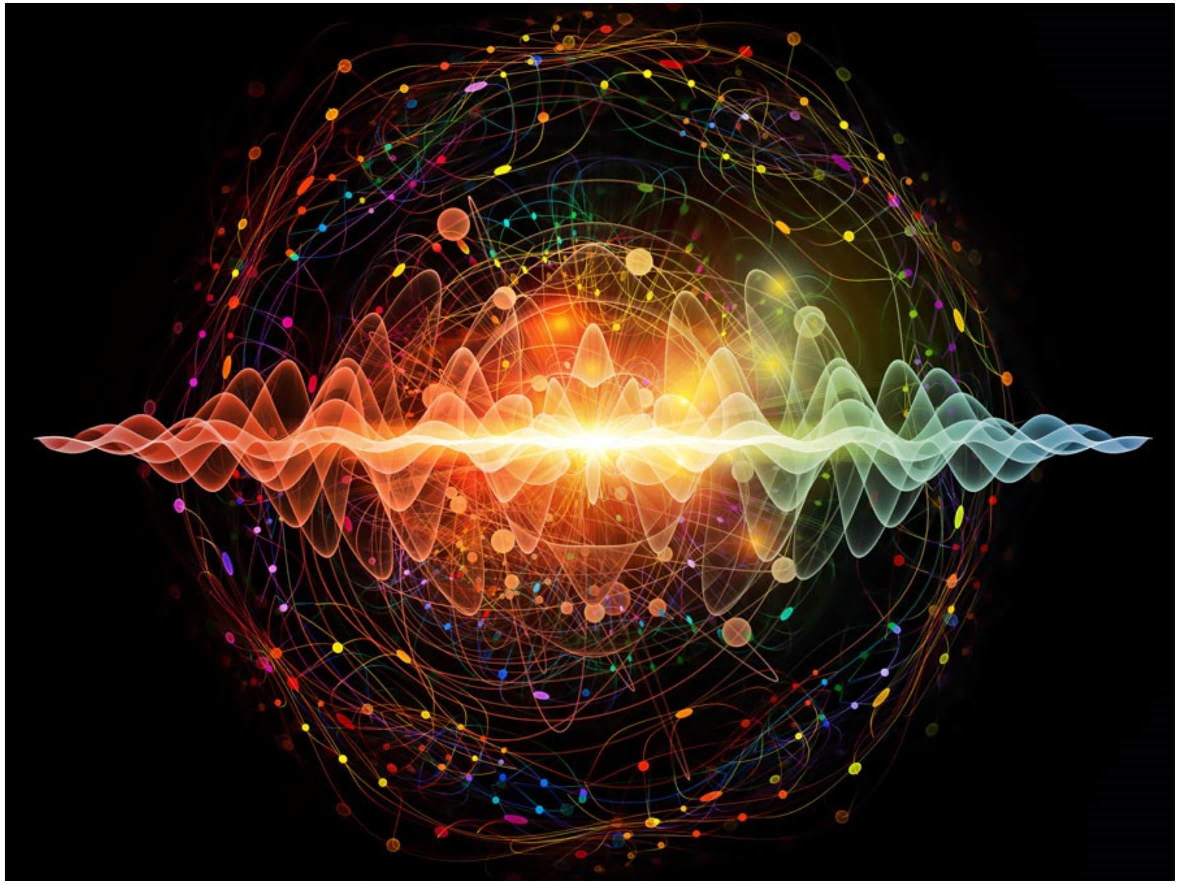
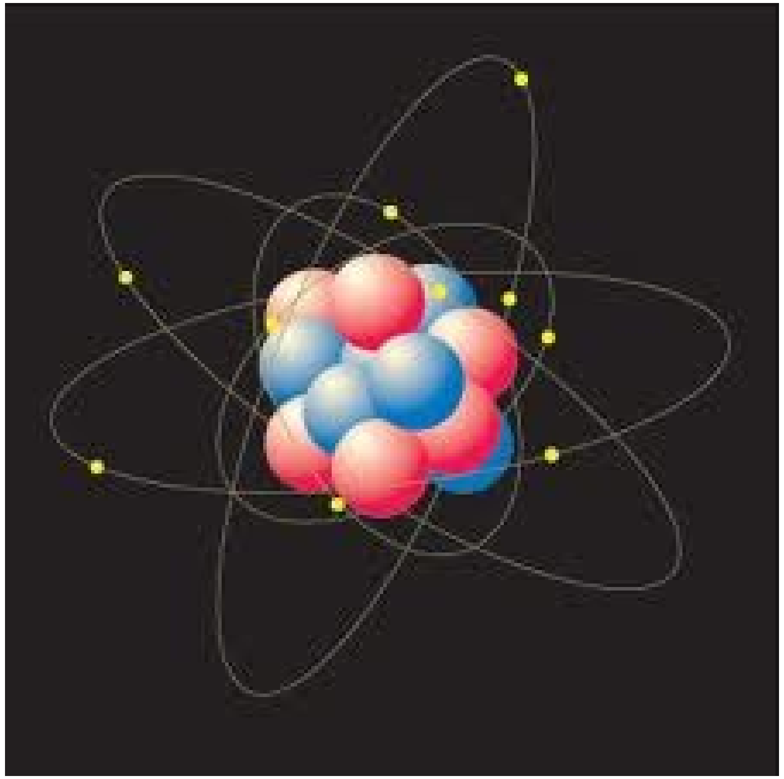
1. Overview



Quantum physics

Theory of nature at small scales and low energies for atoms, light, electrons, … , anything small.

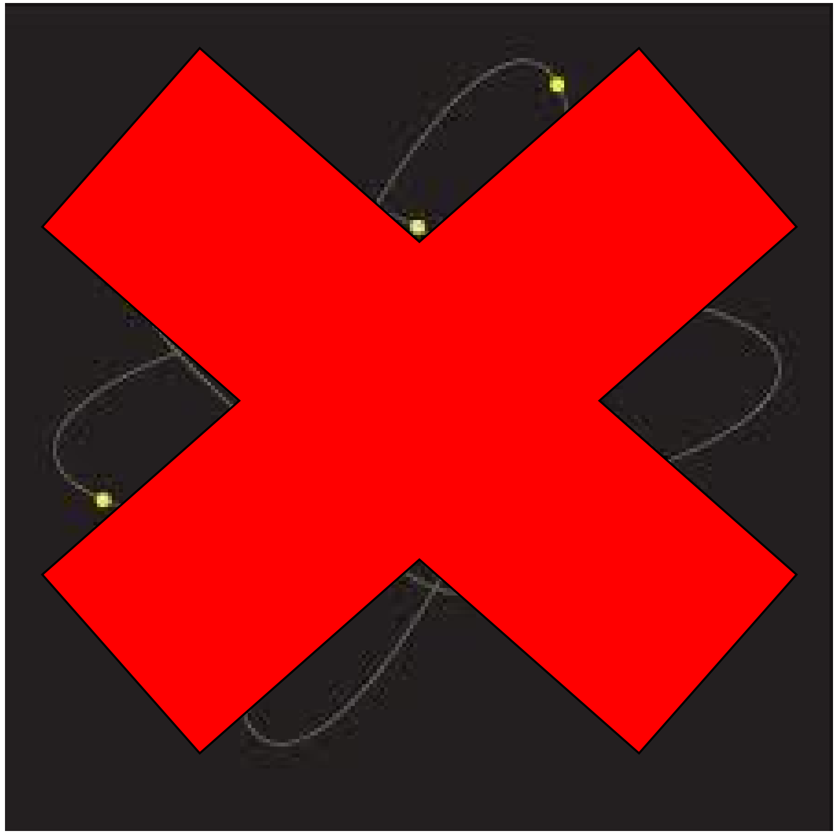


Most precisely tested theory in the history of science!

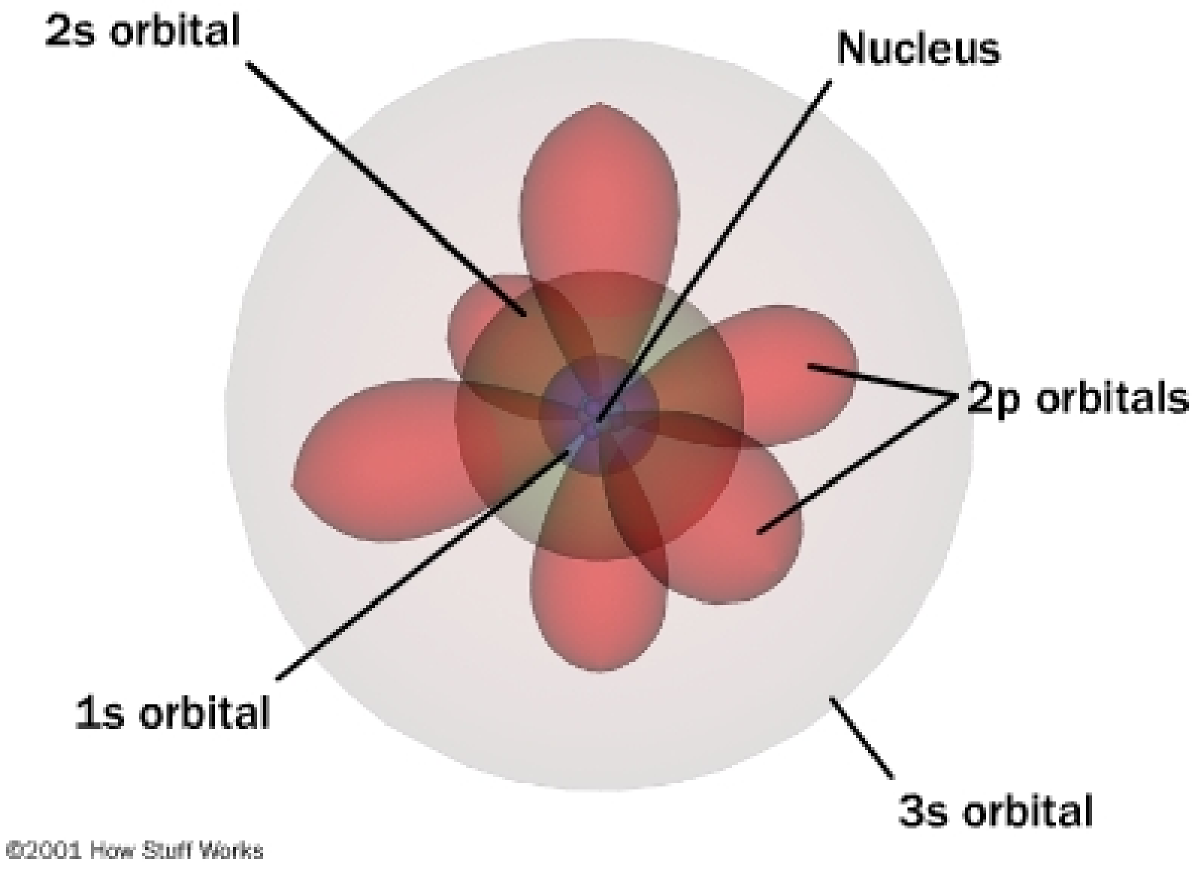
Yet still has several puzzling aspects which still confound modern day physicists and philosophers.

Quantum physics

Actually this picture of the atom is wrong – it is classical!



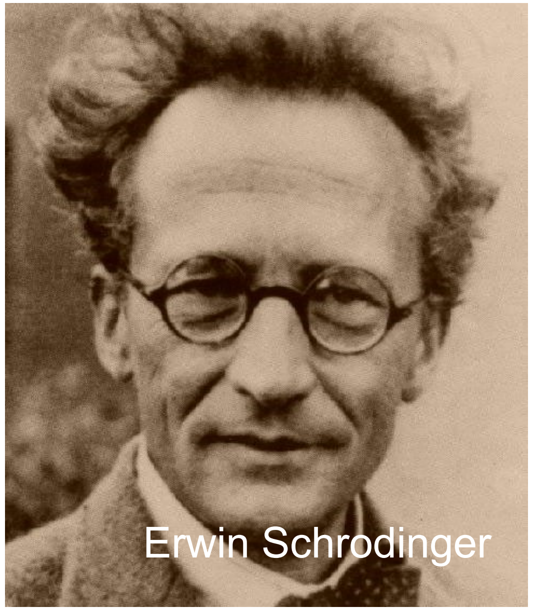
Quantum physics

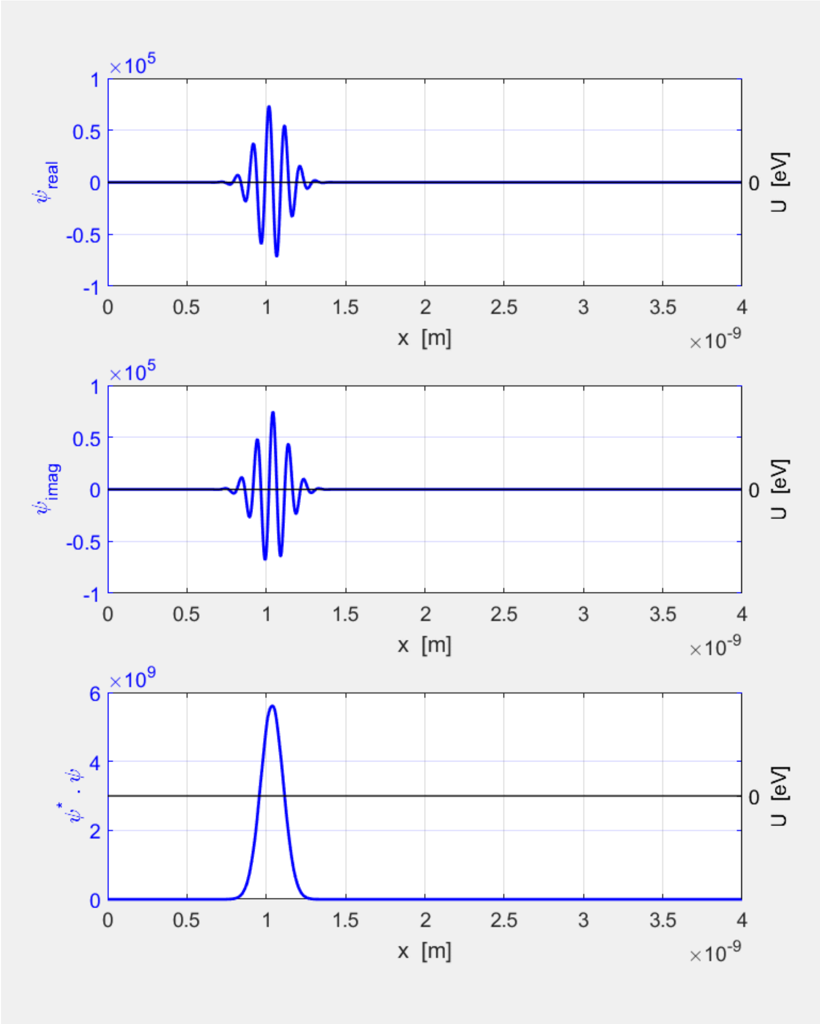


Objects are not particles!

Everything is actually a wave!

Schrodinger wrote down an equation that tells us how the waves change in time





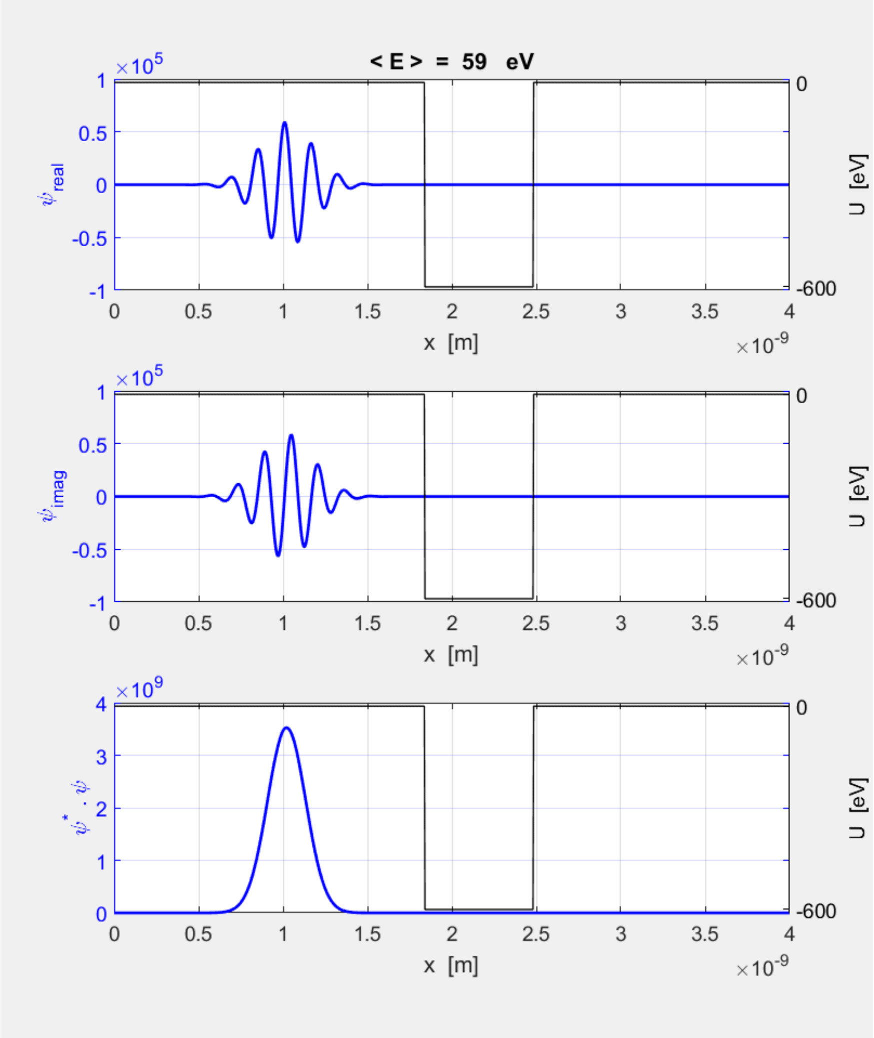
$$\boxed{i\hbar \frac{\partial}{\partial t}\Psi(x,t) = \left(-\frac{\hbar^2}{2m}\frac{d^2}{dx^2} + V(x,t)\right)\Psi(x,t)}$$

Schrodinger's equation

An object smashing into a wall

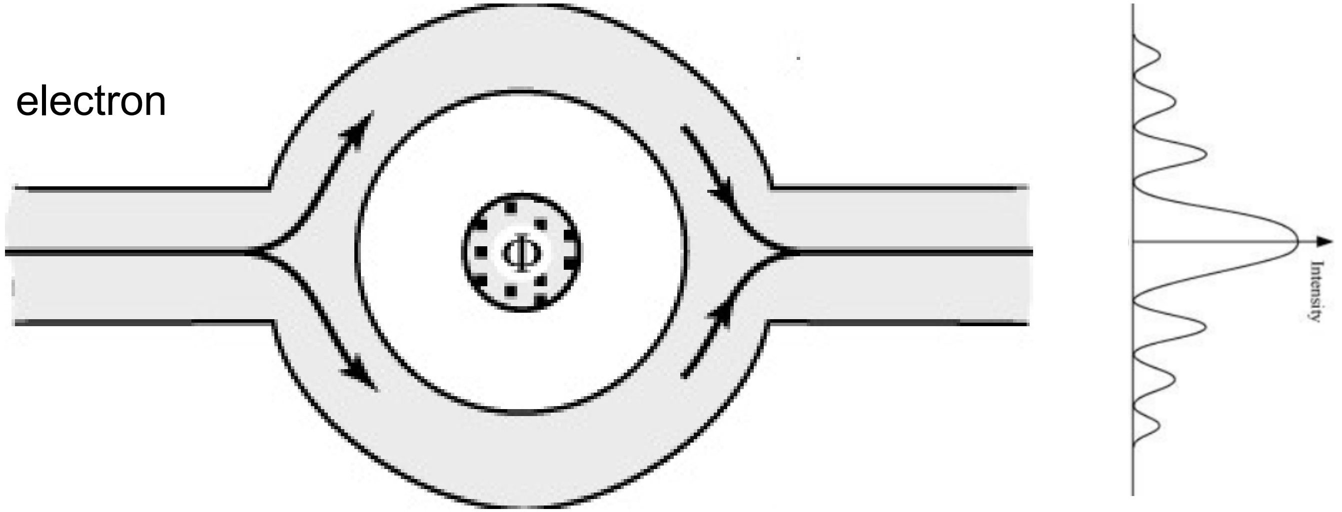
Classical physics

Quantum physics

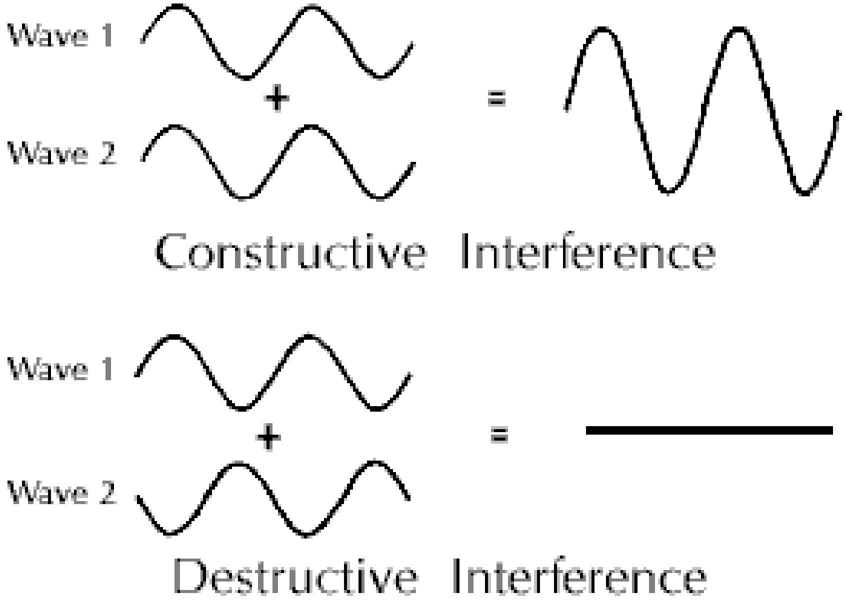


Where is the shark? Where is the wave?

Particles can be in two places at once

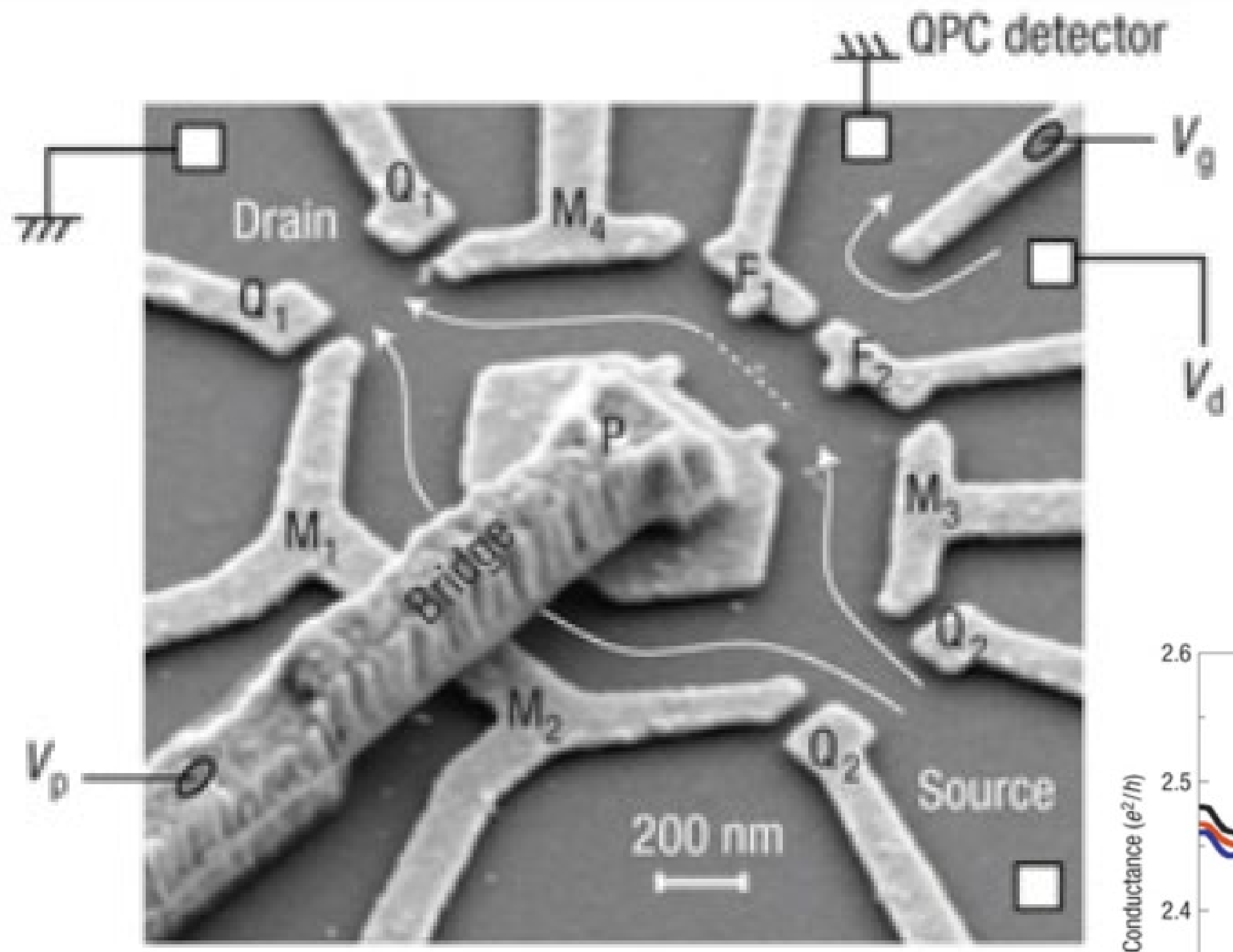


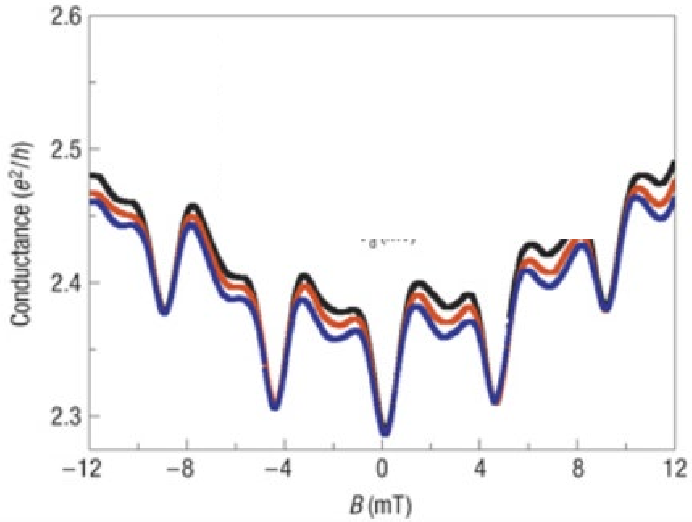
Interference by changing the arm lengths or threading magnetic field through the ring



The electron interferes with ITSELF. It is in two places at once!

Electron interference in real life (lab)

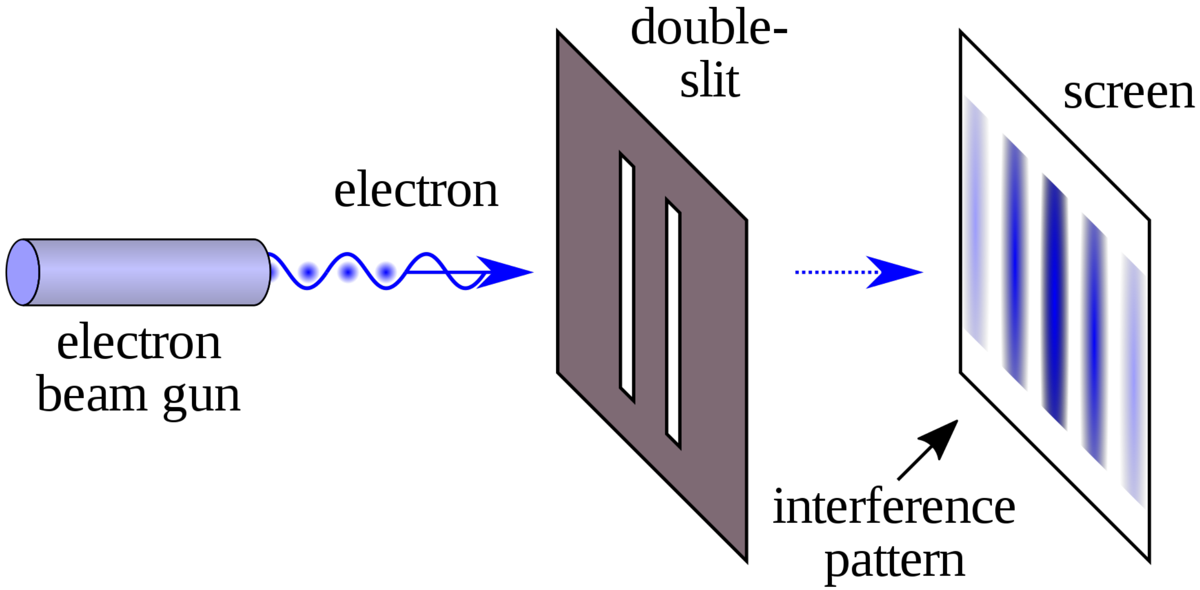


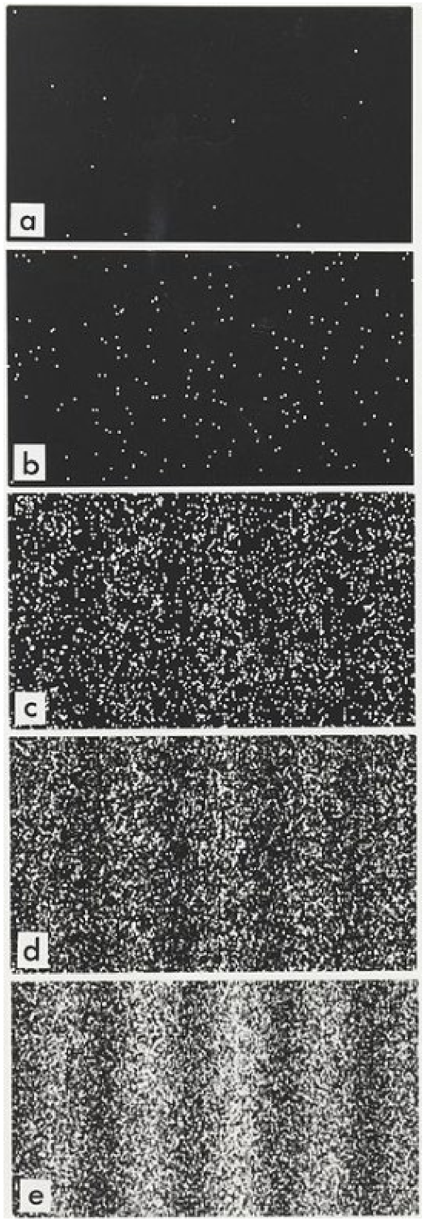


Chang Nature Physics 4, 205 (2008)

But it’s a particle too!

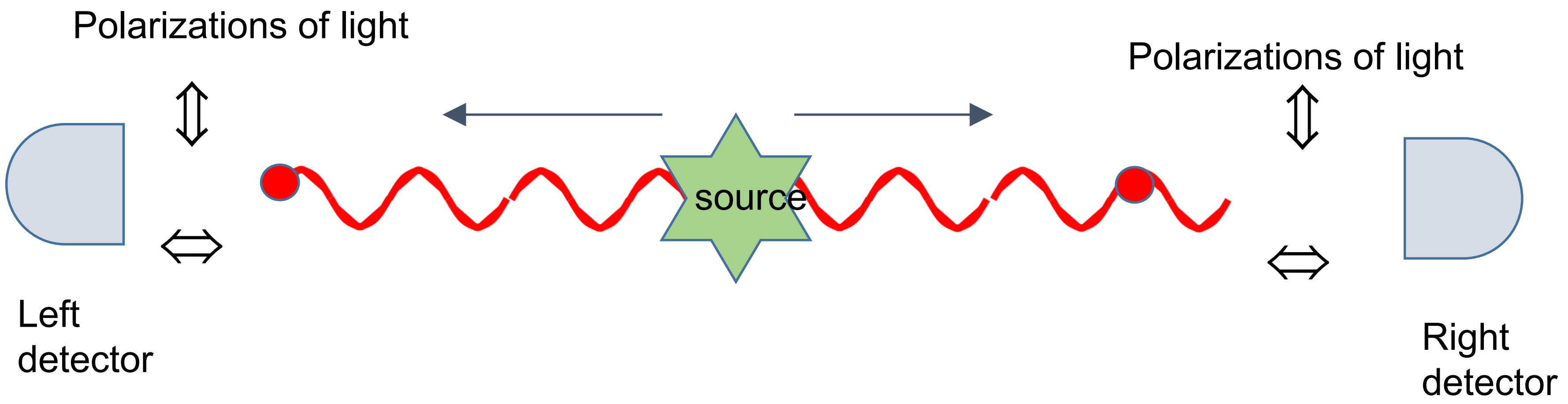
Electrons create an interference pattern so its definitely a wave, but electrons arrive one by one.



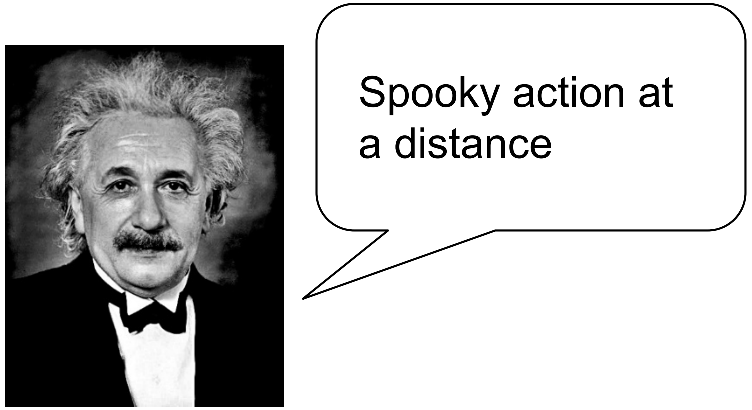


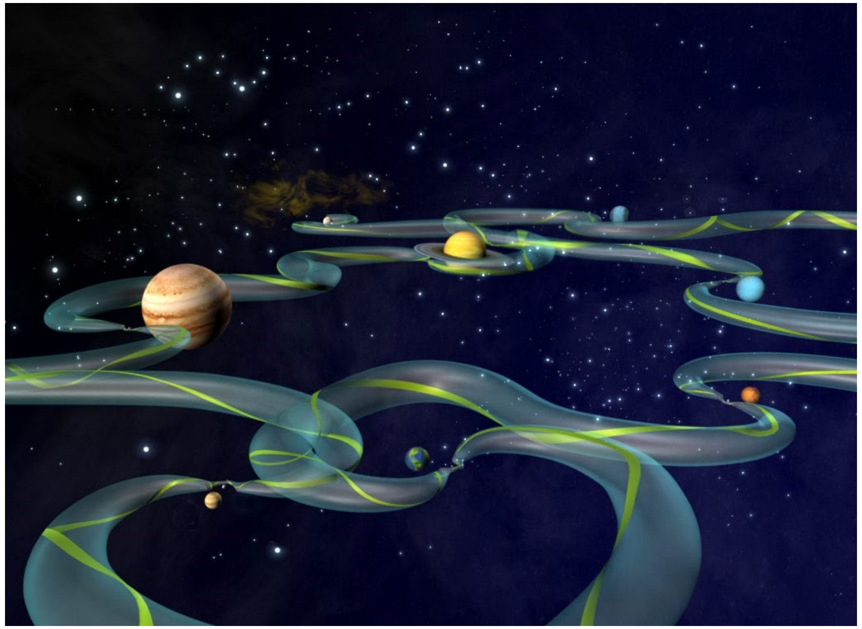
Wave-particle duality: Everything is a wave and a particle at the same time!

Other quantum weirdness: Entanglement

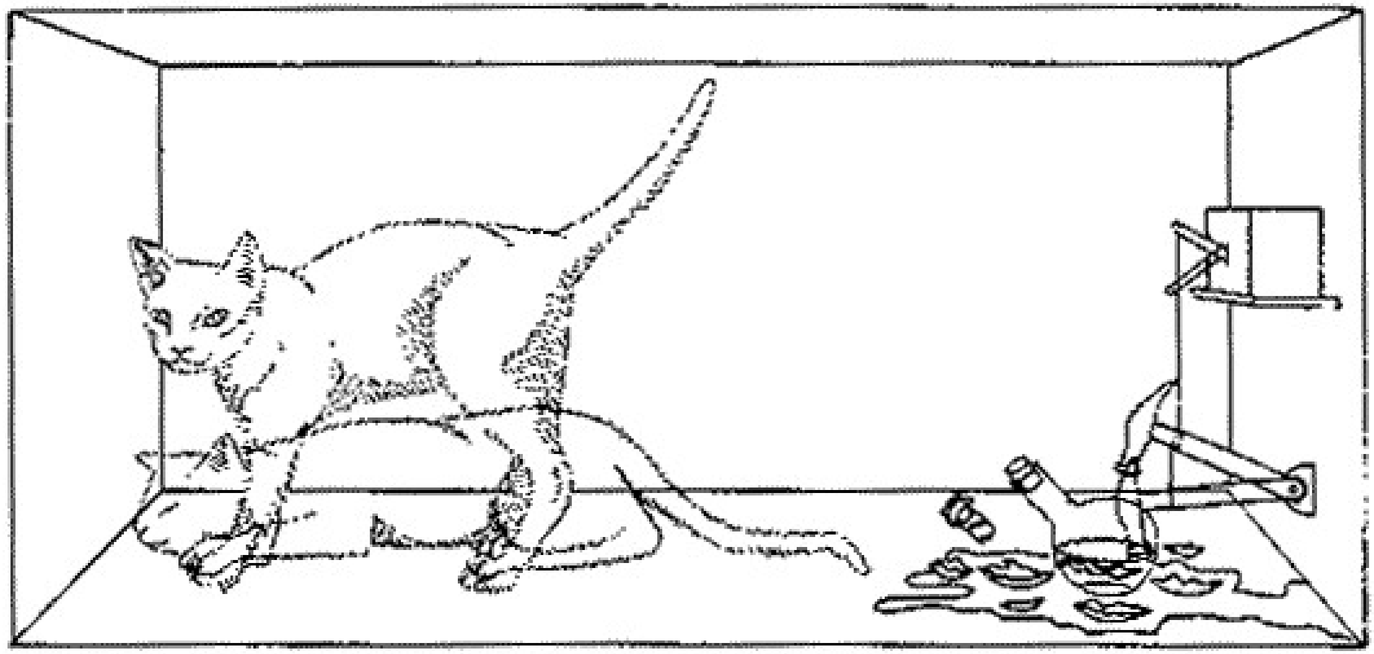


Left and right detectors always give the same result, although randomly.



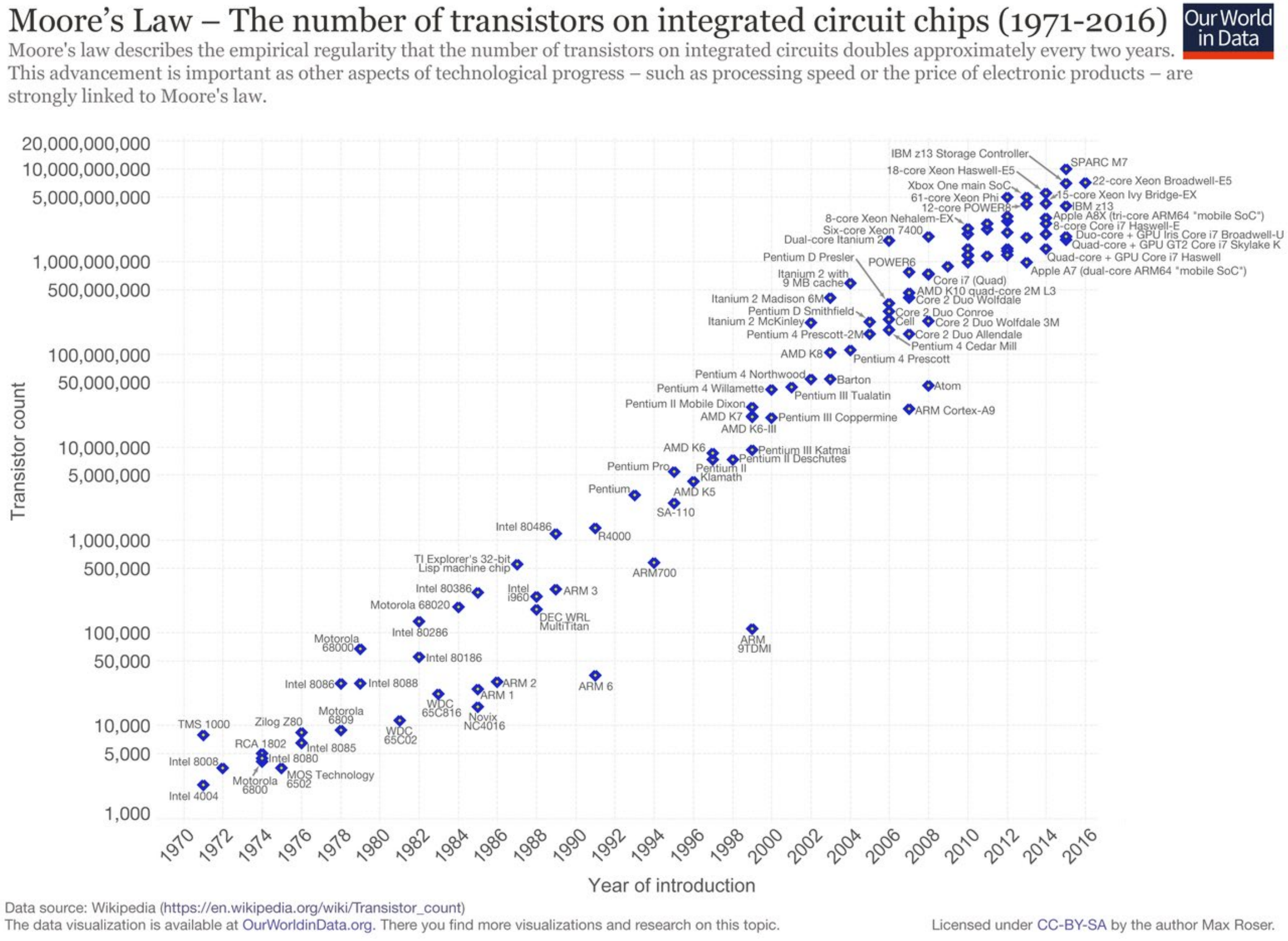


Quantum paradoxes: Schrodinger's cat



A cat is penned up in a steel chamber, along with the following device. In a Geiger counter, there is a tiny bit of radioactive substance, so small, that perhaps in the course of the hour one of the atoms decays, but also, with equal probability, perhaps none; if it happens, the counter tube discharges and through a relay releases a hammer that shatters a small flask of hydrocyanic acid. If one has left this entire system to itself for an hour, one would say that the cat still lives if meanwhile no atom has decayed. The first atomic decay would have poisoned it. The [quantum state] of the entire system would express this by having in it the living and dead cat smeared out in equal parts.

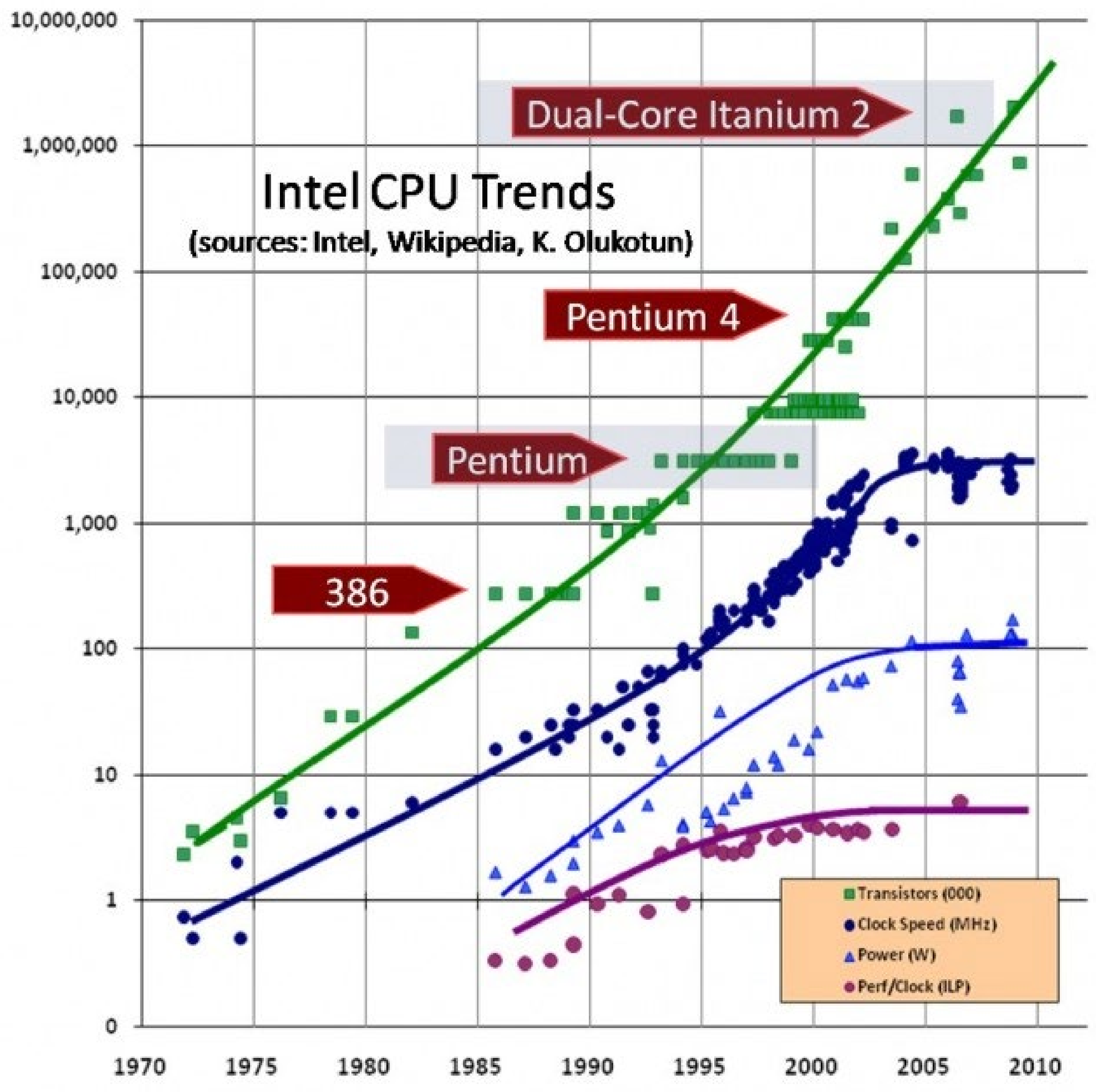
End of Moore’s Law is upon us



Moore’s law: Number of transistors double every 18-24 months

Bob Colwell, former Chief architect Intel: “For planning horizons, I pick 2020 as the earliest date we could call [Moore's law] dead,” (August 2013)

Jason Huang Nvidia CEO “Moore's Law isn't possible anymore.“ (Jan 2019)

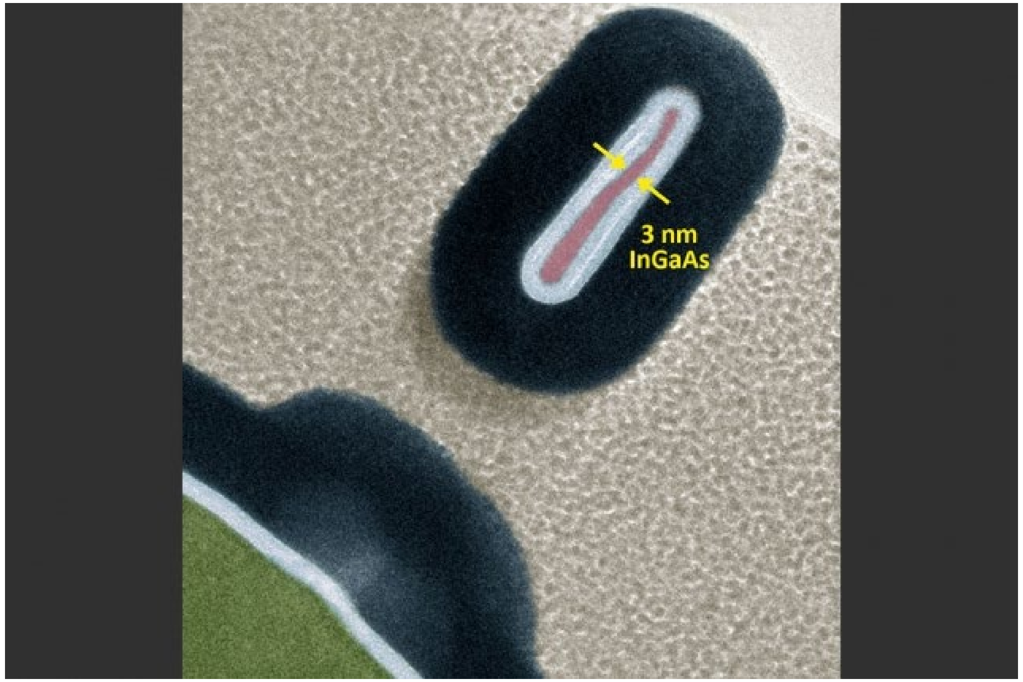


Dennard scaling: Power density stays constant per unit area as transistors get smaller

i.e. reduction in a transistor's linear size by 2, the power it used fell by 4

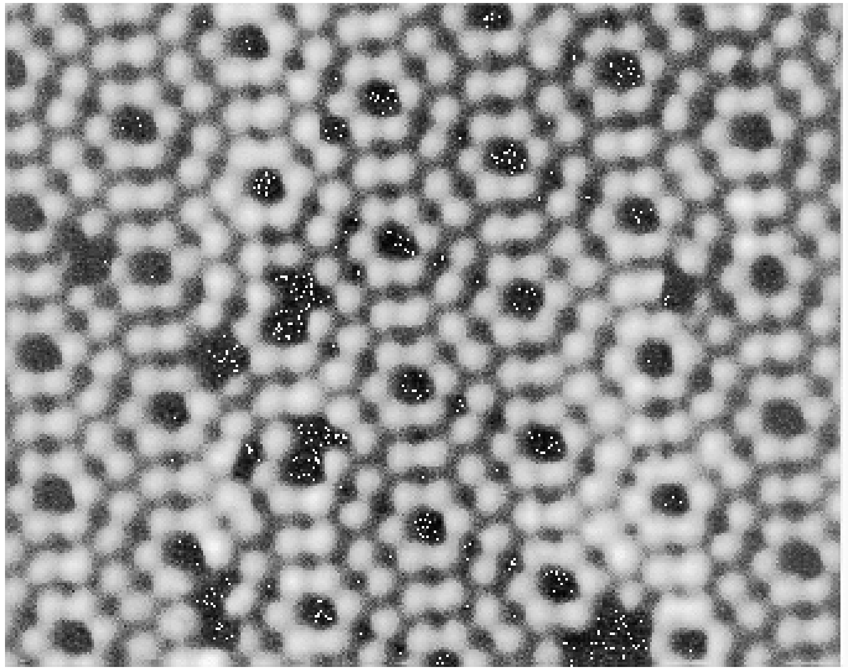
Dennard scaling finished in 2005

What are the barriers?



MIT, Dec 2018

http://news.mit.edu/2018/smallest-3-d-transistor-1207



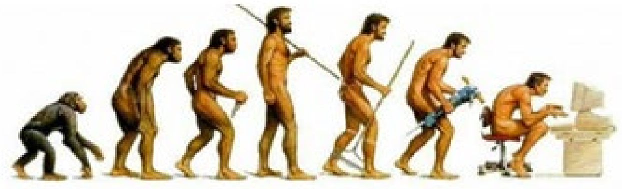
Si atom diameter = 0.42 nm
Ga,As atom diameter=0.36nm

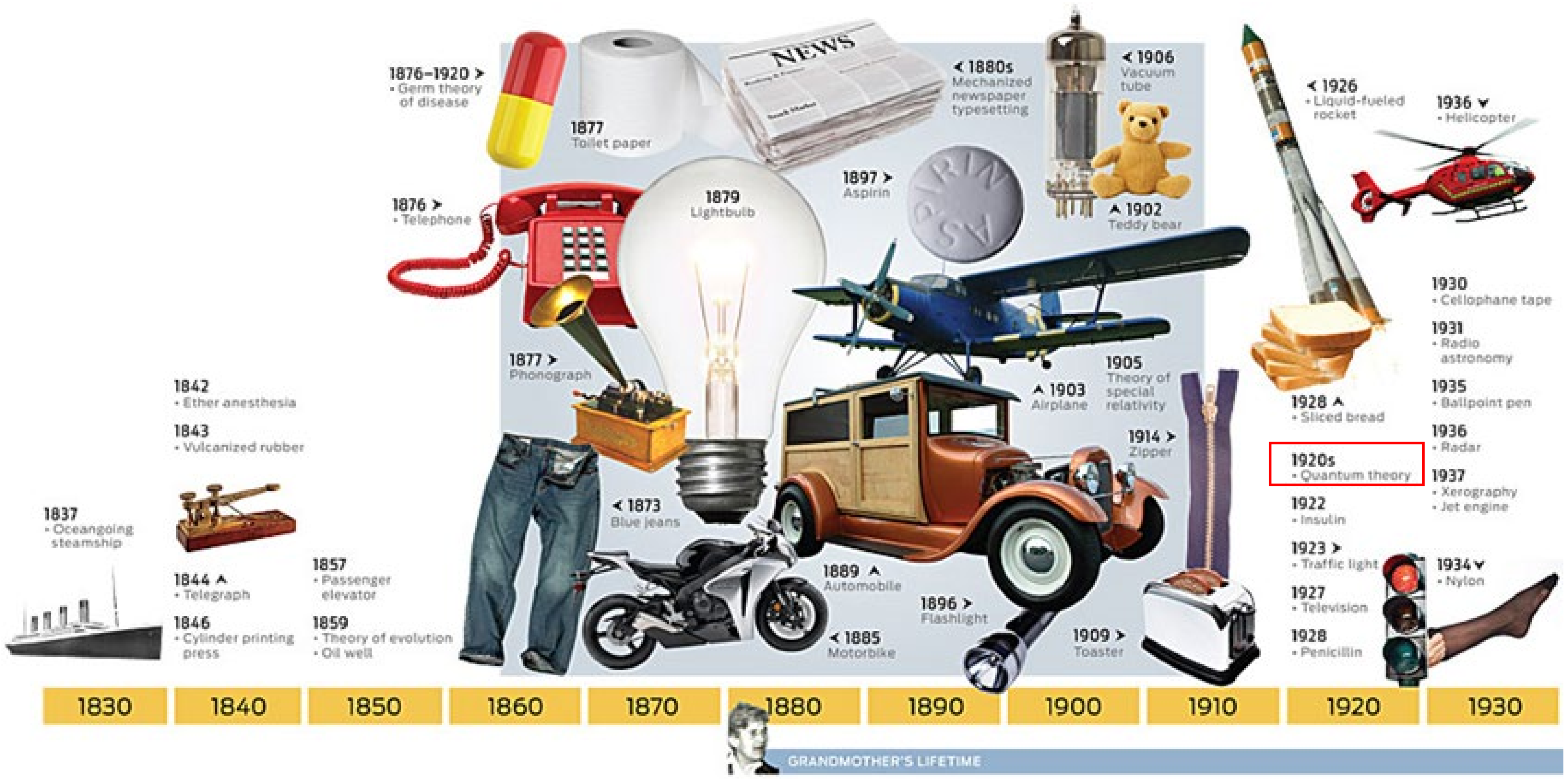
New technology required to get to smaller scales to overcome quantum tunneling effects.
Quantum effects also cause heating

Quantum technologies and the future

We have seen remarkable progress in technology in the last 200 years

Particularly computers have revolutionized the complexity of technologies through information processing

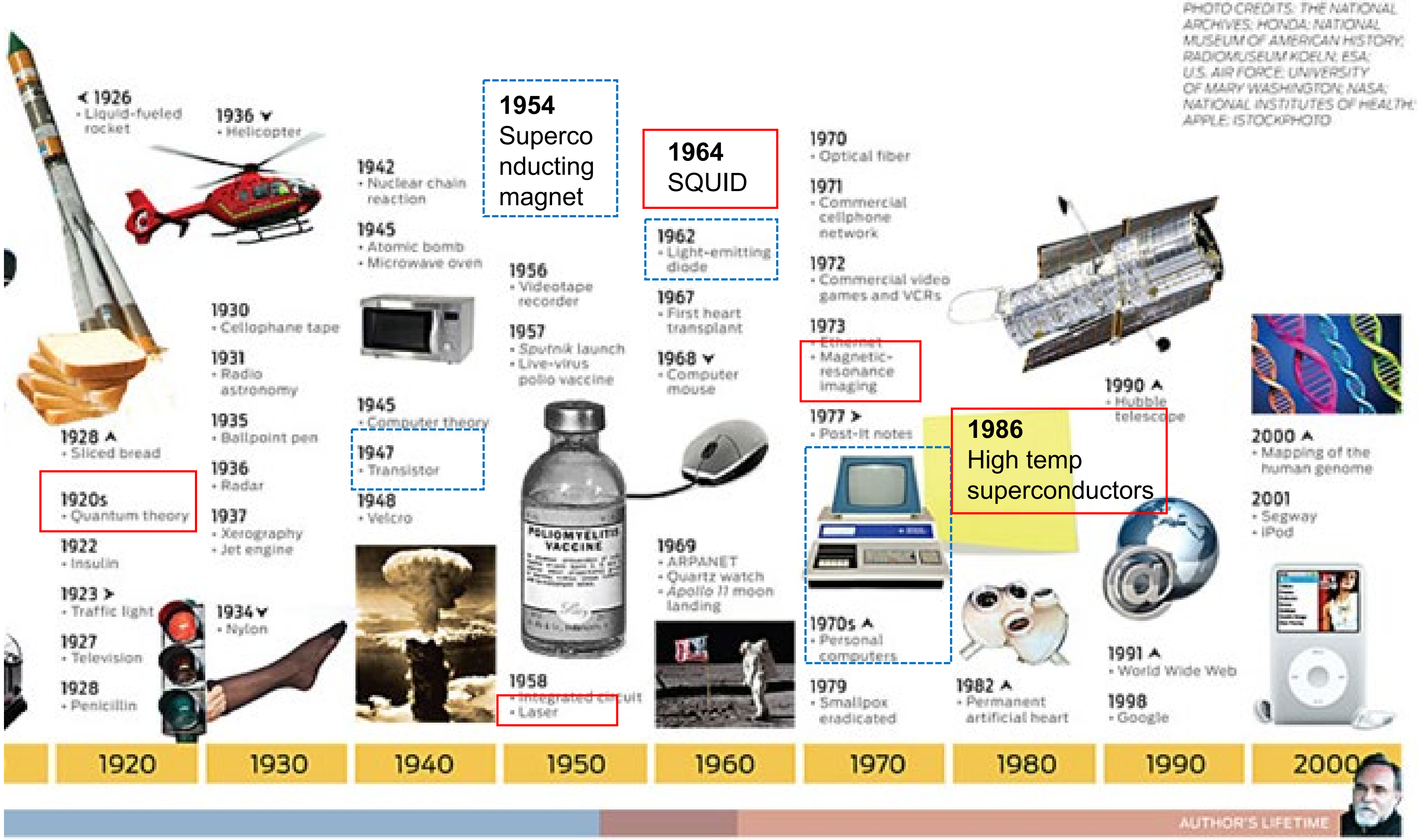




Inventions post-quantum theory

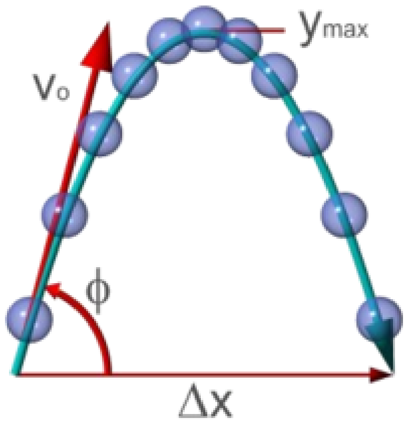
Fully quantum

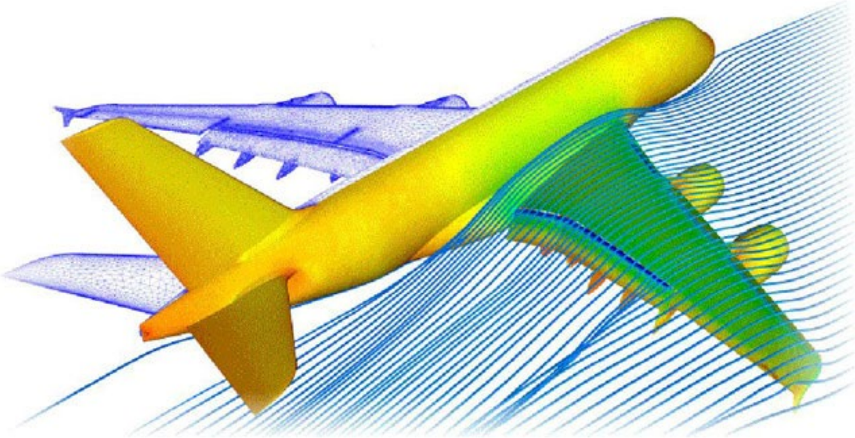
Indirectly quantum

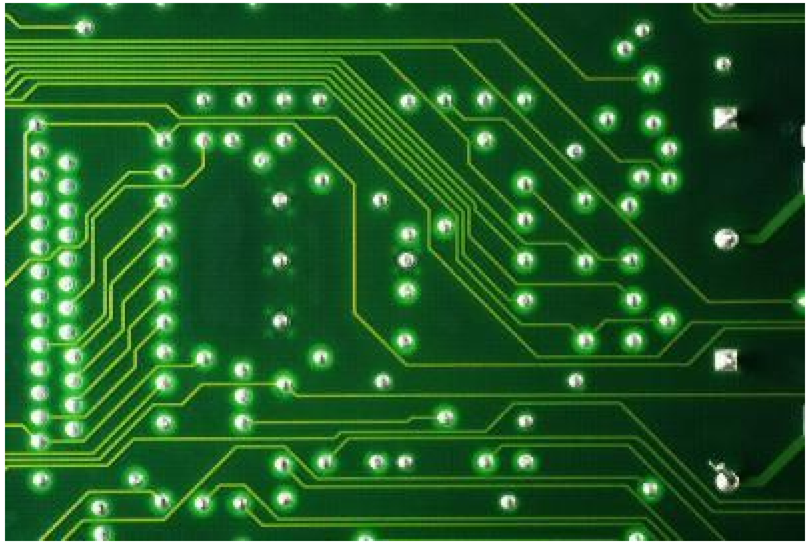


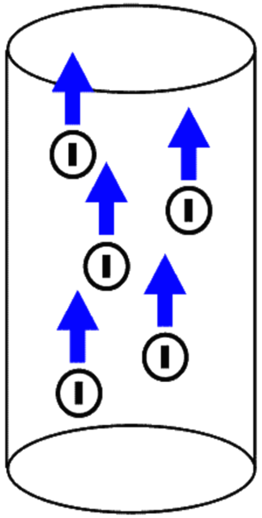
Classical Physics

While there have been several "quantum" based inventions, most are still based on classical physics

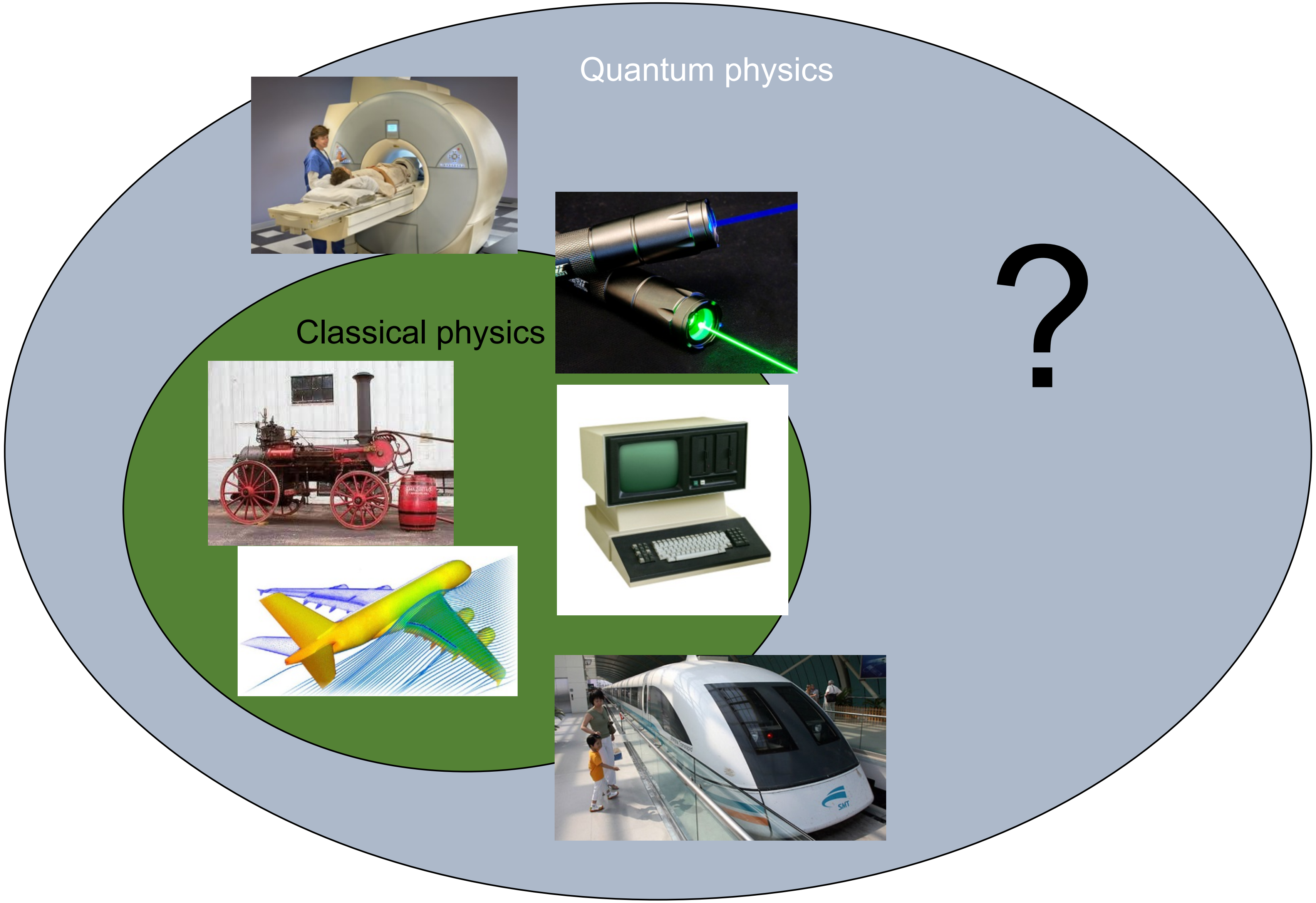






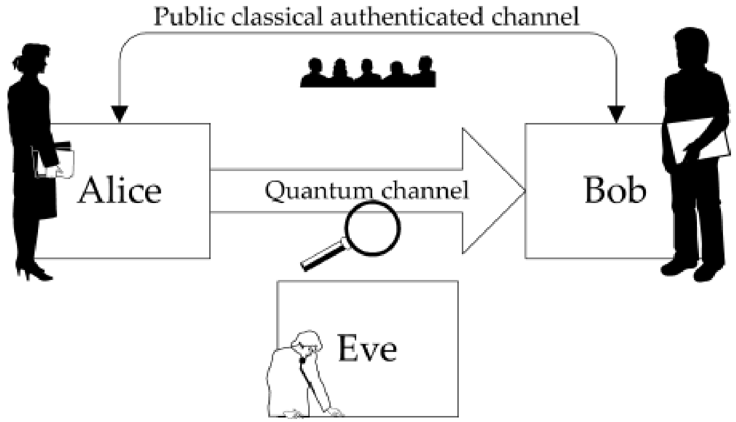


Quantum information technology



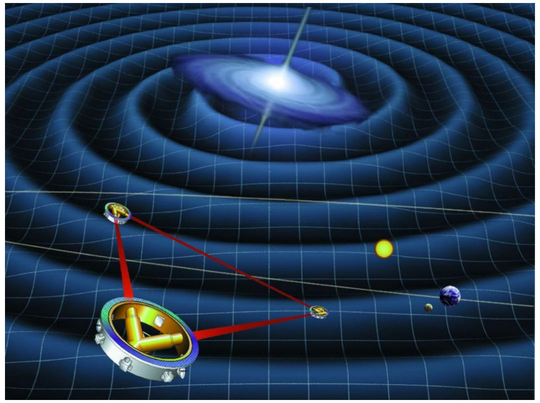
Types of quantum technologies

Quantum key distribution



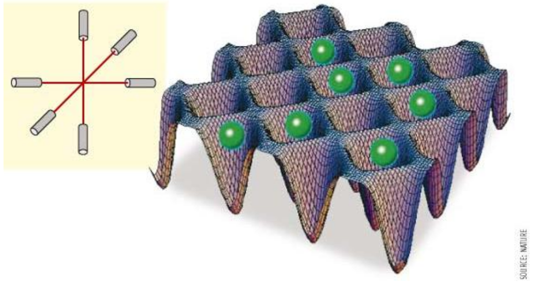
Secure transmission of information

Quantum metrology



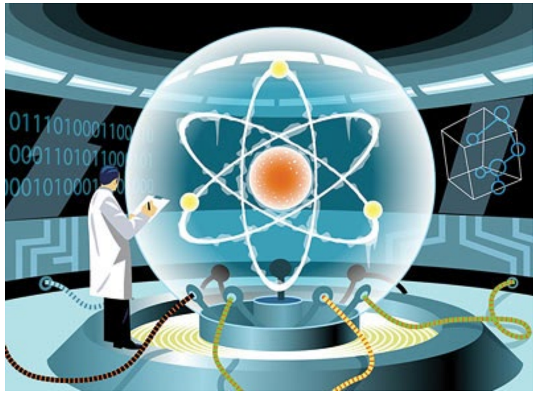
Precision measurements

Quantum simulators



Simulation of complex materials

Quantum computers



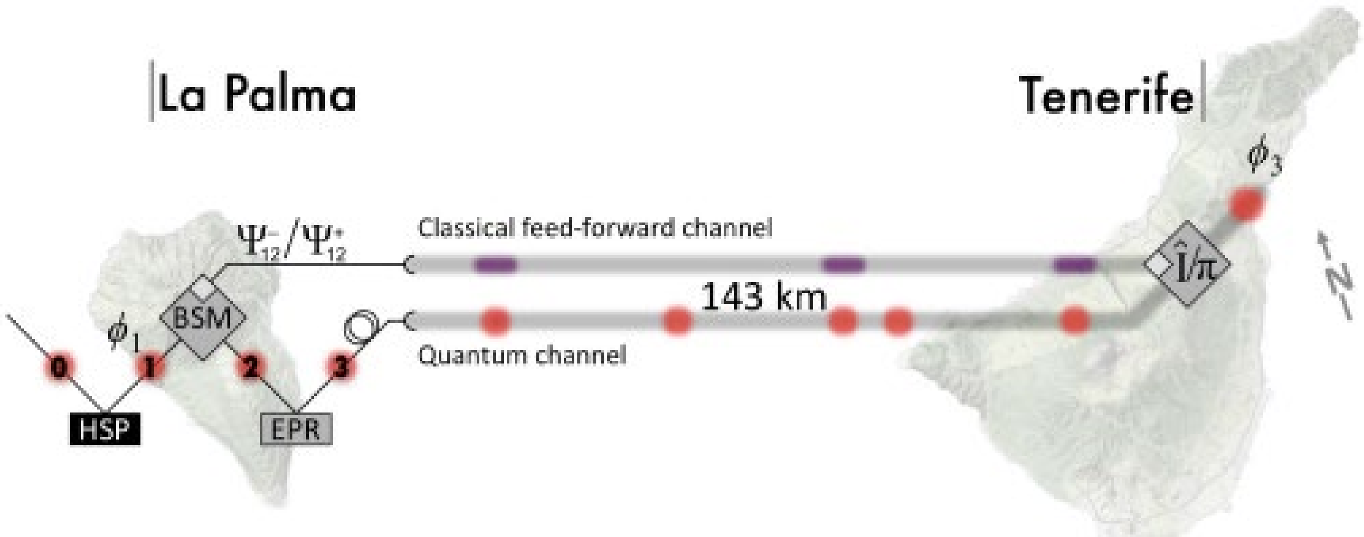
Beyond classical computer algorithms

Long distance quantum communication

Commercial QKD companies: ID Quantique, MagiQ Technologies, QuintessenceLabs, and SeQureNet

Quantum networks: DARPA (MA, USA), SECOQC (Vienna), SwissQuantum, Tokyo QKD, China

Major limitation: Optical fibers can only transmit photons for about 200km



X. Ma, A. Zeilinger. et al. (2012). *Nature* **489** (7415): 269

Quantum communication in China

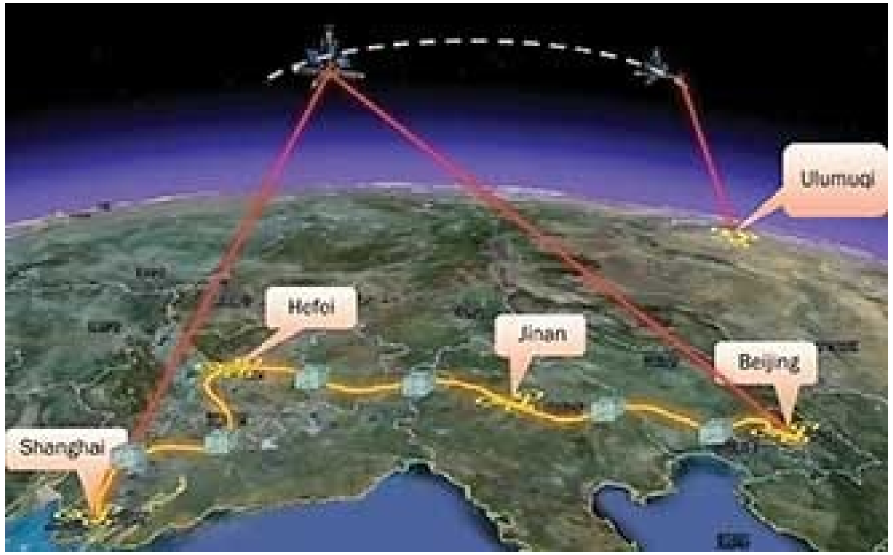
Satellite-based entanglement distribution over 1200 kilometers

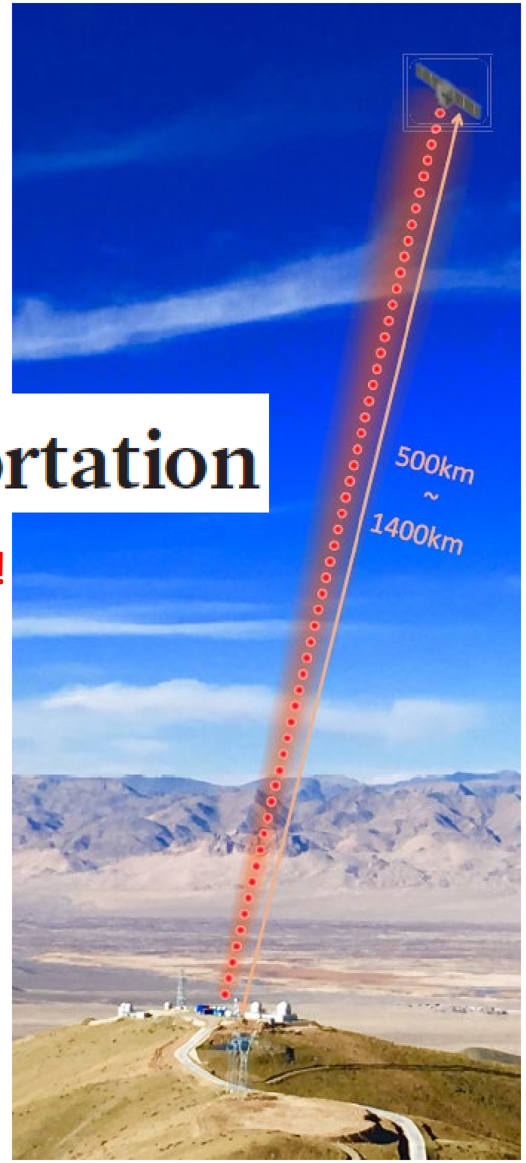
Yin et al., Science 356, 1140 (2017)

Ground-to-satellite quantum teleportation

Ren et al., Nature (2017)

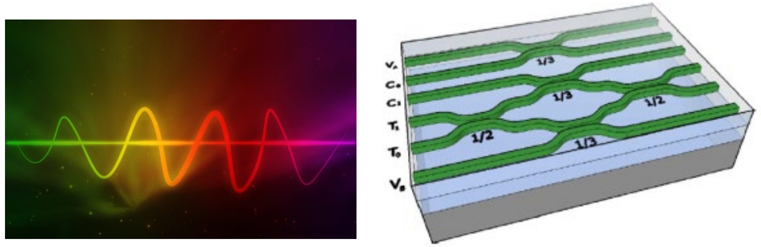
Teleportation up to 1400 km!!!



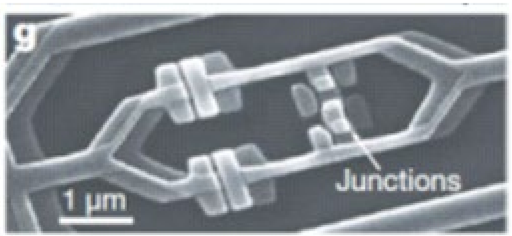


Current key quantum technologies: quantum computing

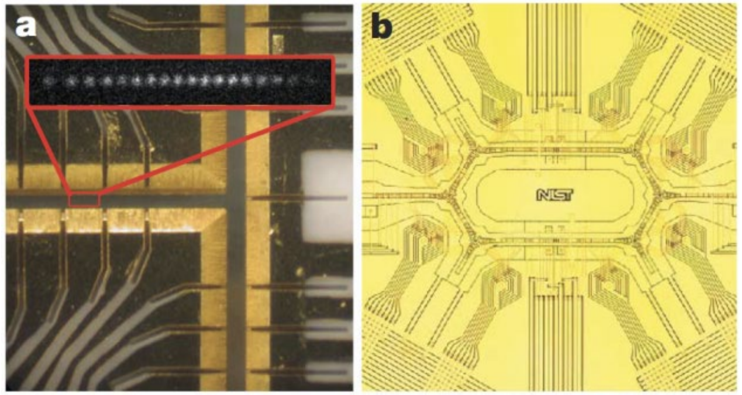
Optics



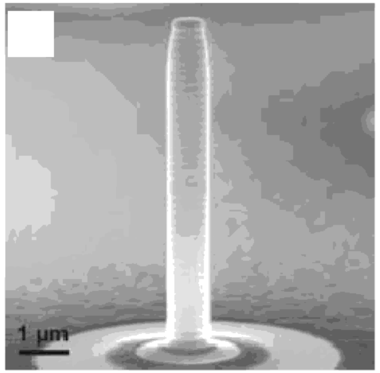
Superconducting qubits



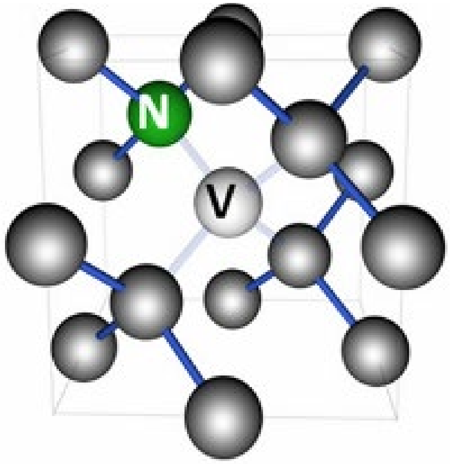
Ion traps



Quantum dots (semiconductors)

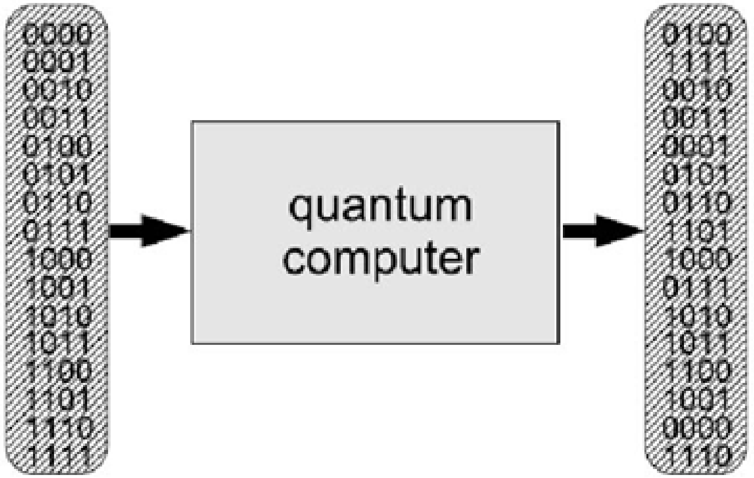


N-V centers (diamond)



Why is a quantum computer faster?

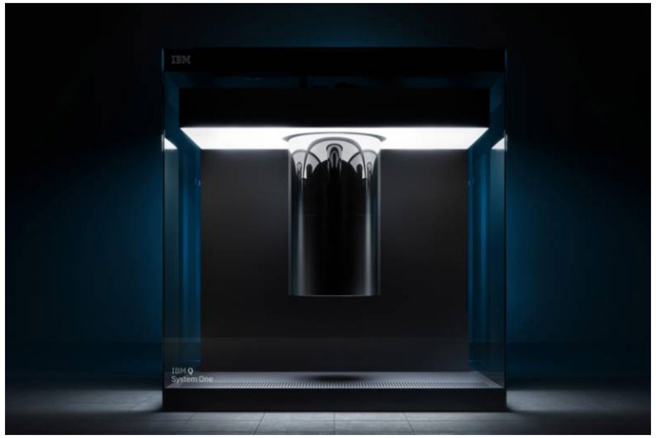
Linear computation



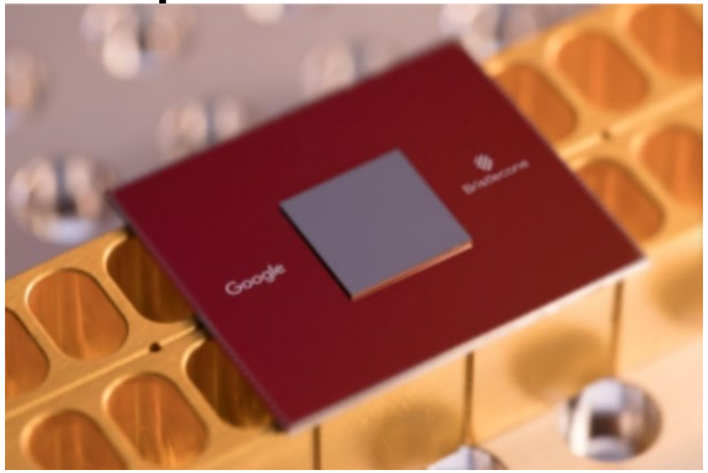
Parallel computation

A quantum computer can process many different inputs all at the same time

Quantum computers for sale!

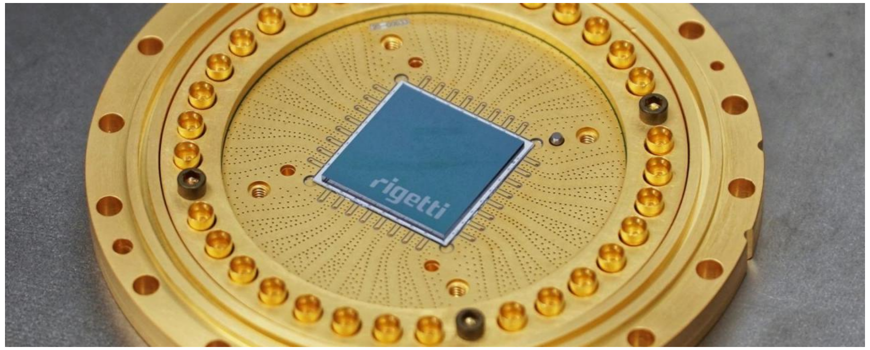


IBM: 50 superconducting qubits



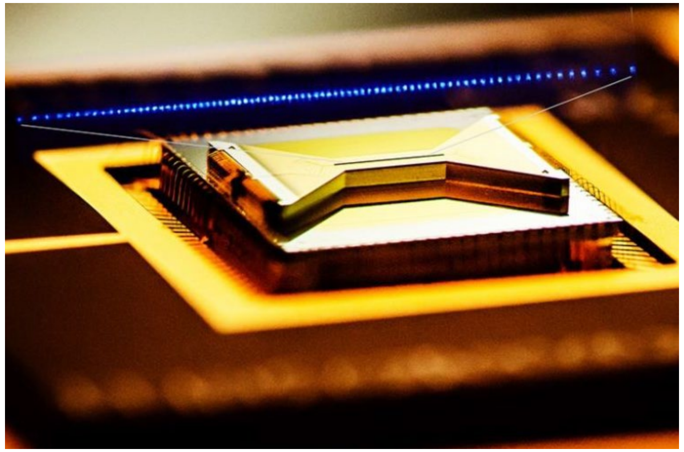
Google: 72 superconducting qubits

Microsoft: Topological qubits in nanowires



Rigetti: 128 superconducting qubit QC in development

D-wave: 2000 superconducting qubit quantum annealing machine



IonQ: Ion trap quantum computer

Aims of this course

- Starting from basic knowledge of calculus and vectors, have a working knowledge of what quantum theory is about and be able to calculate simple quantities.

- Become familiar with the basic aspects of quantum technologies, at a quantitative level.