Spin-Qubits for Quantum Technologies

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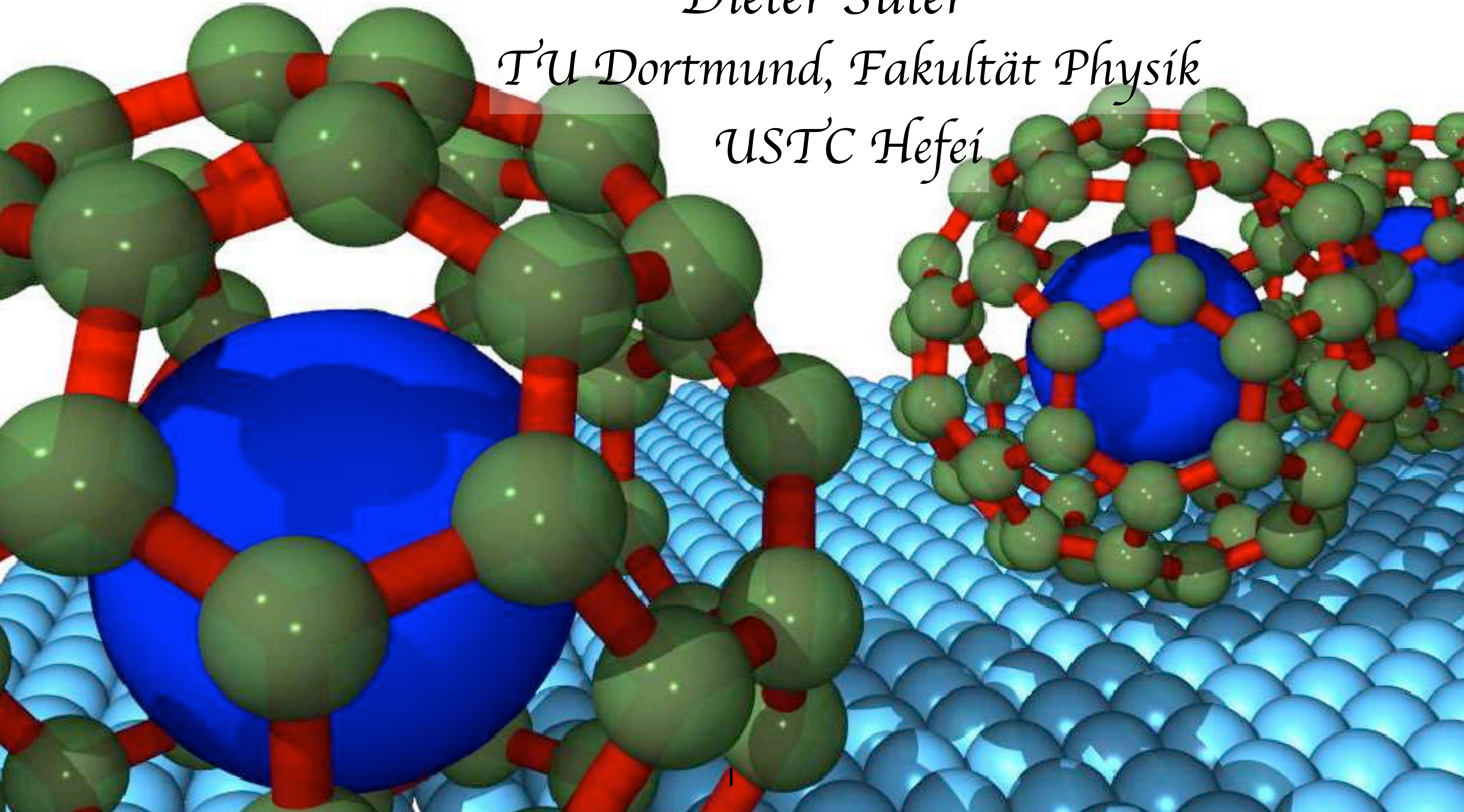


technische universität
dortmund

35 000 Students

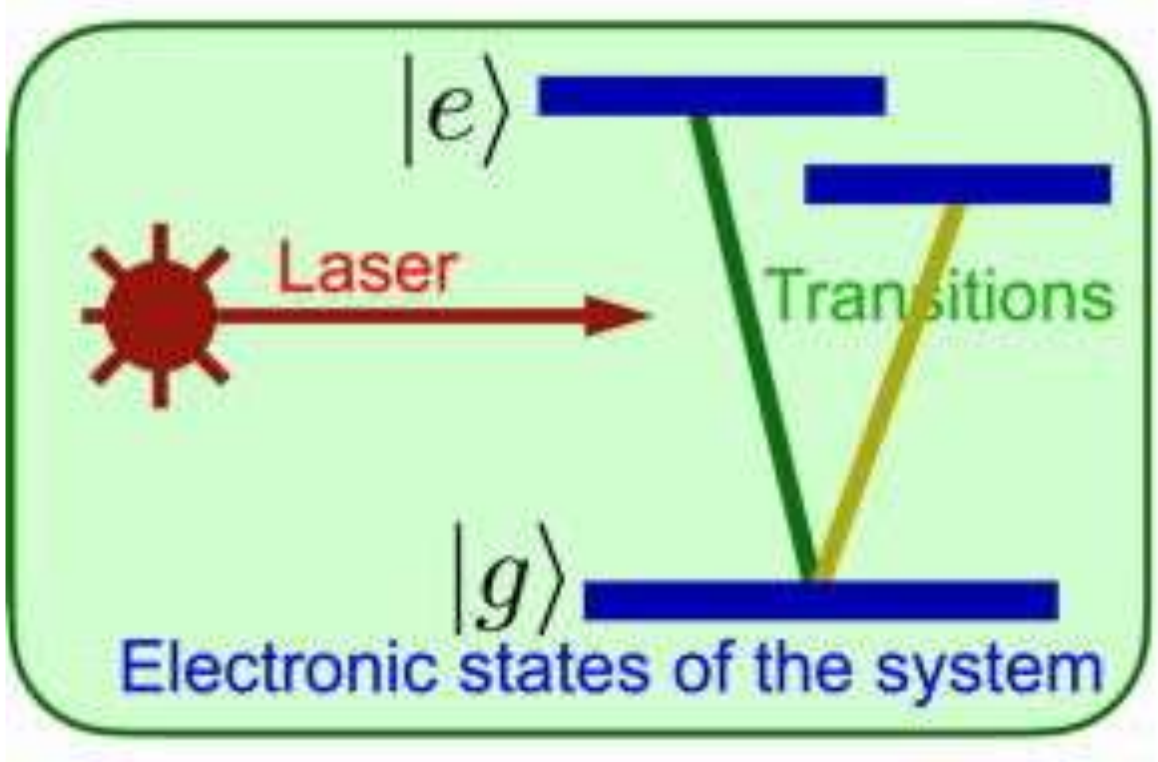
Dieter Suter
University of Science and Technology of China

Hefei

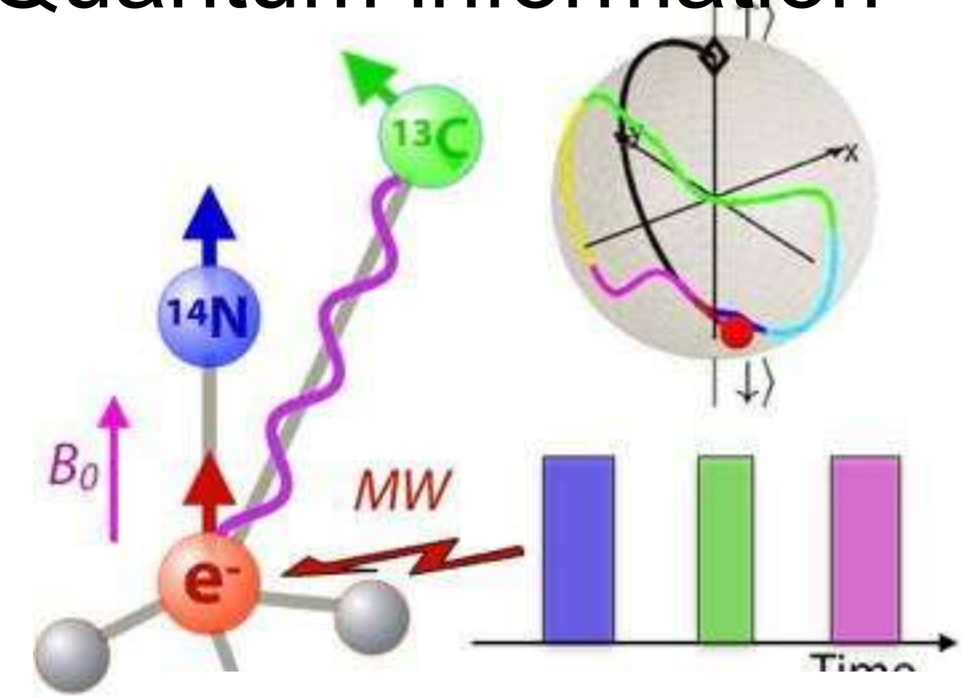
Research Fields

Magnetic resonance

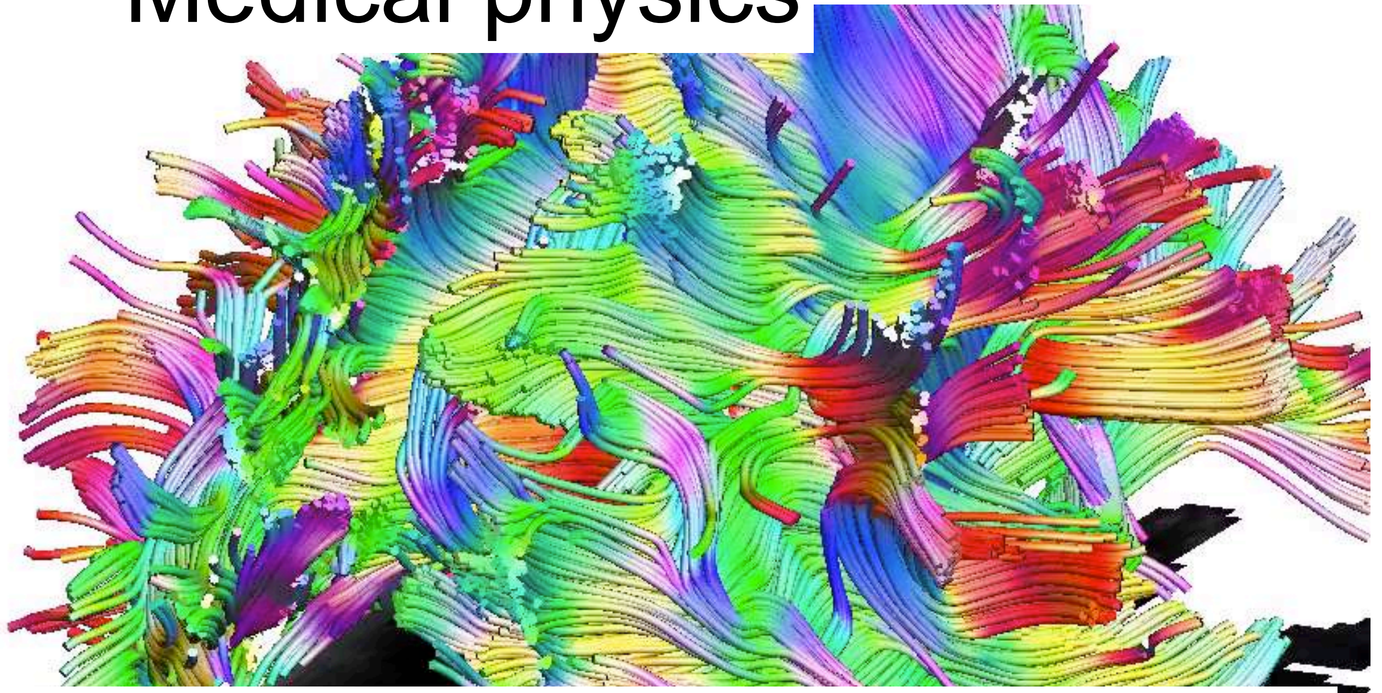
Laser spectroscopy



Quantum information



Medical physics



https://ag-suter.physik.tu-dortmund.de/research-interests/

The "Quantum Revolution"

unesco

INTERNATIONAL YEAR OF
Quantum Science
and Technology

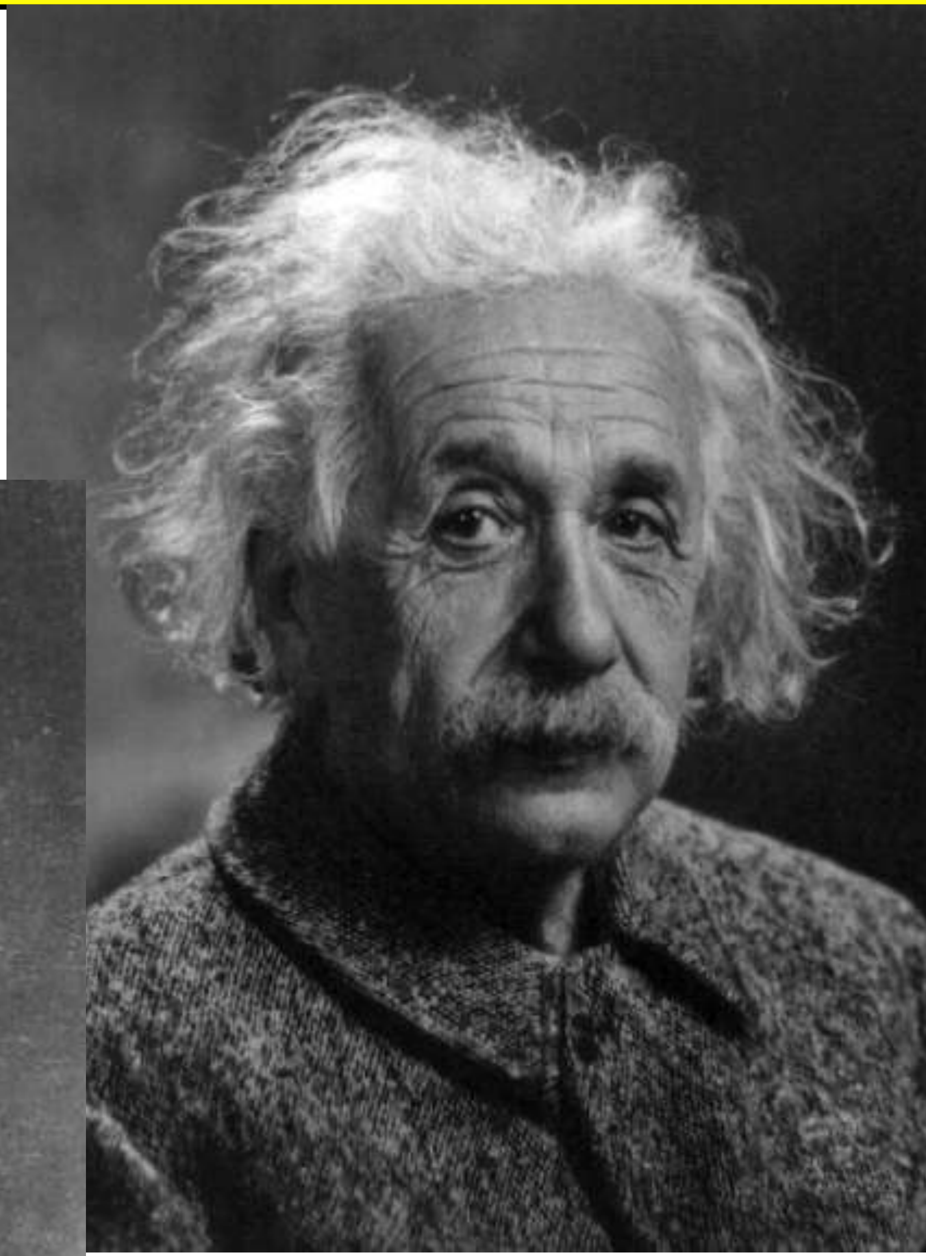
100 YEARS OF QUANTUM IS JUST THE BEGINNING

The 2025 International Year of Quantum Science and Technology (IYQ) recognizes 100 years since the initial development of quantum mechanics. Join us in engaging with quantum science and technology and celebrating throughout the year!

The Quantum Revolution

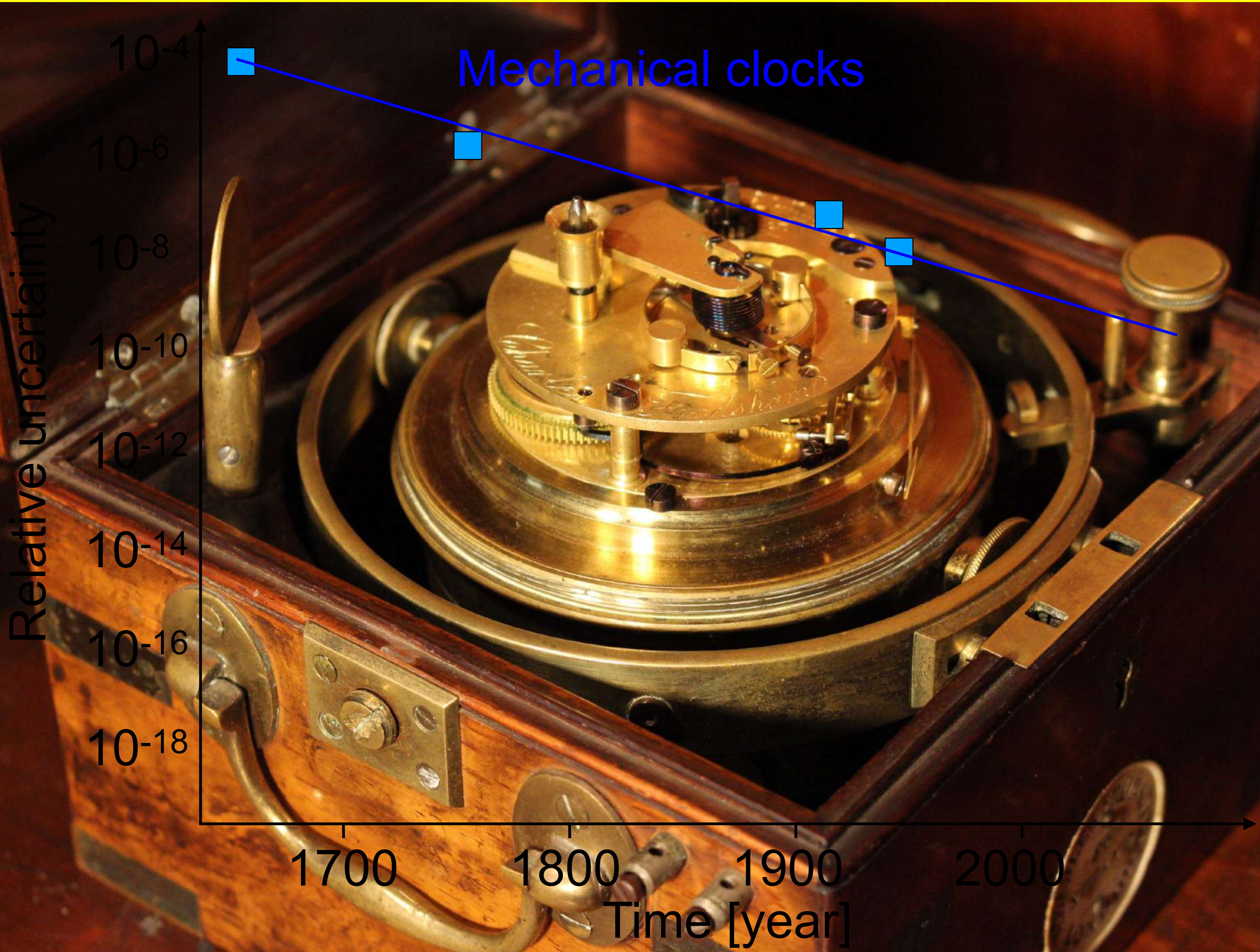
Max Planck
1858 – 1947

Werner Heisenberg
(1901 – 1976)

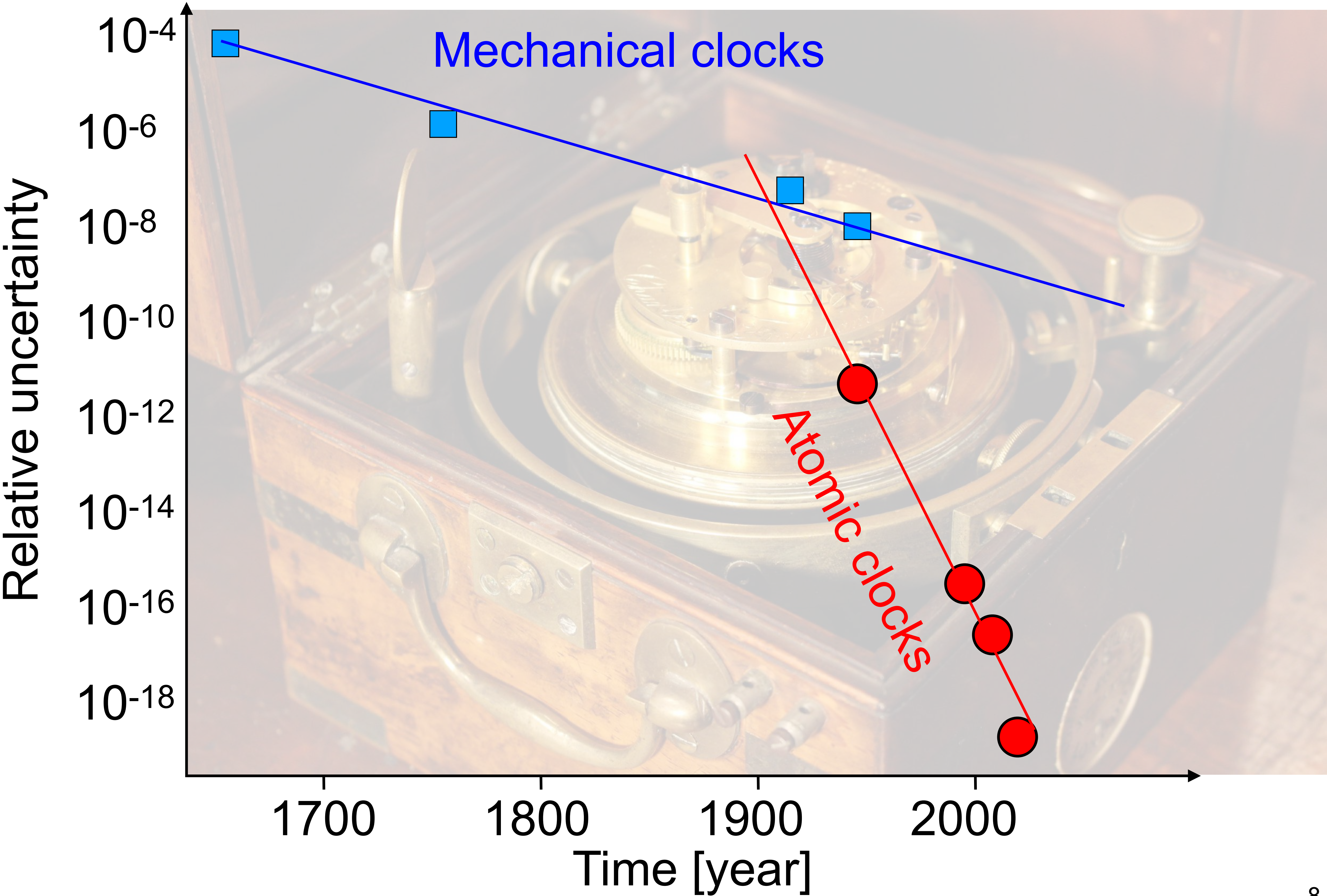


Albert Einstein
1879 - 1955

Clocks


Mechanical clocks
Relative uncertainty
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-18}
1700
1800
1900
2000
Time [year]

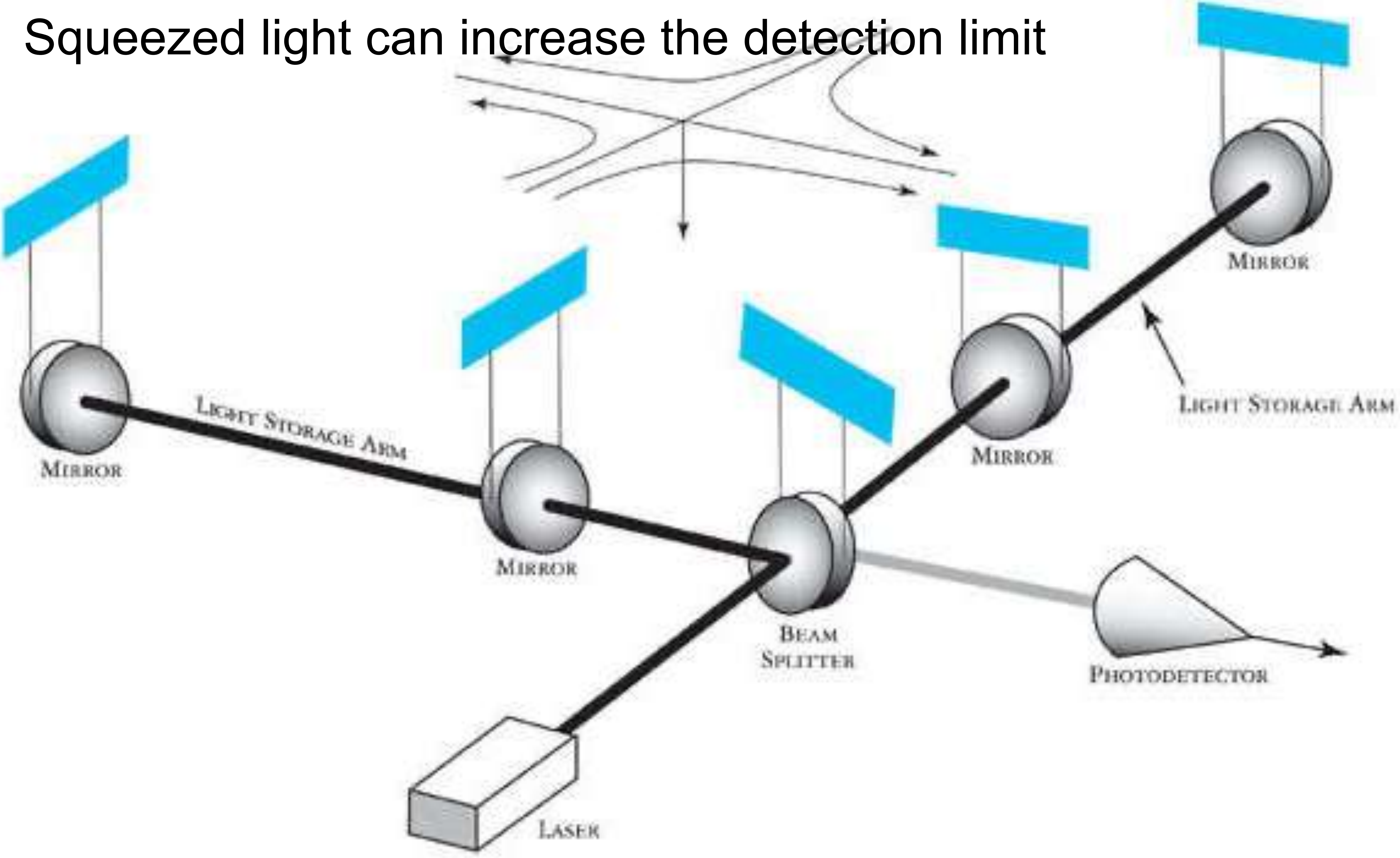
Quantum Revolution



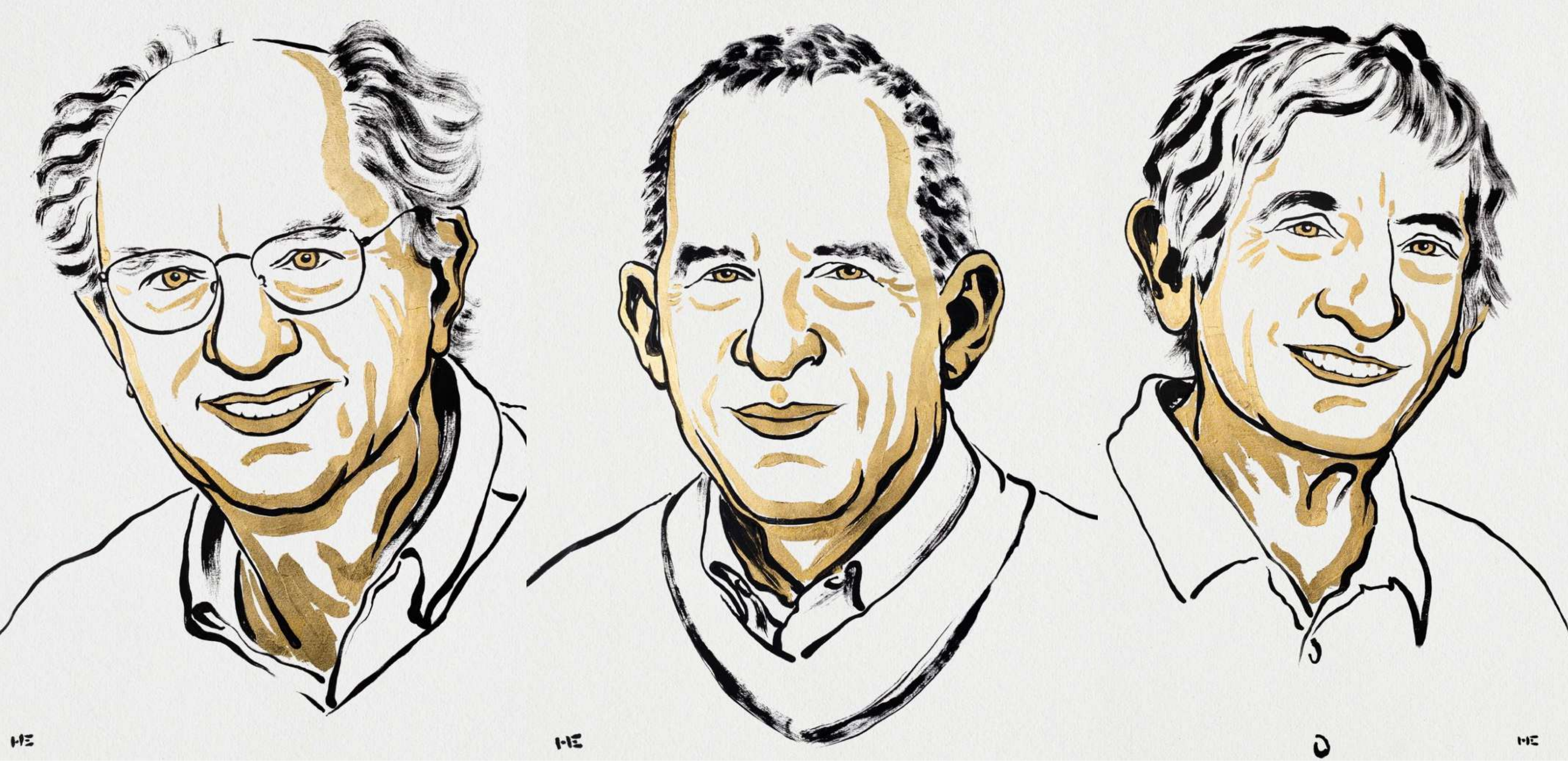
Gravitational Waves

Can detect strain at 10^{-23} level

Squeezed light can increase the detection limit



Nobel Prize in Physics 2025



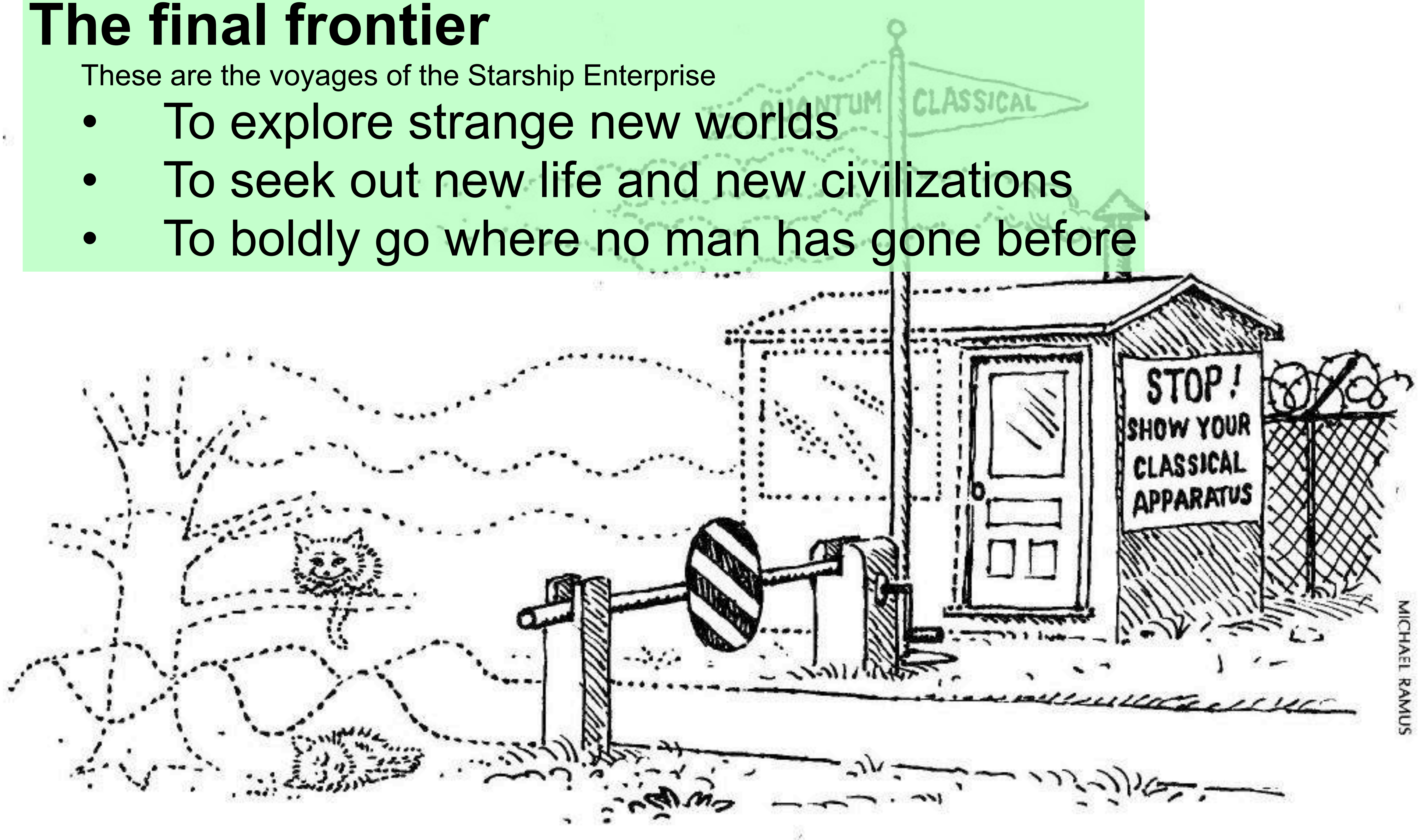
The Nobel Prize in Physics 2025 was awarded jointly to John Clarke, Michel H. Devoret and John M. Martinis "for the discovery of macroscopic quantum mechanical tunnelling and energy quantisation in an electric circuit"

The Quantum-Classical Border

The final frontier

These are the voyages of the Starship Enterprise

- To explore strange new worlds
- To seek out new life and new civilizations
- To boldly go where no man has gone before

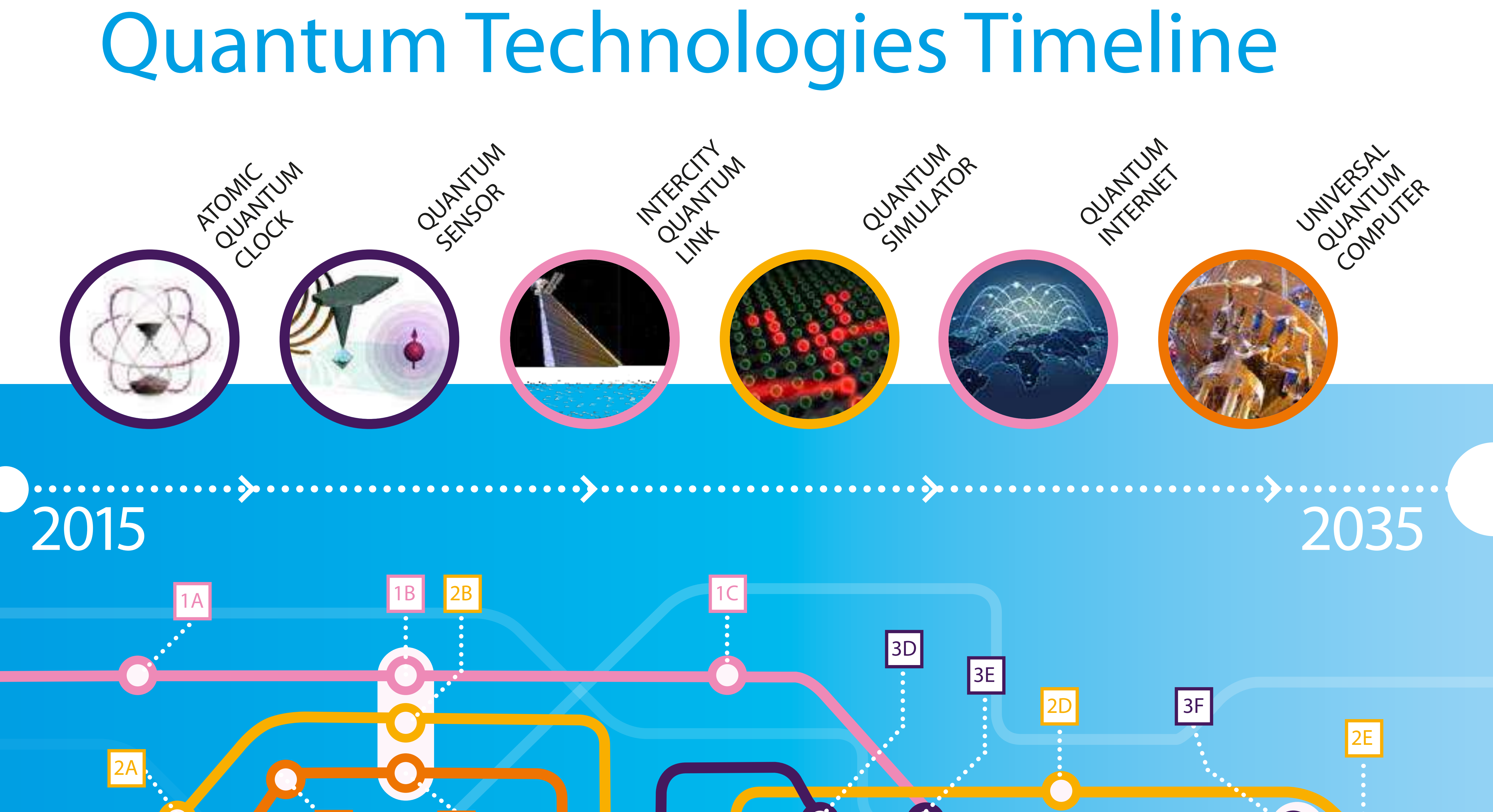


W. Zurek, “Decoherence and the transition from quantum to classical, Physics Today, October 1991.

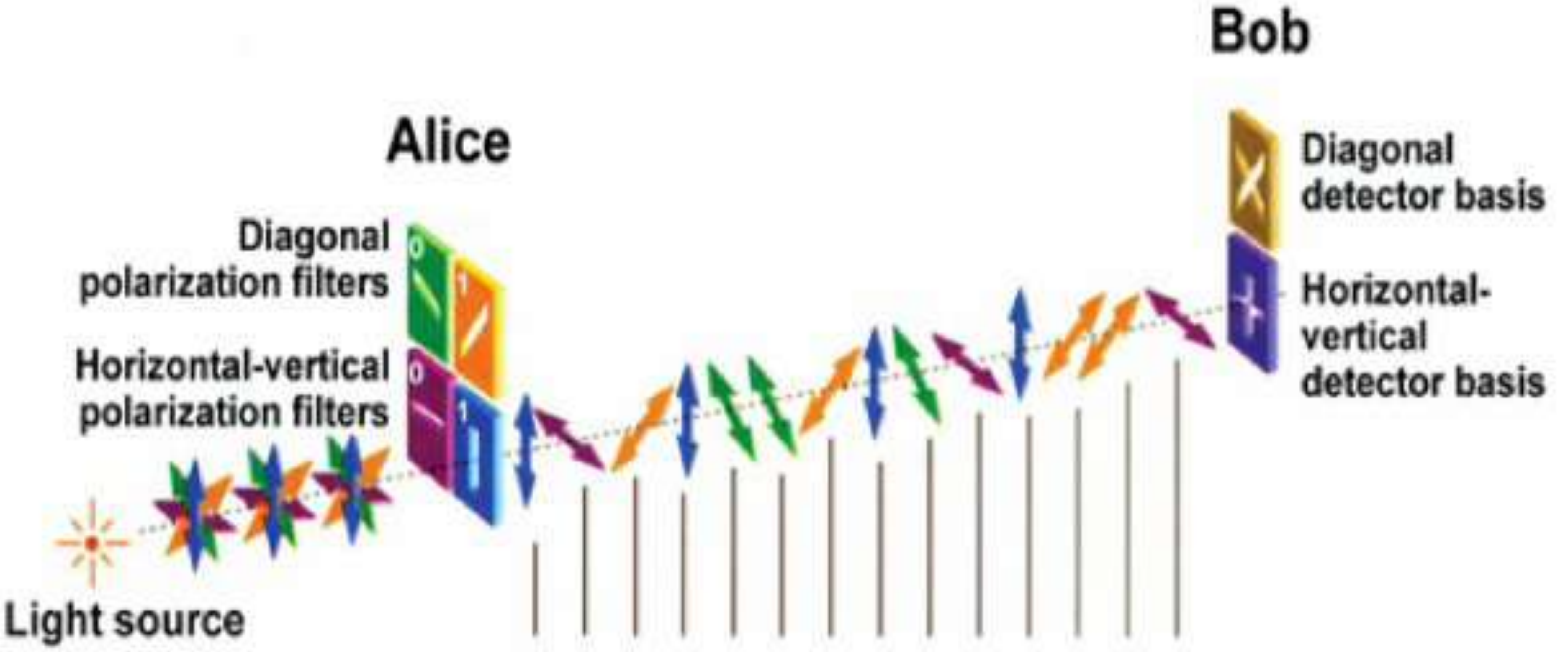
The 2nd Quantum Revolution

Development of technologies that use quantum mechanics ***directly***

EU: Quantum flagship



Communication with Quanta



Alice's bit sequence	1	0	1	1	0	0	1	1	0	0	1	1	1	0
Bob's detection basis	+	×	+	+	×	×	+	+	×	+	×	×	+	+
Bob's measurement	1	0	0	1	0	0	1	1	0	0	0	1	0	0
Retained bit sequence	1	–	–	1	0	0	–	1	0	0	–	1	–	0

Measuring with Quanta

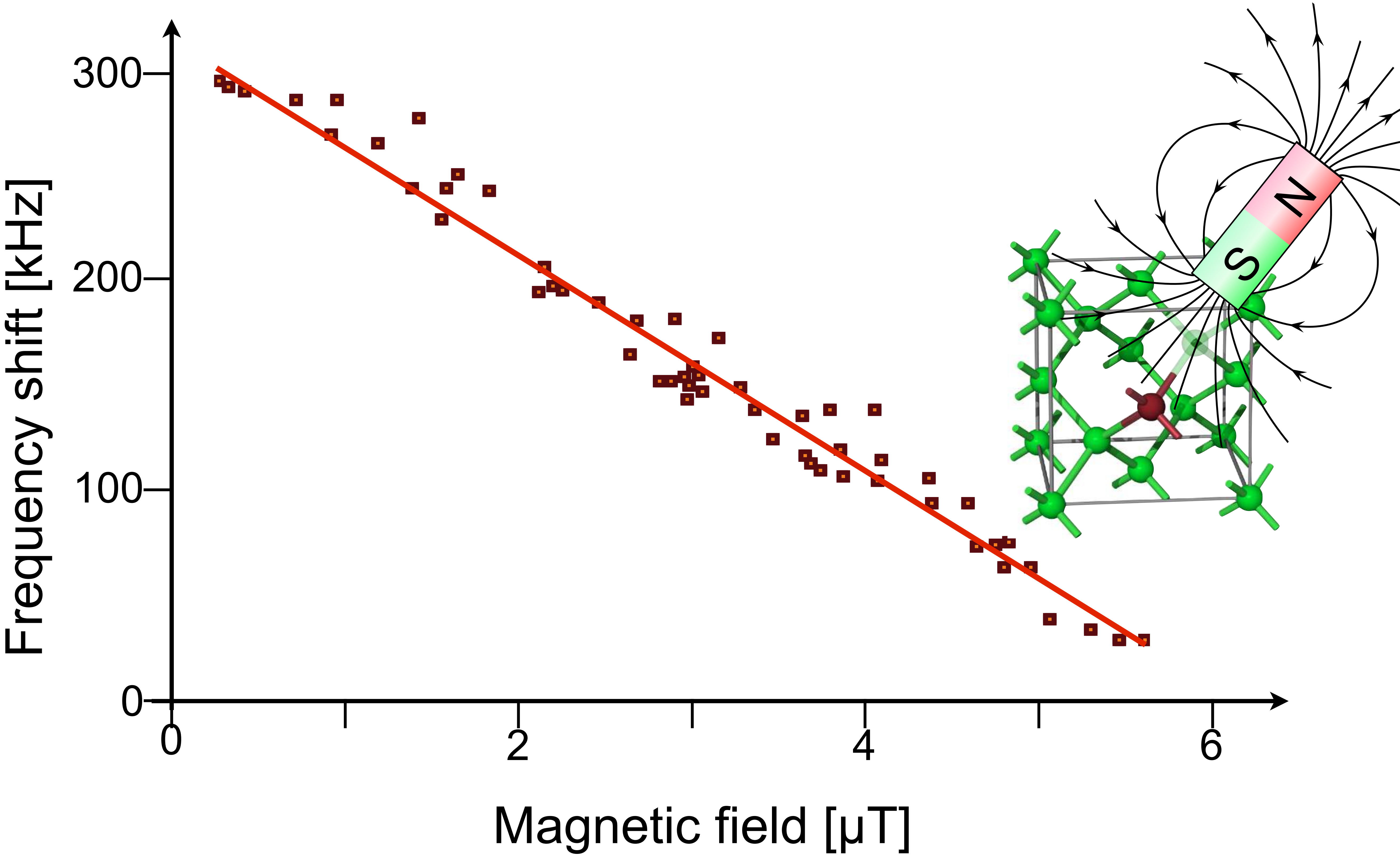
Quantum systems are at the basis of many high-precision measurements

Time

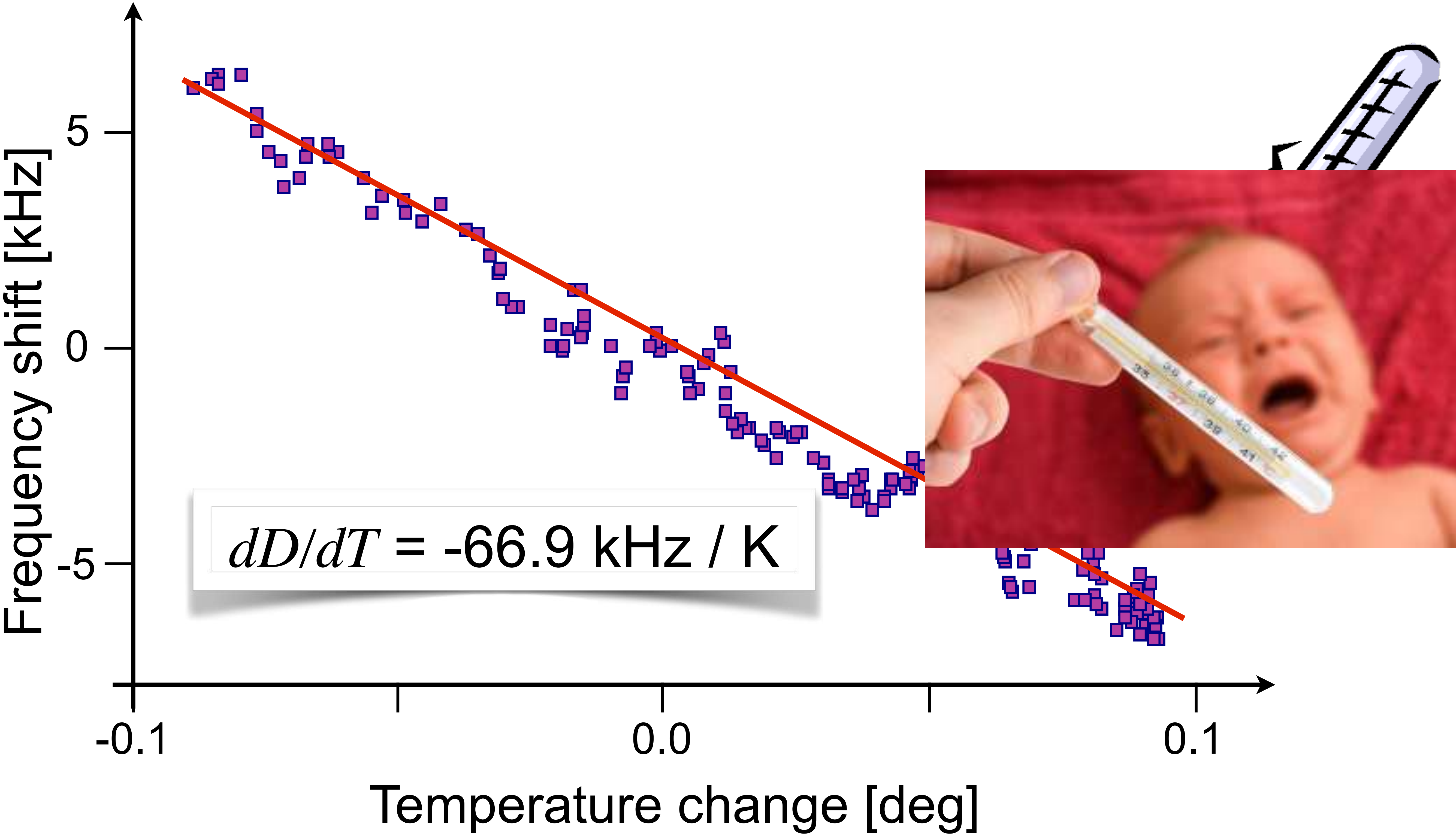
Magnetic field

Temperature

Single Atom Magnetometer



Single Atom Thermometer

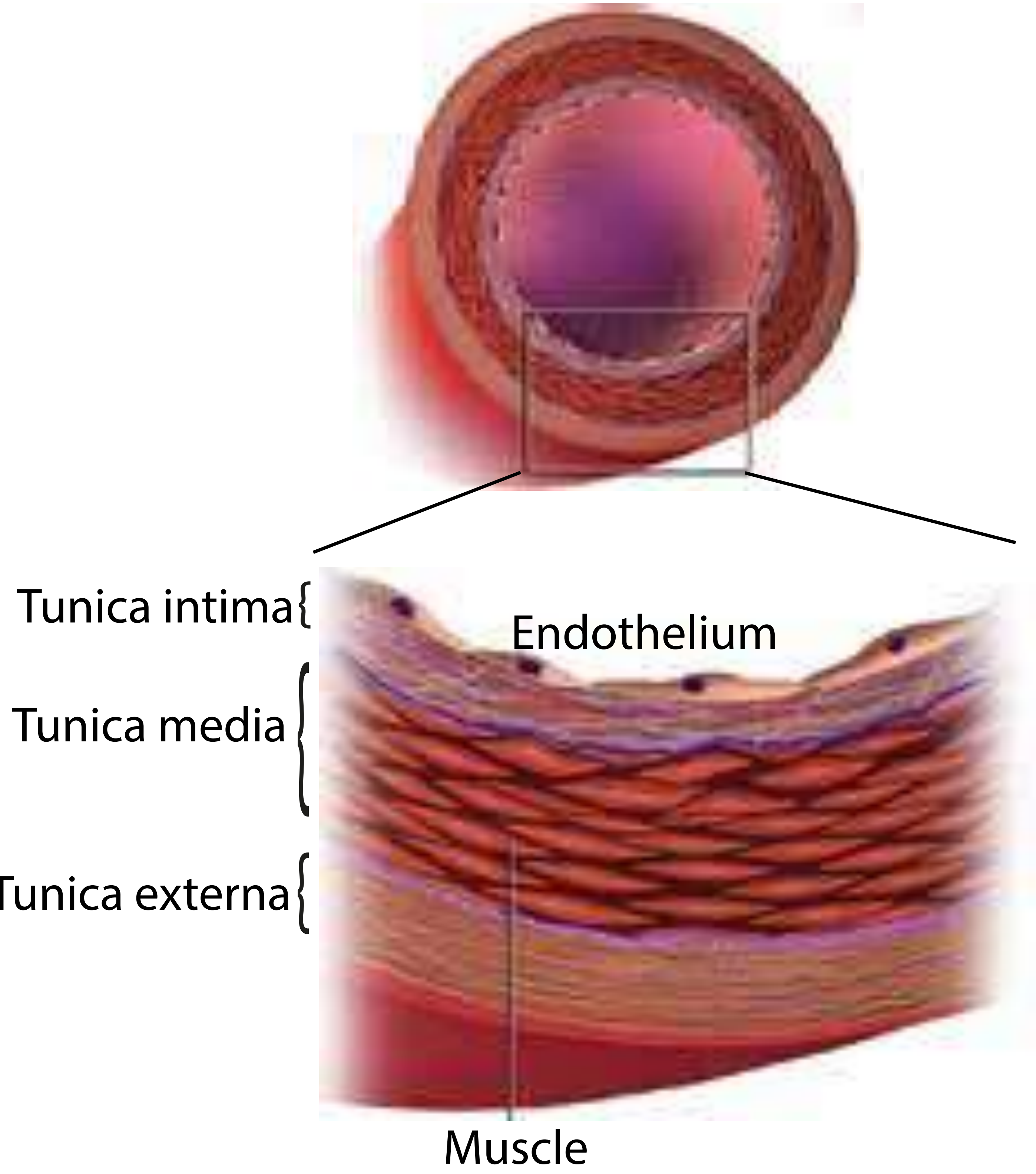


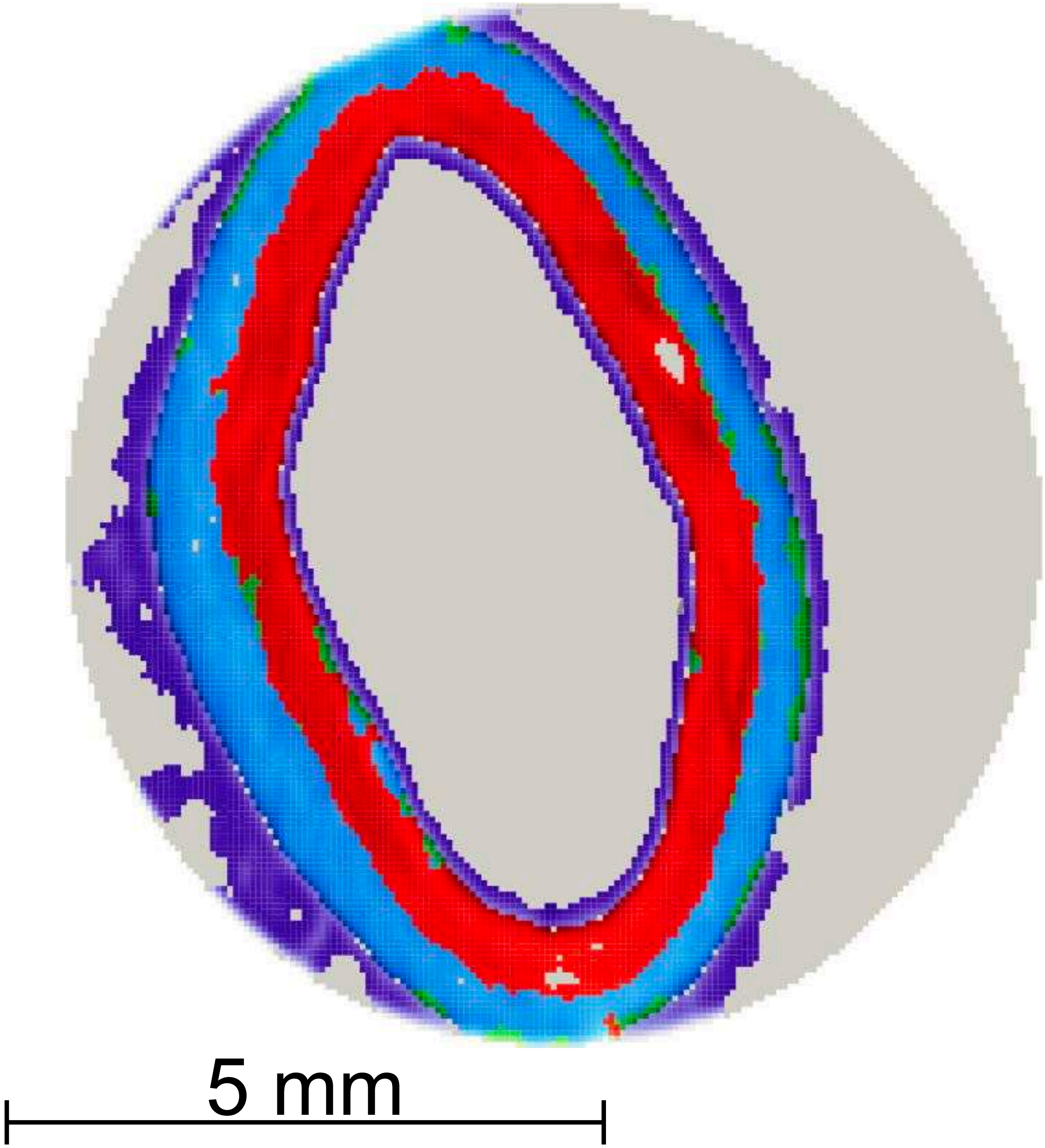
dD/dT = -66.9 kHz / K

Magnetic Resonance Imaging (MRI)

Contrast from Noise

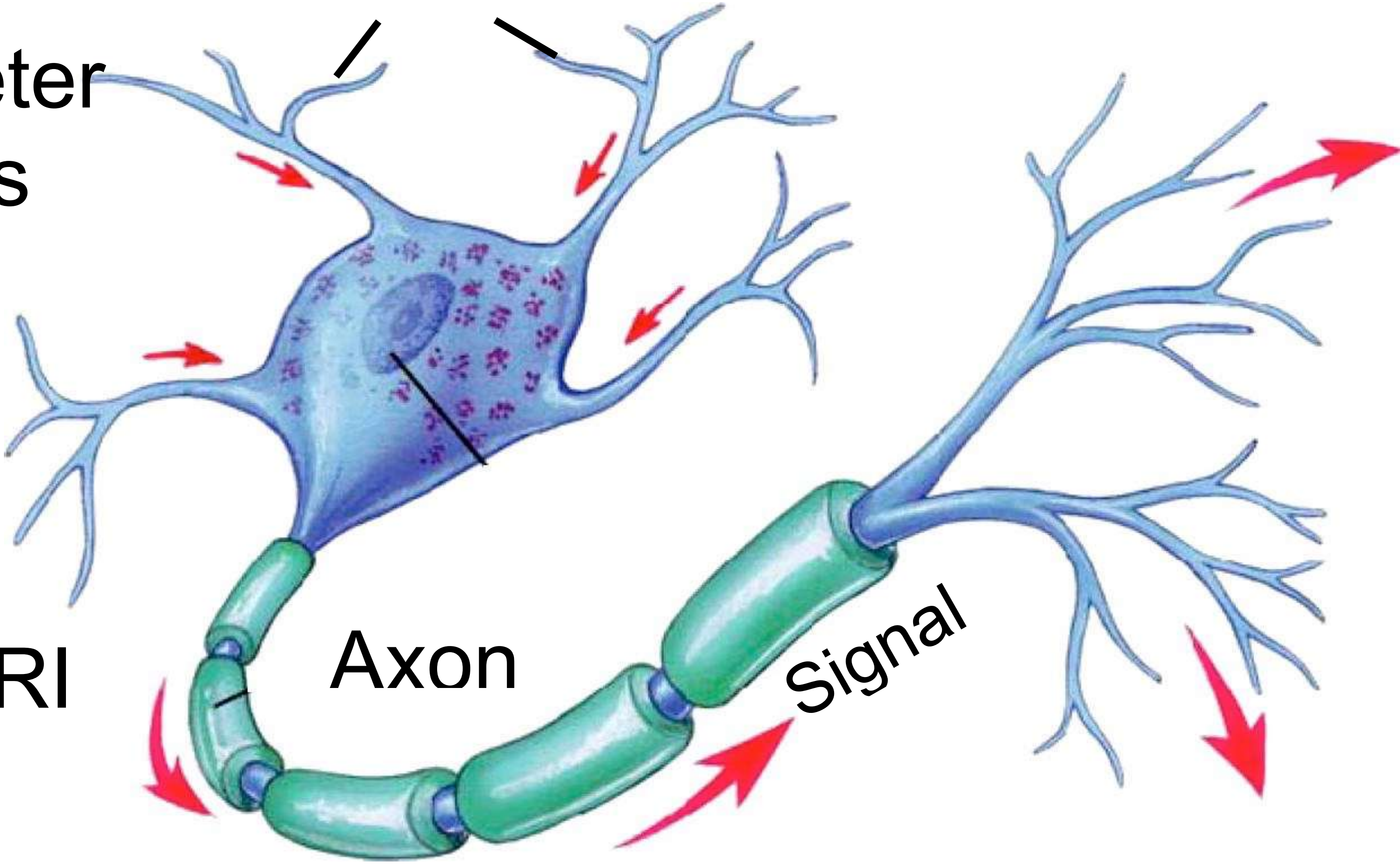
Detect differences between tissues with high resolution and contrast





Limits on Precision

Example : measure diameter and orientation of neutrons

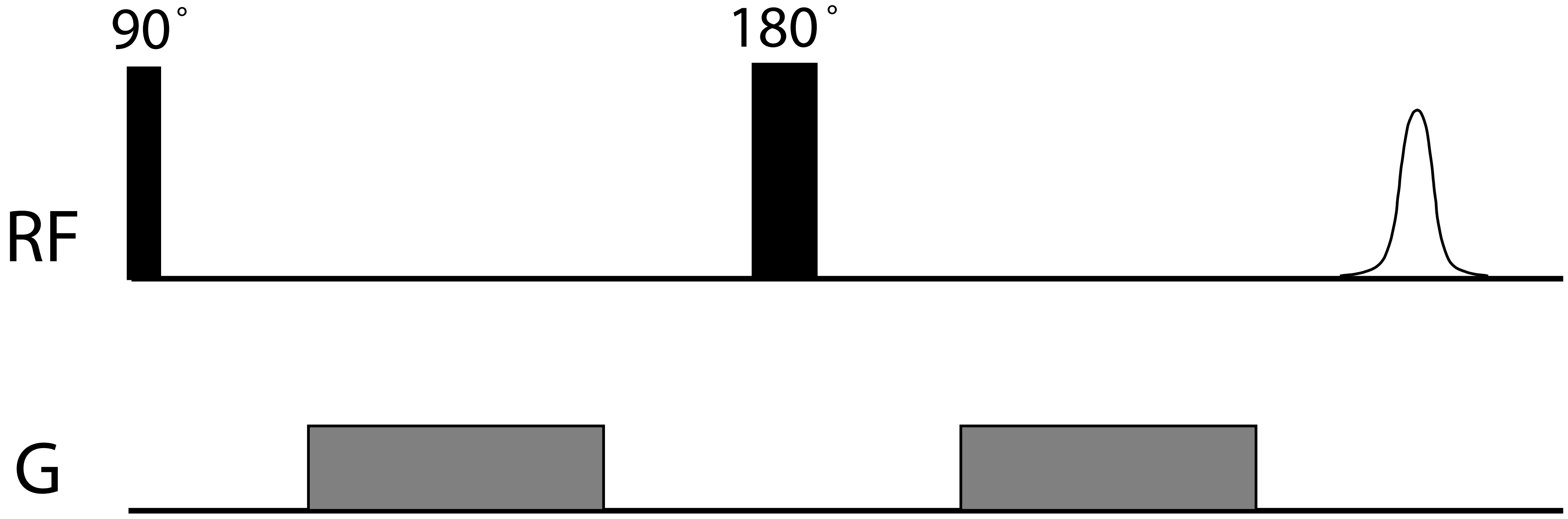


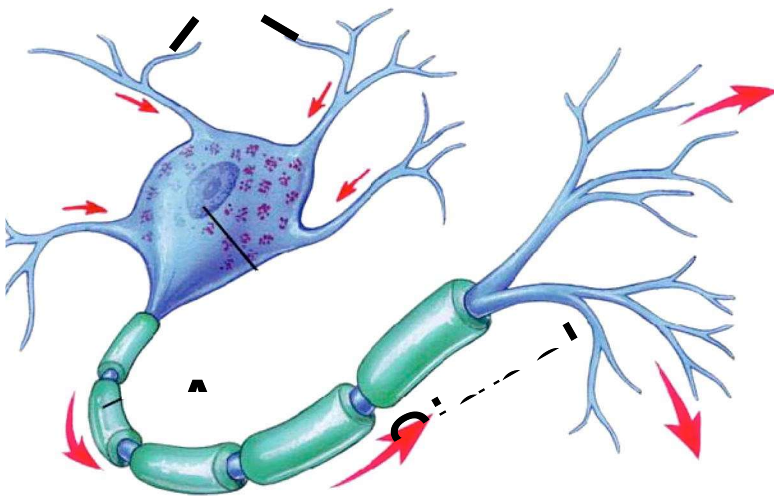
typical diameters (~µm)
are too small for direct MRI

typical diameters (~µm) can be probed by molecular diffusion

Limits on Precision

typical diameters (~µm) can be probed by molecular diffusion

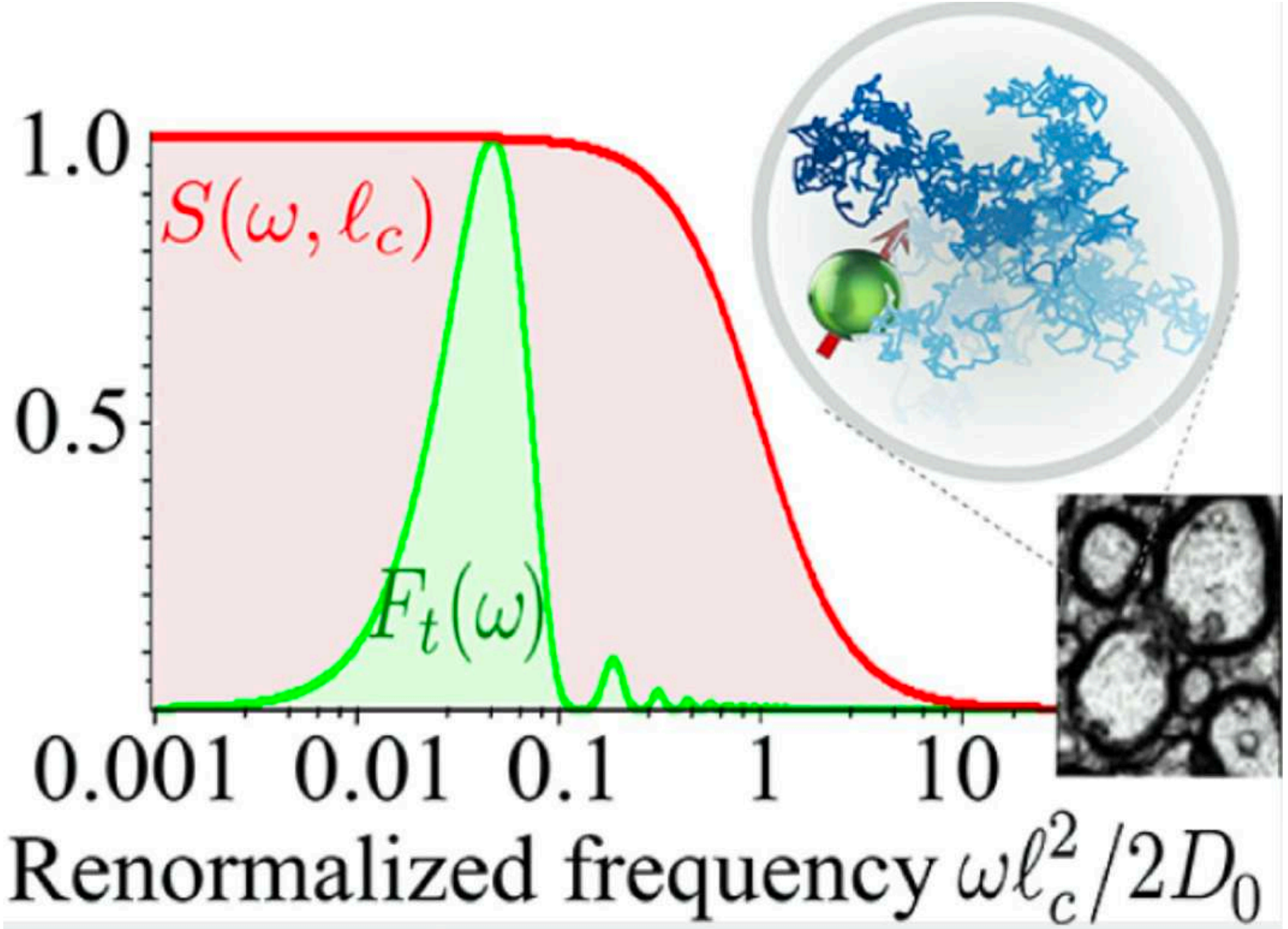




The nuclear Larmor frequency becomes a random variable

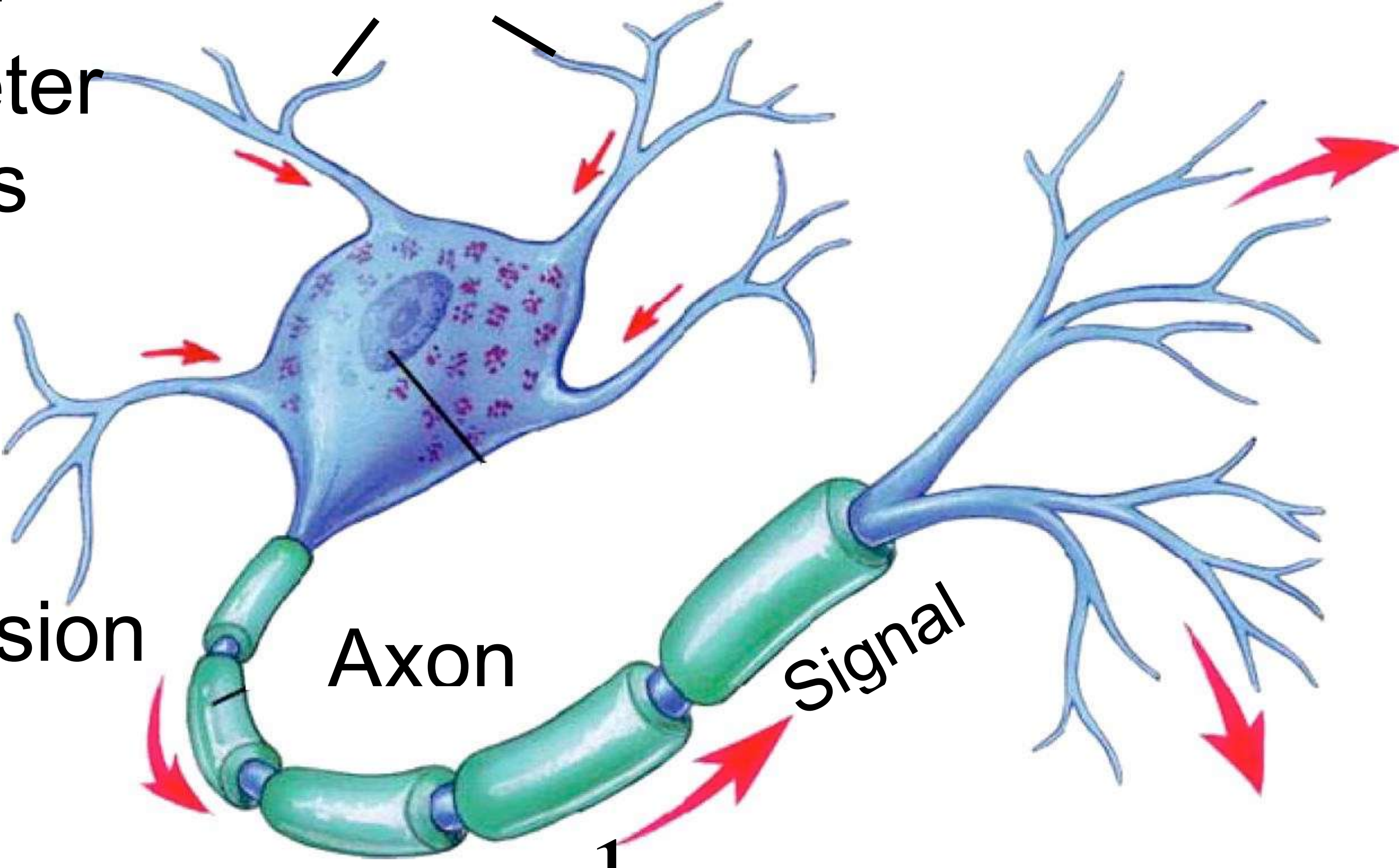
$$\omega(t) = \gamma \overrightarrow{G} \cdot \vec{r}(t)$$

Apply pulse sequence optimised for probing the distribution



Limits on Precision

Example : measure diameter and orientation of neutrons



Quantum sensing:
Measurement process determines ultimate precision

Quantum Cramér-Rao bound $(\Delta\theta)^2 \geq \frac{1}{mF_Q}$

\# repetitions

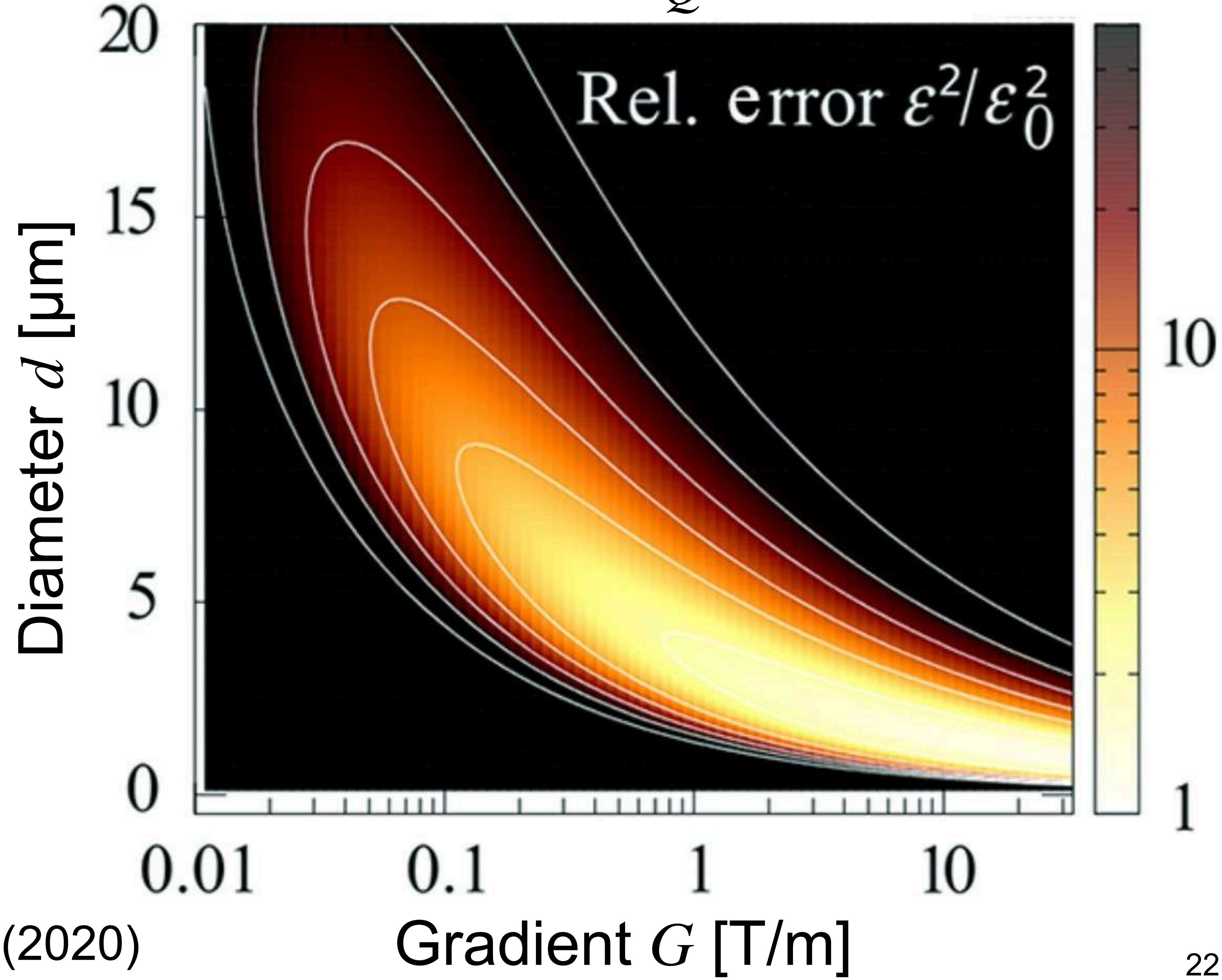
Quantum Fisher information $F_Q = 2\sum \frac{(\lambda_k - \lambda_l)^2}{\lambda_k + \lambda_l} |\langle k | A | l \rangle|^2$

Eigenvalues, Eigenvectors of ρ in eigenbasis of A

Limits on Precision

Quantum Cramér-Rao bound $(\Delta\theta)^2 \geq \frac{1}{mF_Q}$

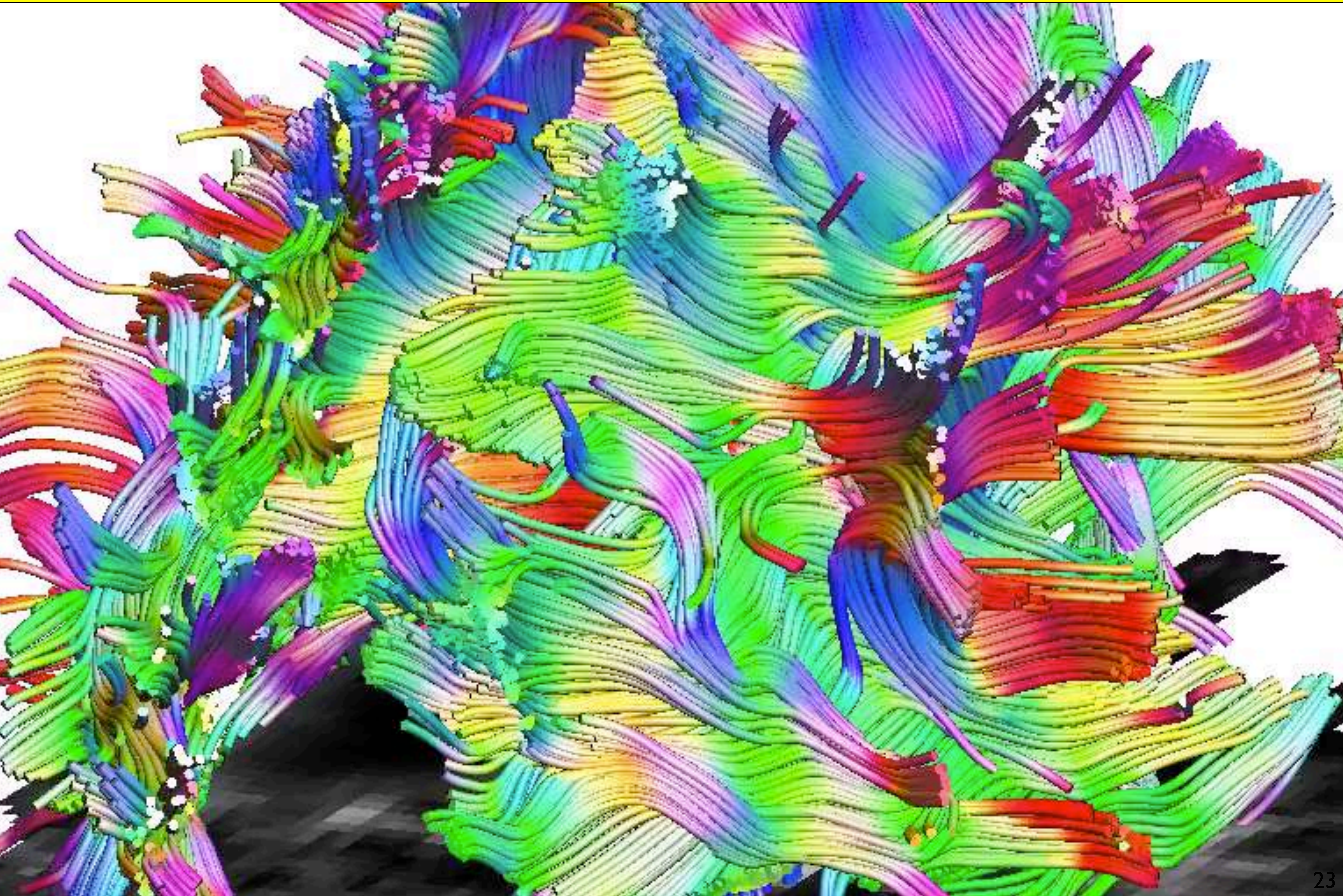
Optimal control parameters



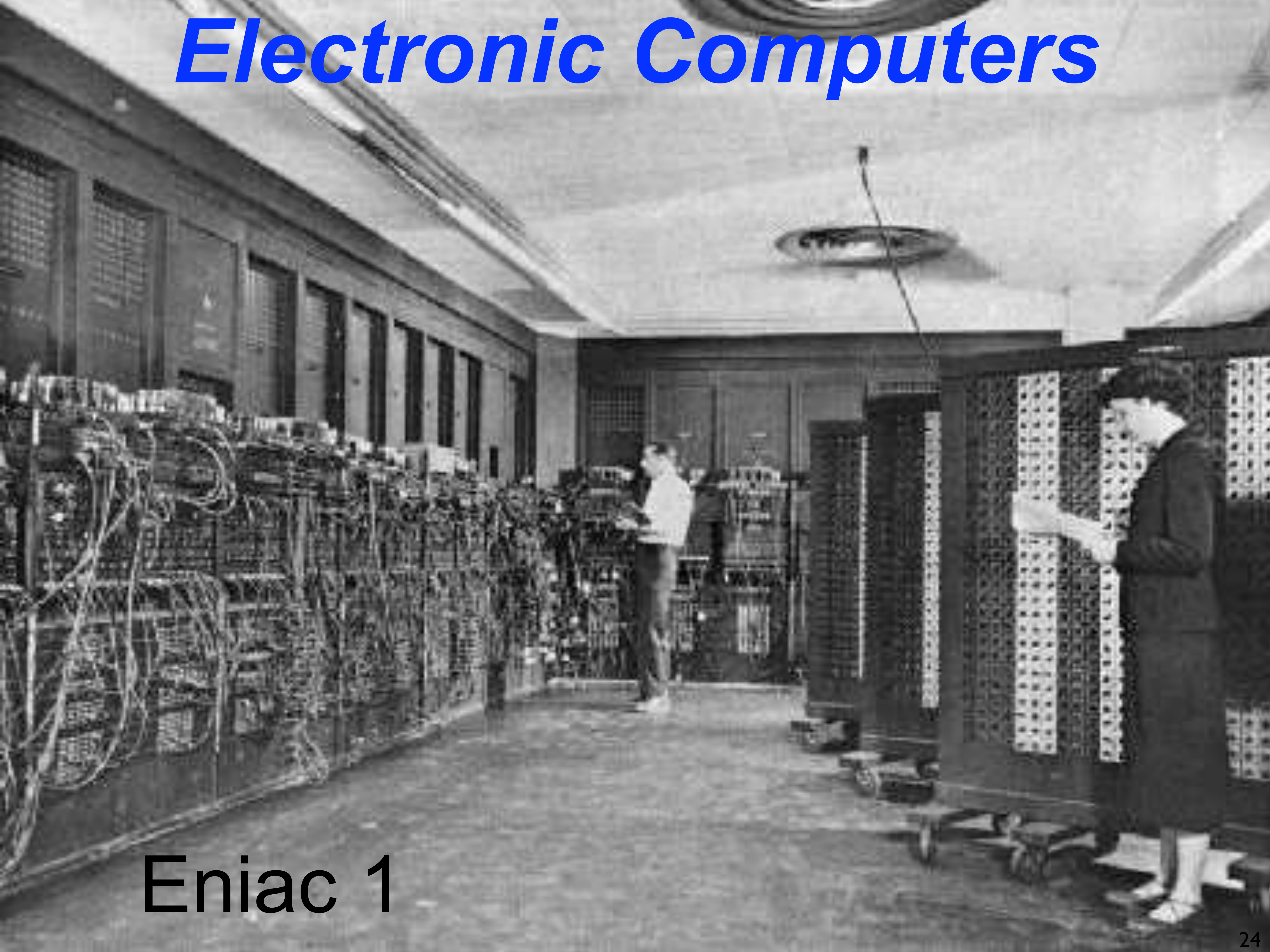
Quantum limits on diffusion-weighted measurements

PR Applied 14, 024088 (2020)

DTI Fiber Tracking



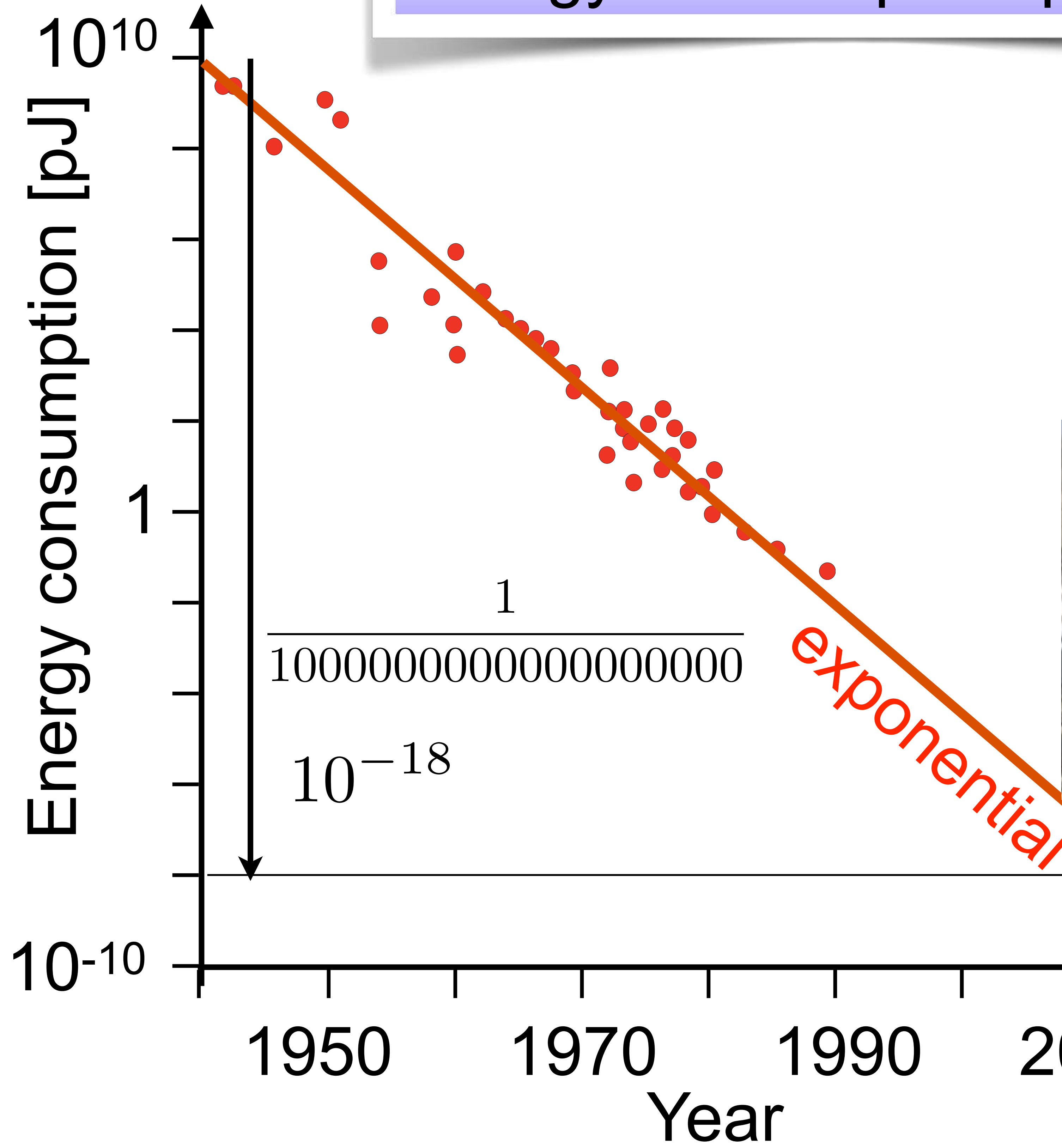
Electronic Computers



Eniac 1

Energy Consumption

Energy consumption per cycle

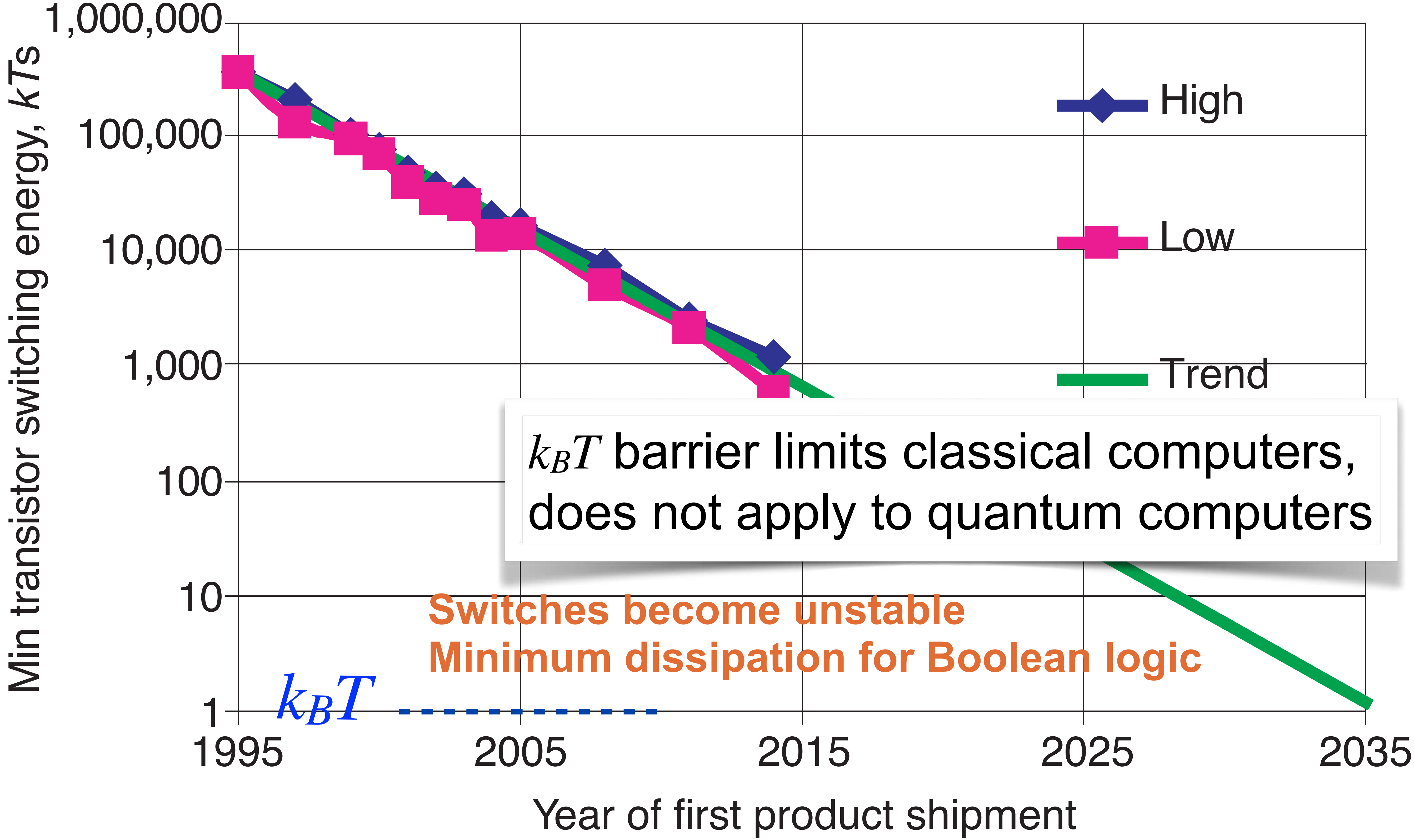


1 PC would consume ~10^{20} W = 10^{11} GW

Earth's surface covered with power stations

Distance 25 m

Switching Energy



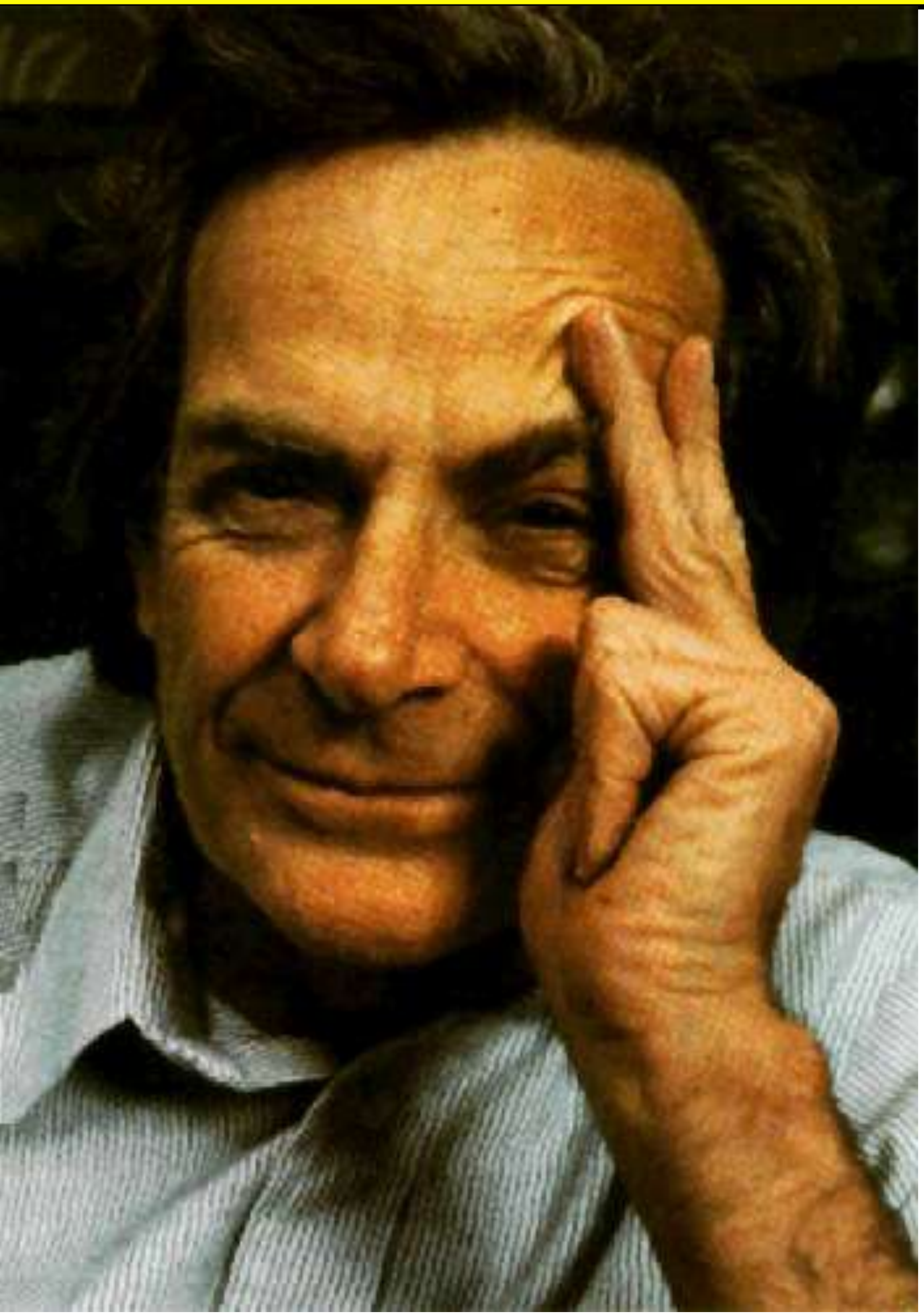
k_BT barrier limits classical computers, does not apply to quantum computers

Switches become unstable

Minimum dissipation for Boolean logic

M. P. Frank, "The physical limits of computing", Computing in Science Engineering 4, 16-26 (2002).

An Example from Physics



1982 Richard Feynman

R.P. Feynman, *'Simulating physics with computers'*, Int. J. Theor. Phys. 21, 467-488 (1982).

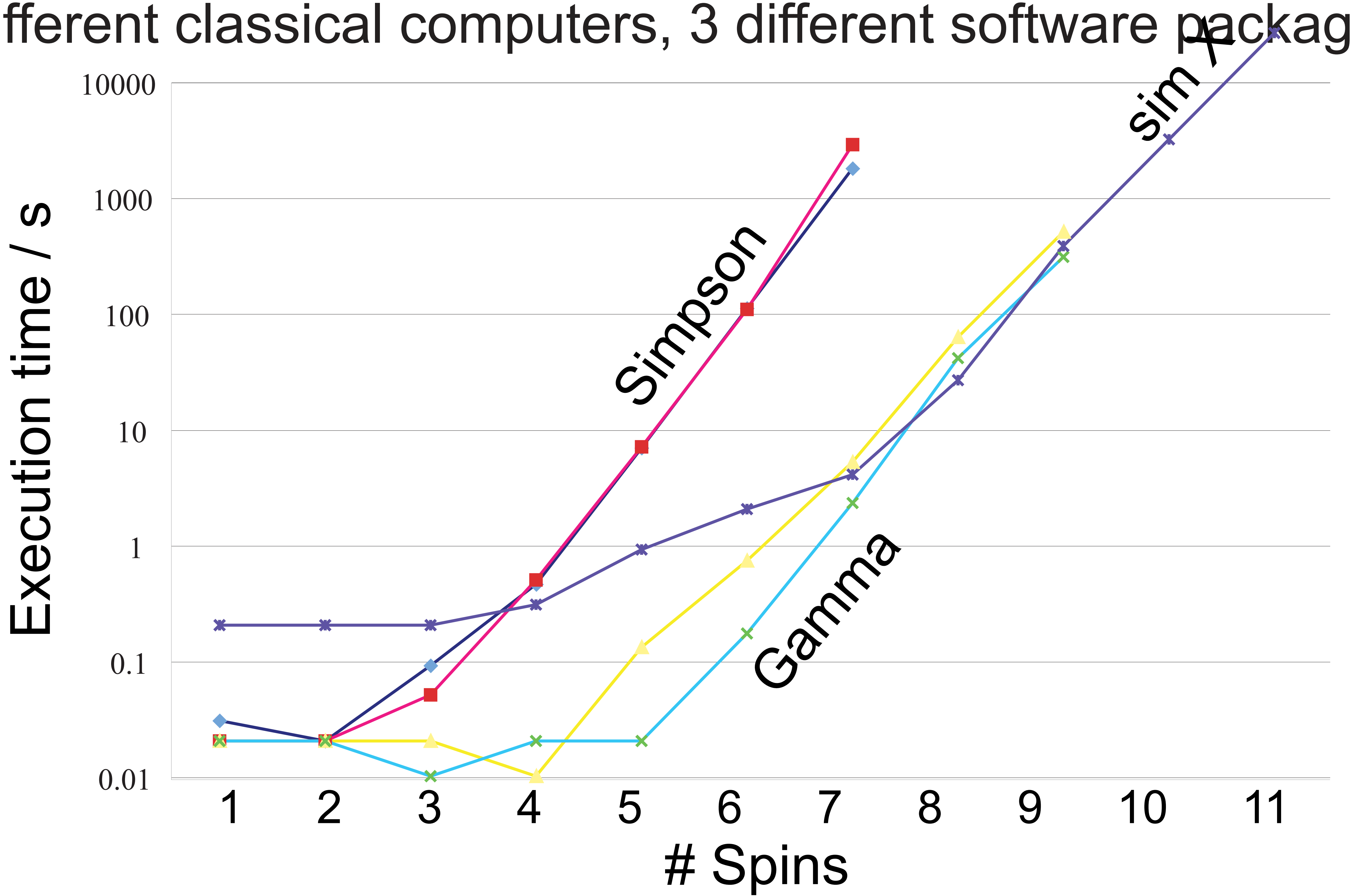
The computational power required to simulate quantum systems grows exponentially with the size of the system.

An Example from Physics

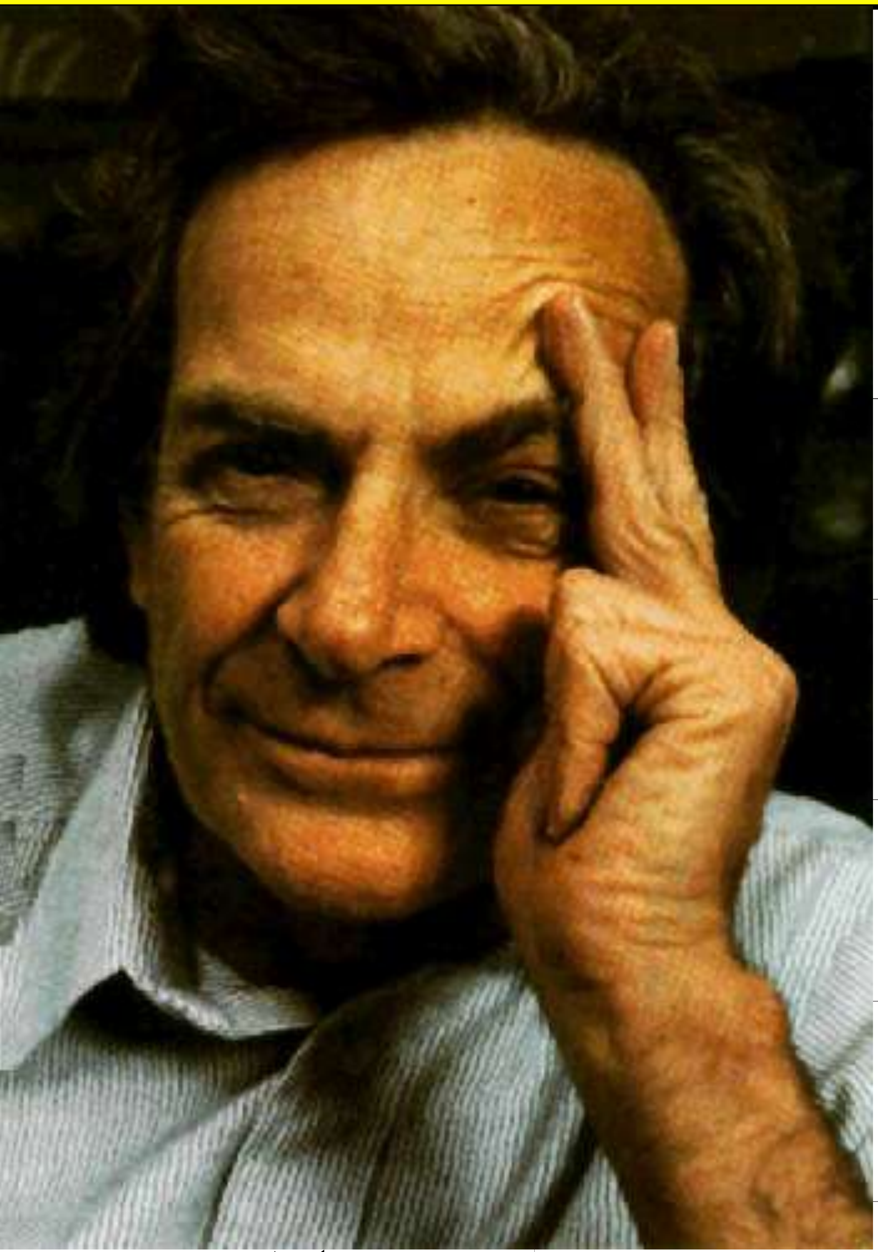
Example: Spin dynamics

2 unitary operations

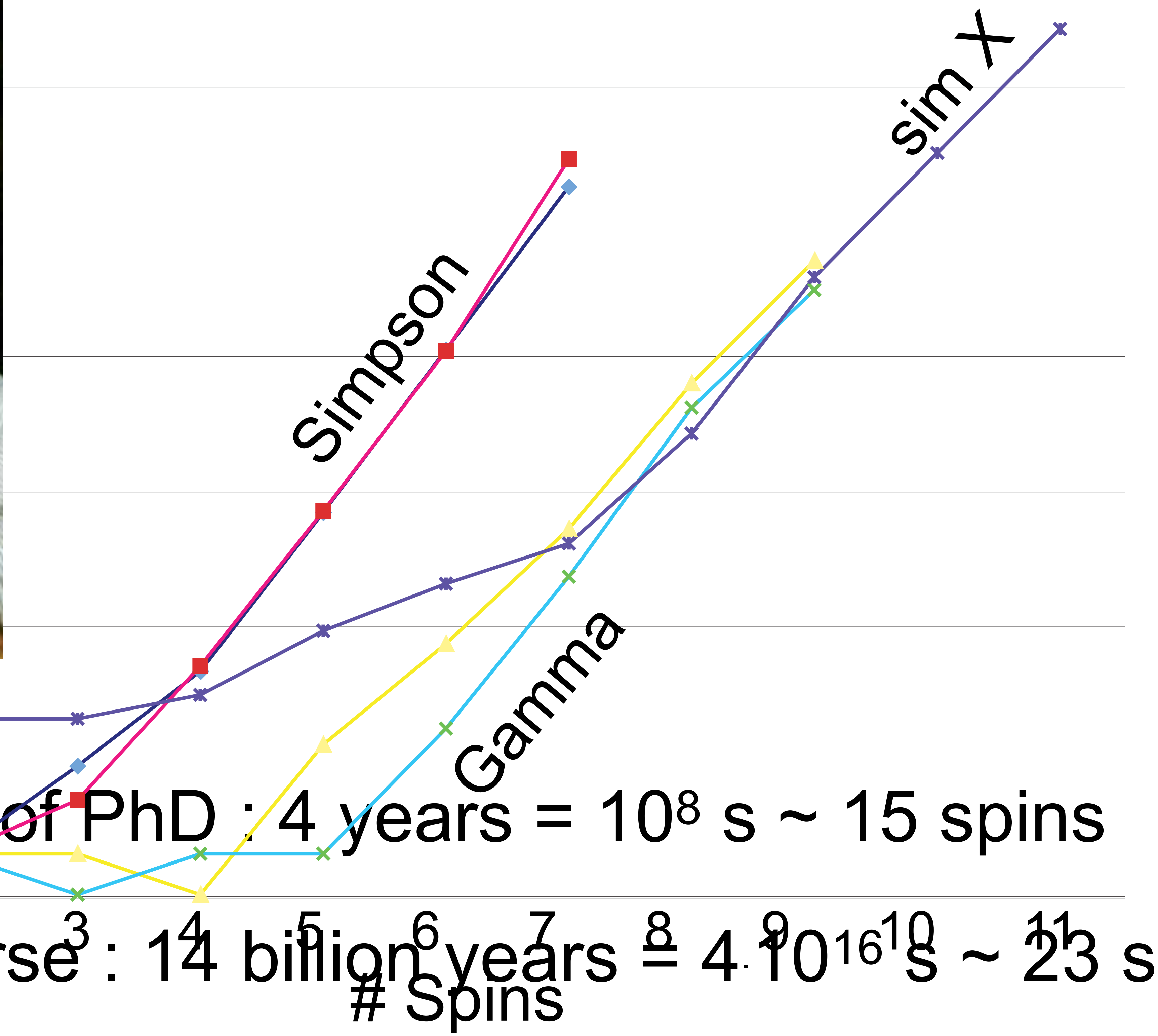
3 different classical computers, 3 different software packages



Exponential Scaling



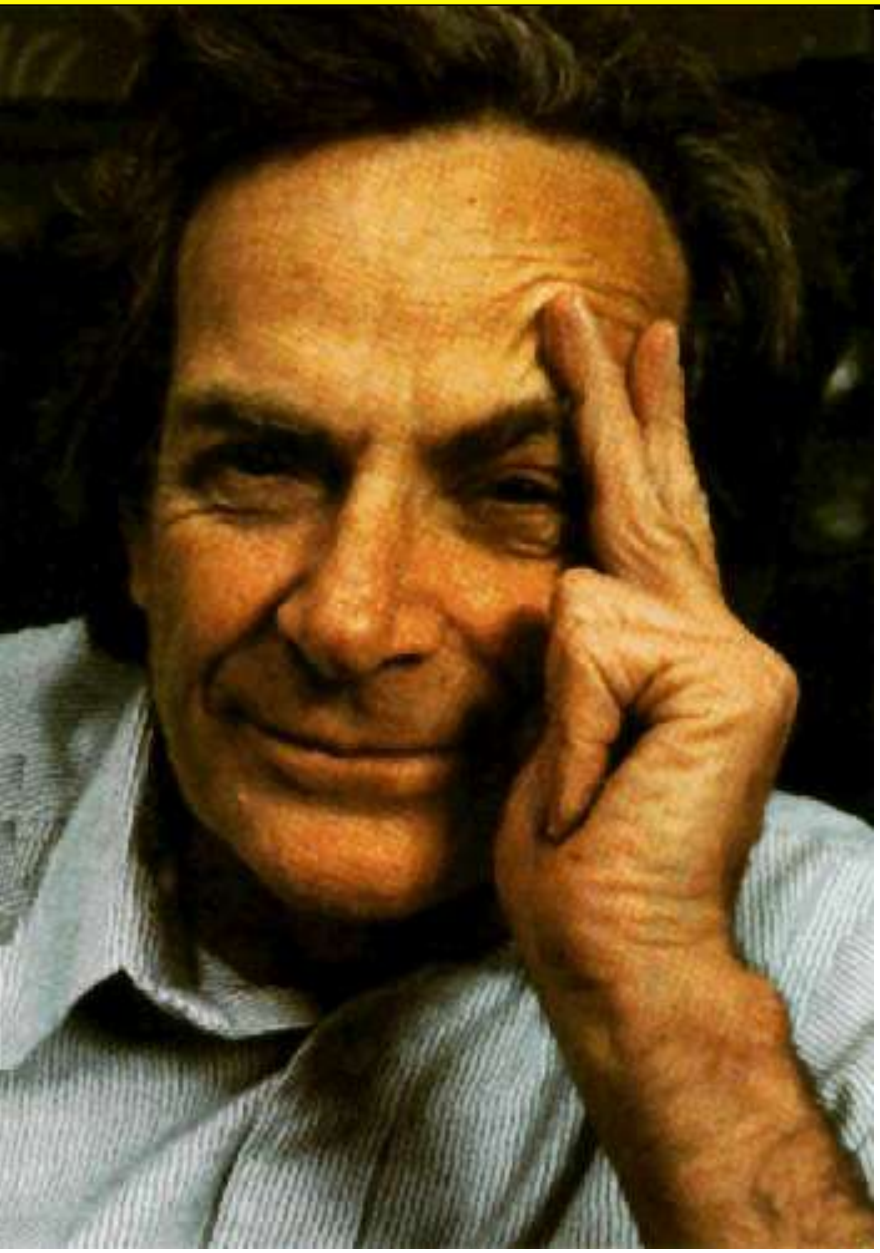
Exponential increase = inefficient



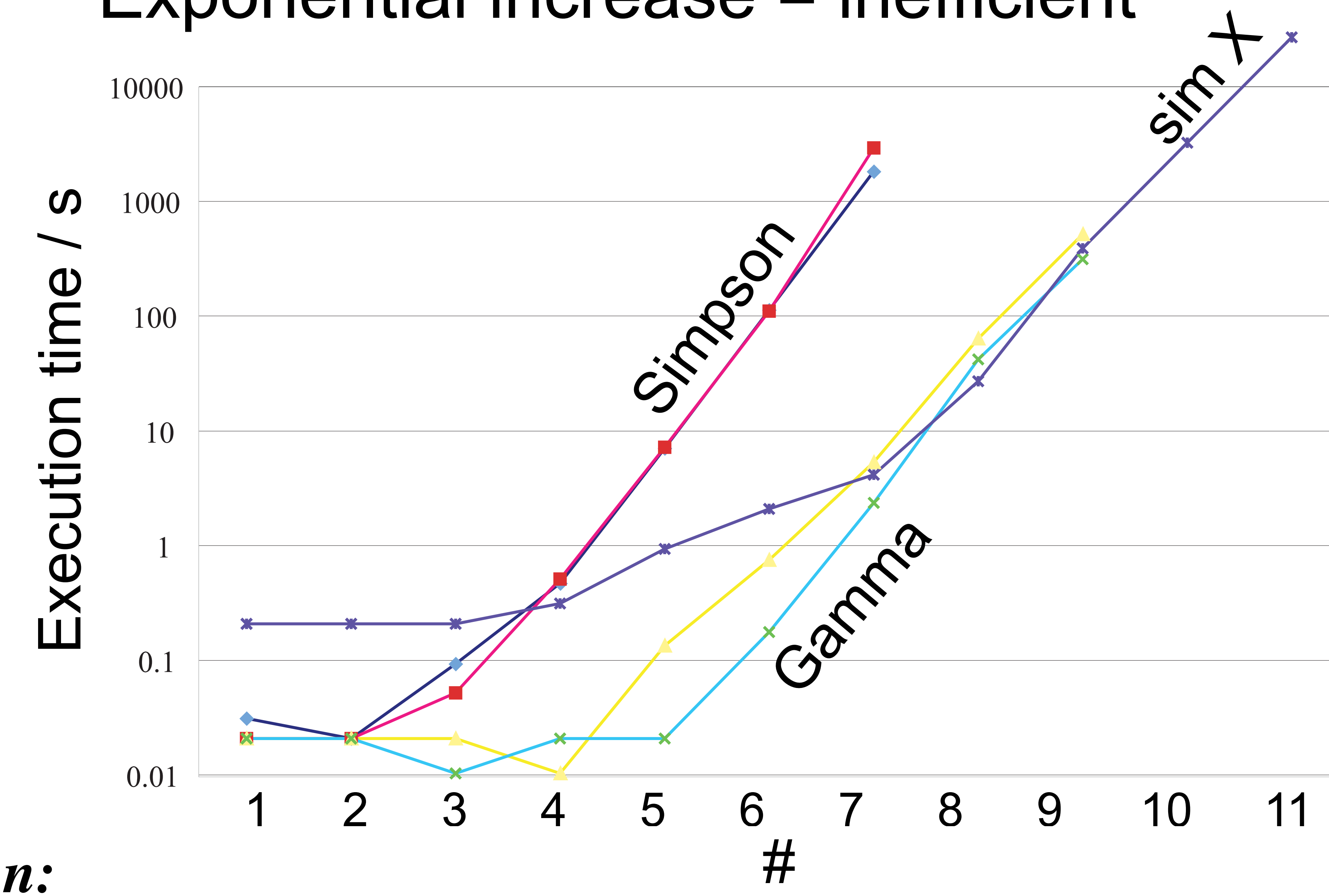
Duration of PhD : 4 years = 10^8 s ~ 15 spins

Age of universe : 14 billion years = $4 \cdot 10^{16}$ s ~ 23 spin

Feynman's Solution



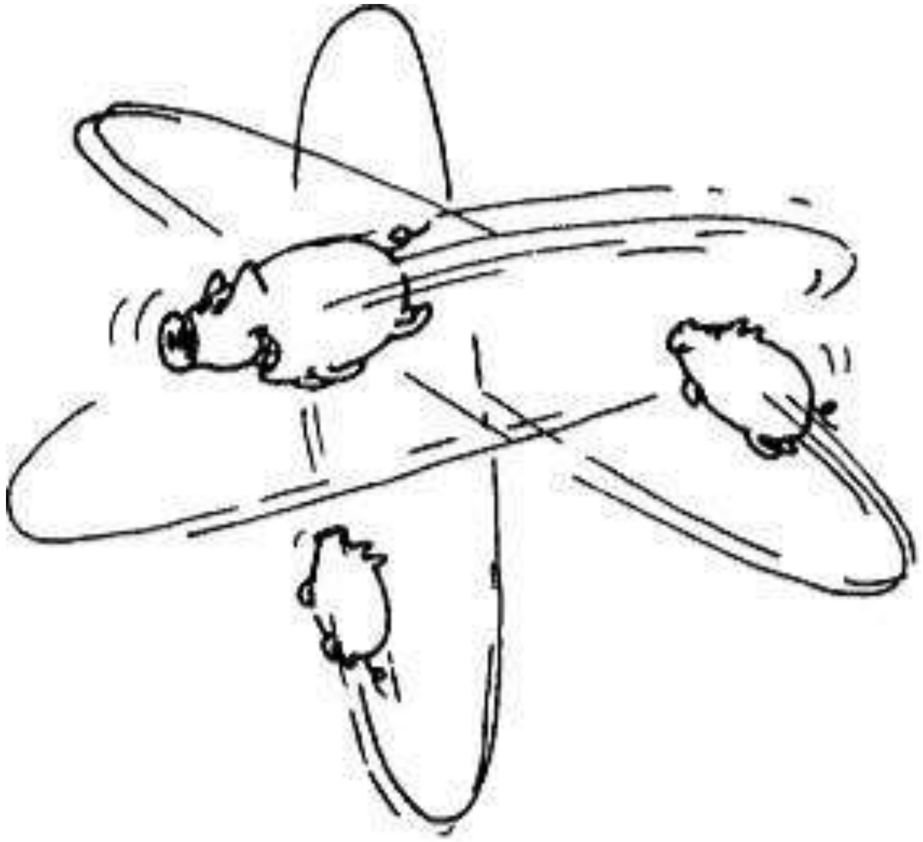
Exponential increase = inefficient



Feynman's proposed solution:

A computer is required that is itself a quantum mechanical

History of QIP



1982 Benioff:
Quantum computers are universal

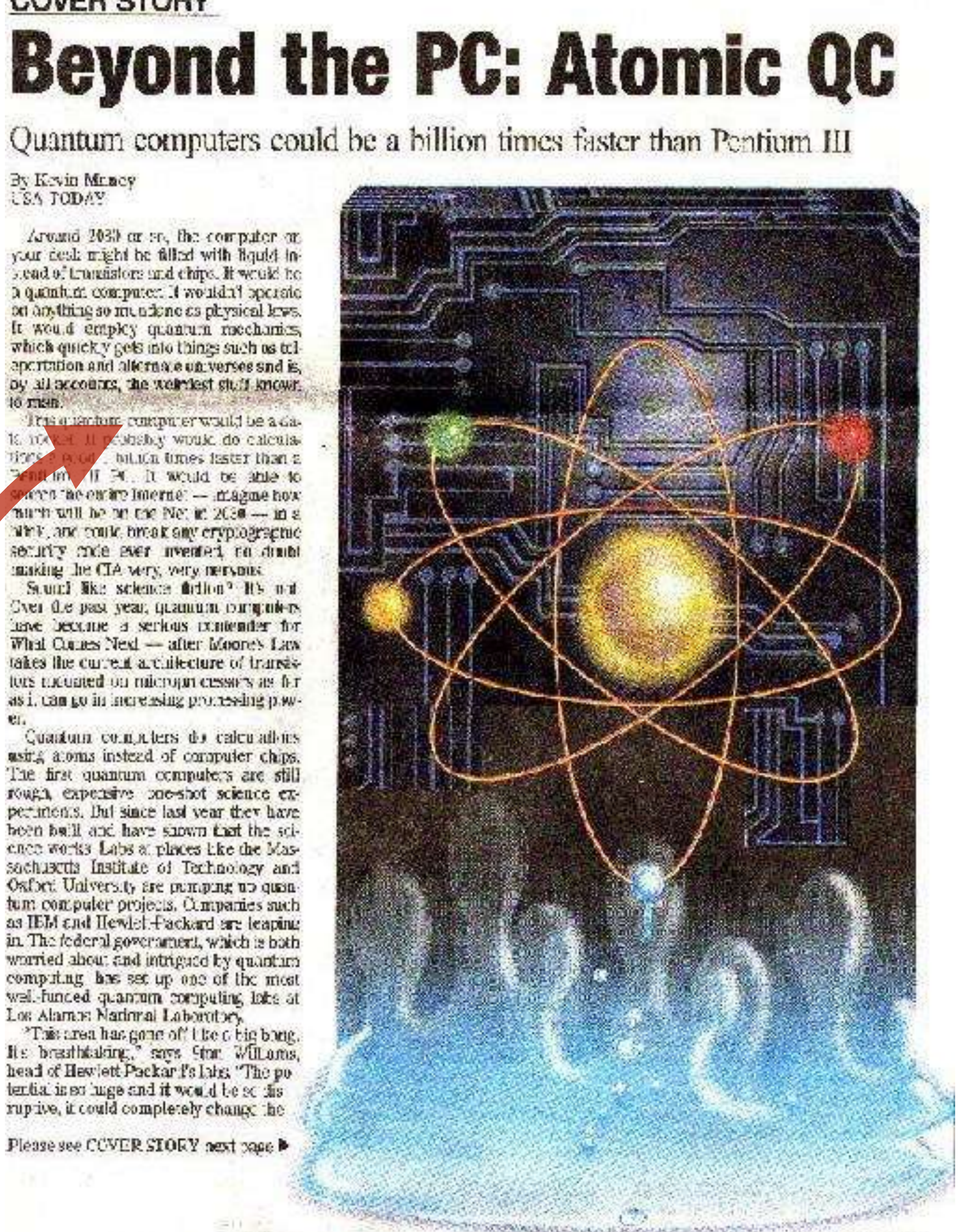
1993 Bernstein, Vazirani and Yao:
Quantum systems are more powerful than classical computers

1994 Coppersmith, Shor:
Quantum Fourier transform, factorization

1997 Gershenfeld, Chuang, Cory, Fahmy, Havel:
NMR Quantum computer

Future Computers ?

It wouldn't operate on anything so mundane as physical laws. It would employ quantum mechanics, ..



COVER STORY

Beyond the PC: Atomic QC

Quantum computers could be a billion times faster than Pentium III

By Kevin Maney
USA TODAY

Around 2030 or so, the computer on your desk might be filled with liquid instead of transistors and chips. It would be a quantum computer. It wouldn't operate on anything so mundane as physical laws. It would employ quantum mechanics, which quickly gets into things such as teleportation and alternate universes and is, by all accounts, the weirdest stuff known to man.

This quantum computer would be a [illegible] rocket. It probably would do calculations a good billion times faster than a Pentium III PC. It would be able to search the entire Internet — imagine how much will be on the Net in 2030 — in a blink, and could break any cryptographic security code ever invented, no doubt making the CIA very, very nervous.

Sound like science fiction? It's not. Over the past year, quantum computers have become a serious contender for What Comes Next — after Moore's Law takes the current architecture of transistors mounted on microprocessors as far as it can go in increasing processing power.

Quantum computers do calculations using atoms instead of computer chips. The first quantum computers are still rough, expensive one-shot science experiments. But since last year they have been built and have shown that the science works. Labs at places like the Massachusetts Institute of Technology and Oxford University are pumping up quantum computer projects. Companies such as IBM and Hewlett-Packard are leaping in. The federal government, which is both worried about and intrigued by quantum computing, has set up one of the most well-funded quantum computing labs at Los Alamos National Laboratory.

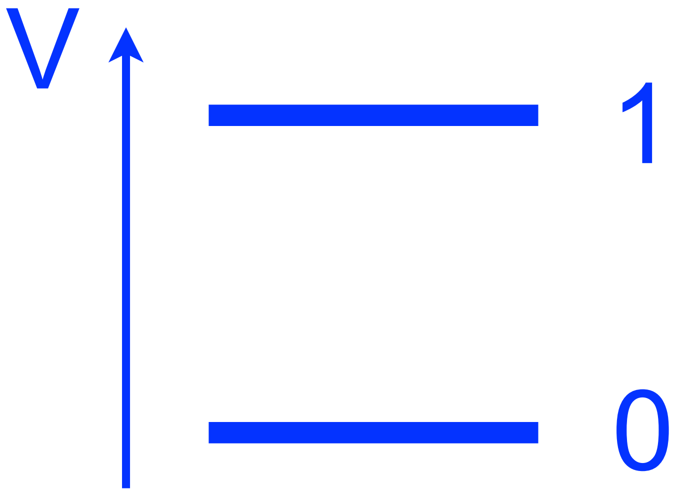
"This area has gone off like a big bang. It's breathtaking," says Stan Williams, head of Hewlett-Packard's labs. "The potential is so huge and it would be so disruptive, it could completely change the

Please see COVER STORY next page ▶

Digital Information

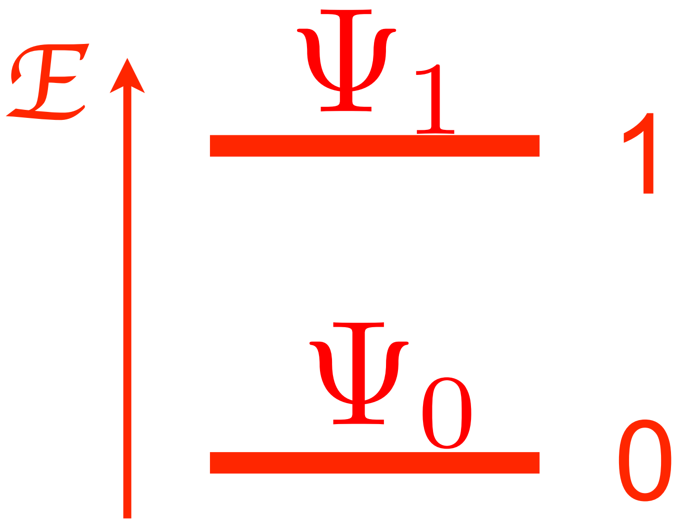
Classical

2 different voltages encode 1 bit



Quantum mechanical

2 orthogonal quantum states encode 1 bit



or

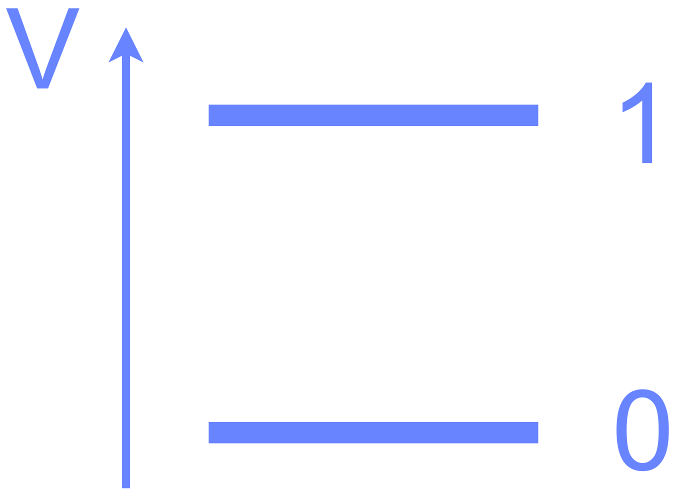
“Qubit”

superposition

Quantum Information

Classical

2 different voltages encode 1 bit



Quantum mechanical

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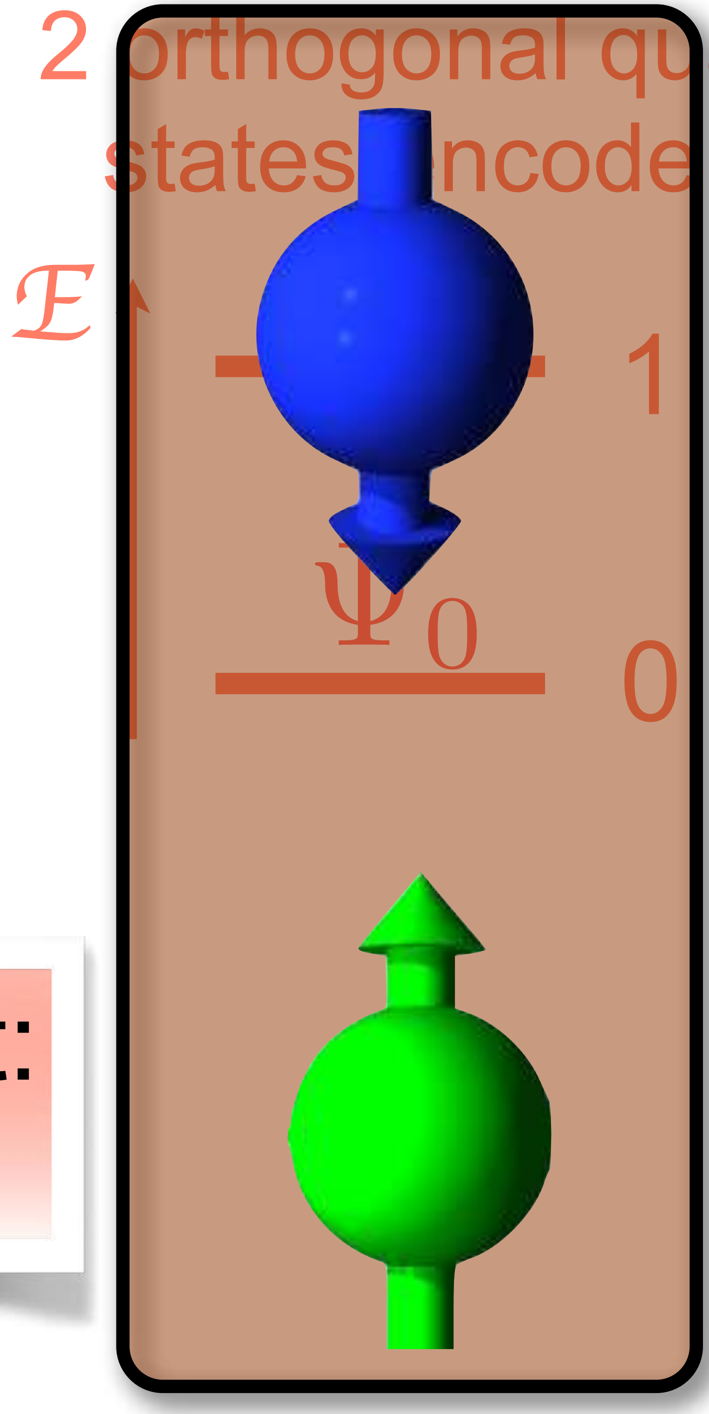
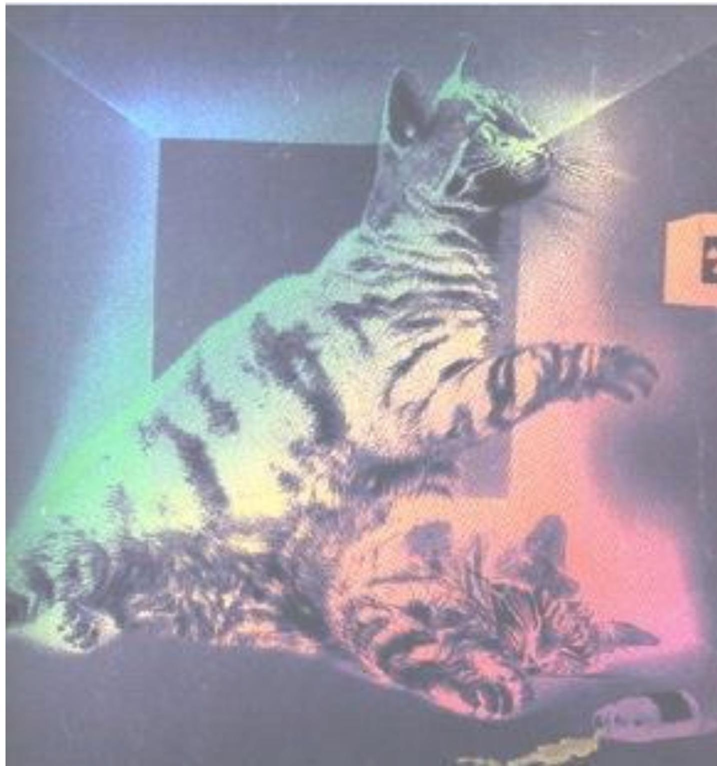


or

“Qubit”

superposition

Natural Qubit:
Spin 1/2

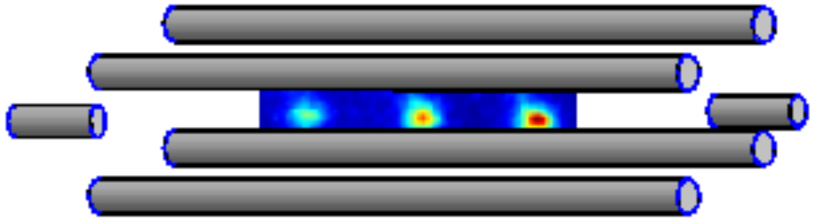


Information Processing

Quantum register

Logical operation

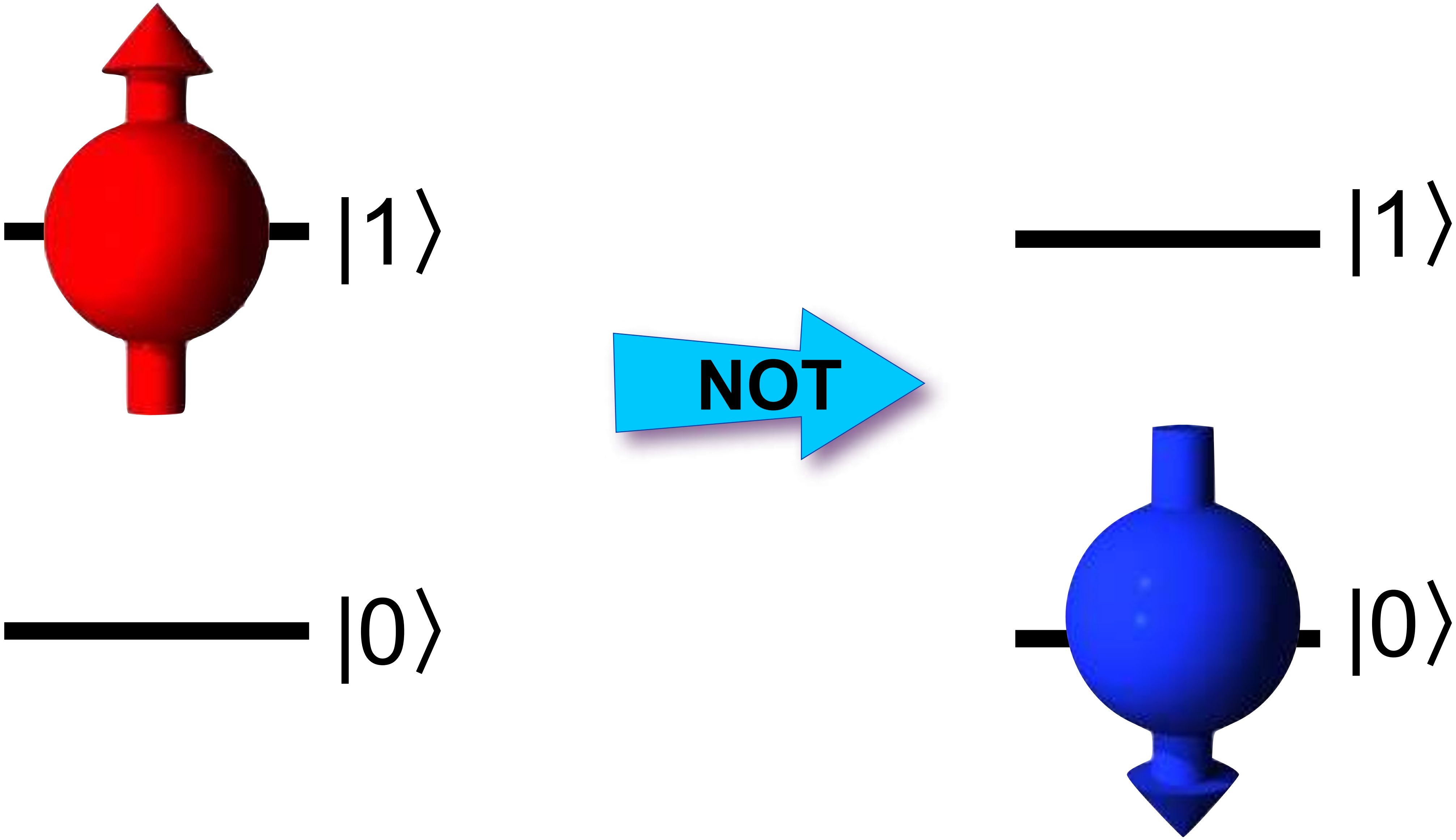
$$\Psi_{out} = U\Psi_{in}$$



- Quantum logical operations are reversible
- No dissipation
- Logical operations driven by control fields

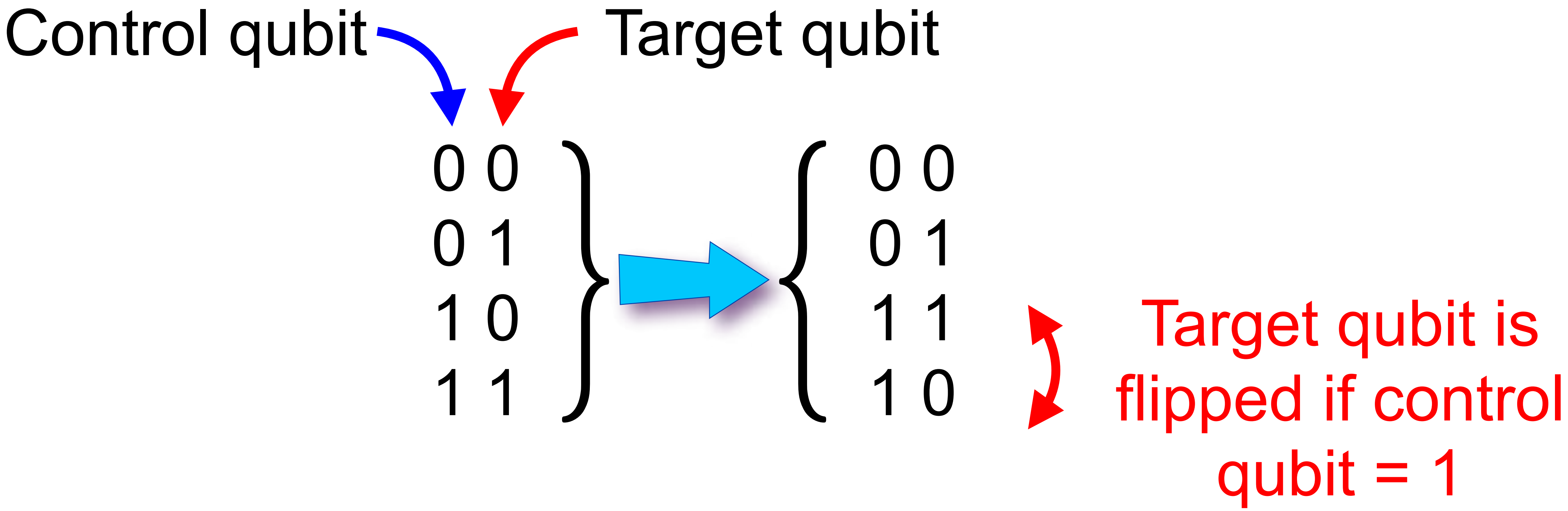
Gates for Qubits

1 qubit, e.g. NOT



2 Qubit Gates

e.g. CNOT



Control qubit

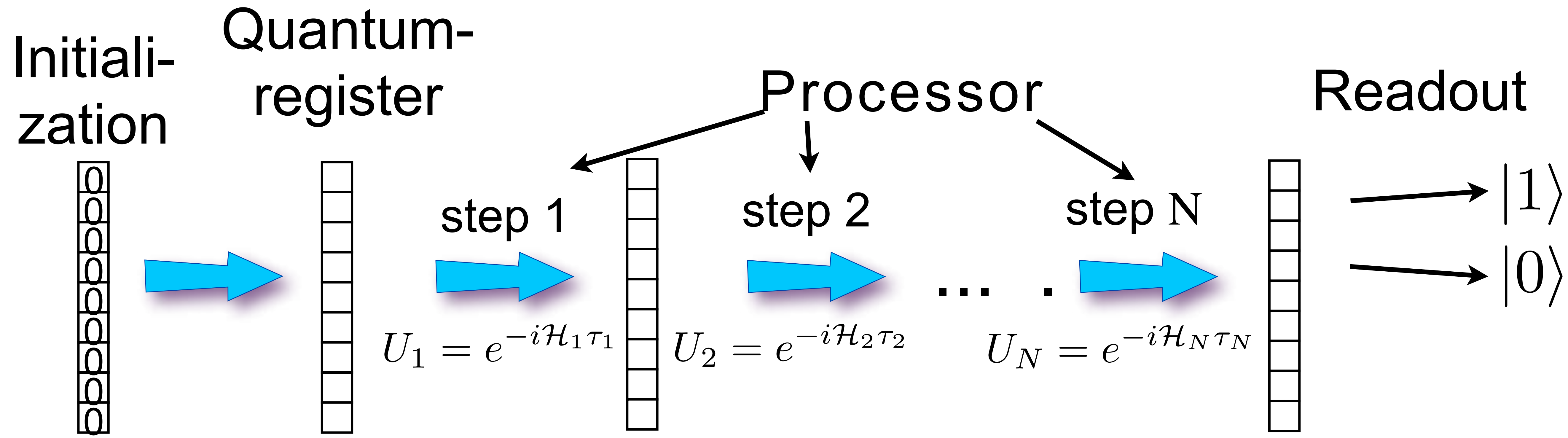
Target qubit

0 0	0 0
0 1	0 1
1 0	1 1
1 1	1 0

Target qubit is flipped if control qubit = 1

Basics of Quantum Computing

The network model



Initialization

Quantum-register

Processor

Readout

0 0 0 0 0 0 0 0 0

step 1

$U_1 = e^{-i\mathcal{H}_1\tau_1}$

step 2

$U_2 = e^{-i\mathcal{H}_2\tau_2}$

… .

step N

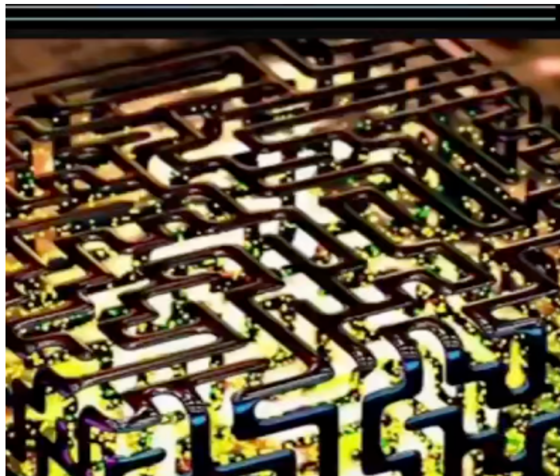
$U_N = e^{-i\mathcal{H}_N\tau_N}$

$|1\rangle$

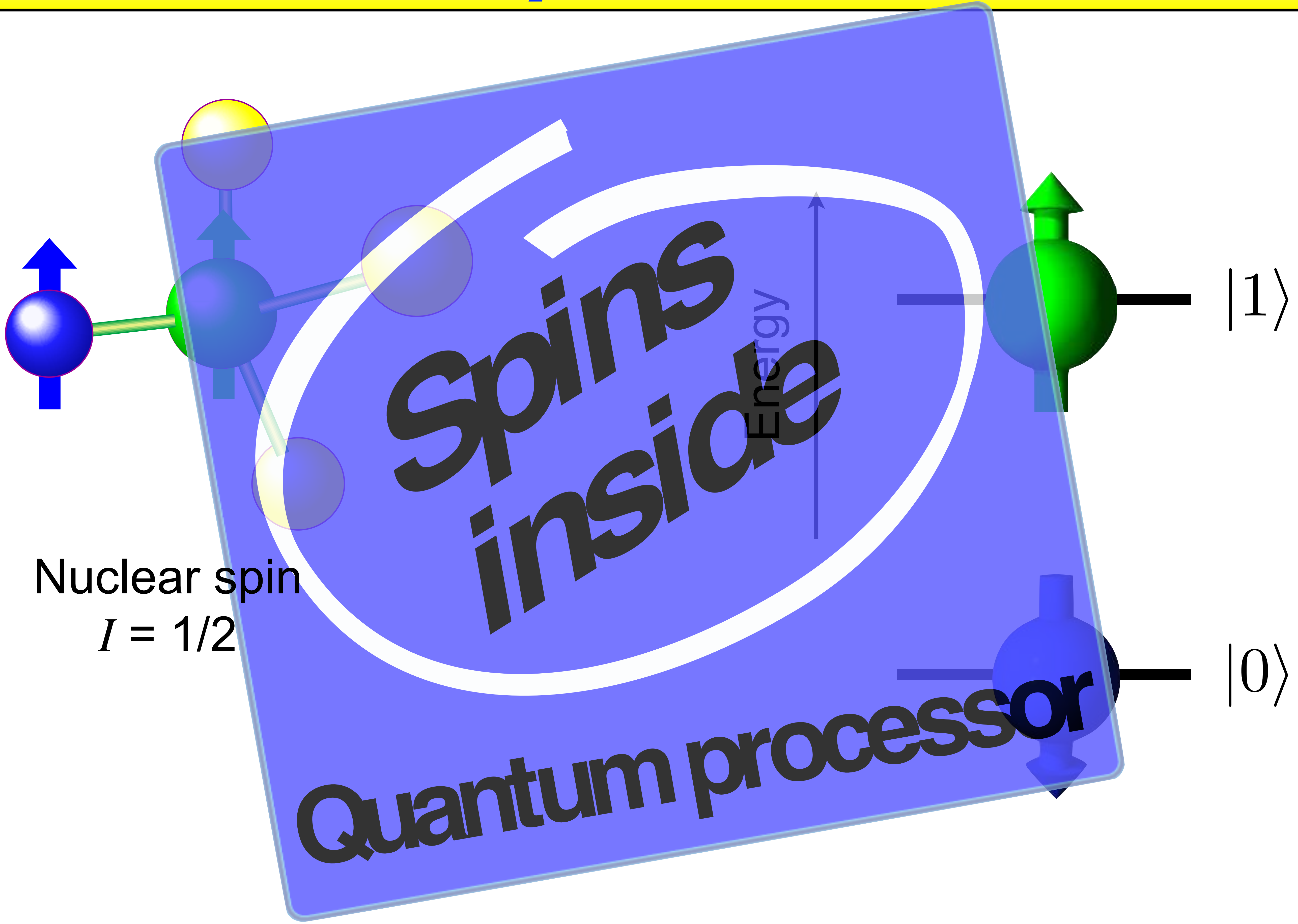
$|0\rangle$

- The power of the implementation depends on the number of qubits in the quantum register: N qubits provide 2^N computational basis states
- Logical operations act on superposition states

→ "Quantum parallelism"



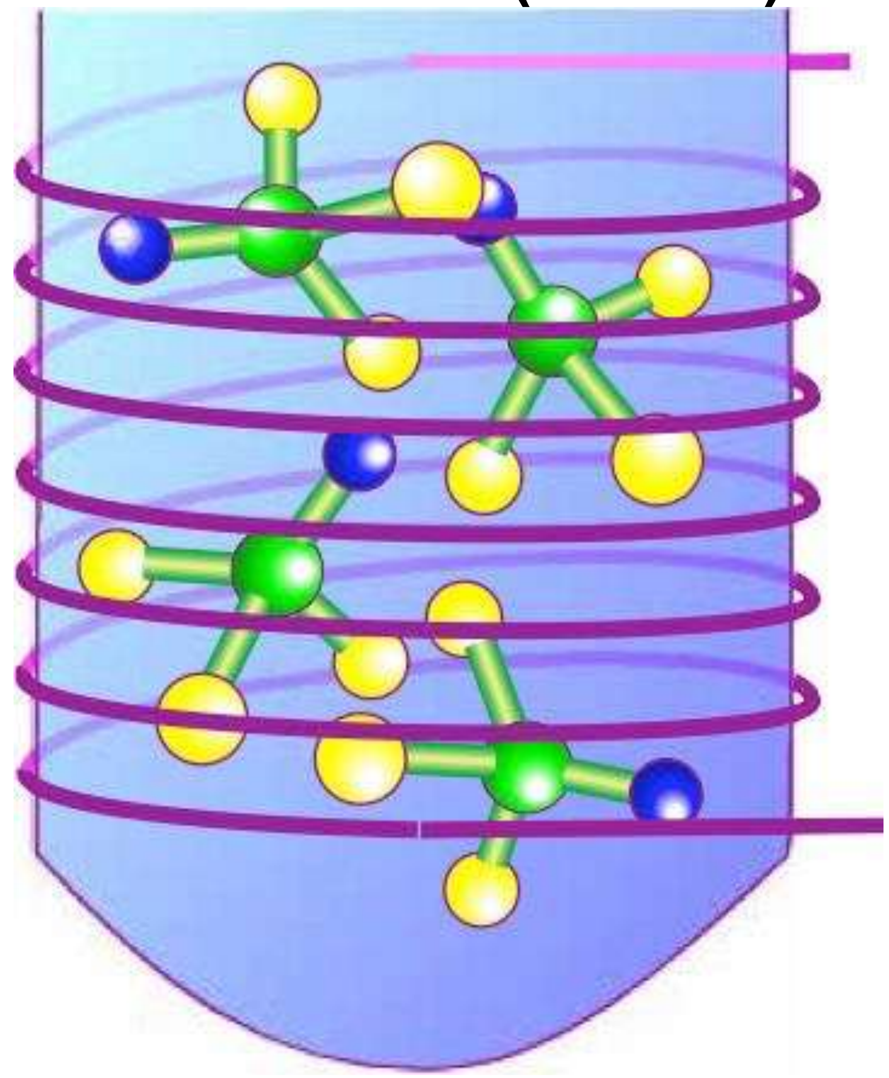
Nuclear Spins as Qubits



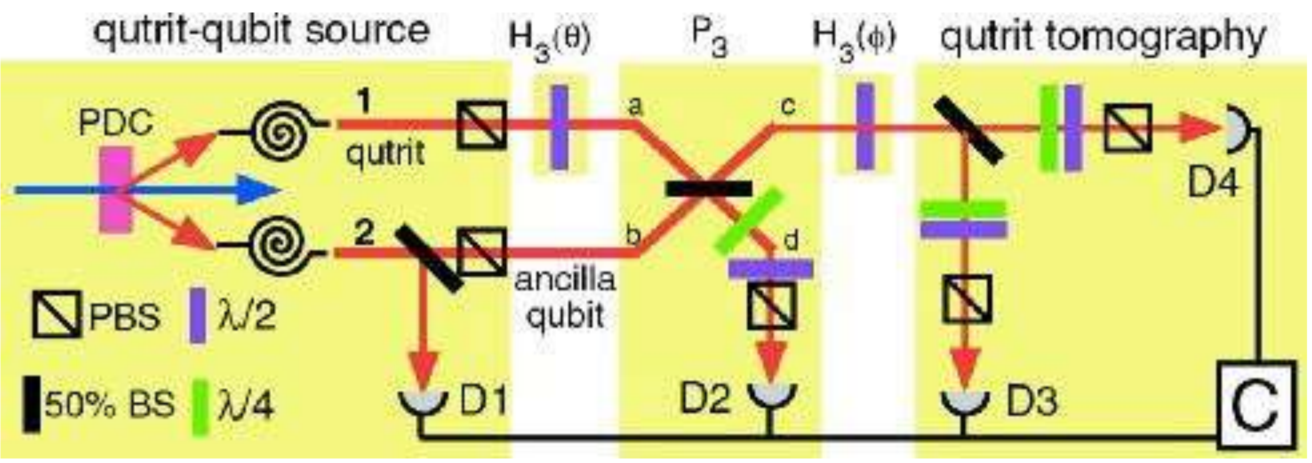
Nuclear spin
I = 1/2

Implementations

- Nuclear Magnetic Resonance (NMR)

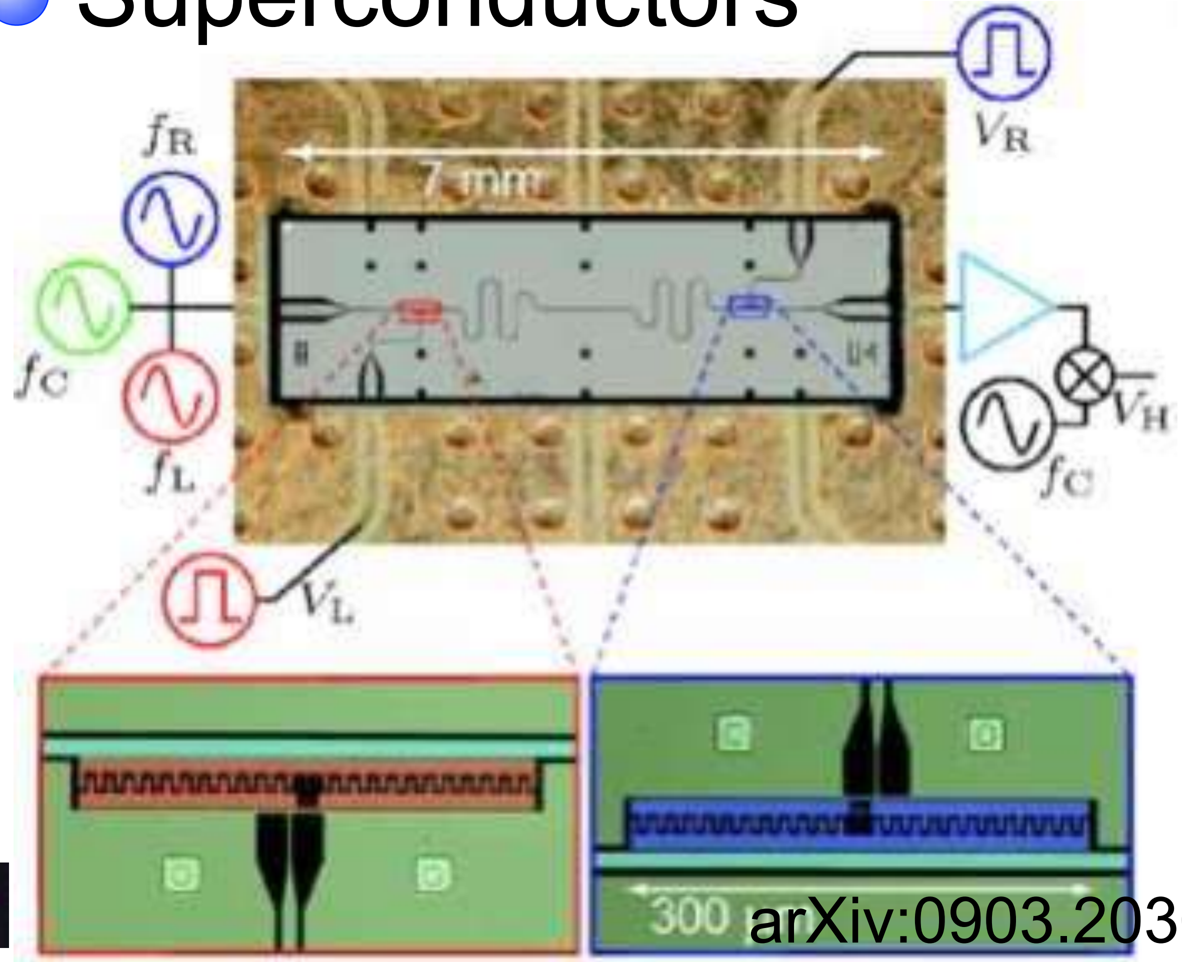


- Photons



PRL 100, 060504 (2008)

- Superconductors



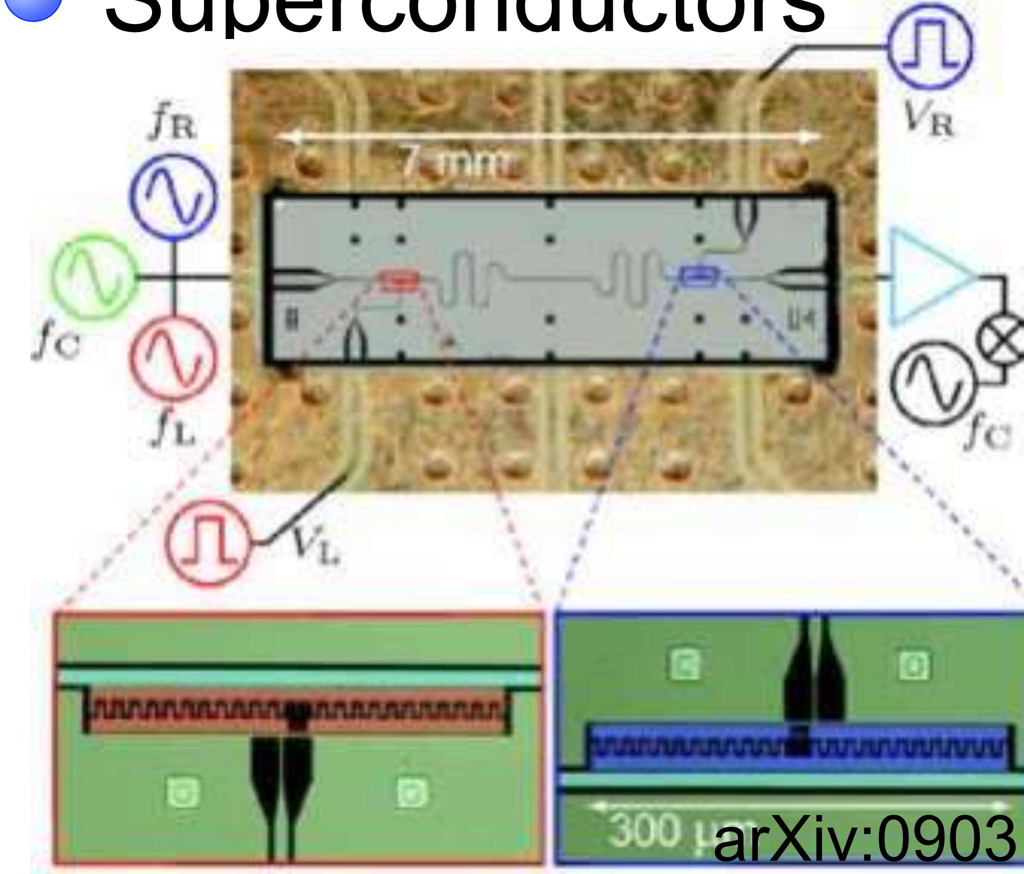
arXiv:0903.2030

- Trapped Ions

... and more, e.g. neutral atoms, defects in solids, quantum dot

Implementations

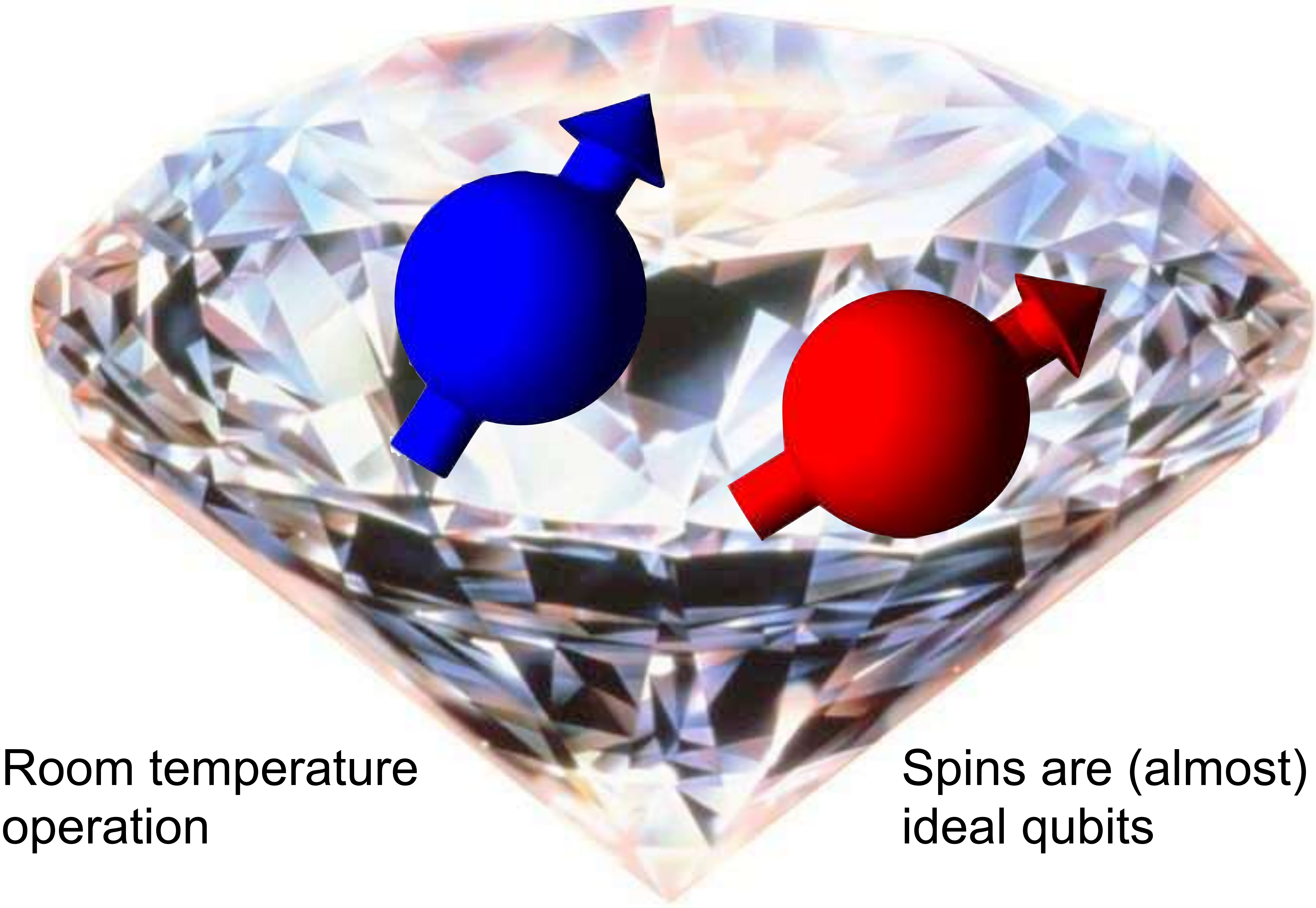
- Superconductors



arXiv:0903

The Nobel Prize in Physics 2025 was awarded jointly to John Clarke, Michel H. Devoret and John M. Martinis "for the discovery of macroscopic quantum mechanical tunnelling and energy quantisation in an electric circuit"

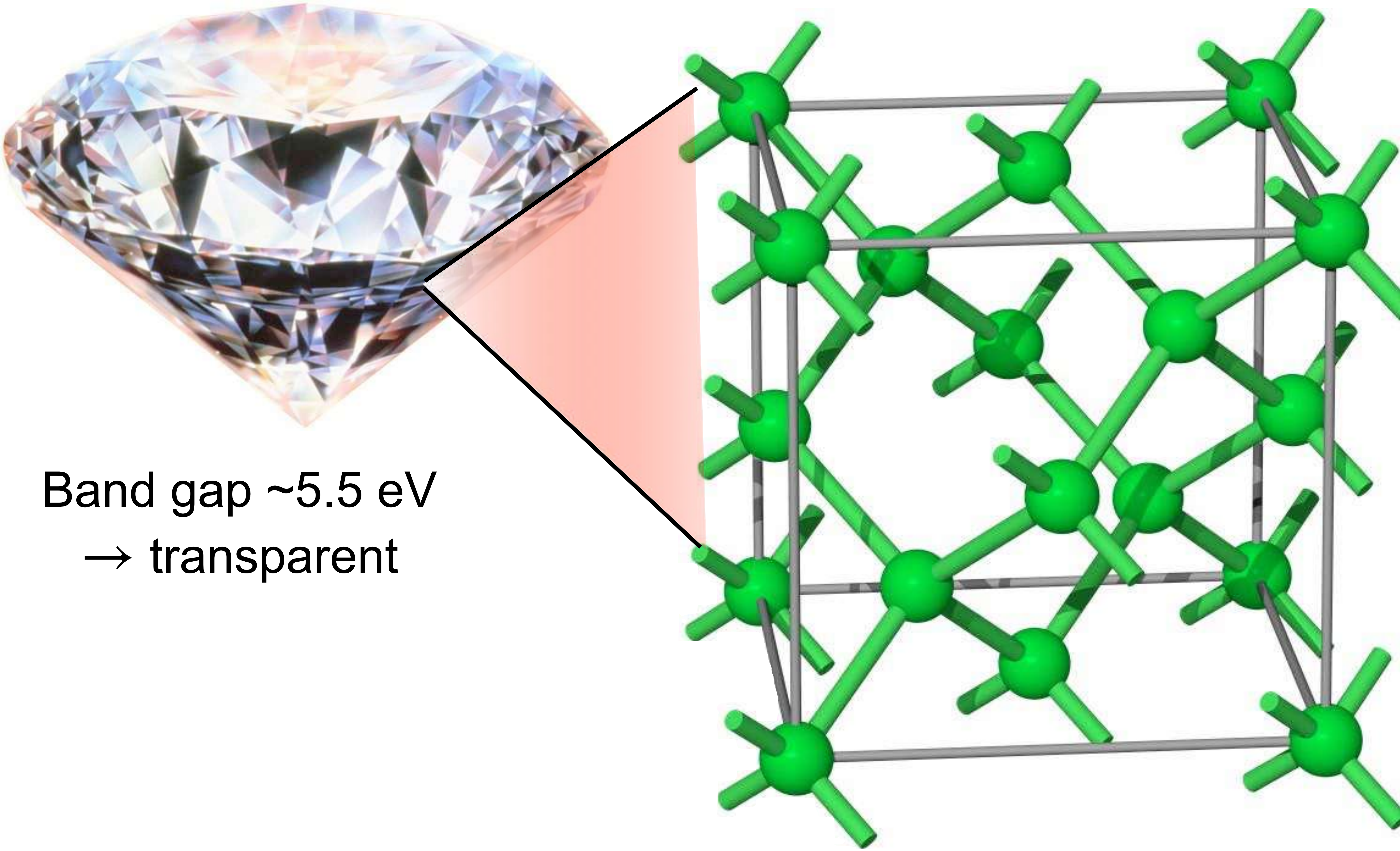
Spins in Diamond



Room temperature operation

Spins are (almost) ideal qubits

Diamond

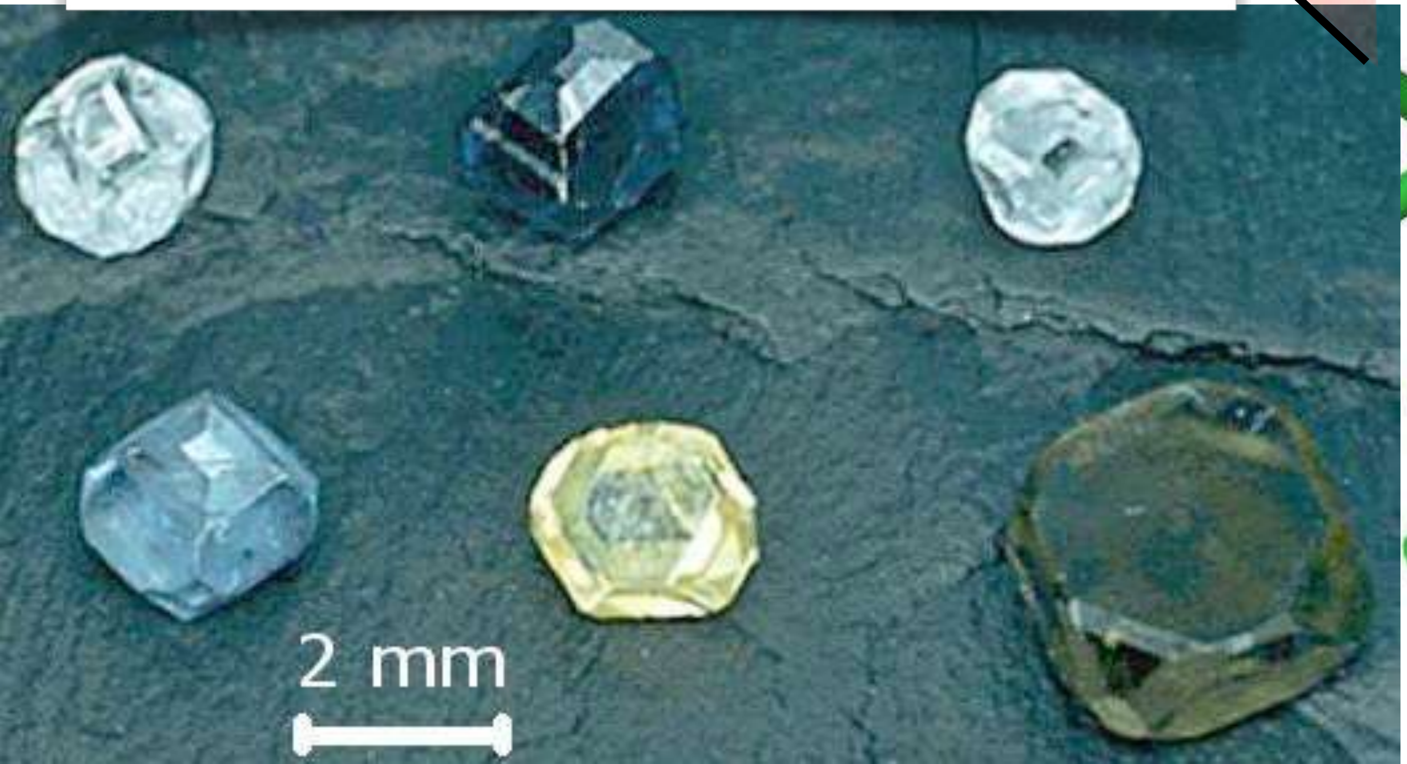


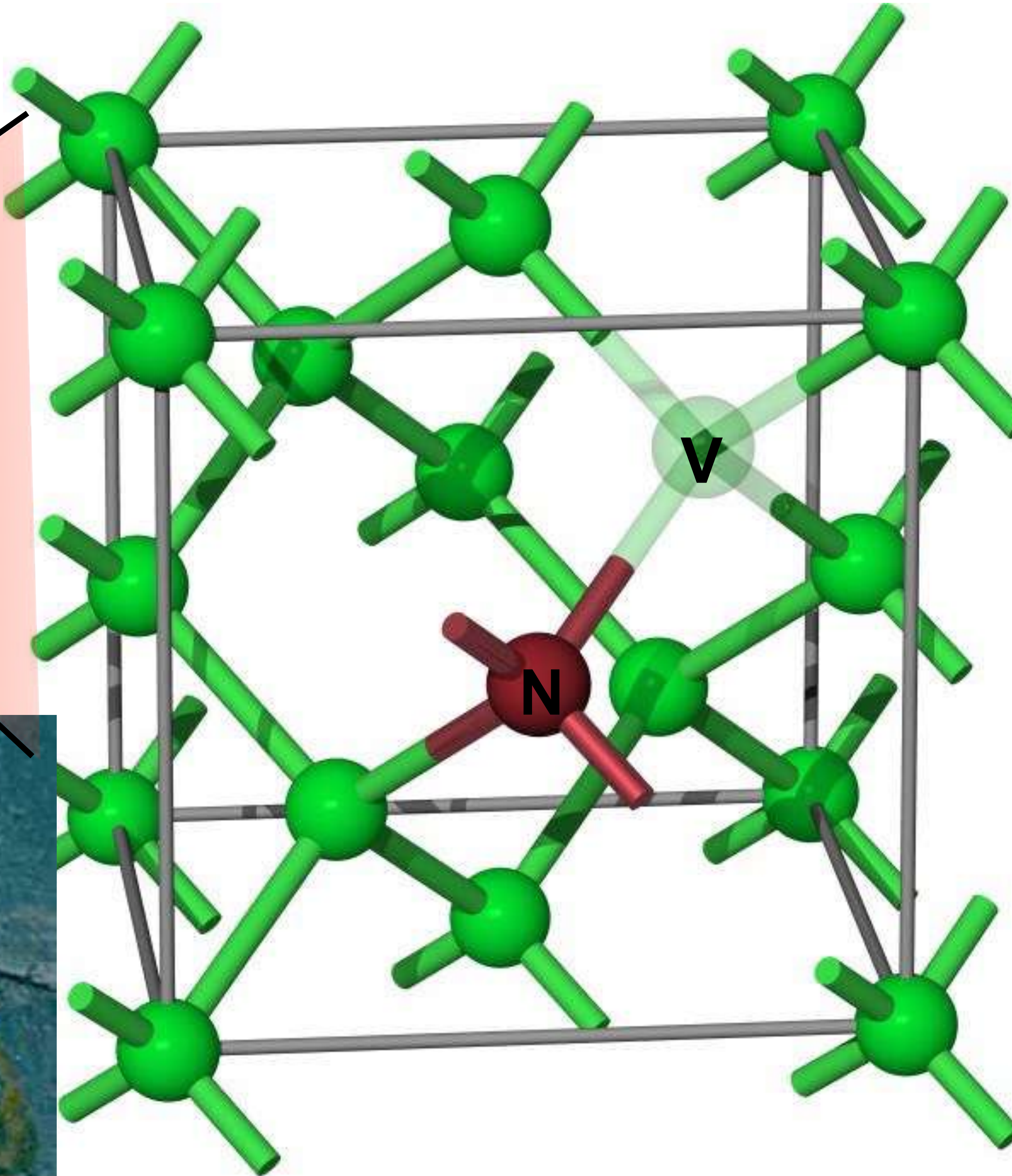
Band gap ~5.5 eV
→ transparent

Diamond

Nitrogen-Vacancy (NV)

Defects make diamonds valuable and interesting!



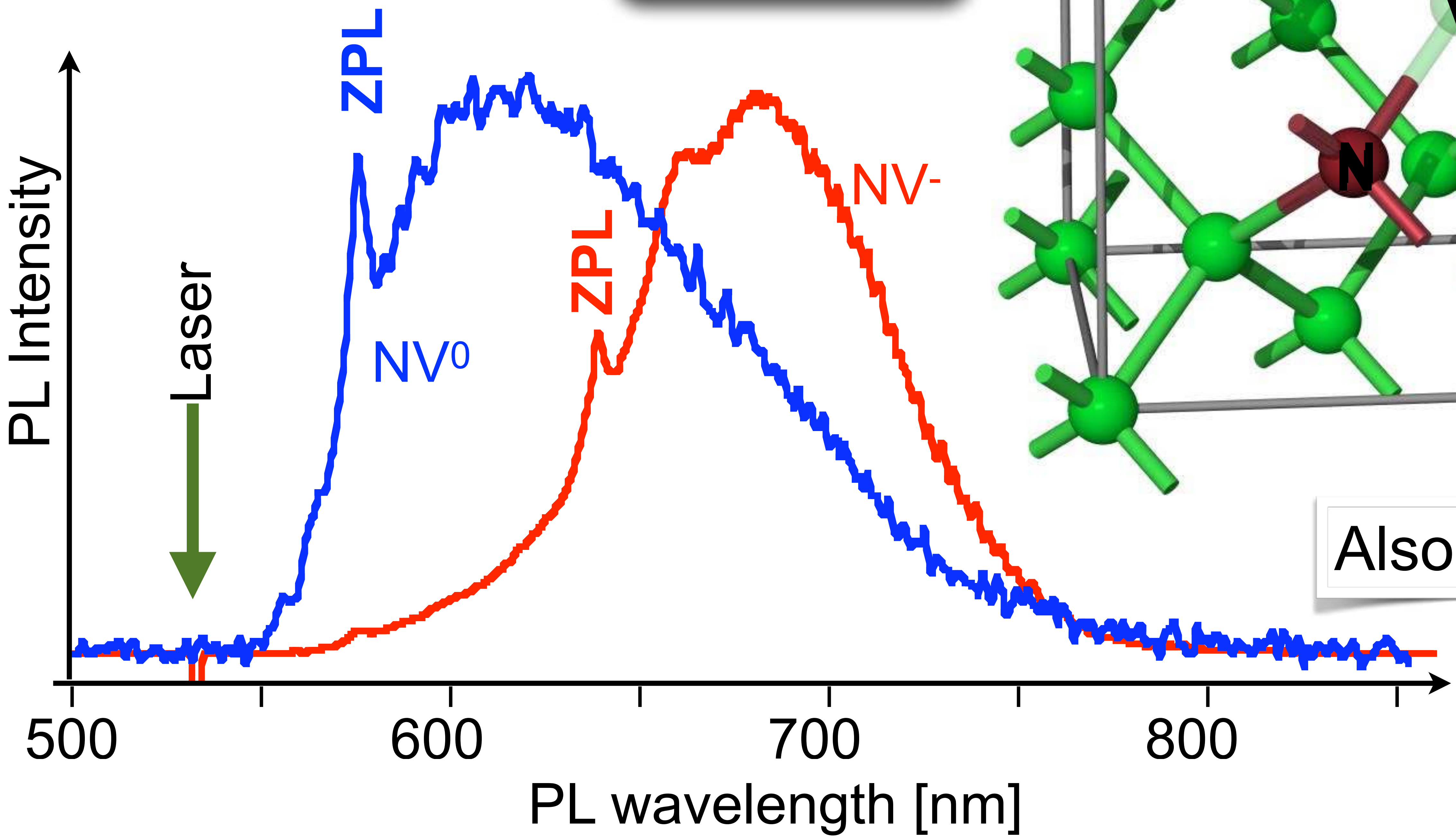


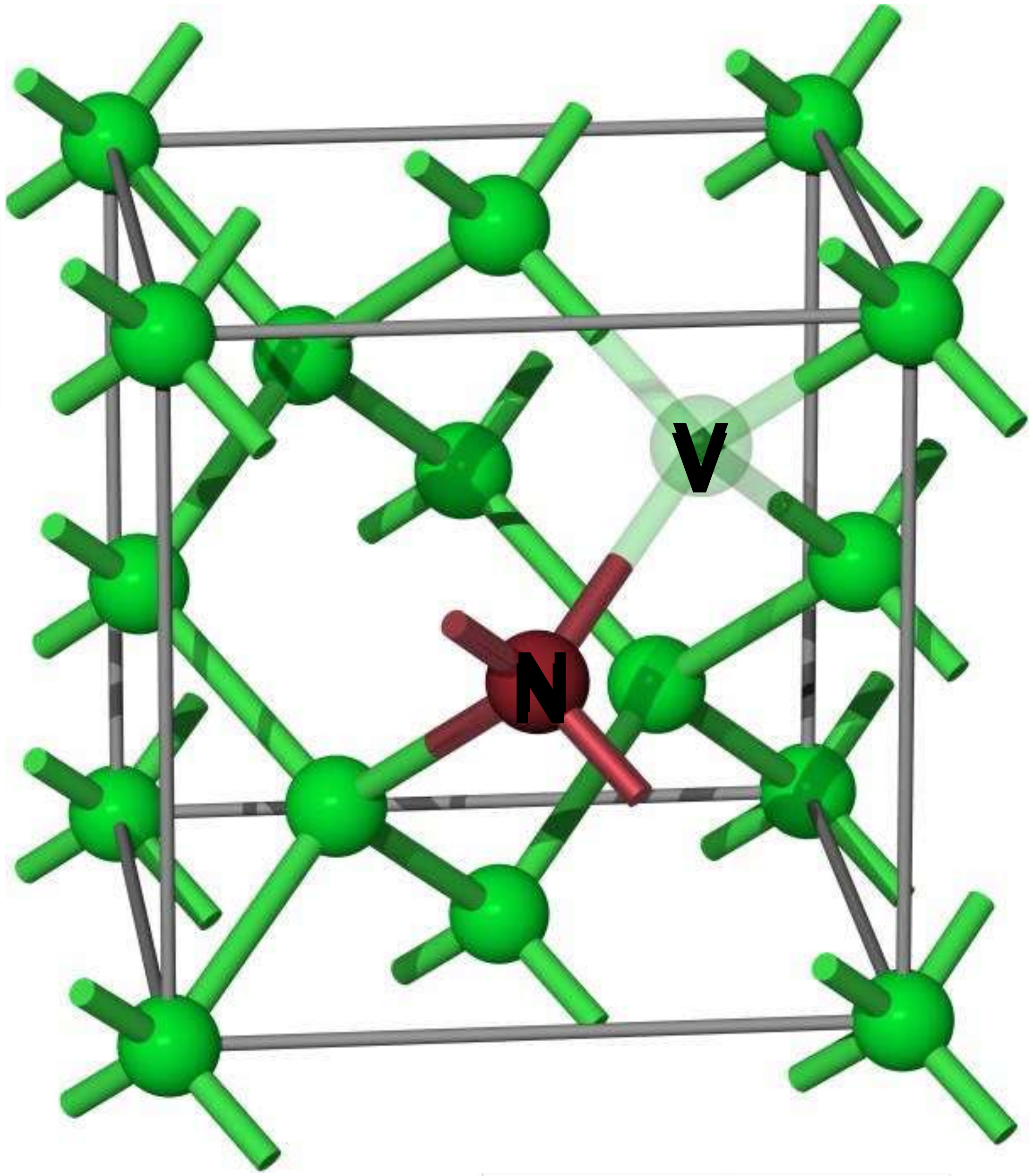
Optical Properties

possible charge states

5 electrons
spin 1/2

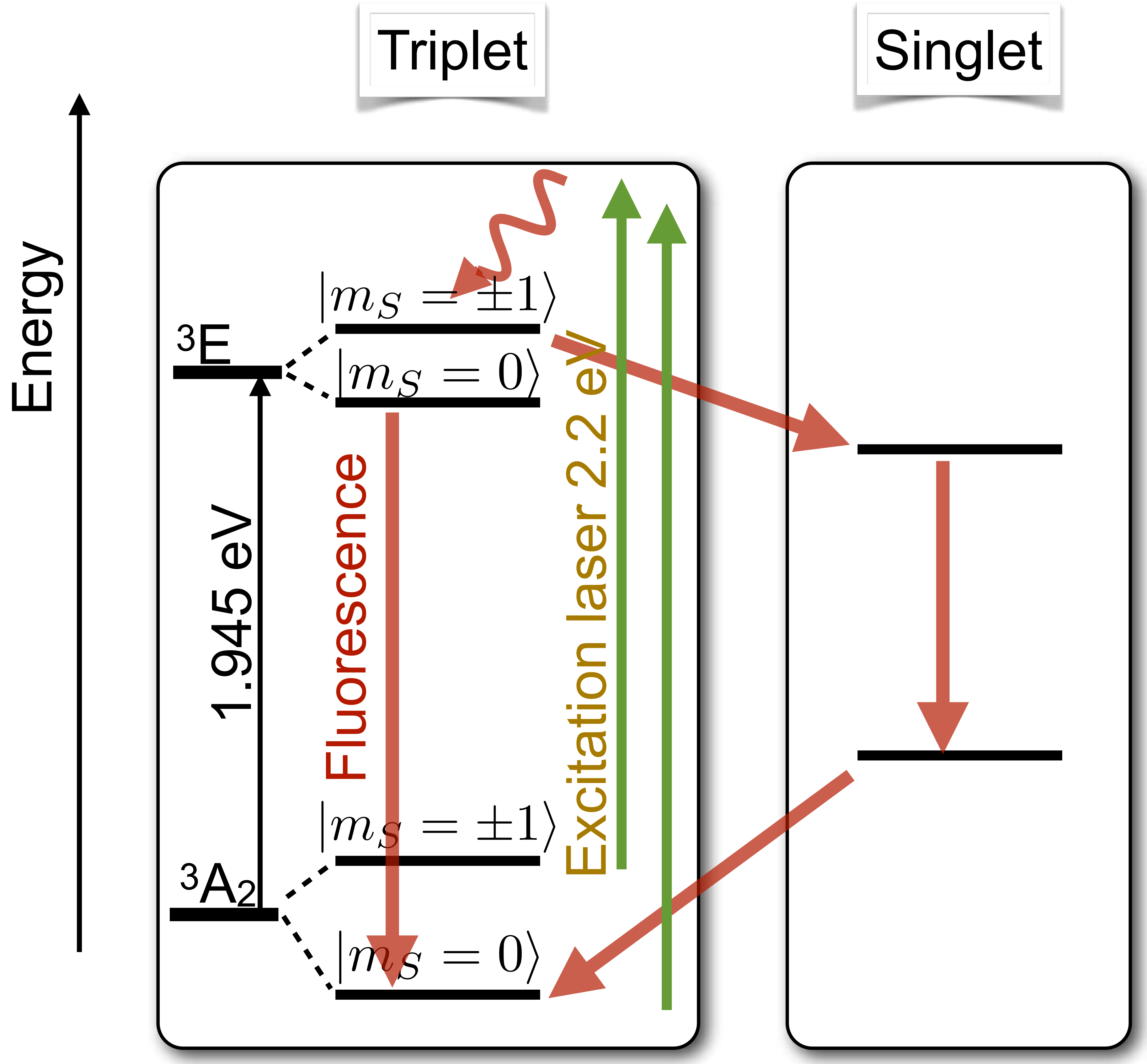
6 electrons
spin 1





Also : NV$^+$

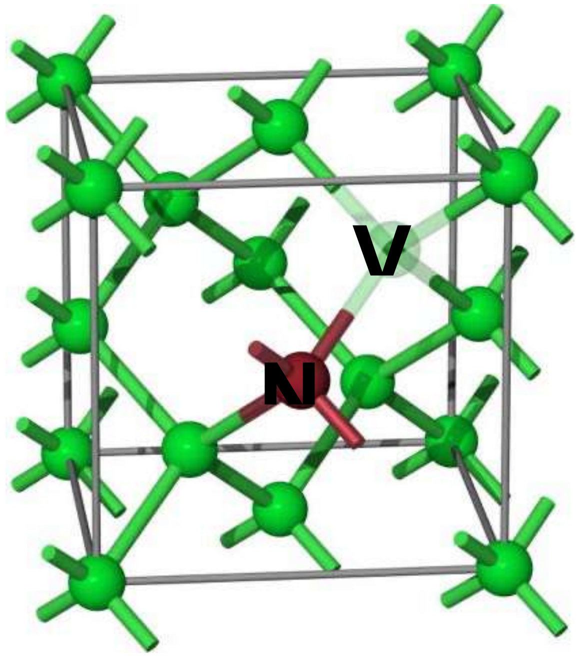
NV Centers : Optical Excitation

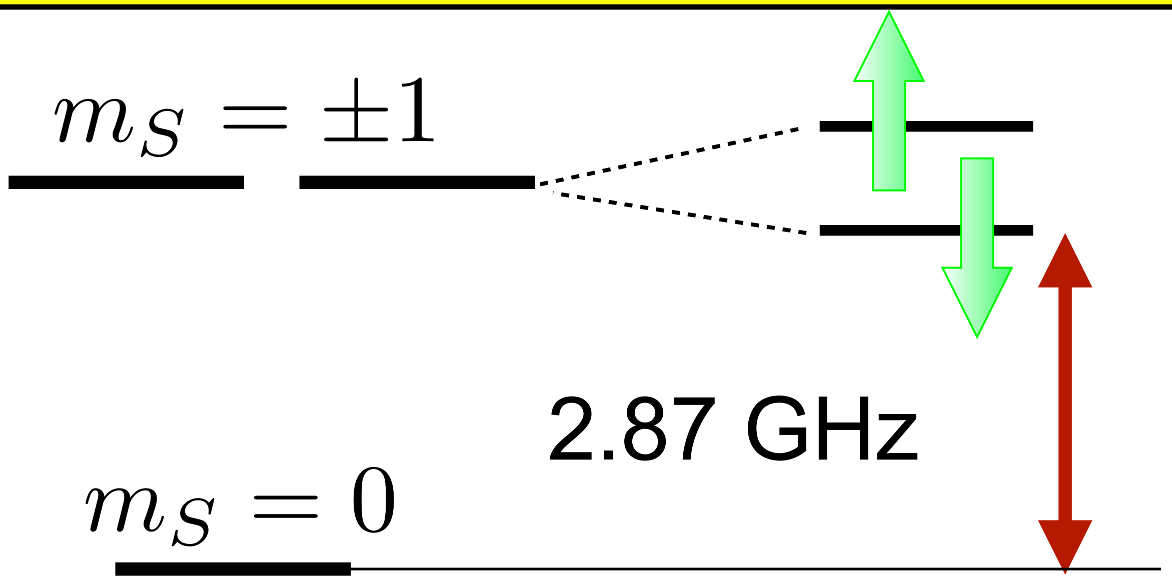


Laser initializes system into $m_S=0$ state

Fluorescence measures spin state

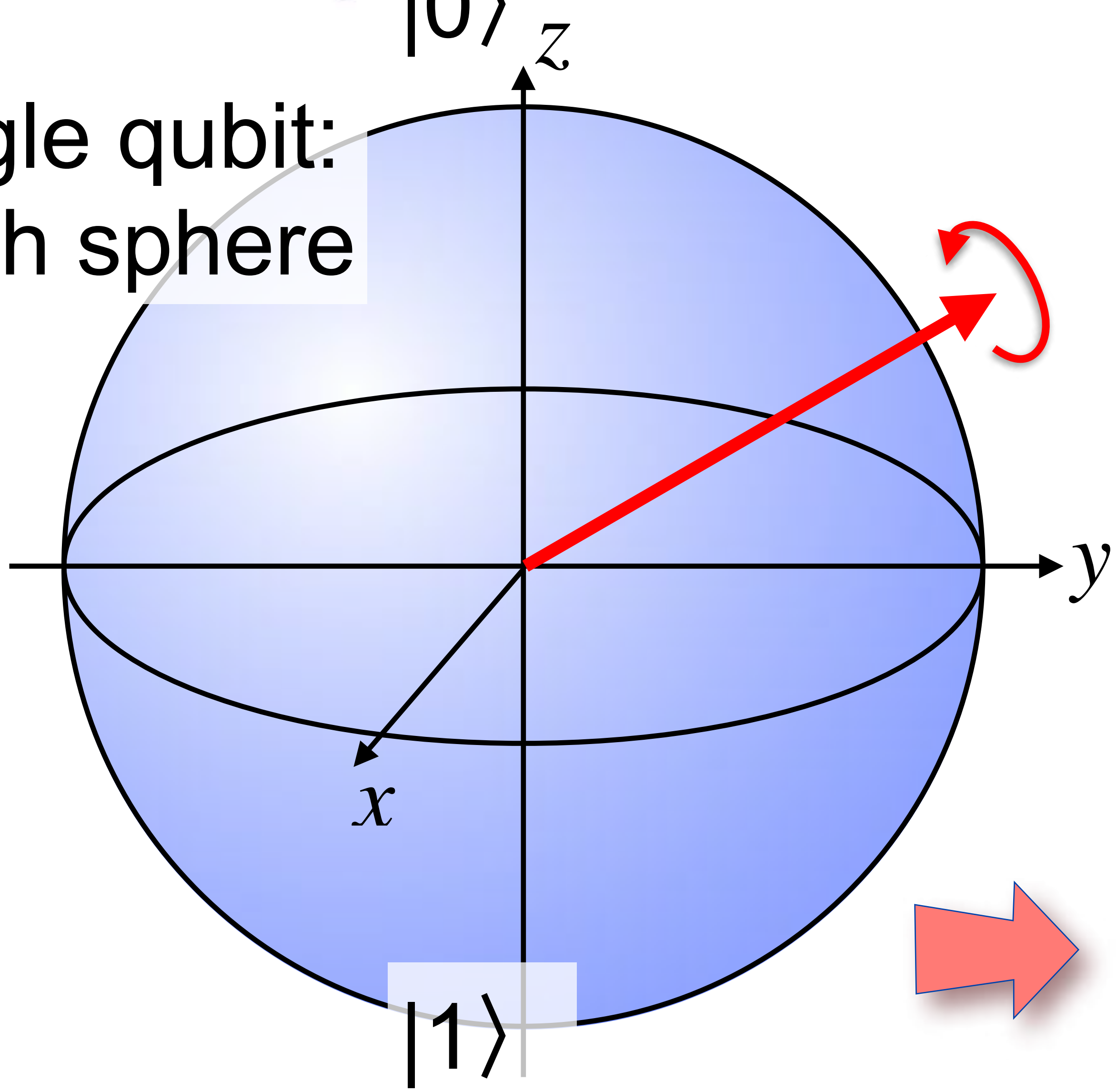
Gates: Electron Spin





Apply resonant MW pulse(s)

Single qubit: Bloch sphere



Pulse generates rotation on Bloch sphere

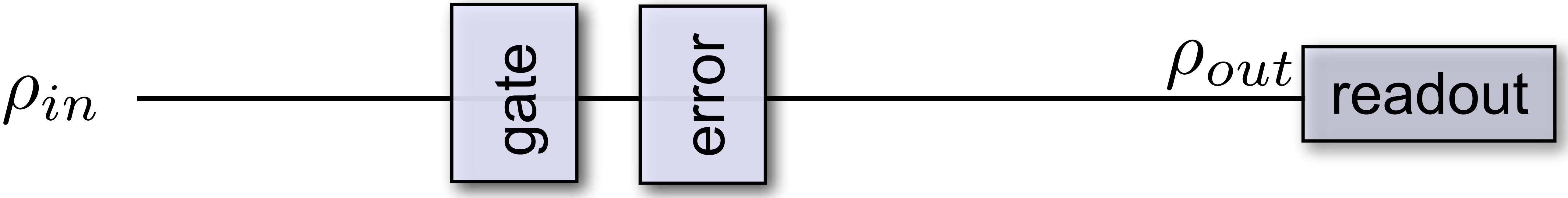
Parameters: Frequency, amplitude, phase, duration

Controls: orientation of rotation axis, rotation angle

→ Arbitrary single-qubit gates

Errors in Quantum Computing

DD cannot completely eliminate errors


ρ_{in}

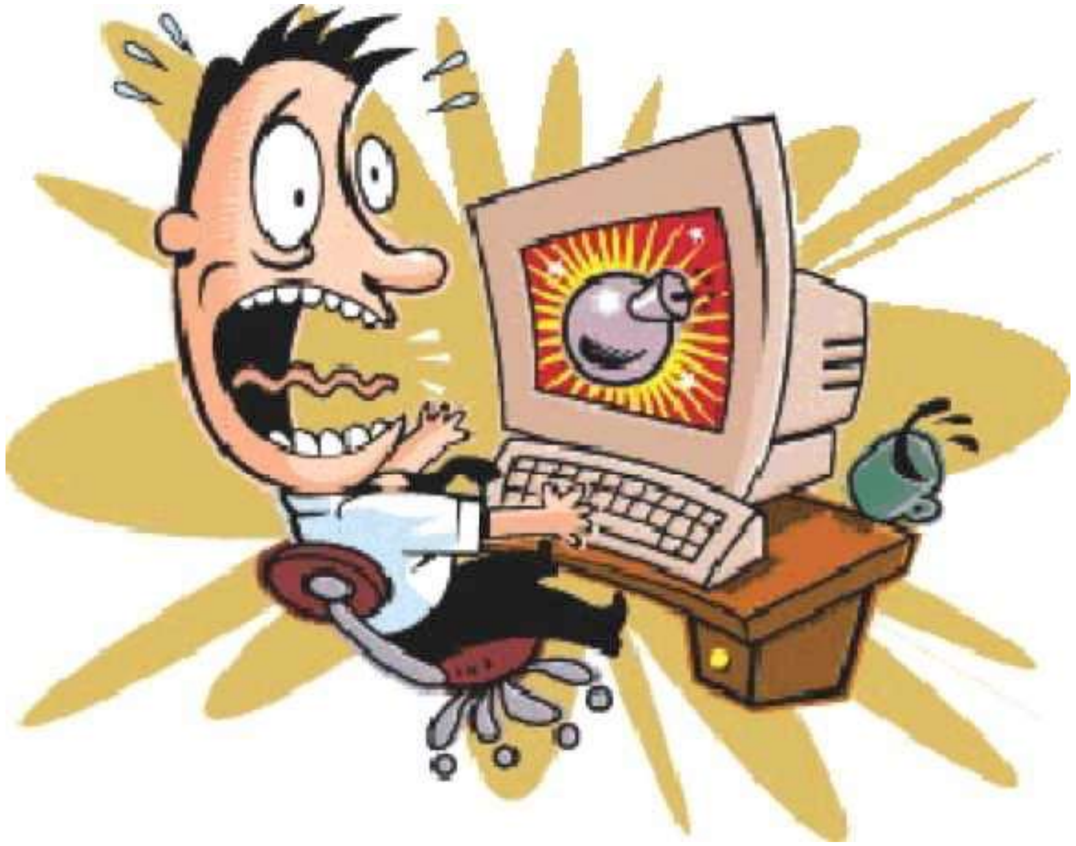
gate

error

ρ_{out}

readout

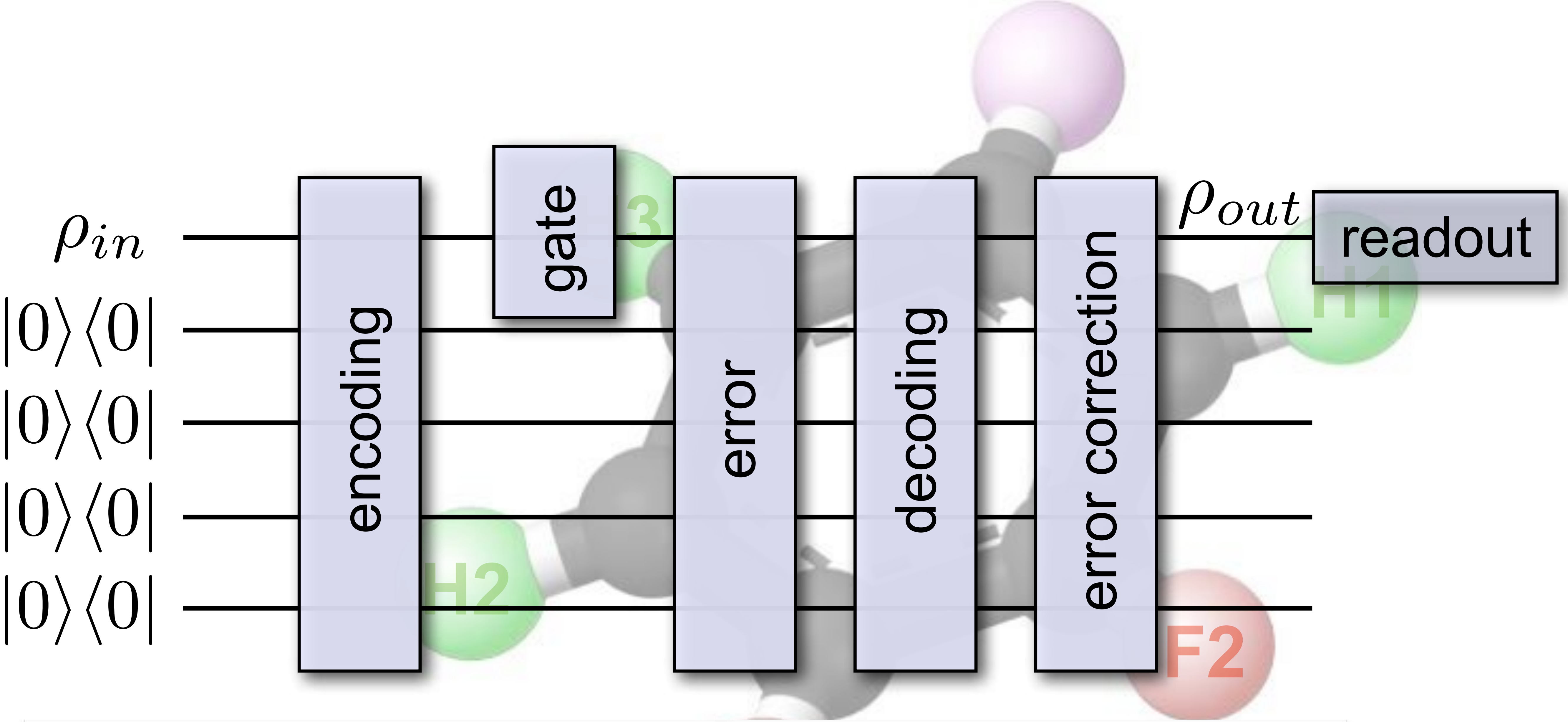
Errors are hard to detect and correct in QIP



… so …

An error correction scheme for quantum information is required

Quantum Error Correction

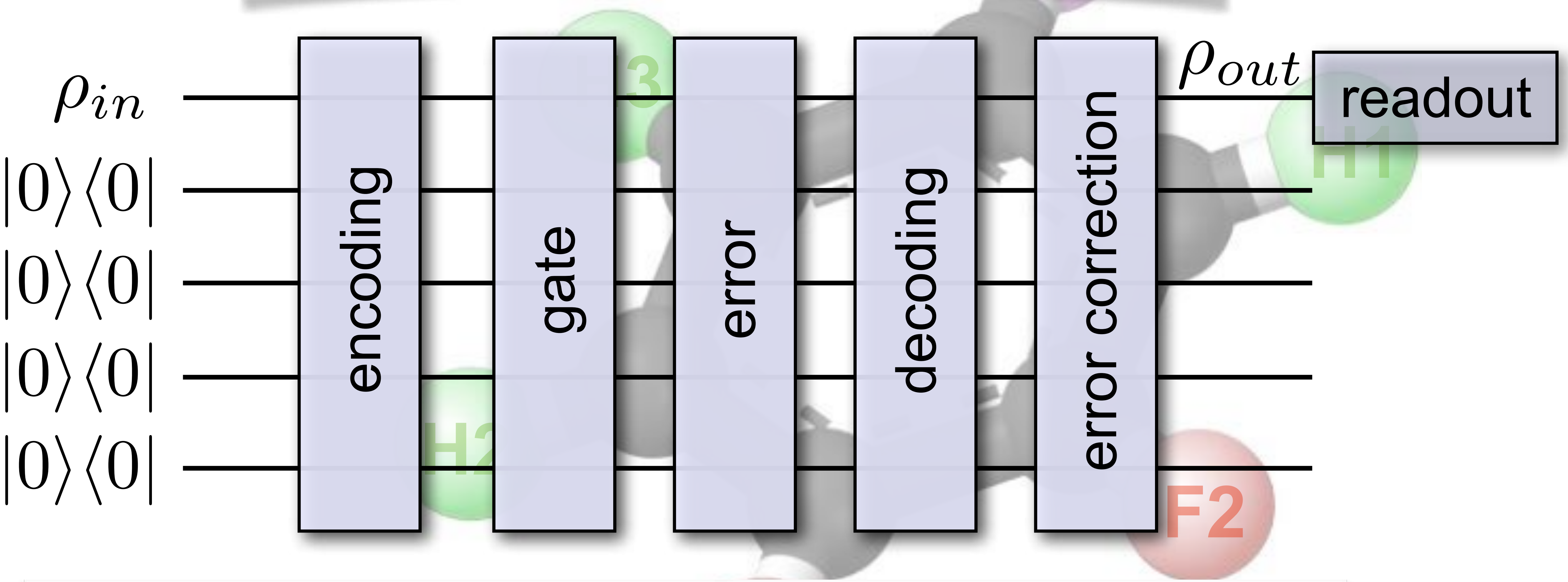


5-qubit code is perfect single-qubit QECC:
Allows correction of all possible single-qubit errors.

R. Laflamme, C. Miquel, J. P. Paz, and W. H. Zurek, Phys. Rev. Lett. 77, 198 (1996).
C. H. Bennett, D. P. DiVincenzo, J. A. Smolin, and W. Wootters, Phys. Rev. A 54, 3824 (1996).

Quantum Error Correction

Is QEC compatible with processing ?



ρ_{in}

$|0\rangle\langle 0|$

$|0\rangle\langle 0|$

$|0\rangle\langle 0|$

$|0\rangle\langle 0|$

encoding

gate

error

decoding

error correction

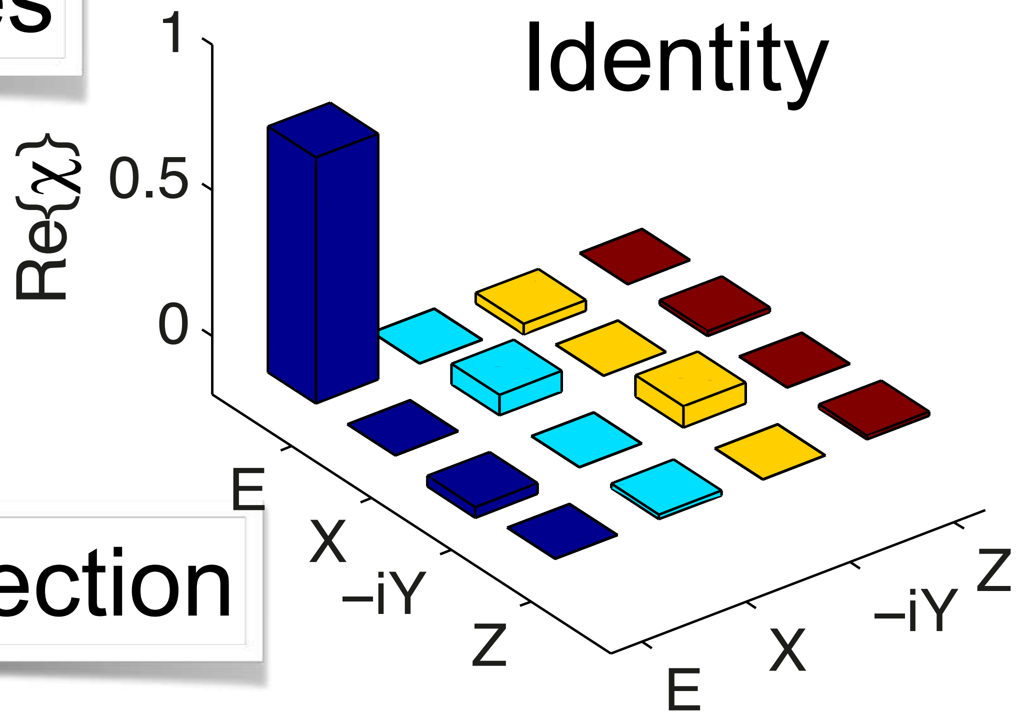
ρ_{out}

readout

5-qubit code is perfect single-qubit QECC:
Allows correction of all possible single-qubit errors.

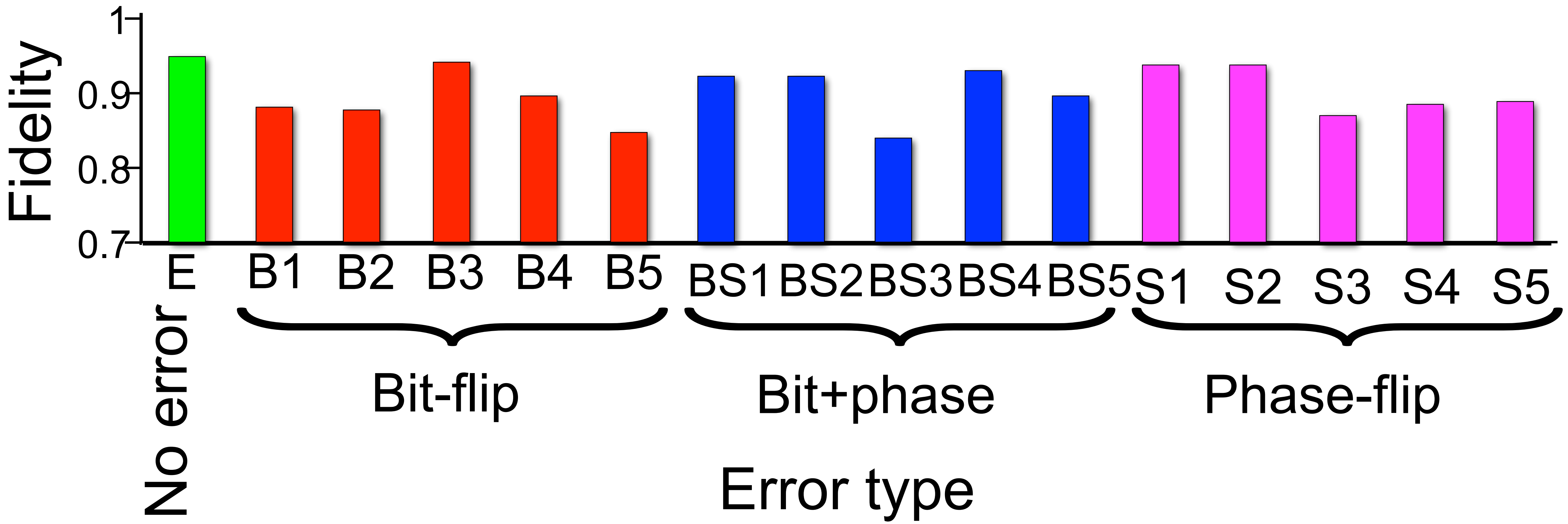
Quantum Error Correction

Process tomography of encoded gates



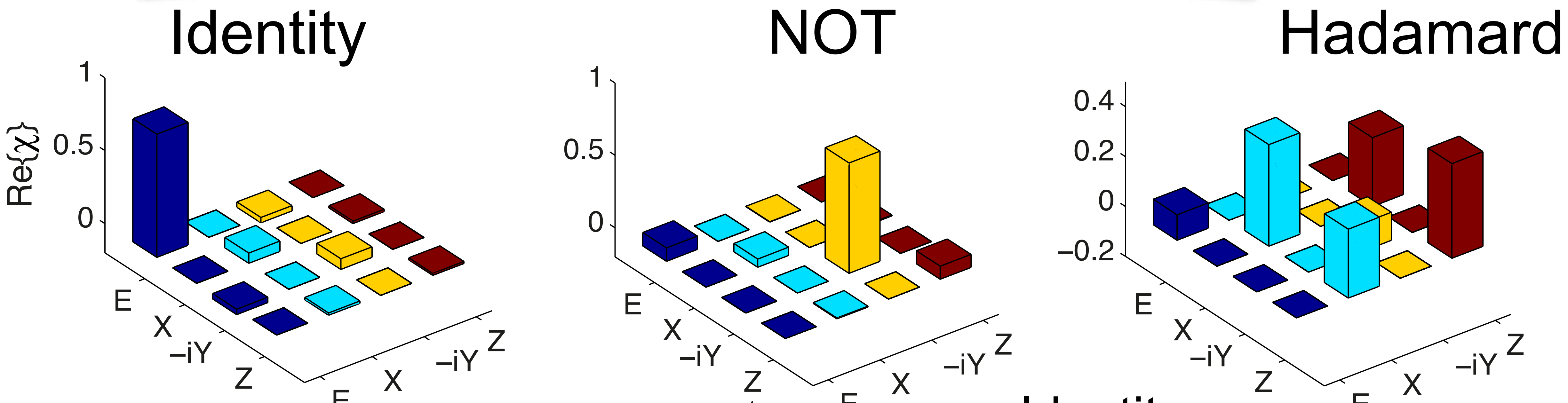
16 possible outcomes:
NoErr, 3·5 = 15 different errors

Test: Apply error operation + error correction



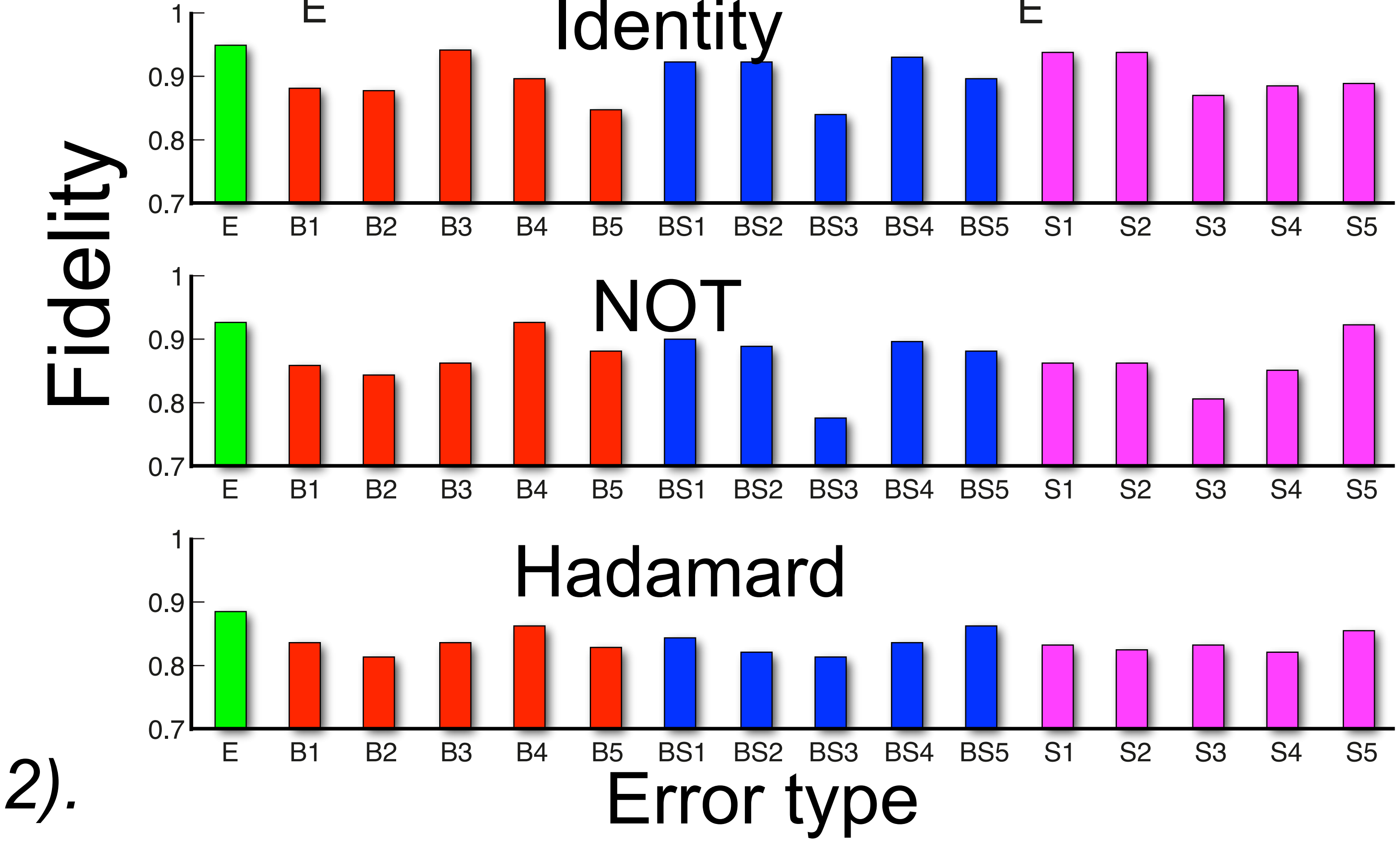
Quantum Error Correction

Process tomography of encoded gates



Individual results:

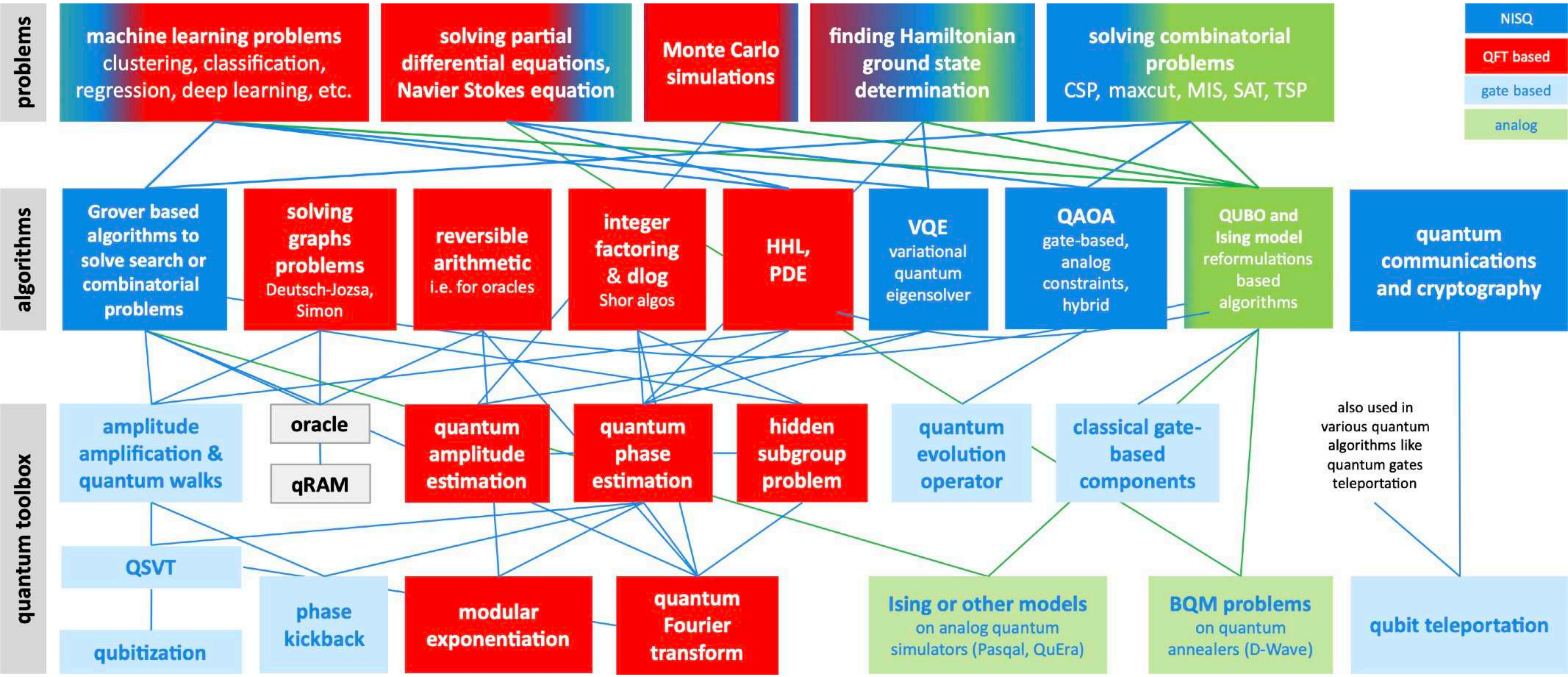
16 possible outcomes:
NoErr
$3 \cdot 5 = 15$ different errors



Phys. Rev. Lett. 109*:100503 (2012).*

Algorithms and Applications

Algorithms are being developed
for present and future quantum computers



NISQ
QFT based
gate based
analog

problems

machine learning problems
clustering, classification, regression, deep learning, etc.

solving partial differential equations, Navier Stokes equation

Monte Carlo simulations

finding Hamiltonian ground state determination

solving combinatorial problems
CSP, maxcut, MIS, SAT, TSP

algorithms

Grover based algorithms to solve search or combinatorial problems

solving graphs problems
Deutsch-Jozsa, Simon

reversible arithmetic
i.e. for oracles

integer factoring & dlog
Shor algos

HHL, PDE

VQE
variational quantum eigensolver

QAOA
gate-based, analog constraints, hybrid

QUBO and Ising model
reformulations based algorithms

quantum communications and cryptography

quantum toolbox

amplitude amplification & quantum walks

oracle

qRAM

quantum amplitude estimation

quantum phase estimation

hidden subgroup problem

quantum evolution operator

classical gate-based components

also used in various quantum algorithms like quantum gates teleportation

QSVT

qubitization

phase kickback

modular exponentiation

quantum Fourier transform

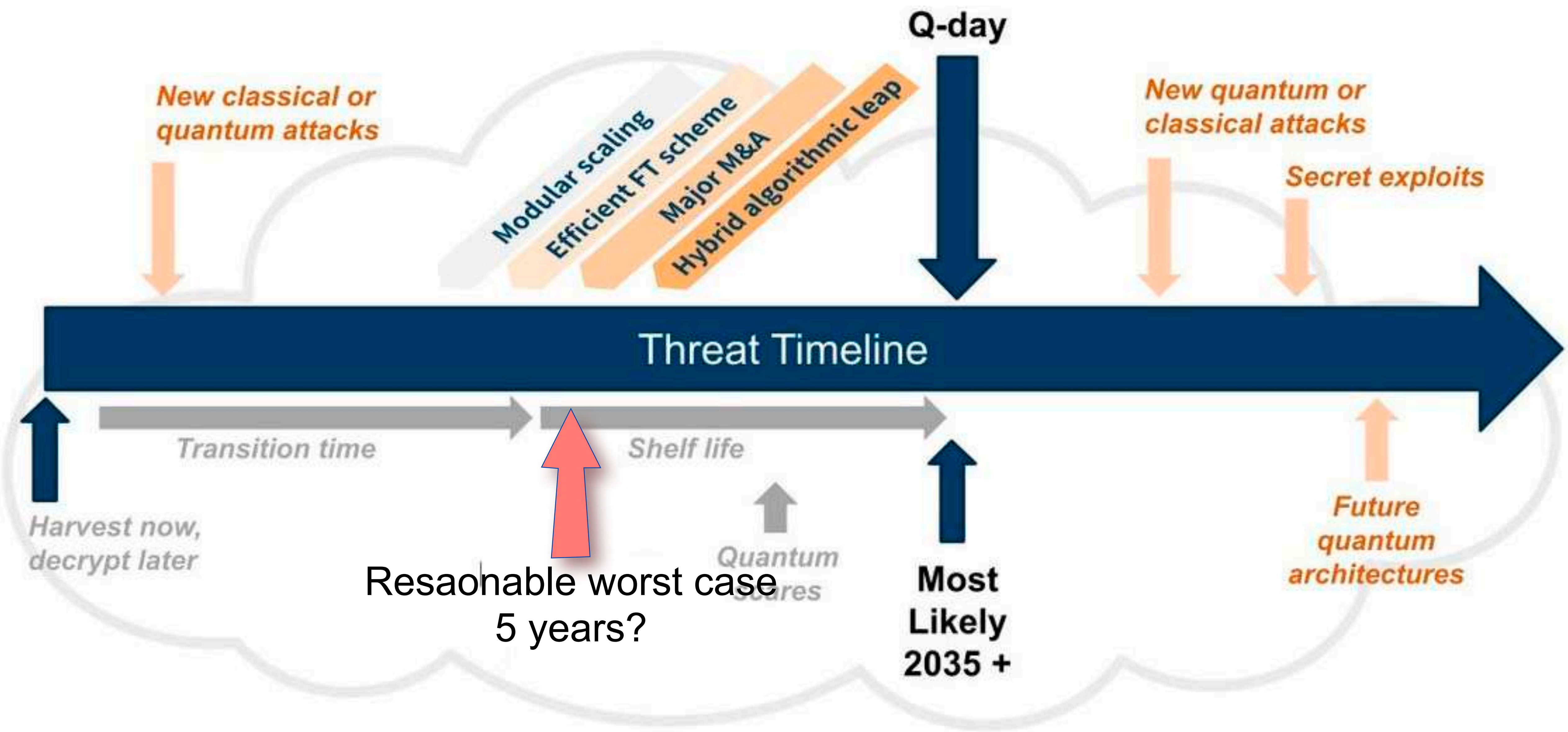
Ising or other models
on analog quantum simulators (Pasqal, QuEra)

BQM problems
on quantum annealers (D-Wave)

qubit teleportation

Threat to Privacy

"Q-Day" :
Quantum computers are sufficiently powerful to crack RSA-2048



Resaonable worst case
5 years?

2025: Google Quantum AI reduced RSA-2048 factoring requirements from 20M to <1M qubits.

Impact on Cyber Security

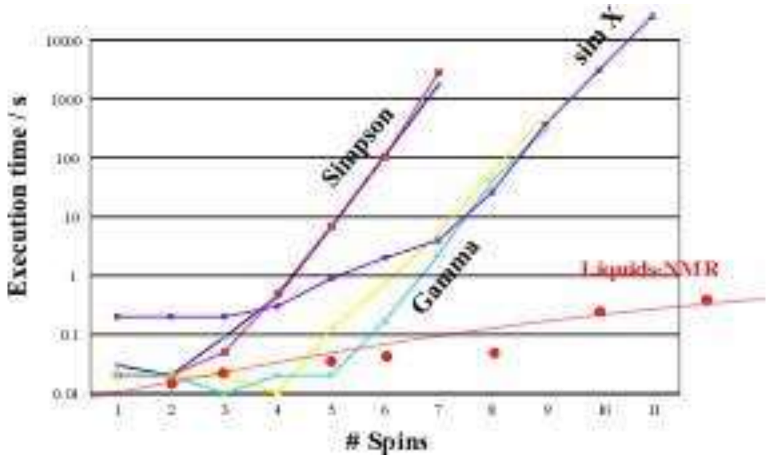
In April 2024, the European Commission’s Recommendation led the NIS Cooperation Group to publish a unified roadmap by 23 June 2025 with the following points:

By end-2026: all Member States must begin transitioning to PQC, starting with inventories, stakeholder outreach, and risk assessments.

By end-2030: critical infrastructure (e.g. energy, telecoms, finance) must have fully transitioned to quantum-safe encryption.

By end-2035: Migration to cover all medium- and low-risk systems.

Will it Work ?



Will quantum computers replace classical computers?

No !

Will quantum computers be useful ?

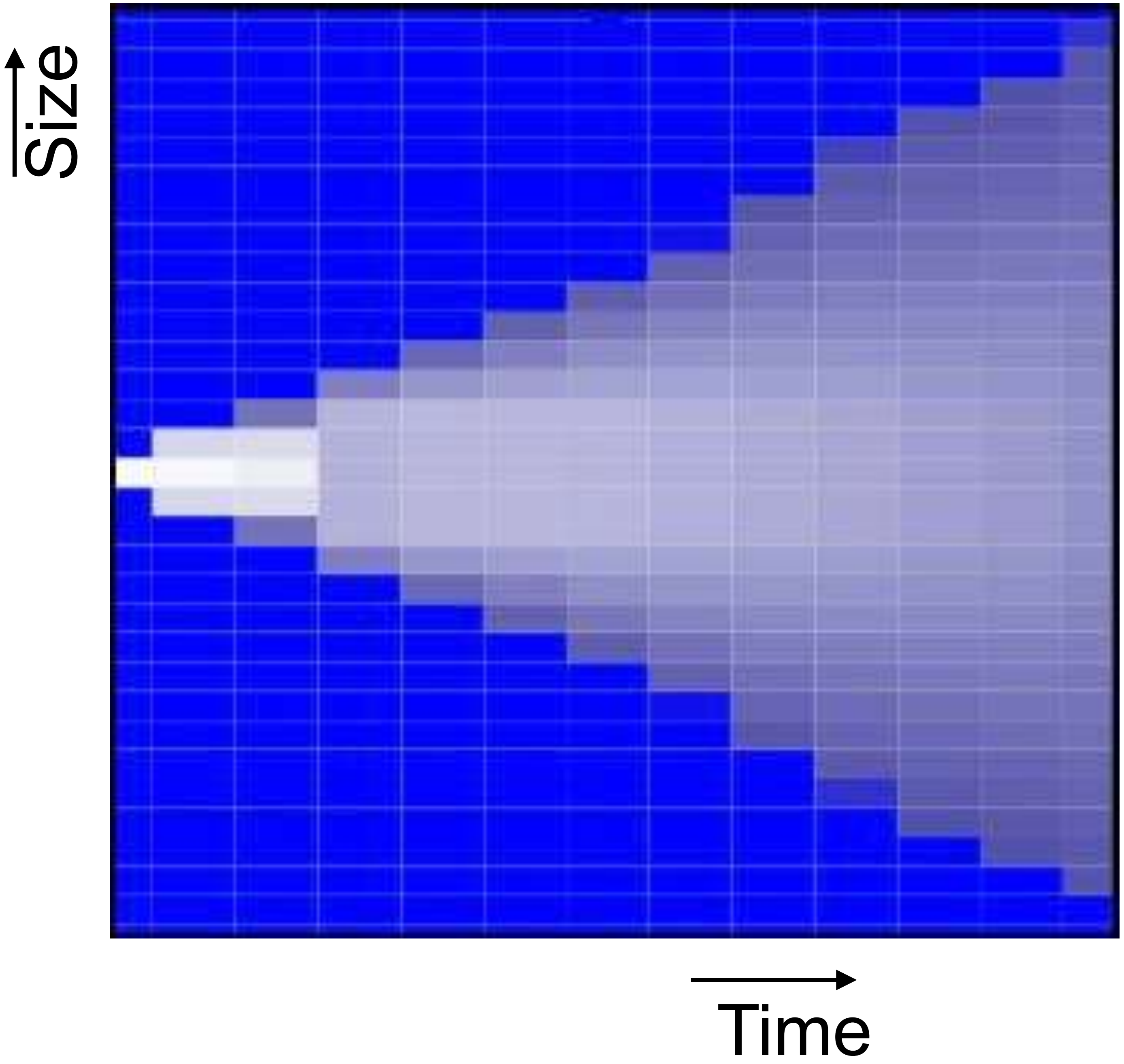
Yes !

Answer 1: Yes, they are! Quantum computers are useful for quantum simulations.

Quantum Simulations : Localization

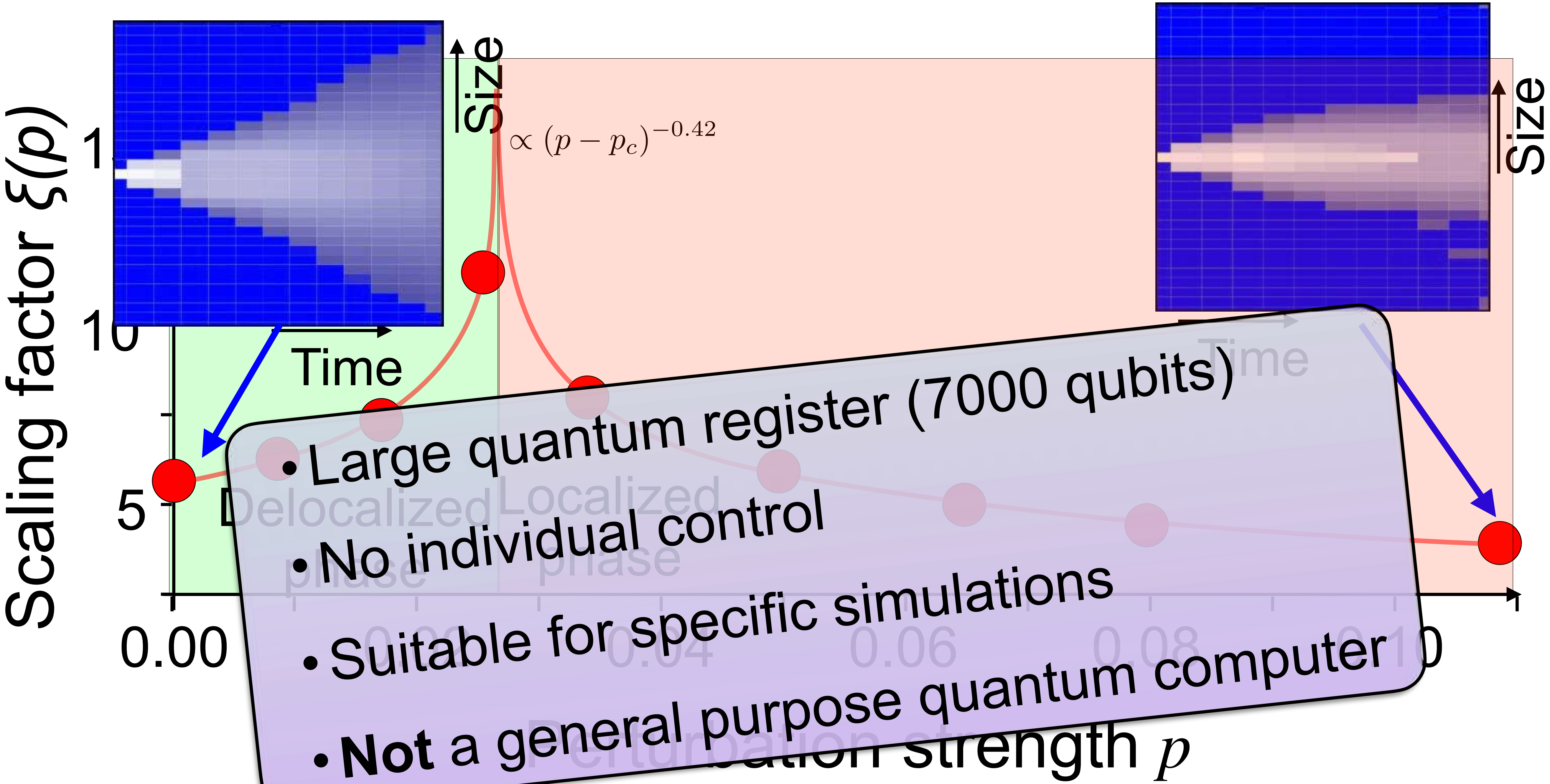
Why are some physical systems localised in space?

Physical system: nuclear spins



Quantum Simulations : Localization

Qubit system: nuclear spins

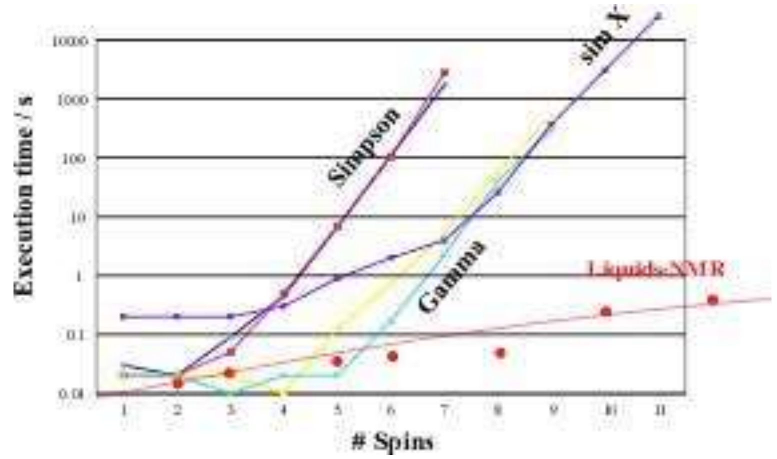


- Large quantum register (7000 qubits)
- No individual control
- Suitable for specific simulations
- **Not** a general purpose quantum computer

Experimental observation of a phase transition in the evolution of many-body systems with dipolar interactions

G. A. Álvarez, D. Suter, R. Kaiser, Science 349, 846 (2015).

Will it Work ?



Will quantum computers replace classical computers?

No !

Will quantum computers be useful ?

Yes !

Answer 1: Yes, they are! Quantum computers are useful for quantum simulations.

Answer 2: Yes, since future computers will use quantum effects.

Answer 3: The most important applications of any sufficiently advanced technology are always created by this technology. (Kroemer,1995: The lemma on new technologies)

Conclusions

- Quantum technologies offer novel and enhanced devices for a vast range of applications.
- The most advanced fields are quantum communication and quantum sensing.
- Quantum simulation and quantum computing are becoming competitive.
- Avoiding and correcting errors is essential.

Thank you for your attention!