Quantum Physics

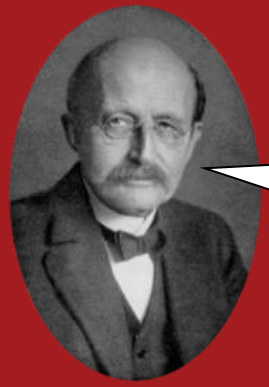
Klaus Mølmer
Niels Bohr Institute

M.Sc day NBIA
8 October 2024

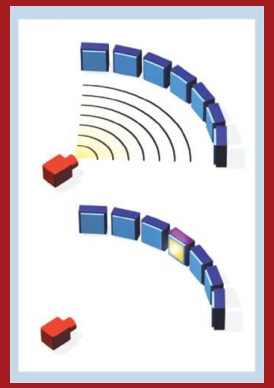
UNIVERSITY OF COPENHAGEN

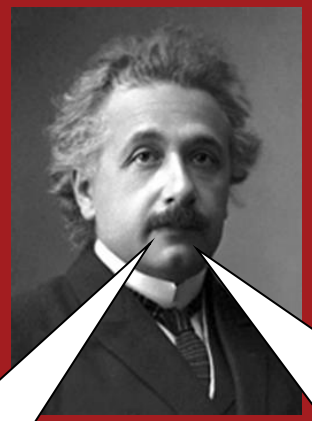
The early quantum physics

Planck and Einstein



Radiation energy is *exchanged* by quanta $E = h \cdot f$, 1900

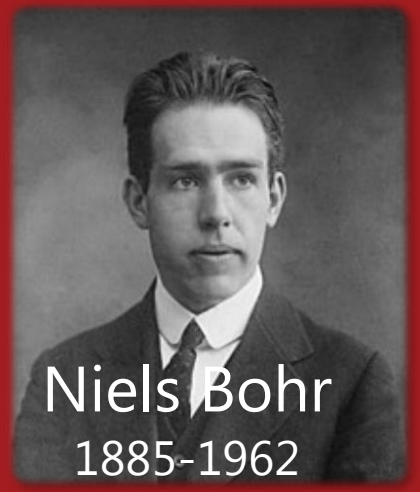


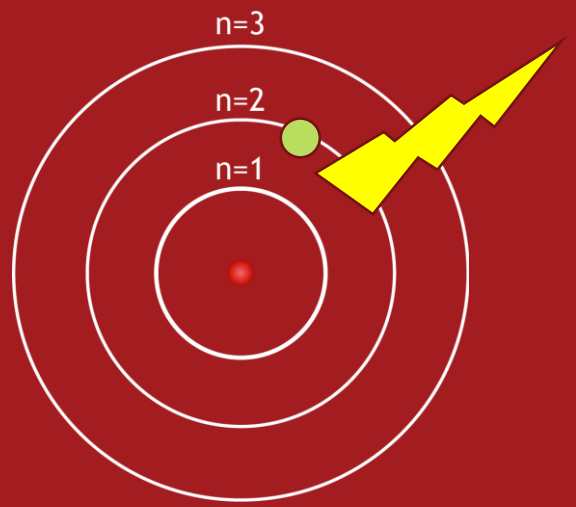


Light *are* quanta that form a wave. 1905

What happens to the wave when the light quantum is detected?

Bohr and Quantum Jumps

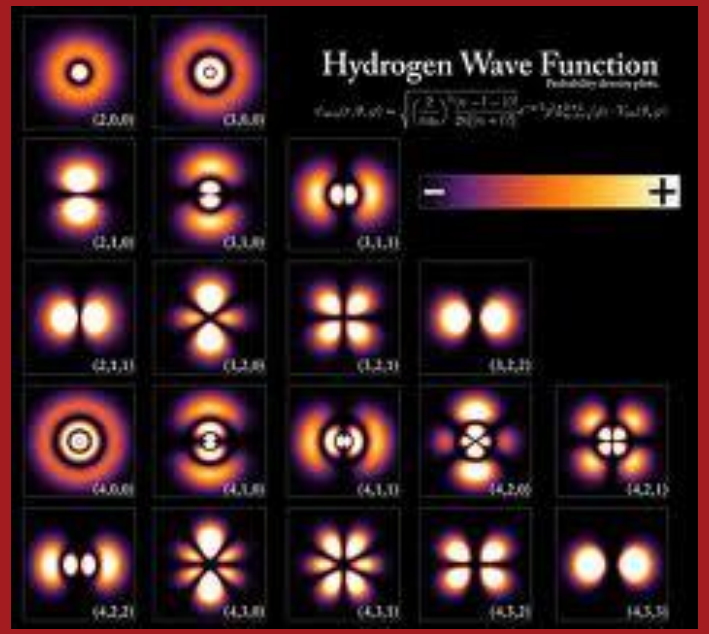




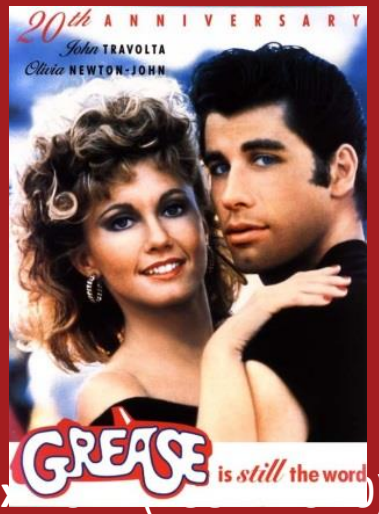
Bohr's postulates explain that all atoms emit (and absorb) light quanta at only definite frequencies.
Equation yields 5 (7) digits for Hydrogen
Equation is 15 % off for Helium

Quantum Mechanics, Schrödinger's wave equation .

$$i\hbar\frac{d}{dt}\Psi(\vec{r},t)=\left[-\frac{\hbar^2}{2m}\Delta+V(\vec{r})\right]\Psi(\vec{r},t)$$



Erwin Schrödinger
(1887 -1961)



Max ( )

States, |ψ>, ρ

Observables A, eigenvalues a

Probabilities P(a),

mean values <A>

Projection postulate, |ψ> → |a>

The meaning of ψ

Einstein:
"Hidden, *real*" motion?

Schrödinger:
Real, physical wave?

Quantum Mechanics, Schrödinger's wave equation .

$$i\hbar\frac{d}{dt}\Psi(\vec{r},t)=\left[-\frac{\hbar^2}{2m}\Delta+V(\vec{r})\right]\Psi(\vec{r},t)$$

If quantum theory is correct, it signifies the end of physics as a science

I do not like it, and I am sorry, I ever had anything to do with it.

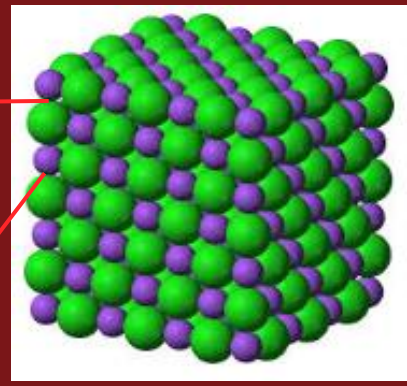
Those *who are not shocked* when they first come across quantum mechanics cannot possibly have understood it

Niels Bohr

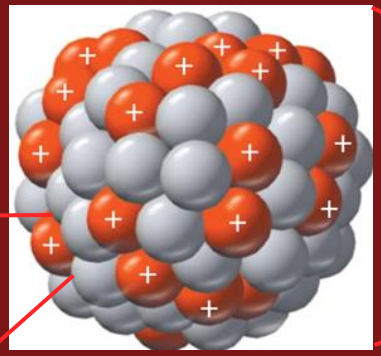
All mikroscopical physics is quantum physics

We can predict properties and quantities (with up to 12 digit precision)

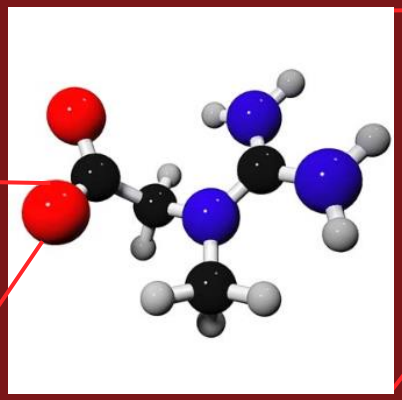
Physics of solids



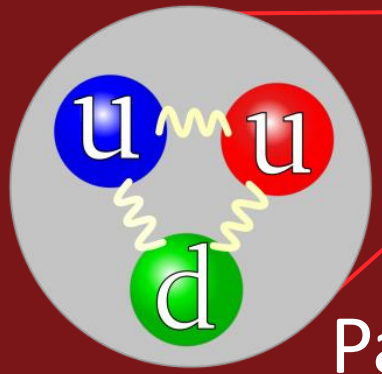
Nuclear physics



Atomic physics



Chemistry



Particle physics

Quantum physics and technologies ("First Quantum Revolution")

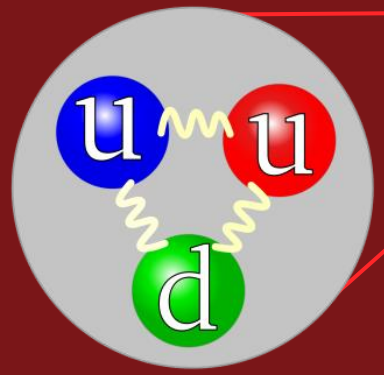
Transistors
→ Computers

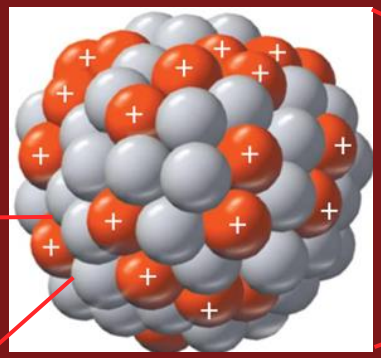
Nuclear medicine

PET scanners

Diagnostics

Chemical industry

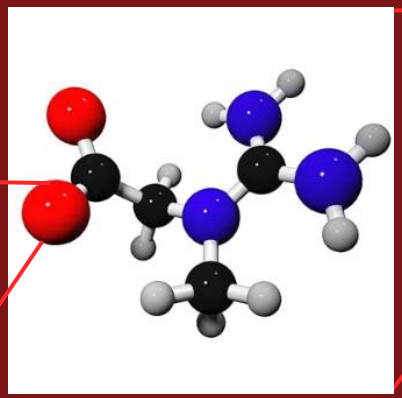




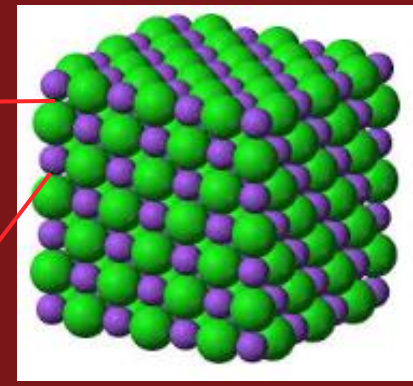
Nuclear power

Laser

GPS



Nano-technology



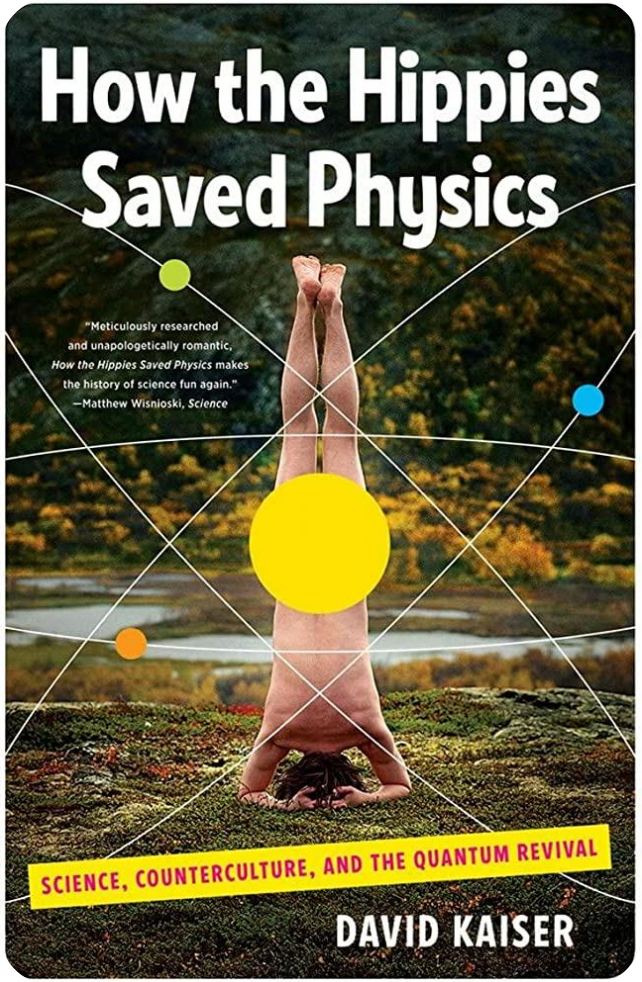
Materials

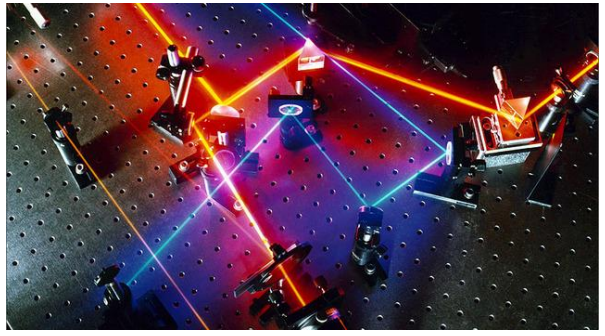
From quantum physics to quantum (information) technology

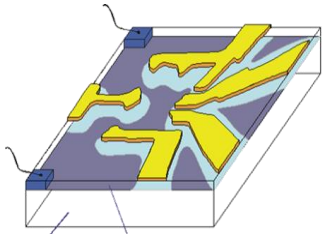
Uncertainty and randomness
Particle and wave
Collapse of wave function

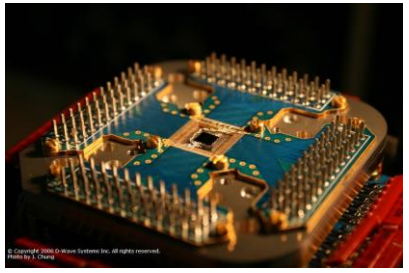
John Bell to Alain Aspect:
"Do you have a
permanent position ?"

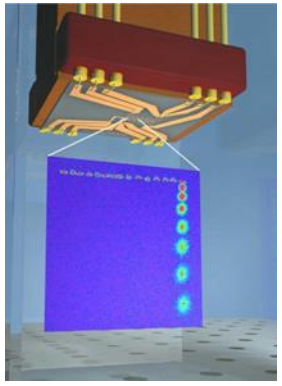
1970'es
Scattered
"what if" ideas
& "LSD and CIA"









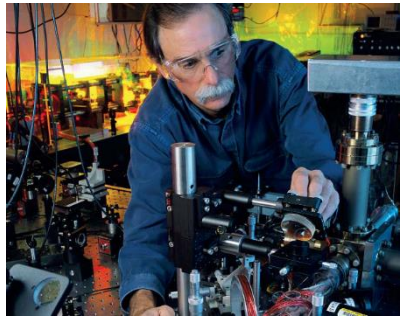


From Quantum Optics

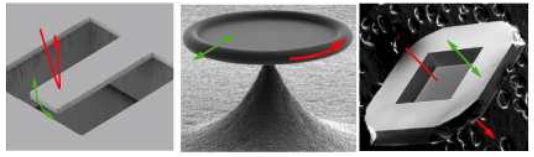
Atoms
Ions
Photons
Cavities
Travelling fields
…

to ”Bits and Pieces”

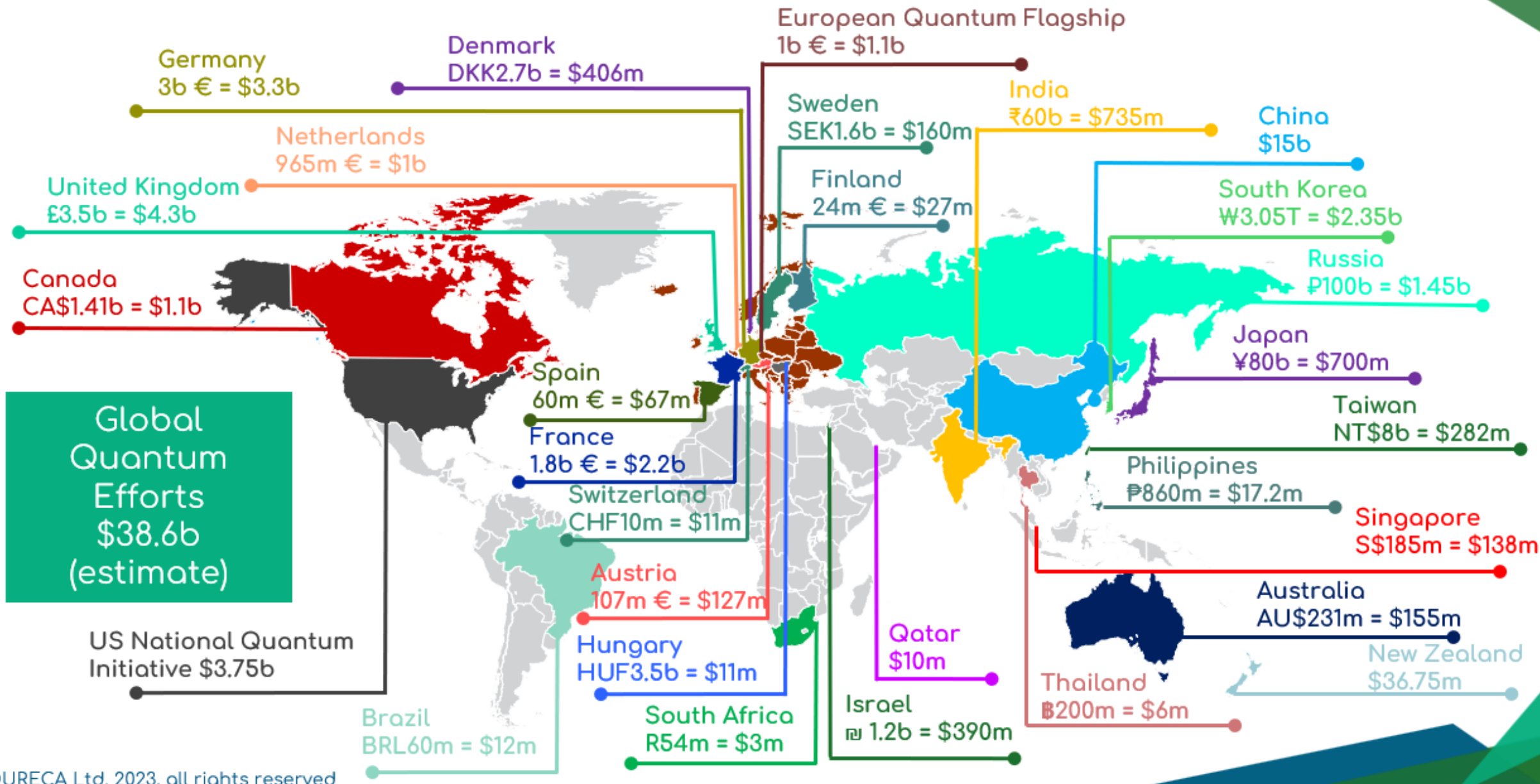
Quantum dots
Superconductors
Magnons
Cantilevers
Microwaves
Accoustic waves
…



… to quantum sensors, quantum memories and quantum bits



Quantum effort worldwide



Who are we, and what are we doing

NBIA

Currently no permanent staff in quantum, but
Excellent assistant professors come and go.

NQCP

Kim Splittorf, quantum system dynamics
Frederik Nathan, new quantum bits
Vincent Michal, spin qubits, AI
Gemma Solomon, quantum algorithms

Steano Paesani, photonics computing

Quantum Section, NBI

Anders Sørensen, quantum communication, optical computing
Klaus Mølmer, quantum measurements, light matter interfaces

Eugene Polzik, quantum sensing
Peter Lodahl, solid state light emitters (artifical atoms)
Leonardo Midolo, integrated photonics
Jörg Helge Müller, cavity QED, superradiant lasing
…

Condensed Matter Section, NBI

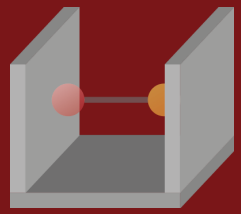
Karsten Flensberg, mesoscopic component
Jens Paaske, superconductivity, transport
Brian Andersen, superconductivity

Morten Kjærgaard, SC quantum computing
Jesper Nygaard, nano-devices

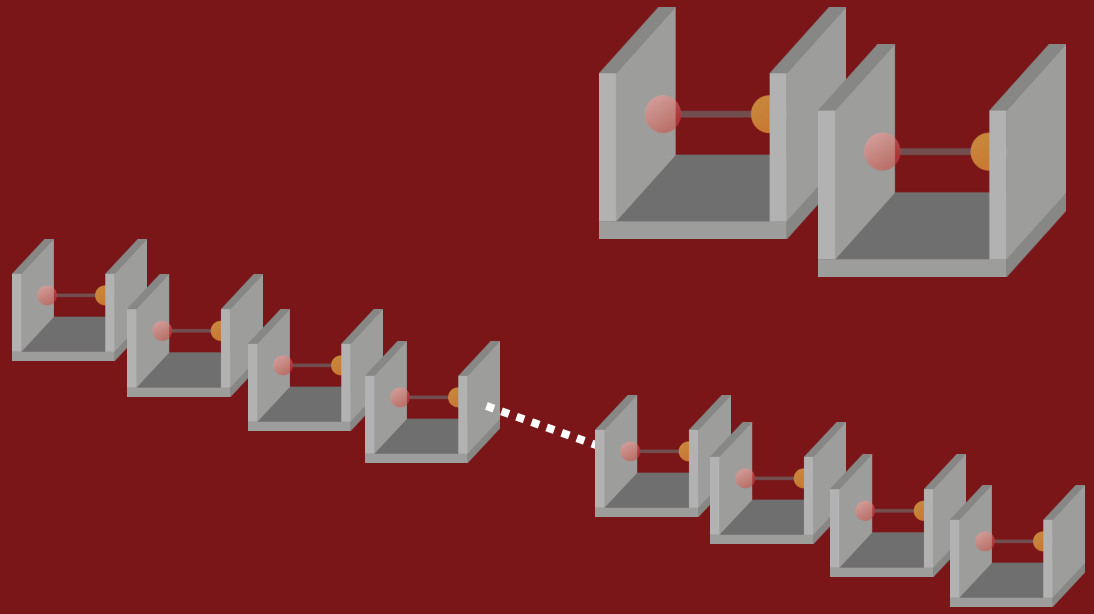
Quantum physics and technologies ("Second Quantum Revolution")

Wave function:
particle both left and right

"Quantum bit": 0 *and* 1



Two values/calculations *at the same time* on one single device!



Two quantum bits: 00 *and* 01 *and* 10 *and* 11
(2 x 2 = 4 values/calculations *at the same time*

Ten quantum bits:
2 x 2 ⋯ = 1024 calculations *at the same time*

100 quantum bits: 30-digit number of calculations *at the same time* on one single device

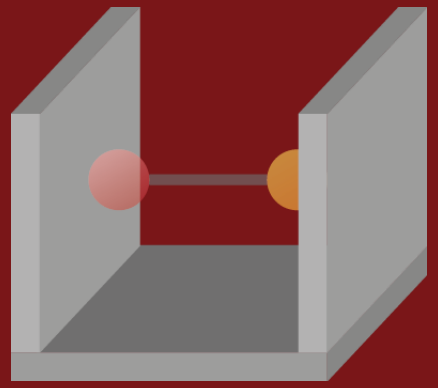
World's largest computer does "only" an 18-digit number of calculations per second

How to use a quantum computer

One-bit operations,

NOT: 0 ↔ 1

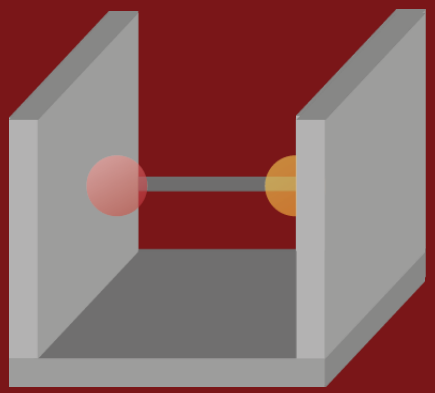
Must work "without looking".



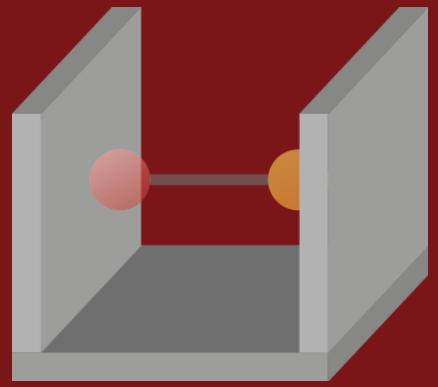
Must preserve "superposition"

Two-bit operations,

C-NOT:

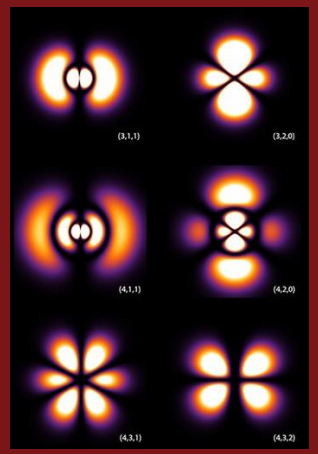


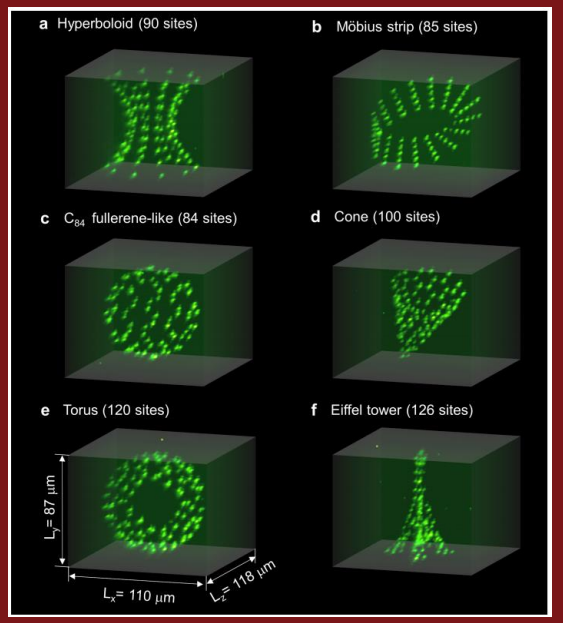
"Control": 0 and 1



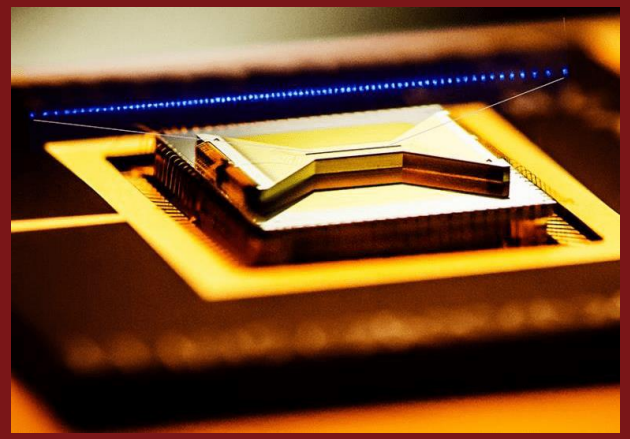
"Target": ?

Quantum computing with trapped atoms and light





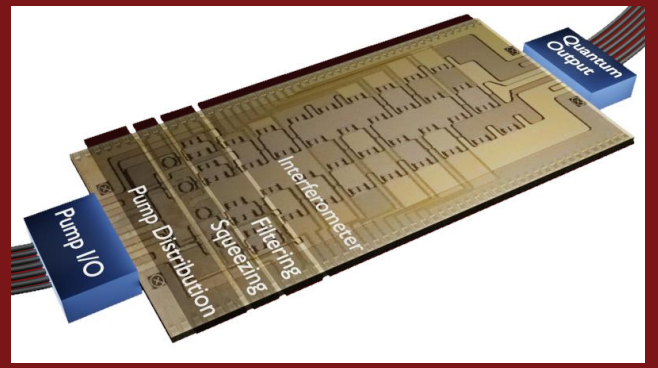
Annealing,
optimization on graphs,
chemistry
(Paris Sud / Pasqual)



Simulations
Chaos and
scrambling
(Duke / IonQ)

Trapped atomic ions
best gates (99.98%),

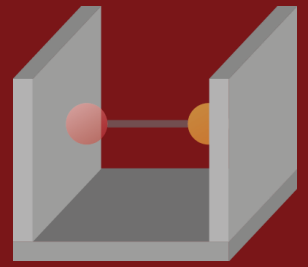
Neutral atoms



Sampling,
machine
learning
(Xanadu)

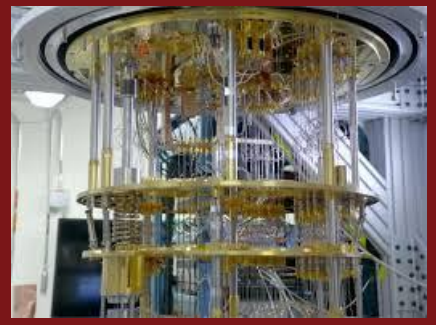
Photons

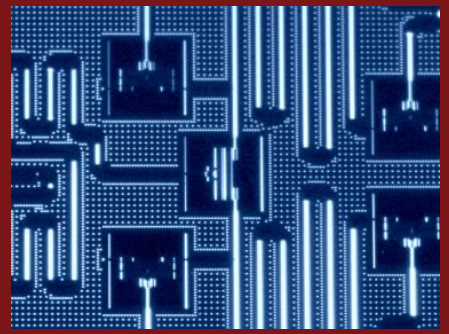
Quantum-elektronic circuits



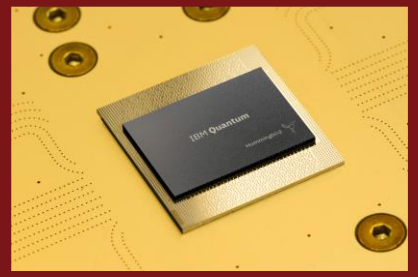
Elektronics, where currents are quantized and run in different directions at the same time.

→ Superconductors
→ Temperature: 1/100 degree above ‘absolute zero’, i.e., minus 273,15 °C

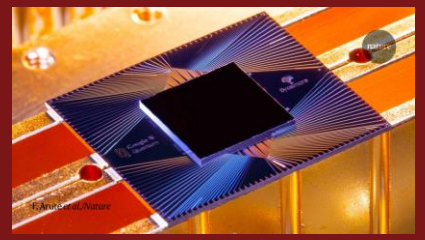




IBM, Google, QuaFu, Baidu, Intel,
D-Wave, Microsoft,
Chalmers, Helsinki, Delft, ETH, Tokyo...



IBM Hummingbird

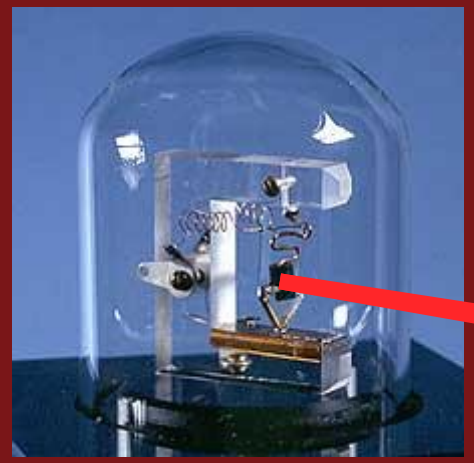


Google Sycamore

Other ”chip-based” approaches with
spin ”impurities” in solids:
Copenhagen, Sydney, Delft, Basel, Princeton, London

From research to useful applications

One person's computer is another person's sensor:
Atoms and circuits are (also) clocks, accelerometers, radio receivers, microphones,
→ Navigation
→ Trace element analysis
→ Diagnostics (medicine)



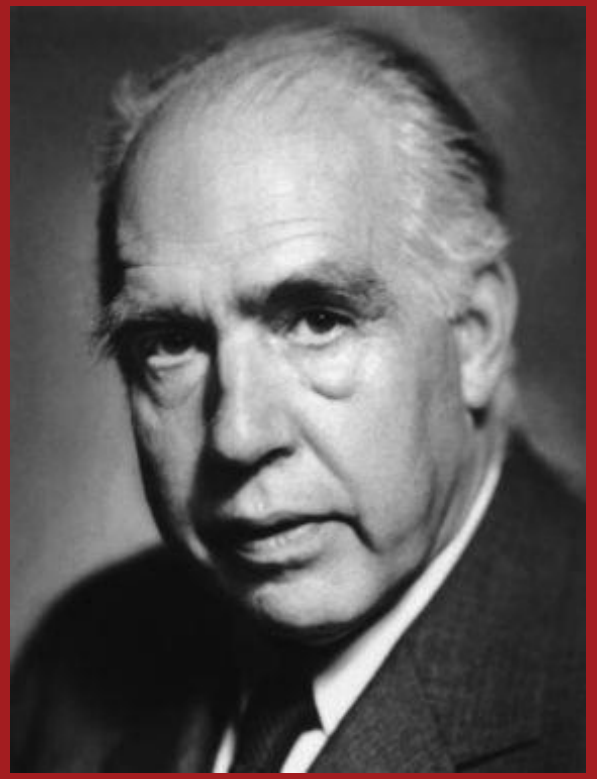
The first transistor (1947)

First commercial application of (a single) transistor

Hearing aids !

Billions of transistors per chip

”If we should one day wake up and realize it was all just a dream, we would still have learned something. ”



Why not learn it during an M.Sc. study with NBIA/NBI ?