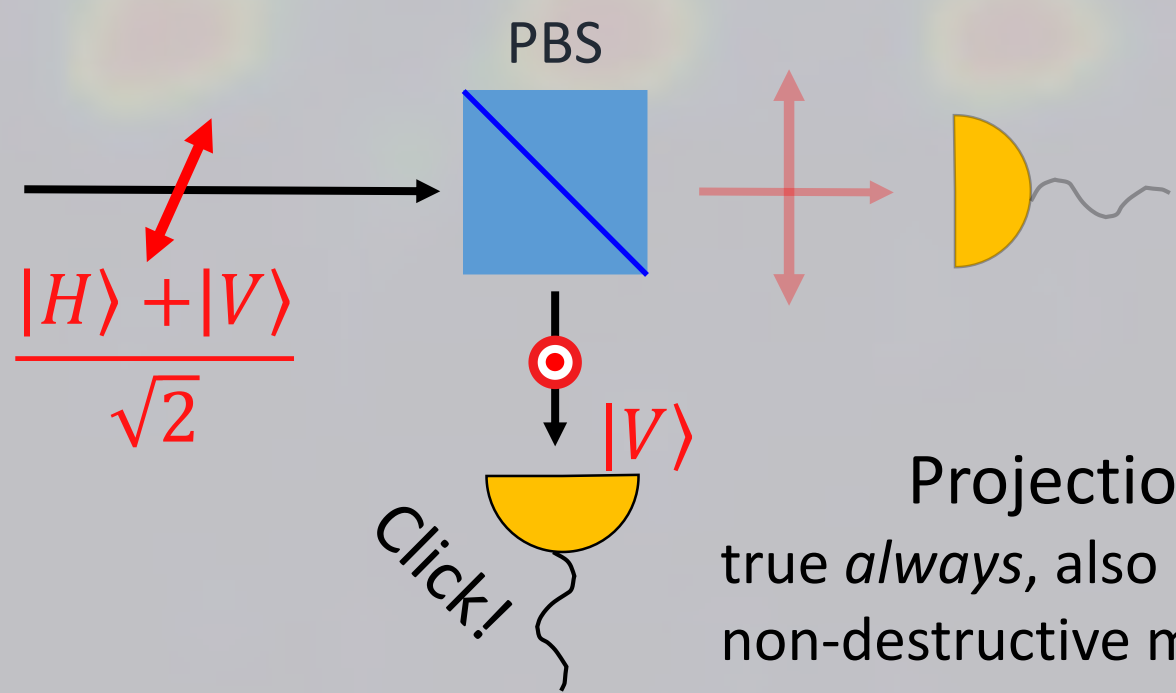

Projection!

true *always*, also in case of non-destructive measurements

A few ingredients

«Interactions»

Making the quantum evolution of a particle conditional on the state of a second particle

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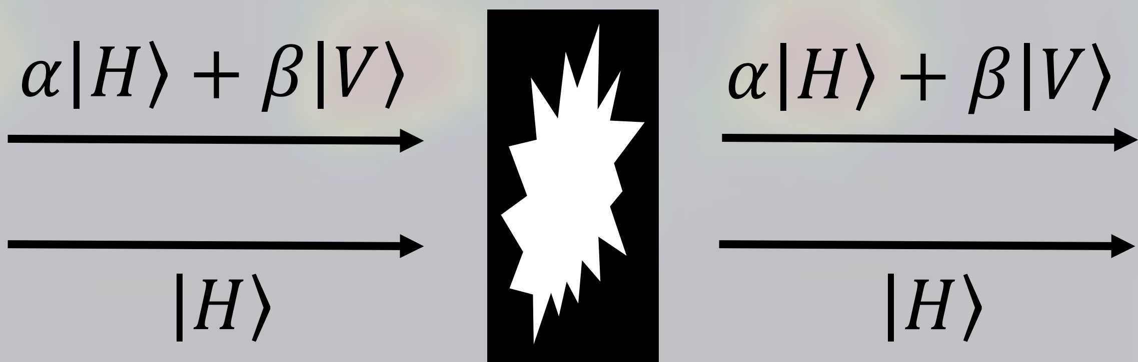
Making the quantum evolution of a particle conditional on the state of a second particle

Example: a conditional NOT



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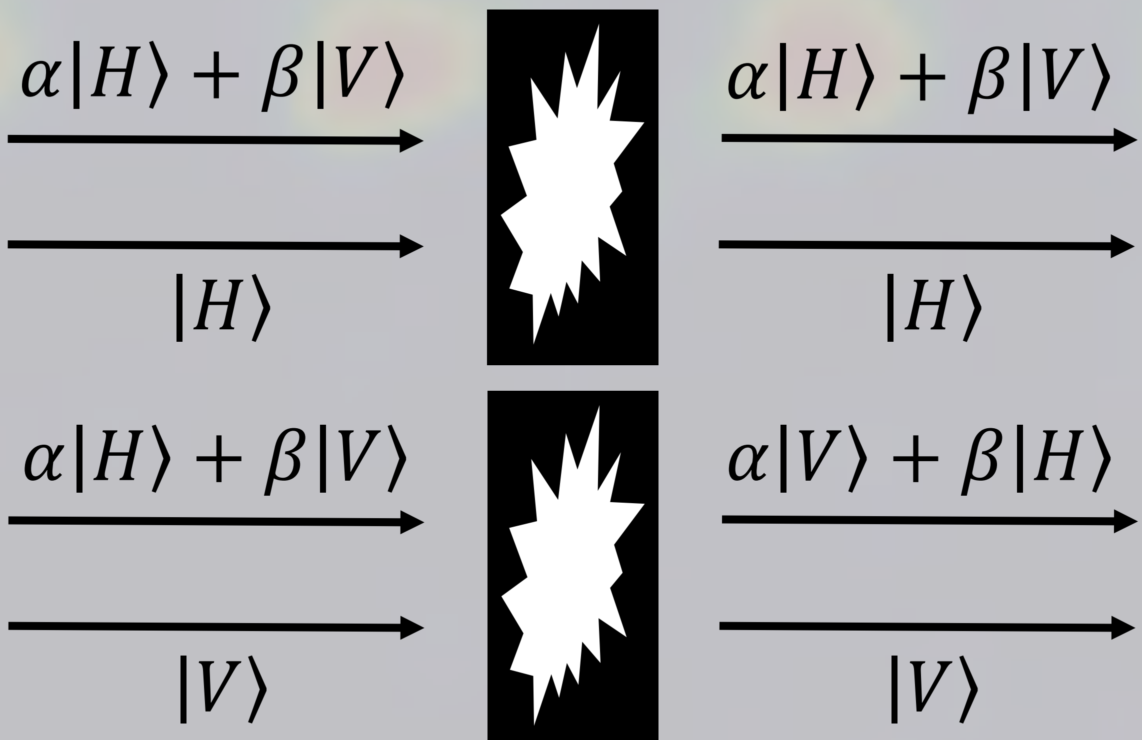

Coherent!

Non-classical!

A few ingredients

Summarizing

- A two-level system
- Superposition principle
- Projective measurement
- Interactions

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- A two-level system
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That sounds easy!

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- A two-level system
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- Interactions

That sounds easy!

... not really ...

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Quantum chryptography

Projective measurement

Measuring the quantum state CHANGES the quantum state

Quantum chryptography

Projective measurement

Measuring the quantum state CHANGES the quantum state

Can we use this property to implement an intrisically safe communication channel?

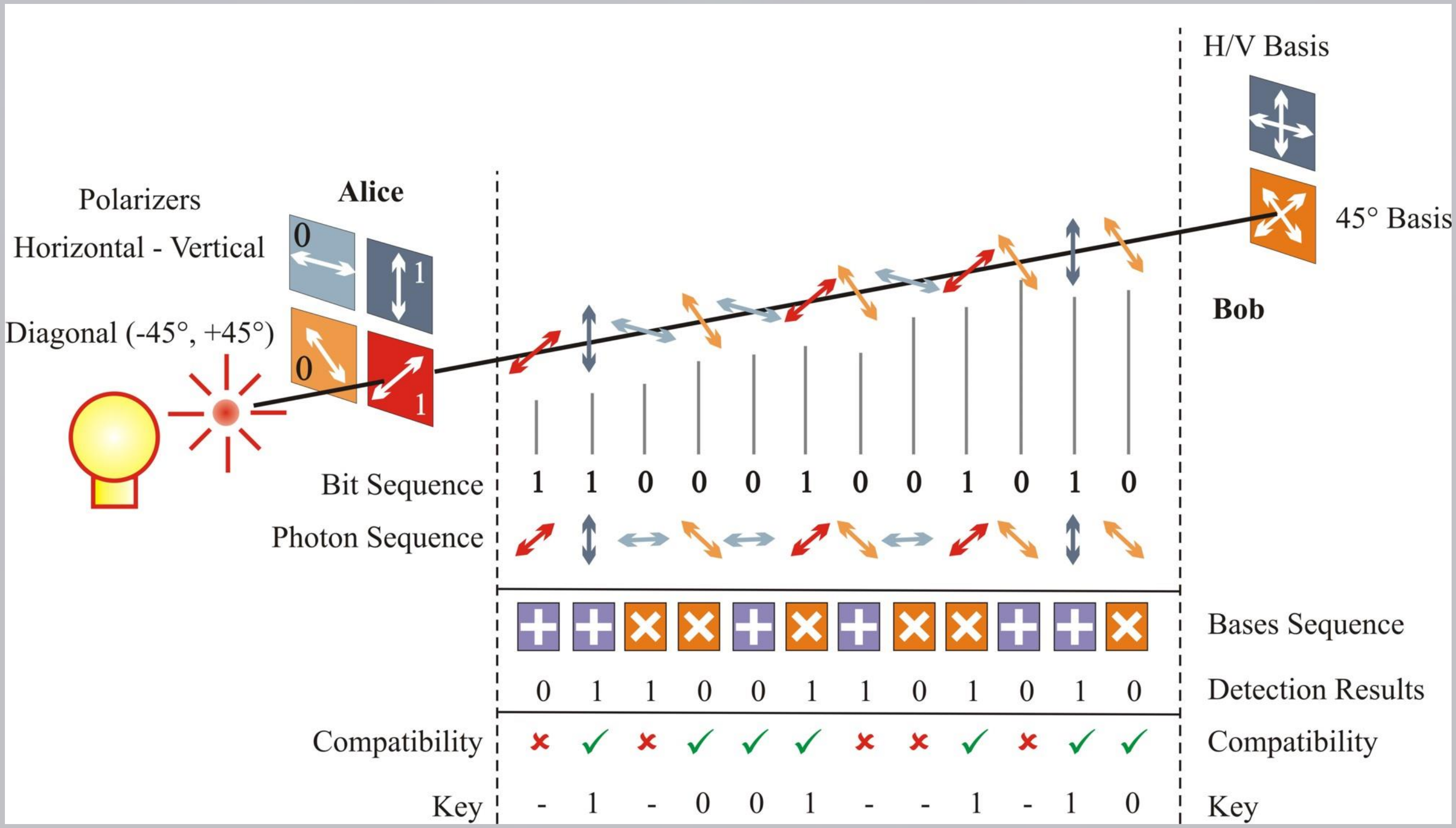
QUANTUM CRYPTOGRAPHY: PUBLIC KEY DISTRIBUTION AND COIN TOSSING

Charles H. Bennett (IBM Research, Yorktown Heights NY 10598 USA)
Gilles Brassard (dept. IRO, Univ. de Montreal, H3C 3J7 Canada)

Bennett, C.H. and G. Brassard.
Proceedings of IEEE International Conference on Computers, Systems and Signal Processing, 175, 8 (1984)

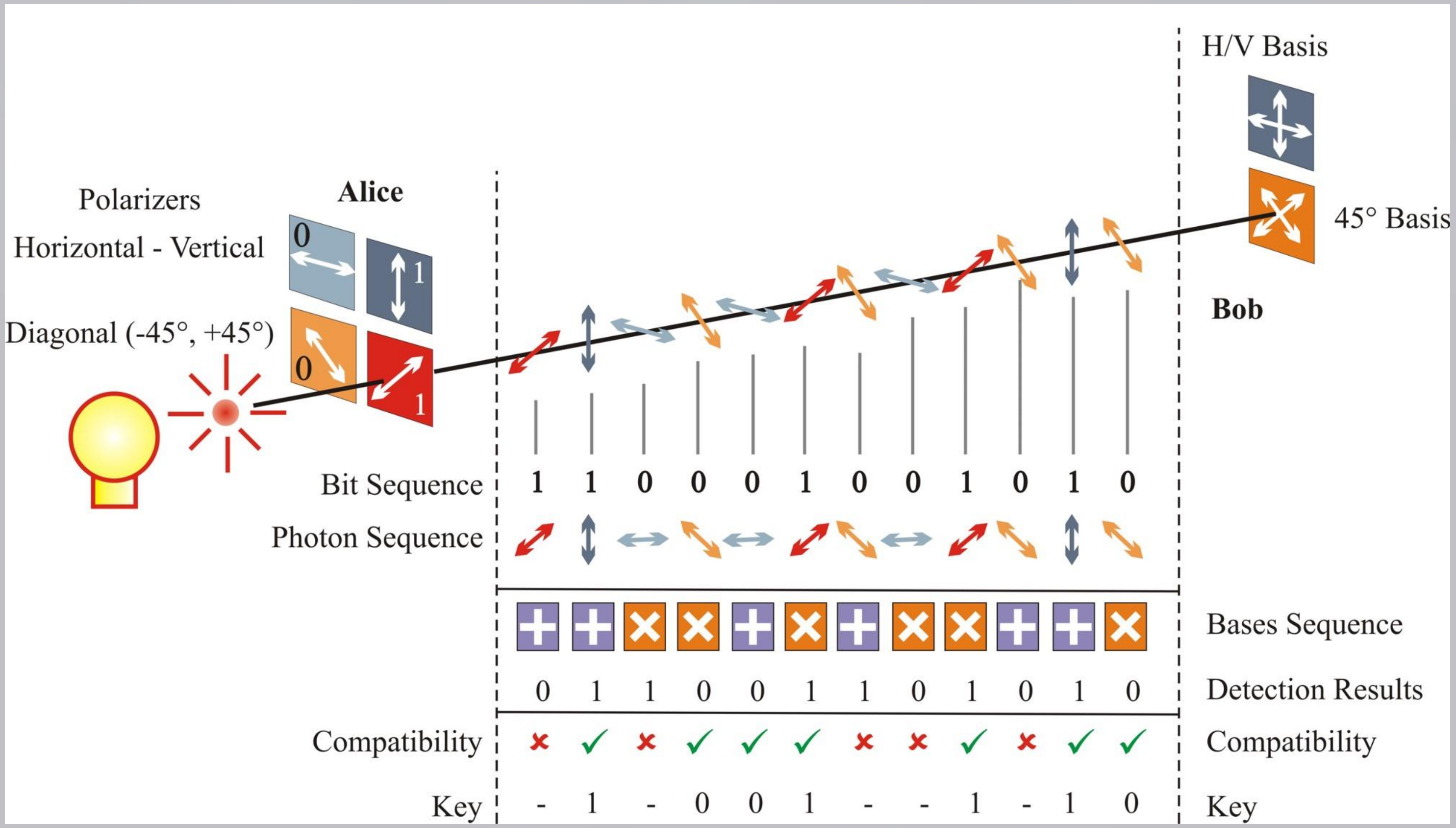
The BB84 protocol

1- Alice sends N photons to Bob, encoding the *classical* information in the light polarization, randomly either in the H-V or in the +45°-45° polarization basis



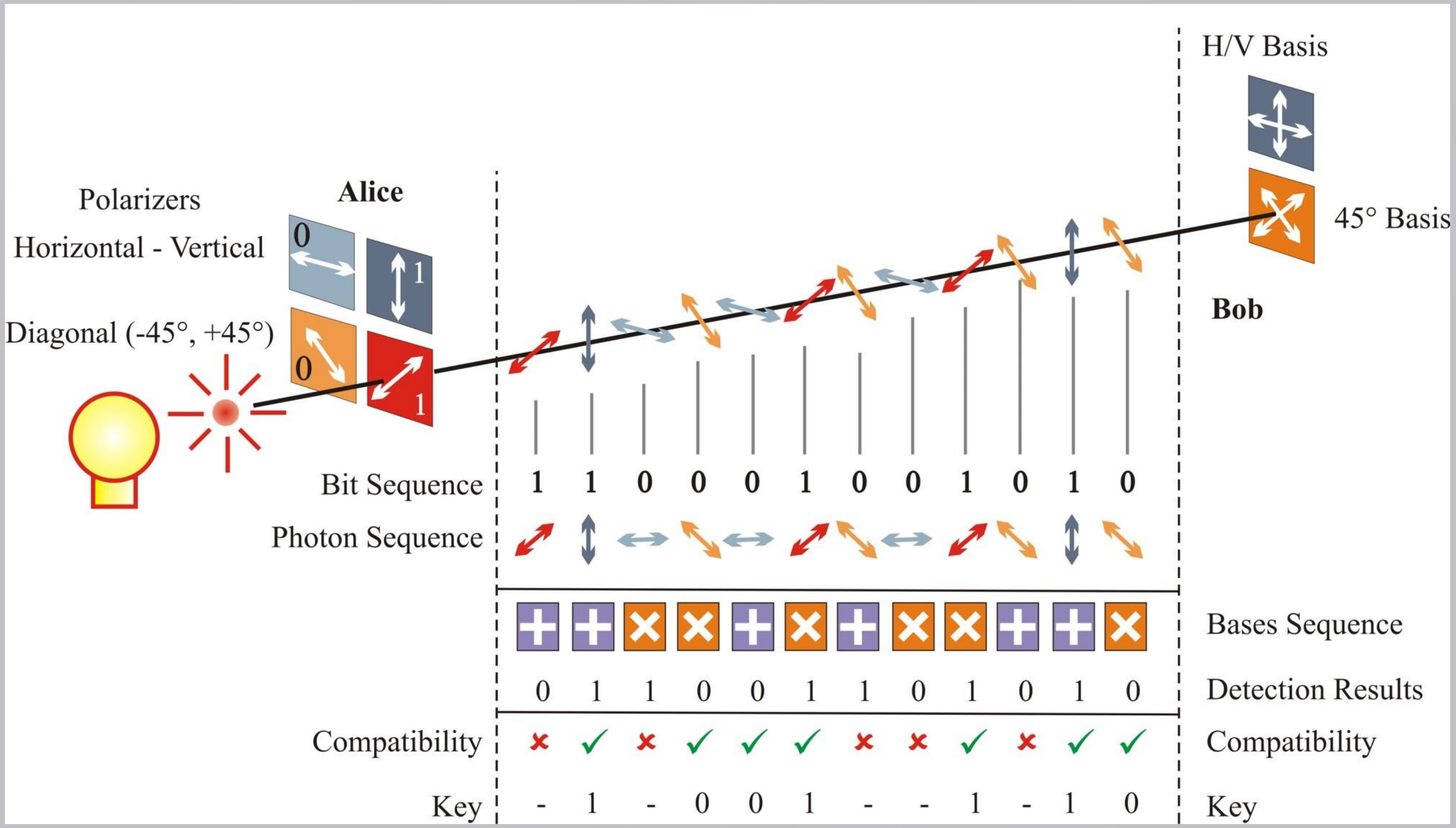
The BB84 protocol

2- Bob chooses randomly the basis for his measurement



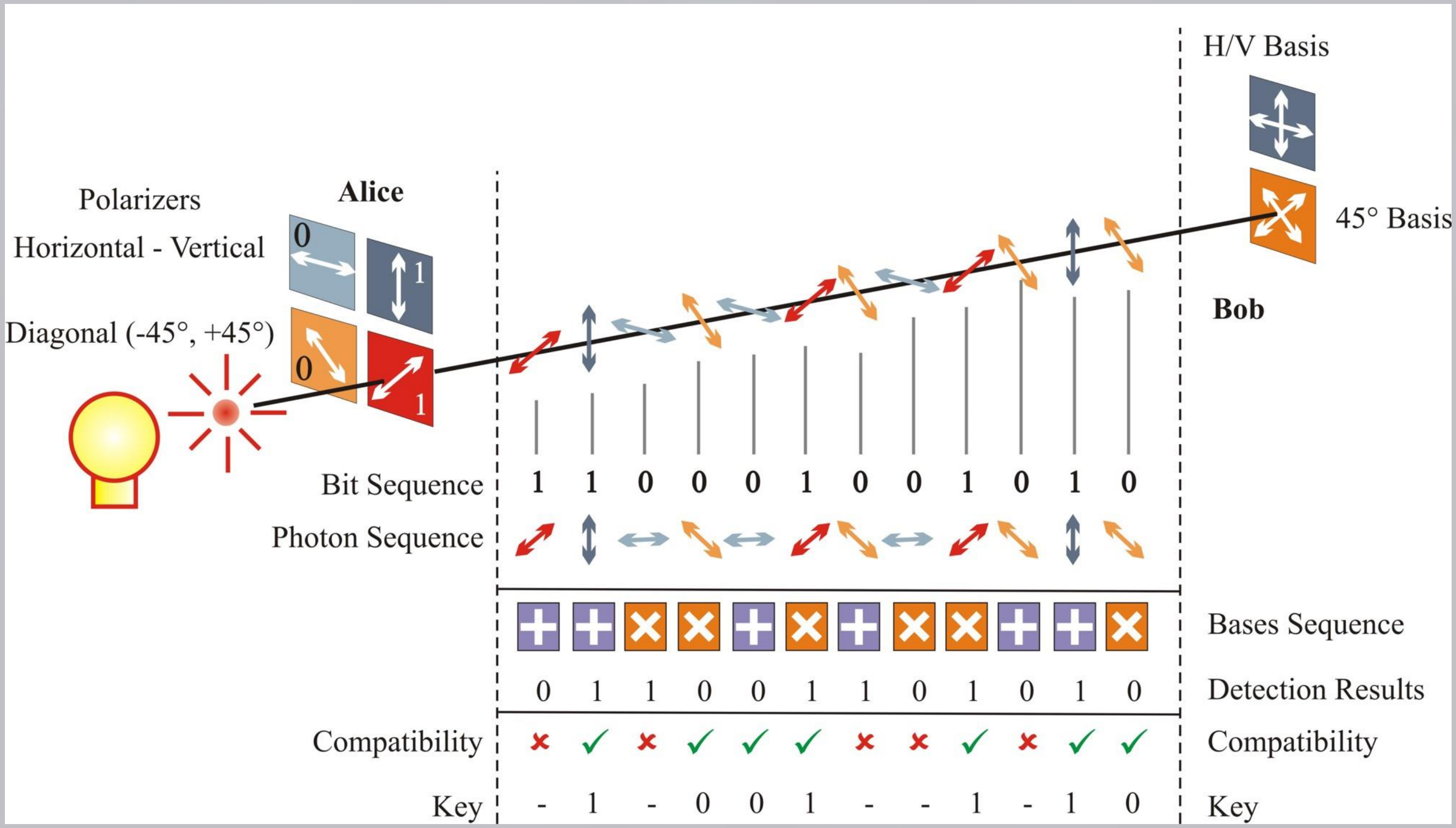
The BB84 protocol

3- Bob shares publicly his basis sequence with Alice



The BB84 protocol

4- Alice and Bob choose n photons to check the safety of the channel – the probability that an evesdropper is undetected is $\mathbf{(3/4)^n}$



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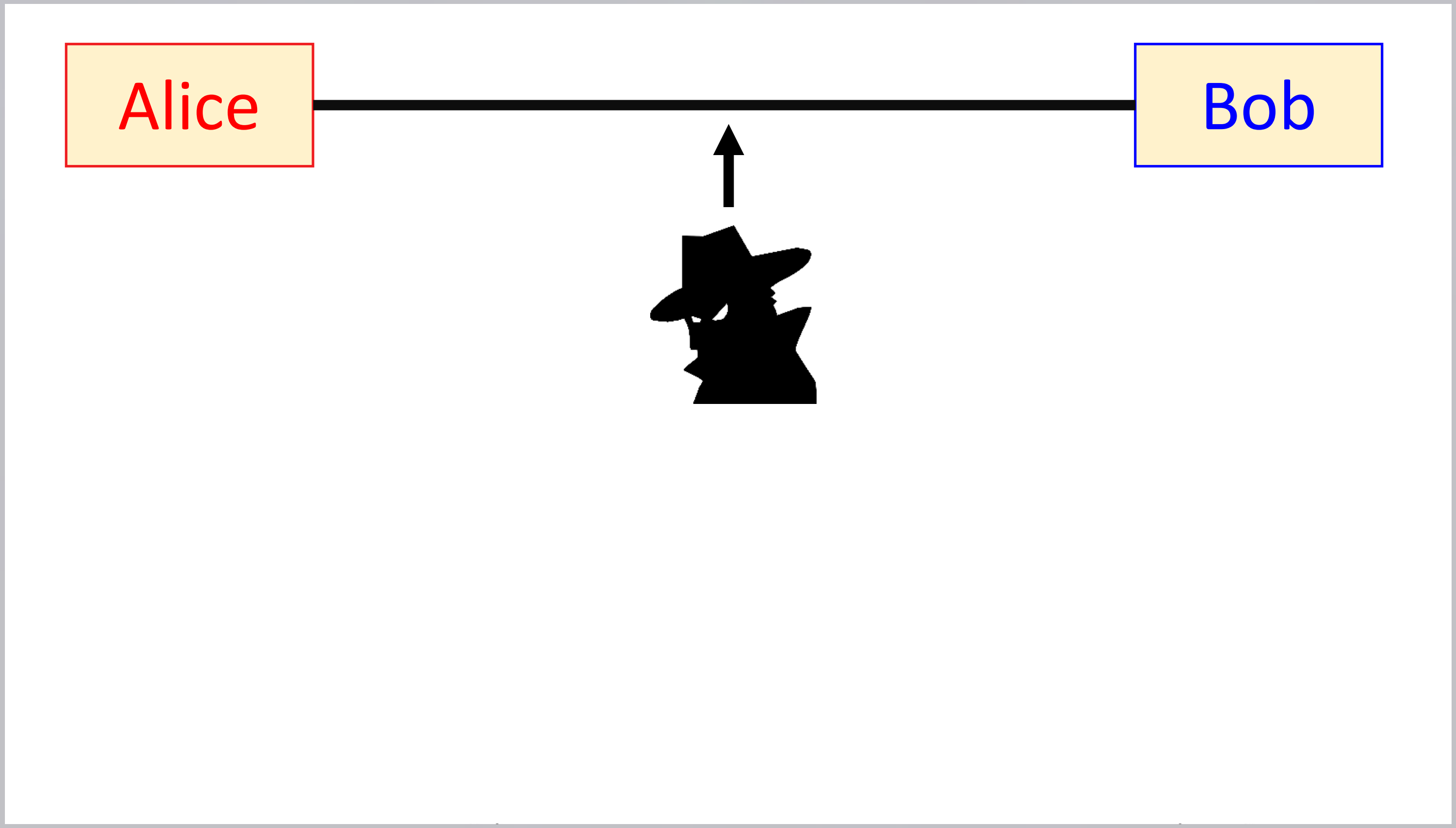

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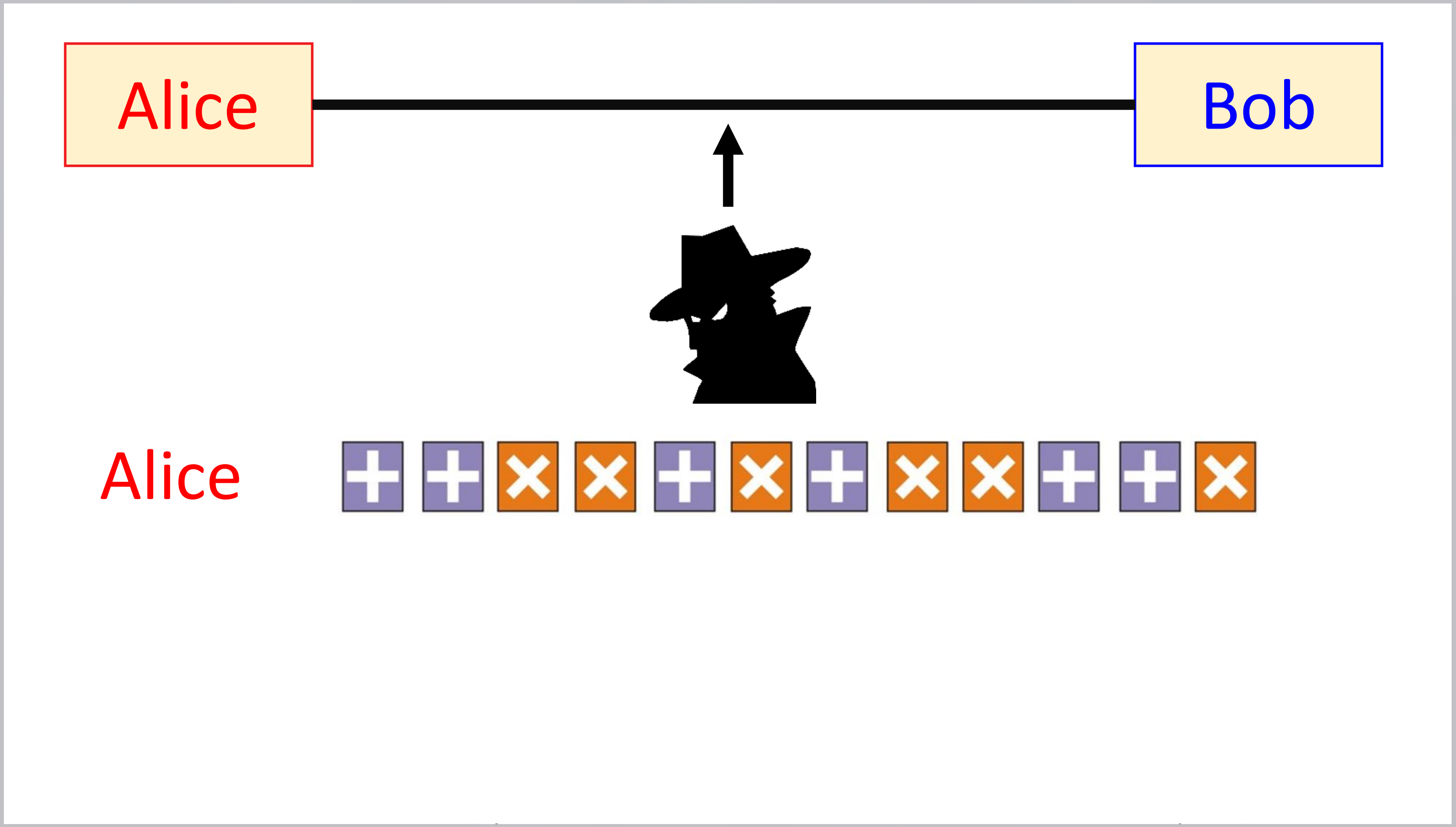

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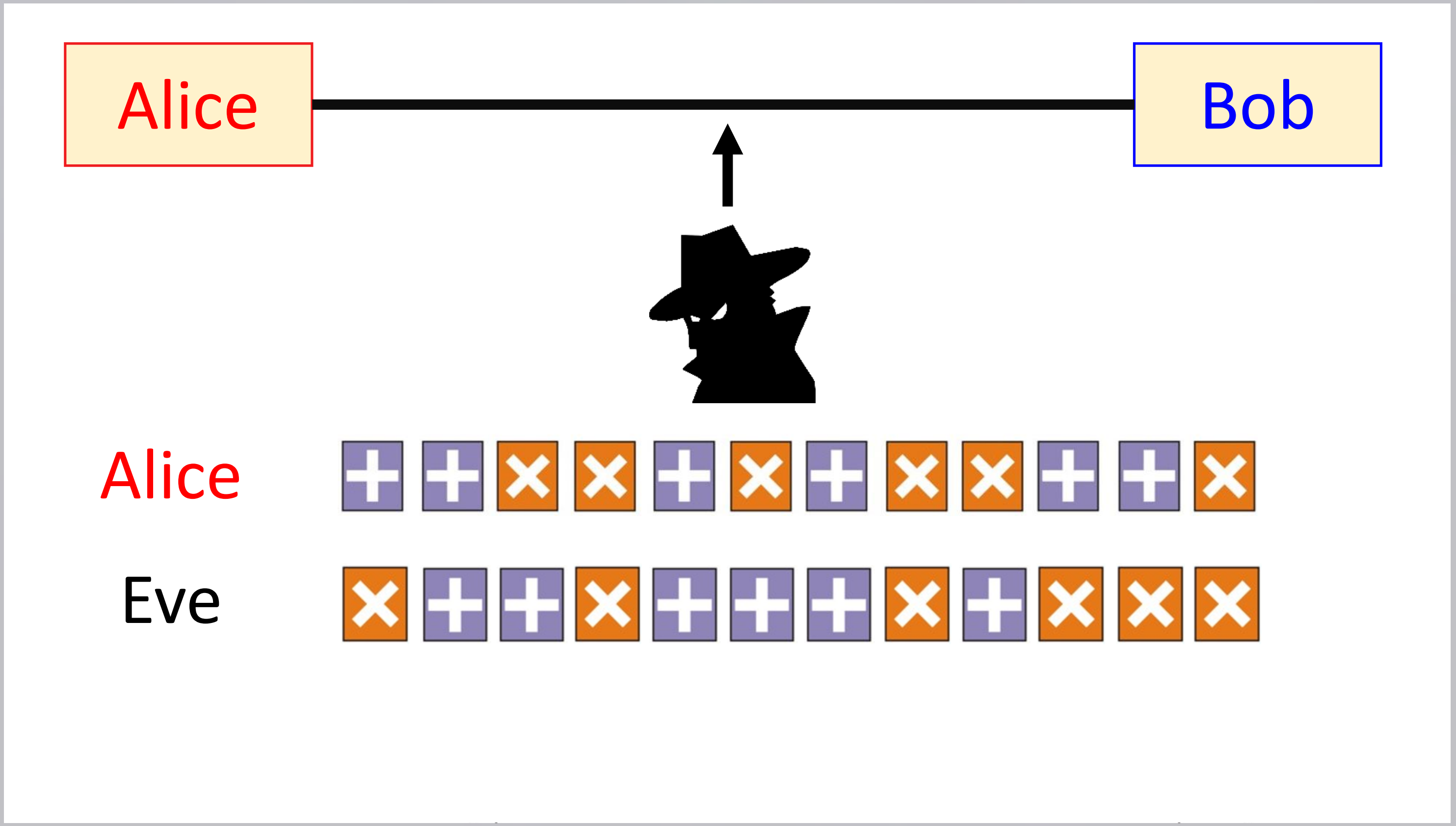

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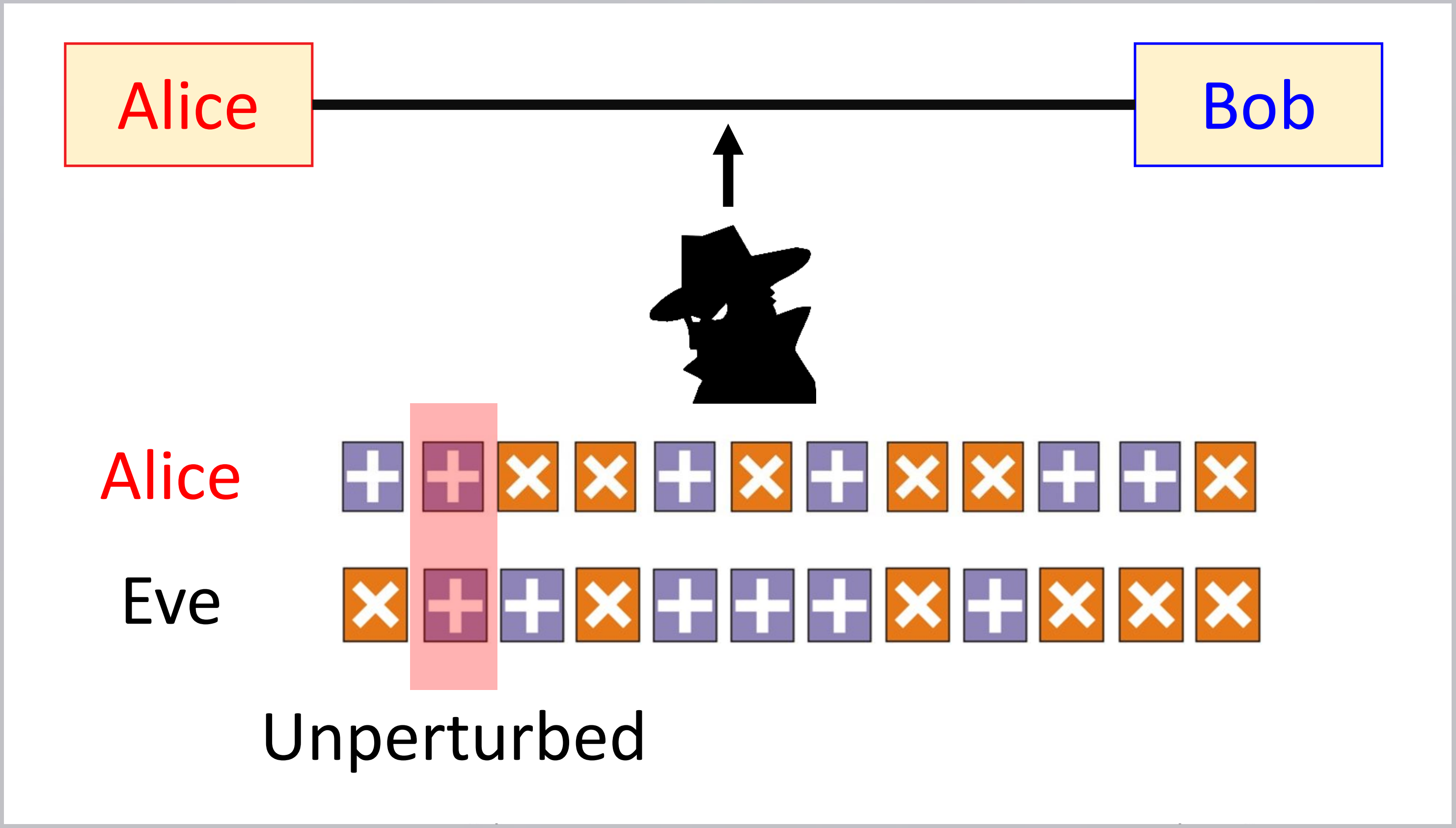

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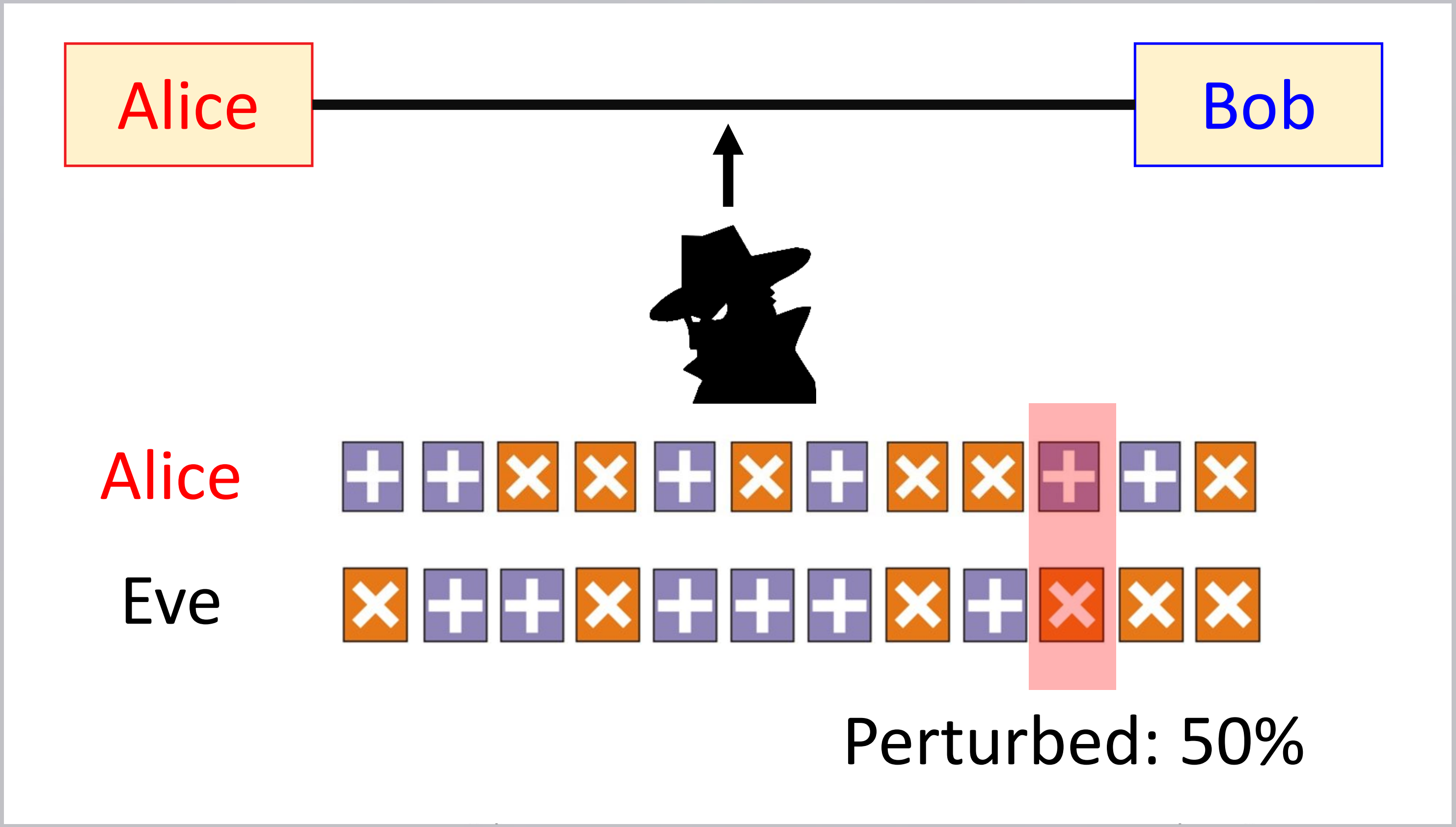

Commercial quantum chryptography

Currently limited by losses in optical fibers (approx. 100Km) → **Space!**

The Economist

Quantum cryptography

Heisenberg's certainty principle

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

Commercial quantum chryptography

QUANTUM OPTICS

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]*

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100Km) → **Space!**

Hei

The Swis

Experimental Satellite Quantum Communications

Giuseppe Vallone,[1] Davide Bacco,[1] Daniele Dequal,[1] Simone Gaiarin,[1] Vincenza Luceri,[2] Giuseppe Bianco,[3] and Paolo Villoresi[1,*]

[1]*Dipartimento di Ingegneria dell'Informazione, Università degli Studi di Padova, Padova 35131, Italy*
[2]*e-GEOS spa, Matera 75100, Italy*
[3]*Matera Laser Ranging Observatory, Agenzia Spaziale Italiana, Matera 75100, Italy*

(Received 13 April 2015; revised manuscript received 26 May 2015; published 20 July 2015)

Outline of my talk

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2. Quantum Cryptography
3. **Quantum computers**
4. Quantum simulators
5. Precision measurements and sensing
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Quantum computation: the origins

Since early 1980s a few theorist begun speculating over a quantum computer

Proc. R. Soc. Lond. A 400, 97–117 (1985)
Printed in Great Britain

Quantum theory, the Church–Turing principle and the universal quantum computer

By D. Deutsch
Department of Astrophysics, South Parks Road, Oxford OX1 3RQ, U.K.

(*Communicated by R. Penrose, F.R.S. – Received* 13 *July* 1984)

It is argued that underlying the Church–Turing hypothesis there is an implicit physical assertion. Here, this assertion is presented explicitly as a physical principle: 'every finitely realizible physical system can be perfectly simulated by a universal model computing machine operating by finite means'. Classical physics and the universal Turing machine, because the former is continuous and the latter discrete, do not obey the principle, at least in the strong form above. A class of model computing machines that is the quantum generalization of the class of Turing machines is described, and it is shown that quantum theory and the 'universal quantum computer' are compatible with the principle. Computing machines resembling the universal quantum computer could, in principle, be built and would have many remarkable properties not reproducible by any Turing machine. These do not include the computation of non-recursive functions, but they do include 'quantum parallelism', a method by which certain probabilistic tasks can be performed faster by a universal quantum computer than by any classical restriction of it.

International Journal of Theoretical Physics, Vol. 21, Nos. 6/7, 1982

Simulating Physics with Computers

Richard P. Feynman
Department of Physics, California Institute of Technology, Pasadena, California 91107

Received May 7, 1981

be understood very well in analyzing the situation. And I'm not happy with all the analyses that go with just the classical theory, because nature isn't classical, dammit, and if you want to make a simulation of nature, you'd better make it quantum mechanical, and by golly it's a wonderful problem, because it doesn't look so easy. Thank you.

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Dep

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The principle: a quantum world can be described only by a quantum device

The goal: a quantum computer

Internation

Si

Department of Physics, California Institute of Technology, Pasadena, California 91107

Received May 7, 1981

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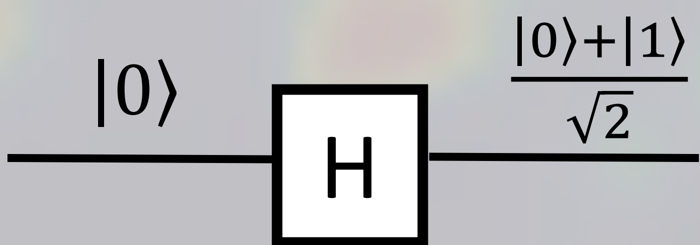

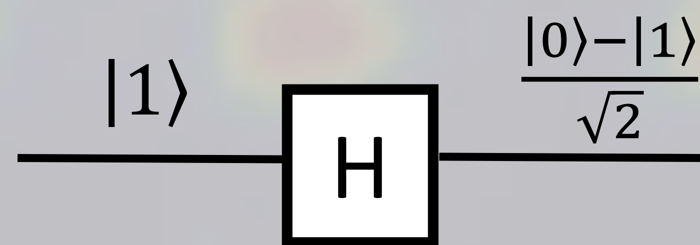

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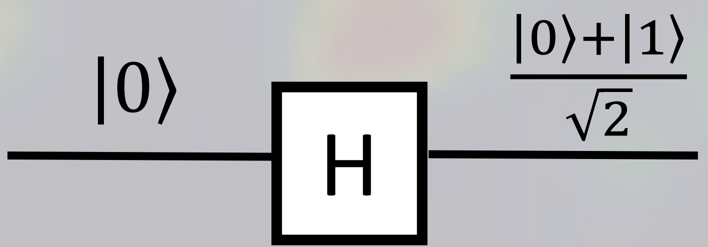
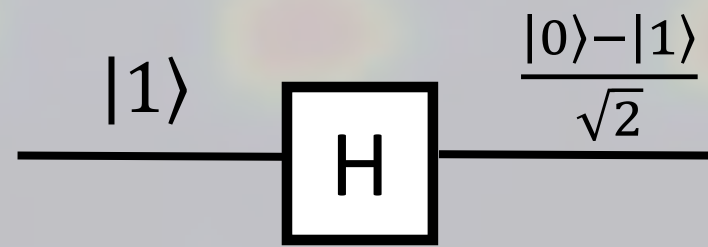
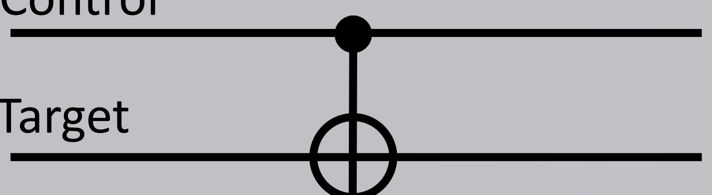




3. A two-qubit conditional gate, e.g. the controlled-NOT



$\|0_C\|0\rangle_T \rightarrow \|0\rangle_C\|0\rangle_T$
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Quantum algorithms

Mainly **three** quantum algorithms

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Recognize a fake coin (with two haeds or two tails) with one measurement

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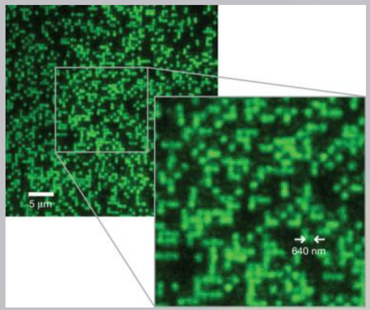
3. Shor's algorithm

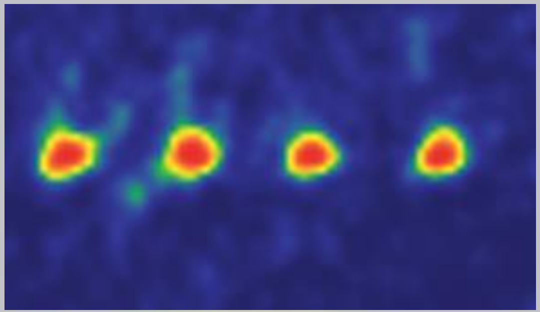
The time needed to factorize a number depends polynomially (exponentially in a classical computer) on the number size

Quantum hardware

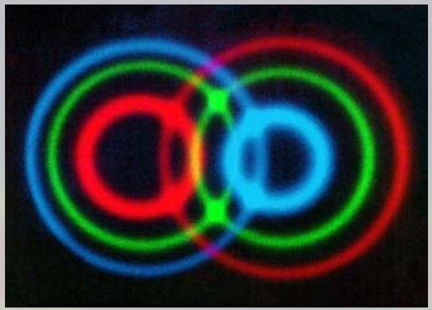
Neutral atoms



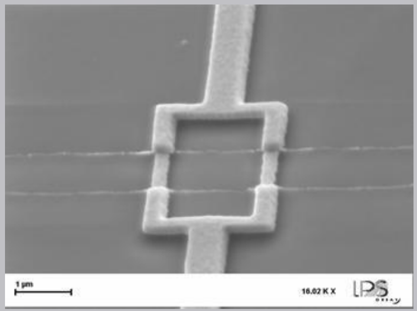
Ions



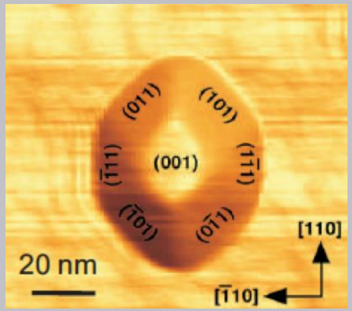
Photons



Squids



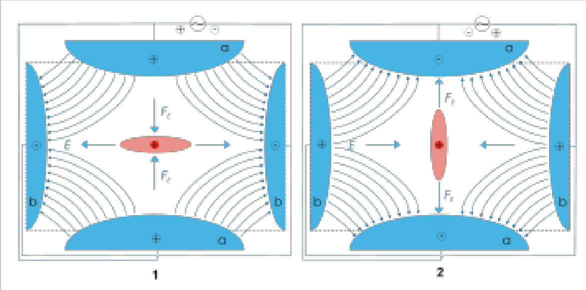
Quantum dots



... and many others

Trapped ions

A great resource for quantum technologies!



Trapping with electric fields (current record: **6 months**)

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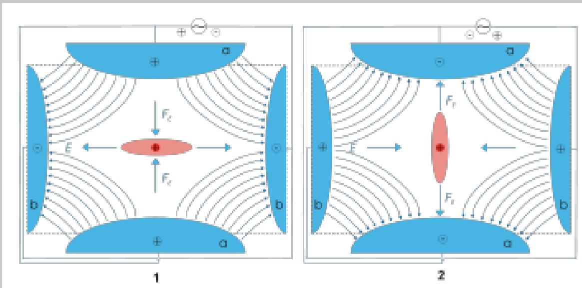
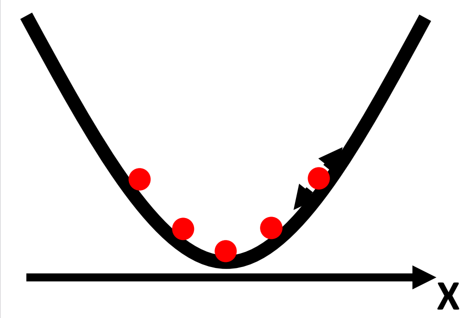
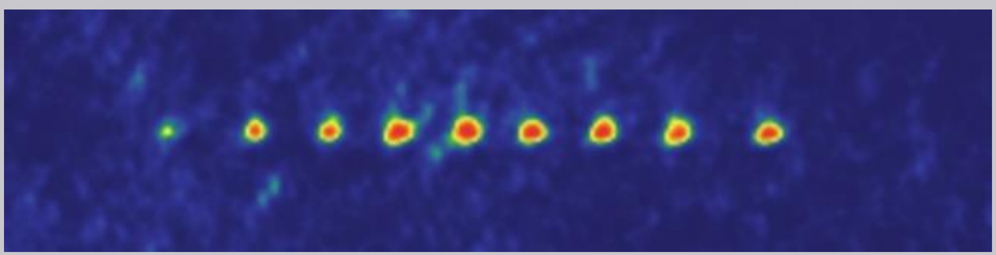


Trapping with electric fields (current record: **6 months**)

Crystal-like structure due to Coulomb repulsion





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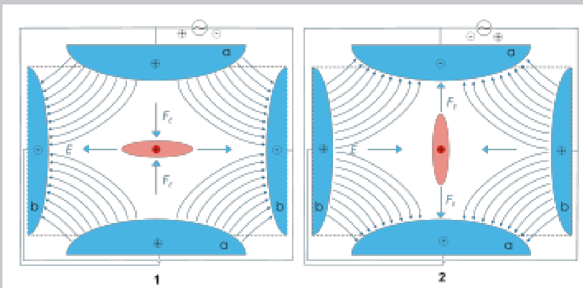

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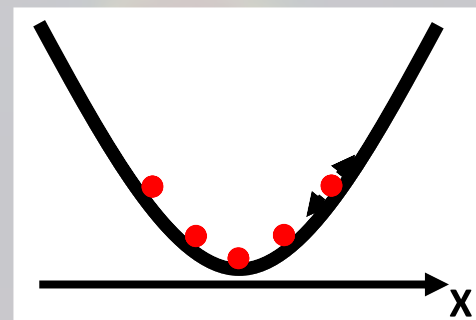

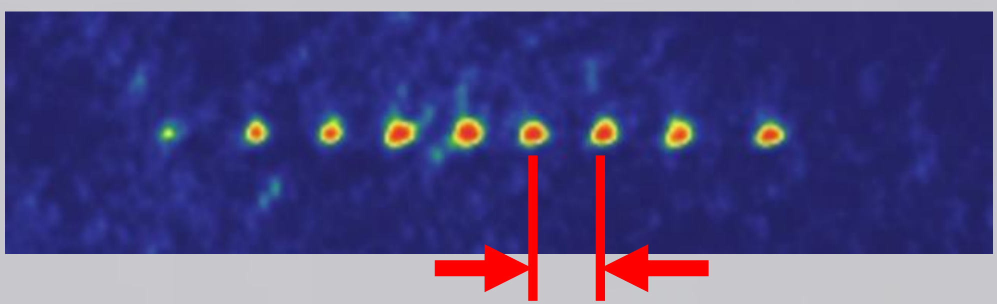

d~10 μm

Trapped ions

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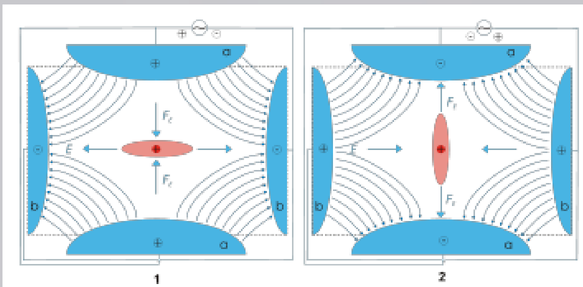

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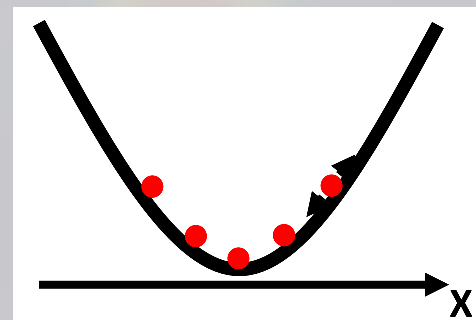

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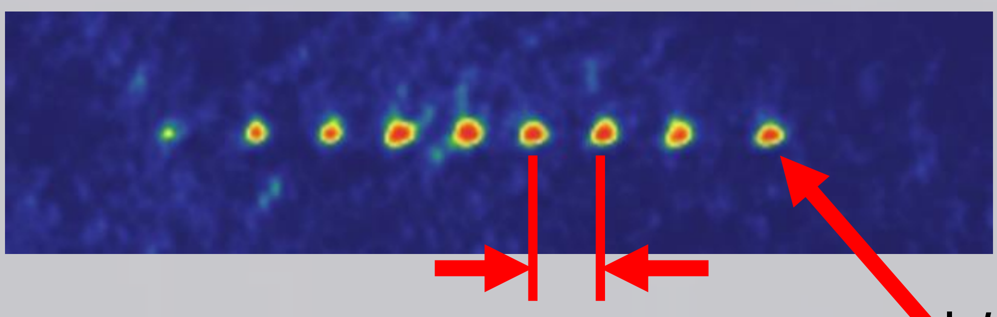
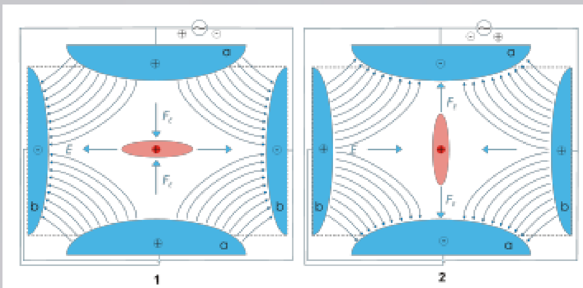


d~10 μm

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

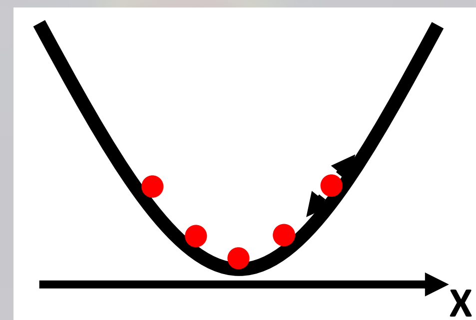
Trapped ions

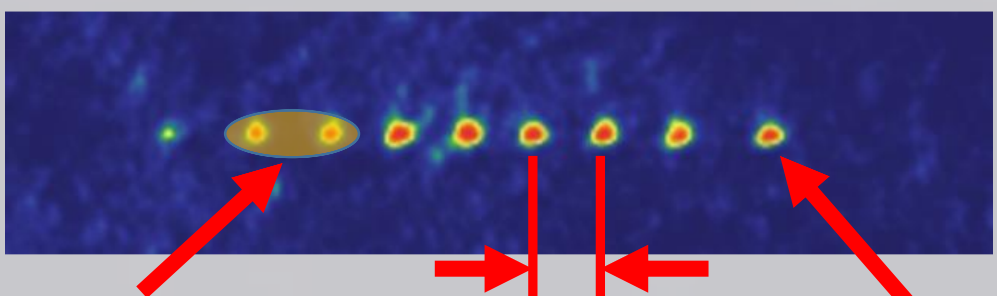
A great resource for quantum technologies!



Trapping with electric fields (current record: **6 months**)

Crystal-like structure due to Coulomb repulsion





$|\Psi^-\rangle$ d~10 µm $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$

Trapped ions

A great resource for quantum technologies!

First teleportation of a matter particle

Deterministic quantum teleportation of atomic qubits

M. D. Barrett[1*], J. Chiaverini[1], T. Schaetz[1], J. Britton[1], W. M. Itano[1], J. D. Jost[1], E. Knill[2], C. Langer[1], D. Leibfried[1], R. Ozeri[1] & D. J. Wineland[1]

ing with electric fields

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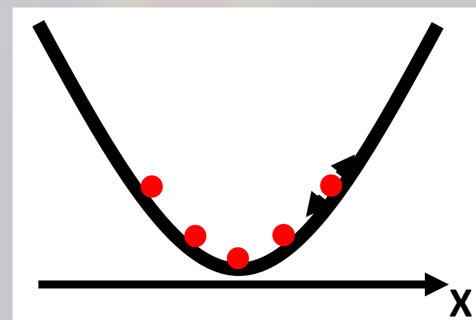
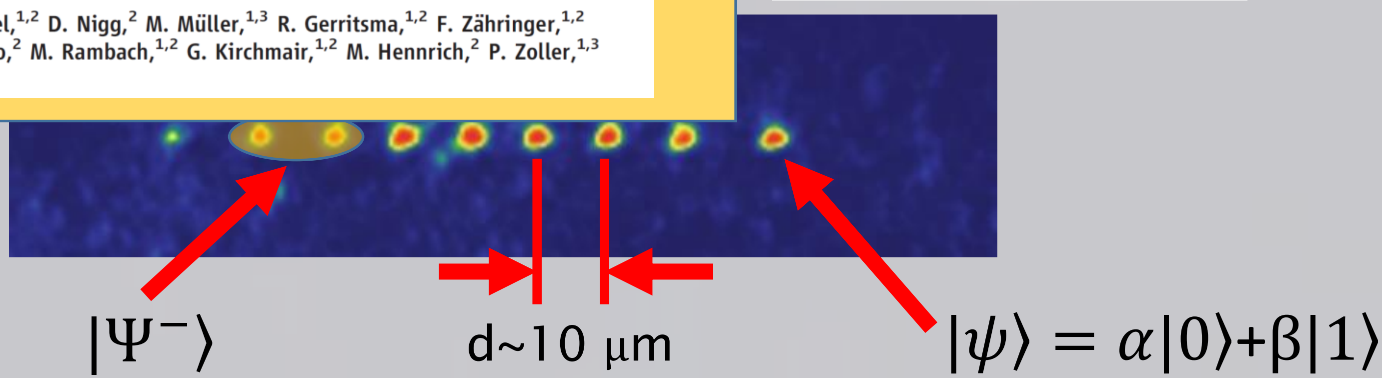


Largest Universal Quantum Computer

Universal Digital Quantum Simulation with Trapped Ions

B. P. Lanyon,[1,2*] C. Hempel,[1,2] D. Nigg,[2] M. Müller,[1,3] R. Gerritsma,[1,2] F. Zähringer,[1,2] P. Schindler,[2] J. T. Barreiro,[2] M. Rambach,[1,2] G. Kirchmair,[1,2] M. Hennrich,[2] P. Zoller,[1,3] R. Blatt,[1,2] C. F. Roos[1,2]



Trapped ions

A great resource for quantum tech

ing with

nt reco

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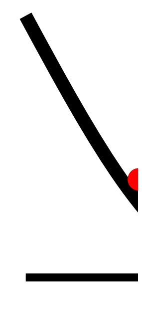
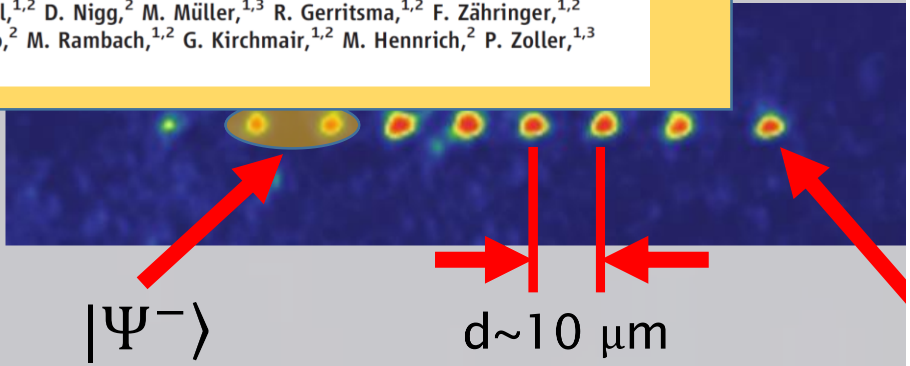
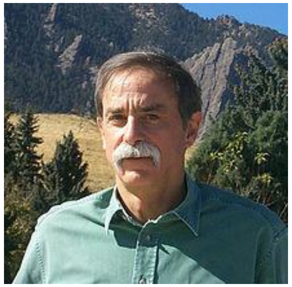
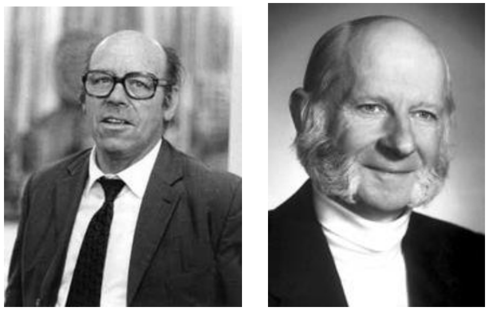




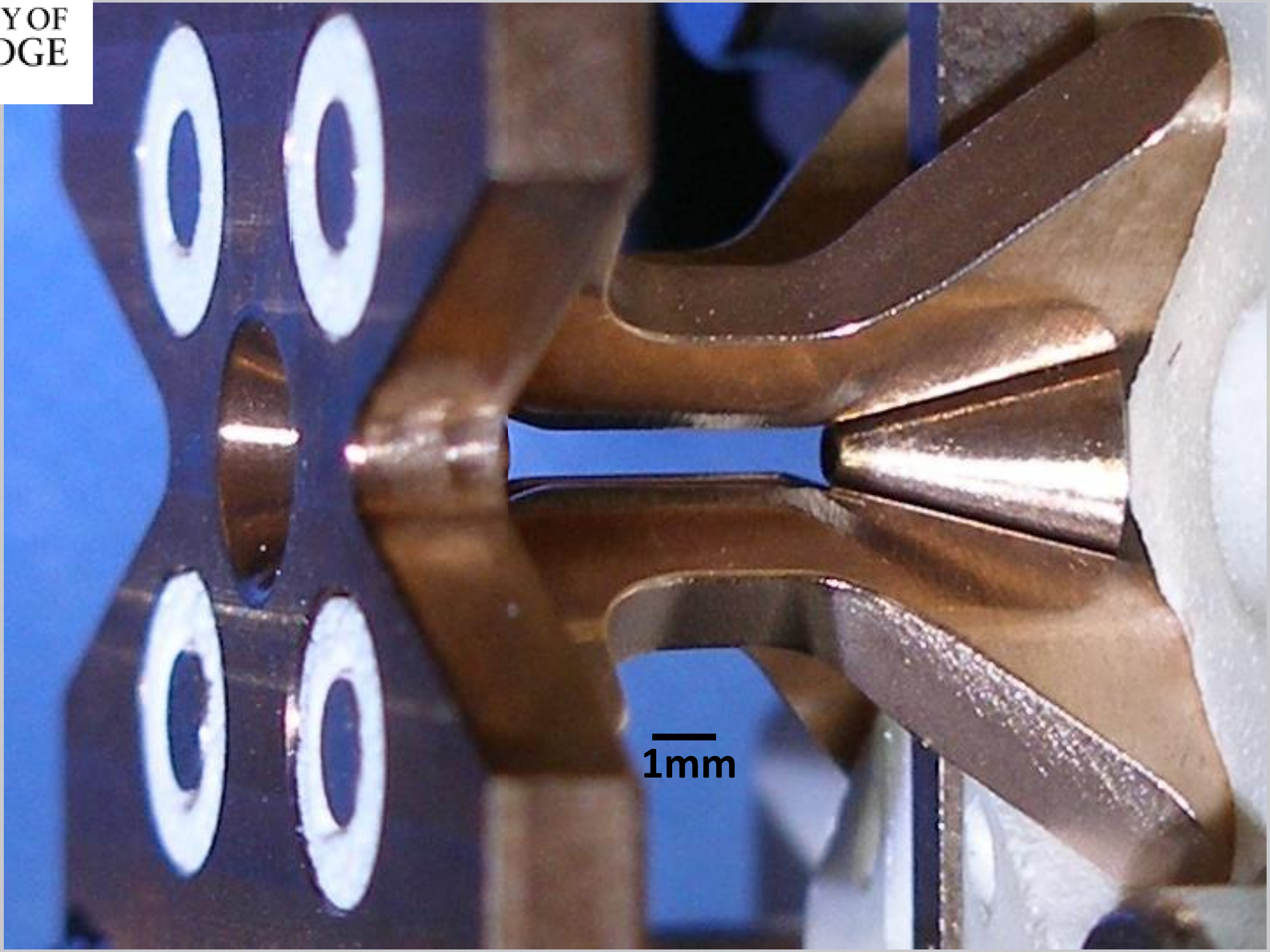


2012



1989

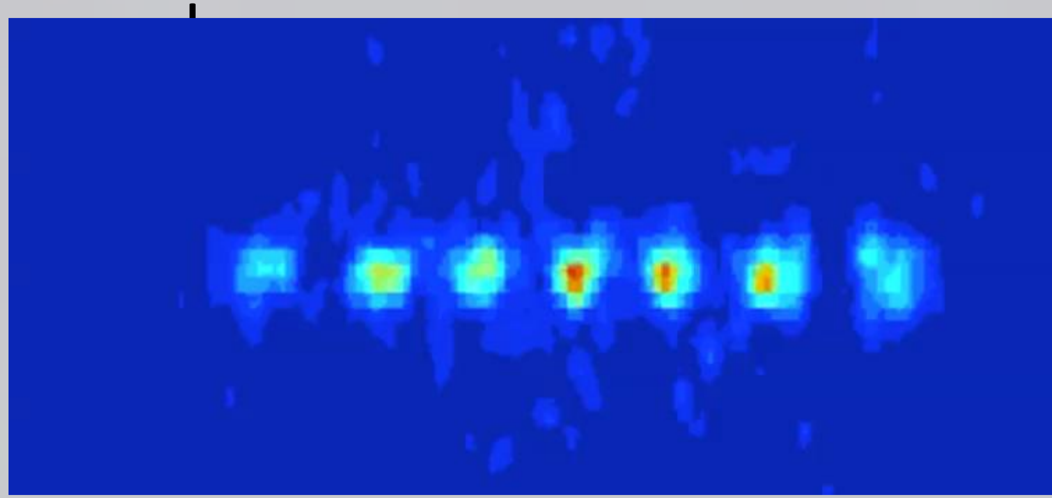
Ion trap



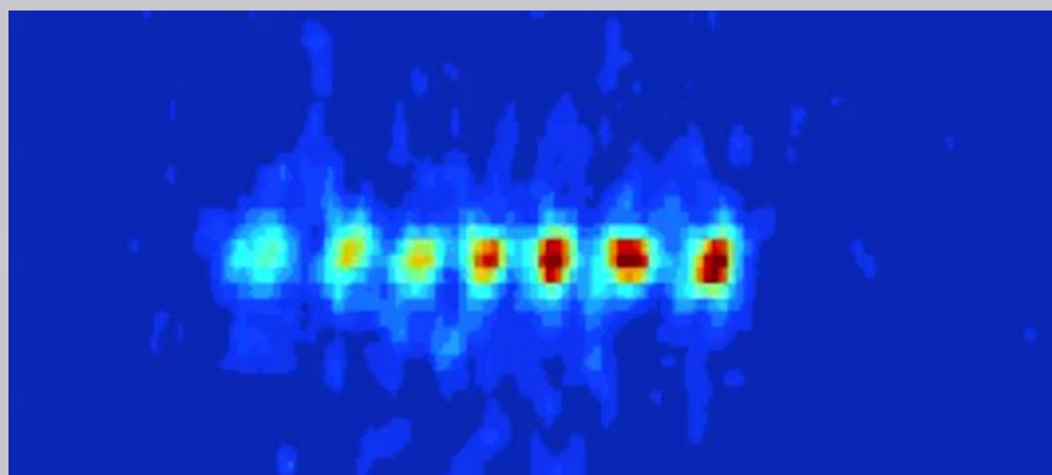
Controlling ion motion at the quantum level

The ions in the crystal experience quantized excitation

Dipolar mode



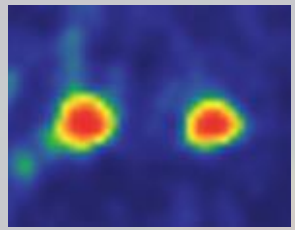
Breathing mode



H.C Naegerl et al. Opt. Expr. **3**, 89 (1998)

Conditional gates with trapped ions

Ion motion can be used to engineer ion-ion interactions and generate entanglement: **the Cirac-Zoller gate**



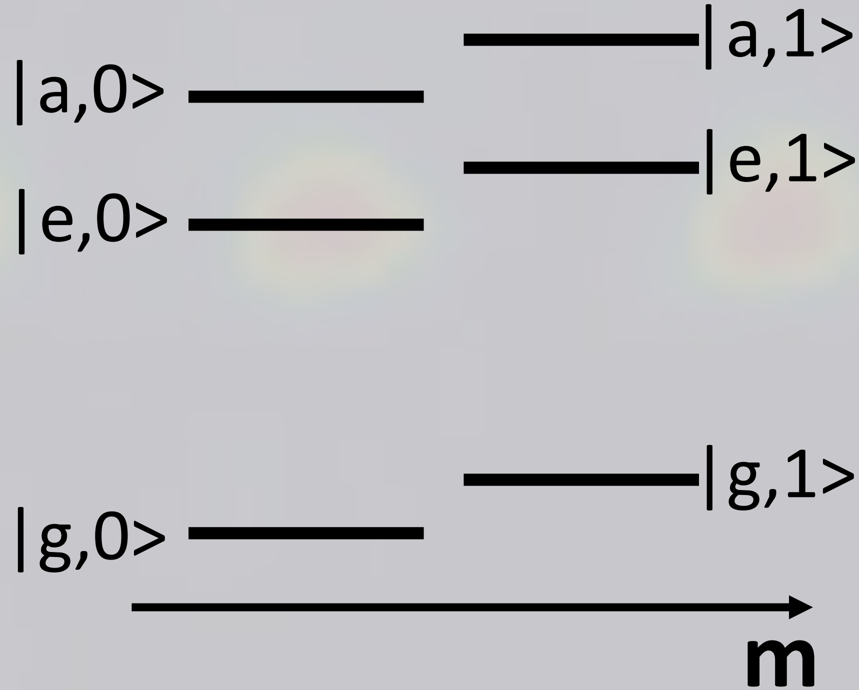


Table of states

|g,g,0>

|g,e,0>

|e,g,0>

|e,e,0>

J.I. Cirac, P. Zoller PRL **74**, 4091 (1995)

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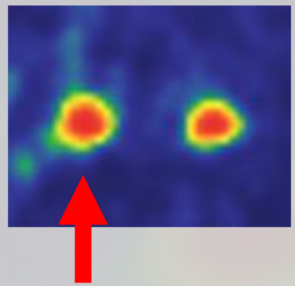
Step 1: π-pulse on ion A



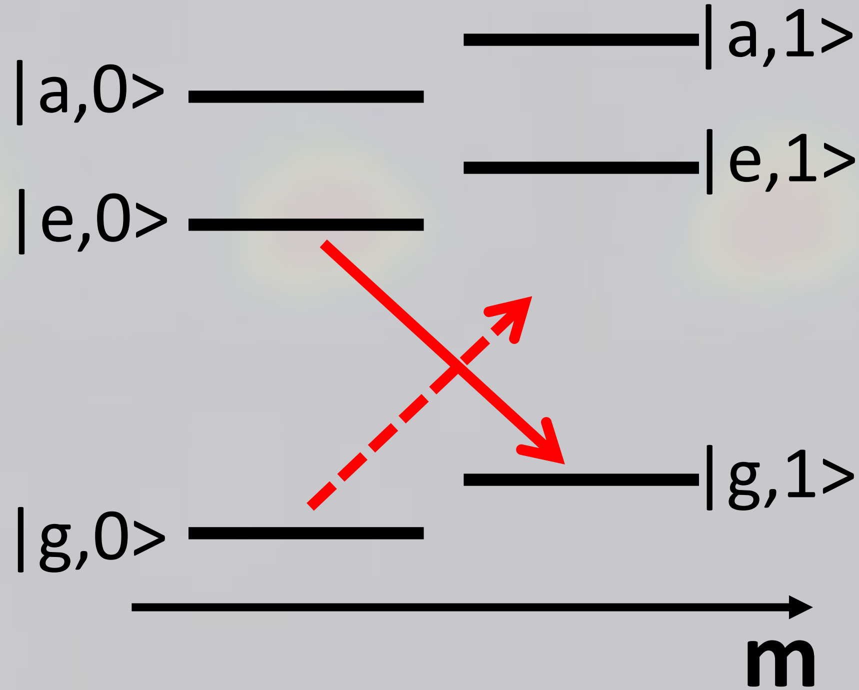


Table of states

|g,g,0> → |g,g,0>

|g,e,0> → |g,e,0>

|e,g,0> → |g,g,1>

|e,e,0> → |g,e,1>

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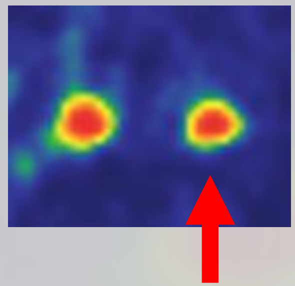
Conditional gates with trapped ions

Ion motion can be used to engineer ion-ion interactions and generate entanglement: **the Cirac-Zoller gate**

Step 1: π-pulse on ion A

Step 2: 2π-pulse on ion B



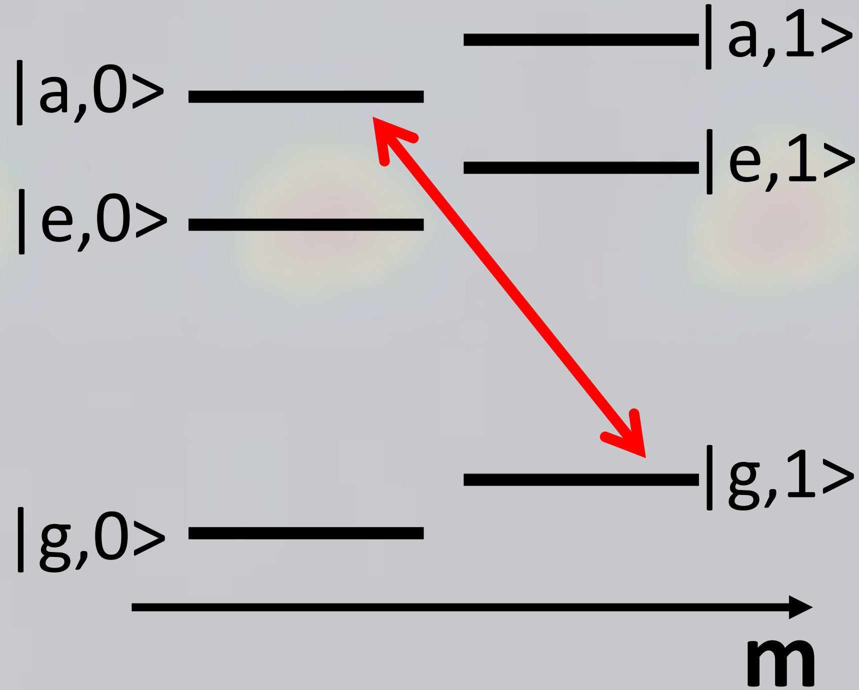


Table of states

|g,g,0> → |g,g,0> → |g,g,0>

|g,e,0> → |g,e,0> → |g,e,0>

|e,g,0> → |g,g,1> → -|g,g,1>

|e,e,0> → |g,e,1> → |g,e,1>

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Step 2: 2π-pulse on ion B

Step 3: π-pulse on ion A

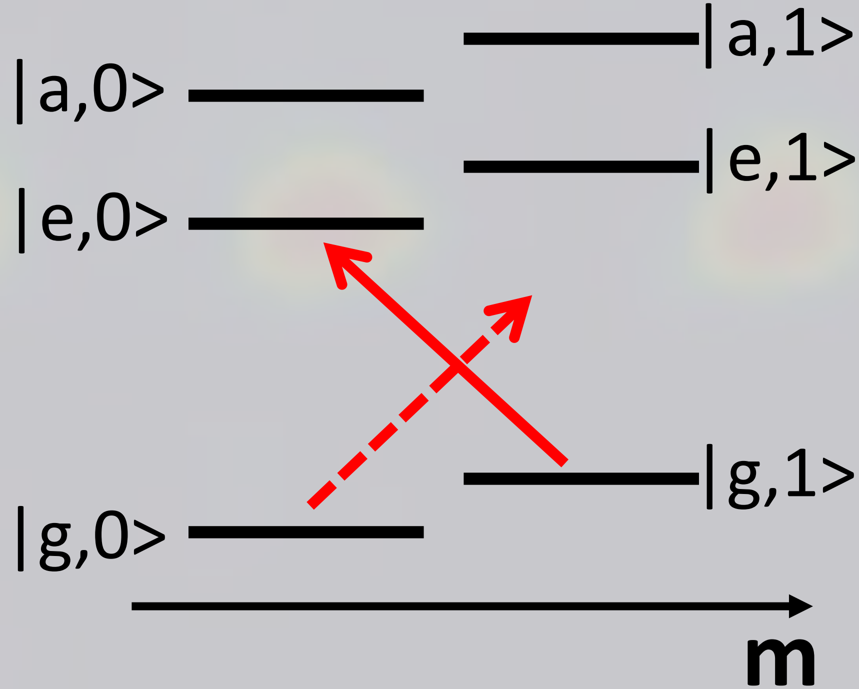


Table of states

|g,g,0> → |g,g,0> → |g,g,0> → |g,g,0>

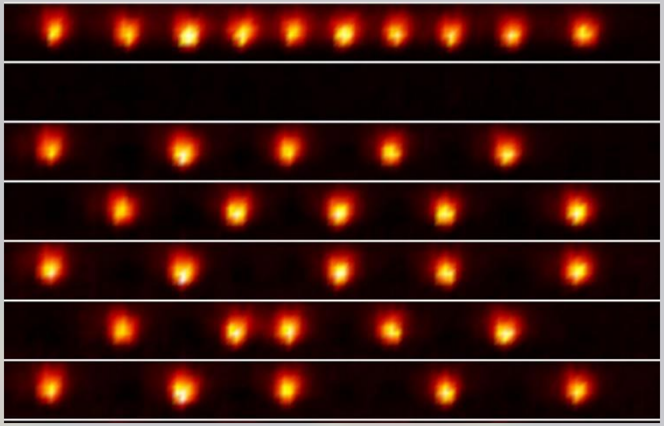
|g,e,0> → |g,e,0> → |g,e,0> → |g,e,0>

|e,g,0> → |g,g,1> → -|g,g,1> → -|e,g,0>

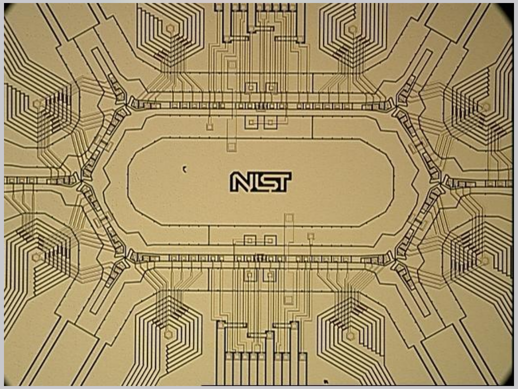
|e,e,0> → |g,e,1> → |g,e,1> → |e,e,0>

J.I. Cirac, P. Zoller PRL **74**, 4091 (1995)

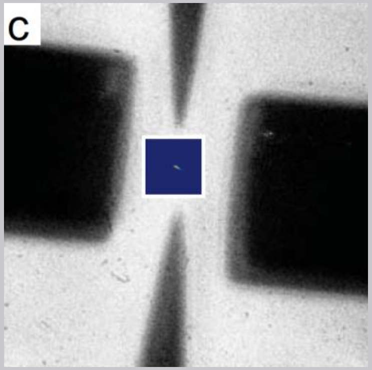
Ion based quantum computers today



Chris Monroe group (JQI Washington)
Rainer Blatt group (Innsbruck)
N_{ions}>20 (towards 50)



Ion traps on semiconductor chips (NIST, JQI, ...)



Ion traps in cavities for quantum internet (Bonn, Sussex,...)

Outline of my talk

1. Introduction to basic concepts of quantum physics
2. Quantum Cryptography
3. Quantum computers
4. **Quantum simulators**
5. Precision measurements and sensing
6. Perspectives and conclusions

A quantum simulator

A few slides ago..

International Journal of Theoretical Physics, Vol. 21, Nos. 6/7, 1982

Simulating Physics with Computers

Richard P. Feynman

Department of Physics, California Institute of Technology, Pasadena, California 91107

Received May 7, 1981

be understood very well in analyzing the situation. And I'm not happy with all the analyses that go with just the classical theory, because nature isn't classical, dammit, and if you want to make a simulation of nature, you'd better make it quantum mechanical, and by golly it's a wonderful problem, because it doesn't look so easy. Thank you.

Simulate Nature by «re-creating» an Hamiltonian on a **known system** that can be controlled and manipulated

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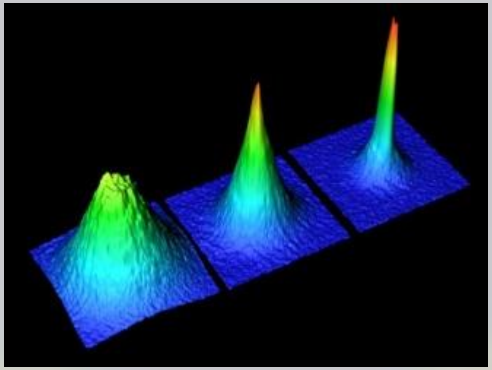
Simulate Nature by «re-creating» an Hamiltonian on a **known system** that can be controlled and manipulated

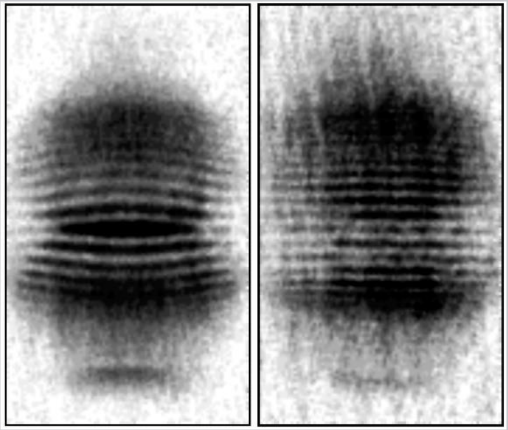
How this system should be?

- Quantum
- Controllable
- Made of many particles

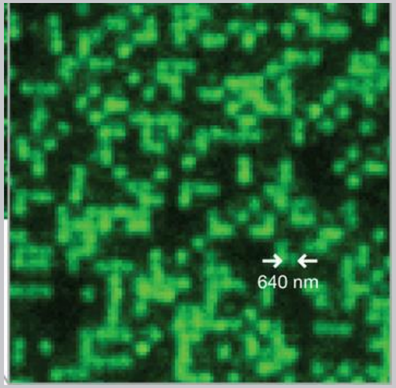
Ultracold atoms

Large (>10^5 atoms) sample of **ultracold** (T<100nK) bosons/fermions





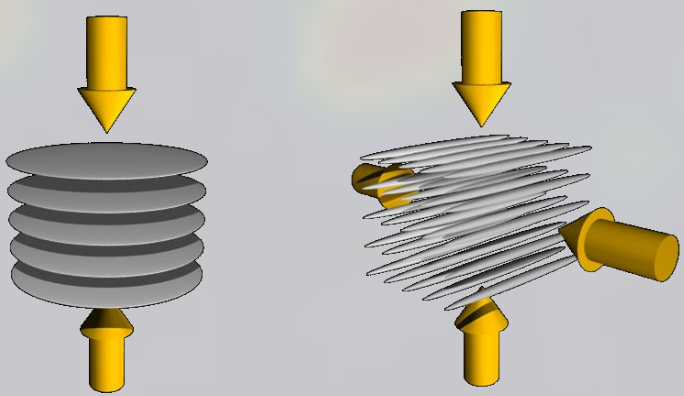
Coherent dynamics



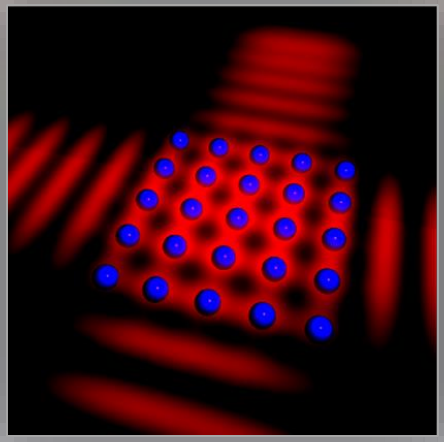
Tunable interactions and **single atom** addressability

Quantum simulation with ultracold atoms

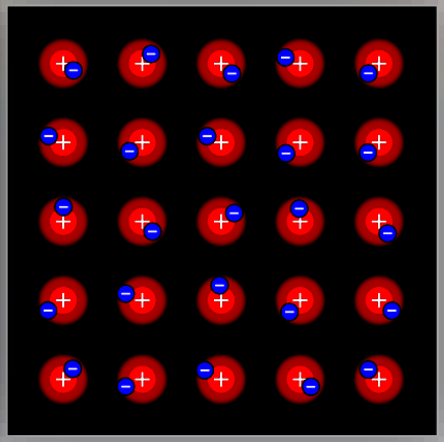
Atoms can be arranged periodically by imposing potentials through laser interference (optical lattice)



Atoms in optical lattices



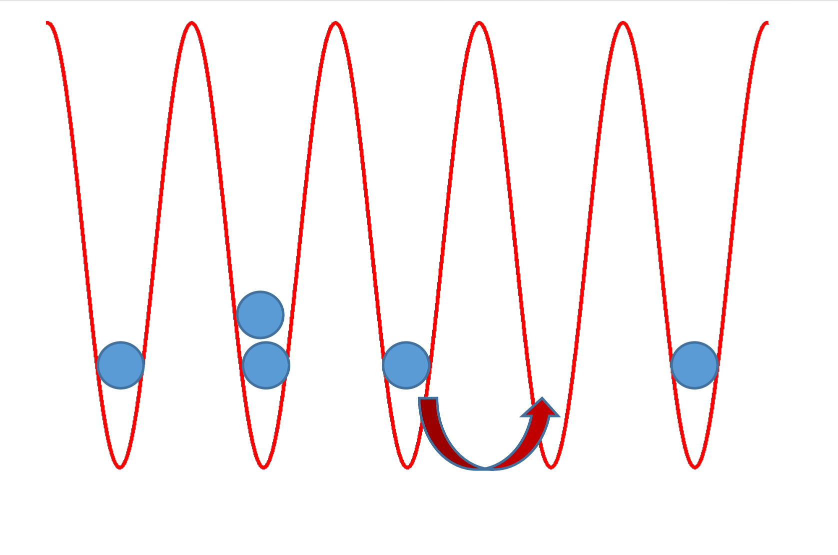
Electrons in solids



Quantum simulation with ultracold atoms

Manipulating the energies of the problem

1. Tunneling t
   (lattice height)



Quantum simulation with ultracold atoms

Manipulating the energies of the problem

1. Tunneling t
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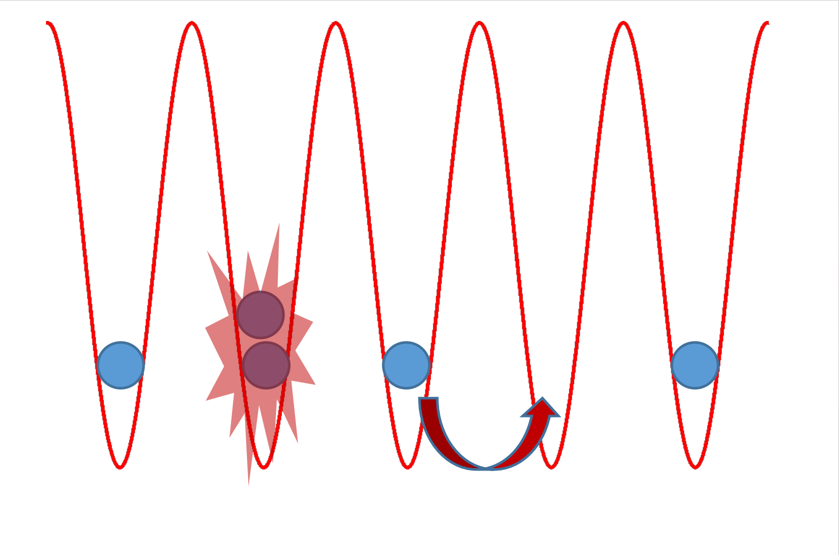
2. Interactions U
   (Feshbach resonances)



Quantum simulation with ultracold atoms

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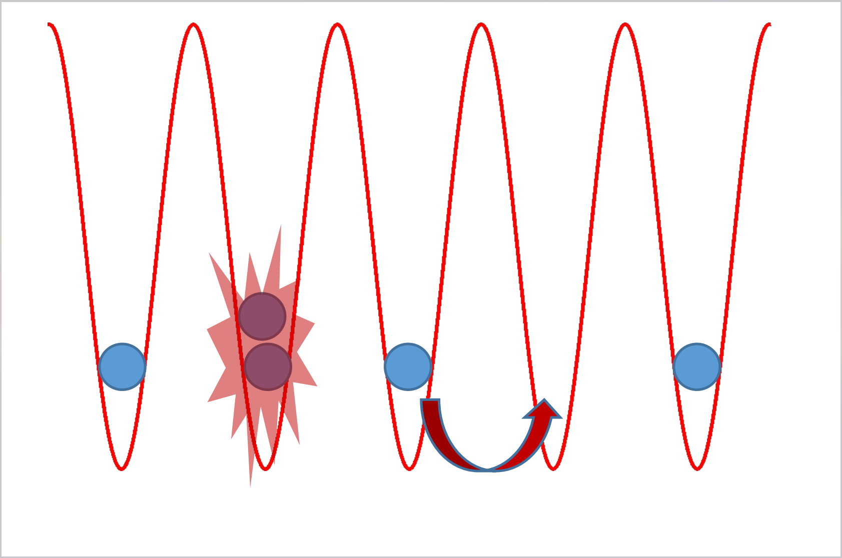
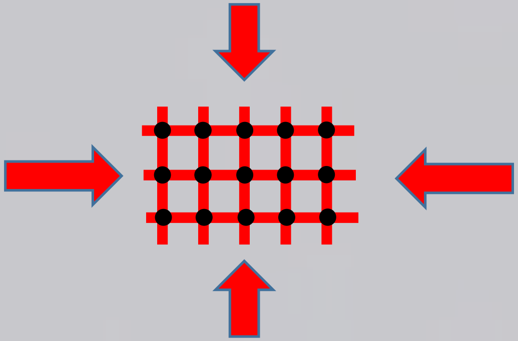
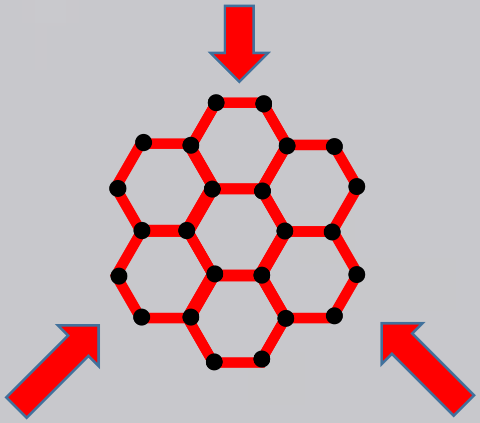


3. Shape of the lattice
(cubic lattice,
graphene...)





Simulating the Bose-Hubbard Hamiltonian

Bose-Hubbard Hamiltonian

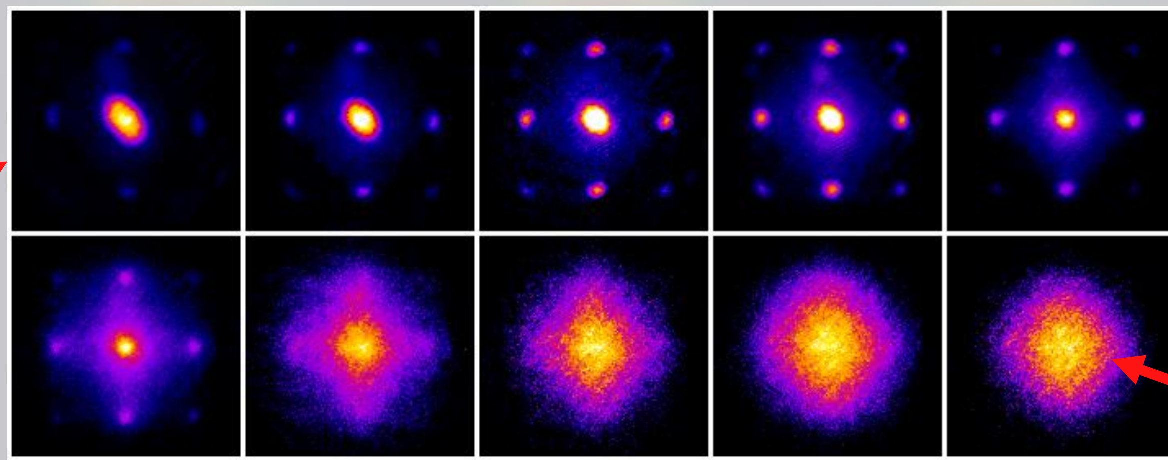
$$H = -t \sum_{\langle i,j \rangle} a_i^{+} a_j + \frac{U}{2} \sum_i a_i^{+} a_i (a_i^{+} a_i - 1)$$

Simulating the Bose-Hubbard Hamiltonian

Bose-Hubbard Hamiltonian

$$H = -t \sum_{\langle i,j \rangle} a_i^{+} a_j + \frac{U}{2} \sum_i a_i^{+} a_i (a_i^{+} a_i - 1)$$

SF

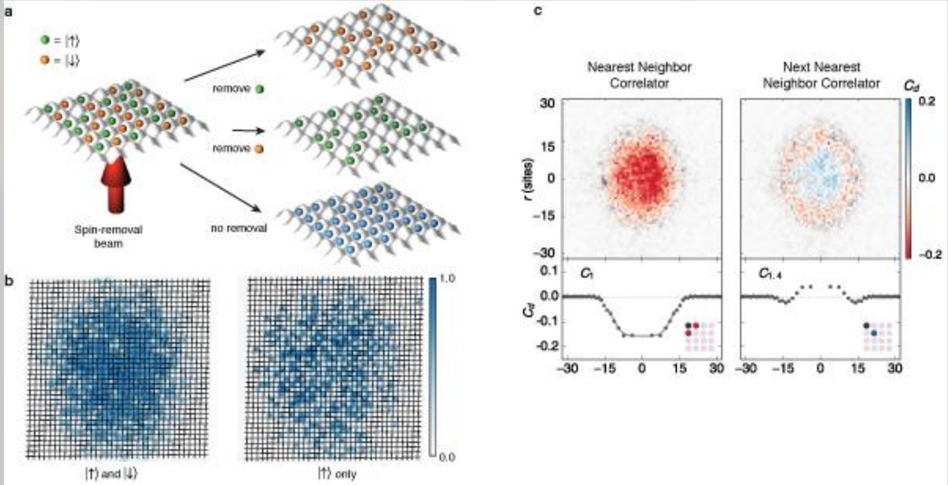


MI

Superfluid-Mott Insulator **quantum** phase transition!

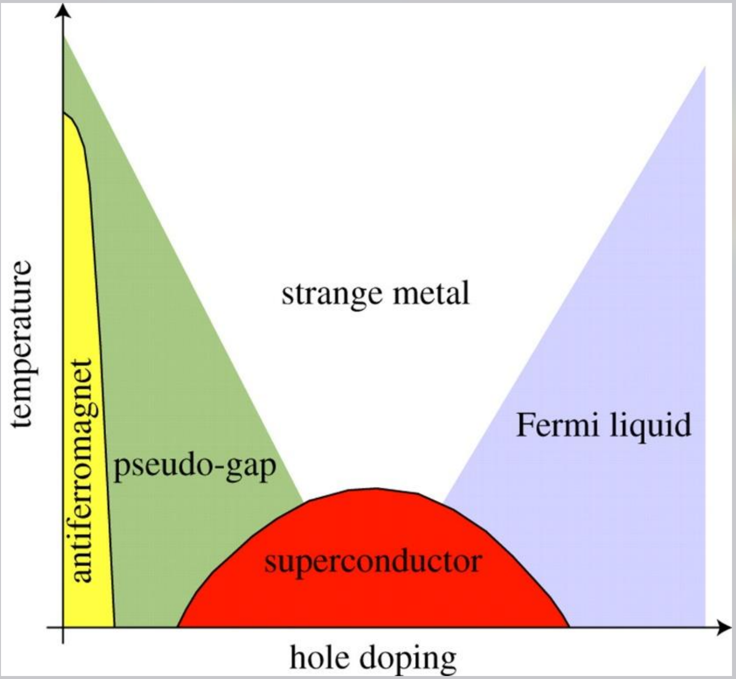
Simulating the Fermi-Hubbard Hamiltonian

Why is that important? In its fermionic version it could be responsible for high-temperature supeconductivity!



Mazurenko et al. Nature 545, 462(2017)

Ultracold atoms antiferromagnet



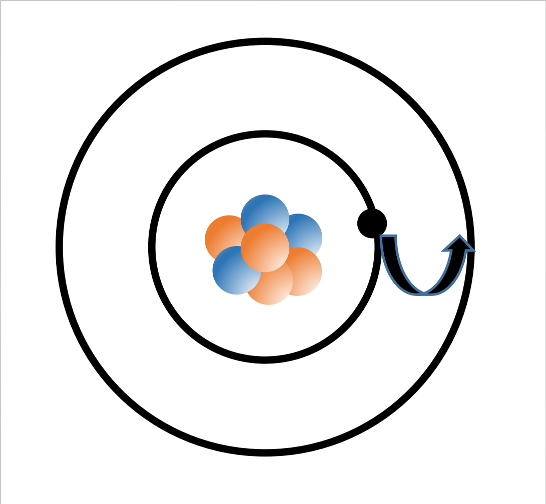
Cuprates

Outline of my talk

1. Introduction to basic concepts of quantum physics
2. Quantum Cryptography
3. Quantum computers
4. Quantum simulators
5. **Precision measurements and sensing**
6. Perspectives and conclusions

A quantum oscillator

A two-level system



Electronic orbitals

$|g\rangle, |e\rangle$

$$E = h\nu$$

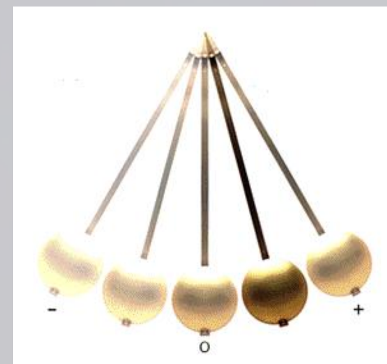
By performing spectroscopy
I measure an energy
→ I measure a **frequency**

I can measure **time**

An atomic clock

In order to measure time I need two things:

- *Something that oscillates*
- *Something that counts*



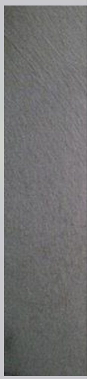
The faster a physical system oscillates, the most accurate is the measure of time

The next step

In order to measure time I need two things:

- So

- So



1918

32 768
osc. / second

1955

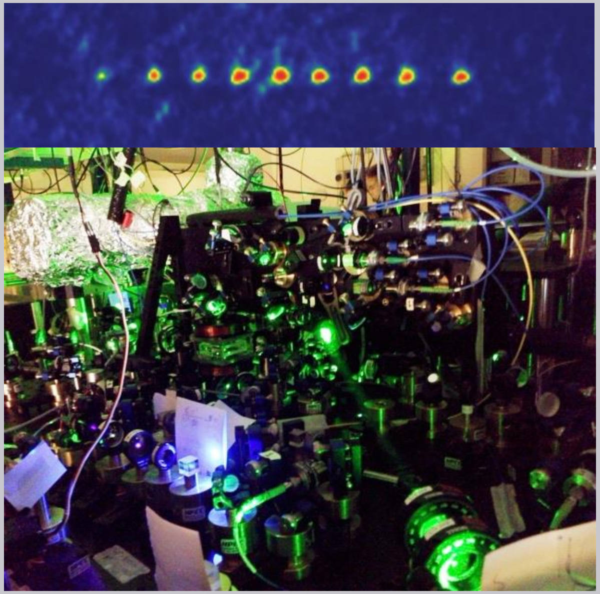
9 192 631 770
osc. / second

The f

accu

An atomic clock

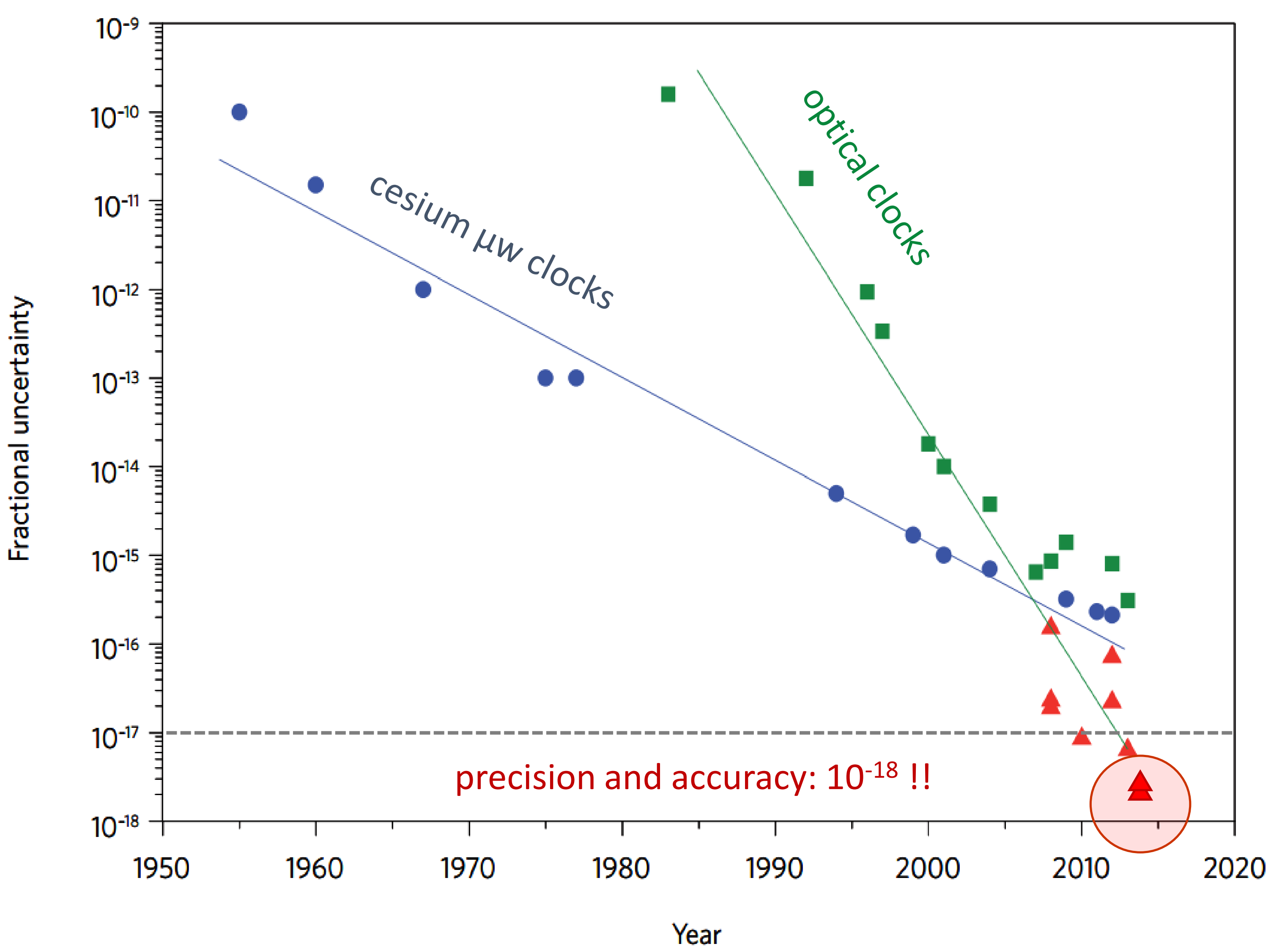
Moving from measuring microwave transitions to **optical transitions**



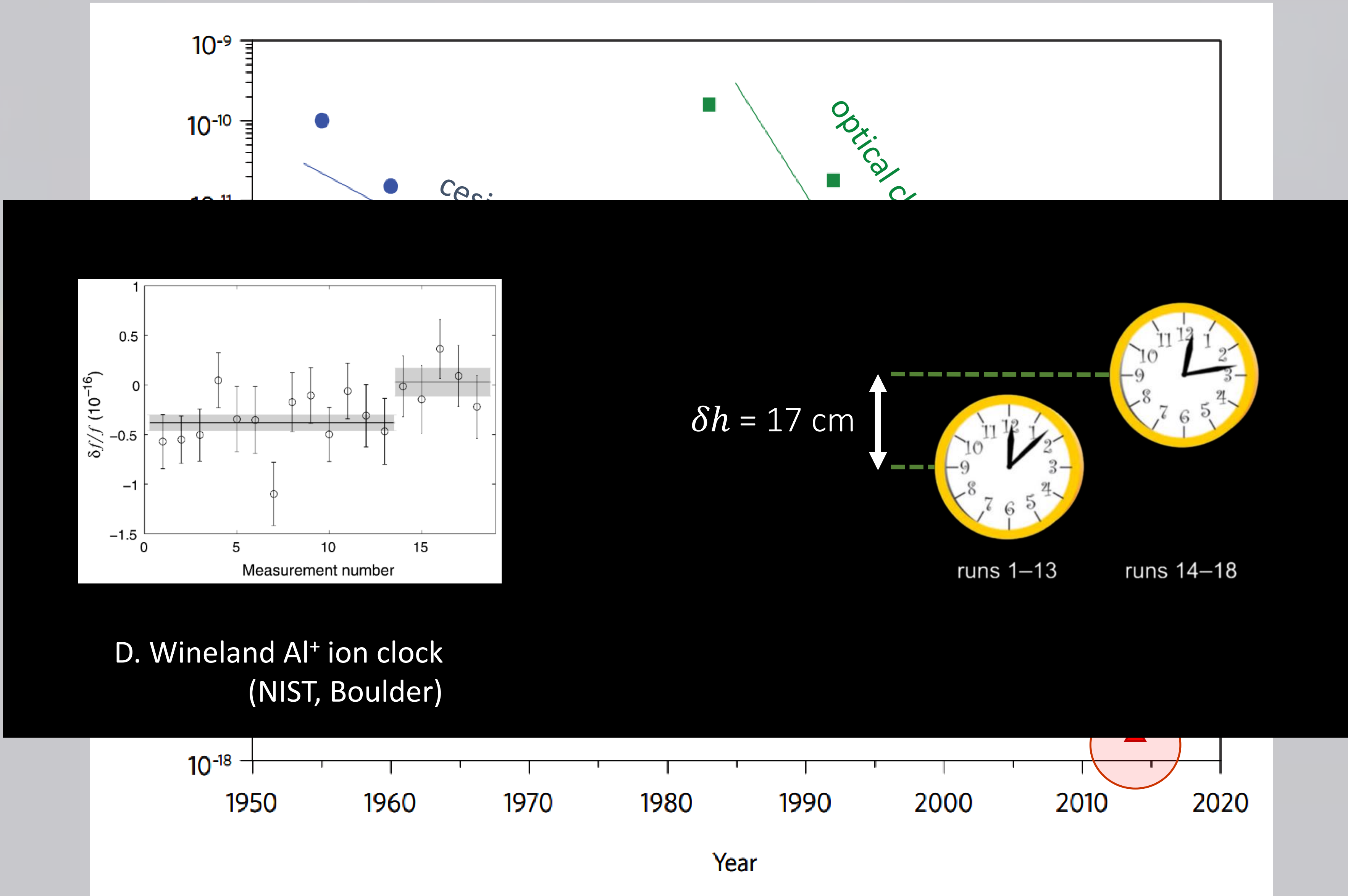
9 192 631 770
osc. / second

518 295 836 590 863
osc. / second

How precise a clock can be

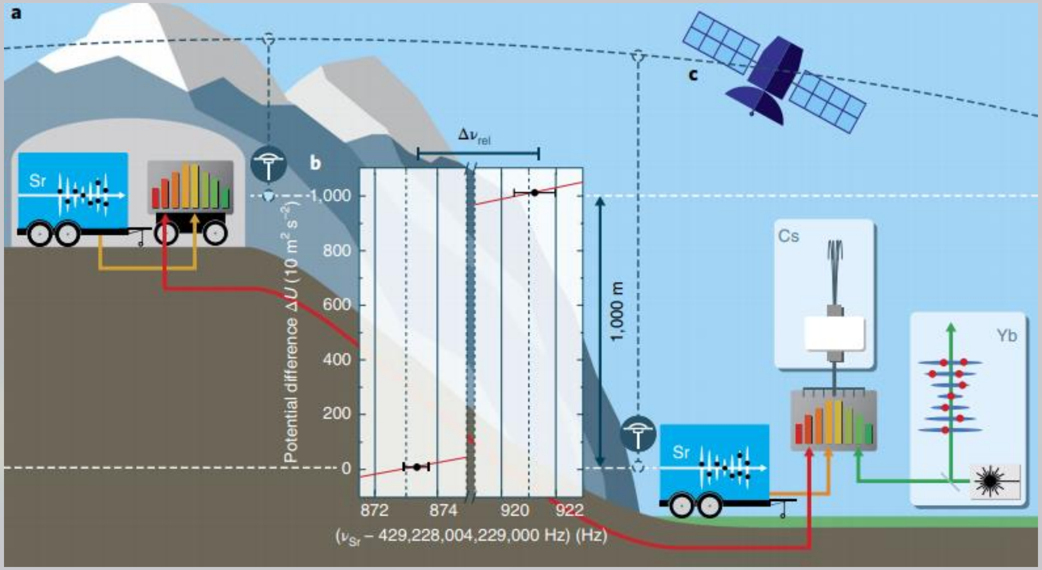


How precise a clock can be



D. Wineland Al^{+} ion clock
(NIST, Boulder)

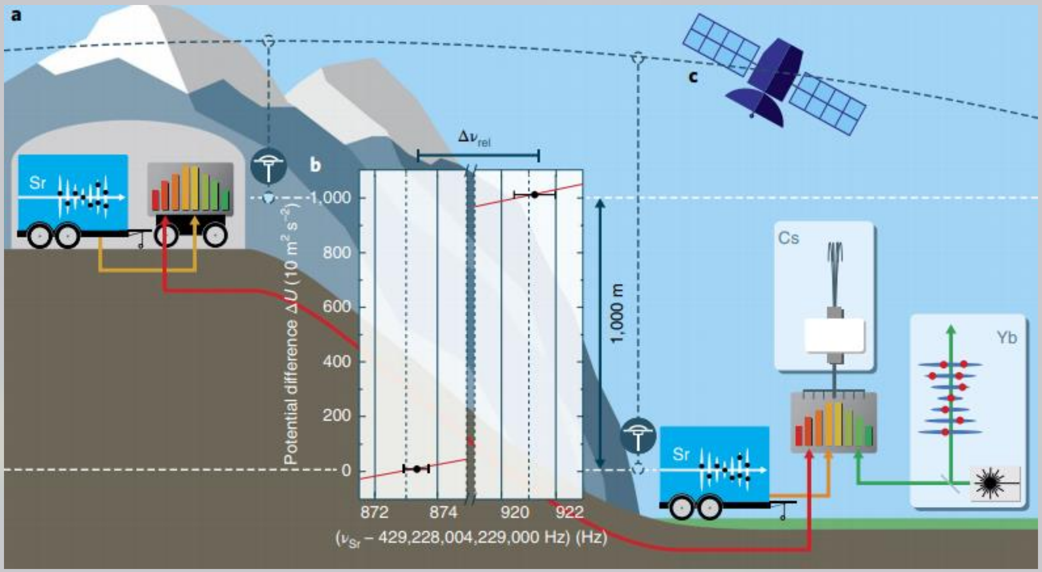
Applications: relativistic geodesy



Grotti et al. Nature Phys. 2018

Measuring differences in height of approx. 1cm **locally**

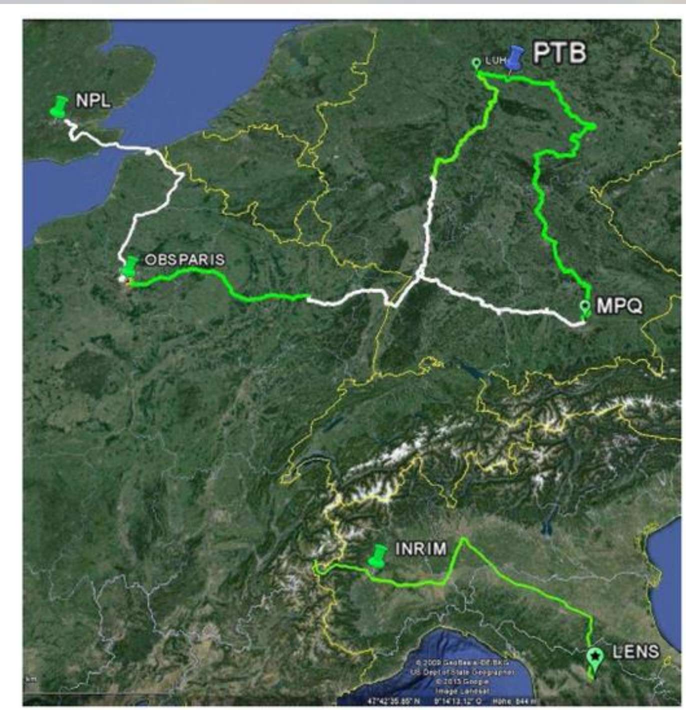
Applications: relativistic geodesy



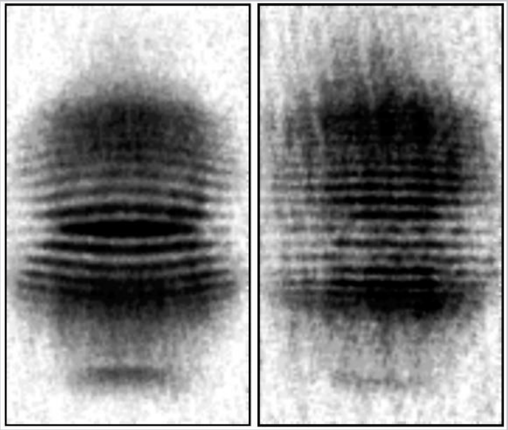
Grotti et al. Nature Phys. 2018

Measuring differences in height of approx. 1cm **locally**

Part of a broader project of developing a **net of optical fibers** disseminating a precise, optical oscillator

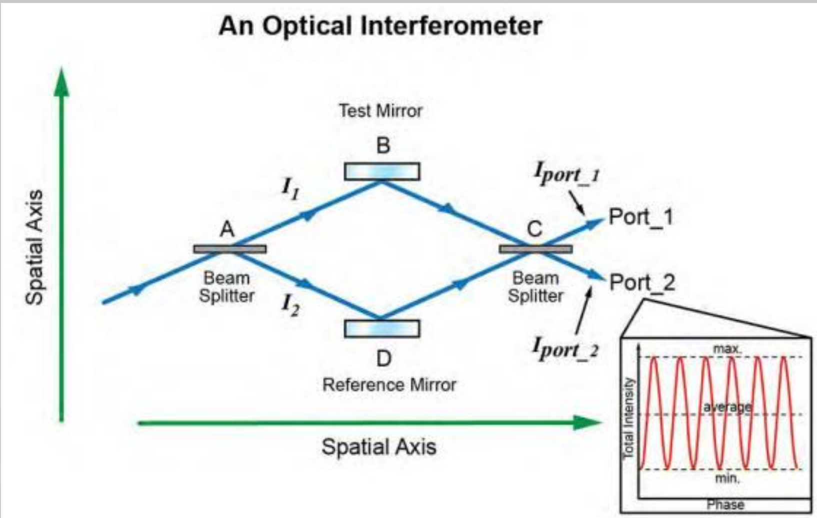


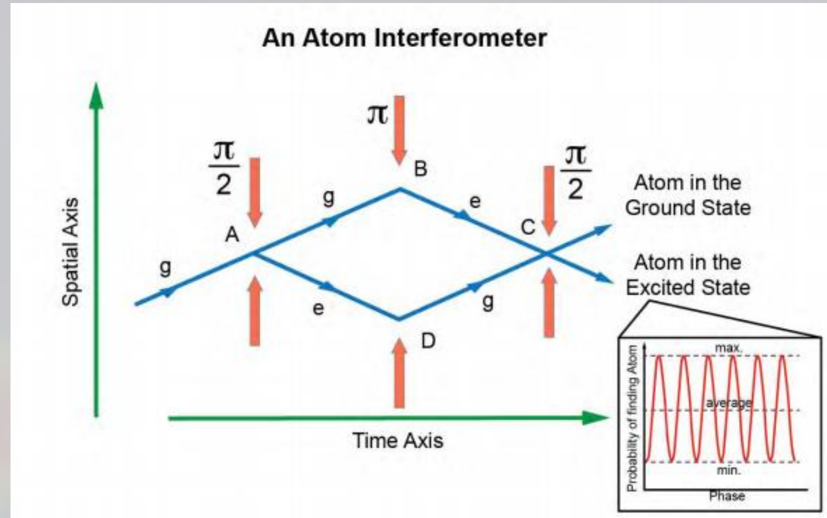
Matter wave interferometry

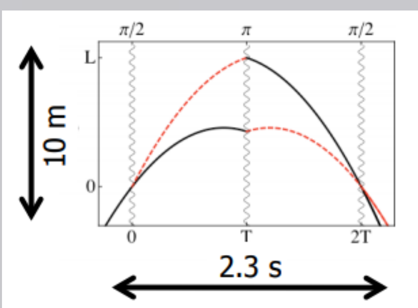


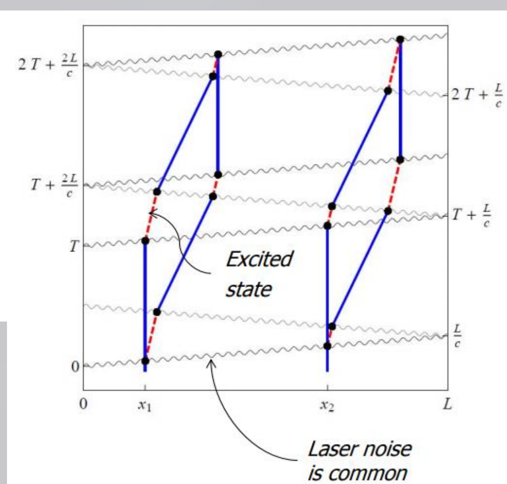
Can we use matter waves for precision interferometry?

Gravitational waves detector









Stanford University
Kasevich group

Two spatially separated interferometers detect the travel time of light
Strain sensitivity comparable to LISA

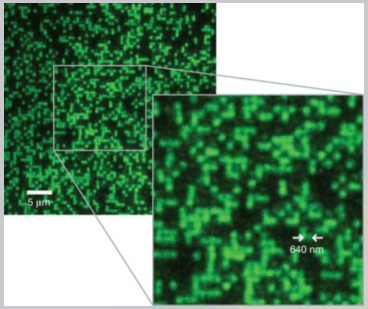
J. Hogan, et al., Gen Relativ Gravit 43, 7 (2011)

Outline of my talk

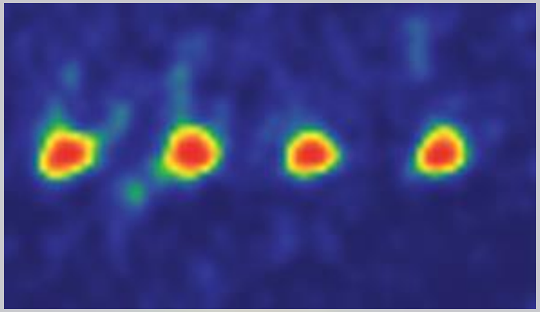
1. Introduction to basic concepts of quantum physics
2. Quantum Cryptography
3. Quantum computers
4. Quantum simulators
5. Precision measurements and sensing
6. **Perspectives and conclusions**

Hybrid quantum systems

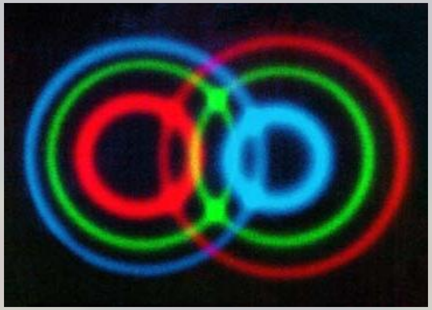
Neutral atoms



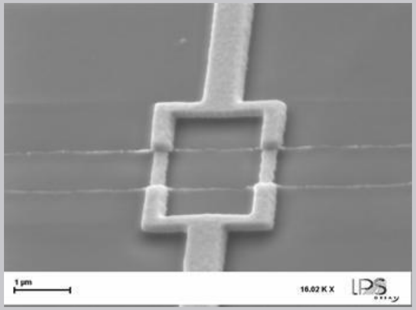
Ions



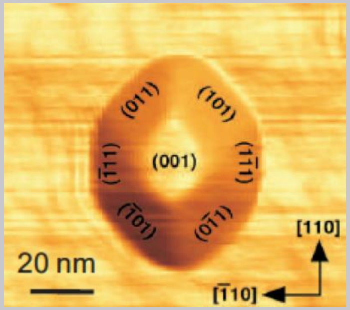
Photons



Squids



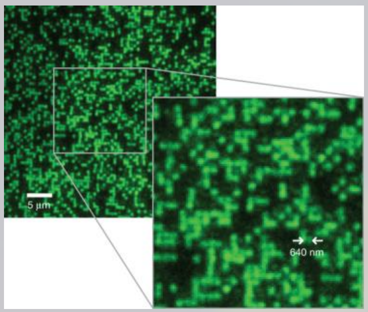
Quantum dots



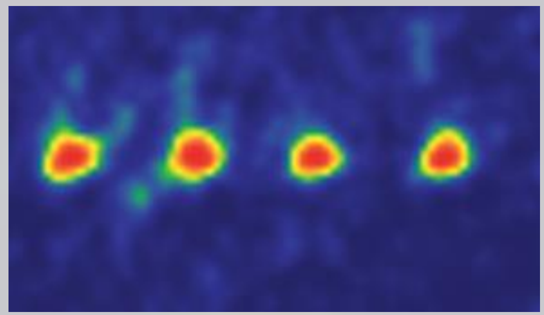
... and many others

Hybrid quantum systems

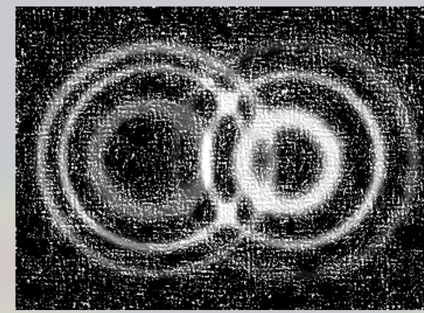
Neutral atoms



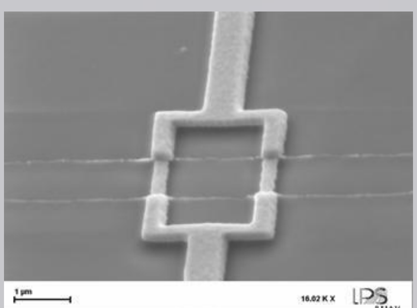
Ions



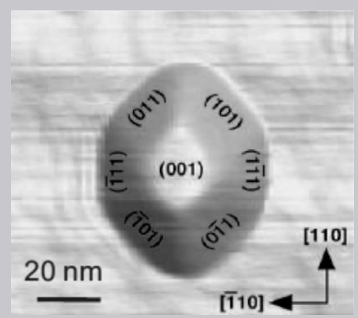
Photons



Squids



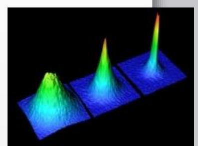
Quantum dots



... and many others

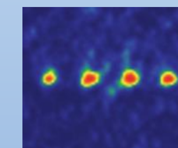
A hybrid quantum system of atoms and ions

Quantum degenerate atoms



- Macroscopic quantum system at nano Kelvin temperature
- Collective quantum states of 10^6 particles
- Very long coherence times

Ultracold trapped ions



- Single particle detection and manipulation
- Pristine source for quantum information processing & precision spectroscopy

+ Interactions

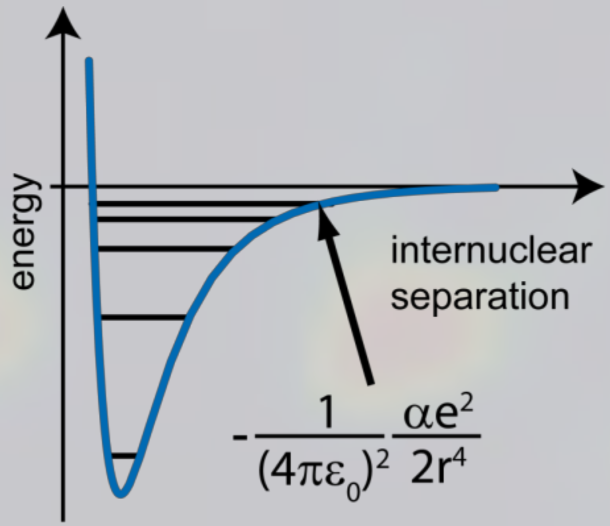
Hybrid quantum system

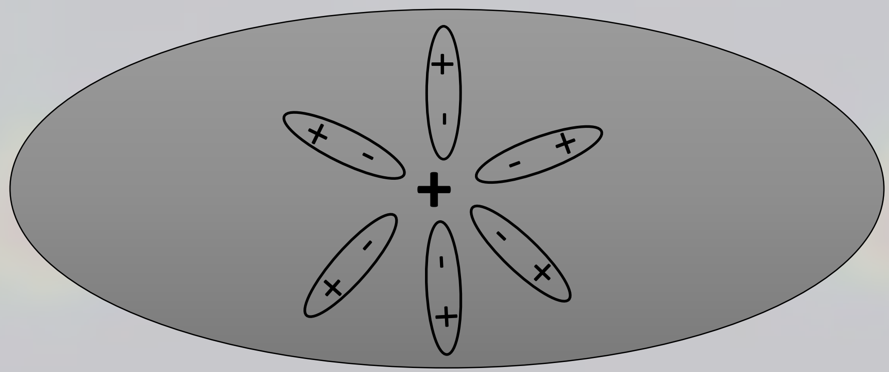
A new approach to

- **Ultracold collisions & quantum chemistry**
- **Quantum information processing and decoherence**
- **Quantum many-body physics with impurities**
- **Metrology**

Atom-ion interactions

Charge-induced dipole interaction: R^{-4} scaling





Longer ranged than atom-atom interactions!

R* ≳ 100nm

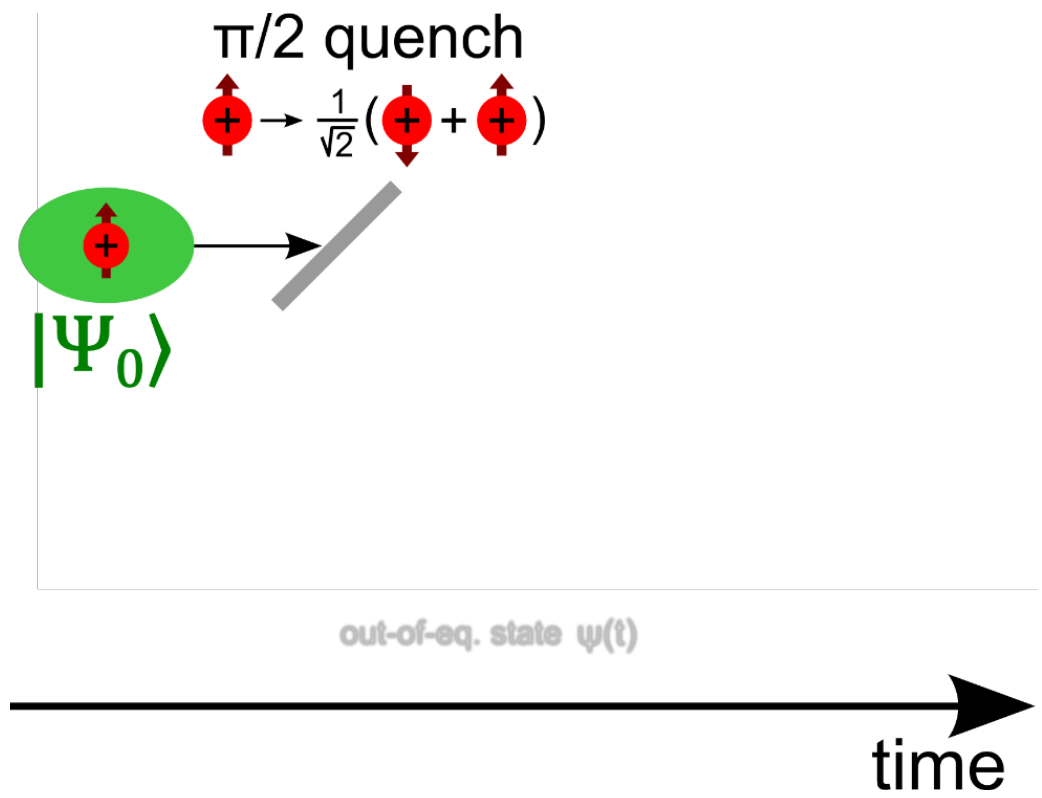
The longest interaction potential for which one can write a pseudo-potential approximation

Review: C. Sias, M. Koehl, arXiv 1401.3188

A Schroedinger-cat interferometer

M. Knap et al. PRX **2**, 041020 (2012), L. Mazzola et al. PRL **110**, 230602 (2013) ...

A Schroedinger-cat interferometer



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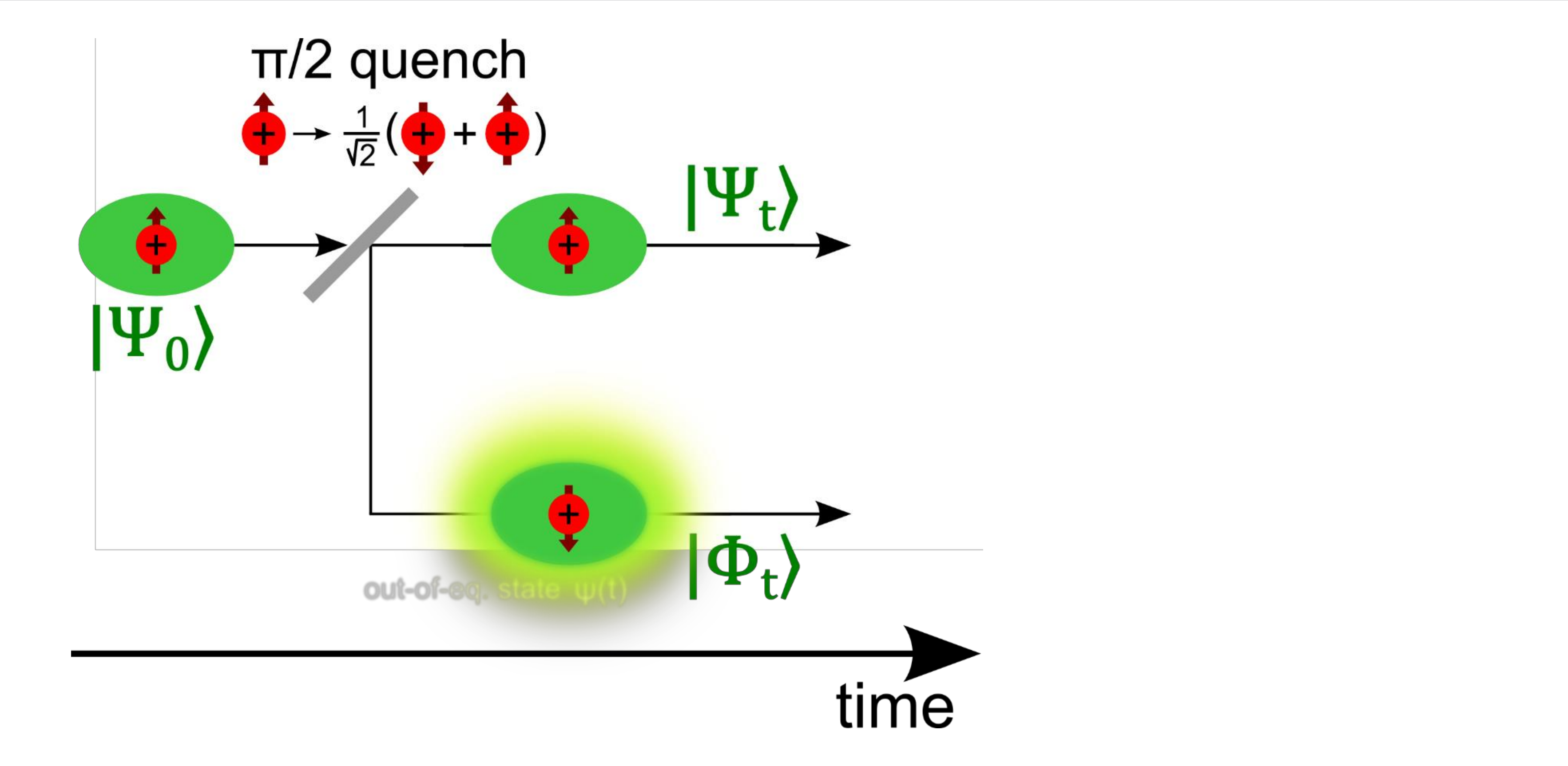

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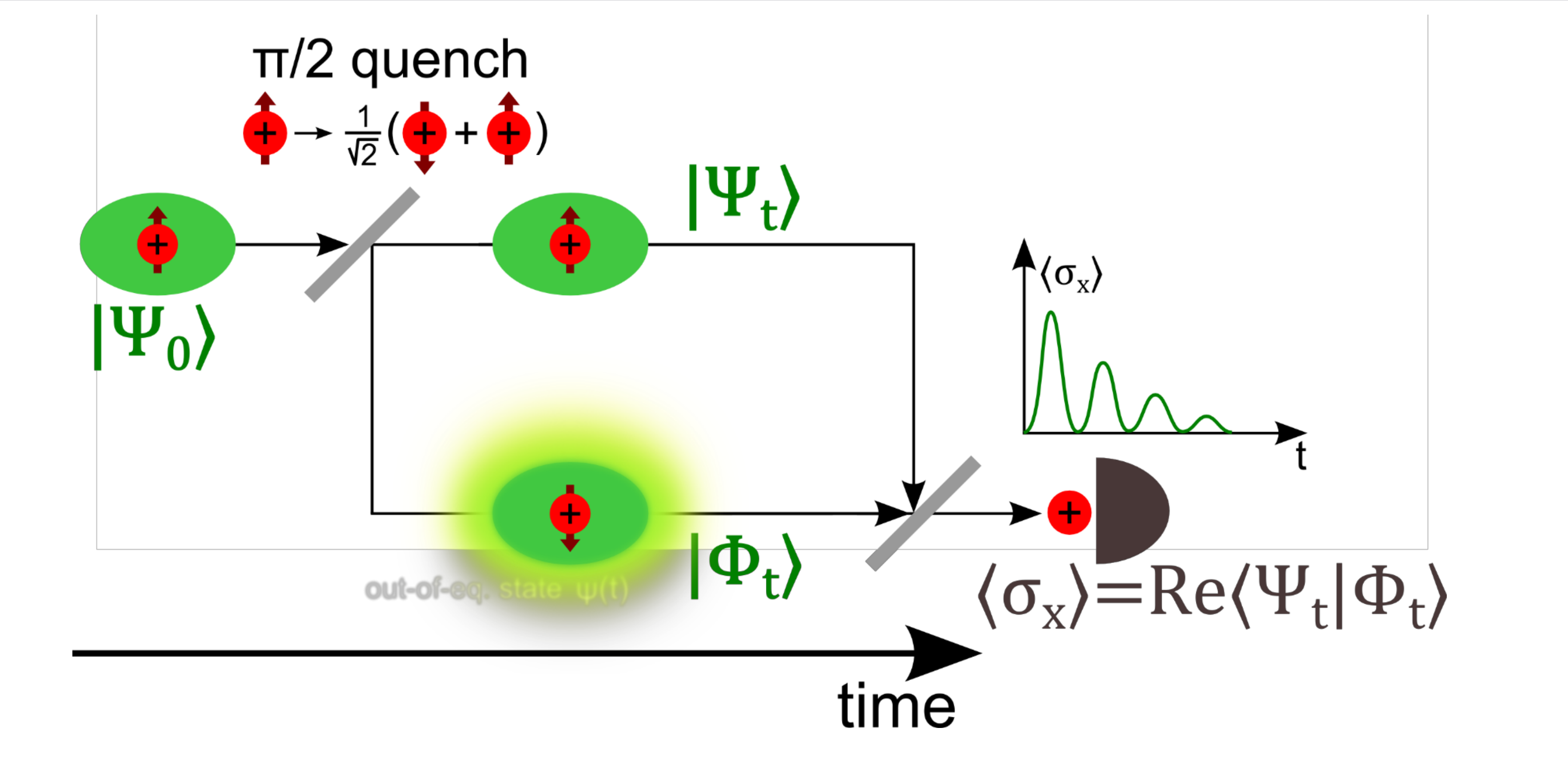

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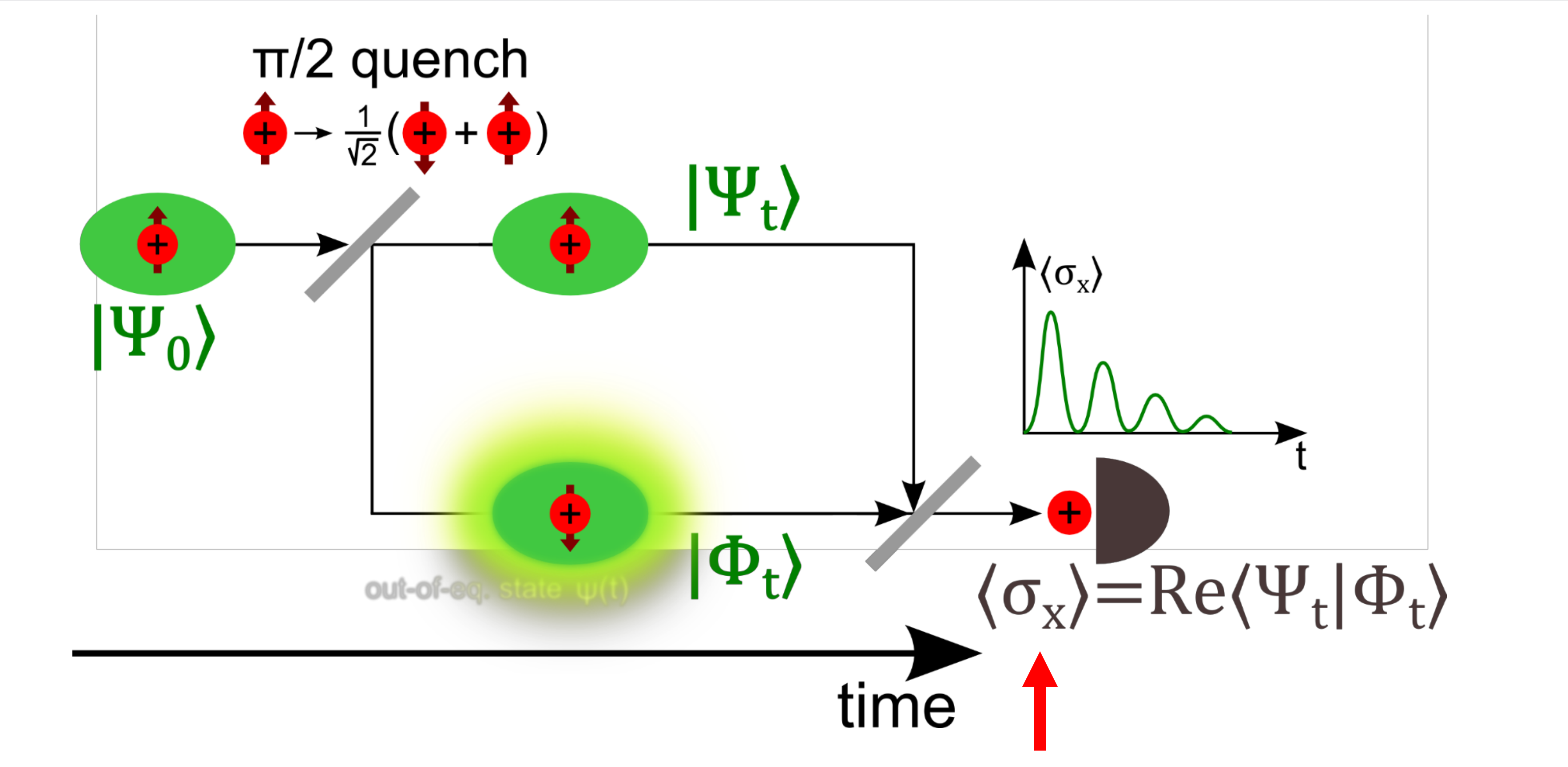
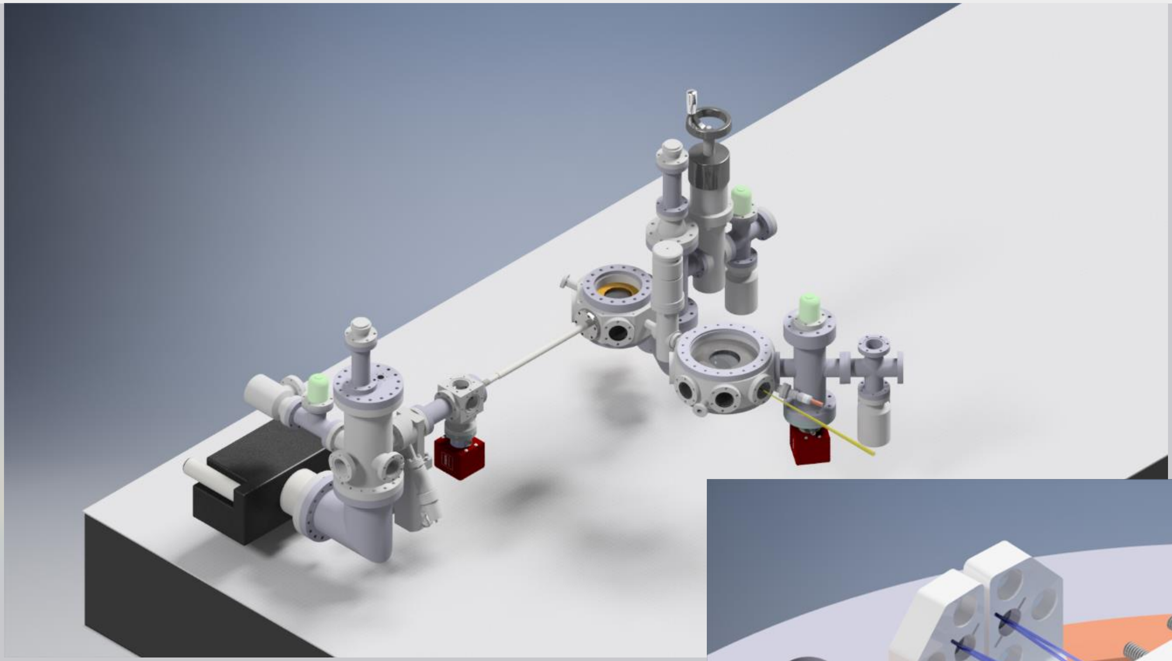


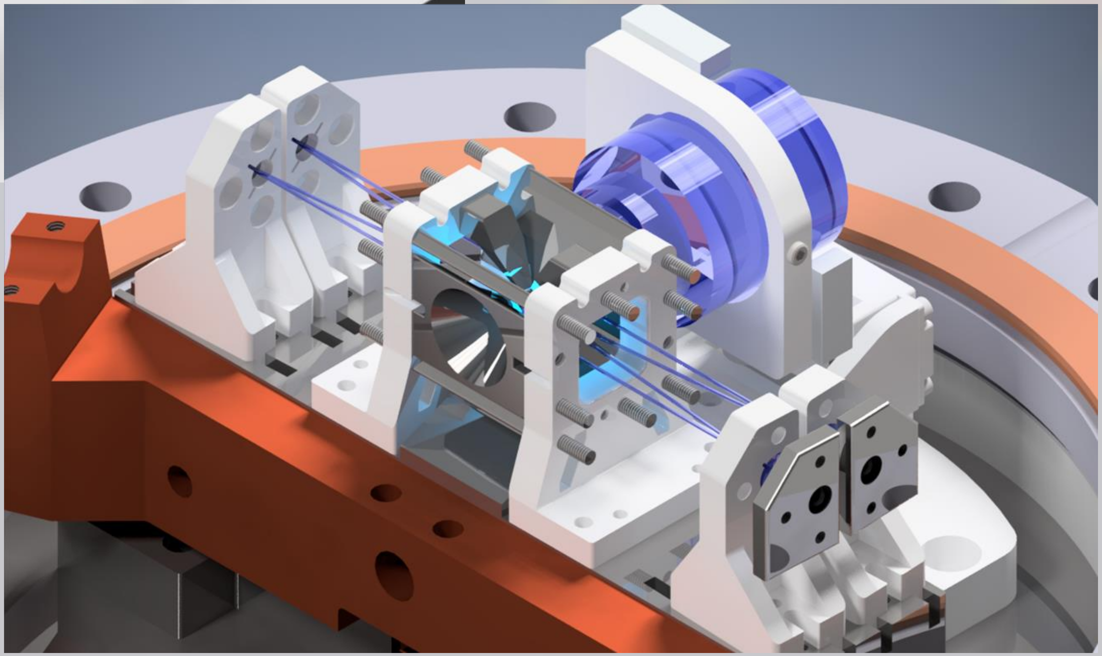
M. Knap et al. PRX **2**, 041020 (2012), L. Mazzola et al. PRL **110**, 230602 (2013) ...

Simulating **out-of-equilibrium** quantum mechanics and testing **quantum thermodynamics**

A complicated machine.. on its way



First ion trapping experiment in Italy



The team and funds

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Amelia Detti

PhD. opportunities!

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The future

European Union: a **1 billion**, **10-year-long** flaship just started