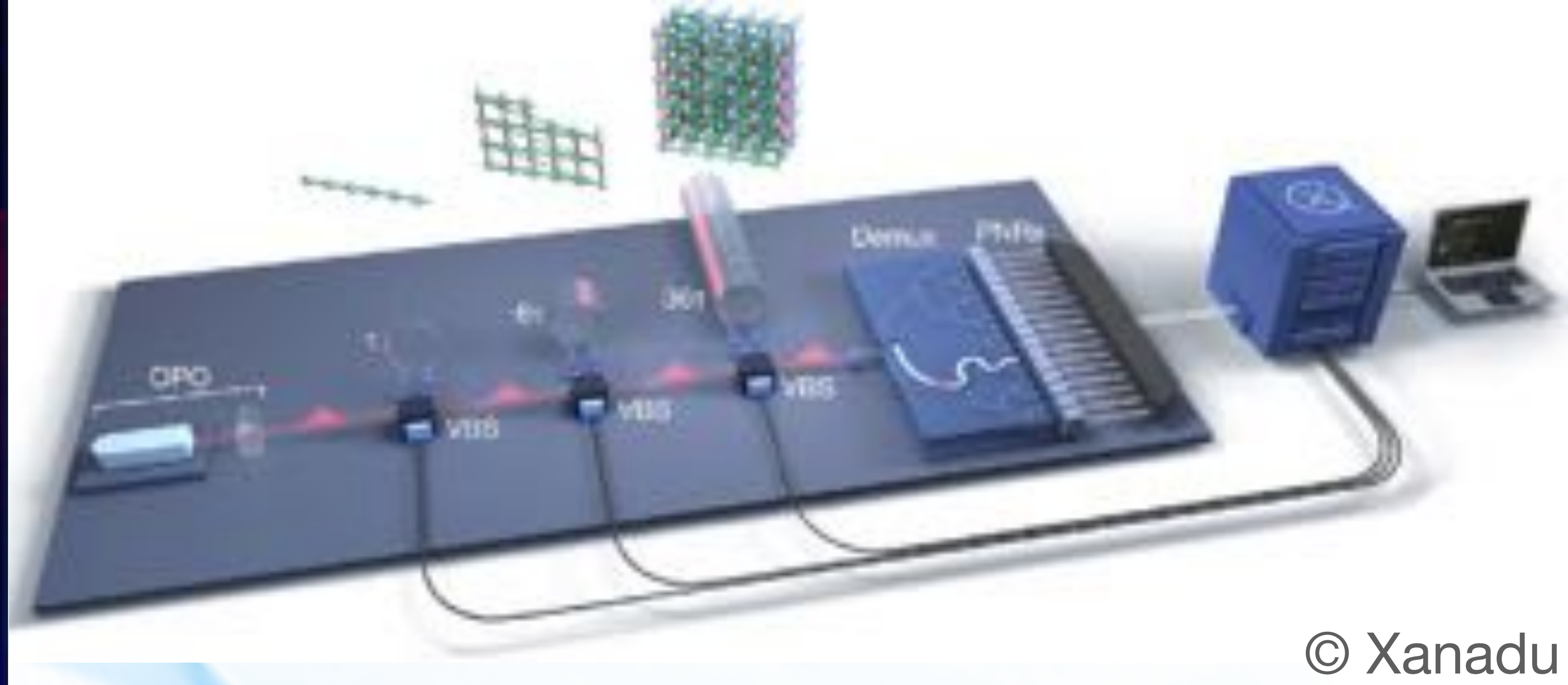
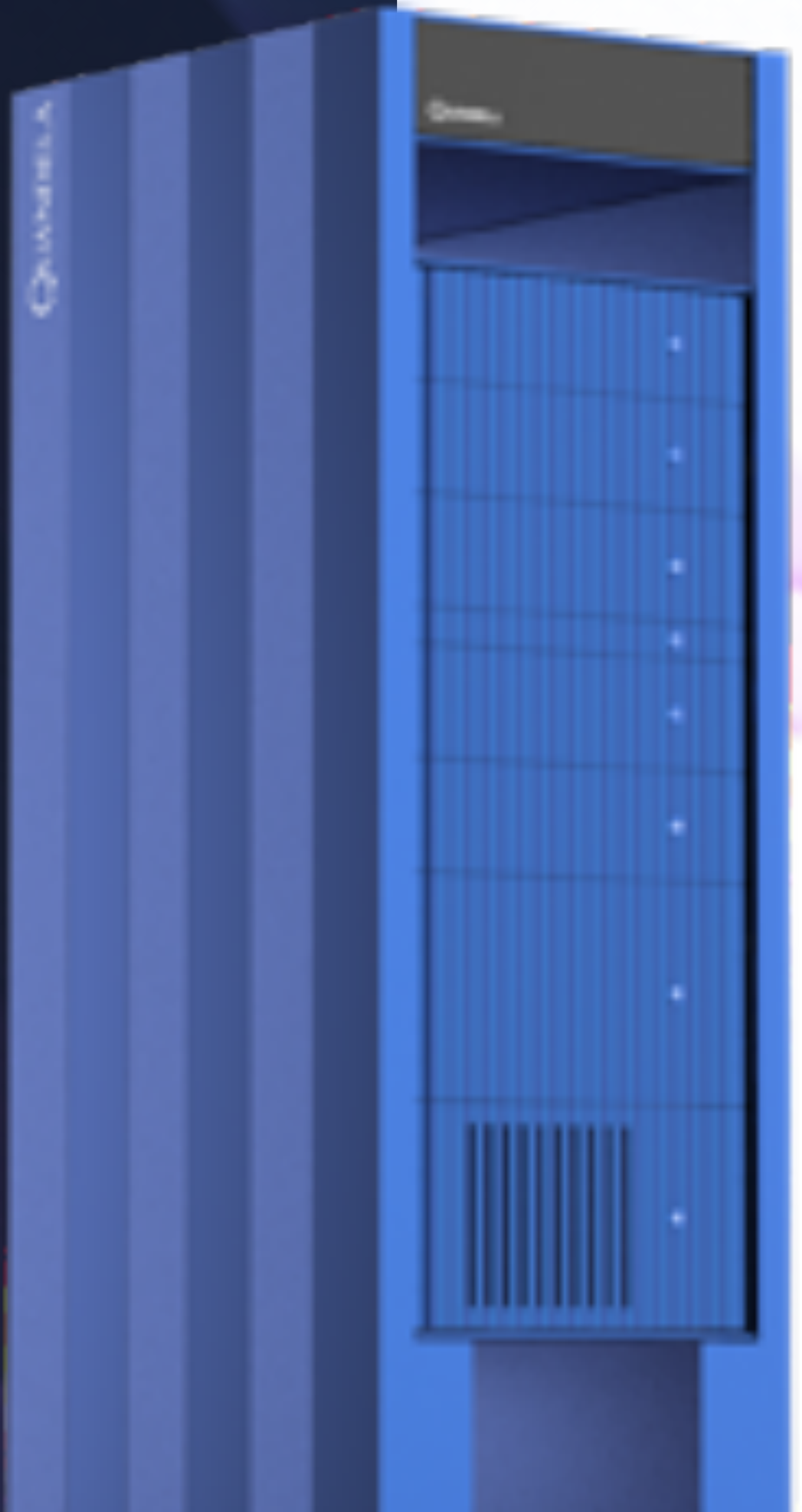
QUANDELA

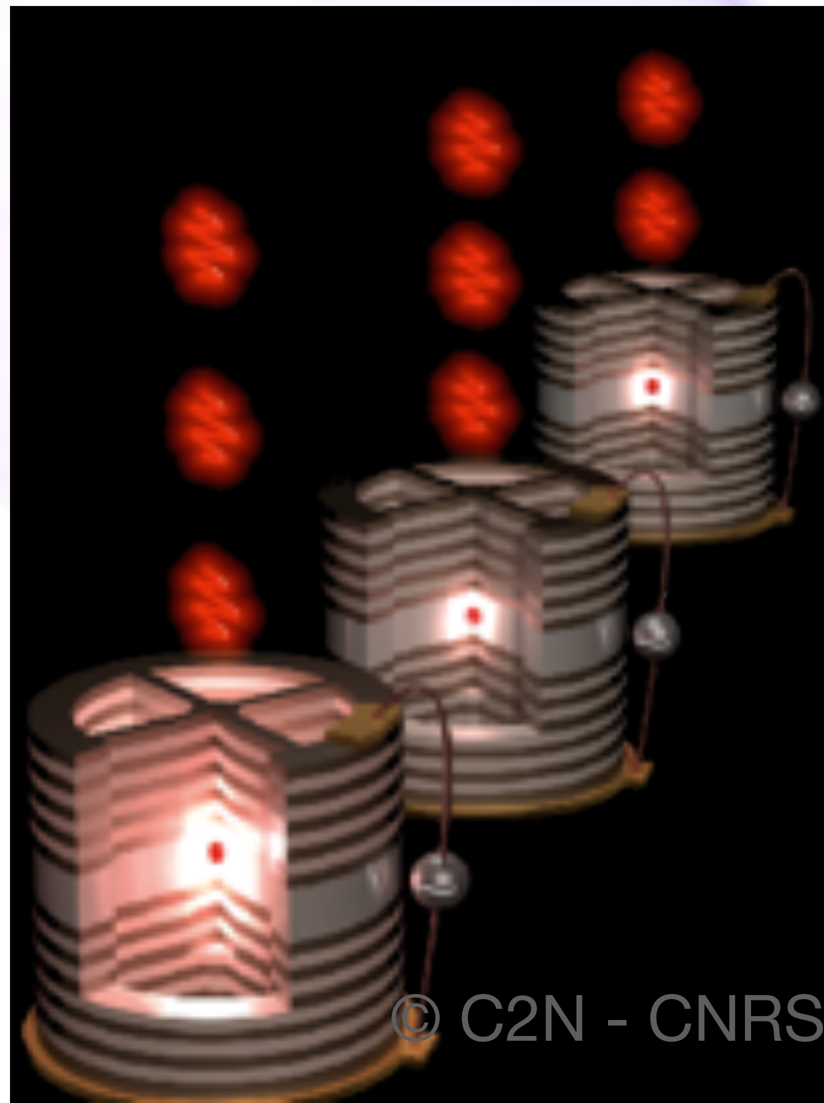




# L'ordinateur quantique

—

# Principes, technologies, défis




Présentation à l'IMT Atlantique - 25 novembre 2022

Boris Bourdoncle

# A hot topic

The Guardian view on quantum computing: the new space race
Editorial

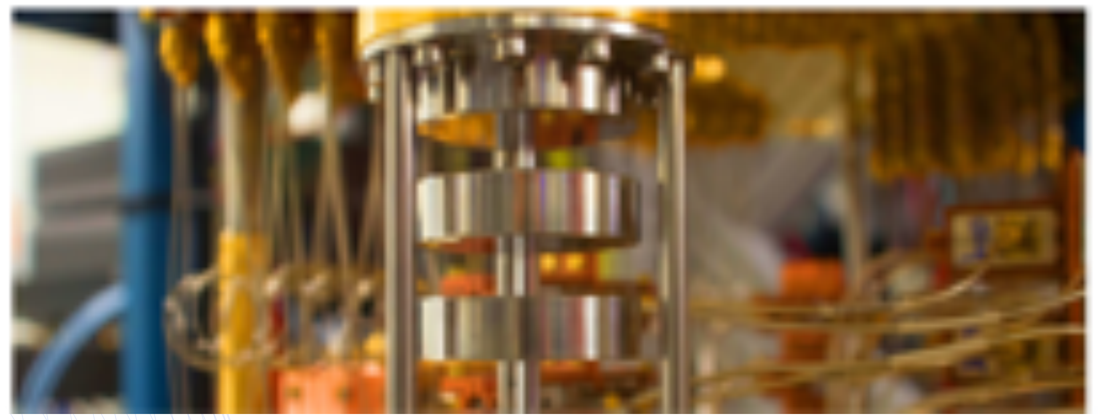
The main use of quantum technology might not be to hack existing systems but to create unhackable communication networks of the future

China will open a $10 billion quantum computer center and others also investing in quantum computing

Brian Wang | October 10, 2017


MIT Technology Review

Computing Dec 22, 2018
President Trump has signed a $1.2 billion law to boost US quantum tech



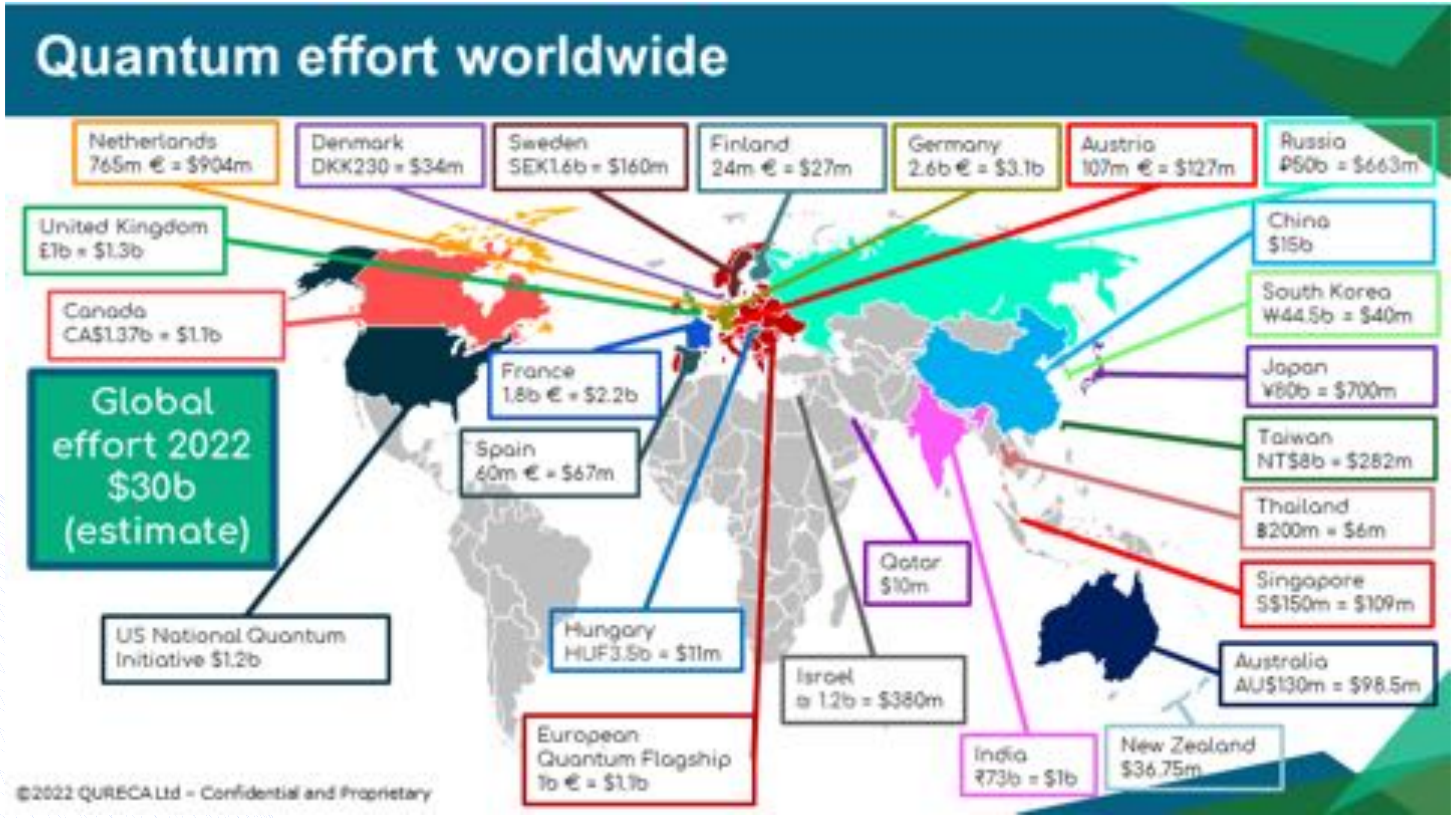
Quantum USA Vs. Quantum China: The World's Most Important Technology Race

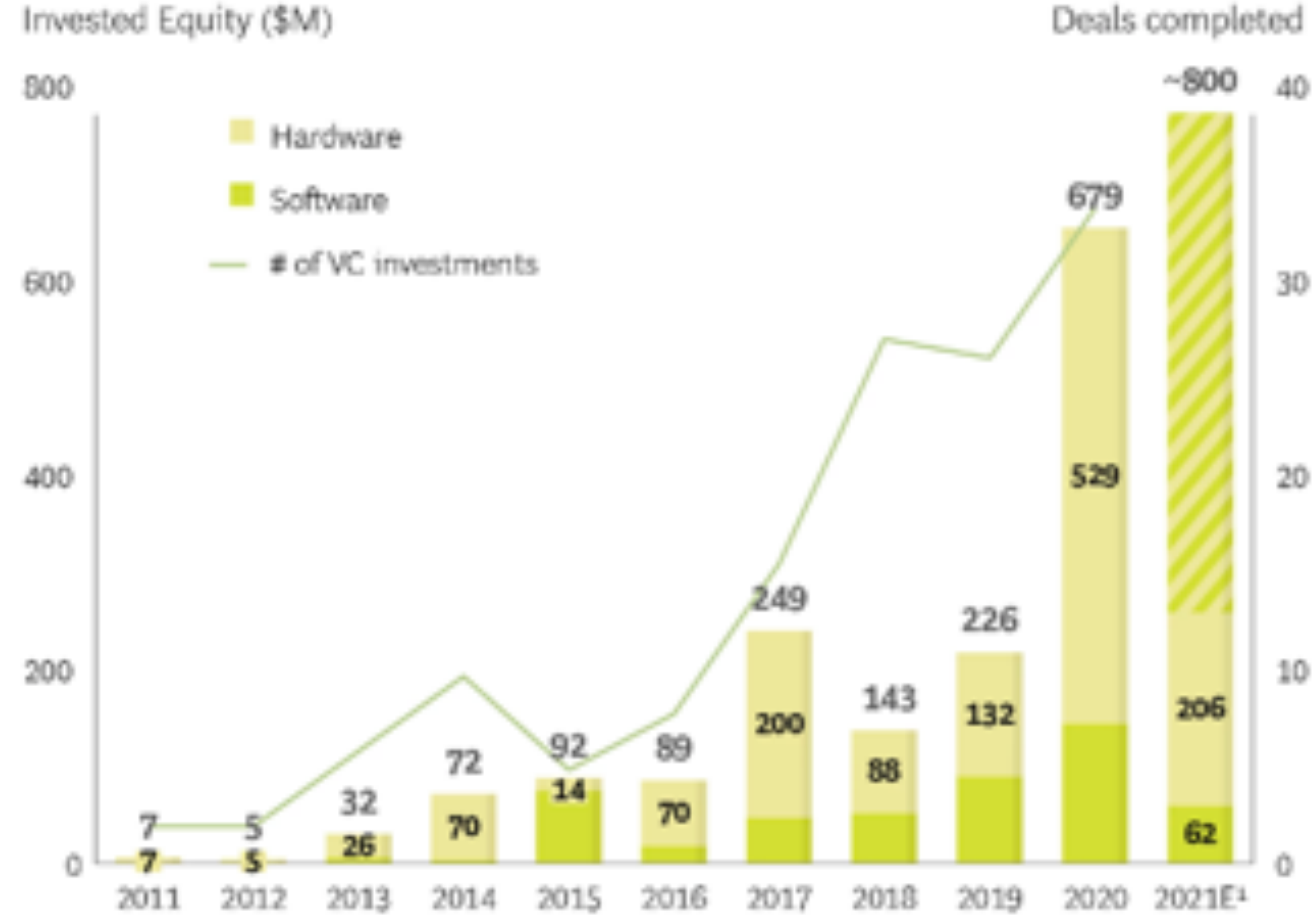
Moor Insights and Strategy Contributor
Cloud
*Straight talk from Moor Insights & Strategy tech industry analysts*

cnrs
Le CNRS
La Recherche

Premiers lauréats pour l'initiative européenne sur les technologies quantiques

# A hot topic

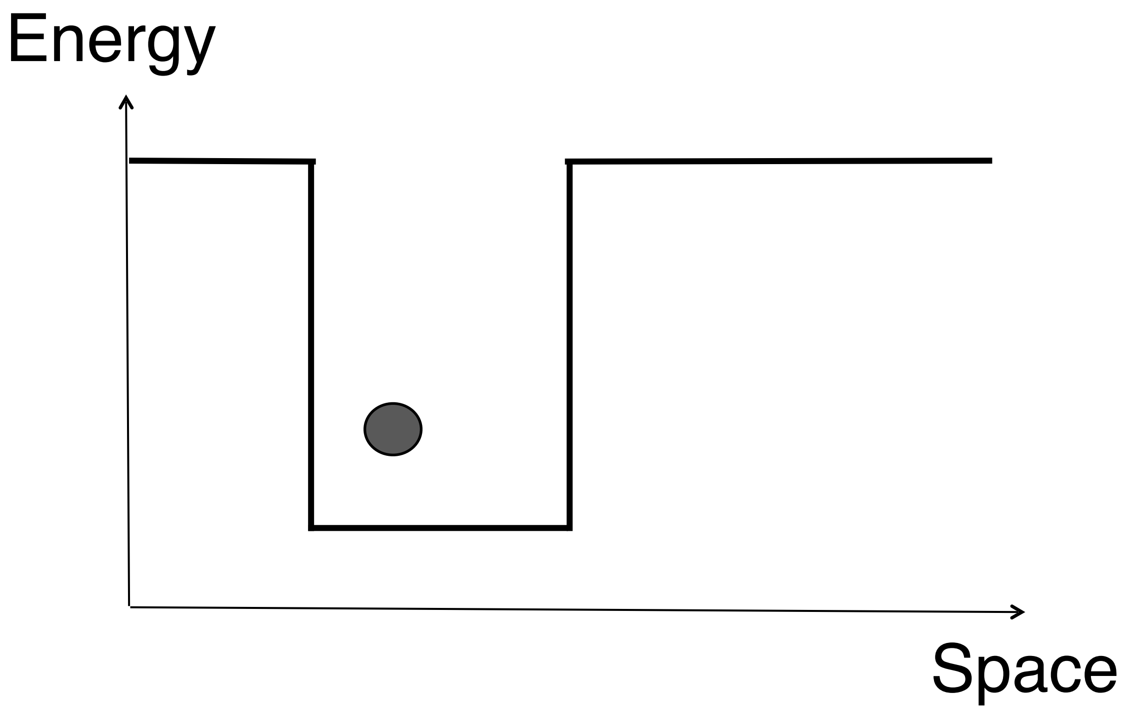


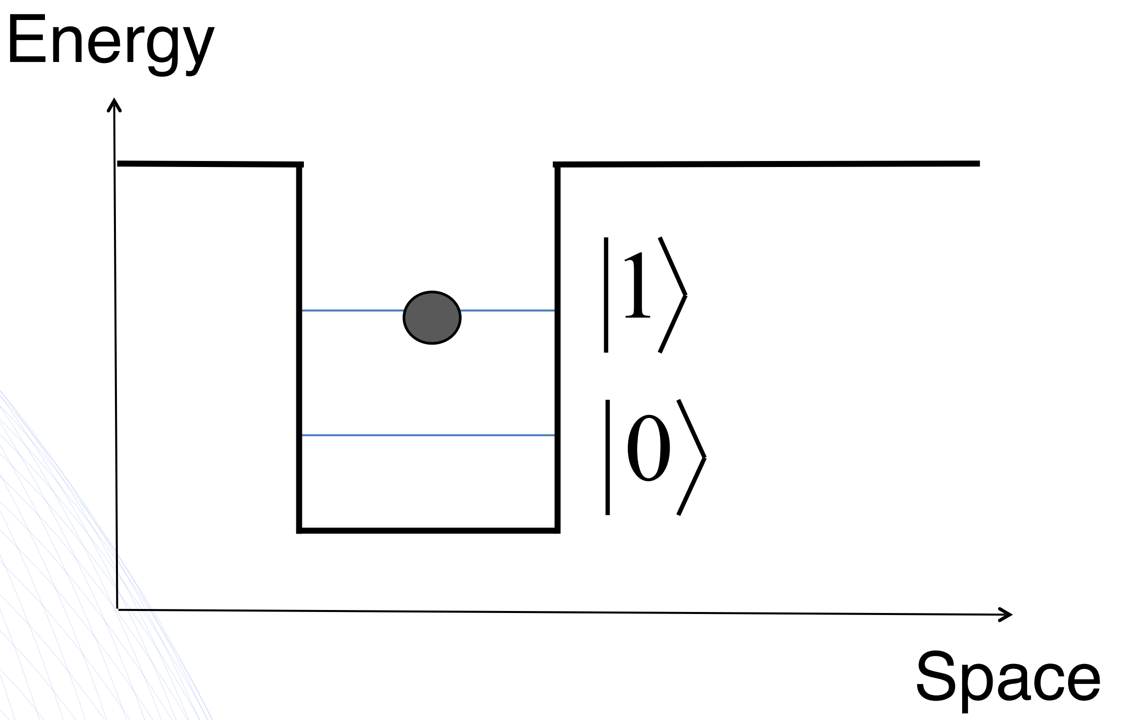




Sources: PitchBook (as of June 7, 2021), BCG analysis.

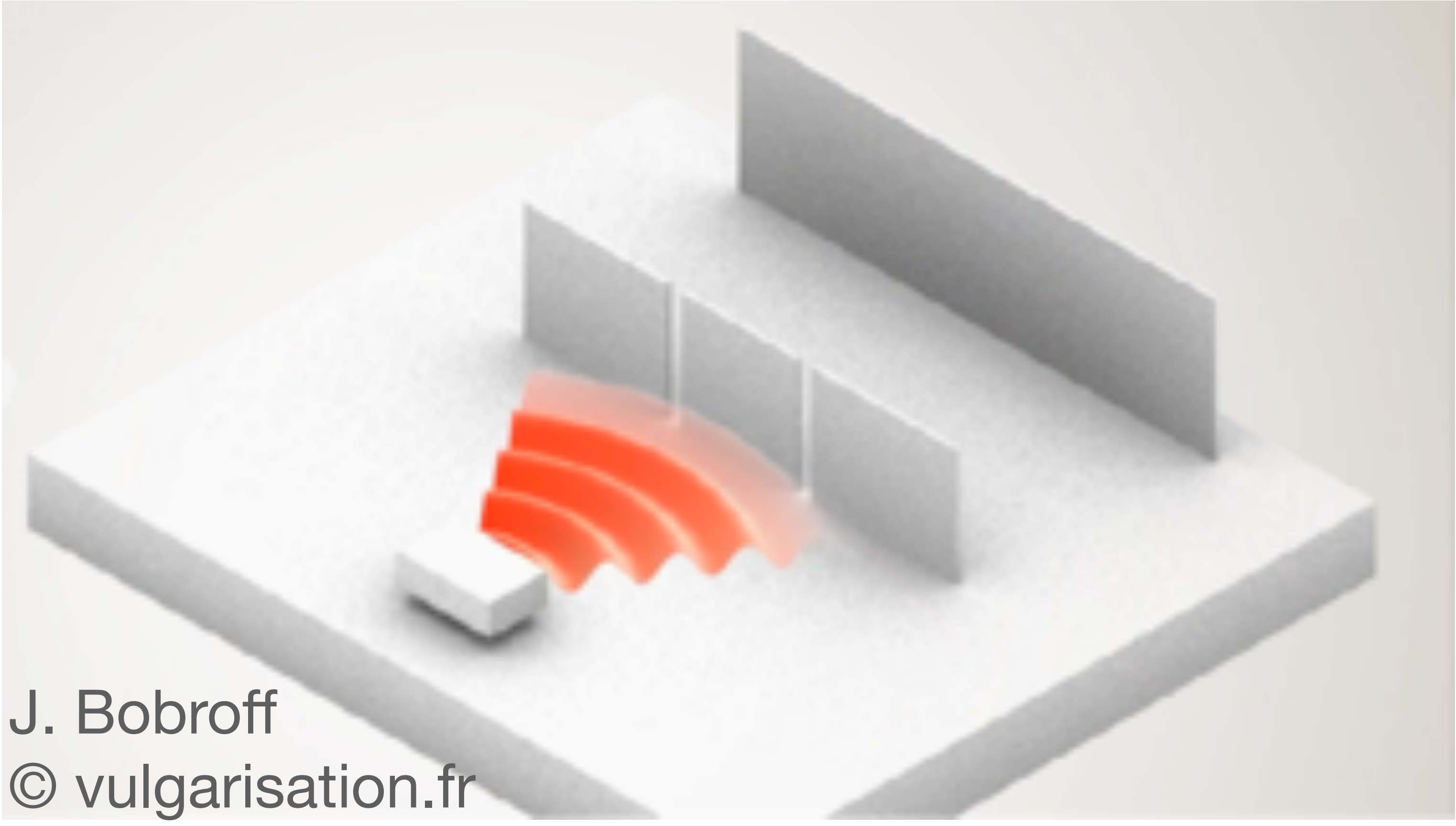
¹E=estimate for full year.

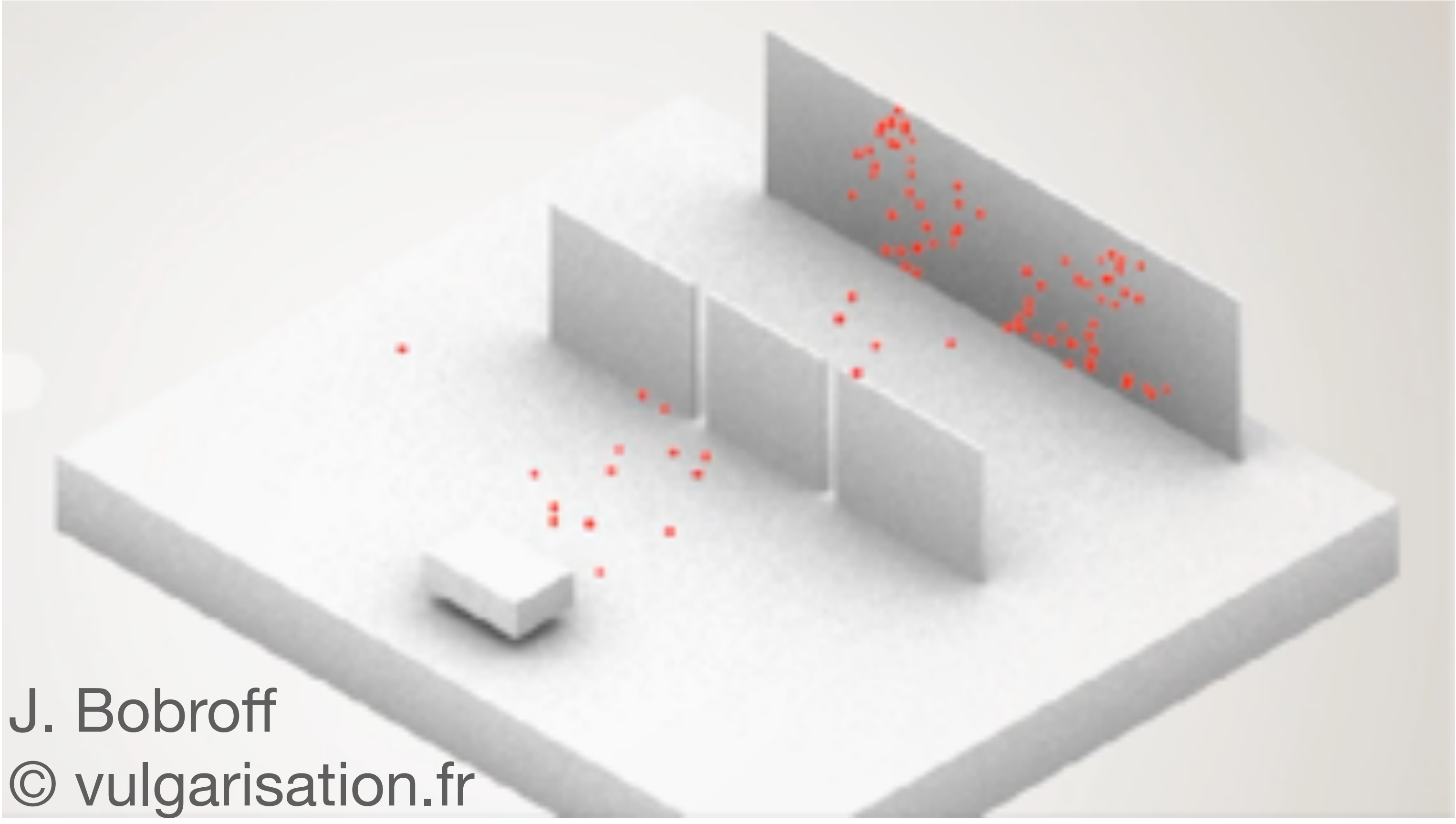
# From quantum mechanics…



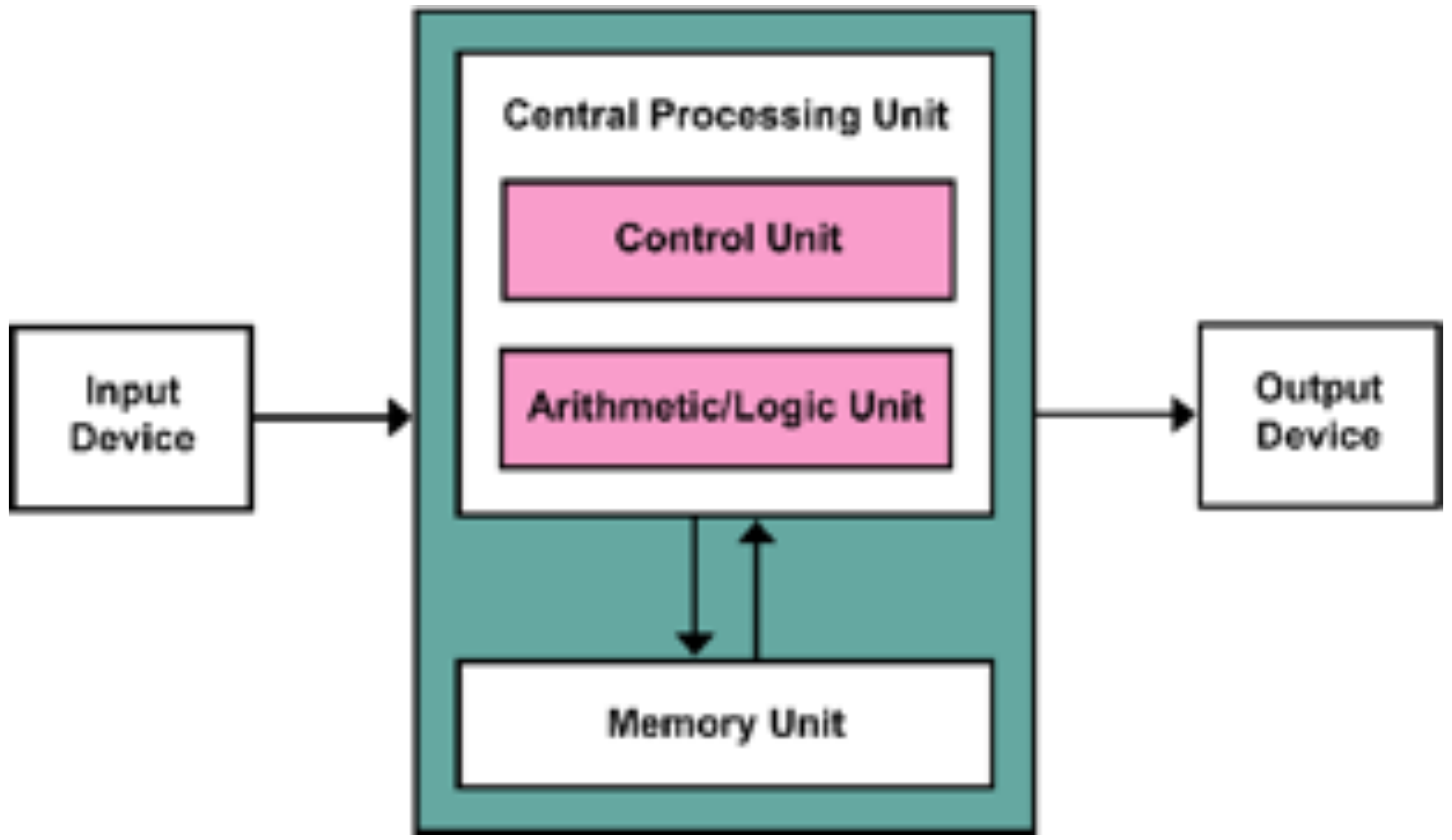

**QUANTISED ENERGY LEVELS**



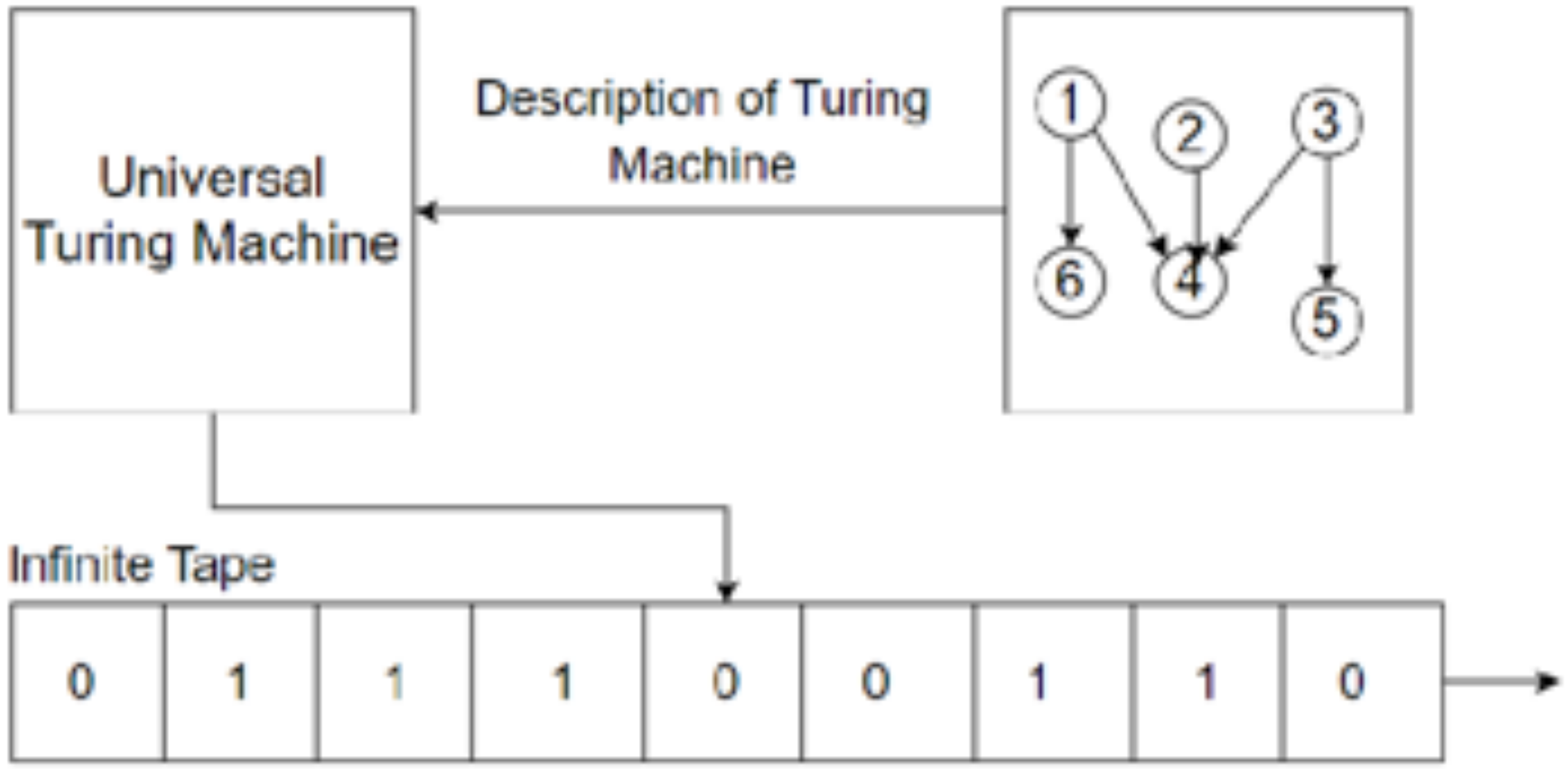




**WAVE—PARTICLE DUALITY**

# … and information theory…




**VON NEUMANN ARCHITECTURE**

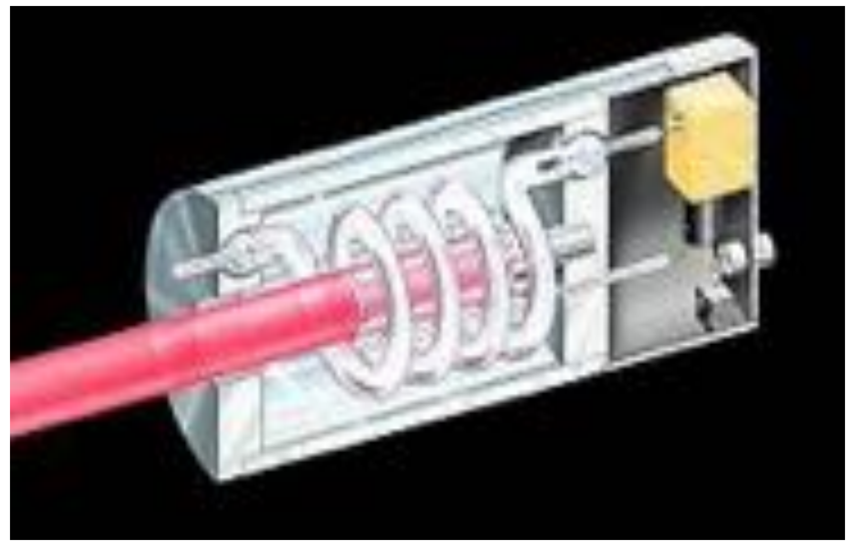



$$H(X) = -\sum_{i=1}^{n} P(x_i) \log_b P(x_i)$$

**SHANNON ENTROPY**

# … to one quantum revolution…

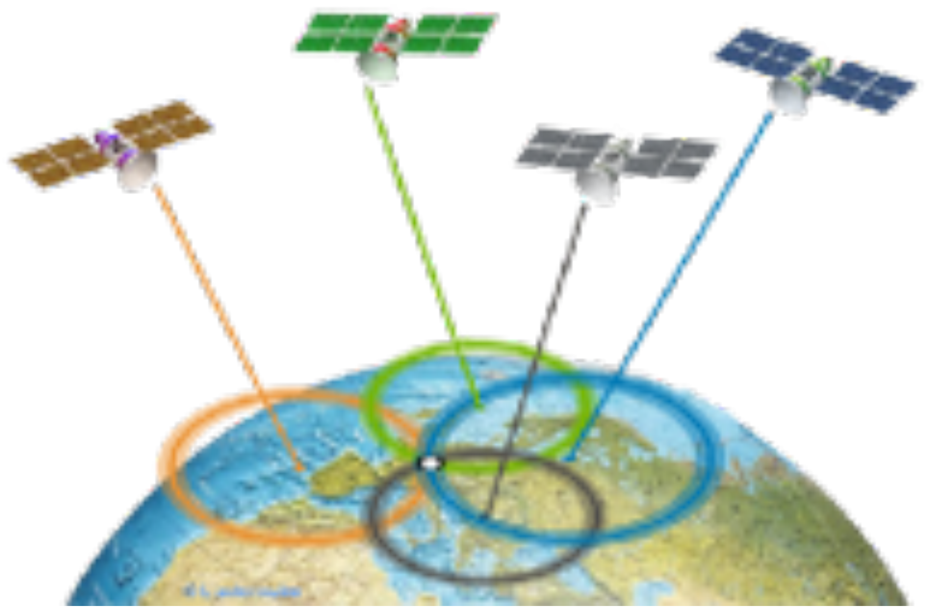

TRANSISTOR



LASER

LASER DIODE

MRI



GPS

SMARTPHONES

COMPUTERS

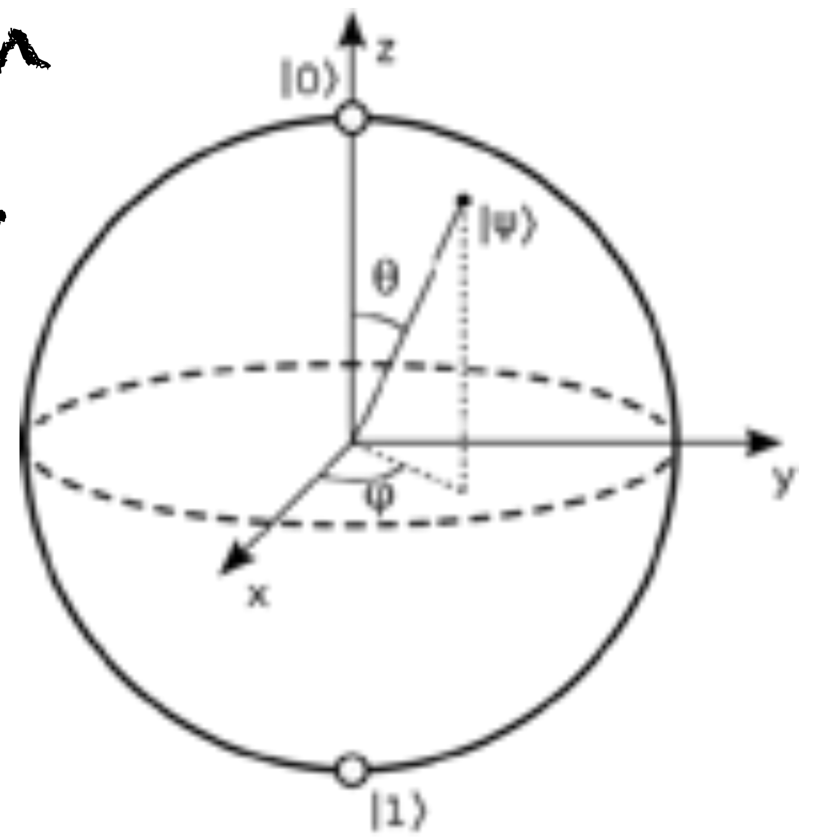
# … and the next!

## SUPERPOSITION

Classical bit: 0 or 1

Quantum bit: $\alpha|0\rangle + \beta|1\rangle$

The information gets quantum!



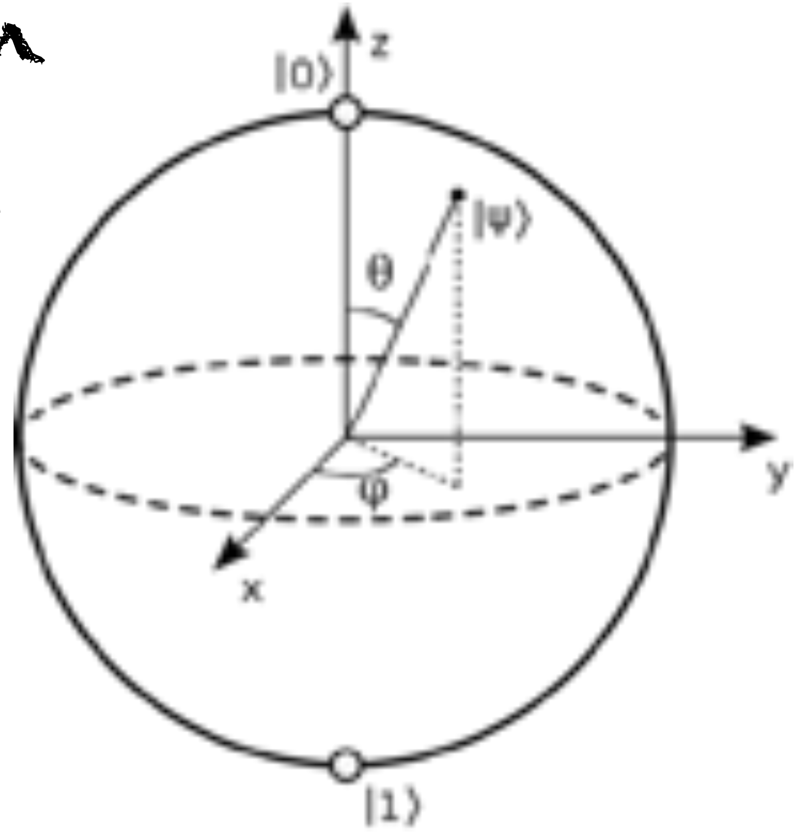
# … and the next!

## SUPERPOSITION

Classical bit: 0 or 1

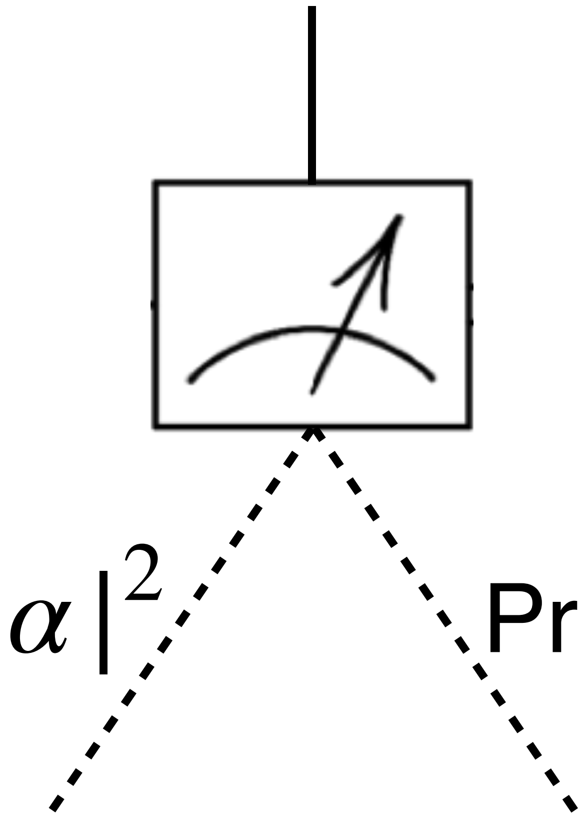
Quantum bit: $\alpha|0\rangle + \beta|1\rangle$

The information gets quantum!




## MEASUREMENT

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



Pr = $|\alpha|^2$

Pr = $|\beta|^2$

Result '0'
State $|0\rangle$

Result '1'
State $|1\rangle$

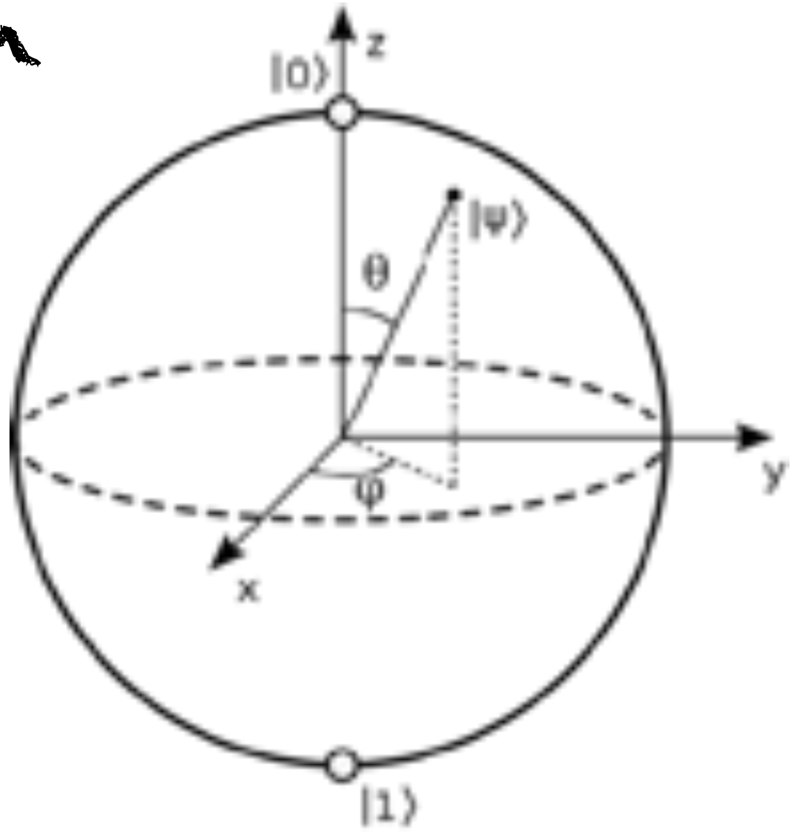
# … and the next!

## SUPERPOSITION

Classical bit: 0 or 1

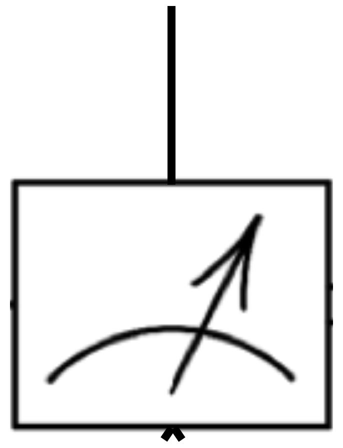
Quantum bit: $\alpha|0\rangle + \beta|1\rangle$

The information gets quantum!




## MEASUREMENT

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



Pr = $|\alpha|^2$

Pr = $|\beta|^2$

Result '0'
State $|0\rangle$

Result '1'
State $|1\rangle$

## ENTANGLEMENT

$$|\Psi\rangle = \frac{|01\rangle + |10\rangle}{\sqrt{2}}$$

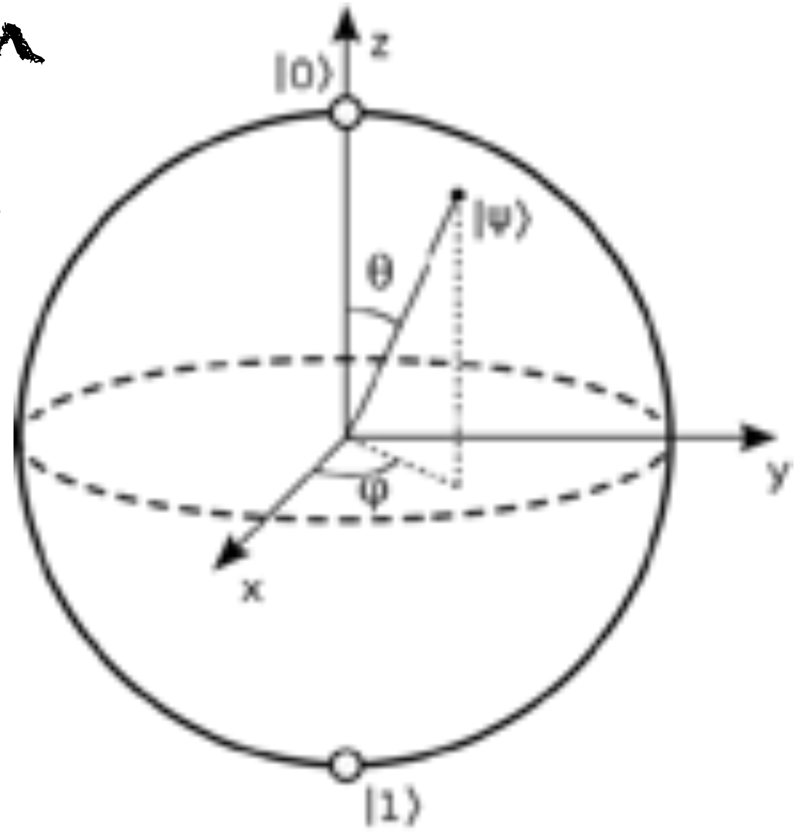
# … and the next!

## SUPERPOSITION

Classical bit: 0 or 1

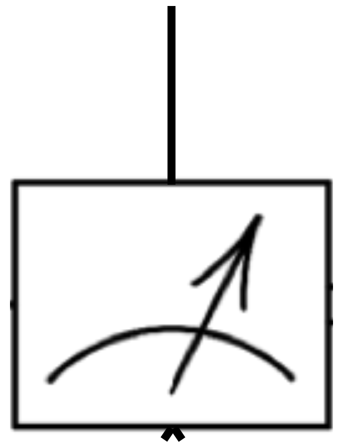
Quantum bit: $\alpha|0\rangle + \beta|1\rangle$

*The information gets quantum!*




## MEASUREMENT

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



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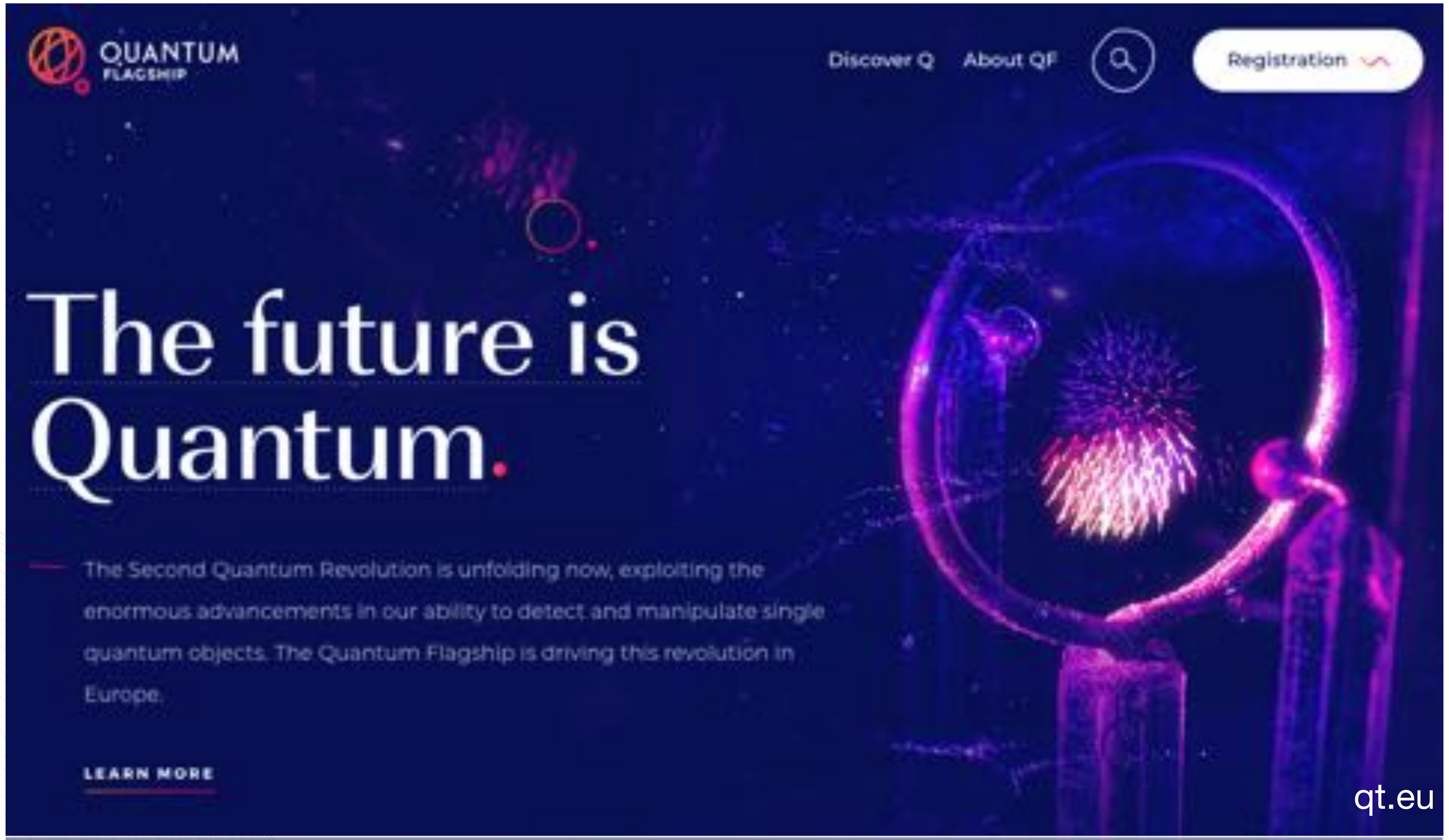
State $|1\rangle$

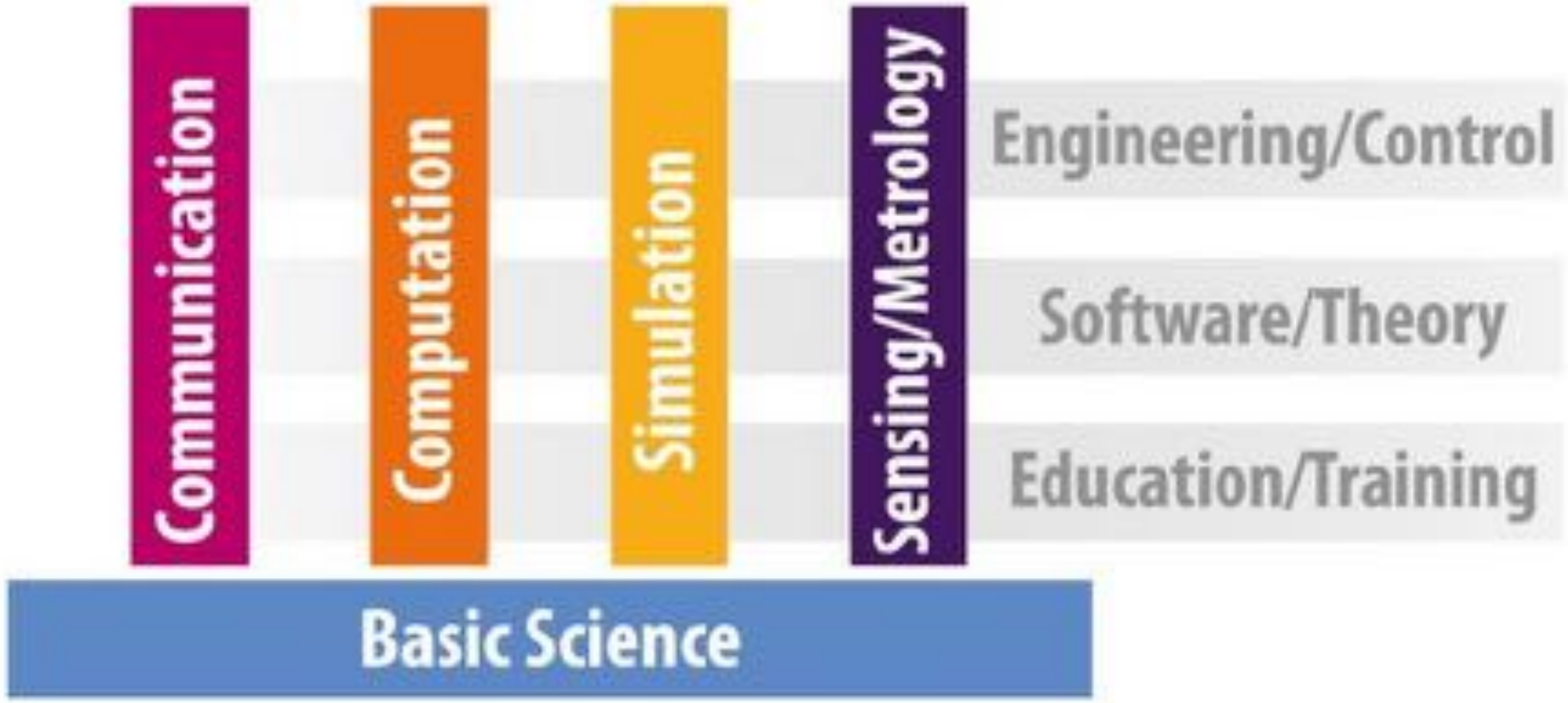
## ENTANGLEMENT

$$|\Psi\rangle = \frac{|01\rangle + |10\rangle}{\sqrt{2}}$$

## NOBEL PRIZE IN PHYSICS 2022

# Applications of the 2nd quantum revolution




**New Journal of Physics**

IOP Institute of Physics

ROADMAP

The quantum technologies roadmap: a European community view

Antonio Acin, Immanuel Bloch, Harry Buhrman, Tommaso Calarco, Christopher Eichler, Jens Eisert, Daniel Esteve, Nicolas Gisin, Steffen J Glaser, Fedor Jelezko, Stefan Kuhr, Maciej Lewenstein, Max F Riedel, Piet O Schmidt, Rob Thew, Andreas Wallraff, Ian Walmsley and Frank K Wilhelm

# What makes a good quantum computer

## DiVincenzo's criteria

1. A scalable physical system with well-characterised qubits
2. The ability to initialise the state of the qubits
3. Long relevant decoherence times
4. A universal set of quantum gates
5. A qubit-specific measurement capability

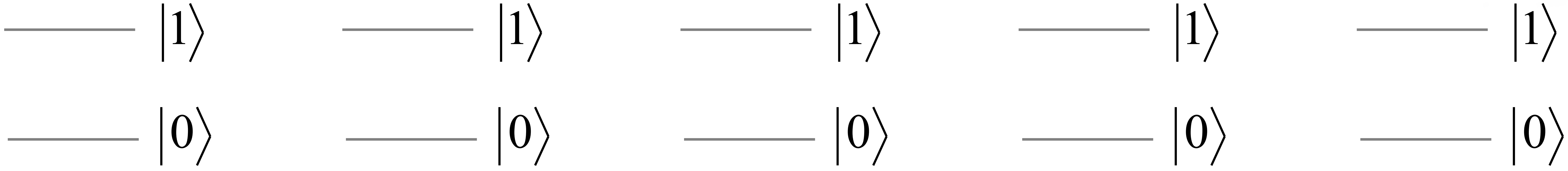
Fortschr. Phys. **48** (2000) 9–11, 771–783

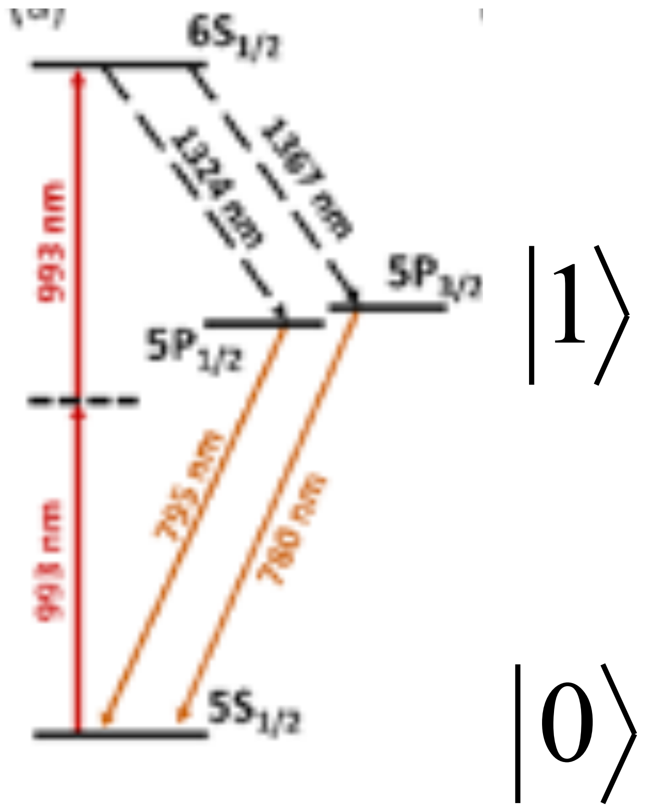
**The Physical Implementation of Quantum Computation**

David P. DiVincenzo

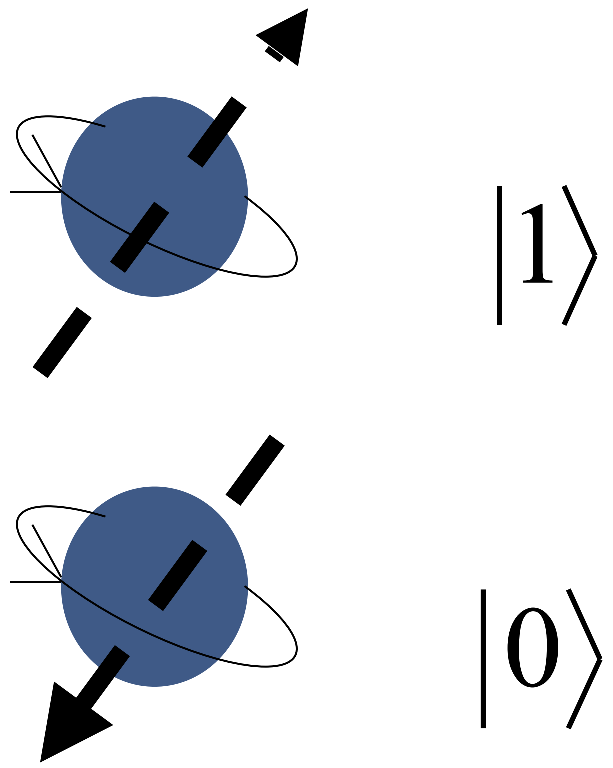
IBM T. J. Watson Research Center, Yorktown Heights, NY 10598 USA

# A scalable system with well-characterised qubits

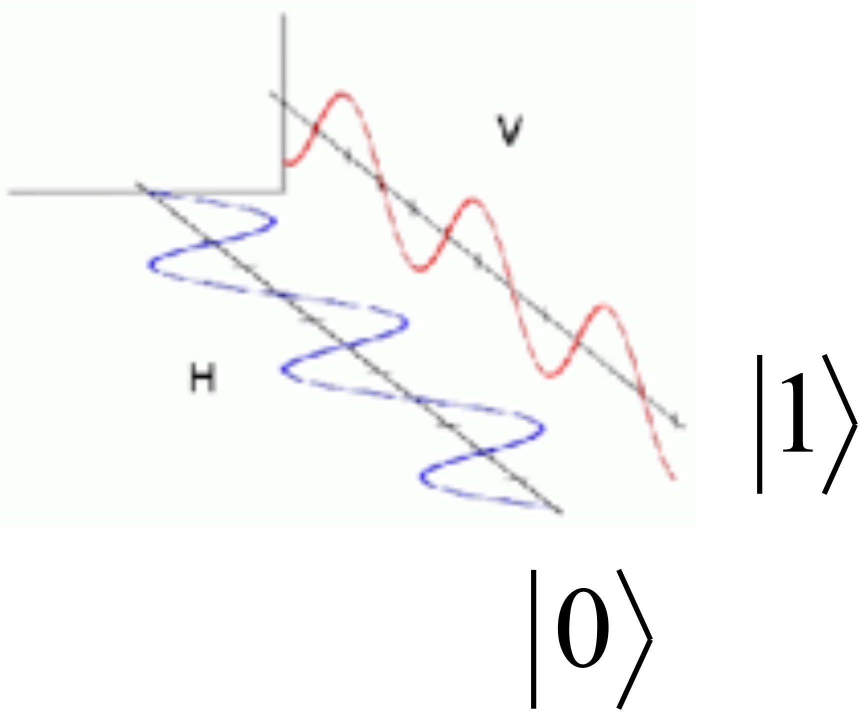



**ATOM + ENERGY LEVELS**

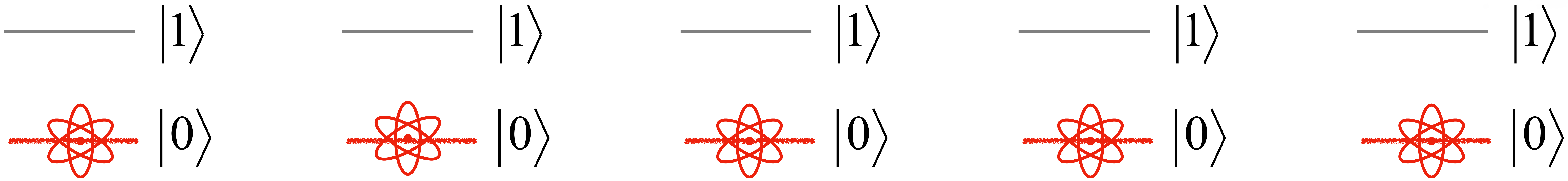



**ELECTRON + SPIN**

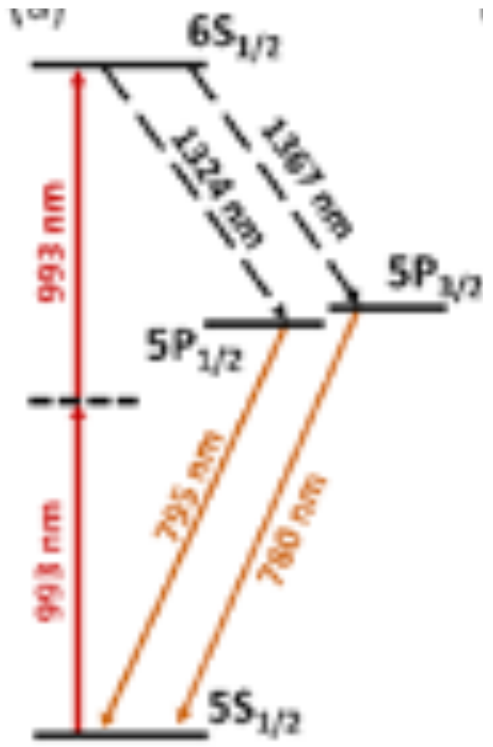



**PHOTON + POLARISATION**

# The ability to initialise the state of the qubits



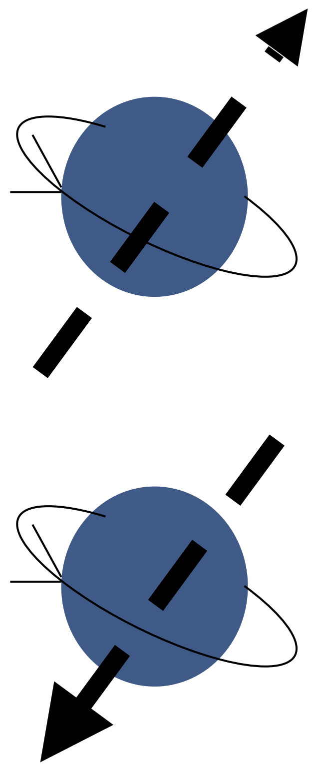

Optical pumping




$|0\rangle$

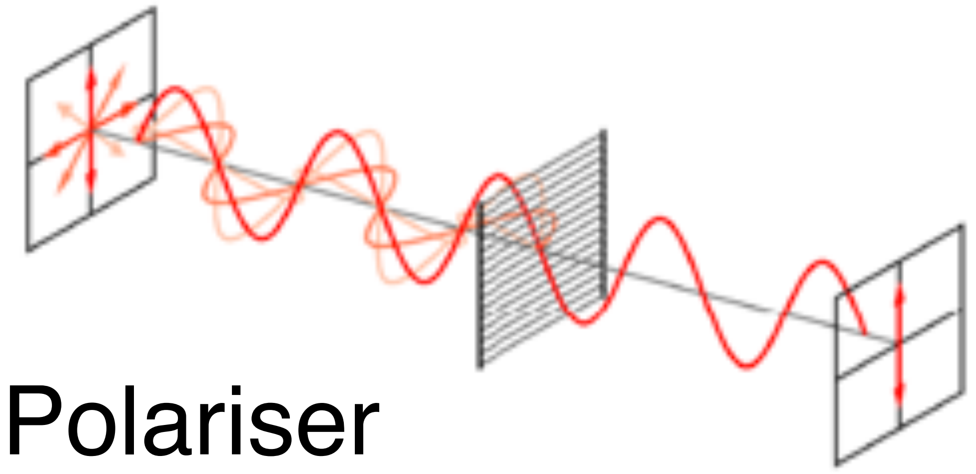
**ATOM + ENERGY LEVELS**

Microwave control



$|0\rangle$

**ELECTRON + SPIN**

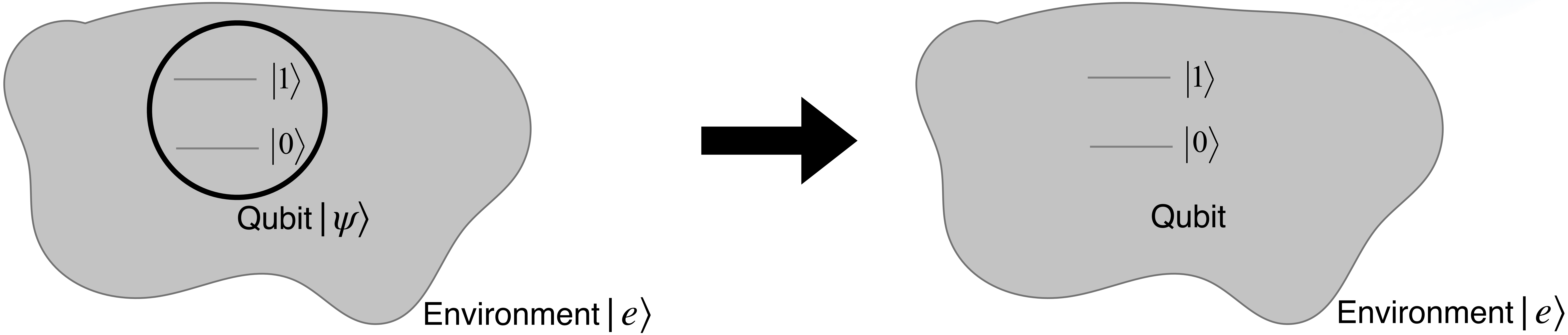


Polariser

$|0\rangle$

**PHOTON + POLARISATION**

# Long relevant decoherence time




$$\rho = |\psi\rangle\langle\psi| \otimes |e\rangle\langle e|$$

$$\mathrm{Tr}_e(\rho) = \begin{pmatrix} p_1 & 0 \\ 0 & p_2 \end{pmatrix} \neq |\psi\rangle\langle\psi|$$

**DIFFICULTY:** We need isolated qubits to avoid decoherence **BUT** We need interactions to control the qubits and make them interfere

# A universal gate set

Universal = can implement any unitary transformation $\Rightarrow$ *continuous!*

Hadamard — **H** — $|0\rangle \rightarrow (|0\rangle + |1\rangle)/\sqrt{2}$

$|1\rangle \rightarrow (|0\rangle - |1\rangle)/\sqrt{2}$

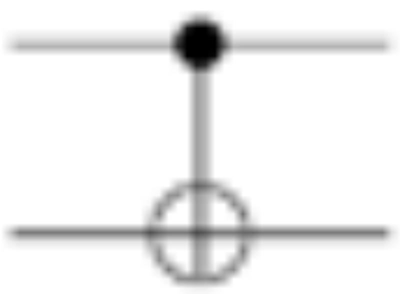
S gate — **S** — $|0\rangle \rightarrow |0\rangle$

$|1\rangle \rightarrow i|1\rangle$

T gate — **T** — $|0\rangle \rightarrow |0\rangle$

$|1\rangle \rightarrow e^{i\pi/4}|1\rangle$

C-NOT gate

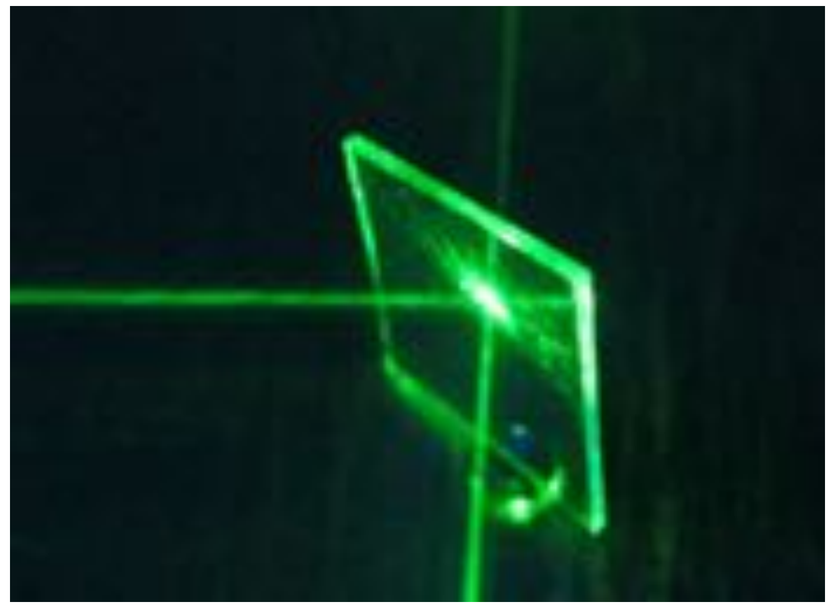


$|00\rangle \rightarrow |00\rangle$

$|01\rangle \rightarrow |01\rangle$

$|10\rangle \rightarrow |11\rangle$

$|11\rangle \rightarrow |10\rangle$

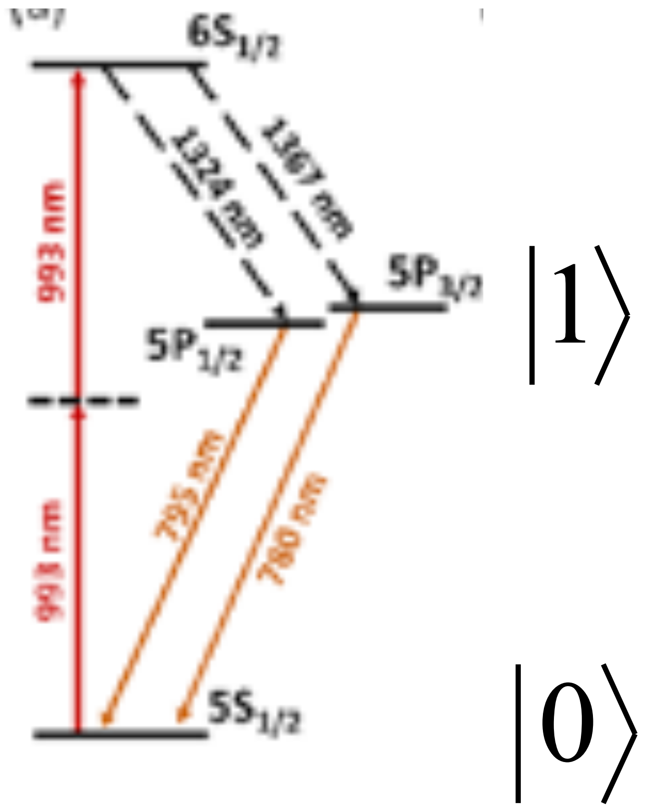


$\Rightarrow$ **3 SINGLE QUBIT GATES + 1 TWO-QUBIT GATE = APPROXIMATE ALL UNITAIRES**

# A qubit-specific measurement capability

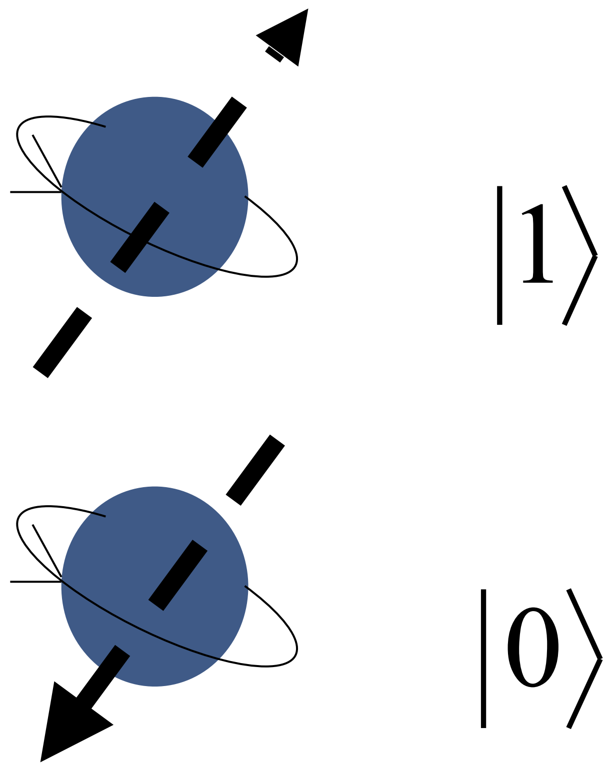
$|1\rangle$ or $|0\rangle$ ? $|1\rangle$ or $|0\rangle$ ? $|1\rangle$ or $|0\rangle$ ? $|1\rangle$ or $|0\rangle$ ? $|1\rangle$ or $|0\rangle$ ?

Fluorescence

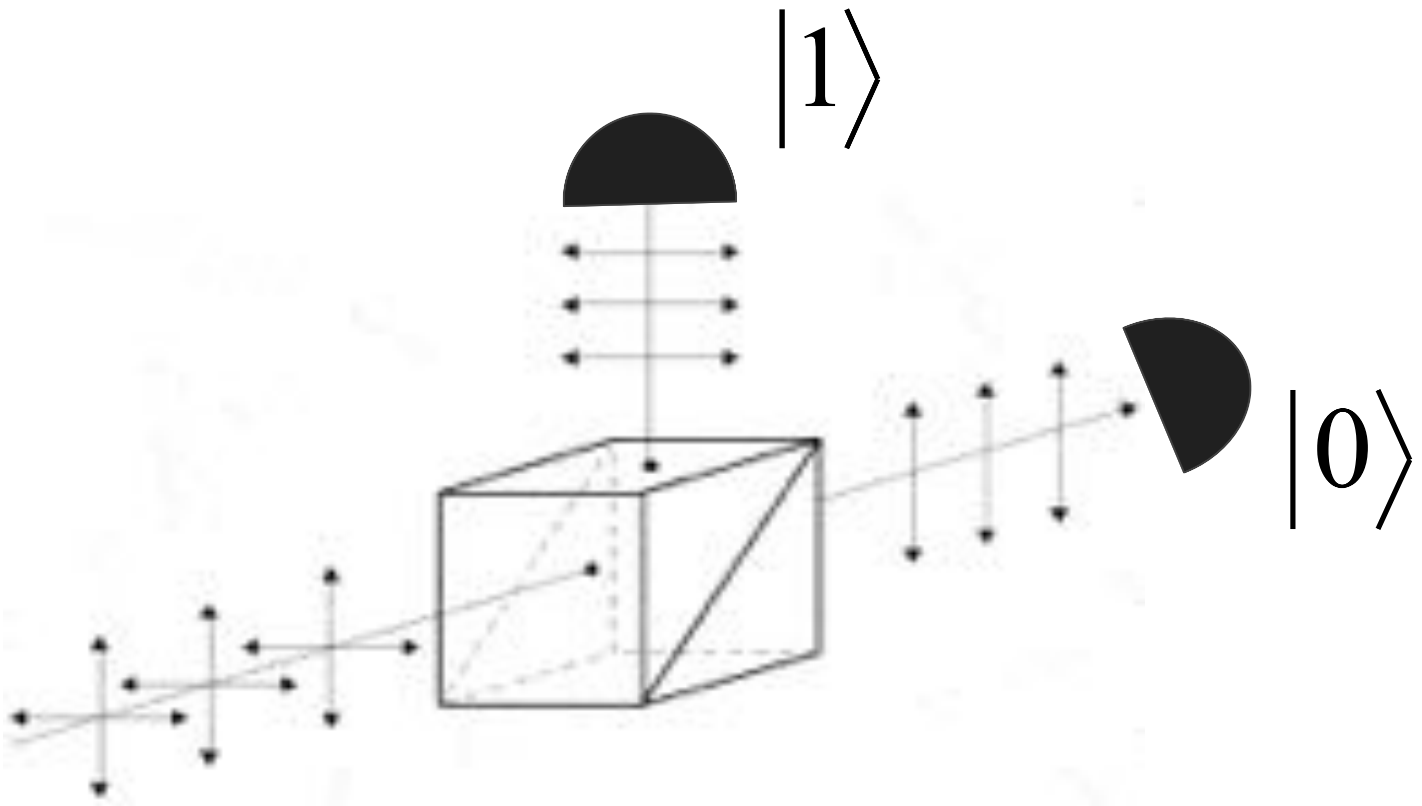



**ATOM + ENERGY LEVELS**

Microwave readout




**ELECTRON + SPIN**

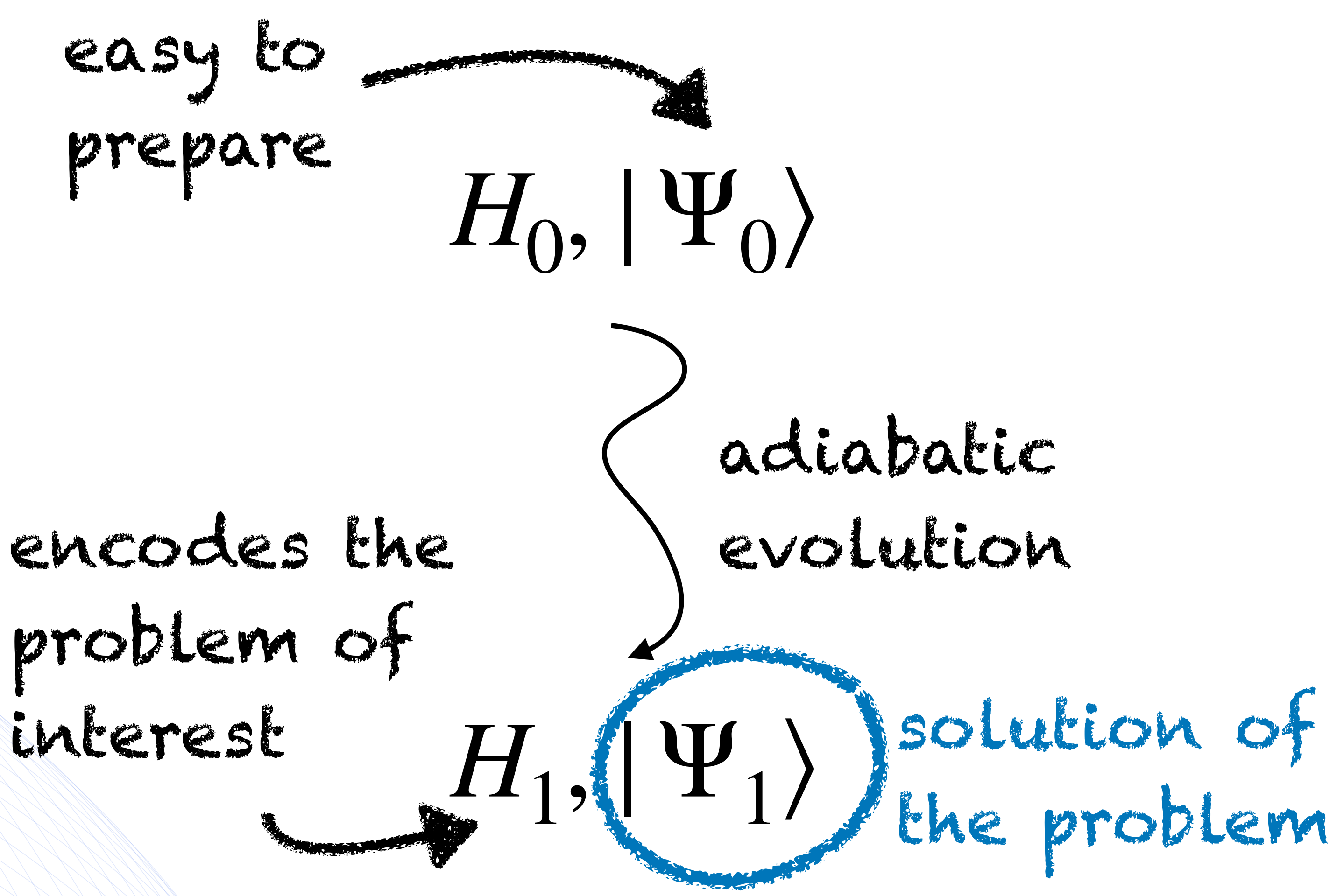



Polariser + single photon detectors

**PHOTON + POLARISATION**

# Models of quantum computing

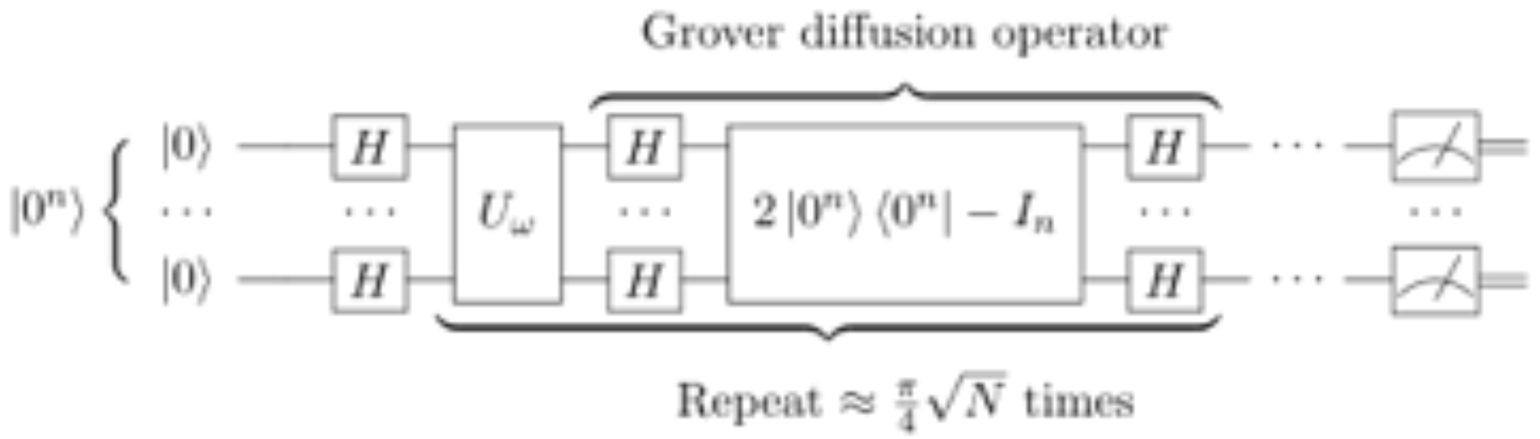
## ADIABATIC QUANTUM COMPUTING

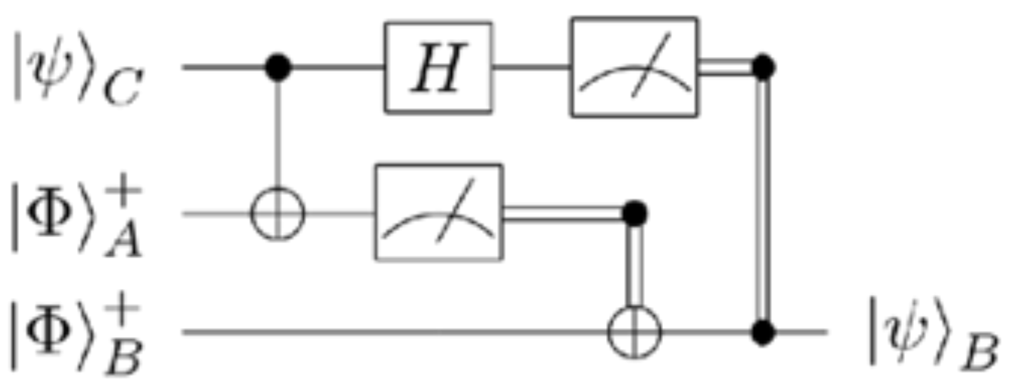



Not necessarily adiabatic: quantum annealing

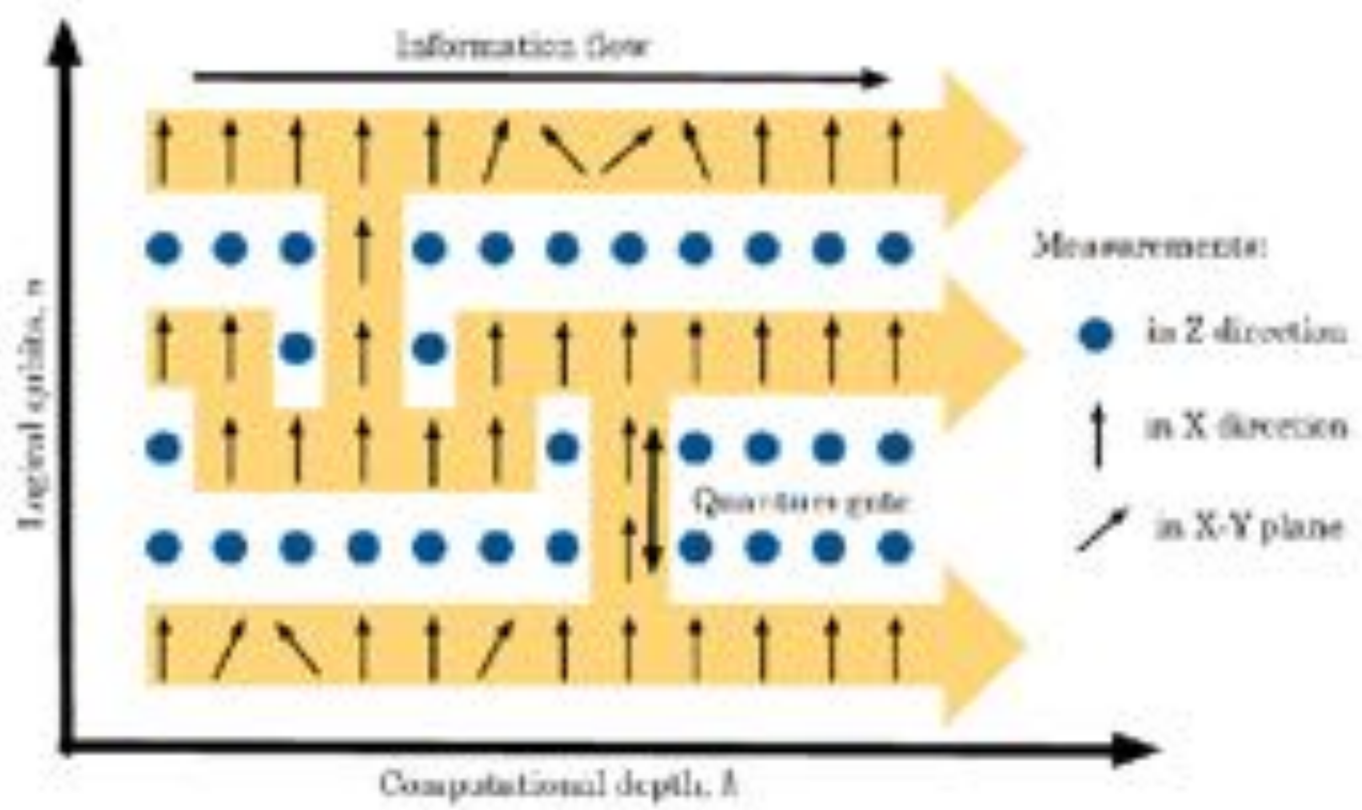

©D-Wave

## GATE-BASED QUANTUM COMPUTING




## MEASUREMENT-BASED QUANTUM COMPUTING

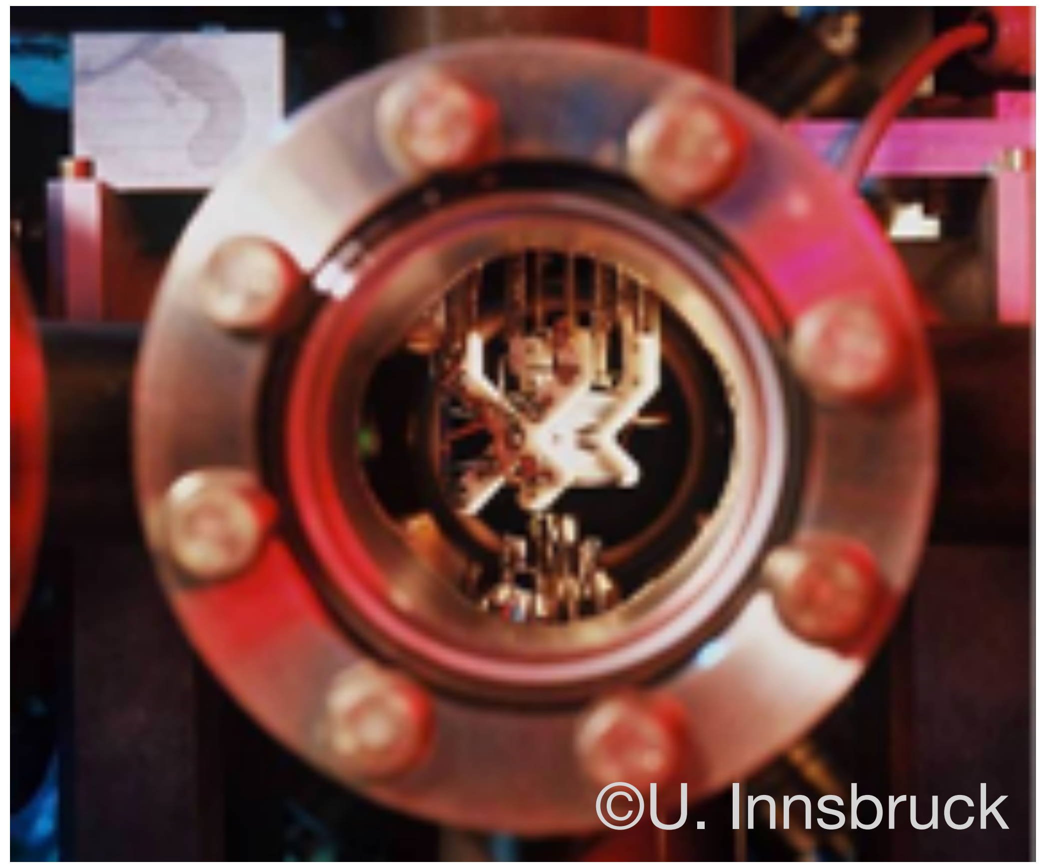



PHYSICAL REVIEW A **68**, 022312 (2003)

**Measurement-based quantum computation on cluster states**

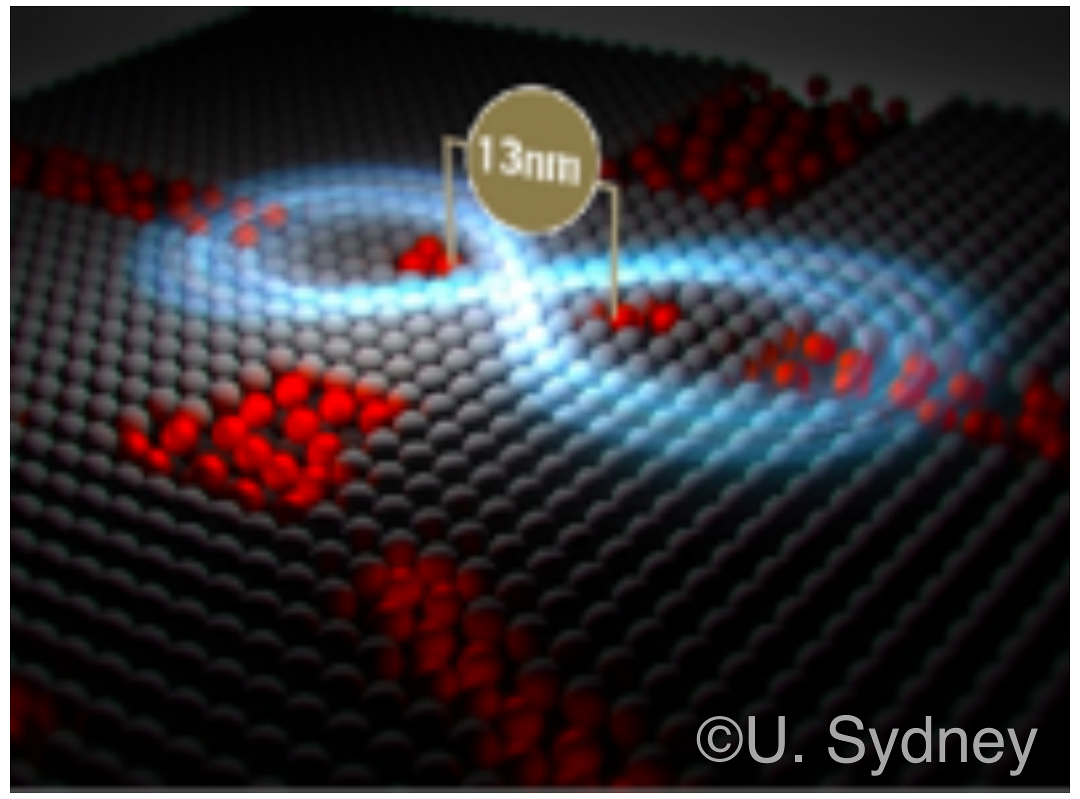
Robert Raussendorf, Daniel E. Browne,* and Hans J. Briegel
*Theoretische Physik, Ludwig-Maximilians-Universität München, München, Germany*
(Received 18 February 2003; published 25 August 2003)

# Physical implementations of a quantum computer

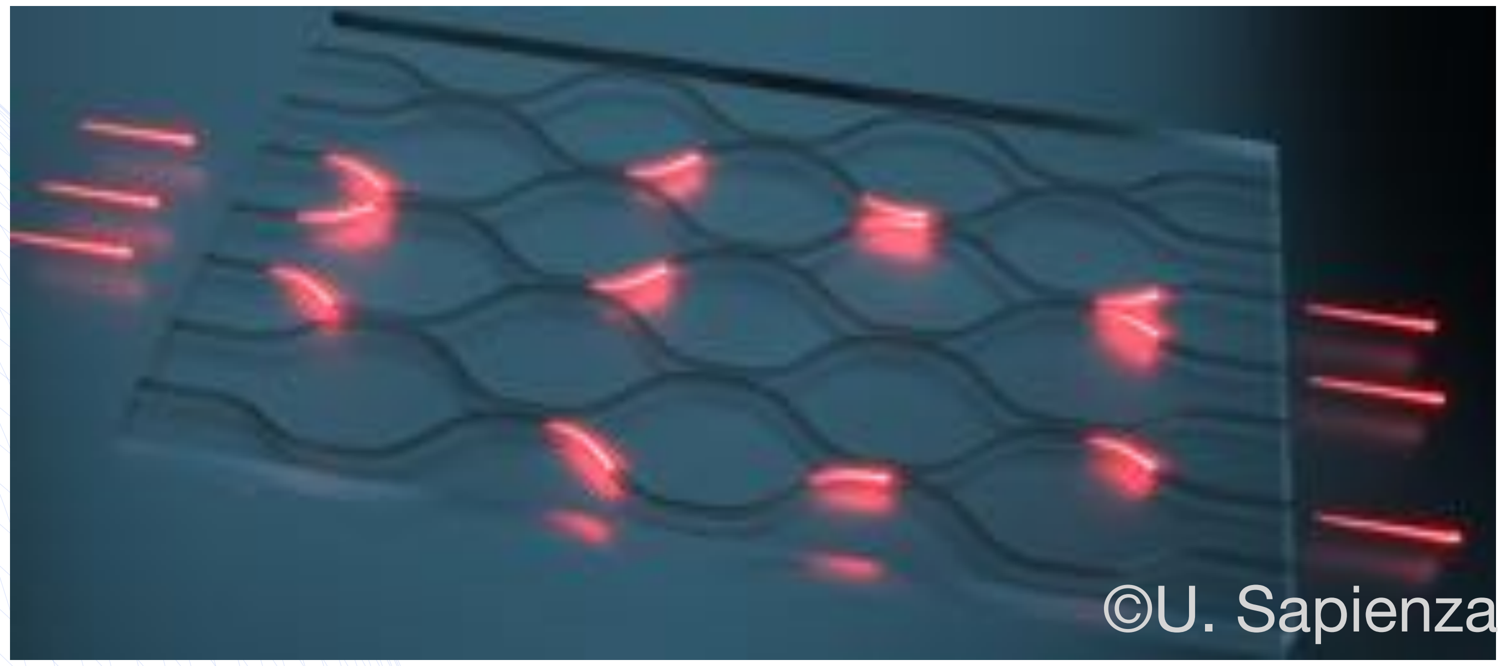



**TRAPPED IONS**

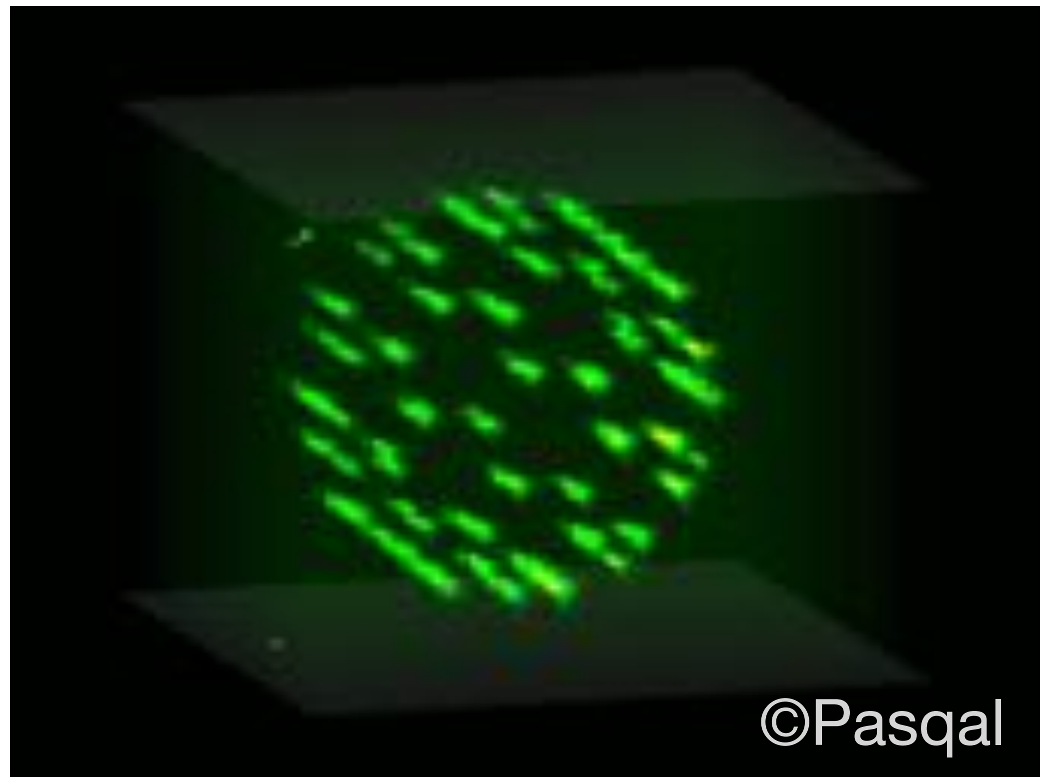

**SUPERCONDUCTING QUBITS**




**SILICON QUBITS**



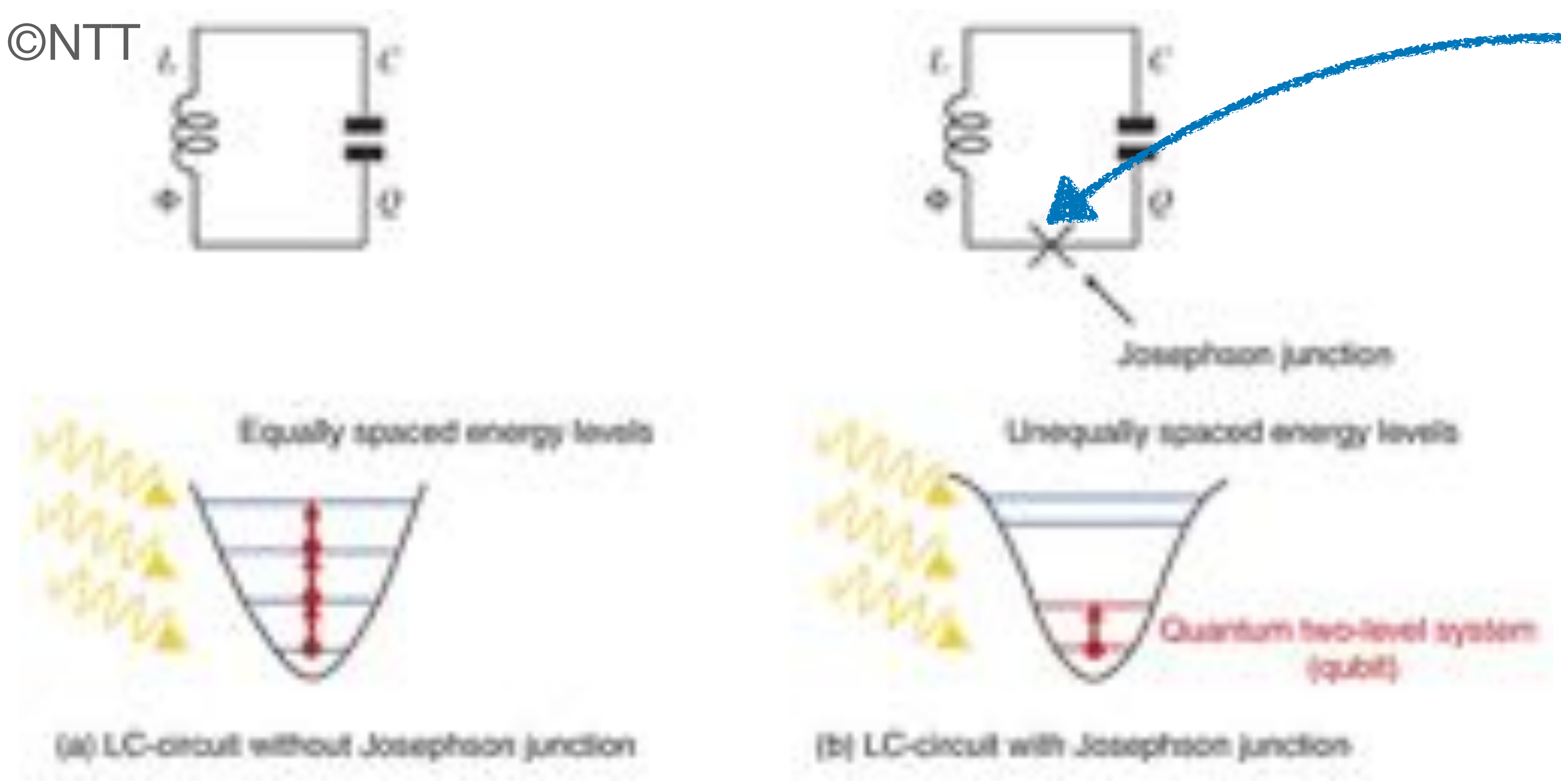

**PHOTONS**

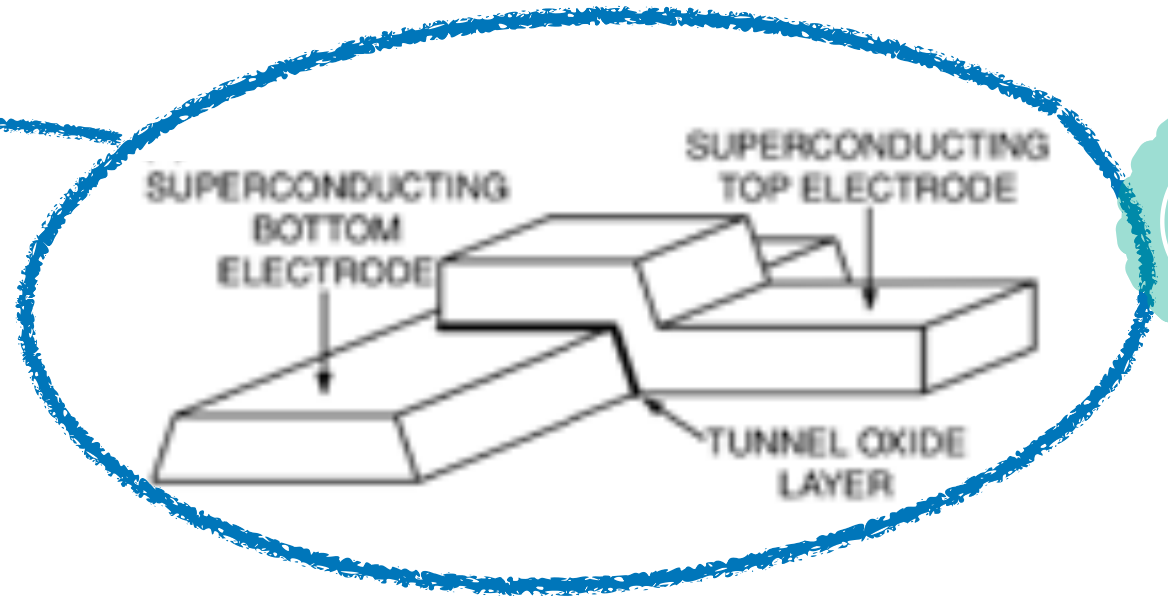



**NEUTRAL ATOMS**

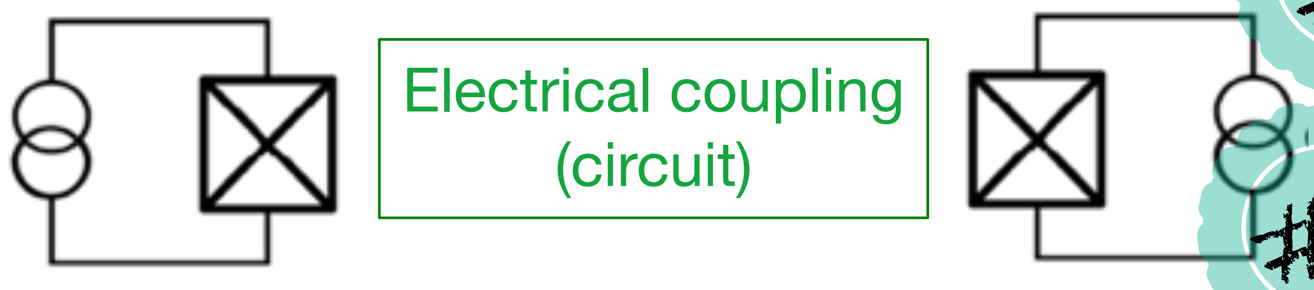
# Superconducting qubits



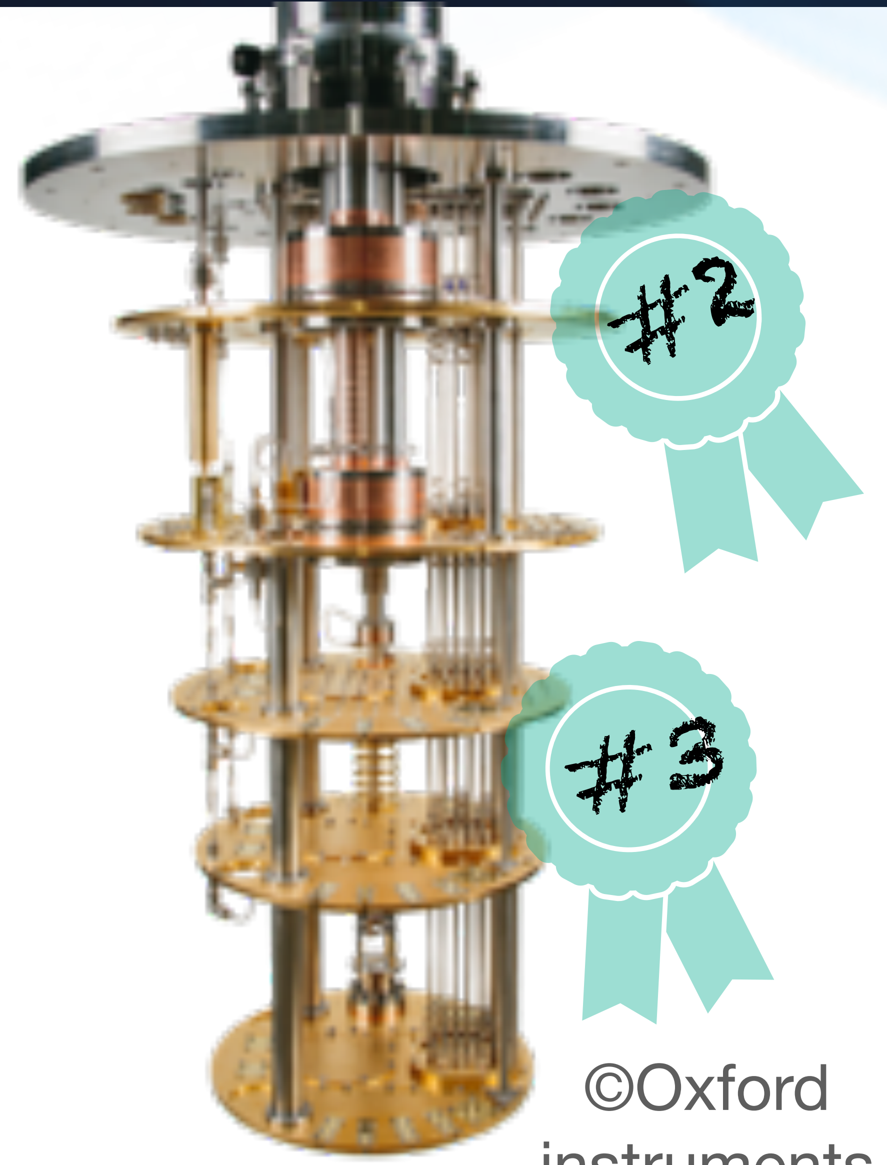



#1

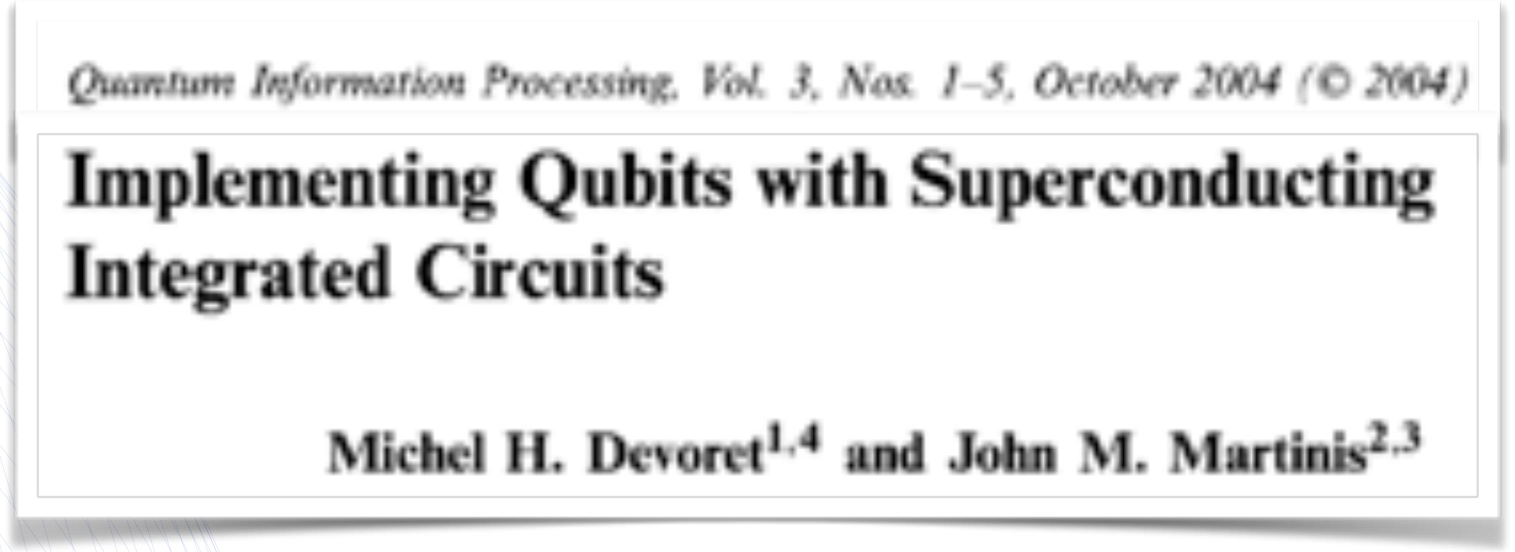



#4 #5



#2 #3

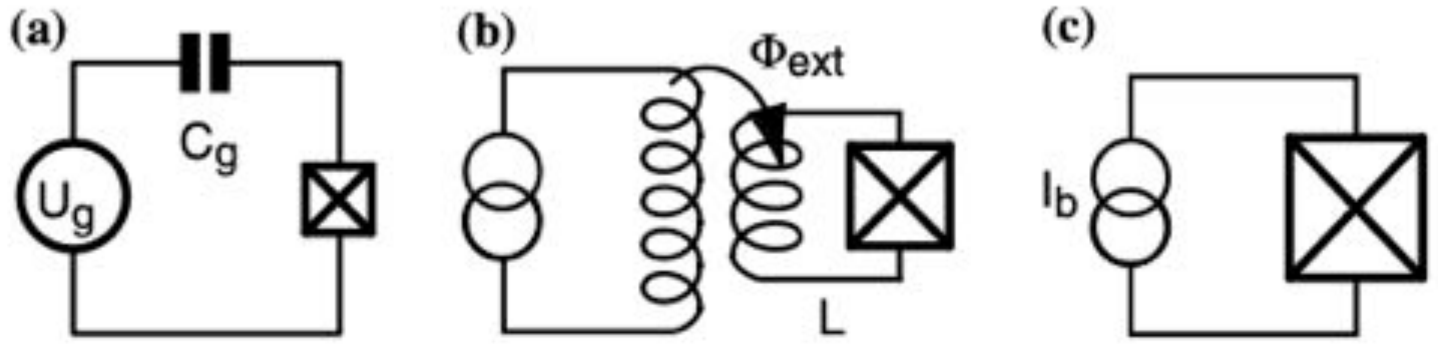



Quantum Information Processing, Vol. 3, Nos. 1–5, October 2004 (© 2004)

**Implementing Qubits with Superconducting Integrated Circuits**

Michel H. Devoret[1,4] and John M. Martinis[2,3]

IQM intel OQC IBM Google




Charge qubit (transmon)

Flux qubit

Phase qubit

rigetti

amazon

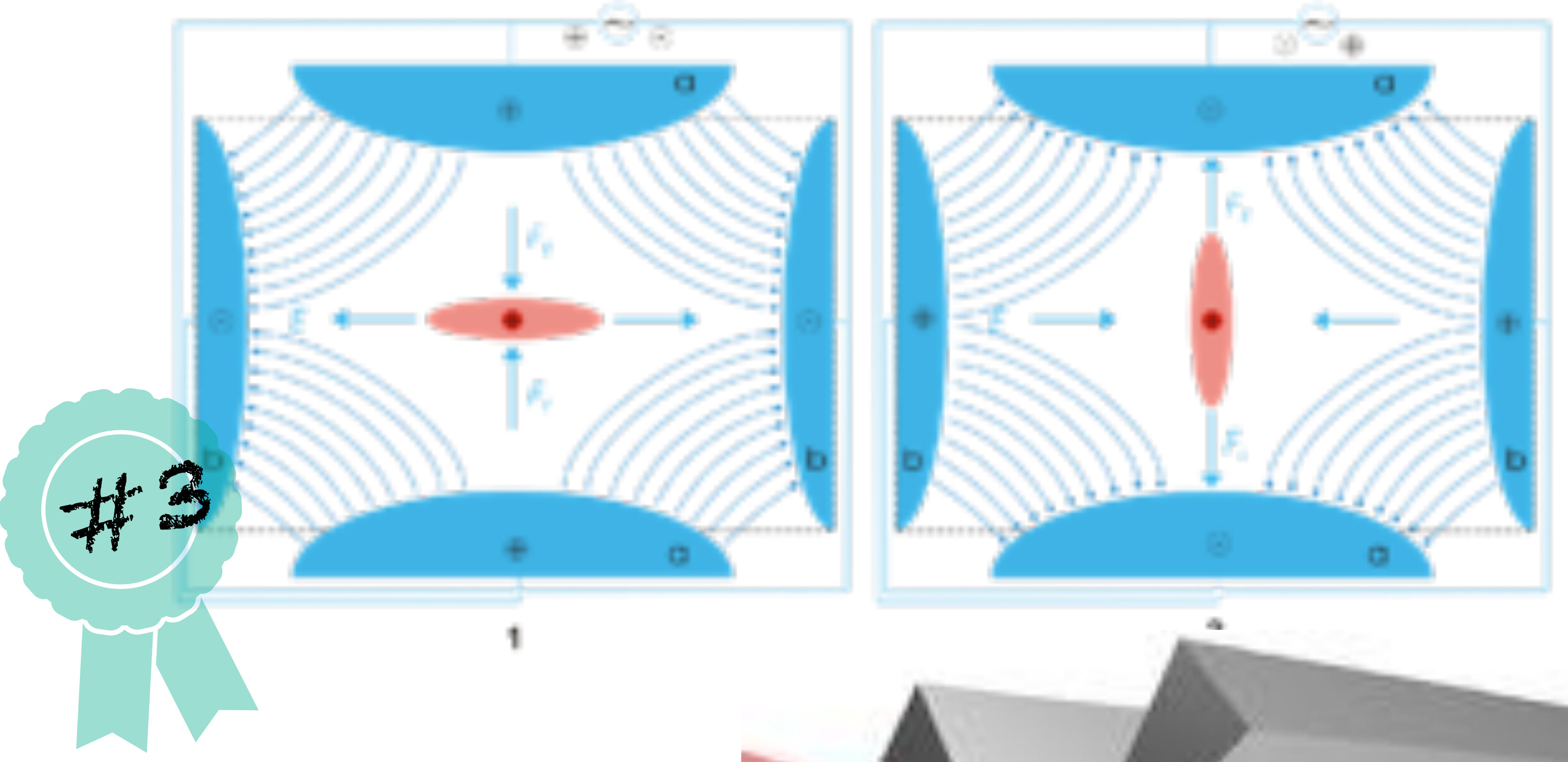
ALICE & BOB

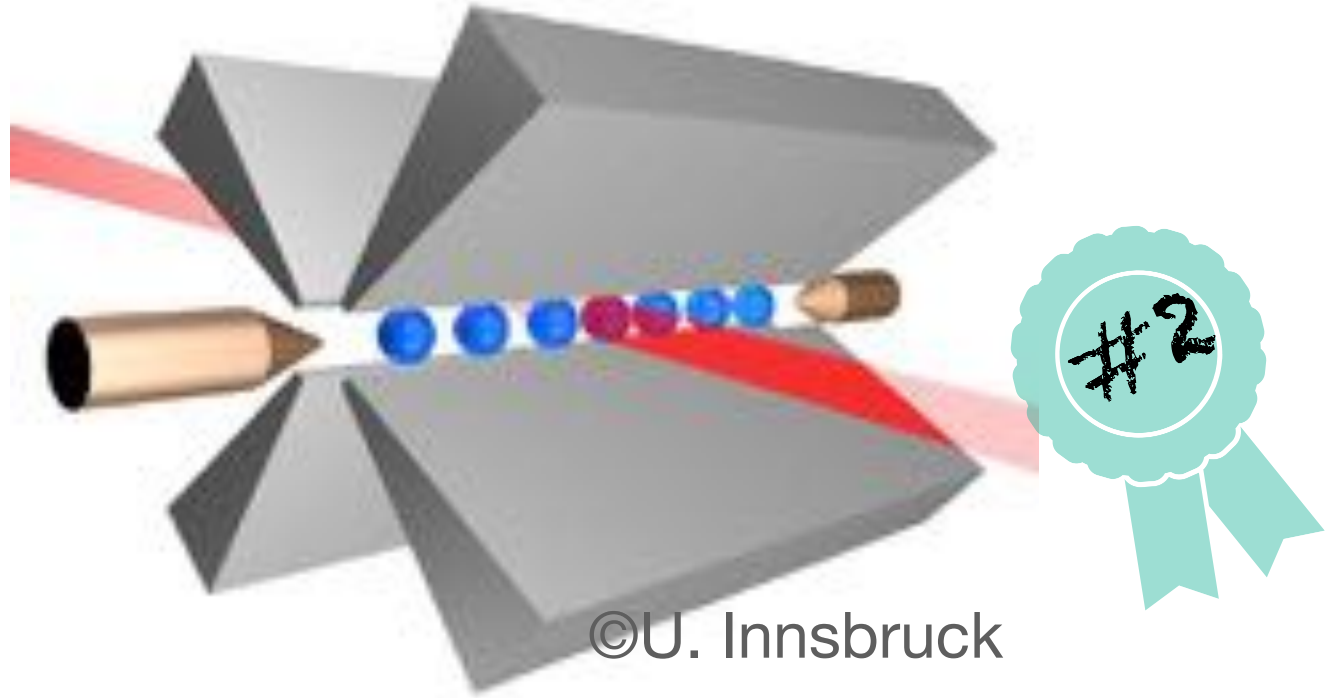
# Superconducting qubits

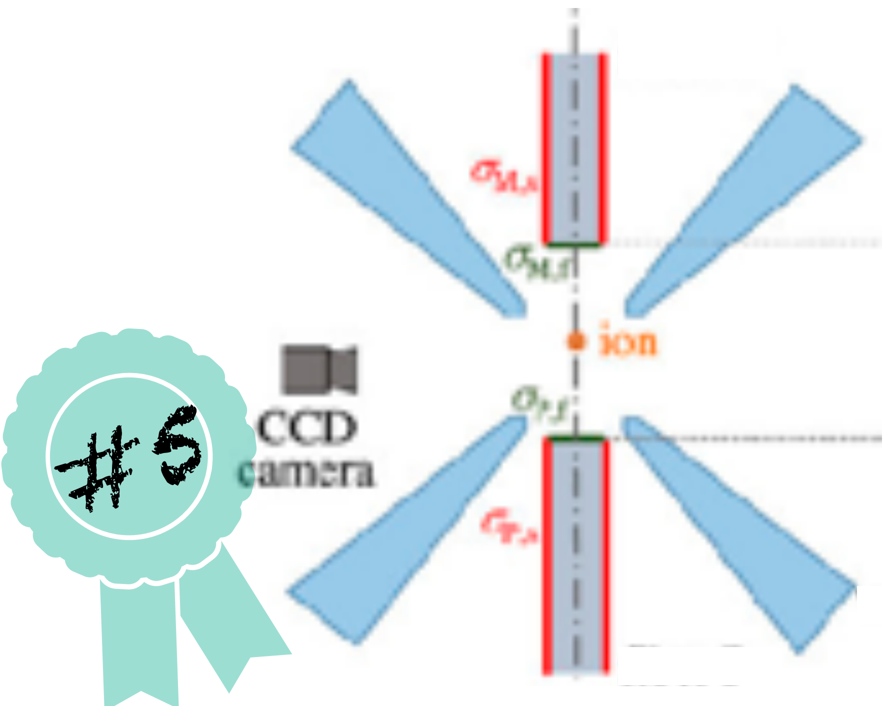
- Electronic
- Several degrees of freedom
- Easy and fast control

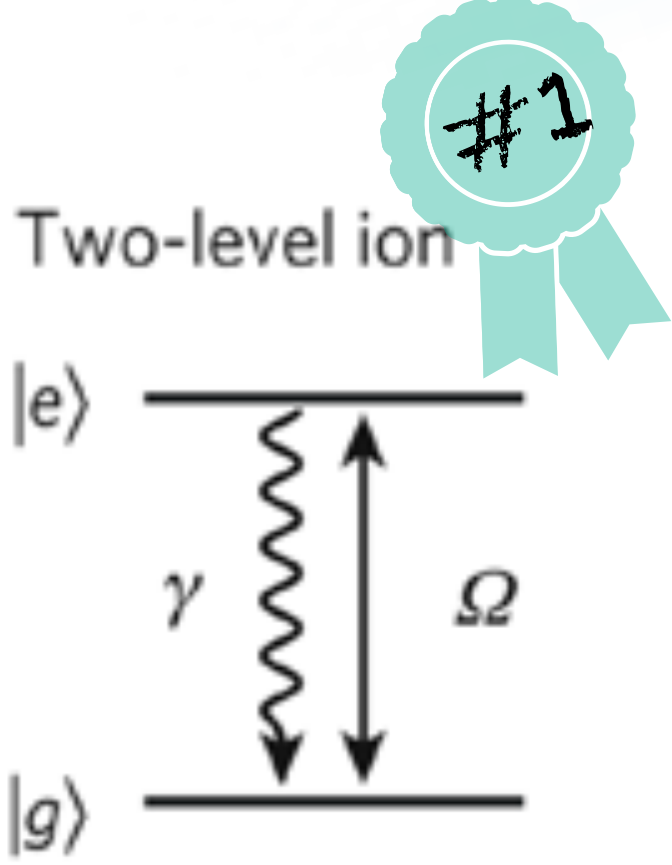
- Cryogeny (~mK)
- Noise
- Decoherence
- Crosstalk
- Wiring and connectivity

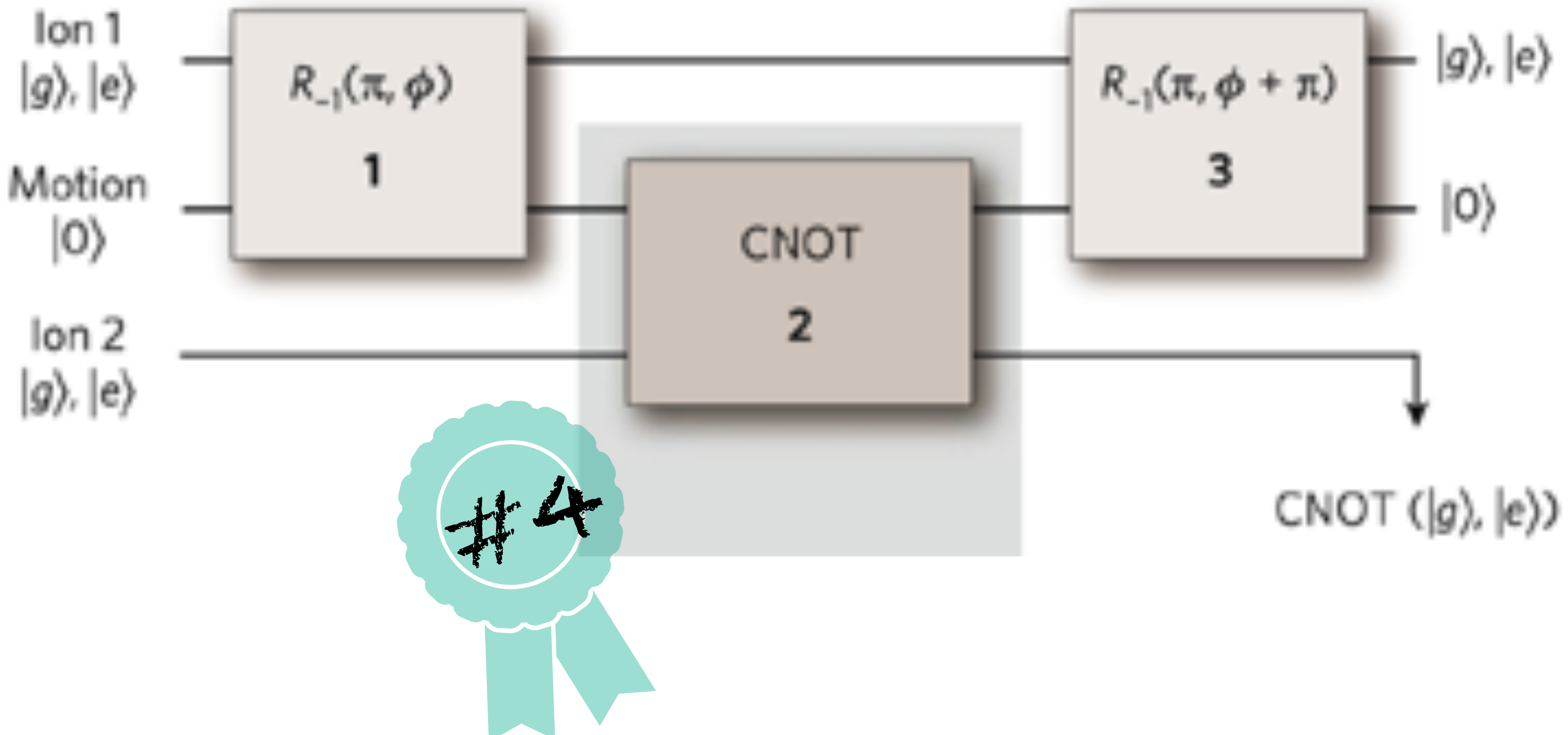
# Trapped ions





VOLUME 74, NUMBER 20 PHYSICAL REVIEW LETTERS 15 MAY 1995


**Quantum Computations with Cold Trapped Ions**


J. I. Cirac and P. Zoller*
*Institut für Theoretische Physik, Universität Innsbruck, Technikerstrasse 25, A-6020 Innsbruck, Austria*



(Received 30 November 1994)


AQT

IONQ

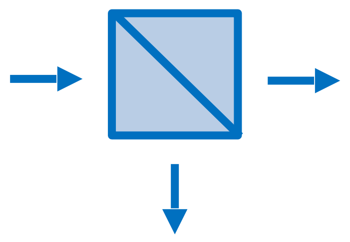
QUANTINUUM

# Trapped ions

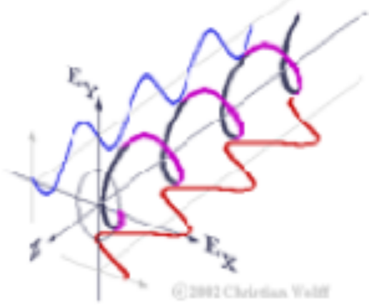
- Long coherence
- Connectivity
- 4K to room temperature

- Scalability (1D structure)
- Size
- Operation time

# Photons



Path



Polarisation

OAM

$\sqrt{p_0}|0_a\rangle + \sqrt{p_1}e^{i\alpha_1}|1_a\rangle$

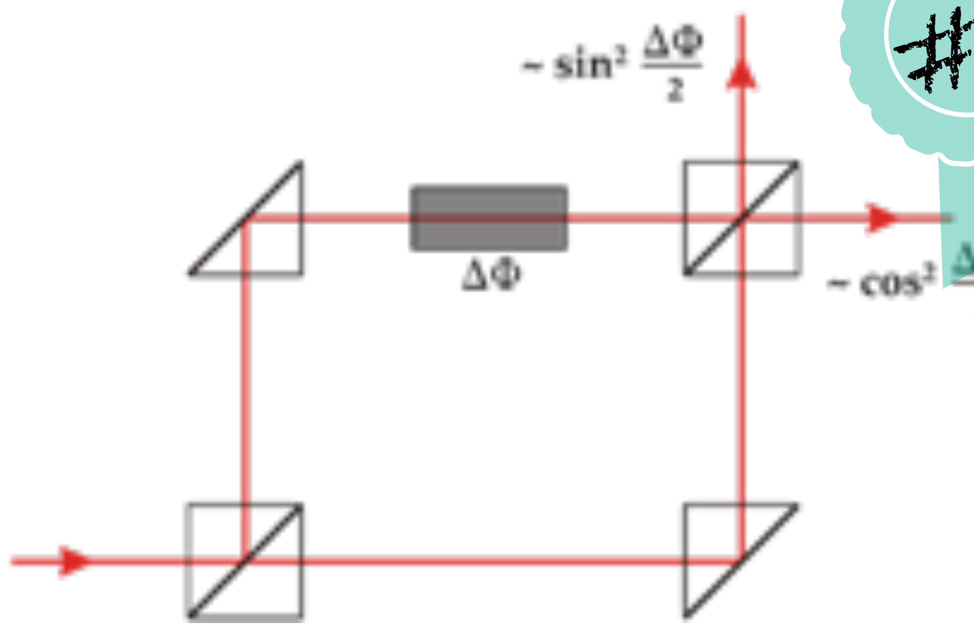
Photon number

…

#1

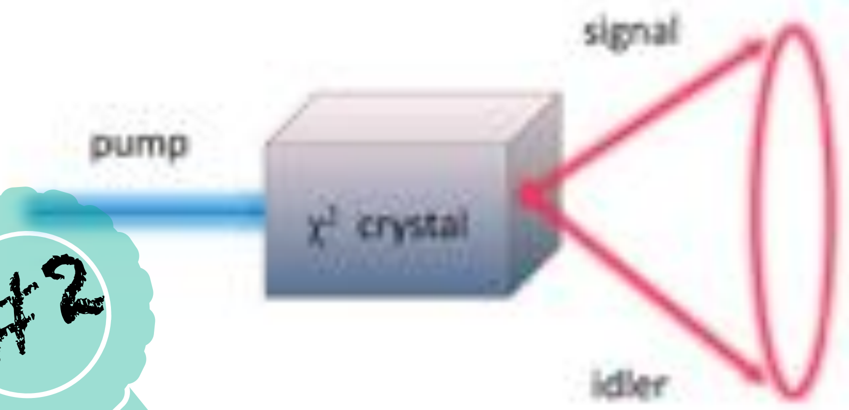
No decoherence

#3




#4

#2




**A scheme for efficient quantum computation with linear optics**

E. Knill, R. Laflamme & G. J. Milburn

*Nature* 409, 46–52 (2001) | Cite this article

38k Accesses | 4127 Citations | 57 Altmetric | Metrics

#5

©Scontel

**DISCRETE VARIABLE**

Ψ PsiQuantum

QUIX QUANTUM

ORCA Computing

**CONTINUOUS VARIABLE**

XANADU

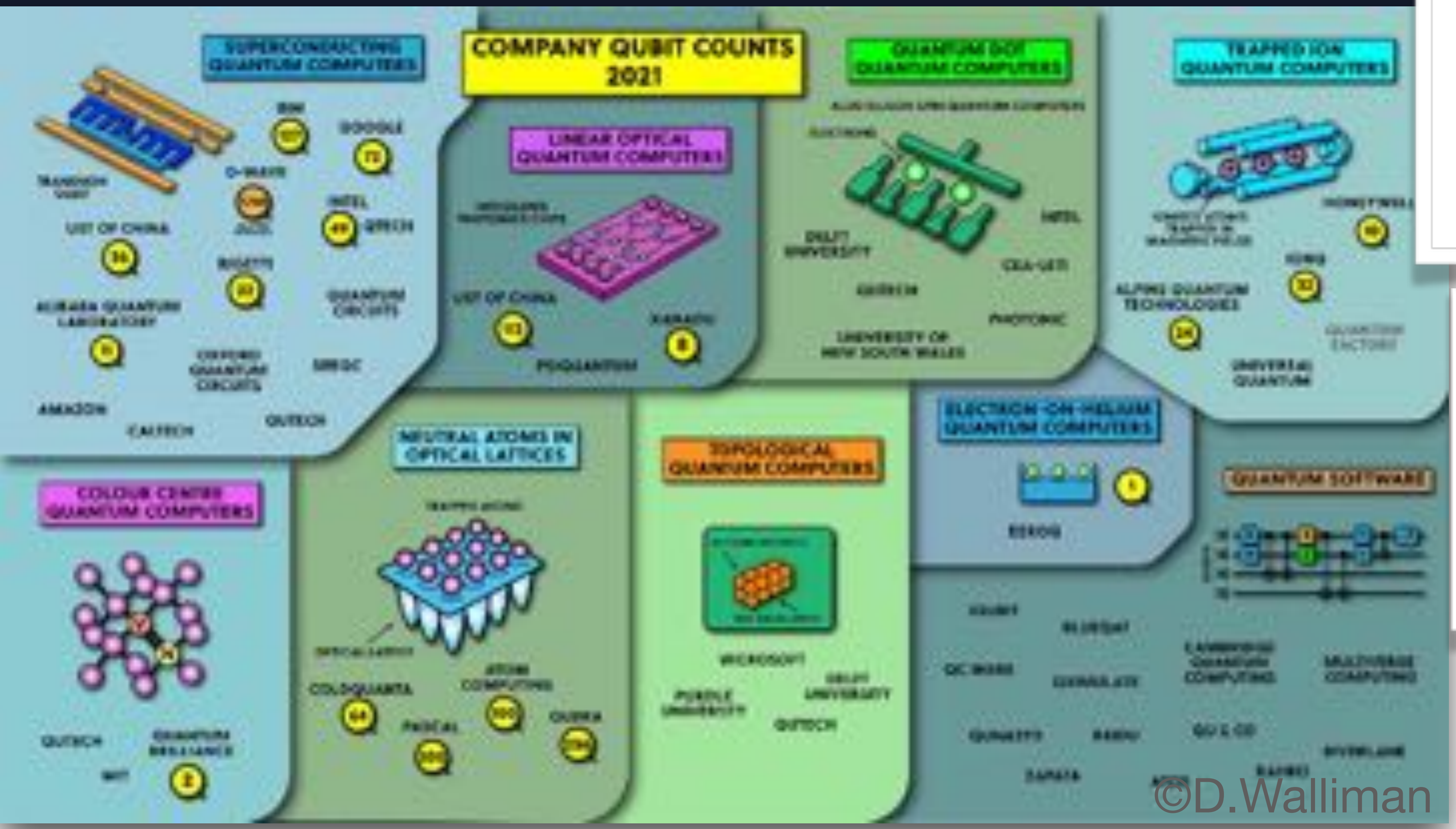
# Photons

- Long coherence
- Connectivity
- 4K to room temperature
- Connection with network
- Single-qubit gates

- Photon loss
- Source efficiency
- Two-qubit gates

# Several platforms, many actors

# Benchmarking




NUMBER OF QUBITS

Assessing the quality of near-term photonic quantum devices


Rawad Mezher and Shane Mansfield

Quandela SAS, 7 Rue Léonard de Vinci, 91300 Massy, France


Characterizing quantum supremacy in near-term devices


Sergio Boixo, Sergei V. Isakov, Vadim N. Smelyanskiy, Ryan Babbush, Nan Ding, Zhang Jiang, Michael J. Bremner, John M. Martinis & Hartmut Neven



Nature Physics 14, 595–600 (2018) | Cite this article

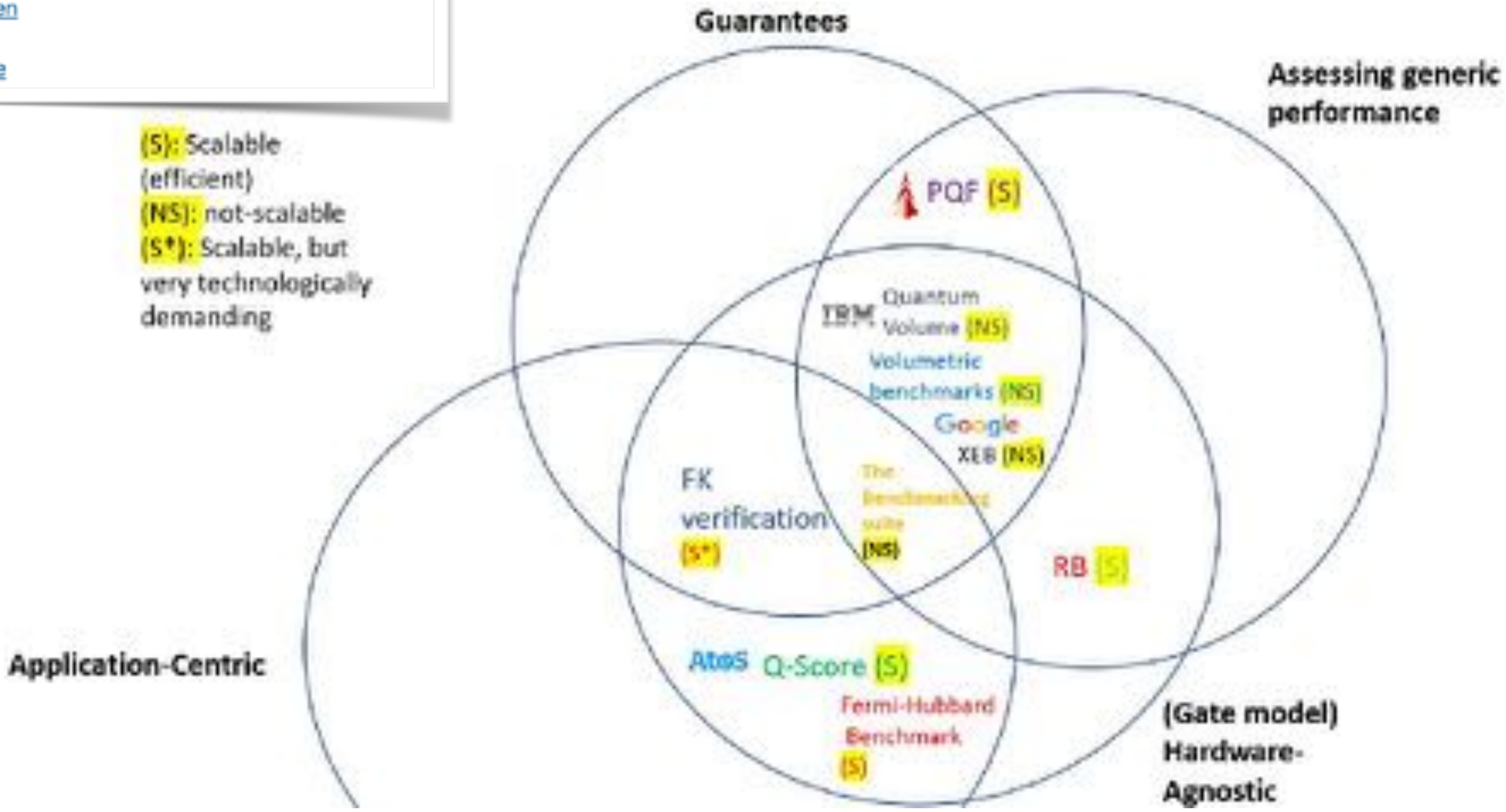


PHYSICAL REVIEW A 100, 032328 (2019)


Validating quantum computers using randomized model circuits

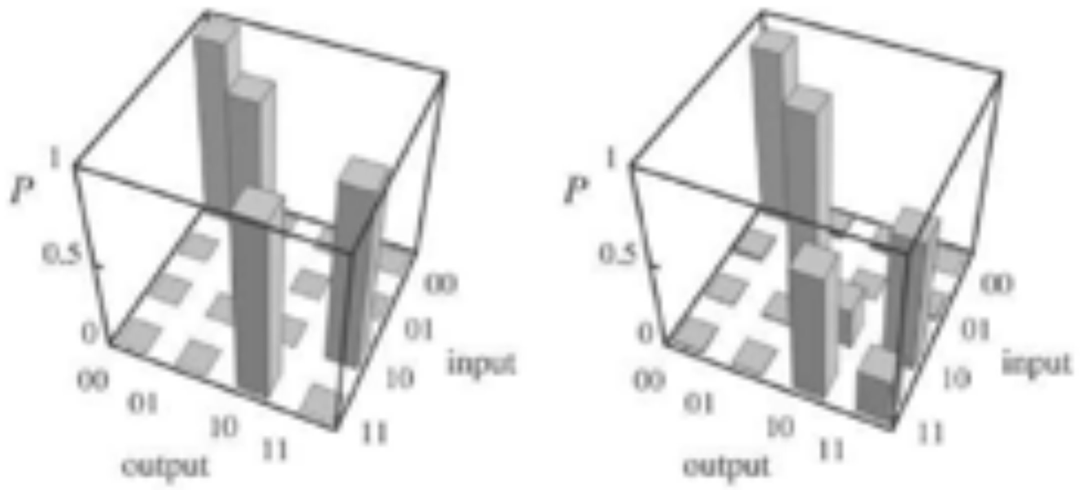

Andrew W. Cross,* Lev S. Bishop,† Sarah Sheldon, Paul D. Nation, and Jay M. Gambetta

IBM T. J. Watson Research Center, Yorktown Heights, New York 10598, USA



CONNECTIVITY



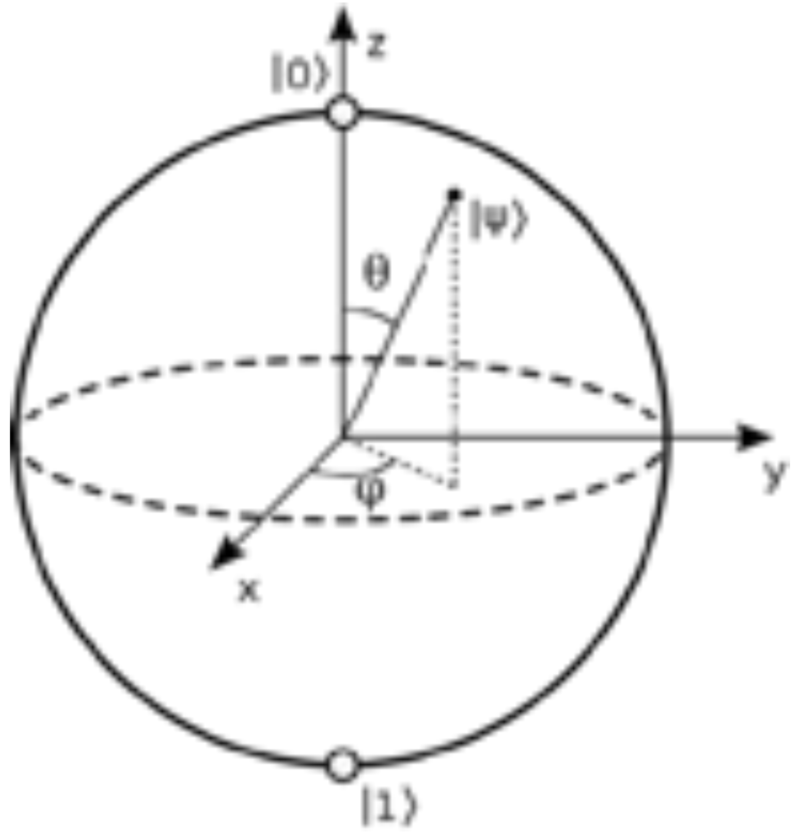

1- AND 2-QUBIT GATE ERROR

METRICS

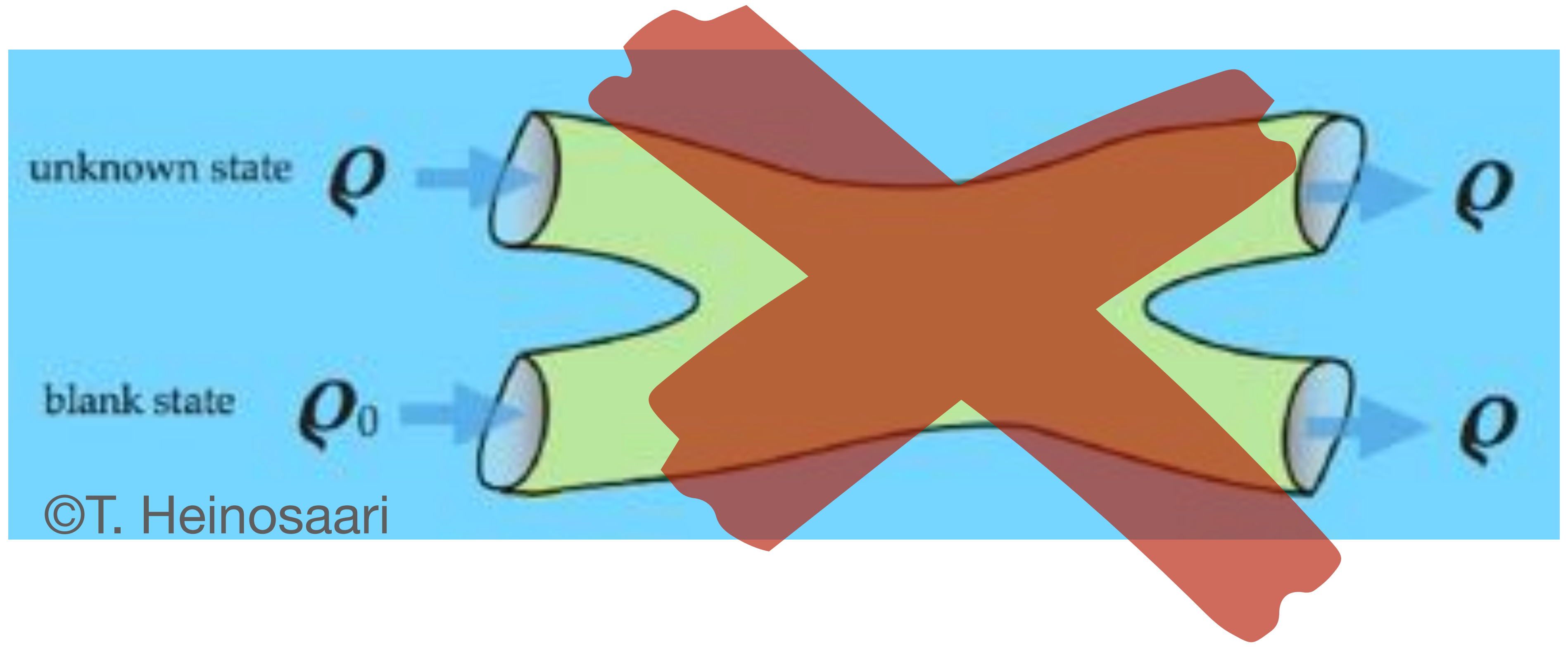
# The issue of errors in quantum computing

## CONTINUOUS ERRORS

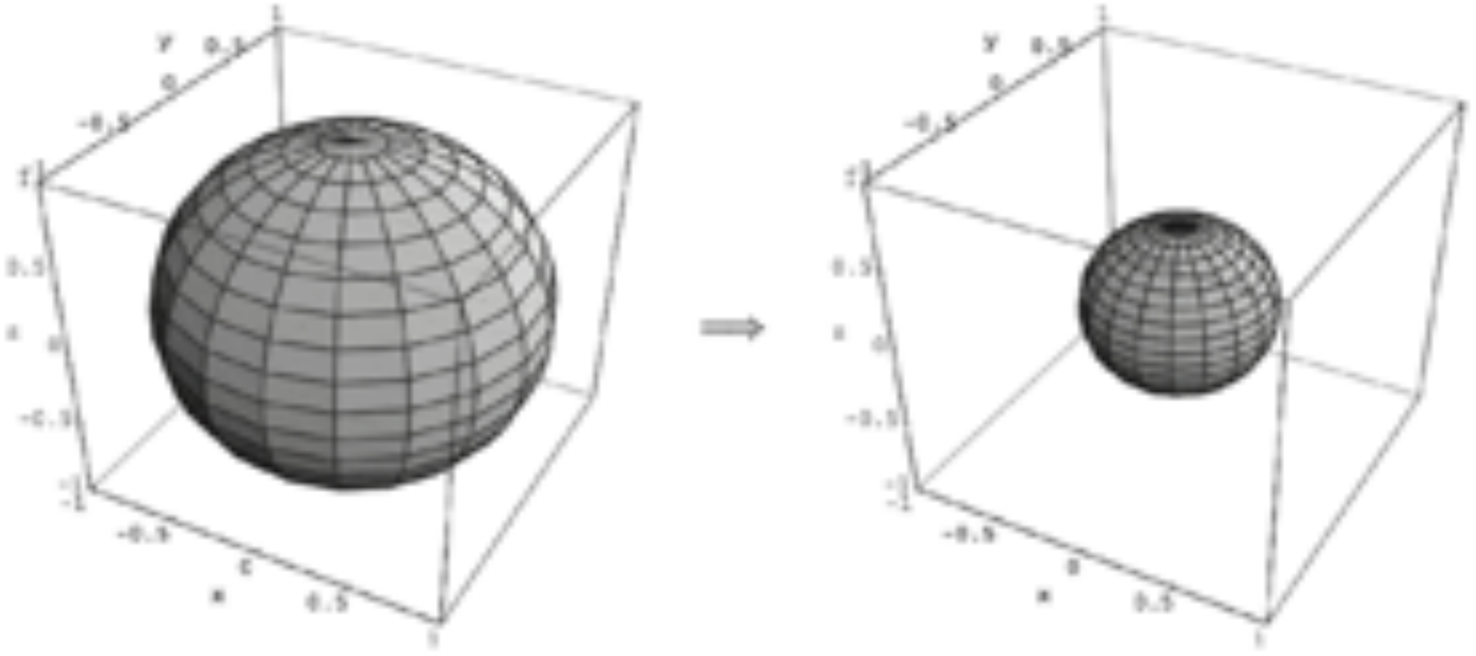
Quantum bit: $\alpha|0\rangle + \beta|1\rangle$



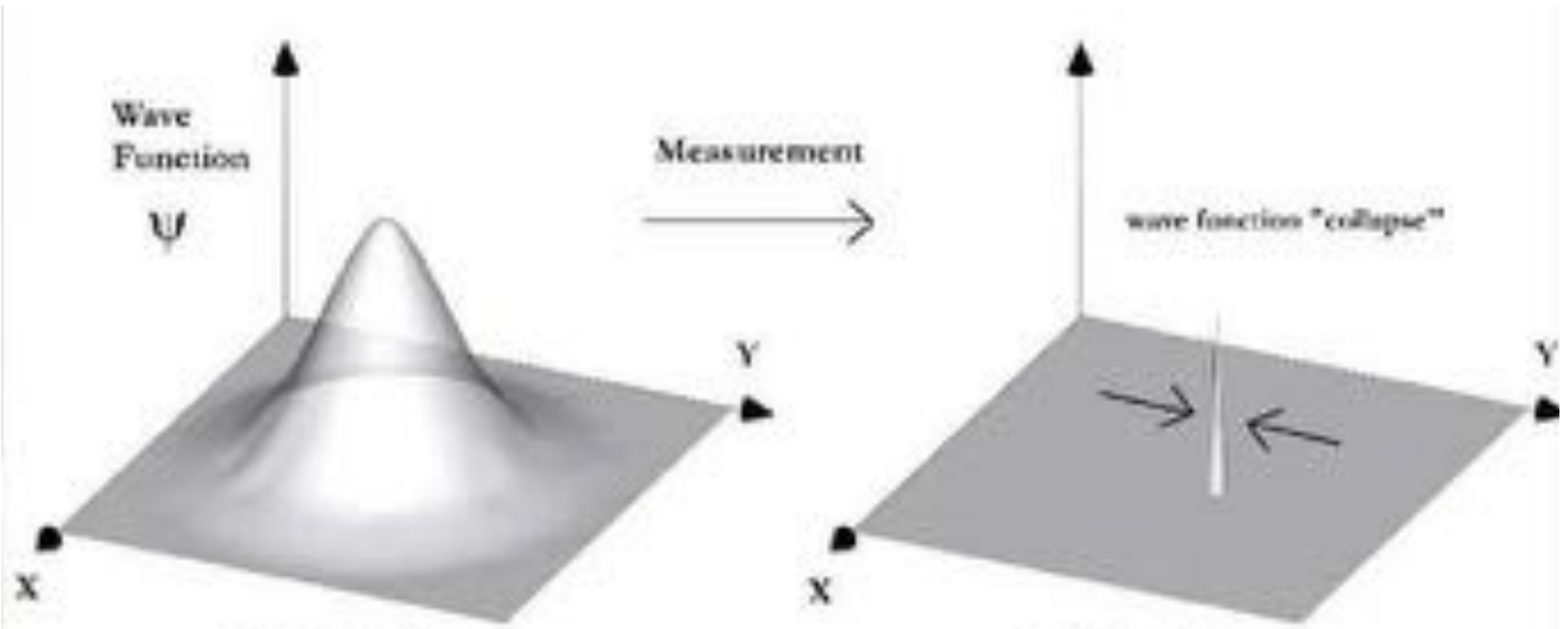

## NO CLONING




## DECOHERENCE

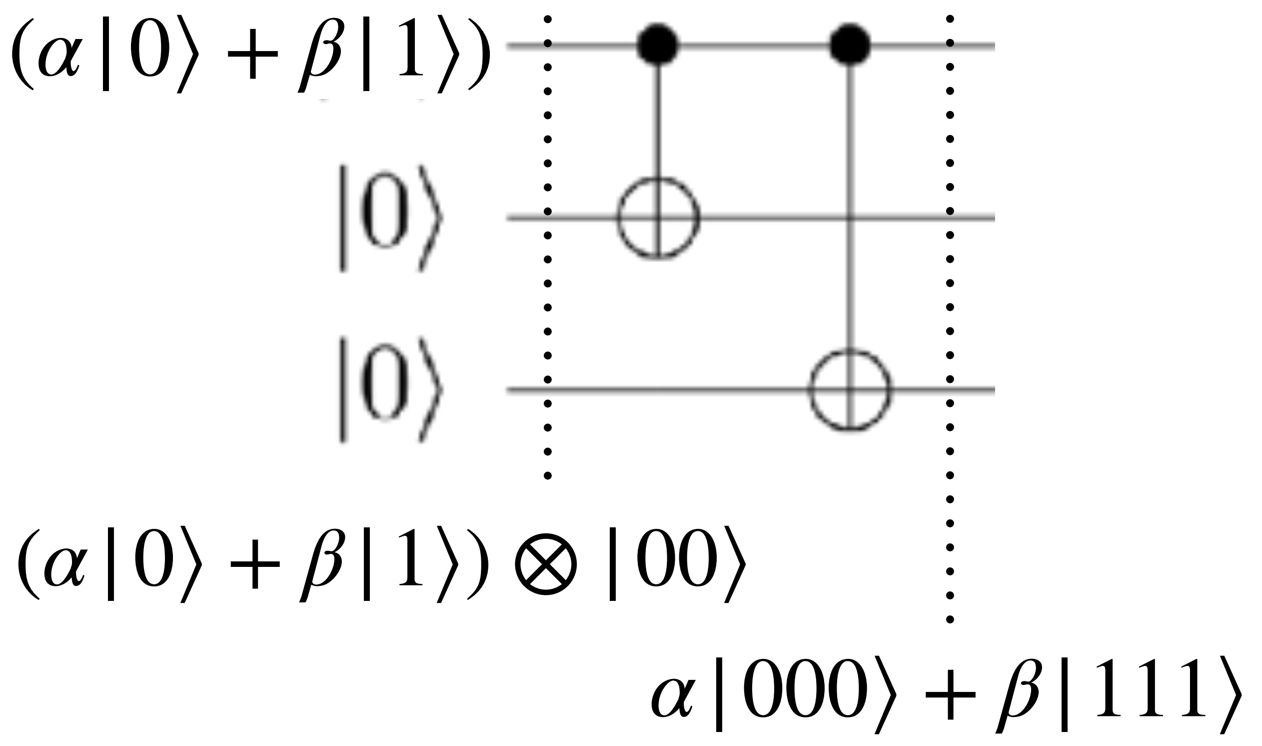


## MEASUREMENT COLLAPSE

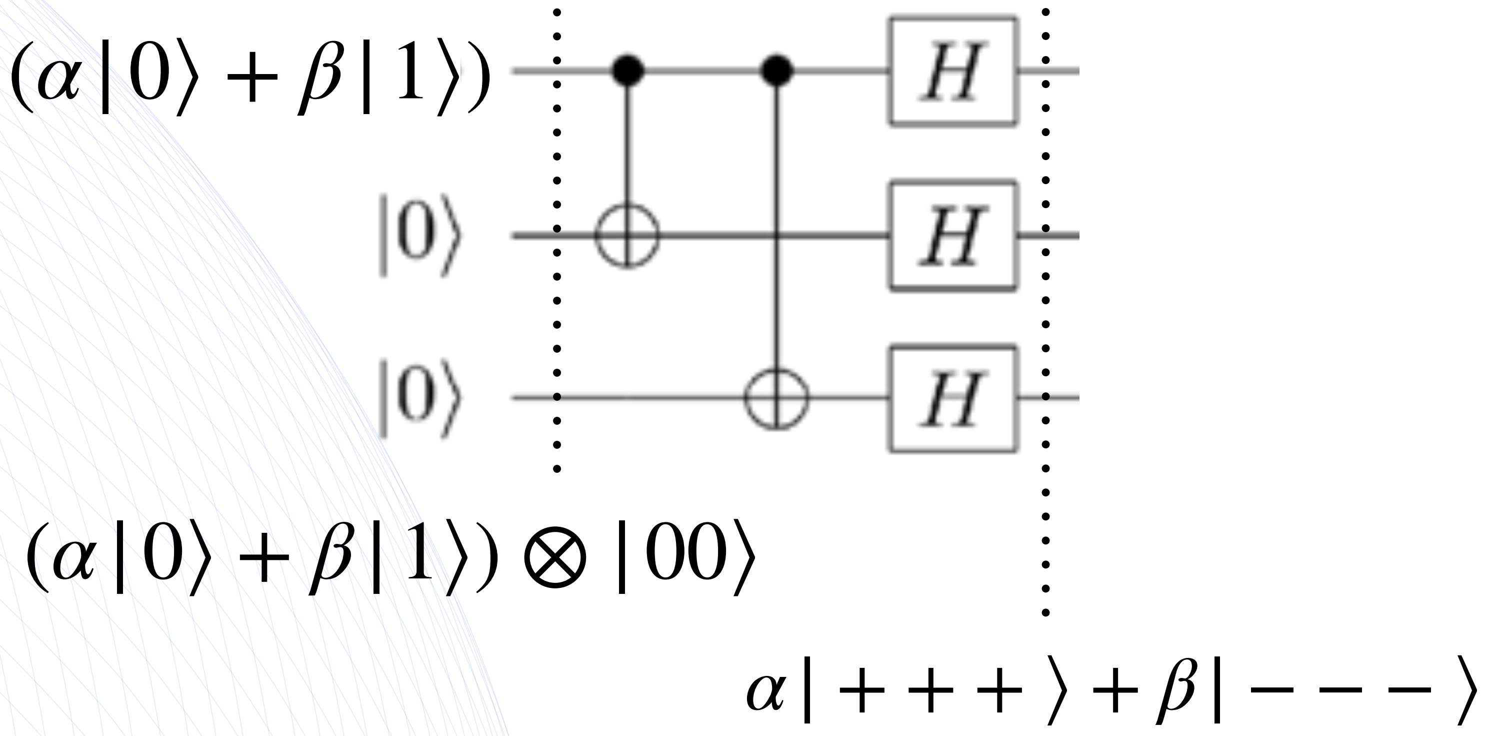


# Long term: Error correction + fault tolerance

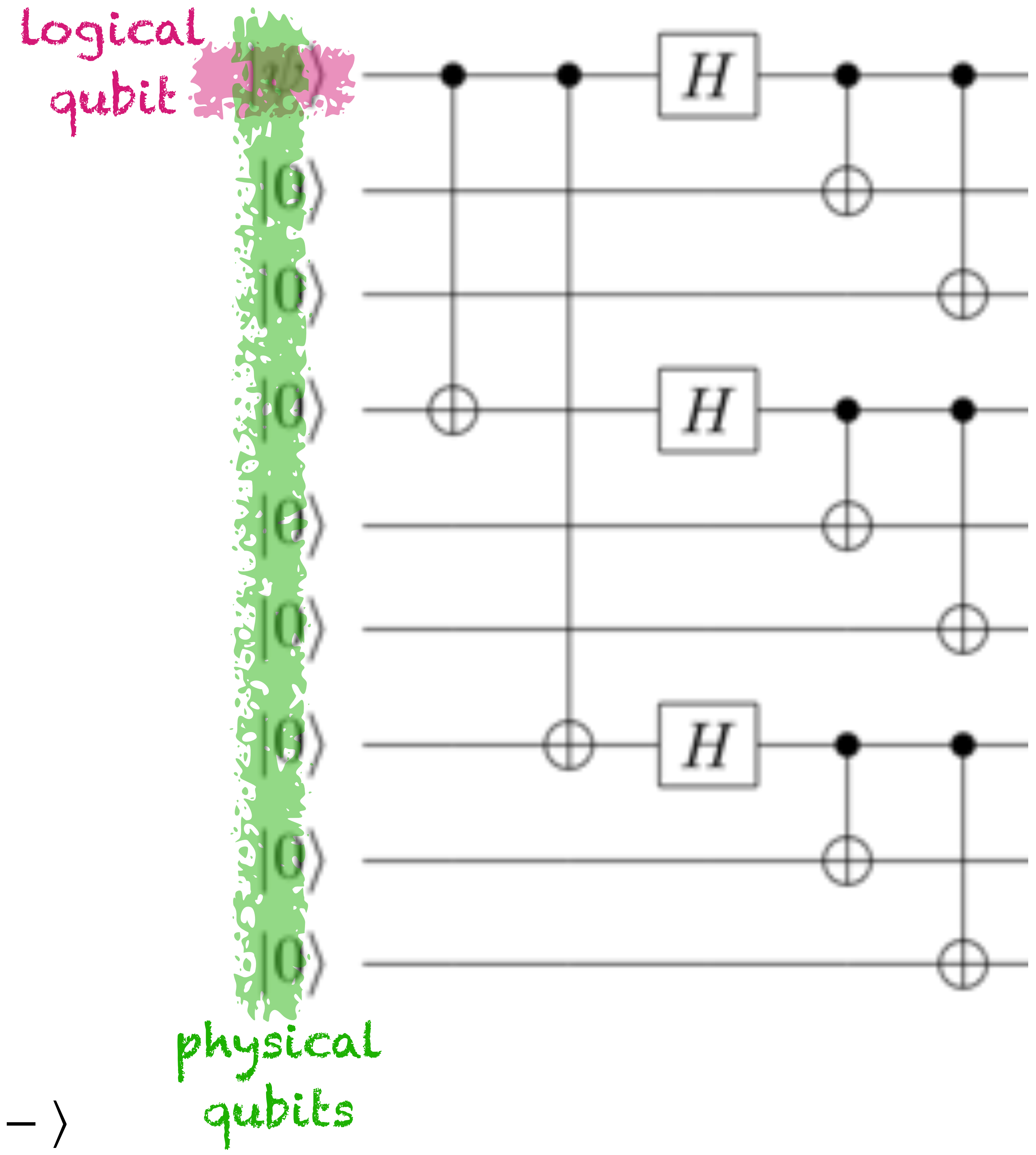
## BIT FLIP



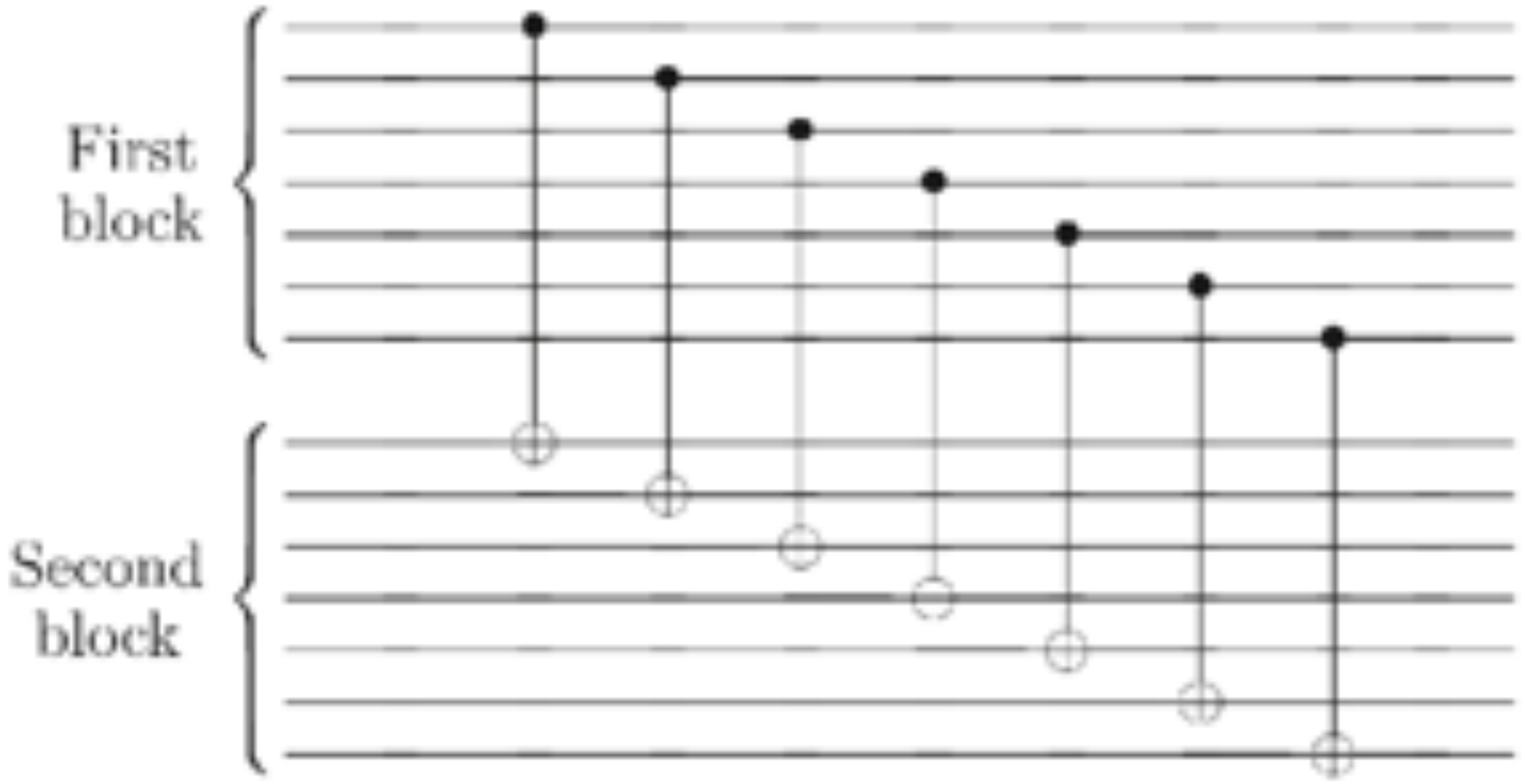

## PHASE FLIP




## BIT+PHASE: SHOR CODE



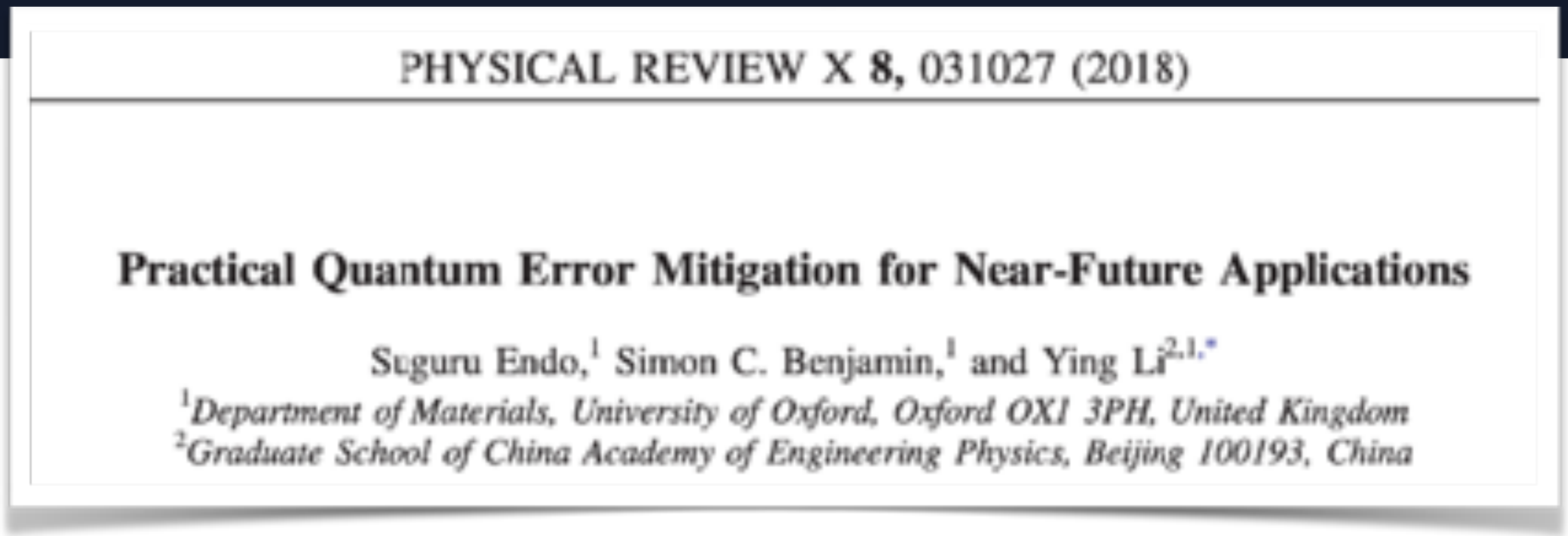

## FAULT-TOLERANCE




## THRESHOLD THEOREM

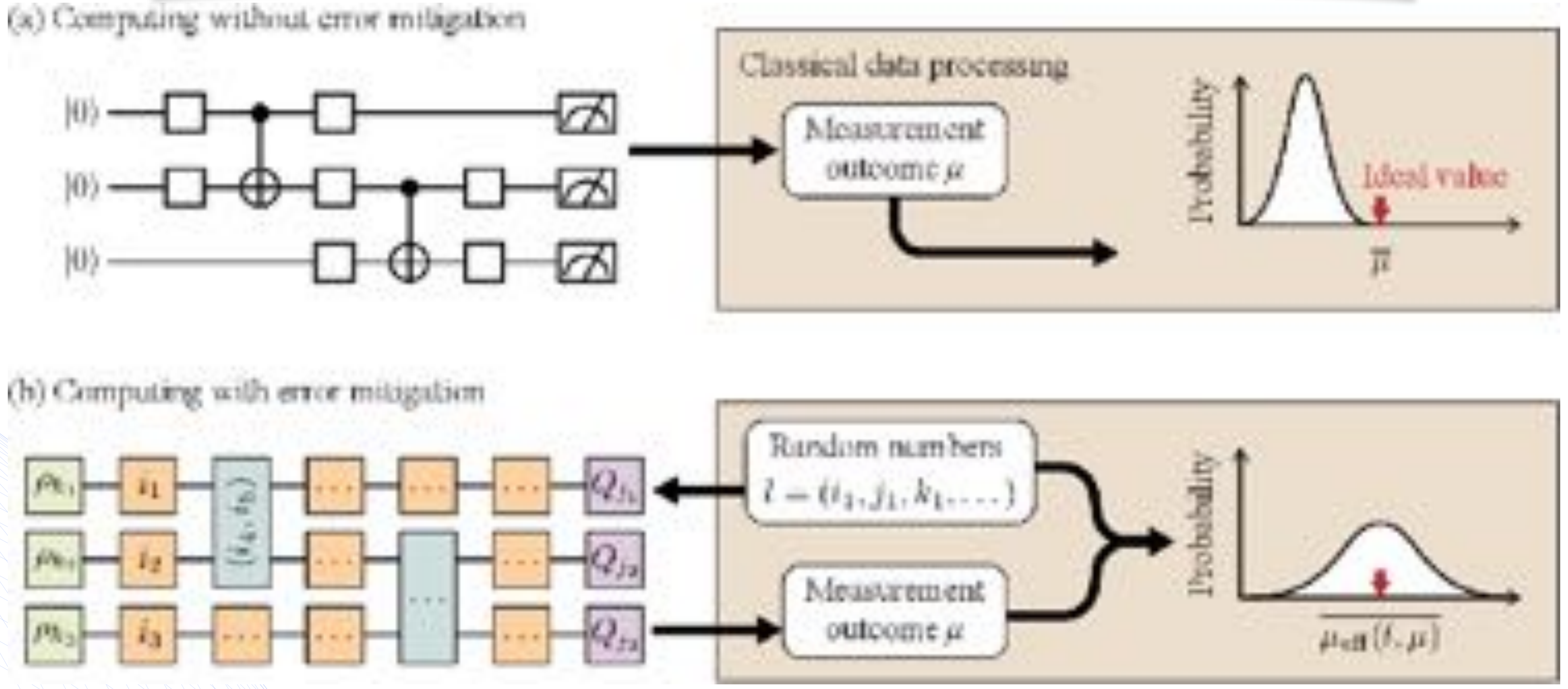
**The threshold theorem**: Provided the noise in individual quantum gates is below a certain constant threshold and obeys certain physically reasonable assumptions, it is possible to reliably perform an arbitrarily long quantum computation, with only a small overhead in the size of the circuit necessary to ensure reliability.

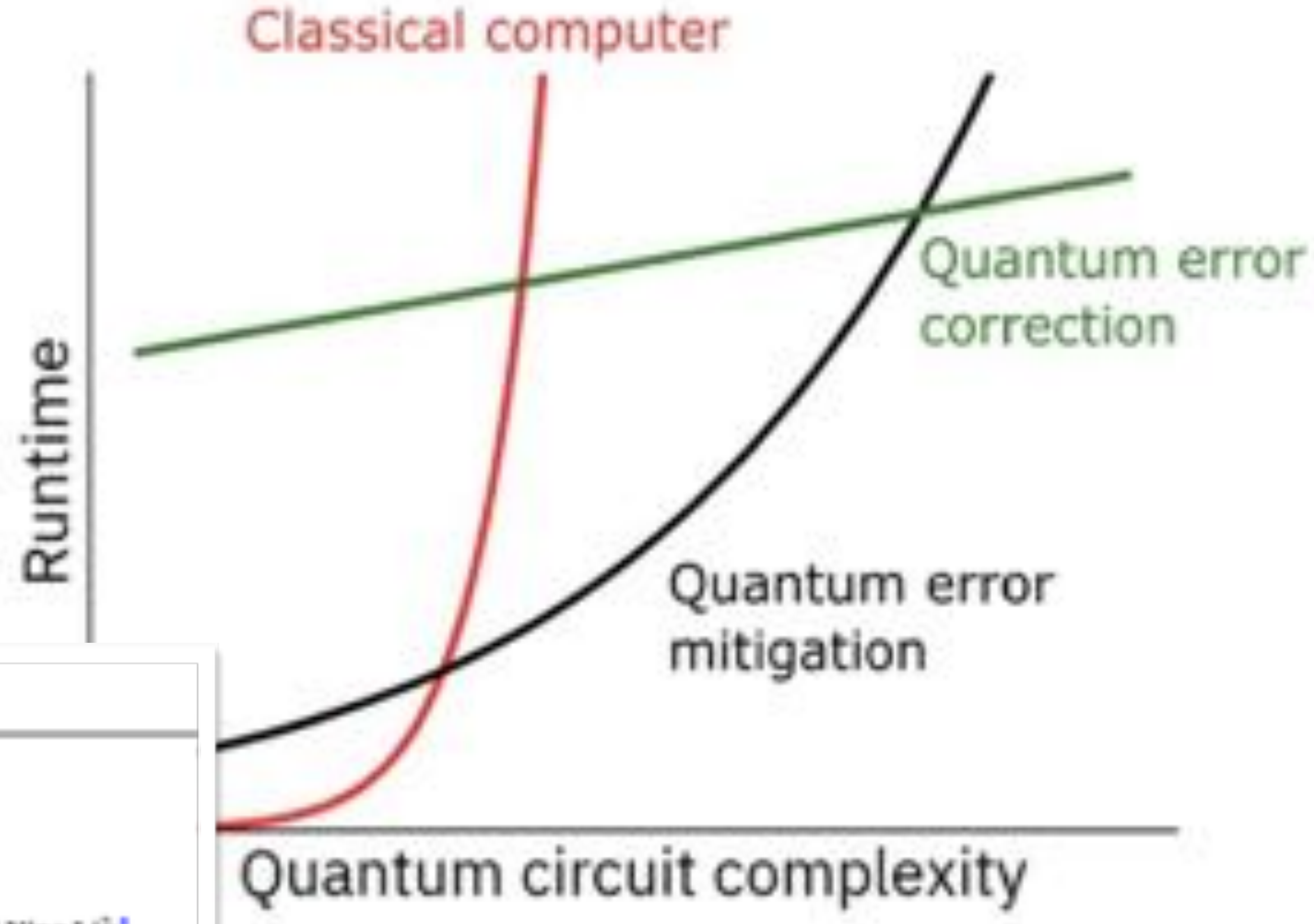
# Short term: Error mitigation

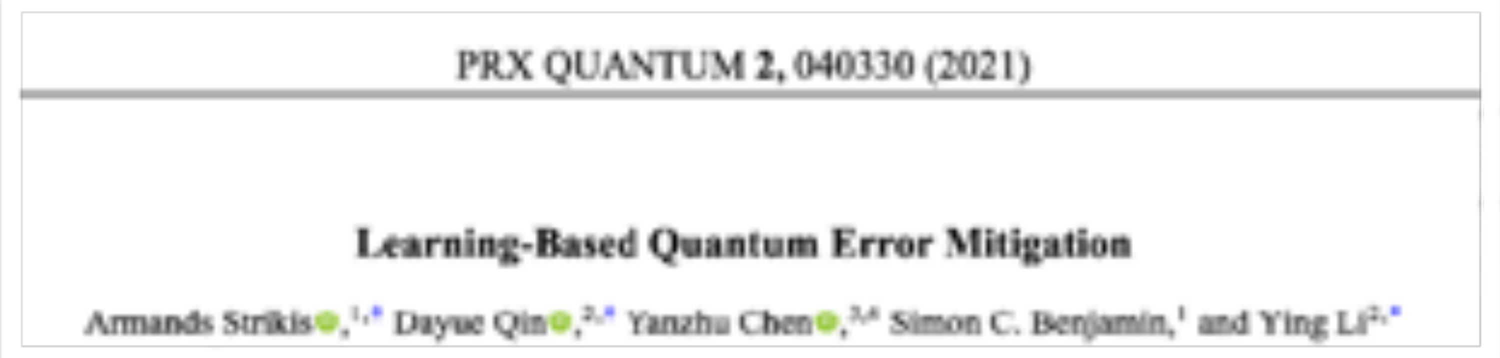

PHYSICAL REVIEW X **8**, 031027 (2018)

**Practical Quantum Error Mitigation for Near-Future Applications**

Suguru Endo,[1] Simon C. Benjamin,[1] and Ying Li[2,1,*]
[1]*Department of Materials, University of Oxford, Oxford OX1 3PH, United Kingdom*
[2]*Graduate School of China Academy of Engineering Physics, Beijing 100193, China*

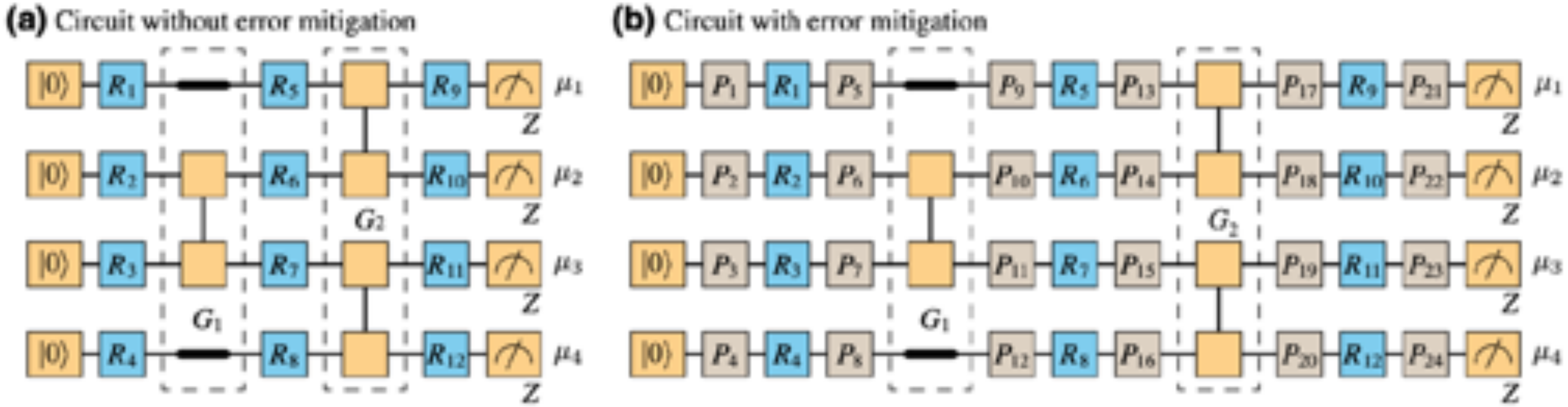




PRX QUANTUM **2**, 040330 (2021)

**Learning-Based Quantum Error Mitigation**

Armands Strikis,[1,*] Dayue Qin,[2,*] Yanzhu Chen,[3,4] Simon C. Benjamin,[1] and Ying Li[2,*]



# Quantum computational advantage

**QUANTUM COMPUTING AND THE ENTANGLEMENT FRONTIER**

JOHN PRESKILL

*« …characterize computational tasks performable by quantum devices, where one could argue persuasively that no existing (or easily foreseeable) classical device could perform the same task, disregarding whether the task is useful in any other respect. »*

## Quantum Computing in the NISQ era and beyond

John Preskill

Institute for Quantum Information and Matter and Walter Burke Institute for Theoretical Physics, California Institute of Technology, Pasadena CA 91125, USA

30 July 2018

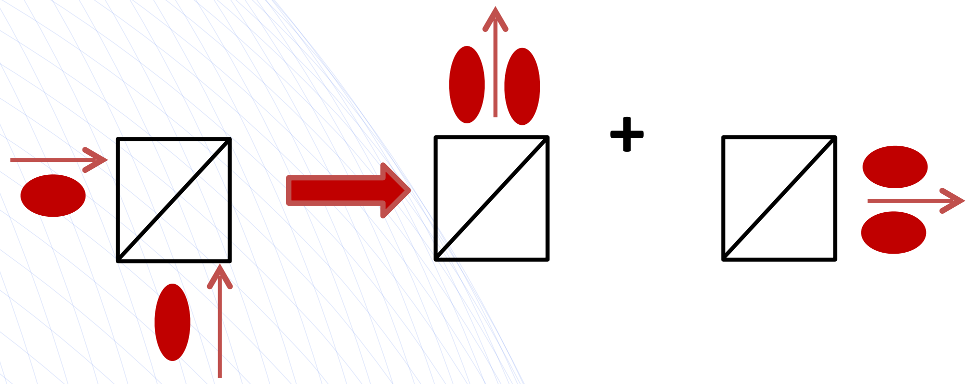
## Quantum supremacy using a programmable superconducting processor

Frank Arute, Kunal Arya, Ryan Babbush, Dave Bacon, Joseph C. Bardin, Rami Barends, Rupak Biswas, Sergio Boixo, Fernando G. S. L. Brandao, David A. Buel, Brian Burkett, Yu Chen, Zijun Chen, Ben Chiaro, Roberto Collins, William Courtney, Andrew Dunsworth, Edward Farhi, Brooks Foxen, Austin Fowler, Craig Gidney, Marissa Giustina, Rob Graff, Keith Guerin, … John M. Martinis + Show authors

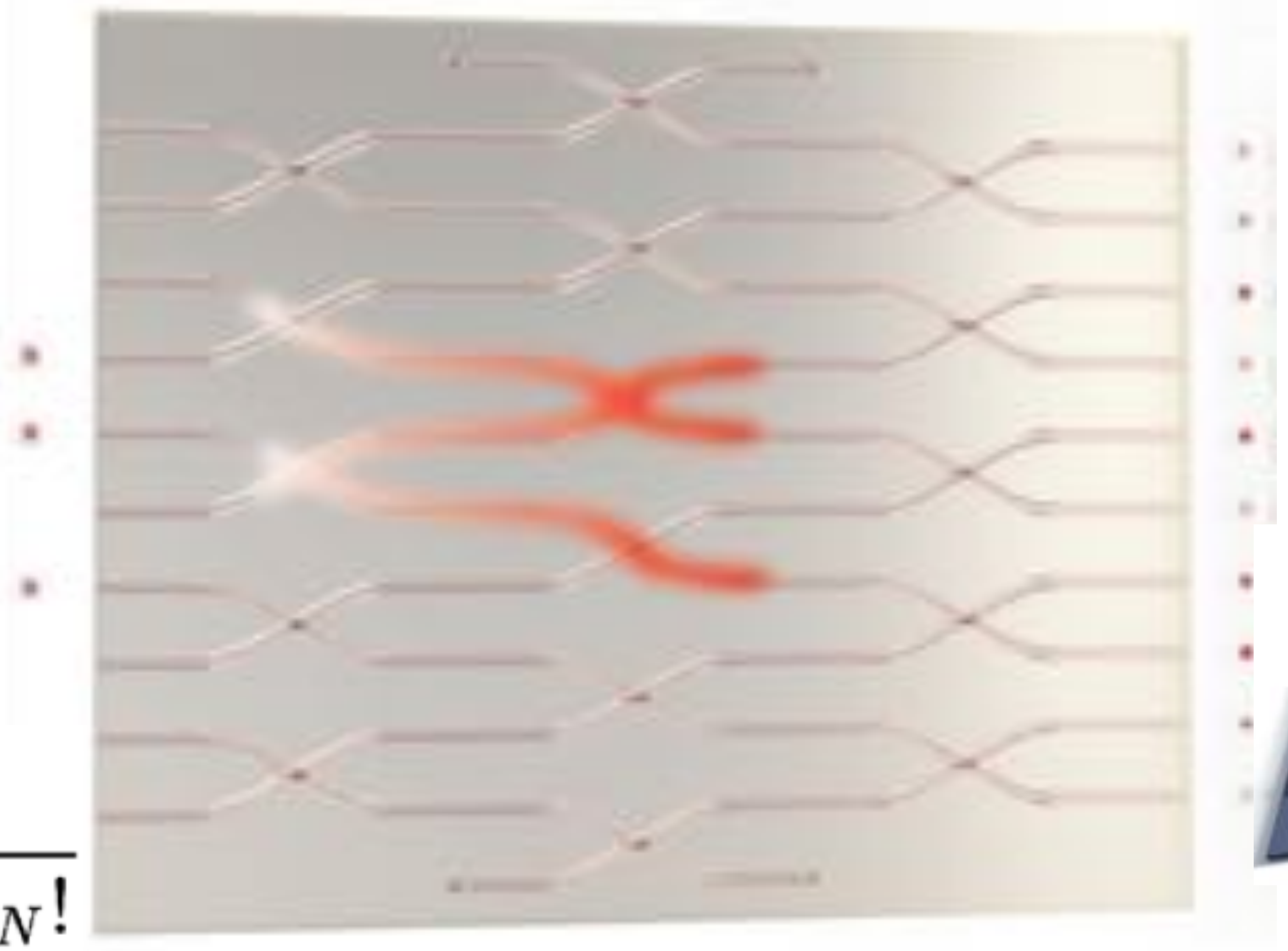
Nature 574, 505–510 (2019) | Cite this article



$$\hat{U}_{\mathrm{BS}}(\theta,\phi) = \begin{array}{c} \\ \langle 1,0| \\ \langle 0,1| \end{array} \begin{array}{cc} |1,0\rangle & |0,1\rangle \\ \left(\begin{array}{c} \cos(\theta) \\ ie^{i\phi}\sin(\theta) \end{array}\right. & \left.\begin{array}{c} ie^{-i\phi}\sin(\theta) \\ \cos(\theta) \end{array}\right) \end{array}$$



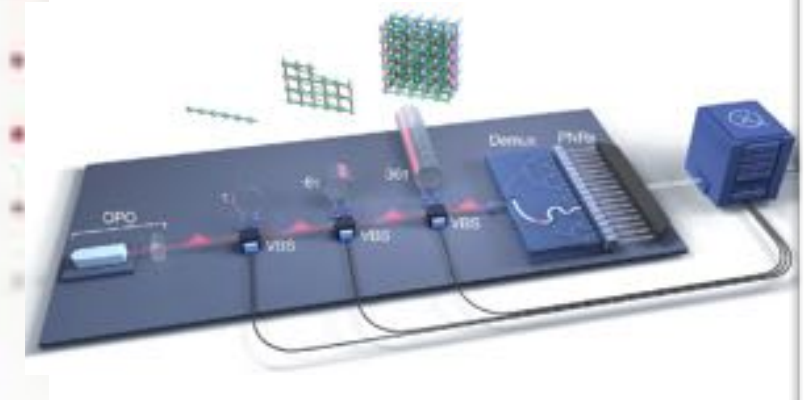

$$p(t_1, t_2, \ldots, t_N) = \frac{|\mathrm{Perm}\, U_{S,T}|^2}{t_1! \cdots t_N! s_1! \cdots s_N!}$$



## Quantum computational advantage using photons

HAN-SEN ZHONG, HUI WANG, YU-HAO DENG, MING-CHENG CHEN, LI-CHAO PENG, YI-HAN LUO, JIAN QIN, DIAN WU, XING DING, YI HU, PENG HU, XIAO-YAN YANG, WEI-JUN ZHANG, HAO LI, YUXUAN LI, XIAO JIANG, LIN GAN, GUANGWEN YANG, LIXING YOU, ZHEN WANG, LI LI, NAI-LE LIU, CHAO-YANG LU, AND JIAN-WEI PAN fewer Authors Info & Affiliations

SCIENCE • 3 Dec 2020 • Vol 370, Issue 6523 • pp. 1460-1463 • DOI: 10.1126/science.abe8770



## Quantum computational advantage with a programmable photonic processor

Lars S. Madsen, Fabian Laudenbach, Mohsen Falamarzi. Askarani, Fabien Rortais, Trevor Vincent, Jacob F. F. Bulmer, Filippo M. Miatto, Leonhard Neuhaus, Lukas G. Helt, Matthew J. Collins, Adriana E. Lita, Thomas Gerrits, Sae Woo Nam, Varun D. Vaidya, Matteo Menotti, Ish Dhand, Zachary Vernon, Nicolás Quesada & Jonathan Lavoie

Nature 606, 75–81 (2022) | Cite this article

# Applications

SIAM J. COMPUT. Vol. 26, No. 5, pp. 1484–1509, October 1997
© 1997 Society for Industrial and Applied Mathematics 009

POLYNOMIAL-TIME ALGORITHMS FOR PRIME FACTORIZATION AND DISCRETE LOGARITHMS ON A QUANTUM COMPUTER*

PETER W. SHOR†

Factorisation with exponential speedup

A fast quantum mechanical algorithm for database search

Author: Lov K. Grover Authors Info & Claims

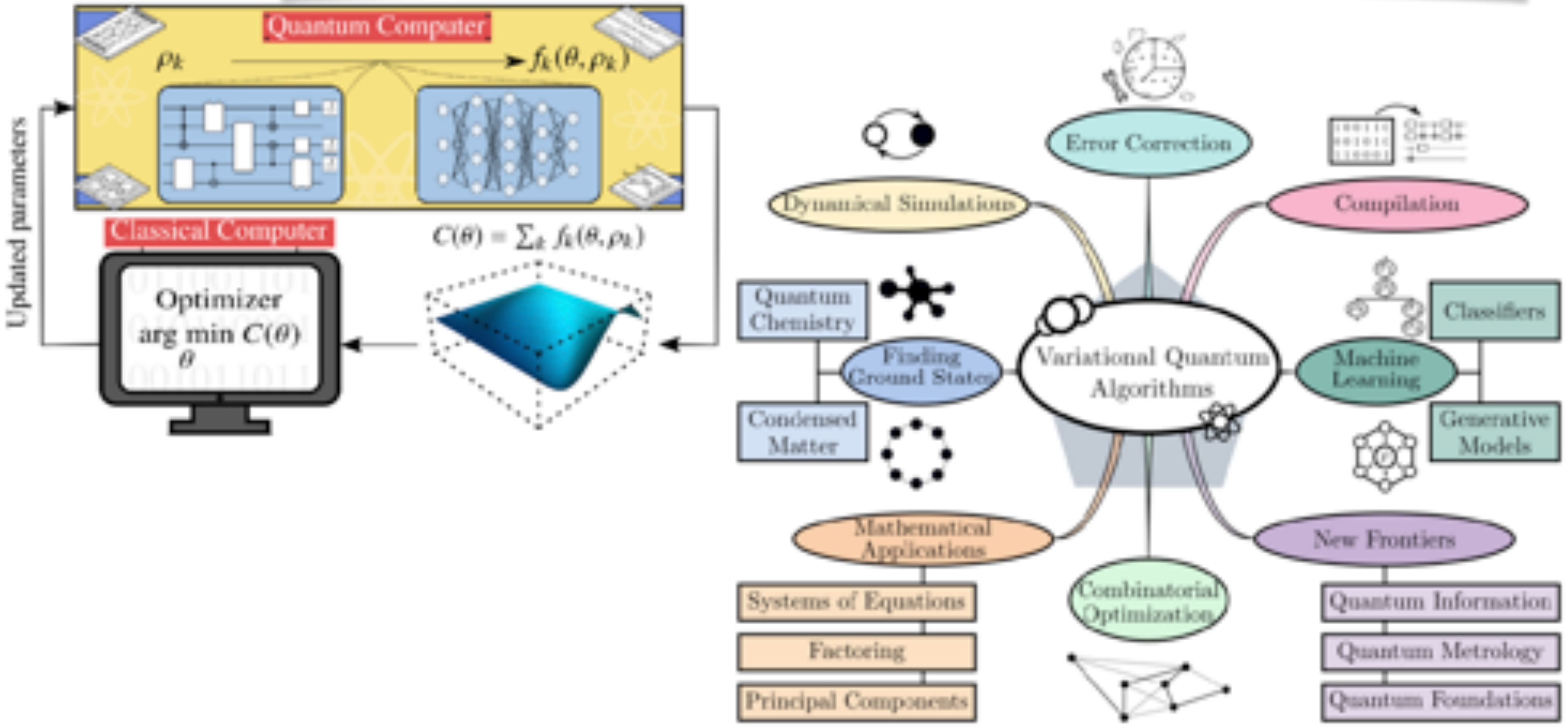
STOC '96: Proceedings of the twenty-eighth annual ACM symposium on Theory of Computing • July 1996 • Pages 212–219 • https://doi.org/10.1145/237814.237866

Unstructured search with quadratic speedup

## Variational quantum algorithms

M. Cerezo, Andrew Arrasmith, Ryan Babbush, Simon C. Benjamin, Suguru Endo, Keisuke Fujii, Jarrod R. McClean, Kosuke Mitarai, Xiao Yuan, Lukasz Cincio & Patrick J. Coles

*Nature Reviews Physics* 3, 625–644 (2021) | Cite this article



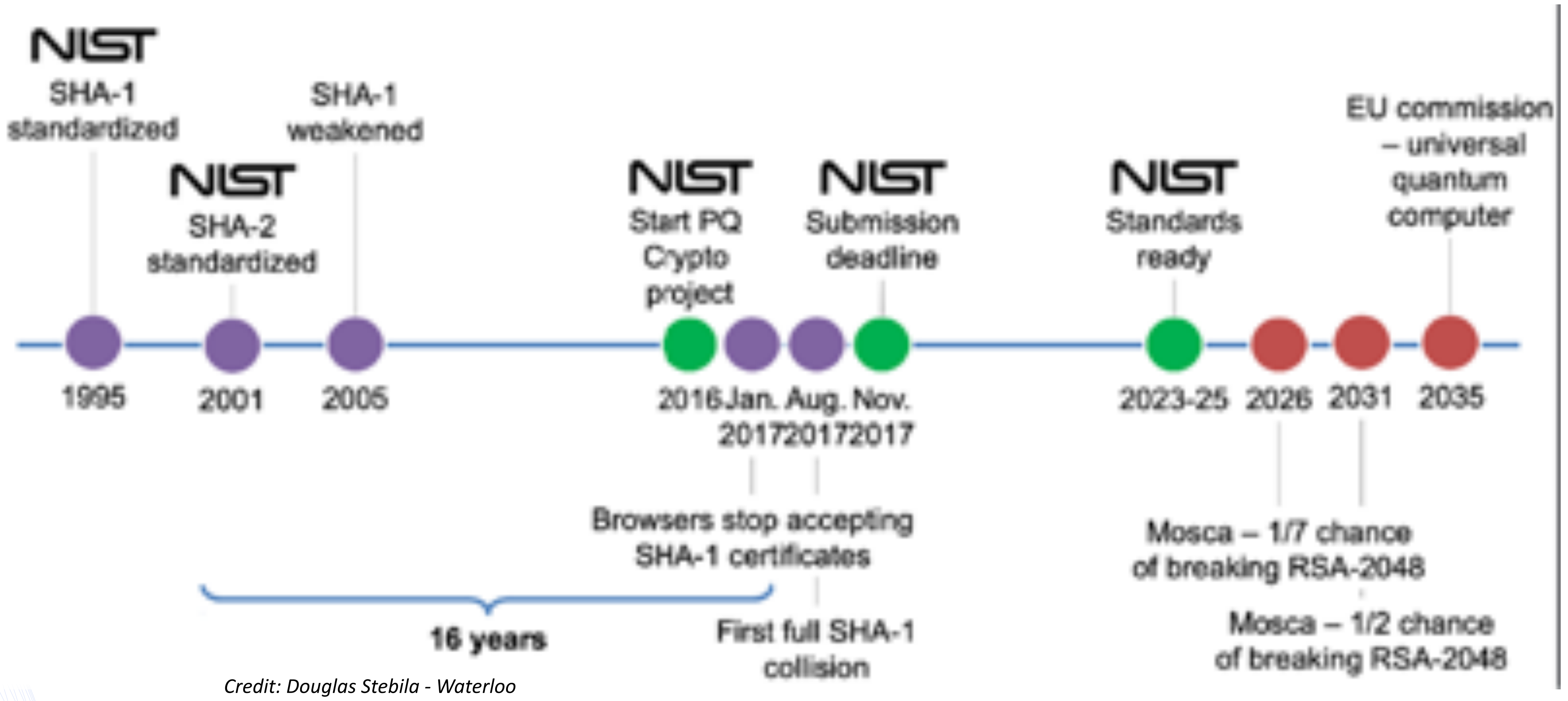
# Applications

SIAM J. COMPUT. Vol. 26, No. 5, pp. 1484–1509, October 1997
© 1997 Society for Industrial and Applied Mathematics 009

**POLYNOMIAL-TIME ALGORITHMS FOR PRIME FACTORIZATION AND DISCRETE LOGARITHMS ON A QUANTUM COMPUTER***

PETER W. SHOR[†]

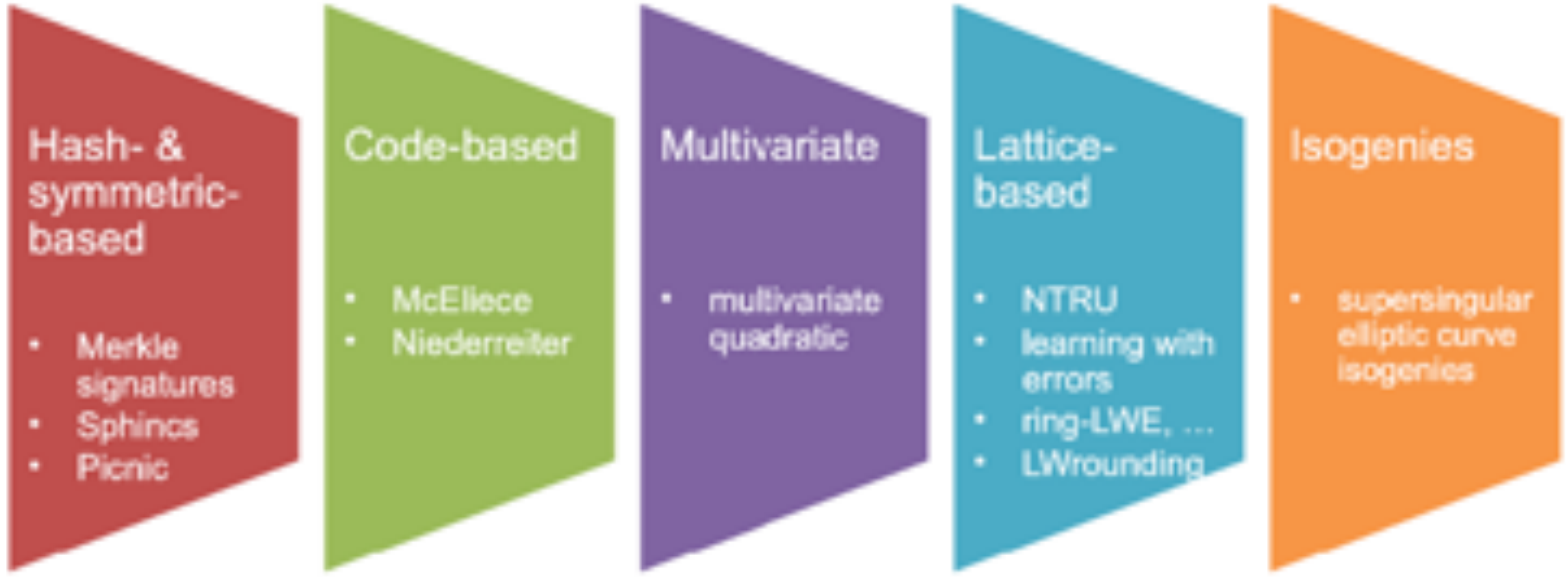
NIST time line to define new encryption standards




*Credit: Douglas Stebila - Waterloo*

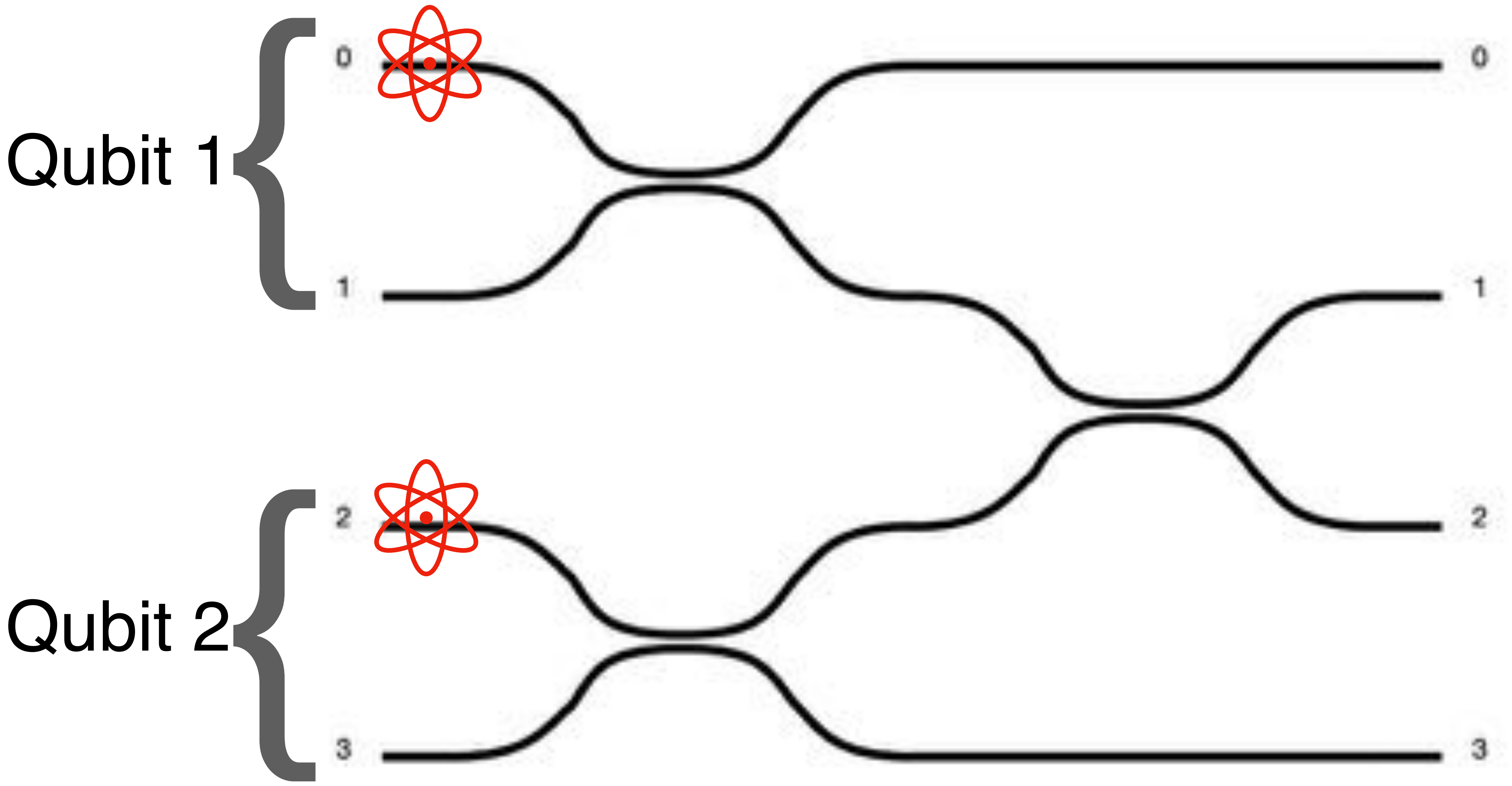
## Post-quantum crypto

Classical crypto with no known exponential quantum speedup

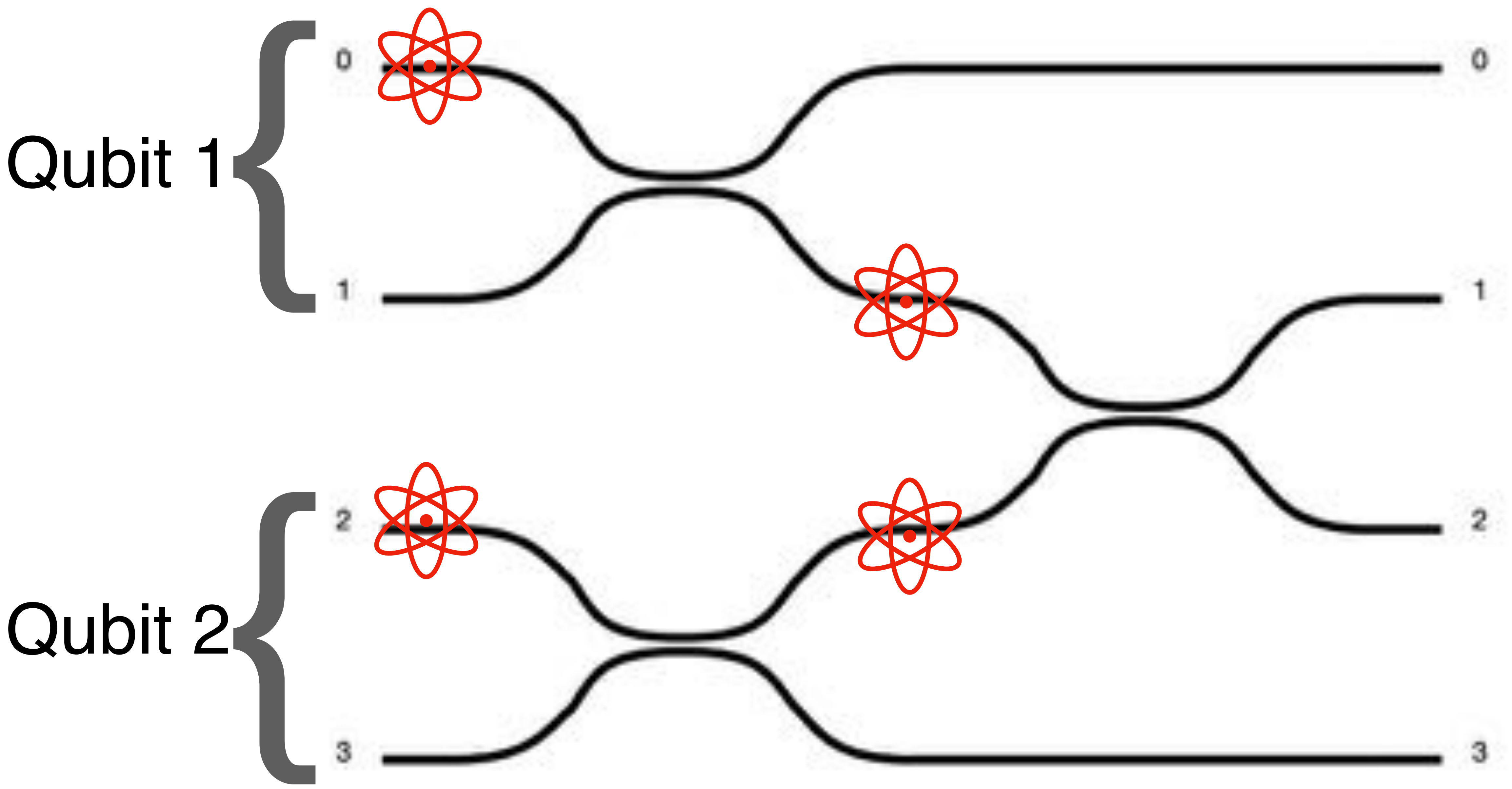


# Photonic quantum computing at Quandela

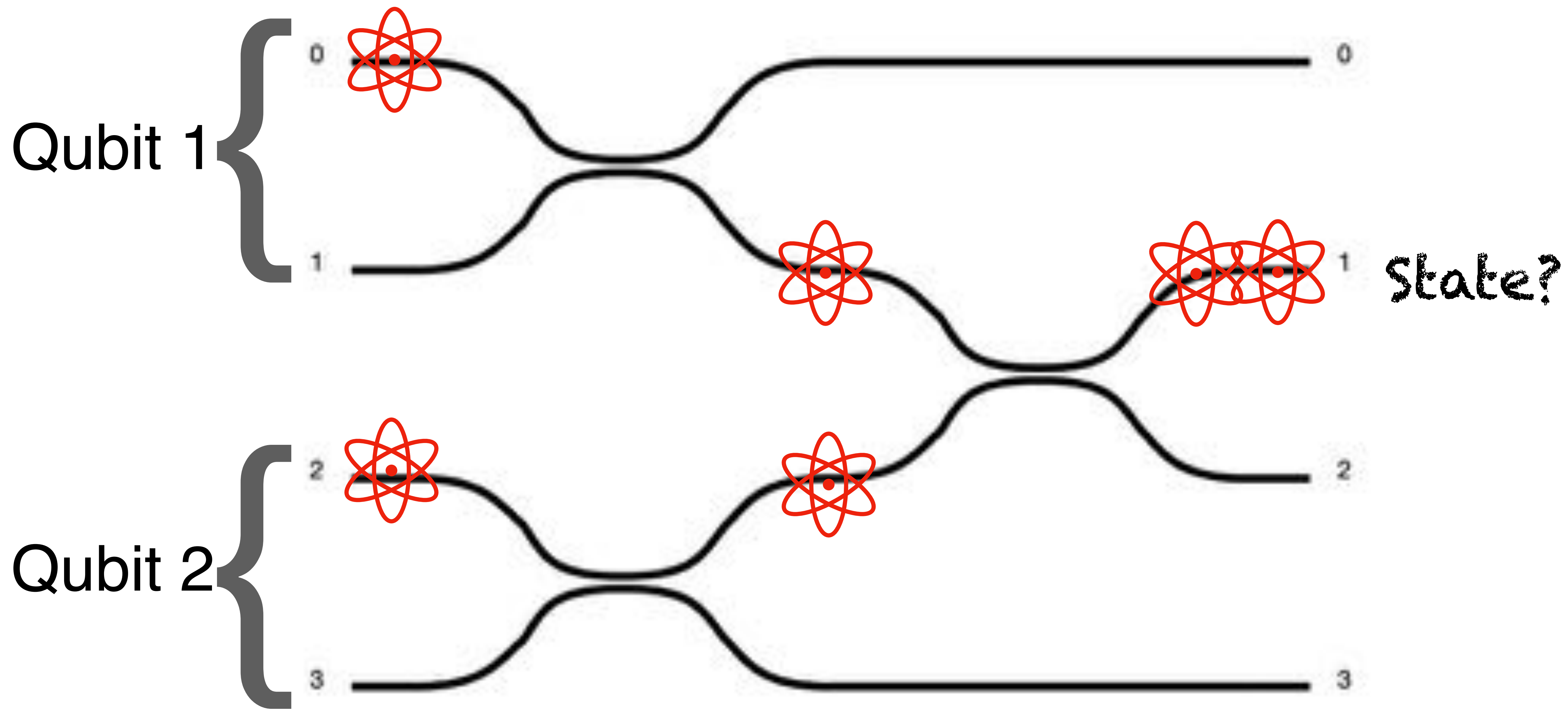
# Photonic quantum computing at Quandela



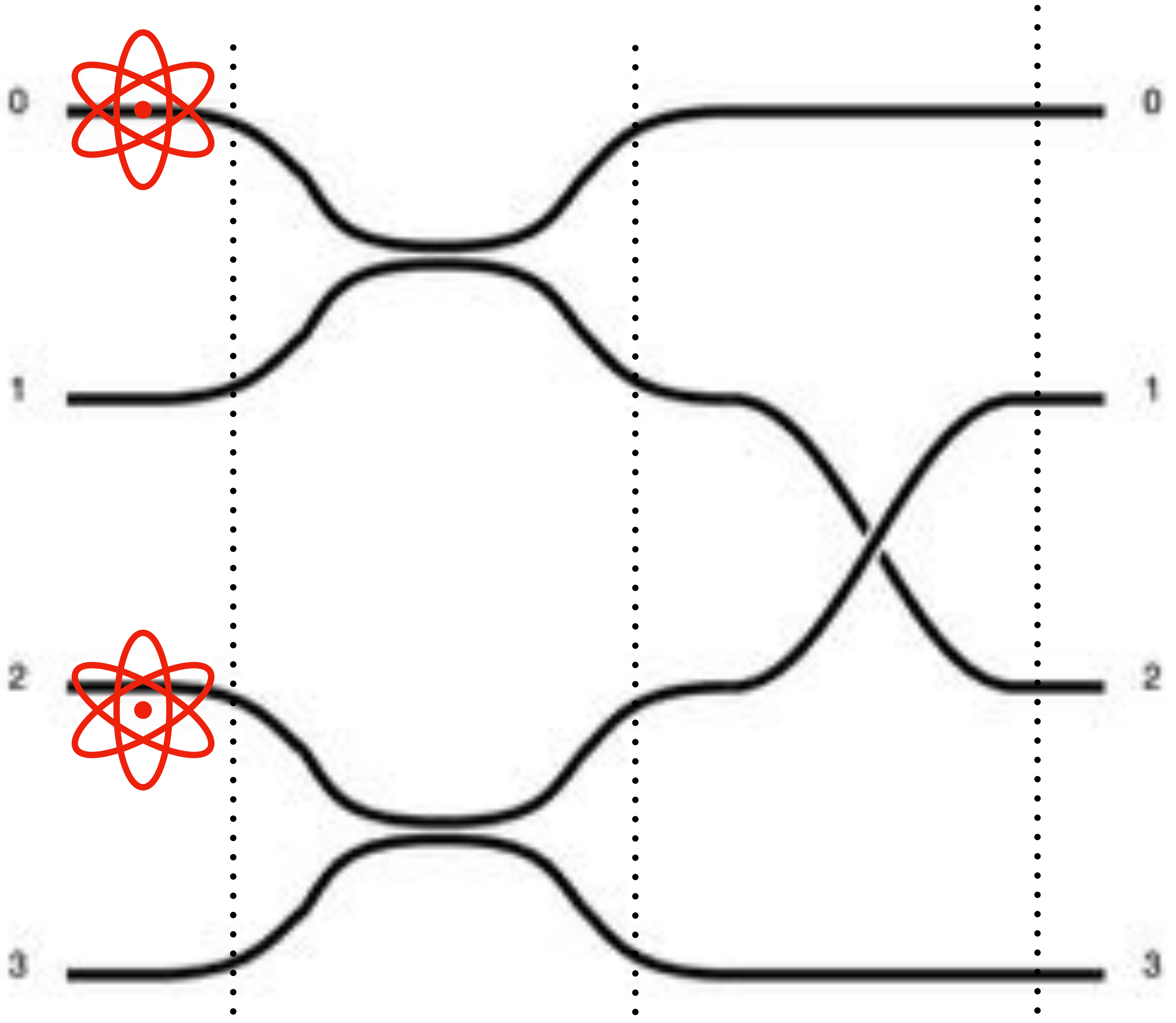
# Photonic quantum computing at Quandela



# Photonic quantum computing at Quandela



# Photonic quantum computing at Quandela

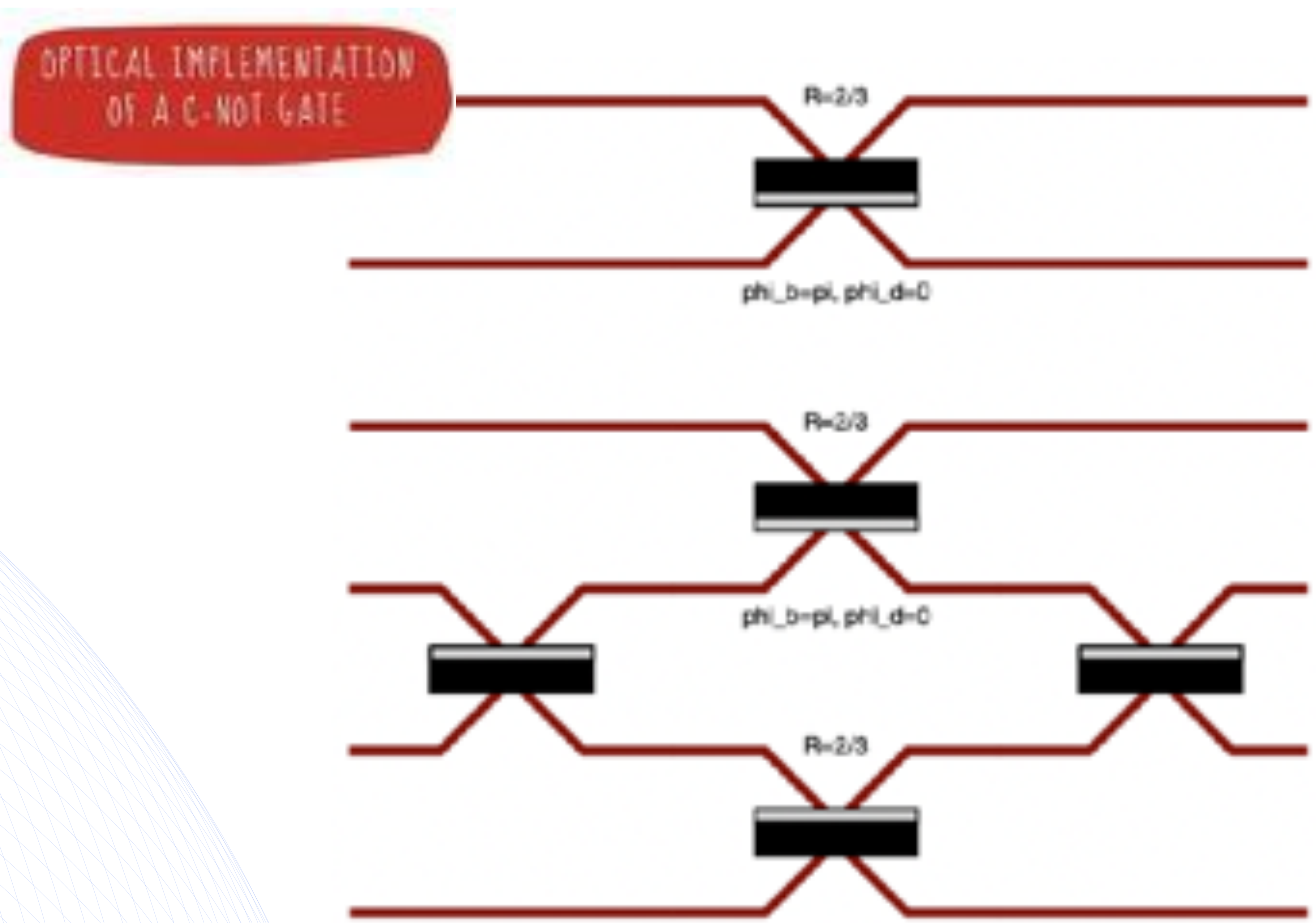


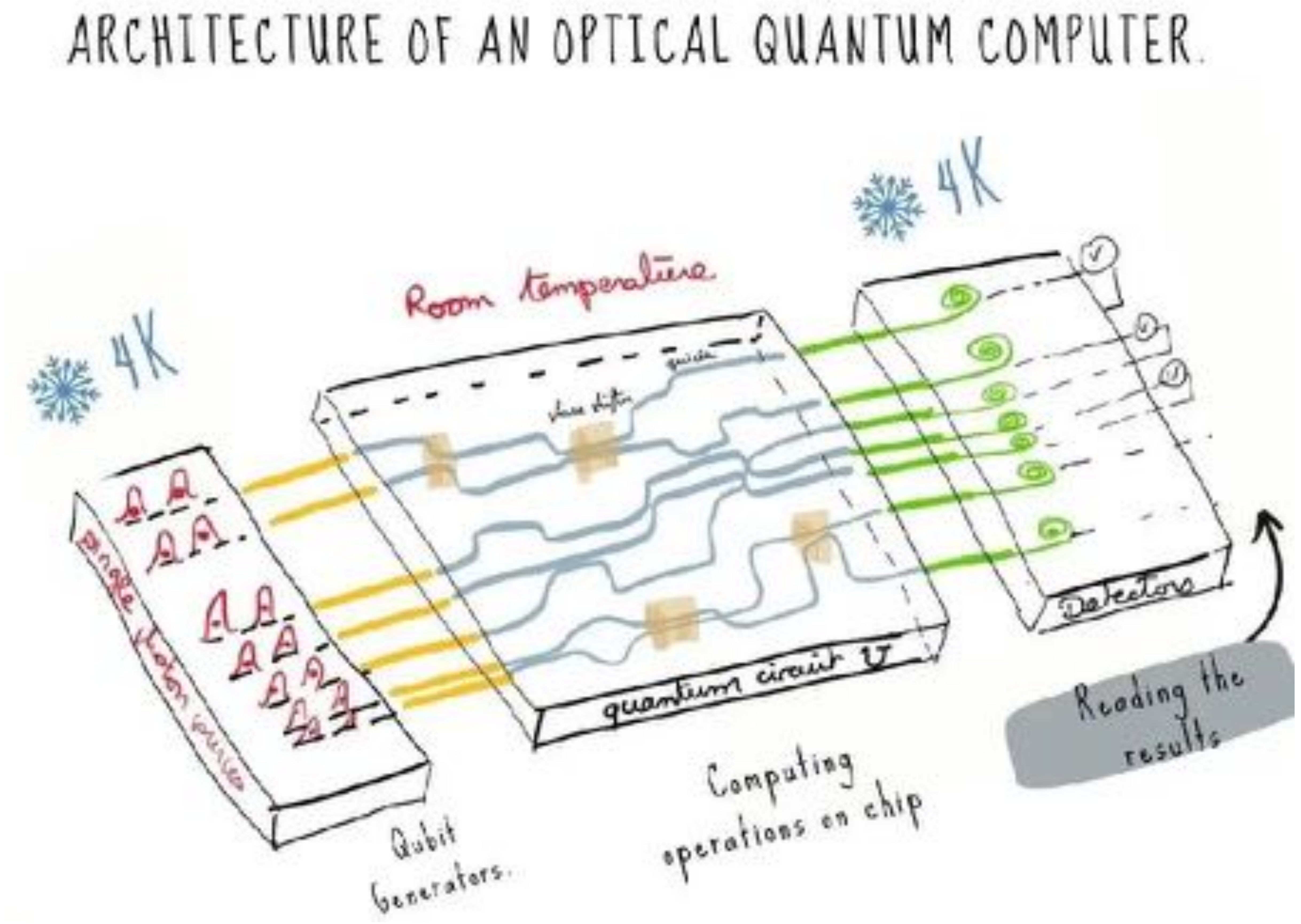

$|1, 0, 1, 0\rangle_F$

$|1, 1, 0, 0\rangle_F + |1, 0, 0, 1\rangle_F + |0, 1, 1, 0\rangle_F + |0, 0, 1, 1\rangle_F$

$|1, 0, 1, 0\rangle_F + |1, 0, 0, 1\rangle_F + |0, 1, 1, 0\rangle_F + |0, 1, 0, 1\rangle_F$

# Photonic quantum computing at Quandela



# Quandela

**SHOWROOM - HEAD OFFICE**

7 Rue Léonard de Vinci, Massy, France



**CLEANROOM – SEMICONDUCTOR DEVELOPMENT**

10 Boulevard Thomas Gobert, Palaiseau, France

**PARIS OFFICES**

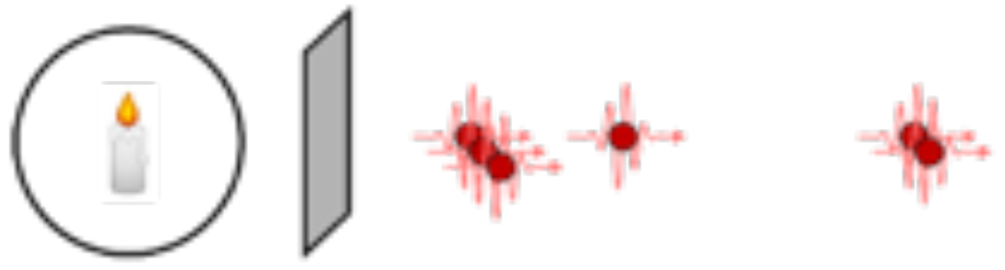
40 Rue du Louvre, Paris, France



**MUNICH OFFICES**

Rumfordstraße 39, 80469 Munich, Germany

# Hardware at Quandela



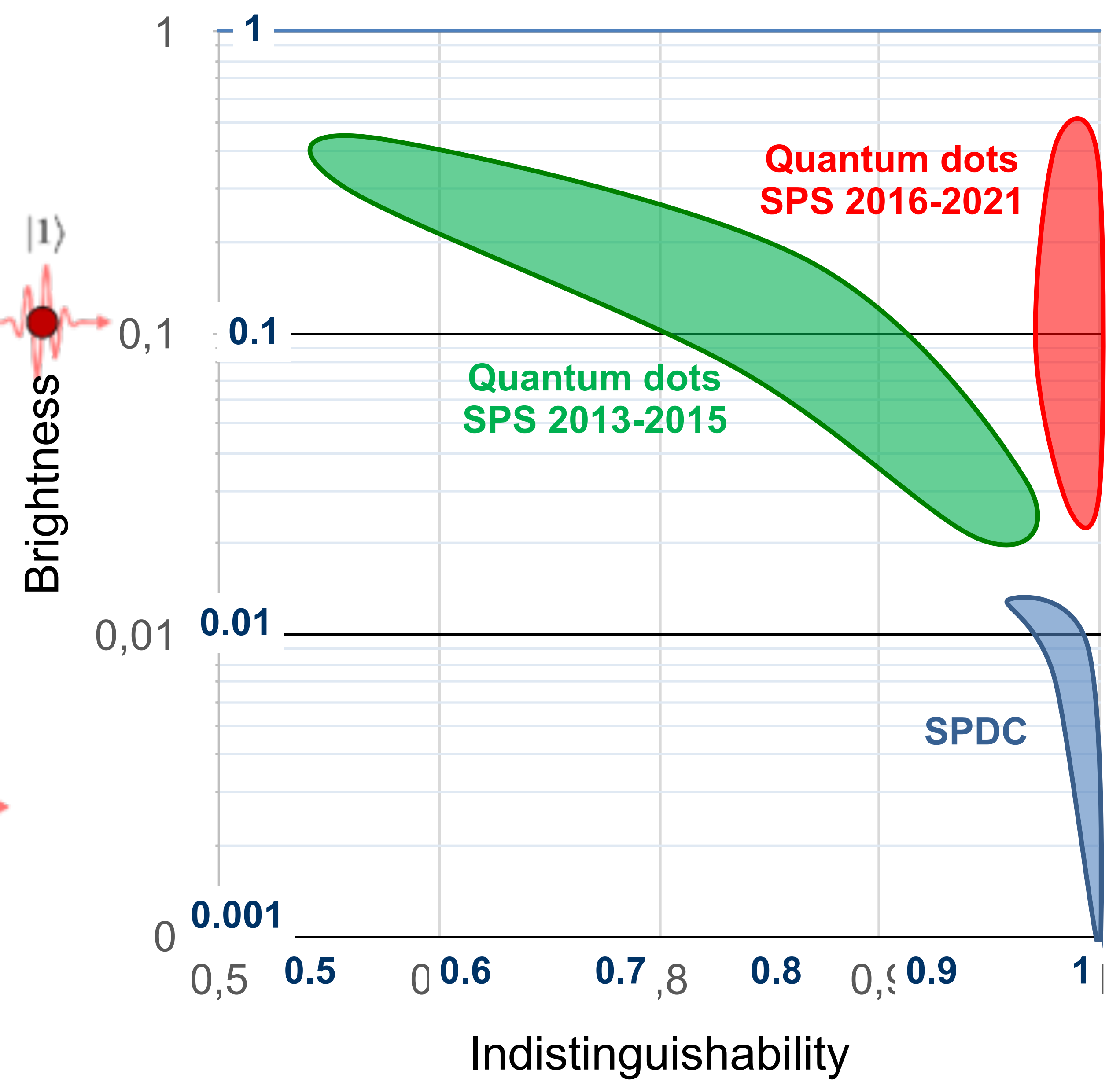
**PURITY**

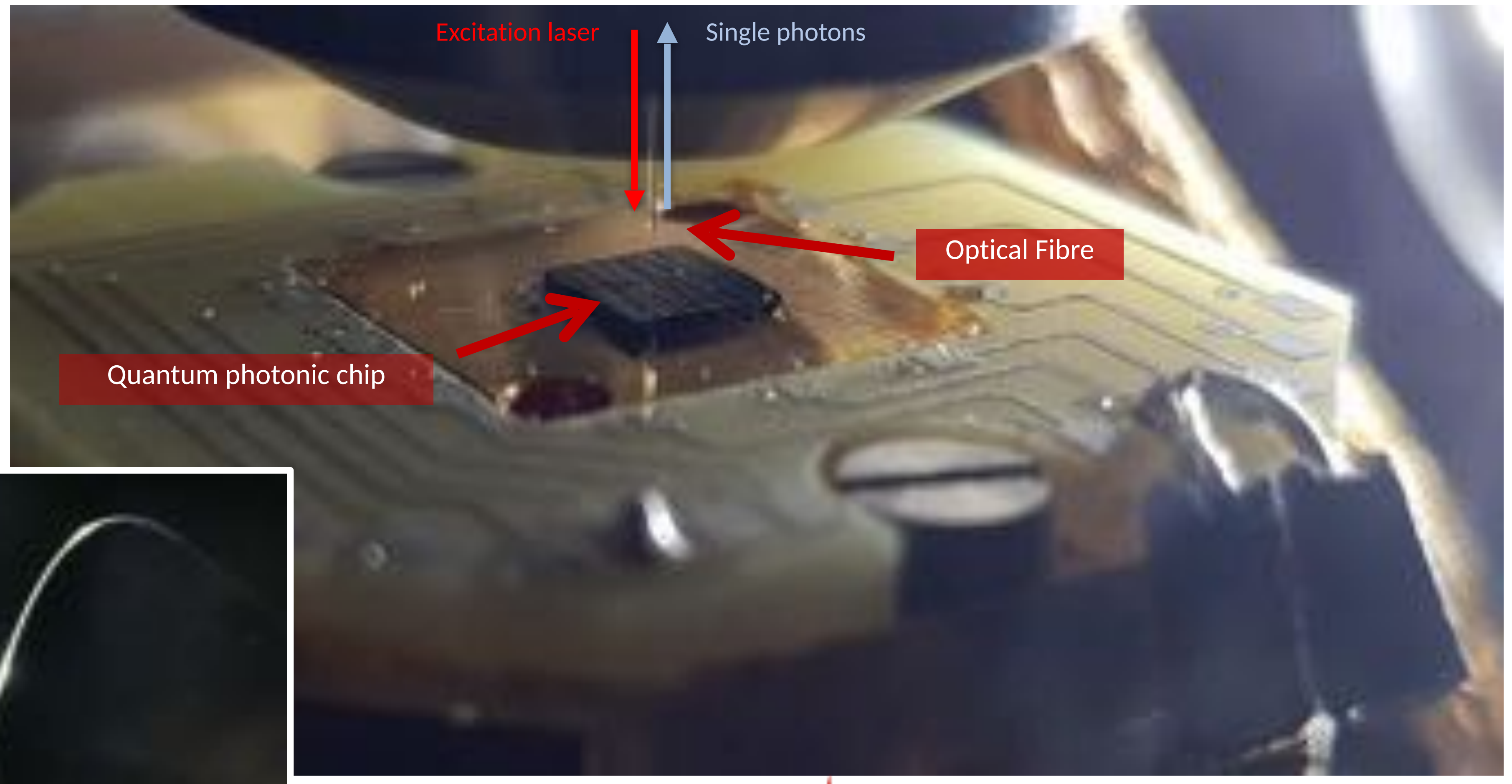
**BRIGHTNESS**

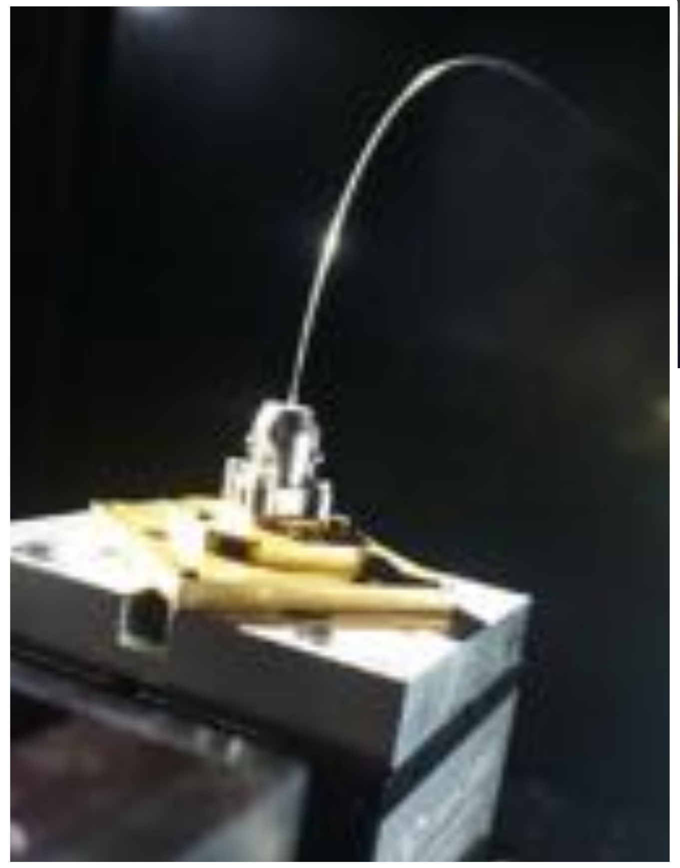
**INDISTINGUISHABILITY**

**High-rate entanglement between a semiconductor spin and indistinguishable photons**

N. Coste,[1] D. Fioretto,[1] N. Belabas,[1] S. C. Wein,[2,3] P. Hilaire,[4,2] R. Frantzeskakis,[5] M. Gundin,[1] B. Goes,[3] N. Somaschi,[2] M. Morassi,[1] A. Lemaître,[1] I. Sagnes,[1] A. Harouri,[1] S. E. Economou,[6] A. Auffeves,[3] O. Krebs,[1] L. Lanco,[1,7] and P. Senellart[1]



eDelight

# Software development at Quandela

**Perceval: A Software Platform for Discrete Variable Photonic Quantum Computing**

Nicolas Heurtel[1], Andreas Fyrillas[1,2], Grégoire de Gliniasty[1], Raphaël Le Bihan[1], Sébastien Malherbe[3], Marceau Pailhas[1], Boris Bourdoncle[1], Pierre-Emmanuel Emeriau[1], Rawad Mezher[1], Luka Music[1], Nadia Belabas[2], Benoît Valiron[4], Pascale Senellart[2], Shane Mansfield[1], and Jean Senellart[1]

PERCEVAL



☞ cloud.quandela.dev

Le Monde

ACTUALITÉS | ÉCONOMIE | VIDÉOS | DÉBATS | CULTURE | LE GOÛT DU MONDE | SERVICES

**La puissance d'un ordinateur quantique testée en ligne**

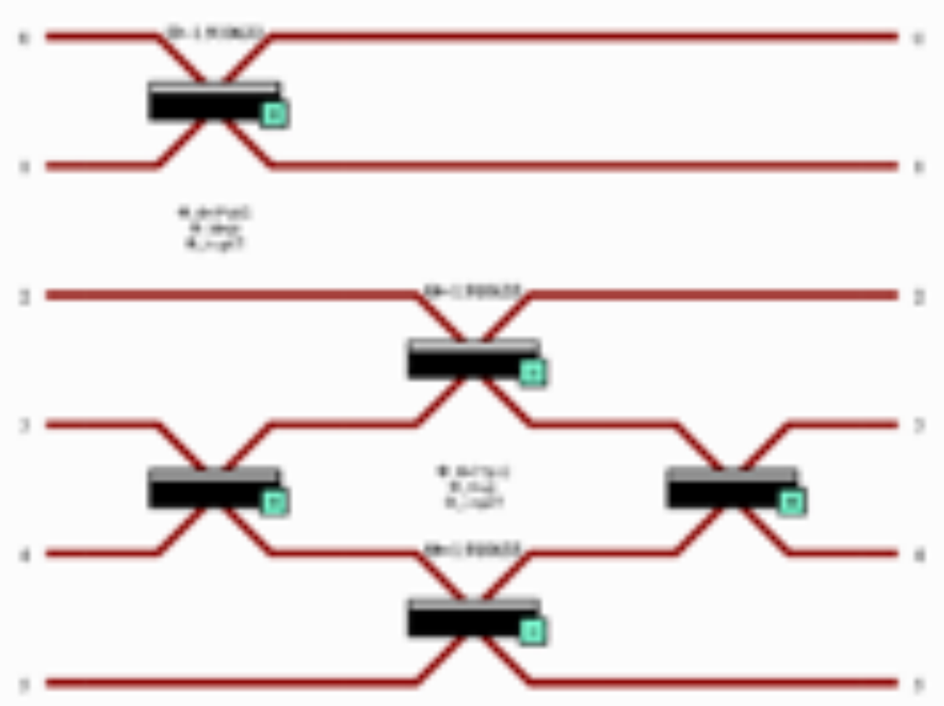
La start-up française Quandela a réuni, lors d'un hackathon, des étudiants et des chercheurs pour résoudre des problèmes à l'aide d'une machine qui fonctionne avec des « qubits » photoniques. Une avancée européenne qui vient concurrencer les Américains et les Britanniques.

# Software development at Quandela

☞ perceval.quandela.net

```
[2]: cnot = pcvl.Circuit(6, name="Ralph CNOT")
     cnot.add((0, 1), pcvl.BS.H(pcvl.BS.r_to_theta(1/3), phi_tl = -np.pi/2, phi_bl = np.pi, phi_tr = np.pi / 2))
     cnot.add((3, 4), pcvl.BS.H())
     cnot.add((2, 3), pcvl.BS.H(pcvl.BS.r_to_theta(1/3), phi_tl = -np.pi/2, phi_bl = np.pi, phi_tr = np.pi / 2))
     cnot.add((4, 5), pcvl.BS.H(pcvl.BS.r_to_theta(1/3)))
     cnot.add((3, 4), pcvl.BS.H())
     pcvl.pdisplay(cnot)
```

[2]:



```
states = {
    pcvl.BasicState([1, 0, 1, 0]): "00",
    pcvl.BasicState([1, 0, 0, 1]): "01",
    pcvl.BasicState([0, 1, 1, 0]): "10",
    pcvl.BasicState([0, 1, 0, 1]): "11"
}

ca = pcvl.algorithm.Analyzer(p, states)
ca.compute(expected={"00": "00", "01": "01", "10": "11", "11": "10"})
pcvl.pdisplay(ca)
print("performance=%s, fidelity=%.3f%%" % (pcvl.simple_float(ca.performance)[1], ca.fidelity * 100))
```

| | 00 | 01 | 10 | 11 |
|---|---|---|---|---|
| 00 | 1 | 0 | 0 | 0 |
| 01 | 0 | 1 | 0 | 0 |
| 10 | 0 | 0 | 0 | 1 |
| 11 | 0 | 0 | 1 | 0 |

performance=1/9, fidelity=100.000%

PHYSICAL REVIEW A
covering atomic, molecular, and optical physics and quantum information

Highlights Letters Recent Accepted Collections Authors Referees Search

Linear optical controlled-NOT gate in the coincidence basis

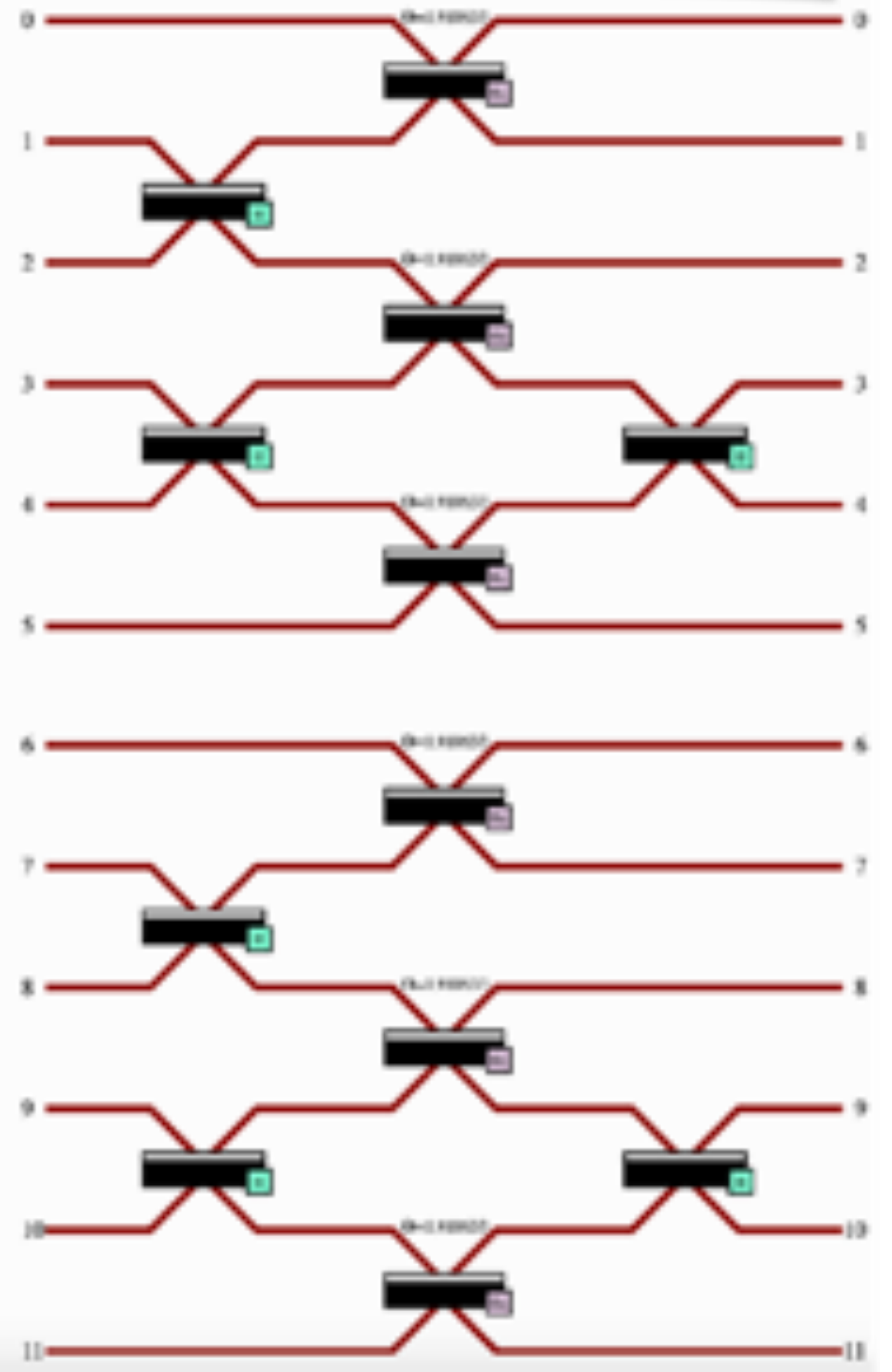
T. C. Ralph, N. K. Langford, T. B. Bell, and A. G. White
Phys. Rev. A 65, 062324 – Published 20 June 2002

**Shor's Quantum Factoring Algorithm on a Photonic Chip**

Alberto Politi, Jonathan C. F. Matthews, and Jeremy L. O'Brien  Authors Info & Affiliations

Science • 4 Sep 2009 • Vol 325, Issue 5945 • p. 1221 • DOI: 10.1126/science.1173731

```
[5]: circ = pcvl.Circuit(12)

     # qubit modes
     # for qubit states 0, 1
     x1 = [1, 2]
     f1 = [3, 4]
     x2 = [7, 8]
     f2 = [9, 10]
     # auxiliary modes
     am1 = [0, 5]
     am2 = [6, 11]


     # H gates
     for q in [x1, f1, x2, f2]:
         circ.add(q, pcvl.BS.H())

     # CZ gates
     for x, f, am in [(x1, f1, am1), (x2, f2, am2)]:
         circ.add((am[0], x[0]), pcvl.BS(pcvl.BS.r_to_theta(1/3)))
         circ.add((x[1],  f[0]), pcvl.BS(pcvl.BS.r_to_theta(1/3)))
         circ.add((f[1], am[1]), pcvl.BS(pcvl.BS.r_to_theta(1/3)))

     # H gates
     for q in [f1, f2]:
         circ.add(q, pcvl.BS.H())

[6]: print("Optical circuit for Shor's algorithm")
     pcvl.pdisplay(circ)
```



# Thank you for your attention!

# Some resources

## Quantum Computing in the NISQ era and beyond

John Preskill

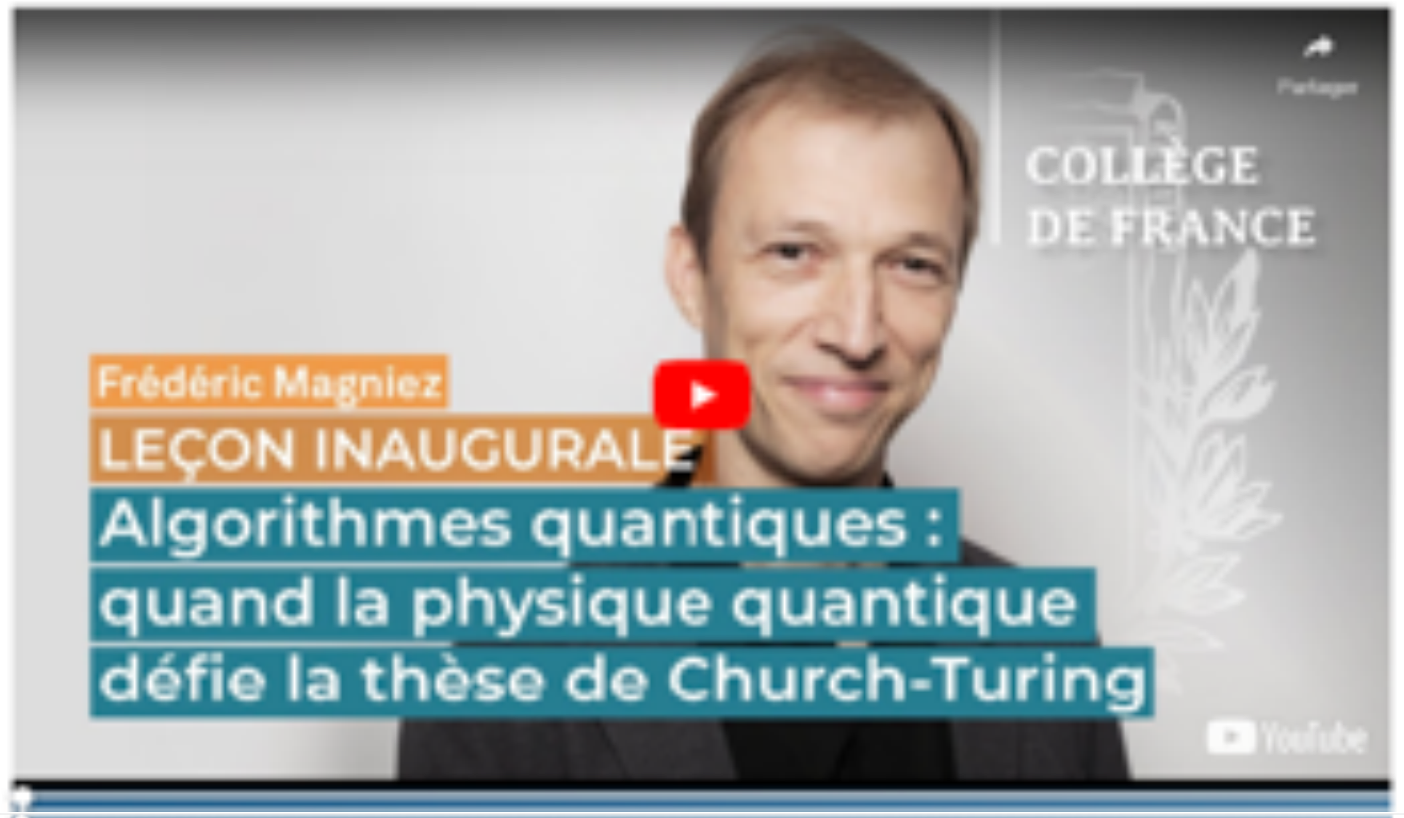
Institute for Quantum Information and Matter and Walter Burke Institute for Theoretical Physics, California Institute of Technology, Pasadena CA 91125, USA
30 July 2018

## Introduction to Quantum Information Science Lecture Notes

Scott Aaronson[1]

## Lecture Notes for Physics 229: Quantum Information and Computation

John Preskill
California Institute of Technology




## Frédéric Magniez
## Cours, séminaires, colloques

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2020 - 2021

07 avr 2021 → 09 juin 2021
Cours
Frédéric Magniez
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